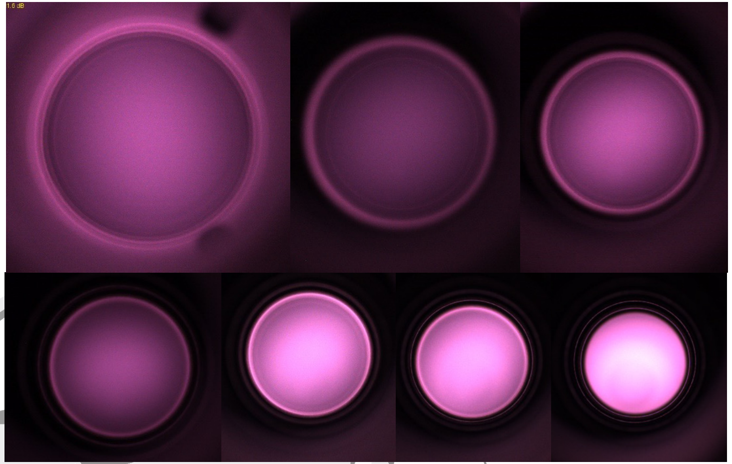
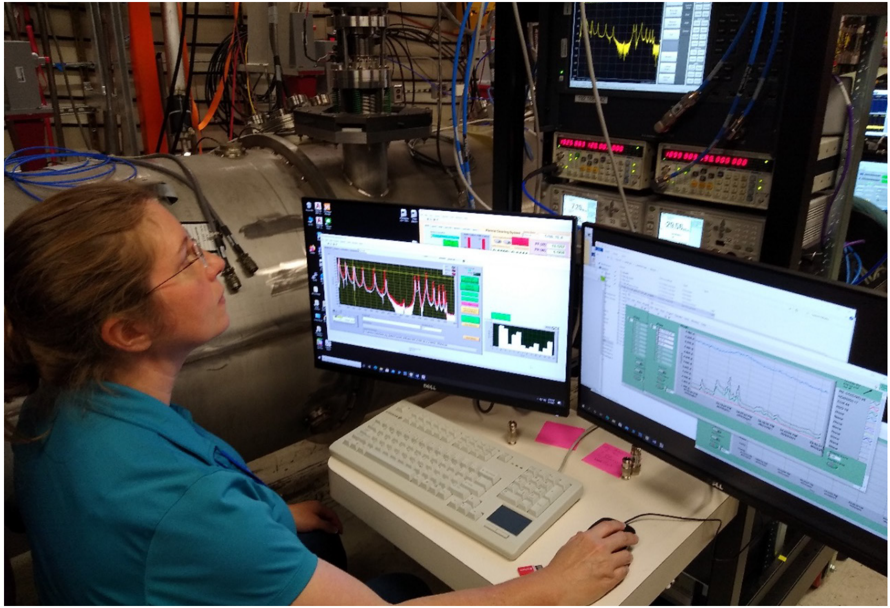
Plasma Processing SRF Cavities at Jefferson Lab





Tom Powers, Tiffany Ganey and Natalie Brock

North American Particle Accelerator Conference

Aug. 8, 2022

Jefferson Lab

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DOE SC Lab funding announcement Lab-20-2310

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JSA

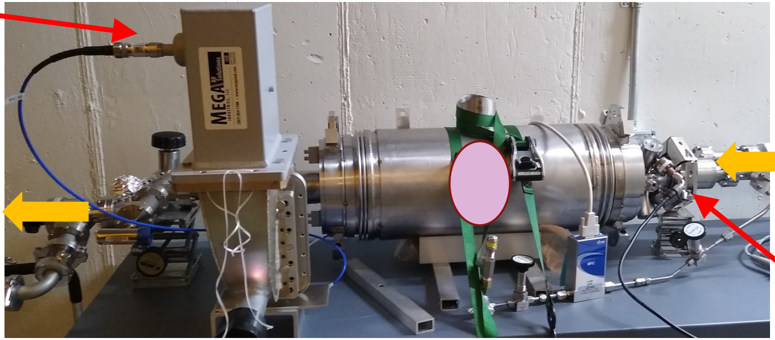
JLAB Plasma Processing Program Overview

- Current Program started in 2019.
- We built up the following systems to support plasma processing in CEBAF as well as in our development program.
  - 5-channels of RF system, 4 designed for processing cavities in the accelerator tunnel and one for use in the off line system.
  - Two gas supply carts capable of supplying a variable mixture of two gases with controlled flow and pressure.
  - Two 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 where we have done 27 vertical tests which were done before and after plasma processing usually with different gas mixtures.
- We processed two cryomodules both were removed from the machine for reprocessing and rebuild.
- We are 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

RF Monitor Port

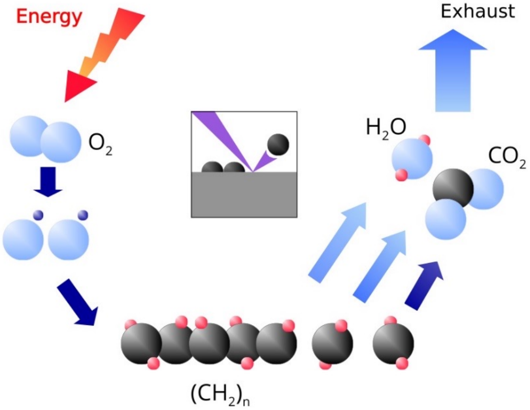
Process Gas With CO_2, CO and H_2O, etc.



