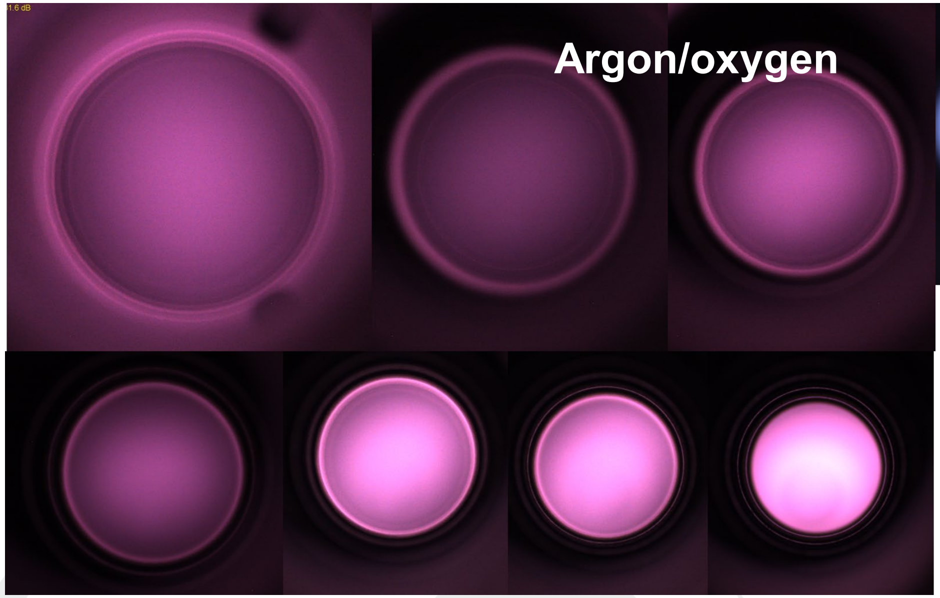
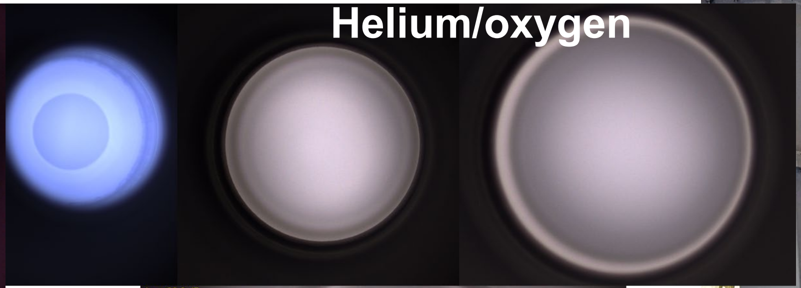
An Overview of Plasma Processing of SRF Cavities at JLAB



C100 Cavity, Cells 1, 2, 3, 4, 5, 6, 7



Cells 7, 5/6, 4/3, 2/1

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DOE NP PI exchange Dec. 2, 2024

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JSA

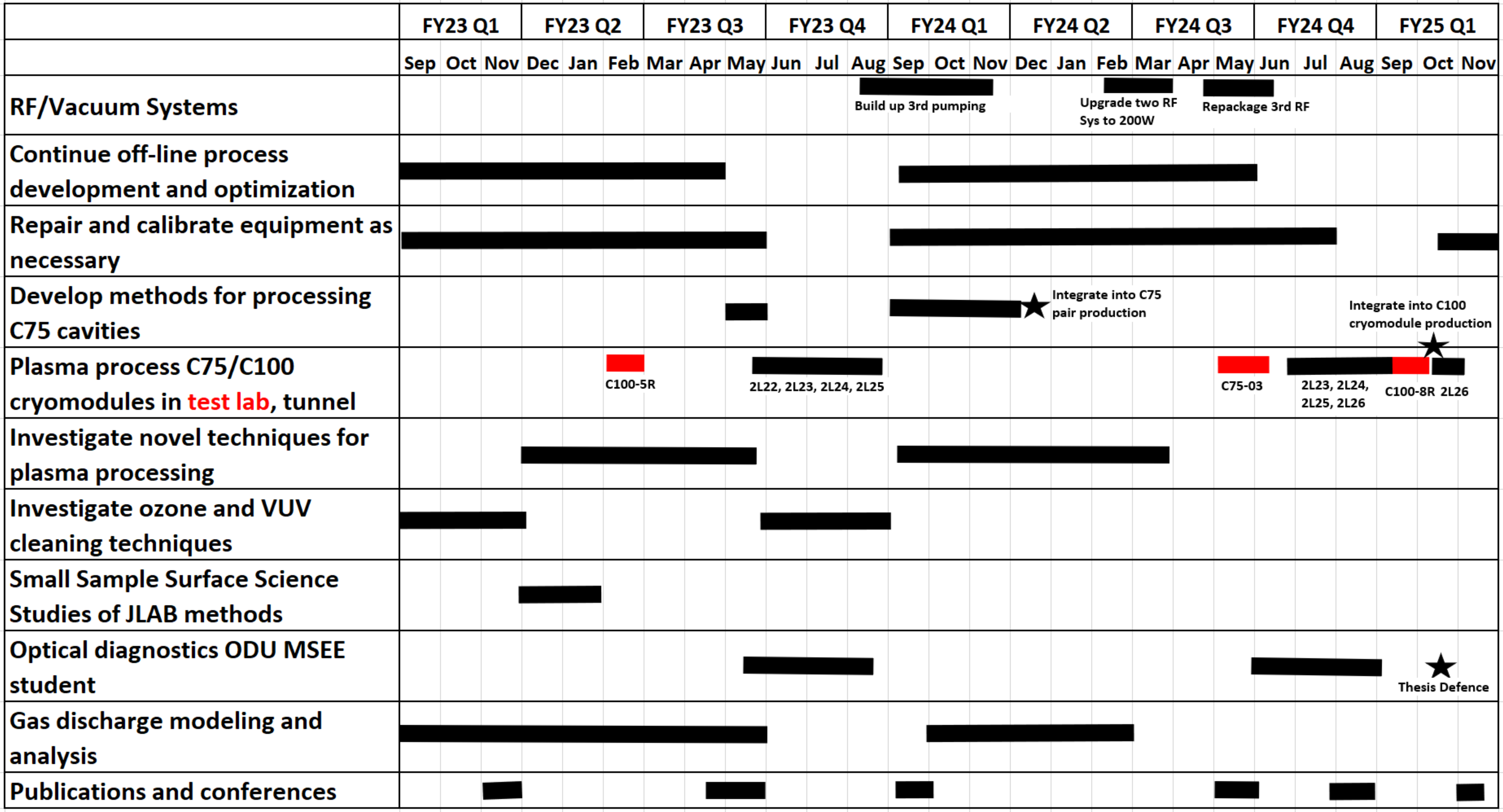
Description of the program

- **Work done using JLAB internal accelerator R&D funds prior to this award demonstrated that we could establish and control the plasma generation in a CEBAF C100 cavity on a cavity-cell basis. Additionally, we used DOE R&D funds awarded in FY19, to build up a minimal set of hardware in support of the experimental program. As stated in the FOA proposal, these previously awarded funds were used to supplement this award in FY20.**
- **The program described in this presentation allowed JLAB to**
  - **Add more RF and vacuum hardware so that we can process up to 2 cryomodules in-situ simultaneously.**
  - **Train more staff for processing cryomodules in the CEBAF.**
  - **Continue the vertical (cold cavity) testing program.**
  - **Process cryomodules in the SRF test lab and in the in situ in the CEBAF accelerator, 92 cavities in 12 cryomodules.**
  - **Preform simulations for understanding the gas dynamics of a plasma in CEBAF cavities.**
  - **To develop methods for in situ processing C100 and C75 cavities.**
  - **To investigate novel techniques for ignition of plasmas in SRF cavities at room temperatures.**
  - **To investigate the use of other gas mixtures, and processing techniques.**
  - **Continue the program through Feb. 2025.**

	FY22*	FY23	Totals
a) JLAB allocated	$650,000	$603,000	$1,253,000
c) Actual costs to date**	$650,000	$568,000	$1,218,000

** As of 30 Sept. 2024

Deliverables and schedule



Current program at JLAB started in 2019

- We built up 6 RF systems. 4 for C100 cryomodules and 2 for C75 cryomodules.
- We built up 2 gas supply systems and three vacuum systems with differentially pumped RGAs.
- In November 2020 we started a robust vertical testing program. To date we have completed 37 plasma processing / vertical test cycles with different gas mixtures, pressures, etc.
- We processed 4 cryomodules in the test lab facilities. Two as part of the process development a and 2 as part of the production process before installing them in CEBAF.
- We integrated plasma processing into the C75 production cycle after clean assembly and before the first vertical test.
- We processed 9 cryomodules in-situ in the CEBAF accelerator using machine operator support for the current round.
- We are ramping up our ozone cleaning program which will be used for processing the warm girders between cryomodules.
- Plasma ignition simulations using COMSOL with a goal of understanding and tuning surface interactions.
- Supported a graduate student doing his masters thesis work on plasma diagnostics.

Plasma processing program from November 2022 to present

Cavity testing of C100 cavities in the Vertical Test Area and off line plasma facility

- Continued the experiments in the vertical test area to optimize processing of C100 cavities. The process is to:
  - Plasma process using different gas mixtures
  - Vertically test
  - Contaminate the cavity with hydrocarbons using a 93% argon 7% methane mixture
  - Vertically test
  - Repeat
- By avoiding the clean room cycle we were able to perform one plasma process and test cycle per week.
- Being able to test so frequently without interrupting other production and R&D activities is possible only because of the JLAB's vertical test facility which has six shielded test dewars and a dedicated helium supply system.
- Based on these experiments, we have switched from the standard 1% to 2% oxygen/neon mixture used by Fermi and SNS to:
  - Initially using an argon/oxygen mixture processing one day with 1% oxygen followed by a 20% oxygen mix a day or two later.
  - After a series of experiments with helium/oxygen gas mixtures, we found that a 6% oxygen/helium gas mixture was more effective than an argon/oxygen gas mixture.

Plasma processing program from November 2022 to present

C75 cavity process development

- We developed the protocols necessary to establish and control the plasma within that cavity type.
- We modified the vertical test stand so that we can process C75 cavities and confirm that it will improve the multipacting properties.
- We processed a C75 cryomodule in the test lab.
- We integrated plasma processing into C75 pair production.

Ozone Processing

- We set up the systems to do ozone processing of a C100 cavity as part of a vertical testing cycle similar to what was done with plasma.

Processing of C100 Cryomodules since Oct 2022

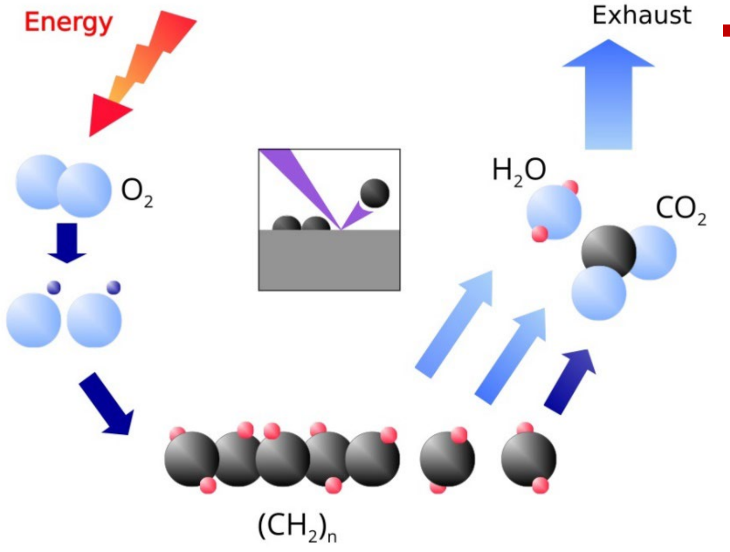
- Processed 2 C100 and 1 C75 cryomodules in the test lab prior to installing them into CEBAF.
- We developed the necessary documentation for processing cryomodules in situ in CEBAF.
- We processed and 9 C100 cryomodules in situ in CEBAF, 4 in May/June 2023 and 5 in Aug/Sept/Oct. 2024
- We built up a third vacuum cart and one more channel of RF so that we can process up to 2 cryomodules simultaneously.
- We trained machine operators to assist in plasma processing cryomodules.
- We are training machine operators to recharacterize cryomodules after plasma processing (field emission onset, maximum operating gradient and Qo as a function of E).

