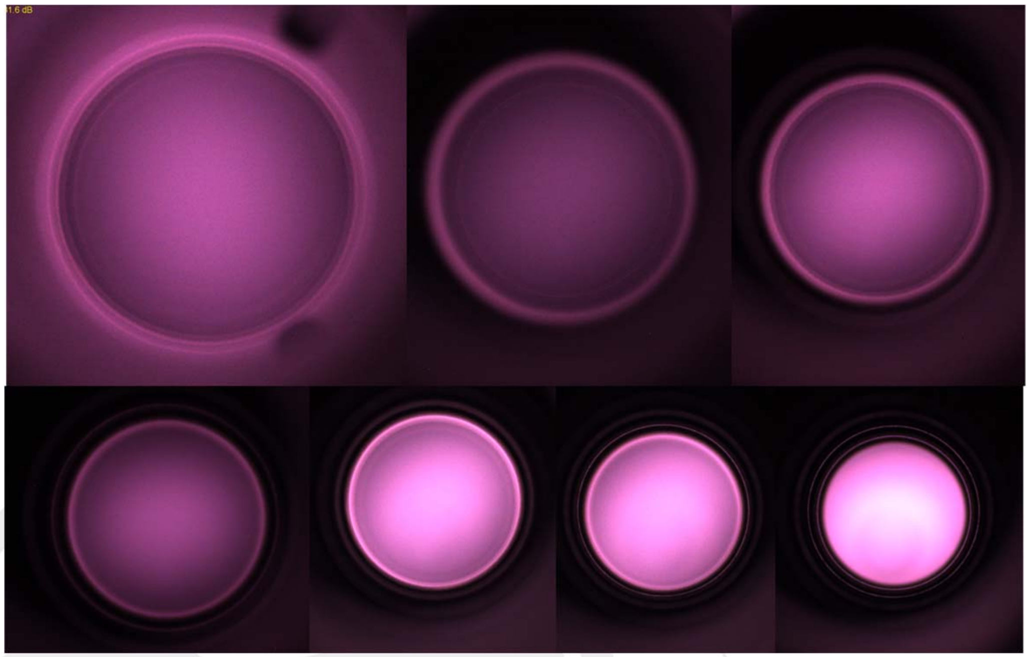
Plasma Processing of SRF Cavities



Tom Powers and Tiffany Ganey
Feb. 19, 2021

Jefferson Lab

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

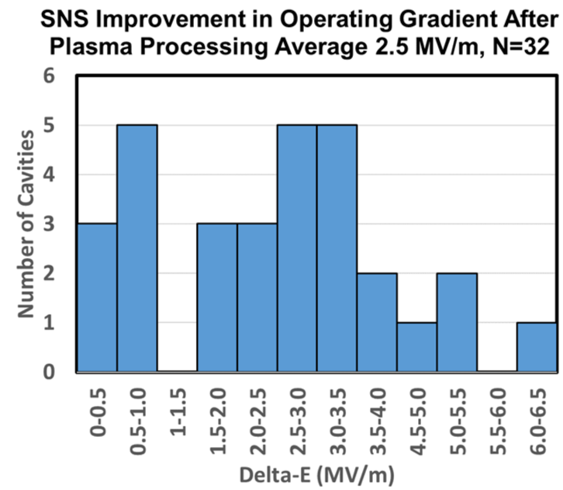
U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Why Use Plasma Processing

Industrial Uses

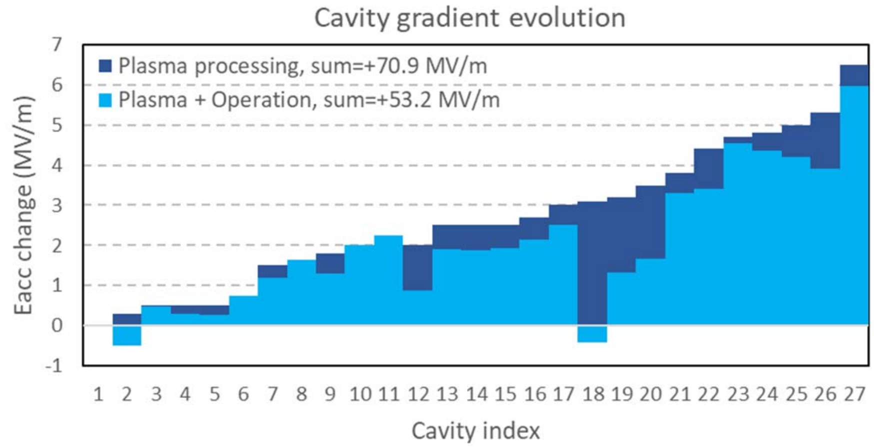
- **Plasma processing is a common technique for removing hydrocarbons from surfaces and improve the wettability of the surface.**
- **It has the capability to treat complex shapes and can be tuned to deliver surface specific properties.**
- **Princeton Scientific Corporation has a line of chamber based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

