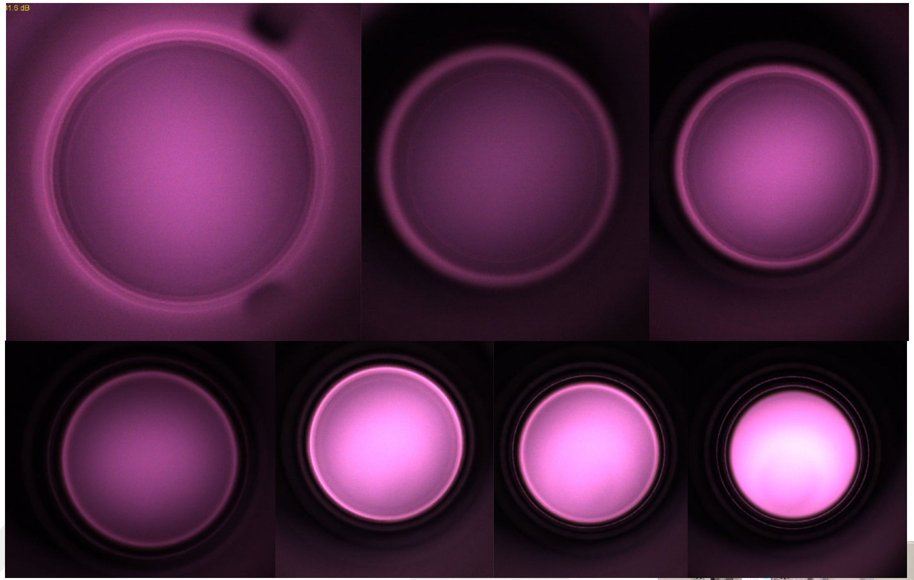
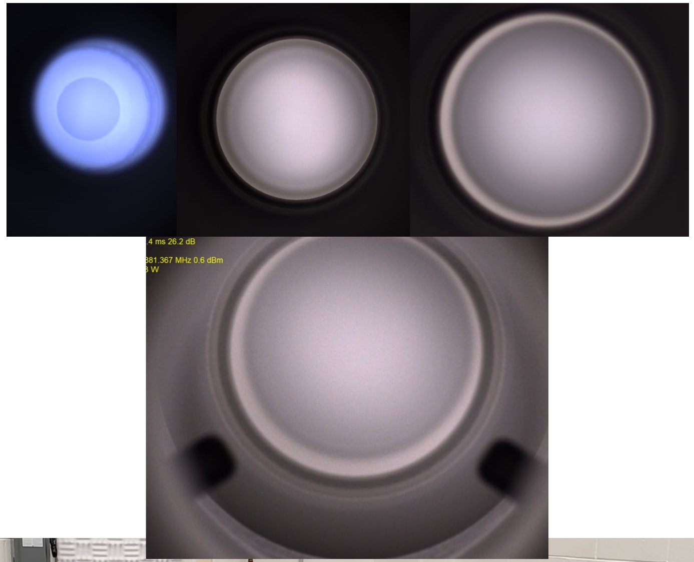
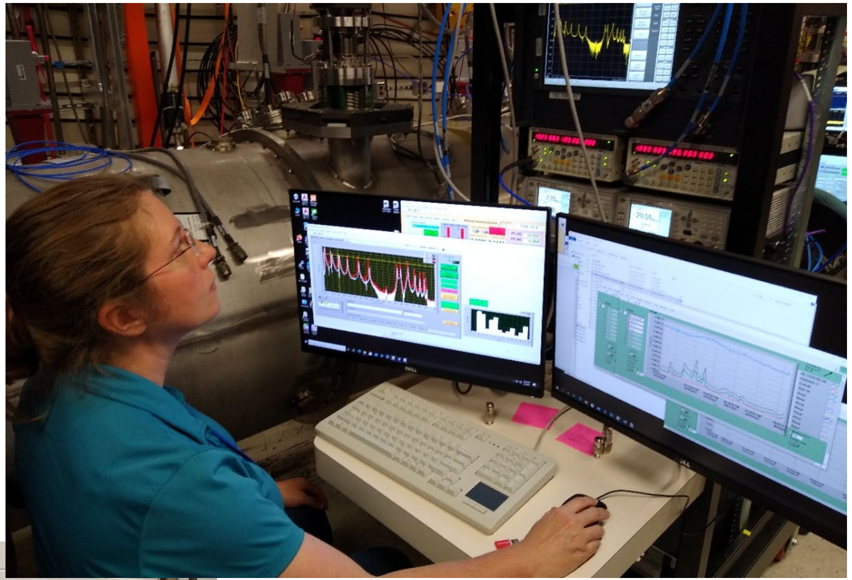
Plasma Processing At Jefferson Lab







Tom Powers, PI
7 Dec. 2023

Other contributors:

Tiffany Ganey
Natalie Brock
Roger Ruber
Nabin Raut (Post Doc)

Vacuum and RF support in CEBAF
Effort led by Frank Humphry

- **CEBAF Vacuum Group**
- **SRF Cavity Clean Assembly Group**
- **SRF Chemistry Group**

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Description of the program

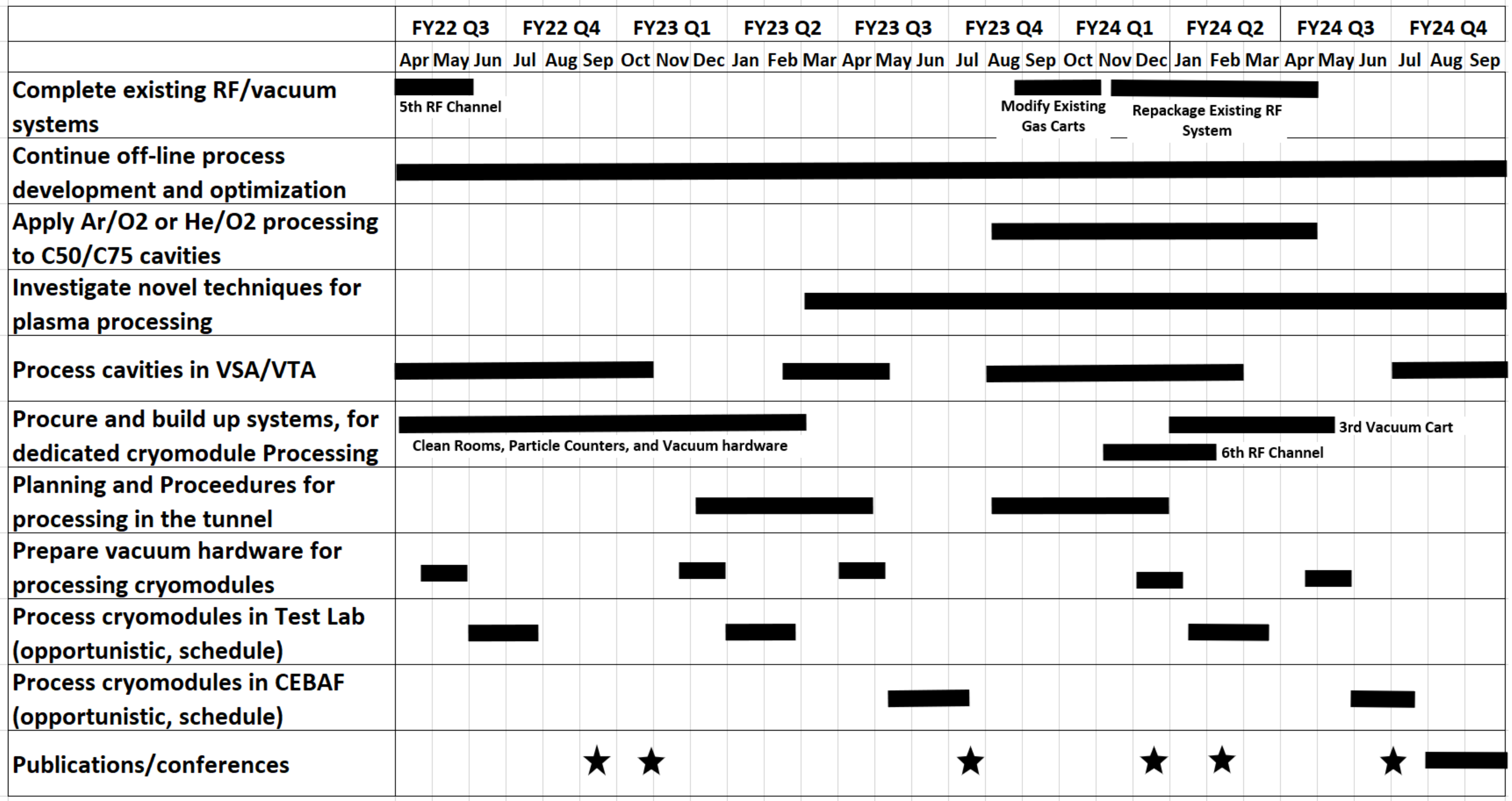
- Work done using JLAB internal accelerator R&D funds prior to this award demonstrated that we could establish and control the plasma generation in a CEBAF C100 cavity on a cavity-cell basis. Additionally, we used DOE R&D funds awarded in FY19, to build up a minimal set of hardware in support of the 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 is allowing JLAB to
  - Add more RF and vacuum hardware so that we can process up to 3 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.
  - Preform simulations for understanding the gas dynamics in CEBAF cavities.
  - To develop methods for in situ processing C20/C50/C75 cavities which do not have external HOM couplers.
  - 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 Sept. 2024.

	FY22*	FY23	Totals
a) JLAB allocated	$650,000	$603,000	$1,253,000
c) Actual costs to date**	$650,000	$94,540	$744,540

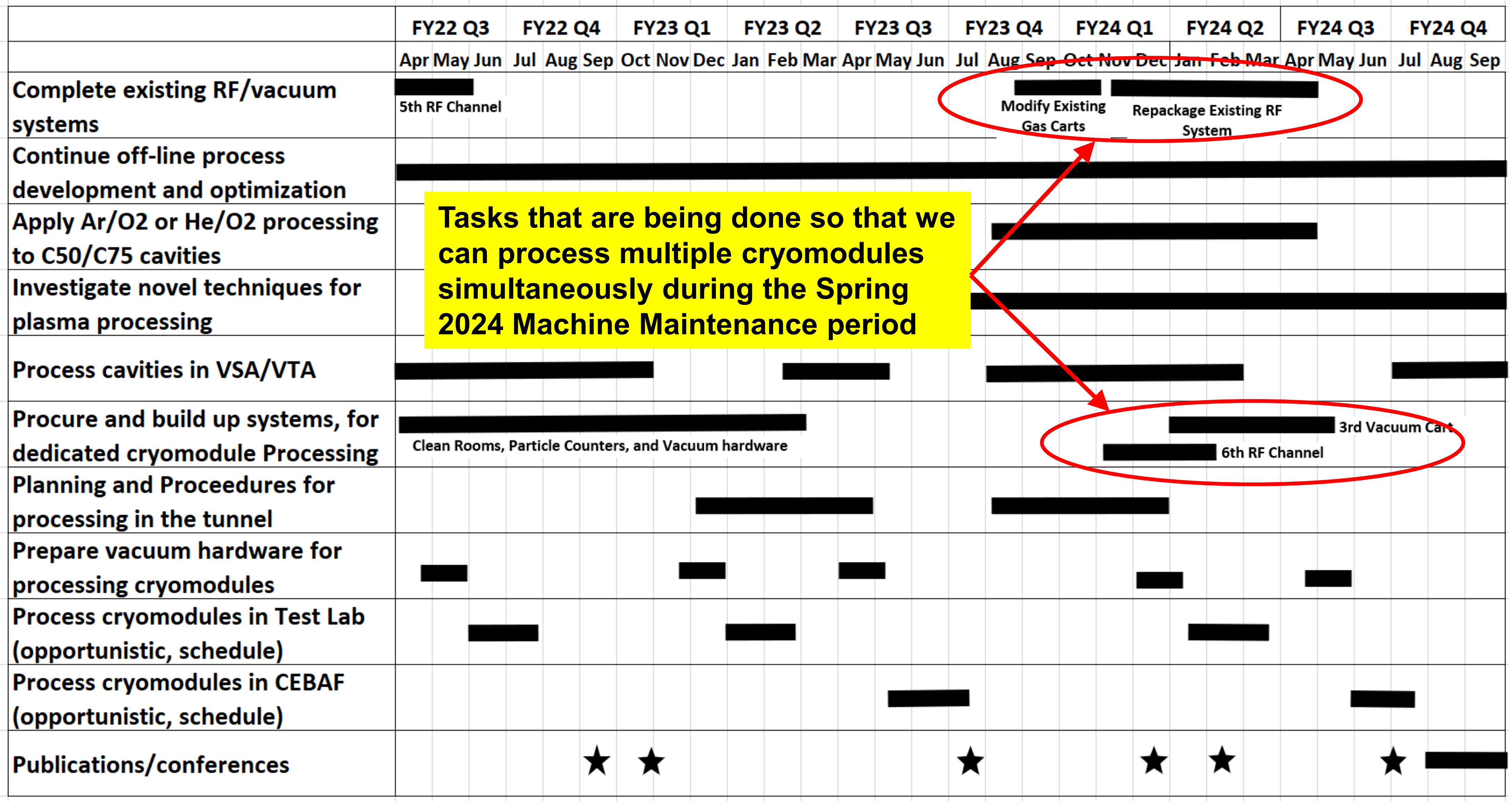
*1 Sept 22 through 30 Aug. 23

** As of 11 Nov. 23

Deliverables and schedule



Deliverables and schedule



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 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 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 started the planning and parts procurement to make plasma processing C75 cavities as part of the production process prior to them being vertically tested.