Overall summary, issues Sept. 2022 to Oct. 2024

- **Supply chain issues especially with electronics required a second request for a no cost extension.**
  - **Mass flow controllers ordered in March 2022 were due in Sept. 2022 finally arrived in July 2023.**
  - **Gas filter compatible with ozone 20 weeks.**
  - **Ozone sensor 24 week lead time.**
  - **Portable clean room delivery was 6 months late but were still in time for use in the CEBAF**
- **Clean room staffing issues, coupled with other priority projects initially reduced our ability to perform the vertical testing portion of the program.**
  - **Mitigated by using an argon-methane plasma to contaminate the cavities between plasma processing cycles in order to reduce the number of clean room cycles.**
  - **Still an issue when we do need to reprocess the cavity.**
- **JLAB safety lock out tag out safety stand down from May through Aug. 2024 delayed plasma processing in the CEBAF accelerator.**

Reactive Oxygen Plasma Processing

C100 Off-Line Bench Setup



O_2 is cracked in the plasma to atomic oxygen which breaks down the hydrocarbons

- SRF "Standard" Recipe
  - Room temperature mix of inert gas (argon or neon) and a few percent oxygen
  - Flow gas through cavity at a few tens of standard cubic centimeters per minute
  - Pressure in the cavity between 50 and 300mTorr
  - Apply RF (10 to 600 W depending on system, gas species, pressure and cell) to ignite plasma in one cell, LCLS II and JLAB C100 via HOM ports, JLAB C50/C75 and SNS via the fundamental power coupler.
  - Move from cell to cell by changing the RF frequency usually with two sources.
  - Maintain the plasma for 30 to 120 minutes in each cell
  - Monitor cracked hydrocarbon residuals of H, CO2, CO and H2O

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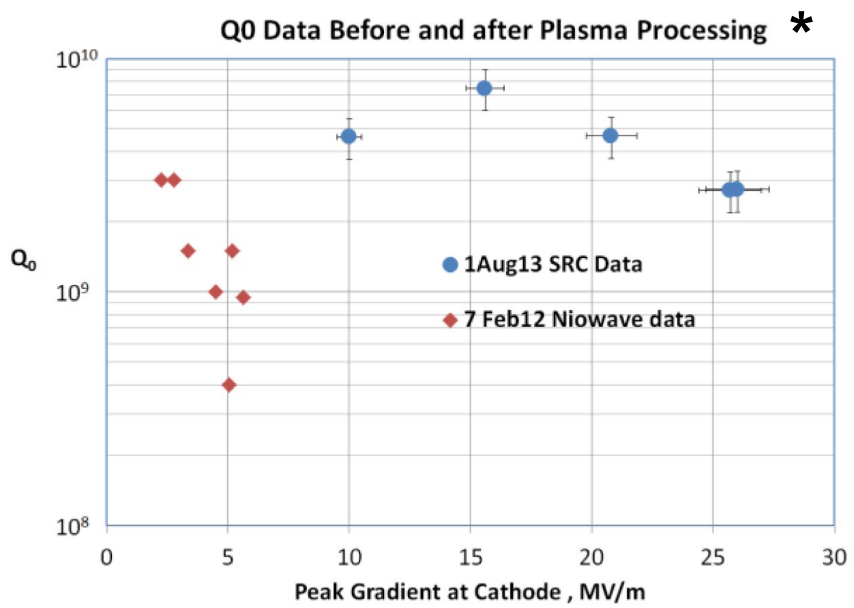
Examples of Plasma Processing



Industrial Uses

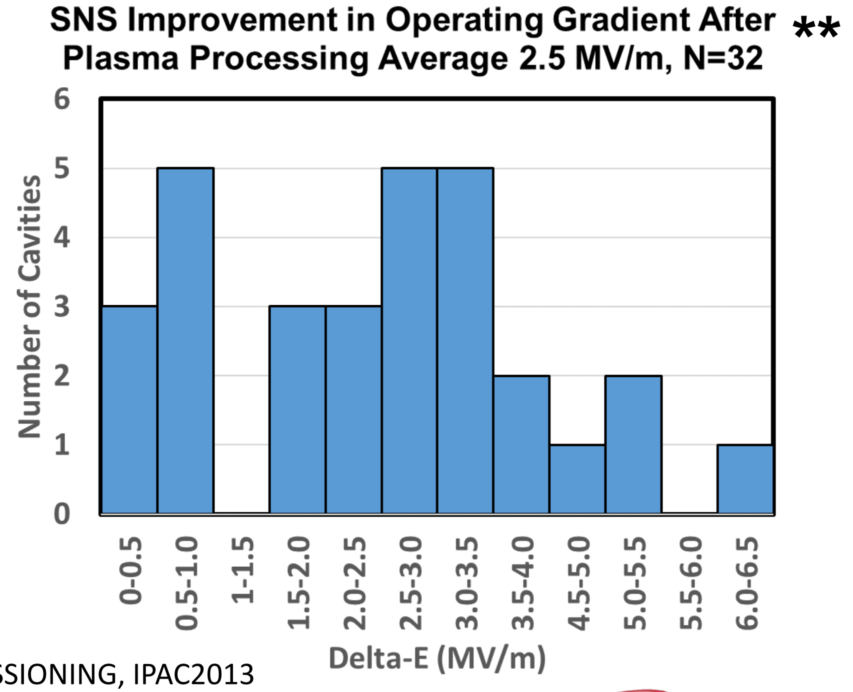
- Plasma processing is a common technique for removing hydrocarbons from surfaces and improve the wettability of the surface. Princeton Scientific Corporation has a line of chamber based plasma processing systems that use the same approach.

WiFEL gun at University of Wisconsin

- 2012 Bob Legg, based on the work at JLAB and ORNL, led an effort at the Synchrotron Radiation Center located at University of Wisconsin, the WiFEL SRF gun cathode surface fields improved from 6 MV/m to 26 MV/m.

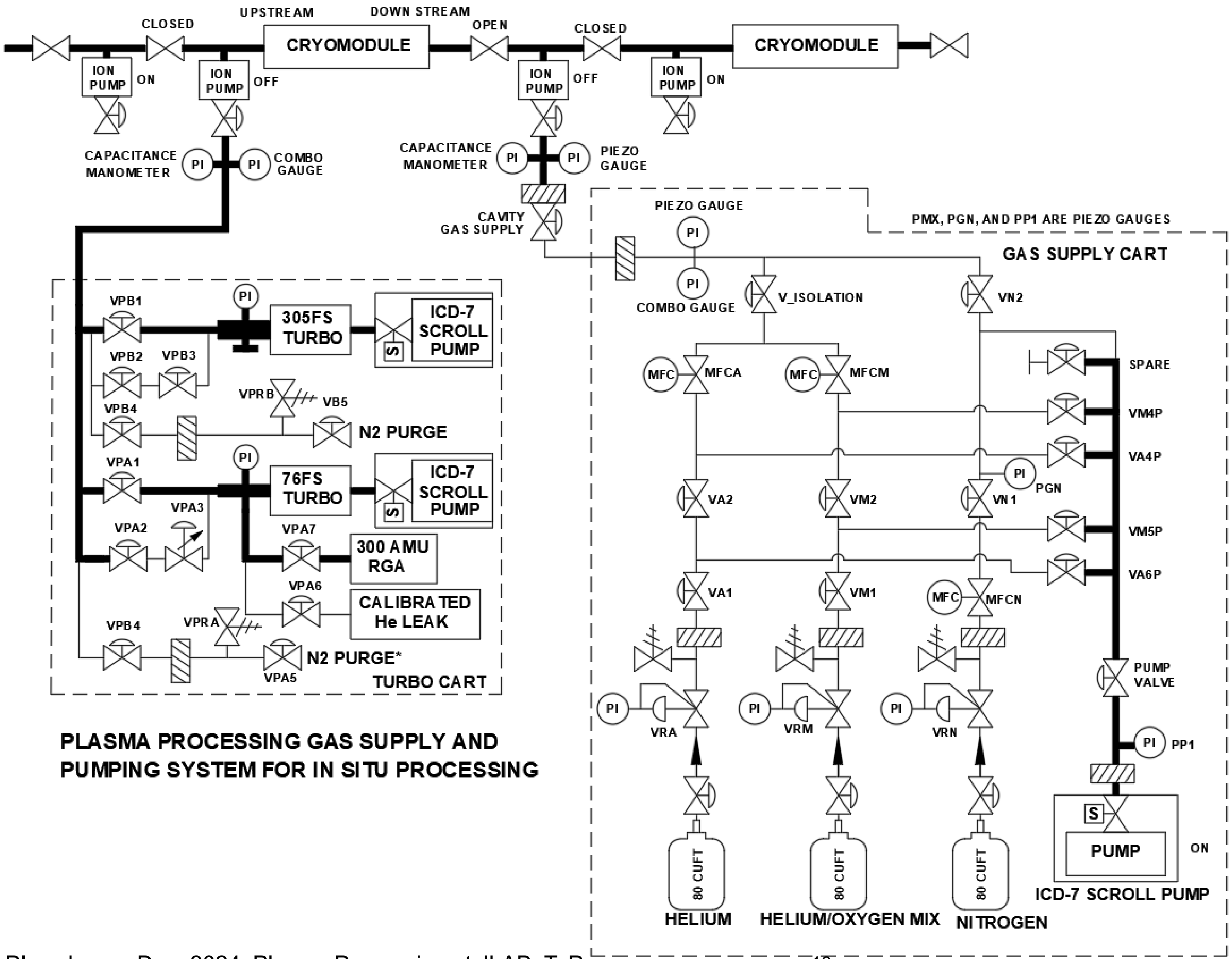
SNS at Oak Ridge National Lab

- 2015-2018 Marc Doleans lead an effort to process 32 cavities in the SNS linac improving the gradients an average of 2.5 MV/m. The work was done during scheduled maintenance periods. After 3 years of operation most of the processed cavities are still doing well. More recently they did a smaller number of cryomodules.



*J. Bisognano, et al, WISCONSIN SRF ELECTRON GUN COMMISSIONING, IPAC2013

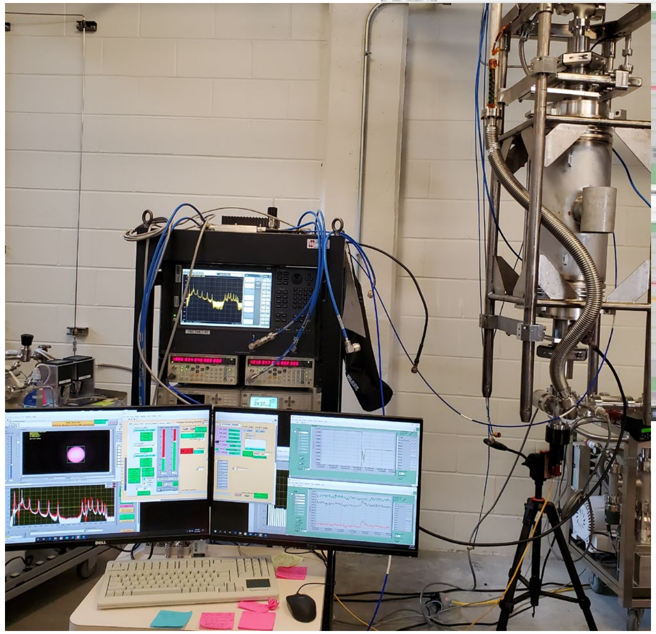
** Marc Doleans, ORNL personal communication.

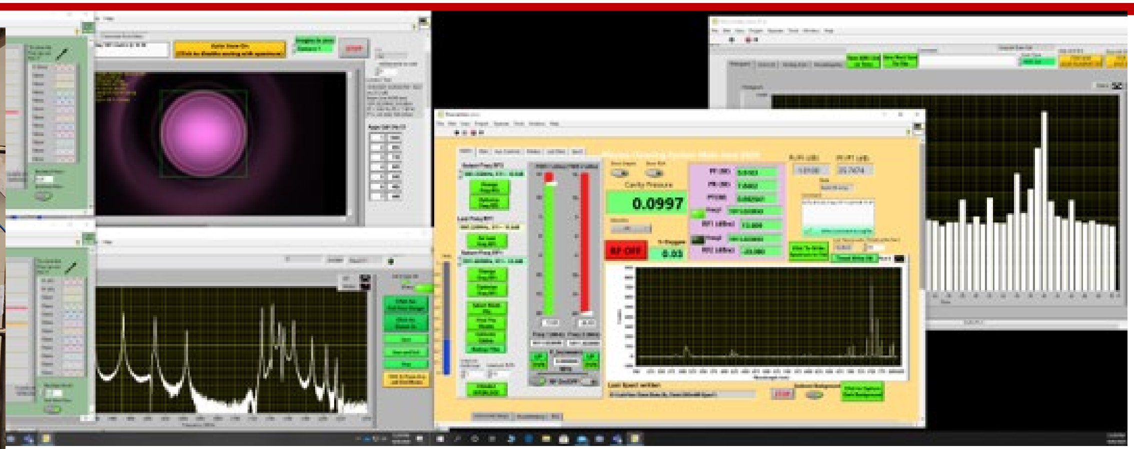


PLASMA PROCESSING GAS SUPPLY AND PUMPING SYSTEM FOR IN SITU PROCESSING

- **P&ID drawing of gas supply and pumping systems configured for processing a cryomodule in the CEBAF accelerator.**
- **Using 2 Mass flow controllers (MFCM) allowed us to simultaneously regulate the pressure and the oxygen percentage of the process gas.**
- **The same gas supply and vacuum carts are used in the vertical test area as well as when processing C75 cavities in the clean room.**

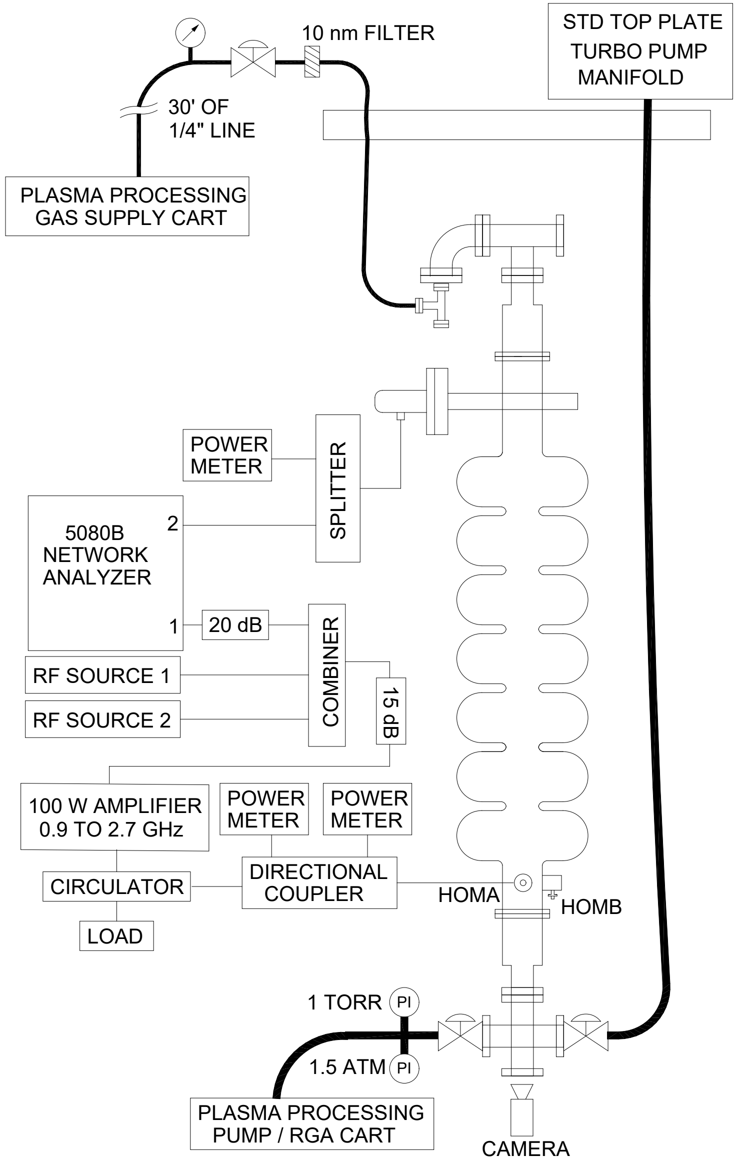
Vertical Test Stand Setup C100 RF System





The purpose of vertical testing is to establish procedures and judge the effectiveness of the methods with cavities under various conditions as well as to test novel techniques.