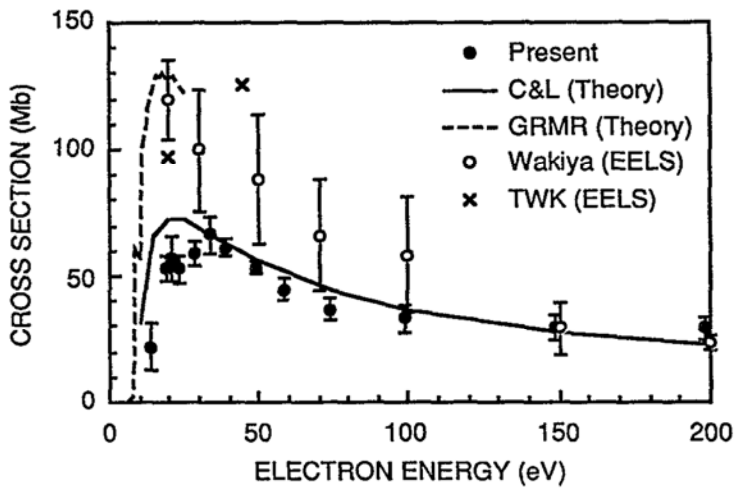
- **2015-2018 Marc Doleans at ORNL lead an effort to processed 32 cavities in the SNS linac improving the gradients an average of 2.5 MV/m. The work was done during scheduled maintenance periods. After 3 years of operation most of the processed cavities are still doing well.***



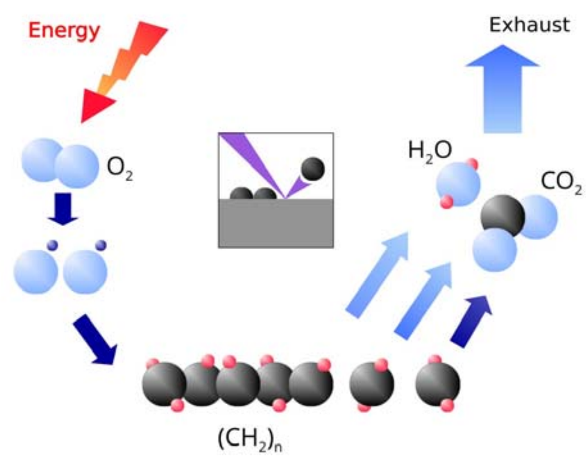
*Marc Doleans personal communications

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.*

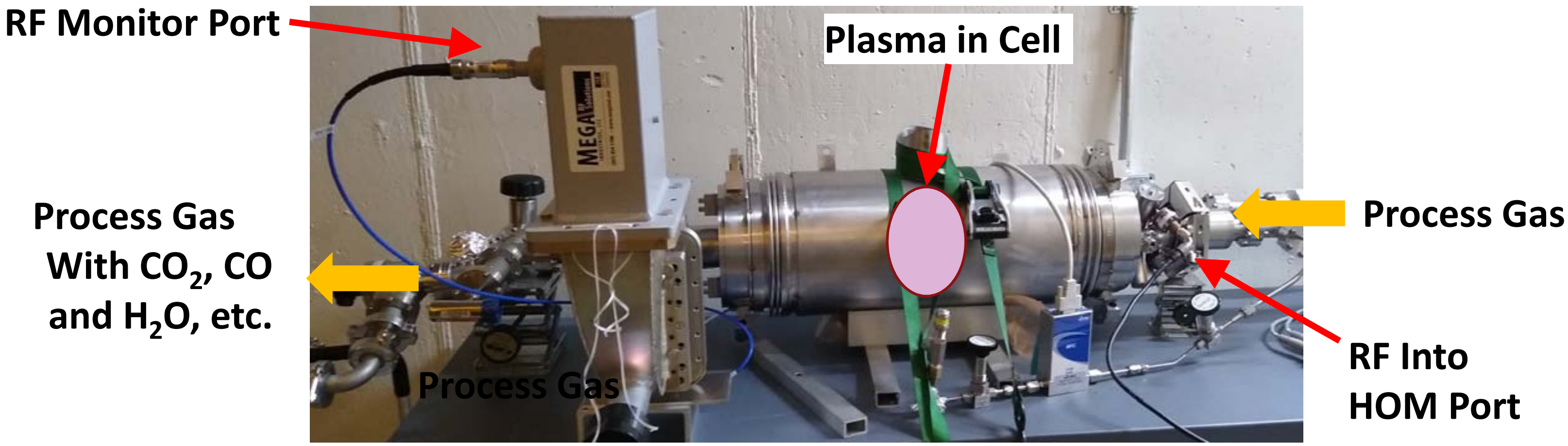


Dissociation Cross Sections and excitation cross sections for electron impact on O_2**



