Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications

Catalog of Responses

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Resumes and materials marked as copyrighted have been omitted.

Proposed Action

DOE's Proposed Action is to develop guidance that can be used in making decisions to support the State of Hawaii in achieving the HCEI's goals.

For the Hawaii Clean Energy Draft PEIS, DOE and the State of Hawaii identified 31 clean energy technologies and activities associated with potential future actions and grouped them into five clean energy categories:

- Energy efficiency,
- Distributed renewable energy technologies,
- Utility-scale renewable energy technologies,
- Alternative transportation fuels and modes, and
- Electrical transmission and distribution.

For each activity or technology, the Draft PEIS identifies potential impacts to 17 environmental resource areas and potential best management practices that could be used to minimize or prevent those potential environmental impacts.

Document Availability

The Hawaii Clean Energy Draft PEIS is posted at *http://hawaiicleanenergypeis.com* and *http://energy.gov/nepa/eis-0459-hawaii-clean-energy-programmatic-environmental-impact-statement.* To obtain a compact disk (CD) of the Draft PEIS, contact Dr. Summerson at the address under **ADDRESSES** above, online at *http://hawaiicleanenergypeis.com,* or by email to *hawaiicleanenergypeis@ee.doe.gov.* Printed copies of the complete PEIS are available at:

- Hawaii State Library, 478 South King Street, Honolulu, HI 96813.
- Lanai Public and School Library, 555 Fraser Ave, Lanai City, HI 96763.
- Wailuku Public Library, 251 High Street, Wailuku, HI 96793.
- Molokai Public Library, 15 Ala Malama, Kaunakakai, HI 96748.
- Hilo Public Library, 300 Waianuenue Ave, Hilo, HI 96720.
- Kailua-Kona Public Library, 75–138 Hualalai Road, Kailua-Kona, HI 96740.
- Lihue Public Library, 4344 Hardy Street, Lihue, HI 96766.
- Kaneohe Public Library, 45–829 Kamehameha Highway, Kaneohe, HI 96744.

DOE will provide a printed copy of the Summary or complete Draft PEIS upon request. However, due to the size of the document (approximately 60 pages for the Summary and 1,300 pages for the complete Draft PEIS), DOE recommends that interested parties take advantage of the download or CD options. If a printed copy is required, contact Dr. Jane Summerson at the address above or by email to *hawaiicleanenergypeis@ee.doe.gov*.

Public Hearings

The Department invites interested parties to provide comments on the Draft PEIS at public hearings to be held May 12 through May 22, 2014, at:

- May 12: Kauai, Kauai War Memorial, Convention Hall, 4191 Hardy Street, Lihue, HI 96766.
- May 13: Hawaii, Kealakehe High School, 74–5000 Puohulihuli Street, Kailua-Kona, HI 96740.
- May 14: Hawaii, Aunty Sally Kaleohano's Luau Hale, 799 Piilani Street, Hilo, HI 96720.
- May 15: Maui, Pomaikai Elementary School, 4650 South Kamehameha Avenue, Kahului, HI 96732.
- May 19: Molokai, Kaunakakai Elementary School, 30 Ailoa Street, Kaunakakai, HI 96748.
- May 20: Lanai, Lanai High & Elementary School, 555 Fraser Avenue, Lanai City, HI 96763.
- May 21: Oahu, Kawananakoa Middle School, 49 Funchal Street, Honolulu, HI 96813.
- May 22: Oahu, James B. Castle High School, 45–386 Kaneohe Bay Drive, Kaneohe, HI 96744.

Each hearing will begin at 5:00 p.m. and end at 8:30 p.m. Each hearing will start with an open house (5:00–5:45), when Federal and State personnel and their contractors will be available to answer questions in an informal setting. The open house will be followed by a presentation (5:45–6:00) by Dr. Summerson, who will describe the PEIS, the NEPA process, and the methods that can be used to submit comments. During the remainder of the hearing, interested parties may present oral comments to DOE. A court reporter will transcribe the comments presented at each hearing. Individuals wishing to speak at a hearing should register when they arrive. DOE will initially allot three minutes to each commenter to ensure that as many people as possible have the opportunity to speak. More time may be provided, as circumstances permit. Written comments may be submitted at the hearing or by the other methods described in **ADDRESSES** above. DOE will give equal consideration to oral and written comments in preparing the Hawaii Clean Energy Final PEIS.

Issued in Washington, DC, April 14, 2014.

Patricia A. Hoffman,

Assistant Secretary, Office of Electricity Delivery and Energy Reliability.

[FR Doc. 2014–08848 Filed 4–17–14; 8:45 am]

BILLING CODE 6450–01–P

DEPARTMENT OF ENERGY

Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications

AGENCY: Office of High Energy Physics, Office of Science, Department of Energy.

ACTION: Notice of request for information (RFI).

SUMMARY: The Office of High Energy Physics, as DOE's lead office for long-term accelerator R&D, invites interested parties to provide input on a possible new program to perform R&D leading to advances in particle accelerator technology used in energy and environmental applications.

DATES: Written comments and information are requested on or before May 19, 2014.

ADDRESSES: Interested persons may submit comments by email only. Comments must be sent to *EnergyEnvironmentRFI@science.doe.gov* with the subject line ''Stewardship RFI Comments''.

FOR FURTHER INFORMATION CONTACT: Dr. Eric R. Colby, (301)–903–5475, *Eric.Colby@science.doe.gov.*

SUPPLEMENTARY INFORMATION:

The Challenge

With world energy consumption predicted to grow by 56% between 2010 and 2040,[1] innovations that reduce pollutants from energy production, improve energy efficiency of industrial processes, and develop cost-effective techniques to clean up water and destroy environmental toxins will become increasingly important both to sustaining economic growth, and to protecting the environment.

Accelerator technologies have been demonstrated to have significant impact in each of these areas,[2 3 4 5] but have not reached a sufficient level of technical maturity and economy to be widely adopted.

The Response

The U.S. Department of Energy, acting through the Office of High Energy

[1] International Energy Outlook 2013, *http://www.eia.gov/forecasts/ieo/.*

[2] R. Hamm, M. Hamm, *Industrial Accelerators and Their Applications,* (World Scientific, Singapore: 2012).

[3] *Environmental Applications of Ionizing Radiation,* W. Cooper, R. Curry, and K. O'Shea, Editors, (John Wiley & Sons, New York: 1998).

[4] ''Accelerators for America's Future'', *http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Report.pdf* (2009).

[5] Office of High Energy Physics Accelerator R&D Task Force Report, May 2012 *http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Accelerator_Task_Force_Report.pdf.*

Physics in the Office of Science, has developed a program in Accelerator Stewardship to serve as a catalyst in transitioning accelerator technologies to applications beyond High Energy Physics.

The Stewardship Program will apply the scientific and technical resources of the DOE accelerator R&D program to facilitate developing accelerator technology innovations into practice.

Accelerator technology includes the accelerator structures, high power radio frequency and microwave sources and systems, high efficiency high-voltage pulsed-power systems, particle beam transport using magnetic components, and high power targets for producing secondary beams. Sophisticated superconducting magnets and accelerators now routinely produce magnetic and electromagnetic fields of unsurpassed strength, power, and quality. Accelerator technology also includes computer control and automation systems, supporting laser systems, safety systems, and diagnostics.

Accelerators produce high power particle beams of electrons and protons that have been used to generate a wide array of intense secondary beams, principally neutrons and photons. Spectral control of both primary and secondary beams has become sophisticated, allowing beams to be specifically tailored to meet demanding application requirements.[6]

The Stewardship Program will pursue several technical ''thrust areas'', each of which will address an identified group of technically related challenges that, if solved, will result in high impact to society.

In the process, high technology will be transferred from the DOE accelerator R&D program into broader use, new public/private partnerships will be fostered, and high quality high technology jobs will be created.

Request for information: The objective of this request for information is to gather information about opportunities for research and development of accelerator technologies to address national challenges in energy and the environment.

The questions below are intended to assist in the formulation of comments, and should not be considered as a limitation on either the number or the issues that may be addressed in such comments. All comments will be made public.

[6] ''Accelerators and Beams: Tools of Discovery and Innovation'', APS–DPB brochure, *http://www.aps.org/units/dpb/upload/accel_beams_2013.pdf.*

The DOE Office of High Energy Physics is specifically interested in receiving input pertaining to any of the following questions:

Application Areas With High Impact

1. What are the most promising applications of accelerator technology to:

a. Produce safe and clean energy?

b. Lower the cost, increase the efficiency, or reduce the environmental impact of conventional energy production processes?

c. Monitor and treat pollutants and/or contaminants in industrial processes?

d. Monitor and treat pollutants produced in energy production?

e. Increase the efficiency of industrial processes with accelerator- or RF/microwave-based processes?

f. Treat contaminants in domestic water supplies and waste water streams?

g. Treat contaminants in the environment at large (cleanup activities)?

h. Produce alternative fuel sources?

i. Address critical environmental or energy related issues not already mentioned?

2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?

3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?

For Each Proposed Application of Accelerator Technology

Present State of the Technology

4. What are the current technologies deployed for this application?

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

6. Does the US lead or lag foreign competition in this application area?

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

8. How is accelerator technology used in the application?

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

11. What are the perceived and actual market barriers for the final product?

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

16. What collaboration models would be most effective for pursuing joint R&D?

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?[7]

20. In what ways are the R&D needs not met by existing federal programs?

21. At what point in the manufacturing development cycle would external support no longer be needed?

22. What metrics should be used to assess the progress of a stewardship effort?

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Depending on the response to this RFI, a subsequent workshop may be held to further explore and elaborate the opportunities.

Issued in Washington, DC, on April 8, 2014.

Michael Procario,

Acting Associate Director, Office of High Energy Physics.

[FR Doc. 2014–08846 Filed 4–17–14; 8:45 am]

BILLING CODE 6450–01–P

DEPARTMENT OF ENERGY

Federal Energy Regulatory Commission

Combined Notice of Filings

Take notice that the Commission has received the following Natural Gas Pipeline Rate and Refund Report filings:

Filings Instituting Proceedings

Docket Numbers: RP14–722–000.

[7] See *http://manufacturing.gov/* for an NNMI program description.

Energy Environment RFI

From: Alexander Burke <alexandertburke@gmail.com>
Sent: Tuesday, May 20, 2014 7:24 AM
To: Energy Environment RFI
Cc: Colby, Eric
Subject: Stewardship RFI Comments
Attachments: Richter 1994 Letter to Science.jpg; Email_from_WKH_Panofsky.pdf

Most promising application of accelerator technology to "Produce safe and clean energy" is Heavy Ion Fusion (HIF). Heavy ion accelerators are the most promising ICF driver candidate for commercial fusion energy (see attachments – Letter to Science by Burton Richter; email from the late W.K.H. "Pief" Panofsky). A new program of Accelerator Stewardship could be an excellent platform for a fresh look and assessment by the HEP community. Indeed, it is difficult to imagine how this "best bet" for commercial fusion can be successfully won without the HEP community playing a central role in the effort.

Basic technical obstacle (challenge) is to accelerate, transport and focus multi-megajoule, sub-microsecond, non-relativistic ion beams. Space-charge dominated, +1 charge state, peak currents at pellet orders of magnitude beyond what has been achieved in any accelerator. All of this clearly recognized in 1976, when HIF construct first considered by ICF, HEP and FES communities, yet technical assessments of HIF were positive. Basis for this optimism regarding HIF's prospects, despite large gap between existing vs. required accelerators, was 50 years of experience with the flexible, scalable, precise nature of accelerators, together with the simple, efficient mechanism of heavy ion energy deposition in fusion targets.

My startup company, Fusion Power Corporation (FPC), has accelerator concepts and innovations that further bolster HIF's prospects. FPC is eager to work with the HEP community, both in the U.S. and internationally, to further develop the enabling technology, in order to "close the gap" with the demanding requirements of heavy-ion drivers for energy production. During this process -- which should involve academic and industrial partners at an early stage -- if technical assessments continue to be positive, a large commitment of both public and private resources to achieve HIF-based commercial IFE, will at some point be called for. Private investors and industrial interests should lead this effort, with the national labs and regulatory agencies in supporting roles.

Process needs to be step-by-step. Taxpayers should not be "on the hook" for a long-term HIF R&D program. Premise should be that HIF is most promising of all known candidates for commercial fusion energy. If that premise proves false -- if technical obstacles are identified which significantly lower HIF's prospects -- public funding for HIF should be discontinued.

A market barrier for HIF is requisite size and cost of accelerator system. This barrier is perceived as making final energy products, e.g. electricity, prohibitively expensive. Actual barrier is initial capital costs rather than overall profitability. FPC uses analogy of petrochemical industry developing Giant oil field, costing many billions although eventual profitability can be very high. One reason economics and potential profitability of HIF has been underestimated is the dominant paradigm and perceived desirability of 1-2 GWe power plants. This preconception makes it easy to overlook highly economical "sweet spot" of HIF, which is energy production comparable to Giant oil field of 100 GW. FPC's conceptual power plant produces 100 GW of thermal energy, which is converted "on site" not only to electricity but also large quantities of hydrogen, liquid fuels, freshwater, and other high-value energy intense products. Filling out the numbers: FPC proposes accelerator system to deliver 20 MJ to direct-drive cylindrical pellet with high efficiency, including heavy-ion fast ignition pulse, and achieve energy gains on the order of 500, i.e., 10 GJ yield per pulse, or ~2 BOE (Barrels Oil Equivalent). For comparison, National Ignition Facility (NIF) delivers 2 MJ to indirect-drive Hohlraum target, with low efficiency due to laser-matter physics. FPC's baseline design is 10 pps (pulses per second) driving 10 or more reaction chambers, such that each chamber pulses at 1 pps or less. 10 GJ x 10 pps = 100 GW.

The HEP community has a long history of building accelerators that work as designed. All we need to know is: Will this one work?

Responses to some numbered questions:
6:The U.S. lags behind Germany and Russia in heavy-ion driver R&D, especially with respect to direct-drive cylindrical pellets with fast-ignition, a promising "breakthrough" method.
10:LBNL and PPPL; GSI in Darmstadt; ITEP in Moscow; HIRFL in Lanzhou.
12:FPC has patent pending on Single-Pass RF Driver (SPRFD) design. FPC sees much room -- and need -- for proprietary accelerator technology on the "driver" side of HIF, and some on the "pellet/chamber" side as well.
13:Around TRL 5, between Development and Demonstration.
14:Top experts in accelerator physics and engineering, ICF physics (pellet design), both fission and fusion reactor design.
15:Strong mix of all three, but with industry leading and driving the R&D.
17:All DOE accelerator labs can be leveraged.

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From: Lwin, Ellie On Behalf Of Panofsky, W. K. H.

Sent: Monday, January 23, 2006 11:49 AM

To: Burke, Alexander

Subject: RE: Next step for HIF in China

Dear Alex,

…

My views are in essence as follows: the support of the diverse fusion programs in the world in general and the US in particular are badly unbalanced since the different technologies are supported through different parts of the governments and are monitored by different Congressional committees. Specifically, magnetic confinement fusion is a separate program, with a long tradition. Laser inertial confinement fusion is supported through military programs, while heavy ion fusion is supported as an adjunct to the general research programs. As a result, I conclude that research and development on heavy ion fusion is significantly under-supported.

To summarize, although I strongly support increased R&D funding for HIF, my opinion does not go beyond a judgment of unbalance.

Best Wishes,

Pief

Energy Environment RFI

From: Hershcovitch, Ady <hershcovitch@bnl.gov>
Sent: Thursday, May 01, 2014 2:46 PM
To: Colby, Eric; Energy Environment RFI
Cc: Roser, Thomas
Subject: Request for Information on a Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications

To Whom It May Concern or Dr. Eric R. Colby:

Subject: Stewardship RFI Comments

Dear Dr. Colby,

A comment regarding the Stewardship of Accelerator Technologies for Energy and Environmental Applications RFI in the section of “Application Areas With High Impact”, item f. “Treat contaminants in domestic water supplies and waste water streams?”

My suggestion is to remove question mark in item f, since it is a promising application of accelerator technology. At BNL we are developing novel enhanced electron beam propagation technique for large scale water purification (DOE Patent Hold). Additionally, in the area of water recycling the US is lagging behind countries like Israel and Spain.

Sincerely yours,

Ady Hershcovitch

Collider-Accelerator Department
Brookhaven National Laboratory

Thomas Roser
Department Chair
Collider-Accelerator Department
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phone: 631-344-7084

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From: Alan Todd <todd@aesprin.com> on behalf of Alan Todd <alan_todd@mail.aesys.net>
Sent: Monday, May 19, 2014 9:39 AM
To: Energy Environment RFI
Cc: Rob Bullis; Tim Myers; John Rathke
Subject: Stewardship RFI Comments

19-April 2014
AES-14-L-030

Dr. Eric Colby
US Department of Energy

Subject: Stewardship RFI Comments

Dear Dr. Colby,

Advanced Energy Systems (AES), Inc. is pleased to submit this response to the recent US DoE Accelerator Stewardship RFI.

We believe there are many potential environmental remediation applications for accelerators that could significantly benefit worldwide quality of life. These include applications that treat pollutants and contaminants in water supplies and waste streams, in industrial processes and in energy production. Specific applications include the processing of flue gas to remove NOx/SOx, the processing of wastewater streams to remediate pharmaceuticals and other pollutants, the treatment of domestic water supplies and the processing of sludge. All of these processes have been discussed for twenty years or more and in many cases have been tested up to the pilot plant level, but none have succeeded in penetrating their specific markets. For all environment remediation applications, unit processing cost, throughput and availability are the key metrics for market acceptance by the highly risk averse customer base. For most of the applications listed, the reason that acceptance has not occurred is usually marginal if any cost advantage over existing systems meaning there is little impetus to replace existing processes with “risky” accelerator technology, and/or unacceptable availability. These are the hurdles that any accelerator-based remediation system must overcome.

Electron beam (e-beam) irradiation has been demonstrated as an effective technology for destroying pollutants and pathogens found in water supplies, industrial/medical wastewater and other contaminated media (sediments and sludges). This technique involves injecting high-energy electrons (1-7 MeV) into aqueous solutions of contaminants. The key advantage of electron beams is that they are the most efficient process for generating hydroxyl radicals and other reactive species. These reactive species in turn attack organic solutes resulting in a series of reactions that lead to chemical dissolution and sterilization. There is no need for additional additives. This implies there is no need for supplying and storing quantities of chemicals and there are no left over chemical residues from the process. A unique aspect of electron beams as compared to other technologies is the ability to penetrate solid and opaque materials. UV and chemical processes do not penetrate into solids or opaque liquids and may not be entirely effective in liquids with suspended solid materials. This means e-beams can be used for sterilization and for degrading harmful chemicals in a larger range of materials and situations. On the other hand, very large UV system are seeing deployment for the treatment of domestic clear water streams in the US and accelerator-based systems do not seem to have a clear cost advantage to displace the UV technology. Hence the target markets must focus on accelerator technology discriminators.

Electron beam irradiation has been slow to catch on in the treatment of water supplies, wastewater and industrial waste. A few demo projects and even fewer pilot plants have been built over the years; however, these have never been on the scale necessary to convince potential customers that the technology is a mature option. In comparison with other technologies the main drawbacks usually cited are that e-beam technology is not flexible enough to handle variable loads, requires a high technical expertise to maintain the systems, has questionable system reliability, and lacks an established track record. Improvements in e-beam technology can now address all the technical issues. What are needed are demonstrations leading to pilot projects of sufficient size to establish the track record necessary to prove it is a viable technology. DoE National Laboratory expertise and infrastructure could be utilized to significantly leverage focused demonstrations.

In cost comparisons, electron beams are often competitive with other technologies. The main differences between the environmental applications and other industries where e-beams have been successfully deployed is that the former requires larger capacity with scalability, and more efficient, reliable, low-maintenance systems. Prior environmental remediation studies have, for the most part, utilized CW electrostatic accelerators. The reason for this is that electrostatic accelerators were less expensive, more efficient, and higher powered as compared to the RF accelerators available at the time. The main disadvantages of electrostatic accelerators are that they are typically very large and to function at their maximum power and beam energy, must operate close to their break down point. This impacts reliability and necessitates a very clean and well-conditioned machine which increases service requirements. CW electrostatic accelerators also usually operate at lower beam energies typically < 1 MeV, which limits penetration depth, a discriminator of accelerator-based processing, and increases the engineering challenges of delivering material to the device. The IAEA-supported flue gas treatment pilot plant at Pomorzany in Poland is an example of a case where the plant was successful at reducing NOx/SOx emissions as advertised but the poor availability of the accelerator system has compromised subsequent deployment.

Advances in electron beam accelerator design and technology in the last decade have improved the efficiency and economics of RF-based accelerators so that they are now a viable option for environmental applications. Improvements have been made in current, reliable electron guns, higher-powered and more efficient RF sources, as well as new innovative compact and efficient RF accelerator designs. The impetus for many of these improvements have come about from accelerator advances developed by U.S. National Laboratories and security applications. These new RF accelerators are scalable to higher power and can be designed for deployment on mobile platforms such as trucks or in a container. A mobile RF accelerator would have the advantage of being easily deployed to the point of use such as an environmental clean up site, a disaster site requiring emergency water treatment facilities, or a new demo facility. High-powered RF accelerators have proven highly reliable in many applications with months of continuous operation.

RF accelerators offer the advantage of being both capable of higher beam energy and reliability as compared to an electrostatic accelerator. Higher beam energy both increases the beam penetration into the medium being irradiated and makes more efficient use of the beam deposition profile. This impacts performance in a number of desirable ways. It reduces scanning requirements, delivers a more uniform deposition and helps to increase performance efficiency. It also allows larger and thicker objects to be processed offering new opportunities for e-beam processing. Previously, high-powered RF accelerators utilized klystrons because of the stable frequency needed for driving resonant cavities. However, improvements in cost-effective and efficient magnetron technology have greatly improved the frequency stability making the technology viable for the stable, efficient, high-power sources needed for these remediation applications. Higher power generally leads to increased overall system efficiency and reduced unit operating costs. It also increases the throughput that can be obtained from a single device and can reduce overall capital costs when a certain capacity level is required. The efficiency of an RF accelerator can now overlap the efficiency of the best electrostatic accelerators.

We believe the noted improvements in RF accelerator technology and reliability warrant a new look at using accelerator-driven e-beam technology for the treatment of pollutants and contaminants in water supplies and waste streams, in industrial processes and in energy production. To be successful, a pilot project of sufficient size is needed to prove the technology is viable, reliable and scalable for use by remediation customers and utilities. The optimum way to proceed is a partnership of Industry with National Laboratories that will leverage Laboratory infrastructure and accelerator expertise to deliver the pilot demonstration(s). AES strongly supports the DoE effort to facilitate accelerator-based environmental remediation progress under the auspices of the Accelerator Stewardship program.

Sincerely,

Alan Todd
Co-President, Advance Energy Systems

--
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Energy Environment RFI

From: Tremaine, Aaron M. <aaront@slac.stanford.edu>
Sent: Monday, May 19, 2014 1:53 AM
To: Energy Environment RFI
Cc: Hettel, Bob; Tremaine, Aaron M.
Subject: Stewardship RFI Comments
Attachments: A_Tremaine_DOE_Stewardship_RFI.pdf

Attached are Stewardship RFI Comments regarding High-flux Compton sources for nuclear waste diagnostics.
Please feel free to contact with any questions

Aaron

Aaron Tremaine, PhD, MBA
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SLAC National Accelerator Lab
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May 19, 2014

High-flux Compton sources for nuclear waste diagnostics

Stewardship RFI Comments
EnergyEnvironmentRFI@science.doe.gov

Aaron Tremaine
SLAC National Accelerator Laboratory

Inverse Compton Scattering (ICS) can produce photon beams for discriminating nuclear materials and thus useful for safety, storage and nonproliferation of nuclear waste. ICS, where an electron beam collides with a laser pulse generating upshifted Compton photons ($E_{compton}$~E_{laser} x γ^2) is a compact method to produce relatively bright x and gamma rays. Active interrogation of nuclear materials using ICS gamma sources have been proposed using two detection methods: 1) 1-4 MeV photons for Nuclear Resonance Detection (NRF) and 2) 10-20 MeV photons for Photo-fission driven detection.

In NRF, a photon beam at the NRF energy of a material will be absorbed and re-radiated in 4π by the target nuclei. Detection can either come from the 4π re-emission or detection of a notch in the ICS spectrum after interaction. The NRF fingerprint for materials is unique, due the multiple, extremely narrow band absorption cross sections, and detection requires a high flux, low bandwidth (<1%) photon source. In Photo-fission, the photon beam induces fission in the target, producing daughter nuclei that then decay delayed gammas and neutrons, which are the signature of fissionable material. Photofission cross sections are quite broad (materials are not easily discriminated) and detection requires a source of high flux photons over a very broad band (multiple MeVs).

Two closed form ICS parameters have been derived [W. Brown] for the total photon flux, N_γ, and on-axis Bandwidth, dE_γ/E_γ

$$(1) \qquad N_\gamma = \frac{N_L N_e \sigma}{2\pi(\sigma_e^2+\sigma_L^2)}$$

$$(2) \qquad \frac{dE_\gamma}{E_\gamma} = \frac{dE_L}{E_L} + \frac{2d\gamma}{\gamma} + \frac{\varepsilon_n^2}{\sigma_e^2} \qquad \text{(on axis)}$$

where N is the number of photons/electrons for Compton, Laser and electron beam, σ beam spot size of laser and electron beams, σ_t is the Thomson cross section, dE/E the bandwidth of Compton and laser, dγ/γ energy spread of electron beam, and ε is the emittance. Flux, Eq. 1, increases as the overlap density of laser photons and electrons increases. However, the on axis bandwidth (Eq. 2) is mainly determined by the emittance term (last ratio) and increases as the electron beam spot size decreases. In order to achieve 10^7 total photons/shot and small band width a la Eq. (2), high brightness beams from photo-injectors are required, making the pulse lengths on the order of ps and less. In essence, strongly focusing the beams will increase the flux, at the expense of the increased bandwidth. For narrow bandwidth NRF detection, the emittance ratio becomes critical, but does not play much of a factor for photo-fission driven detection.

The mission of understanding and possibly deploying systems for nuclear waste interrogation moves beyond just design architecture of ICS sources. ICS sources would need to exceed performance of the "brute force" methods currently constructed based on bremsstrahlung gamma radiation similar to the DTRA ISIS program current using on an S-Band accelerator delivering 60 μA, 60 MeV electrons on the Bremsstrahlung target. In addition, DTRA, through a Phase I SBIR, funded a compact NRF and photo-fission ICS laser accelerator driver study and design with no build out or deployment follow-on of such a system.

Furthermore, the detection system options for both NRF and Photofission need to be analyzed (e.g. detection resolution, dwell times, scanning need, sensitivity, distance for detection, photon beam hardening/bandwidth… etc), which can have a varying influence on the photon source requirements. Once the characteristics of the source requirements are known, delving into the ICS architectures becomes much more focused.

The detection sensitivity and speed required for NRF can have orders of magnitude consequences over the photon source flux required within a bandwidth. In fact, changing the accuracy, percent by weight, or detection speed (dwell time) one requires can easily determine whether a superconducting machine or room temperature machine is needed. However, given that the NRF and Photofission cross sections are well known and centered around 2 MeV and 15 MeV, respectively, basic design leads to a few facts. The accelerator will need to be around 300 MeV for NRF and 750 MeV for photofission, assuming a near 1μm interaction laser.

NRF considerations:

1. High brightness electron beams, usually photo-injector running in the 10s of pico Coulombs
2. Narrow bandwidth radiation (1%) at interrogation target (dependent on detection requirements and capabilities)
3. High reprates, as the bandwidth and flux per pulse are essentially fixed from the e-beam and laser parameters; flux is increased from reprate.
4. Beam hardening (aperture or spectrometer filter)
5. Roughly 300 MeV electrons assuming a solid state IR laser
6. High average power or rep rate IR laser, recirculation, long laser pulse ICS architectures

Photofission considerations:

1. Roughly 700 MeV electrons
2. High average power or rep rate IR laser, possible recirculation, long laser pulse ICS architecture
3. Could use photo-injector, or possibly thermionic, as bandwidth (emittance) is not a limiting factor

ICS uses a laser, and the laser architecture would have to be studied

1. Recirculation
2. High average power or long pulse in which an electron bunch train interacts with 1 laser pulse
3. Use high average power FEL as interaction (this could increase size and cost)

ICS machines used in nuclear materials detection can be broken down into the following areas.

1. Injector: needs to provide the average current and emittance for a given detection architecture
2. Accelerator: needs to accelerate and preserve emittance for a given current
3. Interacting Laser: Needs high average capabilities, laser recirculation or long pulse, or using a high average FEL laser as the interaction.
4. Photon beam hardening and scanning: More specific for NRF to maintain small bandwidth
5. Detection scheme and criteria
6. Detection system: Will determine what is being measured to what accuracy, and is the final determinant of the source parameters.

Below are responses to the guidelines from the "Stewardship RFI Comments".

Accelerator technology can play a critical role in bringing these machines to fruition. Superconducting machines can provide the necessary rep rates for accurate and fast NRF detection, however, the limiting technology for ICS is the complementary laser performance needing equivalent reprates, or high average power long pulse operation. As a note, a pulsed ICS interaction for these applications require several hundred mJ per pulse of IR or green laser running between 10kHz and 1 MHz depending on detection accuracy and speed. For the accelerator, these rep rates are easily achieved in superconducting machines, with lower end performance possible with normal conducting.

Importantly, the detection scheme and accuracy/sensitivity/dwell time determines the requirements on the ICS machine and needs to be integrated into any program pursuing SNM detection, assumed here to be NRF and photofission.

Another critical element in architecture is size and portability. Superconducing machines are not easily mobile and would most likely have material brought to a Superconducting ICS facility. Mobile machines relying on room temperature are feasible, but the % by weight, accuracy and speed of detection would have to be relaxed. The available laser technology is critical on design, or if in a large facility, possibly an FEL driven ICS light sources, like the HIGS (High Intensity Gamma-ray source) at Duke.

Other market applications are 20-150 keV x-rays for oncology and medical imaging. Here the, ICS spectra might deliver less dose to patients, and improve image quality because of the narrower ICS bandwidth when compared to bremsstrahlung.

The LLNL group has pursued ICS for multiple applications, one of them being NRF detection and discrimination of nuclear materials. LLNL is using x-band to demonstrate a compact and potentially mobile ICS source, while recognizing that superconducting may be required for extremely sensitive and accurate NRF detection. LLNL has received DNDO funds and funded multiple LDRDs on the topic.

Besides the smaller, deployable machines of interest to US homeland security applications, ELI NP, the European Extreme Light Infrastructure –Nuclear Physics project will construct a large ICS machine, based on a C-band LINAC in Romania. The machine will be tunable up to 20 MeV gamma photons driven by a linac delivering 720 MeV for ICS collisions with access to two 10 PW, short pulse lasers. One of ELI-NP's applications is "to map the isotope distributions of nuclear materials or radioactive waste remotely via Nuclear Resonance Fluorescence (NRF)".

The labs that would provide the greatest leverage in this area would LLNL (ICS, nuclear detection, and lasers), SLAC (accelerator, light source and beam dynamics), and FERMI and JLAB (high brightness superconducting technologies).

Energy Environment RFI

From:	Carlsten, Bruce E <bcarlsten@lanl.gov>
Sent:	Monday, May 19, 2014 6:47 PM
To:	Energy Environment RFI
Cc:	Rej, Don
Subject:	Stewardship RFI Comments
Attachments:	LANL RFI Response.pdf

Dear Dr. Colby

I have attached the coordinated LANL response to your Stewardship RFI. Please do not hesitate to contact us for any clarifications.

Best regards,

Bruce

Los Alamos National Laboratory
Response to the Request for Information for the Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications

This response is intended to augment the material already discussed in the May 2012 Office of High Energy Physics Accelerator R&D Task Force Report, *http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Accelerator_Task_Force_Report.pdf*.

Energy

Previous HEP studies on accelerator applications for energy have largely focused on accelerator-driven systems (ADS), including nuclear waste transmutation (accelerator transmutation of waste, ATW), where a high-power proton beam drives a subcritical reactor core to produce electrical power and/or transmute nuclear waste. This kind of ADS leads to enhanced safety because the core remains subcritical at all times and offers increased flexibility with fuel. Here we provide (1) a more complete description of ATW and outline the value of such a program, (2) a discussion of how the increased flexibility of nuclear fuel with an ADS scales even to spent nuclear fuel, (3) use of ADS to generate alternative, non-nuclear, fuel sources, (4) the use of accelerator-based radiography to characterize nuclear fuels to extend the lifetime of these fuels, and (5) the alternative use of laser-driven ion beams for driving fusion. This response specifically focuses on accelerator applications for which an R&D program can leverage existing capabilities within DOE National Laboratories. These Laboratories have the required accelerator and nuclear-facility infrastructure needed to safely develop and test the required technology. Reproducing this infrastructure in industry for the R&D would be unnecessarily expensive.

1. Accelerator Transmutation of Waste

Although the Office of High Energy Physics Accelerator R&D Task Force Report mentions ATW, there is no accompanying detail or outline of its benefits to the Nation. Because LANL considers this a high priority accelerator application, here we provide a basic review of ATW. A large portion of the nuclear waste stream can be transmuted in commercial power reactors while producing energy to offset the cost of transmutation. Dedicated transmuters using accelerators that focus on transmuting the minor actinides, i.e., the heavy isotopes of plutonium and higher elements, and some fission products can be an efficient, cost effective approach to enabling the expansion of nuclear power and assist in addressing the disposition of existing used nuclear fuel.

Multi-tier approaches have been evaluated in which plutonium (with uranium and/or minor actinides in some approaches) are burned in first passes through first-tier thermal-spectrum power reactors, with the residuals being subsequently passed to second-tier systems using sub-critical fast-spectrum accelerator-based transmuters. Past studies have shown that this approach addresses the major issues relating to the expansion of nuclear power: (1) This approach will improve public safety by reducing radiotoxicity of spent nuclear fuel below that of source uranium within a few thousand years and reduce maximum predicted peak dose to future inhabitants of a region containing a repository by at least 99% in comparison to current predictions. (2) This approach will provide benefits to the repository program by reducing the long-term heat load of spent nuclear fuel by at least 90% after 500 years as compared to unprocessed spent fuel; preclude the possibility of future criticalities by reducing and degrading the transuranic content; and reduce the mass of commercial spent fuel by separating the uranium and either recycling the uranium or diverting it to alternate disposal. (3) This approach will reduce the proliferation risk from plutonium in commercial spent fuel by reducing or potentially reversing the buildup of the inventory of plutonium in nuclear fuel cycle, and reversing the long-term trend of plutonium build-up from the once-through fuel cycle; reducing the inventory of plutonium passing to the nuclear waste repository by 99% and decrease the fissile fraction within that plutonium; and minimize the risk of plutonium diversion throughout the alternate fuel-cycle and materials-handling processes. (4) This approach will improve prospects for nuclear power by providing a viable and economically feasible waste management option for commercial spent nuclear fuel, minimizing the technical risk to achieve solutions to nuclear waste challenge, and improving upon ES&H characteristics of the once-through fuel cycle.

2. Accelerator-Driven Subcritical System for Energy Production from Spent Nuclear Fuel

Accelerator-driven subcritical systems have been proposed as an alternative reactor design that uses a proton accelerator to produce neutrons to maintain the nuclear chain reaction in a subcritical assembly, i.e. one in which the number of neutrons produced by fission is less than those being absorbed. Early on, ADS has been promoted as an energy amplifier that uses naturally abundant Th-232 as fertile material to breed fissile U-233 that is then used as nuclear fuel in the ADS. In the US, however, it is presently not economically viable to use ADS for energy production using the thorium fuel cycle. Also, previous proposals to use ADS as a thermal reactor for energy production were met with skepticism from the electrical utility companies due to reliability issues of the high-power proton accelerators and associated safety issues with a thermal neutron reactor.

A unique feature of ADS is its ability to utilize spent nuclear fuels containing low levels of fissile materials, ~1% U-235 and ~1% of Pu-239, and other actinides. We envision the spent fuels must be reprocessed to remove fission products, but the fissile actinides do not have to be separated. By burning these low-enriched spent fuels deeper with ADS-generated fast neutrons, one not only produces energy but also breeds new fuel from U-238 while destroying the long-lived minor actinides. An added benefit is the reduction of spent nuclear fuels that are presently stored in temporary storage sites across the US.

Technology Description and Challenges A typical linac-based accelerator system for ADS includes a high-current proton ion source and a radio-frequency quadrupole (RFQ) accelerator as the initial accelerator stage (up to a few MeV in kinetic energy). This is usually followed by a conventional Alvarez-style drift-tube linac (DTL) to accelerate the beam to approximately 100 MeV in kinetic energy and finally, several sections of superconducting RF (SRF) cavities to reach a final energy near 1000 MeV where the cross section for spallation neutron production begins to flatten out. Other variations of accelerator structures are proposed and are under development. Before the concept of ADS burning spent fuel can be seriously considered for energy production, two major challenges have to be addressed: the frequency of faults of the proton accelerator and the safety features unique to the ADS, e.g. proton beam windows. While a commercial nuclear reactor operates with 90% up time with no faults, proton accelerators typically have 80% up time with several beam trips a day. One possible approach to improving reliability is to have redundancy in all the accelerator subsystems. This redundancy is practical for the ion source and the RFQ, but may not be feasible for the SRF accelerators. Reliability of high-power accelerator technologies is an appropriate accelerator stewardship focus.

3. Use of an Accelerator-Driven System to Produce Alternative Fuels

Synthetic fuel production is quite feasible but is energy intensive. High-power accelerator technology can be applied to produce carbon-neutral synthetic fuels and to convert both coal and natural gas to diesel fuel and gasoline without additional CO_2 production and at low cost. A typical system would consist of an accelerator-driven subcritical reactor that burns non-enriched Uranium, Thorium, or spent fuel from nuclear reactors in a eutectic molten-salt fuel to generate the reaction heat and high temperatures needed to convert natural gas and Carbon into liquid fuels for vehicles through the Fisher-Tropsch process (CH_2 fractionation) and to produce electricity to run the plant. Such a system can also contribute to reducing the current inventory of long-lived nuclear waste by burning spent fuel without reprocessing. Accelerator-based systems have not yet been deployed for this application. Presently deployed demonstration projects and commercial development are primarily focused on using solar energy or other renewal forms such as geothermal to generate the electrical power needed. Electrolytic and catalytic synthesis systems are used for remediation of power plant flue exhaust as the source of carbon. Conventional biodiesel and ethanol fuels are produced from agricultural resources and fossil fuels. Methanol is typically produced using CO_2 from flue exhaust and hydrogen from electrolysis of water as feedstock, and then combing the two to produce methanol. Importantly, ADS technology has the potential to make industrial-scale synthetic fuel production feasible while also addressing the long-term nuclear waste issue.

Technology Description and Challenges An ADS system using a MegaWatt (MW) SRF proton linac to produce spallation neutrons to drive a subcritical reactor system can be used as the source of electricity and reaction heat for synthetic fuel production. In an efficient system, enough energy is produced by the reactor to both operate the accelerator and produce synthetic fuel after startup. It may even be possible to supply additional energy to the power grid. The technology challenges are the same as discussed in (2) above.

4. Characterization of Nuclear Fuels

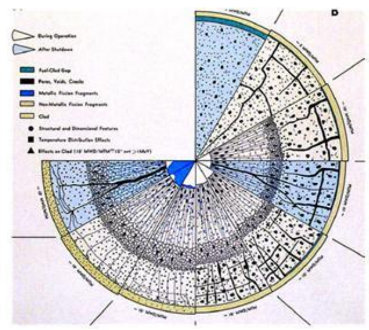

Figure 1. Schematic evolution of fuel pin microstructure during use.

This topic is considered a priority area by LANL's Civilian Nuclear Program Office based on the current direction of DOE's Office of Nuclear Energy. Recently, interest in nuclear energy in the Unites States has surged with increased efforts to extend the lifetime of the current fleet of reactors and to develop advanced reactors which operate at higher temperatures and use fuel to higher burn-up. Safety margins and predictions of the engineering performance of nuclear reactor fuel rely on modeling codes used to predict dimensional change, stress state and fission gas release as a function of burn-up and temperature history. Thermal conductivity is the single most important material parameter in these codes and is heavily dependent on microstructure e.g. grain morphology, porosity, etc. To date, empirical and phenomenological descriptions of the evolution of the microstructure of fuel materials are used to calculate the thermal conductivity, but this leaves huge uncertainties and necessarily results in large safety margins and inherently inefficient use of resources as well as increased production of waste. From historical post irradiation examination, it is clear that the microstructures of nuclear fuels evolve during in-reactor service. During operation, the temperature of the fuel pin can vary from 1500C to 500C over the 5mm radius from the center to the cooled outer diameter. The extreme thermal gradient drives radial grain growth and void migration in the ceramic fuel, which degrades thermal conductivity and facilitates transport of fission products which is important in the case of cladding failure. Figure 1 shows a cartoon of the microstructural evolution of a ceramic fuel pin observed at various stages of use. The first slice represents the initial heat-up and continuing clockwise represents aging in-reactor. The specific microstructural changes shown in the figure are driven by the thermal gradient that develops during service. In ceramic fuels, grains grow in the direction of extreme thermal gradient, that is radially, while voids elongate along the gradient. Cracks develop during the first thermal cycle due to the stresses associated with the strong thermal gradient. Fission products, in particular, xenon and krypton, migrate to grain boundaries where they find short cut paths to release from the pellet. All of these changes in the microstructure affect both the thermal conductivity and transport of fission products in ways which we can neither predict accurately nor fully understand.

Proton radiography has been used for many different applications and has found use in reconstructing microstructures through the use of multiple images taken at various locations to form 360º tomographs of the object. Using this technique, the exact location of defects, such as voids or inclusions can be exactly resolved. Recently, proton tomography was applied to evaluating a set of surrogate nuclear fuel rods with engineered defects to evaluate the tomography capability at LANSCE. The results of the proton tomography on the surrogate nuclear fuel rods demonstrated that voids and density variations in pellets can be located and their physical sizes and orientations can be determined with a resolution of about 80 microns. Absolute density can also be measured to accuracies within a few percent. Further refinements in analytic techniques have also demonstrated that void distributions according to their sizes can be estimated.

Technology Description and Challenges Proton radiography requires a low-power, GeV-class proton accelerator, with similar components (an ion source, RFQ, DTL structure, and RF cavities) as in ADS systems (due to the low power, the RF cavities can be either SRF or room temperature). The accelerator technology is by itself not challenging, but additional development of proton radiography to refine this diagnostic technique is needed. Two possible technology directions are possible. First, a central facility with high-resolution proton radiography system can be envisioned for developing a science-based stewardship approach to extending fuel rod lifetimes. Alternatively, less expensive distributed proton radiography systems can be considered which would be co-located with nuclear power plants for near real-time analysis.

5. Use of Laser-Driven Ion Beams for Igniting Inertial-Fusion Targets

High power-density ion beams hold significant promise for fusion, specifically for fast ignition (FI) of a pre-compressed DT fuel assembly. FI requirements are well understood. Contrary to conventional ICF, where the same long-pulse driver pulse is used to compress and ignite the fuel, in FI the compression and ignition processes are separate and may be optimized independently, providing higher fusion yields for the same driver energy investment. The National Ignition Facility (NIF) laser has already demonstrated efficient compression of the DT fuel, even if ignition is not achieved yet. Given the large power density requirements, ion beams driven by high-intensity lasers in plasmas offer a very promising path for FI as an alternative to conventional heavy-ion beam technology. Laser driven ion-beams have already demonstrated many of the necessary ion-beam performance parameters needed for ignition, although not all at once. An appropriate stewardship focus would be to demonstrate improved performance (efficiency, high ion energy and low energy spread) and beam focusing with existing facilities, thus developing the understanding needed before scaling up to an integrated proof of principle experiment.

Non-Energy Specific Applications

Proton radiography also has potential application in increasing the efficiency of industrial processes. As manufacturing techniques move more towards customized, sophisticated single-component fabrication, proton radiography could provide active feedback for manufacturing processes, greatly reducing the time to develop custom components and reducing the amount of trial, error, and testing in developing techniques. Proton radiography has demonstrated its ability to directly observe microstructures during alloy melt and solidification. It could be used for near real-time materials processing studies, and allow for rapid cycle feedback for process modifications in advanced manufacturing techniques such as friction welding, roll bonding of layered materials, and additive manufacturing.

Fusion Power Corporation
www.fusionpowercorporation.com
8880 Cal Center Dr., Ste 400, Sacramento, California, 95826, USA

May 14, 2014

Department of Energy
Washington, DC

Sent via email to EnergyEnvironmentalRFI@Science.doe.gov

Subject: Stewardship RFI Comments

Dear Sirs:

The Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications is laudable but has severe problems. There is no doubt that our Energy supply has a problem. There is little doubt that we have an Environmental problem that is caused by our desire for access to energy. And there is no doubt that rising costs of energy were, and will again be, a major driving factor in our long sought Economic recovery. ***The proposed program seeks to address these problems but will fail to do so if it is implemented in the manor that is proposed.***

First of all, we need an ***applied research effort*** that focuses our considerable scientific and engineering resource base on the provision of a base load energy supply from an energy source that is not carbon based. The new energy source cannot increase the risk of catastrophic hazards that can result from fission accidents or the increase in availability of fissile material that can be used to make dirty bombs. The new effort has to be directed toward the enabling of accelerator driven heavy ion (HIF) fusion. The method of doing this was endorsed by hundreds of scientists and recommended to ERDA, DOE's predecessor, as a program in need of implementation - but alas that program was never implemented. ***RF accelerator driven fusion needs to be implemented immediately.***

At the time of the debacle in the late 1970s and early 1980s, the research activities in accelerator driven fusion were within the Weapons portion of the appropriation for ERDA and then DOE. The appropriation committees rightfully said this was not an appropriate activity of the Weapons program for it was not a weapon and the hearing language and notes seem to indicate that a separate office was to be formed for the pursuit of fusion energy for the civilian sector. This resulted in a prohibition for spending money in the Weapons program for heavy ion accelerator driven fusion, but no new office was formed in which to nurture this effort.

The home of the effort cannot be in the High Energy Physics division. HEP is driven by a goal of making advances in science and technology that will enable new technologies, not the ***application of existing technology*** to the provision of new sources of energy. A new and separate division whose total focus is the application of existing science and engineering knowledge to the solution of an urgent national need is required. The new office will need to be able to pass some of its funding to existing divisions, such as HEP, if and when a problem is identified that needs new technology to be developed.

As an officer of a company that is attempting to implement this old technology, I am well aware of the chicken and egg problem. My potential investors want to see a prototype built, the very thing that was recommended to and by ERDA and turned down in 1980. This proof of concept effort is what government needs to do most urgently.

The paramount goal of New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications has to be ***the implementation of acceleration driven FUSION to solve the energy problem***. Anything beyond that is not essential.

As to specific comments re: the document:

The summary statement of the program is too limiting. There is a need for long-term development of accelerator technology but there is an even greater need to ***apply*** what we already know to the solution of societies most pressing problem – the nexus between energy, environment, and economic well-being. At a minimum, the program needs to specifically incorporate an '**Apollo-like effort**' for the immediate application of what we now know about accelerators to the provision of an effective driver for the fusion ignition reaction. This effort was initially proposed by the accelerator community in 1980 but has never been funded. Improvements in accelerators, GigaHertz power supplies and multi-GigaHertz communication and control technology all mean that we could do a much better job now than in 1980. What is currently lacking is leadership, focus, and goal oriented action like was present in the lunar Apollo program. It is DOE's responsibility to put forth a program that has this **leadership**, **focus**, and **goal** orientation.

The Challenge is understated. The growth in population alone will require a 56 percent increase in energy availability. The replacement of aging facilities will require a 40 percent replacement of old technology by new energy source technology in the same period. And neither of these numbers account for the provision of energy to under supplied populations on a worldwide basis. Energy is a critical commodity in addressing the climate threat issues as well as national security concerns at home and worldwide. Many estimate that this increase alone requires a near doubling of energy availability. This new energy cannot come from fossil carbon bearing fuels, even if they might be available, for the added CO_2 would have unacceptable consequences on ocean acidity, sea level rise, public health, and potential for climate change. Without a new low cost energy source we cannot afford to stop burning coal and we cannot afford the energy cost of sequestration of CO_2. The challenge has to be a direct commissioning of a new energy source through the application of accelerators to the provision of a reliable high energy driver to make IFE fusion possible within a decade. Yes, it will be necessary to improve technology, and surely this improved technology will result in improved ways to make future systems better, but the overall effort must not wait on the maturation of all of the technology for this would mean that current urgent operating needs of society would not be met in a timely way.

Stewardship is the wrong term. NASA did not propose a Stewardship program to go to the moon. Instead, they proposed a ***goal oriented mission to undertake a concerted national effort*** involving government, academia, and industry to focus on the delivery of rockets and life-life support systems to support the Mission. DOE must assume a role equivalent to the one NASA assumed during the Apollo program to implement Fusion energy program using advanced accelerators as the driver for the fusion reaction. An '**Apollo like**' program is needed. DOE needs to step up and make this happen. Government's commitment and leadership is necessary for this urgent and economic changing event. We do not need another long drawn out research program like ITER or NIF. We need focus and a program with goal oriented decision-making.

Comments on specific issues raised:

1. **Most promising application.** The ***implementation of a new clean energy source must be the primary goal***, ASAP. All other topics under question 1 must be secondary other than item h – the use of the resultant *fusion energy to produce a carbon neutral clean fuel*. An additional topic needs to be added, namely the *efficient production of fresh water*, from saline or contaminated supplies of water, using the waste heat generated by the facility. The climate threat is a water supply threat and the only solution is to desalinate or re-mediate non-potable water supplies.
2. **Regulations.** Regulations must be developed at national and local level for the regulatory activities for fusion. These regulations *must treat Fusion as a new source of energy* that is not burdened by some of the outmoded regulations that apply only to fission. Yes, they are both thermonuclear but dramatically different.
3. **Metrics.** The only metric that should be used is the *successful completion of an accelerator driven fusion power plant within a decade*.
4. **Current technologies used.** The present state of the technology for RF accelerators is probably sufficient for this application. The primary need is for the *demonstration of viability of an accelerator as a driver of the fusion reaction*. We do not need more energy per ion in the ion beam. What we do need is the demonstration of accelerators that deliver higher numbers of ions to the target. The know-how is there but no accelerator facility in the world has the capability to deliver a pulse of energy sufficient to cause ignition. This can be done by more current in the ion source (a very difficult and challenging task best avoided) or via the use of multi-source and multi-isotope accelerators that can deliver all the current from many sources to the target in a simultaneous fashion. The means of doing this was demonstrated in the 1970s but never systematically applied. The target pellet for a fusion reaction is limited in size and thus higher ion energy is not desired because the energy penetrates through the target rather than being deposited within it.

5. **Potential impact.** An accelerator driven fusion power plant would totally revolutionize the power industry and would assist in national security and global peace (energy wars would no longer be necessary). It also would provide a path to the lessening of the use of carbon bearing fuels thereby ameliorating the climate and environmental impacts cause by the discharge of CO_2.
6. **Lead or lag.** The US lags at present – it has done nothing in this area for decades. State of the art accelerators are in Europe or in the Far East (Japan, China, and Korea).
7. **Obstacles**. The primary obstacle is **money** followed by **leadershi**p followed by **focus**. ***There has to be a national commitment to make fusion work.*** The theoretical work has been done, models have been developed, ideas abound, but there is no funding to demonstrate viability. This need for demonstration is urgent and is perhaps best done in conjunction with a national laboratory such as INEL.
8. **Application of technology.** For a fusion reaction to take place using an RF accelerator as driver a solid target containing D-T fuel is axially compressed to a density of 50 to 100 times normal density and then heated to 10s of millions of degrees on axis by a latter portion of the beam pulse. This heating event is known as fast ignition and sufficient beam energy is necessary to raise the temperature of the compressed fuel to 50,000,000 to 100,000,000 ^{o}K. Timing accuracy at a few nanosecond level is needed. This timing accuracy is not an insurmountable issue since the accelerator will need to operate at 2 to 4 Gigahertz. We do it today in our HD TVs and cell phones all the time.
9. **Limitations of current technology.** At present the current delivery of the accelerator is the limiting factor. Storage rings cannot be used because they degrade the emmittance of the beam. Spot size must be kept to about 50 microns. Micro-bunch integrity created in the initial RFQ has to be maintained throughout beam acceleration and can only be relaxed during the final approach of the beam to the target. The beam will need to be charge neutralized after final focusing about 5 meters from the target. *These performance requirements can all be met by existing technology.* Most likely, the technology of accelerators in 1975 would have been sufficient. However, the improvements used in modern communication technology make the power delivery and beam control much better than it would have been in 1975.
10. **Is accelerator technology adequately known**. FPC is well down the road in implementing this technology. We have pending patents on several key steps and our modeling leads us to believe the desired result can be accomplished within ten years given sufficient leadership and funding. Other institutions involved in similar research include: Institute of High Energy Physics, Moscow, Russia; GSI, Darmstadt, Germany; and BNL in New York.
11. **Market barriers.** The primary barriers to private investment are lack of a prototype, lack of government leadership, and lack of regulatory policy framework for fusion reactors. At present our only real investor interest has been coming from Mexico and China. Federal loan guarantees will be needed for the first system built if it is to be in the US. Fusion power plants cannot be made small and

still deliver low cost energy. The energy required to initiate fusion is very large and the delivery of such energy in a controlled fashion will always require a costly driver. The result is that future fusion facilities will always be larger than normal utility scale power plants. Our modeling suggest that a system delivering as little as 6 GWe can be operated economically but the economy of scale arguments would prefer a system that delivers more than 30 GWe. Thus the barrier is what to do with the energy. The largest grid node in the US has a capacity of about 8 GW. Thus transmission, most likely DC transmission, to several grid nodes will be necessary to deliver to the market. The alternative is to use the excess energy generation capacity to produce H_2 via high temperature electrolysis and its subsequent conversion of the H_2 to synthetic liquid fuel. LANL has examined this possibility in their Green Freedom report and it appears to be economically viable at today's fuel prices.

12. **Proprietary data.** The details of beam manipulation enhance the ion beam intensity and to compress the beam energy are considered proprietary. Otherwise, the technology is generally public although the procedure for operating the accelerator as a driver system has been granted a patent in Russia. Similar patents are pending or being considered by the US, PCT countries, China and India.
13. **Readiness level.** The overall readiness level is currently TRL 6 in my view. All component readiness levels are greater than TRL 6 but lack of a demonstration facility precludes a level higher than TRL 6. Many components are commercially used and thus TRL 9 would be appropriate for them. Basically, RF accelerators are known to work as designed and thus accelerators are a TRL 9 item. But no existing system can deliver the current needed thus, without an operational unit a high current RF accelerator must be limited to TRL 6.
14. **Skills needed.** Physicists and/or engineering physicists are required and are probably available in sufficient quantity. A fundamental understanding of classical physics is necessary as well as knowledge in modern specialty areas. All aspects are well enough known to proceed to a prototype – with one exception – **money**. A prototype will cost about 15 to 20 billion US dollars.
15. **Resources needed.** A mix specialties from a number of existing national laboratories (BNL, LANL, LBNL and INEL) and various universities (MIT, UMaryland, Princeton, Berkeley and others) have the necessary expertize for this effort. Numerous small industries and some large industries have all expressed interest in working with us in this effort. The effort needs to be led by an industrial concern that is committed to seeing fusion developed as a major source of base-load energy. Given adequate resources, FPC, although very small, is willing to take on this task.
16. **Collaboration models.** We believe overall leadership needs to be from a government-sponsored activity, like NASA in the Apollo program. DOE can provide this leadership but it cannot be at the Division level. It must be higher in the organization at a level comparable to ARPA-E. It could be ARPA-E but their aversion to fusion related projects suggest that a new Directorate is needed.

17. **Partnering.** Yes, partnering with National Laboratories (as mentioned in 15 above) would be beneficial provided they can work on a **schedule that is geared to have an operating system in a decade**.
18. **Cost sharing.** Cost sharing is desirable but must be flexible. Most of the industrial partners that would be most useful are small operations for which cost sharing would be a burden. We want this activity to proceed rapidly. Thus cost sharing should not be a requirement. Our goal, and the US goal should be, is a demonstration unit in a decade. For a small company, searching for cost sharing funds from investors for a project with a payoff a decade or more later is likely to be counterproductive.
19. **Interaction with NNMI.** There are many areas where NNMI interaction might be appropriate. The patents for this effort are US patents that have been applied for in other countries as well. This should be a US effort. There are many areas where the application of automation could provide beneficial outcomes. By 2050 the world needs to install perhaps as many as 200 of these systems each at a general cost of 20 billion (perhaps as high as 80 billion if all the economies of scale are utilized – electric, liquid synthetic fuel, and potable water). Developing the automated technology in the US would be of long-term economic benefit.
20. **Unmet needs.** All US funds for fusion currently go to ITER or NIF neither of which will make a prototype of a power plant in the foreseeable next two decades. There are virtually no funds available for alternative means of achieving fusion. The need is for something like $350 to $500 million per year for a three year period, during which one or more designs could be achieved. Subsequent to the design phase, a funding level of $5 billion per year will be needed for a five year period to implement one or more designs. After that, industry should be able to fund the build-out but it may require that federal loan guarantees be available for part of the early build-out effort. The US alone will need 30 of these facilities operating by 2050 if we are to reduce our carbon emission significantly. It should also be noted that if 10 percent of the funds we now spend on National Security and oil imports were reallocated to fusion development a total conversion of our base load energy system could be completed in a few years. Some these funds could be use for fusion energy production as we move to producing synthetic carbon neutral liquid fuels, no need for oil imports. It removes a whole series of ‘hot spots’.
21. **Maturity.** External support other than perhaps some loan guarantees would not be required after the first of the systems has been shown to be operational. But if national or international commitment relative to carbon footprint reduction are paramount, then a more rapid build-out will be imperative and more of the first 6 to 10 plants may need to be subsidized. Fusion power will be very lucrative from a profit making perspective, but the initial cost is so high that it may be best to encourage the conversion from carbon based fuels to a carbon free energy source, fusion, via tax incentives or loan guarantees.

22. **Metrics.** In my view this is not a stewardship effort **nor should it be**. ***It is necessary and mandatory effort to assure the sustainability of our society.*** The only metric is success as defined by an operating fusion power plant in a decade.
23. **Other factors.** *The primary factor is to get our economy back onto an abundant, low cost and virtually inexhaustible supply of base load energy and to move us away from fossil liquid fuels through the production of synthetic liquid fuels from the* CO_2 *in the air and ocean*. But there is a major secondary benefit as well. The fusion reactions produces a very large amount of high quality heat. It may be possible through advanced Magnetohydrodynamic (MHD) technology to make a direct conversion of this heat to electricity through interactions between the plasma generated by the burning D-T and an external magnetic field. This could make the energy extraction even more efficient. Current modeling efforts assume 35% to perhaps 41% efficiency. MHD could be better than 75% efficient. But in either case, large quantities of waste heat are present. With a bit of ingenuity this waste heat can be used to distill water from either seawater or from non-potable sources. Water will soon become the limiting item in many parts of the country – the next world crisis. We need to make use of this waste heat. Calculations indicate that the use of the waste heat could produce a Nile river volume of distilled water for each 6 plants built. Water is necessary for all living organisms, for urban life and for food production. With the loss of the snow/ice fields due in part to climate change our constant supplies of water are limited. Assuring a water supply may be the real source of national well-being in the coming decades.

Thus end my formal comments. I hope they are found to be useful.

Sincerely

Charles E. Helsley

Charles E. Helsley
President
Fusion Power Corporation

email: fusionpower@hawaii.rr.com
cell: 808 927-4614

Energy Environment RFI

From: Colby, Eric
Sent: Monday, May 19, 2014 5:59 PM
To: Energy Environment RFI
Subject: FW: Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications
Attachments: Accelerators for Energy and Environment_IIT_May_2014.pdf

-----Original Message-----
From: Daniel Kaplan [mailto:kaplan@iit.edu]
Sent: Monday, May 19, 2014 5:45 PM
To: Colby, Eric
Cc: Russell Betts; Grant Bunker; Carlo Segre; Pavel Snopok; Linda Spentzouris; Zack Sullivan; Jeff Terry; Yagmur Torun; John Zasadzinski
Subject: Re: Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications

Dear Eric,

In response to the DOE's Request for Information, we attach the contribution from IIT.

Best of luck in this important endeavor!

Dan

Accelerators for Energy, Security, and the Environment

Members of the Physics Dept., Illinois Institute of Technology

19 May 2014

The Illinois Institute of Technology is pleased to offer ideas and recommendations to the DOE in response to this RFI. The faculty and administrators listed below have extensive experience in accelerator based R&D and the recommendations given in this report reflect many years of interaction and understanding of the partnership between university and DOE laboratories, including FNAL, ANL and BNL. Many of the ideas draw upon issues raised in the Office of High Energy Physics Accelerator R&D Task Force Report (May 2012).

Contributors:

- Russell Betts – *Dean of the College of Science; Prof. of Physics*

  Dean R. Russell Betts has extensive experience in atomic, nuclear and high-energy physics. He served as spokesperson of the APEX experiment at Argonne and spearheaded the U.S. effort to resolve the Positron Peak Problem, and more recently led a group in studies of high-energy density QCD matter (quark matter) at Brookhaven National Laboratory's Relativistic Heavy Ion Collider and at CERN's Large Hadron Collider. He is co-author of over 200 articles and book chapters, and is a Fellow of the American Physical Society.

- Grant Bunker – *Chair, Physics Department; Prof. of Physics*

  G. Bunker has worked on developing technology and applications of accelerator-based synchrotron radiation for 37 years, and is the author of a textbook on XAFS spectroscopy. He served as the founding director/developer of the BioCAT facility (Sector 18) at Argonne's Advanced Photon Source for biophysics research. More recently he served as Associate Dean for Research in the College of Science and Letters at IIT.

- Dan Kaplan – *Director, Center for Accelerator and Particle Physics; Prof. of Physics*

  Over his four-decade career in particle and accelerator physics, D. Kaplan has collaborated on and led experiments at Fermilab as well as the Cornell Electron Storage Ring and the ISIS synchrotron at RAL. Since 1998 he has collaborated on Muon Collider and Neutrino Factory R&D, and he leads the U.S. university consortium on the Muon Ionization Cooling Experiment at RAL. His work is funded by the Dept. of Energy, the National Science Foundation, Argonne National Lab, Fermilab, and the Muon Accelerator Program.