- Plasma processing is done in the vertical staging area while the cavity is still mounted to the vertical test stand.
- A network analyzer is used to measure frequency shifts while processing
- A camera was used so that we could verify the cells with plasma and gain confidence in the RF based approach for determining plasma location.
- Exhaust gas was monitored with an RGA



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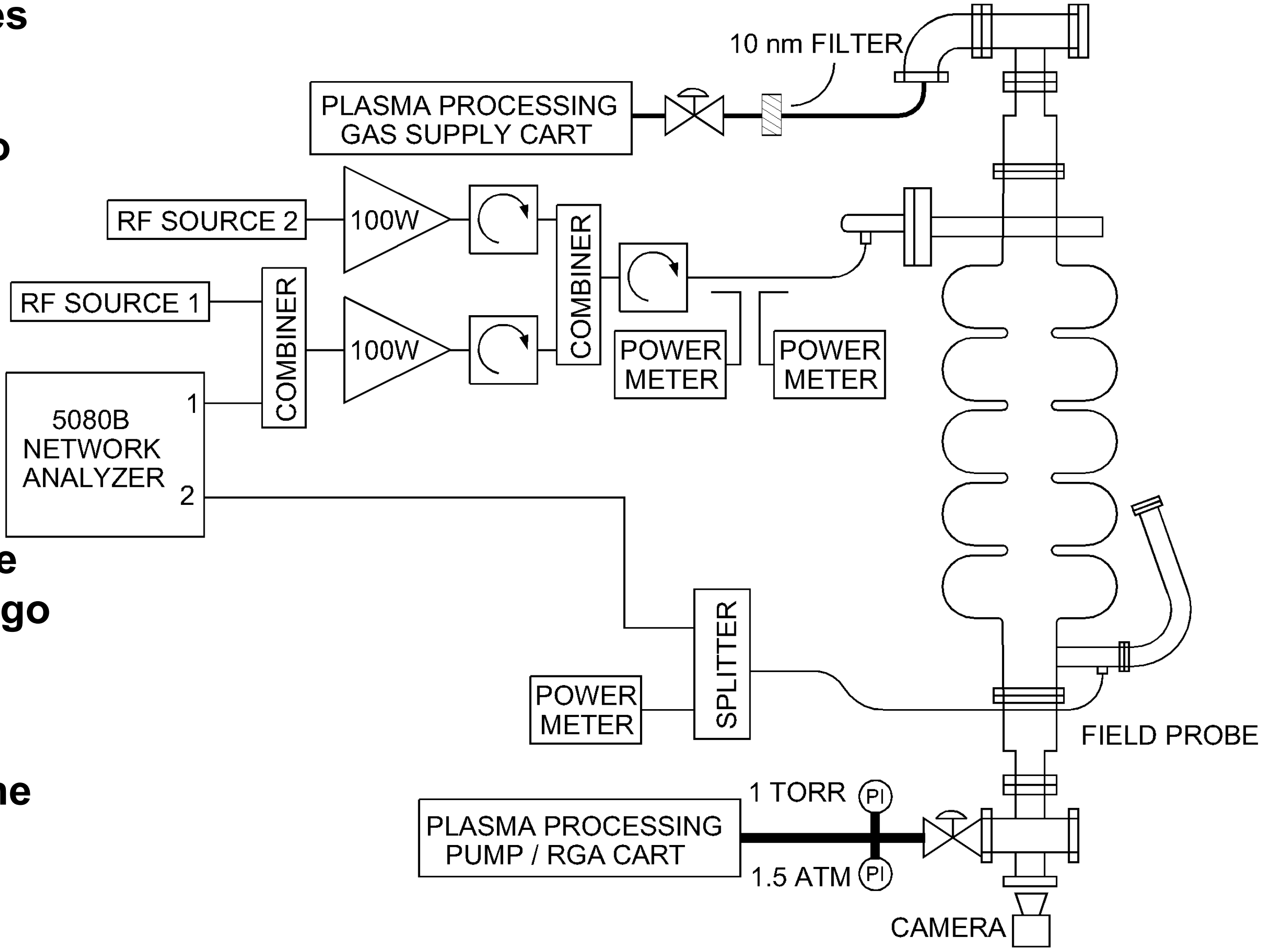
C75 Cavity Setup

- The FPC does not couple well to the desired HOM modes in a C75 cavity (S11 of -0.8 dB, -1.4 dB and -2.5 dB.)
- For this reason it takes about 30 W of RF at the cavity to produce and maintain a helium/oxygen plasma.
- The way that we apply to frequencies to a cavity is to
  - Apply the first frequency to establish the plasma.
  - Leave the first frequency on with a constant drive power.
  - Turn up the second RF source.
- When we did this we found that saturation effects on the amplifier caused the amplitude of the first frequency to go down as we turned the second source up.
- This reduced the Debye shielding and meant that we could not go from cell 3 to cells 2 and 3 by turning on the cell 2/4 frequency.
- Rather than wait several months for a higher power amplifier we purchased a second 100 W amplifier which was off the shelf.



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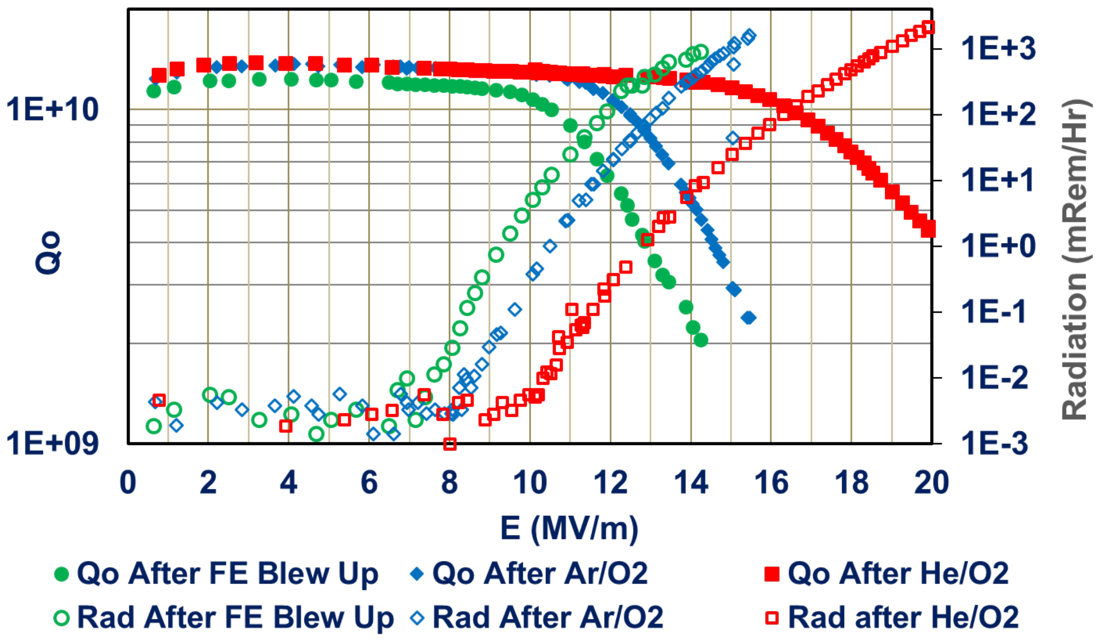
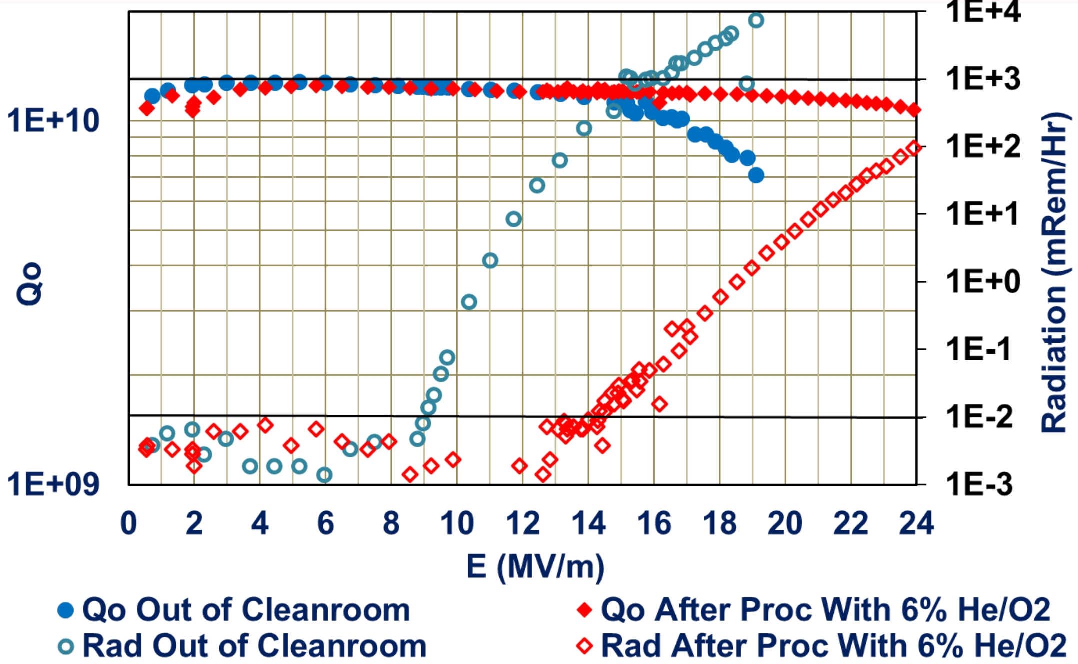
VTA results that resulted in us changing from argon/oxygen to helium/oxygen

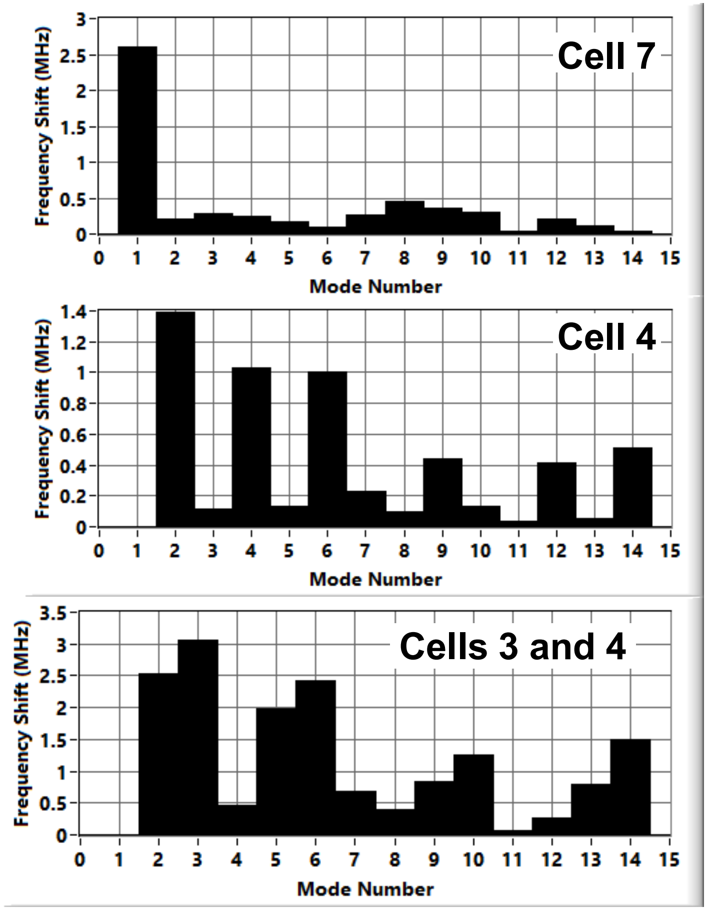


- After a series of experiments we decided on a protocol of processing with 1% oxygen/argon followed by 20% oxygen/argon.
- About a year later we started experimenting with helium/oxygen.
- We processed a blown up field emitter using argon/oxygen then processed it with 2% oxygen/helium and got an additional 2 MV/m improvement.

