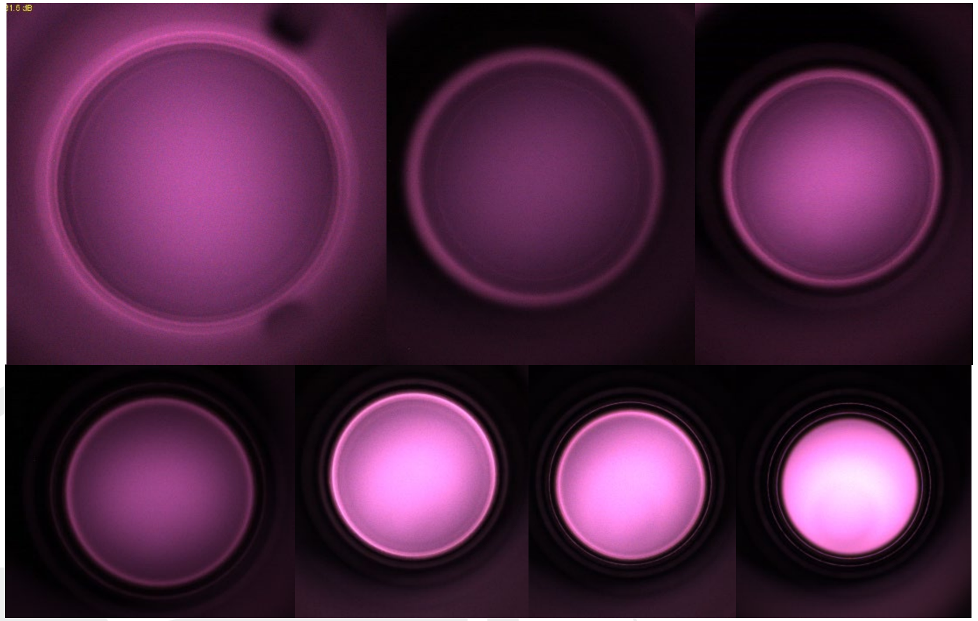
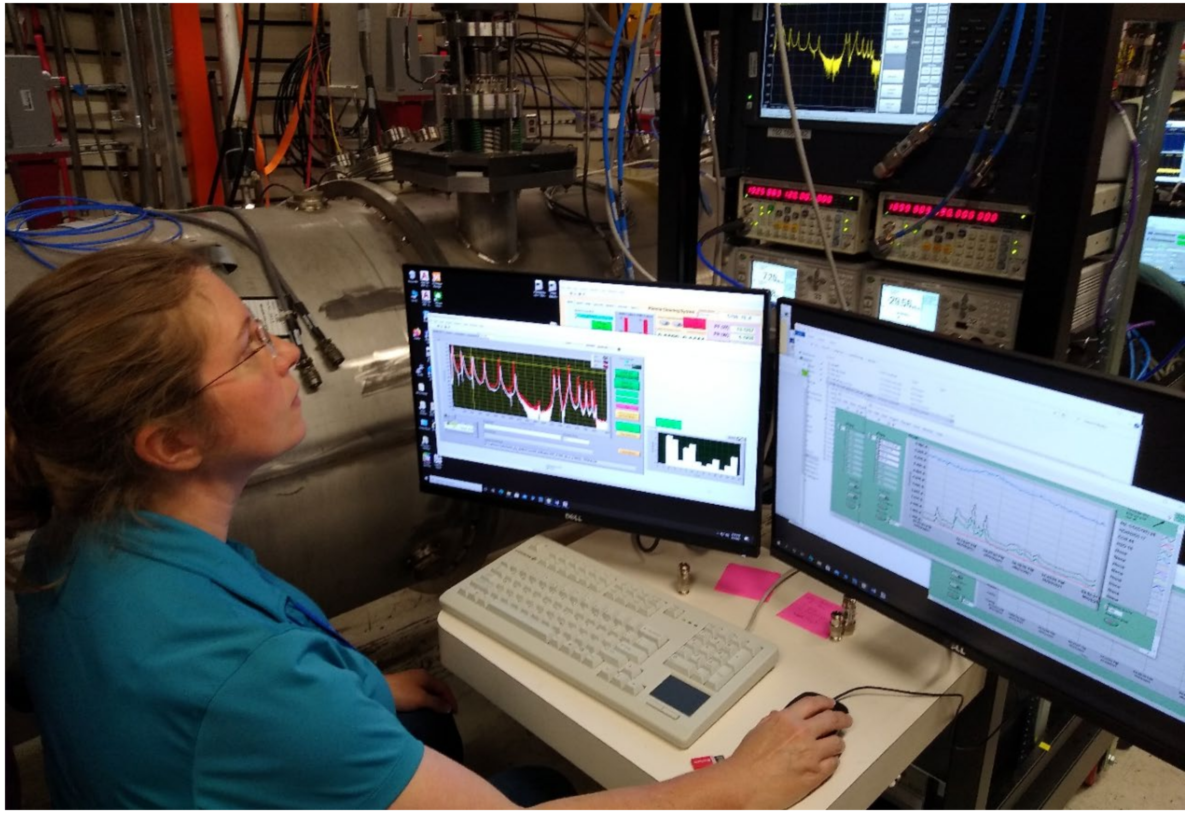
Plasma Processing SRF Cavities at Jefferson Lab





Roger Ruber on behalf of

Tom Powers, Tiffany Ganey and Natalie Brock

TTC Meeting, 13 October 2022

Jefferson Lab

Funding provided by SC Nuclear Physics Program through DOE SC Lab funding announcement Lab-20-2310

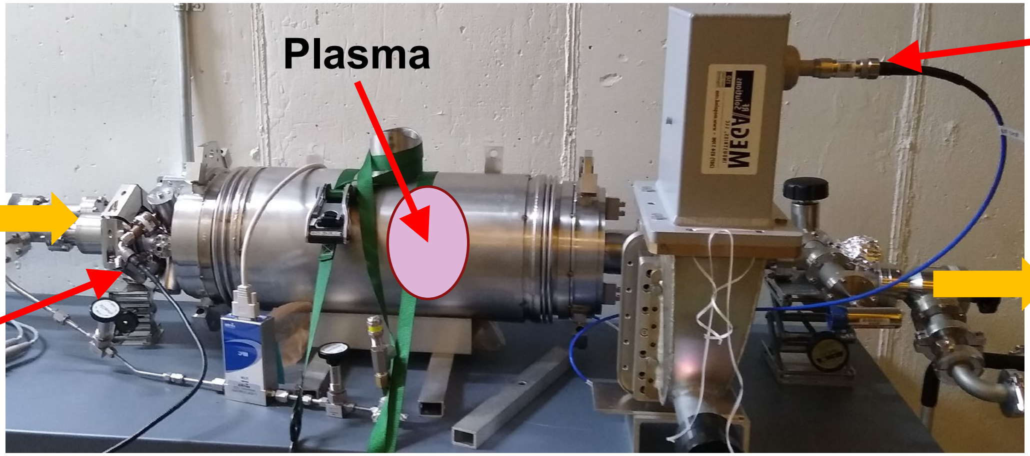
U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

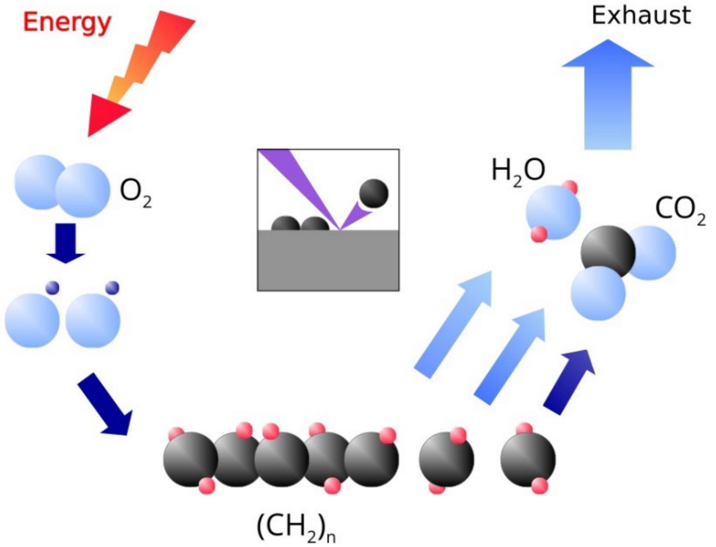
JLAB Plasma Processing Program Overview

- Current Program started in 2019:
  - goal is to process installed cryomodules and improve the overall energy reach of CEBAF.
- Built up systems to support plasma processing in CEBAF and our development program:
  - 5-channels of RF system,
    4 for processing cavities in the accelerator tunnel and 1 for offline development system;
  - 2 gas supply carts capable of supplying a variable mixture of two gases
    with controlled flow and pressure;
  - 2 vacuum carts each with a 300 l/s turbo pump and a 70 l/s turbo pump
    which is part of a differentially pumped RGA system.
- In November 2020 we started a robust vertical testing program:
  - 27 vertical tests, before and after plasma processing usually with different gas mixtures.
- Developing in situ cryomodule plasma processing for CEBAF:
  - 2 cryomodules were removed from CEBAF and plasma processed offline before refurbishment;
  - currently developing plans and procuring the remaining equipment to process multiple cryomodules in the CEBAF tunnel during an upcoming maintenance period.