Process Gas

RF Into HOM Port

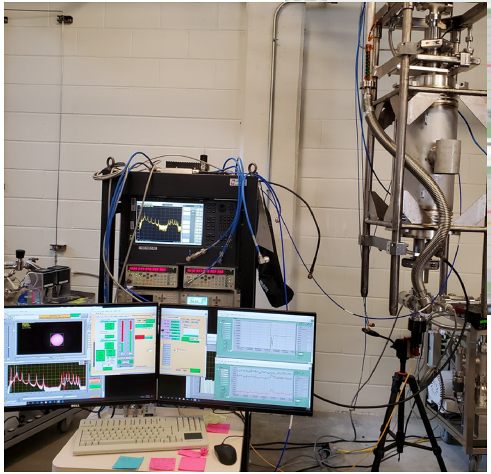
C100 Off-Line Bench Setup

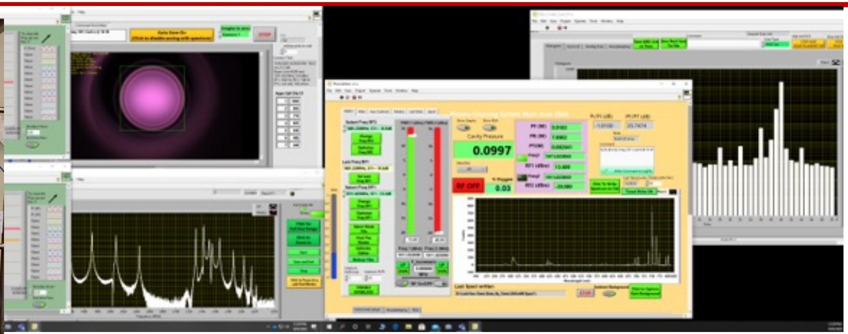


O_2 is cracked in the plasma to atomic oxygen which breaks down the hydrocarbons

- **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, CO2, CO and H2O

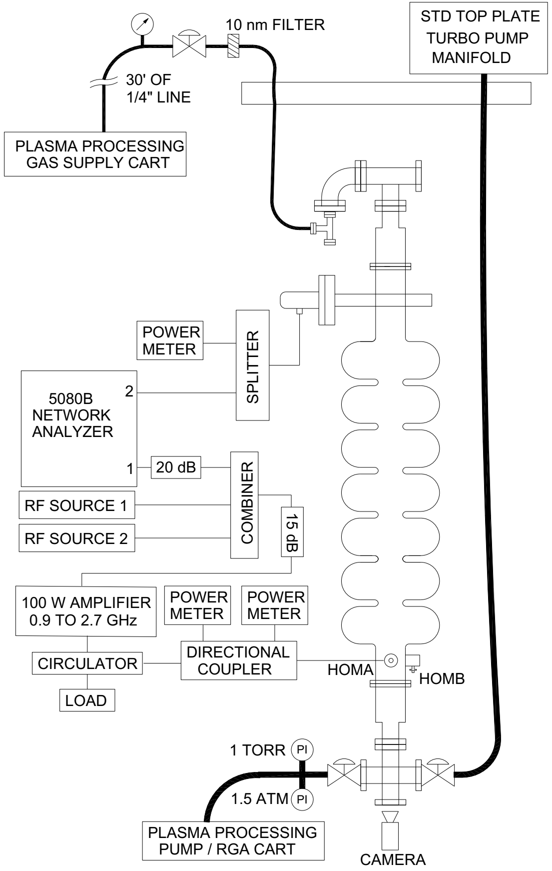
Vertical Test Stand Setup



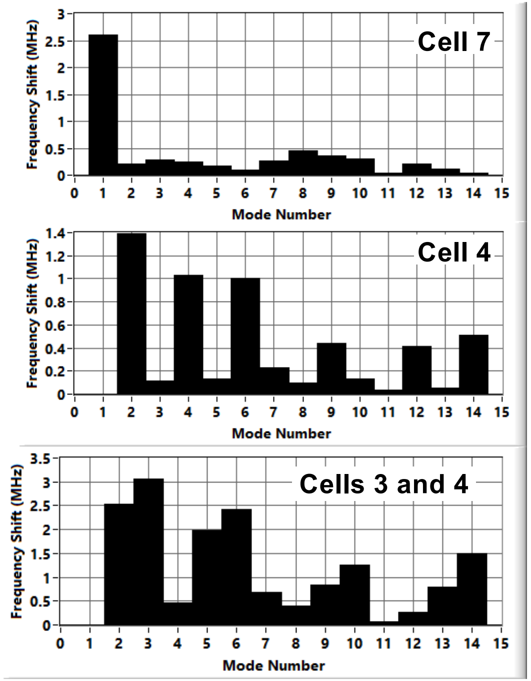


The purpose of vertical testing is to establish procedures and judge the effectiveness of the methods with cavities under various conditions as well as to test novel techniques.