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

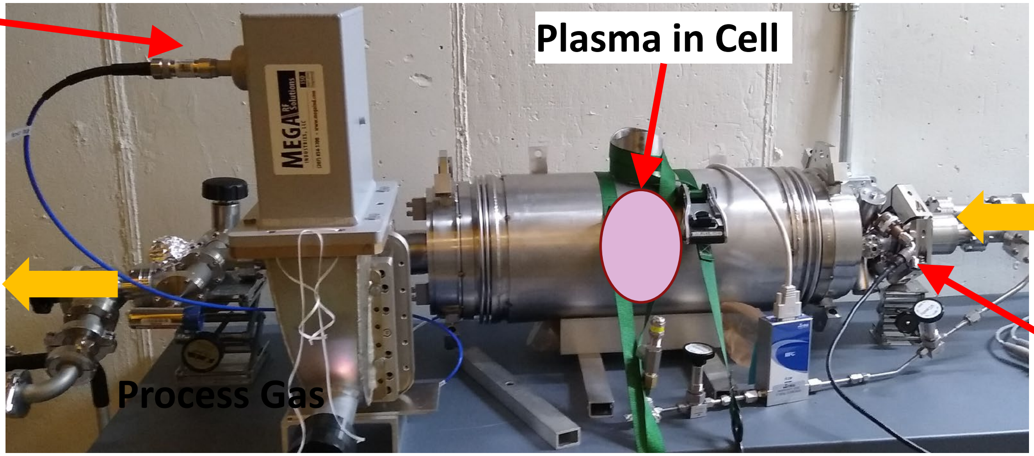
- We processed our second cryomodule (C100-5) in the cryomodule test facility after it was removed from CEBAF for rebuild. Although it had significant improvement it was decided to rebuild the cryomodule prior to re-installation.
- We processed 4 cavities in third cryomodule (C100-10R) after rebuild and prior to it being installed in CEBAF.
- We did the planning for and completed the necessary documentation for processing cryomodules in-situ in CEBAF.
- We processed 4 cryomodules in-situ in CEBAF.
- We started the process of building up one more vacuum cart and one more channel of RF so that we can process up to 3 cryomodules simultaneously in CEBAF.
- Started training additional staff to assist in in-situ plasma processing during accelerator maintenance periods.

Jefferson Lab

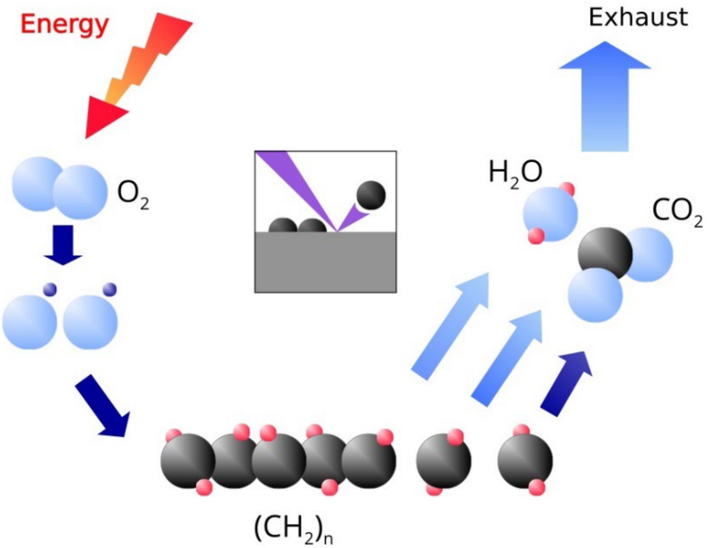
Overall summary, issues Sept. 2022 to Dec. 2023

- **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 is reducing 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.**

Reactive oxygen plasma processing



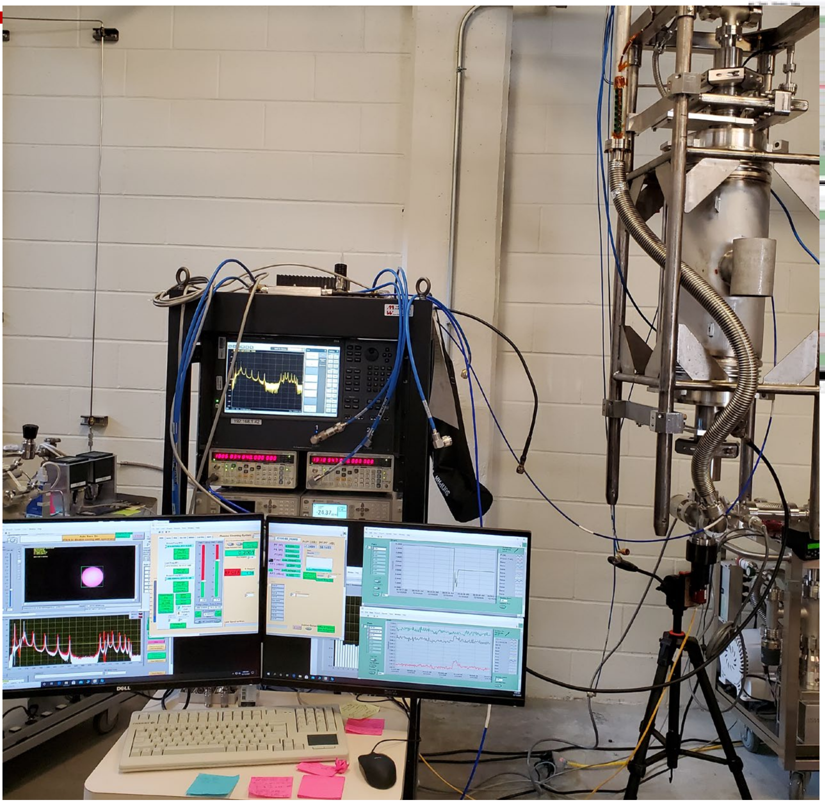
C100 Off-Line Bench Setup

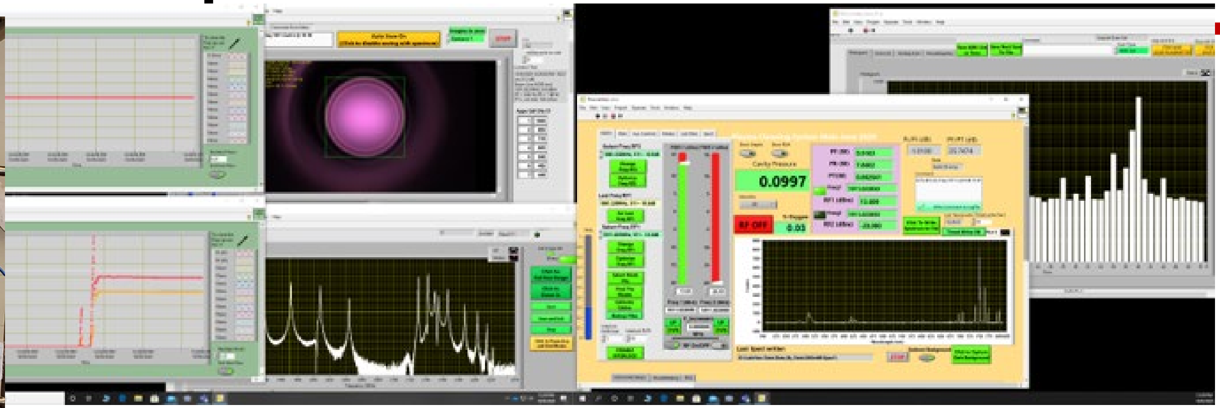


O_2 is cracked in the plasma to atomic oxygen which breaks down the hydrocarbons

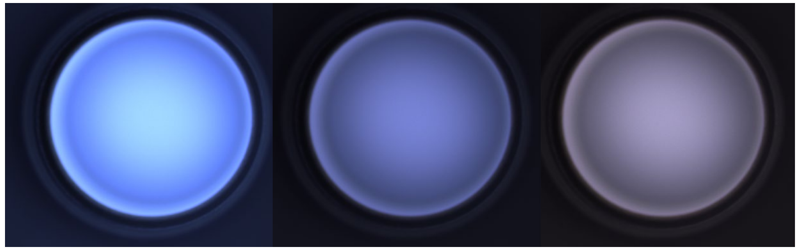
- **SRF "Standard" Recipe**
  - Room temperature mix of inert gas (argon, helium or neon) and a few percent oxygen
  - Flow gas through cavity at a few tens of standard cubic centimeters per minute
  - Pressure in the cavity between 50 and 300 mTorr
  - Apply RF (10 to 600 W depending on system, gas species, pressure, cell and cavity type) to ignite plasma in one cell, LCLS II and JLAB C100 via HOM ports, JLAB C20/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

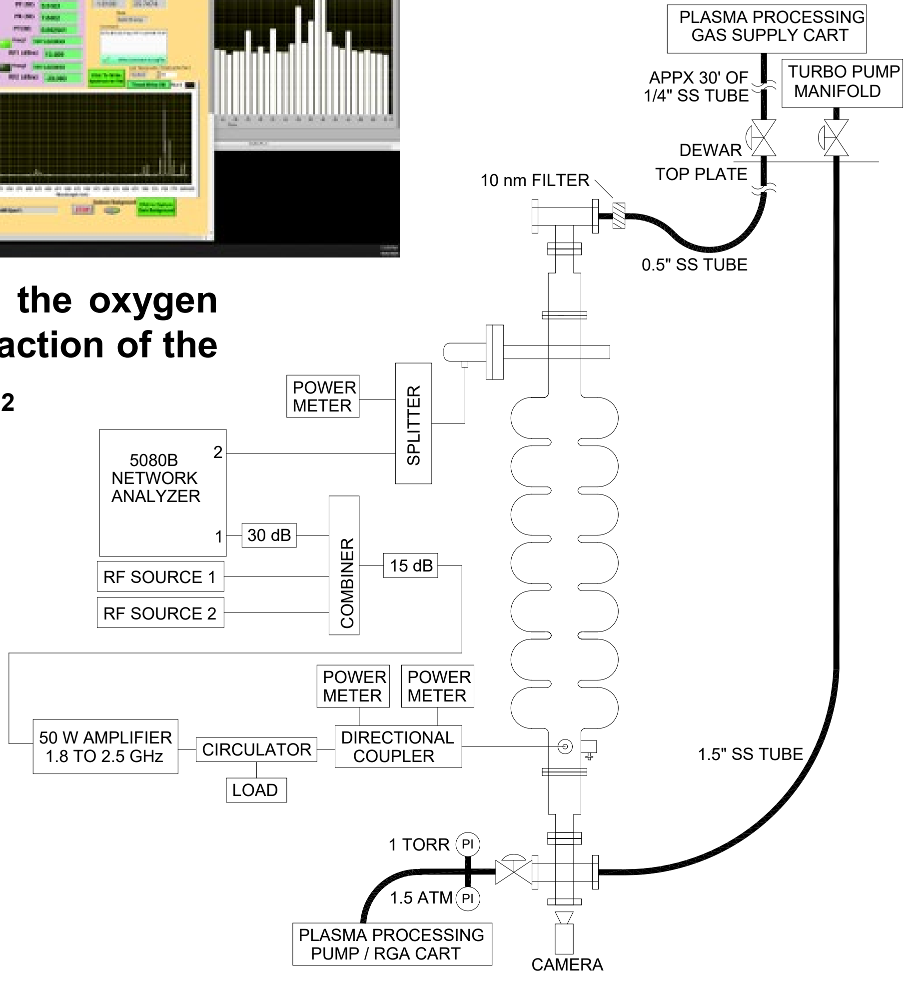
JLAB Vertical Test Stand Setup





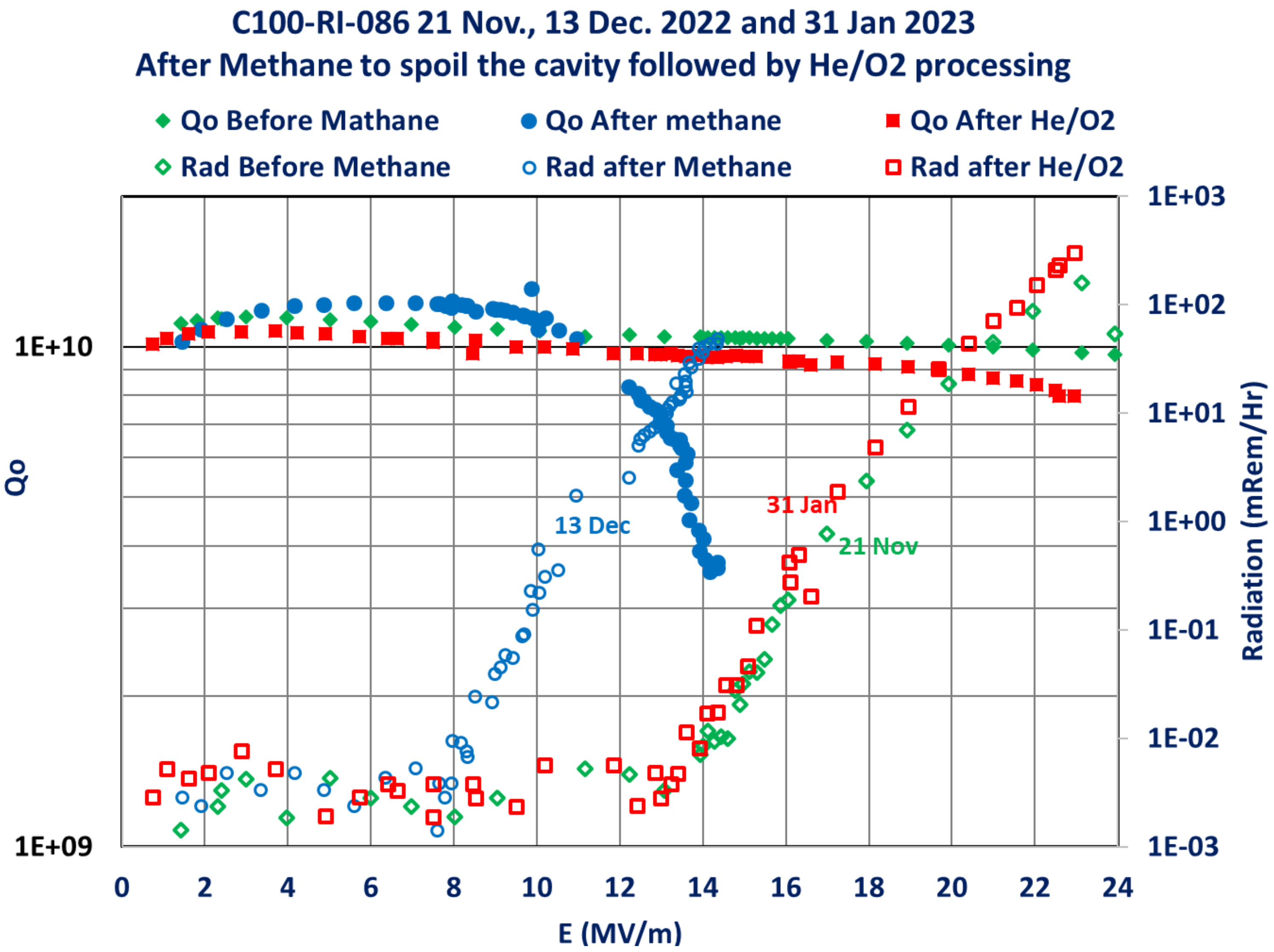
Helium/oxygen discharge changing color as the oxygen content went from 3.8% to 5.6% because a fraction of the oxygen was used to produce H_20, CO and CO_2