Reactive Oxygen Plasma Processing



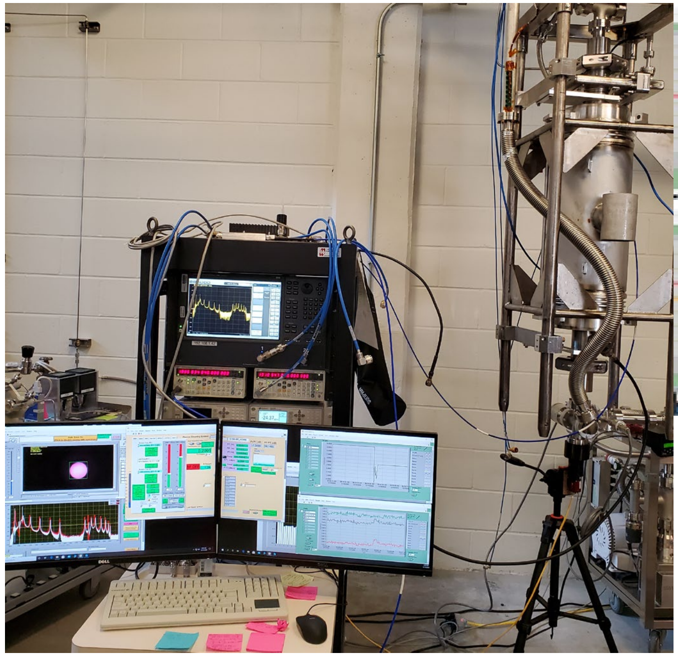
C100 Off-Line Bench Setup



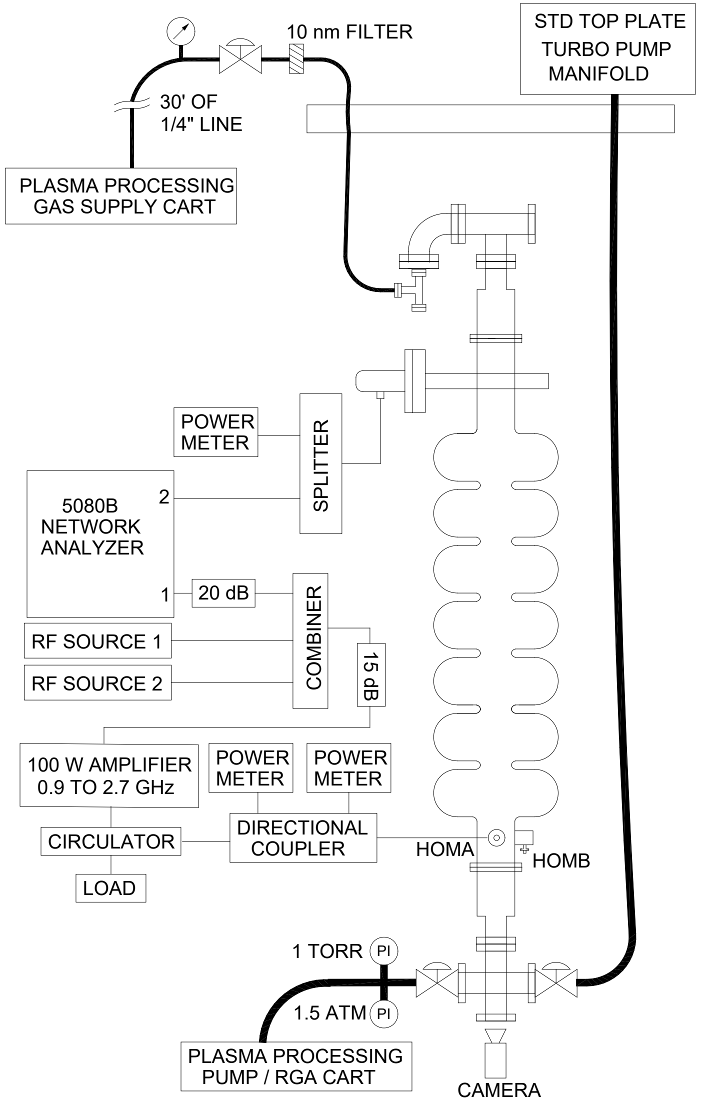
O_2 is cracked in the plasma to atomic oxygen which breaks down the hydrocarbons

- **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 200 mTorr;
  - 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_2, CO_2, CO and H_2O.

Vertical Test Stand Setup

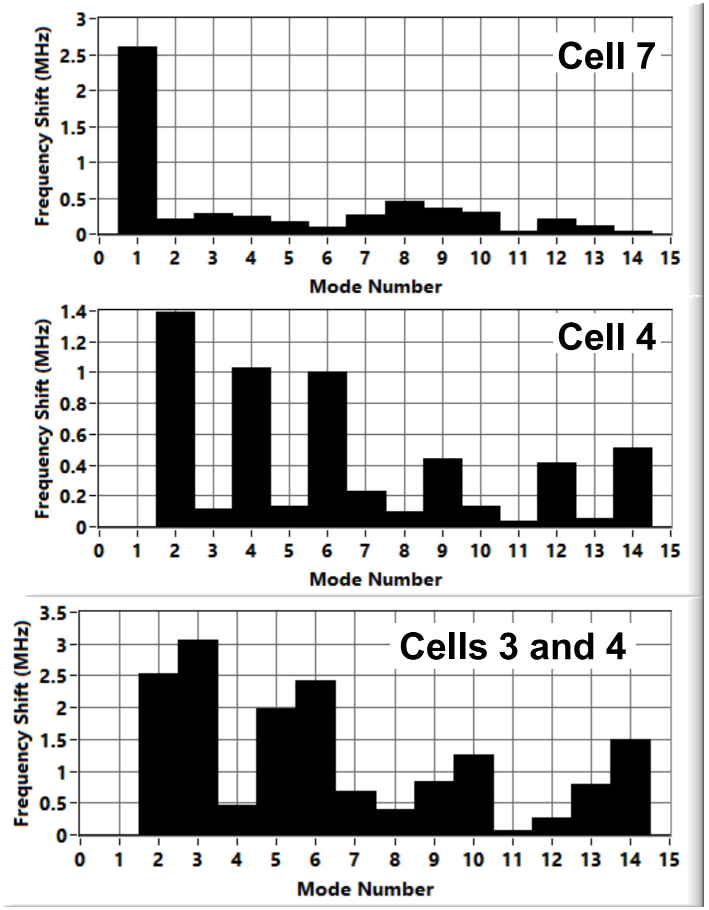


The purpose of vertical testing is to **establish procedures and judge the effectiveness** of the methods with cavities under various conditions as well as to test novel techniques.

