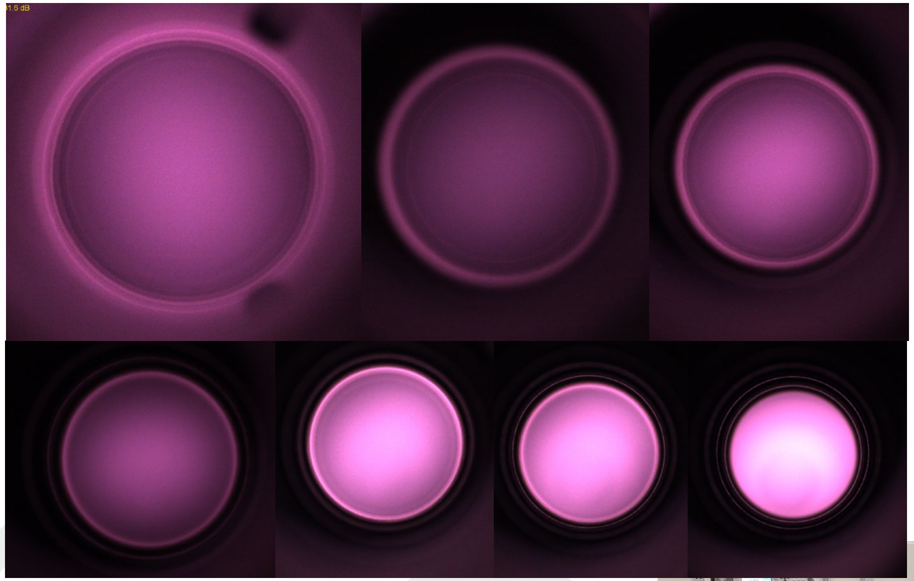
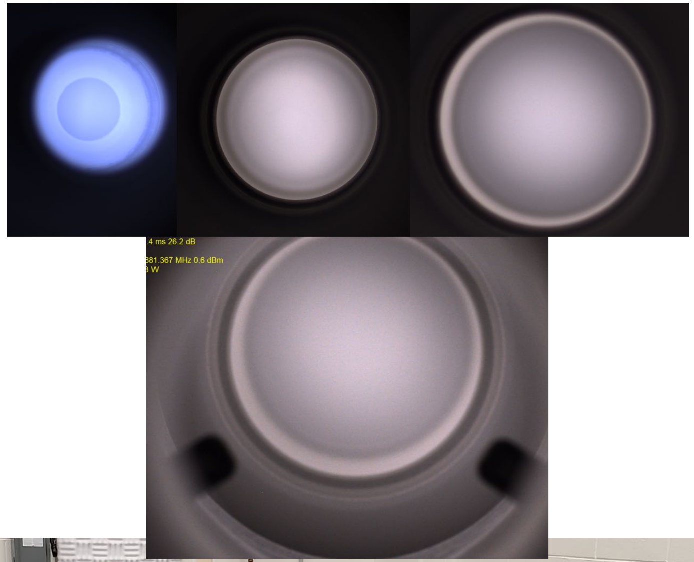
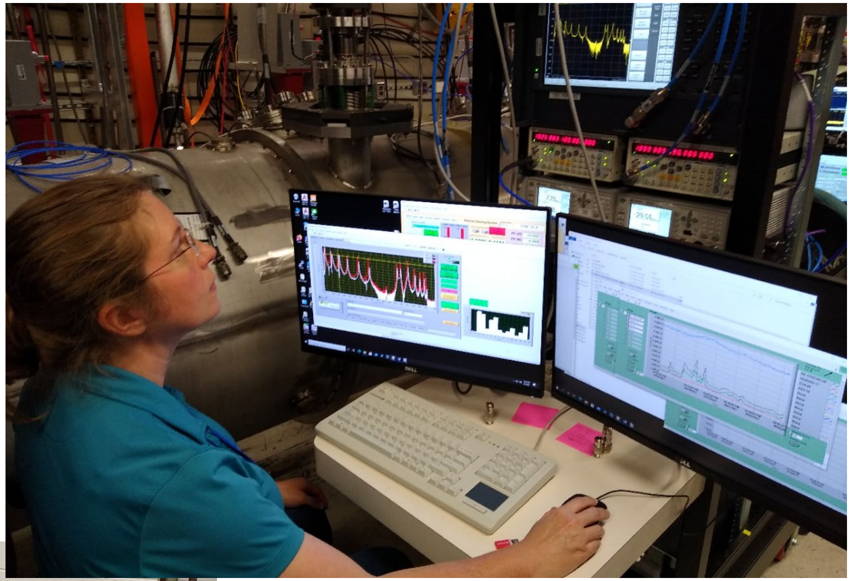
Plasma Processing At Jefferson Lab







Tom Powers, JLAB

Marc Doleans, ORNL

29 Nov. 2022

Jefferson Lab

Other contributors:

JLAB:	ORNL
Tiffany Ganey	Chris Mahan
Natalie Brock	
Roger Ruber	
Nabin Raut (Post Doc)	

ODU

Chunqi Jiang EE Dept. Faculty

Zachary Caudell* MSEE student

*Part of DOE sponsored Virginia Innovative Traineeship in Accelerators Program

U.S. DEPARTMENT OF ENERGY | Office of Science | JSA

Description of the program

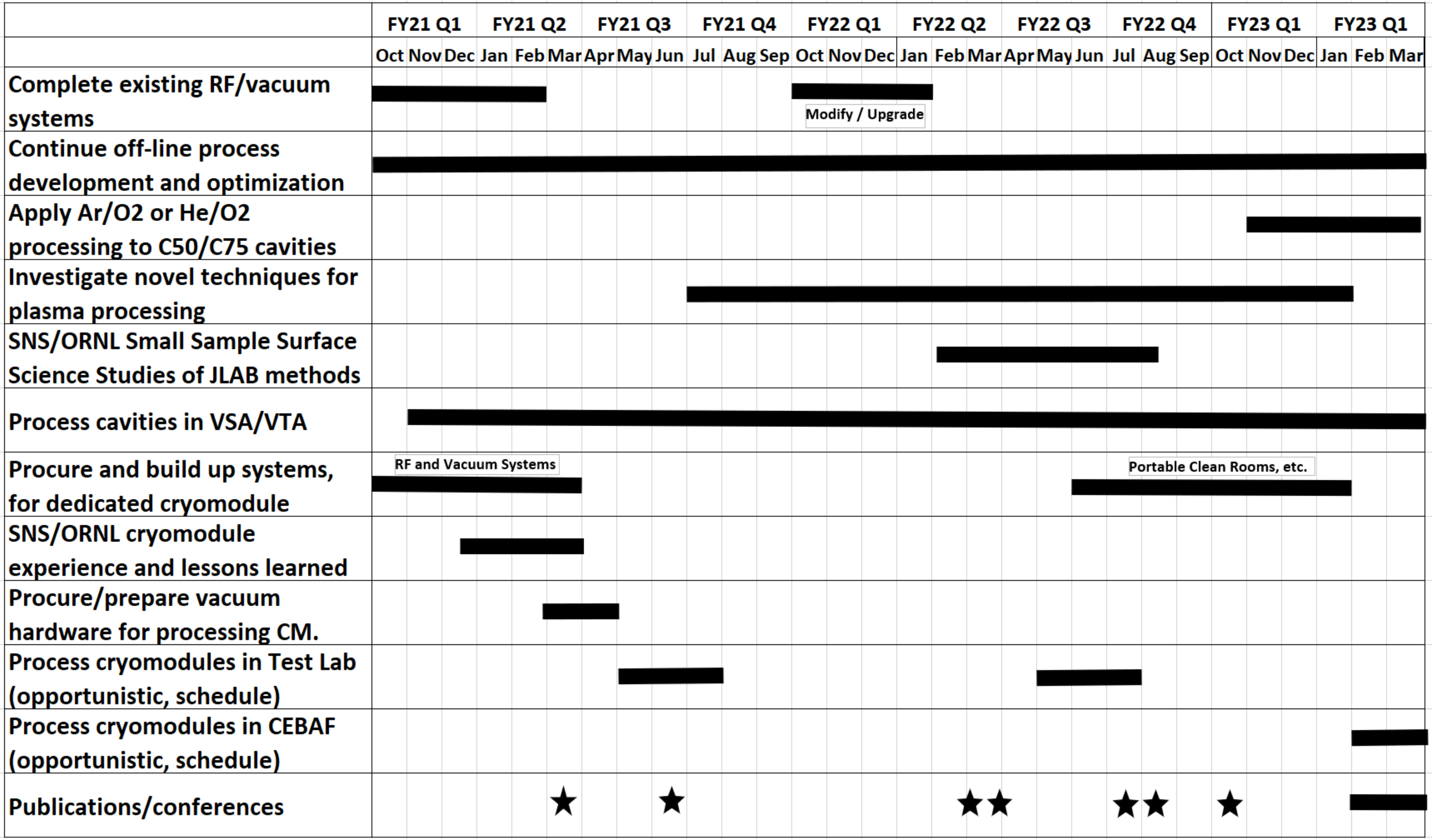
- Work done using JLAB internal accelerator R&D funds prior to this award demonstrated that we could establish and control the plasma generation in a CEBAF C100 cavity on a cavity-cell basis. Additionally, we used DOE R&D funds awarded in FY19, to build up a minimal set of hardware in support of the 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
  - Apply more labor to the project
  - Obtain specific support from ORNL, which is a leader in plasma processing of SRF cavities.
  - To build up the infrastructure necessary for processing multiple cryomodules in the CEBAF accelerator simultaneously.
  - Increase the vertical (cold cavity) testing program.
  - Process cryomodules in the SRF test lab and, as programmatic limitations permit in the CEBAF accelerator.
  - 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 April 2023* and beyond**.
    *A no cost extension was requested and granted in June 2022.
    **JLAB was awarded follow-on funding for 2 more years in Aug. 2022

	FY20	FY21*	Totals
a) JLAB allocated	$607,500	$607,500	$1,215,000
b) ORNL allocated	$93,500	$93,500	$187,000
c) Actual costs to date*	$701,000	$541,883	$1,242,883

*As of 1 Oct. 2022

Deliverables and schedule



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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
  - 30 full cycles of RF test, plasma process, RF test cycles in the vertical test area.
  - 25 of these were since Nov. 2021.
- Completed an extensive number of bead pull measurements and ignition studies to understand the effects of having an open cable on the second HOM coupler.
- Developed software, for processing multiple cavities simultaneously in a cryomodule. Some of the features are:
  - Regulated process pressure control
  - RF power control and measurement
  - Mode identification software
  - 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.**
- **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.**

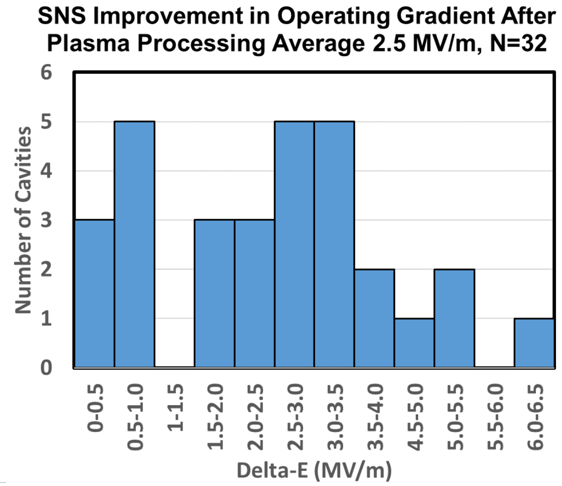
Overall summary, issues FY22

- The principle investigator is out for 2 months starting Oct. 2021 due to surgery.
- Supply chain issues especially with electronics required an early request for a no cost extension.
  - Network analyzer 18 Weeks.
  - Mass flow controllers ordered in March 2022 were due in Sept. 2022 new shipping date 6 Jan 2023.
  - Gas filter compatible with ozone 20 weeks.
  - Ozone sensor 24 week lead time.
  - Delays in getting the ORNL mini SIMS repaired.
- 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.