- **The purpose of vertical testing is to establish procedures and judge the effectiveness of the methods with cavities under various conditions. Later it will be 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 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**

Results of processing with helium oxygen

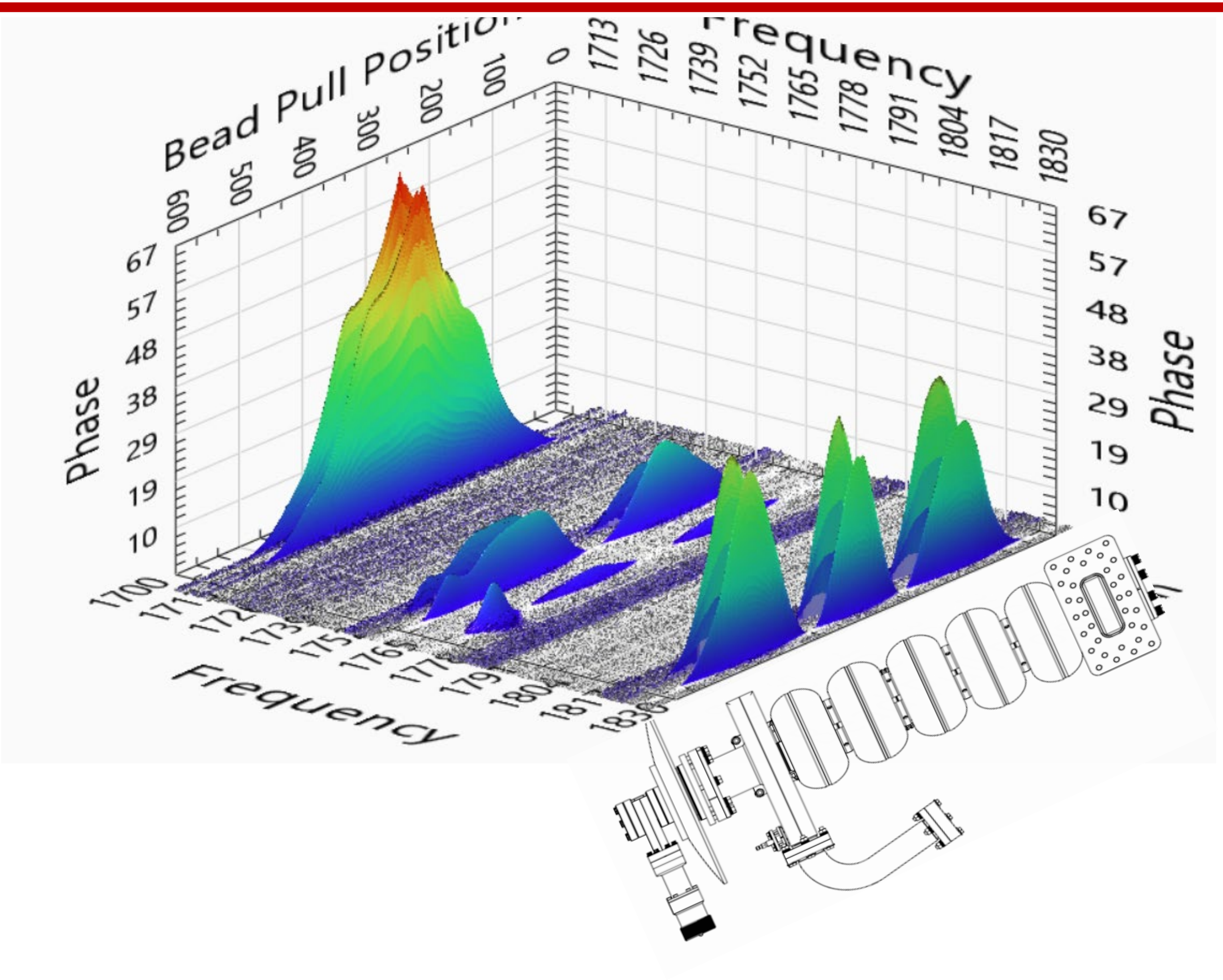


- The cavity was processed multiple times with argon/oxygen and helium/oxygen gas mixtures

- The cavity surface was contaminated with a methane/ argon plasma which reduced the FE onset by 6 MV/m

- Processed 2 cycles with 6% oxygen 94% helium and improved FE onset by 6 MV/m.

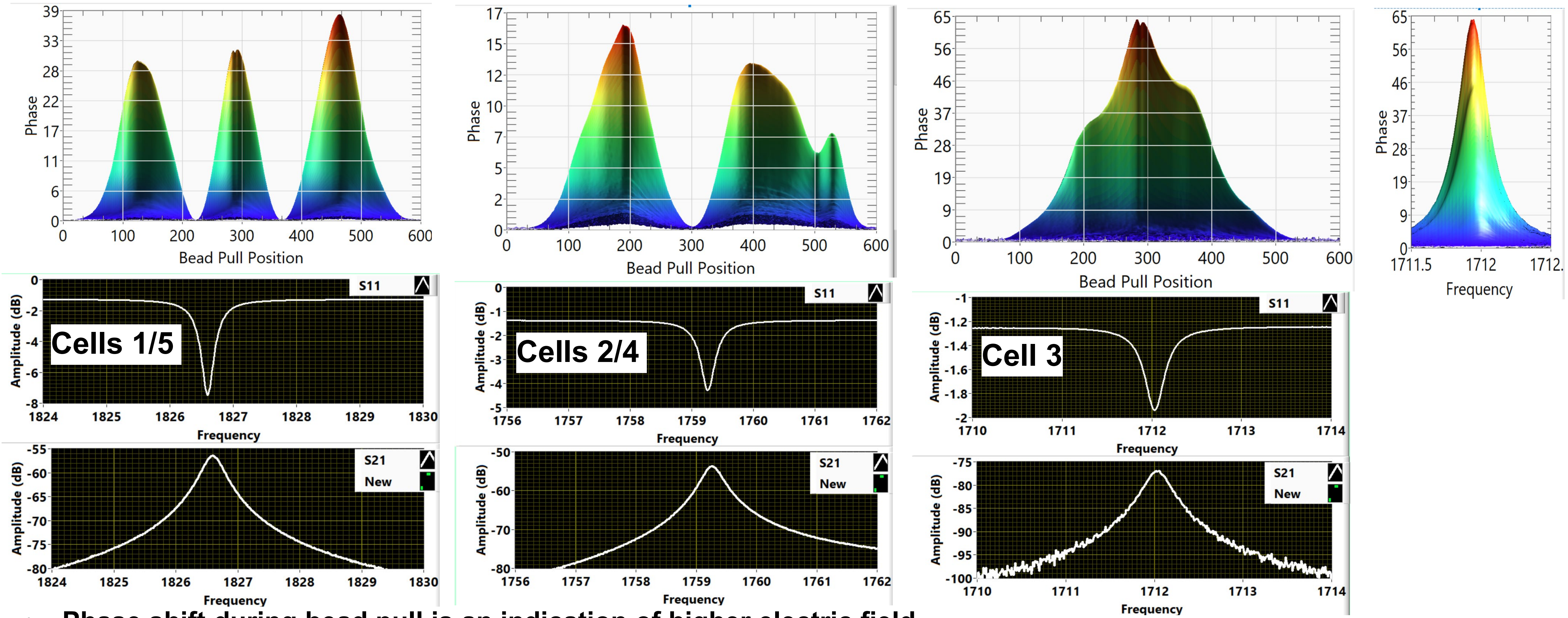
C75 bead pull measurement with swept network analyzer traces



- Normally a bead pull measurement is made at a fixed frequency with a bead that is moved through the cavity at a constant velocity.
- In these measurements we move the bead through the cavity using a stepper motor; stop at each step and record a network analyzer trace.
- We use a 3D plot coupled with S21 and S11 measurements to investigate promising modes.
- In this case the critical mode is one which puts the highest fields in the cell furthest away from the fundamental power coupler.

Jefferson Lab

Bead pull and network analyzer measurements of selected C75 modes

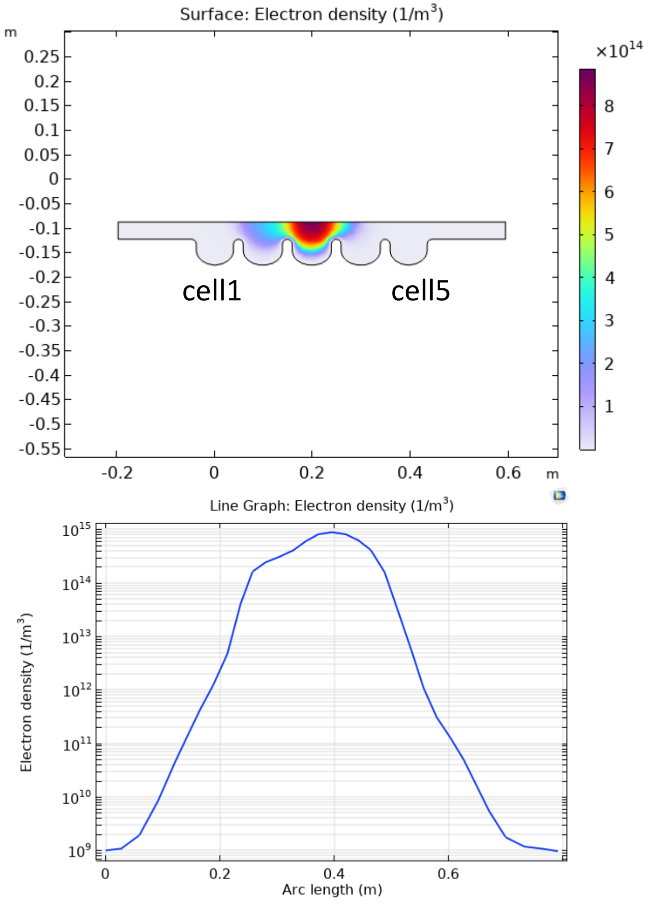


- **Phase shift during bead pull is an indication of higher electric field.**
- **Left three upper plots are projections of the phase shift as the bead is moved along the cavity axis. The far right is a projection in the frequency domain of the 1712 MHz, cell 3, mode.**
- **S11 being more negative indicates increased power going into the cavity at that frequency.**

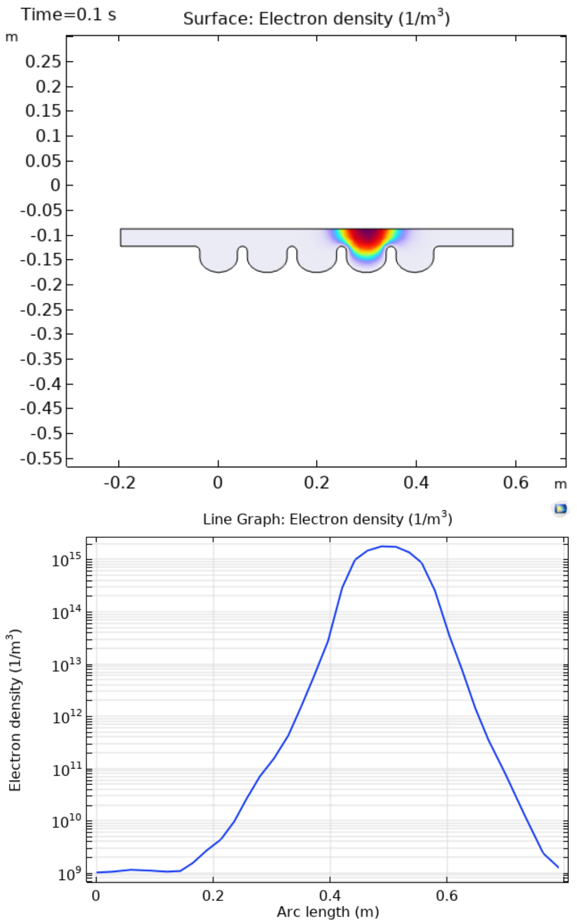
Jefferson Lab

Ignition studies of C75 cavities, simulations (Nabin Raut)