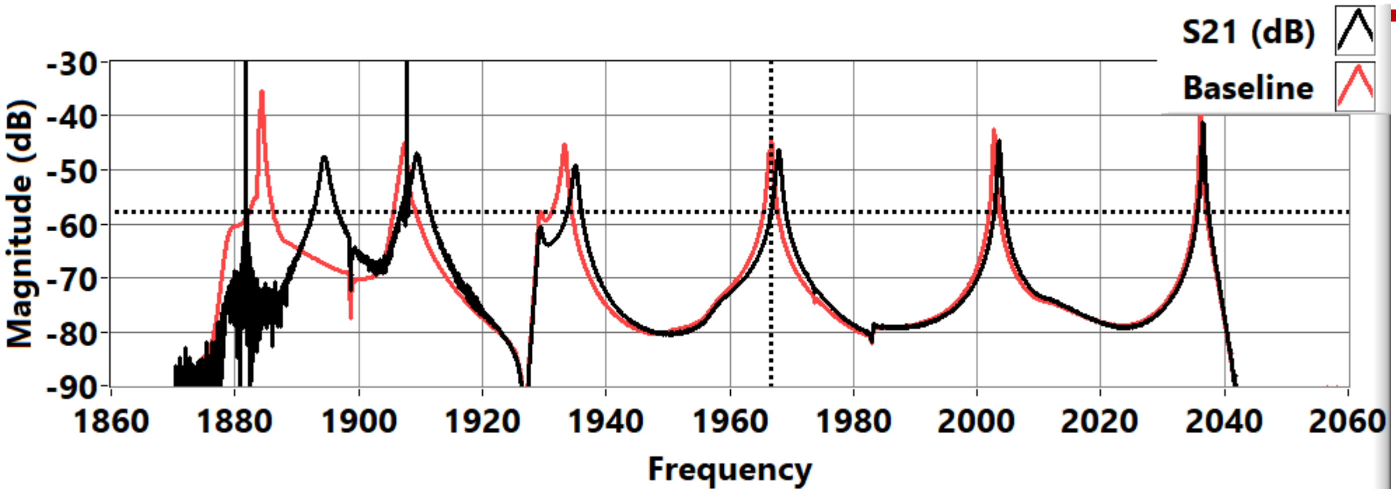


- We followed that with a series of experiments with different gas mixtures of helium and oxygen at different pressures and oxygen percentages
- Out of clean room (blue) Process twice with 6% oxygen 94% helium (Red)
- Demonstrated that helium/oxygen is an effective gas mixture.

Using an S21 Measurement to Characterize and Locate the Plasma



Measured Mode Shifts

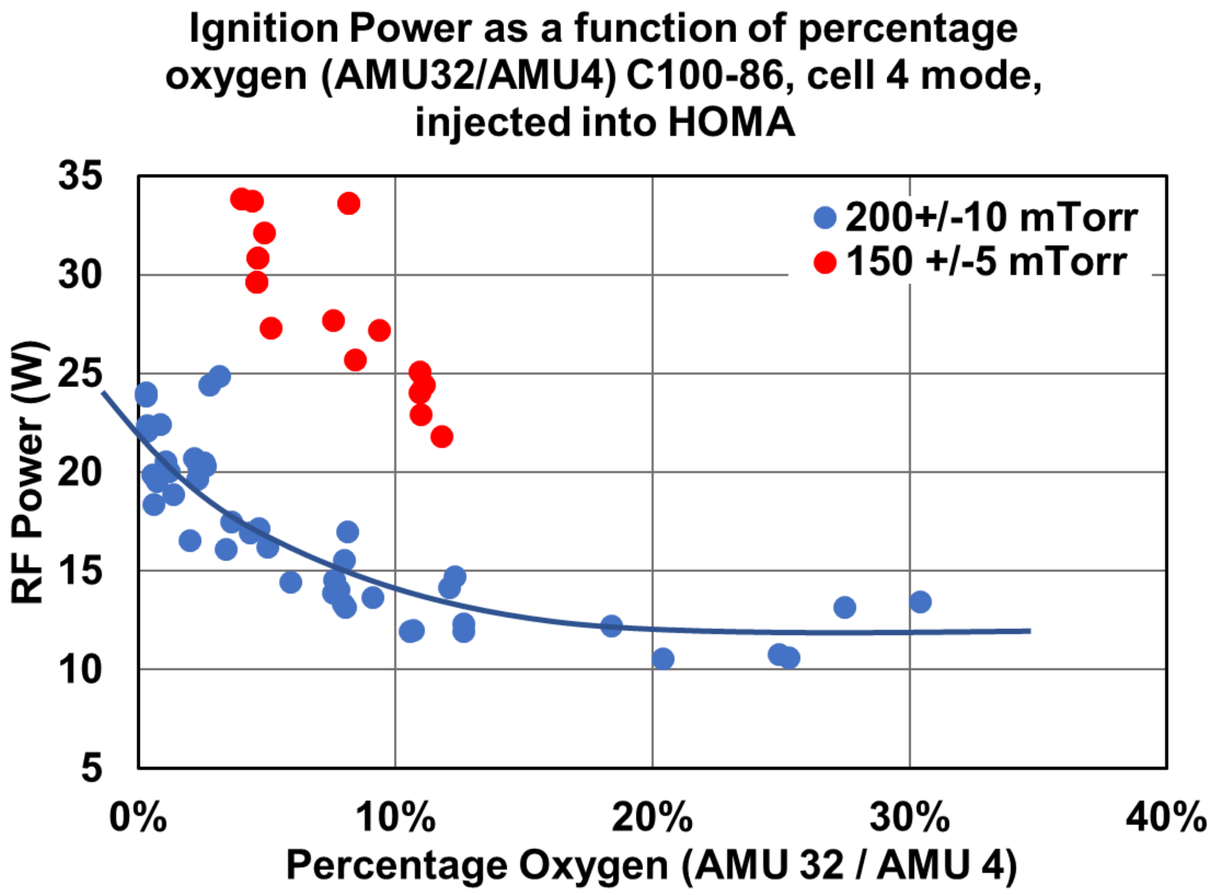


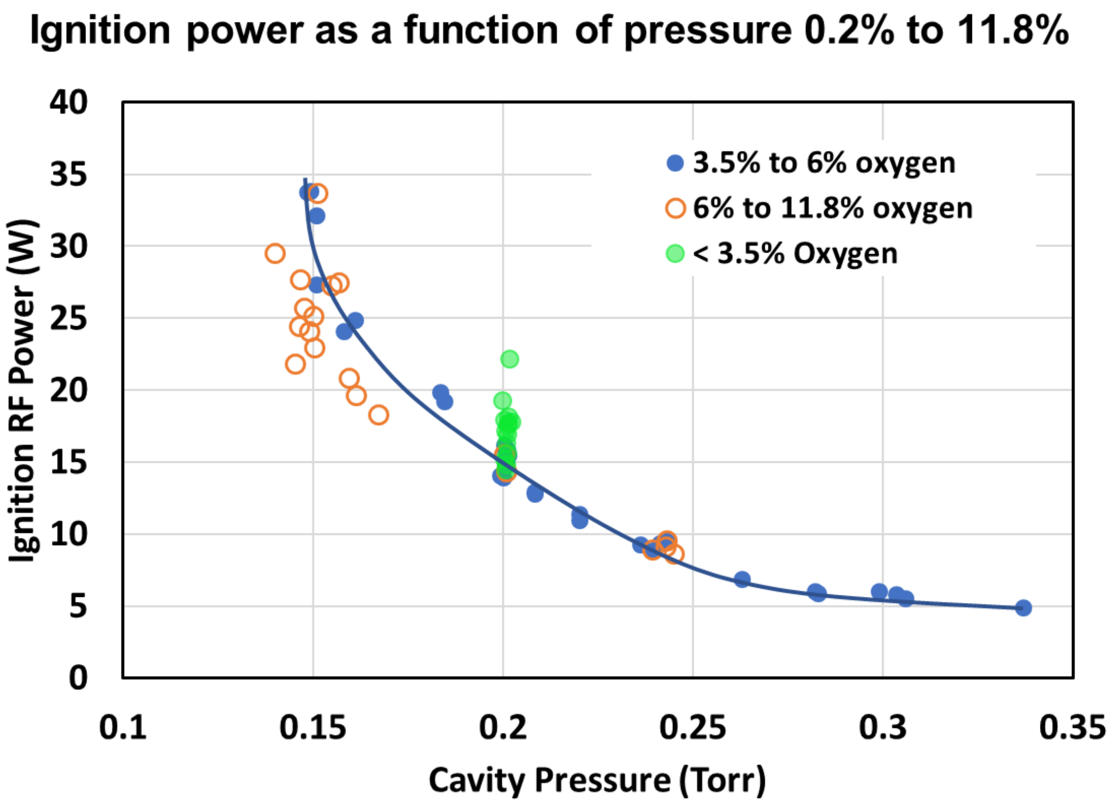
Cavity S21 with (black) and without (red) Plasma in cell 7

6 modes shown we use 14 modes out to 2.2 GHz

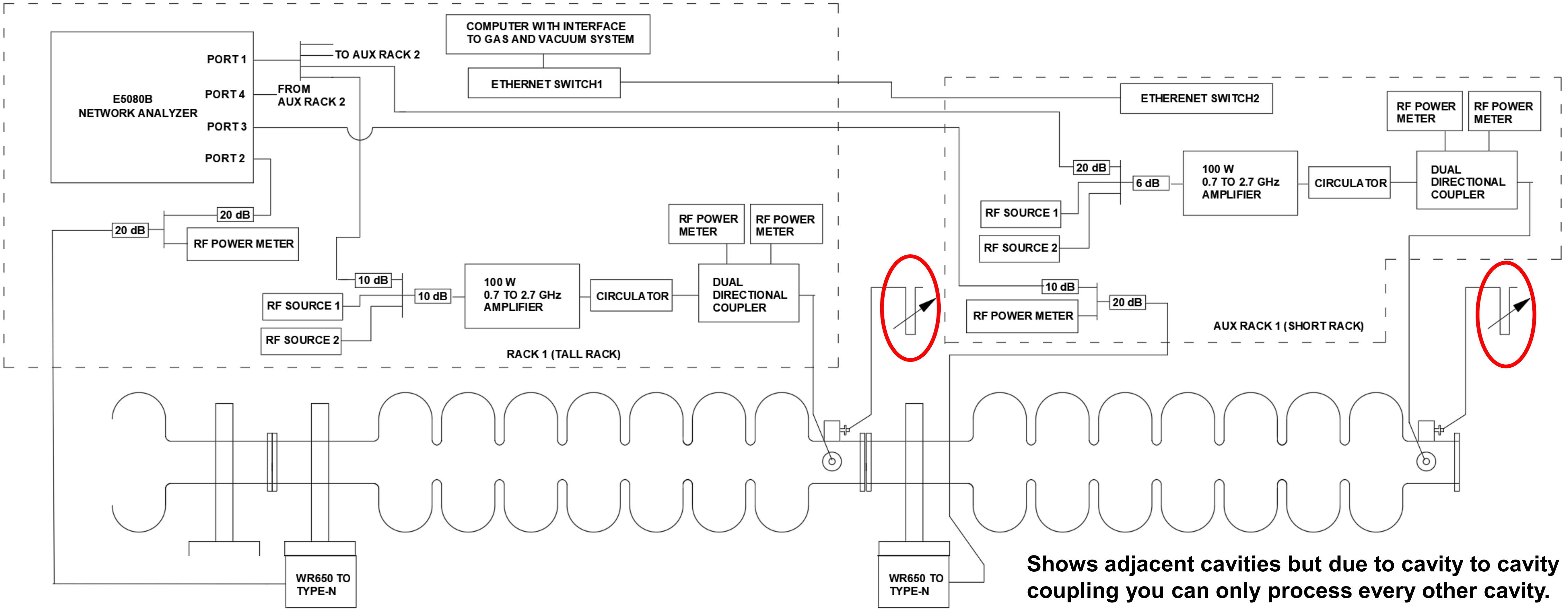
- **A low level network analyzer signal is applied to the input of the amplifier and the "probe" signal was fed back to port 2 on the network analyzer.**
- **The dielectric constant is reduced where there is plasma. The higher the plasma density the lower the dielectric constant.**
- **Each mode is affected differently depending on the location of the plasma and the mode pattern, e.g. no frequency shift for a mode with no field in the ignited cell.**
- **Initially we looked at a live S21 plot. Then both a baseline and a live plot. Then we added a feature to our system where the frequency shift per mode is presented live while we are processing.**
- **This method allows us to confirm the plasma location without a camera.**

Helium oxygen ignition C100 cavity cell 4 mode





RF System Block for Processing Multiple C100 Cavities Simultaniously



Shows adjacent cavities but due to cavity to cavity coupling you can only process every other cavity.