- Carlo Segre – *Duchussois Leadership Chair; Director, Center for Synchrotron Radiation Research and Instrumentation; Prof. of Physics*

  C. Segre's research centers around the structure and electronic properties of complex materials including superconducting, magnetic, catalytic, and energy-storage materials. Experimental techniques include material synthesis through arc-melting, powder metallurgy, and advanced chemical methods; structural characterization of the samples performed by x-ray powder diffraction and x-ray absorption fine structure; and measurement of electronic properties by resistivity, magnetic susceptibility, and x-ray absorption spectroscopy. Current interests include structural and electrochemical properties of advanced battery materials; in-situ structural studies of catalytic materials for use in fuel cells; structural and electronic properties of magnetoelectric materials and other perovskite materials prepared in the form of nanoparticles and thin films; local structural studies of structural materials for use in nuclear reactors, including in-situ corrosion studies and characterization of nano-crystalline inclusions in steels; and development of x-ray optics for synchrotron radiation experimentation.

- Pavel Snopok – *Asst. Prof. Physics*

  P. Snopok is an accelerator physicist working for over a decade on problems of designing, simulating and optimizing muon-based accelerators and fixed-field alternating-gradient accelerators (FFAGs) as well as improving current simulation tools for matter-dominated lattices such as ionization cooling channels. He holds a joint appointment with Fermilab. His work is funded by the Dept. of Energy and the Muon Accelerator Program.

- Linda Spentzouris – *Assoc. Prof. of Physics*

  L. Spentzouris's current research concerns the role of accelerator component design and materials on beam dynamics of particle accelerators. This has included control of photocathode figures of merit by design, Fermilab Booster beam dynamics due to magnet impedance, electron emission in accelerator environments, and use of metamaterials in accelerating structures. Her work has been funded by the National Science Foundation, the Dept. of Energy, and Argonne National Lab.

- Zack Sullivan – *Assoc. Prof. of Physics*

  Z. Sullivan is a particle physics theorist who has worked closely with experimentalists to improve particle detection techniques for over 20 years. He is a long-time visiting scientist in the High Energy Physics Division of Argonne National Laboratory, and has ongoing interactions with the National Security portion of the Chemical Sciences and Engineering Division. His work is funded by the Dept. of Energy.

- Jeff Terry – *Prof. of Physics*

  J. Terry has been involved with research improving accelerators and using accelerators to damage materials. His work on accelerators has focused on creating novel photocathodes through the growth of multilayers to tailor the beam emittance properties. The photocathodes have been grown using molecular beam epitaxy and pulsed laser deposition. He has also used proton and ion beams to damage materials used in fission and fusion reactors. His work in this regard involves the characterization of the damage mechanisms using synchrotron radiation techniques. His work is funded by the Dept. of Energy and the National Science Foundation.

- Yagmur Torun – *Assoc. Prof. of Physics*

  Y. Torun has worked for over a decade on problems associated with developing intense, low-emittance muon beams. Currently his research is focused on the development of high-gradient normal-conducting RF cavities for muon reacceleration in ionization-cooling channels. His work is funded by the Dept. of Energy and the Muon Accelerator Program.

- John Zasadzinski – *Paul and Suzi Schutt Endowed Chair of Science; Prof. of Physics*

  J. Zasadzinski has served as a collaborator and visiting scientist at Argonne Lab for more than thirty years working in the area of superconducting and magnetic materials. More recently he has served as the lead P.I. in a university consortium that includes IIT, Northwestern, U.Chicago, U.Illinois/Chicago which has been involved with surface studies of Niobium for superconducting RF cavities in collaboration with FNAL. He is currently working on the development of superconducting photocathodes for XFELs. His research has been funded by the Dept. of Energy and the National Science Foundation.

Introduction

We see important opportunities and challenges at the interface between accelerator physics and condensed matter physics/materials science. These efforts comprise accelerator physics in the service of energy applications, national security, environmental mitigation/remediation, industrial processing, and design and development of new materials, as well as materials physics in the service of accelerator physics. Some of the more promising areas are described below. We first discuss some examples of accelerator applications to energy, security, and the environment, and conclude with examples of the potential impact of materials science on accelerators (and vice versa).

I. Accelerators for Energy

Energy applications will rely primarily on accelerator driven systems (ADS). The linac will consist of a proton beam accelerated by SRF cavities which then strikes a spallation target that converts the proton beam into neutrons. The neutrons will be used to control the fission of a material such as thorium. In this case the ADS system is an energy amplifier. Also, such systems might be used mitigate the problems of nuclear waste by transmutation, while at the same time serving as a source of nuclear energy. While the technology for ADS exists, there are a number of materials-related issues. Liquid spallation targets are easier to cool but there are reactions of the heated liquid target with the steel housing. There are also issues of the steel chamber degrading due to neutron bombardment.

Another option is fixed-field alternating-gradient (FFAG) accelerators. A variety of designs are under study (and some have already been built) for the acceleration of protons, heavy ions, electrons and muons, with possible application to ADS as well as cancer therapy, industrial irradiation, boosting high-energy proton intensity, and neutrino production. Multi-MW proton driver capability remains a challenging, critical technology for many core HEP programs, as well as for ADS. Recently, the concept of isochronous orbits has been explored and developed for nonscaling FFAGs[1] using powerful new methodologies in FFAG accelerator design.[2,3] Such an FFAG machine provides a new path to deliver high power with high efficiency, and also reliably from the standpoint of fixed magnetic fields and fixed RF frequency. Significant work is progressing on a stable, high-intensity, 1 GeV isochronous FFAG along with development and characterization of novel magnets with the nonlinear radial fields required to support isochronous operation.[4]

Recommendations:

- Materials R&D to mitigate problems from neutron irradiation of reactor materials. Investigate coatings of steel with carbides and nitrides.
- Investigate coatings of steel to mitigate problems of the surface degradation from Pb/Bi alloy liquid targets. These include in-situ studies of degradation using x-ray scattering studies at the APS.
- Support continued investigation of the FFAG option for extreme-intensity beams.

II. Accelerators for the Environment

An important class of industrialized accelerators is those that are used for food sterilization and environmental remediation. There are many examples of problems for which technical solutions are still in development. Ships entering the Great Lakes region dump their ballast when they get to harbor. The ballast water can carry unwanted microbes and invasive biological agents. There is no convenient systematic way to handle the problem,[5] although it is considered serious enough to be policed to the extent possible. Another example is the recent loss of powdered food aid packages meant for communities with serious food shortages. When packages are discovered to be contaminated, the entire shipment is often dumped.

Accelerators for sterilization and environmental remediation exist, and are commercialized, but there is a need for a class of accelerators that is more compact at the higher power (10-100 kW), more continuously operable and cheaper.[6] There is a need both for end use of the electron beam, and for x-radiation that can be produced by the electron beams. X-radiation has a greater penetration depth, but lower energy deposition.[7]

Reasonably high-power accelerators are more efficient if they are superconducting, so typically continuously run machines have superconducting acceleration structures. One technology for electron beam generation, the RF gun, currently does not have an implementation with a superconducting photocathode. The development of SC photocathodes would enable such guns to run at higher gradient, increasing the continuous beam power available in a constrained space.

Research and development of high gradient dielectric structures is being pushed to higher frequencies (and so the structures are more compact). At the smallest scale work needs to be done to understand and mitigate the breakdown limits,[8,9] and the technology eventually must be transferred to industry. High frequency, compact dielectric light sources are also being investigated.[10]

These are only a few examples of the role of material research and development in the realization of truly compact machines. Accelerator components at high fields are typically performance limited, and could be improved through material design. Investigation of coatings, materials and design is crucial for progress in this area, as well as for discovering a path for efficient industrial production of these components. Coatings are often used to achieve desired performance from a device. There are many techniques for applying thin coatings, or achieving thin surfaces; however research is needed to optimize materials as well as their method of application. On the larger scale of a complete integrated compact device, successful implementation would also require detailed beam dynamics simulation. Further development of simulations to handle unusual materials and geometries complements development on the material side.

Recommendations:

- Develop compact, low-cost, SRF-cavity-based electron accelerators.

- Develop compact, low-cost, dielectric-based electron accelerators and light sources.

- Materials R&D to reduce costs of SRF cavities below that of high-purity Nb which is ~ $200k (materials, fabrication, postprocessing) for a 1.3 GHz nine-cell cavity. Investigate the coating of Cu and Al with superconducting thin films, and of thin-walled Nb cavities with Cu. Coat single cell cavities of Cu made by hydroforming. Coat cavities made of cast aluminum with superconducting thin films of Nb or higher-transition-temperature superconductors. We note the recent success at ANL in the fabrication of high-quality MoN films (Tc ~ 12K) by atomic layer deposition, a technique that can coat conformally an SRF cavity on both the inside and outside.

- Actively investigate superconducting photocathodes to develop high average current CW linacs. The use of XFELs for basic science and defense will require CW operation. This means electron sources that deliver pC of charge at > MHz repetition rate. This necessitates the use of superconducting photocathodes to be integrated into the SRF linac with minimal reduction of quality factor, Q. Novel concepts and new materials will be required as Nb itself is unsuitable.

Additional Recommendations:

- DOE sponsorship of Graduate Fellowships in Accelerator Science and Engineering to develop a trained workforce.
- Establishment of an SRF based test linac at FNAL for university and industry. We envision some type of modular facility whereby a single cell or nine-cell SRF cavity (e.g. made by thin film coating of Cu or Al) can be tested by inserting it into a linac. Another example would be the testing of a superconducting photocathode. Such a facility might serve as a training instrument for university faculty and students or industry employees.

III. Accelerators for Security

Various accelerator applications have been proposed to search for and characterize contraband isotopes that might be smuggled onto shipping containers by terrorist groups or enemy agents.[11] Although Congress has mandated the development of such harbor-protection technologies, none has yet been shown to be feasible. One novel approach is to use a pulsed neutron source. Any fissile material will lead to a longer decay time for the neutron detection. A compact, pulsed neutron source will require a high-gradient linac. Materials R&D is required in order to develop SRF cavities with accelerating gradient beyond the current 35 MV/m of Niobium.

Another example is the potential use of intense, penetrating, low-energy muon beams. Such beams could solve the challenge of providing the necessary intensity for direct muon tomography of hidden fissile materials, as well as create muonic atoms within fissile materials, resulting in the emission of characteristic gamma rays that are penetrating and can be detected at some distance (commonly referred to as Standoff Detection). The technology to produce such beams is a spinoff of existing efforts to design high-energy Muon Colliders and Neutrino Factories. The value of such infrastructures as the Ports of New York City or Los Angeles and their surrounding areas justifies the urgent investigation of all such potential solutions.

Recommendations:

- Develop designs for small, portable muon sources that can be used to scan cargo vessels as they enter port, and plan and carry out any needed feasibility demonstrations.
- Determine the correct balance between scanning time and radiation dose for low-energy intense muon beams.
- DOE should seek to coordinate activities with DOD and NNSA related to the use of accelerators for security. This should include (but not be limited to) development of a compact neutron or muon source for detection of hidden fissionable materials on ships.

IV. Materials Science and Accelerators

There are multiple areas of interest where materials science and accelerator research overlap. These range from the materials used in accelerator cavities through the targets used to produce neutron beams. Small, portable accelerators capable of producing intense beams will also become very important in the study of radiation damage in materials in the near future.

One of the most useful facilities for the real time study of radiation damage in materials has been the IVEM-Tandem microscope at Argonne National Laboratory. The IVEM is a Transmission Electron Microscope with *in situ* capability to irradiate a specimen with an ion beam while observing the damage in real time. This is a unique facility due to the size of the accelerator and the microscope. Many more facilities of this type could be constructed if small, intense, portable accelerators were available. One potential application for accelerators of this type is coupling to linac coherent light sources and synchrotron radiation facilities.

In the past decade, synchrotron radiation studies of radiation damage have proven very useful in determining mechanisms of radiation damage in materials ranging from semiconductor devices for space applications[12] to nuclear fuels.[13] The high energy x-rays available at third-generation synchrotrons with ring energies up to 8 GeV allow for probing thick samples under a variety of conditions. To date, samples have been irradiated at other facilities and then characterized with synchrotron radiation, using x-ray absorption spectroscopy. It was thereby shown that neutron irradiation caused large grains to be split by dislocation loops resulting in roughly spherical particles with radius of 9 Å. These *ex situ* studies have been very beneficial but the capability to do much more exists. Simultaneous irradiation with either ions or neutrons could be studied in near-real time using the synchrotron radiation facilities if compact accelerators could be developed to fit in the small footprint of a beamline at a synchrotron radiation facility.

In fact, the XMAT (extreme materials) team,[14] of which the Illinois Institute of Technology is a member, proposes to build an x-ray beamline with an ion accelerator for *in situ* irradiation. This facility would allow the study of radiation damage in near real time. Currently, diffraction patterns at high photon energy have acquisition time on the order of seconds. This would allow easy monitoring of changes in crystal structure at dose rates of 25 displacements per atom (dpa) per hour available with current accelerator technology that fits within the beamline footprint.[14] However, the nuclear energy community is interested in doses as high as hundreds of dpa. These experiments would take multiple hours to complete on a single sample even though the x-ray measurements themselves are much faster. This could be improved by the development of higher brightness accelerators with small size.

Materials science can be used to study corrosion reactions of PbBi which is of interest to both the accelerator community as a target but also as a potential liquid for heat transfer in both nuclear reactors and solar thermal plants. The use of lead (Pb) and lead–bismuth eutectic (LBE) liquid-metal coolants has become a focus of current Generation IV fast reactor designs, proposed for nuclear-waste transmutation and for use as small, proliferation-resistant reactors with sealed cores and 30-year lifetimes. Added benefit for the national hydrogen initiative can be obtained from such reactors if temperatures of 800º C can be achieved, as it then becomes possible to directly produce hydrogen from water. While there has been much experience with Pb and LBE cooled reactors in Russia (over 80 reactor-years), current operating temperatures for such reactors remain at 550º C because of the accelerated corrosion and embrittlement observed at higher temperatures. The ability to move to the desired higher temperatures, therefore, depends on developing new corrosion-tolerant materials or coatings.

Much research has been done on the corrosion tolerance of materials — from steels to refractory metals to ceramics to surface-modified materials.[15,16,17,18,19] Many of these studies have focused on the performance of steels, such as 316L, commonly used in current reactors in order to understand their resistance to corrosion at 550º C. It has been shown that chromium (Cr) in steel acts as an inhibitor to corrosion in the presence of low concentrations of oxygen through the formation of a protective oxide coating of $FeCr_2O_4$ spinel. This coating, however, degrades at temperatures significantly above 600º C as the protective oxides are no longer thermodynamically favored. These studies have been conducted in static and flow conditions for time periods on the order of thousands of hours but they all involve post-exposure characterization of the materials by techniques such as electron microscopy, x-ray diffraction, photoemission and fluorescence spectroscopy.

Recommendations:

- Develop small-footprint, high-brightness accelerators (electron or proton) to be coupled to modern characterization facilities. Even better for nuclear materials studies would be compact accelerators coupled with a target to produce neutrons. One potential target for neutron generation would PbBi eutectics. This leads to another potential area of materials science research, since PbBi is known to corrode many structural materials.[20]

- Develop *in situ* techniques that can be used to probe the surface interactions of Pb or LBE with candidate coated structural materials at elevated temperatures (up to 1000º C) and in real time, thereby permitting the direct observation of the fundamental chemical mechanisms that lead to corrosion. Development of corrosion-resistive coatings is critical to both the energy science community as well as the accelerator community which is interested in Pb and PbBi targets in spallation neutron sources and for neutron and muon production. Research in these areas has the potential to impact a very large number of scientific areas, exemplifying the strong coupling between the accelerator and the materials physics communities.

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Energy Environment RFI

From: Colby, Eric
Sent: Wednesday, May 14, 2014 11:31 AM
To: Energy Environment RFI
Subject: FW: Fusion Energy
Attachments: President.doc

From: Ellis Katz [mailto:elliskatz@gmail.com]
Sent: Saturday, May 10, 2014 5:51 PM
To: Colby, Eric
Subject: Fusion Energy

Dear Sir: for your information, I have sent the attached letter to the the President, U.S.A. and have also submitted the following text to the Federal Register:

I am a retired Aerospace Engineer/Executive of the Apollo Progam and have been devoted to the proposition that
Fusion Energy is the Answer to our Energy and Pollution problems. I am also aware of the advanced work being done by the Fusion Power Corporation (www.fusionpowercorporation.com) which calls for the application of Accelerator Driven Heavy Ions to achieve Fusion. See the attached letter I have directed to the President.to initiate a Commission for Fusion Energy.
See attached file(s)

Ellis Katz, Encino, CA

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Tuesday, May 20, 2014

President, U.S.A
White House
Washington, D.C.

Dear Mr. President:

As a grateful citizen, I applaud your historic accomplishments for the American people: You are winding down two wars you neither starter nor wanted, brought us out of a serious Recession, and have, at last, given our people a much needed Health Care program. These alone would be a lasting tribute to your Presidency.

More recently ("National Climate Assessment") you have alerted the nation (and all peoples) to the growing threat of Climate Change. You have well stated the problem: *Unless we limit our emissions of carbon into the atmosphere, we shall surely destroy our beautiful green earth; our oceans and lakes, our lands and vegetation, and our way of life*. This, Mr. President, was a moving and eloquent statement of the "Problem".

Within my lifetime, our Nation has faced two other threatening Problems: Mr. Truman (of blessed memory) initiated Project Manhattan to end the Second World War and Mr. Kennedy initiated Project Apollo to meet the growing threat of Soviet dominance in Space.

Now, Mr. President, I urge you to to consider, in light of your climate assessment, PROJECT FUSION ENERGY. *The goal of this project would be to create an alternative to our dependence on fossil fuel and its concomitant pollution of our earth.*

Fusion Energy is acknowledged as a viable "doable" source of virtually unlimited energy without the hazards of pollution, safety or radioactivity by leading scientists and environmentalists. Much has been written on the subject and is currently being approached on an international scale, matters of which your Science Advisor is well aware.

I ask that you initiate a "FUSION ENERGY COMMISSION" with the goals of recommending an action plan for the scientific and industrial development of this energy source and for educating and stimulating our Leaders and Public to the "wonders" in store for a "Brave New World". In this respect I suggest the Commission be co-chaired by two of our most esteemed technological and entrepreneurial citizens: Mr. Warren Buffet and Mr. Bill Gates.

Thank you Mr. President, and may I wish you and your Family the very best of Health and Happiness.

Yours truly, Ellis Katz*

Cc: Warren Buffet, Bill Gates, Todd Park (Chief U.S. Technology Officer)

* **Ellis Katz is a Retired Aerospace Engineer who held Executive Positions on several Major Programs, including Apollo**

Energy Environment RFI

From: Meot, Francois <fmeot@bnl.gov>
Sent: Monday, May 19, 2014 5:49 PM
To: Energy Environment RFI; Colby, Eric
Cc: Roser, Thomas; Horak, William C; Brown, Nicholas; Todosow, Michael; Meot, Francois
Subject: "Stewardship RFI Comments" - Response to the DOE Office of High Energy Physics RFI
Attachments: ResponseToRFIonStewardshipOfAcceleratorTechnologies.docx; ResponseToRFIonStewardshipOfAcceleratorTechnologies.pdf

Dear Sir,

Please find, attached, the answer to the DOE OHEP request for input on "opportunities in the application of accelerator technology to energy and environmental challenges", by the ADS-Reactor working group, on behalf of BNL Collider-Accelerator and Nuclear Science and Technology departments.

With our best regards,

François Méot, Nicholas Brown, Michael Todosow BNL C-AD and NSTD

Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications.

A joint response to the DOE request for information regarding "new R&D programs leading to advances in particle accelerator technology used in energy and environmental applications" by BNL Collider-Accelerator and Nuclear Science and Technology departments

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Authors : F. Méot (C-AD), N. Brown, M. Todosow (NSTD)

A classic Accelerator Driven System (ADS) for the transmutation of radioactive waste from spent nuclear fuel (SNF) or for the production of energy consists of a high-power proton accelerator, a heavy metal target for the production of spallation neutrons, and a subcritical blanket where the bulk of the reactions/power production occur. The experience of the joint efforts of the expert teams from the Nuclear Science and Technology and Collider-Accelerator departments in the BNL Accelerator Driven System – Reactor (ADS-R) Working Group suggests that a Stewardship program would have the potential to foster innovation and progress in these applications, i.e., the utilization of high power accelerators coupled to sub-critical blankets for the management of spent fuel from nuclear reactors and energy production. A synergy between multiple skill centers, in an effort to strengthen the relationships and cross-fertilization, would fit in well with the spirit of the proposed Stewardship Program by stressing the need to enable collaboration between experts in the accelerator and reactor communities since ADS systems for waste management or energy production require the expertise of both. Industry and university partnership networks are an essential part of such building such a synergy.

A Stewardship program would ideally be an inter-disciplinary, collaborative framework that would foster the development of novel and cross-disciplinary solutions to the issues associated with the use of ADS for the transmutation of nuclear waste and/or for energy production. This would include identifying, and contributing to solving, technical, economic, sustainability, safety, reliability, proliferation, and screening issues, with the aim to foster effective R&D and to position participants (primarily DOE Labs for the accelerator-related issues as well as for the target and blanket), to be able to identify needed feasibility demonstrations and deployments, and execute the required RD&D. The aim would be to identify and fill the gaps in accelerator transmutation system methods, as related to the management of increasing volumes of high-level waste from power reactors, fission product stockpiles, and minimization of long-lived actinides to improve repository performance. This would foster transformational R&D that is connected to core capabilities, as found in such DOE Laboratory as BNL for example, in Accelerator Science and Technology, Applied Nuclear Science and Technology, Chemical and Molecular Science, and Materials Science.

Application Areas With High Impact

Present technologies deployed to fulfill world's energy needs include fossil fuels (~80%), renewable energies (~15%) and nuclear energy (~5%). Nuclear energy, with 437 reactors in 31 countries, provides 10% of the world's electricity. The largest part is in the USA with 19% of the electricity from nuclear plants, France has the highest percentage, 80%, whereas 30% of electricity production in EU is from nuclear origin. Nuclear energy has a low carbon footprint, and, compared to fossil energies for instance, very limited waste generation. However, nuclear safety, nuclear waste management, and other environmental and proliferation risks, remain as obstacles to enhanced implementation these energy systems, and the challenges that need to be addressed. The ADS-Reactor technological concept is seen as a path toward a safe and clean-energy future. It has the potential for lowering the cost, increasing the efficiency, and reducing the environmental impact of energy production compared to conventional processes. An ADS-Reactor R&D program has the potential of extended spin-offs of accelerator science, to the other four Grand Challenges identified in the Office of High Energy Physics Accelerator R&D Task Force Report, Medicine, Industry, Defense, Discovery Science.

1. What are the most promising applications of accelerator technology to:

a. Produce safe and clean energy?

- ADS has the benefits of carbon-free production of energy as do critical nuclear reactors
- Coupling of accelerator and subcritical blanket introduces some new challenges
- ADS based "Energy Amplifier" was proposed by Carlo Rubbia and supported for several years by several countries in Europe. Currently being promoted by Aker Solutions in UK

d. Monitor and treat pollutants produced in energy production?

- Proposed in Accelerator Transmutation of Waste (ATW) and Advance Accelerator Applications (AAA) programs under DOE-NE to transmute/burn selected radioactive wastes in reactor spent fuel to reduce its radiotoxicity and improve repository performance
- Several proposed concepts/proponents (e.g., MYRRAH, SMART)

h. Produce alternative fuel sources?

- Can be used to produce fissile material for use in ADS and critical reactors and potentially eliminate the need for enrichment

2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?

- No regulations exist for ADS which couples a sub-critical reactor with a high-powered accelerator. The Blanket has most of the same issues as critical reactor (source term, decay heat, containment)

3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?

- Similar metrics used in the recently completed Evaluation & Screening of Fuel Cycle Options by DOE-NE would be applicable, including traditional "economics-related" metrics and existence of market incentives/barriers; capital at risk; existing infrastructure.

For Each Proposed Application of Accelerator Technology

Present State of the Technology

Current technologies deployed for the proposed application are primarily based on LWR (PWR essentially) power reactors, and waste management policies such as MOX fuels or storage. Accelerator technology has the potential to revolutionize waste management methods (nowadays essentially relying on storage), based on recycling the spent fuel components including high level waste, possibly in closed fuel cycles, in complement to other technical solution as fast reactors. ADS systems have specific properties such as, allowing flexibility in fuel composition including use of neutron-poison actinides and other non-fissile fuels, in addition to intrinsic enhanced safety. The US has been, and still is, pioneering in these initiatives as well as in many technological systems involved in ADS-R systems [1,2]. However the US is noticeably absent from the scene in many challenging ADS based waste management R&D programs, such as those currently underway in Europe (the full scale technology demonstrator project MYRRHA), China, India, Japan (first, 150MeV proton driver to core connection, 2009), Russia, South Korea.

4. What are the current technologies deployed for this application?

- Fossil fuelled systems (80%)
- Critical nuclear reactors (5%)

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

- Will offer benefits in burning/transmuting selected radioactive isotopes from spent fuel for waste management purposes.

6. Does the US lead or lag foreign competition in this application area?

- MYRRAH is active, funded project in Europe
- China, India and Japan have various levels of involvement in ADS for production of fissile material and/or transmutation
- Niche studies in US for DOE-NE

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

The present state of the technology allows building and operating a demonstrator. The reactor component is comparable to existing installations, and precursors of the required MW class accelerator and spallation target technologies are already in operation in a number of places (PSI, LANSCE, SNS). Accelerator and spallation targetry are *sine-qua-non* components in this application. The accelerator may represent up to 10-15% of the ADS-R investment cost, and require, depending on the technology, up to several tens of MW operation power. As an example, the 85MWth MYRRHA experiment business plan accounts for a 10% efficiency, 15MW operation power, for its 600MeV, 1.5MW super-conducting proton linac [6]. Technical accelerator performance may in some aspects be a limitation in the use of accelerators. For instance, an industrial ADS-Reactor in the GWth range may require up to 30-50MW power beam, depending on reactor technology and the mission of the plant. Accelerator efficiency is thus crucial and justifies superconducting technology R&D programs. Reliability, including stable delivery of the proton beam and footprint on the target is another crucial criterion, with needs beyond those that are currently demonstrated/achievable at existing high power accelerator installations. The accelerator-reactor interface, including beam shaping and delivery, diagnostics, window and spallation target, neutron flux optimization, have been demonstrated at the MW level, however the engineering experience and database for ADS application are very limited, multi-MW beam power scales require furher R&D.

- Issues in all these areas will require R&D efforts

8. How is accelerator technology used in the application?

- High-powered accelerator produces spallation neutrons from a heavy metal target to support/drive a subcritical blanket to produce 100s of megawatts of power and/or transmute isotopes.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

- Cost of accelerator as add-on to subritical blanket which is essentially a reactor
- Wall-plug to beam-power conversion a drain on over-all net power generated
- Reliability comparable to other sources of power production

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

Existing efforts aimed at developing the ADS process, include the MYRRHA demonstration experiment in Europe, dedicated R&D programs in China, India, Japan, etc. The construction and operation of high power proton accelerators in the US, such as LANSCE, the precursor to SNS, the highest beam power at present, and other Los Alamos LEDA programs, participated in these efforts. These R&D programs, past and on-going, constitute a multi-decade staged approach, from transmutation demonstration (typically, 1GeV, 1-2MW beam power) to industrial scale power generation (1-2GeV beam, tens of MW), with an increasing progression towards technological complexity.

11. What are the perceived and actual market barriers for the final product?

Societal and market barriers for the final product are those common to conventional nuclear power reactors. As to the former, they are matters of safety, carbon footprint, non-proliferation. As to the latter, difficulties are in the complexity, the expertise required for operation, maintenance, which the accelerator component could increase further relative to a purely reactor-based implementation depending on technological choices. Technical barriers are a matter of accelerator electrical power efficiency (wall plug-to-beam power), beam reliability and redundancy/fault-recovery issues, development of magnet and RF superconducting technologies, hands-on maintenance criteria, beam-reactor interfacing issues as high power beam delivery, spallation target and its coupling to the reactor core, etc.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

The present state of the technology allows building and operating a demonstrator. However, the readiness level of the accelerator technology for this application varies depending on the mission and on the accelerator type. Technical readiness for the various accelerator concepts and components, and for their integration, needs be established through a dedicated development program, covering accelerator technology, target technology, beam dynamics simulations, redundancy methods, reliability. Defining the roadmap of such a development program, is an effort that could readily be started in a DOE Laboratory as BNL, in the frame of a multiple-directorate collaboration.

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Cross-disciplinary solutions to the issues associated with accelerator driven transmutation of nuclear waste and energy production are necessary to best carry out the required R&D. Typical resources to warrant success of an R&D program are, core capabilities in Accelerator Science and Technology, Applied Nuclear Science and Technology, Chemical and Molecular Science, Materials, Condensed Matter Science. An R&D program would be best managed by a cross-disciplinary steering group, comprised of experts from, at least, Accelerator and Reactor directorates, and including partnership with national nuclear industry companies, small business, Universities, and, including partnering between DOE laboratories, in the – very successful - model of the SNS project.

- Accelerator and reactor expertise in design, manufacture and operation

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

- Partnering with DOE National Lab is essential because that is where the expertise with the needed accelerator technology lies (BNL, FERMI, ORNL, J-Lab, LANL)

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Energy Environment RFI

From:	Gerald Seidl <gseidl@headworksusa.com>
Sent:	Saturday, May 17, 2014 1:54 PM
To:	Energy Environment RFI
Subject:	Stewardship RFI Comments
Attachments:	RFI accelarator technologies for E&E applications(1).docx

Gentlemen,

Please find attached the requested comments

Best regards

Gerald Seidl
Co-Founder & Sr. Vice President

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Watch Headworks Co-Founder Gerald Seidl
explain our products during his WEFTEC interview - click here!

Response to Notice

Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications (A Notice by the Energy Department on 04/18/2014)

HeadworksBIO has responded to the Notice of Request for Information (Rfi)

1. What are the most promising applications of accelerator technology to:
   Response:
   Electron beam (eBeam) technology is becoming a potentially viable process in waste water and waste residuals treatment but a better understanding of mechanisms of eBeam is required so that it can be optimized in various green industries such as the wastewater reuse and/or waste residual value-added product development. The eBeam process has dropped an order of magnitude in cost and improved in efficiency in order of magnitude. It is being considered for a wide range implementation for environmental applications (Reimers et.al., 1986, Reimers et.al. 2000 and Sandberg and Reimers, 2013). The specific arena of its applications is in municipal waste water treatment, waste residual reuse/disinfection and *in situ* remediation. In summary the following factors are causing the emergence of the technology
   (b) Lower the cost, increase the efficiency, or reduce the environmental impact of conventional energy production processes?
   (f) Treat contaminants in domestic water supplies and waste water streams?
   (g) Treat contaminants in the environment at large (cleanup activities)?
2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?
   Response:
   At present, the application of waste residual disinfection has been known for 20 years and is documented in the USEPA municipal sludge regulations (503 regulations). As we learn, how to synergistically apply with other chemicals and biological process, it will be further be applied in the 21st century (Reimers and Fitzmorris, 2009). Federal, state or local regulators need to consider several factors when evaluating a new treatment technology. It is necessary to elucidate all the advantages and disadvantages of the treatment technology, safe waste disposal practices, and worker safety along with the compliance rules from other sources like drinking water, nutrient disposal and biosolid land application regulations (EPA # 816-R-05-004).
3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?
   Response:
   The metrics are related to cost and efficiency of the eBeam processing equipment to specific applications. As in the food and medical industry (Reimers et.al., 1998, Pillai, 2014), this same phenomenon will be noted in the waste water industry (industrial and municipal).
4. What are the current technologies deployed for this application?
   Response:
   Ionizing irradiation as a disinfection technology is not new. Research conducted in the 1970's, 80's and 90's has shown that ionizing radiation is effective at disinfecting municipal sludge and other residuals. A pilot scale cobalt-60 based sludge treatment plant has been in operation in India for many years. Low energy eBeam technologies for wastewater treatment have also been

demonstrated. However, for processing large volumes of solids containing sludge, high energy (10 MeV) eBeam irradiation is required to achieve deep penetration through the solids. Information involving high energy (10 MeV) eBeam technology for wastewater treatment was extremely limited until recently (Pillai and Reimers, 2010).

Electron beam (eBeam) does not involve the use of any radioactive isotope sources. Electron beams are generated from regular electricity using specialized equipment called linear accelerators. The single most important value of this technology is that it can be switched on and switched off (unlike gamma irradiators) (Pillai, 2014). Since this technology relies on electricity, issues of isotope safety and security in handling radioactive isotope transportation, and disposal are non-existent. Because of this, the number of eBeam irradiation facilities has grown to 1500 worldwide and outnumber gamma irradiation facilities by almost 10:1 (Hamm and Hamm, 2012). Most recent estimates suggest that eBeam systems account for approximately $80 billion of added value to commercial products. A variety of linear accelerator configurations have been developed since the 1950's. Different applications of the –beam technology require different linear accelerator configurations especially in terms of eBeam energy (Table 1).

Table 1: Current commercial applications of accelerators of varying energy (adapted from Cleland, 2012 and Pillai et al., 2013)

Application	Preferred Electron Beam Energy
Surface curing of materials/polymers	80-300 kilo electron volts (KeV)
Shrink film treatment	300-800 kilo electron volts (KeV)
Wire and cable cross linking	0.4 – 3 million electron volts (MeV)
Food Pasteurization, Medical device sterilization	3-10 million electron volts (MeV)

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

   Response:

   Yes, accelerator technology certainly have potential to revolutionize its utilization in deriving products from wastes. They are poised to produce Class A biosolids at a much cheaper cost than other current treatment technologies. Currently it costs about $800 per dry ton to produce Class A biosolids for a 10 MGD size plant. Economic analysis was specifically commissioned by Headworks Bio™ to ascertain the economic potential of the eBeam process for the Class A treatment of municipal sludge and the creation of value-added products. The eBeam process appears to be economically viable in developing fertilizers, soil amenders, and/or enhancing the anaerobic digestion process. Our analysis showed that the Class A product can be produced at a cost of $150-$450 depending on the type of the post stabilization treatment used after eBeam and the solids content (needs to be optimized) (Sandberg and Reimers, 2013).
6. Does the US lead or lag foreign competition in this application area?

   Response:

   US currently lags foreign competition in this application area. Several countries like South Korea, Brazil and India leads using accelerators for variety of applications including industrial and domestic waste water treatment and for obtaining bio-fertilizers (Pillai, 2014).
7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

   Response:

   There are several obstacles that need to be addressed for this technology to be adopted for waste water treatment and sludge processing application. Following are the comments on each of the issue

Technical: Presently, the application of electron beam (eBeam) processes for the wastewater industry is poised for pilot scale validation. Headworks Bio™ along with their technical partners National Center for Electron Beam Research (NCEBR) at Texas A & M University) is currently researching for the development and commercialization of eBeam based technologies for environmental remediation, enhanced therapeutics and for enhancing food quality and safety. Results of this proposed study will move these tested value-added products beyond the criteria developed in the 503 regulations. The idea would make Value-Added Products of the 21st Century (Reimers et.al. 2013). The eBeam technology has a greater intensity than the X-ray but lower penetration potential.

Regulatory and operational: As mentioned earlier unlike gamma irradiation, Electron beam (eBeam) does not involve the use of any radioactive isotope sources. Electron beams are generated from regular electricity using specialized equipment called linear accelerators. Several workshops should be organized to spread the regulatory compliance and operational safety across USA by Department of Energy (DOE) along with Environmental Protection Agency (EPA) to promote this treatment technology.

Economic: As mentioned earlier Economic analysis was specifically commissioned by Headworks Bio™ to compare eBeam with the existing treatment technologies. Our analysis indicates eBeam process to be most economically viable option for generating Class A product depending on the respective marketability (Sandburg and Reimers, 2013).

8. How is accelerator technology used in the application?

   Response:

   A variety of linear accelerator configurations have been developed since the 1950's. The ability to penetrate materials and products is dictated by the energy of the electrons (measured by electron volts or million electron volts (MeV) that are generated by the accelerator. The higher the energy, the greater will be the penetration into the material. The penetrating potential of eBeam depends not only on the thickness of the product to be irradiated, but primarily on the areal density of the material. The areal density is defined as the product of the physical depth/thickness of the material (termed "d" measured in cm) and the density (termed "δ" measured in g/cm^3) of the material. Thus, aerial density is dδ, the units of which are g/cm^2. This solids content is two-fold. The higher the solids content the lower the penetration but lower the solids content higher the flow through issues. Therefore there will be an optimum solids content and density depending upon the waste medium (Pillai, 2014).

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

   Response:

   No. The ability to penetrate materials and products is the most important parameter that determines the performance of the process. There is a direct linear relationship between the accelerator energy and its ability to penetrate materials of varying areal densities. The ***accelerator operating power*** (measured in kilowatts, KW) dictates the irradiation processing rates, or in other words, the product processing throughput. Thus, for use in wastewater industry applications, careful consideration needs to be placed on choosing the appropriate power. Generally, it can be assumed that high power accelerators are needed for the wastewater industry. The cost to increase the power (KW) is going down as the competitive market increases. This is an extension to Question 8.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

    Response:

At present the application of eBeam is expanding in the private and offshore industries with respect to medical, food and automotive industry. In the municipal market the usage is slowly developing. Optimal pilot plant studies should be conducted in United States to evaluate the process and to understand underlying mechanisms. This testing will refine the particular accelerator design to specific waste treatment or application.

11. What are the perceived and actual market barriers for the final product?

    Response:

    The market values for the waste water and residuals products has not come to an operational market. The cost of eBeam is coming to down to where the disinfected biosolids EQ will be less than its disposal in the landfill and/or land application ($200-$250/dry ton).

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

    Response:

    Nonproprietary aspects is the operation of eBeam process itself. The integrated physical, biological, chemical treatment and stability with eBeam for different applications are patentable and proprietary. This noted with the applied patent by Texas A&M University (Pillai and Reimers, 2011).

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

    Response:

    The eBeam process is ready to penetrate within the next year. The problem is related to the final refinement with synergisms of the chemical, biological and physical factors related to the eBeam process in vario0us waste arenas. This requires some industrial support to initiate an economic model for profit. The treatment operation is with medium to large scale plants (greater than 20 MGD) (Sandberg and Reimers, 2013)or specific niche markets with high profit margins (i.e., medical sterilization) (Pillai, 2014).

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

    Response:

    In order to advance this technology to the market place there is the need for some process refinement in the range of $100,000-200,000 and the process pilot testing in the range of $0.5-1.0 million to advance this technology. For example the Houston Class B processes could be converted to Class A processes which will cost around $5-$10 million to utilize eBeam while retrofitting Class B aerobic digestion and alkaline stabilization processes would be $9 million dollars (Reimers, 2014).

15. What mix of institutions (industrial, academic, and lab) could best carry out the required R&D, and who should drive the R&D?

    Response:

    The integration of industry (Headworks Inc.,) driving the technology to the market place coupled with academic institutions (Texas A&M University national center for eBeam research) would push eBeam into the waste product development and wastewater reuse in the market place. This could enhance with the assistance of Department of Energy labs such as Argonne national lab.

16. What collaboration models would be most effective for pursuing joint R&D?

    Response:

    A stated in Question 15 this would use assistance of the industry (Headworks Inc.,), academia (Texas A&M University), government (DOE)

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

    Response:

    The partnering with DOE national lab at Argonne would be beneficial to industrial companies such as Headworks and other municipalities such as Chicago Metropolitan Sanitary District, which is close to Argonne national lab. Headworks Inc., and Texas A&M University could integrate efforts with Illinois accelerated research center which is under the direction of Robert Kephart. Chicago has one of the largest waste treatment facilities and has been a leader in waste treatment innovations.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

    Response:

    Cost share would be a benefit for the company, but it could entail development for industry's ability to immediately move technology into the real world.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

    Response:

    The NNMI major role is to implement innovative technologies into market place by assisting industry, government and academia to develop new technologies. Obviously this organization together with DOE would greatly assist a company like Headworks Inc., and Texas A&M in taking the eBeam technology to market place in the waste field.

20. In what ways are the R&D needs not met by existing federal programs?

    Response:

    The R&D needs to assist the pre application phase and pilot phase to implement eBeam in the waste field. This would entail a development of mobile pilot eBeam facility that could be utilized in different industrial settings. The cost of a mobile system would be in the range of $2-$3 million dollars.

21. At what point in the manufacturing development cycle would external support no longer be needed?

    Response:

    After the pre-application and pilot testing the cost estimates indicating that eBeam is economically viable would be substantiated. The niche markets could be ascertained and develop new industries in the United States. A Tulane D.O.E. report elucidates this potential in the 1980s (Reimers et.al. 1986).

22. What metrics should be used to assess the progress of a stewardship effort?

    Response:

    The metrics for ascertaining the viability of eBeam in various waste treatment settings is related to sustainability. This relates to the assessment of economics, environmental application uses and social acceptance of the given technology to be implemented in producing reusable waste water, value added products from residuals which are acceptable to the general public. In the assessment of green technologies looking at economics, environmental and social acceptance is called triple line assessment. The stewardship of DOE in application of eBeam processes appears to be imperative.

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

    Response:

    After 22 questions have been resolved, there is a need to develop an outreach program to educate the public of the value of this green technology.

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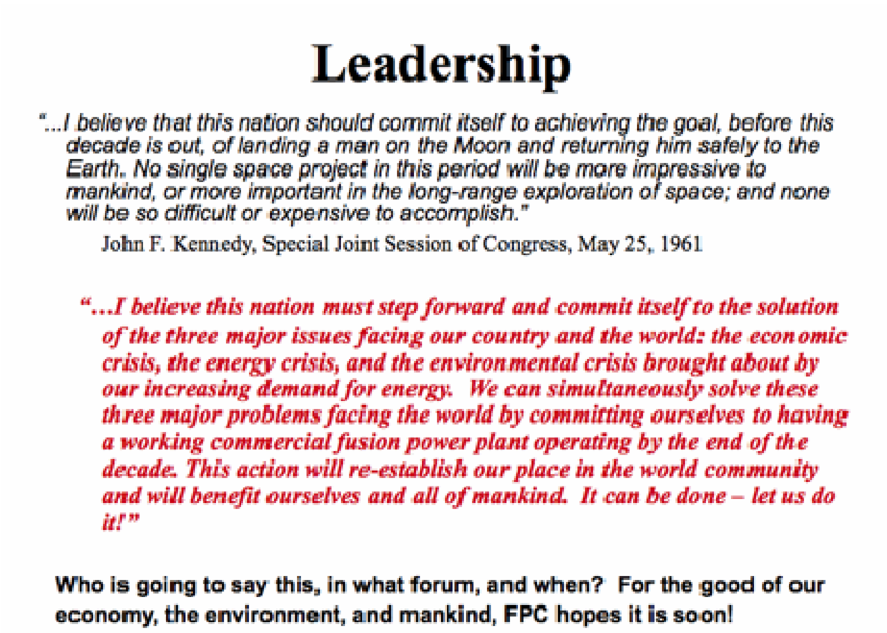
Energy Environment RFI

From: Hal Helsley <hhelsley@wildblue.net>
Sent: Monday, May 19, 2014 6:39 PM
To: Energy Environment RFI
Cc: Colby, Eric; Hal Helsley
Subject: Re: Stewardship RFI Comments

This is the blank spot re-sent ...



Hal Helsley
hhelsley@wildblue.net
"If you don't make a difference, think about who will!"

On May 19, 2014, at 2:43 PM, Hal Helsley wrote:

Your request for the development of a possible new program to perform R&D leading to advances in particle accelerator technology used in energy and environmental applications **misses the need**. A Stewardship Program, no - a program to build a fusion energy generation system. We have the know how now ... it just need a federal blessing.

The *missing part in the development of accelerators for use in the development of fusion as an energy source* is "**leadership on the federal level**" and "**a home**" for such at a high level in the DOE. Currently there is NO PROGRAM nor OFFICE to support RF Accelerator

Driven Heavy Ion Fusion. Where in the budget are the funds to develop fusion - RFADHIF?? There are none!

"Stewardship" implies a caretaker position, we, our country and the world, under the LEADERSHIP of the US, **need action** ... a page from Fusion Power Corporation's booklet on developing HIF within ten years says it all ... **We need a Federal Leadership Position** not Stewardship.

Accelerator technology is well developed, ***the need is to build a "prototype system"*** using many well known technologies, just put together in a creative, innovative way to have fusion in small batches for fusion energy system. This was presented at the "18th International HIF" conference in Germany in 2010, but nobody from DOE was there ... then again at "Accelerators for HIF" at Berkeley in 2011(that was history in the making, I was there), again you were missing, as was the science press community! Then at the "19th HIF Symposium" in 2012 - where were you?? **Where have you been** in RFADHIF?

For 37 years the scientific community has supported accelerator driven HIF "as the way to go", the 'conservative' approach to fusion energy - "no show stoppers" ...from the Foster Report to Congress, to C. Martin Strickley's letter in Physics Today, October 2012. We have spent billions on NIF, which in 1992 was said, by respected scientists, to have major flaws, but nothing on RFADHIF. We are spending millions on ITER, a great research project but not likely a fusion energy generator in the near future. It is time to move to the process that can become the power source for tomorrow ... RFADHIF. Never heard of it ... well ... its research was done prior to your working lifetime - in the 1970's.

Application Areas With High Impact

1. What are the most promising applications of accelerator technology to:

a. Produce safe and clean energy? **RFADHIF as proposed by a small California Corporation - Fusion Power Corp.**

b. Lower the cost, increase the efficiency, or reduce the environmental impact of conventional energy production processes? **They, FPC, propose costs per kw at less than fossil fuel and without GHG**

c. Monitor and treat pollutants and/or contaminants in industrial processes? **No highly radioactive waste.**

d. Monitor and treat pollutants produced in energy production? **NA ... few at construction activity**

e. Increase the efficiency of industrial processes with accelerator- or RF/microwave-based processes? **a greater than 50 to 1 (100:1 like old oil.**

f. Treat contaminants in domestic water supplies and waste water streams? **can generate carbon neutral synthetic liquid fuels to fit the current distribution system, low cost electricity (no GHG) and potable water from sea water**

g. Treat contaminants in the environment at large (cleanup activities)? could i guess?

h. Produce alternative fuel sources? **yes, see above ('Green Freedom' from LANL)**

i. Address critical environmental or energy related issues not already mentioned? **safe ... no meltdown potential nor radioactive waste storage problems**

2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?
Support their development proactively

3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?
Can use similar metrics as fission reactors ... see the poster that was present at 19th HIF Symposium by FPC

For Each Proposed Application of Accelerator Technology

Present State of the Technology

4. What are the current technologies deployed for this application? **Major system components:**

- **Computerized Control Systems**
- **Ion Sourcing System ("Ion Hotel")**
- **High Voltage DC Pre-Accelerator System**
- **RF Linear Accelerator (Linac) Complex**
- **Ion Beam Conditioning and Manipulation Systems**
- **Fuel Pellet and Sabot Manufacturing Facility**
- **Multiple HIF Reaction/Containment Chambers**
- **Lithium Handling and Vacuum Pumping Systems**
- **System Startup DC Power System**
- **Advanced Heat Exchange Systems**

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible? **YES ... fusion energy generation ... a new energy paradigm.**

6. Does the US lead or lag foreign competition in this application area? **Lag ... Russia has given FPC a patent for their process**

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted? **Federal recognition and support - commercial investors**

8. How is accelerator technology used in the application? **The energy supply - heavy ion acceleration**

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application? **Multiple ion sources and initial construction costs are large for private investors**

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application? **Strong interest by China and Mexico to build the first one**

11. What are the perceived and actual market barriers for the final product? **Initial financing .. could use a government guaranteed loan program for the first one (or prototype) - next facilities will not need any such support!!**

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary? **??? the way current technologies are sequenced???**

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application? **TRL 6**

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase? **$$$$$ & Federal Leadership**

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D? **LBNL, INL, Brookhaven for computer simulation**

16. What collaboration models would be most effective for pursuing joint R&D? **Joint National Lab(INL) and FPC cooperative effort.**

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage? **INL, LANL and LBNL**

18. Should cost sharing be considered for a grant or contract to pursue the R&D? **No**

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?(7) Should have a high value for national security issues

20. In what ways are the R&D needs not met by existing federal programs? **No current program or funding!!!**

21. At what point in the manufacturing development cycle would external support no longer be needed? **After the first "prototype"**

22. What metrics should be used to assess the progress of a stewardship effort? **Successful power generation**

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes? **Federal LEADERSHIP and political will! ... National Security issues. Global warming and job creation highly impacted.**

Energy Environment RFI

From: jerryniowave@gmail.com on behalf of jerry hollister <hollister@niowaveinc.com>
Sent: Wednesday, May 21, 2014 4:51 PM
To: Energy Environment RFI
Cc: Dr. Terry Grimm
Subject: Stewardship RFI Comments
Attachments: Niowave Superconducting Electron Linacs.pdf

Good afternoon,
In response to your Request for Information, I am attaching the summary portion of our recent advertising campaign for commercial superconducting accelerators. If you desire further details, I am happy to provide more information regarding each of the applications noted in our attached summary.

Best regards,

Jerry Hollister
Chief Operating Officer
Niowave, Inc.
1012 N. Walnut St.
Lansing MI 48906-5061
(517) 230-7417 (mobile)
(517) 999-3475 (secondary)
hollister@niowaveinc.com
www.niowaveinc.com

Superconducting Electron Linacs

At Niowave, Inc., superconducting electron linear accelerators (linacs) are being built to tackle America's high-tech challenges in fields as diverse as health care and national security. Niowave is aggressively pursuing commercial markets for compact versions of superconducting electron linacs:

- Medical Radioisotopes (without the need for a nuclear reactor or highly enriched uranium)
- Free Electron Lasers (high power tunable lasers at wavelengths not available today)
- X-ray Sources (active interrogation, food irradiation and medical equipment sterilization)
- Neutron Sources (high-intensity fast and thermal neutron flux without a nuclear reactor)

Over the past 30 years, the Department of Energy has developed superconducting particle accelerators for the largest and most powerful atom smashers ever built. These huge machines accelerate electrons and atoms to nearly the speed of light to understand the makeup of matter and how the universe works. That quest continues on many machines around the world today, with each of these machines costing roughly a billion dollars each. Much like Space-X has adapted NASA technology for commercial space applications, Niowave has adapted this technology for use in compact, cost efficient accelerators for a number of commercial applications.

Figure 1. A niobium superconducting accelerating structure being processed in the Niowave cleanroom

In the simplest terms, superconductivity is used to efficiently accelerate electrons to high velocity and energy. The kinetic energy of the electrons is then used as a tool for a number of purposes. Niowave has pioneered the development of complete turn-key superconducting electron linacs that operate at 4 Kelvin for a broad range of commercial applications. In addition to the niobium accelerating structure (see Figure 1), the complete system includes the liquid helium refrigerator, high power microwave source, radiation shielding and licensing from the Nuclear Regulatory Commission. A conceptual layout of the complete system is shown in Figure 2. This integrated system enables a company or university research group to quickly and inexpensively use the electron beam for their research or industrial process. Key applications and the associated parameters for the superconducting linac are summarized in Table 1.

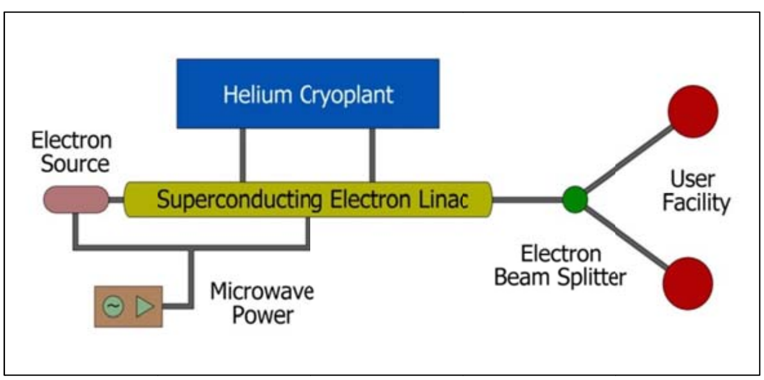


Figure 2. Conceptual Layout of the Niowave Superconducting Electron Linac used for various applications

Table 1. Applications of Superconducting Electron Linacs and associated beam parameters

Application	Beam Energy	Beam Current	Beam Power
Medical Radioisotopes	40 MeV	2.5 mA	100 kW
Commercial FEL & X-ray and Neutron Sources	2-40 MeV	2.5 mA	5-100 kW
Energy Recovery Linac for High Power FEL & X-ray and Neutron Sources	2-40 MeV	25 mA	50-1,000 kW

Energy Environment RFI

From: Igor Kaganovich <ikaganov@pppl.gov>
Sent: Monday, May 19, 2014 5:27 PM
To: Energy Environment RFI
Subject: "Stewardship RFI Comments"
Attachments: RFI_negative ions.docx

May 19, 2014

Dear Colleagues:

Please find in the attachment a RFI on "Plasma Science for Negative Ion Beam Accelerators ."

We are very enthusiastic to support the Stewardship Program.

Sincerely, Igor Kaganovich

Deputy Head of PPPL Theory Department

Secretary of 66th Annual Gaseous Electronics Conference

Associate Director of DOE Center for Predictive Control of Plasma Kinetics: Multi-phase and Bounded Systems

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Principal Physicist Phone: 609-243-3277

Plasma Physics Laboratory, MS-17 Fax: 609-243-2418

Princeton University E-mail: ikaganov@pppl.gov

P.O. Box 451 Express: Sayre Drive

Princeton, NJ 08543-0451 at Route 1

You can visit PPPL's

beam dynamics website at http://nonneutral.pppl.gov.

low temperature website at http://w3.pppl.gov/~ikaganov/

Plasma Science for Negative Ion Beam Accelerators

Princeton Plasma Physics Laboratory

In reply to the Notice of Request for Information (RFI), Princeton Plasma Physics Laboratory (PPPL) is hereby expressing the commitment to participate in the proposed new Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications. PPPL research team is already working on a number of plasma and accelerator projects supported in part by DOE. Negative ion beams are used in variety of applications, most importantly in producing neutral beams for ITER and various surface treatments.

The project would focus on theoretical study of negative ion beam systems with the objective to provide guidelines for the development of industrial and environmental accelerator-driven systems.

At Princeton Plasma Physics Laboratory we have expertise in various aspects of plasma physics, atomic physics, gas discharge physics, plasma surface interaction, all employed to advance complex science of negative ion beams. This unique set of expertise can propel our group to be world leaders in negative ion beam programs, subject long underfunded in USA.

Extracting negative ions from a plasma to form an ion beam is generally a quiet different phenomenon from extracting positive ions from a plasma. In almost all cases in which positive ions are extracted (except for positive ions extracted from strongly electronegative discharges, such as halogens) the plasma is a conventional electron-ion plasma, with the sheath characteristics dictated by the ambipolar diffusion competition between highly mobile electrons and the much less mobile positive ions.

The sheath characteristics are likely to be much different for negative ion extraction. When negative ions are extracted from halogen plasmas, it is often the case that the extraction plasma has all the characteristics of an ion – ion plasma, composed almost entirely of positive ions and negative ions of nearly the same mass, with very few electrons. In such cases, the mobility of the dominant negative and positive charge carriers is similar, so ambipolar diffusion does not lead to much of a sheath potential drop.

However, in the case of negative ion extraction from weakly electronegative plasmas, such as hydrogen, the situation is much less clear. The negative ion yield usually has to be enhanced by adding cesium, which lowers the electron work function of surfaces, and may also serve other beneficial purposes. In addition, there is usually a magnetic field across the extraction plasma to impede the flow of electrons and to alter the energy distribution of those which reach the extraction plane. In addition, an electrostatic bias field is often applied to the plasma near the extraction plane to alter the electron flow. Furthermore, there are perhaps as many as several reactions occurring among charged particles and neutrals in the region of the extraction plasma. All of this makes the real situation complicated, and the exact character of the plasma, and the sheath, whether mainly electron – ion, ion – ion, or more likely, some intermediate state, harder to determine. The further complication of the magnetic fields in the extraction plane renders modeling even more challenging.

Accordingly, detailed modeling of negative ion extraction which tried to incorporate the several intersecting physical processes would be useful, especially if it explored a range of sheath conditions, ranging from essentially pure ion – ion ones to essentially pure electron – ion plasmas, with a range of intermediate conditions. Comparing such modeling to measured quantities in the source and in the extracted beam (divergence, effective temperature, and co-extracted electron fractions, among others) might allow one to set better constraints upon the description of what is occurring in ion source extraction plasmas, and might lead to better extractor and accelerator designs.

Igor Kaganovich, Principal Research Physicist

Larry Grisham, Principal Research Physicist (retired)

Energy Environment RFI

From: ceo@atdco.com
Sent: Thursday, May 15, 2014 9:45 PM
To: Energy Environment RFI
Cc: Jacob G. Appelbaum, PhD
Subject: Stewardship RFI Comments

First of all I would like to express my strong support for the DOE initiative regarding exploratory workshop on Energy & Environmental (E&E) applications of particle accelerators.

I would limit my comments to E&E applications of electron beam accelerators that require high electron beam power at relatively modest electron energies. These E&E applications may include electron beam treatment of gases at atmospheric pressures as well as treatment of flows of liquids and solid particulates organized to enable effective e-beam energy deposition inside the treated volume.

Examples are numerous ranging from removal of SO_{x}/NO_{x} in industrial flue gases to direct conversion of natural gas into hydrocarbon liquids, from recycling of produced water in oil/gas operations and wastewater in oil refineries to treatment of water and soil contaminated by oil spills, and to e-beam driven pyrolysis of biomass particulates to generate stable bio-liquids for use as fuel or specialty chemicals.

High throughput, high energy dose applications listed above require accelerator units featuring electrons with low to medium energies of 0.5-2.5MeV, and in some cases even between 0.75-1.5MeV, and very high e-beam powers in 1MW range.

Two most critical economic parameters of industrial e-beam processing are capital cost per unit of e-beam power ($/MW) and electrical wall-plug efficiency (WPE) of the installed e-beam accelerator respectively. The use of relatively modest electron energies for most E&E applications points out to direct current (DC) e-beam accelerators with demonstrated WPE close to 90-95% for most advanced designs.

Despite some progress in reduction of capital costs in $/MW of installed e-beam power in the past 15 years the achievements have been quite modest and high capital costs per e-beam power remains one of the main hurdles in implementation of e-beam accelerator technologies.

Thus emphasis shall be given to development of new designs of 0.5-2.5MeV electron accelerators to allow further reduction of capital costs initially down to $2M/MW with potential reduction due to economies of scale to $1M/MW of installed e-beam power while maintaining high WPE of 90-95% at e-beam power range of 0.5-1.5MW per accelerator unit.

The new generation of electron accelerators for E&E applications shall feature compact modular skid mounted design that allows ground as well as air transportations, and if desired could be mounted on a floating barge. In turn such modular e-beam machines call for the modular shielding bunkers that are also transportable and easy to assemble at the e-beam processing site.

Particular attention shall be given to the development of versatile e-beam output devices featuring dual-side and multi-side irradiation configurations to further increase e-beam utilization efficiency, to the design of novel composite materials for use in e-beam output foils as well as efficient foil cooling systems to further decrease accelerator maintenance costs.

In conclusion US lags behind other countries such as Russia and Japan in design and manufacturing of compact and potentially transportable, high e-beam power and high WPE DC accelerators capable to of continuous operation in excess of 120,000 hours, and US lags significantly behind countries such as China, Korea, Poland, Bulgaria, Brazil and even Middle East when it comes to practical implementation of e-beam technologies for E&E applications.

So, what do we need to do?

The US government support in advancing accelerator technologies for E&E applications shall be directed to enable multiple collaborative consortiums between US National Laboratories with large human and infrastructure resources and small innovative US companies.

Multiple fast track demonstration projects both in accelerator design and manufacturing and their E&E applications shall be highly encouraged and supported with government funding to the point when such technologies could attract venture capital investment.

Sincerely,

Jacob G. Appelbaum, PhD, CEO
Advanced Technology Development, Inc.
4830 NW 43rd Street, Suite 47
Gainesville, FL 32606-4600
Tel. 1(352) 575-0342 (of)
Tel. 1(215) 917-6404 (mob)
E-mail: ceo@atdco.com

Energy Environment RFI

From:	John Madey <kingcrab@hawaii.rr.com>
Sent:	Wednesday, May 14, 2014 4:24 AM
To:	Energy Environment RFI
Subject:	Optimized inverse-Comptonb tunable X-ray sources as a thrust area for Accelerator Stewardship Program
Attachments:	Cavity-Enhanced X-Ray Sources.pdf

This is to recommend an effort dedicated to the development and commercialization of optimized, integrated, optical cavity enhanced, tunable inverse-Compton X-ray accelerator and analytic systems for includion in the proposed Accelerator Stewardship Program.

The DoE's pioneering efforts to make intense, tunable synchrotron radiation-based X-ray sources available for basic and applied research has proven to have transformative impact in the basic and applied materials, energy and medical sciences. That effort is now being extended to enable the studies at even higher intensities and improved time resolution using the Linac Coherent FEL Light Source at SLAC.

Given these extraordinarily successful pioneering efforts, what is now needed is the means and capability to make a more broadly available, more compact and less expensive version of these pioneering facilities available for the on-site use of the mineral and petroleum, manufacturing, pharmaceutical and pollution abatement industries that could benefit from the integration of X-ray imaging, structural and analytic methods as integrated parts of their own facilities.

The key to the attainment of the high average X-ray beam powers and brightnesses needed for these applications appears to be the use of an optical storage cavity that can integrate the phase-coherent power of a picosecond mode locked laser to achieve the circulating optical powers needed to achieve efficient up-conversion to the X-ray region using a medium energy (29-50 MeV) electron accelerators, an approach that mirrors the development of high Q resonant radio frequencu and microwave structures in years past as the backbone for nearly all present accelerator systems.

Indeed, many of the challenges to be solved in the practical development of such cavity-enhanced inverse-Compton x-ray sources mirror the challenges met- and solved - during the development of present-day accelerator systems, but shifted into the region of optical wavelengths with the special problems that arise from the need for the highly phase coherent, high rep rate laser systems needed to drive these optical storage cavities to the challenge of achieving the nanometer-scale dimensional tolerances and thermal stabilities required for reliable operation.

At the same time, the development of these sources offers the opportunity to capitalize on the advanced status of present day microwave gun, linear accelerator, detector and data acquisition technology, and to achieve - through the integration of the advanced laser systems, optics, and controls needed to achieve the benefits of the use of optical storage cavities in these systems - an impressive range of transformative X-ray source and systems capabilities in the near term and at relatively modest cost.

Special notice should also be given to the unique capabilities of these optimized inverse-Compton light sources to extend the range of photon energies available fot more advanced applications deep into the high energy x-ray and gamma ray regions without the limitations in brightness that apply to the present generation of synchrotron radiation sources.