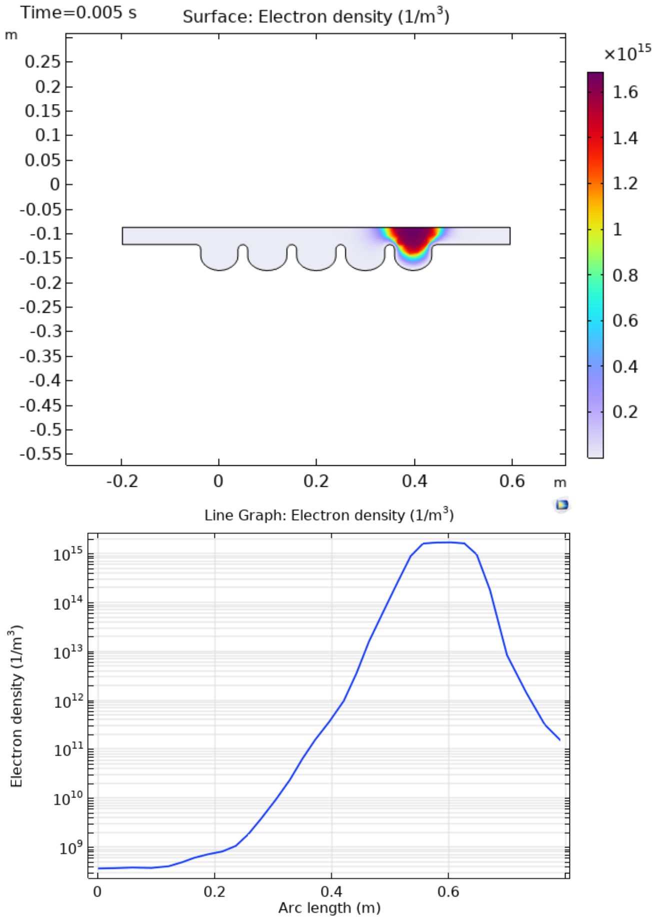
Center cell



Cell 4



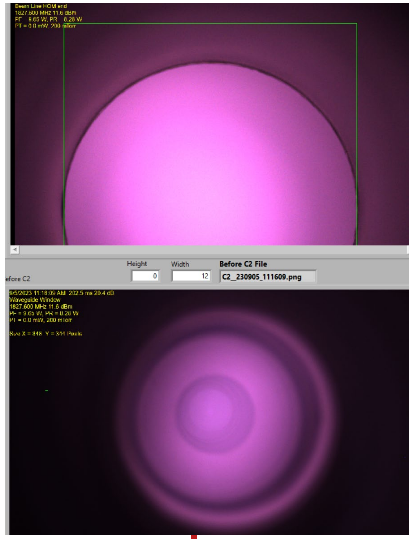
Cell 5



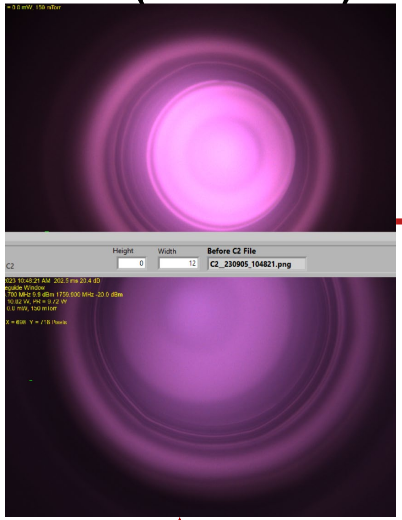
- **Electron and ion densities simulated with baseline EM field profiles from microwave studio and >50 gas cross sections.**
- **Next step is to feed the 3D dielectric constant profile back in to microwave studio**
- **After we iterate through that process we will examine the ion and electron surface interactions.**

C75 Plasma ignition observed with two cameras (Tiffany Ganey and Nabin Raut)

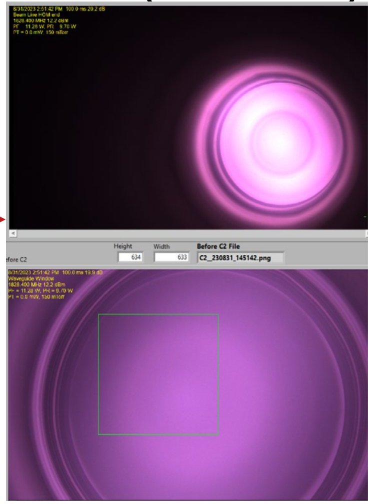
Cell5 (1827 MHz)



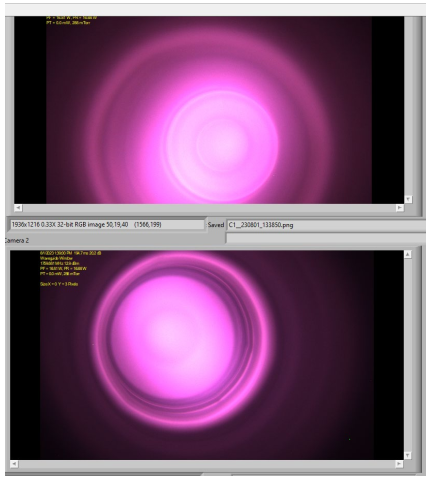
Cell2 (1759 MHz)



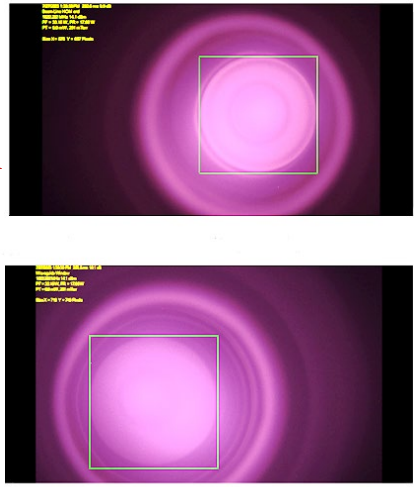
Cell1 (1827 MHz)



Cell4 (1759 MHz)



Cell3 (1712 MHz)



- **Experiments preformed in off line plasma processing facility.**
- **Cavity with fundamental power coupler window and HOM loads installed.**
- **HOM waveguide cutoff 1966 MHz. We got breakdowns in the region of the HOM loads at higher frequencies.**
- **Upper image is camera on cell 5 end.**
- **Lower image is camera is on cell 1 end.**
- **Cell 1 is defined as the cell closest to the fundamental power coupler.**
- **We were able to demonstrate that we could walk the plasma from cell 5 to cell 1.**

Note: Cameras were not always equal distance from the center cell

Cryomodule Processing 2022 and 2023

June 2022 C100-5

- Plasma processed using argon/oxygen in the cryomodule test facility (CMTF) after it came out of the tunnel and before it was to be rebuilt.
- FE onset data was taken before and after processing.

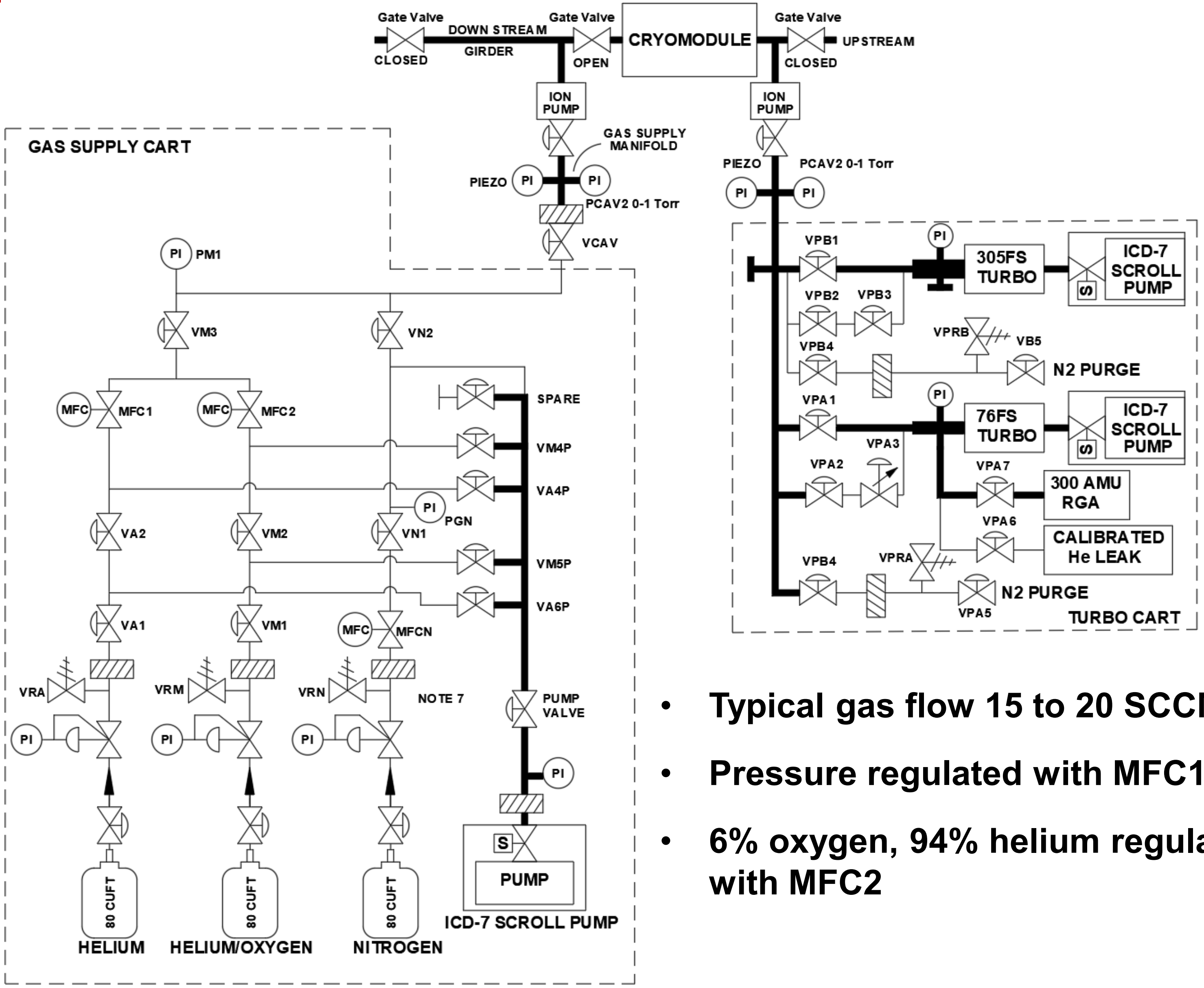
January 2023 C100-10R

- December 2022 RF tested in the CMTF after it was rebuilt
- January 2023 four of the cavities were plasma processed with helium/oxygen due to low FE onset.
- February 2023 it was retested and saw marked improvement on three of the four processed cavities
- In May 2023 it was installed in CEBAF with no degradation as compared to the February test.

In Situ processing of four cryomodules the CEBAF accelerator

- March 2023 field emission onset data was taken opportunistically on 4 cryomodules
- April 2023 the cryomodules were warmed up to room temperature and all of the beam-line gate valves were replaced (this is considered a regular maintenance activity).
- May 2023 four cryomodules were plasma processed in-situ in CEBAF.
- July 2023 post processing field emission onset data was taken

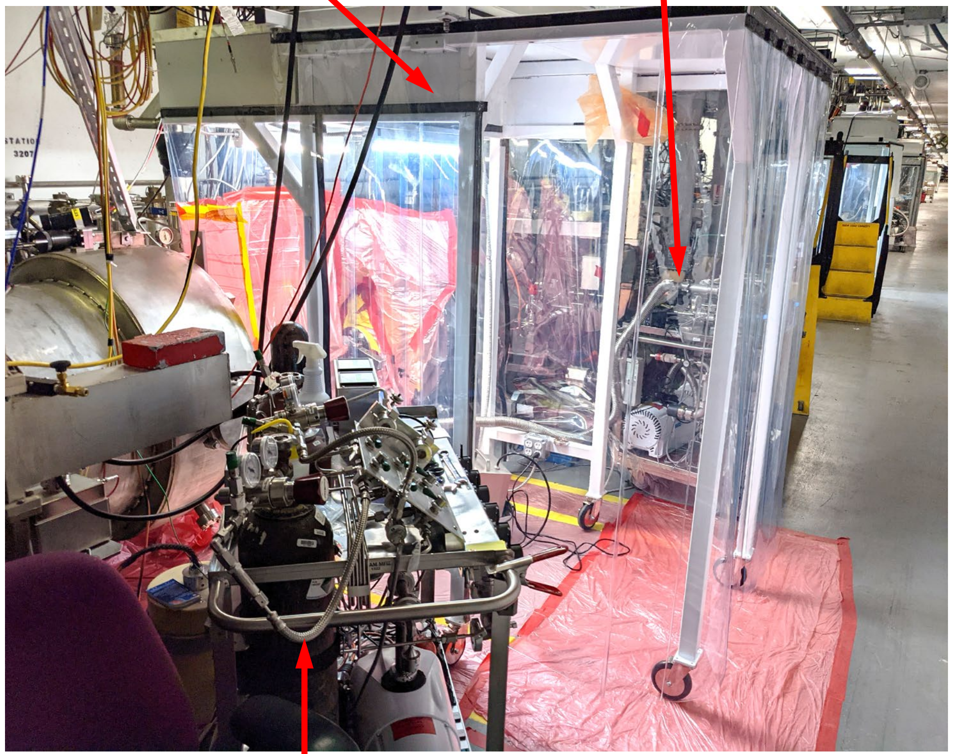
Plasma processing gas supply and pumping systems