*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

Reactive Oxygen Plasma Processing

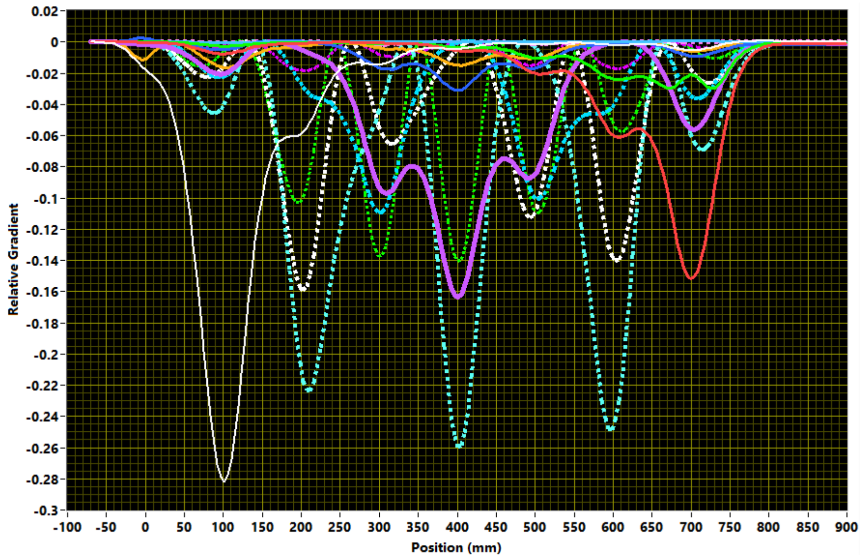


C100 Off-Line Bench Setup

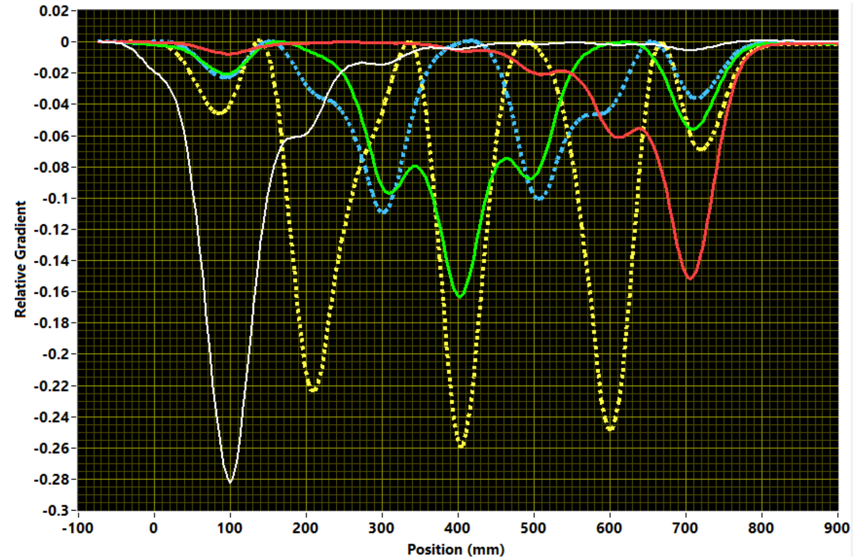
- **SRF "Standard" Recipe**
  - **Room temperature mix of inert gas (argon or neon) and a few percent oxygen**
  - **Flow gas through cavity at a few tens of standard cubic centimeters per minute**
  - **Pressure in the cavity between 50 and 200 mTorr**
  - **Apply RF (1 to 600 W depending on system, gas species, pressure and cell) to ignite plasma in one cell, Fermilab 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 60 minutes in each cell**
  - **Monitor cracked hydrocarbon residuals of CO_2, CO and H_2O**

Method for Igniting a Plasma in a Specific Cell, C100 Cavity

Relative Electric Field in the Center of a C100 Cavity Based on Bead Pull and S11 Data.



TE111 All Polarizations and Modes



TE111 Polarization/Modes Used

- **TE111 HOM modes have high fields in the center of the cells and produce a uniform plasma.**
- **In addition to simulations we did bead pull measurements in order to understand the relative electric fields as a function of HOM modes and polarizations. Off axis data was used to understand field enhancement at the HOM antenna tips on a mode by mode basis.**
- **Based on the bead pull data we decided to use the first 5 TE111 modes and to use the polarization of each mode that had the peak S21 measurement.**
- **To go from cell to cell we start in cell 4 using the $3\pi/7$ mode (solid green line in right plot) then we go to cell 7 (red) then 6 (Yellow dash) then 5 (blue dash). Alternately we start in 4 then go to 3 then 2 then 1. In all cases the jumps are made by using two RF sources. HOM couplers are on cell 1 end.**