It further seems to be the preference of the industries that have attempted to use the new X-ray production, imaging and analytic technologies pioneered at the DoE's facilities to avoid approaches that require too many new innovations, building on past capabilities one step at a time to achieve at the lowest cost and with the least risk the advanced capabilities they need to maintain the competitiveness of their businesses. The abaility to realize a transformative X-ray imaging and analytic capability at the user's site relying primarily on the injector, accelerator and instrumentation technologies already in hand with the addition of the new optical storage cavity technology required for operation would appear to constittue a close match to this long-established business model.

For the reasons summarized above, the cavity-enhanced inverse-Compton approach to the production of high aberage power, near monochromatic, tunable X-ray beams appears to be the approach most likely to transition advanced X-ray analytic and manufacturing techniques to the"factory floor", with the possibilities of further, longer range enhancements in source and instrumentation development promising a key, focussed line of development for the DoE.

It would appear that such a program would constitute nearly an ideal fit to the objectives of the proposed new Accelerator Stewardship Program.

Please see the attached paper "Optimized, Cavity Enhanced Sources for X-Ray Microscopy" presented at the SPIE's conference on x-ray imaging last August in San Diego for further information regarding the concept and transformative capabilities of these sources and systems

Please feel free to contact me at madey@hawaii.edu for any further information you may wish to have regarding these sources and systems.

Sincerely,

John M. J. Madey
Professor of Physics and Astronomy
University of Hawai'i at Manoa

Optimized Cavity-Enhanced X-Ray Sources for X-Ray Microscopy

J. M. J. Madey[a], E. B. Szarmes[a], M. R. Hadmack[a], B. T. Jacobson[b], J. M. D. Kowalczyk[a] and P. Niknejadi[a]

[a]University of Hawai'i at Manoa, Honolulu, HI 96822;
[b]Radia Beam Technologies, Santa Monica, CA 90404

ABSTRACT

It is now widely recognized that the intensity and brightness of inverse-Compton x-ray light sources can be enhanced through the use of a high finesse optical storage cavity. But the criteria for the practical use and optimization of such cavities are less well understood. We will review those criteria and their application to the development of an optimized high brightness $5 - 20$ keV inverse-Compton x-ray source under development at the University of Hawai'i.

Keywords: inverse Compton, optical storage cavity, microwave gun

1. INTRODUCTION

The inverse-Compton mechanism for generation of energetic X-ray and Gamma-ray quanta has long been appreciated as possible means to generate such quanta, particularly for imaging or analytical applications requiring spectral resolution, small source size, and low angular divergence. Indeed, interest in these sources has prompted the development of the first successful turn-key commercial inverse-Compton x-ray source designed for laboratory applications by Lyncean Technologies.[1]

Unfortunately, the complexity of the integrated systems needed for operation of such inverse-Compton sources has tended to obscure the aspects of these systems on which their average power outputs depend, and the means whereby the performance of these systems can be optimized for compact laboratory-based applications.

It is the purpose of this paper to review the essential features of laboratory-scale inverse-Compton systems with the objective of identifying the means available to optimize overall system performance, and further to describe the development of a prototype of such an optimized inverse-Compton source at the University of Hawai'i.

2. OPTICAL PULSE FOCUSING

Inverse-Compton light sources operate by colliding high intensity focused and synchronized counterpropagating relativistic electron and optical pulses as shown in Figure 1. Individual electrons propagating as members of the incident electron beam pulse encounter high photon spatial densities in the counterpropagating optical pulse, and absorb, then re-radiate one or more of the individual photons according to the principles of quantum field theory and special relativity. The re-radiated quanta emerge in a $1/\gamma$ cone centered about the electrons' initial vector directions with wavelengths reduced by a factor of $(1 + \beta)^2\gamma^2$ at $\theta = 0$ and shifted slightly to longer wavelengths by their Compton recoils as shown in Figure 2.

The wavelength of the emitted photons further depends on the angle of emission θ, reflecting the angle dependent transformation of photon energy from the electron rest frame to the lab frame in which both the differential scattering rate and the scattered photon energy are strongly peaked in the direction of the electrons vector momenta. For small scattering angles θ, the wavelength of the scattered photons is increased by the factor $(1 + \gamma^2\theta^2)$.

The energy spread of the backscattered photons is usually limited by collimation of the backscattered photons as required to achieve the desired angular spread and spectral distribution.

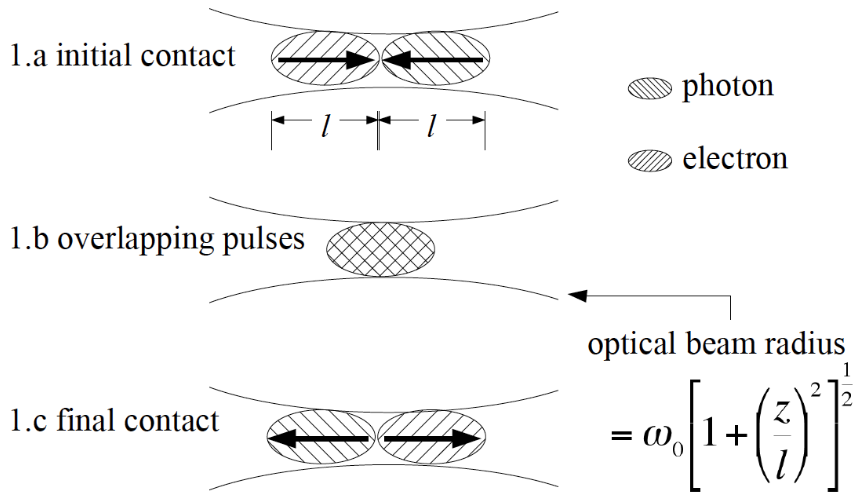

Figure 1. Electrons moving through an optical pulse with a depth of field (Rayleigh parameter) equal to the pulse length l see a nearly constant beam radius.

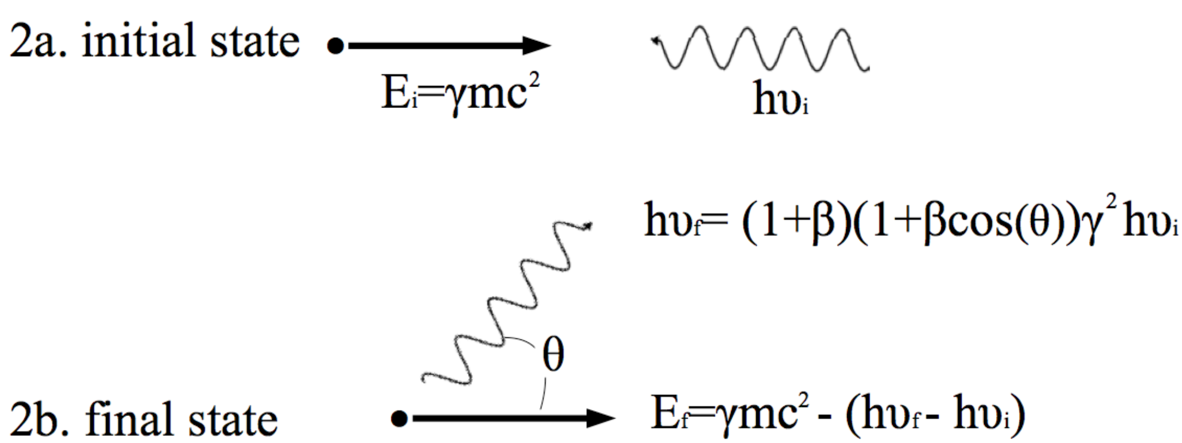

Figure 2. Relationship of the scattering angle θ, initial and final photon and electron energies.

The rate at which the photons comprising the incident optical pulse are scattered by the individual electrons in the incident electron pulse is proportional to the product of the photon spatial density and the Compton cross section. Optimization of the scattering rate required the maximization of the photon density, typically by bringing the incident optical pulse to a focus in the plane at which it collides with the incident electron pulse. The first issue for optimization of these sources is thus the specification of the focal parameters for the colliding pulses relative to their physical lengths.

The focal properties of diffraction-limited optical pulses follow from the properties of TEM_{00} gaussian beams as reviewed in Siegman's classic text on lasers[2] and other optics texts. As related in these works, specification of the focal spot radius determines the beam's depth of field or Rayleigh parameter and also the far field divergence as summarized in the equations:

$$\omega(z) = \omega_0[1 + (z/z_r)^2]^{1/2}\,, \tag{1}$$

$$z_r = \pi\omega_0^2/\lambda\,, \tag{2}$$

Where ω specifies the beam radius at the longitudinal position z, ω_0 the $1/e$ focal spot radius and the Rayleigh parameter z_r the distance from the focus at which the beam radius increases by $\sqrt{2}$.

The photon density at the focal plane can in principle be increased without limit by focusing the incident optical pulse to smaller and smaller spot sizes at that plane. But beam divergence increases in inverse proportion to the focal spot size for both the incident electron and optical pulses, leading to reduced photon densities outside the focal region. Optimal photon density, averaged over the path of the individual electrons in the counterpropagating electron pulse occurs when the optical and electron pulses have the same length and the depth of field, or Rayleigh parameter, for the incident optical pulse is of the order of the optical pulse length as illustrated in Figure 1.

Curiously, the probability that a single electron within the incident electron pulse will scatter a single photon from the counterpropagating optical pulse in this geometry depends only on the instantaneous peak power of the light in the incident optical pulse and is independent of the length of the optical pulse.[3] Longer pulses, focussed to achieve the greater depths of field needed to achieve the greatest time averaged photon densities as seen by counterpropagating electrons, must also have greater focal spot radii leading to averaged photon densities that vary as the inverse of the optical pulse length. The net probability for scattering one of the photons in the incident optical pulse by one of the counter-propagating electrons is thus independent of optical pulse length. .

Although the average radiated power of inverse-Compton light sources can not be increased by increasing the optical pulse length, increased pulse lengths would increase the electrons interaction time with the field and hence the temporal duration of the backscattered photons, thereby reducing their spectral bandwidths. So increased optical pulse lengths can increase the source coherence,[4] making the coherence proportional to the optical pulse energy as opposed to simply the peak optical power.

This effect is significant only for sources in which the bandwidth of the backscattered radiation is not limited by the angular divergence of the electrons in the counterpropagating electron pulse, eg, for e-beam emittances which are small compared to the wavelength of the incident photons and e-beam focal spots which minimize the electrons' angular spread in the plane at which they collide with the counterpropagating optical pulses.

2.1 Non-Linear Effects

Inverse-Compton sources are limited by the onset of non-linear effects that lower the energy of the radiated photons and broaden their spectrum to peak optical powers at which the normalized vector potential a_ω of the optical magnetic field is no greater than unity, typically no greater than 0.3.[5] This constraint restricts the peak optical power P_o to values below the limit:

$$P_0 < a_\omega^2 \left(\frac{mc^2}{e}\right) \pi \frac{c z_r}{\lambda}\ ergs/sec\ [all\ units\ cgs]\,, \tag{3}$$

Assuming an incident optical wavelength of 3 micron, a Rayleigh parameter $z_r = 0.5$ mm, and a limiting vector potential of 0.3, the largest optical power consistent with operation in the linear scattering regime would be 500 gigawatts, a modest number by the standards of present chirped pulse laser systems.

2.2 Average Optical Power Limited by Thermal Distortion

The modest allowable peak optical power and pulse energies for these inverse-Compton sources, together with the low probability of scattering by the individual electrons, suggest that the required optical pulses can most effectively be generated by accumulating the phase coherent optical pulses from a lower power pump laser in a low loss optical storage cavity. Another limit to the peak power of the optical pulses available for use in these cavity-enhanced inverse-Compton light sources is thus set by the inevitable thermal dissipation in the mirrors of the cavity due to their small but finite absorption and scattering loss coefficients.

The figures of the mirrors for storage cavities designed to achieve the small focal spot sizes, focal spot positions, and cavity round trip transit times must be held to exacting tolerances. Experience with the design and operation of comparable resonator mirrors for high average power lasers suggests that the dissipation attributable to the absorption of circulating optical power in these cavities must be held to no more than $1 - 10$ watts. Making allowances for the incident laser power reflected from the input couplers for these cavities, these numbers also define the maximum average power of the pump laser that can be used with these cavities.

The maximum optical pulse energy that can be injected into such a cavity is therefore equal to this thermal limit ($1 - 10$watts) divided by the systems macropulse rep rate, eg, the number of times per second that the cavity is pumped to achieve the circulating powers required for operation. Typical rep rates might range from $100 - 1000$ Hz, allowing dissipated optical pulse energies of from $1 - 100$ millijoules per macropulse.

For purposes of estimation, it is useful to assume that the temporal duration of each injected macropulse is of the order of the cavities free $1/e$ decay time. These numbers ($1 - 100$ millijoules) then represent the maximum possible optical energy that can be stored in the optical cavity during each macropulse.

As will be seen further below, the practical limits to the amount of charge that can be accelerated to the energies required for operation of these inverse Compton sources, of the order of 100 picocoulombs, indicate that the high average electron currents required for operation of these inverse-Compton light sources can only be achieved through operation of their injector and accelerator systems at GHz micropulse repetition rates. It is only at these rates that sufficient numbers of electrons can be directed into the aforementioned optical storage cavities to generate useful quantities of backscattered inverse Compton x-ray or gamma ray photons.

Accordingly, the number of optical micropulses stored at any given time in such optical storage cavities will be of the order of the product of this micropulse repetition rate and their round trip transit times within these cavities. Assuming a GHz rep rate and a 10 nanosecond round trip transit time, that number would be of the order of 10.

With these assumptions, the maximum energy of any single optical pulse in one of the aforementioned optical storage cavity would be of the order of $0.1 - 10$ millijoules. Given typical optical and electron pulse lengths durations of the order of 3 picoseconds, the instantaneous peak power of these circulating pulses could, on the basis of thermal distortion, be no more than $30 - 3000$ megawatts.

It is truly fortunate - if unanticipated - that the practical possibility exists to generate such high but nonetheless modest (by current standards for chirped pulse laser systems) peak power optical pulses in a system configuration that makes possible operation with modest mode locked, phase coherent pump lasers. If the limit to the stored optical pulse energy set by thermal dissipation was lower, the average power output of these cavity-enhanced sources would be limited to a small fraction of that allowed by the underlying physics of the relevant inverse-Compton scattering mechanisms.

2.3 Optical Storage Cavity: Degrees of Freedom

Realization of the micron-scale focal spots needed to optimize the Rayleigh range of the picosecond optical pulses used in inverse-Compton light sources dictates the use of a near-confocal resonator. While that geometry offers the advantage of substantially reduced optical power densities at the resonator mirrors, its sensitivity to errors in the figure and spacing of the resonator mirrors make the near confocal geometry a difficult choice for actual use.

In fact, it is impossible to control both the Rayleigh parameter and the cavity round trip transit time as required to maintain the phase of the circulating optical pulses with the phase of the incident electron pulses and the incoming pulses from the cavitys FEL pump laser with a simple two mirror resonator.

Accordingly, it has been necessary to increase the optical storage cavity's degrees of freedom by implementing a modified four-mirror cavity design as described in the prior literature.[6] While the introduction of these additional optical surfaces do not alter either the peak or average power limits applicable to the optical pulses circulating in the storage cavity, they do significantly complicate the cavity's optical design and also the diagnostics and controls needed to maintain the stability of the cavitys focus and round trip transit time.

3. ELECTRON PULSE FOCUSING

Referring now to the optimization of the equally important electron pulses, particle beams in which the boundaries of the particle's distribution in the two dimensional (x, p_x) and (y, p_y) projections of the particles 6-dimensional phase space distributions can be approximated by simple ellipses having envelopes which have the same form, radial sizes, and angular divergences as the envelope of a TEM_{00} gaussian mode with wavelength equal to the area in phase space that is enclosed by these boundaries when divided by $\beta\gamma mc$.[7] That renormalized area is commonly referred to as the emittance of the e-beam in the (x, p_x) or (y, p_y) phase space.

Typical emittances for the accelerator systems considered for use in inverse-Compton light sources are of the order of a small fraction of the wavelength of the photons in the incident optical pulse, making it possible to focus the electrons to spot sizes much smaller than the optical spot size at the same Rayleigh parameters.

It might seem from the similarity of the envelope equations for the focussed electron and optical pulses that the incident electron pulses in Figure 1 should be focused to the same Rayleigh parameter as for the incident optical pulses, eg, a Rayleigh parameter equal to their pulse length. But that conclusion would not address the effects of the electrons angular divergence on the spectral widths of the backscattered high energy quanta. As noted briefly above, the wavelength of the photons scattered at an angle θ relative to the electrons' velocity vectors is shifted to longer wavelengths by the factor $(1+\gamma^2\theta^2)$. Accordingly, to minimize the electrons inevitable spread in angular divergence on the spectral width of the backscattered quanta the angular divergence of the electrons interacting with the photons in the incident optical pulse must be kept to a minimum.

From Liouville's theorem, the area of the electrons' phase space projections remains constant as the electrons drift through space. Accordingly, the electrons' spread in transverse momenta, proportional to the spread in angular divergence, will be minimized when their spread in transverse position is increased to the maximum value compatible with full coupling to the optical field as they drift through the focus of the incident optical pulses. The electron pulse in Figure 1 should therefore be focused to yield a spot size equal approximately to the focused spot size of the optical pulse to minimize the electrons' angular divergence while maintaining full coupling to the photons in the incident optical pulse.

It also follows from these considerations that the electron sources and accelerators used in these inverse-Compton light sources must be designed to achieve emittances that are small enough in comparison to the wavelength of the incident photons to insure that the square of the product of their angular divergence and Lorentz factors γ at the focal plain is less than the desired fractional spectral width of the backscattered high energy quanta.

3.1 Criteria for Selection of Electron Beam Source

By these means, the probability for scattering individual photons by the individual electrons in the optical and electron pulses of Figure 1 can be optimized without compromising the intrinsic spectral width of the backscattered photons. Having addressed these issues, the remaining challenge is to find and implement the means needed to maximize the number of electrons in the electron pulses of Figure 1 that actually collide with the counterpropagating optical pulses.

To recast this challenge in quantitative terms, what amongst the presently available means can generate the largest number of electrons in the format and time frame needed to collide with the optimized optical pulses discussed above? Equivalently, which amongst the presently existing technologies for generation and acceleration of relativistic, low emittance electron pulses can provide the highest average current when operated to provide the electron pulses in the format needed for operation of these inverse-Compton sources???

Given that average current, the average radiated power of such an optimized inverse Compton radiation source, averaged over all angles of emission and final state photon energies, is:[3]

$$< P >= \frac{2\pi^2}{3} r_0^2 \frac{P_0}{c\lambda_f} \frac{< i >}{e} \; ergs/sec \; [all\ units\ cgs] \,, \tag{4}$$

where $r_0 = 2.8 \times 10^{-13}$cm and λ_f=backscattered photon wavelength.

The optimization of average x-ray radiated power thus requires the optimization of the product of peak optical power and time-averaged current of the electrons in the pulse trains formatted to interact with the incident optical pulses.

A wide variety of electron sources are available and have been considered for use in connection with these inverse-Compton light sources. including laser pumped photocathode guns coupled with normal or superconducting accelerators, thermionic microwave guns coupled with pulsed room temperature linacs, and laser wakefield electron sources and accelerators. The charge per second that these sources can inject into the electron pulse format needed to collide during every pulse with the optical pulses circulating in an optimized optical storage cavity as described above are listed in Table 1[8–10] for a macropulse rep rate of 100 Hz.

Table 1. Time Averaged Currents for Candidate Electron Sources.

	Thermionic Microwave Gun	Laser Photocathode Super -conducting Accelerators	Laser Wakefield Accelerator
Charge /micro-pulse (picocoulombs)	70	11	10
Micropulse Rep Rate	2.9 GHz	88 MHz	1 kHz
Micropulse Length (microseconds)	8	8	8
Macropulse Rep Rate (Hz)	100	100	100
Time-Ave Current (microamperes)	160	0.77	0.001

The average electron current available from these sources, as defined above, is highest for microwave thermionic electron guns based on their ability to operate at the GHz rep rate electron pulse trains needed to interact with the GHz rep rate optical pulses circulating in reasonably-dimensioned optical storage cavities as described above. These thermionic microwave guns also have the demonstrated emittances needed to achieve the narrow linewidths typically regarded as desirable for high power inverse-Compton light sources.

The next best choice for service as an electron source for these sources is, according to Table 1, laser photocathode superconducting accelerator technology. But the lower charge per bunch and electron pulse repetition rates of these sources leave them at a fundamental disadvantage as compared to accelerators based on thermionic microwave gun technology, as summarized in Table 1.

The constraints on pulse format imposed by the use of optical storage cavities could in principle be relieved by dispensing with this storage cavity means and returning to the use of a high peak power laser pump operated to deliver optical pulses in the format favored by the proposed electron source technology. But the loss in peak optical power implied by a transition to cw operation would drastically reduce the average radiated x-ray power and brightness at the average currents for those alternate electron sources

Accordingly, the most favored choice for use as an electron source for optimized inverse-Compton light sources appears to be thermionic microwave gun technology with its capability for operation at high GHz rep rates, high charge per micropulse, and low emittance.

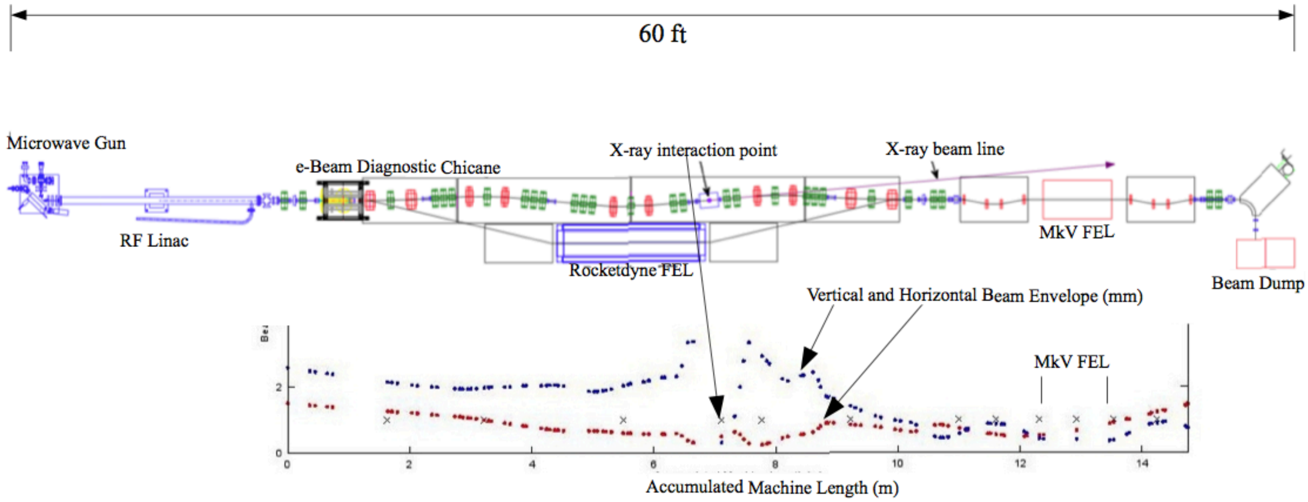

Figure 3. Scale drawing to University of Hawai'i optimized inverse-Compton x-ray source: beam line schematic and the micro focus solution.

4. DESIGN OF THE OPTIMIZED UH INVERSE-COMPTON X-RAY SOURCE

It has been these considerations that have led to the design for an optimized inverse-Compton x-ray source prototype at the University of Hawai'i. The electron source for the system, a high charge per bunch, 3 GHz rep rate thermionic gun serves as the injector for a 45 MeV SLAC-type linac. As shown in Figure 3, the electron pulses from the linac in the UH design are first brought to a focus to collide with the optical pulses circulating in a specially designed optical storage cavity, then refocused to drive a mid infrared, phase-locked infrared free electron laser whose output is mode-matched to coherently pump the circulating optical pulses in the storage cavity.

Most of the accelerator, beam transport, FEL and power subsystems shown in Figure 3 predated this project. But in addition to the new optical storage cavity needed for this project, major upgrades to the high power rf system to achieve the phase and energy stability needed for operation,[11] and to the diagnostics and controls needed to measure, control, and stabilize the transverse positions of the colliding 30 micron radius electron and optical pulses[12,13] have been implemented as reported in the prior literature.

The design of the optical storage cavity for this system must fulfill the multiple, potentially conflicting objectives regarding the simultaneous stabilization of the position and Rayleigh parameter for the cavity's optical focus, its round-trip transit time, the frequency of its longitudinal modes relative to the modes of the pump laser's resonator and the phase of the incoming electron pulses. These unique and unprecedented optical requirements, together with the active controls needed achieve these functions, have constituted the project's major new engineering effort.[14]

The third major engineering effort has been required to stabilize the energy, phase and pulse shape of the electron pulses generated by the systems microwave thermionic gun against the adverse effects of time dependent beam loading due to the change in cathode temperature during each macropulse. The stability of the temperature of the emitting surface of the cathode in this approach is achieved by pre-heating the cathode surface with a microsecond-duration 100-millijoule level IR laser pulse. The decay in cathode surface temperature due to diffusion of this thermal pulse into the body of the cathode compensates for the rise in temperature during the subsequent emission of the electron pulses needed for system operation, stabilizing those pulses against the effects of time-dependent beam loading.[15]

4.1 Projected Specifications

The projected specifications for this systems are as summarized in Table 2. The peak circulating optical powers, electron pulse charge, optical and electron pulse train duration and rep rates are based on the actual historical performance of the system's microwave thermionic gun and FEL pump, limited as required by the fundamental constraints on the peak and average optical powers of the optical pulses circulating in the optical storage cavity as elaborated above.

Table 2. Operating parameters, Average Power Output and Brightness for the UH Optimized Inverse Compton X-ay Source.

Pump Laser Wavelength	3 μm	Storage cavity length	0.472m
Pump Laser Peak Power	4 Mwatt	Laser and e-Beam radii at focus	24 μm
Pump Laser and e-Beam Micropulse durations	2 psec	Peak circulating optical power	3 Gwatts
Pump Laser and e-Beam Micropulse rep rate	2.9 GHz	Average radiated x-ray power	0.5 mwatt
e-Beam Macropulse Length	8 μsec	X-ray photon energy	13 keV
Pump Laser and -Beam Macropulse rep rate	20 Hz	Average radiated x-ray Brightness	1.3×10^{12}*
Time-averaged electron current	30 μA	$*Photon/sec - mm^2 - mrad^2 - 0.1\ \%Bw$	

The data in this table assumes a macropulse repetition rate of 20 Hz to minimize the risk of thermal distortion of the mirrors for the optical storage cavity. Higher repetition rates may prove possible. Operation at the 100 Hz macropulse repetition rate assumed in Table 1 would increase the average radiated x-ray power and brightness by a factor of five.

The forthcoming tests of this prototype system to operate at its design specifications clearly represent a key test of the criteria for inverse-Compton source optimization as elaborated above as well as the functionality of the engineering solutions developed to support operation as outlined in section 4.0 above.

The forthcoming tests of this system may also prove decisive with respect to the future direction of compact laboratory-scale x-ray source development as can be inferred from a comparison of the brightness projected for the optimized UH inverse-Compton x-ray source and the brightnesses presently delivered or estimated for the major competing source technologies. Of particular note, the projected time-averaged brightness for the UH x-ray source is five orders of magnitude higher than the brightness presently achieved by Lyncean's compact storage ring inverse-Compton source,[16] and within one order of magnitude of the brightness projected for the proposed $50 million dedicated regional storage ring-based bend magnet soft x-ray sources.[17]

The UH inverse-Compton source is also superior in its ability to generate higher energy x-rays or gamma rays by increasing the length or number of sections of its linac or decreasing the wavelength of its laser pump. The use of a tuneable FEL as a laser pump for the systems optical storage cavity also offers the unique capability to quickly and easily shift the wavelength of the generated x-rays for measurements of differential absorption or differential fluorescence yields. Multiple, independently pumped optical storage cavities could also be added to the UH design to provide multiple independently tunable x-ray beam lines for simultaneous use in different experiments.

The projected ability of the optimized UH inverse-Compton x-ray light source to exceed or nearly match the capabilities of the presently existing or proposed new x-ray sources will need to be carefully considered in future decisions regarding the directions for source and facilities development in this field.

4.2 Present Status

The microwave gun, linac, phase-locked pump FEL and their new diagnostics and controls are presently operational. This next year will be devoted to tests of the ability of these subsystems to achieve and maintain the precisely positioned, phased and focused electron and optical pulses needed for operation of the integrated system.

Bench tests of a prototype optical storage cavity and its diagnostics and controls to validate the design of these subsystems are also planned for this next year. Tests of the integrated system UH inverse-Compton x-ray source are planned for 2015 contingent on the availability of funds for those tests.

Discussions are also currently underway to explore the possible integration of the UH inverse-Compton x-ray source with a zone-plate based 10 keV x-ray microscope.

ACKNOWLEDGMENTS

This work was supported in part by the Department of Homeland Security through grants number 2010-DN-077-ARI045-02 and 2011-DN-077-ARI055-02.

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Energy Environment RFI

From: Colby, Eric
Sent: Wednesday, May 14, 2014 11:29 AM
To: Energy Environment RFI
Subject: FW: Stewardship RFI Comments.

From: jwylie39@aol.com [mailto:jwylie39@aol.com]
Sent: Friday, May 09, 2014 11:16 PM
To: Colby, Eric
Subject: Stewardship RFI Comments.

I applaud the initiative of the DOE in formulating a new program in Stewardship of Accelerator Technologies for Energy and Environmental Applications. It is urgent that such an initiative take place.

I am an engineer that has worked in the food production and processing industry for much of my life but I began my career in the design of booster rockets for the Apollo program. The can-do and must-do attitude of the Apollo program was essential to the sending of a man to the moon. I think a similar program to bring fusion power on-line within a decade would be very useful for the US at this time. It would help provide national energy security, provide base-load power, and create hundreds of thousands of well paying jobs. And it would be a beginning step to get the world off of coal and thus save the environment. In the food-processing business I made my reputation by Applying known technology to problems that had not been solved. Look, study, listen, and apply with leadership.

We need to approach our energy-economy-environment problem the same way that the Apollo program approached the landing on the moon. We urgently need a large solution – not a bunch of photocells or wind machines that only work part of the time. We must have a new source of cheap base load energy.

I made an extensive review of our alternatives some years ago for my own education and planning purposes. I was discouraged by what I found. Ideas are plentiful but successful demonstrations are rare and most of them are self serving or depend upon government subsidy. Fusion was the one exception. But alas, there is no source of funding to pursue fusion at either a small or large scale.

Thus your new program is a breath of fresh air. Solving the energy problem is the only way to solver the environmental one. We cannot manage climate change without rapidly decreasing our carbon based fuel consumption. And we cannot afford the unwanted consequences of fission energy – its long term storage of highly radioactive material that in the wrong hands can be use to make devastating weapons. We must have fusion brought on line as soon as possible.

As a young engineer in the 1970's I heard about the potential about the use of heavy ions beam as drivers of the fusion reaction. This was very promising and I understand that process was endorsed by hundreds of scientists as the conservative way to approach fusion. But then all the discussion died and we suddenly were using lasers and magnetic fields to do the job that particle accelerators were supposed to do. Now, three decades later, were are no nearer to a successful fusion system than we were decades ago. But now we have a major energy problem staring us in the face. We need a solution and your program seems ideal for that purpose.

But having been part of the Apollo program I know the need for leadership, not stewardship. Stewardship tends to preserve the status quo while leadership sets a high goal and steadfastly demands that they be achieved. We need leadership in energy – not stewardship.

You need to formulate your program to provide a focus, a goal, and to provide leadership – preferable as a presidential directive just like Kennedy did for the Apollo program. John V. Wylie, BSME UC Berkeley, 1962. Retired. Phone in Mexico, from US 01152-443-323-6109

Energy Environment RFI

From: Vuskovic, Lepsha <lvuskovi@odu.edu>
Sent: Monday, May 19, 2014 3:37 PM
To: Energy Environment RFI
Subject: RFI
Attachments: RFI.docx

Dear colleagues,

You will find in the attachment a RFI on "Plasma Science for Accelerator and Accelerator-Driven Systems."
Our multi-institution team is very enthusiastic to support the Stewardship Program.

Sincerely,

Lepsava Vuskovic
Professor of Physics
Old Dominion University

Plasma Science for Accelerators and Accelerator-Driven Systems

Old Dominion University

Thomas Jefferson National Accelerator Facility

Princeton Plasma Physics Laboratory

In reply to the Notice of Request for Information (RFI), Old Dominion University (ODU), Thomas Jefferson National Accelerator Facility (TJNAF) and Princeton Plasma Physics Laboratory (PPPL) are hereby expressing the commitment to participate in the proposed new Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications. PPPL and ODU research teams are already working on a number of projects supported in part by DOE. Those projects could be grouped together in a R&D sub-program with a tentative common title **"Plasma Science for Accelerators and Accelerator Driven Systems"**, which would cover most of the application areas of high impact from the list No.1. The program would be concentrated around an experimental accelerator-driven system with the objective to test the ideas and concepts proposed for the new accelerator technology, study beam-matter interaction, propose new application projects, and provide guidelines for the development of industrial and environmental accelerator-driven systems.

Our current activity combines expertise in various aspects of plasma physics, atomic collision, and gas discharge physics, employed to advance plasma science that aims to resolve a number of problems faced in the progress of contemporary accelerators, accelerator-based light sources, and accelerator-driven systems. Our ODU team is developing plasma processing (etching, thin film deposition etc.), plasma cleaning, and beam production technologies, all for the purpose of improving performance of the accelerator cavities or inventing and advancing new compact light sources and accelerator-driven systems. There is still a wide gap in the understanding of practical plasmas in the accelerator cavities, which are a rather complex medium governed by physical laws involving their composition, structure, electromagnetic fields, radiation, and interfaces with solid or liquid walls. As a consequence, the accelerator science per se is full of unresolved problems related to plasma-solid interfaces and the dynamics of non-neutral plasma systems. Phenomenology of the plasma-solid interface includes a rich collection of surface processing and plasma structure examples that still remain unexplained and utilized in practice. We are developing generic experiments and models that reflect the actual geometry and processing objectives of accelerator cavities. In a separate set of experiments we are studying charged particle transport from the solid side of the solid/vacuum interface of contaminated walls at actual operational conditions to resolve the effect of secondary electron emission on the multipactor and field emission phenomena.

Accelerator-driven systems involve interaction of the particle beam with solid, liquid and gaseous matter. A particle beam typically consists of an electron or ion "bunch", which are essentially one-component plasmas (OCP). Therefore, beam-target interaction is carried on in the collision of the OCP with a solid, liquid or gaseous target. The phenomenology of beam-matter interaction is rich in effects that require quantitative description in the terms of plasma and fluid dynamics, and the development of relevant insight and knowledge requires expertise beyond the realm of nuclear physics and accelerator science.

This plasma science program will build on the studies performed in recent years that have demonstrated the effectiveness of ionizing radiation including electron beams or in combination with other treatments, in the decomposition of refractory organic compounds in aqueous solutions and in the effective removal or inactivation of various microorganisms and parasites. The application of electron beam processing for drinking water, wastewater and groundwater treatment offers the promise of a cost effective processing.

The program will contribute to the development of a system that will lift the state of accelerator research in the United States, which is in threat of losing the leading status that it has in this area. There are a few examples in the world of the direct application of accelerator-driven system in industrial and environmental application. For instance, the MYRRHA project in Belgium will demonstrate an accelerator-driven system for producing nuclear power and transmuting nuclear waste to a form that decays much faster to a stable non-radioactive form. In China and Poland, accelerators are used for treatment of flue gases and their conversion into fertilizers. An industrial-scale water treatment plant using electron beams is operating in Daegu, Republic of Korea, to treat industrial-size textile wastewater. It has demonstrated that the process is a cost effective technology when compared to conventional treatment. The regular operation of this facility provides operational data on reliability and additional data for a detailed economic evaluation. It is our intention to test our own, current, and proposed design ideas for technically and financially sound accelerator treatment projects.

In the United States, which has traditionally led the world in the use, development, and application of accelerator technology, current focus is on nuclear and particle physics programs. To achieve the potential of particle accelerators to address national challenges will require a sustained focus on developing transformative technological opportunities, accompanied by changes in national programs and policy. Our proposed collaboration would constitute an example of such activity, and we believe that it would respond directly to the Stewardship Program.

The central unit of this sub-program would be a compact high-current, high-power (1-5 MW), and moderate-energy electron beam accelerator. The size of this accelerator, based on the superconducting radio-frequency technology, would be up to 10 m, so that it can be installed at the PPPL, together with target and instrumentation units. The accelerator will serve to study the plasma and fluid dynamic problems of high-power beam interaction with solid, liquid, and gas target materials of interest for the development of energy and the environment. The accelerator would be designed and built by TJNAF Center for Advanced Studies of Accelerators (CASA) and Accelerator Science Divisions with the help of ODU's Center for Accelerator Science and commissioned by PPPL, specifically for pulsed power, plasma, and fluid dynamic studies of the beam-target interactions. The Stewardship Program requires synergy of a multitude of disparate expert approaches. Most current beam-target interaction projects are conducted by nuclear physicists. However, large industrial projects involving accelerator-driven systems require plasma physics and fluid dynamic expertise that will be provided by PPPL.

Our goals are to perform research, develop guidelines, acquire and transfer practical knowledge for designing and building the wastewater and effluent gas treatment plants, and probably nuclear waste treatment facilities. We are currently preparing detailed experimental plan to address these problems, which we intend to contribute in future workshops on this Stewardship Program.

ODU's Center for Accelerator Science:
Leposava Vuskovic, Professor and Eminent Scholar
Svetozar Popovic, Research Professor

TJNAF:
Geoffrey Krafft, Director CASA

PPPL:
Yevgeny Raitses, Principal Research Physicist
Igor Kaganovich, Principal Research Physicist

Energy Environment RFI

From: Kemp, Mark <mkemp@slac.stanford.edu>
Sent: Tuesday, May 20, 2014 12:35 AM
To: Energy Environment RFI
Cc: Fazio, Michael V.; Hettel, Bob
Subject: Stewardship RFI Comments

1. What are the most promising applications of accelerator technology for energy and environment?

The 2009 Executive Order 13514 requires 28% greenhouse gas reduction at United States federal research facilities. As RF systems have a very large impact on power usage, improving efficiency will reduce greenhouse gasses, and therefore directly address the presidential mandate. However, not only large accelerator laboratories benefit from improved RF systems. A recent DOE report identified RF sources as a very high priority for applications in industry, energy and the environment, defense and security, and discovery science.

As such, RF source efficiency is a challenge that is important to both DOE accelerator laboratories as well as commercial entities. Focused R&D on this important technology will have far-reaching benefits.

3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?

a) Reduction in total energy consumption per year

b) Percentage energy consumption reduction for the particular process

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

There are still technical hurdles which must be overcome for very high efficiency, high power RF systems. Without a proven technology, commercial entities will be slow to adopt. DOE laboratories can help jump-start new technologies.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

For commercial applications, the present RF systems provide mediocre performance. However, high performance RF sources may provide additional capability that is presently not achievable (e.g. operation in remote environments with little power).

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

There are relatively few US commercial developments on high-efficiency RF sources. There is some development activity in both Asia as well as Europe on high efficiency sources; primarily stemming from accelerator laboratories. There is some activity at SLAC on high efficiency vacuum electronics.

11. What are the perceived and actual market barriers for the final product?

One perceived barrier is reliability and operational experience with a new product. In many cases, commercial entities are risk-adverse when developing new designs. Much of the time, old designs are recycled. This prevents wholesale improvement upon the state of the art.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

System level integration will likely be non-proprietary, but particular components or aspects of the design may become proprietary.

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

RF source development typically replies upon a combination of design and engineering expertise as well as manufacturing and test capabilities. There are relatively places in the US which would be able to successfully produce a technology from scratch.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

The best R&D would likely be a partnership between industry and a national lab. Certain national labs can produce the designs through the prototype and testing phases, but the design and final versions should be developed in industry/lab partnerships.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Partnering with a National Laboratory would be critical in any development. SLAC National Accelerator Laboratory would provide the greatest leverage.

20. In what ways are the R&D needs not met by existing federal programs?

For accelerator programs, RF sources are developed specifically for accelerator needs. What is needed is a complementary program for commercial needs. In this way, both areas benefit.

21. At what point in the manufacturing development cycle would external support no longer be needed?

Once a full-scale product is developed, industry should take over the development process.

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Mark Kemp, Ph.D.
2014 IPMHVC Technical Program Co-Chair
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Energy Environment RFI

From:	Peter McIntyre <mcintyre@physics.tamu.edu>
Sent:	Monday, May 19, 2014 7:10 AM
To:	Energy Environment RFI
Cc:	Colby, Eric; William Horak; Saeed Assadi; Nathaniel Pogue; Phongikaroon, Supathorn; Michael Simpson
Subject:	Stewardship RFI Comments
Attachments:	ADAM white paper.pdf; ADAM overview.pdf; Strong focusing cyclotron.pdf; financials 5-19-2014.xls
Importance:	High

Attached are files concerning a breakthrough technology for using high-power proton beams to destroy the transuranics in spent nuclear fuel. I believe that this could prove to be the most important appellation of accelerators ever in history.

Respectfully submitted,

Dr. Peter McIntyre
Mitchell-Heep Professor of Experimental Physics
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Accelerator-Driven Subcritical Fission in a Molten Salt Core: cost-effective destruction of transuranics in spent nuclear fuel

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A collaboration of scientists at Texas A&M University, Brookhaven National Lab, the University of Utah, and Virginia Commonwealth University are developing a method for accelerator-driven subcritical fission in a molten salt core (ADAM) that can destroy the transuranics in spent nuclear fuel (UNF) and pay for the process by selling the co-generated electricity at a levelized cost of electricity (LCOE) of $80/MWh(2013). This accomplishment is a game-changer that could resolve the long-standing nuclear waste dilemma and remove one of the most dangerous safety issues that has undermined public support for nuclear power.

The transuranics in spent nuclear fuel (UNF) are the most enduring hazard of nuclear power. The transurances are the elements beyond uranium in the periodic table. Only trace abundances exist naturally on Earth because they are all radioactive, typically by emitting an energetic alpha particle. They are extremely radiotoxic, and most have decay half-lives of 10,000-200,000 years. They are made in abundance as an unwanted byproduct of nuclear fission: on average transuranic nuclides are produced by neutron capture on ^{238}U at about the same rate as ^{235}U nuclides fission in a power reactor. The transuranics are chemically active metals, and most are highly soluble in ground water.

Present-day nuclear policy is based upon a once-through strategy. A power reactor operates with a ~90 ton fuel assembly, the reactor operates for 5 years using that fuel, then the fuel assembly is replaced and the spent fuel is stored indefinitely, not reprocessed. The spent fuel contains ~0.6 ton of fissionable ^{235}U, 1.8 tons of transuranics, and 6 tons of fission products. The accumulation of spent fuel has is now 70,000 tons, with a total radiotoxicity of $>10^{13}$ Sv (one Sv of ingested radiotoxic element can produce a significant risk of death). Long-term storage is a dubious option. The thin zircaloy cladding on fuel pins was designed to be stable against corrosion for a century; how can Man possibly assure isolation of such a lethal substance for 300,000 years into the future? The only responsible thing to do with the transuranics in spent nuclear fuel is to destroy them. The challenge is how to do so affordably.

Attached are two papers that describe the ADAM technology and the technical innovations that make it possible. The transuranics are extracted into molten salt using the processes of electroprocessing that have been developed and proven at ANL, INL, and PRIDE. The fuel salt is transferred to a subcritical core vessel, in a configuration that has a criticality of 0.97. Fission is driven by injecting a beam of 800 MeV protons directly into the molten salt. The ADAM core is designed to support an ultrafast neutron spectrum that is required to effectively drive fission in the transuranics. That requirement limits the size of each core to ~1.7 tons of TRU (the TRU content extracted from one batch of UNF), which generates 290 MW_{th} of fission heat. The ADAM core operates in the temperature cycle 575-675 C, which provides >40% system efficiency for electric generation. Allowing for the house power needed to operate the accelerator, each ADAM core produces 90 MW_e of net electric power.

The idea of using ADS fission to destroy transuranics has been proposed many times. The key issue that makes or breaks it is the economics: *can ADS destruction of transuranics pay for itself?* The answer to that question depends critically upon the amount of proton beam power that can be realistically produced by an accelerator, and the cost and complexity of the overall system. ADAM utilizes a new innovation in accelerator technology, the strong focusing cyclotron (SFC) which is described in an accompanying paper. By integrating strong-focusing in an isochronous cyclotron a CW current of >12 mA can be accelerated to 800 MeV. That is 6 times more beam power than has ever been possible, and truly opens a new chapter for high-power applications of proton accelerators. As will be seen below, ADAM makes it possible to put transuranic destruction into practice in-scale to the huge inventory, and *ADAM facilities can pay for themselves with a levelized cost of electricity of $80/MWh(2003), comparable to gas-fired electric generation*

We have developed an overall plan for the phased development of ADAM. Phase 1 is a 3-year period of R&D during which prototypes of all core technical innovations are built and tested in practice.

Phase 2 is the 3-year construction and operation of a subscale ADAM core, which is driven by a 150 MeV SFC to produce a criticality of k_{eff} ~0.5, and generate ~6 MW_{th} of fission heat. The subscale unit could be commissioned first with a lanthanide surrogate salt, so that many of the critical systems for a full-scale ADAM unit can be tested in operation before any actinides are introduced into the core.

Phase 3 is the 2-year construction and operation of a first ADAM system driven by an 800 MeV, 12 mA SFC. These three developmental phases have a total projected cost of $1 billion, and would be funded by federal grants, either from DOE or from the Nuclear Trust Fund.

Phase 3 is the construction and operation of the first full-scale ADAM facility, housing a 4-in-1 SFC stack driving 4 290 MW cores. The construction of the facility would be financed by $2 billion of industrial revenue bonds, with yield of 4% which is typical today for utility construction bonds. Because ADAM is a new technology, it will be necessary for the federal government to guarantee the bonds for the construction of the first unit. Thereafter the track record of the first unit should provide sufficient risk reduction to support conventional bonds, and indeed the revenue stream from the first facility would provide sufficient operating capital to build a second unit within ~5 years after it retires its bond debt.

The financials for the above scenario are presented in the attached spreadsheet. Its assumptions are as follows:

- Electric power revenues of $80/MWe.
- Bond financing at 4% yield, interest paid as accrued and principal retired by year 18.
- UNF disposal fee of $365/kg fee charged to the Nuclear Fuel Fund for the UNF that is processed to destroy its transuranics and safely dispose of its fission fragments. That is the amount which DOE has collected from utilities for this purpose. We assume that it is paid to the venture when the UNF is processed to extract the transuranics into molten salt.
- Disposal of fission fragments in stabilized forms in conventional medium-level disposal sites – fee currently ~$1000/ton.
- Inflation of 3%/year.

ADAM is the first-ever method by which UNF can be processed to remove and destroy the transuranics and safely store the shorter-lived fission products, in a financial picture in which the method pays for itself with an LCOE that is in line with present commercial rates. It is a true game changer for removing the most enduring hazard of nuclear power safely and economically. It is only possible thanks to the development of the strong-focusing cyclotron, and we propose support for the phased development within DOE's envisaged Stewardship Program.

ACCELERATOR-DRIVEN SUBCRITICAL FISSION TO DESTROY TRANSURANICS AND CLOSE THE NUCLEAR FUEL CYCLE*

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Abstract

A design for accelerator-driven subcritical fission in a molten salt core (ADAM) has been made for the purpose of destroying the transuranic elements in used nuclear fuel as fast as they are made in a conventional nuclear power plant. The oxide fuel is extracted from the used fuel assemblies into molten chloride salt using pyroprocessing, and the transuranic, uranium, and fission product salts are separated into three batches using electroseparation. The transuranic salt is then transferred to a subcritical core, with neutron gain 0.97. The core is driven by 800 MeV proton beams from a 12 mA CW strong-focusing cyclotron. The transuranics are destroyed and the fission heat is used to produce electric power. Simulations of many potential failure modes have been performed; the core cannot reach criticality in any failure-mode scenario considered. It operates as an energy amplifier with an energy gain ~5.5.

INTRODUCTION

Today nuclear power plants generate 20% of the electric power in the United States [1]. Until recently nuclear power comprised 20% of the grid in Germany and 30% in Japan, but Germany has moved to end their nuclear power production and Japan has idled their reactor fleet. Those decisions reflect a growing public concern about the safety of nuclear power. The meltdowns at Three Mile Island [2], Chernobyl [3], and Fukushima [4] underscore that this abundant source of energy can also produce extreme hazards.

The most enduring hazard of nuclear power is the large quantity of hazardous radioisotopes in used nuclear fuel (UNF). The most dangerous among those are transuranics (TRU, elements beyond uranium in the periodic table). The transuranics contained in the ~70,000 tons of UNF in the US have a radiotoxicity $>10^{13}$ Sv and half-lives of 10^5-10^6 years. The present accumulation of UNF also still contains about 1/3 of the entire US reserves of uranium. Long-term storage would pose the risk unto the generations of future release of immense radiotoxicity, and would sequester a major portion of available uranium resources. ADAM has been designed to offer an alternative: to destroy the transuranics, to recover the uranium for future use, and to produce 10x more energy than was produced in the first use of the fuel.

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ADAM OVERVIEW

ADS Core Neutronics

The individual ADS core must be sized to optimize the normalized burn rate $\dot{T}/T$; i.e. to minimize the TRU inventory required to sustain core operation. Figure 3 shows the energy dependence for neutron capture on ^{238}U (which breeds TRU) and for n-induced fission of the dominant TRU isotopes. The fission cross sections for most TRU isotopes are significant only for ultra-fast neutrons (>1 MeV). Optimization of fast spectrum for the ADAM core places strong constraints upon the core size and geometry and upon the fuel salt composition. The optimized core is shown in Figure 1, and its neutronics properties are summarized in Table 1. In its spectrum 20% of the neutrons have >1 MeV energy. It operates with a neutron gain k_{eff} = 0.97, produces 280 MW_{th}, and requires a 10 MW proton driver. The optimized burn rate is $\dot{T}/T$ = 5.6%/year, corresponding to a destruction time of 18 years.

Fuel salt preparation and reconditioning

The fuel salt for the ADAM core is a eutectic of $TRUCl_3$, UCl_3, and NaCl. It is prepared by a sequence of

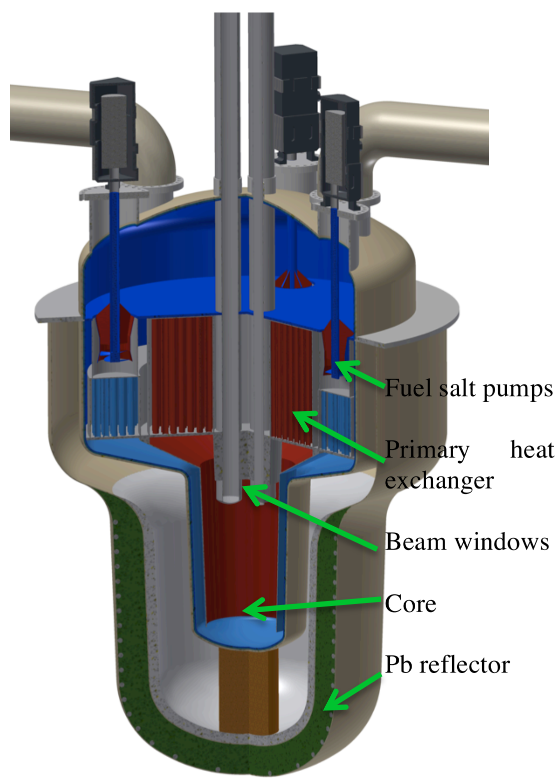

Figure 1. ADS molten salt core assembly.

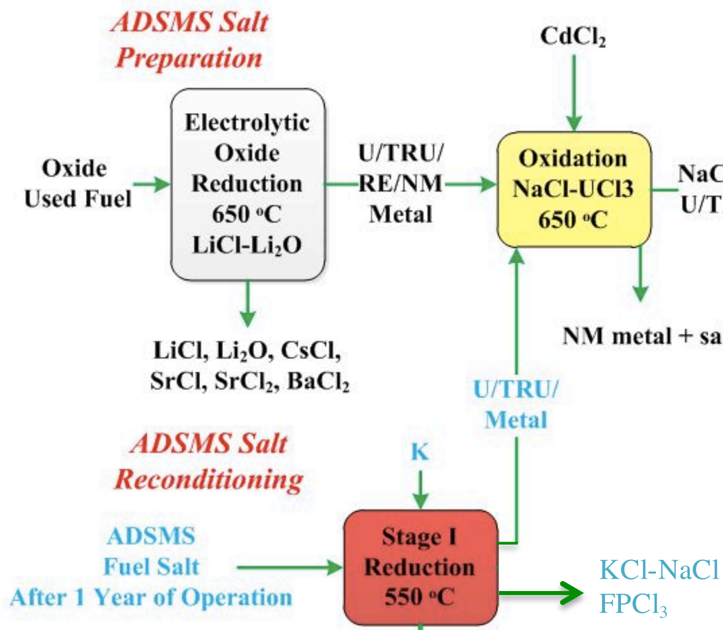

Figure 2. Pyroprocessing and electro-separation processes used to prepare the fuel salt.

reduction and oxidation steps, shown in Figure 2. Fuel assemblies are chopped and crushed, and the oxide fuel is extracted from its Zircaloy cladding into molten salt (pyroprocessing [5]). Successive oxidation and reduction steps are used to plate out the uranium and to separate the remnant into separate batches of $TRUCl_3$ and $FPCl_3$ (FP = fission products). All of the steps of this electro-processing have been developed into small-scale practice at ANL, INL, and KAERI [6].

The ADAM fuel salt contains as molar constituents $TRUCl_3$ (15.2%), UCl_3 (13.6%), NaCl (70%), and $FPCl_3$ (1.2%) [7]. The fuel salt has a melt temperature of 525 C and a boiling point of ~1500 C. The primary heat exchanger is integrated directly into the Ni vessel, and operates with an inlet temperature of 675 C and outlet temperature of 575 C.

As the ADAM core burns TRU its k_{eff} decreases. We modulate the proton beam power to maintain constant thermal power in the cores (increase the drive beam power from 8 MW to 10 MW) for a period of 3 months. At the end of 3 months we restore k_{eff} to its starting value by adding 90 kg of $TRUCl_3$. We can continue doing this for 5 years (20 cycles), at which time the fuel salt is transferred back to the electro-processing system, the accumulated $FPCl_3$ is removed, and the fuel salt is returned to the core vessel to begin another 5-year operating period.

Proton driver

Each ADAM core requires a total of 12 mA of 800 MeV continuous proton drive beam. We have developed a design for a two-stage strong-focusing cyclotron (SFC) that can provide that performance [8]. The acceleration sequence is shown in Figure 4. It begins with acceleration of 100 mA CW to 6.5 MeV in the 350 MHz LEDA rf quadrupole (RFQ) [9]. The beam is then subharmonic-modulated, split into three 117 MHz beams, and passed through a sequence of 6-D collimators to yield three beams each with a normalized emittance < $1\pi 10^{-6}$m and a phase width ±5°. The beams are then injected into a 3-stack of 100 MeV strong-focusing cyclotrons.

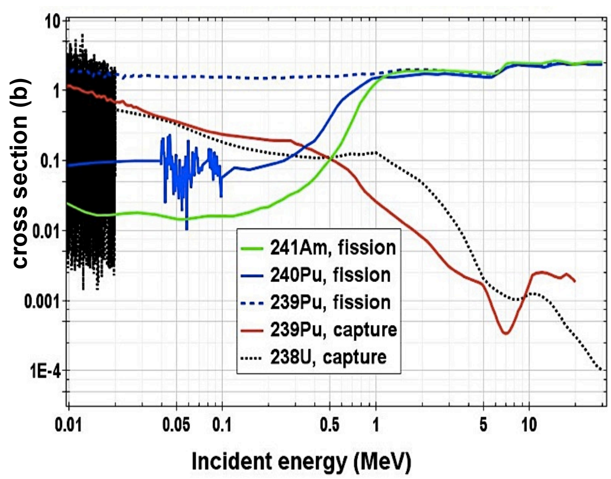

Figure 3. Energy dependence of cross sections for fission and capture by 238U and the dominant transuranics.

Table 1. Main parameters and TRU-burning performance of ADAM core compared to fast critical reactor designs.

System	ADAM	SFR	GFR	LFR	
Net TRU Destruction	0.84	0.74	0.76	0.75	g/MW$_t$-day
System Power	**290**	**840**	**600**	**840**	**MW$_t$**
Outlet Temperature	665	510	850	560	C
Thermal Efficiency	44	38	45	43	%
Power Density	200	300	103	77	W/cc
TRU Inventory	**1733**	**2250**	**3420**	**4078**	**kg**
Fuel Volume Fraction		22	10	12	%
TRU Enrichment	53	44 - 56	57	46 - 59	% TRU/HM
Fuel Burnup	129.5	177	221	180	GWd/tHM
dTRU'/TRU	**0.056**	**0.086**	**0.049**	**0.048**	**/year**

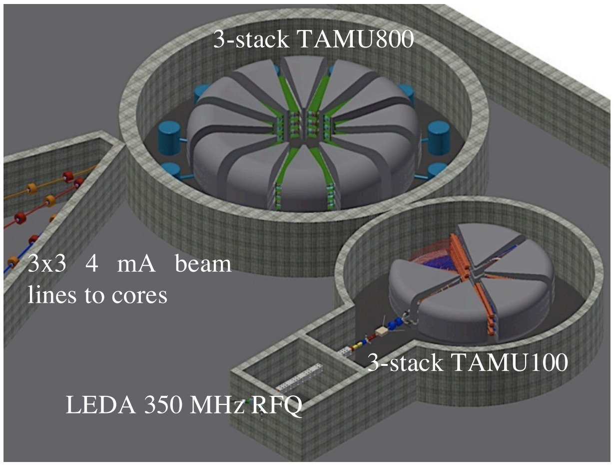

Figure 4. Acceleration chain for an ADAM site.

The world-record CW beam power for a proton accelerator is the PSI isochronous cyclotron [10]. It produces 2.2 mA CW at 590 MeV. Two issues pose the main limits to beam current in a cyclotron: the succeeding orbits overlap strongly so the defocusing action of space charge is exacerbated; and it has only weak focusing so that the betatron tunes migrate throughout acceleration and cross multiple resonances. We solved both of these problems in the SFC by incorporating two new elements: superconducting ¼-wave slot-geometry cavities that provide sufficient energy gain per turn to fully separate the orbits; and beam transport channels that provide alternating-gradient strong focusing to maintain constant betatron tunes throughout acceleration.

The details of the SFC design have been presented previously [8]. Three SFCs are configured as a flux-coupled stack, in which the dipole field for each SFC is created by a pair of cold-iron flux plates (Figure 6b) that are supported within a warm-iron flux return so that Lorentz forces on each flux plate cancel [11].

The superconducting cavity and beam transport channels are shown in Figure 6. The Nb superconducting cav-

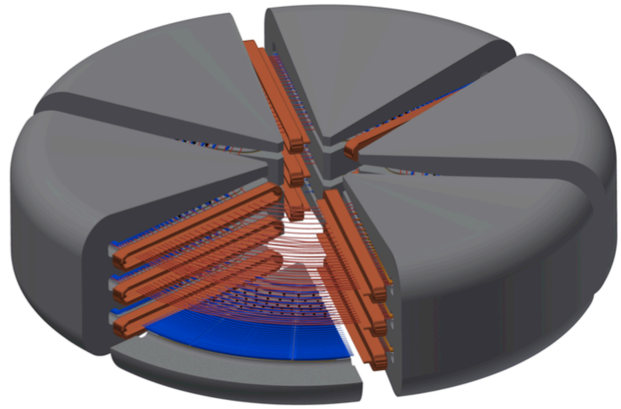

Figure 5. 3-stack of 100 MeV strong-focusing cyclotrons, with cutaway to show cavities, BTCs, and orbits.

ity operates at 4.2 K and produces a ~2 MV acceleration. It is designed with fairly conservative surface field limits – 21 MV/m, 54 mT, and has provisions to suppress multipacting [12]. The rf power for each cavity is delivered to a linear array of input couplers, distributed along the upper and lower lobes of the cavity as shown in Figure 6a. Each coupler is driven by a solid-stage power source, and the linear array makes it possible to deliver input power in the same spatial distribution that is delivered to the circulating orbits of beam, so that beam loading does not drive transverse modes.

The beam transport channel (BTC) contains a single layer wire-wound Panofsky quadrupole winding and a window-frame dipole winding, both utilizing the superconductor MgB_2 which operates in the 15-20 K temperature range. An arc-shaped BTC is aligned along each equilibrium orbit in each sector as shown in Figure 6b, and is configured as an F-D doublet. The dipole winding is used to maintain precise isochronicity on all turns.

A companion paper [13] presents studies of the beam dynamics of the SFC for low-loss acceleration of high-current proton beam. We find that the elimination of overlapping orbits, the control of betatron tunes, and the

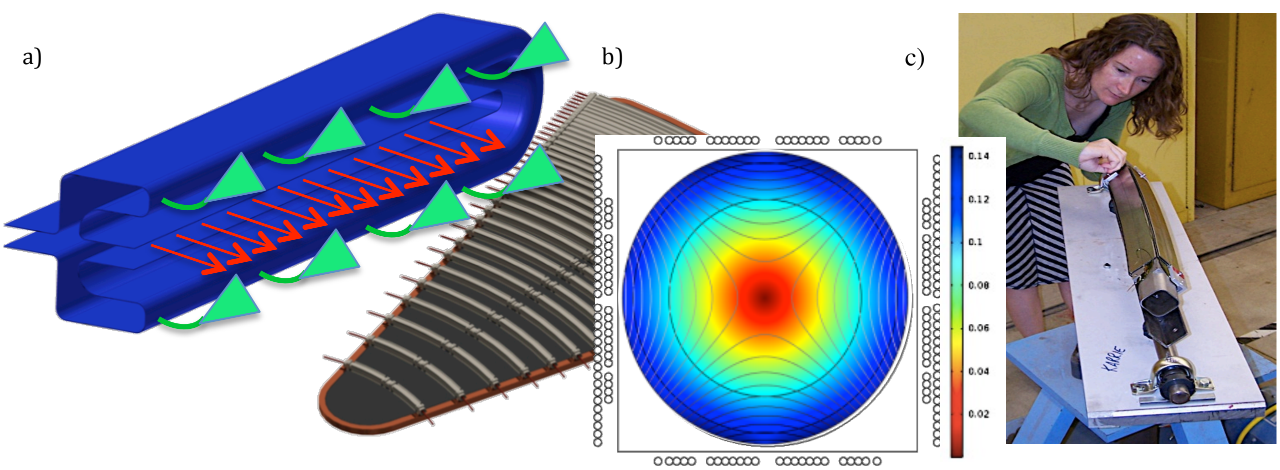

Figure 6. Innovations in the strong-focusing cyclotron: a) 117 MHz ¼-wave superconducting cavity with linear array of input couplers (green); b) beam transport channels on a flux plate; c) detail of the MgB_2 windings on a BTC and its quadrupole field distribution (max gradient 6 T/m).