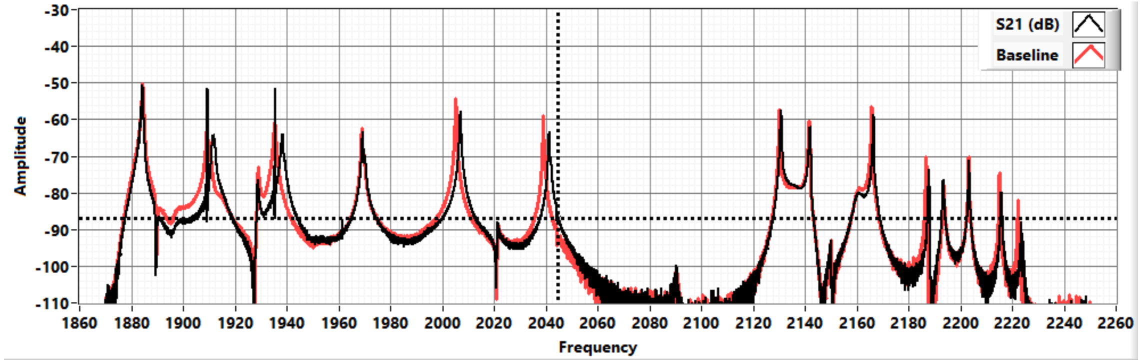
- **Plasma processing is done in the vertical staging area while the cavity is still mounted to the vertical test stand.**
- **A network analyzer is used to measure frequency shifts while processing**
- **A camera was used so that we could verify the cells with plasma and gain confidence in the RF based 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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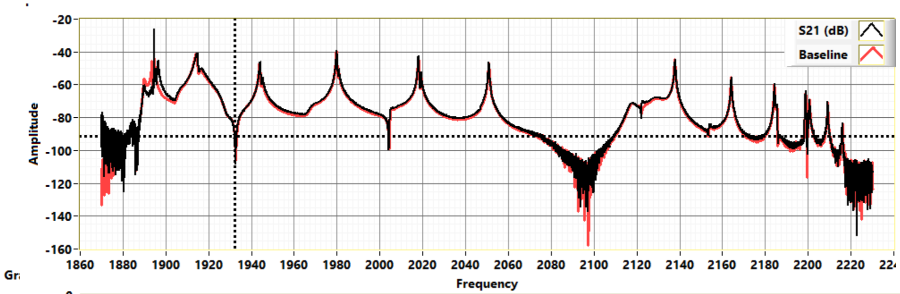
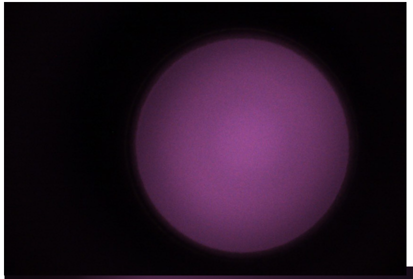
Detecting Coupler Breakdown Using a Network Analyzer

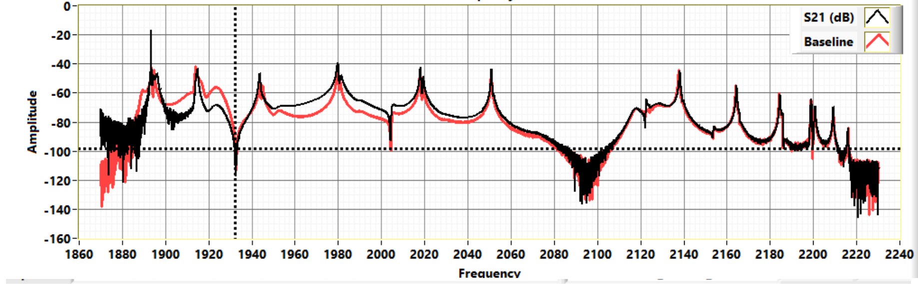
Nominal plasma on/off (black / red) measurements with plasma in cell 7.

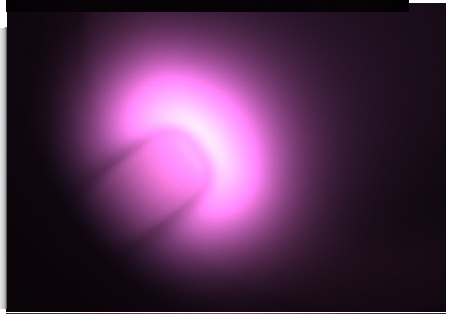




Not a terrible fault mode diffuse discharge at probe tip.

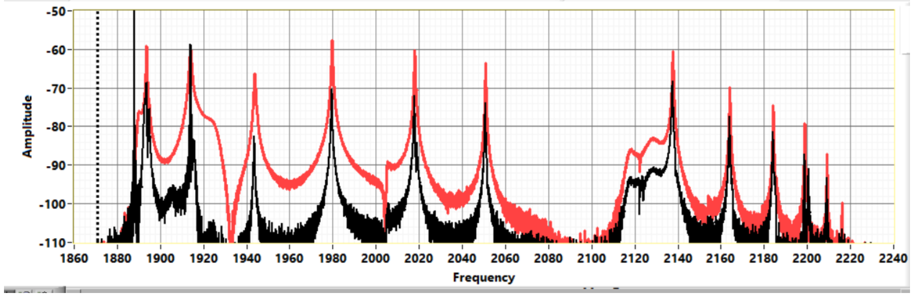
Typical signals for plasma on HOM antenna tip with RF on/off (black / red).