Why use plasma processing

Industial Uses

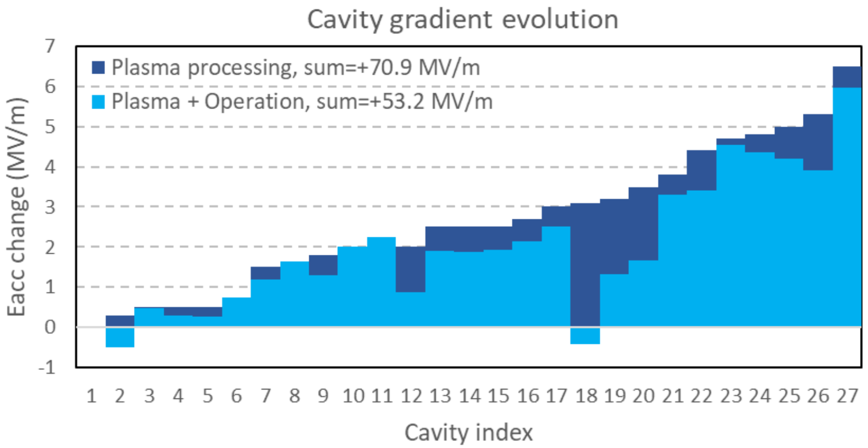
- Plasma processing is a common technique for removing hydrocarbons from surfaces and improve the wettability of the surface.
- It has the capability to treat complex shapes and can be tuned to deliver surface specific properties.
- Princeton Scientific Corporation has a line of chamber based plasma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



Early SRF Successes

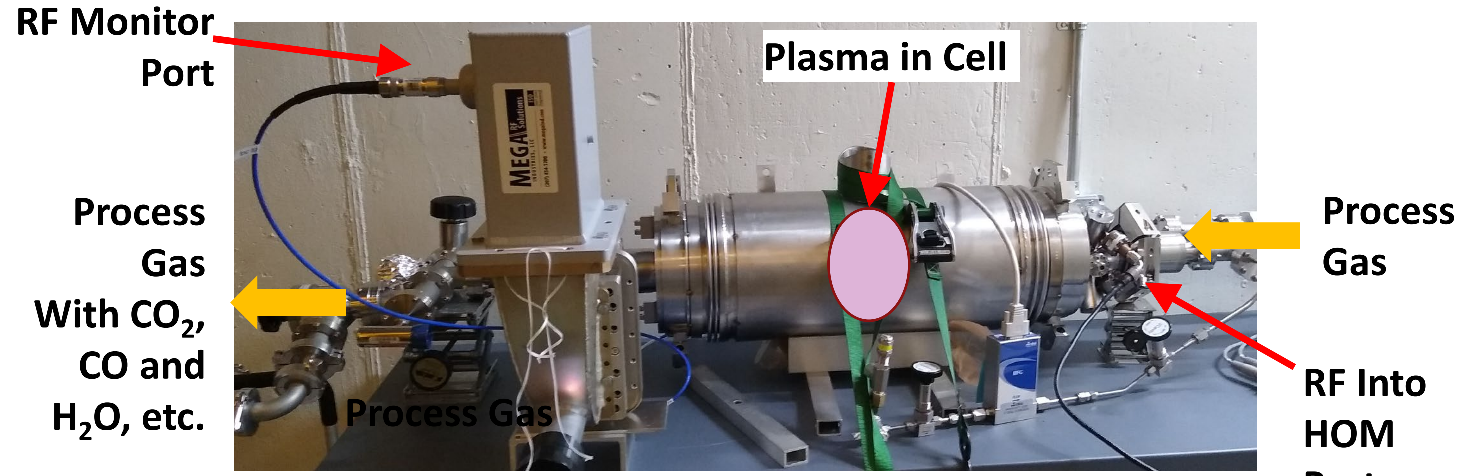
- 2012 Bob Legg, based on the work at JLAB and ORNL, led an effort at the Synchrotron Radiation Center located at University of Wisconsin, the WiFEL SRF gun cathode surface fields improved from 6 MV/m to 26 MV/m.

- 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.*

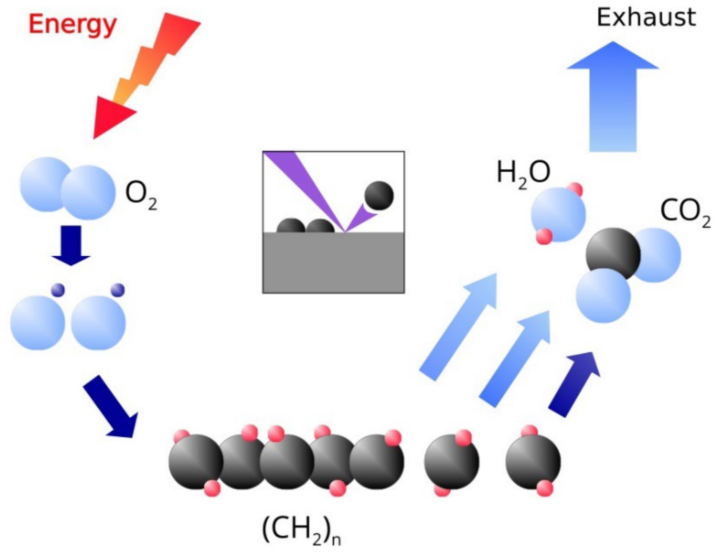


*Marc Doleans personal communications

Reactive oxygen plasma processing



C100 Off-Line Bench Setup



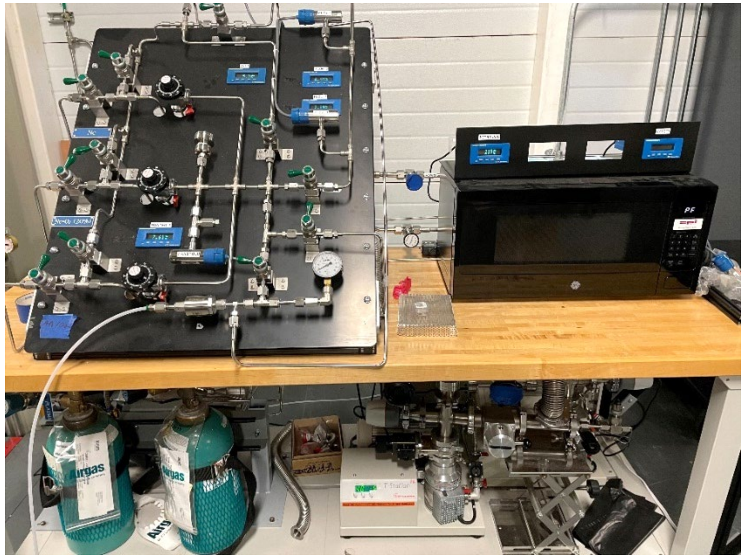
O_2 is cracked in the plasma to atomic oxygen which breaks down the hydrocarbons

- **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

Study impact of argon-oxygen plasma on copper (1)

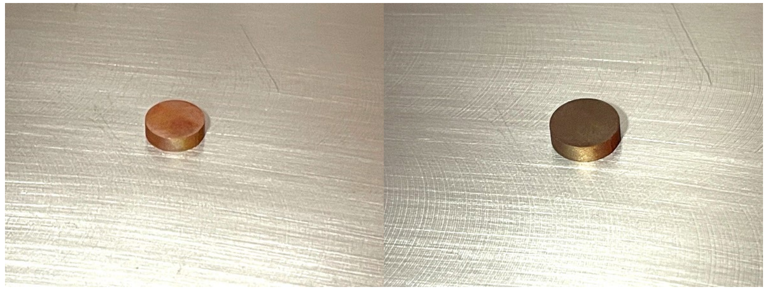
- Cu surfaces near Nb cavities in JLab cryomodules
  - In power coupler and coupling antennas (field probe and HOM)
  - Possible damage during plasma processing using oxygen
  - Surfaces study on small copper samples conducted to evaluate risk

- Methodology
  - Manufactured 10mm diameter oxygen-free high thermal conductivity (OFHC) samples m
  - Plasma process samples using R&D station at ORNL
    - Sample is cooled by contact with 20 degC base plate inside plasma processing chamber
  - Study effect of plasma using
    - Secondary ion mass spectrometry to evaluate surface oxidation
    - Kelvin probe to determine work function
    - Surface imaging and sample weight

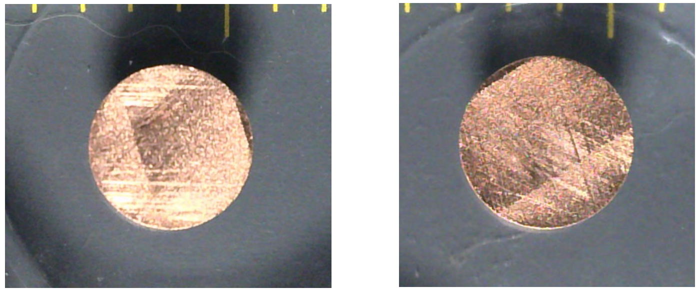


Study impact of argon-oxygen plasma on copper (2)

- Mitigating surface heating is critical
  - 20 min uninterrupted plasma processing at highest RF power setting (1000W) leads to excessive oxidation of the copper surface
  - Shortening cycles to 2min-on 2min-off cycles and lowering power to 100W prevents excessive oxidation
- Effect of Oxygen concentration
  - 40 min of active plasma and various concentration of oxygen in Ar/O2 mixture
  - Work function of the copper surface is increased after treatment due to
    - Reduction of hydrocarbon contaminants at surface
    - Formation of a thin oxide layer
  - Highest oxygen concentration (20%) leads to
    - highest work function
    - largest increase of the copper oxide layer

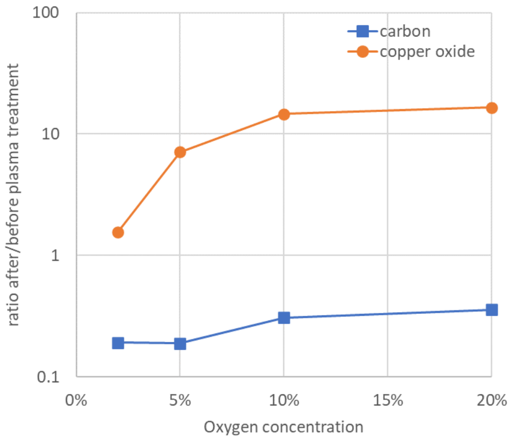


excessive oxidation due to heating during plasma processing



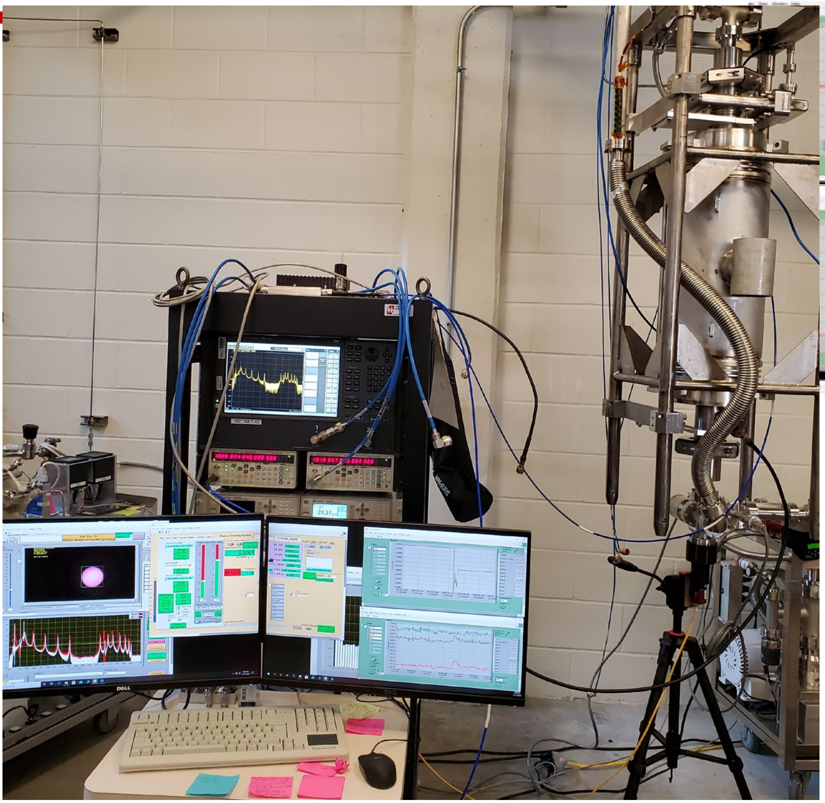
No excessive oxidation observed at reduced power and shortened cycles in plasma processor

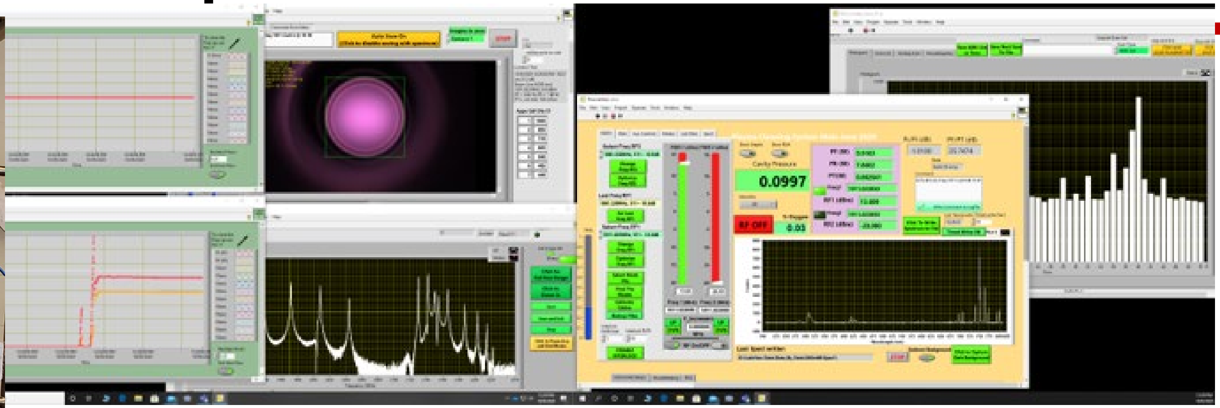
O2 concent. (%)	WF change (meV)
2	267
5	479
10	514
20	595



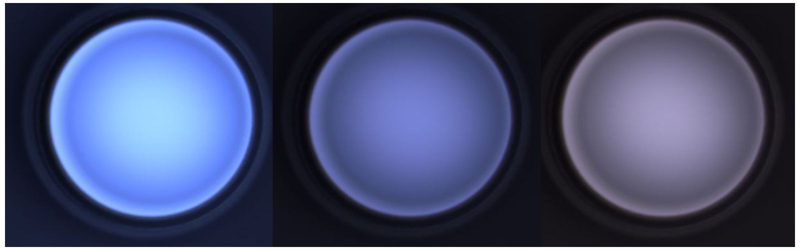
Higher oxygen concentration leads to largest increase of work function but also increased oxide layer