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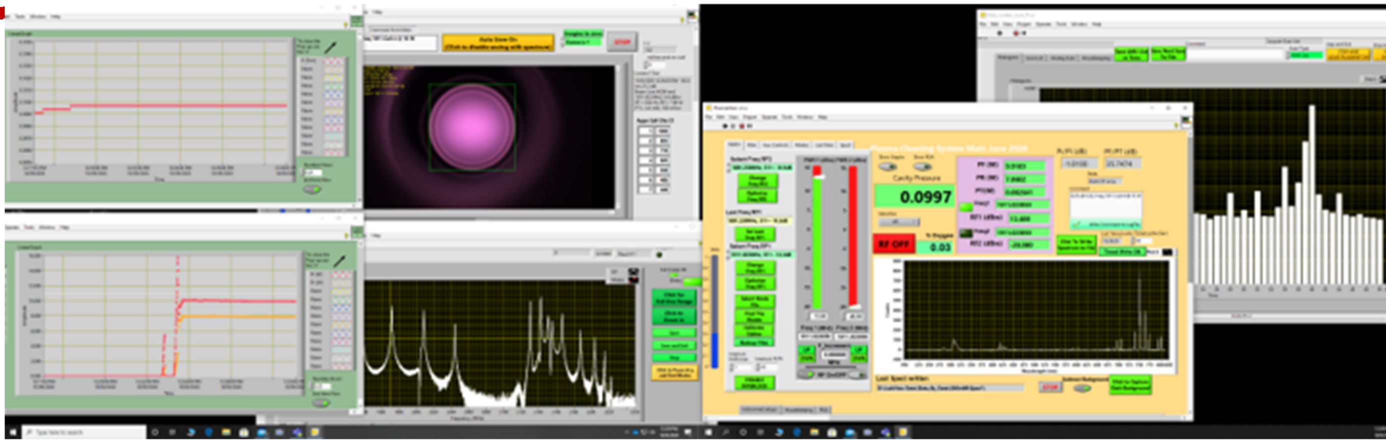
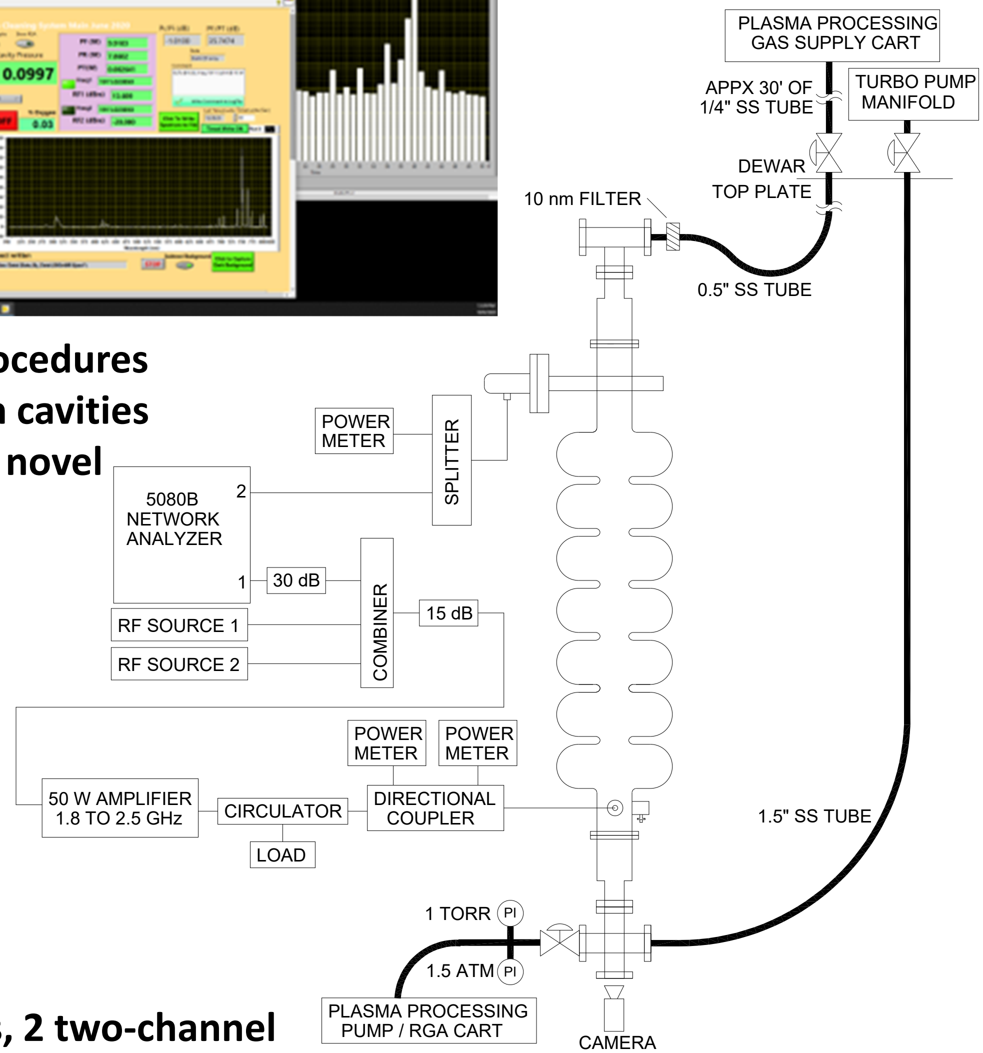
JLAB Vertical Test Stand Setup





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

Note: JLAB has 2 gas supply and pumping systems, 2 two-channel RF systems and a one-channel RF system.

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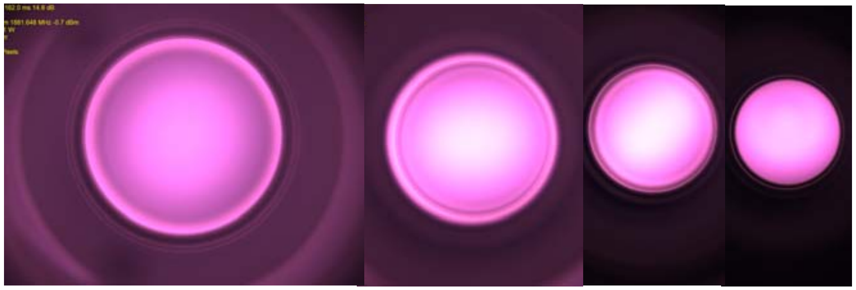
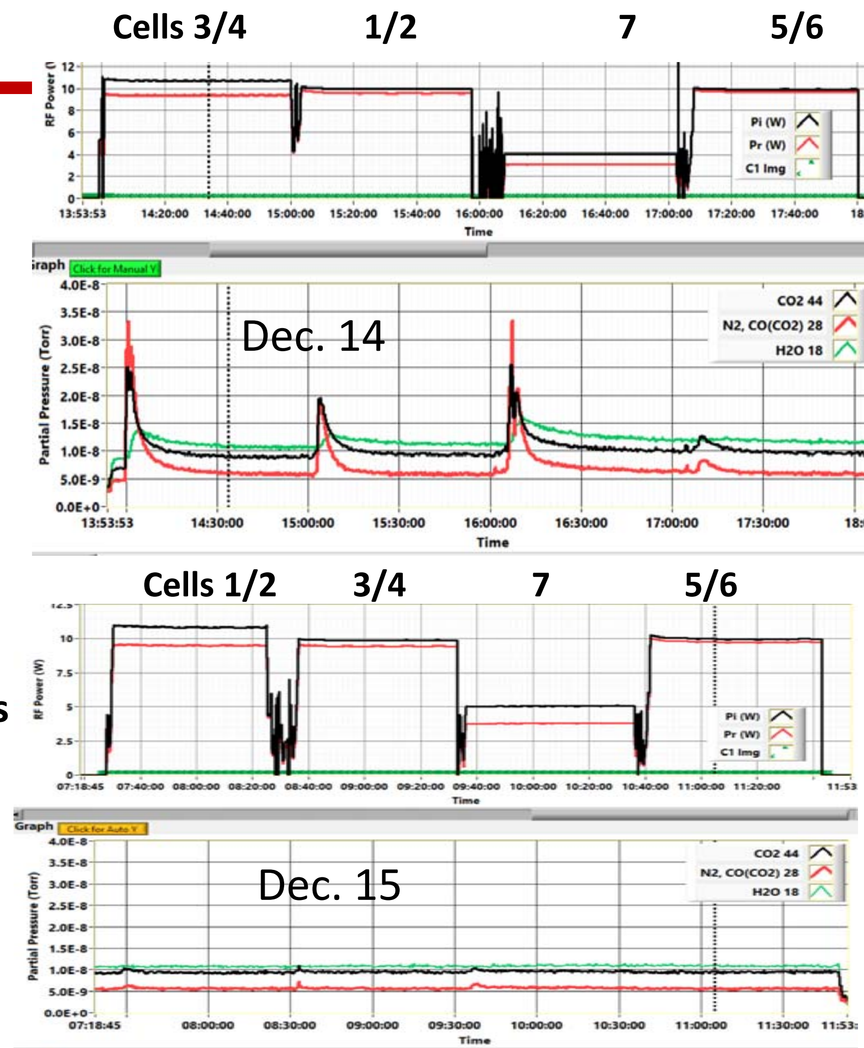
First Vertical Processing Dec. 2020