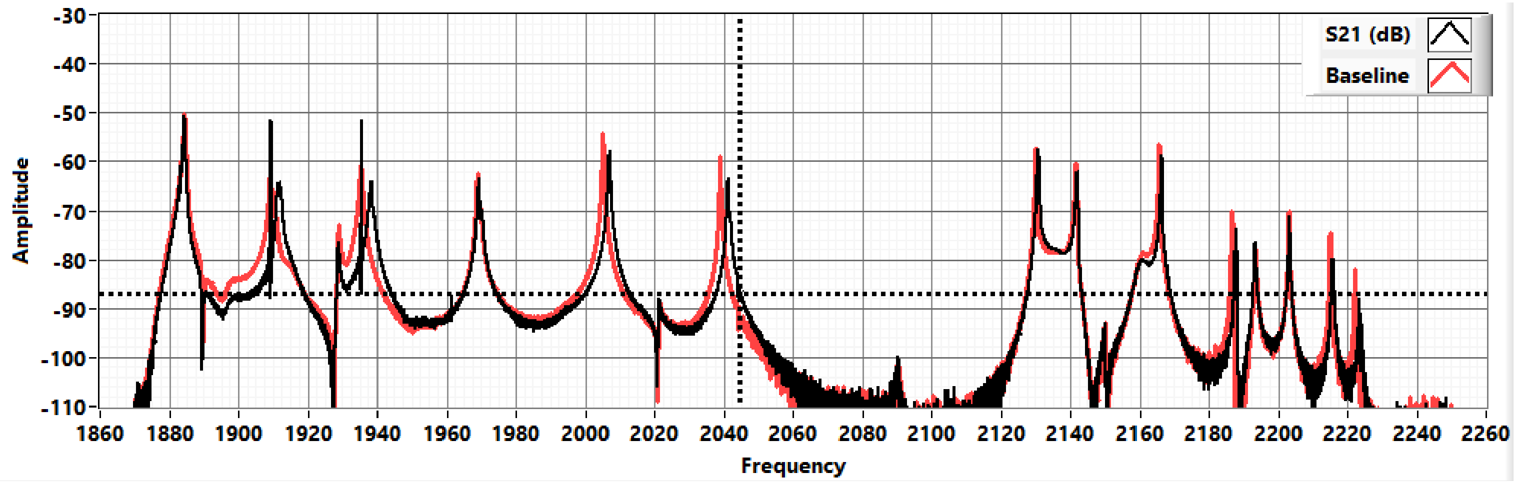


- Plasma processing is done in the vertical staging area while the cavity is still mounted to the vertical test stand.
- A network analyzer is used to measure frequency shifts while processing
- A camera was used so that we could verify the cells with plasma and gain confidence in the RF based approach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

Using an S21 Measurement to Characterize and Locate the Plasma



Measured Mode Shifts



Cavity S21 with (black) and without (red) Plasma in cells 3 and 4

- 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.

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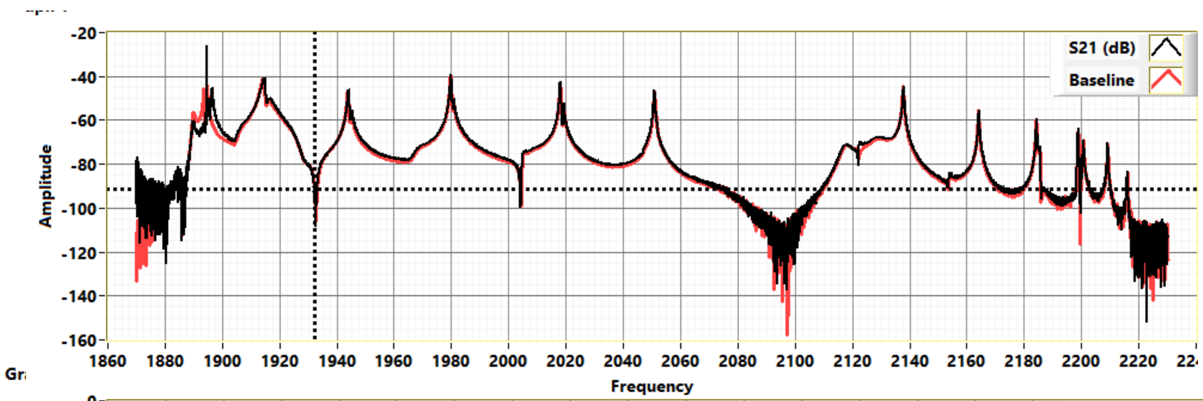
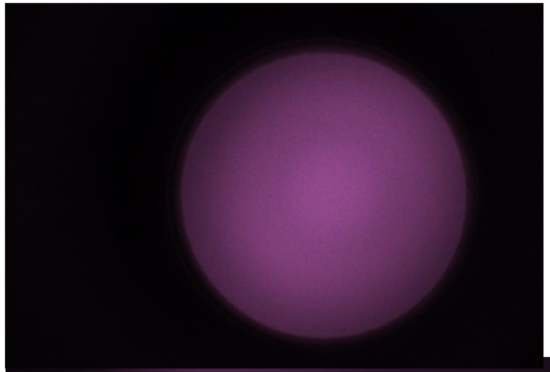
Detecting Coupler Breakdown Using a Network Analyzer

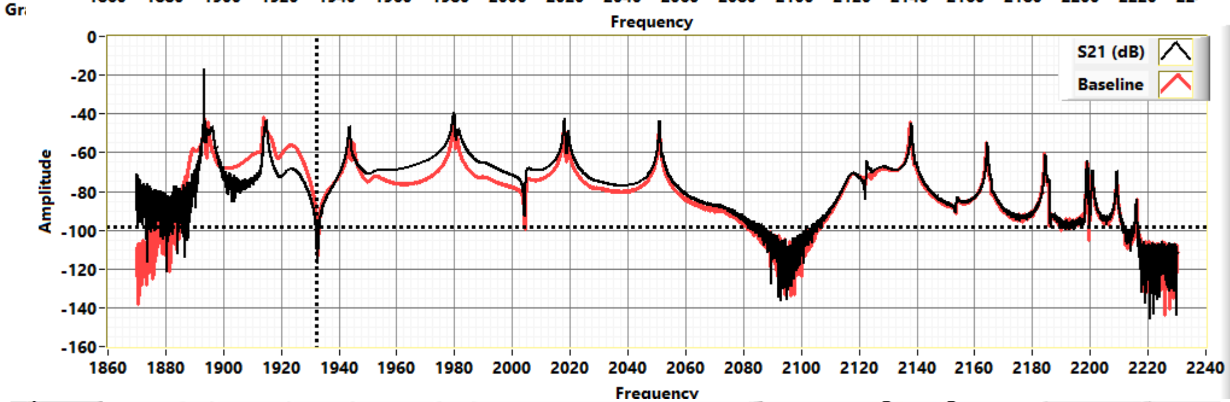
Nominal plasma on/off (black / red) measurements with plasma in cell 7.

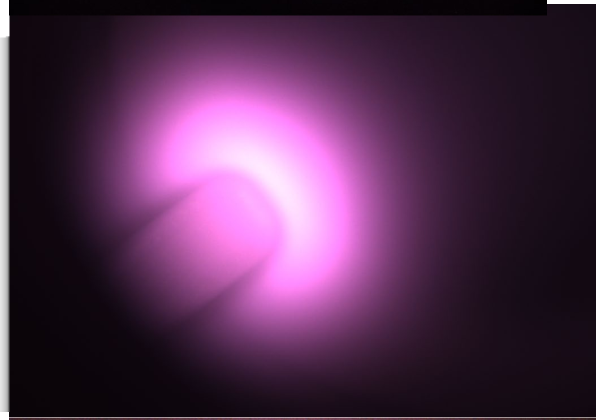




Not a terrible fault mode diffuse discharge at probe tip.

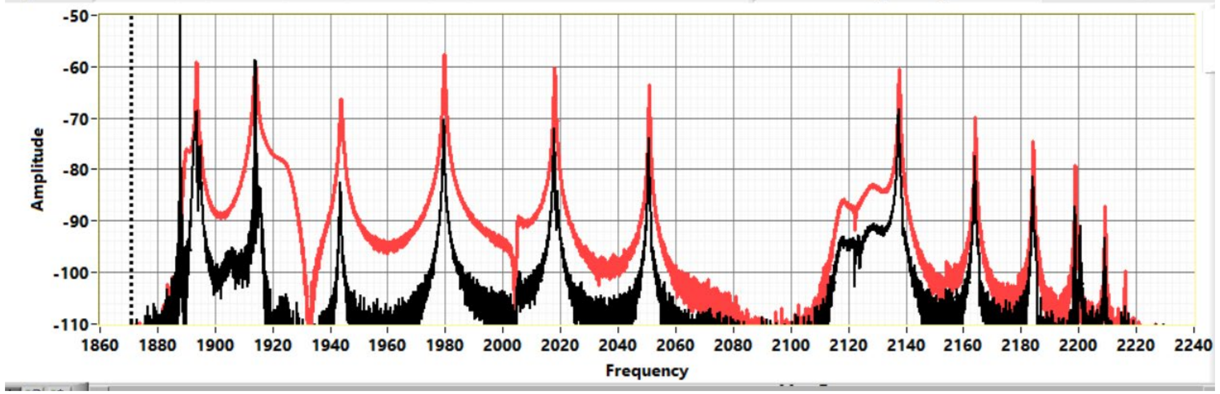
Typical signals for plasma on HOM antenna tip with RF on/off (black / red).