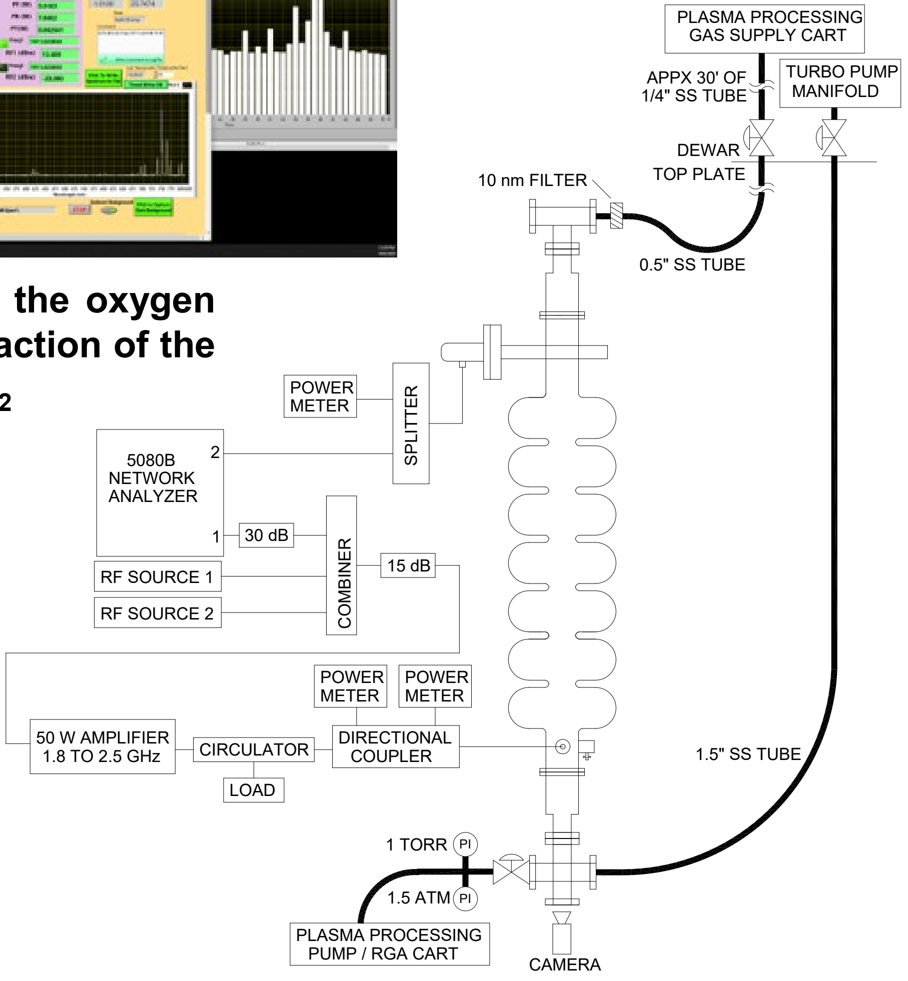
JLAB Vertical Test Stand Setup





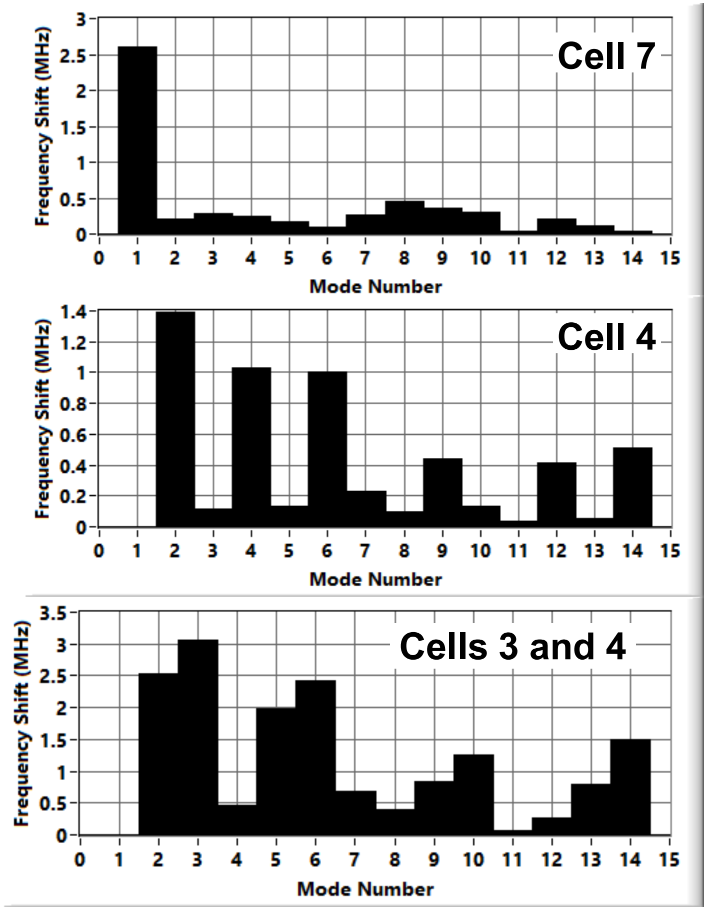
Helium/oxygen discharge changing color as the oxygen content went from 3.8% to 5.6% because a fraction of the oxygen was used to produce H_20, CO and CO_2



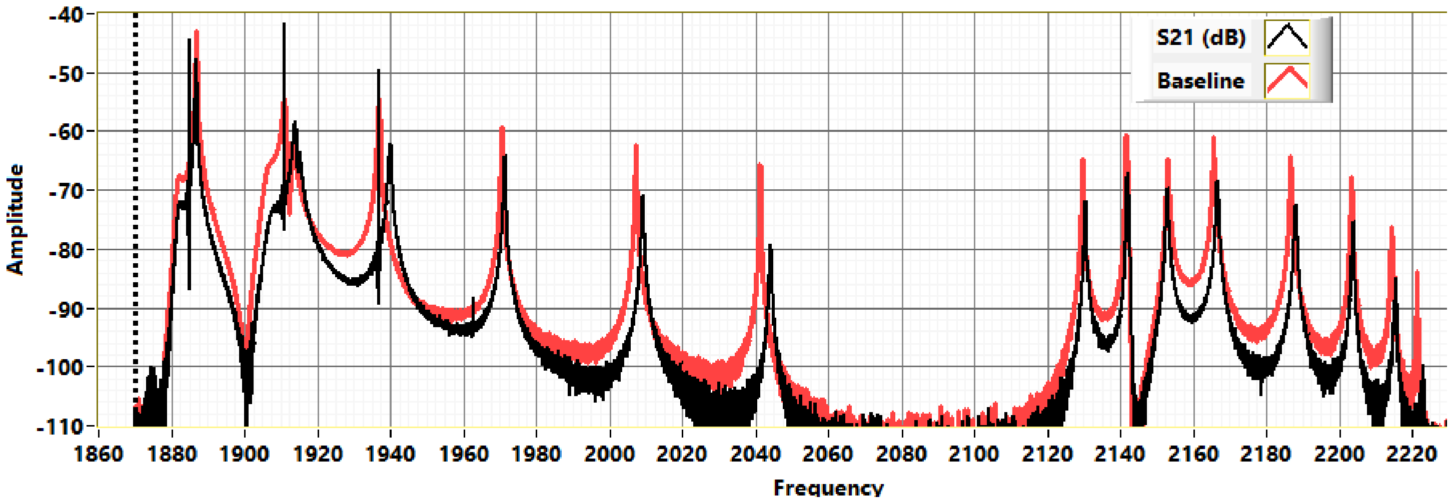


- **The purpose of vertical testing is to establish procedures and judge the effectiveness of the methods with cavities under various conditions. Later it will be to test novel techniques.**
- **Plasma processing is done in the vertical staging area while the cavity is still mounted to the vertical test 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**

Using S21 measurement to characterize and locate plasma



Measured Mode Shifts



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

- 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.

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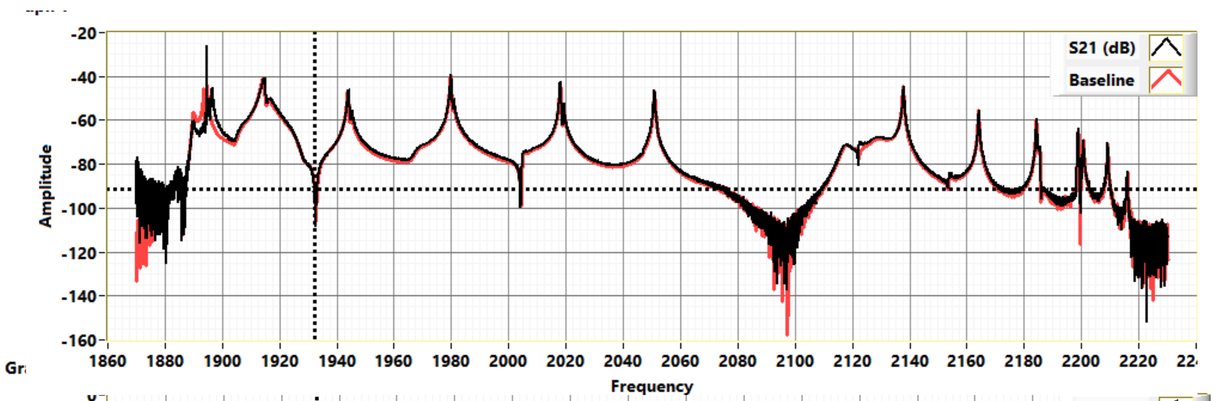
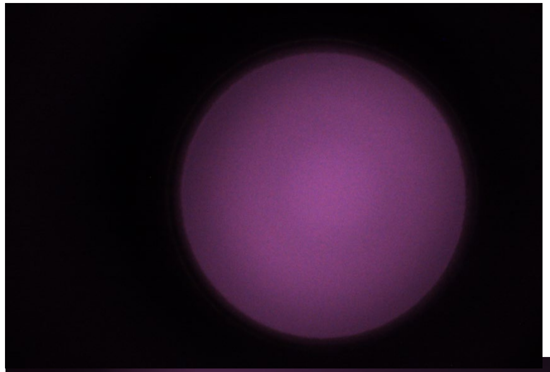
Detecting coupler breakdown using network analyzer

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

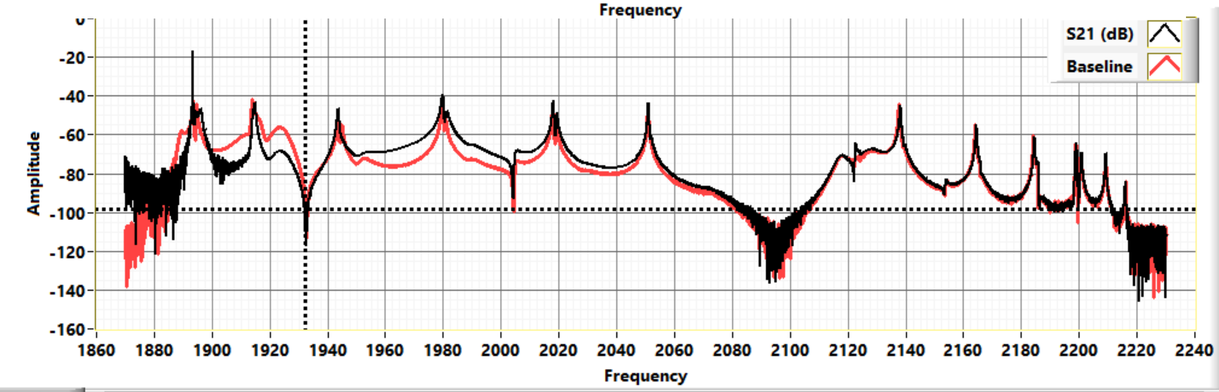
Nominal plasma on/off (black / red) measurements with plasma in cell 7.

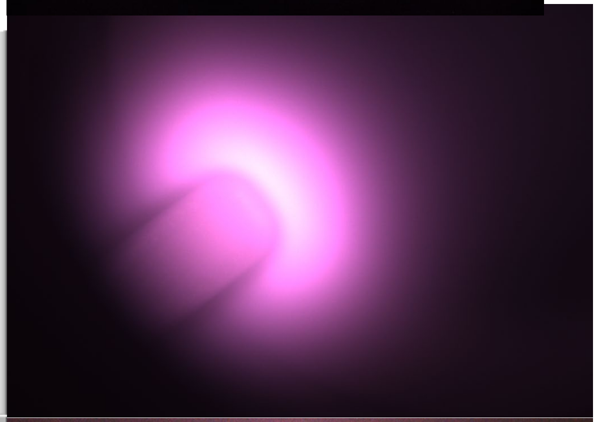




Not a terrible fault mode diffuse discharge at probe tip.

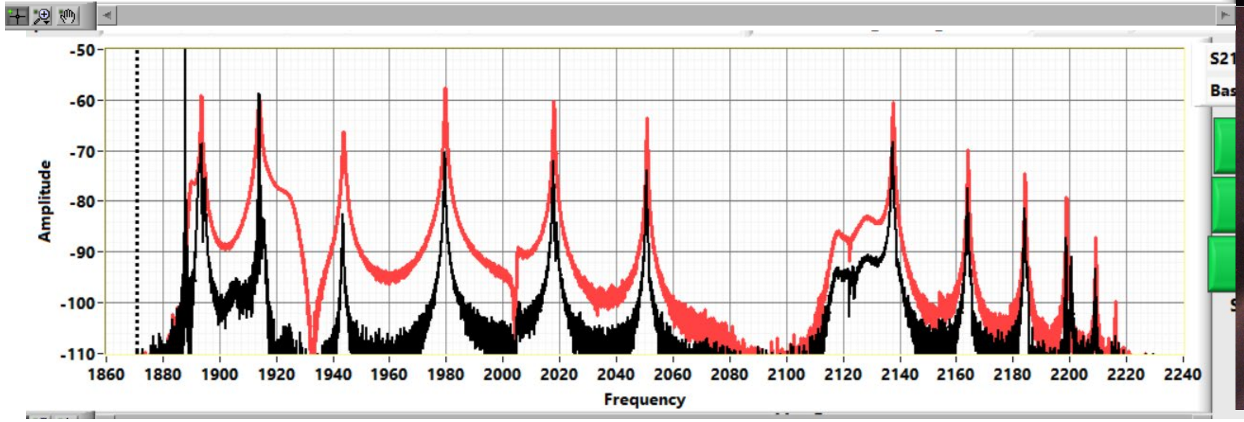
Typical signals for plasma on HOM antenna tip with RF on/off (black / red).