Images of Plasma, cells 1/2 , 3/4, 5/6, and 7 where cell 1 is at the HOM coupler end of the cavity

- Two cell ignited simultaneously was verified in the off-line test setup using two cameras.
- Two cells at once done by applying two frequencies at once.
- Processing two cells at once is 40% faster.
- The first processing cycle produced the most hydrocarbon residuals.
- Very little hydrocarbon residuals produced when the cavity was reprocessed 20 hours later as well as 2 weeks later.



RF Power and partial pressure of $C0_2$, CO and H_2O during processing

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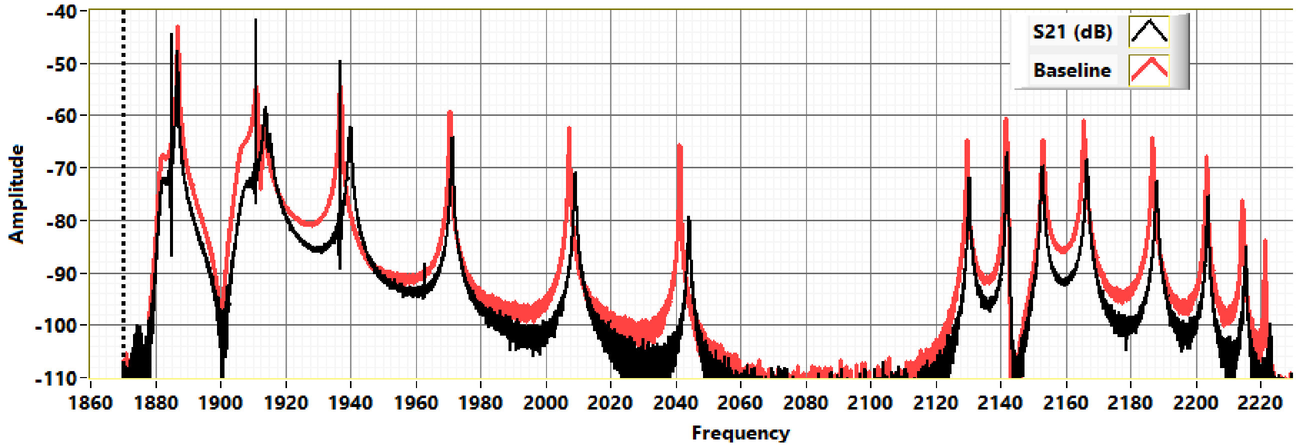
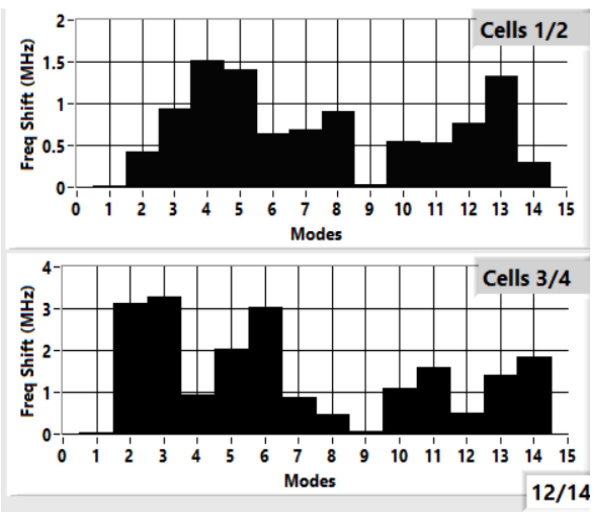
Using S21 Measurement to Characterize and Locate Plasma

We use a method similar to that developed at Fermilab where 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.