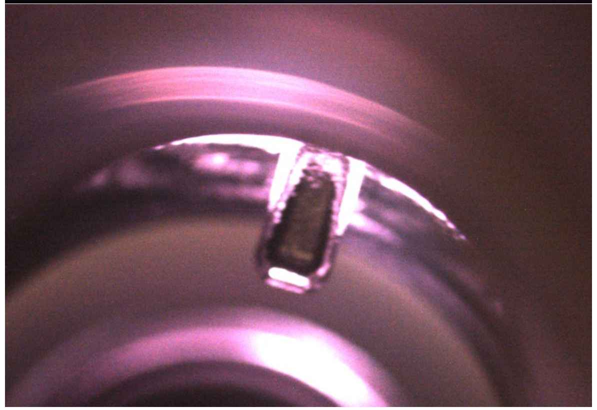




This one is bad as it is an arc like discharge in the tube containing the coupler feedthrough antenna.

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





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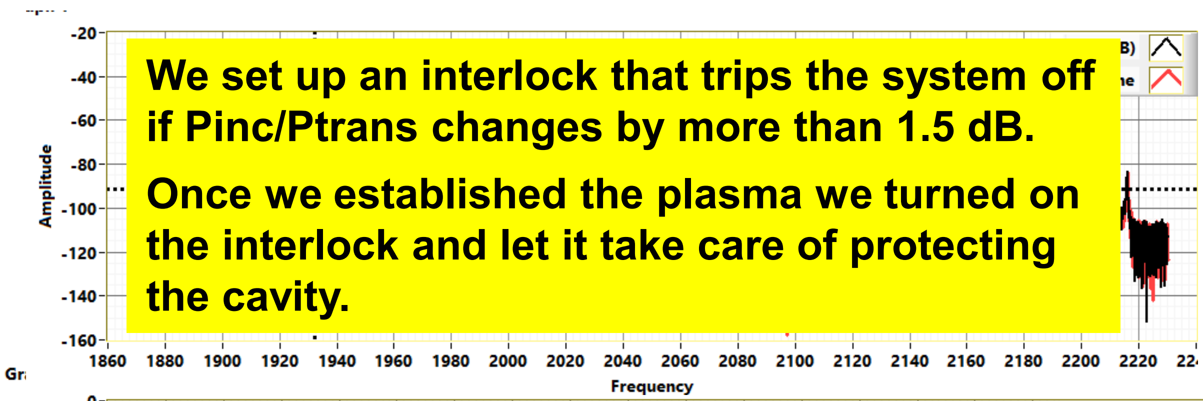
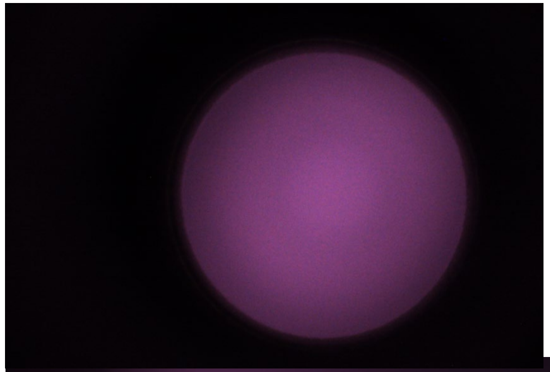
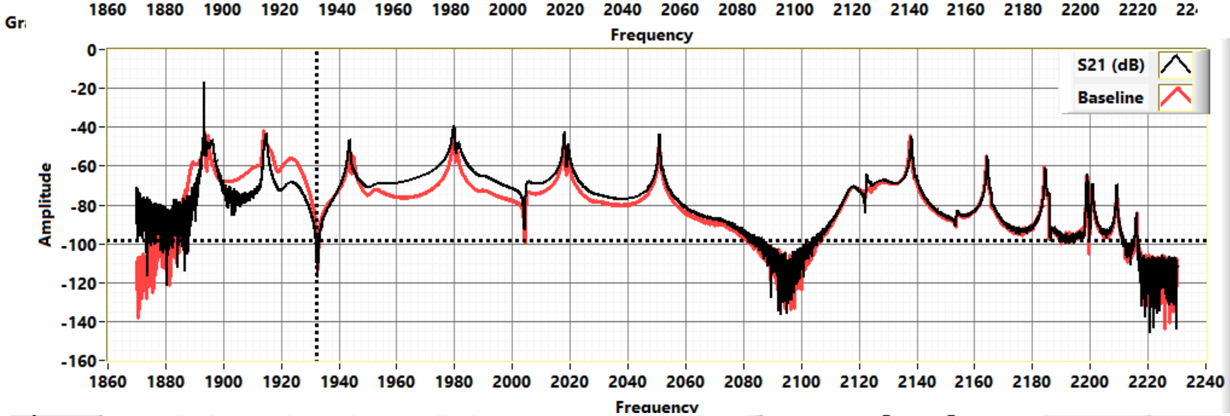
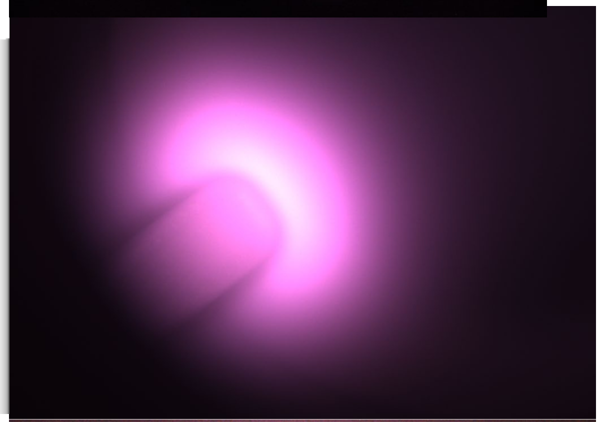


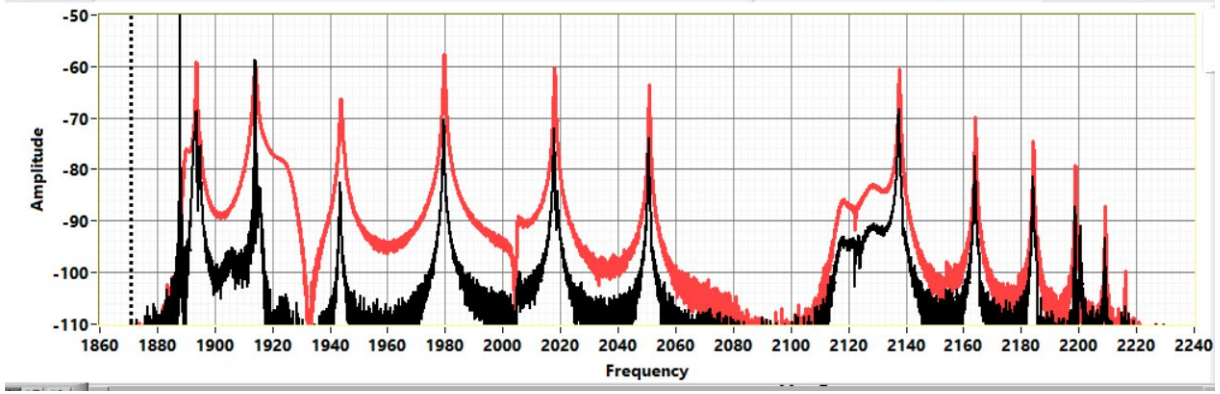
We set up an interlock that trips the system off if Pinc/Ptrans changes by more than 1.5 dB.

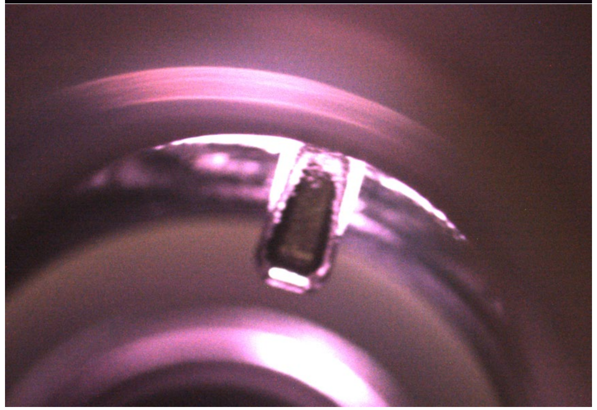
Once we established the plasma we turned on the interlock and let it take care of protecting the cavity.