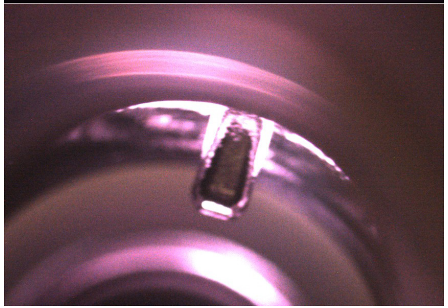




This one is bad as it is an arc like discharge in the tube containing the coupler feedthrough antenna.

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





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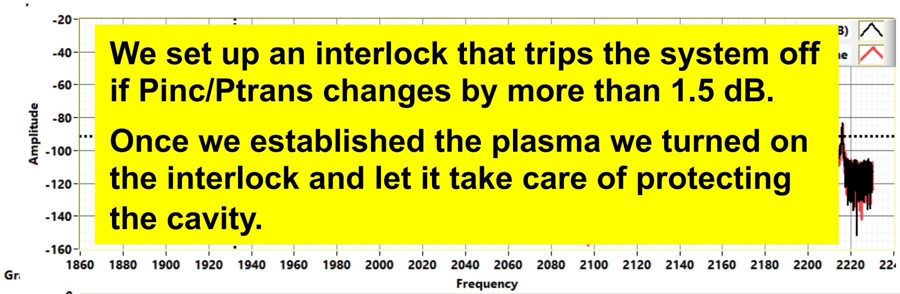
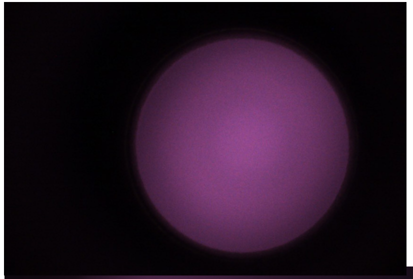


We set up an interlock that trips the system off if Pinc/Ptrans changes by more than 1.5 dB.

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



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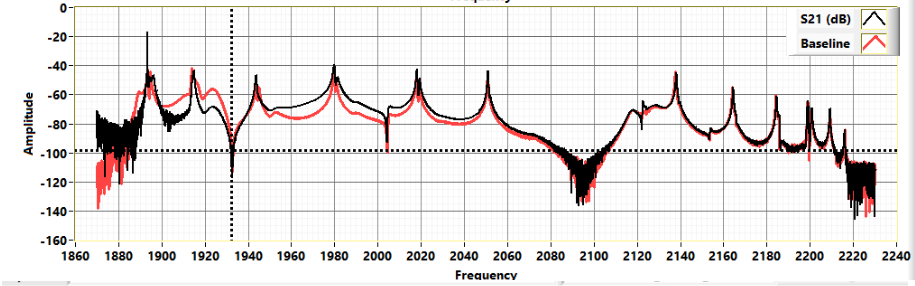

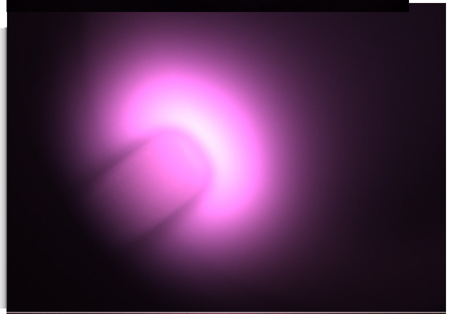

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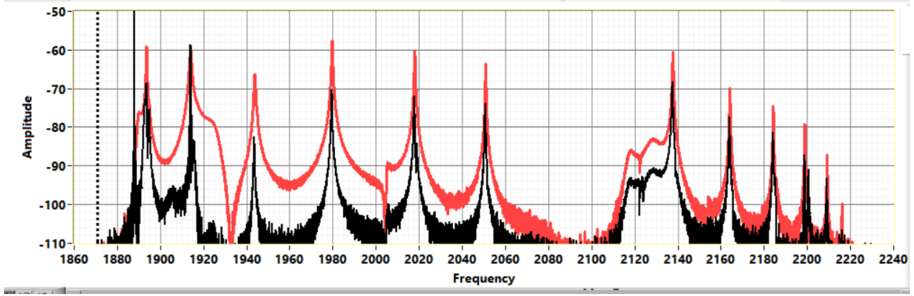

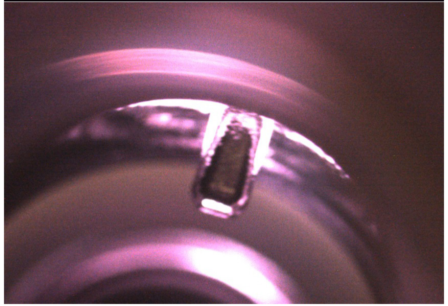

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Plasma Processing Program From November 2021 to Present

- Starting in Nov 2021 we began a series of tests in order to optimize the oxygen content in the 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.