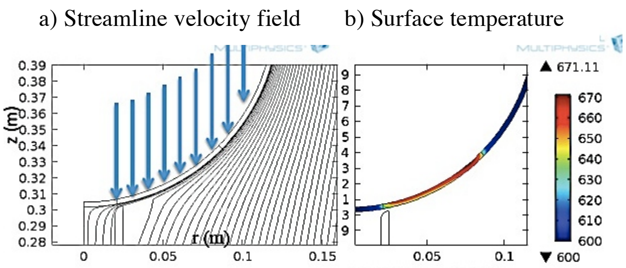

Figure 7. a) Molten salt flow on a proton beam window; b) Temperature profile on the window with 4 mA beam.

suppression of transverse mode excitation by wake fields enables us to maintain stable acceleration of 12 mA CW through both SFCs to 800 MeV energy without beam breakup and with low loss for injection and extraction.

Delivery of 4 mA proton beam into molten salt

Each core requires a total of 12 mA drive beam. In order to operate within presently achieved beam window limits, we chop the proton beam after the RFQ to deliver ~10 μs bunch trains for acceleration, we split the 800 MeV bunch trains from each SFC to feed 3 transport lines, and we deliver the 3 bunch trains to 3 hemispherical Nb windows (Figure 1). The closed-circuit flow of molten salt in the core is channelled to deliver a chimney flow to cool each beam window, as simulated in Figure 7.

Safety considerations

The molten salt provides the spallation target and heat transfer medium for the beam windows, and it cannot be shocked by interruption of drive beam. All ADS designs that utilize a core based upon solid fuel pins have the problem that interruptions of drive beam (which happen every day at any extant accelerator) would thermally shock the fuel cladding which can lead to cracking.

All of the fuel salt is completely contained within the Ni core vessel and 5 shells of outer structure throughout a 5-year operating period. By contrast all previous core designs using molten salt pass the molten salt frequently through external circuits for reprocessing and reconditioning, opening the risk of leaks.

The core vessel contains a removable inner vessel (in contact with the fuel salt) made from a single-piece of CVD Ni with no weld seam, which is resistant against molten salt corrosion. The Ni is much more robust against embrittlement from neutron damage in the ultra-fast spectrum of the ADAM core than it would be for a thermal spectrum. The CVD Ni vessel is encased in a spiral-wrap Hastelloy-N structure that provides mechanical support for the Ni can. An array of K vapor heat pipes is bonded to the outer surface of the Hastelloy shell and passively heat-sinks its surface to ~400 C during normal operation (consuming ~2 MW of heat) and during power and cooling failure modes. Maintaining the temperature of the Hastelloy at 400 C preserves its high tensile strength and toughness, which would be compromised if the Hastelloy operated at core temperature.

Many failure modes have been modeled, including loss of primary and/or secondary heat exchanger, loss of drive beam, loss of controls, and cracking of the core vessel. No failure mode studied can lead to leaking fuel salt beyond the multi-layer vessel, and no failure mode can produce criticality.

IMPLEMENTATION TO DESTROY TRANSURANICS

The ADAM core is sized to optimize the destruction of transuranics $\dot{T}/T$. Three ADAM cores are required to destroy TRU at the same rate that it is produced in a typical GW_e nuclear power plant. Figure 8 shows the site plan for an ADAM facility containing three cores and a 3-stack SFC proton driver. It is appropriate in capacity to co-locate with an existing power plant, process its spent nuclear fuel, destroy the transuranics, recover the uranium, and generate uranium.

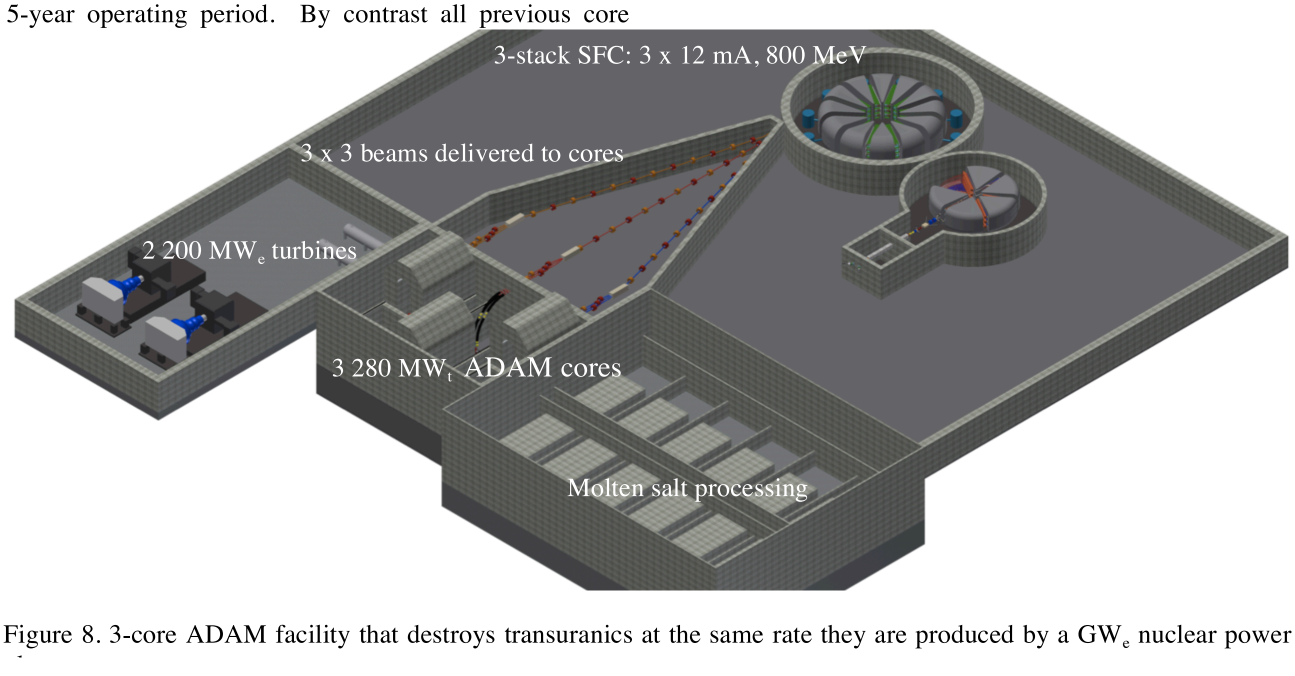

Figure 8. 3-core ADAM facility that destroys transuranics at the same rate they are produced by a GW_e nuclear power

The three cores in an ADAM facility produce 3x290 MW_t of heat, which generates ~44%x870 = 380 MW_e. The SFC systems operate with ~50% efficiency, so it requires ~3x10MW/50% = 60 MW_e to operate the ADAM unit. The ADAM installation therefore is essentially an energy amplifier with a gain ~5.5. For as long as the adjoining GW_e power plant operates, its companion ADAM facility will generate ~320 MW_e of co-generated power to augment the plant's GW_e output while it destroys its hazardous waste.

Table 1 summarizes the performance parameters of the ADAM core, and compares them with the performance of several fast critical reactors that have been designed to destroy transuranics [14]: SFR is a sodium-cooled fast reactor; GFR is a high-temperature He gas-cooled fast reactor; and LFR is a molten lead-cooled fast reactor. Notably the ADAM core performs as well or better than any critical core design, and conveys the benefits for safe subcritical operation discussed above. ADAM provides a feasible candidate method to destroy the transuranics in used nuclear fuel and close the nuclear fuel cycle.

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We wish to thank Dan Barth (Friatech NA) for his help in designing molten salt pumps for the heat exchanger, and Jesse Johns (Texas A&M) for simulations of transient dynamics of the ADAM core. Michael Simpson (University of Utah) and Suprathorn Phongikaroon (Old Dominion University) are collaborating with us in developing the molten salt processing technology. Paul Madden (Oxford) and Matthieu Salanne (Université Pierre et Marie Curie) have collaborated with us in developing molecular dynamics models for the fuel salt. We wish to thank all members of the External Review of the ADAM project who conducted an in-depth review in January 2013: Ed Temple, Rick Baartman, Robert Hamm, Edward Hoffman, Pete Miller, Steve Myers, Bojan Petrovic, Gary Rochau, and Mark Williamson. It is a pleasure to acknowledge helpful discussions with Marvin Adams, Abe Clearfield, Richard Garwin, Il-Soon Hwang, and Burton Richter.

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NONLINEAR BEAM DYNAMICS STUDIES OF HIGH-INTENSITY, HIGH-BRIGHTNESS PROTON DRIVERS *

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Abstract

Space charge effects, beam losses, wake fields, and orbital control are significant collective effects that affect beam dynamics. The strong-focusing cyclotron incorporates helical orbits with a strong-focusing lattice and high-gradient cavities. It makes it possible to fully separate orbits and suppress interaction between bunches on neighboring orbits. We simulate nonlinear synchro-betatron coupling and explore methods to use the tools of strong-focusing to suppress beam blowup mechanisms.

INTRODUCTION

The Accelerator Research Lab at Texas A&M University is developing designs for a strong-focusing cyclotron (SFC) as a high-current (12 mA CW) proton driver for ADS fission [1], production of medical isotopes, and neutron damage studies [2]. The purpose of this paper is to explore how the unique features of the SFC can be used to control nonlinear dynamical effects that limit beam current in accelerators.

Particle motion in the SFC is described in terms of six phase space coordinates ($x, x', y, y', \Delta E, \Delta\phi$). The lattice of the Strong Focusing Cyclotron (SFC) requires inclusion of longitudinal or synchrotron motion as one cannot decouple longitudinal and transverse planes past mid-plane analysis. In this case synchrotron motion causes modulations of the parameters or forces and sidebands appear as a result in the tune space. The effects of synchrobetatron couplings and resonance-crossing should become dominant as intensity increases or bunch length elongates.

The SFC lattice combines periodic quad-focusing elements [FD] with common sector magnets and RF cavities, and in this respect it is similar to a combined-function synchrotron. The orbits however are spirals, and dynamics is strongly dependent on initial conditions, and in this respect it is similar to linacs. This results in synchrotron sidebands [1] in the betatron motion with chromaticity as developed by Orlov [2] and synchrobetatron resonances caused by chromaticity as analyzed in a review by Suzuki [3]. The SFC lattice is highly regulated by the arrangement of superconducting beam transport channels (BTCs) [4], Mobius-geometry RF cavities [5], and low-field superconducting sector dipoles [6] to produce matched beta function [β_x, β_y], dispersion [D] and D' to manage emittances. We simulate the SFC as a spiral transmission line, and we include forces from error fields, wake fields, cavity-coupling of bunches, and space charge.

Designs have been developed for a 6-sector 100 MeV SFC (TAMU100, shown in Figure 1) and for a 12-sector 800 MeV SFC (TAMU800) for which TAMU100 would serve as injector. A key element of the SFC is its use of the beam transport channels (BTC), installed along the equilibrium trajectory or each orbit in each sector as shown in Figure 1b. Each BTC contains an FD doublet of Panovsky quadrupoles (up to 6 T/m, used to local tune) and a window-frame dipole (up to .02 T, used to control isochronicity).

Simulation of beam dynamics in both SFCs starts by tracking a 4D map of a bunch propagating through the lattice elements and interacting with EM fields, similarly to the kick codes COSY-INFINITY, Elegant, MADx, and CERN Mathematica. We have started with that framework and added complexity to the simulation as the design progresses. The framework utilizes a combination of mathematical scripts based on COSY-INFINITY fed by Madtomma. Tracking is made using CSRtrack. Figure 2 shows the elements of one cell of an SFC lattice.

We impose a shell on the kick code that operates a simultaneous quadratic optimization, in which we can optimize up to 48 variables that define the isochronous orbits. The framework has evolved to include space charge, chromatic effects, and evolution of bunch-length.

Beam position monitors are provided in a gap at the end of each sector for each orbit. In the planning for commissioning of TAMU100, we plan to inject low-power beam into the first two turns of the lattice with RF off and capture it on a retractable beam dump. That will enable us to verify injection matching and BTC alignment before

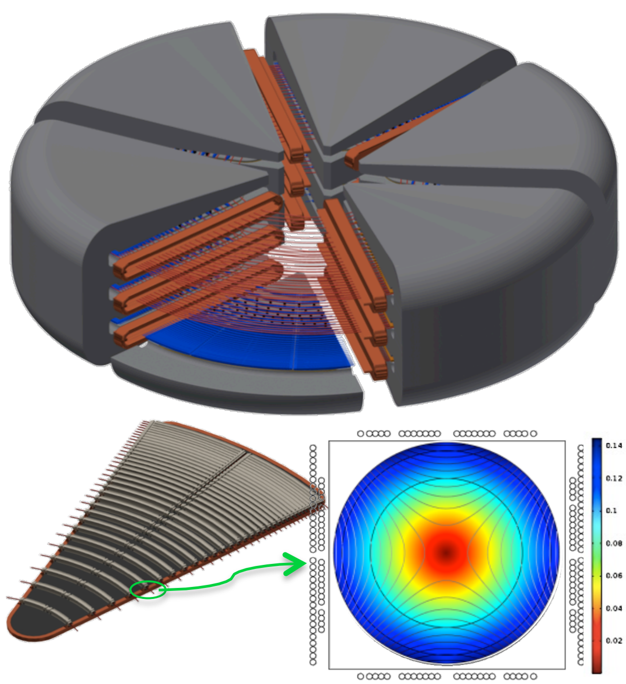

Figure 1. a) 3-stack of 100 MeV SFCs, with cutaway to show superconducting cavities, BTCs, and orbits; b) detail of a sector dipole flux plate and the arced BTCs.

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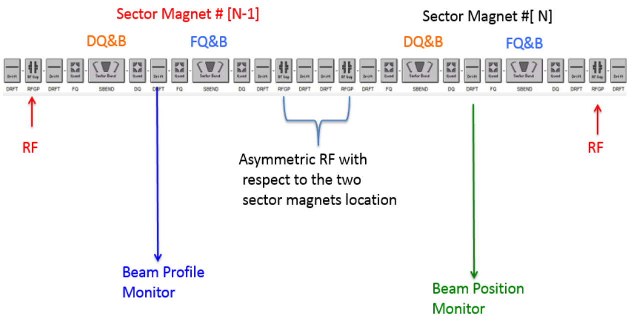

Figure 2. Lattice elements in the tracking simulation of one cell (sector dipoles) of the SFC lattice.

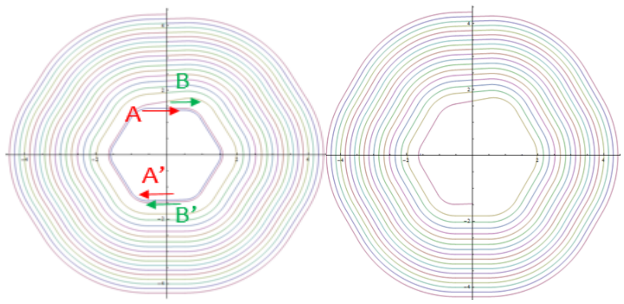

Figure 3, Reference orbits in the 6-sector TAMU100, before and after optimization of the injection orbit.

'threading the needle' of orbits with acceleration. The retractable beam dump can also be traversed to dump the beam after any desired orbit.

Figure 3 shows a first example of how the BTCs convey benefit in optimizing the SFC. Figure 3a shows a reference orbit for TAMU100 in which the orbit was launched from the extraction point and tracked back to injection, optimizing for isochronicity, maintaining stable phase advance in all cells, and holding constant betatron tunes from injection to extraction to a favorable operating point. Figure 3b shows a second optimization in which the optimization of the first two orbits was added to the optimizer criteria.

BEAM DYNAMICS STUDIES

We have studied beam dynamics using the tools described above. We established that the BTC quadrupoles can be grouped into 6 families (3x, 3y) and still provide excellent control with which to set tunes to any desired operating point and hold it there throughout acceleration.

We implemented a similarly grouped set of sextupoles at the exit from each sector to provide control of chromaticity, and a set of beam position monitors that will enable us to develop a correspondence between simulation and actual operation of the accelerator. With those tools, we proceeded to simulate the phase space dynamics of bunches, starting with low current and increasing to our design value.

Figure 4 shows Poincare plots for the 1σ-5σ contours of a bunch in a 3.5 mA 162 MHz SFC, tuned to hold (ν_x,ν_y) = (3.196, 3.241). The first three plots show that the phase space has very regular motion throughout acceleration with no particles reaching the BTC apertures.

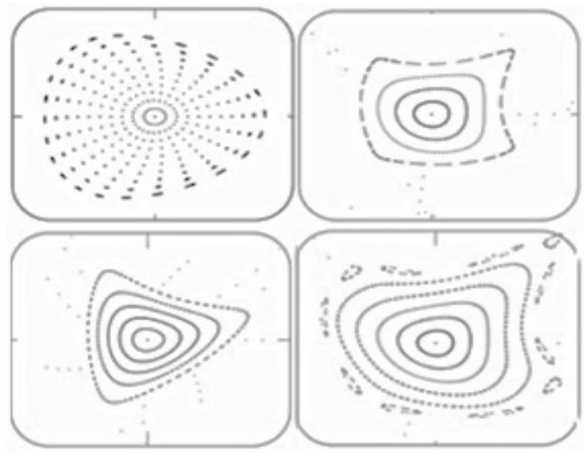

Figure 4. Poincare plots of a 3.5 mA 116 MHz bunch as it is accelerated in an optimized TAMU100 lattice.

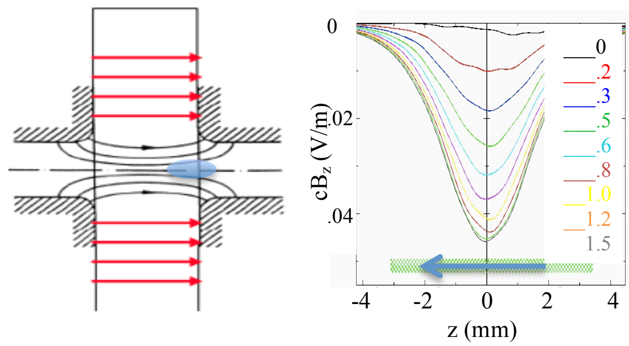

Figure 5. Effect of space charge on longitudinal bunch dynamics: a)bunch passing through cavity; b) longitudinal field inside bunch showing asymmetry from space charge.

For the last plot ν_x was moved near a 7th-order resonance. By the 9th orbit (40 MeV) beam breakup is evident on the 5σ plot. This result gives an example of the simulation at work, and it underscores the importance of controlling tune in a high-current cyclotron.

The nonlinearity and couplings are essentially due to two factors. First, off-momentum particles that go through cavity and then the edge of the sector magnet will go under a different chromatic affect. One aspect of this is shown in Figure 5b, where the space charge of the bunch produces asymmetric fields in the center of the bunch. Such chromatic effects result in synchrobetatron coupling.

We simulated the acceleration of the bunches in a 10 mA CW beam, for a favorable operating point and for tunes near 3rd- and 5th-order resonance. The favorable-tune case produced Poincare plots similar to those of Figure 4a-c; the cases near resonance are shown in Figure 6. When the tune is near a 3rd order resonance, clumping is evident by end of the 2nd orbit and the clumps can be seen driven apart. Similar clumping is evident when the tune is near a 5th order resonance, but clumps remain close. In both cases the beam was lost by 20 MeV. We conjecture that the clumps are driven apart in the 3rd order case by fringe fields of the sector dipoles and by cavity fields, both of which couple to 3rd order in the 6-sector lattice. For a favorable tune, clumping was not observed until near 100 MeV, and the beam profile remained intact.

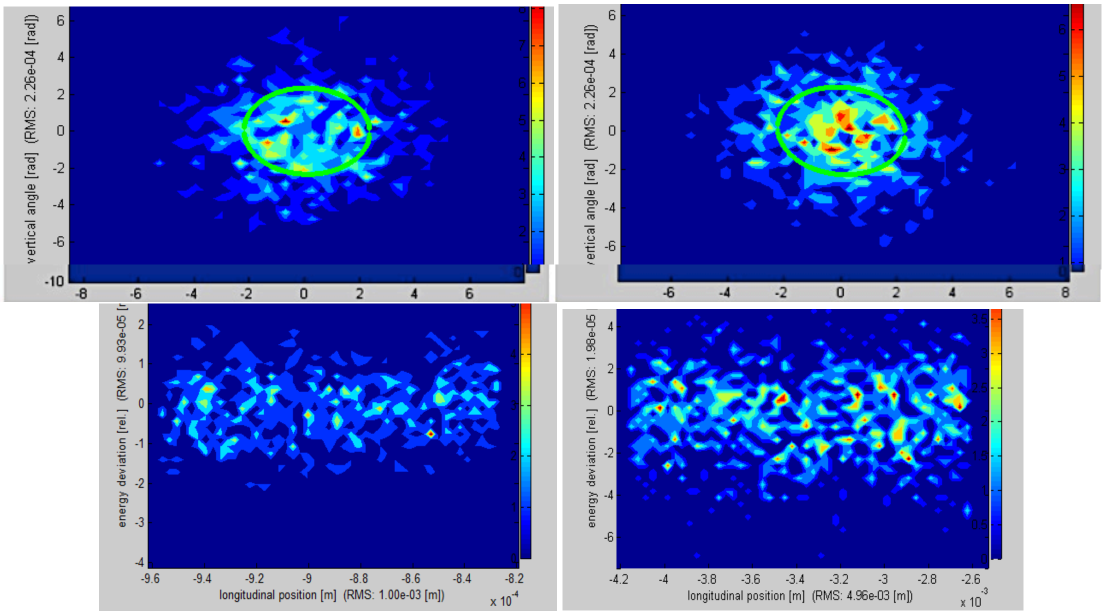

Figure 6. a) Beam breakup in transverse phase space after 2nd orbit when tune is near 3rd order and 5th-order resonances; b) beam breakup in longitudinal phase space when tune is near 5th order resonance.

Figure 7 shows similar dynamics for the longitudinal phase space of bunches in a 10 mA beam with favorable tune. ΔE grew from ±5° at injection to ±6° at extraction; Δϕ increased by 30%; the bunch was accelerated without loss from the 20 MV bucket.

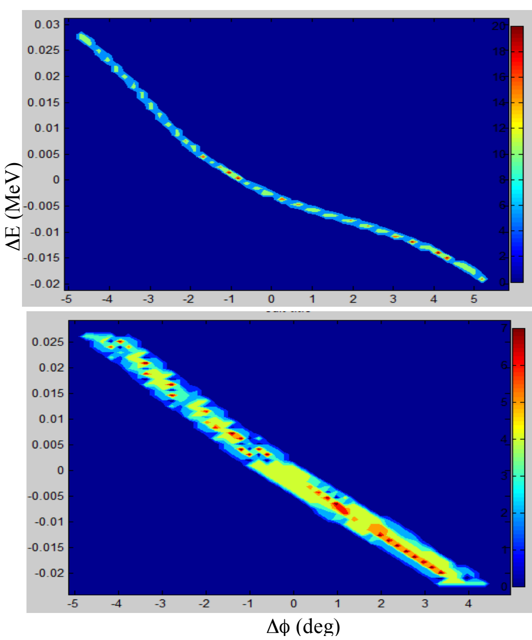

Figure 7. Longitudinal phase space of a bunch in a 10 mA beam: a) after first half-turn; b) 100 MeV.

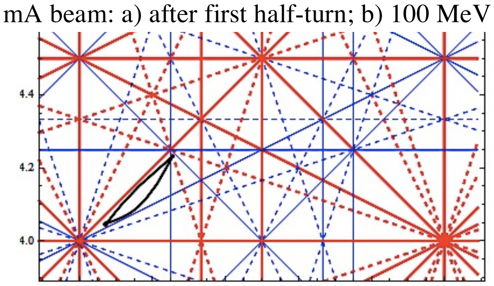

Figure 8. Tune distribution of points on the 5σ trajectory for a favorable tune.

Figure 8 shows a map of the tunes of individual particles on the 5σ contour of a bunch in 10 mA beam, accelerated using a favorable operating point. The tune can be positioned so no resonance crossing occurs, even at 5σ.

CONCLUSIONS

The above results are the beginning stages of a systematic investigation of non-linear dynamics in our strong-focusing cyclotron as it accelerates >10 mA of proton beam to 800 MeV for ADS fission and other applications.

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Energy Environment RFI

From: Peter McIntyre <mcintyre@physics.tamu.edu>
Sent: Monday, May 19, 2014 7:32 AM
To: Energy Environment RFI
Cc: Colby, Eric; William Horak; Saeed Assadi; Nathaniel Pogue; Akhdiyor I Sattarov
Subject: Re: Stewardship RFI Comments
Attachments: AND proposal.pdf

Importance: High

Attached is a proposal that was submitted in 2013 to the NE Division for its IRP program. It was not funded. It concerns a new method to produce extremely high neutron damage in samples using intense proton beams from a strong-focusing cyclotron. This approach is far less expensive and more workable than any method previously proposed, and the need for high-flux fast neutron damage studies grows with each year, in fission, in fusion, and in materials science.

Respectfully submitted,

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Technical Project Narrative

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Accelerator-Based Neutron Damage Testing

Technical Work Scope ID: IRP-RC –Simulation of Neutron Damage for High Dose Exposure

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Los Alamos National Laboratory – Stuart, Core Materials Technical Lead

Table of Contents

1 Program Overview

NEUP funding is requested to develop a user-friendly accelerator-based neutron damage (AND) facility for testing of advanced reactor materials. It leverages the use of the world's highest-current CW RFQ accelerator (1) and a newly proven sheet-flow lithium target technology to build (2) an AND facility that can evolve to provide direct fast neutron damage of >100 dpa/year.

The collaboration will put into service the Low Energy Demonstration Accelerator (LEDA) Radio Frequency Quadrapole (RFQ) accelerator and the Argonne National Lab (ANL) technology for sheet-flow Li targetry, and commission liquid metal targetry into high-power practice for the first time. This AND-1 facility will produce a neutron damage rate of ~7 dpa/year, with a mean neutron energy of 2.37 MeV.

The collaboration will undertake studies to compare the dynamics of neutron damage from different energy spectra on sample materials. These samples will be compared to materials that are irradiated using ions, which are currently used as a surrogate to achieve high dpa in materials. It is the contention of the collaboration that surrogate work, which is an important field of study and can provide valuable information, does not produce the same effects as neutrons damage. Thus for high levels dpa studies a high flux neutrons source is required. As a consequence, the samples produced during the irradiation studies will be compared to samples irradiated by AND-1 showing that an accelerator-based source can simulate reactor neutron damage.

For this purpose will develop a sample library of candidate advanced reactor materials from existing libraries and from new exposure runs. The library will contain existing samples from archives at Los Alamos National Lab (LANL) as well as samples irradiated in the SINQ spallation source. As part of the AND program samples will be irradiated at Oak Ridge National Lab (ORNL) in HFIR and the planned BOR-60 program of DOE. The library will span a highly relevant range of: damage effects from proton-only to neutron-only damage irradiation, neutrons with thermal to fast energies, and temperatures representative of Gen-IV reactor designs. A coordinated program of experimental characterization and modeling will be used to extract a big picture of how the several dominant mechanisms of damage operate at high dose in the candidate materials and the effects of neutron spectrum, temperature, and corrosion on the damage dynamics.

The AND-1 facility will be designed, constructed, and commissioned within the first 2 years and will begin irradiating sample in the third year. During the three-year program, a sequence of experiments will be staged at HFIR and other irradiation facilities which will them be compared to sample libraries to illustrate damage mechanism differences in different flavor of irradiation. This program will benefit programs led by DOE, LWR-sustainability, Advanced Reactor R&D, SMR program and AFC program, and it can provide licensing evaluation of material performance needed by NRC.

In parallel with the commissioning of the AND-1 and the demonstration that it can mimic reactors, a conceptual design for the AND-2 facility, based upon the strong focusing cyclotron pioneered at Texas A&M, will be developed as a means to create a neutron damage facility capable of 100 dpa/year. It has a projected cost of ~$30 million, It will be the only affordable method to directly produce >100 dpa/year in advanced reactor materials.

Five of the co-investigators on the AND project are tenure-track faculty or research personnel about to enter tenure-track: Sunil S. Chirayath (Texas A&M), Celine Hin (Virgina Tech), Xinyu Huang (University of South Carolina), Mike Short (MIT), and Beatta Tyburska (Wisconsin), Jinsuo Zhang (OSU). They will be each carrying independent roles in AND with productive research at that critical point in their careers.

Notably, Texas A&M University is committing $500,000 to support construction of the building and infrastructure that will house the AND-1 facility.

2 Motivation

The motivation for the proposed research is stated extremely well in the charge to the recent Workshop on Ion Implantation as a Neutron Irradiation Analogue (IINIA) (3):

> *"Ion Implantation is widely used as a (relatively) low-cost, rapid means of introducing radiation damage in materials. Heavy ions (often self-ion, of the same atomic species as the main constituent of the alloys being tested) are used to introduce displacement damage, as are high-energy protons. Lower energy light ion (H, He) implantation can be used to simulate the effects of the production of these elements by transmutation. Several facilities worldwide can perform multiple simultaneous implantations (e.g. of self-ions and H and/or He), or can perform TEM in-situ studies of ion-irradiation. Ion-irradiated specimens, with a damaged layer typically less than 1µm deep, have been studied by TEM, atom-probe, etc., and it has recently become possible to perform "micromechanical" tests directly on ion–implanted materials.*
>
> *Despite the convenience of these techniques, and the large number of studies carried out over many years using them, it is still unclear how the radiation damage thus produced is related to that produced by neutrons. There are very large differences between ion-irradiation and neutron irradiation in dose rates, damage densities and the subsequent balance between defect production, migration and annealing. As an increasing number of new materials are now being assessed for use in fission and fusion power generation, the use of ion-irradiation to assess their likely in-service behavior is an important topical issue."*

Neutron damage to reactor materials is a pacing issue for advanced reactor development. It paces the most important themes in reactor technology:

- to understand the mechanisms and dynamics of extremely high dpa neutron damage effects under relevant operating conditions;
- to simulate experimentally the phenomenon of radiation-induced creep and fatigue by sustaining *in-situ* stress-strain measurement during n irradiation;
- to predict the operating life of containment vessels and other key components in currently operating reactors, which will ultimately determine their useful life;

- to develop novel cladding and structural materials that can survive prolonged irradiation in aggressive operating environments;
- to develop novel materials for advanced reactors. Generation IV designs require variously high temperature, high pressure, interface with corrosive fluid media, and fast neutronics (4).

There are very limited capabilities for delivering high-dose neutron damage in the present world. The US has no fast reactor; the highest dose capabilities in the US are HFIR (5) and ATR, at dose rates of ~few dpa/yr. None can support *in situ* strain measurement or exposure to corrosive environment during irradiation. The highest dose capability lies in Russia, which operates BOR-60 (6) and BN-600. The prospects for future high-dose facilities appears to be dwindling in presently. SNS does not support high-dose radiation damage studies and the long-proposed ANS will cost $3 billion (7). The proposed IFMIF facility is under construction, but may take another decade to complete (8).

The absence of the ability to deliver direct multi-dpa neutron damage to samples has motivated the effort over the past two decades to mature dual ion beam irradiation as a surrogate for neutron damage. To compliment these efforts, development molecular dynamics codes that can model both ion damage and neutron damage in a material are used to predict how damage mechanisms will operate in any given material. That dual effort has matured into a robust understanding of both what one can simulate with confidence and what one cannot. The present understanding was reviewed at the Workshop on Accelerated Nuclear Energy Materials Development (9) and at IINIA (10). Li (11) summarizes the key mechanisms of neutron damage in metals and ceramics that can be modeled in MD and discusses which of these mechanisms can be simulated with ion damage:

- Point defects and defect clusters diffuse to form dislocation loops, dislocation networks, stacking fault tetrahedra, voids, and precipitates;
- Radiation induced segregation, and precipitation
- Transmutation produces H and He, which can either form voids in the lattice or migrate and accumulate at grain boundaries;
- if the material is in contact with a corrosive liquid at its surface, swelling and voids at the grain boundaries dramatically accelerate corrosion through the material;
- in ceramics the dislocations can induce crystalline-to-amorphous phase transition;

All of the above phenomena result in the degeneration of oxidation resistance, and thermal and mechanical properties, such as: hardening, embrittlement, swelling, and creep.

The problem that ultimately remains is that the tools of ion irradiation and MD modeling can go far to describe damage and to correlate it with the mechanisms that produce it, but they cannot reliably predict the effects of high-dose neutron damage in an advanced reactor material without prior prototypic reference experiments. In order for prediction three phenomenon must be investigated: 1) the balance of dislocations and annealing, 2) the energetics of H and He formation, 3) and their dependences on lattice dynamics are necessary for prediction. These relations can only be achieved by actually exposing the material to high-dpa neutron damage and analyzing its microstructure and functional properties before and after damage. New

simulation tools also need to be developed in order to study the microstructure evolution under high-dpa neutron damage over a long period of time and its effects on mechanical properties.

To illustrate this problem, we cite two examples, one with a radiation-resistant ceramics and the other with radiation-resistant metal.

Zinkle (12) finds that ion damage in ceramics is a balance between two sets of processes. The magnitude of the two processes is significantly greater in ion damage than in neutron damage. The first process is the high stopping power of ions produces much more direct and inelastic displacement damage, but ionization diffusion promotes the local repair of displacement damage – second process. He concludes that “under different irradiation conditions (electronic stopping powers), ionizing radiation can lead to either a substantial enhancement or suppression of radiation resistance in ceramics”. The translation from studies using ion irradiation and MD modeling would have to balance these two competing effects to predict a (smaller!) effect due to neutron damage. So how can we reasonably predict the outcome for high-dpa neutron damage of SiC CNC materials currently under development?

Various US researchers (13) have studied high-dpa neutron damage (100-200 dpa) in several ferritic-martensitic and ferritic ODS alloys that have been developed for their resistance to void swelling. Several of those materials retain their mechanical properties up to doses as large as 170 dpa, yet similar materials with slightly different compositions have dramatically less radiation resistance. It is problematic to ever reproduce or predict such dramatic effects from accelerated ion damage and MD modeling because in many cases the net effects in the simulated results are from balancing the dominant competing processes produced by ionization, which absent in neutron damage. These examples emphasize the critical need in a robust source of affordable, accessible high-dose neutron damage to develop advanced materials for the next generation of nuclear fission and fusion reactors. This is the motivation for the AND proposal.

3 Project Objectives

The overall project objective is to provide the U.S. the domestic capability to test candidate materials for advanced reactors to >200 dpa within a short time frame. Such a facility would rapidly reduce the time required to identify material lifetimes as well as qualification and licensing time. Comparisons between the reactor neutrons, accelerator neutrons, and accelerated ion will be performed and models predicting/fitting these results will be created to provide a theoretical basis for prediction of future work.

AND-1 will create the foundation for accelerator based facilities, cement such facilities use as a surrogate for reactor spectra, and produce ~7 dpa/year. To achieve these objectives within the 3-year period of the IRP, a detailed computational modeling effort and extensive experimental program will be initiated to demonstrate the viability of the AND-1. Once achieved, construction and operation of AND-1 will provide the foundation for AND-2, a >100 dpa facility.

3.1 Study fast neutron damage using reactors and spallation sources

The collaboration will conduct neutron damage exposures with samples of the materials of most interest for advanced reactor designs. The test matrix will include HT-9, T-91, ODS steels, Ferric alloys, Austenitic stainless steel, and SiC and CMC materials. TEM and tensile samples will be prepared and then analyzed after damage by the 8 collaborating university teams.

HFIR exposure. A total of 4 experimental fast neutron irradiations will be contracted at HFIR which will utilize an irradiation capsule to suppress thermal neutrons. The samples will be located in the center of the reactor which should provide .5 dpa per cycle. HFIR has ~8 cycles per year which will allow the investigator to insert or remove samples at the collaborations discretion.

Samples archived at LANL and PSI. A considerable archive of damaged specimens from reactor exposures and from earlier damage studies using LANSCE beam spallation have been accumulated at LANL. A set of samples from PSI's SIN-Q facility is also available to the collaboration. Samples from both LANL and PSI will be selected to span the parameter space in neutron spectrum, proton content, and sample temperature for each material to establish a multi-variable topology map such that trends and dependence can be formulated and modeled.

Exposures at BOR-60 and in the next STIP target. The collaboration has arranged to obtain damaged samples of many of the above materials listed from the BOR-60 exposure that has been contracted between DOE and Rosatom (14). The group has also arranged to submit a sample tube for inclusion in the next target assembly for the SIN-Q spallation target, which produces ~60% proton- 40% neutron damage. It is unfortunately anticipated that samples from both exposures will become available for examination near or after the end of our proposed IRP project. Our collaboration plans to extend its work together through that time to include studies of those samples in the library results. The delay illustrates in clear terms the dilemma that confronts efforts today to study the damage mechanisms from direct neutron damage – *it requires an extended period of time to produce results with existing facilities.*

3.2 Modeling studies of ion and neutron damage.

Radiation damage affects a material's properties and microstructure as a result of physical processes interacting over time and length scales. Multi-scale modeling approaches are required for reliable predictions. The modeling of defect-mediated phase transformations is required, not only for understanding the influence of microstructural changes on properties (such as fracture/creep resistance and corrosion), but also for manufacturing. Different microstructural features such as a high density of small precipitates and clusters, dislocation loops, cavities, and regions of enhanced solute concentration have different coupling to phase nucleation and growth. The balance of these features depends on the synergistic interaction with environmental variables, such as irradiation temperature, dose rate, helium production and alloy composition.

We will use multi-scale simulations to compare the above studies of neutron damage to similar studies of ion-damaged samples and of samples that have been irradiated with a mix of protons and neutrons at LANL and STIP. Of particular interest are the balance between producing dislocations and annealing dislocations, for which the balance is radically different in the dynamics of neutron- and ion-induced damage, and the roles of H and He generation.

3.3 Damage data correlation and equivalence relationship development with uncertainty quantification

A relational multi-scale database of experimental and computational results will be compiled. Sensitivity/uncertainty evaluations will be performed for the sample materials considered. The integration of theoretical, computational, and experimental data sets will be used to develop reliable multi-scale damage correlations between different types of test irradiations. Additionally, such correlations will be drawn between test irradiations and actual operating conditions anticipated. These relations will account for energy spectra, displacement dose rates, transmutation production rates for He and H, defect kinetics, and temperature effects.

3.4 Build, commission, and operate AND-1.

The LEDA RFQ delivers 6.5 MeV proton beam with 100 mA CW current. The sheet-flow Li target will operate with 10 m/s flow velocity and 650 kW heat transfer. The system will produce ~8 dpa/year fast neutron damage in the contents of an assembly of independent sample tubes in the target volume. It is anticipated that AND-1 will be commissioned in the third year of the IRP.

AND-1 building, infrastructure- A facility will be designed and built house the AND-1 system. Shielded vaults will be constructed inside the facility for the LEDA and the target chamber with infrastructure for RF power and cooling systems.

LEDA- LEDA was built and commissioned in the mid-1990s where it met its design performance and was subsequently decommissioned in 2003. The LEDA RFQ proton accelerator will be moved from LANL to Texas A&M, installed in the AND-1 vault, and re-commissioned.

Li Target- Development of a 650 kW sheet-flow Li target system will occur that follows closely upon the successful development at ANL for the RIA/FRIB project. The parameters for sheet flow are closely similar to those operated successfully at ANL, except new heat transport is required to remove excess heat.

3.5 Design, costing, and performance projection for AND-2.

The collaboration envisages a follow-on program, which will be proposed to other sources, for an upgrade of AND-1 to deliver >100 dpa/year of fast neutron damage. The proton beam from LEDA would be modulated, split into three beams, and accelerated to 100 MeV energy in a strong-focusing cyclotron (SFC) (15). The beams can be directed into two target regions. The first places 5 samples in between to sheets of lead on which proton are bombarded at an oblique angle producing > 100 dpa in one of the samples. The second target area take all three beams and places 21 samples in the center of three lead sheets. The angle of the beam on the sheets can be changed such that the mean energy of the neutron flux can be altered. As the mean energy of the neutron decreases, so the does the dpa. An example, a mean energy of 5 MeV (15 degrees) produces 15 samples receiving 55 dpa and 6 samples with 44 dpa. Comparing these results with beams perpendicular to the lead flow (8 MeV mean energy), there are 12 samples receiving a minimum of 80 dpa, 6 with 62 dpa, and 3 with 40 dpa. An innovation in the correlation of neutron spectrum to angle with the proton beam is used to deliver a fast spectrum in one target region (mean n energy ~3 MeV), and high-energy spectrum in a second target region (mean n energy ~8 MeV) simultaneously. AND-2 could thus serve the needs for materials development both for advanced reactors and for the classic first-wall problem for fusion.

The above five objectives build a foundation for a truly game-changing advance in neutron damage science for advanced reactor materials. Each objective draws upon the experience and collective strengths of the collaboration. The AND-1 commissioning will develop first-ever experience in the technology necessary to create the >100 dpa/year AND-2 facility and to provide a credible basis for its need in the community.

4 Proposed Scope Description

This chapter presents details of the proposed research scope for the four areas indicated above. A detailed explanation of the work entailed in each research areas, the deliverables, and schedules are expounded upon in their respective sections. The scope is over the three year program but also illustrates the vision the collaboration has for future investigations that heavily depend on the work accomplished in this IRP. The work will be continually related to the results desired by the DOE and the implications of the work to the future of reactors and DOE initiatives.

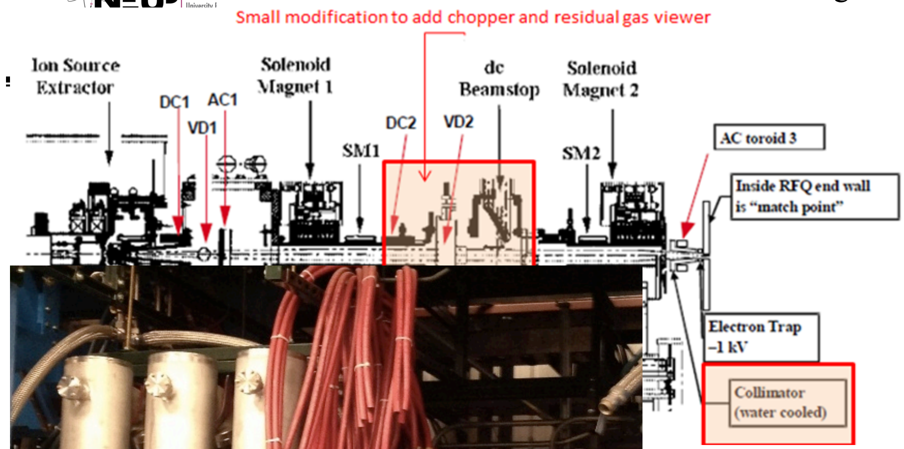
4.1 AND-1 Accelerator Commissioning

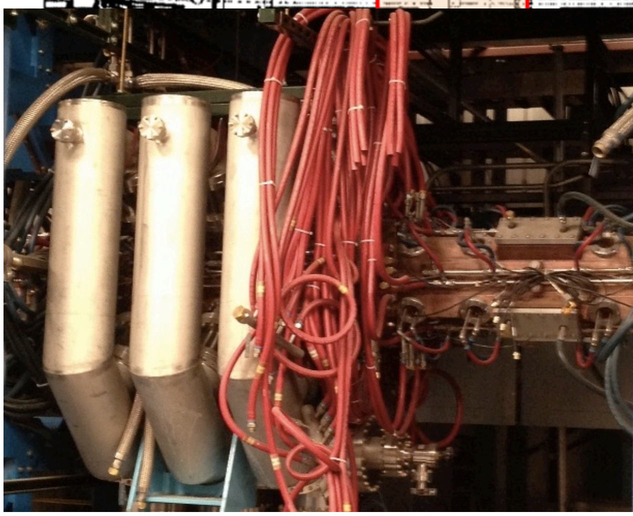
Lead: P. McIntyre (TAMU); **Team:** S. Assadi, N. Pogue, A. Sattarov.

The collaboration proposes to move LEDA to Texas A&M along with pulsed RF power source, power supplies, transformers, and waveguides from LANL. CW power supplies will be obtained from CERN and refurbished for insertion after the RFQ's re-commissioning with a sheet-flow Li target downstream.

LEDA RFQ is well studied and in excellent shape to be transferred to the Texas A&M. So, we do not expect to have any difficulty aligning and installing it onsite. The expected beam is similar to the papers shown by Lloyd Young (16) and Vernon (23). The collaboration has followed the recipe of modeling the RFQ as much as the literature shows which includes the first 32 cm into the RFQ. The models developed have matched previous work which shows a change in the transverse focusing from 3.088 to 6.981.

In the works cited, the RFQ exit energy is 6.7 MeV, but in these models the parameters were altered such that the exiting energy is 6.5 MeV. This discrepancy is due to the RF power required to operate the RFQ at its best performance.





nd innovations that
ccelerator

Figure 1: LEDA Accelerator with umbilicals attached inside the movable frame

These criteria make LEDA the perfect choice for the front end of our 100 dpa neutron irradiation system. The LEDA will provide the necessary beam to the Li target to generate approximately 8 dpa per year for the AND-1 system and as well as the emittance to travel through the cyclotron to the Pb target for the AND-2 system.

The LEDA RFQ, shown in Figure 4, is one of the extremely few RFQ accelerators that has achieved CW proton beam operation (17). Initially built as the front end of the APT project, the LEDA is currently sitting in storage being un-utilized. The device has successfully accelerated 100 mA of protons from 75 keV to 6.7 MeV and has run for 111 hours with a minimal current of 90 mA. The LEDA has also accelerated 106 mA of proton beam through the RFQ with a 96% transmission rate.

The RFQ did not fully function when ran within its design parameters. The skilled scientists testing LEDA increased the RF fields by 10% above design, increased the quality of the vacuum, added an electron trap at the entrance, and moving a solenoid closer to the RFQ (1). These changes allowed the RFQ to operate CW and achieve 98.7 mA with 6.7 MeV proton for over 3.3 hours with only a few short interruptions (18).

The collaboration proposes to move LEDA to Texas A&M along with pulsed RF power source, power supplies, transformers, and waveguides from LANL. CW power supplies will be obtained from CERN and refurbished for insertion after the RFQ's re-commissioning with a Li target downstream.

4.1.1 LEDA rf quadrupole accelerator

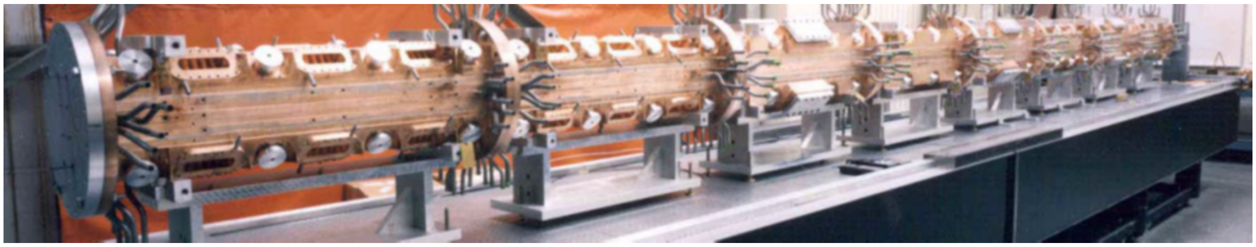


Figure 3: The LEDA RFQ without any of the umbilicals attached to the exterior. The 8 meter long accelerator is comprised of four 2 meter long sections. The cavity uses approximately 2 MW of power when operating, dissipating most of the energy into heat taken out by the cooling system (17).

The LEDA RF quadrupole (RFQ) accelerator offers an exceptional opportunity to create a dedicated accelerator-based neutron damage facility, with fast neutron flux up to 8 dpa/year for samples of ~5 cm^2 size. The LEDA was built at Los Alamos National Lab twenty years ago as the injector for their APT program (Accelerator Production of Tritium). The LEDA parameters are shown in Table 1 (1). It produces a continuous wave (CW) 100 mA beam of protons at 6.5 MeV kinetic energy with good emittance. It was successful in providing CW current during its operation – no small feat for an RFQ design. It has been operated sporadically over its lifetime and is currently in storage at Los Alamos in pristine condition, Figure 2 (19). We have negotiated the long-term loan of the LEDA system to Texas A&M University, and propose to install it in an above ground vault. The proton beam will then be directed to a liquid lithium target. The Li targetry will be developed for CW operation using the techniques and technology developed at ANL. The LEDA and Li target will operate together to form the first stage of the dedicated fast neutron test facility, AND -1.

The LEDA structure, shown in Figure 8, is mounted as a full assembly on a movable frame. Thus the machine can be reinserted without disassembling the accelerator. This drastically reduces the time required to re-commission. The water cooling (a crucial part of the infrastructure since the RFQ must be kept within a half degree), vacuum systems, and other cooling lines need to be evaluated as to their current status after the hiatus. It is anticipated that only minor repairs and upgrades will be required. However the RF controls have been dismantled and need to be reconfigured. This is not anticipated to be a problem as Dr. Saeed Assadi lead the Controls, Diagnostics, and Machine protection group at FRIB and Controls group at SNS.

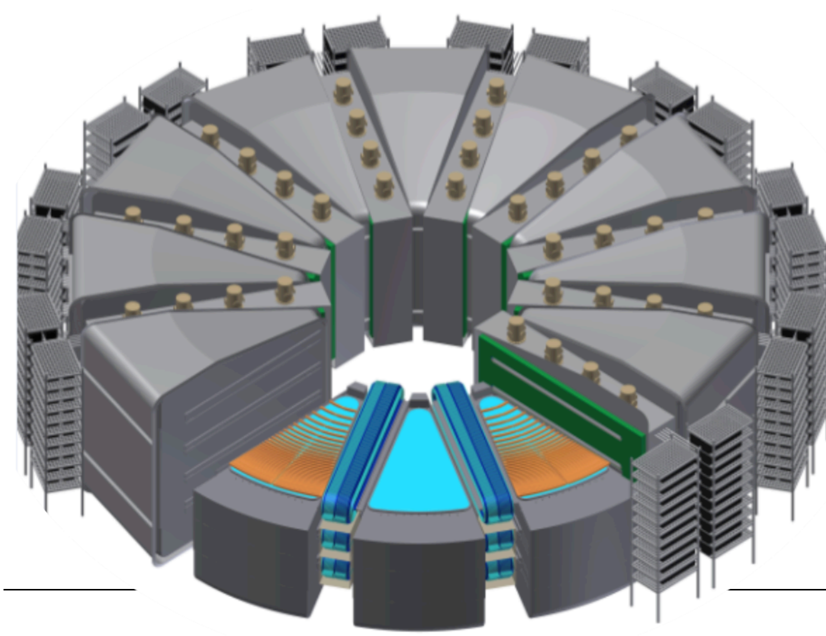


Figure 4: The 100 MeV cyclotron: The 4 sector SFC has 3 stacked cyclotrons that each have a set of superconducting RF cavities. The cavities (blue), the quad focusing channels (orange), and flux coupe stack are the 3 innovations added to allow

4.1.2 Ion Source

Table 1: The parameters for the LEDA RFQ developed at Los Alamos National Lab, which achieved CW operation is one of the few RFQ to achieve that accomplishment (1).

TABLE 1: APT/LEDA RFQ SPECIFICATIONS

PARAMETER	VALUE
Frequency	350.00 MHz
Particle	H⁻
Input Energy	75 keV
Input Current	105 mA
Input Emittance, trans./norm.	0.020 π-cm-mrad rms
Output Energy	
Output Curren	
Output E	
Transmission	
Duty Factor	
Peak Surface I	
Average Struc	
Average Bean	
Average Total	
RF Feeds	
Average Heat	
Maximum Lo	
Resonant Seg	
Brazed Sectio	
Slug Tuners	
Length	
Weight	
Inlet Coolant	
Operating Ten	

The LEDA source is currently on loan to Argonne National Lab until 2015. At the moment the device is being utilized by Michigan State University for studies associated with the FRIB project. If the LEDA source remains dedicated at its current location, a source can be readily designed by A&M personnel, or the LEDA source could be re- manufactured to specifications.

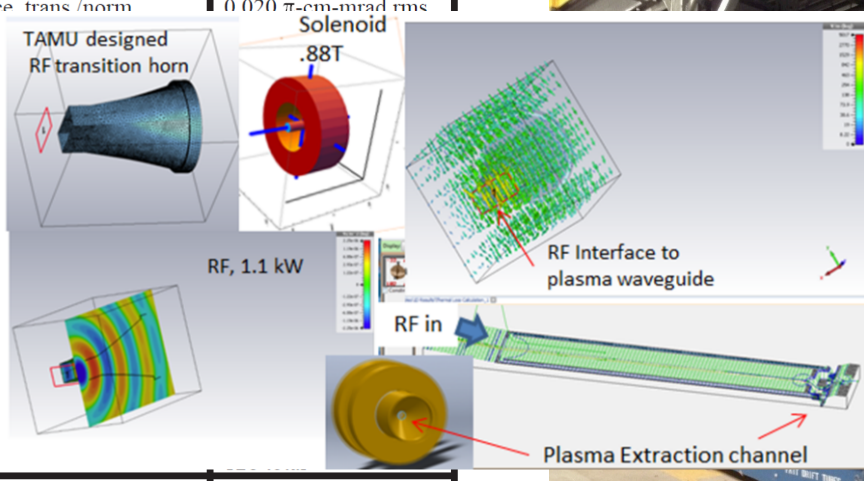
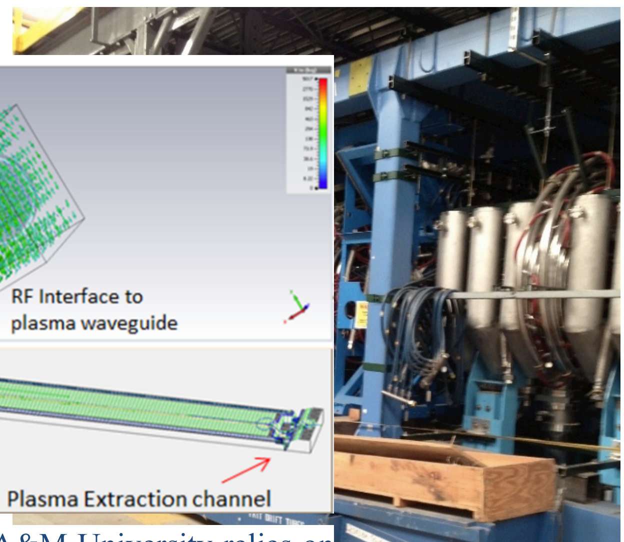


Figure 6: Integration of LEDA at Texas A&M University relies on defining interfaces and modeling components to assure LANL beam production quality on time. The images above are the components modelled, designed, and improved by A&M Sr. Res, Sci., S. Assadi, for the source and injection to the LEDA RFQ.



...ccelerator as it sits in ...nains still full assem- ...e allowing one to as- ...semble it fairly quickly (19).

The LEDA ion source was originally designed by CLR for the 50 keV Chalk River Injector Test Stand (20). That source had gone under two iterations of improvements by the LANL LEDA team. Recently, as of 2012, the source was used at MSU for studies of Lithium stripping at Argonne National Laboratory. This source is fully operational as shown in Figure 10.

Table 2: Parameters required of the source and the LEBT

Parameter	Required	Status
Energy (keV)	75	75
Current (mA)	110	117
Duty factor (dc)	100	100
Duty factor (pulsed) (%)	1 (10Hz, 1 ms)	To be tested
Reliability (%)	98	96 - 98
Lifetime (hr)	>168	168
LEBT exit emittance (πmm-mrad)	0.20	0.20
H, gas flow (T-l/s)	.04 -.10	.05-.09

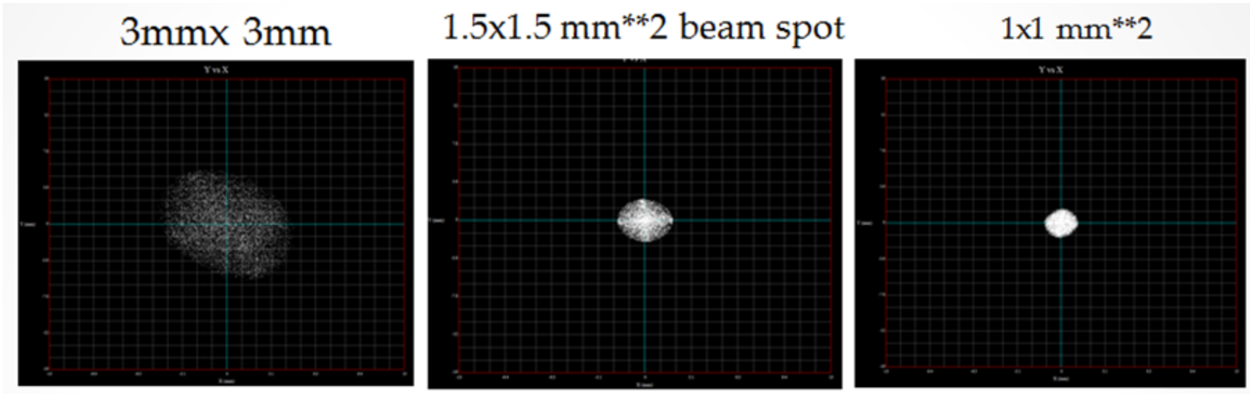


Figure 7: TRACE 3D simulations for the beam from the source to the LEBT. The accelerator group optimized the solenoid settings of Trace-3D such that the output of the simulation provides the design value given by LANL scientists during design and commissioning of the LEDA.

At Texas A&M University, we have designed components that are suitable to integrate this source to our specifications. Two examples of importance are the RF coupler to the plasma chamber and the meniscus to extract the beam from the chamber. These components are fully modeled using CST microwave studio and ANSYS-HFSS, shown in Figure 3. The crucial components that are needed to guarantee the success of the INTEGRATED physics specifications are designed or modeled in-house at the Texas A&M University irrespective of their condition or original physics analysis.

4.1.3 Low Energy Beam Transport (LEBT)

The source requirements for the LEBT and subsequent LEDA RFQ are given by L.D Hansborough, et al (21).The table of physical requirements from 21 is shown from completeness.

The accelerator team is using the RFQ matching conditions for the solenoid in the LEBT of the LEDA, ~2.7 kG. Trace3D (22) plots of the beam path and most importantly size, were prepared using the parameters and conditions set forth by the work Smith et. al. performed with LEDA (23) which are shown in Figure 5. The beam size is of the utmost importance to provide excellent emittance for not only the AND-2 but also provide excellent beam shape for bombarding the Li target in AND-1.

Smith also showed, regarding the error studies and tolerances, that "The LEDA injector will provide a range of beam centroid motion at the RFQ match point. Error studies show that if the input phase space distributions are centered on the RFQ axis to within ±0.2 mm in position and ±10 mrad in angle, the transmission degrades by <1%." Thus solenoid lenses needs to be aligned to meet these tolerances, Figure 7, keeping losses low and reaching maximum beam current, causing higher dpa.

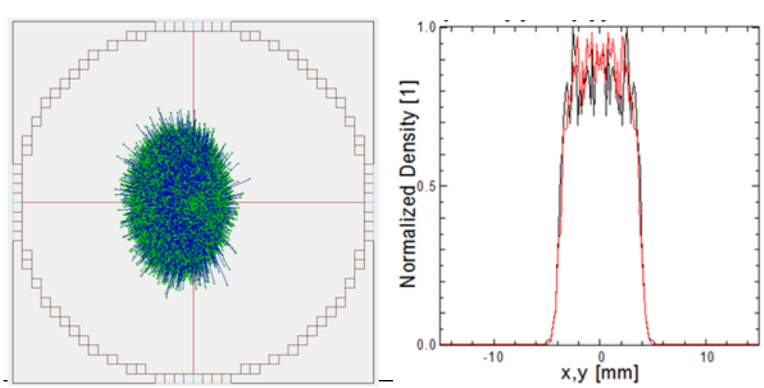


Figure 8: 6D KV distribution that is used for the case stud-

Case No.	Extrac-tor to Sol#1, cm	Sol#2 to RFQ Match Point, cm	SCHAR RFQ ε_{in}, π mm mrad	PARM-TEQM RFQ ε_{in}, π mm mrad	PARM-TEQM RFQ ε_{out}, π mm mrad	RFQ trans-mission %
1	87.58	40.70	0.228	0.226	0.214	93.0
2	57.58	40.70	0.220	0.218	0.206	92.7
3	87.58	25.70	0.204	0.202	0.200	93.4
4	57.58	25.70	0.189	0.188	0.196	92.7
5	87.58	45.70	0.246	0.244	0.225	91.9
6	87.58	50.70	0.383	0.382	0.251	79.2
7	87.58	55.70	0.456	0.467	0.274	77.2

Figure 9: LEDA LEBT is a two solenoid design with length shown for the best case (23).

Texas A&M is providing provisions in the concrete padded area, where the LEDA complex will be located, to meet or exceed the specifications for ground motion as well as the facility construction and installation alignment tolerances to the original designer's requirements. But there will be inevitable misalignments between the ion source, column, and RFQ that can produce centroid errors in excess of these tolerances. The LEBT steering system will permit rapid, on-line correction of these errors and our controls system will provide feedback to orbit corrections and target spot size location.

To study the beam optics and space charge effects for the AND-1 and AND-2 phases, well-established beam conditions per (21, 23) are required. One common distribution used for these studies is the 6D KV distribution, which will be common for all case studies. This distribution retains the transverse direction as uniform, which is less restricted than Waterbag or Gaussian distributions. Simulations utilize 350k particles as a standard that form the database of the beam studies for the accelerator. A sample of that distribution is shown in Figure 6.

We have provision for three additional systems for the LEDA LEBT that the current system does not have enacted:

1. A simple low energy chopper was added to prevent the beam from accelerating to 6.7 MeV through the RFQ by forming pulsed beam and on-demand beam. This feature will allow the source to operate normally but limit beam as "ON Demand". This will also minimize radiation production in the facility. It should be mentioned that the same peak energy as is currently required to sustain the operational conditions of the LEDA RFQ, with the added caveat that the TAMU LLRF requires feed-forward compensation for the beam loading of the RFQ to form a pulsed machine.
2. Gas stripping analyzer chambers will be created with inexpensive cameras and inserted into the LEBT to measure transverse beam profile continuously to the RFQ.
3. Collimating systems are located prior to the RFQ to ensure that the beam fits within the LEDA parameters and reduces halo (previously shown by Stovall,(24)), with a set of water cooled apertures.