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Plasma Processing Program Nov. 2021 to Present

- Started a series of tests to optimize oxygen content in the process gas:
  - plasma process using different gas mixtures;
  - vertical test;
  - contaminate the cavity with hydrocarbons,
    - using a 93% argon 7% methane mixture;
  - vertical test;
  - repeat.
- By avoiding the clean room cycle, able to
  - perform one plasma process or contaminate and test cycle per week.
- Being able to test so frequently without interrupting other production and R&D activities is possible only because JLAB's vertical test facility has 6 shielded test dewars and a dedicated helium supply system.
- Based on these experiments, switched:
  - from standard 1% to 2% oxygen mixture used by Fermi and SNS;
  - to 1% oxygen followed by a 20% oxygen mixture a day or two later.
- This testing program will continue, for the foreseeable future:
  - the next experiments will be with different noble gasses.

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
9-Jan	10-Jan	11-Jan	12-Jan	13-Jan	14-Jan	15-Jan
16-Jan	17-Jan	18-Jan	19-Jan	20-Jan	21-Jan	22-Jan
23-Jan	24-Jan	25-Jan	26-Jan	27-Jan	28-Jan	29-Jan
30-Jan	31-Jan	1-Feb	2-Feb	3-Feb	4-Feb	5-Feb
6-Feb	7-Feb	8-Feb	9-Feb	10-Feb	11-Feb	12-Feb
13-Feb	14-Feb	15-Feb	16-Feb	17-Feb	18-Feb	19-Feb
20-Feb	21-Feb	22-Feb	23-Feb	24-Feb	25-Feb	26-Feb
27-Feb	28-Feb	1-Mar	2-Mar	3-Mar	4-Mar	5-Mar
6-Mar	7-Mar	8-Mar	9-Mar	10-Mar	11-Mar	12-Mar
13-Mar	14-Mar	15-Mar	16-Mar	17-Mar	18-Mar	19-Mar
20-Mar	21-Mar	22-Mar	23-Mar	24-Mar	25-Mar	26-Mar

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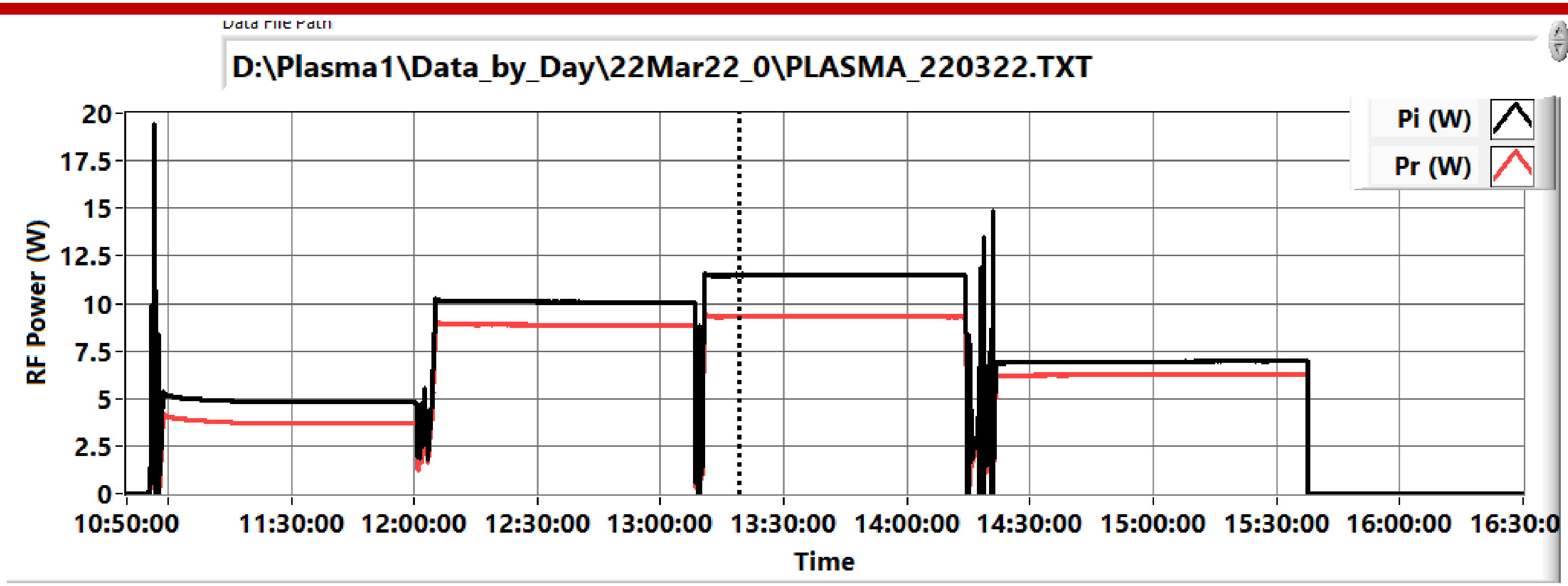
27-Jun	28-Jun	29-Jun	30-Jun	1-Jul
4-Jul	5-Jul	6-Jul	7-Jul	8-Jul
11-Jul	12-Jul	13-Jul	14-Jul	15-Jul
18-Jul	19-Jul	20-Jul	21-Jul	22-Jul
25-Jul	26-Jul	27-Jul	28-Jul	29-Jul

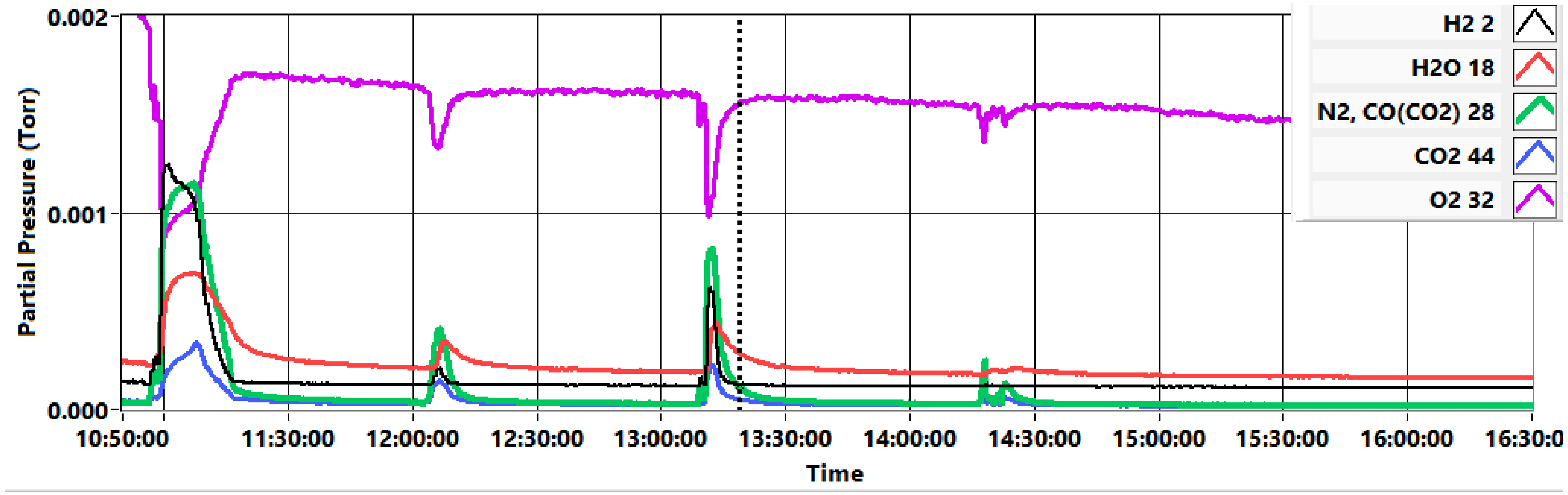
Cavity Vertical RF Test
Plasma Process
Vent to Air
Cryomodule RF Test
Cryomodule Process

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

- 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%.



- Violet trace is oxygen.
- Lower traces are hydrocarbon residuals (H_2, H2O, CO, CO_2).
- Partial pressures scaled to the pressure at the exit of the cavity.
- Oxygen content reduces when used to produce water, carbon monoxide, and carbon dioxide.