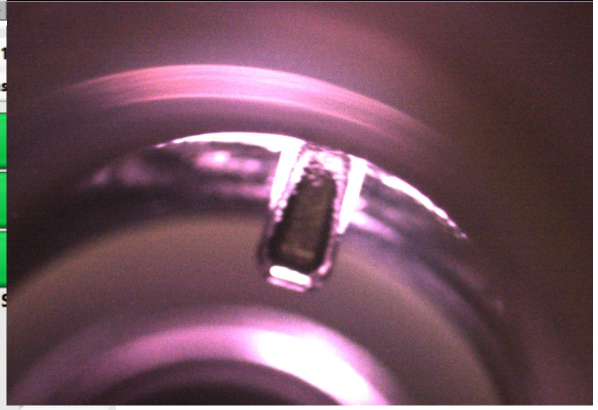




This one is bad as it is an arc like discharge in the tube containing the coupler feedthrough antenna.

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





Plasma processing program from November 2021 to present

- Starting in Nov 2021 we began a series of tests in order to optimize the oxygen content in the argon/oxygen process gas where we would:
  - 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.

Sun	Mon	Tues	Wed	Thurs	Fri	Sat
14-Nov	15-Nov	16-Nov	17-Nov	18-Nov	19-Nov	20-Nov
21-Nov	22-Nov	23-Nov	24-Nov	25-Nov	26-Nov	27-Nov
28-Nov	29-Nov	30-Nov	1-Dec	2-Dec	3-Dec	4-Dec
5-Dec	6-Dec	7-Dec	8-Dec	9-Dec	10-Dec	11-Dec
12-Dec	13-Dec	14-Dec	15-Dec	16-Dec	17-Dec	18-Dec
19-Dec	20-Dec	21-Dec	22-Dec	23-Dec	24-Dec	25-Dec
26-Dec	27-Dec	28-Dec	29-Dec	30-Dec	31-Dec	1-Jan
2-Jan	3-Jan	4-Jan	5-Jan	6-Jan	7-Jan	8-Jan
Sun	Mon	Tues	Wed	Thurs	Fri	Sat
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20-Mar	21-Mar	22-Mar	23-Mar	24-Mar	25-Mar	26-Mar
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15-May	16-May	17-May	18-May	19-May	20-May	21-May

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15-Aug	16-Aug	17-Aug	18-Aug	19-Aug
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12-Sep	13-Sep	14-Sep	15-Sep	16-Sep
19-Sep	20-Sep	21-Sep	22-Sep	23-Sep
26-Sep	27-Sep	28-Sep	29-Sep	30-Sep
3-Oct	4-Oct	5-Oct	6-Oct	7-Oct
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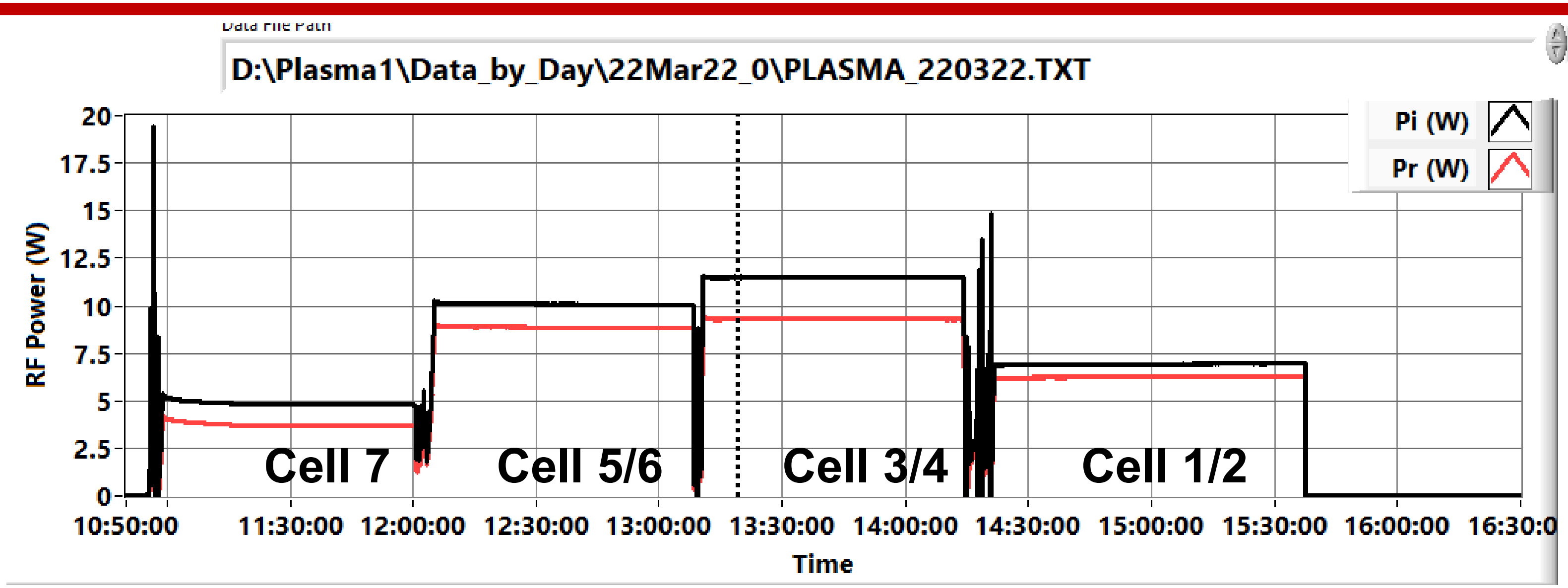
14-Nov	15-Nov	16-Nov	17-Nov	18-Nov
21-Nov	22-Nov	23-Nov	24-Nov	25-Nov

Cavity Vertical RF Test
Plasma Process
Vent to Air
Cryomodule RF Test
Cryomodule Process
Clean Room Cycle

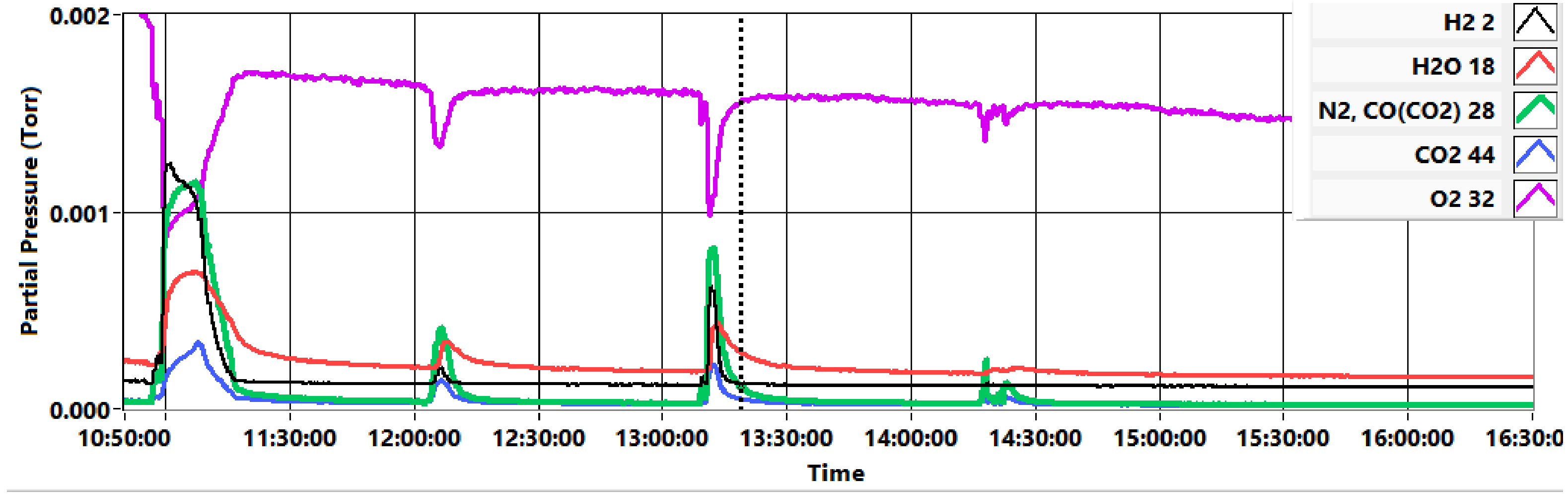
- Based on these experiments, we have switched from the standard 1% to 2% oxygen mixture used by Fermi and SNS to processing one day with 1% oxygen followed by a 20% oxygen mix a day or two later.
- In Aug 2022 we started a series of experiments with Helium/Oxygen Gas mixtures.
- This testing program will continue, for the foreseeable future.
- In the spring we will follow the helium/oxygen experiments with a series of experiments using ozone rather than a plasma. This will be followed by learning how to process C20/C50/C75 cavities.

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.