- **Typical gas flow 15 to 20 SCCM**
- **Pressure regulated with MFC1**
- **6% oxygen, 94% helium regulated with MFC2**

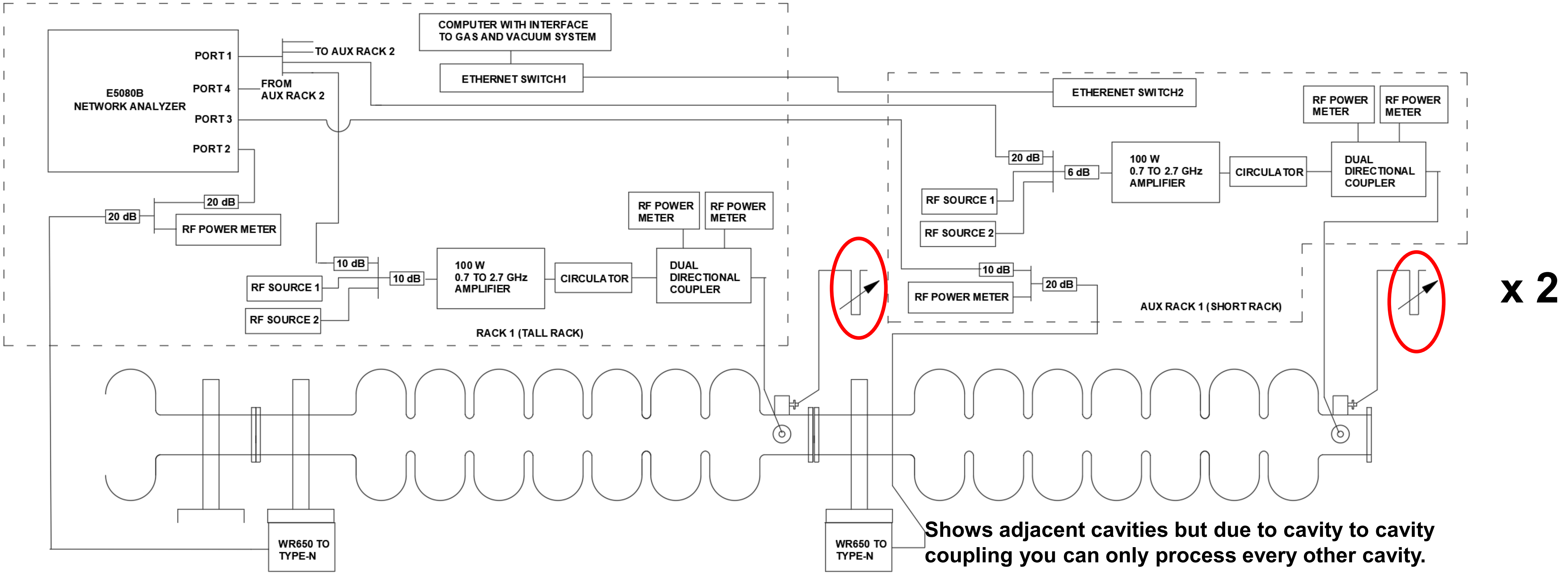
Telescoping clean room

Turbo pump cart with differential RGA



Gas supply cart

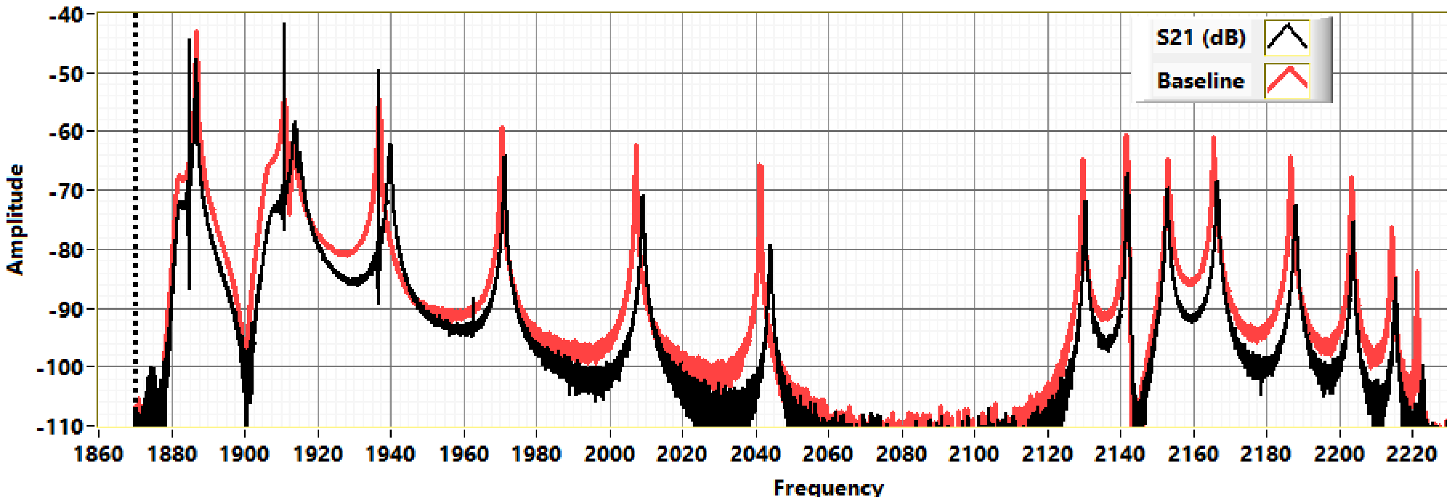
RF system block diagram for processing four cavities at once.



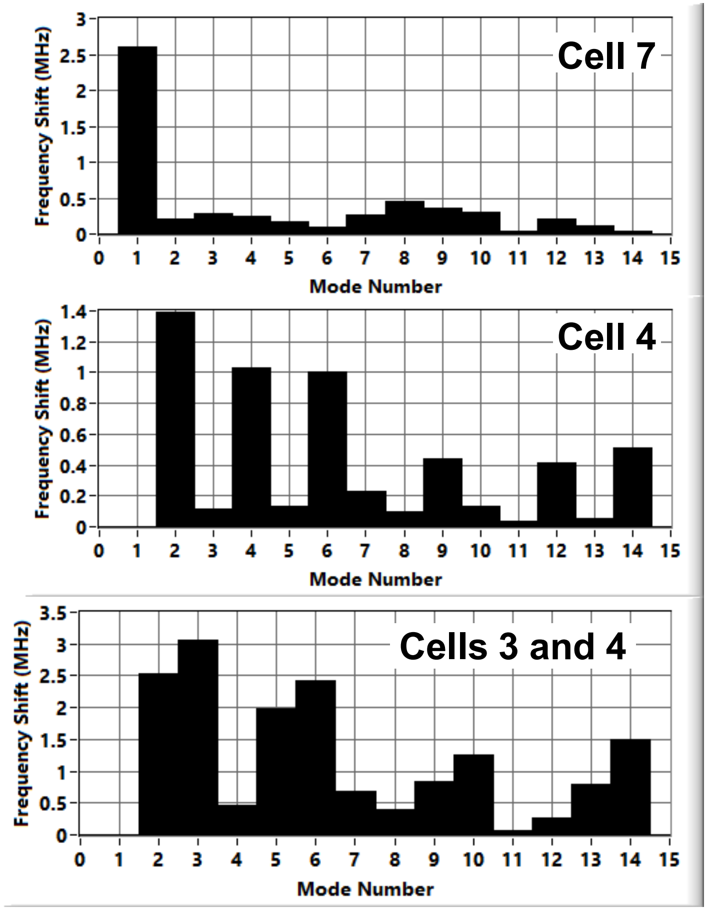
- Same general setup as was used for vertical testing except:
  - 4 Port network analyzer used to measure S21 for up to 3 cavities at once.
  - Phase shifter added to second HOM port because of the effects of coupling from one HOM port to the second HOM port
  - Another identical setup was used simultaneously which allowed us to process 4 cavities at a time.

Jefferson Lab

Using S21 measurement to characterize and locate plasma



Cavity S21 measurement and frequency shift by mode for cell 3 and 4 ignited.



Measured Mode Shifts

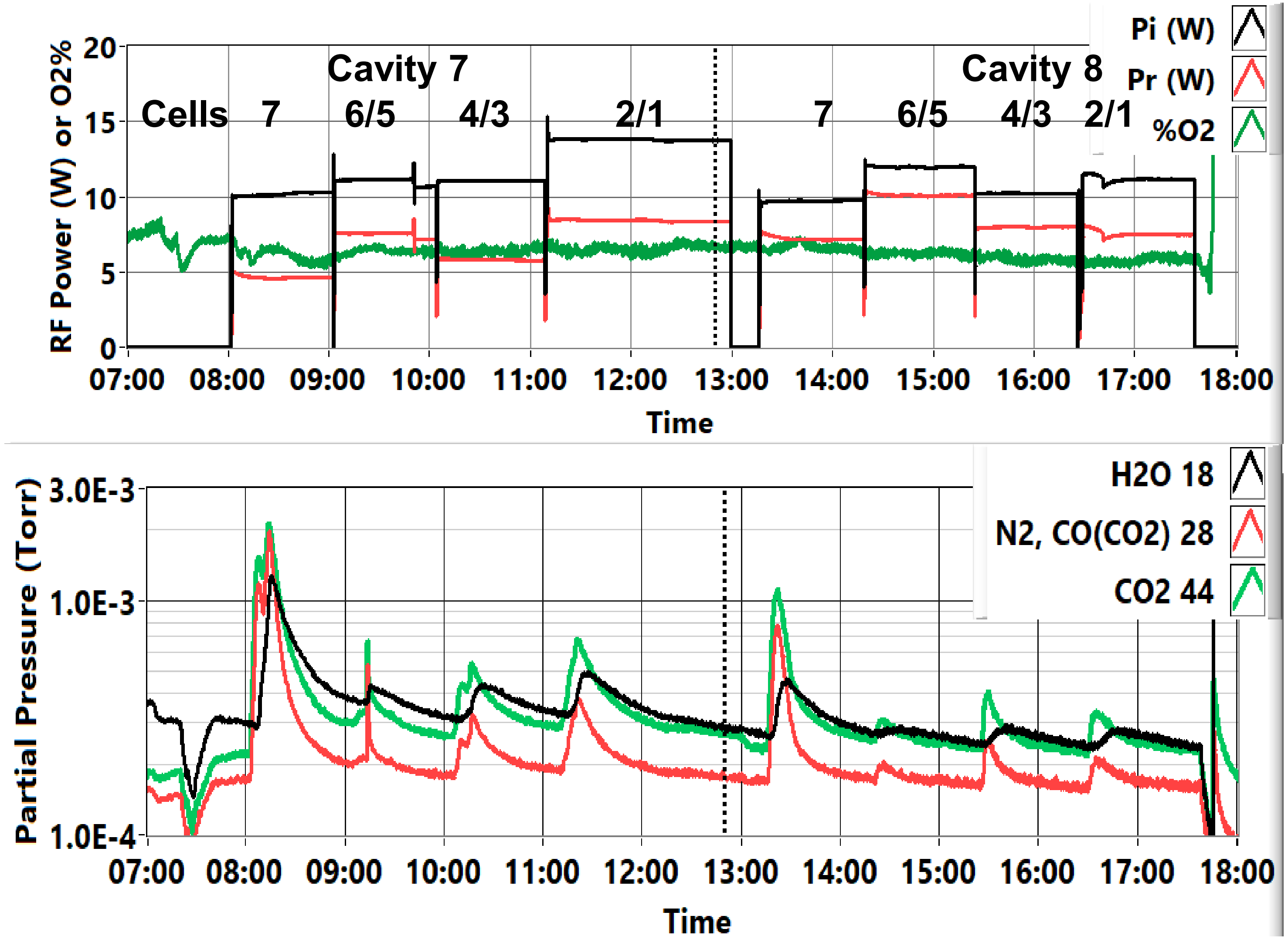
- A low level network analyzer signal is applied to the input of the amplifier and the “probe” signal was fed back to port 2 on the network analyzer.
- The dielectric constant is reduced where there is plasma. The higher the plasma density the lower the dielectric constant.
- Each mode is affected differently 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.
- The frequency shift per mode is presented live while we are processing.
- This method allows us to confirm the plasma location without a camera.

Processing cryomodules in the CEBAF accelerator

- We processed 2 cells at once and 4 cavities at a time.
- Schedule to process a cryomodule is nominally 4 days
  - Day 1 setup RF and characterize cavities
  - Day 2 Process 8 cavities once
  - Day 3 Pause so that hydrocarbons can redistribute
  - Day 4 Process 8 cavities a second time
- We did a 11 hour split shift with one person coming in at 7 AM and the other person staying until 6 PM.
- It was very straight forward for one person to process 4 cavities simultaneously.
- 4 cryomodules were processed over a 3 week period, 5 days a week, 11 hours per day.

Two of 4 channels of the RF system in the tunnel.