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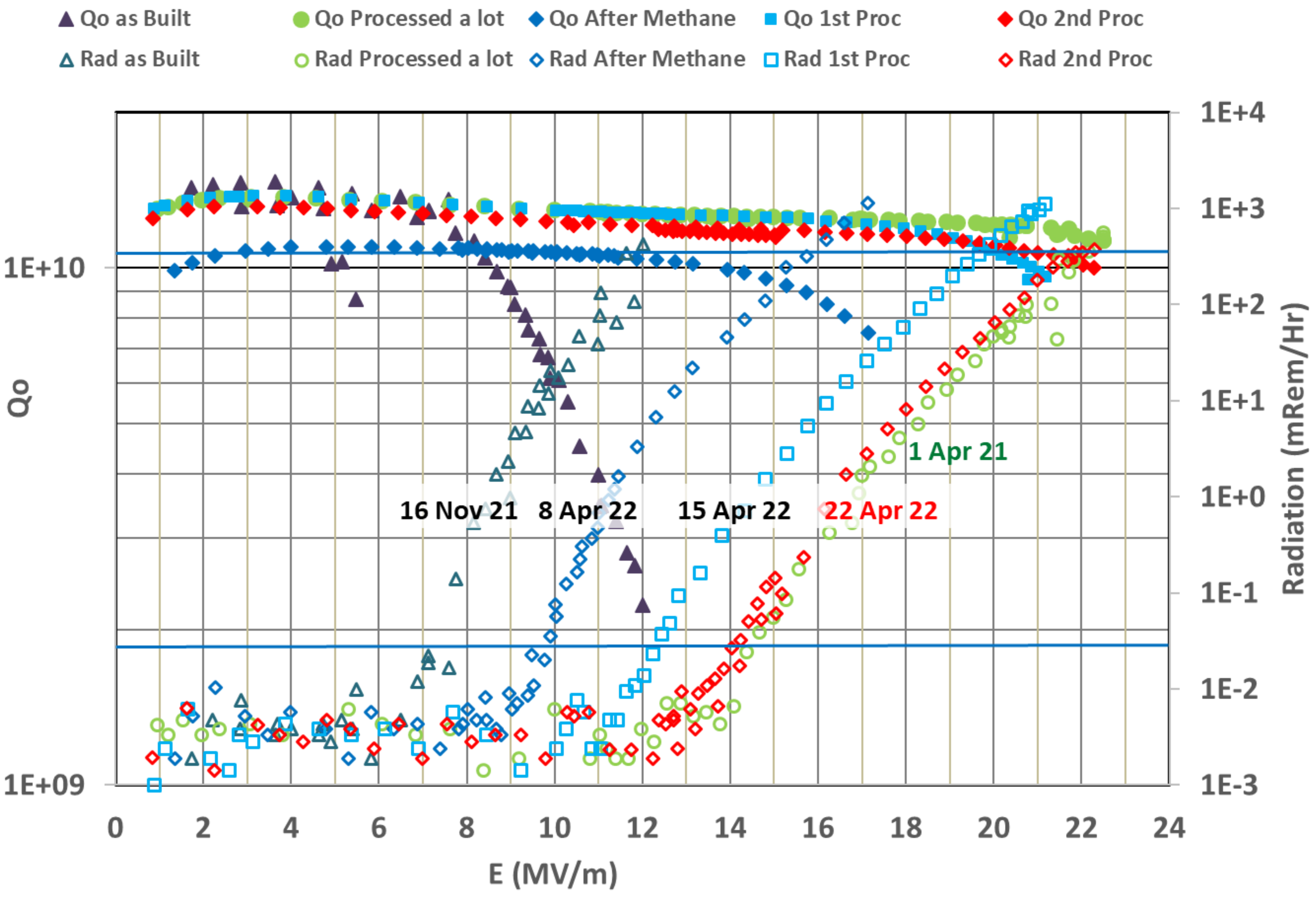
Cavity C100-86 Improvements After Plasma Processing



- Out of the clean room, Field Emission (FE) onset at 7.5 MV/m (16 Nov.21, **purple**)
- Processed several times, the last time with 20% oxygen gas mixture to get FE onset at 14.7 MV/m (1 Apr.21, **green**).
- Methane plasma deposits hydrocarbons on the surface and resets FE onset to 9.5 MV/m (8 Apr.22, **dark blue**)
- Plasma process with 1% oxygen FE onset at 12.2 MV/m (15 Apr.21, **light blue**)
- Plasma process with 20% oxygen repeat FE onset at 14 MV/m (22 Apr.21, **red**)
  - FE at operating gradient 18 MV/m from >1 rem/h to <0.008 rem/h.

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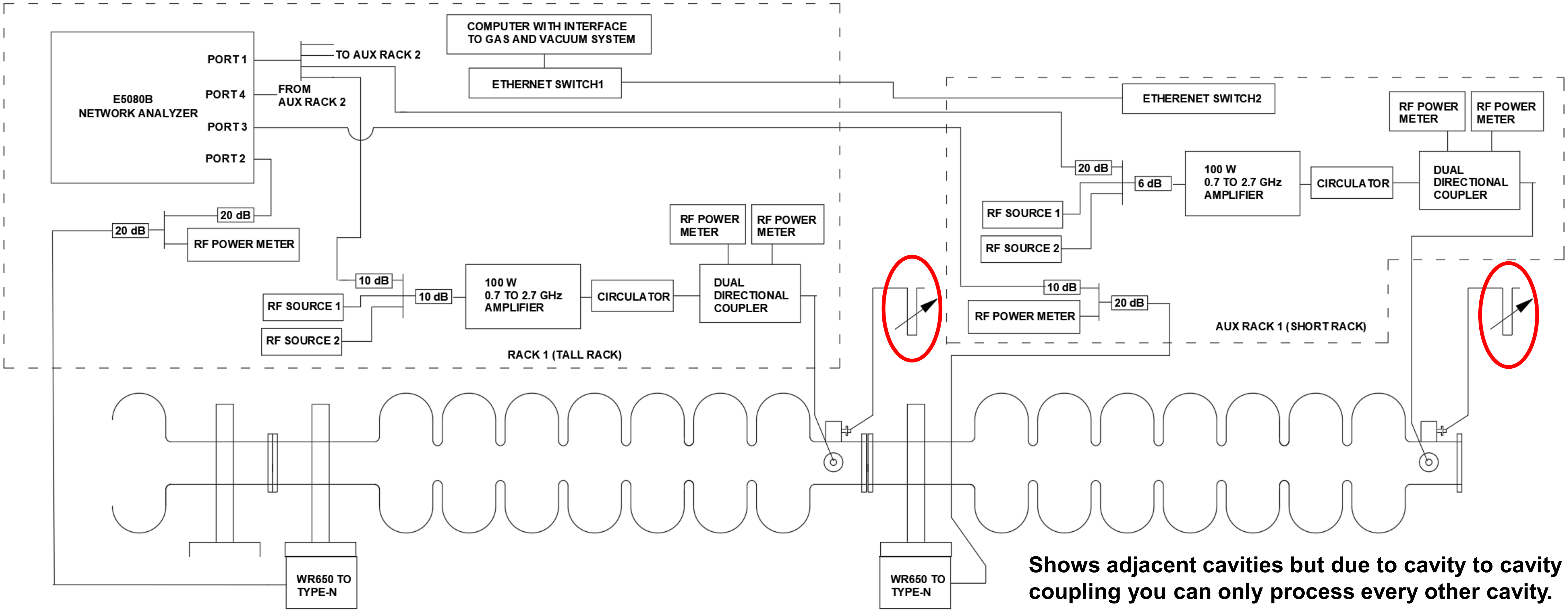
Cryomodule Processing

- The program goal is to process installed cryomodules and improve the overall energy reach of CEBAF:
  - operating gradient limited, among others, by low field emission onset causing high radiation;
  - every year one or more cryomodules are removed for refurbishment.
- Test on cryomodule C100-5:
  - worst performing C100 cryomodule in CEBAF (winter 2021-2022);
  - operating at 75 MeV while producing about 15 rem/h neutron dose in the middle of the girder.
- Cryomodule C100-5 was moved from the tunnel to the JLab cryomodule test facility where it was:
  - cooled to 2 K and field emission properties were measured;
  - warmed up to room temperature;
  - cavity S11/S21 properties were characterized as a function of phase shifter and the correct phase shift was determined;
  - plasma processed with 1% oxygen – 99% argon followed by processing with 20% oxygen, 80% argon;
  - cooled to 2K and the field emission properties were remeasured.
- The plasma processing part of the effort took 4 days:
  - using 4 RF systems, we demonstrated that we could process 8 cavities in one 10-hour shift;
  - demonstrated that it was easy for one person to process 4 cavities at once.
- Although the performance was improved by plasma processing it was decided to disassemble the cryomodule for rebuild and reinstallation into CEBAF next spring.