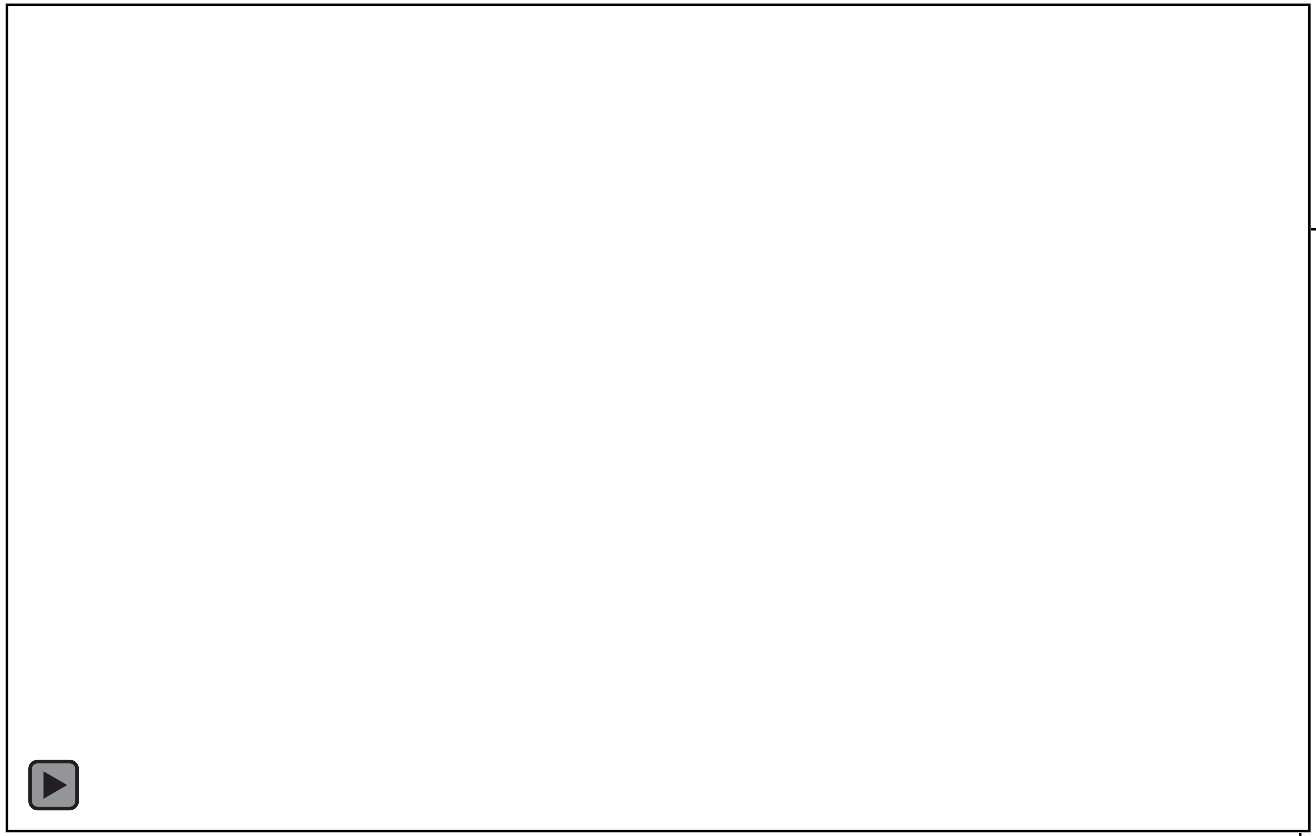
- Same general setup as was used for vertical testing except:
  - 4 Port network analyzer used to measure S21 for 3 cavities at once.
  - Phase shifter added to second HOM port

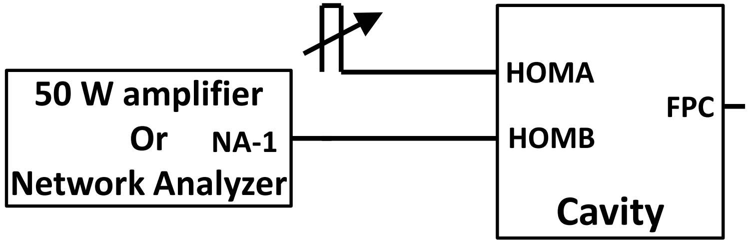
Why use phase shifters on C100 cryomodules?

- The cables between the HOM couplers and the connectors on the vacuum vessel are 10' +/- 1". This amounts to a 270° randomness in phase.
- There is strong coupling between HOMA and HOMB couplers in the TE111 frequency band.
- The coupled signal goes to the end of the unused cable and is reflected back and tries to drive or suppress the mode because of the fixed but random phase length of the cable.
- This was particularly important for the mode which excites the cell closest to the HOM couplers, cell 1.
- The first steps in processing a C100 cavity is to:
  - Do a series of 72 calibrated S11/S21 measurement of the cavity at 5° increments on the phase shifter.
  - Analyze the data and determine a phase shifter position that provides a reasonable S11 and S21 focusing on the cell 1 and cell 4 frequencies.
  - Create a file with the 5 modes at that phase shifter position.

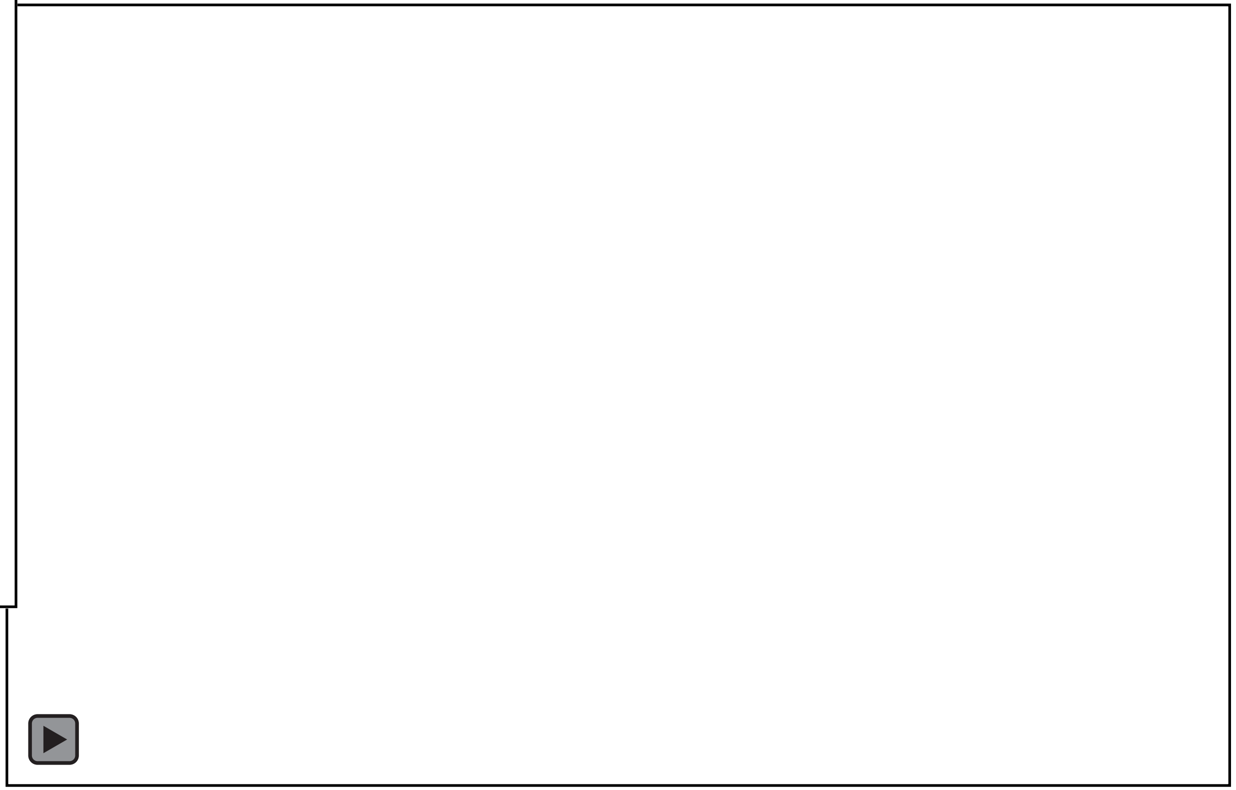
Effect of changing the phase shifter through 360 degrees on the modes for cells 1, 7, and 4

Cell 1 (left) and 7 (right)

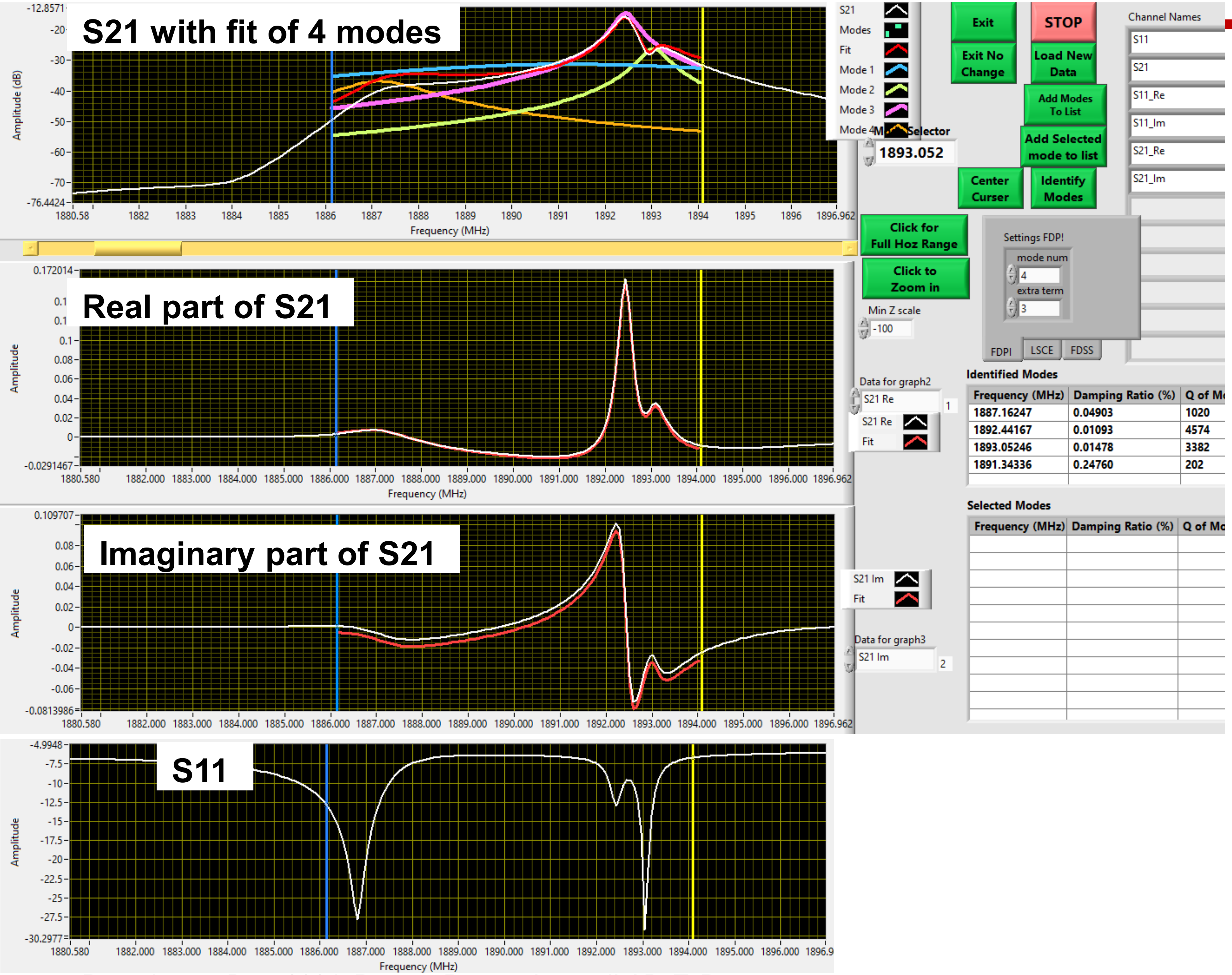




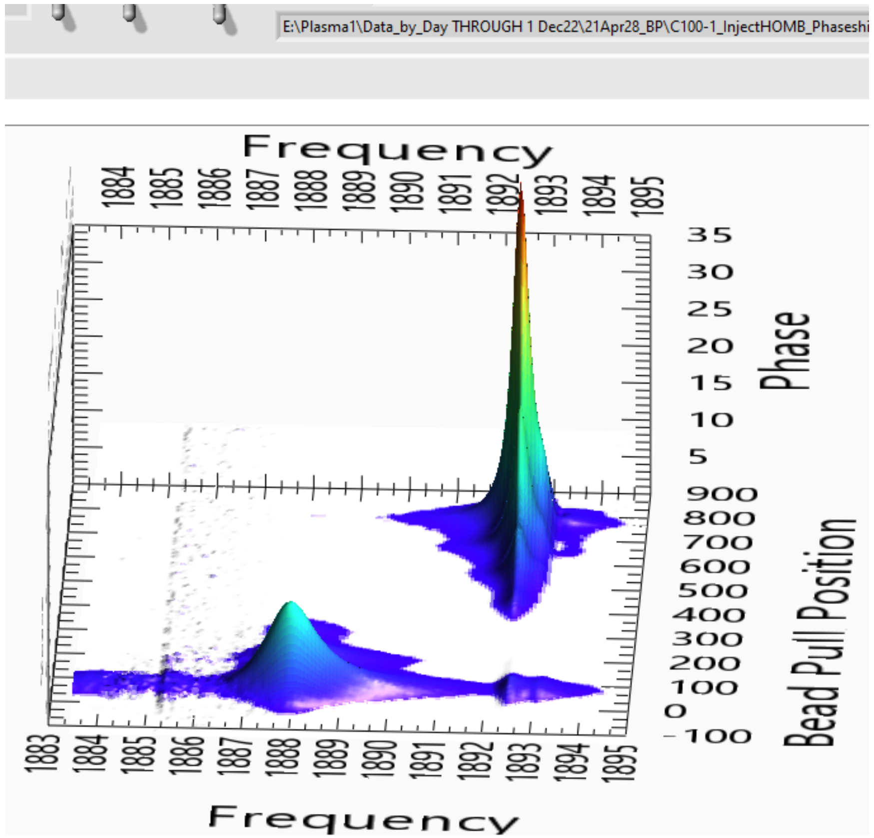
Cell 4



Using modal fitting software to identify the cell & mode



- Both data sets taken with same phase shifter setting
- From time to time the cell 1 mode is at a higher frequency than the cell 7 mode