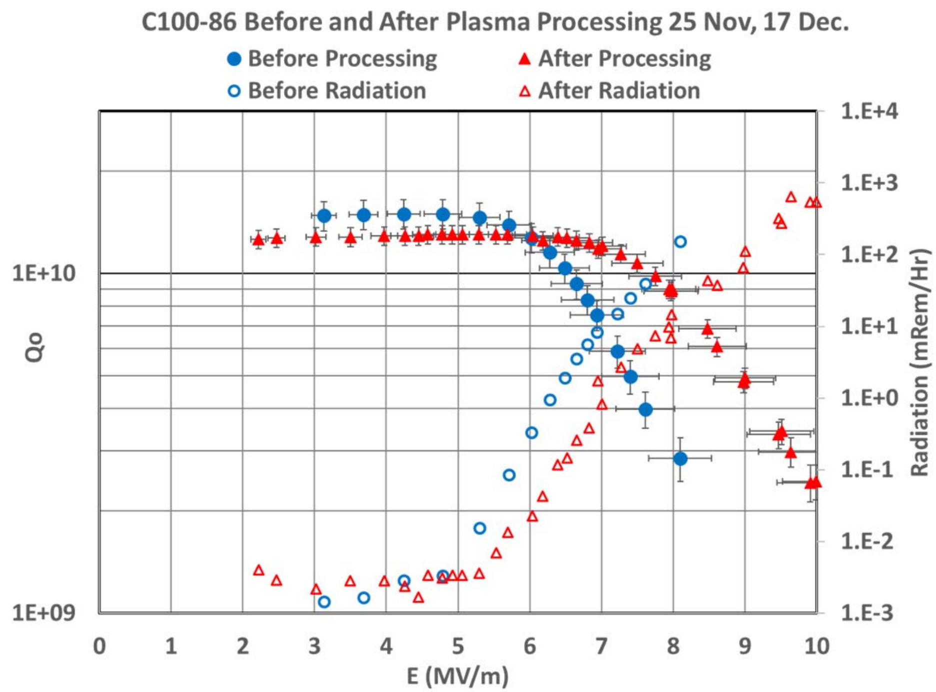
Cavity S21 measurement and frequency shift by mode for cell 3 and 4 ignited.

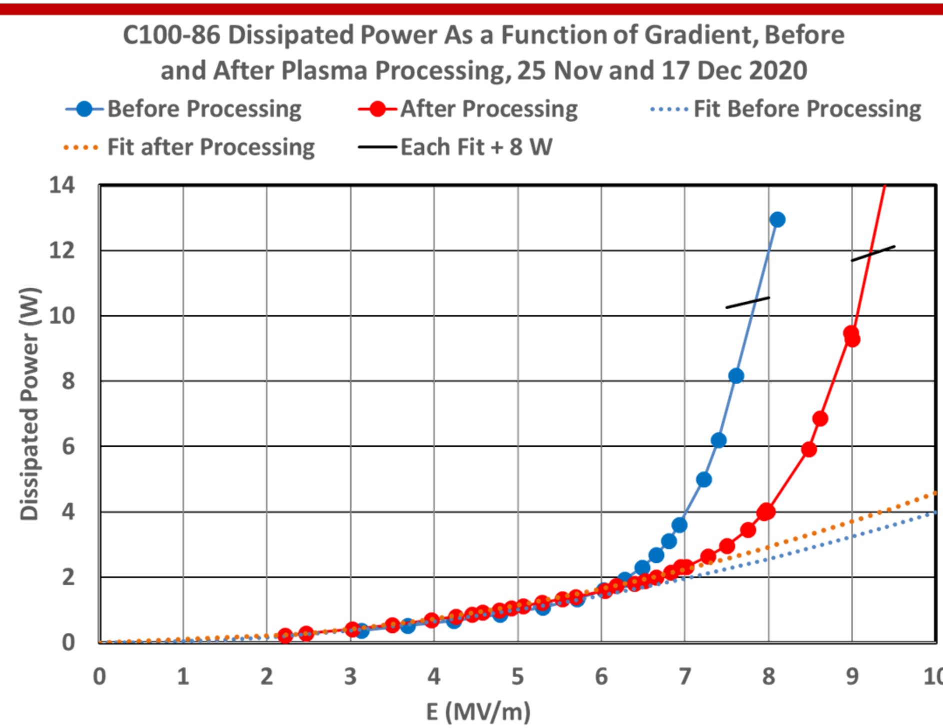


Mode Pattern for cells 1/2 and 3/4 ignited.

- **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.**

Vertical Test Results Before and After Processing





- **Cavity used had field emission onset that was well below modern day standards.**
- **Radiation onset improved by 0.5 MV/m after processing**
- **Above onset, field emission radiation at gradient was improved by an order of magnitude.**
- **I did a second order fit of dissipated power as a function of gradient below field emission onset and assume that the excess dissipated power is due to FE (old school from early 1990s).**
- **Operational gradient improved from 7.8 MV/m to about 9.2 MV/m (18% improvement). Note: For this cavity, 8 W field emission power produced about 100 mRem/hr.**