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

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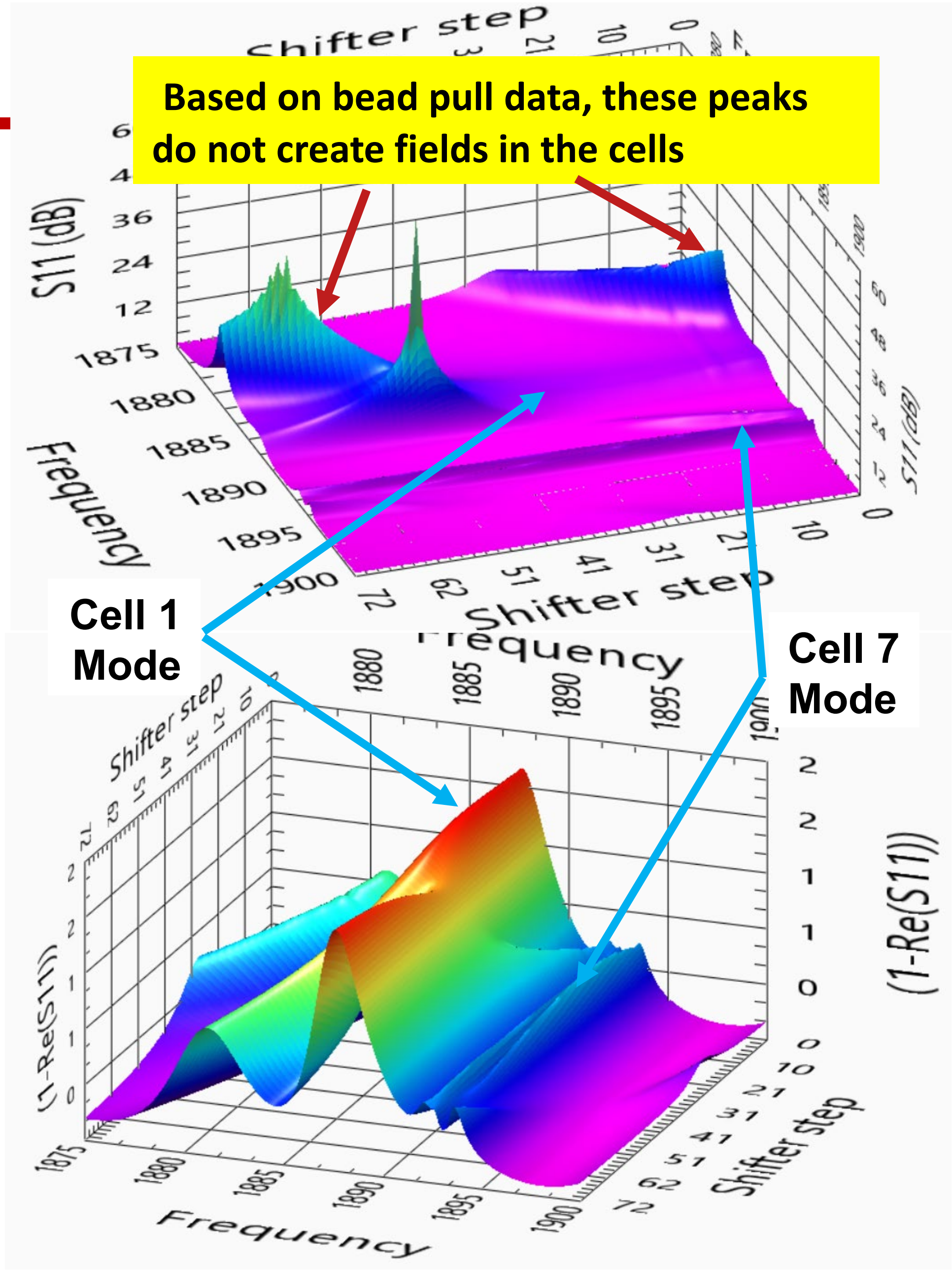
Why is the Phase Shifter Necessary

- 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 HOM-A and HOM-B couplers in the TE111 frequency band.
- 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. Of special interest are the modes for cells 1 and 4.
- 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.



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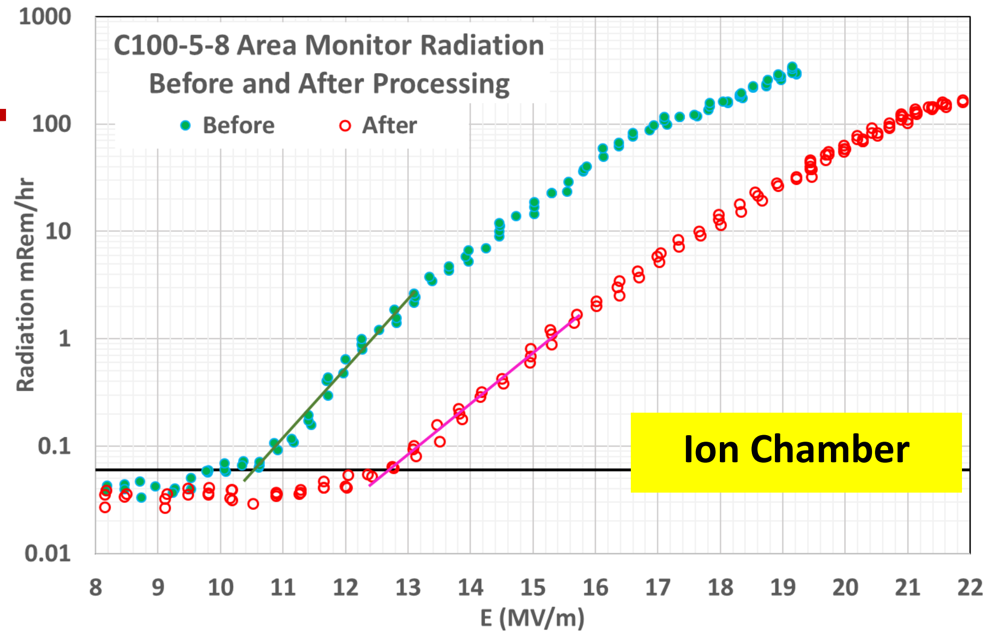
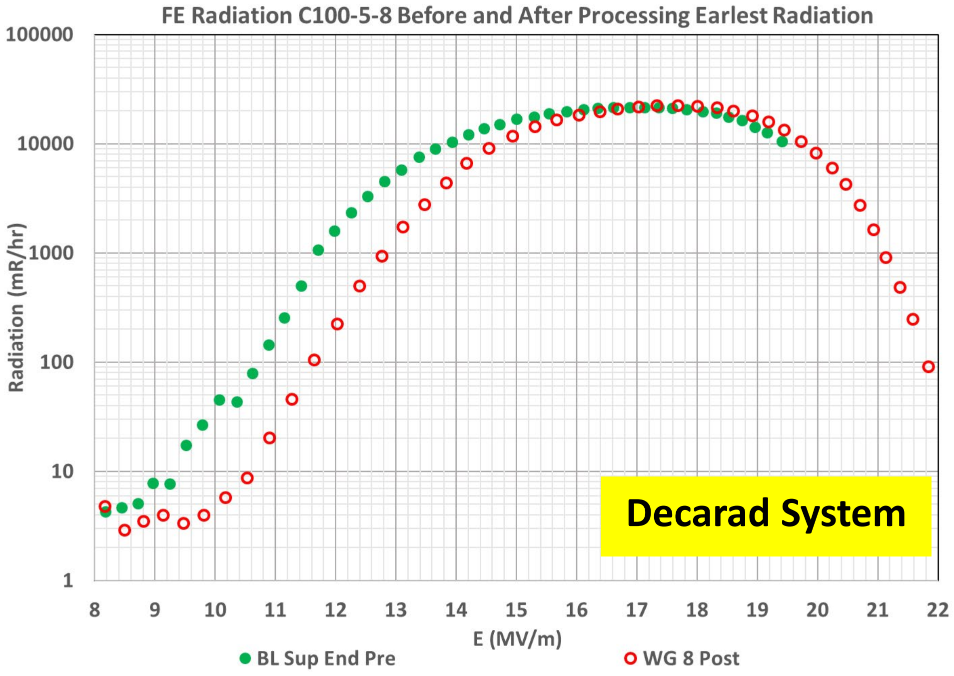
Reduction in Radiation at 18 MV/m

- 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;
  - but it tends to saturate at higher radiation levels.
- Ion chamber area monitor is much better for comparing radiation levels at higher gradients.
- Slightly different onset values on a cavity by cavity basis, but the overall improvement results were within 10% of each other.