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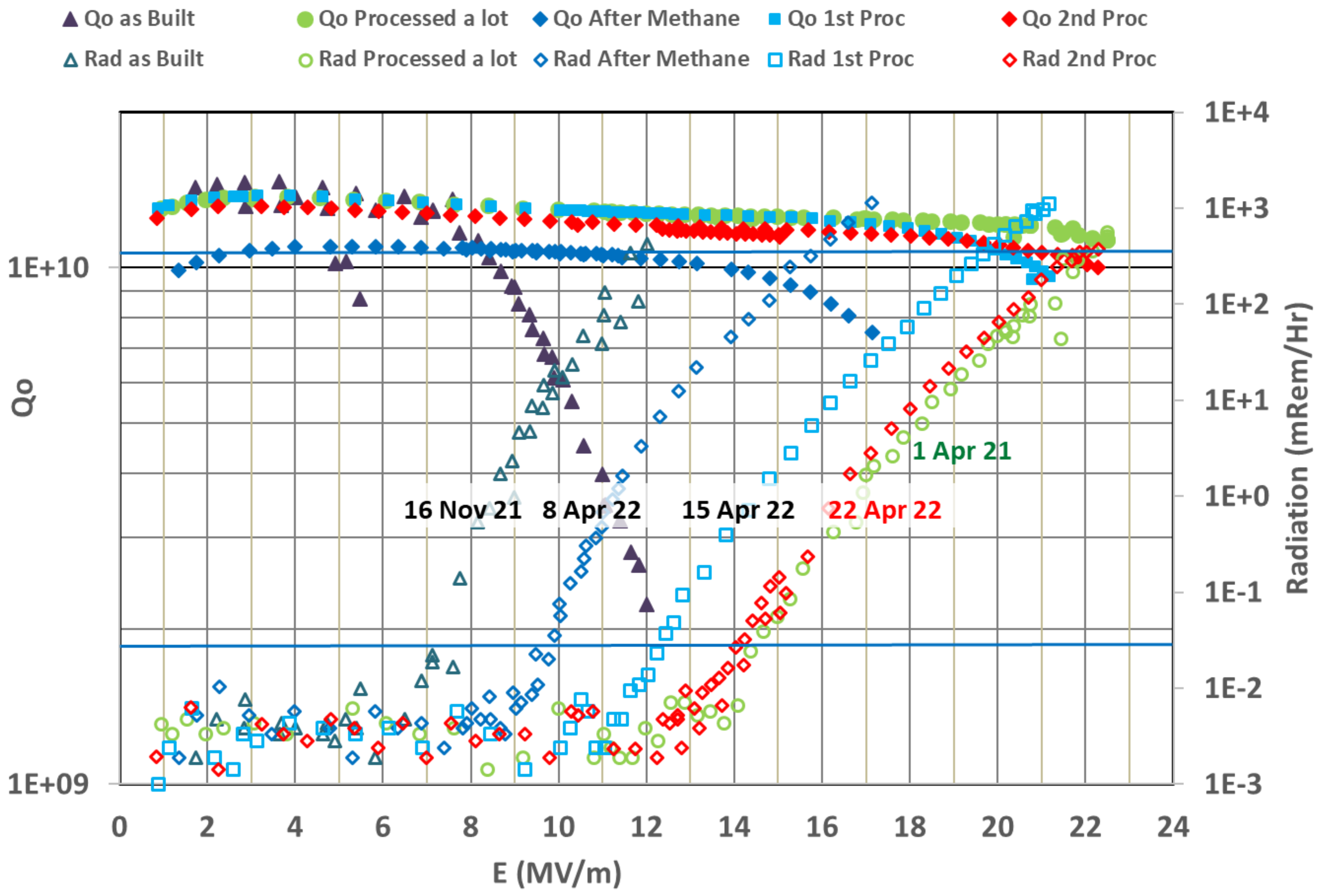
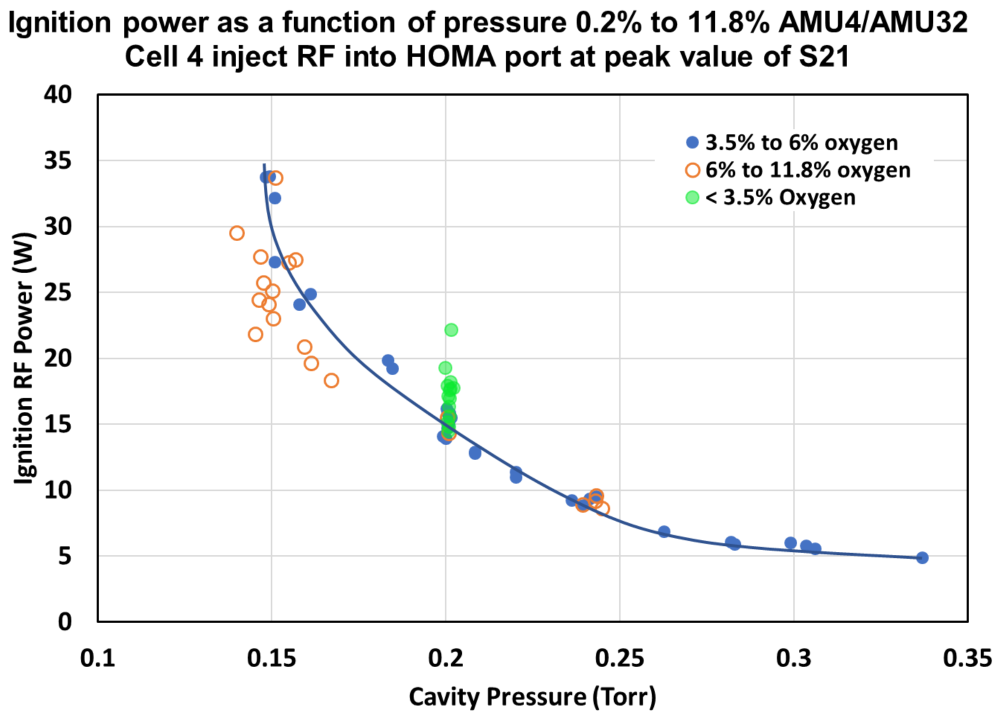
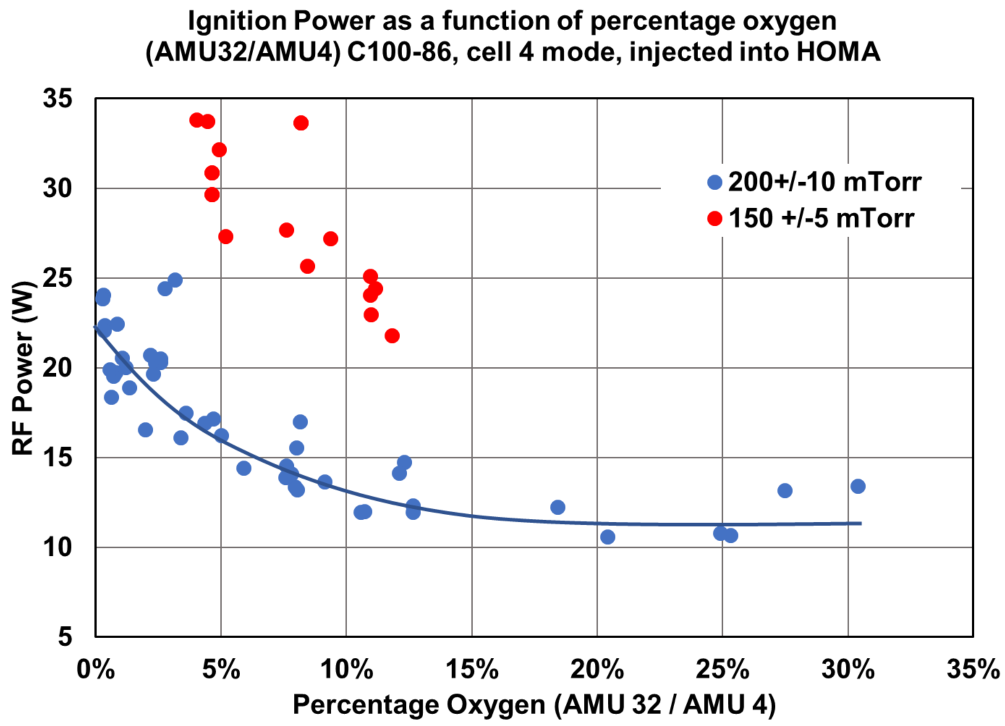
Cavity C100-86 improvements after plasma processing with argon/oxygen



- **Field Emission (FE) onset out of the clean room 7.5 MV/m**
- **Processed several times the last time with 20% oxygen gas mixture to get to the 1 April results (Green) FE onset of 14.7 MV/m**
- **Methane plasma used to deposit hydrocarbons on the surface and reset the FE onset to 10 MV/m (8 Apr. results)**
- **Plasma process using 1% oxygen (15 Apr. results) followed by processing with a 20% oxygen gas mixture (22 Apr. results) in order to repeat the results of FE onset at 14 MV/m**
- **Final results is the red data plots FE at the operating gradient of 18 MV/m was improved from >1 Rem/hr to less than 0.008 Rem/hr.**

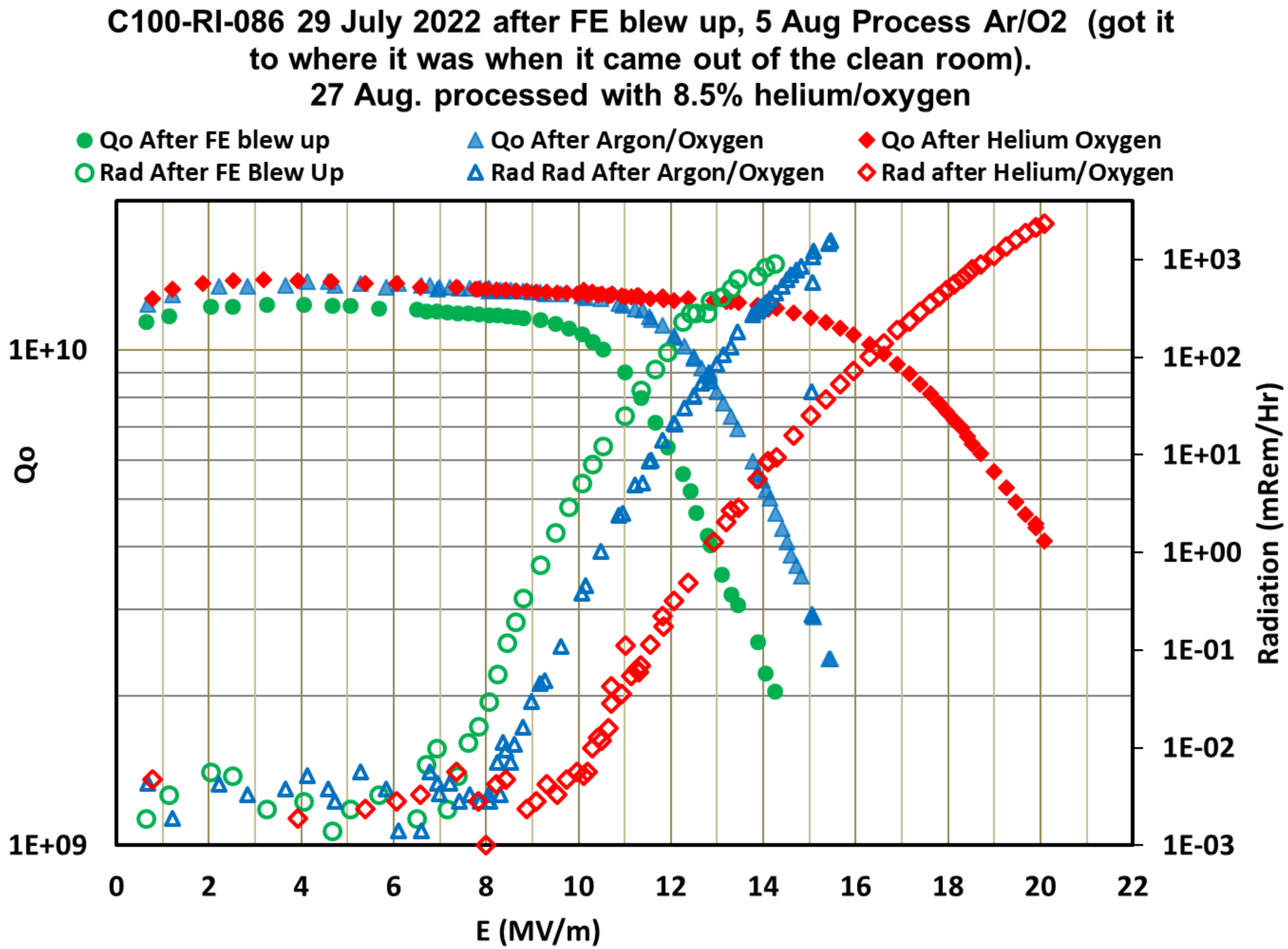
Ignition power as a function of pressure and oxygen content for helium





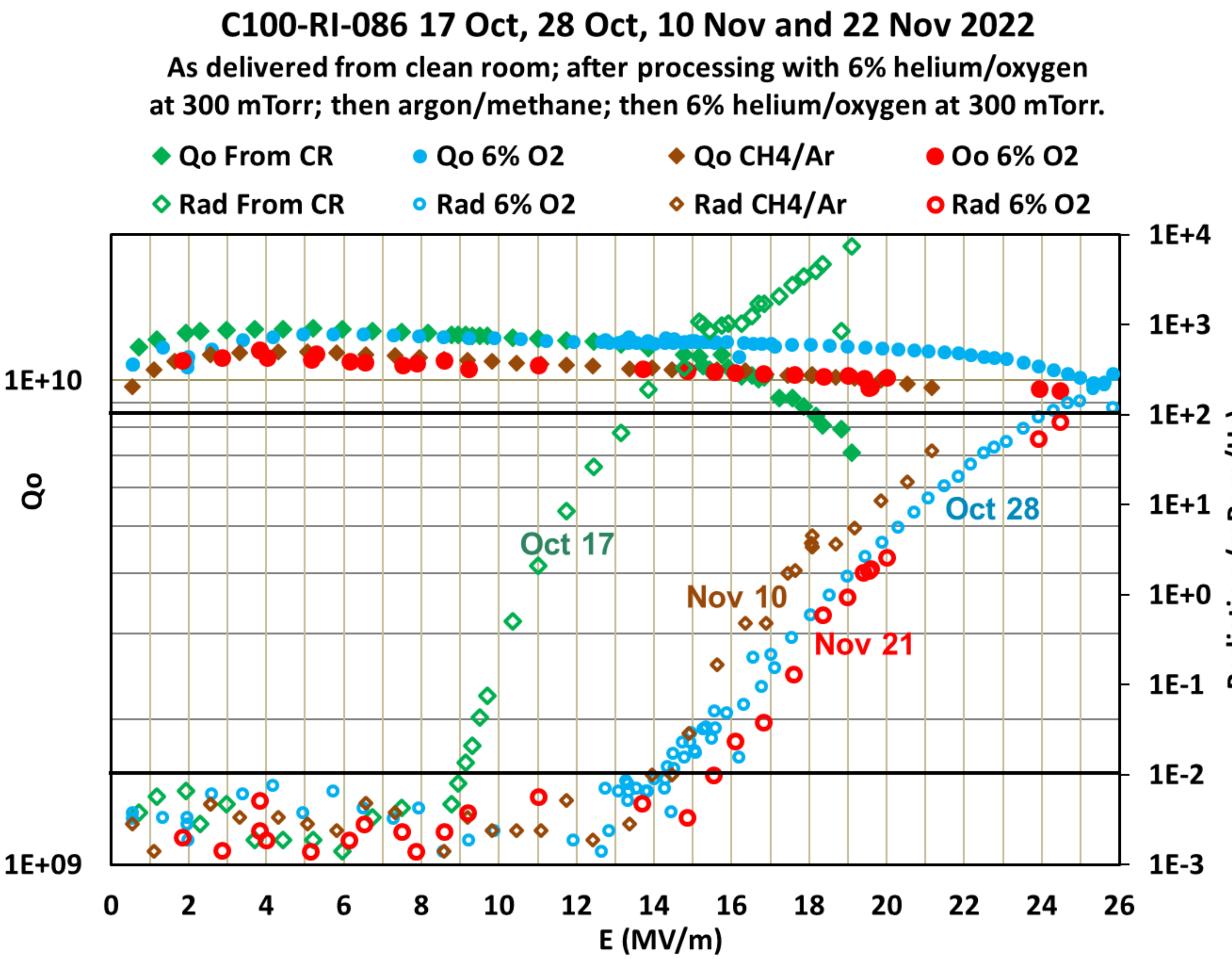
- Data indicated that it took a moderately higher power to ignite the plasma in helium oxygen as compared to argon.
- There is dependence on the oxygen content
- Ignition is statistical in nature, e.g. if you are patient and stay at a given power just below prompt ignition the plasma will often ignite 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.**

Most resent results processing with helium oxygen



- We sent the cavity back through the clean room and it came back with a field emitter that turned on a 9 MV/m (green diamonds).
- We processed with 6% helium/oxygen at 300 mTorr and improved FE onset by 5.25 MV/m (blue diamonds)
- We tried to degrade the cavity with a methane/oxygen plasma without much success as FE onset only went down by 0.25 MV/m (brown diamonds).
- We processed it again with 6% helium and it improved to 15.5 MV/m or 6.5 MV/m better than when it came out of the clean room (red circles).
- From an operational standpoint field emission radiation at 18 MV/m, which is the nominal operating gradient of a C100 cavity, went from 4 Rem/hr to 0.0004 Rem/hr.
- Note the drop in Qo is due to residual magnetic fields.