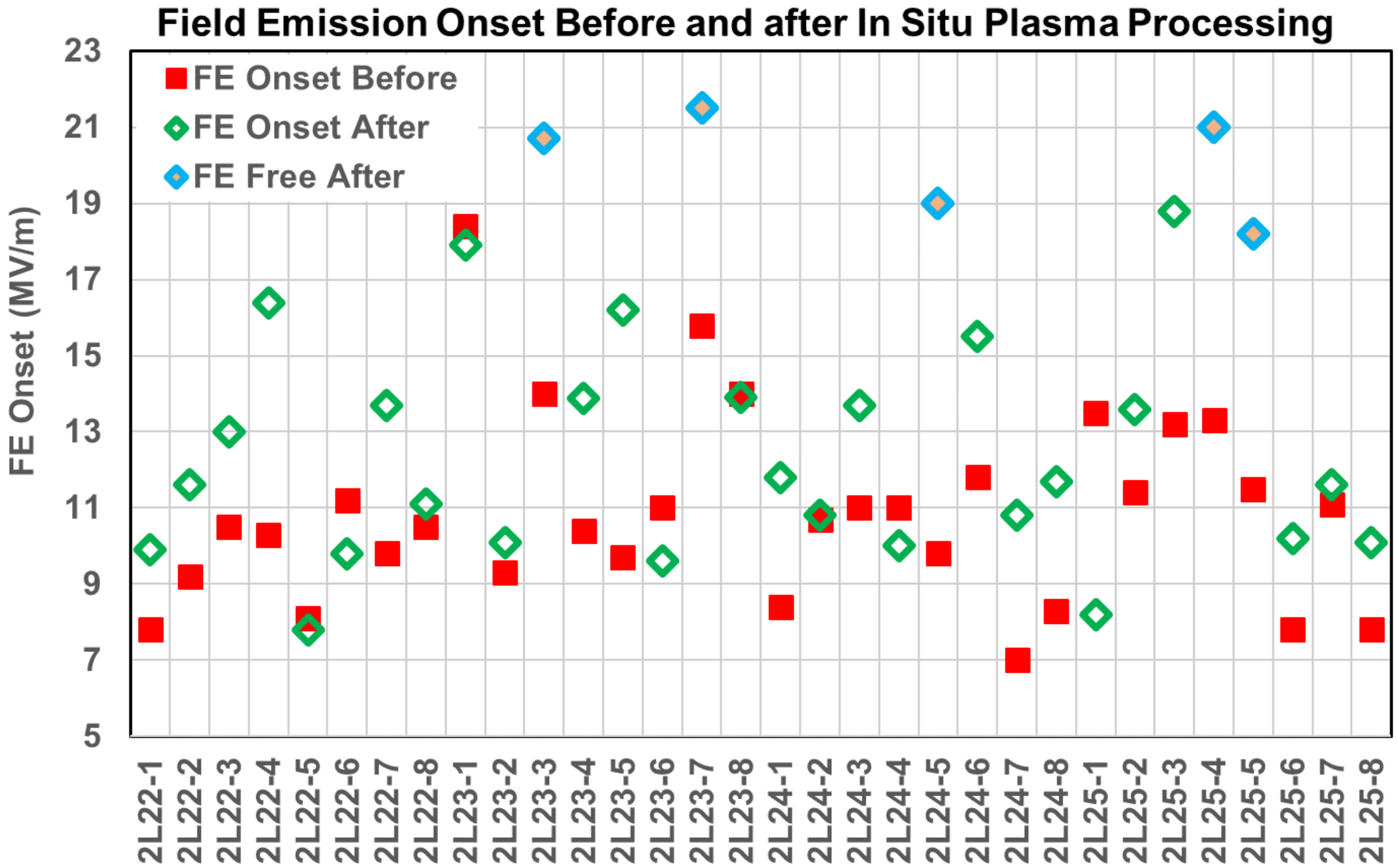
RF power and hydrocarbon residuals produced while processing a cryomodule



RF power and partial pressure of hydrocarbon residuals when processing 8 cavities in one shift

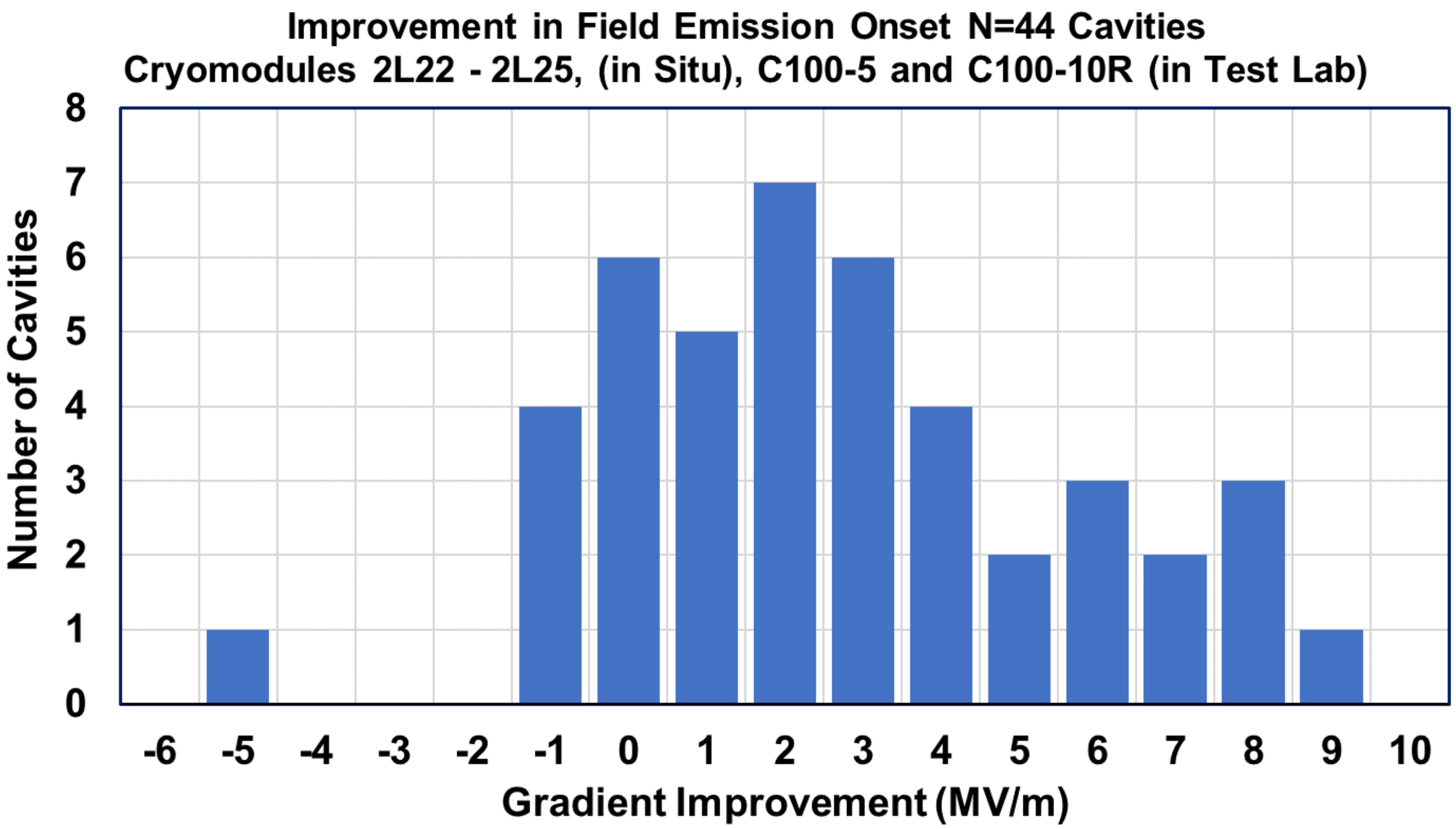
- In addition to monitoring the frequency shifts of the HOM modes due to the plasma we monitored the hydrocarbon residuals which are produced by the plasma.
- Significant amounts of hydrocarbon residuals were produced on the first processing pass.
- A much smaller amount was produced on the second pass.
- Note: The hydrocarbon residuals were produced by 4 cavities which were operated simultaneously.

Cavity by cavity FE onset before and after in-situ plasma processing



- Field emission onset data taken opportunistically in February and March 2023.
- Post processing field emission onset data taken in July 2023, at the end of the scheduled accelerator down.
- 2L25-1 got significantly worse, possibly due to the introduction of particles when valves were changed.
- All of the cavities had field emission when we started.
- 5 of the cavities were field emission free after processing.

Improvement in field emission after plasma processing



- Average improvement in field emission onset was 2.7 MV/m.
- 40 of the 44 cavities that were processed were in cryomodules that also had their beam line gate valves replaced.
- The 4 cryomodules processed in-situ had a 59 MeV improvement in FE onset.
- 6 of the 44 cavities went from field emitting to field emission free after processing

	FE Free Before (MeV)	FE Free After (MeV)	Delta (MeV)
C100-5	59.7	71.5	11.8
C100-10R	95.6	105.4	9.8
2L22	54.2	65.3	11.1
2L23	71.8	86.6	14.8
2L24	54.6	72.3	17.7
2L25	62.7	78.2	15.5

Jefferson Lab

Summary

- We continue to have a robust plasma processing program R&D program using the JLAB vertical test area and off line plasma processing facility.
- We developed the a set of protocols for processing C75 cavities and are making plans to incorporate plasma processing into the production process as a means to overcome the multipacting problems associated with those cavities.
- We processed 2 cryomodules in the cryomodule test facility in June 2022 and January 2023 respectively. We also processed 4 cryomodules in-situ in CEBAF in May 2023.
- The results of processing 4 cryomodules in CEBAF demonstrated that in-situ plasma processing of C100 cryomodules can provide a substantial improvement to their field emission properties.
- We are preparing the hardware so that we can process up to 3 cryomodules in-situ in CEBAF simultaneously.
- We are training additional staff and starting to do the planning for processing multiple cryomodules in the CEBAF accelerator during the spring 2024 scheduled accelerator down.

Acknowledgements

In-Situ Processing in the CEBAF accelerator

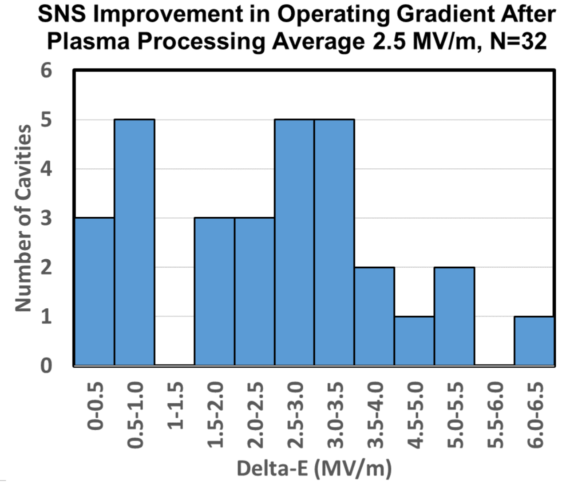
- Tiffany Ganey and I led the effort and did all of the actual processing.
- Frank Humphry led most of the vacuum effort.
- The program was supported by the
  - SRF cavity production technicians, clean assembly work
  - SRF chemistry group, vacuum parts cleaning and prep
  - CEBAF vacuum technicians, logistics and clean assembly work in CEBAF tunnel
  - CEBAF cryogenic technicians for u-tube operations and
  - CEBAF high power RF technicians for waveguide work.

Backup Slides

Why use plasma processing

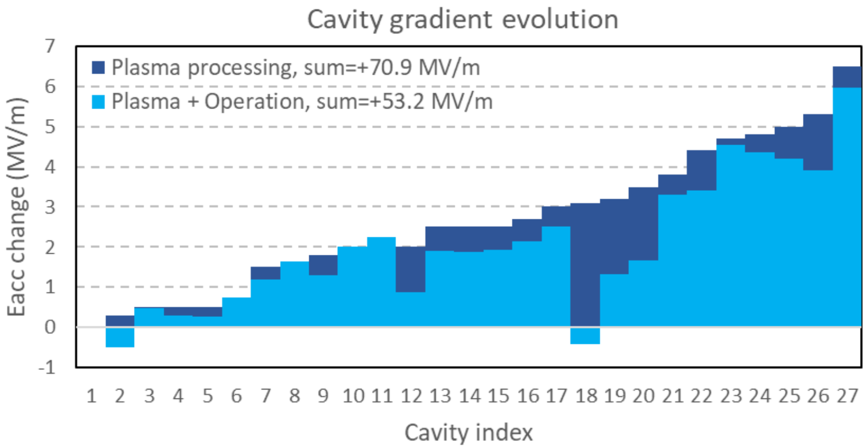
Industial Uses

- Plasma processing is a common technique for removing hydrocarbons from surfaces and improve the wettability of the surface.
- It has the capability to treat complex shapes and can be tuned to deliver surface specific properties.
- Princeton Scientific Corporation has a line of chamber based plasma processing systems that use the same approach.