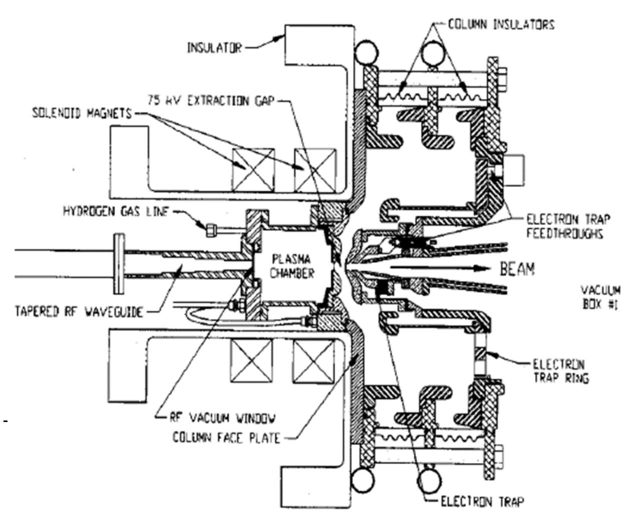


Figure 10: LEDA target as designed by CLR for the Chalk River Injector Test Stand (20).

4.2 AND-2

In order for AND-2 to generate 100 dpa per year, it requires the beam be accelerated to higher energy. The AND-2 design uses a novel design for a strong-focusing cyclotron (SFC), shown in Figure 11. The SFC is similar in essence to the isochronous cyclotron at the Paul Scherrer Institute (PSI), which is currently the highest-power proton accelerator. The AND-2 system is comprised of the LEDA accelerator and a flux coupled stack of three SFCs. The proton beam is broken into three separate lines where each beam is sent to its own dedicated cyclotron. Once accelerated by the cyclotrons the beams are directed to the Lead target where they spall off neutrons.

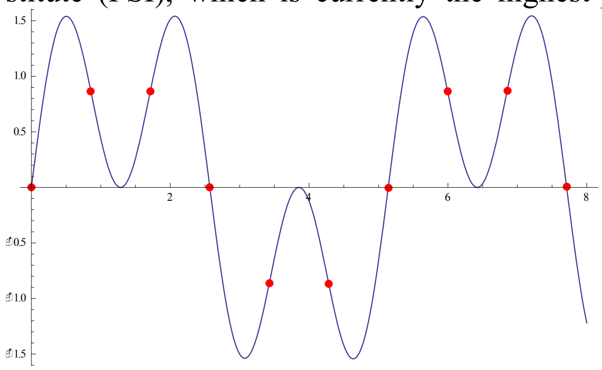


Figure 11: The spectrometer system uses two cavities operating at 58.3 MHz and another at 175 MHz to either increase or decrease the energy to allow different trajectories for 3 beams in the uniform magnetic field. The graph is an overlay of the two modes with the bunches indicated in red. The three beams (+,-,0) all have two bunches each. A single cavity (58.3 MHz) could be used if the particle speed were higher

4.2.1 Separation Scheme

The LEDA produces a CW 100 mA beam at 350 MHz that must be broken into three beams to feed the cyclotrons. Two strategies have been devised as methods to separate the beams: spectrometer and kicker.

The spectrometer utilizes two distinct cavities, one operating at 58.3 MHz and the other 175 MHz, to accelerate one third of the bunches, decelerate a third, and leave another third untouched. The bunches then enter a ~.4 T dipole field that then separates the bunches into three distinct beams. At the end of the dipole a 5 cm transverse separation has been created allowing transport channels to take each beam to their respective cyclotrons. After the beams are separated, the individual beam are passed through a single cavity that accelerates the beam (750 keV) to the same energy level as the highest beam produced, 7.25 MeV. The cavity shape is similar to the shape of the cyclotron cavities, but axisymmetric, and therefore readily constructed will have the same eccentricities during operation.

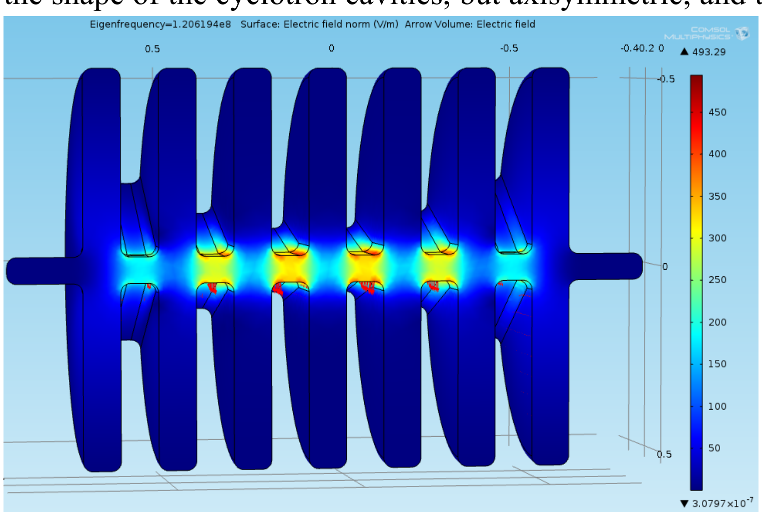


Figure 12: First iteration of the 6 cell kicker for the separation strategy. This cavity can provide 2 degrees of deflec-

The kicker strategy requires a multi-cell cavity that will provide enough of a transverse kick such that an angle of 1.3 degrees is achieved with in a 1.5 meter long length. It has been identified that this length is the maximum travel the beam can have the beam growing in emittance. A cavity has been designed by adapting the same style of cavity used at Fermilab for Project X (25), which itself is an adaptation of a LHC cavity (26). The cavity design shown in Figure 13 has 6 cells and provides 150 keV of kick in the vertical direction required for the beam in drift to achieve a separation of 5 cm between each of the three beams. The 5 cm separation allows beam transport channels, identical to those used in the cyclotron, to take the beam to their respective stacks in the SFC.

The 350 MHZ LEDA RFQ output beam current had reached the record level of 110 mA at LANL prior to decommissioning (23). This amount of proton beam can easily be divided to provide a steady 6.7 MeV proton CW beam into many cyclotrons. TAMU cyclotron are designed with frequencies around 100 MHz. In this case, division by three or 117 MHz is a suitable frequency.

The cavity RF phase with respect to the reference RF, the RFQ in this case, will be indexed by 2π/3. The indexing is absolute. This is to assure the beam split and preventing to pile up beam in one cyclotron. LLRF and Machine protection system, in conjunction with the timing system, will be under finite state machine. The Panofsky-Wenzel theorem (27) which relates the transverse Voltage [V_x] to the variation of the longitudinal electric field is valid for all kicker cavities.

$$V_x = \int \frac{F_x}{q} d_z = \int (E_x + cx\, B_y).\, d_z = -\frac{ic}{\omega} \int (\nabla_t E_z) d_z$$

As mentioned above, we are using TEM-type deflecting mode cavities similar to Jab and Fermilab Project-x due to being compact cavity, or also known as a beam separator at CEBAF. Thus the kicker should provide enough separation to extract the three beams with good emittance such that they can be delivered to the cyclotrons.

4.2.2 The Strong Focusing Cyclotron

The SFC, which is of interest for many applications, utilizes three innovation that allow large currents at high energy. The first innovation is to use superconducting RF, constructed out of Niobium, to provide sufficient energy gain (~3 MV/turn, ~30 total orbits) such that orbits do not overlap. This provision eliminates the space charge interactions between bunches on successive orbits. There are two superconducting cavities located within the gaps between the 4 sectors of the magnet.

Each sector magnet has a pair of windings that generate ~1 Tesla that are wrapped around a cold-iron flux plate. The unique feature about these sectors is that three of these pairs are stacked upon one another and share a common flux return, or a flux coupled stack. In this configuration, three identical apertures are situated above one another with a 1 m spacing all within one footprint. A key part to keep efficiency high it to use superconducting technology again for the windings, in this case MgB_2. All magnet windings utilize MgB_2 superconductor, operating in the temperature range 15-20 K. The stack of flux plates is supported within a warm-iron flux return using low-heat-load tension supports.

The each cavity accelerates the 24 parallel beams simultaneously providing the space for curved beam transport channels located in the aperture of each sector magnet (Figure 14). Each transport channel houses an alternating-gradient pair of Panofsky quadrupole lenses to provide strong-focusing transport, and a window-frame dipole winding to provide correction of bend field for isochronicity as well as to provide ample orbit separation for injection and extraction.

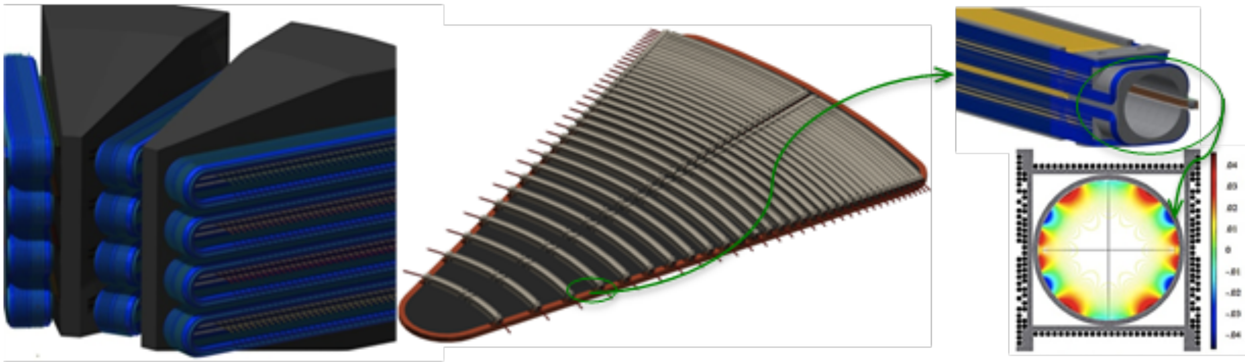


Figure 13: Left Superconducting cavities in blue. Middle: a sector magnet with a FODO lattice of quad focusing channels which tightly control the beam to allow high current. Right: close up of Quad and magnetic field cross section.

In all previous cyclotrons (including PSI) weak focusing is provided by the fringe fields between sectors or from 'hill/valley' contouring of the sector poles. Using such weak focusing it has never been possible to lock the betatron tunes or avoid resonance crossing during acceleration. Strong focusing is used for that purpose in all synchrotrons and linacs, but has never before been possible in a cyclotron. The beam transport channels in the SFC are used to control beam size and achieve transport of larger beam current. The three innovations can be seen together in Figure 11. Our simulations show that these innovations should pro-vide reliable low-loss acceleration and transport of a 15 mA, 100 MeV proton beam in each SFC. Each SFC in turn delivers the 3 beam at 120 degrees of separation to Pb targets generating 140 dpa.

4.2.3 Lithium Target for AND-1 and Lead Target for AND-2

Once the protons have navigated their way through the LEDA (AND-1), the neutrons are delivered to a windowless lithium liquid target. The protons bombard the high velocity – thin sheet - liquid metal jet and generate neutrons via the reaction ^{7}Li (p,n) ^{7}Be. This interaction has a large cross section for protons of this energy compared to other candidate elements (such as lead), and thus produce a high flux of neutrons. Even with a high cross section, for every incident proton only .2% of the time a neutron is generated. Though the efficiency is low it still produces a high flux of neutrons. The target must be molten because it is the only target type that can support the ~700 kW of power delivered by the beam, which is why a solid Beryllium (higher cross section than Li) target cannot be used.

The liquid Lithium is forced through slit forming a flowing sheet of molten metal, which then falls as a sheet flow, approximately 5cm wide, into a reservoir tank. The liquid in the tank is pumped through a heat exchanger and then pumped back to the slot iris. This closed loop approach has been developed at Argonne National lab and is was planned to be used at facilities such as FRIB and RIKEN, but for stripping purposes.

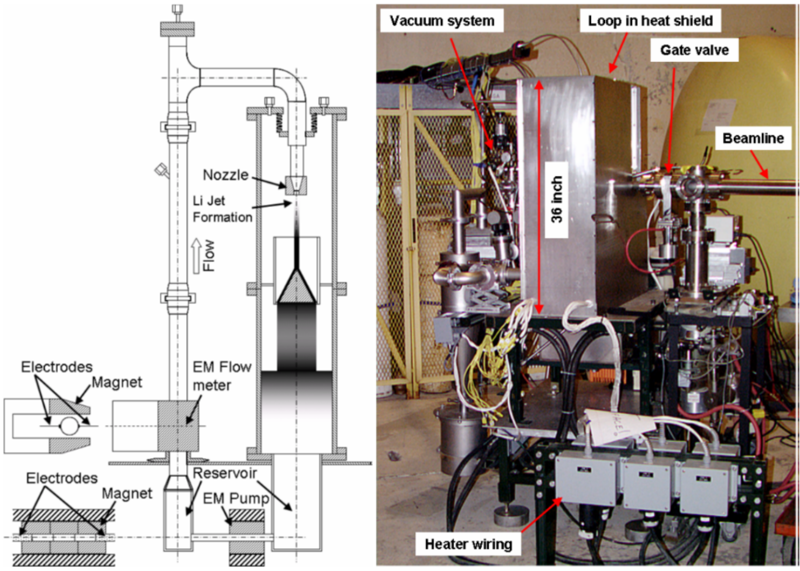


Figure 14: Schematic and picture of the Lithium target constructed at Argonne National lab (2).

The parameters for the AND-1 lithium target is shown in Table 3. These parameter are far more conservative than those tested in previous experiments. The AND system can produce at most 1.5 MW/cc. This power density is substantially lower than the 4.1 MW/cc electron beam used to test the device (2). Bombarding the flow with this much energy did not affect the flows stability nor the uniformity. Though less demanding in the power requirements, the thickness of the flow is less than half the thickness previous experiments had used, yet the proton beam does not penetrate the molten sheet.

The penetration depth of the proton in the molten metal is only about 1- 1.5 mm. Thus a ~2mm thick target contains the Bragg peak and thus will block any protons but not impede the neutrons formed from the reaction. To ensure that the sheet is unaffected by the intense power being deposited, the metal sheet flow at a rate of 20 m/s limiting the temperature increase to 375 C. The temperature must be kept as low as possible to ensure that lithium vapor is not formed which might interfere with the uniformity of the flow, which would cause perturbation of the neutron flux, or possibly travel up the beam line.

Table 3: Lithium Target parameters for the AND-1 system.

Target	Liquid Li sheath
Thickness, mm	1.5-2
c_p (@400C), J/g K	4.23
k (@400C), W/m K	48
ρ, g/cc	0.5
Viscosity(@400C), Pa s	3.74e-4
Beam energy, MeV	6.5
Beam current, mA	100
σ_{rms}, cm	1
Heat load on target, kW	650

These subtle details and eccentricities of these molten targets is why it is critical to have the support and collaboration from our expert collaborators at ANL. The other key feature was that since the target is windowless, there is no barrier into the accelerator. A vacuum of 10^{-6} Torr was preserved using turbo and diffusion pumps, (2). In addition, the beam pipes are bent to prohibiting any droplets of vapor from entering the accelerator itself. The diagram and image of the Lithium targets that were constructed are located within Figure 15.

4.3 Neutron Damage from the reactor exposures, AND-1 and AND-2.

Accelerator - Lead: S. Assadi (TAMU) - **Team:** N. Pogue (TAMU), A. Sattarov (TAMU)

Materials - Lead: S. Maloy (LANL) - **Team:** S. Chirayath (TAMU), X. Huang (USC), T. Knight (USC), M. Short (MIT), B. Tyburska (UW), J. Zhang (OSU).

4.3.1 Overview

Neutron irradiation is sought to determine the characteristics, mechanical properties, and life-time of structural and component materials for fast, advanced, accelerator, and fusion reactors. Currently there are no high-flux fast reactors or high-flux mixed spectrum reactors capable of reaching the desired levels (200 dpa, using the accepted standard model) in a few years, thus the community has turned to the only available alternative, ions. However, the damage generated by neutrons is quite different than that produced by ions, which do not mimic damage in a reactor core. Ions cause damage by ionization loss as it travels through the material cause substantially large amount of displacement compared to neutrons. However during this same process the ions also anneal the material much more than neutrons, which only act by direct contact with the nucleus.

It is goal of this topic to demonstrate that neutrons from an accelerator are sufficient and comparable to those of the available cores for irradiation. Additionally, demonstration of the manner in which the collaboration intends to create the ~7 dpa/year using AND-1 and the ~100 dpa/year in AND-2 phase will be presented in the following discussion.

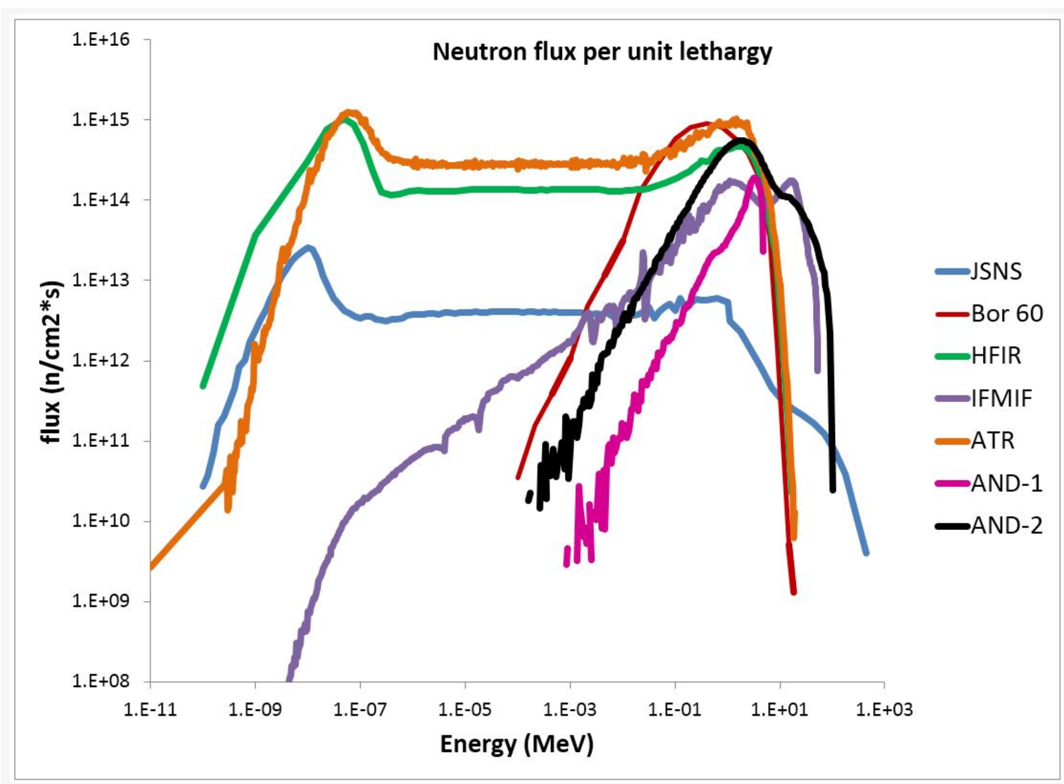


Figure 15: Comparison of the neutron flux and energy spectrum of various facilities around the world, and those currently under design.

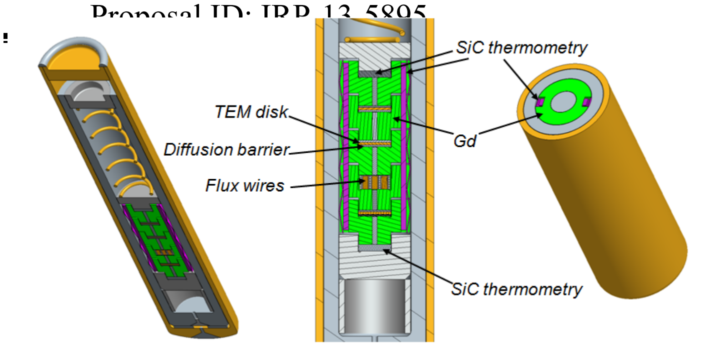


Figure 16: HFIR Irradiation Capsule Design for a Previous Texas A&M University Fast Neutron Irradiation Experiment

4.3.2 HFIR – S. Chytharil (TAMU)

ORNL-High Flux Isotope Reactor (HFIR) is an intense neutron source for research purposes and operates at a power of 85 MWth. HFIR provides a variety of in-core irradiation facilities, of which central (31 positions) and peripheral (6 positions) flux trap target positions are most suitable for the fast neutron irradiation experiments on fuel cladding materials. The peripheral target positions provide the highest fast neutron (neutron energy > 0.183 keV) flux of 1.2 x 10^{15} n/cm^2/s. Fast neutron flux is important to the experimental studies on dpa of cladding materials because fast neutron induced threshold reactions such as (neutron, proton), (neutron, alpha), etc. are responsible for producing dpa in materials. Approximately 8 HFIR cycles are performed per year, which can then provide an accumulated 4 dpa per year to the samples. The temperature of the coolant inside the HFIR varies from 49 °C at the inlet to 69 °C at the outlet. During the execution of the IRP research it may be determined that higher temperatures may be sought, thus the collaboration is investigating methods and designs to reliability increase the temperature to much higher temperatures that would be close to the environments of fast and advanced reactors.

Since HFIR is a thermal reactor, the peripheral target position will also consist of thermal neutron flux (2.5 x 10^{15} n/cm^2/s) in addition to the fast neutron flux of 1.2 x 10^{15} n/cm^2/s. Suitable irradiation capsule will be designed to reduce the thermal flux by employing thermal neutron absorption (Gadolinium) shield around the cladding material samples. The capsule will be provided with neutron flux measurement wires and SiC (Silicon Carbide) material for thermometry. The schematic of the HFIR irradiation capsule design for fast neutron irradiation experiments used by S. Chirayath is shown in Figure 19.

Table 1 - Comparison of Russian and U. S. Reactors

	SM-2 AZ	HFIR	BOR-60	EBR-II	FFTF
Thermal Power	100	85[a]	55	62.5	295[b]
Neutron Flux, x10^{15} n/cm^2-s:					
Total	3.5	4.0	2.0	2.6	5.6
Thermal (<0.5 eV)	1.5	1.6	-	-	-
0.5 eV to 0.1 MeV	1.0	1.3	0.22	0.45	1.9
> 0.1 MeV	1.0	1.1	1.8	2.3	3.1
> 1 MeV	0.6	0.6	0.5	0.6	0.6
dpa/y (Fe)	27	26	24	33	34
He,appm/y (Fe)	15	9.3	12	3.5	3.5

[a]HFIR is capable of operation at 100 MW.
[b]FFTF is capable of operation at 400 MW.

Figure 17: Comparison of the different reactors in the US and Russian Federation (28).

4.3.3 BOR-60- Stu Maloy (LANL)

In addition to samples being placed in HFIR for irradiation, the collaboration has secured the use of samples from BOR-60 reactor in Russia as part of the 123 Agreement between the United States and the Russian Federation. The collaboration has made an agreement to assist in this program by performing sample preparation and analysis. The collaborations' involvement is contingent on the

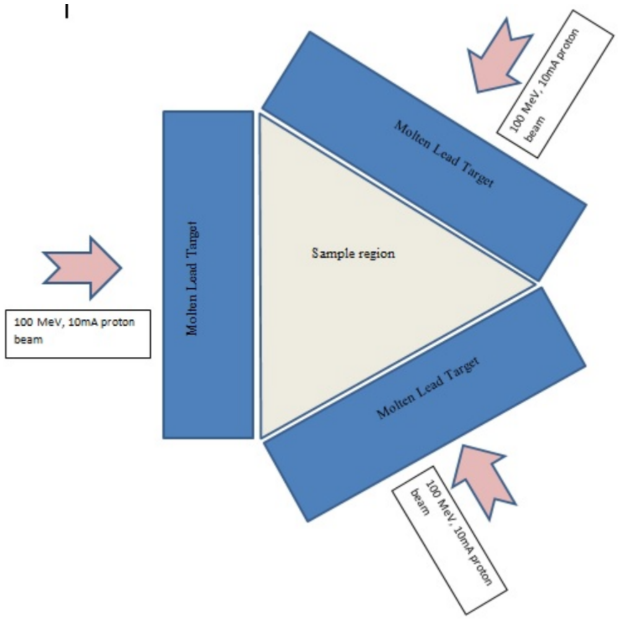


Figure 18: Diagram of the AND-2 irradiation chamber.

success of the IRP. The BOR-60 facility is a fast sodium cooled reaction that began operation in 1969. The BOR -60 reactor is lower energy (55 MWth) than HFIR but has a larger fast fraction (28). It can be operated with 90% enriched uranium oxide or mixtures as high as 40% plutonium oxide. The normal operating temperature for the BOR-60 is between 340 to 1000^{o}C which matches the entire range of interest for the work presented here. Depending on the exact location contracted within the reactor, the flux can range between 3.8*10^{13} to 1.2*10^{14} n/cm^{2}-s. With these fluxes the highest damage level that can be achieved is 18 dpa/year within the BOR-60 core.

These two reactors will provide the main method of irradiating of the samples put forward by the collaboration. It is the goal to use these two facilities to provide a means to understand the process by which the material is alter as a function of neutron damage. The HIFR facility with its short cycle provides the means to extract and insert samples on a regular basis allowing the collaboration to have a good understanding of damage progression. The BOR-60 can provide the samples with large dpa such that the long exposures can be mapped as well. The fluxes, without shielding, are compared in Figure 16. It is anticipated to see that the damage is an equal across most parameters.

4.3.4 AND-1 DPA

The AND-1 delivers a 100 mA proton beam to a ~1 mm thick neutrons target that causes a nuclear reaction producing neutrons. The spectrum of neutrons produced by the AND-1 and the AND-2 are shown in **Error! Reference source not found.**. Utilizing the spectrum illustrated, dpa calculation were performed using a modified Kinchin and Pease model as is performed in the code SPECTER. The mean neutron energy for the AND-1 is 2.37 MeV, and for the AND-2 it is 6.99 MeV. Modifications of the model had to occur because the neutron energy range covered in SPECTER is only up to 20MeV. As a consequence modification were made to account for new cross sectional data up to 150 MeV. The dpa calculations presented use the new library when evaluated.

Number of displaced atoms generated by primary knock-on atom (PKA) of energy E (damage energy) is given as:

$$N_d = \frac{0.8}{2E_d}E,$$

E_d is defined as the threshold energy. The threshold energy has typical values from 10-90 eV for most metal. The case analyzed here is for Ni, which has a 40 eV threshold energy. If one knows the number of displaced atoms one can then calculate the DPA cross section for neutrons for a material as

$$\boldsymbol{\sigma_{DPA}(E) = \frac{0.8}{2E_d}\Sigma(E)}$$

Here $\boldsymbol{\Sigma(E)}$, the damage energy cross section (eV barn), for natural Ni was extracted from ENDF/B-VII.1 using Janis3.4 software (29). DPA rate of the sample irradiated by neutron flux

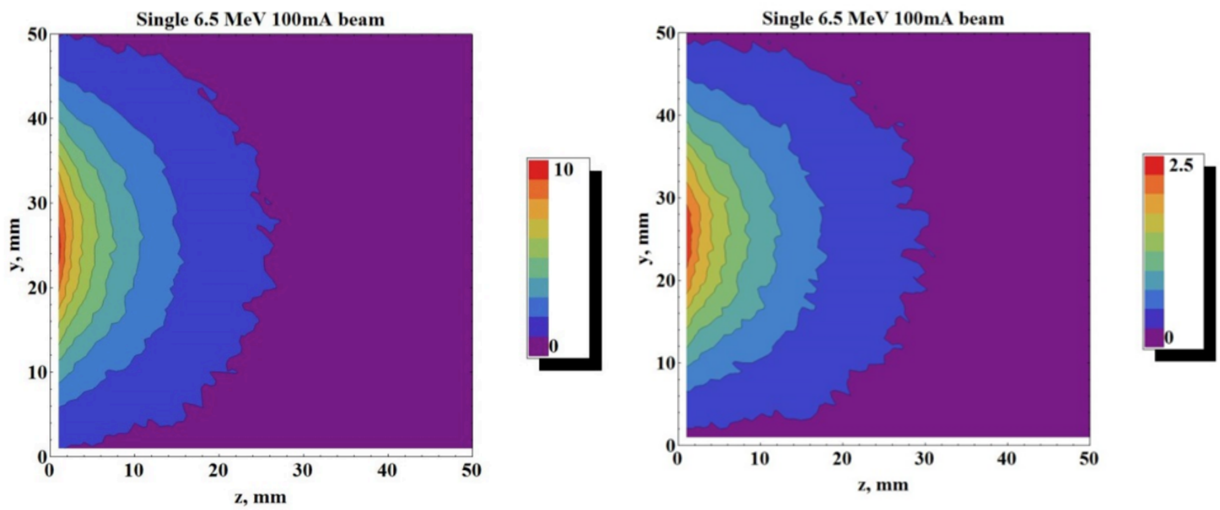


Figure 19: Left: The DPA received by a nickel sample bathed in the neutron flux, generated by the 6.5 MeV protons, directly behind the Lithium target. Right: Heat generated by the beam in

$\boldsymbol{\varphi(E)}$ then is given as

$$DPA = \int \sigma_{DPA}(E)\varphi(E)dE$$

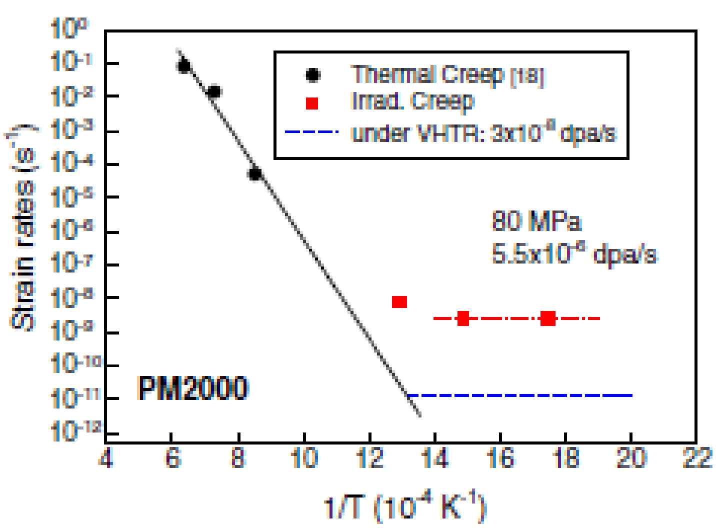


Figure 20: Temperature dependence of creep rates of PM2000 without irradiation (solid line), under He-implantation (dash-dotted), and expected for VHTR conditions (dashed line).[3]

Thus using the neutron flux and the dpa cross section for Ni the estimated total dpa/year can be calculated. The dpa for a Nickel sample placed in the AND-1 neutron flux is shown in Figure 17, where the samples are placed directly behind the Lithium Target. Additionally the energy deposited in the form of heat at different locations of test region may be determined. The heat load deposited from that flux is shown in Figure 17.

Stress and Creep

The AND-1 will be ideally suited for performing critical in situ mechanical property measurements under irradiation including creep, fatigue and fatigue crack growth measurements. These mechanical tests require long term tests at specific temperatures and are strongly affected by the high flux of point defects present under extreme irradiation conditions. Previous results have shown that ex situ creep testing results are different from results from testing in situ (30, 31). Figure 18 shows irradiation creep rates measured on PM2000 under He implantation (32). AND-1 would be able to perform similar measurements under high dose reactor irradiation conditions at prototypic reactor irradiation temperatures, which cannot be done with ions nor in reactors. *It is very difficult to perform such measurements in reactor because of the space limitations and the sensitivity of load cells and strain measurements to the extreme reactor conditions.*

4.3.5 AND-2

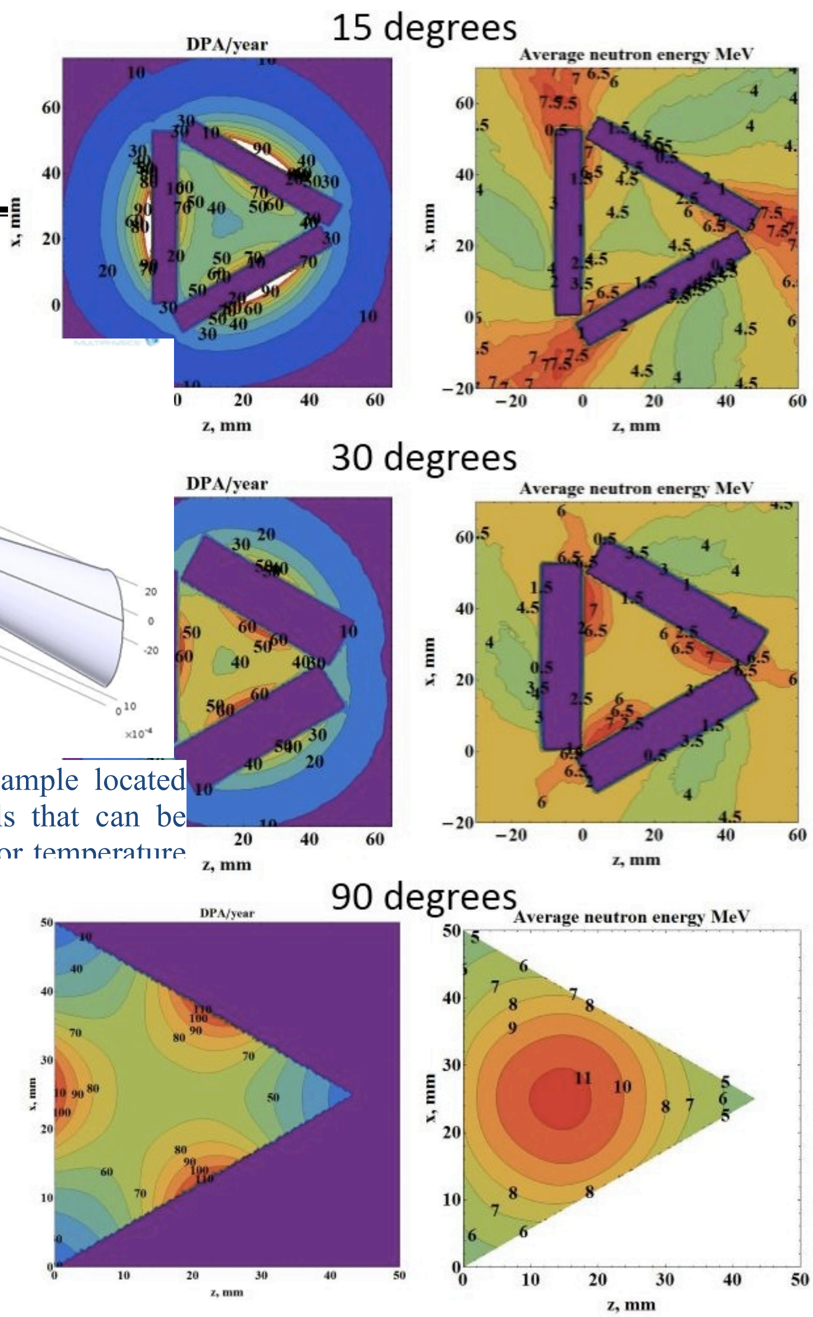
During the second phase of the AND system, the energy of the proton beam will be increased dramatically. This will generate a median energy of the neutrons of 6.69 MeV compared to the 2.37 MeV generated by AND-1. The flux of neutrons is 10 higher in across all energies and the fast fraction is significantly higher as seen in **Error! Reference source not found.**. One important segment of the fast fraction is the flux of 14 MeV neutrons. This energy is of utmost importance to the fusion community looking at first wall irradiation.

Table 4: Lead target parameters for the AND-2

Target	Liquid Pb sheath
Thickness, mm	18
c_p, J/g K	0.16
ρ, g/cc	10
viscosity	32mP
Beam energy, MeV	100
Beam current, mA	10
σ_{rms}, cm	0.5
Heat load on target, kW	100

The three 100 MeV, 10 mA beams produced by the flux coupled stack cyclotrons are brought to 120 degrees angles to one another, as shown in Figure 21. These beams are then bombarded on a molten lead sheet flow similar to the lithium target for the AND-1. The parameters for the molten lead target are shown in Table 4. As a consequence of using lead as the target, and having a higher energy, there is a larger probability of producing a neutron per incident proton, about 35 %. This is a factor of 175 higher than AND-1, and thus a significantly higher flux is obtained. This produces higher energy neutrons than are desired for some studies. By bombarding the target at an acute angle the energy spectrum can be softened to more amenable energies. Thus the system can be tuned for a desired energy or a single sample can be placed in a single location where the spectrum matches the need.

The damage produced by the higher energy particles also induce more damage to the sample because of the substantive issue of H and He production. This mechanism of damage is 30 to 100 times more destructive to the materials structure than epithermal or thermal neutrons, as well as any mechanisms they can produce. Taking into account all these details heat load generated in a Nickel sample and the dpa as a function of position are shown in Figure 22.



4.3.6 3.2.5 AND Sample

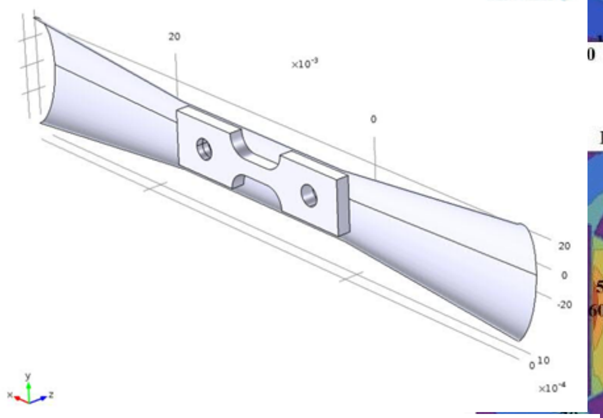


Figure 22: Miniature tensile sample located within a cooling/fluid channels that can be inserted into the neutron flux for temperature

design

Figure 21: The three beam of the SFC are aimed at different angles producing different mean energies for the sample area that can hold 21 samples. The angle indicated is off the target fave and are all arranged clockwise. The mean energy are as follows: 15 deg – 4.5 MeV, 30 deg – 5.5 meV, and 90 deg – 8

The samples in both the AND-1&2 will see a heat deposition. As consequence, the samples need to be cooled. Investigating the most extreme scenario for sample heating, the heat deposition in AND-2, at a strategy was devised to maintain the sample at a specified temperature. Samples at max DPA zone will receive up to 100W/cc, so helium gas cooling as possible way to control sample temperature was modeled. A heat load of 100 W/cc was applied to standard tensile specimen made of nickel that was placed inside of elliptical cooling channel, Figure 23, with 2 atm of room temperature He gas purged in at velocity of 0.05 l/s through the channel.

The temperature across the sample can be maintained within five degrees. Thus temperature control can be achieved to a reasonable level of control. In addition we have devised a scheme in which to place sample is a corrosive environment to allow simulation of any environment sought.

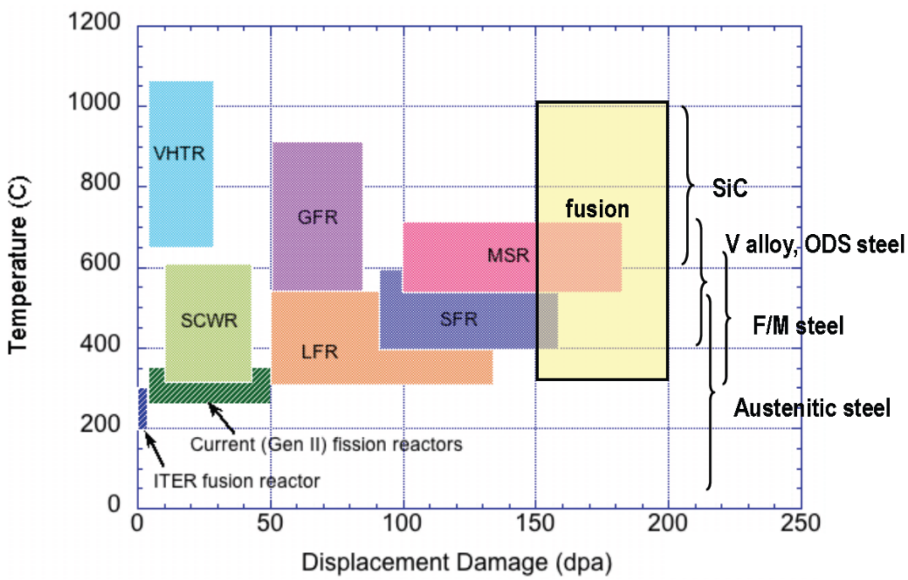


Figure 23: Operational domains in nuclear engineering (**Error! Bookmark not defined.**).

4.3.7 Summary

The first stage of the AND system should provide the proof that an accelerator based system can produce comparable results to nuclear reactors in terms of damage received by sample. It is our assertion that accelerators can be used for both neutron and ion irradiation (of which the LE-DA could provide both), but that because of the nature of the two types damage that neutrons must be produce to simulate neutron damage in reactors. The first stage is to instill confidence and prove the technology that an accelerator can produce via spallation on a lead target, 100 dpa per year using the technology illustrated above.

4.4 Experimental studies of neutron damage

The research plans of each of the participating material science teams are presented below. In all cases the experimenters will prepare samples of their materials for the exposures at HFIR, BOR-60, and STIP, and select existing samples from their previous research and from the librar-ies at LANL and PSI. Following sections summarize plans for the HFIR experimental program, and for sharing samples in the coming BOR-60 exposures. Finally the spectra and dose rates of the present facilities are compared with what will become available with AND-1 and AND-2.

There are several areas of research that need to be explored in order for fast reactors and ad-vanced reactor to become a reality. Several different flavors of materials have been identified to be serious candidate for these types of environments. It is therefore very important to test these materials at the extreme condition they may be subjected. Below are a series of materials that of interest to the collaboration and to the community. The material, its properties, prior research, and what knowledge is hoped to be obtained in this IRP is expounded upon below.

For current and next generation nuclear reactors it is of paramount importance to be able to qualify their materials and assure their reliable behavior in anticipated performance domains. Long-term behavior of traditional materials in extended operation conditions and behavior of novel materials being exposed to radiation fields must be evaluated to assure safe and reliable operation of nuclear reactors. Gaining such evaluations is needed in the licensing process for life extensions of existing reactors and new reactor applications. The spectrum of materials ranges from fuels and in-core structures to reactor vessels, primary piping and in-containment components (33). Material degradation can lead to increased maintenance needs, decreased reliability, excessive downtimes, etc. Thus it has a potential for impeding viability of existing nuclear power plants and challenge deployment of new emerging nuclear reactor technologies. It is recognized that performance characteristics and availability of qualified materials significantly impact economic competitiveness of nuclear power (34). Furthermore, material qualification and licensing has traditionally been a lengthy multi-decade testing process due to the need to reach performance limits expected for the materials. Thus, accelerated evaluation of nuclear materials for qualification of their performance in anticipated operation domains and licensing is critically needed.

This proposal address the critical need to overcome material limitations through the science-based accelerated testing approach allowing to emulate decades of degradation of materials through high-dpa physics-equivalent neutron irradiation environment with the ability to test in representative thermo-mechanical and material compatibility conditions.

4.4.1 Radiation Resistance of Gen IV Composite Alloys- Short

The successful implementation of Generation IV (Gen IV) reactor technologies hinges upon the successful development of advanced materials. Gen IV designs push the physical limits of power density, temperatures, burn-up, corrosion tolerances, and other aggressive environmental conditions. Simultaneously providing structural integrity and corrosion resistance is a particularly challenging problem. Many attempts have been made to develop single alloys to perform both functions, such as for the lead-bismuth eutectic fast reactor (LBEFR) (35, 36, 37), but without significant success. Functionally graded composites (FGCs) have recently shown more promise (38), as layers can be designed and tuned for individual functions. However, the integrity of the interface under irradiation is of the utmost importance.

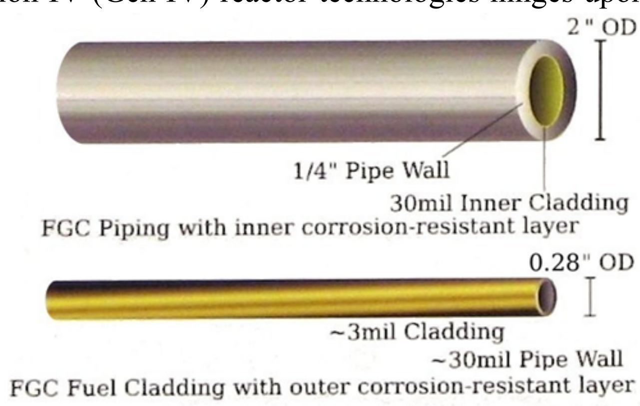


Figure 24: FGC product forms for the LBEFR (38)

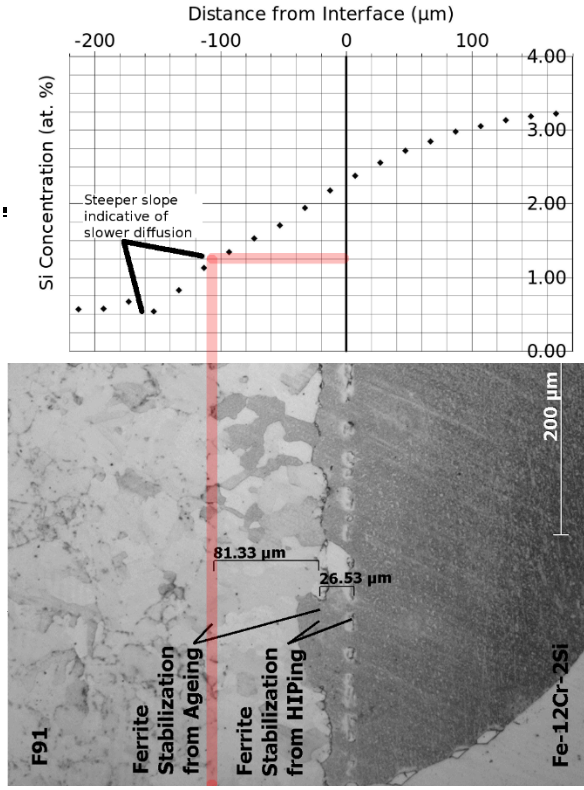


Figure 26: FGC diffusion couple aged at 800°C for 600hr, with Si concentration pro-

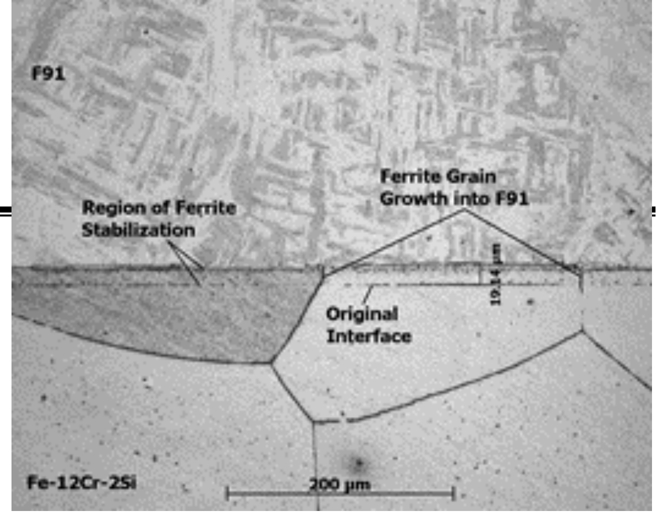


Figure 25: As-HIPed diffusion couple of the FGC, 100x (39)

Background: FGCs for the LBEFR: Recently, Short and Ballinger have developed a functionally graded composite of alloys T91 and Fe-12Cr-2Si (38, 39), which is showing the potential to alleviate the old corrosion allowance of 550°C for the LBEFR without compromising the structural integrity of core components. T91 provides the structural backbone, as its creep resistance (imparted by finely dispersed carbides & carbonitrides (40)) exceeds even that of HT-9, an alloy developed for the EBR-II sodium cooled reactor, at 650°C (41). The FGC can be made as both coolant piping and fuel cladding, as shown in Figure 25, using domestically available industrial-scale processing techniques, such as weld overlaying and co-extrusion.

Corrosion experiments have shown excellent resistance to LBE attack by Fe-12Cr-2Si, while diffusional experiments have shown manageable interdiffusion between T91 and Fe-12Cr-2Si (see Figures 2-4). These all point to an exceptionally stable FGC.

Radiation Effects on the FGC: The one major question left unresolved is its performance under irradiation. The FGC has shown a graded, microstructurally sound interface (see Figure 27). A sustained fast neutron flux the LBEFR is expected to deleteriously change the FGC in the following ways:

1. Irradiation may lead to enhanced diffusional mixing, diluting the concentration of silicon in Fe-12Cr-2Si (compromising corrosion resistance) while simultaneously encouraging carbon migration out of T91 (depleting its strength).

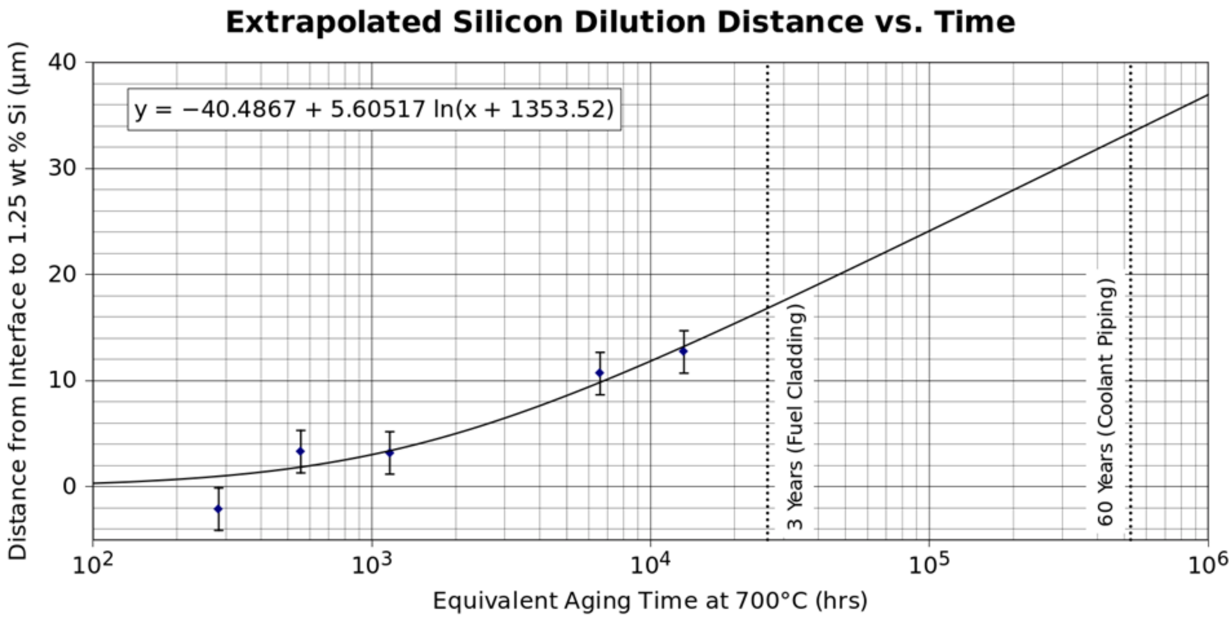


Figure 27: Extrapolated distance of minimum Si content to maintain FGC corrosion resistance at 700 C vs. time (39)

2. Irradiation is expected to dissolve the carbides & carbonitrides in T91, leading to a lowered creep strength, and eventually to void swelling under a very high dose (100-200dpa).
3. Void swelling in the purely ferritic Fe-12Cr-2Si near the FGC surface could lead to localized attack sites by LBE, resulting in faster corrosion.
4. Reductions in ductility, increases in hardness, and other mechanical changes to the FGC could increase the possibility of FGC layer delamination under an applied stress. In particular, the defect sink provided by the layer interface may lead to increased porosity, severely degrading the interface between the two alloys.

All four of these effects must be studied by a high neutron dose *in the bulk* before the FGC can be qualified as ready for LBEFR designs. Existing low-energy proton sources may not provide representative radiation profiles, as the fundamental damage mechanisms for protons (Coulombic) differ from those for neutrons (nuclear) at lower proton energies of a few MeV. Ion irradiation, while able to reach high doses in short times, suffers from a very low range in steels. As seen in Figure 1, the interface of the composite may lie hundreds of microns beneath the surface for fuel cladding, and millimeters below for coolant piping. Reactor-based neutron sources, such as BOR-60 and HFIR, provide precisely the testing capabilities required, but are often lacking in both dose rate and availability. Therefore, the AND proton-neutron damage facility provides the ideal and most efficient route to quantifying the radiation effects mentioned above for the LBEFR FGC.

Experiments to be performed on FGC samples: We intend to use the AND facility to investigate the four irradiation-based effects on the FGC, to determine whether it is truly suitable for use as fuel cladding in a high burnup fast reactor. Following irradiation, the following investigations will be performed to match up with the radiation effects to be studied above:

1. SEM/EDX investigation of the interface after irradiation with high-resolution WDX lin-escans, to determine if enhanced irradiation-induced mixing takes place
2. Creep testing of the as-irradiated FGC, to determine if a reduction in creep strength occurs after irradiation
3. Static corrosion experiments in LBE at temperatures up to 715°C, to compare with unirradiated FGC corrosion samples (37) to determine if corrosion rates are accelerated
4. Tensile and creep tests from room temperature to 700°C, to investigate the possibility of layer delamination under an applied stress, and to determine if new mechanical failure modes are introduced as a result of irradiation.

Interfaces within the collaboration: The work performed by MIT will be directly simulated by Prof. Chaitanya Deo of Georgia Tech, who will be directly simulating neutron damage of our FGC material as part of this IRP. Our experiments will validate her models, and her models will help lead to a mechanistic understanding of radiation damage in our FGC and other composite systems. Stuart Maloy of LANL will be a key collaborator, having been the primary national lab contact for the past ten years of lead-bismuth FGC development. He is currently overseeing synergistic studies of flowing lead-bismuth corrosion of our Fe-12Cr-2Si alloy at high coolant velocities of 8 m/s in LANL's DELTA loop.

The simulations performed by Prof. Jinsuo Zhang on HT-9 and Kumar Sridharan on HT-9 and ferritic/martensitic ODS steels will serve as comparisons to those of T91 (one layer of our FGC) performed by Prof. Deo of Georgia Tech. HT-9 is also the next candidate material for the structural layer of the FGC, and Jinsuo's & Kumar's efforts will help us decide whether to switch to HT-9 or continue work with T91 for the next iteration of the FGC. Radiation induced segregation to the T91-FeCrSi interface is of particular interest in our FGC system, and this will be explicitly treated by Kumar's simulations.

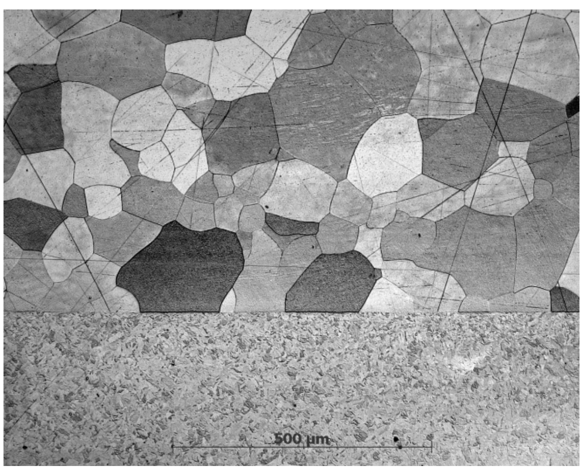


Figure 28: Micrograph of the as manufactured FGC, 100x. Irradiation induced mixing is a key concern for the FGC (39).

Specific Review Criteria: The IRP solicitation specifically calls for advanced reactor materials and neutron damage capabilities not currently available anywhere in the world. Qualifying the aforementioned FGC for service in a lead-bismuth fast reactor or lead fast reactor would require end-of-life radiation damage information, which is utterly unattainable in today's reactors (such as BOR-60 or HFIR) in a reasonable amount of time. Therefore, the AND facility would fulfill this need, and the FGC provides a poster child for a material that, if properly qualified, would change the landscape of viable Generation IV nuclear technologies. Correlating neutron damage from existing test reactors (BOR-60 or HFIR) with low- and high-dose ion irradiation will both allow for extrapolation of structural properties of the composite and its interface, plus evaluate the ability of ion irradiations to simulate the neutron damage which will eventually be provided by the AND facility.

This work on the lead-bismuth corrosion resistant FGC is highly synergistic with, but not overlapping, an existing project between MIT and Los Alamos National Lab on corrosion resistance of the aforementioned FGC in the flowing lead-bismuth DELTA loop.

The first year of the project will oversee neutron and ion irradiation of the FGC, at either BOR-60 or HFIR, respectively. Years two and three will be dedicated to analysis of the microstructural and mechanical properties of the irradiated FGC, with specific foci on structural material properties (creep lifetime, tensile strength, shear strength at the interface) as compared to unirradiated material. Grain structure evolution and irradiation damage will be quantified as functions of dose and distance from the FGC interface using the FIB to mill out TEM samples at different depths in the FGC.

At the end of the IRP, we hope to have an accurate picture of how our FGC will behave under simultaneous thermal aging and irradiation. Effects such as interfacial radiation induced segregation, porosity evolution at the interface, and structural property changes at/near the FGC interface will be quantified and extrapolated to end-of-life doses for the LBEFR (estimated at 60-100dpa). These changes in mechanical properties as a function of distance from the interface will give guidelines for how thick to make the FGC's structural layer, especially in relation to combined thermal/irradiative dilution of T91's properties due to proximity to the FeCrSi layer of the FGC.

4.4.2 Irradiation damage at/near steel/corrosion layer interfaces of HT-9 in LBE: Nanoscale materials characterization and image analysis- J. Zhang (OSU)

The objective of this task is to characterize the microstructure and microchemistry evolution at/near steel/corrosion layer interfaces of irradiated specimens of HT-9. HT-9 specimens will be first tested in a high-temperature lead-bismuth loop to form corrosion/oxidation layer, and the corroded specimens will be irradiated in AND-1, AND-2, BN-600 and ion beams up to different dpa. Microstructure and microchemistry at/near steel/corrosion layer interfaces will be characterized using nano-scale materials characterization tools. Advance image analysis tools will be applied to accurately study the microstructure evolution due to irradiation damage. This task will correlate the evolution of microstructure and microchemistry with materials properties such as mechanical and thermal properties of the steel.

Background: The proposed research task will focus on HT-9 (Fe-12Cr-1Mo-0.5W-0.5Ni-0.25V-0.2C in wt%) steel which is an important structural material for high radiation applications such as fast, fusion and spallation neutron driven power devices (42).

Ferritic/martensitic (F/M) steels, including HT-9, have been widely applied to nuclear power plants as well as conventional power plants. They are considered primary candidates of cladding materials for Gen-IV fast reactor concepts, for example, liquid metal-cooled (liquid sodium, liquid lead, and lead-bismuth eutectic) (43), because of their physical and thermal properties such as the high thermal conductivity and low thermal expansion, and their good radiation resistance such as high swelling resistance. Their swelling at high temperature is about 0.2% per dpa up to

200 dpa, while for austenitic steels, the rate is about 1.0% per dpa (44). A comparison of irradiation swelling behaviors for HT-9 and other commercial materials is shown in Figure 30 (42).

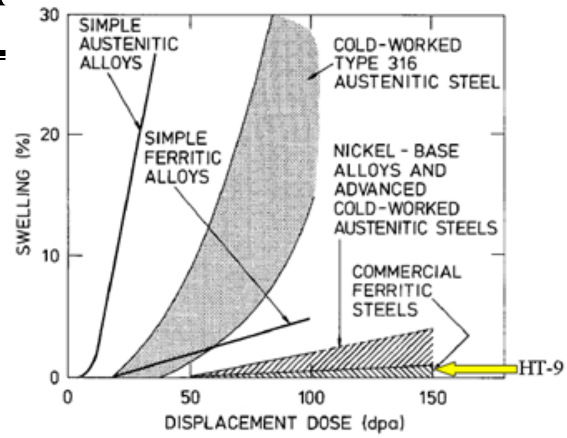


Figure 29: Swelling comparisons between HT-9 and other potential cladding materials.

HT-9 steel, as a first generation of F/M steels, has been under development since 1960's for power-generation applications, and later 1970's where research for elevated-temperature materials started in earnest with the Clinch River Breeder Reactor (CRBR) Program. Originally, it was deemed that F/M steels would be useful for in-core application only, yet over the past 40-years and especially with the Gen IV nuclear systems designs, the F/M steels have gained acceptance for in-core (i.e., cladding, wrappers, and ducts) and out-of-core applications (i.e., RPV, piping, and components). Based on CRBR program and other related programs, a large amount of pre- and post-irradiation properties data on HT-9 have been developed for applications in fast fission and fusion reactor structures(45). Extensive databases on irradiation embrittlement of HT-9 obtained using ion beam surrogate irradiation are available (46). However, no information on correlating surrogate irradiation data to neutron irradiation damage in a fast reactor core environment is currently available.

Most of advanced nuclear reactor coolants including lead-bismuth eutectic are corrosive to structure materials. Ways to protect structural material surfaces against chemical environments that degrade the material through corrosion and oxidation have been studied for power generation, storage, and heat transfer applications. One effective method can be a surface layer that bonds strongly to the material substrate yet is itself inert to the chemical reaction of the corrosion environments. For example, the protective oxide film for fuel pin cladding materials in lead-bismuth cooled nuclear reactors (47). Extensive studies on the protective ability of the self-healing oxide film have been conducted in both advanced reactor designs (48).

One of the major unknowns in the development of cladding materials for advanced nuclear reactors is the effect of neutron irradiation on the corrosive degradation of the material. Neutron irradiation damage to the physical and chemical properties of the protective film and substrate steel can affect the stability of the protective film. The types of damage at the film interface areas by irradiation are schematically shown in Figure 31. There are several effects of radiation on microstructure and phase stability that could affect the formation and stability of the protective oxide layer (49). Radiation by energetic particles produces defects in lattices that change the mass transport properties in materials. In the case of oxides, this may enhance mobility of cations and accelerate oxidation/corrosion. Radiation also induces segregations of alloying elements through spinodal decomposition or nucleation and growth. For instance, it was found that fission neutron irradiation of austenitic steels leads to enrichment of Ni and Si, and depletion of Cr at the grain boundaries. Such microchemistry changes, with the attendant changes in mobility, can substantially change the oxidation process of multi-component alloys.