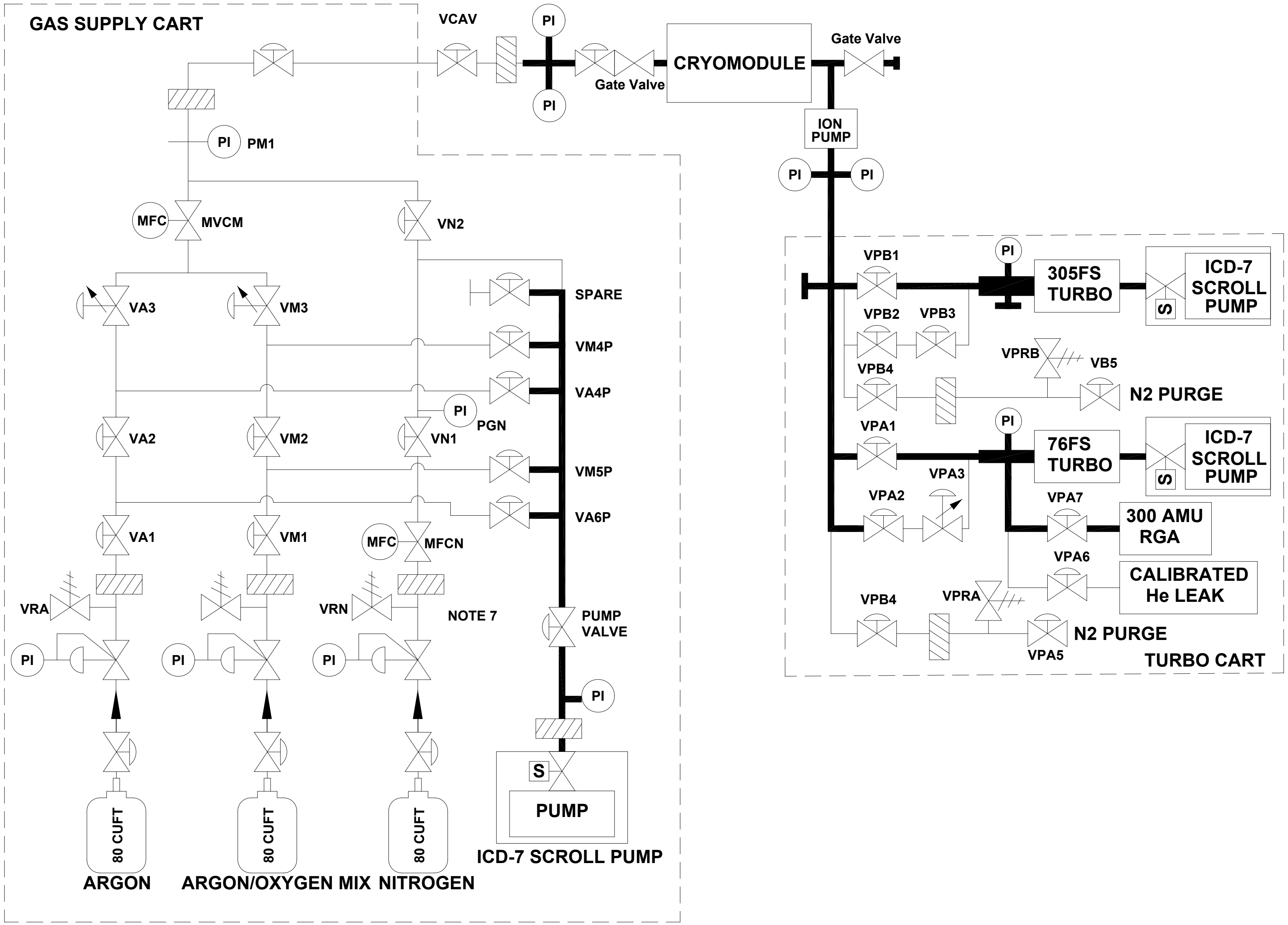
Cryomodule processing in the test bunker

- **June 2021, we processed a C100 cryomodule, C100-10, in SRF test bunker that was severely degraded due a catastrophic failure of a viton seal on a beam line valve. The results showed a minimal improvement.**
- **May/June 2022 we processed a second C100 cryomodule, C100-5, in the SRF test bunker that had recently been operating in CEBAF at 75 MeV with 15 Rem/hr neutron dose in the middle of the down stream girder. At the time it was the worst preforming C100 cryomodule in CEBAF.**
- **We used one of the gas supply carts and pumping/RGA carts and the 4 channels of RF system that were built for use in the CEBAF tunnel to process the cryomodule in the JLAB cryomodule test bunker.**
- **We processed the cryomodule with 2% argon/oxygen followed by 20% argon/oxygen**

Goals of testing cryomodules in the test bunker

- **For both tests:**
  - **Training**
  - **Developing procedures**
  - **Developing software**
  - **Proving system design was adequate.**
- **For the second test: To demonstrate that we could improve a cryomodule enough that it would be worth it to process multiple cryomodules in the CEBAF tunnel in FY23.**

Cryomodule C100-5 plasma processing gas and vacuum setup, June 2022



- We replaced the gate valves in the event that we had spectacular results and were able to return the cryomodule to service.
- The gas supply and pumping carts were moved from the vertical test facility and used for processing the cryomodule
- Pump cart was connected to the valve on the ion pump on the cavity 1 end of the cryomodule.
- Gas was injected into the beamline at the cavity 8 end of cryomodule.
- Note: the plan in CEBAF is to connect the pump cart to the same valve and the gas supply cart to an existing valve on an ion pump in the down stream girder.

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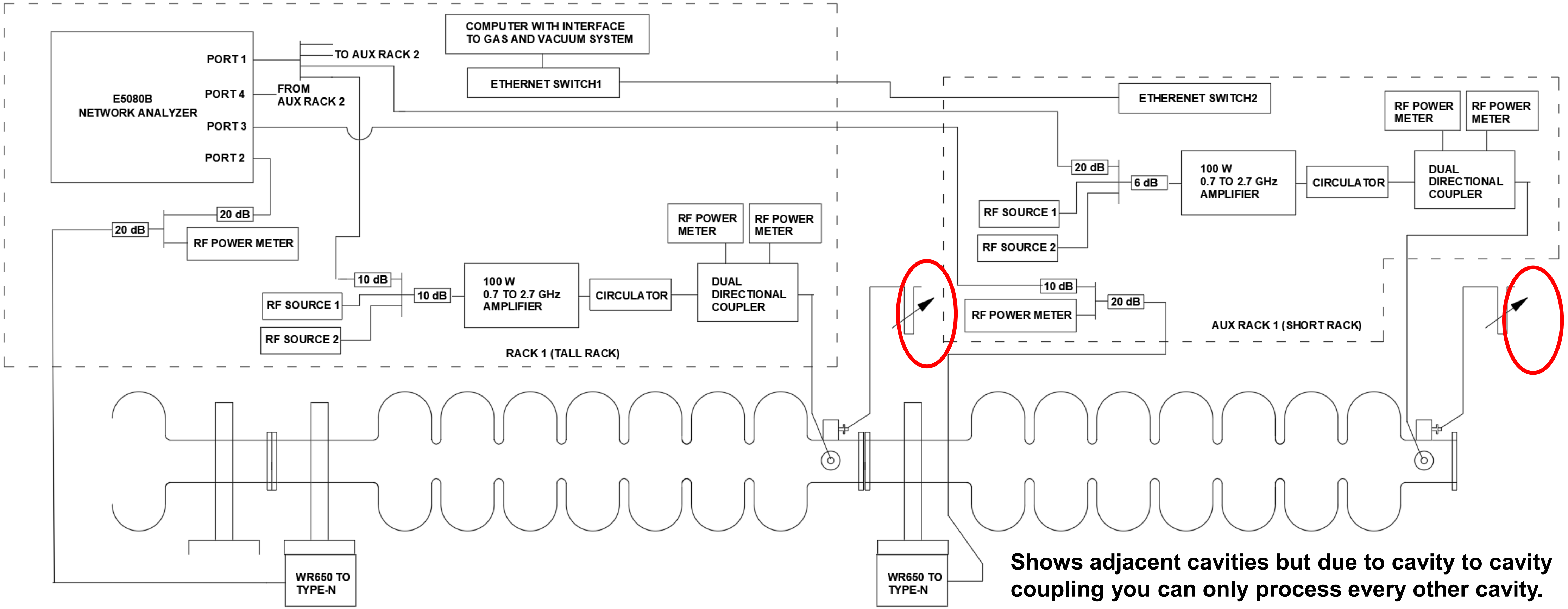
RF system block diagram for processing cryomodule C100-5

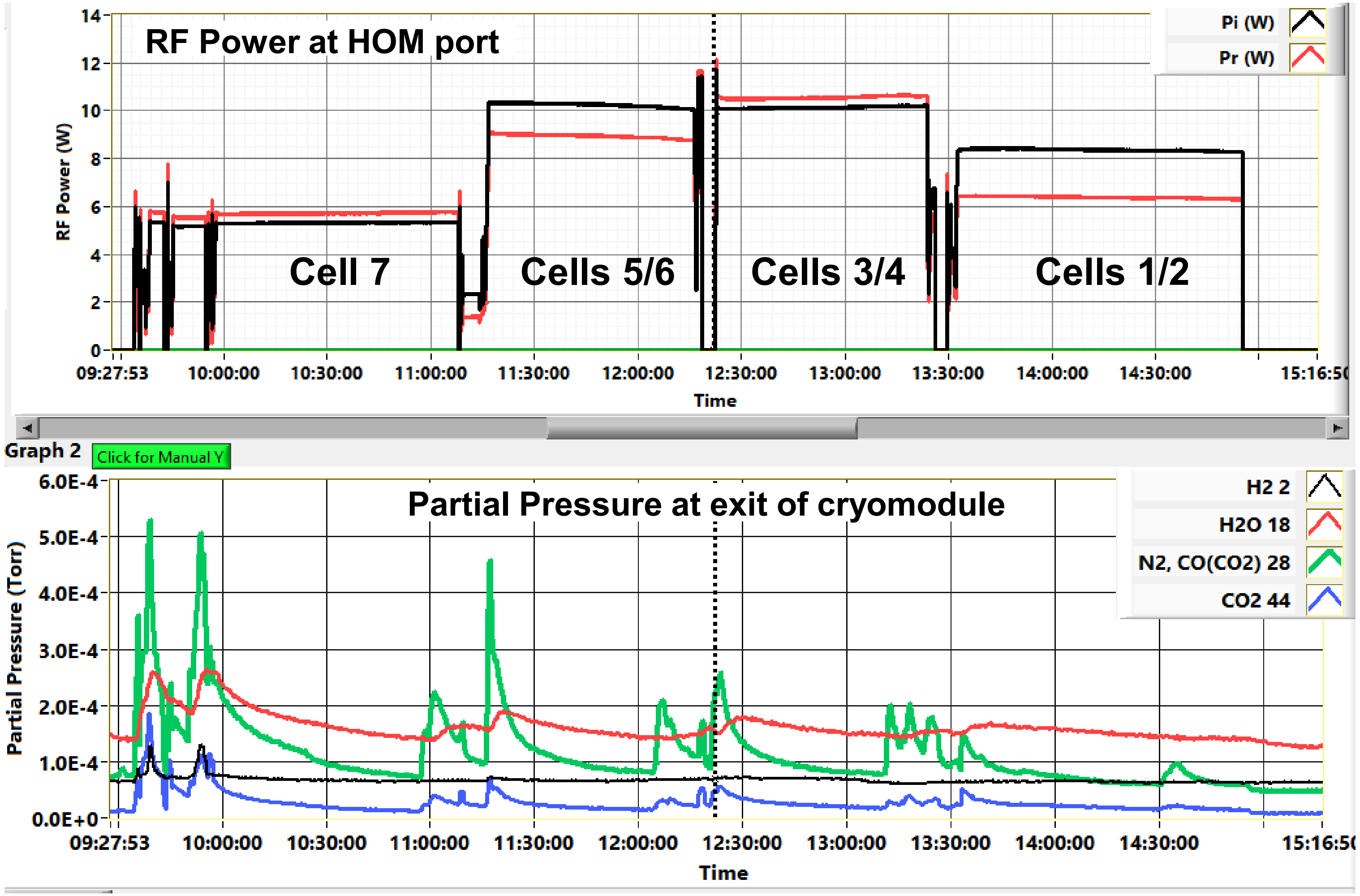


Shows adjacent cavities but due to cavity to cavity coupling you can only process every other cavity.