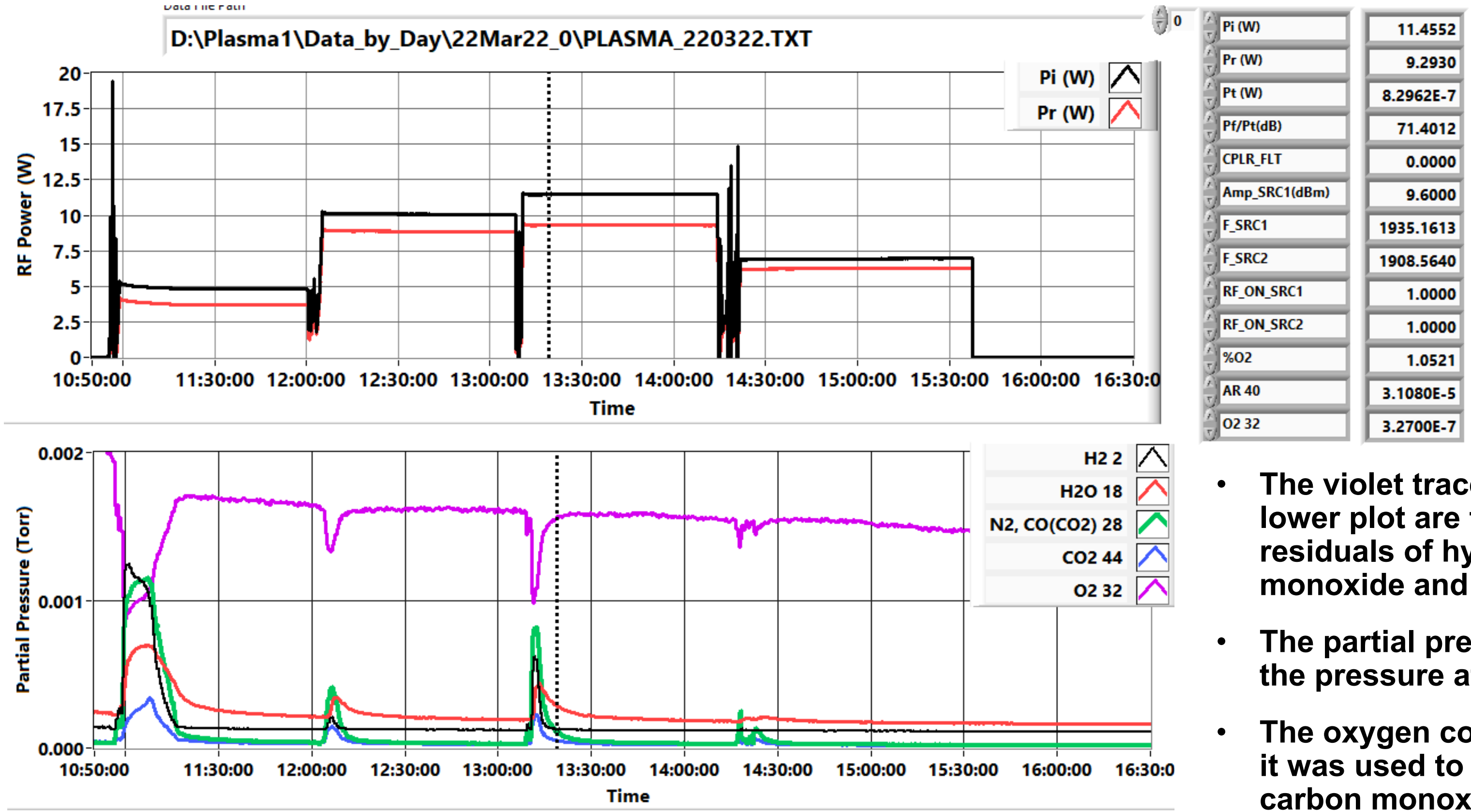
Sun	Mon	Tues	Wed	Thurs	Fri	Sat
14-Nov	15-Nov	16-Nov	17-Nov	18-Nov	19-Nov	20-Nov
21-Nov	22-Nov	23-Nov	24-Nov	25-Nov	26-Nov	27-Nov
28-Nov	29-Nov	30-Nov	1-Dec	2-Dec	3-Dec	4-Dec
5-Dec	6-Dec	7-Dec	8-Dec	9-Dec	10-Dec	11-Dec
12-Dec	13-Dec	14-Dec	15-Dec	16-Dec	17-Dec	18-Dec
19-Dec	20-Dec	21-Dec	22-Dec	23-Dec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

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

- 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 6 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 processing one day with 1% oxygen followed by a 20% oxygen mix a day or two later.
- This testing program will continue, for the foreseeable future. The next experiments will be with different noble gasses.