Early SRF Successes

- 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.
- 2015-2018 Marc Doleans at ORNL 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.*



*Marc Doleans personal communications

Jefferson Lab

Overall summary, progress since Oct. 2020

- Built up two gas supply systems and two turbo pump/RGA systems
- Built up and commissioned 3 RF systems,
  - Two are two-channels systems and are designed for use in the CEBAF accelerator.
  - One is for use in the off line process development facility.
- Completed modifications to a vertical test stand and performed
  - 36 full cycles of RF test, plasma process, RF test cycles in the vertical test area.
  - 31 of these were since Nov. 2021.
- Completed an extensive number of bead pull measurements and ignition studies for C100 and C75 cavities.
- Developed software, for processing multiple cavities simultaneously in a cryomodule. Some of the features are:
  - Regulated process pressure and oxygen content control
  - RF power control and measurement
  - Mode identification software
  - Novel method for bead pull measurement and data analysis
  - Selection of frequency based on desired cell
  - Automatic ignition routine
  - Automatic plotting of mode shifts,
  - Characterizing effects of phase shift of cable on second HOM coupler,
  - HOM coupler breakdown interlock
  - Automatic data logging and display

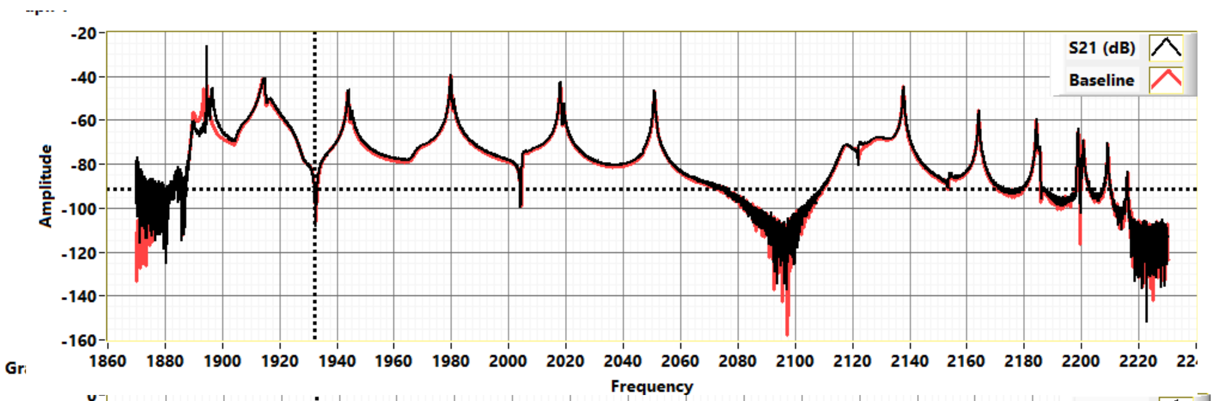
Overall summary, progress since Oct. 2020 (continued)

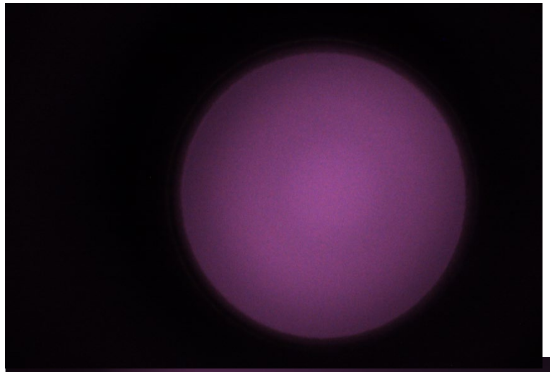
- Processed cryomodules C100-10 and C100-5 in the JLAB cryomodule test bunker.
- Finalized all procedures, protocols and safety documents necessary for processing C100 cryomodules in-situ in CEBAF.
- In-situ Processed cryomodules 2L22, 2L23, 2L24 and 2L25 in CEBAF
- Procured the hardware and built up the first version of an ozone generator system which will be used to test the concept in the off-line processing area with a planned migration to the vertical test area.
- We did plasma processing of copper samples followed by SIMS measurements to insure that we did not damage the copper surface.
- We did a long term processing study 50 hours on cell 7 of a C100 cavity to insure that we did not damage the copper plating on the interior of the waveguide transition or on the field probe antenna.
- Much progress made in using COMSOL plasma physics simulation software which will help us understand
  - The distribution of the plasma within the cavities
  - The ion/electron interactions with the surface
  - Changes in the electromagnetic fields within the cavity due to the 3D distribution of the plasma.

Detecting coupler breakdown using network analyzer

We have an interlock to protect the cavity from HOM coupler breakdown.

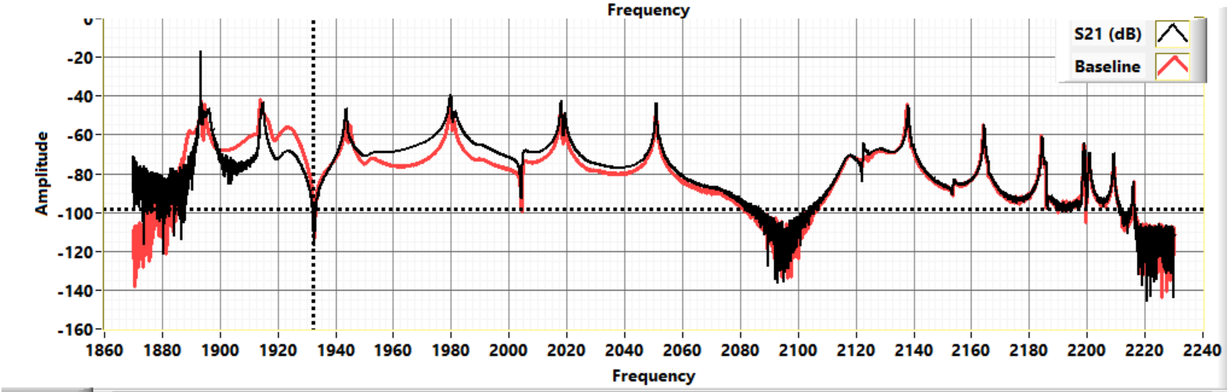
Nominal plasma on/off (black / red) measurements with plasma in cell 7.

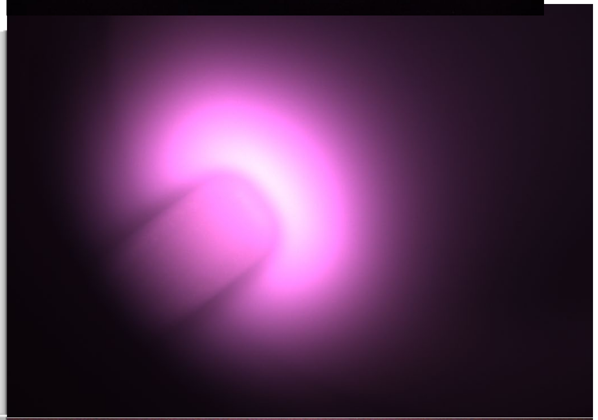




Not a terrible fault mode diffuse discharge at probe tip.

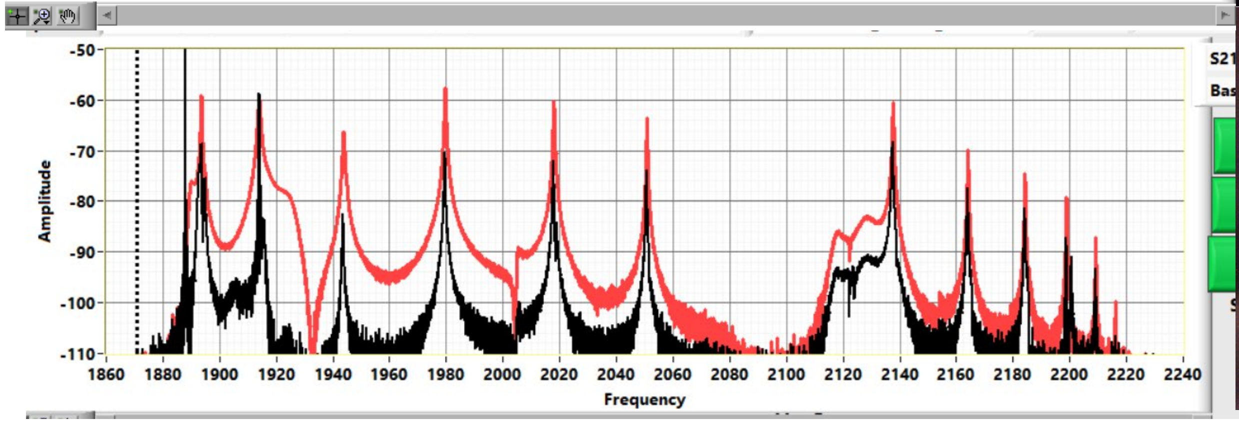
Typical signals for plasma on HOM antenna tip with RF on/off (black / red).

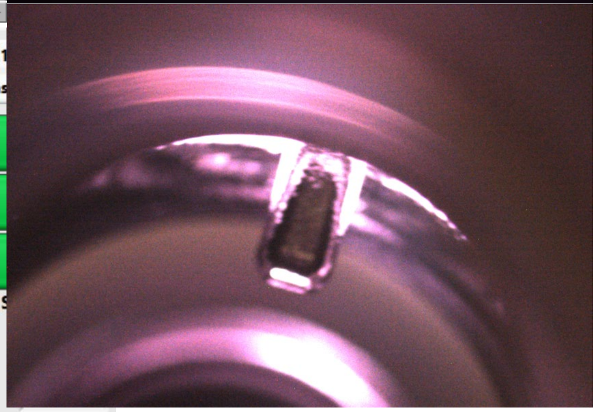




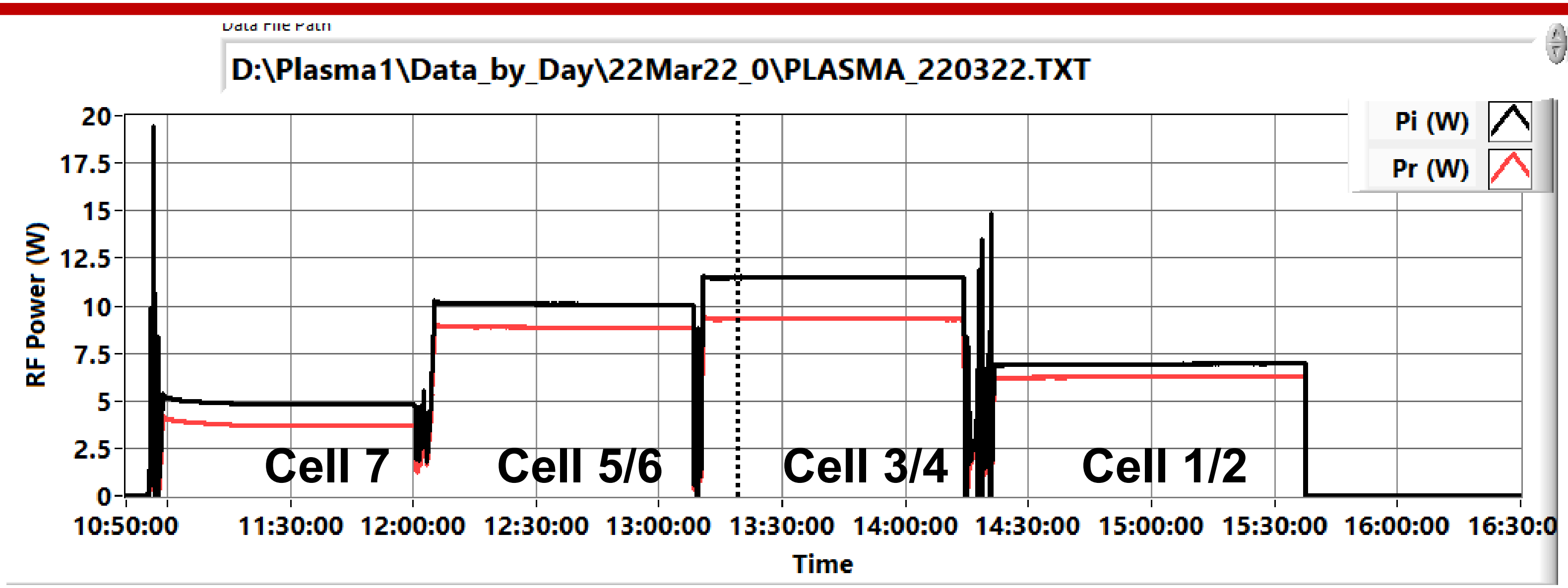
This one is bad as it is an arc like discharge in the tube containing the coupler feedthrough antenna.