Average reduction in radiation at nominal operating gradient 18 MV/m was a factor of 6.6

Area Monitor Data (mR/hr) at 18 MV/m			
CAV	**Before Radiation**	**After Radiation**	**Reduction**
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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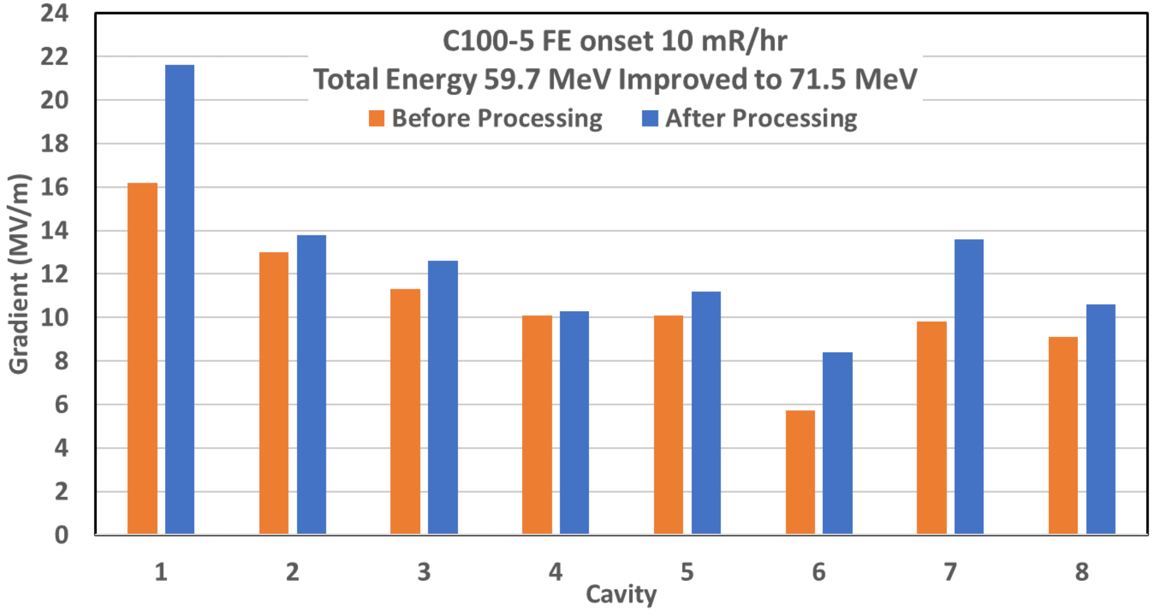
C100-5 Field Emission Results

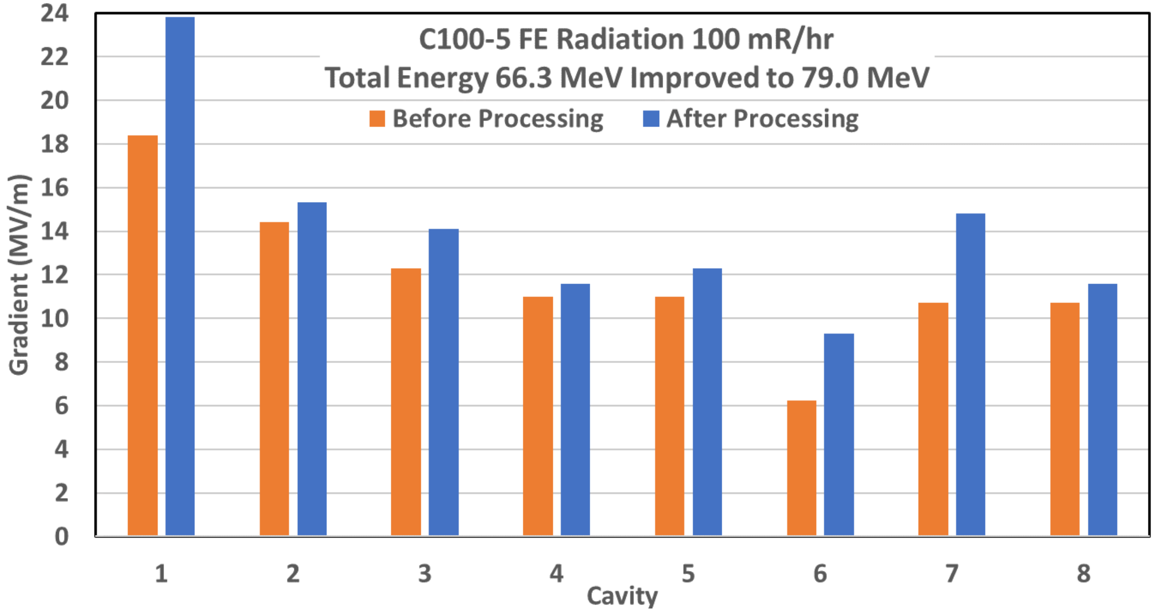
CAV	Before Processing (MV/m)			After Processing (MV/m)			After minus Before (MV/m)			(MV/m)
	10 mR/hr	100 mR/hr	1000 mR/hr	10 mR/hr	100 mR/hr	1000 mR/hr	10 mR/hr	100 mR/hr	1000 mR/hr	Last CEBAF Gradient*
1	16.2	18.4	21.8	21.6	23.8	24	5.4	5.4	2.2	17.0
2	13.0	14.4	15.8	13.8	15.3	17.3	0.8	0.9	1.5	13.5
3	11.3	12.3	13.3	12.6	14.1	16.4	1.3	1.8	3.1	13.1
4	10.1	11.0	12.8	10.3	11.6	13.2	0.2	0.6	0.4	12.6
5	10.1	11.0	12.0	11.2	12.3	13.5	1.1	1.3	1.5	12.9
6	5.7	6.3	6.8	8.4	9.3	10.3	2.7	3.1	3.5	13.5
7	9.8	10.7	11.7	13.6	14.8	17	3.8	4.1	5.3	10.3
8	9.1	10.7	11.7	9.1	10.7	11.7	1.5	0.9	1.1	14.2
Average Values (MV/m)										
	9.1	**10.7**	**11.7**	**10.6**	**11.6**	**12.8**	**2.1**	**2.3**	**2.3**	**13.4**
Energy MeV										
	59.7	**66.3**	**74.1**	**71.5**	**79.0**	**87.2**	**11.8**	**12.6**	**13.0**	**75.0**

- Measurement system was “Decarad”: 10 Geiger Muller tubes placed along the cryomodule.
- For each measurement the sensor that crossed the threshold at the lowest gradient was used.
- Depending on the radiation patterns one sensor was chosen for the before processing measurement result while another might be chosen for the after processing measurement result.

C100-5 Summary of Improvements

- The plasma processing part of the effort took 4 days.
- Demonstrated that:
  - using 4 RF systems, we could process 8 cavities in one 10-hour shift;
  - it was easy for one person to process 4 cavities at once.
- Improved:
  - field emission onset from 59 MeV to 71.5 MeV or an improvement of 11.6 MeV;
  - 100 mR/h radiation level from 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.**





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Summary

Vertical Testing Program

- Robust vertical test program in place which allows us to quickly perform experiments relating to process development.
- Controlled contaminating the surface with a methane gas mixture allows to process and perform a vertical test once per week.

C100-5 Cryomodule Processing

- None of the cavities in C100-5 were degraded by plasma processing.
- Demonstrated that, with 4 channels, one person can process 8 cavities one time in one 10 hour shift.
- We gained confidence that it is worth it to process cryomodules in the tunnel:
  - >11.5 MeV improvement in all field emission metrics and a reduction in high field FE radiation by a factor of 6.
  - a 13 MeV improvement on 3 cryomodules is like dropping a full C50 cryomodule into the linac!

Plan Forward

- Continue to improve processes, software, etc. using systems in the VTA and off line system.
- Investigate using other gas combinations and further optimize the gas mixture protocols:
  - first positive results from helium/oxygen, but need more experiments to verify repeatability.
- Start trying to understand how we might process C50 and C75 cavities.
- Planning to process up to three cryomodules during the spring 2023 maintenance period.

Acknowledgements

- None of this effort would be possible without the **support of the technical staff** in the chemistry area, clean room, vertical test area and cryomodule test facility.

What my colleagues are doing rather than being here giving the talk