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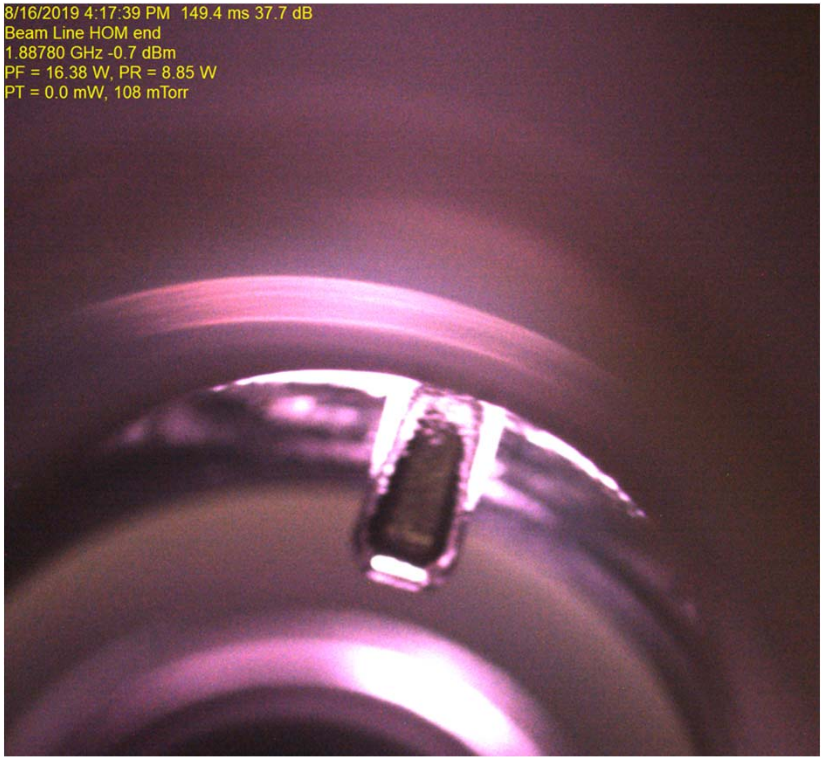
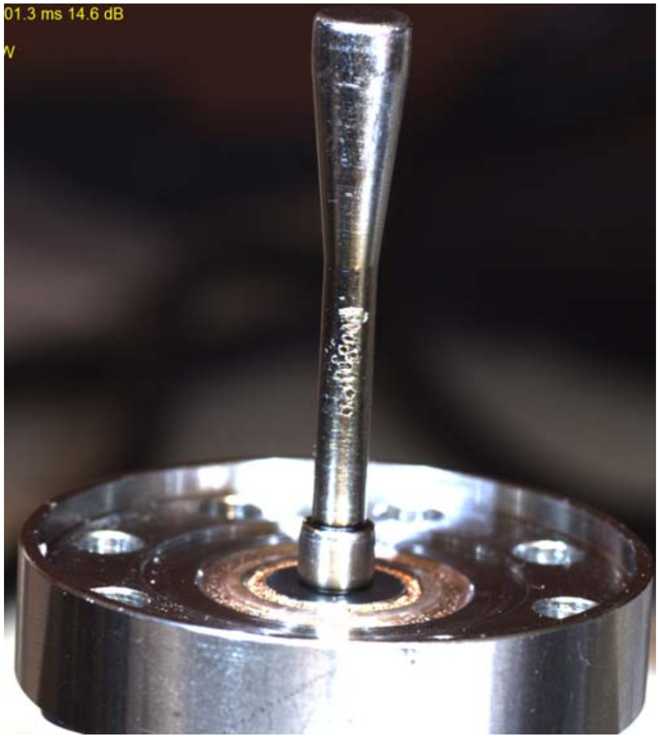
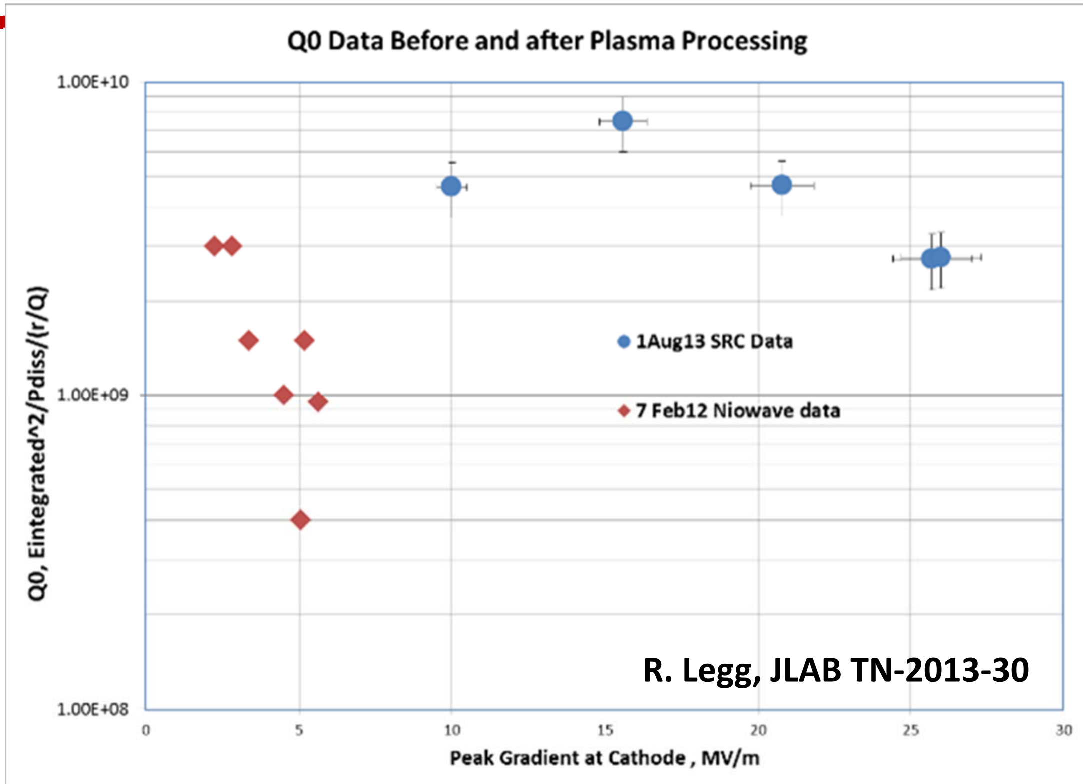
HOM Coupler Breakdown (Something always goes wrong!)