- **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 because of the effects of coupling from one HOM port to the second HOM port**
  - **One more computer with a 2-port network analyzer and 2 more channels of RF system were used which allowed us to process 4 cavities at a time.**

C100-5 processing protocol

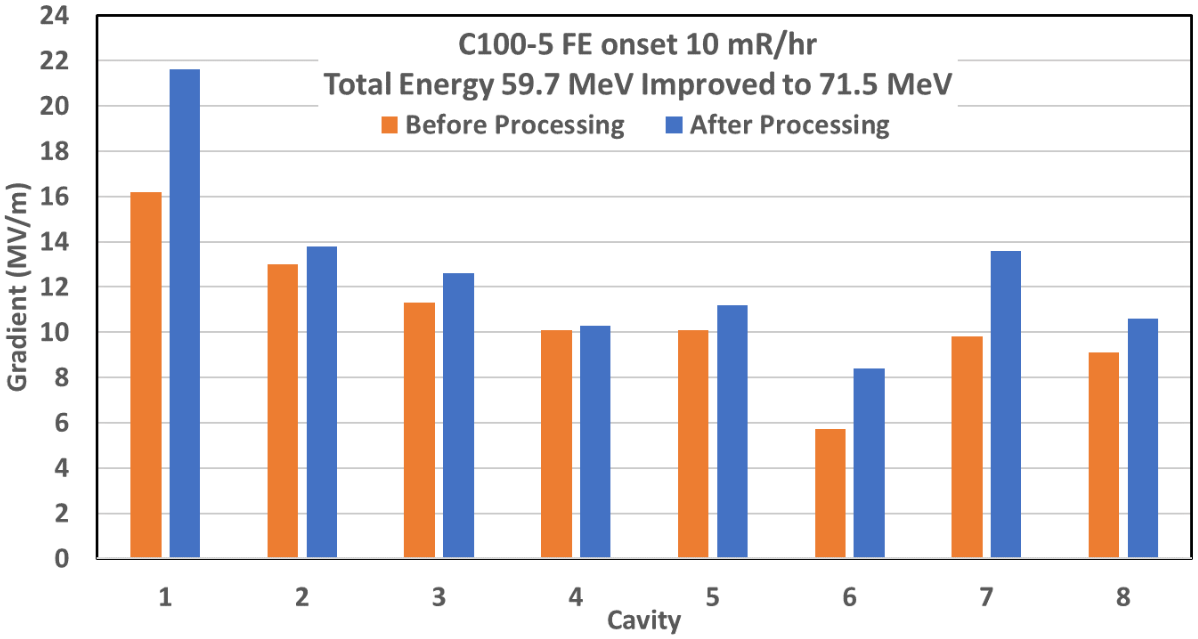
- The cryomodule field emission properties were characterized before and after processing.
- Processed cells in the following order 7, 5/6, 3/4, and 1/2.
- Each cell or pair of cells was processed for 1 hour.
- Each cavity was processed twice, once with argon and 2% oxygen and once with argon and 20% oxygen.
- In general hydrocarbon residues were released when we changed cells with a larger amount the first time that we did the first cell in each cavity.
- 4 cavities were processed at once. Because of this we were able to process all 8 cavities in one 10 hour shift.

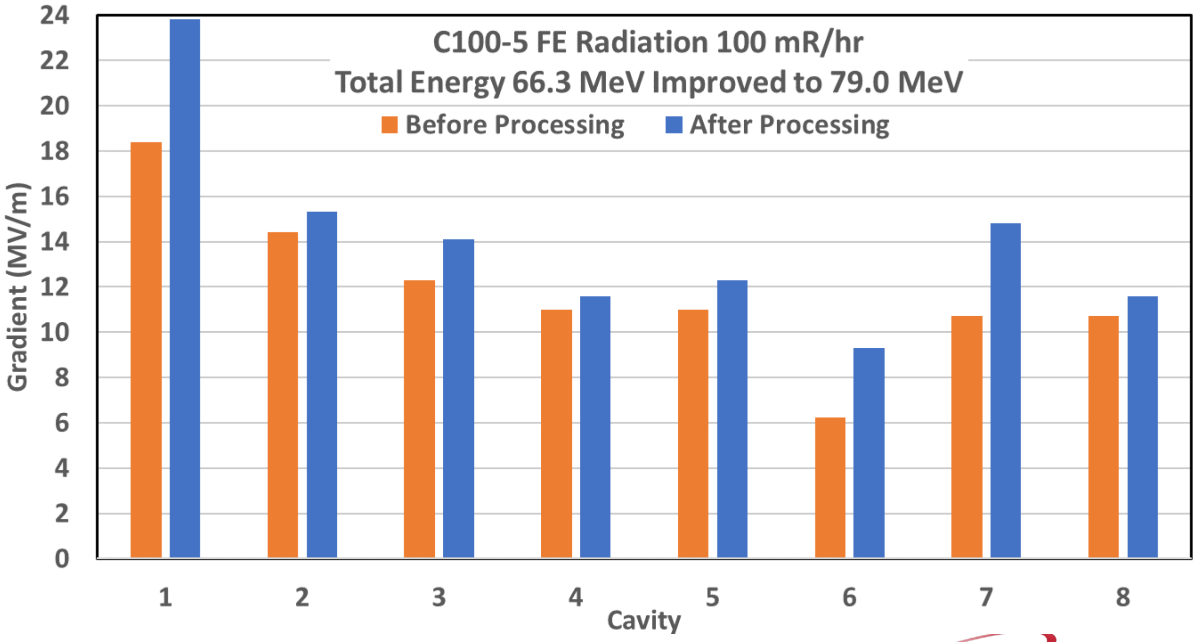


Extra peaks in the hydrocarbon residue plots occurred when we moved the plasma from cell to cell in other cavities in the cryomodule.

Summary of improvements to C100-5

- **Demonstrated that it was easy for one person to process 4 cavities at once.**
- **The plasma processing part of the effort took 4 days.**
- **Field emission onset improved from 59 MeV to 71.5 MeV or an improvement of 11.6 MeV.**
- **100 mRem/hr radiation level 66.3 MeV to 79 MeV or an improvement of 12.6 MeV.**
- **Cavity by cavity radiation levels at 18 MV/m reduced to an average of 15% of that prior to processing**
- **Operating the cryomodule at an increased energy of 13 MeV would mean operating the cryomodule at 88 MeV.**
- **We demonstrated the value of plasma processing C100 cryomodules in situ in CEBAF.**
- **Although the improvements were sufficient to prove the value of processing cryomodules in the tunnel it was decided to rebuild the cryomodule with a goal of building a field emission free cryomodule.**





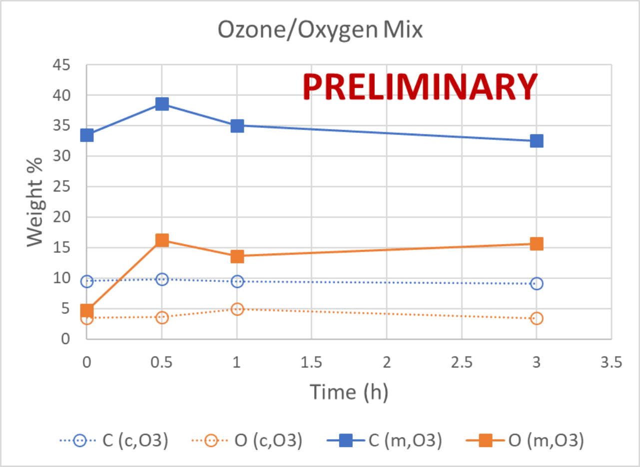
Ozone processing – status & first results

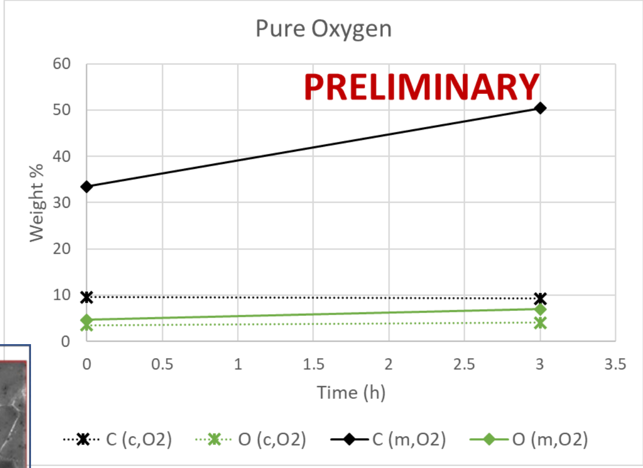
Status

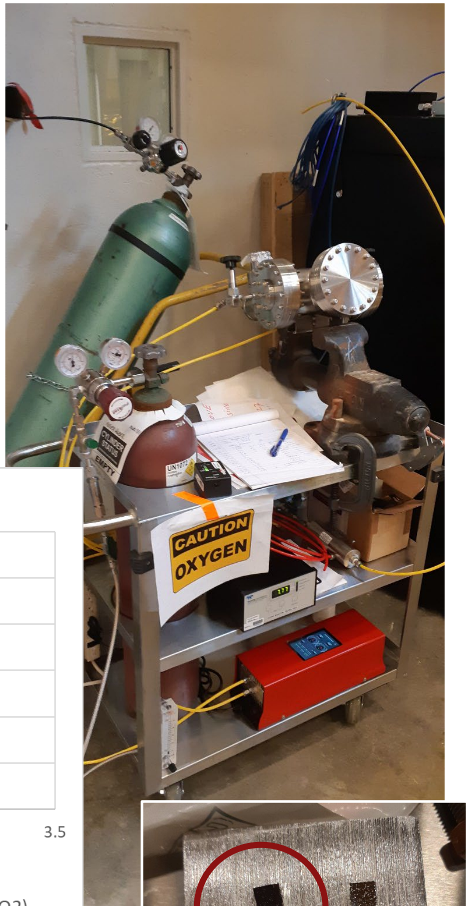
- **Test runs with simple set-up:**
  - **“Sharpie” polluted sample (m);**
  - **“clean” sample (c);**
  - **three runs with ozone/oxygen mix (O3);**
  - **one run with pure oxygen (O2).**
- **Analyzed with Energy-dispersive X-ray spectroscopy :**
  - **determine surface concentration C, O, Nb.**

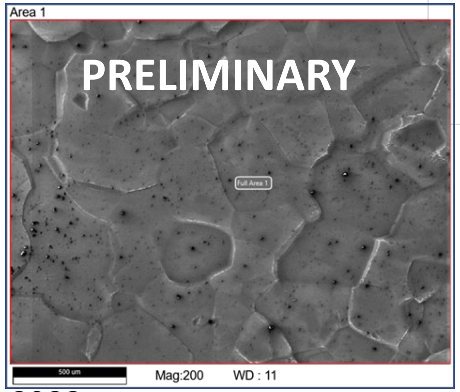
• Preliminary Results

- **no simple conclusion yet, ozone concentration not stable;**
- **visually, samples look clean after 1 h ozone processing;**
- **SEM images show residue;**
- **evolution of C & O concentration under discussion**









polluted sample

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Plans for the mid term future*

- Use argon/methane plasma to contaminate cavities and experiment with plasma processing using different gas mixtures in the JLAB vertical test area, currently the gas mixture is helium/oxygen.

- Continue investigating ozone processing of vacuum surfaces.
  - Off line sample tests
  - Hydrocarbon removal using the cavity and pumping systems in the off line test facility.
  - Hydrocarbon removal from the surface of a cavity in the vertical staging area followed by testing in the vertical test area.
  - Determine if it is feasible and worth it to use the methods on cryomodules or warm beam lines in CEBAF.

- Processing multiple cryomodules in situ in the CEBAF tunnel.
  - Continue to develop plans, procedures, safety documents, and travelers necessary for processing cryomodules in the CEBAF accelerator.
  - Receive and assemble the portable clean rooms that will be used to process cryomodules in the CEBAF accelerator.
  - Improve gas supply system in order to make it easier to control the ratio of oxygen to noble gas.
  - Process multiple cryomodules in the CEBAF accelerator in FY23-Q3

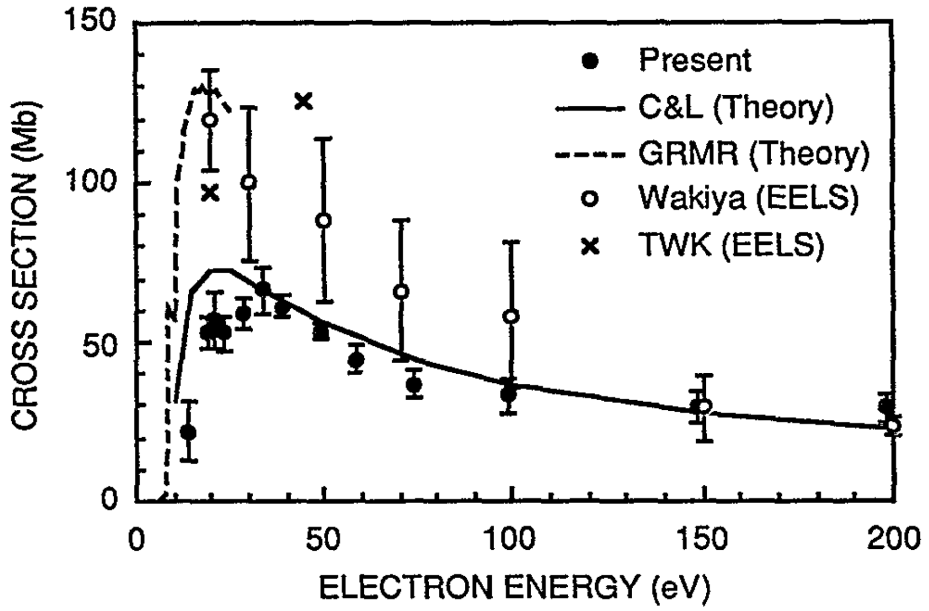
- Basic research
  - Model C20/C50/C75 cavities in order to come up with approaches to produce and control a plasma on a cell by cell basis.
  - Based on the models, bead pull data, etc. produce plasmas in C20/C50/C75 cavities in the off line system.
  - Have a JLAB post doc and ODU graduate students perform plasma simulations and model cavities.
  - Have an ODU graduate student do optical spectroscopy studies so that we can benchmark the plasma simulations.

*Using the remainder of existing funds plus new funds awarded in Sept. 2022.