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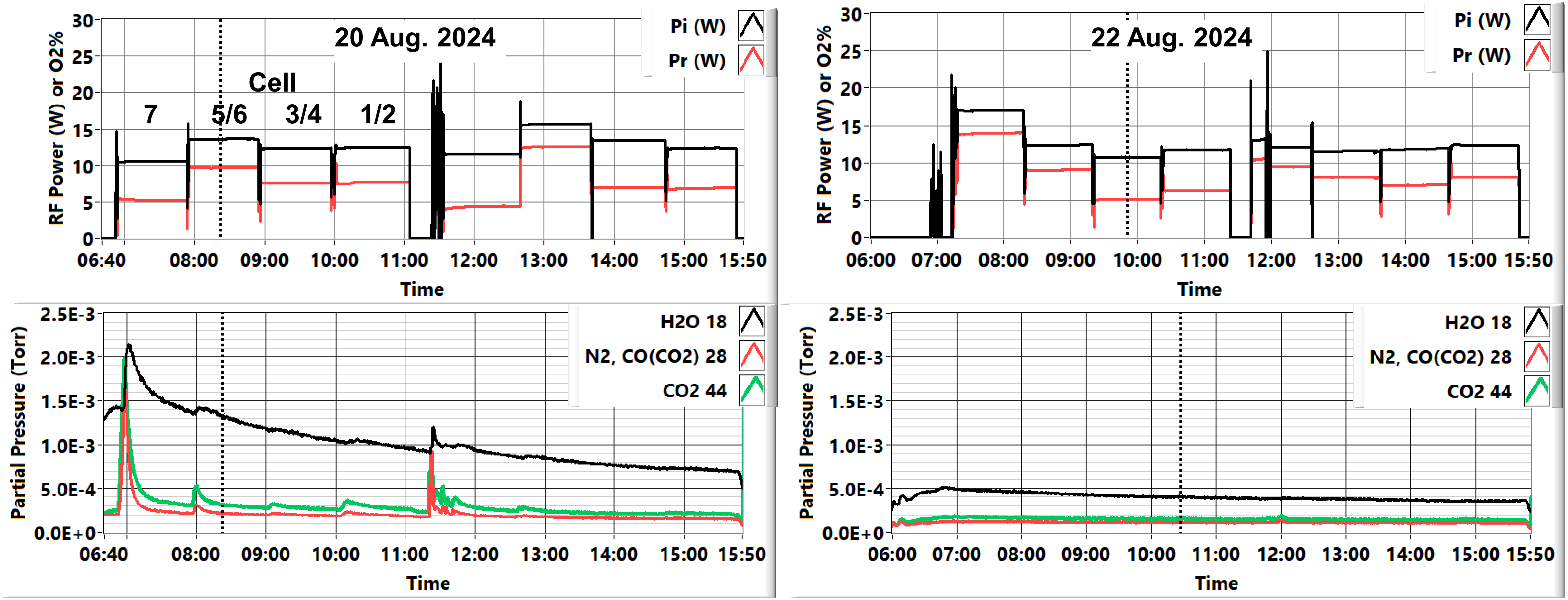
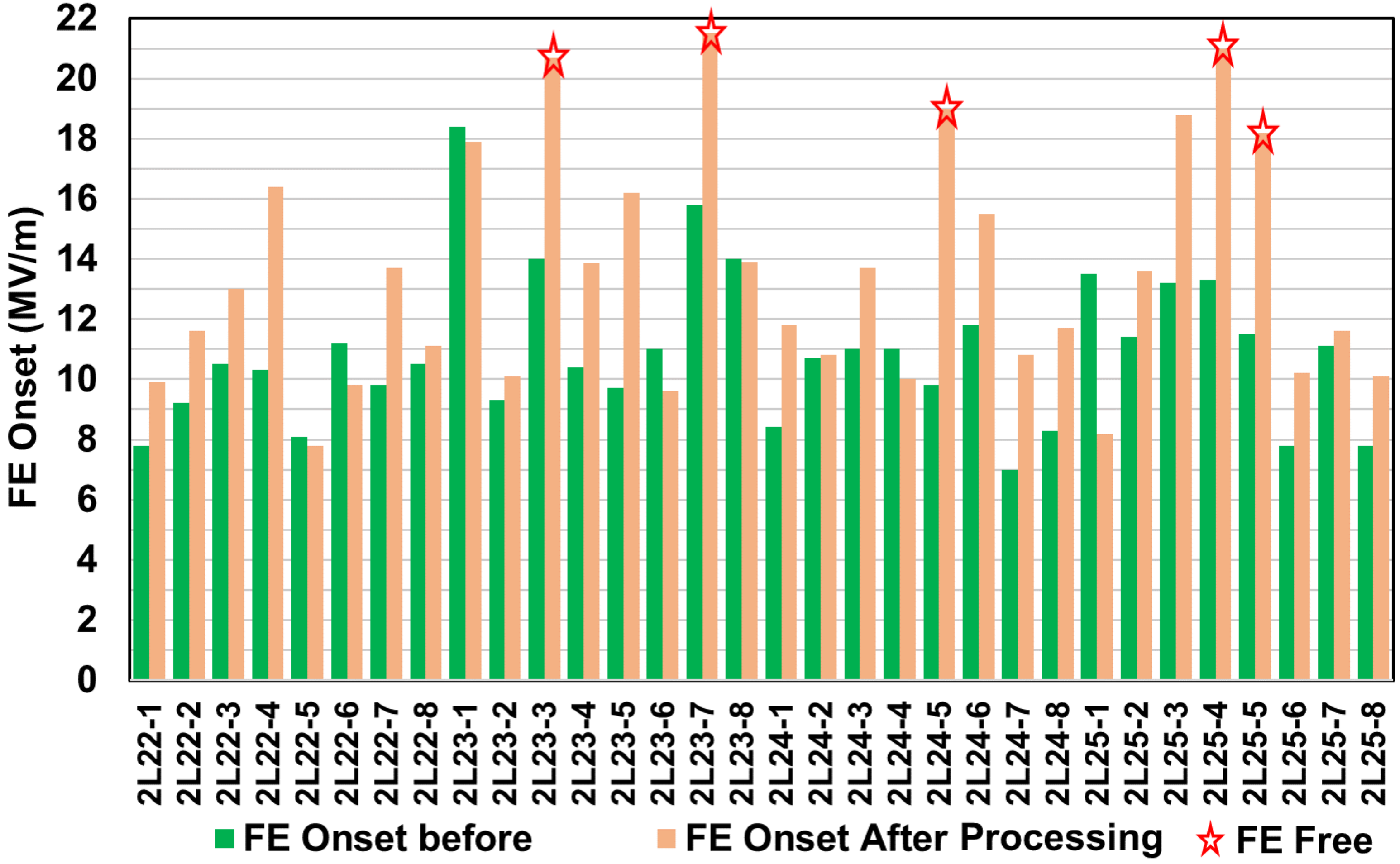
RF power and partial pressure of hydrocarbon residues exiting a cryomodule



- Plasma processing cryomodule 1L25 on 20 Aug and 22 Aug. No processing on 21 Aug.
- Partial pressure is that exiting the cryomodule, e.g. multiply RGA signal by (Exit_Pressure) / [RGA(He) + RGA(O2)]
- Total exit pressure of 300 mTorr, Inlet gas flow 14.4 SCCM.

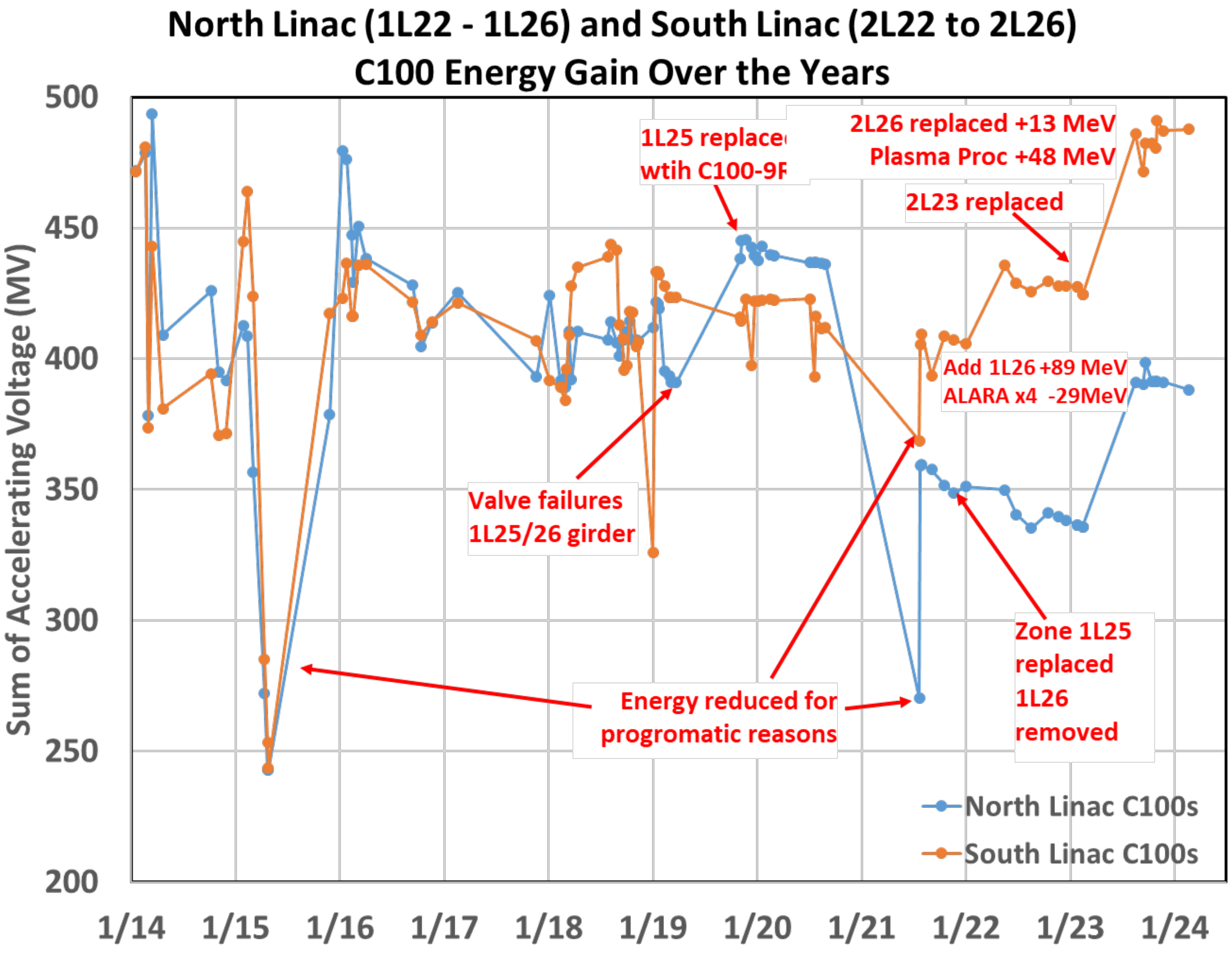
Cavity by cavity results after plasma processing 2L22 through 2L25



- Processing occurred in May 2023.
- Cryomodules 2L22, 2L24 and 2L25 had been in operation for more than 12 years.
- Cryomodule 2L23 was refurbished and installed in the spring of 2022.
- All cavities had field emission prior to processing.
- 5 cavities were field emission free after processing.
- Beam line valves adjacent to cavities 1 and 8 were replaced as matter of routine maintenance.
- Cavity 2L25-1 degraded by 5 MV/m.

Historic operating energy of C100 cryomodules in CEBAF

- Archived data of the operating voltage of the last 5 cryomodules in the north and south linac.
- Data extracted at quasi random times.
- The design operating energy is 500 MeV.
- In general the operating energy is as high as possible in order to reduce the trip rate in the rest of each linac.
- In Aug 2021 we started optimizing the gradients to "minimize" the neutron dose in the middle of the beam line between cryomodules.
- Plasma processing allowed us to operate the south linac C100s at 98% of the design operating gradient while reducing the radiation dose from 15 Rad/hr to 10 Rad/hr neutrons.