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



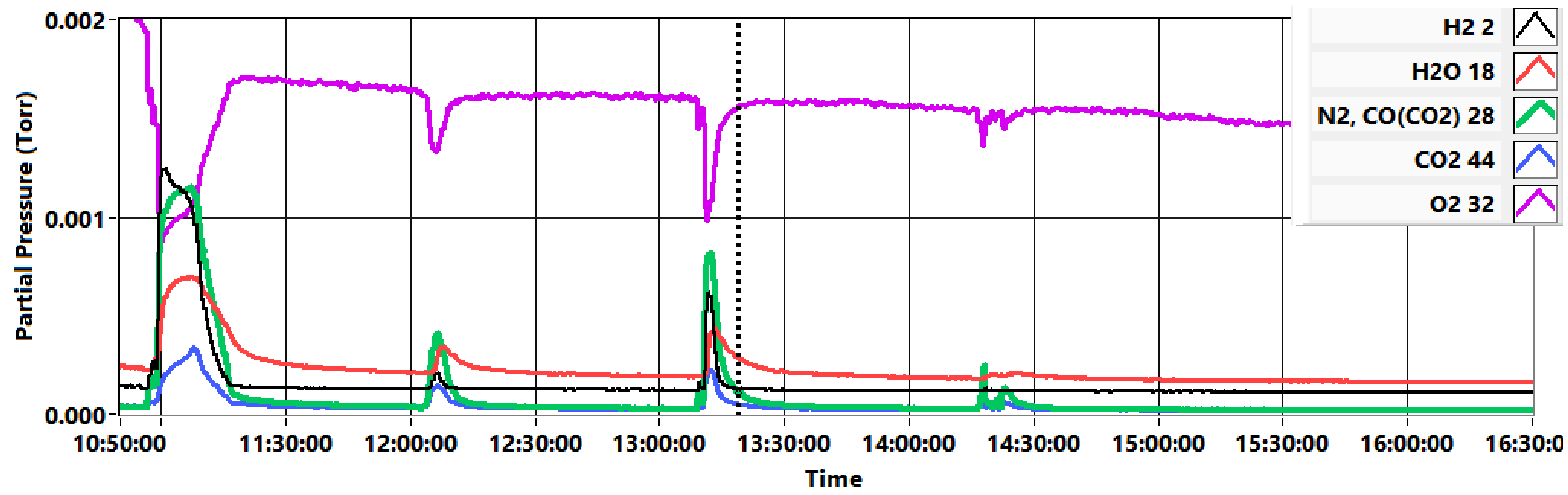


Typical processing cycle in the vertical test area



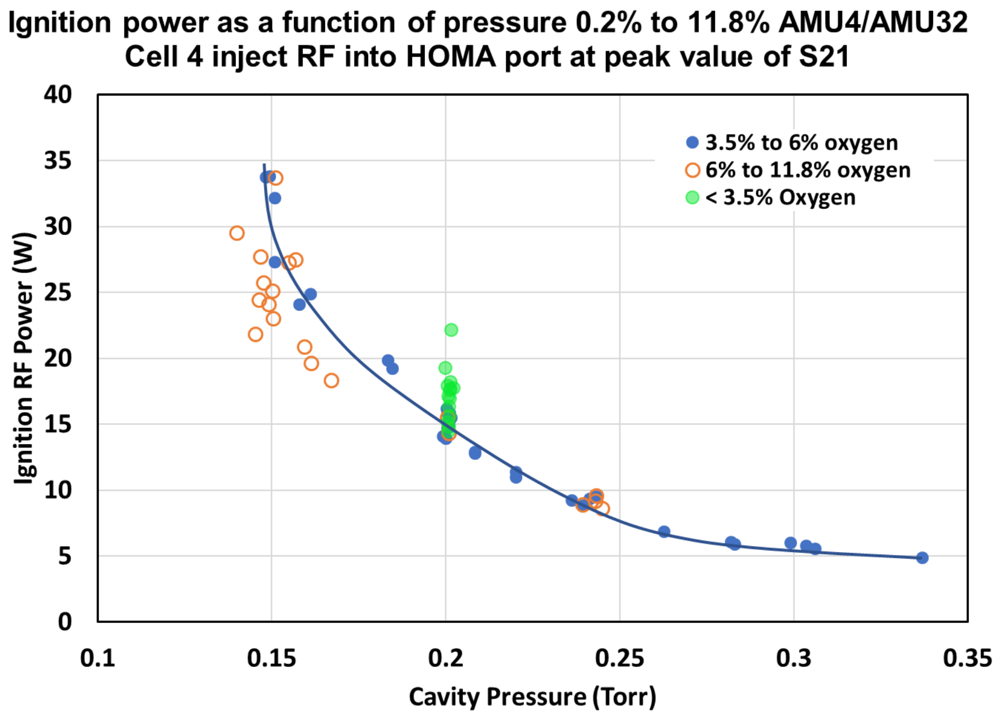
Pi (W)	11.4552
Pr (W)	9.2930
Pt (W)	8.2962E-7
Pf/Pt(dB)	71.4012
CPLR_FLT	0.0000
Amp_SRC1(dBm)	9.6000
F_SRC1	1935.1613
F_SRC2	1908.5640
RF_ON_SRC1	1.0000
RF_ON_SRC2	1.0000
%O2	1.0521
AR 40	3.1080E-5
O2 32	3.2700E-7

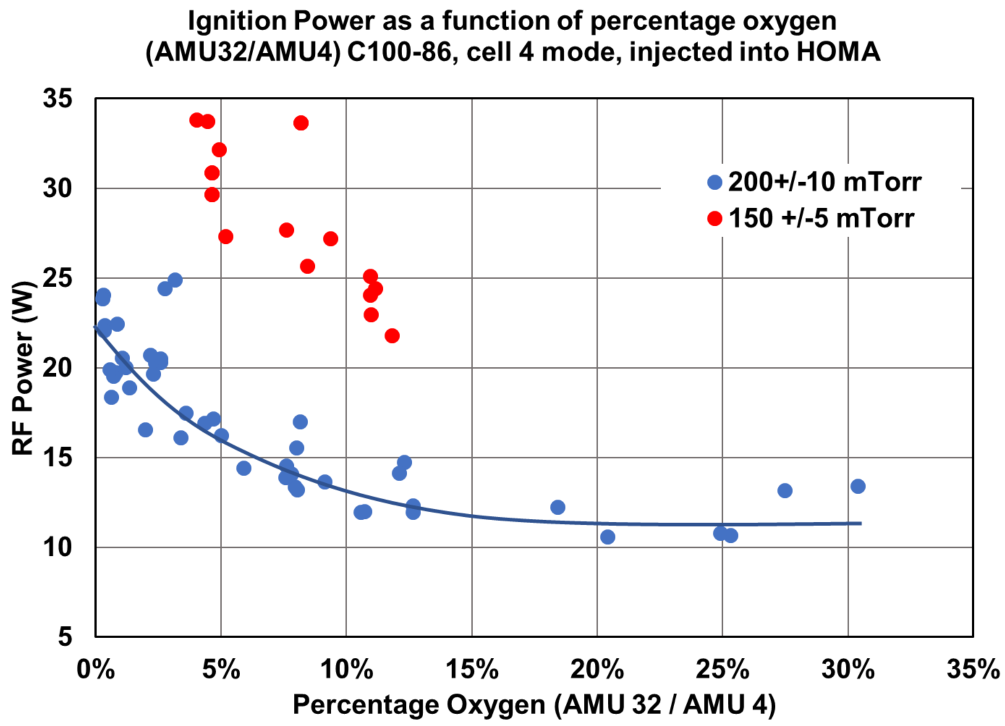
- The Upper Plots are incident and reflected power calibrated to the input of the HOM port.
- Processing 2 cells at the same time reduces the processing time by 40%



- The violet trace which is oxygen, the lower plot are the hydrocarbon residuals of hydrogen, water, carbon monoxide and carbon dioxide.
- The partial pressures are scaled to the pressure at the exit of the cavity.
- The oxygen content was reduced as it was used to produce water, carbon monoxide, and carbon dioxide.

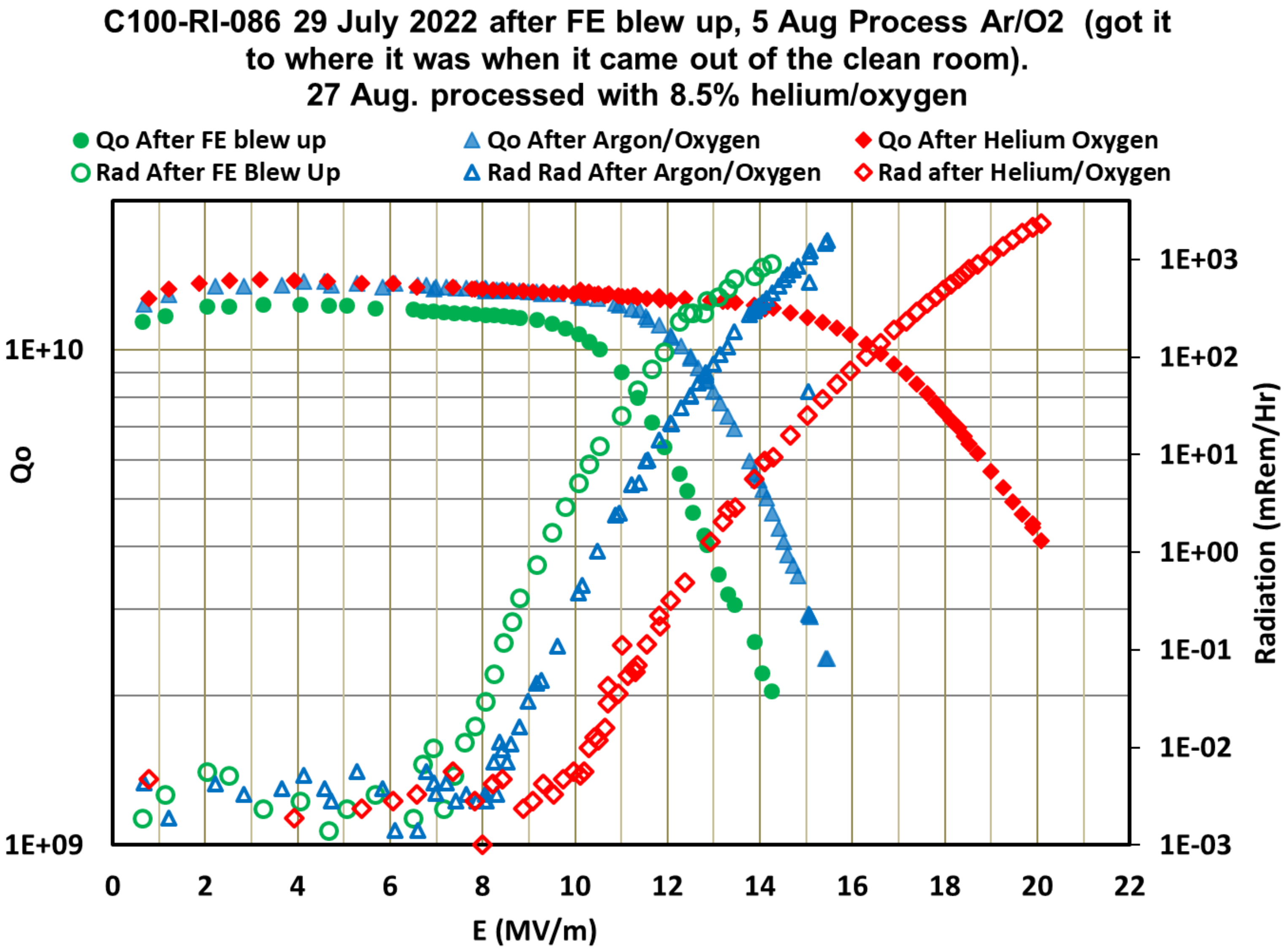
Ignition power as a function of pressure and oxygen content for helium





- Data indicated that it took a moderately higher power to ignite the plasma in helium oxygen as compared to argon.
- There is dependence on the oxygen content
- Ignition is statistical in nature, e.g. if you are patient and stay at a given power just below prompt ignition the plasma will often ignite after 30 seconds.
- Once ignited at higher pressure one can lower the pressure, while maintaining the discharge.
- So far we have done processing at 50 mTorr, 100 mTorr, 200 mTorr and 300 mTorr.
  - 50 mTorr - difficult to do and we saw no improvement
  - 300 mTorr, easy to ignite the plasma very few breakdown issues

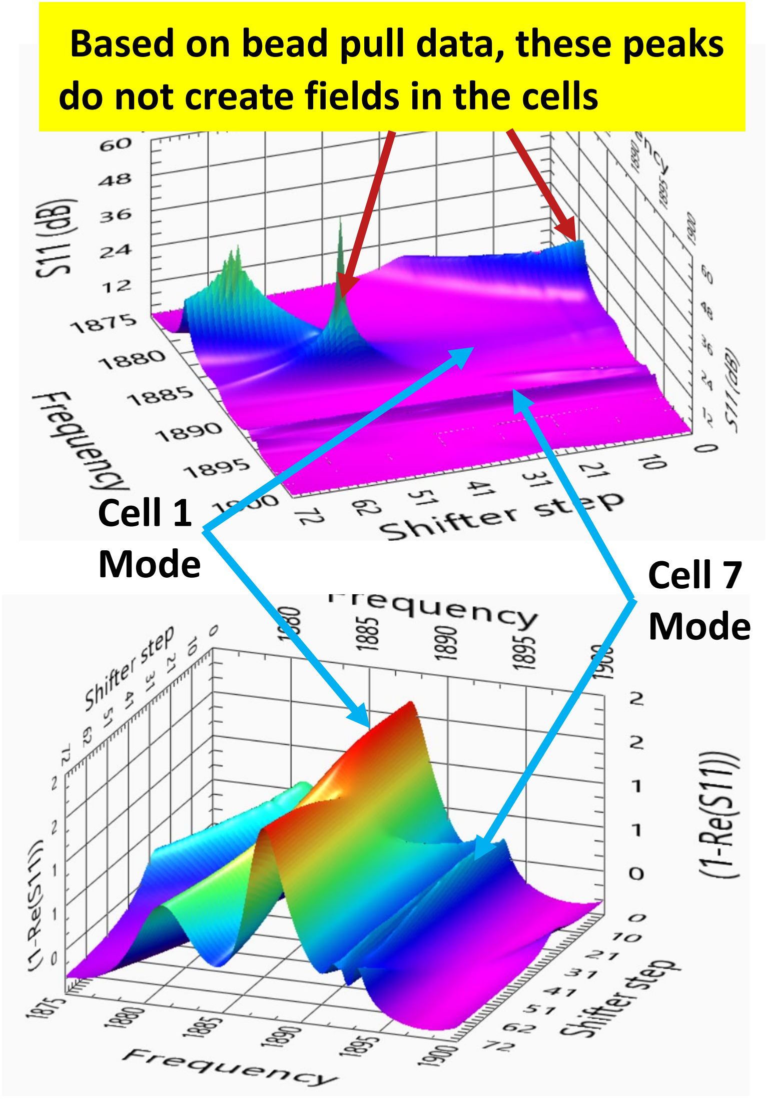
First results processing with helium oxygen



- After we blew up a field emitter (green circles) we processed with the standard 1% to 2% argon/oxygen followed by 20% argon/oxygen and got about 1 MV/m improvement (Blue Triangles).
- We followed this by processing with a 8.5% helium/oxygen gas mixture and improved it another 2 MV/m (Red Diamonds).
- **Helium/oxygen improved a cavity that was not improving any more with argon/oxygen.**
- **Promising first results.**

Jefferson Lab

Why is the phase shifter necessary



- 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.
- After extensive bead pull experiments we decided to use an open circuit phase shifter on the unused port, measure the S11 and S21 parameters of the system and choose a phase that provides favorable RF properties for exciting the different modes.
- One of the main issues is the Cell 1 mode. If one tries to operate at the phase settings with large losses that do not couple into the cells the couplers will experience breakdowns without establishing a plasma in the cells.