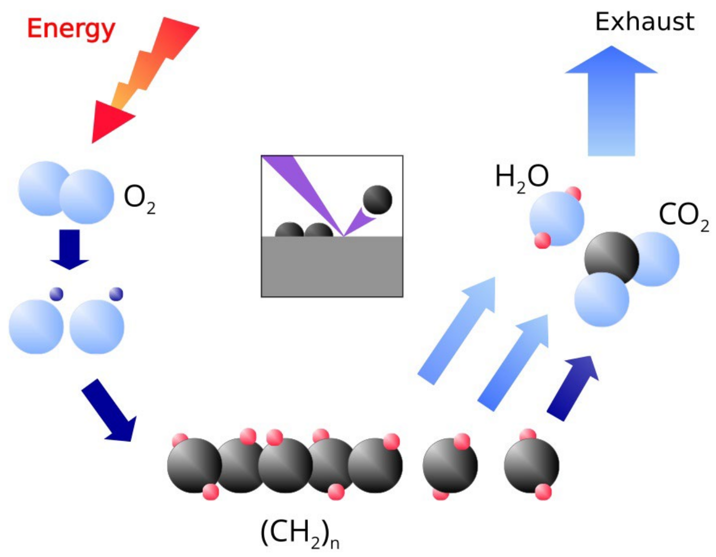
Backup Slides

Plasma processing basics, current SRF technique

- Using a room temperature plasma, as is currently done, is not an ion bombardment process like standard 2K or 4K helium processing.
- An RF glow discharge is established with a gas mixture that contains a small amount of oxygen.
- Free electrons with an energy in excess of about 10 eV crack the oxygen into free oxygen.
- Free oxygen reacts with the hydrocarbons on the surface cracking it into molecules such as H_20, $C0_2$ and CO which are removed from the cavity with the process gas.
- Removal of hydrocarbons from the surface increases the work function and reduces the secondary emission coefficient both of which improve the field emission properties of the niobium surface.*



Dissociation Cross Sections and excitation cross sections for electron impact on O_2**



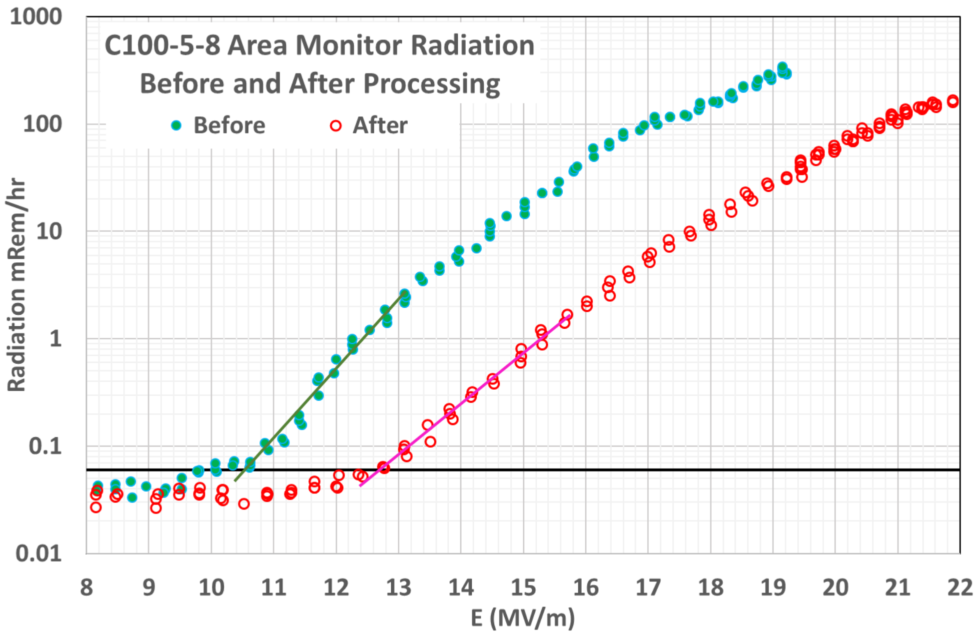
*Tyagi, et.al., Applied Surface Science 369(2016) 29-35.
P.C. Cosby, J. Chem. Phys. **98, 9560 (1993); https://doi.org/10.1063/1.464387

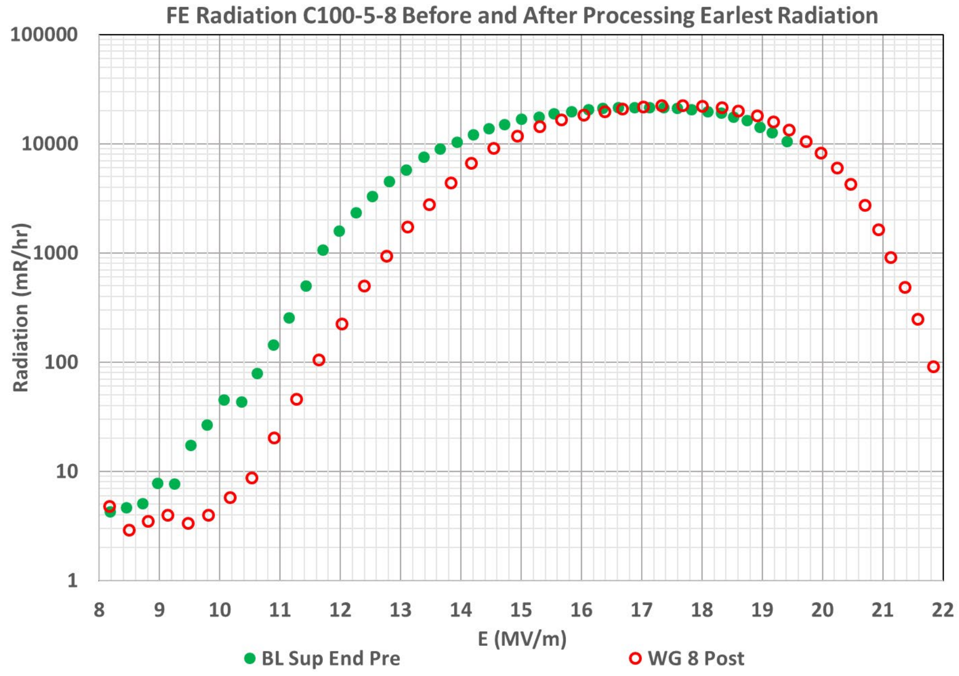
C100-5 reduction in radiation at 18 MV/m

- While the Geiger Muller tubes in the decarad system are very good for determining radiation onset because of the large number of channels and the directionality of the bremsstrahlung radiation, it tends to saturate at higher radiation levels.
- The area monitor which is an ion chamber was much better for comparing radiation levels at higher gradients.
- While the two systems gave slightly different onset values on a cavity by cavity basis, the overall improvement results were within 10% of each other.

Average reduction in radiation at nominal operating gradient was a factor of 6.6

Area Monitor Data (mR/hr)			
CAV	Before Radiation at 18 MV/m	After Radiation at 18 MV/m	Reduction at 18 MV/m
1	9	0.04	0.4%
2	50	25	50.0%
3	1300	200	15.4%
4			
5	2000	300	15.0%
6			
7	4000	60	1.5%
8	150	13	8.7%
		Average	15.2%





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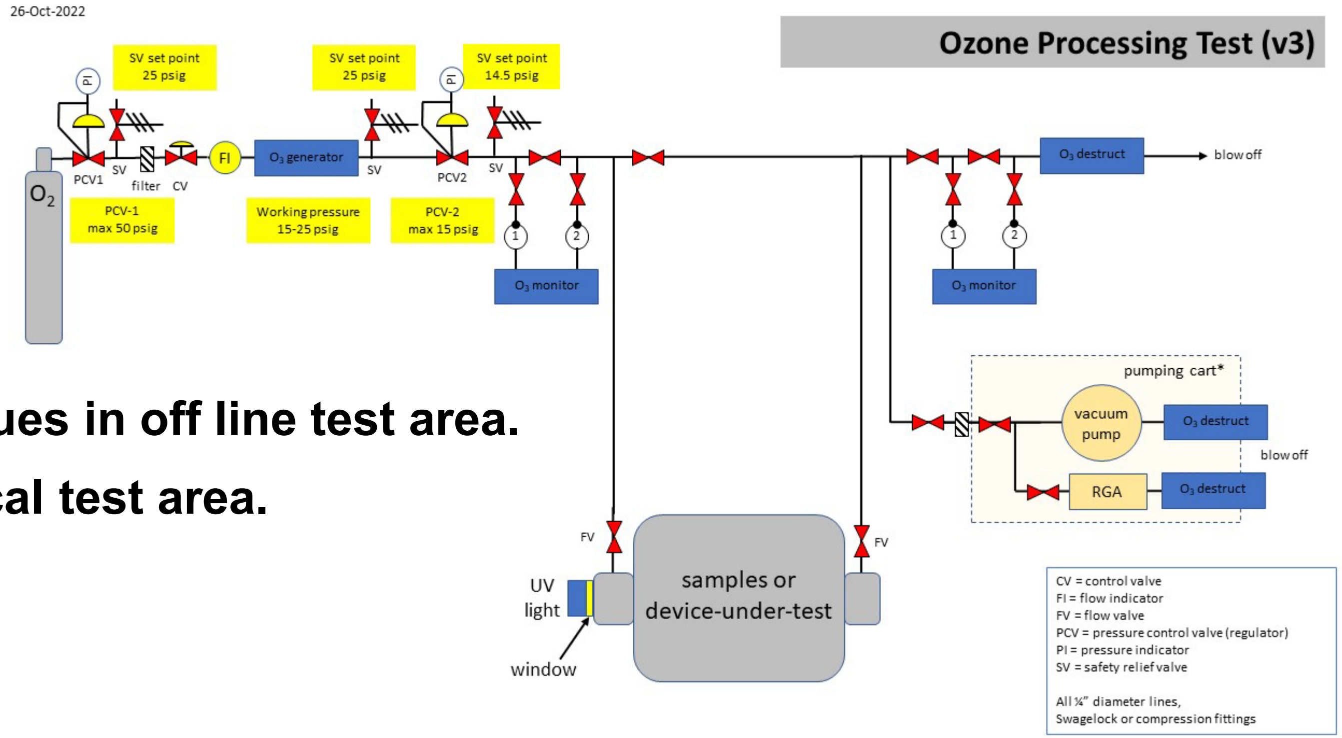
Ozone processing

Issues

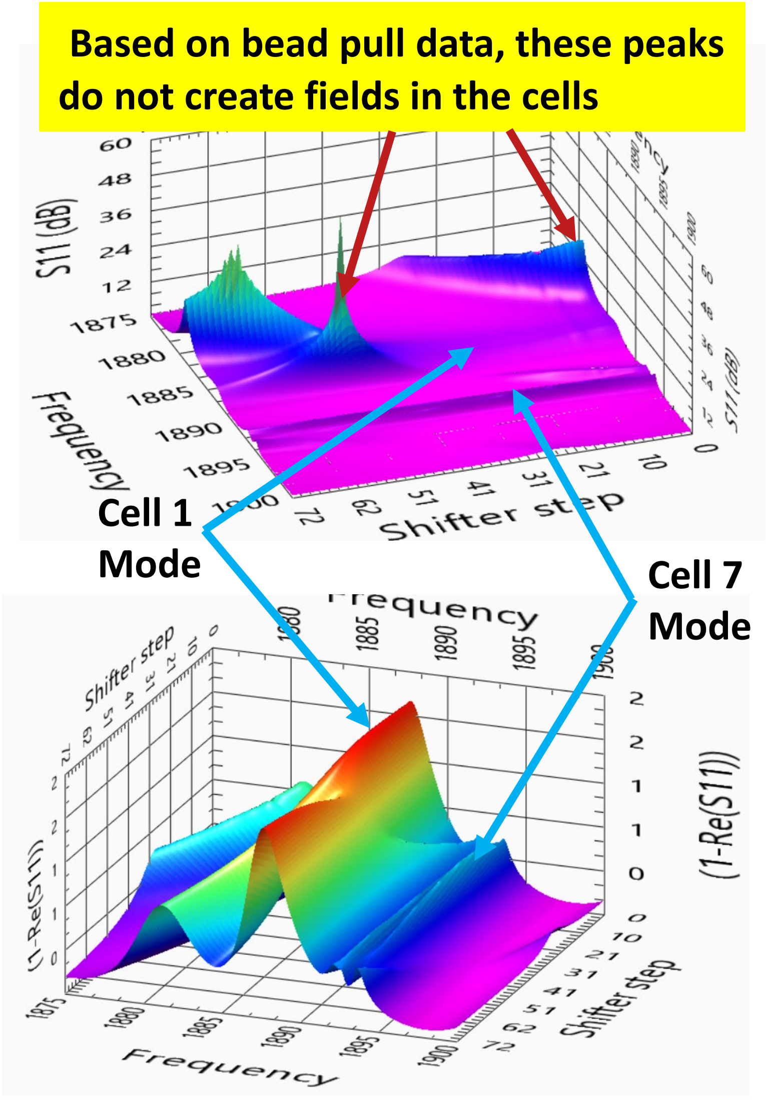
- **Improve safety:**
  - **area monitoring ozone sensor,**
    - **to ensure automatic generator is switched-off if the area ozone level exceeds authorized level,**
    - **parts out of stock at vendor, delivery expected in December;**
  - **inline ozone sensor after test volume,**
    - **to ensure safe opening by verifying system purge with pure oxygen after switch-off ozone generator,**
- **Improve stability ozone concentration:**
  - **increase oxygen pressure in generator,**
    - **oxygen compatible regulator out of stock, no delivery time given, on back order.**



Future work

- **Repeat sample tests;**
- **Test on cavity with inline RGA to monitor residues in off line test area.**
- **Test on a cavity followed by RF testing in vertical test area.**

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.