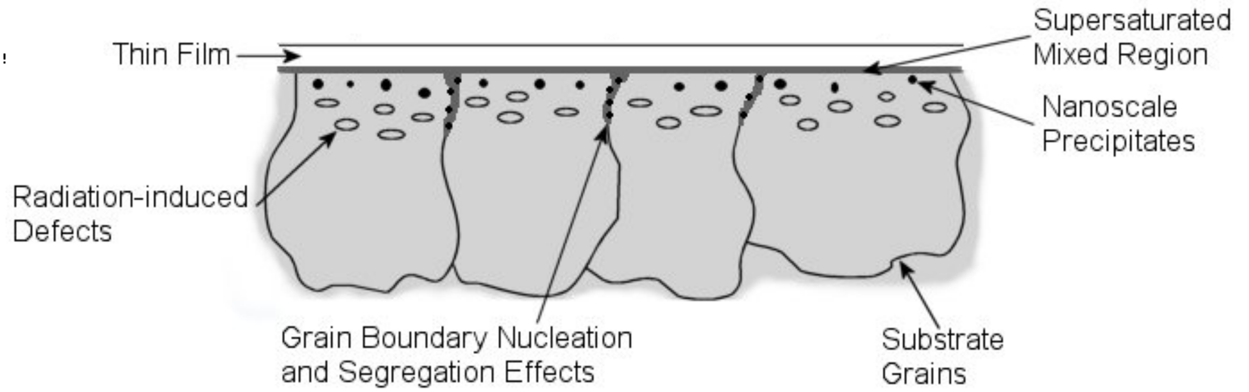


Figure 30: Types of irradiation damage at near interface area

Experiments: HT-9 specimen will be first tested in a high-temperature lead-bismuth material test loop to form the oxidation/corrosion layer on the steel surface. The corrosion testing conditions, especially the oxygen concentration, will be well controlled. The oxygen concentration in the flowing LBE will be controlled as low as 0.01 ppm, and the testing temperature will be 500-550 ^{o}C. The corrosion tests will be last 3000 hours for forming a protective oxide layer in well conditions. The specimens with pre-formed corrosion/oxide layers will be irradiated in AND-1, AND-2, BN-600 and ion beam up to different dpa (maximum 200 dpa), then irradiated specimens will be collect for material characterization.

Nanoscale material characterization: Materials irradiation performance is dominated by the evolution of microstructure and microchemistry. We will extensively examine and measure the microstructure and microchemistry at/near corrosion/oxide/steel interfaces of pre- and post-irradiated specimens using advanced nanoscale materials characterization technologies. The surface and near-surface oxide features and irradiation damage will be analyzed using a high-resolution field-emission gun (FEG) scanning electron microcopy (SEM). The FEG, the semi-immersion objective lens, and the in-lens secondary electron detector together provide a high-resolution (1.5 nm @30 kV resolution). The SEM is also equipped with electron backscattered diffraction (EBSD) for determining the orientation of crystalline grains and energy dispersive spectroscopy (EDS) for microchemistry analysis.

More detailed microstructure, precipitates at grain boundaries, and compositions of the mixture layer of corrosion and irradiation damage will be analyzed using scanning transmission electro microcopy (STEM) coupled with EDS analysis. The STEM/TEM samples will be prepared using cross-sectional focused ion beam (FIB). TEM examination and analysis will be performed on a Titan3 80-300 Probe-Corrected Monochromated (S)TEM which is a state of the art of the system for the highest spatial resolution nano-analysis operated between 80 kV to 300 kV. Surface oxide products (including sizes, shapes, micro-cracks and porosities), surface and interface morphologies and microstructures, and defects at grain boundaries will be examined and analyzed. EDS and EELS (electron energy loss spectroscopy) can be performed simultaneously to create spectrum image during TEM analysis. The EDS system can be used to analyze elemental compositions down to the sub-nm range. EELS is capable of measuring atomic composition, chemical bonding, valence and conduction band electronic properties, surface properties, and element-specific pair distance distribution functions. The gatan image filter (GIF) operation is embedded in the (S)TEM user interface, enabling a rapid elucidation of the elemental distribution throughout the oxide layers at the crack tip area.

Image analysis: The experimental TEM images and the simulation images from our simulation tasks are compatible, which make it possible to link them to obtain both experimentally and theoretically a fundamental understanding of irradiation effects and extend experimental and simulation results to broad ranges of applications of parameters.

To accurately link the experimental data after long-term exposure to irradiation with the simulation results, the advanced image analysis method will be applied. This image analysis can provide new insights into various property implications and physical phenomena associated with grain boundaries and microstructure evolution. This approach represents a paradigm shift from traditional approaches of conventional imaging and image analysis and is anticipated to increase our understanding of grain boundary structure and its property implications to higher level of understanding with associated technological benefits. Based on the image and geometry analysis results, the experiments and modeling can work in concert, which makes it possible to correlate the property changes of materials to the evolutions of microstructure and grain boundary. The proposed task will provide a comprehensive experiment-simulation-modeling-theory. As a result, a methodology for understanding the high-temperature irradiation and oxidation of materials will be developed, as well as a predictive capability that will be applicable to a broad range of materials that are considered for use in advanced nuclear system designs.

Validation: Our results will be validated by extensive comparisons between our measurements with available irradiation performance of HT-9. These comparisons will correlate our results by material characterization and image analysis to the equivalent exposure of neutron irradiation in the appropriate reactors.

4.4.3 Irradiation studies of SiC and SiC CMC- X. Huang – T. Knight (USC)

Zircaloy clad has been used successfully in light water reactor (LWR) for decades. The Fukushima Daiichi nuclear power plant accident in 2011 highlighted some of the previously known weaknesses of Zircaloy clad in accident conditions, namely, the lack of high temperature strength and the production of hydrogen (explosion hazard) by exothermic reaction with water at high temperature. Numerous research and development efforts have been started or restarted on alternative claddings with enhanced accident tolerance. The alternative cladding concepts currently being pursued include ceramic coating on Zircaloy cladding, surface and bulk modification of Zircaloy cladding, and silicon carbide (SiC) all ceramic cladding. All with potential to offer improved safety margin during accident conditions. The SiC cladding with its much high temperature tolerance, can potentially enable increased fuel burnup and even higher core power density for improved power economics. A major concern of silicon carbide cladding is its intrinsic brittleness. Using strong SiC fiber reinforcement in a SiC matrix, the SiC_f/SiC_m composite can acquire a pseudo-toughness through microstructural toughening mechanisms, such as fiber/matrix sliding and micro/macro crack defection. SiC_f/SiC_m composite material has been intensively studied in aerospace industries for turbine and hypersonic airframe structural applications, has demonstrated good strength and toughness up to 1600°C. However, it remains to be proven whether SiC_f/SiC_m composite clad can fully contain fission gases, in light of the possibility of pervasive micro-cracking and other material state change under exposure to typical LWR conditions and fast neutron fluence.

Objectives: It is our objectives to investigate the effects of neutron irradiation on the mechanical behavior of SiC_f/SiC_m composite cladding tube for LWR, particularly (a) the effects of irradiation on the toughness of composite tube, and (b) fission gas containing capabilities.

Silicon carbide ceramic composite has been intensively researched in the context of fusion applications. It has been established that SiC composite has the ability to operate at much higher temperature with good tolerance to neutron irradiation. Irradiations up to 100dpa has been conducted. Near stoichmetric betaphase SiC with low level of oxygen was found to have superior resistance to neutron irradiation damage. However, the pyrolytic carbon interface between SiC fiber and SiC matrix remains a concern after high dosage of neutron irradiation. The change of interfacial properties may greatly affect the toughness of composite, which is essential for its accident tolerance. In addition, the irradiation studies of fusion applications was not conducted in the environment representative of LWR, i.e., lower temperature with exposure to liquid water. The effect of neutron irradiation on SiC matrix microcracking and hermeticity has not been studied as extensively as other mechanical properties.

At USC, the PIs have developed methods for very high temperature internal pressure test that closely simulates the accident conditions. The proposed test configuration is also amenable for in situ gas permeability (across the cladding) measurement using electrochemical method. This provides a quantitative metric for the fission product gas retention of the cladding. The basic methodology is illustrated in Figure 32.

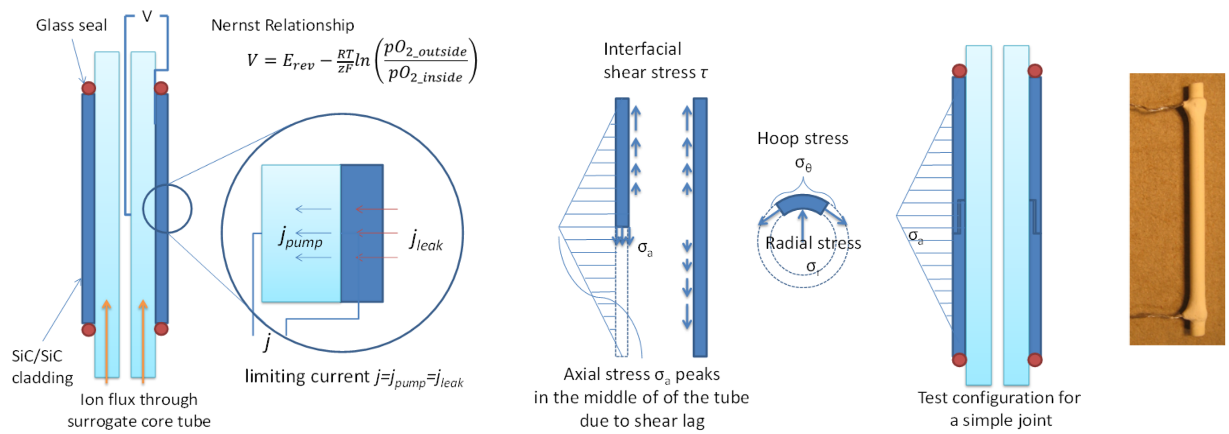


Figure 31: Proposed test schemes for SiC/SiC cladding tube and joint using a surrogate core tube; (right) a Nernst glower bar: L=45mm, dia=2.7 mm in dia.

Preliminary work has been conducted to evaluate the practicality of the proposed test scheme. Some of the results are shown in Figure 33. It was found that the Nernst glower implemented can be heated close to 1680ºC in air in a controlled manner. A non-contact 3D digital image correlation method has been used to measured surface strain distribution on the hot sample surface with good results. Electrochemical potential was measured as oxygen partial pressure was varied on one side of the YSZ surrogate tube. Good, repeatable (almost linear) correlation was observed, as predicted by the Nernst equation.

A 3-yr program is proposed. The PIs will coordinate with the SiC composite fabrication laboratory of General Atomics, who will provide silicon carbide composite tubular specimens for characterization and testing at USC. Mechanical and gas permeability properties are strongly dependent on SiC structural characteristics. Samples with one layer of SiC_f/SiC_m composite, one layer of SiC monolithic, and the combinations of the two (duplex design) types, will be studied and compared. The tubes will have physical dimensions close to LWR fuel cladding. The first year work will focus on the development and qualification of the proposed test methodology. Samples will be irradiated in the Bor-60 reactor and tested at USC after irradiation. The Co-PIs at USC are licensed to handle the low activity SiC specimens following irradiation. The lab is licensed and has the necessary equipment for processing and handling radioactive materials and has a large amount of experience with uranium, thorium, refractory metal carbides such as ZrC, and hydrides of uranium.

The mechanical and thermal properties of the cladding are important to understanding its performance in reactor and predicting failure. For ceramic claddings such as SiC with a high elastic modulus (compared to Zircaloy) and no plastic deformation (unyielding in pellet-clad interaction), very high interfacial pressures between the pellet and cladding can be developed sufficient to fracture the cladding which would fail in a brittle manner. Also, this large interfacial pressure

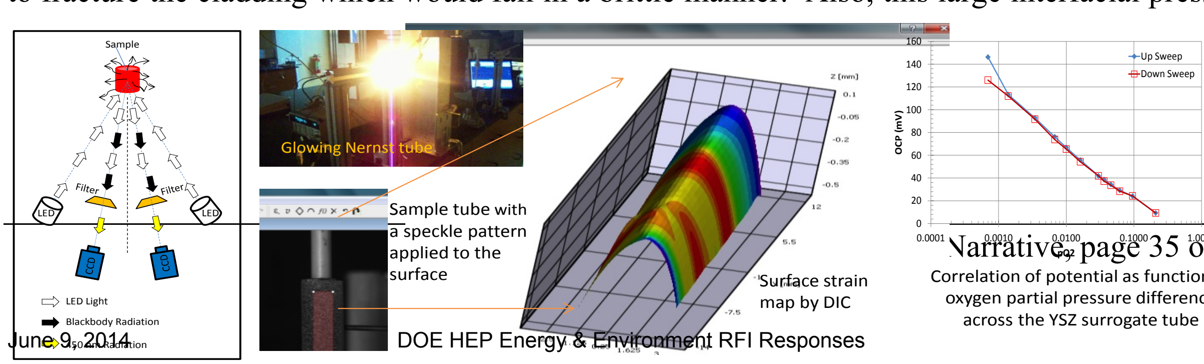


Figure 32: Preliminary study on the internal pressure test using a solid Nernst glower tube.

causes phenomena that were previously of only marginal significance and thus ignored (such as creep of the fuel) to now have an important role in pellet-clad interaction (PCI). Changes in SiC thermal and mechanical properties with irradiation are important to adequately inform these models of PCI. This effort is focused on understanding the changes to SiC properties with irradiation. The modeling effort will utilize the Moose/Bison series of fuel performance codes under development over the past several years in an effort led by the Idaho National Laboratory (INL). To capture complex phenomena such as surrounding PCI, this code system incorporates 3D capability taking advantage of massively parallel computing environments. Further, it aims to be more mechanistic in modeling and less empirical than earlier codes in order to provide better prediction for advanced fuel/cladding systems where limited data may be available for verification.

The proposed material would enable improved LWR **economics** (through possible power uprates) and **safety** (advancing accident tolerant fuels research) and is also a promising material for fusion reactors. Better understanding the effect of irradiation on the mechanical properties will benefit a number of DOE programs including the program on LWR Sustainability. The Co-PIs at USC are currently working with General Atomics and Westinghouse on a DoE funded project studying SiC_f-SiC_m composite as an accident tolerant fuel cladding for LWR. It is expected that the proposed irradiation study afforded in this program will bring further collaboration with General Atomics and Westinghouse; both are leading players in US nuclear industry. The Co-PIs will seek collaboration with the lead institution and other participating members of this proposal to help elucidate the underlying neutron damage processes (at solid state defect level) that may impact the macroscopic mechanical properties and failure modes, using tools such as hot FIB/TEM and first principle based simulations.

4.4.4 Damaged induced segregation in HT-9 and the stability of oxide-phase nanoclusters in ODS steels. B. Tyburska (Univ. of Wis.)

BCC Ferritic–martensitic (F/M) steels like HT-9 and oxide dispersion strengthened (ODS) steels are of direct relevance to nuclear reactors as they provide superior void swelling resistance under irradiation compared to FCC austenitic steels. These materials are expected to play an important role as cladding or structural components in Generation IV and other advanced nuclear reactors operating in the temperature range 350°C–700°C and at doses up to 200 displacements per atom (dpa). Even higher dpa levels are desirable to achieve higher fuel burnups, but this is severely limited by our present knowledge on the radiation damage effects at higher dpas. HT-9 is a 12Cr-1Mo-0.5W-0.25V steel that was originally developed for fusion applications, but is being widely considered as a cladding material for fast burner reactors such as the sodium fast reactor (SFR). While ferritic steels have good swelling resistance, the high temperature creep strength of these alloys is lower than austenitic stainless steels. To overcome this challenge oxide dispersion strengthened (ODS) F/M steels have been developed that contain additions of nanoscale (Y, Ti)-oxide nanocluster particles to increase the high temperature strength. These nanoclusters act as pinning sites for dislocations, thereby improving creep strength. Additionally, the nanoclusters are expected to promote recombination of irradiation-produced point defects and trap transmutation-produced He in small, high-pressure bubbles. Since the nanoclusters are critical to the high temperature strength and potentially radiation resistance, their long-term stability under high dpa neutron irradiation is an important concern.

Research Objectives: Our objectives in the proposed research are to investigate the following effects at high neutron flux dpas: (i) the effects of radiation-induced segregation (RIS) in a variety of heats of HT-9 ferritic steels, and (ii) physical and chemical stability of oxide-phase nanoclusters in ODS steels.

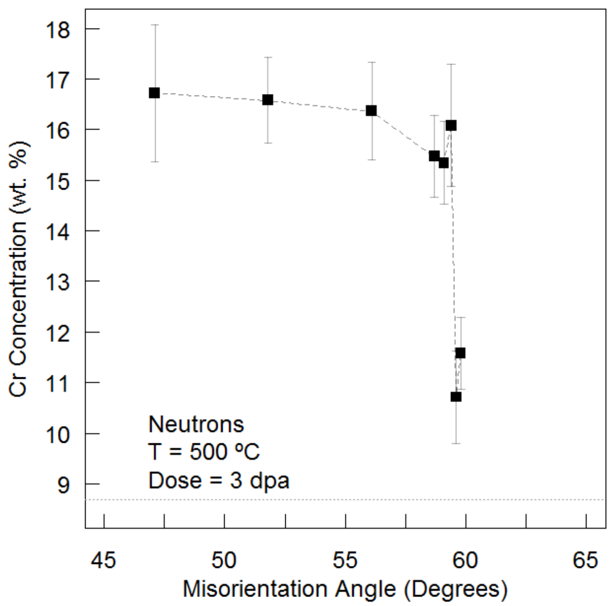


Figure 33: On-boundary Cr concentration in Fe-9%Cr binary alloy as a function of misorientation for high angle grain boundaries near the Σ3 orien-

Our recent studies on 9%Cr ferrtic-martensitic steel NF616 has shown that neutron irradiation at 500°C up to 3 dpa resulted in a notable increase in the Cr concentration at the grain boundaries over the as-received condition (Figure 35). However, our studies on neutron irradiation under similar conditions of Fe-9%Cr binary model alloy have shown that the segregation of Cr to the grain boundaries varies depending on grain boundary type as shown in Figure 34 (50, 51). These results suggest that the RIS response is dependent on the local structure and chemistry present at the grain boundaries. Regardless, it is logical to expect that these effects will be severely exacerbated at higher dpa levels and expected be even more profound in higher Cr con-

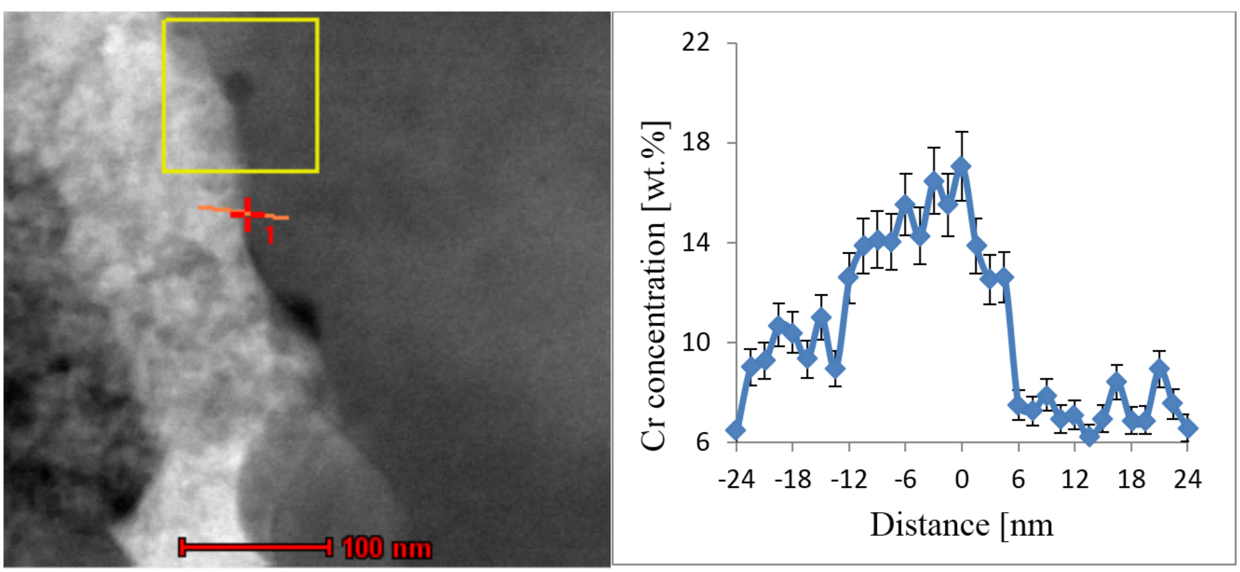


Figure 34: STEM image of a PAGB of NF616 steel neutron irradiated at 3 dpa at 500oC (left) and corresponding line scan for chromium composition across PAGB (right).

tent HT-9 steels. Therefore, the long-term RIS of Cr at and in the vicinity of grain boundaries at high dpa levels must be clearly understood because of its profound effect on creep and embrittlement characteristics of the HT-9 steel.

Our research on 9Cr ODS steels neutron irradiated to 3 dpa at 500°C showed no significant change in the radius, composition and number density of Y-Ti-O nanocluster particles compared to the as-received condition (52). Figure 3 shows the results of atomic probe tomography of the ODS steel before and after neutron irradiation. However, studies of Dubuisson (53) and Monnet (54) at doses up to 100 dpa and high temperatures report dissolution of oxide particles in similar 9%Cr-ODS steels. These studies point to the critical importance of understanding the stability of oxide nanoclusters at high neutron doses. Both radiation stability and mechanical properties would be severely compromised by the dissolution of nanoclusters into the matrix.

As part of a pilot project for the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL), materials of interest for advanced reactor applications, including 9%Cr-ODS steel and HT-9, were irradiated at a variety of temperatures (nominally 300°C-700°C) and total dose accumulations (nominally 3 dpa and 6 dpa). The maximum fast flux in the ATR East Flux Trap where the samples were located is approximately 9.7×10^{13} n/(cm^{2}s) (E > 1 MeV). A dose of 1 dpa in stainless steel is roughly equivalent to a fluence of 7×10^{20} n/cm^2. Using these values, material specimens near the core mid-plane will reach a dose of 3 dpa in approximately 250 Effective Full Power Days (EFPDs) and 6 dpa in approximately 500 EPFDs which corresponds to a damage rate of 1.4×10^{-7} dpa/s. Temperatures of the test capsules were established by thermal modeling and by adjusting the gas- gap distance and are also experimentally by placing silicon-carbide electrical resistivity samples in select capsules. Samples were 3 mm diameter TEM disks and miniature 16 mm tensile samples. At the date of this writing, all samples have been removed from the reactor.

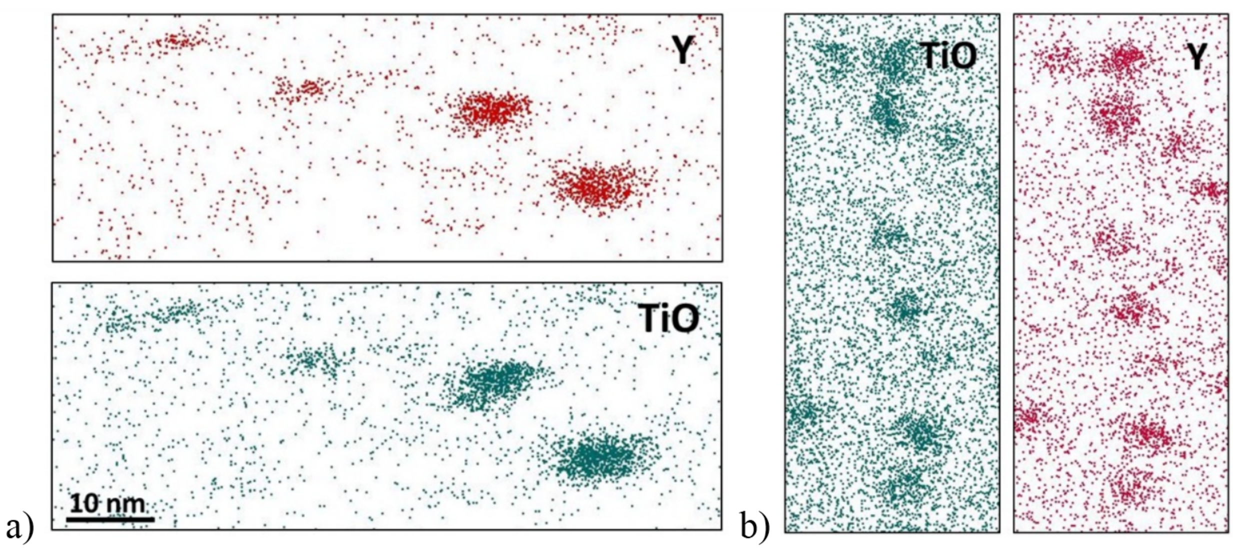


Figure 35: Atomic probe tomography (APT) elemental maps of the (a) as-received (un-irradiated) 9%Cr ODS and (b) neutron irradiated 9%Cr ODS to 3 dpa at 500°C, showing

4.5 Modeling of Neutron damage dynamics

4.5.1 Atomistic and mesoscale modeling of structural evolution during neutron irradiation in composite alloys –C Deo (GaTech)

Recently, Short and Ballinger have developed a functionally graded composite of alloys T91 and Fe-12Cr-2[55]Si as possible structural materials for the lead-bismuth eutectic fast reactor (LBEFR) which is showing the potential to alleviate the old corrosion allowance of 550C for the LBEFR without compromising the structural integrity of core components. This sub-project aims to model long term neutron irradiation behavior in Fe-Cr, Fe-Cr-Si systems in order to determine the behavior of these materials under neutron irradiation.

Atomistic tools such as first principles and molecular dynamics methods will be employed for atomistic calculations of defect energetics[56]. Kinetic Monte Carlo methods and cluster dynamics methods will be used to simulate long-term evolution of radiation-produced defects in these alloys. These tools have been used successfully in the past to simulate hydrogen and helium evolution in pure Fe as well as to study metallic U alloys.

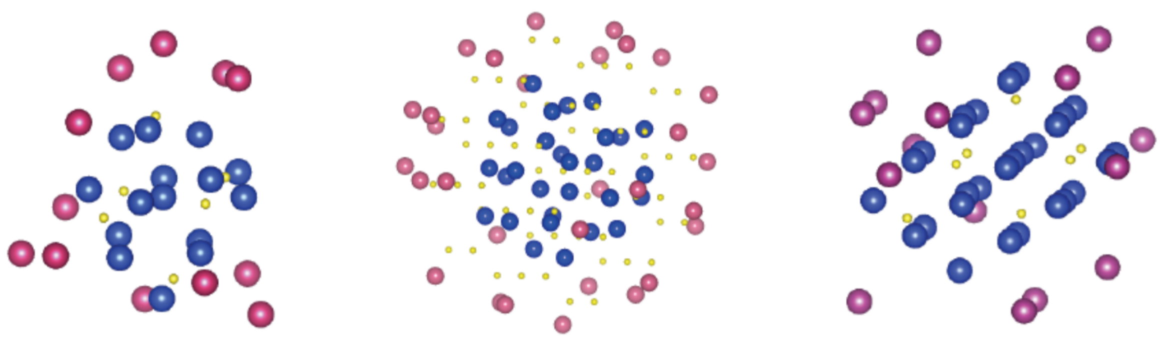
In previous work we have simulated clusters of m hydrogen, j helium, and n vacancies ($H_mHe_jV_n$) in bcc iron. In order to extract the energetic properties of these clusters, it is desirable to find the lowest energy configuration of the gas atoms with the voids. We have achieved this through iterations of conjugate gradient relaxation and Monte Carlo criteria. We first introduced an interatomic potential suitable for describing the interactions between hydrogen and helium.

This potential was used to perform a detailed analysis of the configurations and energetics of a variety of bubbles. We found that the synergistic effects on bubble properties can be explained not through a direct interaction between hydrogen and helium, but through the phenomenon of loop punching. We showed that the presence of hydrogen makes loop punching a more energetically favorable event for a bubble with the required amount of helium. In turn, the growth of the bubble results in a larger free surface onto which hydrogen may be bound.

Objectives:

1) Density functional theory and semiempirical methods will be used to develop an understanding of the Fe-Cr-Si system. Semiempirical interatomic potentials exist for the Fe-Cr system[57]. We will extend the interatomic potential to the Fe-Cr-Si system. We will calculate the binding energies of intrinsic and extrinsic defects with Cr, Si as well as dislocations and grain boundaries using density functional theory based methods. These will also be used to modify appropriate interatomic potentials that describe the interactions between the elements on the materials system. The effect of the alloying elements on the migration pathways and energetics of helium and hydrogen will be studied with these DFT methods as well.

The low energy configurations of hydrogen-helium-vacancy clusters are shown. Vacant lattice sites are pictured as small yellow circles, hydrogen atoms are pink, and helium atoms are blue. Surrounding iron atoms are not pictured. The helium atoms form the core of the bubble, with the hydrogen atoms making up the shell. In general, the helium was not well-ordered, but occasionally highly ordered states such as in (c) were seen.



(a) $H_{12}He_{15}V_6$ cluster (b) $H_{30}He_{30}V_{59}$ cluster (c) $H_{15}He_{28}V_7$ cluster

Figure 36: Examples of model dynamics of H, He, vacancy clusters during neutron damage.

2) Using interatomic potentials developed in previous task and previous work, molecular dynamics calculations will be performed of displacement cascades in Fe-Cr alloys. Point defects created as function of radiation damage will be estimated. Also, compositionally graded materials will be simulated with sharp interfaces (e.g., varying Cr composition in two adjoining layers) will be simulated for the stability of the interface and the ability of the interface to absorb point defects.

3) The atomistic work described above will serve as input to microstructural modeling tools such as Potts kinetic Monte Carlo and rate theory/cluster dynamics calculations of microstructural evolution. Here the focus will be on the segregation behavior of Cr, Si alloying elements in the Fe-Cr-Si system. Diffusion of Cr, Si through the lattice will be simulated with mesoscale models of diffusion in order to develop an understanding of the evolution of microstructure under high dose neutron irradiation.

At the end of three years, an understanding of the evolution of defects at high doses will be presented. Microstructural changes expected as neutron dose is increases will be calculated. Results will be presented as a report. The three tasks will run in sequence. It is anticipated that each task will take one year.

4.6 Irradiation Damage in Nanostructured Ferritic Alloys- C. Hin, (Va. Tech)

The fast growing energy demand in the 21st century will require nuclear energy to play a major role among other possible energy resources. There is a current important challenge in predicting and improving the performance of fission reactor materials. The improvement of creep resistance and corrosion of fuel claddings are two of the principal objectives for the use of advanced ferritic alloys in applications at high temperatures and under extreme environments. Radiation damage and its effects on oxide dispersion strengthening (ODS) materials microstructure and properties result from physical processes which interact on many time and length scales. Multiscale modeling approaches are required for reliable predictions, as well as manufacturing process design. Among ODS alloys, we will study the nanostructured ferritic alloys (NFAs). The modeling of defect mediated phase transformations is required, not only for understanding the influence of microstructural changes on properties (such as fracture/creep resistance and corrosion), but also for the control and optimization of manufacturing. Different microstructural features — such as a high density of small precipitates and clusters, dislocation loops, cavities, and regions of enhanced solute concentration — have different coupling to phase nucleation and growth. The balance of these features depends on the synergistic interaction with environmental variables, such as irradiation temperature, dose rate, helium production and alloy composition.

Objectives: We propose to study the influence of the atomistic microstructure evolutions in NFAs under irradiation. In recent years, many Kinetic Monte Carlo (KMC) algorithms have already been developed to treat various aspects of microstructural evolution changes (58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68). Most of these are based on the rigid lattice approximation (68). The diffusion of atoms occurs by interstitial, interstitialcy, and vacancy mechanisms (58-68). The vacancies that ensure the diffusion of atoms on the substitutional sites can be created and annihilated via a vacancy source and sink located on a special lattice site. Due to the presence of this vacancy source and sink, the vacancy concentration in the simulations reaches its equilibrium value automatically (58-63). Segregation, as well as the competition between homogeneous and heterogeneous precipitation have been studied by including a dislocation or a grain boundary in the algorithm (60-62, 65, 66). In the first KMC simulation involving the heterogeneous precipitation, the grain boundaries were just modelized by a plane where a segregation energy has been added on each site of the plane (Error! Reference source not found.) (62). A lot of progresses have been made by implementing in a KMC a real grain boundary as shown in Figure 39 (61). However, the structure was unrelaxed. In this proposal, we plane to relax the KMC algorithm.

The relaxed KMC algorithm will be based on the KMC algorithm on a rigid lattice. The difference between these two versions of the KMC will be in:

- the use of an inter-atomic potential instead of fixed pair interaction energies in order to

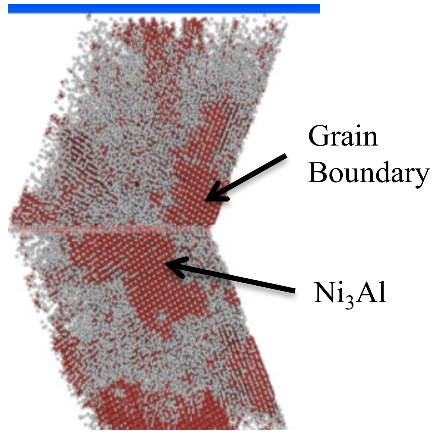


Figure 37: Monte Carlo simulation of Ni_3Al precipitation, next to a grain boundary in a Ni-0.10at.Al at 900K.

obtain interactions between atoms as a function of distance between them.

The advantages of keeping the rigid lattice are manifold:

- Atom, vacancy, and interstitial coordinates are always known.
- The numbers of neighboring atoms as well as the distances between atoms are easy to recalculate at each time step.
- The structure relaxation only occurs around the last jumping atom. This avoids relaxing the whole structure that becomes cumbersome for a large system. Therefore, we just have to recalculate the jump frequencies for the atoms affected by the last jump.

The refined rigid lattice requires that the spacing between each lattice point is small enough to converge toward the relaxed equilibrium structure. We will be able to determine the number density, the size and the shape of the precipitates in bulk and at the grain boundary. These results will be directly compared to experiments carry out by …. This new algorithm will not be limited to improving the knowledge of the structural evolution of NFAs under irradiation, but will also produce new important insight into many materials-related kinetic relaxation phenomena.

In order to understand the microstructure evolution under irradiation, we propose to introduce an irradiation term via a special frequency that will depend on the radiation flux as implemented in (69,70). Another frequency to simulate the transmutation nuclear reaction that yield to the formation of impurities such as He will be introduced into the algorithm.

We propose to utilize different potentials. The interatomic potentials related to rare-earth and transition metals have been determined using the lattice inversion method (71). The self-consistent interatomic potentials for binary and ternary oxides have been determined by fitting to their experimentally measured lattice properties. We will use the Buckingham potential with the parameters given in Table 1 of the reference (72). For the Fe-H interactions, we will use the interatomic potential developed by Stoller (73). The Fe-H interatomic potential includes a three-body term to stabilize the interstitial He defect in the tetrahedral position in the BCC ferritic matrix and provides simultaneous agreement with the forces and energies of different atomic configurations as computed by first principles. We found one interatomic potential to reproduce the He-O interactions (74). This potential will have to be tested by molecular dynamic simulations. We will have notably to ensure that the potential correctly reproduce the diffusion of He in the Y_2O_3 oxides. All the potentials will be tested to reproduce the correct phases in presence.

This work addresses the need of the nuclear community in developing new tools such as the one we are proposing here if we want to accurately reproduce the microstructure evolution of alloys under irradiation over a long period of time and ultimately, develop new robust advanded materials for the fusion and fission reactors.

During the first year, the Ph.D. student will develop the new relaxed kinetic Monte Carlo algorithm. Then for the next 3 months, the algorithm and the potentials will be validated. The algorithm needs to accurately the different diffusion coefficients involved in this study as well as the solubility products of the different phases, e.g., FeO, Y_2O_3, TiO_2, and $Y_2Ti_2O_7$. For the 9 months remaining, we will try different alloy compositions, heat treatment, and dose rates. The results will be compared to experiments performed at HFIR, BOR-60, and STIP by the Wisconsin group.

5 Milestones and deliverables

- Develop data sets to support correlation of mechanical properties with microstructure in a library of samples of interest, spanning the variables of damage type (neutron, ion, or mix) and temperature during exposure.
  - Data set 1 set up for public electronic access Year 2 Q3
  - Data set 2 set up for public electronic access Year 3 Q3
- Develop modeling to simulate key properties of damage dynamics in materials of interest: mobility of H and He produced in the material, loop formation, diffusion, and annealing of dislocations, aggregation of H/He, pinning and release of dislocation loops at nanocluster impurities and grain boundaries.
  - Deo modeling results – publication 1 Year 2 Q2
  - Hin modeling results – publication 1 Year 2 Q2
  - Deo modeling results – publication 2 Year 3 Q2
  - Hin modeling results – publication 2 Year 3 Q2
- Technical design report for AND1 facility, external review Year 1 Q2
- Completion of AND-1 building and infrastructure Year 2 Q2
- Radiation safety and ES/H review of AND-1 facility and research plan Year 1 Q4
- Commissioning of LEDA with low-power proton beam to beam dump Year 3 Q2
- Commissioning of sheet-flow Li target Year 3 Q2
- Deliver low-power proton beam onto Li target Year 3 Q3
- First high-power proton beam on Li target Year 2 Q4

6 Facilities

The AND project will use a number of facilities in its research:

- the Accelerator Research Lab at Texas A&M University: labs for accelerator technology development, rf test bench, magnet fabrication; magnetic field measurement; dedicated HPC computing cluster with all necessary design and simulation codes; clean room assembly area.
- Sample libraries at LANL and at SINQ containing a wide range of n- and ion-damaged samples, with which the experimental program will 'junp-start' while waiting for our own exposures.
- the hot lab of the Materials Research Group at Los Alamos National Lab: receive sample subassemblies from n-damage exposures; clean surface contaminations sufficient measure residual radioactivity and qualified for analysis in non-hot materials characterization facilities at participating universities.
- the hot-FIB in the Center for Advanced Energy Systems (CAES) of the University of Idaho: for samples on which it is desired to examine internal grain structure and defect distributions, CAES hot-FIB will be used to mill deep trenches in sample to expose internal grains, then samples will be re-cleaned to remove surface contamination and qualified for analysis in non-hot materials characterization facilities at participating universities.
- Neutron irradiation facilities at HFIR, BOR-60, and STIP program at SINQ, arrangements as discussed previously and provided in attached supporting letters.

- materials characterization laboratories at all of the experimental materials collaborators at participating universities.

The AND program will itself create a *new* high-dose fast neutron damage facility, AND-1 with unique capabilities for delivering fast neutron damage in an environment where temperature, exposure to corrosive fluids, and application of sustained stress can be done during irradiation.

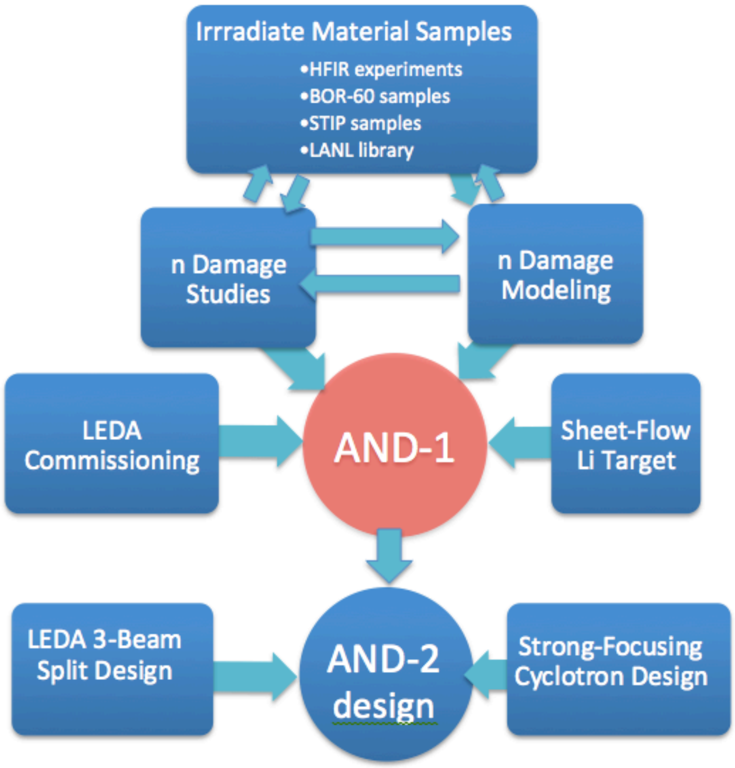
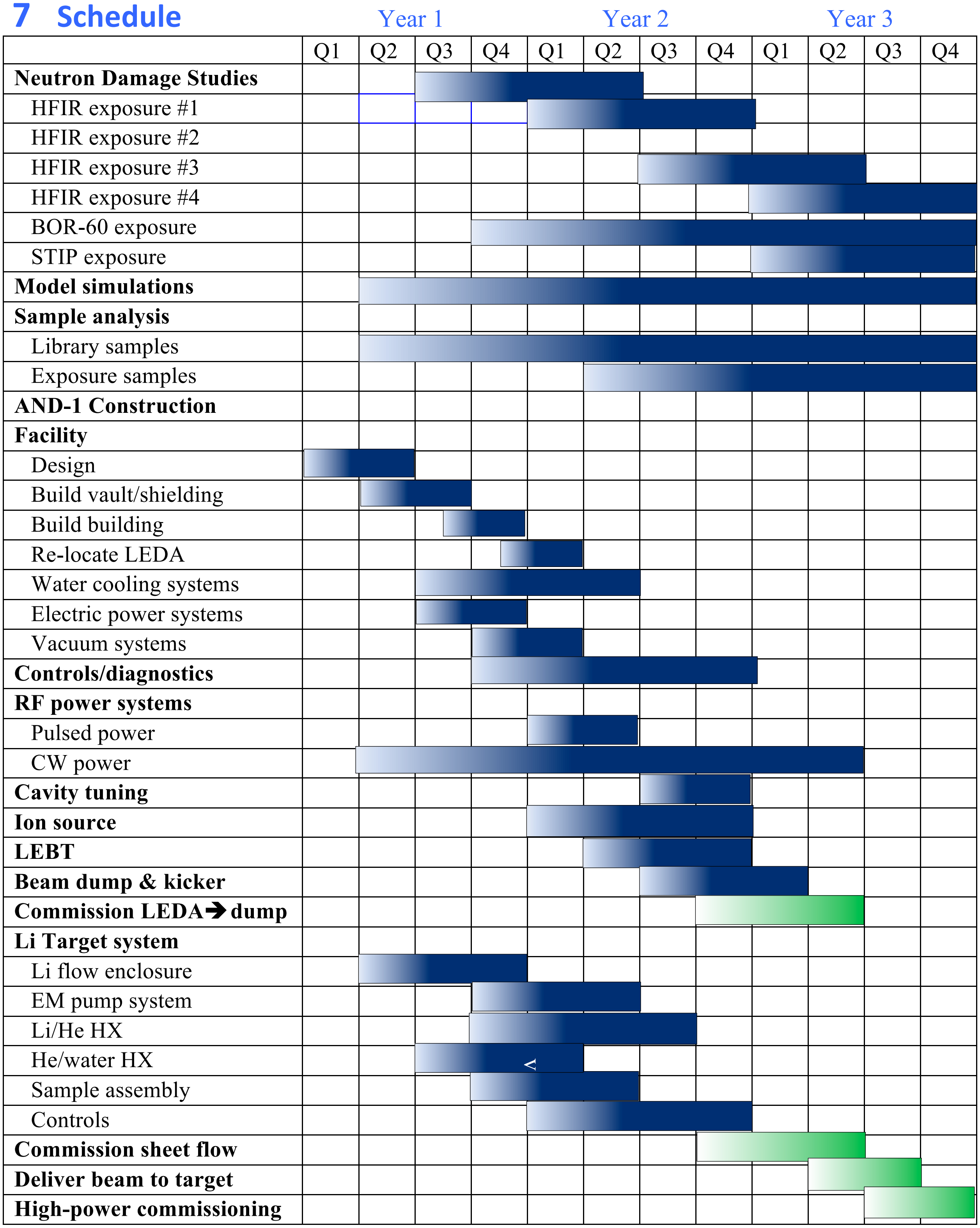


Figure 38. Relationship between project activities and objectives.

Figure 38 shows the relationship between the major project objectives, detailed in Section 3, and the major elements of project schedule, detailed in Section 7, and the project milestones, detailed in Section 5.

7 Schedule


Year 1
Year 2
Year 3
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Neutron Damage Studies
HFIR exposure #1
HFIR exposure #2
HFIR exposure #3
HFIR exposure #4
BOR-60 exposure
STIP exposure
Model simulations
Sample analysis
Library samples
Exposure samples
AND-1 Construction
Facility
Design
Build vault/shielding
Build building
Re-locate LEDA
Water cooling systems
Electric power systems
Vacuum systems
Controls/diagnostics
RF power systems
Pulsed power
CW power
Cavity tuning
Ion source
LEBT
Beam dump & kicker
Commission LEDA→dump
Li Target system
Li flow enclosure
EM pump system
Li/He HX
He/water HX
Sample assembly
Controls
Commission sheet flow
Deliver beam to target
High-power commissioning

8 Roles of Collaborators and Project Management

Texas A&M University (TAMU) will serve as the lead institution and contractor for the AND collaboration. Texas A&M will coordinate monthly teleconferences allowing effective communication for the collaboration and assuring reporting and coordination with DOE programs. The collaboration will prepare Annual and Quarterly Reports describing the work and documenting the results. The Advisory Board will review project reports and provide guidance on further alignment with DOE programs as well as feedback to the team and to DOE. The IRP project leads will report to DOE at the review meetings and at the hosted workshops in College Station as well as through NEUP reporting system.

The AND Director will inform the DOE NE Advisory Panel about AND's plans and progress, and he will seek its advice and criticism to align the project so that it effectively serves DOE NE priorities for reactor material science. In addition, other DOE divisions have interest and stakes in improving the understanding of high-dose fast neutron damage and accelerator-based systems: the NP division (FRIB), the HEP division (high-current proton drivers), the FES division (the first-wall problem), and BES (target lifetime for SNS). The AND director will consult with DOE leadership in those divisions and with national labs with affected interests.

8.1 Experimental materials program

The experimental neutron damage task involves 6 of the collaborating universities plus Dr. Maloy at LANL. Each university group will prepare TEM and tensile samples of materials they plan to study. Dr. Chirayath will coordinate preparation of the capsules and subassemblies for the HFIR exposures. Dr. Maloy will receive the capsules after exposure and prepare samples for PIE in his hot lab. Analysis of microstructure typically benefits from FIB milling of channels in the bulk of a specimen to expose its grain structure. FIB is the only preparation step that poses potential contamination risk in university-based materials characterization labs. FIB preparation work on samples will be done by the University of Idaho team (Prof. Phongikaroon) using the CAES hot-FIB. Thereafter samples will be returned to the university teams so they can perform analyses and characterizations.

Libraries of irradiated samples will be made available through Dr. Maloy at Los Alamos and Dr. Dai at PSI, including ion-damage samples, specimens recovered from high-dose reactor materials, and mixed ion/neutron damage specimens from LANL and PSI STIP. By analyzing those samples and ones from our reactor exposures and later from AND-1 exposure, we will have a basis for systematically spanning the space of ion/neutron and neutron energy to understand the dependences of damage mechanisms for each material.

8.2 Modeling and simulations of neutron damage

The teams from Georgia Tech, Virginia Tech, and Texas A&M will conduct modeling and simulation of neutron damage, as described below. Prof. Tsvetkov will coordinate the modeling effort and sustain coherence between the experimental and modeling tasks.

8.3 AND-1 construction and commissioning

The collaboration will move LEDA from LANL to Texas A&M University, construct a building and shielded vault to house LEDA and the Li target, and install the necessary infrastructure of electric power, RF power, and cooling water.

LANL has committed to make long-term loan of LEDA and its components. The loan will include the two 1 MW 350 MHz pulsed RF power systems that can drive the LEDA cavities for commissioning, as well as the waveguides and associated power supplies and transformers. CERN has agreed to make long-term loan of equivalent 350 MHz CW RF power systems, which are surplus from their long-ago operation of LEP. Their equipment will require significant refurbishing, and we have budgeted for that, such that as the LEDA is commissioned, the CW power supplies may be inserted for full operation. Texas A&M has committed $500,000 cost-sharing which will pay for much of the infrastructure costs.

8.4 AND-2 design and cost analysis

The conceptual design for AND-2 is presented in the Research Plan. It has a projected costs (at pre-conceptual level) of $42 million. The collaboration plans to propose funding for development of the critical systems for the cyclotron stack required for AND-2 from the HEP program. If funded, the work would proceed in parallel with AND-1, so that a mature proposal for AND-2 with serious cost and schedule estimation could be prepared during the first years of AND-1 operation after the end of the IRP project.

Figure 39 shows a schematic of the IRP AND team structure. The team will collaborate among the four tasks described above. Prof. McIntyre will serve as AND Project Director. He will be responsible for reporting to DOE, Texas A&M University, and National Laboratory managements, and he will lead the development of the accelerator-based neutron facility. Prof. Tsvetkov will serve as Collaboration Coordinator and will coordinate the roles of the university collaborators in the materials science and modeling activities. Dr. Maloy will serve as Materials Coordinator, and will coordinate preparation of samples by university collaborators, submission of capsules export control for exposures at HFIR, BOR-60, and STIP, and processing of samples from exposures to prepare them for analysis at university labs.

The multidisciplinary team combines expertise from 8 US universities: Georgia Institute of Technology, the University of Idaho, Massachusetts Institute of Technology, The Ohio State University, the University of South Carolina, Texas A&M University, Virginia Tech, and University of Wisconsin-Madison.

The collaboration has developed working relationships with national laboratories who have committed to specific forms of help in the effort, including John Erickson (LANL, LEDA relocation), Claude Reed (Argonne National Lab, Li target), Gary Bell (ORNL, HFIR), and Olivier Brunner (CERN, RF power systems). The collaboration has received agreement to obtain samples from the BOR-60 exposure that is being planned through a DOE contract with Rosatom. Dr. Maloy is a participant in that contract and will coordinate our access to its samples.

If our proposal is accepted, we will be forming an AND Advisory Board who will provide guidance to the Director and to Texas A&M University on the AND scientific program, its execution, and its context in the national program of reactor material science.

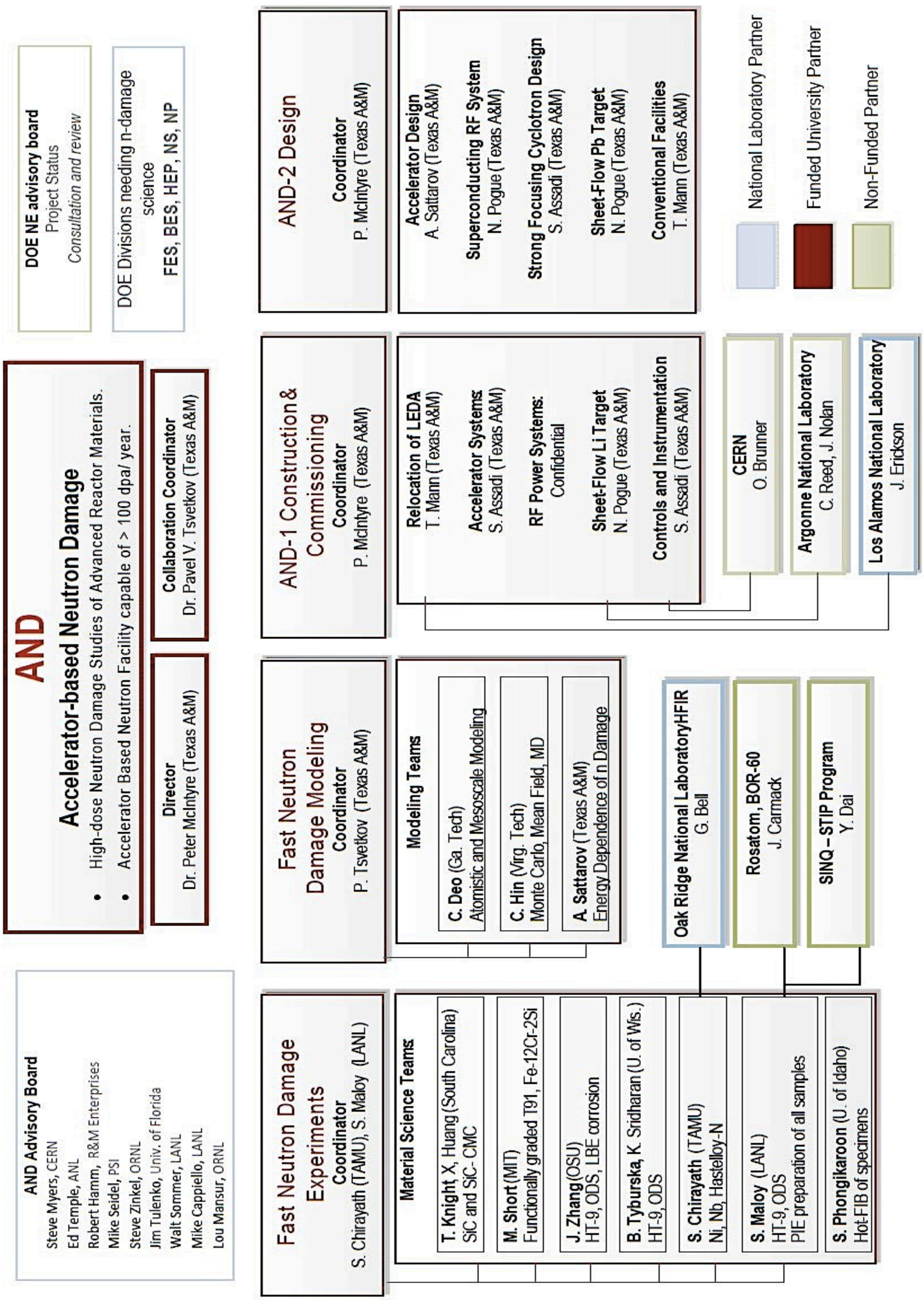


Figure 39 AND Management Plan

9 Unique Challenges

10 Budget Summary, Quality Assurance (QA)

Summary of the proposed IRP ISR Budget

Team		Schedule			Total
University	**University Lead**	**Year 1**	**Year 2**	**Year 3**	
Georgia Tech	C. Deo	54,423	36,980	38,552	**385,396**
University of Idaho	S. Phongikaroon				**799,226**
MIT	M. Strong	17,241	94,637	108,122	**401,939**
Ohio State	J. Zhang	64,247	66,706	69,047	**300,000**
South Carolina	T. Knight	56,779	70,523	72,698	**600,000**
Texas A&M University	P. McIntyre	1,051,021	941,869	907,177	**3,206,338**
Virginia Tech	C. Hin	63,729	70,523		**193,729**
Wisconsin-Madison	B. Tyburska	71,168	73,306	75,504	**219,978**
Los Alamos National Lab	S. Maloy	$100,000	$100,000	100,000	**300,000**
Oak Ridge National Lab	G. Bell	$100,000	$200,000	100,000	**400,000**
Total		**1,678,608**	**1,750,292**	**1,571,100**	**5,000,000**

In addition to the costs that will be funded from the proposed RIP grant, There will be a cost for construction of a 100'x80' insulated metal building, a sub-grade vault with rolling-section radiation shielding, and infrastructure for 5 MVA electric power and 5 MW water cooling, total estimated cost $500,000. Texas A&M University has committed to fund that construction and infrastructure.

1. The TAMU budget of the proposed IRP grant includes funds to cover ORNL HFIR irradiations as well as team management expenses (meetings hosting, advisory board, etc.)
2. Upon award, ORNL HFIR will begin formal discussions to contract for the 4 exposures in HFIR. The expense is budgeted in the TAMU portion of the proposed IRP grant.

11 Quality Assurance (QA) Plan

We will fully comply with the guidance given in the NEUP IRP CFP. We will utilize the existing University and laboratory processes for this purpose as well as directives provided by the NEUP website Quality Assurance documents. A documented quality assurance (QA) process will be established in accordance with standard university procedures and under NEUP guidance prior to project initiation. QA processes will encompass: Proper training of all personnel; Test plan documentation and evaluation; Application of best practices in data acquisition, including instrument calibration, documentation and storage; Clear, concise record keeping for all hardware design, fabrication (including materials pedigree), test, and modeling; Best practices in system prototyping, scaling evaluations, and benchmark development and implementation; Software configuration control; Model verification and validation and verification; Project internal meetings and reporting following monthly and quarterly schedules to assure internal accountability among team members and the lead university; External monthly and quarterly reporting as established by NEUP. The work will be performed under the University's established regulations for conducting research and in accordance with the external peer review requirements of archival scientific journals. The work performed at the national laboratory partners will be carried out in accordance with 10 CFR 851. The proposed work will be conducted in compliance with all US Export Control regulations. We will also fully comply with the additional requirements stated for test planning, implementation and documentation; equipment calibration and documentation; procurement document control; and training and personnel qualification as they will be deemed necessary during the course of the proposed work. Administrative management will be provided by the University's Sponsored Research Service Offices. Sponsored Programs Accounting will provide quarterly billing in accordance with pre-approved budgets.

Overview of the IRP ISR Commitment to the Mandatory Requirements

	Requirement	**IRP Comments**	**E val.**
	Commitment to reporting and budget requirements	We will comply with the quarterly, annual and final reporting requirements.	G o
	10 CFR 851 "Worker Safety & Health Program"	The lab activities, advisory in nature, will be conducted in accordance with 10 CFR 851.	G o
	Export Control	We will comply with all export control laws/requirements pertaining to this IRP.	G o
	Standard Research Subcontract	We will comply.	G o
	Quality Assurance	See the QA statement in Section 11.2; we will comply with QA requirements	G o
	Commitment to prepare additional contract elements	If required, we will comply.	G o

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Energy Environment RFI

From: Peter McIntyre <mcintyre@physics.tamu.edu>
Sent: Monday, May 19, 2014 7:16 AM
To: Energy Environment RFI
Cc: Colby, Eric; Nathaniel Pogue; Akhdiyor I Sattarov
Subject: Re: Stewardship RFI Comments
Attachments: CAARI2002color.pdf

Importance: High

Attached is a paper describing the Coupled Multiplier Accelerator, a novel method by which to produce electron beams with few-MV energy and ~MW dc power, suitable for industrial applications that require radiation processing but have a narrow cost margin in which it must operate. This technology is demonstrated to be effective in destroying organic toxins in water, in flows to 200 gpm. I presented this originally at CAARI2002, and today it seems that its time for commercialization may have arrived.

Respectfully submitted,

Dr. Peter McIntyre
Mitchell-Heep Professor of Experimental Physics
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College Station, TX 77843
(979)255-5531
mcintyre@physics.tamu.edu

Coupled-Multiplier Accelerator Produces High-Power Electron Beams for Industrial Applications

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Department of Physics
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Charles Meitzler

Department of Physics
Sam Houston State University

Abstract. The coupled multiplier is a new approach to efficient generation of MeV d.c. power for accelerator applications. High voltage is produced by a series of modules, each of which consists of a high-power alternator, step-up transformer, and 3-phase multiplier circuit. The alternators are connected mechanically along a rotating shaft, and connected by insulating flexible couplers. This approach differs from all previous d.c. technologies in that power is delivered to the various stages of the system mechanically, rather than through capacitive or inductive electrical coupling. For this reason the capital cost depends linearly on required voltage and power, rather than quadratically as with conventional technologies. The CM technology enables multiple electron beams to be driven within a common supply and insulating housing. MeV electron beam is extremely effective in decomposing organic contaminants in water. A 1 MeV, 100 kW industrial accelerator using the CM technology has been built and is being installed for treatment of wastewater at a petrochemical plant.

INTRODUCTION

Accelerator Technology Corp. and Texas A&M University have developed a high-power electron beam treatment system for treatment of contaminated wastewater using high-power electron beam. A decade of laboratory testing and water chemistry [1,2,3,4] has demonstrated that electron beam treatment is highly effective in dissociating organic contaminants in water. The challenge today is to make e-beam treatment cost-effective for industrial wastewater applications. This requires a new generation of e-beam technology that produces high-power, high-energy electron beams at an affordable cost. During the past three years, ATC has developed the Coupled Multiplier Accelerator A), a completely self-contained high-power electron accelerator that produces 100 kW of beam power at 1 MV, supports multiple independent beams, and has a modest capital cost compared to conventional technologies. All components of the first CMA system (CMA) have been built and the system is currently being installed in its enclosure.

Figure 1 shows the layout of elements within the CMA system. The essential novelty of the CMA approach is that it produces d.c. high voltage in a sequence of modules that are powered in parallel but connected in series electrically. This is in distinction to all previous d.c. high voltage sources, in which power is transmitted in series through a succession of stages., limiting power delivery at high voltage.

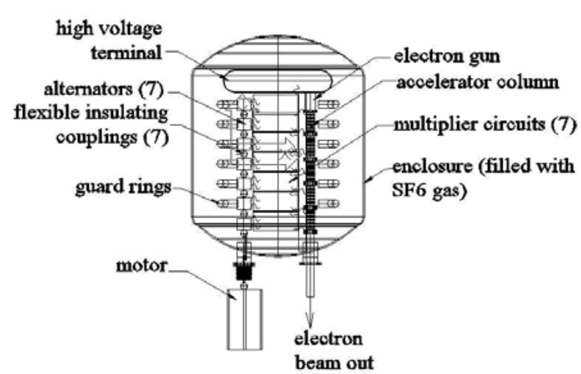

FIGURE 1. Cross section of CMA system.

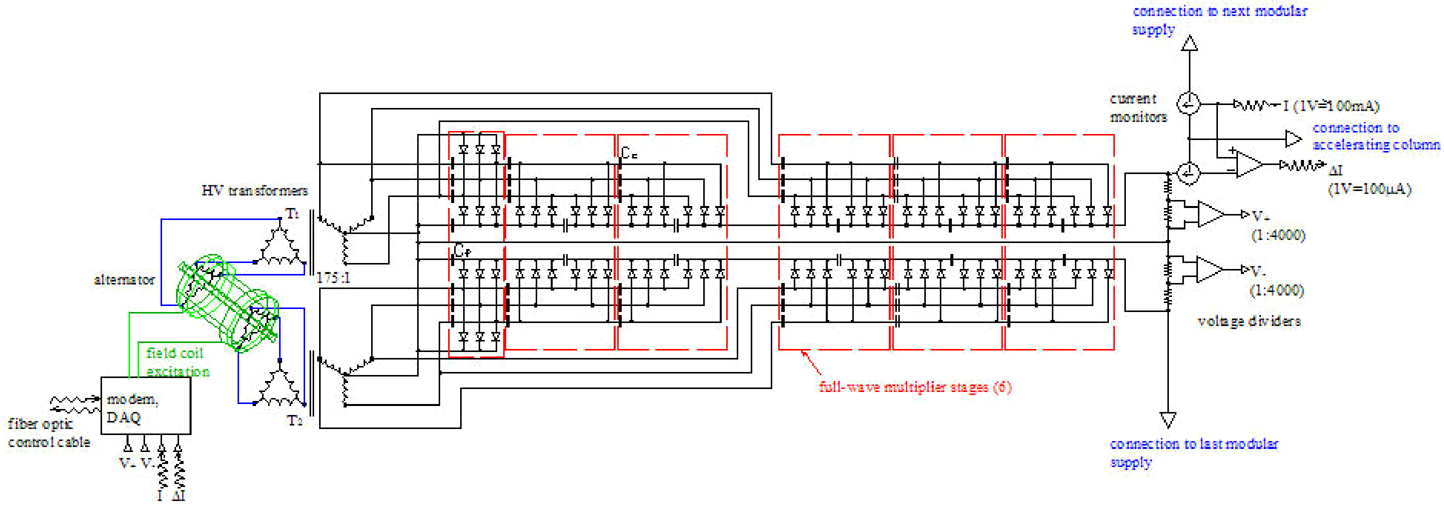

FIGURE 2. Circuit of one CMA module.