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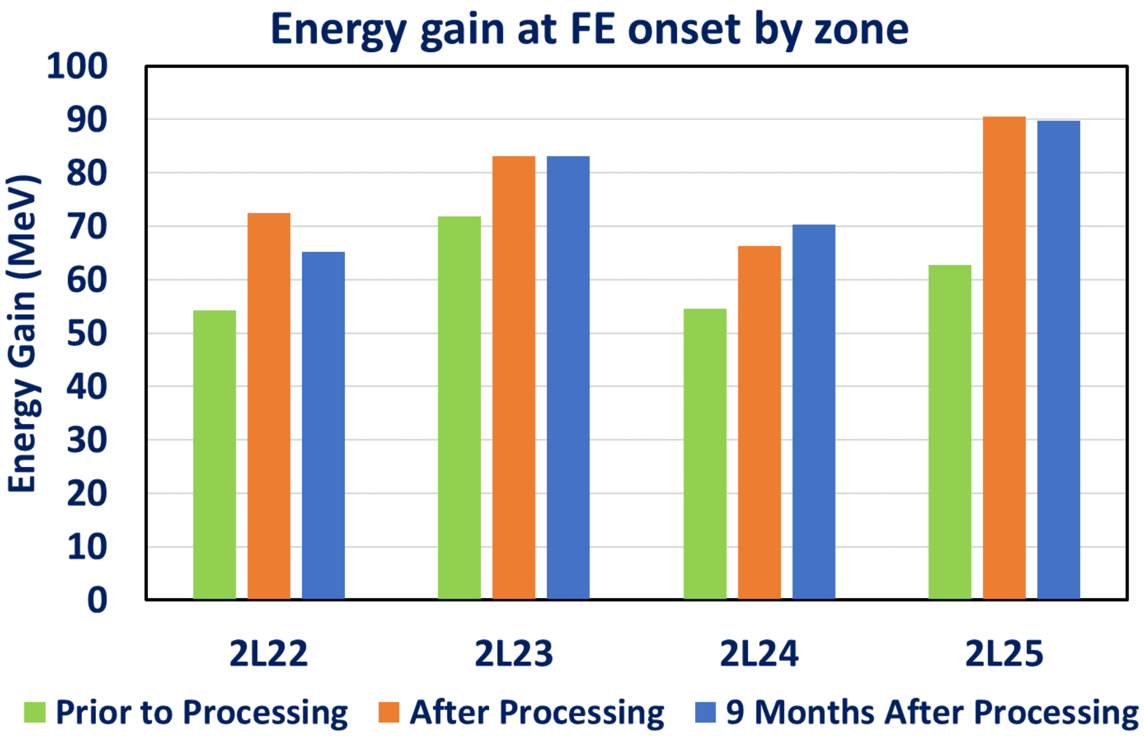
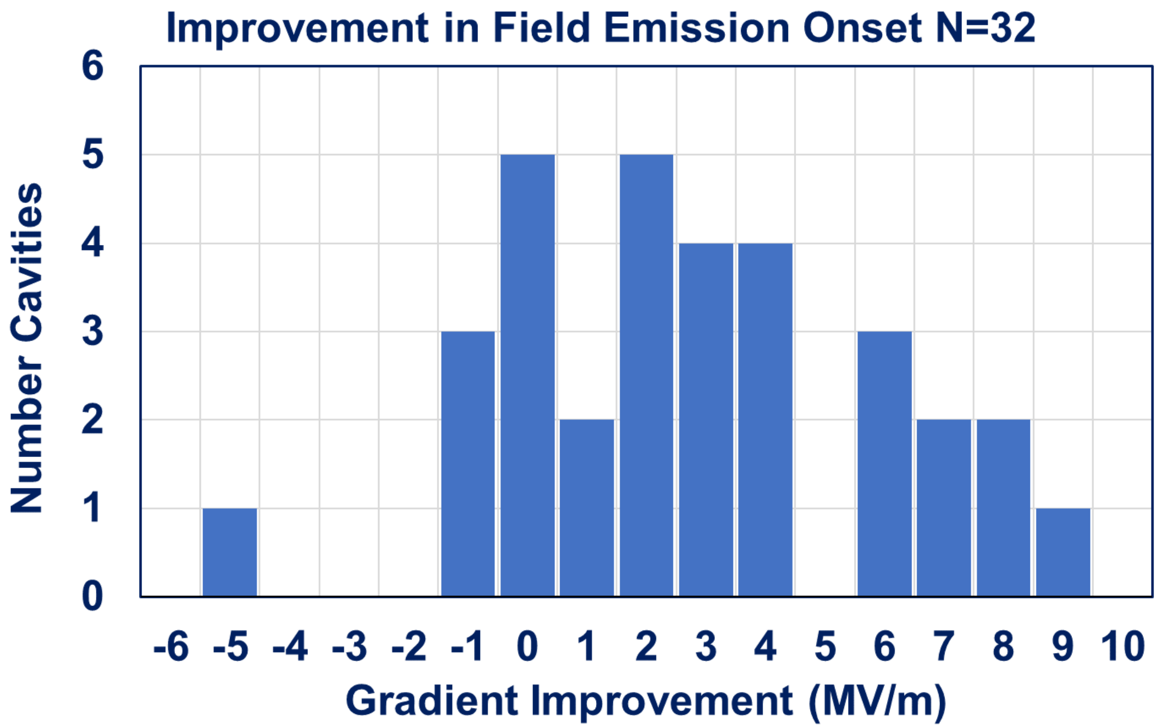
Field emission data for cryomodules that were processed in situ in CEBAF

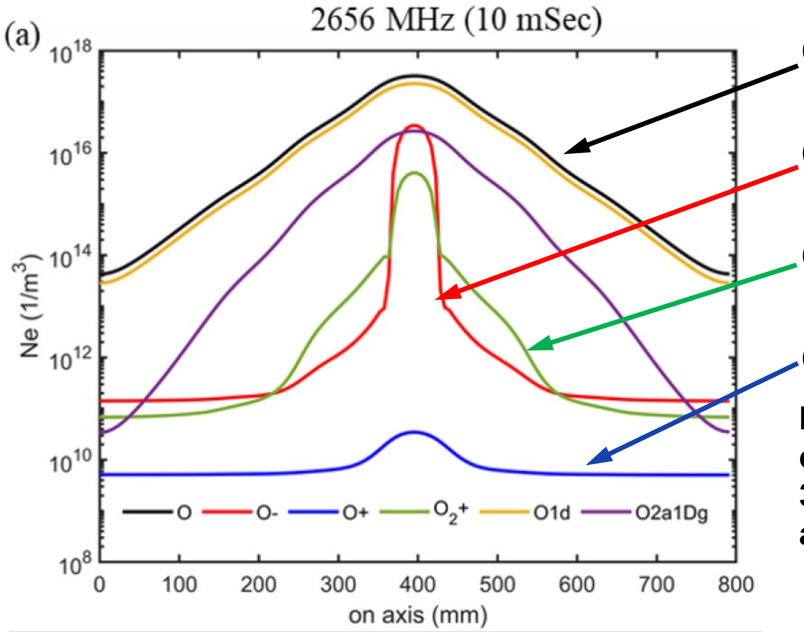




- Cryomodules 2L22, 2L23, 2L24 and 2L25 were plasma processed in situ in May 2023..
- FE onset improved by 59 MeV or an average of 2.7 MV/m
- Post processing FE onset data was taken in Aug. 2023.
- Data after operating for 9 months was taken in the spring of 2024.
- The cryomodules that were plasma processed degraded from 312 MeV to 308 MeV or 1.2%

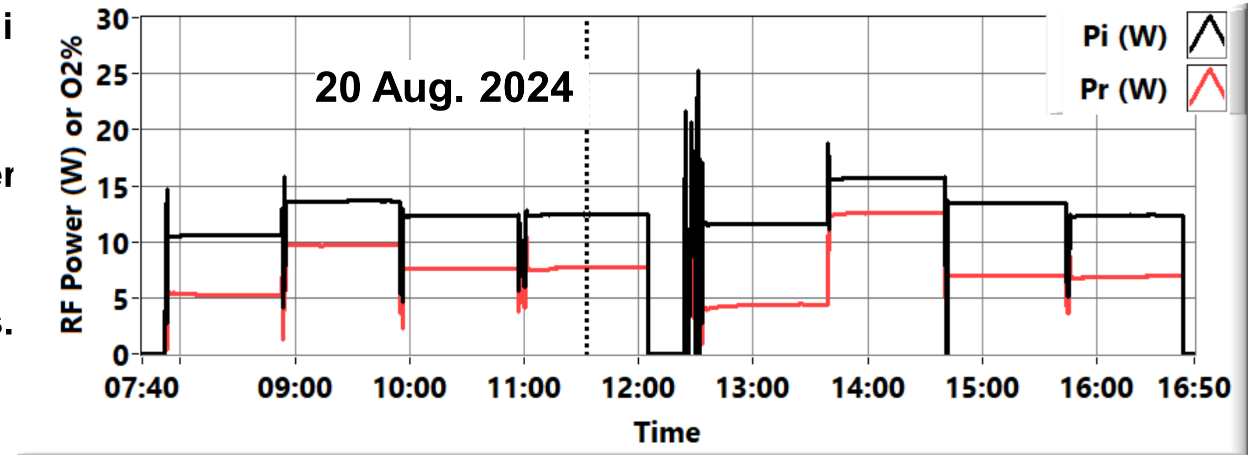
Do we really need to process all of the cells? . . . Future VTA study

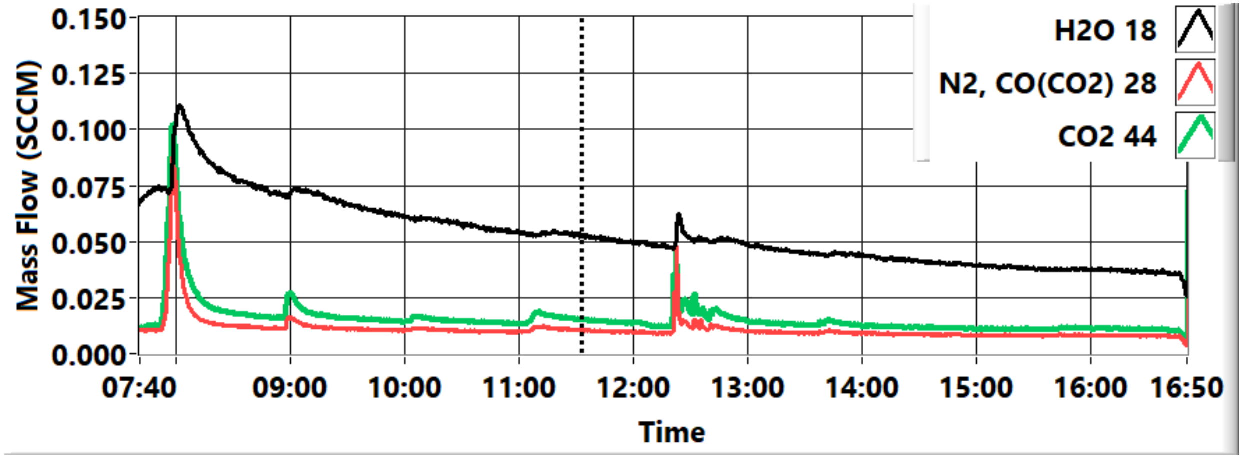
- The hydrocarbon residue production is substantially reduced after the first cell is done and when we switched to the other 4 cavities i the cryomodule.
- The question becomes does the distribution of reactive species sufficient that we do not have to put a plasma in every cell in order succeed.
- This is especially important for spoke and quarter wave cavities where it is difficult to get the plasma to be adjacent to all surfaces.



Note: Center of cells are at 200, 300, 400, 500 and 600 mm

Simulation based spatial distribution of different species of oxygen (molecules, ions, and metastable states) on the axis for one of the modes in a C75 cavity.*





Plasma processing 4 cavities simultaneously. Upper plot is RF power. Lower plot is hydrocarbon residues exiting the cryomodule.

*Raut, N., et al, “Plasma processing on C75 cavities in Jefferson Lab”, IPAC 2024

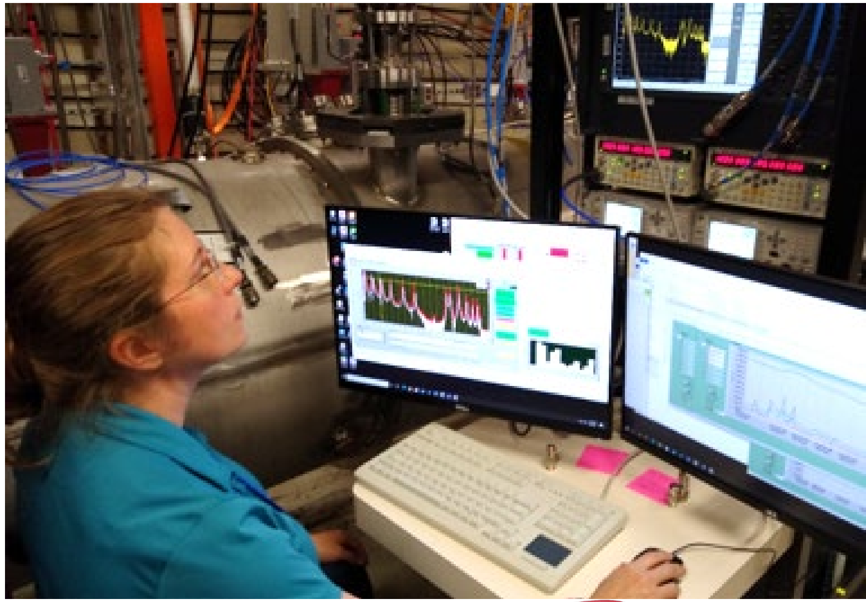
Future plans and acknowledgements

- **Starting in mid December we will remeasure the FE onset characteristics of the 5 cryomodules that were processed this past summer/fall.**
- **We will continue to process C75 cavity pairs and C100 cryomodules as part of the cryomodule production cycle.**
- **In January after they complete upgrades to the helium plant that is used for the test lab, we will restart our vertical test experimental program with the goal of doing 15 to 20 test cycles per year.**
- **Develop the protocols for processing our C20/C50 cryomodules.**
- **Start the planning for processing multiple cryomodules during the next scheduled accelerator down during the summer of 2025.**

Acknowledgements

I would like thank the technical staff in the JLAB cavity production group, chemistry group vertical test area staff, machine RF group and machine vacuum group. Special acknowledgement to Frank Humphries for his support in preparing the cryomodules for plasma processing.