Typical Processing Cycle in the Vertical Test Area

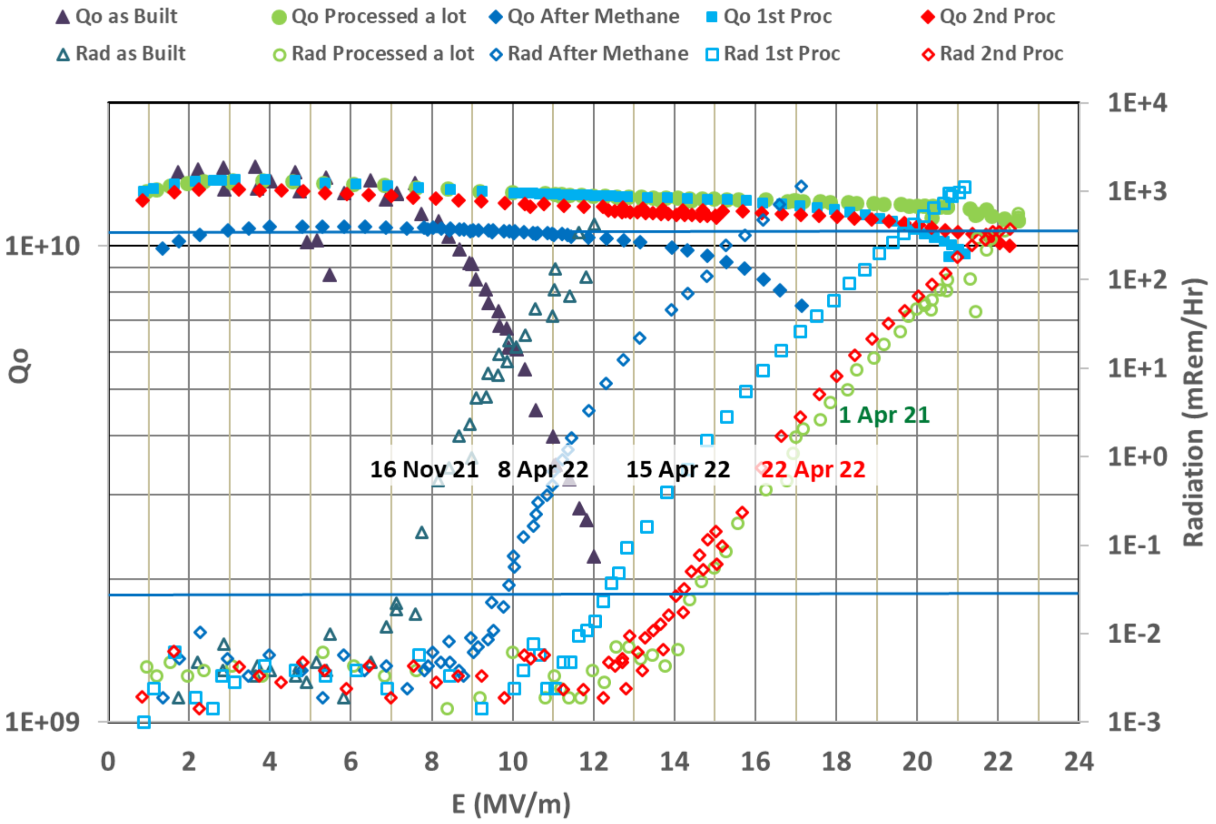


The Upper Plots are incident and reflected power calibrated to the input of the HOM port.

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.**

Cavity C100-86 Improvements After Plasma Processing



- 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.

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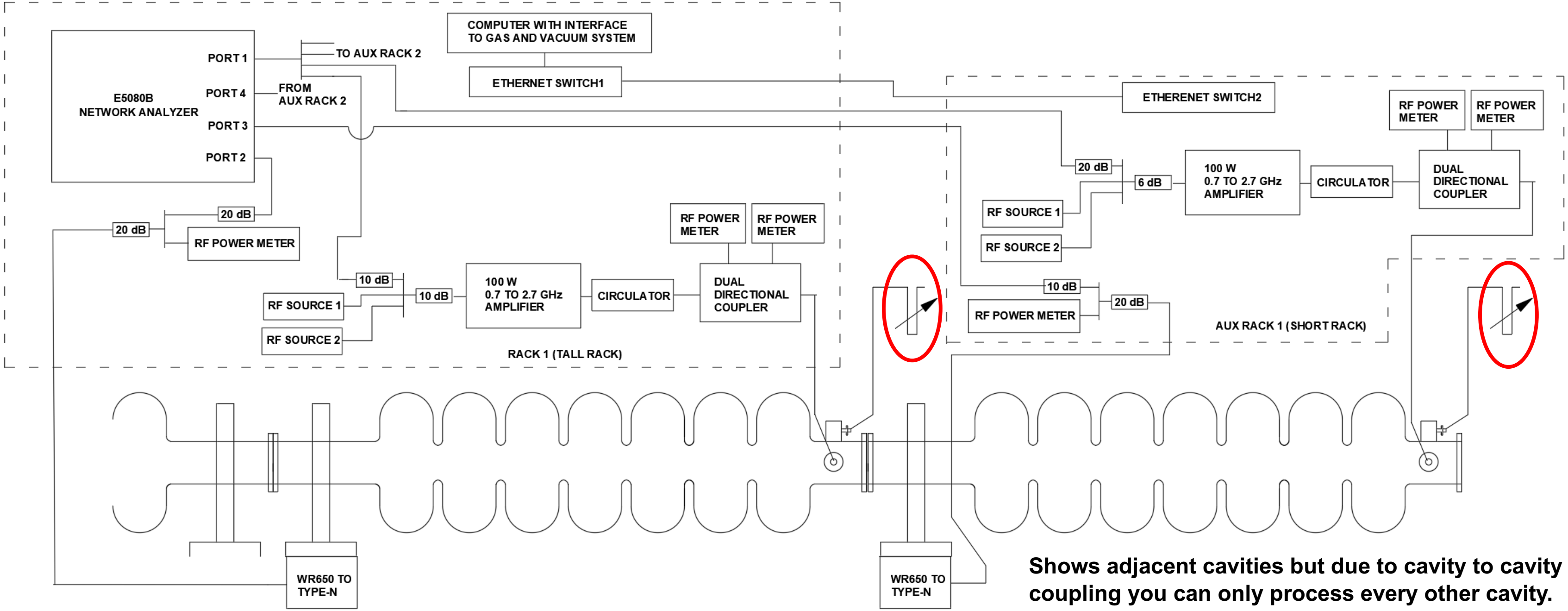
RF System Block Diagram for Processing Cryomodule C100-5