POWER SUPPLY DESIGN

High voltage is generated in a succession of modules, each containing an alternator, a step-up transformer, a high-voltage multiplier circuit, and a control circuit. The modules are connected electrically in series, and are tied to electrodes along the accelerator columns of the electron beams that they power, as shown in Figure 1. The entire system – power supply and accelerator columns – is contained within a steel vessel which is filled with pressurized SF_6 gas to provide dielectric insulation.

The alternators of successive modules are driven as two serial strings by high-power motors (3600 rpm, 125 HP each). The alternator shafts are connected mechanically along each string by means of flexible, electrically insulating couplers, shown in Figure 3. Each coupler consists of a flexible Hytril gland sandwiched between G-10 hubs, coupled to the shafts by steel inserts and keyways. The couplers are tested to convey >300 N·m of torque and to insulate 150 kVdc between shafts when operating in the SF_6 insulating gas within the CMA vessel.

Figure 2 shows the circuitry within one CMA module. Each alternator produces two 3-phase a.c. power outputs (~100 V_{rms}, 60 Hz, 8 kW each). Each alternator output is boosted through a 175:1 step-up transformer and applied to a multi-stage multiplier-rectifier circuit. The multiplier circuit contains 6 full-wave stages, operating at staggered phases. It produces a d.c. output of 120 kV when unloaded, 60 kV under full rated load of 100 mA. The lowest harmonic of ripple in the rectified output is at a frequency f = 4.3 kHz. A relatively modest coupling and filter capacitance (.05 μF for all of the capacitors in Figure 2) suffices to provide a strong suppression of ripple.

Each CMA module is monitored and controlled by a control circuit that is mounted within its enclosure.

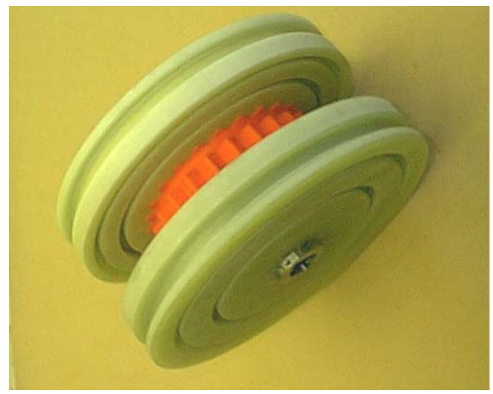

FIGURE 3. Flexible insulating coupler.

The control circuit is powered from the a.c. output of the alternator, and contains a data acquisition board (DAQ) and optical modem. The control circuits of all modules are accessed by fiber optic connection.

The output power of each alternator is controlled by the current in its field coil. This control current is generated by a pulse width modulator located within the control circuit. The d.c. voltage produced by each module is measured using a resistive divider. A comparator senses the difference between this output voltage and a set voltage that is produced by a digital-analog converter in the DAQ circuit. The difference voltage is used to control the field current and thereby regulate the output voltage of each module.

The frequency response of the regulation of the CMA modules is determined by the time $1/f$ = 230 μs between successive charging pulses in the 6-stage multiplier circuit. This fast response makes it possible to provide feed-forward regulation of output voltage during pulsed-mode operation, when an electron beam is square-wave modulated, as discussed below.

FIGURE 4. Pressure tank for 1 MV, 100 kW CMA.

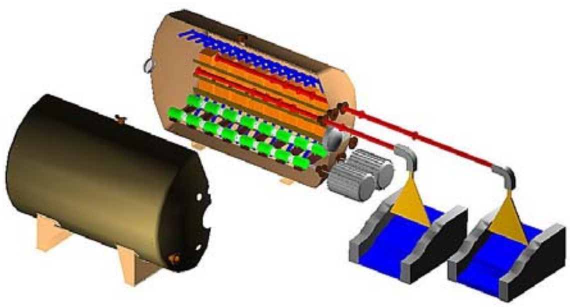

FIGURE 5. CMA system configured to treat wastewater.

PERFORMANCE OF CMA TO DRIVE MULTIPLE ELECTRON BEAMS

CMA was developed to support the operation of multiple independent electron beams, all contained in a common insulating tank and driven from a common d.c. source. The design was driven by the need for such multiple beams for industrial applications in water treatment, food irradiation, and materials processing, where large quantities of a commodity must be processed in multiple parallel process lines.

The CMA supply described above has several unique features for this purpose. First, it is capable of producing very large power. We are building a 1 MV, 100 mA, 3-beam unit for treatment of industrial wastewater. We have designed a 2 MV, 200 kW, 8-beam unit suitable for food irradiation, which is simply a twice-length embodiment using the same modules. Such beam power is not achievable with conventional e-beam technology.

Second, the CMA supply has very small ripple ($\sim 2{\cdot}10^{-3}$ @ full load) and excellent regulation ($\sim 10^{-3}$ idle to full load), which is important for independent operation and stable transport optics of multiple e-beams. The overall efficiency, from a.c. drive of the motors to d.c. at terminal voltage, is ~67%.

Third, all electrical components of the CMA accelerator are contained within the grounded steel vessel. This feature is of considerable importance for industrial applications, where in the event of a spark-down within an accelerator a high-voltage transient could propagate back onto a.c. supply networks and destroy control circuitry throughout a plant. In CMA, the only things that go into the vessel are two rotating shafts and fiber-optic control cables; the only things that come out are electron beams. If a spark-down were to occur inside, its only possible effect would be a cessation of electron beam and an off-loading of the motors.

Fourth, all of the component systems of CMA are inexpensive and reliable. The alternators, rectifiers, capacitors, and control components used in the modules are standard and available from multiple suppliers. The CMA module packaging has been developed to be extremely robust against damage from high-voltage transients. Indeed, a prototype CMA module was put through extensive full-load testing. We deliberately sparked the output to ground without damage.

The control of the CMA modules through field coil excitation makes it possible to start up the motors under no load, and then increase voltage in a controlled and gradual manner. Each control module is instrumented to measure both the supply current delivered and the differential between input and output current (see Figure 2), providing a useful diagnostic for corona or beam interception at intermediate voltage levels.

E-BEAM WATER TREATMENT

Electron-beam treatment has been shown to be highly effective in destroying toxic organic contaminants in water. This effectiveness results from the production of huge concentrations of reactive radicals (OH·, H·) and aqueous electrons e_{aq}^{-} through the ionization of high-energy electrons as they cascade within the water (see Figure 7). These short-lived radicals drive both oxidation *and* reduction reactions at the same time. Since the digestion of aromatic hydrocarbons typically requires a sequence of reactions of both types, e-beam treatment uniquely has the capability to drive digestion all the way to non-toxic end products.

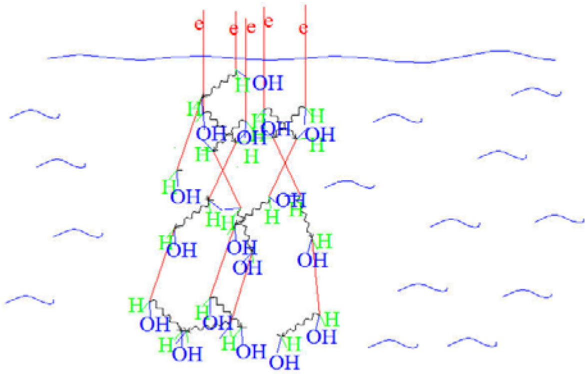

FIGURE 7. Ionization cascade in water makes free radicals.

Cooper [1,2] and others [5] have performed controlled experiments to measure the effectiveness of e-beam destruction of toxic organic compounds and to correlate the results with models of the reaction kinetics [1,2,3]. Figure 6a shows the destruction of phenol in water as observed by Zele *et al.* [5]. A dose of 3 kGy suffices to destroy all of the phenol. Figure 6b shows the formation of several intermediaries that are formed in the first reaction of phenol with the free radicals, and the ultimate destruction in turn of these intermediaries as dose increases, so that the dose of 3 kGy suffices to destroy the intermediaries as well. This ability to drive a succession of destruction reactions, typically both oxidation and reduction, is uniquely possible with electron beam treatment.

CONCLUSIONS

The coupled multiplier accelerator (CMA) is a new technology for high-power MV electron. It uses direct mechanical drive of a succession of series multipliers to achieve higher power, better efficiency, and better regulation/ripple performance than that of conventional few-MV electron accelerators. The first 1 MV, 100 kW CMA unit will be installed at a petrochemical plant and used to treat industrial wastewater.

ACKNOWLEDGMENTS

This work was supported by a grant from the Texas Advanced Technology Program. The authors thank W.J. Cooper (Univ. of North Carolina at Wilmington) for the inspiration to undertake this development.

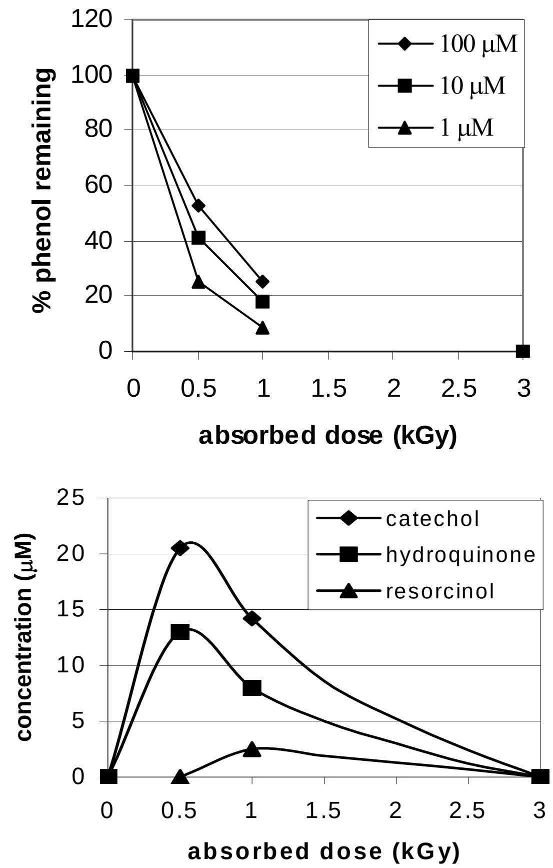

FIGURE 6. Simulation of electron beam treatment of phenol in water as a function of dose, from Ref. 5 : a) destruction of phenol; b) appearance and destruction of intermediaries.

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Colby, Eric

From: Robert Burke <rjburke@sbcglobal.net>
Sent: Monday, May 19, 2014 4:42 PM
To: Energy Environment RFI; Colby, Eric
Subject: Stewardship RFI Comments
Attachments: Heavy Ion Fusion in the US Physics Today Oct2010 CMStickley.pdf; Drake_PTO000028.pdf

Dear Eric,

I want to endorse the Stewardship program in the strongest terms. As you may remember from our meeting at SLAC in March 2010, FPC's plan to commercialize Heavy Ion Fusion is to use the vast databases of accelerator technology and engage the vast resources of the DOE's accelerator program and the vast capabilities of industry to manufacture components and build accelerator facilities that have attracted the wonder of the world. The existence of these vast resources is foundational in the case for HIF's readiness.

HIF began in the US in 1976, based on the enormous capabilities of conventional accelerators. Already by 1976, accelerator technology had the capability of providing the beams needed to ignite fusion pellets.

The Accelerator Stewardship program will provide the needed opportunity to set the record straight about Heavy Ion Fusion in the US.

The two attachments touch on two key points to help the recovery of HIF begin based on all the facts. The PT Letter by C.M. Stickley from October 2010 summarizes the rocky early history of HIF, especially the opposition of the weapons labs. The PT article by Paul Drake puts the High Energy Density Physics program in perspective, and contains a very thoughtful statement on the "sensical" and "nonsensical" aspects of the situation where all ICF in the US is funded for weapons research (page 32).

After NIF fell far short of ignition in 2012, NNSA announced by letter to the editor of the New York Times that their mission did not include development of ICF for an energy source, i.e., what Drake said so well in his 2010 article.

As Stickley notes in the first paragraph of his PT Letter, he wrote after seeing my PT letter in the June 2010 issue. Together, we convinced PT to expedite publication of the letter because of the preparations then being made for the National Research Council's "Study of the Prospects for Power Production from Inertial Confinement Fusion." That study fell far short of treating all the "prospects", and gave short shrift to HIF, despite an invited appearance by Boris Sharkov who head the Russian HIF program as well as the FAIR project at GSI.

There is a "dead hand on the throttle." The NRC report stated as a "conclusion" that ICF progress must await ignition at NIF, although that identical statement was part of the charter for the study from DOE.

No other development could come close to the impact that fusion energy could have on the energy-economy-environment problem.

Heavy Ion Fusion is criticized for being big. Big is what the energy-economy-environment problem is.

HIF was being criticized by the laser fusion advocates in the 1970s for being "too big and costly", long before

NIF was first estimated at $600m and came in at $5billion... and failed ignite a pellet.

A familiar question is "If HIF is so great, why isn't industry doing it with gusto?" My Congressman's Chief of Staff wrote that to me some months before I spent several weeks in DC in the fall of 2009. After she was more informed, her view was "Science and Technology needs to duke it out with Armed Services."

HEP's Stewardship program can be the opening to put HIF back on the tracks in the US.

1. HEP Accelerator Stewardship:
a. Restore understanding in the US of HIF based on mainstream accelerator technology.
b. Clarify the deserved confidence in pellet ignition by heavy ion beams that accrues from the absence of the problems of laser-matter interaction, the ability to deliver much more energy than a laser, the ability to do fast ignition, etc.
2. Provide leadership in DOE's establishment of an Office of Inertial Fusion Energy

I want to provide one last thing, to emphasize that HIF is alive and well outside the US. As you know, Ray Kidder began the ICF program at LLNL and ran it for its first ten years. Ray has been a strong supporter of HIF for decades, and is a senior advisor to Fusion Power Corporation. Last Saturday, Ray sent me the following information, about which he is very enthusiastic.

"The great and timely news is that R. RAMIS and J. MEYER-TER-VEHN have published a landmark paper on HIF. *in Laser and Particle Beams (2014)*, 32, 41-47, @ Cambridge University Press, 2013 0263-0346/13 $20.00 . Title:

"On thermonuclear burn propagation in a pre-compressed cylindrical DT target ignited by a heavy ion beam pulse

"(This paper will super-cede all previous such work, in my opinion, as it provides a more-accurate simulation of the physics). It has an extensive bibliography of similar work, and is a model of clarity typical of MtV."

Again, it is very good to see HEP's plan for a program to steward accelerator technology. This can return HIF to its proper starting point, from which it will be able to move forward rapidly as anticipated in the 1970s.

The challenges are large. The payoff could not be larger. The process needs to be one step at a time.

Sincerely,
Bob Burke

--
Dr. Robert J. Burke
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Chairman of Board
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Energy Environment RFI

From:	Colby, Eric
Sent:	Tuesday, May 20, 2014 10:10 AM
To:	Energy Environment RFI
Subject:	FW: PAVAC responce to the DOE Accelerator Stewardship RFI
Attachments:	DOE PAVAC Response.pdf

From: edinger@pavac.com [mailto:edinger@pavac.com]
Sent: Monday, May 19, 2014 7:29 PM
To: Colby, Eric
Subject: PAVAC responce to the DOE Accelerator Stewardship RFI

Dear Mr. Colby
Please see attached our response to the DOE - RFI. For many years we have a close collaboration with Fermilab and I personally work with Bob Kephart and Slava Yalolev.

I hope our response will help your planning for future use.

Kind regards
Ralf Edinger
President
Pavac

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PAVAC Energy Corp. (USA)
1 (630) 326 9078
204 S.Water St.
Batavia, IL, United States 60510

PAVAC Response

to

Department of Energy Request for Information

on

Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications

Contact:

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Introduction

In response to the Request for Information (RFI) on Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications that appeared in 79 FR 21910, PAVAC is pleased to present a high impact application of accelerator technology to address an importance challenge in energy and the environment. If DOE funding becomes available via the stewardship program, PAVAC and its partner Fermilab are well positioned to undertake successful research and development programs on the technology described below at the new Illinois Accelerator Research Center.

1. What are the most promising applications of accelerator technology?

1.2 Environment: Air: Electron Beam Flue Gas Treatment (EBFGT)

Sulphur and nitrogen oxides (SOx and NOx) emitted in flue gas by fossil-fuel power plants [1, 2] cause acid rain, low-level smog, and, indirectly, alarming climate changes. PAVAC's EBFGT system utilizes accelerator-generated electron beam to effectively convert SOx and NOx into fertilizer without creating waste streams. More importantly, EBFGT is the only flue gas treatment process that provides an additional revenue stream for the industrial facility: $16 million annual profits from fertilizer production for a 630 MW facility.

The EBFGT system also has a two-fold effect on reducing CO_2, a major greenhouse gas. First of all, due to the fact that EBFGT produces fertilizer, emission trading offsets can be used, by calculating the reduction in CO_2 emissions from traditional fertilizer production. Secondly, considering EBFGT as a retrofit solution, the high SOx and NOx removal rates will allow users to place CO_2 capture technologies downstream of the EBFGT facility. Therefore, these facilities with EBFGT will be CO_2 capture ready.

2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?

Technologies should be evaluated on environmental benefit, economic sustainability, and real-world practicality. Regulators should take an evidence-based approach to compare different technologies, and write the regulations around the most effective available technology.

---

1. Ahmed A. Basfar et al., "A review on electron beam flue gas treatment (EBFGT) as a multicomponent air pollution control technology," Nukleonika;55(3):271–277 (2010). Available at http://www.nukleonika.pl/www/back/full/vol55_2010/v55n3p271f.pdf
2. Radiation treatment of gaseous and liquid effluents for contaminant removal, IAEA Technical Meeting, IAEA-TECDOC-1473 (2005). Available at http://www-pub.iaea.org/mtcd/publications/pdf/te_1473_web.pdf

Accelerator technologies have already been safely adopted for a broad range of commercial use. In terms of environment control, accelerator technologies have also demonstrated significant advantages compared to conventional solutions. Thus, regulators should take such evidences into consideration when evaluating accelerator technology.

3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?

Long-term impact of investments can be estimated using the following metrics:

- Environmental Impact
  - Volume of pollutant and greenhouse gas removal (ex. NOx, SOx, CO_2), during combustion of fossil fuel
  - Volume of greenhouse gas emissions (ex. CO_2) offset due to carbon reuse and improvement in energy efficiency
- Economic Benefits
  - Value of GDP created, new business ventures, new job creations
  - Value of accelerator technologies goods exported
  - Value of accelerator technology byproducts
  - Value of Intellectual Property generated, including number of patents and licensing fee
  - Savings due to health benefits because of the improved environment
- Real-world adoption
  - Number of accelerator technologies applicable to users across industries
  - Return of Investment (ROI) in the accelerator technology for the user

Electron Beam Flue Gas Treatment (EBFGT)

Present State of the Technology

4. What are the current technologies deployed for this application?

Current technologies deployed for SOx and NOx removal uses combination of Selective Catalyst Reduction (SCR) and conventional Flue Gas Desulphurization (FGD), which are significantly less cost effective then EBFGT.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes. The EBFGT system effectively converts SOx and NOx into fertilizer without creating waste streams. It is the only flue gas treatment process that provides an additional revenue stream for the industrial facility. According to an independent study, EBFGT reduces the capital cost by ~17%, and operating cost by ~19% compared with conventional system. EBFGT's economic benefits are unachievable by any other flue gas treatment process, and therefore, revolutionizing environmental protection system to be economically sustainable.

6. Does the US lead or lag foreign competition in this application area?

Lag, EBFGT system is currently under research and development in Canada, Eastern Europe, and Middle east, while is full scale demonstration system is in operation in Poland and China

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Current obstacles:

- Technical: The most recent system installed in Poland had reliability issues with the electron beams. This issue is most likely to be overcome with PAVAC's many years of experience in providing electron beam technology to wide range of industrial applications.
- Regulatory: The need for EBFGT is driven by regulatory bodies changing environmental legislation to mandate reduction of emissions.
- Operational: With a test facility, such technical obstacles can be overcome to increase system reliability, while optimizing the operational process to minimize cost.
- Economic: Increase in cost of electricity.

8. How is accelerator technology used in the application?

The energy from the electron beam is used to dissociate, ionize and excite nitrogen, water, and oxygen molecules to form free active radicals. These free radicals will oxidize NO and SO_2 to NO_2 and SO_2, which will form HNO_3 and H_2SO_4 in presence of water. With the added ammonia, these acids are neutralized to ammonium sulfate and ammonium nitrate.

The electron beam can also break CH_4, CO_2, and water into molecular fragments. The fragments can be recombined to form methanol and O_2 under the right condition.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. As a turnkey operation, the EBFGT reactions are initiated inside the chemical reactor by the transfer of energy from accelerated electrons to the flue gas. Thus, this application will require high accelerator reliability. Nevertheless, the cost is low enough to justify use.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

In terms of NOx and SOx removal, there have been EBFGT demonstration facilities in Poland and China. There has been no known effort to break and recombine break CH_4, CO_2, and water into methanol and O_2 with accelerator technology.

11. What are the perceived and actual market barriers for the final product?

As a new technology to be introduced to a market, EBFGT is yet to validate the energy savings in comparison to alternative technologies. However, EBFGT pilot demonstrations have already demonstrated the better efficiency and cost savings. For wide spread EBFGT adaptation, regulation requiring compliance becomes an important driver.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

The basic technology of EBFGT is in the public domain, since many patents have expired. However the accelerator design, process details, and business information, such as the economic analysis area all proprietary.
In addition reaction chemistry has to be advanced and new feedstock developed, such as the use of Urea and lime based reactions.
For a number of types of coal, such a lignite, SCR's do not work and therefore De-NOx technology not available. EBFGT could solve this problem and would allow to clean lignite combustion.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 7
EBFGT technology: TRL 7

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

- Skills: Design, construction, and operation experience with accelerator
- Infrastructure: A testing facility for process development, that will allow operation of high power electron beam testing.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

- Lab: Fermilab is well positioned to support the R&D with PAVAC
- Industrial: Power plants, and accelerator manufacturer
- Academic: Experience in radical chemistry.

16. What collaboration models would be most effective for pursuing joint R&D?

A collaboration across federal and private funding will be most effective for pursing join R&D. Establishing strong partnership will allow sharing of resources and talents to maximize output.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. PAVAC have already worked with Fermilab projects in the past on Super Conducting Frequency cavity projects for Fermilab's accelerator. For the EBFGT project, the combined funding across different collaborations will drive the technology towards deployment.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

At early stages, federal grant will be needed to validate and demonstrate proof for EBFGT as a long-term commercial sustainable system. With these proofs, and along with regulation requirements, accelerator manufacturer and industrial facilities should be willing share the cost at later stages of the development.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices.

20. In what ways are the R&D needs not met by existing federal programs?

We are not aware of any current US funding for this type of technology development.

While the basic ideas for EBFGT have been in place for more than 20 years and several small scale demonstration have shown the technical and economic viability. Wide adoption by industries require full-scale turn-key system. The current technology state, while very promising, falls beyond that which organizations like NSF will fund (they fund Research Projects) but short of the TRL needed encourage adequate private investment. (there are some right now) Organizations like the EPA are regulatory in nature and do not fund this kind of development projects.

Without Federal funds this promising technology will continue to be developed slowly or will be developed off shore. It is likely that an EBFGT development effort launched by HEP via the Stewardship program can encourage significant investment from private industry. This in turn would attract funds from the State, DOE Fossil Energy and/or ARPA-E such that the development effort can move expeditiously to deployment.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial and economic feasibility has been demonstrated and, when regulations are in place to mandate emissions controls

22. What metrics should be used to assess the progress of a stewardship effort?

- For EBFGT: Amount of NOx and SOx remaining in flue gas.
- For combining CH_4, CO_2 and H_2O into methanol and O_2: efficiency and practicality of the process
- For both:
    - TRL progression.
    - Process cost reduction.
    - Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Conservative industry attitudes to new technology. Politics associated with government-imposed requirements for pollution control.

Colby, Eric

From: Robert D. Kephart x3135 03329N <kephart@fnal.gov>
Sent: Friday, May 16, 2014 5:33 PM
To: Colby, Eric; Procario, Michael; Jim Siegrist
Cc: kephart@fnal.gov; Nigel Lockyer; Sergei Nagaitsev
Subject: Stewardship RFI: Accelerator Technologies for Energy and Environmental Applications 79 FR 21910
Attachments: Fermilab Accelerator Stewardship Response.pdf

Dear Eric, Mike, Jim,

I am pleased to provide (attached) Fermilab's response to the Stewardship RFI on Energy and Environment (79 FR 21910).
We see many opportunities for the Accelerator Stewardship Program to have real impact on problems of national importance in this area.

If you have questions or would like additional information please do not hesitate to contact me.

Best Regards,

Bob

Dr. Robert Kephart

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Fermilab Response

to

Department of Energy Request for Information

on

Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications

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Introduction

In response to the Request for Information (RFI) on Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications that appeared in 79 FR 21910, Fermi National Accelerator Laboratory (Fermilab) is pleased to present a list of high impact application areas that provide opportunities for research and development of accelerator technologies to address national challenges in energy and the environment. Fermilab and its partners and collaborators are well positioned to undertake successful research and development programs on the technologies presented below.

The majority of the high-impact application areas described herein involve the use of electron-driven chemistry. An accelerator-generated electron beam can drive chemical reactions that would otherwise take place only at high temperatures and/or under the influence of catalysts. The resultant electron beam process may have a smaller carbon footprint due to its reduced energy consumption. Electron beams are also unique in that they can simultaneously drive both oxidation and reduction reactions in aqueous solutions, allowing the efficient destruction of harmful waterborne organic pollutants. The ability of ionizing radiation to crosslink materials altering their materials properties provides additional opportunities. Although we present a number of specific examples that represent high value opportunities to improve energy efficiency, reduce pollutants from energy production, clean up water, and reduce environmental toxins, it is likely that many additional potential applications will emerge as the technology is developed.

Other applications of accelerator technologies described in this document include accelerator-generated neutrons to produce energy and to treat nuclear waste. We also describe the use of superconducting magnet technology developed for accelerators to allow the construction of smaller, more compact and efficient generators for wind turbines.

IARC Facility

Fermilab foresees that many of the accelerator technologies described herein will be developed at the Illinois Accelerator Research Center (IARC), a new accelerator research and development facility being built at Fermilab. Located on the Fermilab campus, this 83,000 square foot, state-of-the-art facility will house offices, workshop, laboratory, and educational space to design and develop cutting-edge accelerator technologies. IARC also provides access to the technical expertise and facilities of Fermilab. One of the key goals of IARC is to work in cooperation with private industry partners to develop and commercialize new accelerator technology. Funding for IARC comes from a grant from the US Department of Energy and the State of Illinois.

Unlike other facilities, such as the Idaho Accelerator Center or the Texas A&M University Accelerator Laboratory, IARC is designed to house high power (hundreds of KW), lower energy (<10 MeV) electron accelerators needed to make many future applications for energy and environment practical. In addition to the ready availability of the staff and technical resources of a world-class accelerator laboratory, one goal of IARC is to provide high power electron accelerator test platforms that can serve both as a test beds for industrial process development and at the same time allow accelerator cost and reliability optimization. Development of a mobile high power electron accelerator is another IARC objective that could enable in-situ demonstration and validation of many proposed future accelerator applications.

Document Organization

In this document, we provide responses to RFI questions 1, 2, and 3 in the section “Application Areas with High Impact”. For each of the most promising applications identified in the response to question 1, we separately present detailed answers to questions 4 through 23. Subheadings are color coded to assist with document navigation.

Application Areas with High Impact

1. What are the most promising applications of accelerator technology?

1.1 Energy Production and Efficient Industrial Processes

a) Gas to Liquids Conversion

Accelerator-generated electron beams can efficiently break carbon-hydrogen bonds allowing conversion of natural gas and biogas, both of which are mainly methane, to liquid hydrocarbons, which are useful for many applications, including transportation fuels. There are multiple approaches under consideration, including direct creation of long-chain hydrocarbons via removal of protons (i.e. hydrogen) or alternative reactions in which natural gas, CO_2 from a power plant, and water are converted into alcohol creating valuable fuels while lowering overall emissions via reuse of the carbon.

Flare Gas Recovery

An accelerator-generated electron beam may be used to efficiently convert natural gas produced by oil wells to liquid hydrocarbons at the wellhead [1]. At present, it is uneconomical to collect some associated gas, which is consequently flared (burned at the wellhead). In 2011 natural gas flared at well heads worldwide corresponded to 25% of the U.S. annual natural gas consumption with a retail value of about $30 billion. Recent widespread use of fracking technology results even more gas flared in the U.S. For example more than 30% of the gas produced by the Bakken play in North Dakota in 2012 was flared. A mobile accelerator system at the wellhead could convert natural gas to liquids, which could be collected and shipped with the oil. Aside from providing a new source of useful petroleum liquids, flare gas recovery would reduce the emission of greenhouse gases.

Biogas Recovery

An accelerator-generated electron beam may be used to convert biogas to liquid hydrocarbons, which can be used as a chemical feedstock or liquid fuel [1]. (Biogas typically refers to a mixture of gases produced by the breakdown of organic matter in the absence of oxygen. Biogas, which consists mainly of methane, has significant potential as a renewable fuel.) The accelerator system would be installed at the location where the biogas is produced, typically a landfill or anaerobic digester. In addition to increasing energy production, the conversion of methane, a powerful greenhouse gas, to a useful fuel will also reduce global warming.

b) Superconducting Generators for Wind Energy Capture

The use of superconducting magnet technologies developed for high energy physics could allow smaller, more compact and efficient generators for wind turbines [2]. This in turn can allow the manufacture of larger capacity wind turbines, since current designs are limited by the weight of the required generator and gearbox. Use of high temperature superconductors can make the required refrigeration systems simpler and more efficient.

c) Highway Asphalt Treatment

Asphalt is used in approximately 95% of the 2.2 million miles of roads in the US. Tens of billions of dollars are spent every year on roadway repair and maintenance. We propose to use an accelerator-generated electron beam to drive a chemical reaction in asphalt after it has been applied to road surfaces to improve its material properties. Irradiation by a mobile, vehicle-mounted electron-beam source will cause the long-chain hydrocarbons in the bitumen that composes roadway asphalt to cross polymerize to a depth of a few centimeters, which will improve the wear-resistance and weather-resistance of the asphalt

1. A. V. Ponomarev and A. Yu. Tsivadze, “Gas-to-liquid conversion of alkanes by electron beam radiolysis”, Doklady Physical Chemistry, Volume 411, Issue 2, pp 345-351 (2006).
2. Advanced Wind Turbine Drivetrain Concepts Workshop Report, US Department of Energy (2010). Available at http://www.nrel.gov/docs/fy11osti/50043.pdf

[3]. This has the potential to save a large amount of taxpayer dollars and reduce the large carbon footprint resulting from the use of diesel-powered heavy equipment in asphalt road repairs.

d) Accelerator Driven Systems for Energy Production

Accelerator-generated neutrons may be used to maintain a fission chain reaction in a subcritical fuel assembly. This would enable a new generation of nuclear reactors, known as accelerator driven systems (ADS), that can be tuned off merely by stopping an accelerator beam, rather than by inserting control rods and rendering the fuel assembly subcritical [4]. Further, ADS would allow the use as a nuclear fuel of thorium-232, which is three to five times as abundant in the Earth's crust as uranium.

e) Compact Down-Hole Gamma Source

Sealed gamma-ray emitting radioactive sources are used down bore holes by the oil and gas industry to determine the density and composition of the surrounding rock strata [5]. We propose the use of an electron-beam driven gamma ray sources as a replacement for the radioactive source. The accelerator-driven source would be safer and could be modulated as required. We note that the petroleum industry has already expressed an interest in such accelerators.

1.2 Environment: Air

a) Electron Beam Flue Gas Treatment (EBFGT)

Accelerator-generated electron beams can be used to remove pollutants in the flue gas emitted by fossil-fuel power plants [6, 7]. This can be applied to NOx and SOx, which are responsible for acid rain, and to CO_2, a major greenhouse gas. Using electron beams, NOx and SOx can be converted into ammonium nitrate and ammonium sulfate, which can be separated as particulates and subsequently used as fertilizers. Methane can be used in an electron-beam induced process to remove CO_2, resulting in the production of methanol, which can be used as a chemical feedstock. The pollutant removal processes can be applied sequentially to remove NOx and SOx, and then to remove CO_2. When combined with other conventional pollutant removal processes the fully treated flue gas stream is almost free of pollutants.

1.3 Environment: Water

a) Destruction of Organic Materials in Industrial Wastewater

An accelerator-generated electron beam may be used to destroy organic materials, e.g. dyes, pesticides, pharmaceuticals, endocrine disruptors, etc., that would otherwise be released to the environment in a liquid or gas waste stream, or collected for treatment [7].

b) Municipal Waste Water Treatment

An accelerator-generated electron beam may be used to treat the output from municipal waste treatment plants. This treatment method will efficiently kill pathogens, remove pharmaceuticals, and remove odor

3. Je Sung Youm et al., “Elastic property of polyolefin elastomer film cross linked by electron beam irradiation,” Fibers and Polymers, Volume 13, Issue 9, pp 1165-1169 (2012).
4. H. Nifenecker et al., “Basics of accelerator driven subcritical reactors,” Nucl. Instr. and Methods in Phys. Res. A 463 (2001) 428–467.
5. Falah Abu-Jarad, “Application of Radiation Sources in the Oil & Gas Industry and Shortages in their Services,” International Symposium on the Peaceful Applications of Nuclear Technology in the GCC Countries, Jeddah (2008). Available at http://procurement.kau.edu.sa/Files/320/Researches/47387_18847.pdf
6. Ahmed A. Basfar et al., “A review on electron beam flue gas treatment (EBFGT) as a multicomponent air pollution control technology,” Nukleonika;55(3):271−277 (2010). Available at http://www.nukleonika.pl/www/back/full/vol55_2010/v55n3p271f.pdf
7. Radiation treatment of gaseous and liquid effluents for contaminant removal, IAEA Technical Meeting, IAEA-TECDOC-1473 (2005). Available at http://www-pub.iaea.org/mtcd/publications/pdf/te_1473_web.pdf

[7,8]. The result will be a nutrient-rich liquid that can be used as a fertilizer. This will reduce phosphate pollution, a major contributor to eutrophication of surface waters and to algae blooms while at the same time helping to preserve limited phosphate deposits that are currently mined for fertilizer

c) Contaminated Ground Water Cleanup

Industrial Waste

An accelerator-generated electron beam may be used to remove organic contaminants, many of which are on the EPA's National Priorities List, such as gasoline, oil, methyl tertiary butyl ether (MTBE), pesticides, refrigerants and other chemical waste from groundwater [7]. Contaminated ground water would be pumped out of one or more boreholes and treated using a mobile accelerator, which would transform the organic contaminant into far less harmful substances.

Water Supply Treatment

The electron-beam treatment method may also be applied as part of the purification process for water intended for human or animal consumption. Electron-beam disinfection of potable water may be less costly and more environmentally friendly than methods currently used as there is no need for toxic and corrosive chemicals, such as chlorine or chlorine dioxide.

1.4 Environment: Land

a) Municipal Sewage Sludge Treatment

Treating sewage sludge with an accelerator-generated electron beam, rather than disposing of it in a landfill, will provide pathogen-free fertilizer [7, 8] and will also allow recycling of nitrates and phosphates, thereby saving energy and conserving phosphate reserves. This method has the potential to reduce the energy required to created conventional fertilizers and also to reduce agricultural runoff from chemical fertilizers that contaminate waterways.

b) Accelerator Driven Systems for Minor Actinide Destruction

Accelerator-generated neutrons may be used to transmute minor actinides in nuclear waste into stable isotopes. The destruction of minor actinides may render the waste remaining after spent fuel reprocessing safe in decades rather than millennia [9].

2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?

We recommend that regulators identify the most effective available technologies and write regulations around them, bearing in mind cost and safety. In many cases accelerator technology may offer better alternatives than conventional solutions. It is important that regulators be aware of the advantages offered by accelerator technologies. A key element of this awareness is demonstrations at scale and under real world conditions. Similarly, it is important that regulators do not rule out new technologies merely because they involve the use of accelerators or radiation. A growing body of evidence shows that accelerator technologies can be used safely in a broader commercial setting.

8. Y. Avasn Maruthi et al., "Appliance of Electron Beam Technology for Disinfection of Sewage Water to Minimize Public Health Risks," European Journal of Sustainable Development, 2, 4, 1-18 (2013).
9. Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles – A Comparative Study, OECD Nuclear Energy Agency (2002), Available at http://www.oecd-nea.org/ndd/reports/2002/nea3109.html

3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?

Metrics suitable for estimating the long-term impact of investments in new accelerator technologies include:

- Increase in the amount of domestically generated hydrocarbons, reduction in the amount of imported oil, and consequent national security improvements
- Reduction in the volume of CO_2 and other pollutants produced during combustion of fossil fuels
- Overall reduction in greenhouse gas emissions due either to improved energy efficiencies and/or carbon reuse in energy systems
- Value of GDP created
- Value of accelerator-related goods exported
- Value of healthcare savings and improved longevity due to reduced pollution and improved air and ground water quality
- Number of jobs created or retained
- Value of private sector investment in technology
- Number of new businesses created
- Volume of intellectual property generated (number of patents awarded)
- Value of intellectual property generated (value of license fees)

1.1 a) Gas to Liquids Conversion

Present State of the Technology

4. What are the current technologies deployed for this application?

Patents exist for natural gas to liquids chemical processes to convert natural gas to hydrocarbons or methanol. Large-scale Fischer–Tropsch plants exist and are under construction, but these require extensive infrastructure due to the required high temperatures and pressures, catalysts, etc. Many of these chemical techniques cannot be applied at the well head to make use of flare gas due to the cost and scale of the required equipment. Patents exist for alternative technologies to capture flare gas at smaller scales but no existing solution has been proven to be efficient and cost effective.

For biogas, patents exist on chemical processes to convert the methane in biogas to hydrocarbons or methanol. We find no evidence to suggest that these processes have been used in practice on a large scale.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes.

Conversion to liquids of flare gas, an abundant byproduct of oil production, may substantially alter feasibility of its use as a fuel source.

Conversion to liquids of biogas at landfills or anaerobic digesters may substantially improve the economics of biogas production and use as a fuel source. The technology potentially allows transformation of other biologically-produced compounds, such as triglycerides or long chain lipids, into shorter-chain liquid fuels or methane.

6. Does the US lead or lag foreign competition in this application area?

Slight lead. There is no evidence that foreign countries are working on accelerator technology for flare gas or biogas to liquid conversion.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: Gas to liquid process needs further development. A test facility is needed. Low-cost, efficient accelerators are a key requirement. Reliable, thin vacuum windows are needed to efficiently couple the electron beam into the gas.
Regulatory: Permits and accelerator radiation hazards for workers.
Operational: Limited knowledge of accelerator reliability in this application. Additional complexity in the production process argues for turn-key solutions
Economic: Cost of fuels compared with conventional alternatives not known.

8. How is accelerator technology used in the application?

Electron beam breaks C-H bonds in flare gas or biogas (mainly methane); molecular fragments recombine to form liquid hydrocarbons.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need high accelerator reliability at a cost that is low enough to justify use. Turn-key operation will be needed for practical application.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

None are known.

11. What are the perceived and actual market barriers for the final product?

Accelerators are new, unproven technology in this application. Alternative technologies have been proposed and in some cases are being developed but cost, maturity, and scale of required systems are barriers to the use of those alternative technologies.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

A successful gas to liquids technology is potentially highly lucrative. Companies and research organizations working on this technology treat all aspects of the approach as proprietary. Fermilab has signed a Non-Disclosure Agreement with the Gas Technology Institute to explore gas to liquid conversion with accelerators. Once the technology has been demonstrated, we expect that commercial accelerator manufacturers will develop proprietary variants of the required accelerators.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 4 - TRL 5
Conversion technology: TRL 2 - TRL 3

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Accelerator design, construction, and operation experience.
Infrastructure: Suitable facilities for the construction and operation of high power electron accelerators. High-power electron beam test facility for process development.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab, and perhaps ANL
Industrial: Accelerator manufacturer. Natural gas R&D organizations and producers. Biogas producers.
Academic: Institution with experience in organic chemistry.
Other: Gas Technology Institute.

Fermilab should drive the R&D through IARC.

16. What collaboration models would be most effective for pursuing joint R&D?

Models in which federal and private funds can be combined to create high power electron beam test facilities for process development. Access to laboratory staff and infrastructure via partnerships to control costs with shared IP creation and capture for accelerator and process development.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Fermilab could provide the greatest leverage.

A great deal of infrastructure is required for this activity.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. Federal grants are needed for test facilities to demonstrate proof of principle and establish cost estimates. If this idea is judged by industry to be technically and economically feasible, oil and gas producers and accelerator makers are likely willing to cost share the development, especially at later stages

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Engagement with other innovation and manufacturing initiatives is unnecessary at this time. Only after the technology has been proven would it make sense to improve manufacturability to bring costs down. No new manufacturing technology required at this time.

20. In what ways are the R&D needs not met by existing federal programs?

We are not aware of any current US funding for this type of technology development. However ARPA-E is funding some novel gas to liquids research such a use of biologics.

The current technology state, while very promising, falls beyond that which organizations like NSF will fund (they fund Research Projects) but short of the TRL needed encourage private investment. We are not aware of any current US funding for this type of technology maturation and development. Without Federal funds this promising technology will continue to languish or will be developed off shore.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been or can be demonstrated.

22. What metrics should be used to assess the progress of a stewardship effort?

TRL progression.
Process cost reduction.
Gas-to-liquid conversion efficiency.
Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Conservative industry attitudes to new technology.
Technical sophistication of industry: oil and gas industry is technically sophisticated; biogas industry is not.

1.1 b) Superconducting Generators for Wind Energy Capture

Present State of the Technology

4. What are the current technologies deployed for this application?

Conventional generators with gearboxes.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes. A superconducting generator would be substantially smaller and lighter and have higher efficiency than conventional generators. Elimination of gearboxes further reduces mass and complexity. This could allow larger wind turbines, thereby bringing down the cost per watt of wind power.

6. Does the US lead or lag foreign competition in this application area?

Unclear. The technology is being pursued in Europe, Japan, and Korea.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: Challenges are cryogenic refrigeration, AC losses in SC generator windings, reliability, controlling size of generator & refrigerator, and developing self-starting designs.
Regulatory: No more than incumbent technology.
Operational: Unknowns related to reliability and complexity of superconducting generator system compared with conventional generators.
Economic: Unknown cost of superconducting generator system.

8. How is accelerator technology used in the application?

The basic designs and techniques developed for SuperConducting (SC) magnets for HEP accelerators have direct applicability to SC generators for wind turbines. The resulting generators can have much higher power densities than conventional generators and gear boxes resulting in lower weigh for a given power rating. Elimination of the gear box can also improve overall turbine reliability. Ultimately these attributes can allow Turbines of higher power output than is currently possible with conventional generators. Superconducting wire of the type used in high-performance accelerators is substituted for copper wire in generator. Like a ramped HEP accelerator magnet, an AC SC generator has to control AC losses in the windings which ultimately end up in the cryogenics system. New coil designs, winding, insulation, coilheat treatment techniques, magnet protection schemes, etc from both NbTi and Nb3Sn based accelerator magnets are directly applicable to SC generators for wind turbines. Similarly, the extensive SC magnet expertise and infrastructure at HEP labs can be applied to the problem of low cost renewable energy. High Tc magnet and wire development in HEP is also directly applicable.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

The application needs high reliability and high performance SC magnets at a low cost. This is very similar to the requirements on SC magnets for a large accelerator. Control of AC losses is important, similar to a ramped SC magnet in an accelerator.

Use of high Tc conductors has the potential to greatly simplify the required refrigeration systems (e.g. cryogen free systems like cryocoolers) and bring down costs. However both the magnet techniques and refrigeration schemes need additional development.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

The SUPRAPOWER project has received funding from the European Union's Seventh Programme for research, technological development and demonstration. In the US, technology is being pursued by GE, and by several small companies and University of Houston via ARPA-E grants. In a few cases HEP magnet designers are involved but none of these efforts leverages the SC magnet capabilities of a big HEP lab. Fermilab recently teamed with BNL to respond to an EERE FOA by proposing a novel design for a SC wind generator based on an a coil very similar to an accelerator sextapole winding. However, funding is very limited to explore the available phase space of ideas. The EERE proposal requires a lab contribution, a challenge in the current HEP funding environment.

SC wind generators are also being pursued in Japan, and Korea.

11. What are the perceived and actual market barriers for the final product?

Superconducting magnets are new, unproven technology for this application.
A proven generator technology needs to exist and costs for the new technology have to be competitive.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

We expect a market for a large number of systems. Once technology is demonstrated, we expect that commercial superconducting wire and generator manufacturers will develop proprietary variants.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology (superconducting wire): TRL 6 - TRL 7
Superconducting generator technology: TRL 4 - TRL 5

HTC magnet technology TRL 3-4

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Expert superconducting magnet designer, SC wire experts, electrical machine design, and SC magnet construction experience.
Infrastructure: Suitable facilities for the construction and cryogenic test of large superconducting electrical generators. Superconducting wire and materials test equipment.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab, BNL, LBNL
Industrial: Superconducting magnet manufacturer, generator manufacturer.
Academic: Institutions with experience in superconducting magnet and generator design

Fermilab should drive the R&D through IARC using facilities in the Fermilab Technical Division.

16. What collaboration models would be most effective for pursuing joint R&D?

Models in which federal and private funds can be combined with access to laboratory staff and infrastructure via partnerships with shared IP creation and capture.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Fermilab and a lab such as BNL, LBNL, or NREL.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. Federal grants are needed to demonstrate proof of principle and cost estimates. If this idea is judged by industry to be technically and economically feasible, wind turbine and generator makers should be willing to cost share at later stages of the development.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute and the Digital Manufacturing and Design Innovation Institute to improve superconducting generator efficiency and reduce its cost. However these efforts would follow basic proof of principle demonstrations.

20. In what ways are the R&D needs not met by existing federal programs?

ARPA-E and EERE funding is insufficient and has not effectively engaged the SC accelerator magnet expertise and infrastructure at HEP labs.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been demonstrated.

22. What metrics should be used to assess the progress of a stewardship effort?

TRL progression.
Generator performance (efficiency, power per unit volume, power per unit mass).
Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Conservative industry attitudes to new technology.
Importance of levelized cost of energy (LCOE) in the electricity generation industry.

1.1 c) Highway Asphalt Treatment

Present State of the Technology

4. What are the current technologies deployed for this application?

None. The application will build on a base of current commercial practice.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes. Electron beam treatment of asphalt may result in a material with fundamentally superior properties to materials currently in use. This technology has the potential to be disruptive, saving large amounts of taxpayer dollars and reducing the large carbon footprint of asphalt road repair.

6. Does the US lead or lag foreign competition in this application area?

Slight lead. There is no evidence that foreign countries are working on accelerator technology for asphalt treatment.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: Electron beam radiation is known to polymerize hydrocarbons with acceptable polymerization depth and heat input. The largest issue will likely be development and cost of additives, and the fact that bitumen from various sources is different chemically. Shielding a mobile accelerator will be a technical challenge but appears to be achievable based on simulations.
Regulatory: Permits and accelerator radiation hazards for workers.
Operational: Limited knowledge of accelerator reliability in this application.
Economic: Initial cost of this process vs demonstrated long term savings that can be achieved.

8. How is accelerator technology used in the application?

Electron beam causes the long-chain hydrocarbons in the bitumen that composes roadway asphalt to cross-polymerize to a depth of a few centimeters, which will improve the wear-resistance and weather-resistance of the asphalt.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need high power mobile accelerators with high reliability at a cost that is low enough to justify use. Turnkey operation will be needed for practical application.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

None are known. Fermilab has applied for patent protection on this process.

11. What are the perceived and actual market barriers for the final product?

Use of an accelerator is a new, unproven technology in this application. There is added up-front cost vs. the expectation of extended highway lifetime. There is added operational complexity. Trained workers will be needed.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

The technique itself and the actual process are proprietary. Expect market for a large number of mobile accelerator systems of modest cost. Once technology has been demonstrated, expect that commercial accelerator manufacturers will develop proprietary variants.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 4 - TRL 5
Electron-beam cross-polymerization of bitumen: TRL 3

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Accelerator design, construction, and operation experience, high power EB test facility for process development.
Infrastructure: Suitable facilities for the construction and operation of high power electron accelerators. Large site with asphalt roads for demonstration of a mobile accelerator and the actual process at scale prior to full permitting and deployment for public road tests.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab.
Industrial: Accelerator manufacturer. Maker of construction equipment, e.g., Caterpillar. Large chemical company for process development and cost reduction R&D.
Academic: Institution with experience in polymer chemistry.
Other: US Department of Transportation (DoT).

Fermilab should drive the R&D through IARC.

16. What collaboration models would be most effective for pursuing joint R&D?

Models in which federal and private funds can be combined to create high power electron beam test facilities for process development. Access to laboratory staff and infrastructure via partnerships to control early development costs with shared IP creation and capture.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Fermilab including IARC could provide the greatest leverage.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. Federal grants are needed to demonstrate proof of principle and cost estimates. If this idea is judged by industry to be technically and economically feasible, accelerator makers should be willing to cost share at later stages of the development. After initial development, if there is possibility for a large cost saving, the States and the DoT should be willing to cost share. At some point builders of heavy road construction equipment will be natural partners.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices.

20. In what ways are the R&D needs not met by existing federal programs?

We are not aware of any current US funding for this type of technology development.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been demonstrated.

22. What metrics should be used to assess the progress of a stewardship effort?

Physical and mechanical properties of treated asphalt.
TRL progression.
Process cost reduction.
Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Conservative industry attitudes to innovation.
The road construction industry is not technically sophisticated.

1.1 d) Accelerator Driven Systems (ADS) for Energy Production

Present State of the Technology

4. What are the current technologies deployed for this application?

Uranium-based nuclear reactors.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes. The technology enables inherently safe(er) nuclear reactors and the development of thorium-based nuclear fuel cycle. Reactor safety and public concern over safe long term storage of very long lived isotopes present in spent fuel rod assemblies from conventional reactors are a major impediment to expanded use of this powerful carbon free energy source. This technology would also dramatically increase available nuclear fuel reserves.

6. Does the US lead or lag foreign competition in this application area?

Lag. The technology is being pursued in Europe, Japan, China, and India.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: Unknown feasibility of large-scale power generation via ADS.
Regulatory: Difficulty of licensing a new class of nuclear reactors.
Operational: Limited knowledge of accelerator reliability in this application.
Economic: Huge development cost for even proof-of-principle experiments. Unknown cost of electricity generated by ADS.

8. How is accelerator technology used in the application?

Accelerator-generated proton beam generates neutrons, which sustain a chain reaction in an otherwise subcritical assembly of nuclear fuel.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need very high beam power (>10 MW) proton accelerators and very high accelerator reliability for commercial feasibility.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

Research and development aimed at this application are in progress in Japan, China, India, and Belgium. Major new demonstration facilities are planned.

11. What are the perceived and actual market barriers for the final product?

New, unproven technology that is likely to be very expensive (billions of dollars) to develop and demonstrate on a practical scale (hundreds of megawatt facility).
Unknowns associated with lack of public trust in government developed technologies.
Unknowns associated with potential public resistance to a new nuclear technology. Opposition from DOE and U.S. industry groups owning or pushing competing IP in breeder, SMR, or IV generation reactor technology.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Given cost and scope of the project, public funding will likely be required, which means overall technology solution is likely to be developed in the public domain. However, nuclear industry has an extensive IP portfolio and would likely develop IP related to this application.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 4 - TRL 5
Accelerator driven system: TRL 3

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Accelerator design, construction, and operation experience
Infrastructure: Suitable facilities for the construction and operation of high-power proton accelerators. Eventually, a laboratory consortium willing and funded to construct an ADS test facility.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab and other DoE lab(s) with interest in reactor technology.
Industrial: Builders of Nuclear Reactors
Academic: No recommendations at this time.

Fermilab should drive the needed accelerator R&D through IARC and partner with one or more national NE labs to develop the ADS core and associated systems for a demonstration machine. A national facility to burn minor actinides might be government funded and operated.

16. What collaboration models would be most effective for pursuing joint R&D?

Federal funding with construction of a demonstration facility at a National Laboratory and subsequent technology transfer to the private sector.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes this is essential. Fermilab and a lab such as ORNL, Idaho, Los Alamos, ANL,etc.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

No. There is a low probability that a commercial entity would invest in a technology that is so far removed from commercialization unless there are other potential near-term applications.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices.

20. In what ways are the R&D needs not met by existing federal programs?

We are not aware of any current US funding for this type of technology development.

The current technology state, while very promising, is not being funded by either Nuclear Physics or Nuclear Energy. The current technology state is far short of the TRL needed encourage private investment or to permit NRC licenses to be granted. We are not aware of any current US funding for this type of technology maturation and development. Without Federal funds this promising technology will continue to languish or will be developed off shore.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been demonstrated.

22. What metrics should be used to assess the progress of a stewardship effort?

TRL progression.
Progress towards commercial feasibility.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Regulatory environment means new designs for nuclear power reactors are very capital intensive.
Low cost of natural gas and low cost of new gas fired power plants.
Active opposition by portions of the DOE and nuclear industry with technical investments in alternative reactor technologies and/or IP in breeder reactor or alternative technologies.

1.1 e) Compact Down-Hole Gamma Source

Present State of the Technology

4. What are the current technologies deployed for this application?

Gamma sources such as caesium-137 or cobalt-60.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes. An accelerator-driven gamma source would be safer because it can be switched off when not in use. Gamma ray production rate can be varied as required.

6. Does the US lead or lag foreign competition in this application area?

Slight lead. There is no evidence that foreign countries are working on accelerator technology for down-hole gamma production.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: Requires compact accelerators that are capable of operating at high temperature, and a power source that draws energy from the drill string.
Regulatory: Less than incumbent technology: gamma ray source can be switched off.
Operational: Limited knowledge of accelerator reliability in this application. Added system complexity due to size and power limitations as well as difficult down-hole operating conditions.
Economic: Cost vs. benefit uncertain.

8. How is accelerator technology used in the application?

Use electron beam impact on target to create gamma rays.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need high accelerator reliability at a cost that is low enough to justify use. Turnkey operation will be needed for practical application.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

None are known. However, it is known that U.S. oil and gas development organizations are interested in exploring what might be possible.

11. What are the perceived and actual market barriers for the final product?

Accelerators are new, unproven technology in this application. Alternative technologies exist but the accelerator technology might perform better. A cost-benefit analysis is required.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Expect market for a modest number of fairly expensive systems. Once technology has been demonstrated, expect that commercial equipment manufacturers will develop proprietary variants.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 4 - TRL 5
Down-hole accelerator: TRL 2

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Accelerator design, construction, and operation experience
Infrastructure: Suitable facilities for the construction and test of high-power electron accelerators.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab.
Industrial: Accelerator manufacturer. Oilfield equipment company, e.g. Schlumberger.
Academic: Institution with experience in oilfield geology.

Industry can leverage the required R&D through IARC.

16. What collaboration models would be most effective for pursuing joint R&D?

Models in which federal and private funds can be combined with access to laboratory staff and infrastructure via partnerships with shared IP creation and capture.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Fermilab could provide the greatest leverage.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. Federal grants are needed to allow private industry to gain access to lab expertise at acceptable rates. If this idea is judged by industry to be technically and economically feasible, accelerator makers and oilfield equipment makers should be willing to cost share at later stages of the development.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices and with the Digital Manufacturing and Design Innovation Institute to develop a compact accelerator and power supply capable of operating down a borehole. However, these efforts would be follow-on efforts after the initial demonstrations of feasibility.

20. In what ways are the R&D needs not met by existing federal programs?

We are not aware of any current US funding for this type of technology development. Funding from oil/gas industry is small, national lab expertise has not been leveraged.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been demonstrated.

22. What metrics should be used to assess the progress of a stewardship effort?

Accuracy of down-hole geological measurements.
TRL progression.
Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Industry attitudes to new technology.

1.2 a) Electron Beam Flue Gas Treatment (EBFGT)

Present State of the Technology

4. What are the current technologies deployed for this application?

Wet, dry, and semi-dry flue gas desulfurization (FGD) and selective catalytic reduction (SCR) of NOx.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes.
(i) Conversion of NOx and SOx to ammonium nitrate and ammonium sulfate via electron beam irradiation results in the almost complete removal of these pollutants from power plant flue gas. Ammonium nitrate and ammonium sulfate can be used as fertilizers.
(ii) Conversion of CO_2 and H_2O to methanol and O_2 via electron beam irradiation results in substantial removal of this greenhouse gas from power plant flue gas. Methanol can be used as fuel or feedstock for chemical processes. CO_2 sequestion is not required. A liquid air plant at the input of the coal fired plant (e.g. FutureGen 2.0) is not required. Overall plant efficiency should be high.

6. Does the US lead or lag foreign competition in this application area?

Lag. EBFGT Technology is being pursued in Canada, Eastern Europe, China, and the Middle East. A demonstration system is in operation in Poland.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: Demonstration systems work. Process optimization requires a test facility. Accelerator reliability and cost are important technical challenges.
Regulatory: Permits and accelerator radiation hazards for workers. Need for EBFGT is driven by environmental regulations on power plants.
Operational: Accelerator reliability in this application. Increased system complexity.
Economic: Increase in cost of electricity.

8. How is accelerator technology used in the application?

(i) Electron beam breaks NOx and SOx into molecular fragments. Fragments react with ammonia, which is separately injected into the flue gas, to form ammonium nitrate and ammonium sulfate.
(ii) Electron beam breaks CH_4, CO_2 and H_2O into molecular fragments. Under the right conditions fragments recombine to form methanol and O_2.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need high accelerator reliability at a cost that is low enough to justify use. Turnkey operation will be needed for practical application.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

There are demonstration EBFGT facilities in Poland and Bulgaria; none are known in the US. IAEA promoted effort.

There are no known efforts to combine CH_4, CO_2 and H_2O into methanol and O_2 via the use of accelerators. Fermilab is applying for IP protection for this process.

11. What are the perceived and actual market barriers for the final product?

Accelerators are new, commercially unproven technology in flue gas treatment. Alternative technologies exist for NOx and SOx removal but are expensive and appear not to work as well as pilot demonstrations of EBFGT. Energy savings with EBFGT vs water based NOx and Sox removal process need to be validated. Even though lower pollution levels are achieved, the added cost of EBFGT without regulations requiring compliance is a barrier to wide spread EBFGT adoption

There are no known efforts to combine CH_4, CO_2 and H_2O into methanol and O_2 via the use of accelerators so aside from the barriers of introducing a new technology market barriers are unexplored.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Many EBGFT patents have expired putting the basic technology in the public domain. However the accelerator design and process details as well as the economic analysis related to EBFGT as a business are all proprietary. However, early leaders will guard proprietary information closely since this will provide considerable advantages during deployment.

One can expect market for a large number of expensive systems on commercial power plants if the technology is adopted widely. Once the technology has been demonstrated, we expect that commercial accelerator manufacturers will develop proprietary variants.

Techniques to combine CH_4, CO_2 and H_2O into methanol and O_2 via the use of accelerators are proprietary. It is likely that any commercially successful technique will generate large revenues so IP is and will be closely guarded. The accelerator technology is also likely to be proprietary. However the technology for demonstration facilities may not be, particularly if funded with public funds. Once the technology has been demonstrated, we expect that commercial accelerator manufacturers will develop proprietary variants.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 7
EBFGT technology: TRL 7

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Accelerator design, construction, and operation experience.
Infrastructure: Suitable facilities for the construction and operation of high power electron accelerators. High-power electron beam test facility for process development.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab
Industrial: Accelerator manufacturers. Operators of coal-fired power plants. Natural gas producers and oil/gas R&D organizations.
Academic: Institution with experience in combustion chemistry.

Fermilab is well positioned to drive the R&D through IARC. There is considerable industrial interest.

16. What collaboration models would be most effective for pursuing joint R&D?

Models in which federal and private funds can be combined to create high power electron beam test facilities for process development. Access to laboratory staff and infrastructure via partnerships to control costs with shared IP creation and capture.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Private industry already has a partnership with Fermilab. However the lab's ability to contribute is constrained by high costs when such partnerships are carried out as WFO's with full cost recovery. Stewardship funds combined with State and Private funds could have significant leverage in moving this technology towards deployment.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. Federal grants are needed to demonstrate proof of principle and cost estimates. If this idea is judged by industry to be technically and economically feasible, and if pollution control regulations require it, accelerator makers and power plant operators should be willing to cost share at later stages of the development.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices.

20. In what ways are the R&D needs not met by existing federal programs?

We are not aware of any current US funding for this type of technology development.

The basic ideas for EBFGT have been in place for more than 20 years and several small scale demo's have shown that the technology can work. However, commercial deployment requires efficient, high power turn-key systems. The current technology state, while very promising, falls beyond that which organizations like NSF will fund (they fund Research Projects) but short of the TRL needed encourage adequate private investment. (there are some right now) Organizations like the EPA are regulatory in nature and do not fund this kind of development projects.

Without Federal funds this promising technology will continue to be developed slowly or will be developed off shore. It is likely that an EBFGT development effort launched by HEP via the Stewardship program can encourage significant investment from private industry. This in turn would attract funds from the State, DOE Fossil Energy and/or ARPA-E such that the development effort can move expeditiously to deployment.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial and economic feasibility has been demonstrated and when emissions.

22. What metrics should be used to assess the progress of a stewardship effort?

For EBFGT: Amount of NOx and SOx remaining in flue gas.
For combining CH_4, CO_2 and H_2O into methanol and O_2: efficiency and practicality of the process
For both:
TRL progression.
Process cost reduction.
Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Conservative industry attitudes to new technology. Politics associated with government-imposed requirements for pollution control.