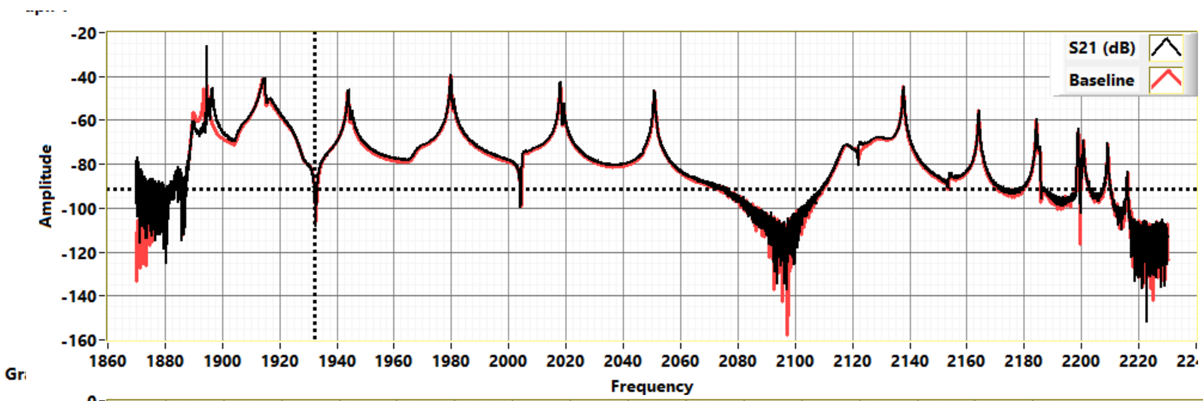
I have to acknowledge my partner in plasma Tiffany Ganey who acted as my hands in the lab for a year when I was working from my den during COVID and who helped organize and make all of this happen up until her recent retirement.

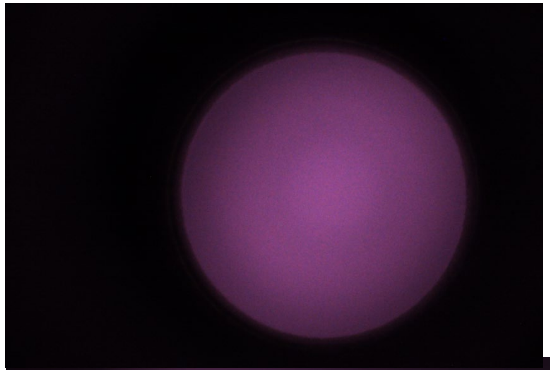


Backup Slides

Detecting Coupler Breakdown Using a Network Analyzer

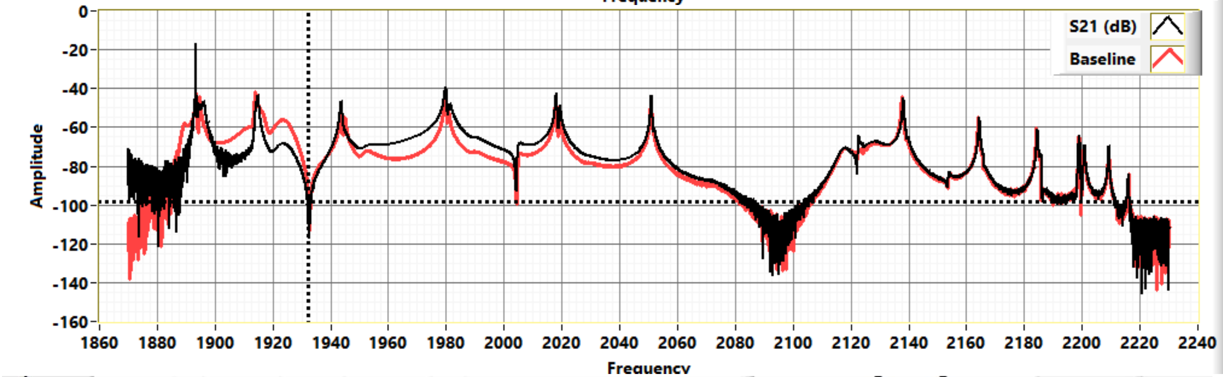
Nominal plasma on/off (black / red) measurements with plasma in cell 7.

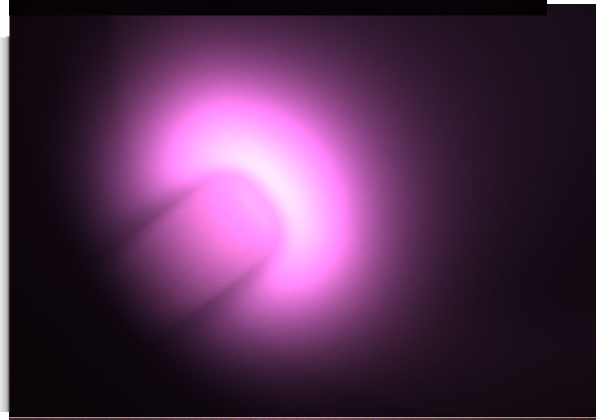




Not a terrible fault mode diffuse discharge at probe tip.

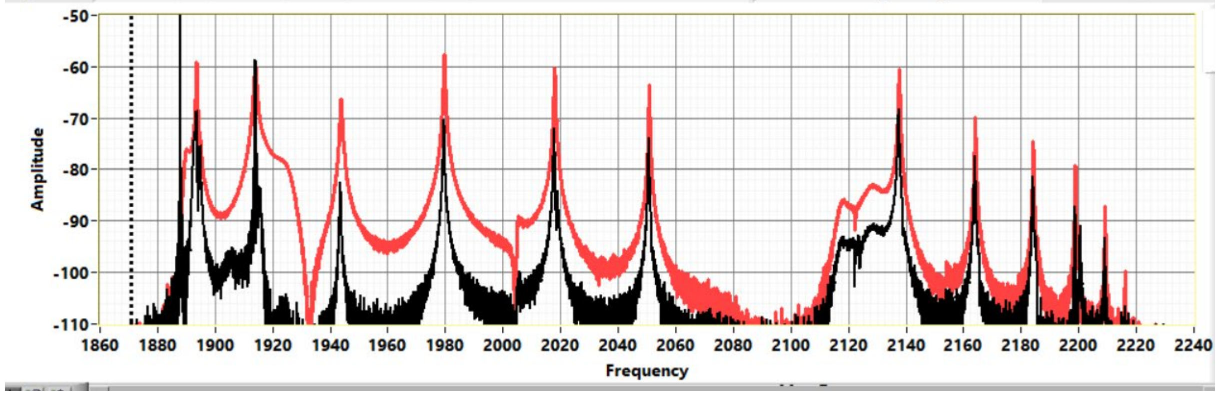
Typical signals for plasma on HOM antenna tip with RF on/off (black / red).

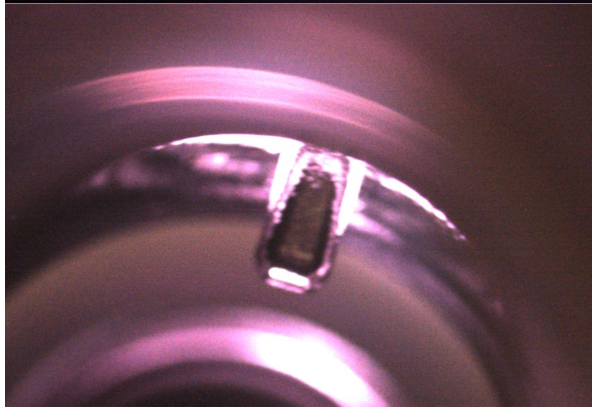




This one is bad as it is an arc like discharge in the tube containing the coupler feedthrough antenna.

Typical RF on/off (black / red) for breakdown within HOM coupler.





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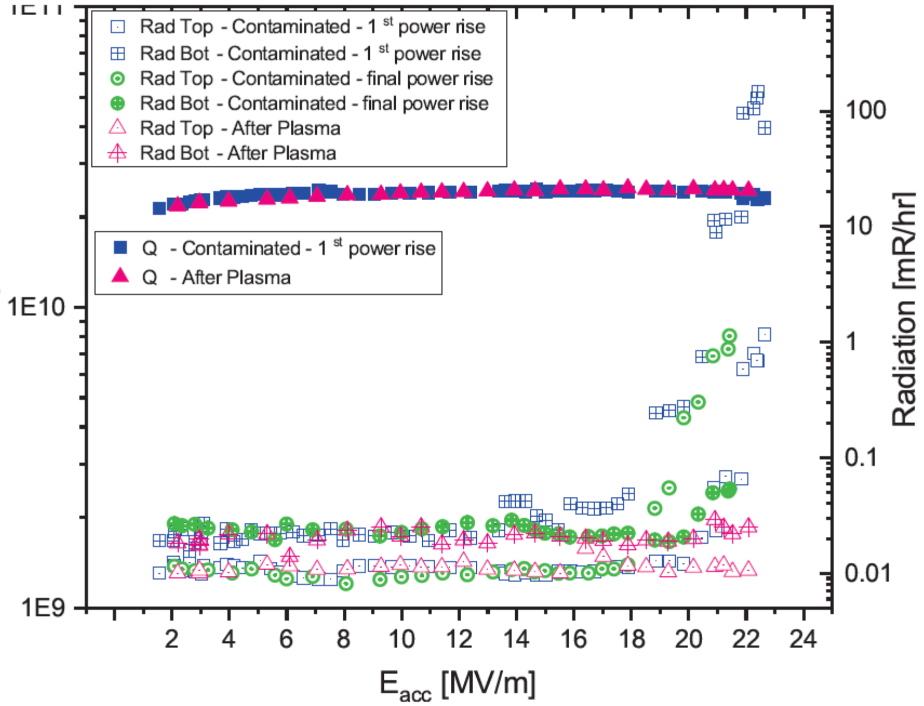
Plasma processing at other labs

Fermi Lab, Paolo Berrutti* and Bianca Biaccone, 2018 –Present.

- Developed methods using neon and oxygen to process LCLS II cavities via the HOM couplers, used HOM modes in PIP II spoke cavities and are working on PIP II elliptical cavities all using a neon oxygen gas mixture.
- Paolo developed the general technique to of using a network analyzer to track changes in the cavity frequencies while processing.
- Demonstrated that one could reduce multipactors in LCLS II cavities in-situ in a cryomodule and that plasma processing did not degrade nitrogen doping.



Recovery after simulated vacuum failure

FRIB, Patrick Tutt and Walter Hartung (2022? To present)

- First trial of plasma processing on a FRIB QWR cryomodule (in test bunker, Jan 2024); cryomodule is now installed into linac tunnel (Aug 2024)
- Plasma processing with dual HOMs for FRIB QWRs: under development (Presented here)
- Plasma processing of FRIB HWR with FPC: first successful trial with before-and-after cold tests (Aug 2024)

(*Paolo is currently at BNL)

More plasma processing at other Labs

IMP Lanzhou, Andong Wu, Yuan He

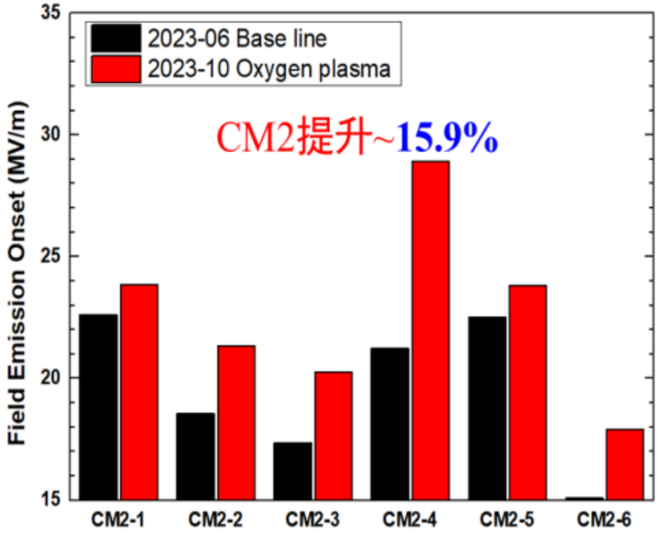
- Combination of helium processing followed by plasma processing.
- Provided a 30% improvement in FE onset with 15% being from active oxygen plasma processing.
- 4 HWR cryomodules processed.

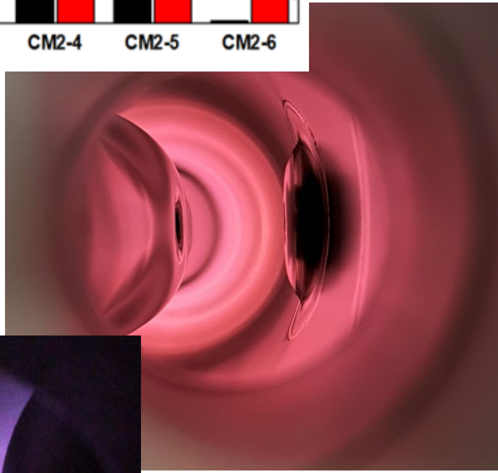
Argonne, Megan McIntyre, Mike Kelly

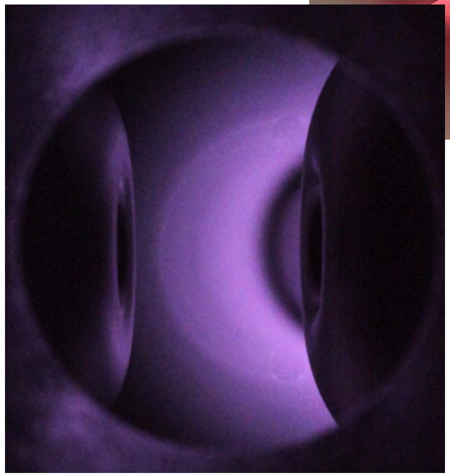
- HWR and QWR structures investigated
- Argon oxygen plasma experimenting with higher order modes and fundamental modes.
- Did experiments from 1 mTorr to 600 mTorr.
- Experiments with biased power coupler and Langmuir probe.

IJC-Lab Paris, Camille. Cheney, D. Longuevergne

- Development of plasma processing procedures for SPIRAL2 QWR (β=0.12)
- Study of fundamental mode, 2nd and 5th harmonics.
- Optimization of processing parameters
- Focus on coupler ignition phenomenon moving to lower pressure and higher frequency.
- Plasma simulations with COMSOL Multiphysics (2D axial symmetry)







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