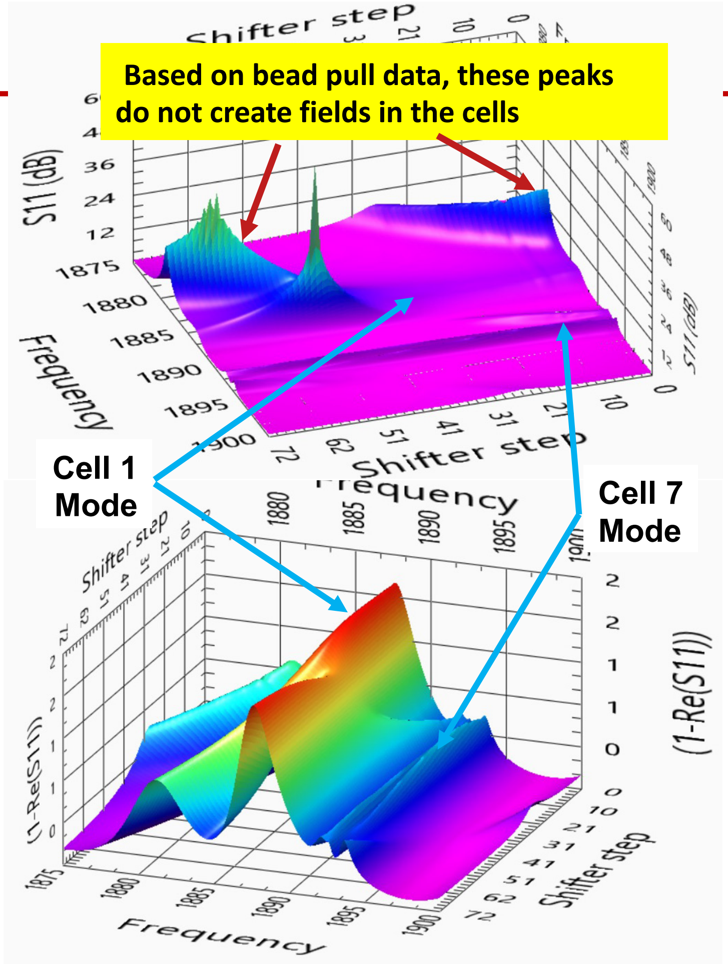


Shows adjacent cavities but due to cavity to cavity coupling you can only process every other cavity.

- **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**

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. Of special interest is 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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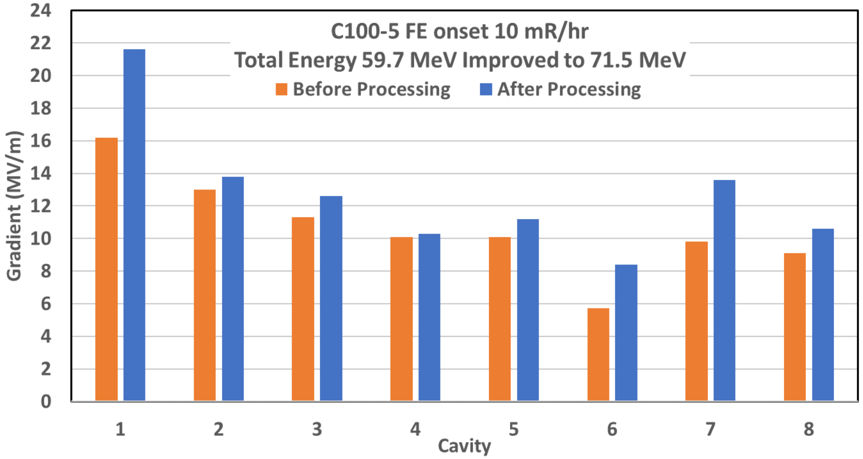
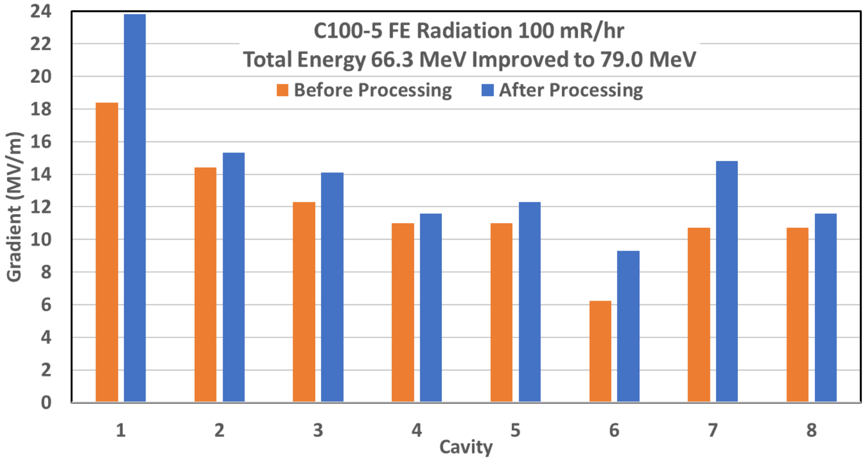
Summary of Improvements to C100-5