1.3 a) Destruction of Organic Materials in Industrial Wastewater

Present State of the Technology

4. What are the current technologies deployed for this application?

Chemical treatment, heat treatment, biological breakdown, dilution

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes. Accelerator-based destruction of organic materials is known to work. Commercially it may be more effective than conventional methods since the technique allows simultaneous creation of oxidation and reduction conditions in irradiated water

6. Does the US lead or lag foreign competition in this application area?

Lag. Technology is currently being pursued in Korea, Europe, and the Middle East. The US had a technical lead in the mid 90's after a study at Miami-Dade, FL showed that electron-beam treatment can break down waterborne organic toxins such as halogenated hydrocarbons. However, this lead has been lost since no such projects have been funded or operated in the US for more than a decade.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: Obstacles remaining are reliable cost effective turn-key accelerators and reliable high power beam windows operating in harsh environments

Regulatory: Requirements on effluents to streams and rivers that demand reduced levels of organic contaminants. Use permits and accelerator radiation hazard permits for workers.

Operational: Limited knowledge of accelerator reliability in this application. Added system complexity.

Economic: Added cost of treatment system only makes sense to industry if they are constrained by regulations not to pollute water released from their site after industrial use.

8. How is accelerator technology used in the application?

Electron beam dissociates water to form H and OH radicals, which can simultaneously oxidize and reduce organics.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need high accelerator reliability at a cost that is low enough to justify use. Turnkey operation will be needed for practical application.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

Several small efforts currently exist. For example, there is a Korean effort to treat dye-contaminated waste water and a Russian effort to clean up groundwater pollution from a rubber plant. There is also an IAEA organized effort to promote this technology but currently there is no funding.

11. What are the perceived and actual market barriers for the final product?

Accelerators are new, unproven technology in this application. Alternative remediation technologies exist. Need is driven by environmental law compliance.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Expect a market for a large number of relatively inexpensive systems. Once technology has been demonstrated, we expect that commercial accelerator manufacturers will develop proprietary variants.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 7
Mobile Accelerator Technology for in-situ demonstrations: TRL 4-5
Organic contaminant destruction technology: TRL 7

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Accelerator design, construction, and operation experience.
Infrastructure: Suitable facilities for the construction and operation of high power electron accelerators. High-power electron beam test facility for process development. A site on which a high power mobile accelerator can be built, tested, and operated without the full suite of State permits.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab
Industrial: Accelerator manufacturer. Firm that generates organic chemical waste. Wastewater treatment companies.
Academic: Institution with experience in organic chemistry.

Fermilab should drive the R&D through IARC.

16. What collaboration models would be most effective for pursuing joint R&D?

Models in which federal and private funds can be combined to create high power electron beam test facilities for process development. Access to laboratory staff and infrastructure via partnerships to control costs with shared IP creation and capture.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Fermilab could provide the greatest leverage.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. Federal grants are needed to demonstrate proof of principle and cost estimates. If this idea is judged by industry to be technically and economically feasible, accelerator makers should be willing to cost share at later stages of the development.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices.

20. In what ways are the R&D needs not met by existing federal programs?

The current technology state, while very promising, falls beyond that which organizations like NSF will fund (they fund Research Projects) but short of the TRL needed encourage private investment. We are not aware of any current US funding for this type of technology maturation and development. Without Federal funds this promising technology will continue to languish or will be developed off shore.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been demonstrated. In this case a highly reliable and cost effective accelerator operating in an industrial environment is required to demonstrate risk, cost, reliability, and effectiveness. This could be accomplished with a mobile accelerator.

22. What metrics should be used to assess the progress of a stewardship effort?

Organic material destruction efficiency.
TRL progression.
Process cost reduction.
Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Conservative industry attitudes to new technology.

Nothing will be cheaper than just dumping such waste if it is allowed. The need completely depends on whether industry is required to clean up pollutants vs dump them into waterways.

1.3 b) Municipal Waste Water Treatment

Present State of the Technology

4. What are the current technologies deployed for this application?

Disinfection of sewage water after secondary treatment by ozone, chlorine, ultraviolet light, or sodium hypochlorite. Algae treatment to remove phosphates and nitrates is under development.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes. Electron beam disinfection of sewage may be less costly and more environmentally friendly than methods currently used. Electron beam systems may be much more compact, allowing their use in existing facilities. Sterilization via radiation may be ideal for systems in which subsequent inoculation by specific bacteria or algae is planned.

6. Does the US lead or lag foreign competition in this application area?

Lag. Technology is currently being pursued in Russia, Korea, Japan, Brazil, and Canada. Last effort in US started in 1988.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: Method has been demonstrated to work but process needs development. Low-cost, efficient accelerators are a key requirement. Reliable, thin vacuum windows are needed to efficiently couple the electron beam into the gas.

Regulatory: Permits and accelerator radiation hazards for workers.

Operational: Limited knowledge of accelerator reliability in this application. Added complexity.

Economic: Cost of treatment and cost of distribution of large volumes of treated water to use locations.

8. How is accelerator technology used in the application?

Electron beam kills microorganisms by destruction of DNA and removes odors by opening of rings in aromatic compounds.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need high accelerator reliability at a cost that is low enough to justify use. Turnkey operation will be needed for practical application.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

Technology is currently being pursued in Russia, Korea, Japan, Brazil, Canada. Last effort in US started in 1988; small effort by Headworks and Texas A&M.

11. What are the perceived and actual market barriers for the final product?

Accelerators are new, unproven technology in this application. Operators of municipal waste plants often are conservative and technically unsophisticated. Alternative technologies exist but added cost, and added complexity are barriers to adoption. Reliable, turn-key solutions with known costs are needed.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Expect market for a large number of systems of modest cost. Likely new IP will be created in the actual treatment system and in the areas of low cost, high efficiency accelerators. Once technology has been demonstrated, we expect that commercial accelerator manufacturers will develop proprietary variants.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 6
Water treatment technology: TRL 6

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Accelerator design, construction, and operation experience. Tests validated by reputable sources so that conservative purchasing agencies will trust claimed performance
Infrastructure: Suitable facilities for the construction and operation of high power electron accelerators. High-power electron beam test facility for process development.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab
Industrial: Accelerator manufacturer. Sewage treatment equipment manufacturer.
Academic: Institutions with an interest in biofuels or experience in public health.
Other: Large municipality with sewage treatment facilities (e.g. City of Chicago) and the desire to develop small demonstration systems into full capability treatment facilities.

DOD: It is possible that DOD might partner to fund development in this area since many naval bases are built in environmentally sensitive areas.

Fermilab should drive the R&D through IARC. Candidate for Federal, State, Municipal partnerships

16. What collaboration models would be most effective for pursuing joint R&D?

Models in which federal and private funds can be combined to create high power electron beam test facilities for process development. Access to laboratory staff and infrastructure via partnerships to control costs with shared IP creation and capture.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Fermilab could provide the greatest leverage.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. Federal grants are needed to demonstrate proof of principle and cost estimates. If this idea is judged by industry to be technically and economically feasible, large municipal waste treatment organizations and accelerator makers may be willing to cost share at later stages of the development.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices.

20. In what ways are the R&D needs not met by existing federal programs?

We are not aware of any current US funding for this type of technology development. Note that organizations like EPA are regulatory in nature so do not support this kind of development.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been demonstrated.

22. What metrics should be used to assess the progress of a stewardship effort?

Amount of contaminants remaining in treated water.
TRL progression.
Process cost reduction.
Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Conservative industry attitudes.
Industry is not technically sophisticated.

1.3 c) Contaminated Ground Water Cleanup

Present State of the Technology

4. What are the current technologies deployed for this application?

For industrial waste cleanup, pump out contaminated ground water, separate and destroy the contaminant. Techniques used include carbon adsorption, air stripping, or biological treatment.

For water supply treatment, disinfect by using chlorine, chlorine dioxide, chloramine, ozone, or ultraviolet light.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

For industrial waste cleanup, electron beam destruction of organic groundwater contaminants may reduce the cost of the treatment process. Electron beam treatment is "once through" process, after which water can be disposed of safely; other methods involve collection of contaminant or collection of water for further treatment.

For water supply treatment, electron beam disinfection may be less costly and more environmentally friendly than methods currently used: there is no need for toxic chemicals. Electron beam disinfection potentially allows use of contaminated water sources for which no other treatment alternative exists.

6. Does the US lead or lag foreign competition in this application area?

Lag for industrial waste cleanup. There was a successful effort in the former Soviet Union to use accelerator technology to clean up contaminated ground water from a rubber plant.

Slight lag for water supply treatment. Technology has been investigated in a handful of other countries. However, there seems to be little current activity in this field. Interest could increase as water shortages appear worldwide.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: The technique has been demonstrated to work, but the process needs development. Low-cost, efficient accelerators are a key requirement. Reliable, thin vacuum windows are needed to efficiently couple the electron beam into the water.
Regulatory: Permits and accelerator radiation hazards for workers.
Operational: Limited knowledge of accelerator reliability in this application. Added process complexity.
Economic: Cost of treatment vs cost of alternative treatment methods and water sources.

8. How is accelerator technology used in the application?

For industrial waste cleanup, the electron beam breaks chemical bonds in organic contaminants. Molecular fragments recombine to form less hazardous substances.

For water supply treatment, electron beam kills microorganisms by destruction of DNA. Electron beam also destroys organic molecules, such as endocrine disruptors.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need high accelerator reliability at a cost that is low enough to justify use. Turnkey operation will be needed for practical application.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

For industrial waste cleanup of contaminated ground water, no current efforts are known.

For water supply treatment the technology has been investigated in a handful of other countries. There seems to be little current activity in this field.

11. What are the perceived and actual market barriers for the final product?

Accelerators are new, unproven technology in this application. Alternative technologies exist. Added cost and operational complexity. Negative public perception of irradiated water.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Expect market for a modest number of relatively inexpensive systems. Once technology has been demonstrated, we expect that commercial accelerator manufacturers will develop proprietary variants.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 6
Water treatment technology: TRL 6

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Accelerator design, construction, and operation experience.
Infrastructure: Suitable facilities for the construction and operation of high power electron accelerators. High-power electron beam test facility for process development.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab
Industrial: Accelerator manufacturer. Water treatment equipment maker.
Academic: Institution with experience in organic chemistry. Institution with experience in public health.
Other: EPA. Municipality with potable water treatment facilities.

Fermilab should drive the R&D through IARC.

16. What collaboration models would be most effective for pursuing joint R&D?

Models in which federal and private funds can be combined to create high power electron beam test facilities for process development. Access to laboratory staff and infrastructure via partnerships to control costs with shared IP creation and capture.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Fermilab could provide the greatest leverage.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. Federal grants are needed to demonstrate proof of principle and cost estimates. If this idea is judged by industry to be technically and economically feasible, water-treatment equipment makers and accelerator makers should be willing to cost share at later stages of the development.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices.

20. In what ways are the R&D needs not met by existing federal programs?

We are not aware of any current US funding for this type of technology development.

Note that organizations like EPA are regulatory in nature so do not support this kind of development.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been demonstrated.

22. What metrics should be used to assess the progress of a stewardship effort?

Amount of contaminants remaining in treated water.
TRL progression.
Process cost reduction.
Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Conservative industry attitudes.
Industry is not technically sophisticated.

1.4 a) Municipal Sewage Sludge Treatment

Present State of the Technology

4. What are the current technologies deployed for this application?

Chemical disinfection of sewage sludge after secondary treatment.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes. Electron beam disinfection of sewage sludge makes it suitable for use as a fertilizer rather than disposing of it in a landfill. This also allows recycling of nitrates and phosphates, thereby conserving phosphate reserves.

6. Does the US lead or lag foreign competition in this application area?

Lag. Technology is currently being pursued in several countries, including India, Saudi Arabia, and Eastern Europe.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Technical: Method has been demonstrated to work but process needs development. Low-cost, efficient accelerators are a key requirement. Reliable, thin vacuum windows are needed to efficiently couple the electron beam into the gas.
Regulatory: Permits and accelerator radiation hazards for workers.
Operational: Limited knowledge of accelerator reliability in this application. Added complexity.
Economic: Cost of treatment and cost of distribution of large volumes of treated sludge to use locations vs value of created product.

8. How is accelerator technology used in the application?

Electron beam kills microorganisms by destruction of DNA and removes odors by opening of rings in aromatic compounds.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need high accelerator reliability at a cost that is low enough to justify use. Turnkey operation will be needed for practical application.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

Technology is currently being pursued in several countries, including India, Saudi Arabia, and Eastern Europe.

11. What are the perceived and actual market barriers for the final product?

Accelerators are new, unproven technology in this application. Alternative disposal methods exist. Added cost and added complexity are barriers to adoption.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Expect market for a large number of relatively inexpensive systems. Once technology has been demonstrated, we expect that commercial accelerator manufacturers will develop proprietary variants.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 6
Sewage sludge treatment technology: TRL 6

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: Accelerator design, construction, and operation experience.
Infrastructure: Suitable facilities for the construction and operation of high power electron accelerators. High-power electron beam test facility for process development.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab
Industrial: Accelerator manufacturer. Sewage treatment equipment manufacturer.
Agricultural: Potential users of produced product.
Academic: Institution with experience in public health.
Other: Municipality with sewage treatment facilities

Fermilab should drive the R&D through IARC.

16. What collaboration models would be most effective for pursuing joint R&D?

Models in which federal and private funds can be combined to create high power electron beam test facilities for process development. Access to laboratory staff and infrastructure via partnerships to control costs with shared IP creation and capture.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Fermilab could provide the greatest leverage.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. Federal grants are needed to demonstrate proof of principle and cost estimates. If this idea is judged by industry to be technically and economically feasible, oil and gas producers and accelerator makers should be willing to cost share at later stages of the development.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices.

20. In what ways are the R&D needs not met by existing federal programs?

We are not aware of any current US funding for this type of technology development.

Note that organizations like EPA are regulatory in nature so do not support this kind of development.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been demonstrated.

22. What metrics should be used to assess the progress of a stewardship effort?

Amount of contaminants remaining in treated sludge.

TRL progression.
Process cost reduction.
Value of commercial investment.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Conservative industry attitudes.
Industry is not technically sophisticated.
Public and regulatory acceptance of the use of the finished product for agriculture

1.4 b) Accelerator Driven Systems for Minor Actinide Destruction

Present State of the Technology

4. What are the current technologies deployed for this application?

Short-term storage at power plants and planned long-term storage underground.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Yes. Destruction of minor actinides can render spent fuel safe in decades rather than millennia. This may remove one major objection to the use of this carbon free energy source.

6. Does the US lead or lag foreign competition in this application area?

Lag. Technology is being actively pursued in Europe, Japan, and India.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Political: US DOE does not support ADS, as it is in conflict with breeder reactor IP owned by US companies.
Technical: Feasibility of large-scale actinide destruction via ADS is unknown.
Regulatory: Licensing of new class of nuclear facility.
Operational: Limited knowledge of accelerator reliability in this application.
Economic: Cost of disposal vs. alternatives is unknown.

8. How is accelerator technology used in the application?

Proton beam generates neutrons which are used to transmute long lived radioactive isotopes into short lived or stable isotopes.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes. The application will need very high beam power (>10 MW). The application will also need high accelerator reliability.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

Facilities demonstrating ADS for minor actinide destruction exist in in Japan, India, and Belgium.

11. What are the perceived and actual market barriers for the final product?

New, unproven technology that is likely to be very expensive (billions of dollars) to develop and demonstrate. Public resistance to transport of nuclear waste to the site for destruction.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Given cost and scope of the project, public funding will be required, which means overall technology solution is likely to be developed in the public domain. However, nuclear industry has an extensive portfolio of IP, some of which may be needed for the application.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Accelerator technology: TRL 4 - TRL 5
Accelerator driven system for minor actinide destruction: TRL 3

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Skills: High power proton accelerator design, construction, and operations experience.
Infrastructure: Suitable facilities for the construction and operation of high-power proton accelerators.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Lab: Fermilab and other DoE lab(s) with interest in reactor technology.
Industrial: No recommendations at this time.
Academic: No recommendations at this time.

Fermilab should drive the R&D through IARC.

16. What collaboration models would be most effective for pursuing joint R&D?

Federal funding to construct one or more national facilities for this purpose.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

Yes. Fermilab and a lab such as ORNL, Idaho, Los Alamos, ANL, etc.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

No since there is a low probability that a commercial entity would invest in a technology that is so far removed from commercialization unless there are other potential near-term applications.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?

Opportunities may exist for collaboration with Next Generation Power Electronics National Manufacturing Innovation Institute to increase accelerator efficiency by developing advanced power conversion devices.

20. In what ways are the R&D needs not met by existing federal programs?

The current technology state, while very promising, is not being funded by either Nuclear Physics or Nuclear Energy. The current technology state is far short of the TRL needed encourage private investment or to permit NRC licenses to be granted. We are not aware of any current US funding for this type of technology maturation and development. Without Federal funds this promising technology will continue to languish or will be developed off shore.

21. At what point in the manufacturing development cycle would external support no longer be needed?

When private industry judges that commercial feasibility has been demonstrated.

22. What metrics should be used to assess the progress of a stewardship effort?

Effectiveness of actinide removal.
TRL progression.
Progress towards commercial feasibility.

Other Factors

23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?

Regulatory environment means new designs for nuclear industry processes are very capital intensive.
Public hostility towards anything to do with nuclear waste.

Energy Environment RFI

From: Suresh Pillai <s-pillai@tamu.edu>
Sent: Sunday, May 18, 2014 12:09 AM
To: Energy Environment RFI
Subject: Stewardship RFI Comments
Attachments: Comments on Stewardship of Accelerator Technologies by National Center for Electron Beam Research, Texas A&M University.pdf

Dear Sir/Madam,
Please see attached for comments from the National Center for Electron Beam Resaerch on the Stewardship of Accelerator Technologies.

Sincerely,

Suresh D. Pillai, Ph.D.
Director, National Center for Electron Beam Research (http://ebeam.tamu.edu/)
Texas A&M University
979.845.2994
eBeam technology to clean, heal, feed, and shape this world, and beyond....

Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications

Response to Request for Information

Suresh D. Pillai, Ph.D.
Director, National Center for Electron Beam Research
Professor of Microbiology and AgriLife Research Faculty Fellow
Texas A&M University, College Station, Texas
Tel: (979).845.2994
Email: s-pillai@tamu.edu

1. What are the most promising applications of accelerator technology to:

Response: The National Center for Electron Beam Research (NCEBR) at Texas A&M University considers wastewater treatment systems as Resource Recovery Facilities (RRF), having significant pools on energy and nutrients. Thus, we view applications of eBeam technology in the area of energy and environmental applications to be of very high priority. Electron Beam (eBeam) technology has a number of applications as it relates to energy and environmental applications. Increasing volumes of industrial and municipal wastewater is a challenge that comes along with urbanization in the US and around the world. Both of these waste streams are potentially abundant sources of (alternate) energy and nutrients. The technology at the *very least* can be used to significantly enhance the efficiency of anaerobic digestion (leading to enhanced methane production), reclaim valuable nitrogen and phosphorus from sewage sludges and effluents, and can potentially *sterilize* all effluent streams that could potential impair the environment (*Pillai and Reimers, 2010*; *Praveen et al., 2013*). More recently, we at the NCEBR have started addressing the utility of this technology for water reclamation and water reuse projects. There are a number of other un-tapped commercial applications of this technology to address emerging issues of nanomaterials, pharmaceutical care personal products, endocrine disrupting chemicals and environmental toxicity. Accelerator technologies can play a pivotal role either singly or in combination with other complimentary technologies.

2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?

Response: Local, regional and federal regulatory agencies have for the most part been very supportive of technologies that involve Radiation Producing Devices (RPD) in terms of permitting and other regulatory compliance issues. For example, the US EPA has already approved the use of eBeam technology at 10 kGy as an approved process to reduce pathogens in municipal biosolids as part of the EPA's PFRP (Processes to Further Reduce Pathogens) in municipal sewage sludges. However, for the rest of the 21st century it is critical that regulatory compliance also consider the economics of the process, the value of the technology in terms of US's global competitiveness, and the ability to increase the science and technology base and infrastructure of this country. Without this incentive from a regulatory compliance stand point, commercial adoption of accelerator technologies will continue to lag behind traditional technologies given the extreme conservative nature of the energy and wastewater industries.

3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?

Response: The metrics to estimate the long-term impact of new investments in accelerator technologies should include a) new jobs creation, b) US competitiveness in commercializing these technologies, d) US workers trained to repair and service accelerator and accelerator sub-systems, d) economics of processes, e) creation of novel products and processes, f) reduction in cost to adopt technology, g) increase in number of US companies involved in accelerator technology development and manufacturing, and h) changes in public perception of accelerator technologies

Present State of the Technology

4. What are the current technologies deployed for this application?

Response: The US water and wastewater industry relies on consulting companies to either design new facilities or upgrade existing facilities. By nature, these companies are rather conservative and thus are very reluctant (other than in very special circumstances) to adopt new technologies. Though the use of accelerator technologies for environmental applications have been proposed for many decades, a vast majority of the practicing environmental engineers have very limited knowledge of the core technology or the advances that have occurred in this technology sphere. Thus, when the opportunity arises to choose technologies for the waste water industry, the default choice has been to go back to the time tested conventional technologies such as lime stabilization, heat drying, etc. These conventional technologies have a rich history of use and thus their economics are well known. Given the lack of a commercial track record for accelerator technologies in the commercial wastewater industry, it is uphill tasks to have decision makers choose accelerator technologies over the time-tested conventional technologies such as chlorination, UV disinfection, lime stabilization, heat drying, etc.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Response: Absolutely, yes. Research and economic studies conducted at Texas A&M University's NCEBR in cooperation with the Water Environment Research Foundation and private wastewater engineering companies such as Headworks Bio, Inc., have shown that eBeam technology will be a paradigm shift in terms of economics and the potential to address multiple contemporary and emerging pollution issues that the US wastewater and drinking water industry faces. Further information about the potential of eBeam technology can be found in the following citations (*Pillai and Reimers, 2010; Praveen et al., 2013; Sandberg et al., 2013*)

6. Does the US lead or lag foreign competition in this application area?

Response: Presently, the US lags behind China and Russia in the development of accelerator systems for commercial applications. There are over a dozen Chinese companies that specialize the development of eBeam and X-ray systems (ranging from low energy to high energy) for commercial applications. China already has commercial (mid to high energy) eBeam systems for treating flue gas as well as for treating wastewater. Russia is actively expanding its low to mid energy eBeam systems for the growing Asian market. Private companies in S. Korea are now partnering with Russian companies to assemble, market and sell commercial eBeam systems around the world.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

Response: A number of factors intrinsic, technical, and economic are obstacles to a rapid commercial adoption of this technology.

Intrinsic Factor: A major intrinsic factor is the lack of awareness of this technology among practicing environmental engineers. The reasons for this could be linked to the leading environmental engineering textbooks lacking any meaningful and substantial discussion of this technology. Thus it is not surprising that the graduating environmental engineers have limited understanding of the core technologies. Once they are employed, this lack of knowledge is exacerbated by widespread misunderstanding and confusion about the technology in terms of energy, power, penetration, dose, etc. There are only limited websites with accurate and reliable information about this technology. This obstacle can only be removed by targeted curricular enhancement program, continuing education, and an effective environmental engineering extension and outreach activity.

*Technical Factor*s The commercially available eBeam technologies do not have the adequate combination of power and energy to meet current wastewater industry needs. In the US, cities that have the resources to invest in eBeam technologies need technology solutions to treat solids and effluents in the 100-200 million gallons per day (mgd) scale. Currently, there are no commercial solutions for this need. Another technical issue that is an obstacle (perceived or real) is the lack of reliability of accelerators especially those that operate in the 10 MeV range. Wastewater treatment plants require significant reliability and system redundancy. There is no data whatsoever on the reliability of high energy accelerator systems that operates in a wastewater environment. Another technical issue is accelerator shielding. There has not been much advancement in shielding material research. Though there has been major advancements in materials sciences, adoption of advanced materials as shielding materials is non-existent.

Economic Factors: The upfront cost to install eBeam technology is a major barrier.

8. How is accelerator technology used in the application?

Response: Please see response to query # 1.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Response: Yes. Currently there are no commercial accelerators in the market that can meet the effluent treatment demands of large US cities. For realistic treatment scenarios the technology has to be able to address effluent wastewater volumes in the 50-200 million gallons per day range. The power and energy requirements for such applications are beyond the scope of any commercial manufacturer anywhere. Add to this the need for system redundancy. It quickly becomes obvious the cost implications of such technology adoption.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

Previous support for such applications was provided by the NSF. However, that support ended in the 1990's. Since then, the support for this technology application has been rather sporadic. The Water Environment Research Foundation supported research in 2010 in Texas A&M University at the NCEBR to provide empirical evidence that eBeam technology can address the municipal wastewater industry needs. The Water Research Foundation also supported a similar study but it focused on drinking water. In 2014, the State of Texas has provided limited funding to the NCEBR to demonstrate the value of eBeam technology for water reuse projects. Beyond these limited funding, funding is this area is severely lacking.

11. What are the perceived and actual market barriers for the final product?
Response: The perceived market barriers are that a)eBeam systems lack penetration, b) the economics are cost prohibitive, c) technology is not at all commercially feasible, d) the technology makes the water radioactive. The actual market barriers are a) lack of technology for real life high volume applications, b) up-front costs, c) lack of US technology vendors, d) lack of skilled personnel to repair and service the installations, and d) lack of effective industry outreach programs

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?
Response: Though the basic technology is open-sourced, it is highly likely that how this technology is combined with other compatible technologies to achieve the deliverables will be proprietary. There will also be IP in system and sub-system design to achieve high power/high energy combination, facility design specifications to achieve system redundancy, as well as IP in materials handling.

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?
Response: In a scale of 1-5 with 5 being the highest TRL, the technology at the present state of science is at 4.

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?
Response: There needs to be an investment in developing skilled manpower to be able to service and repair linear accelerator systems in the US. There needs to be effort spent in developing educational modules to empower environmental engineers to be equipped with state of the science information in linac technology. The DOE needs to invest in developing the technology to deliver adequate power and energy for environmental applications.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?
Response: The R&D should be performed by a consortium involving industrial accelerator manufacturers, national laboratories (to advance the technology) academic institutions (to perform the laboratory testing, validations, and manpower development), and wastewater industry partners (to provide sites for beta testing). Of course this may sound as self-serving; the National Center for Electron Beam Research (NCEBR) has been pioneering the commercialization of eBeam technologies for a variety of industrial applications for over a decade. The NCEBR has two eBeam S-band linacs (15 kW, 10 meV) and one xRay linac (18 kW, 5 Mev) and has a track record of advancing this technology around the world.

16. What collaboration models would be most effective for pursuing joint R&D?

Response: A consortium model for collaboration would be the most effective with tangible deliverables and outcome expectations.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?
Response: One such laboratory is the Illinois Accelerator Research Center which specializes in partnering with private industry in developing commercially viable accelerators.

18. Should cost sharing be considered for a grant or contract to pursue the R&D?
Response: Cost sharing may be feasible for private companies that stand to gain financially from such an initiative. However, for academic institutions and end-users such as wastewater treatment plants cost sharing can be challenging.

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI?
Response: The R&D efforts should engage with other initiatives such as NNMI so that investment in accelerator technologies could open up new job opportunities especially in economically disadvantaged areas as well as spur the development of small businesses surround this emerging market.

20. In what ways are the R&D needs not met by existing federal programs?
Response: The funding to date has not been adequate to enable technology readiness to commercially acceptable levels. The funding to date has allowed to demonstrate the value of this technology to the wastewater and drinking water industry. However, to take this technology to this next stage, investments have to be made to enable adoption by the municipalities etc.

21. At what point in the manufacturing development cycle would external support no longer be needed?
Response: External funding should taper out once one or more large scale water utilities adopt the technology and real-life data (technical, economic and environmental impacts) are obtained. Federal funding is needed to stimulate adoption of this technology.

22. What metrics should be used to assess the progress of a stewardship effort?
Response: The metrics should include a)actual installation of eBeam technology in wastewater plants in the US, b) number of US companies building commercially ready eBeam systems, c) new jobs created, d) workers trained to service and repair eBeam systems, e) private investments in environmental companies designed to exploit this technology

Other Factors
23. Are there other factors, not addressed by the questions above, that impact the successful adoption of accelerator technology for industrial purposes?
Response: The competitiveness of the US accelerator industry is at serious stake. China, Russia and S. Korea are ramping up activities to enter the wastewater industry with low cost (possibly low performing??) accelerator technologies. There are serious concerns about adequate occupational safety system training with overseas equipment manufacturers as well as system

reliability issues. If the wastewater industry is introduced to poor quality and dangerous systems and there are one or more industrial accidents, this would irreversibly push back the technology.

Cited References

Pillai, S.D. and R.S. Reimers (2010). Disinfecting and Stabilizing Biosolids using E-Beam and Chemical Oxidants. Water Environment Research Foundation Report Number U4R06, WERF Publishing, Alexandria, Virginia.

Praveen, C., P.R. Jesudhasan, R. Reimers and S.D. Pillai (2013). Electron beam inactivation of selected microbial pathogens and indicator organisms in aerobically and anaerobically digested sewage sludge. *Bioresources Technology* 144: 652-657

Sandberg, M.A. S.D. Pillai, and R.S. Reimers, (2013). "Economic Assessment of the Competitive Application for EBeam Process in the Treatment of Waste Residuals," Paradigm International, Inc. report to HeadworksBIO, Inc., Houston, Texas

From:	T. D. Waite <twaite@ferrate.biz>
Sent:	Monday, April 28, 2014 5:46 PM
To:	Energy Environment RFI
Subject:	Stewardship RFI Comments
Attachments:	DOE RFI E-beam.docx; Resume[1].pdf
Categories:	Red Category

Dear Sir/Madame:

Please find attached a copy of my comments on your RFI. I have also included a copy of my resume four information, which shows my past involvement with electron beam equipment.

I am pleased that you are considering a new initiative to “re” introduce electron beam technology to the environmental area. I have always believed this technology could contribute in a big way to field of environmental engineering.

Let me know if you need more information, or if I can help with the initiative.

Regards,

T.D. Waite

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Application Areas With High Impact

1. What are the most promising applications of accelerator technology to:

a. Produce safe and clean energy?

b. Lower the cost, increase the efficiency, or reduce the environmental impact of conventional energy production processes?

c. Monitor and treat pollutants and/or contaminants in industrial processes?

Treat contaminants in industrial processes: high-energy electrons can be utilized both for direct radiolysis, and for generating free radicals in aqueous solution. Because most industrial contaminants are present in aqueous solution, or in the gas phase that also contains water, the generation of free radicals via the reaction of electrons with a water molecule is the principal mechanism of interest. The free radicals generated are both powerful oxidants and or reductions that can attack recalcitrant organic molecules. These free radicals can treat a broad spectrum of aqueous waste, toxic sludges, and contaminated air from industry. This use of high-energy electrons should be one of the principal areas explored for use of this technology.

d. Monitor and treat pollutants produced in energy production?

High energy electrons can be utilized in a broad spectrum of pollution control applications for the energy industry. The purification of hydrocarbons for societal use generates countless toxic waste streams that are recalcitrant to normal pollution control technologies. Free radicals generated from electron beam irradiation of aqueous streams, especially the aqueous electron, are effective oxidizers or reducers of complex hydrocarbons. Electron beam technology for destruction of contaminants should also find widespread use in the burgeoning natural gas industry.

e. Increase the efficiency of industrial processes with accelerator- or RF/microwave-based processes?

f. Treat contaminants in domestic water supplies and waste water streams?

A significant amount of research has already been undertaken defining the efficacy of water and wastewater treatment utilizing high-energy electron radiation. A large body of comparative research exists that evaluates differences between high-energy electron beams and radioactive isotopes for irradiating waste waters. While some differences in treatment efficiency exist, based on the rate radiation can be delivered to a wastewater source, the principal result of the research has been that radioactive isotopes are too expensive to utilize at large-scale, and the public is not comfortable handling them. Therefore electron beam accelerators are the preferred form of radiation generation. From a treatment point of view high energy electrons, as well as the free radicals generated by the reaction with water molecules can effectively: disinfect water and wastewater, oxidize recalcitrant organics to a more environmentally acceptable form, reduce halogenated organics to non-toxic forms, and break strong complexes of organics and toxic metals thereby rendering the metals vulnerable to precipitation from solution. In addition, high-energy electrons can disinfect and cause chemical reactions in solutions with high concentrations of suspended solids (wastewater sludge).

g. Treat contaminants in the environment at large (cleanup activities)?

High-energy electrons have been demonstrated to be effective de-contaminants of hazardous waste sites. There are limited technologies available to produce a powerful oxidation (or reduction) capability against many of the toxic industrial compounds contaminating sites around the world. While utilization of this technology would require a pump and treat installation, the technology is capable of effectively cleaning hazardous waste sites.

h. Produce alternative fuel sources?

i. Address critical environmental or energy related issues not already mentioned?

2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?

Regulators at all levels require substantiated proof that a new technology is a cost-effective solution to an environmental problem. This is a tedious process, and usually is the main deterrent to

development of new environmental technologies. Regulatory authorities should be proactive in promoting new technologies that have been shown, at a reasonable level of reliability, to achieve defined treatment goals. This means that regulatory authorities should advocate the utilization of new technologies, and allow variances in permitting of treatment facilities while operating a new technology.

3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?

For Each Proposed Application of Accelerator Technology

Present State of the Technology

4. What are the current technologies deployed for this application?

Many, possibly competing technologies are utilized in environmental applications. High-energy electron beams would compete most directly against other oxidation and disinfection processes.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Accelerator technology does have the potential to revolutionize environmental treatment processes. While many applications of this technology to environmental problems have been demonstrated, even at full scale, the industry itself was not well developed enough to actually enter the environmental treatment arena. Specifically, high current low-energy machines were not readily available at a reasonable cost, therefore the unit cost of water or wastewater treatment was very high when using this technology. Recent advances in the production of low-cost, high current machines means that this technology can now become more cost-effective. In addition many difficult to treat environmental problems have evolved that cannot be addressed with current environmental technologies. High-energy electron beams would be highly competitive for treatment of: toxic groundwater and sludge, landfill leachate, domestic sludge for land application, and countless site-specific industrial applications.

6. Does the US lead or lag foreign competition in this application area?

The US was the leader in demonstrating the environmental applications of high-energy electrons, including the formation of several companies who attempted to enter the field as a business. Over the past 20 years little if any research has been done in this area in the US. In terms of generation of appropriate machines for generating high-energy electrons for this application, the US lags countries such as Korea, Russia, and China.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

The principle obstacles to development of this technology for environmental applications are technical, and economic. From a technical point of view machines required for this application are relatively low voltage (1-2 MeV), but high current (500 ma). Unfortunately, while much industrial research has developed new and efficient accelerators, this work has focused on high-voltage (> 10MeV) low current machines such as LINACS. Machines appropriate for water and wastewater treatment are still not readily available in the marketplace. In addition, high current accelerators are expensive, making the unit cost of water or wastewater treatment quite high. However, the ability of high-energy electrons to destroy recalcitrant organics means that this technology will not have much competition in the environmental arena, regardless of cost.

8. How is accelerator technology used in the application?

See 1 C above

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Yes .... See #7 above

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

Research concerning application of high-energy electrons to water and wastewater systems has ceased to exist over the past 15 years. Also, no real effort has been made to create electron accelerators specifically designed for water and wastewater treatment. The efforts required to

develop this application will be: revive an active research program for environmental applications demonstrating the use of high-energy electrons for selected environmental applications, work with industry to develop an inexpensive low-voltage high current accelerator specifically for environmental applications, and support research on the design of high-efficiency water delivery systems for electron beam irradiation.

11. What are the perceived and actual market barriers for the final product?

The perceived market barriers for this technology initially will be the high capital cost of electron beam generators. This means that a potential client will need to invest large sums of money upfront before a system is even installed and operational, with no guarantees. Another barrier to the market of this product is that very little full-scale treatment efficiency data from electron beam irradiation is available.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Many aspects of the design, and fabrication of electron beam accelerators to be used for water and wastewater treatment would be proprietary, and could be easily protected by patents. In addition, treatment or application patents could also be issued. The concept of generating high-energy electrons, of course would not be proprietary, nor would the radiation chemistry associated with electrons reacting with water.

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

The present technology readiness levels of accelerator technology for environmental applications is very low. As noted above machines that will be utilized for this application do not really exist at this point. However, several machine geometries come close to being utilizable at this time (curtain machines, and ICT machines)

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Both skill and infrastructure would be needed to develop prototype

machines that could be used for environmental applications. This could be done by creating cooperative programs within DOE and selected industries. The application of high-energy electrons for solving selected environmental application would require skills from the environmental engineering discipline, and the infrastructure of a full-scale electron beam facility that was designed to handle large quantities of water, wastewater, and hazardous waste. While there are several electron beam research facilities located in the US, none of them contain machines which would be utilized in an environmental application; therefore useful demonstration of this equipment along with projected costs for environmental applications is not possible.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

Because the principal constraints to development of this technology (as described above) include creation of an efficient least cost electron accelerator with the capacity to treat large volumes of water, and the demonstration of this technology at a large-scale for appropriate environmental challenges. This suggests that the correct mix of institutions would be: academic (environmental engineering, radiation chemistry, mechanical/nuclear engineering, and radiation physics), industrial (electron beam manufacturer with experience on building low-voltage high current accelerators), DoE laboratory, and USEPA. The driver could be the DoE laboratory.

16. What collaboration models would be most effective for pursuing joint R&D?

See above

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

See Above. Argonne ?

18. Should cost sharing be considered for a grant or contract to pursue the R&D?

Yes. From Industry

19. How should R&D efforts engage with other innovation and manufacturing initiatives, such as the NNMI? [7]

Any manufacturing initiatives such as NNMI or NSF's GOALI could easily

be added to this large electron beam initiative. In these cases institutions along with their industrial partners would join in the overall project and provide components that would focus on accelerator equipment design and fabrication.

20. In what ways are the R&D needs not met by existing federal programs?

While some federal programs for R&D cover the development of innovative technologies for environmental use, they focus on the academic component of the technology itself. In order to develop a new technology for environmental application a significant amount of support is needed to actually bring promising technologies to the marketplace. Existing federal programs do not support the demonstration of innovative technologies at a scale sufficient for market development.

21. At what point in the manufacturing development cycle would external support no longer be needed?

Once a prototype of an electron beam system designed for environmental applications is created, and protection is in place then continued external support for manufacturing and development should not be needed. Support for moving the concept into the marketplace would then be needed.

22. What metrics should be used to assess the progress of a stewardship effort?

The metrics utilized to assess the progress of a stewardship effort would be based on progress towards the creation of a new electron beam accelerator system for environmental applications, and the development of science-based results demonstrating the treatment efficacy of high-energy electrons.

Energy Environment RFI

From: Dolgashev, Valery <dolgash@slac.stanford.edu>
Sent: Monday, May 19, 2014 8:05 PM
To: Energy Environment RFI
Cc: Hettel, Bob; Tantawi, Sami
Subject: Stewardship RFI Comments
Attachments: Stewardship of Accelerator Technologies Radiology Linacs Dolgashev Hettel 19may2014.pdf

Hi Eric,

I attached comments on "Compact Accelerators for Non-destructive X-ray Imaging as a Replacement for Isotope-Based Radioactive Sources".

Taking into account our experience with making "microlinac" and recent work on new types of efficient accelerating structures, this may be a program with clear goals and deliverables.

Best regards, Valery

Compact Accelerators for Non-destructive X-ray Imaging as a Replacement for Isotope-Based Radioactive Sources

V.A. Dolgashev, SLAC, 19 May 2014

Abstract:

Industrial isotope-based radiography sources are portable, used in remote sites with little supervision as compared with the nuclear industry or hospitals. This makes them easy to steal, after which they might be used for deleterious purposes, such as making "dirty bombs." Such sources could be replaced with compact electron linac sources which have no residual radioactivity and don't need infrastructure of storing, transporting, guarding and disposing of radioactive materials.

2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?

Isotope-based radioactive sources are reliably inexpensive to acquire and maintain. But these expenses do not include the potential economic effects if a source is stolen or mishandled. An example of economic disaster associated with a mishandled source is the accident that occurred in 1987 at Goiânia, Brazil. Government regulations that tax the use of isotope-based radioactive sources to counteract these eventualities could make compact linac sources an economically viable alternative to isotope-based sources.

4. What are the current technologies deployed for this application?

Industrial radiography sources use isotopes such as Ir^{192}, Cs^{137}, Tm^{170}, and Co^{60}. The Ir^{192} sources, typically 30 to 150 Ci, consist of the actual source inside a portable depleted U shield and a deployment mechanism. They are inexpensive, costing roughly $10K initially for the source and shield mechanism, and then $1.5K for a "reload" several times each year.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Isotope-based radiography source cannot compete with linac in safety: when linac is switched off there is no radioactivity.

6. Does the US lead or lag foreign competition in this application area?

As for now, the cost of compact linacs is prohibitive for use as a replacement to isotope-based sources anywhere in the world.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

The main obstacle to adopting this technology is economical. Inexpensive linacs require investments into the industrialization of linac technology to make them cost-competitive with isotope-based sources. Without government programs that promote the linacs as being inherently safe and incentivize their use, private industry is unlikely to invest in R&D to make them cheaper.

8. How is accelerator technology used in the application?

A linac-based radiography source is a compact accelerator in which a ~1 MeV electron beam is collided with tungsten target to produce X-rays. The X-rays then penetrate the object under inspection and are registered on a film or imaging detector.

9. Does the performance of the accelerator (technical, operational, or cost) limit the application?

Cost is the limiting factor. Currently compact linacs are sold for between 100k$ and 1000k$. To be competitive, the industrially produced linac should cost about 10k$. Marine radar is an example showing that it is possible to produce devices of similar complexity at acceptable prices.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

There are industrial and medical applications that use compact linacs in US, Japan, China and Europe. But none of them have focused on producing linacs inexpensive enough to be cost-competitive with isotope-based sources.

11. What are the perceived and actual market barriers for the final product?

Current price per linac is main market barrier for the product.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Unless developed and kept open by the government, the details of the design would be proprietary.

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

Compact linacs exist; innovations are needed to industrialize their manufacture in a less expensive way.

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

National laboratories like SLAC have the skill and infrastructure to realize linac source prototypes. Collaboration with outside partners is needed to industrialize production.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

National laboratories should drive R&D.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

This problem is a good fit for DOE accelerator laboratories as SLAC, Fermilab, or BNL.

20. In what ways are the R&D needs not met by existing federal programs?

To my knowledge, there is no effort to produce inexpensive linacs for radiography in existing federal programs.

21. At what point in the manufacturing development cycle would external support no longer be needed?

As soon as linac sources are cost-competitive with isotope sources (with or without "safety tax" on isotope sources) the external support would not be needed.

22. What metrics should be used to assess the progress of a stewardship effort?

The metric could be set of successively improved prototypes from a national laboratory and the cost of the industrialized version from industry.

Energy Environment RFI

From: William Graves <wsgraves@MIT.EDU>
Sent: Monday, May 19, 2014 1:12 PM
To: Energy Environment RFI
Subject: Stewardship RFI Comments
Attachments: Stewardship RFI comments-Graves.docx

Dear Dr Colby,
Our comments in response to the Stewardship Energy and Environment RFI are contained in the attached Word document. They contain information that is partly attributable to colleagues who participated in a recent workshop. The relevant comments and authors are noted in the doc.
Please feel free to use these comments for internal DOE discussion, but we should obtain our colleagues permission to make them publicly available. Please let me know when these comments will be made public.
These permissions should not take us long to obtain.
Thanks,
Bill Graves

--

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Submission to DOE HEP Request for Information on Accelerator Technologies for Energy and Environmental Applications

May 19, 2014

This submission identifies the accelerator technologies needed to produce a new generation of intense and compact x-ray light sources (CXLS), and the impact that these compact light sources can have on energy and environmental applications. The CXLS is based on inverse Compton scattering and produces synchrotron-like x-rays with flux and brilliance many orders of magnitude higher than today's best laboratory-scale sources. Today there is an enormous gulf between the x-ray performance of the large synchrotron and FEL facilities at national labs, and the small scale x-ray sources commonly available in industrial and academic labs, but the individual technologies to span this gap with a new generation of x-ray sources are within reach and derive from recent research in high gradient accelerator structures and short-pulse, high average power lasers. The proliferation of modern x-ray science beyond the boundaries of the national labs will have a large societal impact in energy and environmental applications.

X-ray beams are our most powerful probe for the structure and function of materials that are of fundamental importance to energy and environmental technologies such as development of organic photovoltaic materials, membranes for water purification, new catalysts important to industrial processes and processing of natural gas and petroleum products with increased efficiency and reduced polluting side products, and mineral morphology for enhanced oil and gas extraction. However, the ability to study these topics with modern x-ray methods currently requires travel to the major x-ray facilities at national labs. The wide availability of small sources, their ease of use and incorporation into the academic and industrial labs where the development of new energy technologies occurs, and their capability to test new ideas without the barriers of schedule, travel, and expense of the major facilities are features which are very attractive. Yet the best x-ray sources available to scientists and engineers in industrial and academic labs are some 10-12 orders of magnitude less brilliant than the major facilities and cannot take advantage of modern methods in x-ray science. The huge gulf in x-ray performance between today's rotating anode sources and synchrotrons is akin to the difference between computing with an abacus and running a supercomputer. What is needed is a laptop-equivalent that can proliferate the advanced methods developed at the synchrotrons into the industrial and academic labs that are producing breakthroughs in energy production and waste reduction.

Application Areas With High Impact

1. What are the most promising applications of accelerator technology to:

a. Produce safe and clean energy?

X-ray techniques are widely used to characterize the complex absorber and transparent conductor materials that make up photovoltaics (PV) as well as their processing. Thin film and 'emerging' solar cells are possible replacements for the presently used Si cells and offer the potential for lower cost and energy intensity for manufacturing. These include absorbers such as CIGS, CdTe, CZTS, organics, and the recent exciting new hybrid perovskites ($CH_3NH_3PbI_{3-x}Cl_x$).

X-ray diffraction provides important insight into the evolution of crystalline phases (reaction pathways) of PVs during annealing. The x-ray data can then be used to tune or adjust the processing to obtain the more desired phases. Since these films are typically a few microns thick and the annealing rates are slow (degrees/minute), CXLS-based diffraction can be used to follow such processing in real time during manufacturing.

Organic photovoltaics (OPV) are another possible emerging PV technology that may be extremely cheap, due to newspaper like printing of the cells, and can be deployed on flexible substrates, enabling presently unimaginable applications. The OPV structure consists of a blend of polymer donor and typically a fullerene or small molecule acceptor. These spontaneously separate into pure polymer (often semi-crystalline), pure fullerene, and mixed fullerene intimated mixed with amorphous polymer. The precise manner of this separation (domain size, connectivity, purity) and the packing of molecules within the three domains crucially affects the OPV performance. These morphological questions are readily addressable with both small angle x-ray scattering (SAXS) and x-ray diffraction. Given the 100-200 nm thickness of OPV films and the grazing incidence geometry used, CXLS-based SAXS and diffraction can be readily used to address these questions. These characterization approaches also provide structural information during thermal and solvent based processing.

Perhaps the most significant developments in the use of x-rays in research on materials for sustainable energy are measurement methodologies conducted in-situ and operando. These techniques enable researchers to actually watch how functional materials form (synthesis) and operate (function), including degradation. The methods are generically applicable to a huge variety of materials, including batteries, catalysts, photovoltaics, and efficiency materials (e.g, smart windows).

Note: This material is partly based on a talk by Michael Toney, Stanford University

b. Lower the cost, increase the efficiency, or reduce the environmental impact of conventional energy production processes?

It is a general challenge to extract a larger fraction of crude oil than is presently possible from carbonate reservoirs. It is important to characterize by computed x-ray tomography the connectivity and size distribution in three dimensions of the pore-space in the oil-containing rock with a spatial resolution ranging from tens of nanometers to tens of micrometers. Also the surface structure and the chemical composition of the pore-surface are of great importance, and x-ray tomography is an invaluable tool together with more fundamental studies of prepared model surfaces using x-ray reflectivity and diffraction. The materials involved are often proprietary and so having an instrument located directly in an industrial lab is important.

Conventional CT scanning instruments presently available are limited to a spatial resolution of order one micrometer, and the data acquisition time for just one sample is typically 10-20 hours. A spatial resolution of ~200 nm could be achieved with a CXLS source with an acquisition time of ~1 minute. In general for the investigation of bulk properties and buried interfaces as well as 3D strain mapping high energy (>60 keV) x-rays are of great advantage. It is not only the high penetration power but also the possibility to collect diffraction data at very high momentum-transfer which allows, for example, very precise determination of the structure of liquids and amorphous materials. Because the scattering is concentrated in a rather narrow cone large sections of reciprocal space can be imaged at high resolution with standard area detectors. In alloys, for example, one obtains a full picture of long and short range order from a few images of the diffuse scattering. With intense x-ray sources one thus can follow processing of such materials on relevant time scales. Another example is in-situ studies of the propagation of water in oil filled granular matter.

Note: This material is partly based on a talk by Theis Ivan Solling, Maersk Oil

e. Increase the efficiency of industrial processes with accelerator- or RF/microwave-based processes?

X-ray methods have played a key role in the development and characterization of heterogeneous catalysts used in a broad range of industrial processes. X-ray techniques are especially versatile for the examination of catalysts under reaction conditions, i.e. high temperature, high pressure in a reactive gas, due to the high penetration power of x-rays, the tunability of the x-ray energies over a broad range, and the possibility to collect data with high temporal and spatial extent. Many relevant properties such as elemental composition, chemical state, interatomic bond distances, particle sizes and size distributions can be revealed by absorption spectroscopy (EXAFS) and diffraction (SAXS/WAXS). In combination with laboratory-based techniques such as XAFS/Raman and XAFS/IR-spectroscopy there have been numerous specific examples of important improvements of catalyst performance based on such investigations. Pore characterization is of crucial importance for heterogeneous catalysts, because the reactants and products have to be able to enter and exit the catalytic active sites present within the pores. X-ray tomography is well suited to study the pore system of a catalyst and crack formation in catalyst tablets on various length scales.

Regarding the CXLS, the relatively broad energy bandwidth is of particular advantage for absorption spectroscopy since the entire EXAFS spectrum may be obtained in a single exposure on an area detector without any optical element in the beam line. The small source size combined with collimating optics make SAXS studies particularly potent, because the relatively broad energy bandwidth enables a flux comparable to that from large facilities, but with the source located within the industrial labs where the process development takes place.

Note: This material is partly based on a talk by Alfons M. Molenbroek, Topsoe

f. Treat contaminants in domestic water supplies and waste water streams?

Water purification and water waste treatment are two of the most important challenges of the 21st century. Development of new membrane technologies, including the use of aligned carbon nanotubes, bio-based water channels, and nano-composite barrier layers with interfacial water channels, suggest promising new possibilities for low-energy purification to replace high-energy consuming evaporative processes.

The fabrication of nanofibers can be accomplished by a variety of methods, including electro-spinning and a combination of chemical/mechanical processes, especially for cellulose, as a form of green sustainable resource material. Advances in electro-spinning and fundamental synchrotron x-ray scattering studies on nascent cellulose crystals have provided the insight needed to use the fibrous format with varying pore sizes for applications from micro-filtration via ultra-filtration to nano-filtration and reverse osmosis.

The composite mats forming the membrane contain fibers with diameters ranging from sub-nanometer up to several micrometers and the membrane performance is closely related to dimensions of the fibers and their size distribution. Small angle x-ray scattering (SAXS) and electron microscopy (TEM) are the indispensable and complementary methods to obtain this information. The CXLS is particularly well suited to SAXS because it has a small source size, which can be transformed by x-ray optics to a small angular divergence, and an x-ray beam intensity comparable to that available at large facility SAXS instruments, due to its few percent bandwidth.

Note: This material is partly based on a talk by Benjamin Hsiao, Stonybrook University

For Each Proposed Application of Accelerator Technology

4. What are the current technologies deployed for this application?

The current technologies are either x-ray tubes based on rotating anodes that are compact and widely used in industrial home laboratories, or large $billion scale facilities at the national labs. The performance of the x-ray tube matured decades ago and is fundamentally limited to relatively low brilliance by the method of bremsstrahlung production. The large facilities will always have the best performance but require that the experiment be scheduled in advance and brought to the synchrotron, conditions that inhibit widespread industrial production and serendipitous scientific discovery.

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

Recent advances in high gradient linac design at SLAC are ideally suited for very small (~1 meter long), bright electron linacs with very high efficiency. The small size and high efficiency enable use of low power RF sources with a single small klystron resulting in a total cost and size that is similar to common analytical lab equipment while providing x-ray performance that is many orders of magnitude beyond the x-ray tube and approaches the brilliance and flux of a bending magnet beamline at a synchrotron. Placing such sources into manufacturing facilities and academic labs is not possible today, but will be enabled by this R&D, and will have a revolutionary impact on many areas of science and technology.

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

There are no important technical, operational or regulatory hurdles to adopting the technology. The recent development of the high efficiency RF structures significantly reduces its cost, making the device economically competitive. The novelty of the approach demands a prototype demonstration to prove that the x-ray output can meet its performance goals before it is widely adopted.

8. How is accelerator technology used in the application?

A compact linac produces a high-brightness electron beam that generates x-rays via ICS. There are several key technologies involved including the RF cavity design, solid-state high power, high repetition rate modulator and compact klystron, automated controls, and diagnostics to measure and feedback on the high brightness electron beam properties. The accelerator is placed directly into the laboratory or manufacturing facility where the environmental work is performed.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

Each of these topics are critical. The technical accelerator performance, particularly its high efficiency, excellent stability, and high repetition rate are required in order to meet the x-ray production goals. A compact source is designed to operate in a commercial or academic setting and must be highly automated and operationally simple to run with a small staff. In order to have the greatest impact the cost should be as low as possible while meeting the performance goals.

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

X-rays generally are widely used as a probe of structure and function of materials important to energy and environmental applications described above. There are several efforts worldwide to demonstrate ICS x-ray production including private industry (Lyncean Technologies, which produces a small ring-based ICS source), a collaboration in France (ThomX), efforts at LLNL to produce high energy gamma rays for nuclear applications, low repetition rate experiments at BNL, and efforts at KEK and other labs in Japan. However none of these efforts combine the high brightness electron beam, compact size, high repetition rate, and low cost that is possible with the latest developments in linac technology.

11. What are the perceived and actual market barriers for the final product?

The capital and operating costs, size, operational complexity, reliability, and staffing needs are all important to the market success of a compact x-ray source based on accelerator technology. The physics and engineering of the device are relatively straightforward but it is important that a significant effort is made to transition the technology to a size, and level of complexity and reliability that a broad base of academic and industrial users who are not accelerator experts can purchase, install in existing labs, and maintain.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

The linac, laser and laser cavity, and x-ray optics will all have proprietary elements, some developed with federal funding. The basic physics of ICS are non-proprietary.

<u>Defining the Stewardship Need</u>

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

The linac technology is at TRL 3: active R&D is initiated.

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Existing national lab engineering and manufacturing facilities can advance the linac technology. Expertise in ICS x-ray source physics, high power lasers and x-ray optics and science that resides within academia is needed to advance to a full CXLS prototype.

15. What mix of institutions (industrial, academic, lab) could best carry out the required R&D, and who should drive the R&D?

The RF cavity design and small klystrons powered by solid state modulators are appropriate for development at a national lab and in industry, possibly through the SBIR program. The integration of the accelerator with lasers and x-ray beamline elements into a functional prototype x-ray source should be done at a university outside of the national lab setting to show that this approach is viable. The demonstration of the x-ray science relevant to energy and environmental applications should be demonstrated by both academic and industrial partners on the prototype device.

16. What collaboration models would be most effective for pursuing joint R&D?

An integrated project with the accelerator development carried out at a national lab and the x-ray source design and integration done at a university will be most effective. The integration should be done outside of a national lab to show that a large staff of accelerator experts is not required to operate and support the device.

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

The accelerator technology has been primarily developed within SLAC's x-band high gradient research. SLAC remains the most capable developer of high performance copper linac structures and should produce one or more prototypes. Quantity manufacturing should be transferred to industry.

20. In what ways are the R&D needs not met by existing federal programs?

There is no federal R&D program currently addressing development of high-performance compact light sources.

21. At what point in the manufacturing development cycle would external support no longer be needed?

Numerous labs and industrial partners have indicated strong formal interest in obtaining a CXLS after a prototype device successfully demonstrates its performance goals. External support would no longer be needed after the prototype demonstration, which could occur within 3 years of initial funding.

22. What metrics should be used to assess the progress of a stewardship effort?

Successful production of the high efficiency linac, then production of a prototype CXLS and demonstration of its x-ray properties. Finally the device should succeed in the marketplace and be transferred to industrial production.

Colby, Eric

From: Wim Leemans <wpleemans@lbl.gov>
Sent: Monday, May 19, 2014 1:37 PM
To: Colby, Eric
Cc: Siegrist, Jim; Gillo, Jehanne; Murphy, James; Farkhondeh, Manouchehr; Lessner, Eliane; Soren Prestemon; Thomas Schenkel
Subject: Re: Request for Information on Accelerator Technologies for Energy and Environmental Applications
Attachments: Response to DOE HEP RFI on Accelerator Stewardship-May14-2014.pdf

Dear Eric,

Attached is input per your request for EERE relevant applications. We have not included EUV-FEL as an application although some of the developments we list would be of benefit to the recent interest of building very high average power FELs operating at 13.5 nm for the lithography industry.

Please let me know if you need anything else at this point. I look forward to your feedback.

With best regards,

Wim

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On Apr 21, 2014, at 8:58 AM, Colby, Eric <Eric.Colby@science.doe.gov> wrote:

> Dear Colleague,
>
> We wish to call your attention to a Request for Information (RFI) that has posted in the Federal Register.
>
> DOE's Office of High Energy Physics is asking for community input on opportunities for developing particle accelerator technologies that address challenges in Energy and Environmental applications. This input will be valuable as we consider opportunities for inclusion in a potential future funding opportunity under the Accelerator Stewardship program.
>
> The RFI may be found at: https://federalregister.gov/a/2014-08846.
>
> Please consider providing your input, and forward the RFI to potentially interested parties.
>
> We look forward to a robust community response.
>
> Eric R. Colby, Ph.D.
> SC-25 Office of High Energy Physics
> Office of Science
> U. S. Department of Energy
> (301)-903-5475

May 19, 2014

Input in response to DOE HEP RFI on Accelerator Stewardship, Accelerator for Energy and Environment

Soren Prestemon, Thomas Schenkel, Wim Leemans

Lawrence Berkeley National Laboratory

Below, we highlight a series of exciting accelerator R&D areas with different levels of maturity and technology readiness levels that we believe could be promising areas of investment for the Accelerator Stewardship program.

1. Superconducting coatings in RF accelerator structures for energy savings
   a. RF-accelerator structures are widely employed in the DOE complex and in industrial applications. Significant cost savings and performance enhancements would come with mature superconducting RF technology, in particular when expensive bulk niobium structures could be replaced with reliable niobium coatings. Bulk Nb based SC RF is being developed and deployed commercially and we have been in contact with industrial partners. We suggest the development of Nb coating technology for SC RF as a development area for the Stewardship program. An aggressive future step is the leap to coatings based on high temperature s superconductors that could operate at liquid nitrogen temperatures.
2. Mini-accelerators for environmental monitoring
   a. Combining advances in MEMS and NEMS (micro- and nano-electromechanical systems) with miniaturized accelerator components (electron and ion sources, beam transport and detection) can enable novel sensors for environmental monitoring, such as miniature mass spectrometers and chip based accelerators. Connecting networks of reliable sensors enables more accurate monitoring of trends e. g. in gas emission or in support of logging operations. We suggest that investing in this area can lead to advanced sensors and instruments with increased performance and reduced cost. The opportunity can be realized by tapping into currently disconnected areas of expertise in accelerator physics (including modeling and simulation), micro- and nano-fabrication and environmental science. While simple proof-of-concept devices have been demonstrated, we see a significant development opportunity when expertise in these areas is connected in a stewardship program and in close connection with industrial partners. The resulting developments also promise to benefit HEP's core mission of discovery science e. g. through the invention of novel instrumentation that enhances the performance of accelerator facilities.
3. Intense Ion Beams for Energy and Environmental R&D
   a. We see this area is in a lower TRL category but we see significant application potential in Energy and Environmental topics because of recent advances. Short pulse ion beams enable pump-probe type studies with ion beams as the pump or excitation pulse. This allows us for the first time to track radiation damage evolution on short time scales, e. g. on

pico to nano seconds. While electronic effects from radiation have been tracked in situ for a long time, understanding the evolution of lattice damage has not. We believe that investment in this area can greatly benefit the basic understanding of radiation damage in areas such as biological systems, space electronics and nuclear materials. Furthermore, in collaboration with industrial partners, materials with tailored responses to radiation can be engineered, e. g. for nuclear waste storage or advanced structural materials for use in high radiation environments. The technological basis for these ion-beam based pump-probe experiments is two-fold: a) induction linacs with drift-compressed ion beams, and b) ion beam pulses from laser-plasma acceleration. We suggest that investment in this area will lead a) to advances in our basic understanding of the limits in our ability to control intense ion beams, b) it will boost our fundamental understanding of lattice damage evolution and its interplay with electronic excitation effects, and c) it will enable the development of advanced materials e. g. for next generation nuclear fuels, reactor components, waste storage and radiation tolerant electronics. Two promising energy applications of intense ion beams are Accelerator Driven Systems (ADS - the accelerator based transmutation of nuclear waste and power production in critical or subcritical fission reactor systems) and inertial confinement fusion with Heavy Ion drivers (HIF, Heavy Ion Fusion). Advances in this area would also greatly benefit the HEP investment in the Intensity Frontier.

4. Application of high-field magnet technology for the processing of industrial flow-streams
    a. High Gradient Magnetic Separators (HGMS) have been in use in industry since the 1970's. The last decade has seen resurgence in interest in the use of HGMS systems for industrial processes, including areas as diverse as ore separation, industrial waste sludge treatment, industrial bioprocessing, high-level radioactive waste treatment, and magnetic cell-separators. Key to this resurgence is the ability of industry to produce reliable magnets with multi-Tesla fields. An alternative technique, Open Gradient Magnetic Separation (OGMS), utilizes for example quadrupole fields to provide radial separation of magnetic particles in flow streams. Both techniques require magnet technologies, and both would benefit from existing HEP high-field magnet technology. In particular, HEP high field quadrupoles and high-field large bore dipoles and solenoids are applicable to these processes and may significantly impact the scale and efficiencyies of the processes. There is excellent overlap between HEP needs and industry needs in both large and small-scale magnet systems:
        i. For large-scale magnets, up-front cost-reduction is critical both to HEP and to industry, particularly for application to large-scale industrial waste processing,
        ii. For small-scale, high-field and/or high-gradient magnet systems, developments may be relevant to HEP areas such as laser-plasma accelerators and mini accelerators; such magnet systems may be ideal for future industrial applications in biology, in particular for cell-separators.