- 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.
- 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 mR/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.





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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.
- Using a methane gas mixture to contaminate the surface in a controlled manner is allowing us to process and perform a vertical test as fast as once per week.

Overview of C100-5 processing

- More than 11.5 MeV improvement in all field emission metrics and a reduction in high field FE radiation by a factor of 6.
- 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. A 13 MeV improvement on 3 cryomodules is like dropping full C50 zone 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 such as helium/oxygen, and further optimize the gas mixture protocols.
- Start trying to understand how we might process C50 and C75 cavities.
- Develop a plan that is integrated with cryomodule swaps, to process at least 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.
- I would like to especially thank Tiffany Ganey and Natalie Brock who are providing extensive support in making this program happen.

Backup Slides

C100-5 Cryomodule Processing

- Prior to removal from CEBAF, this cryomodule was operating at 75 MeV while producing about 15 Rem/hr neutron dose in the middle of the girder.
- It was removed from the machine for reprocessing and rebuild because it was the worst preforming C100 cryomodule in the machine.
- The cryomodule was moved from the tunnel the JLAB cryomodule test facility test bunker where was:
  - Cooled to 2 K and field emission properties were measured
  - It was warmed up to room temperature
  - The cavity S11/S21 properties were characterized as a function of phase shifter and the correct phase shift was determined.
  - It was plasma processed with 1% oxygen – 90% argon followed by processing with 20% oxygen, 80% argon.
  - It was cooled to 2K and the FE properties were remeasured..
- **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.**
- **The plasma processing part of the effort took 4 days.**
- Although the performance was improved by plasma processing it was decided to disassemble the cryomodule for rebuild and reinstallation into CEBAF next spring.

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

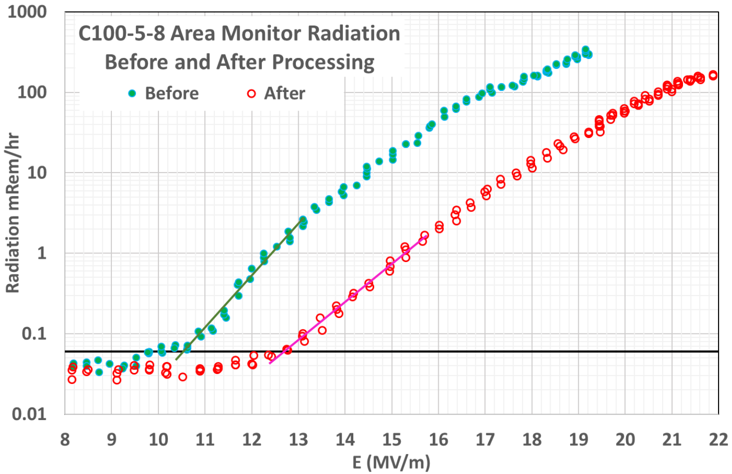
- **Measurement system was 10 Geiger Muller tubes placed along the cryomodule.**
- **For each measurement the sensor that crossed the threshold at the lowest gradient was used.**
- **Depending on the radiation patterns one sensor was used for the before processing measurement while another might be used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

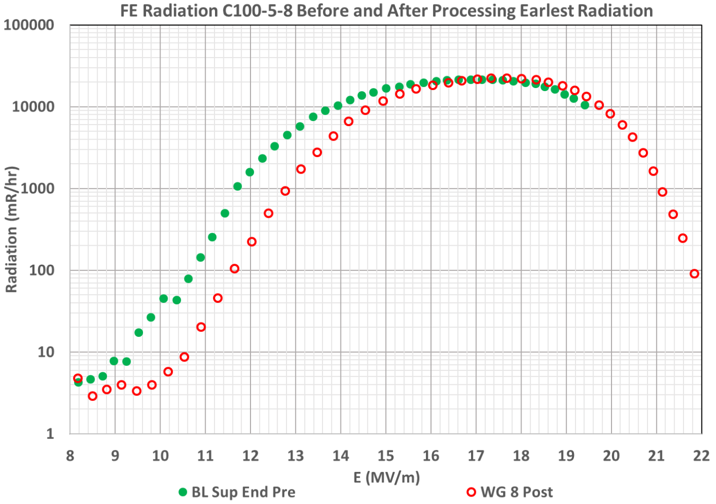
Reduction in Radiation at 18 MV/m

- 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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