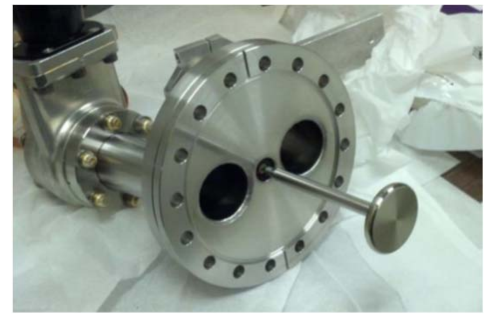


- **The purpose the first set of experiments was to determine if we could ignite a plasma in the individual cells of a C100 cavity via the HOM ports.**
- **During that process we had several coupler breakdowns some of which were sustained for a minute or two. This lead to damage to the niobium HOM coupling antenna.**
- **Subsequently we developed an RF based interlock and have not damaged any more coupling antennas.**

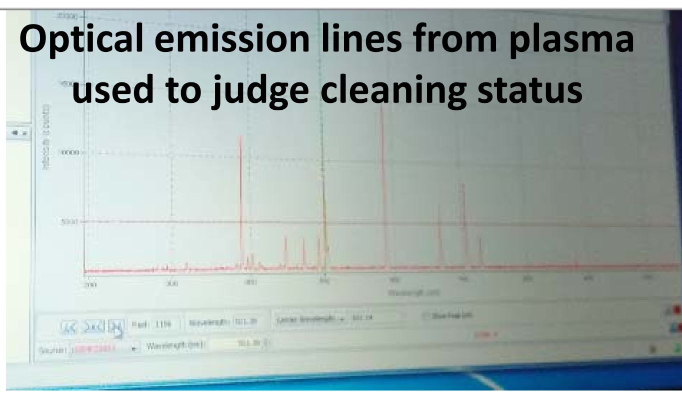
Plasma Processing of 200 MHz WiFEL SRF Gun at SRC



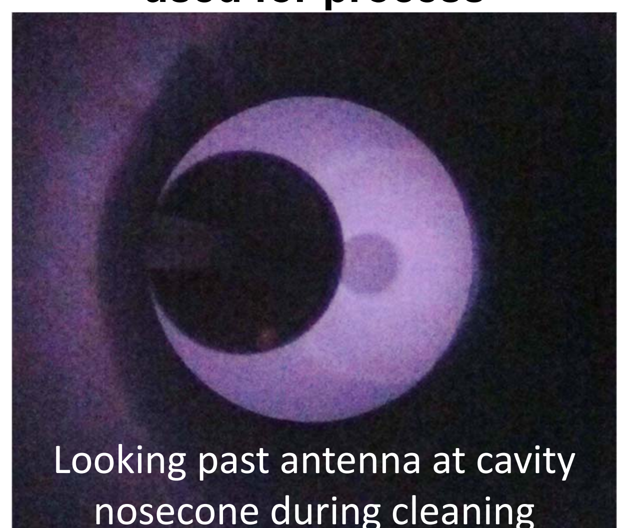
- **Argon/oxygen gas mixture**
- **Optical spectroscopy used to determine when the processing was complete.**



Special antenna used for process



Optical emission lines from plasma used to judge cleaning status



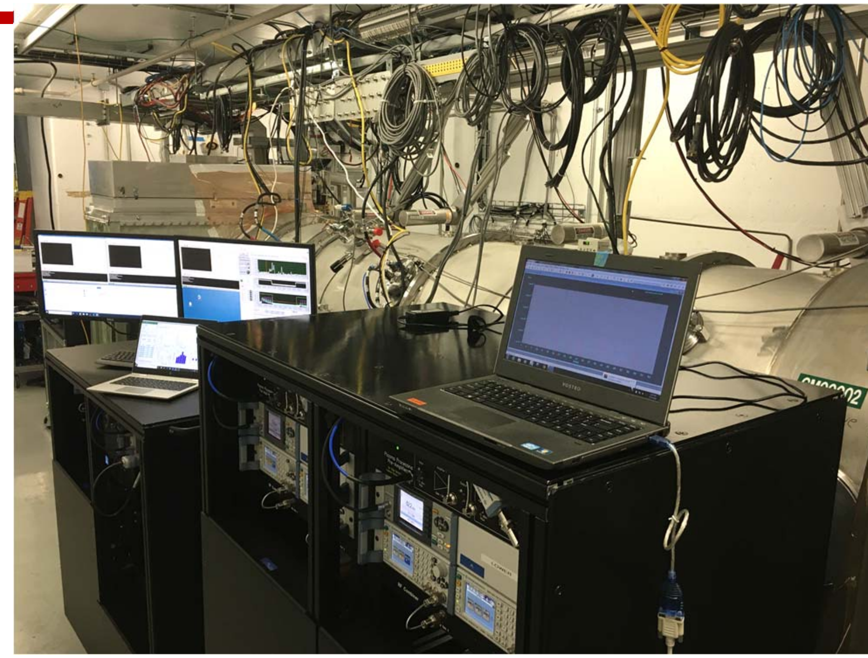
Looking past antenna at cavity nosecone during cleaning

*Bob Legg, personal communications

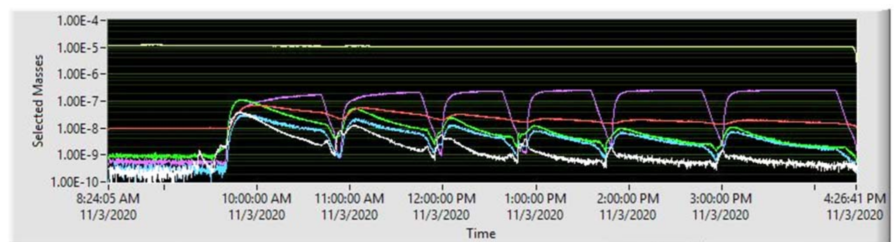
Work supported by DOE Award DE-SC0005264

Plasma Processing for SNS Proton Power Upgrade is Underway*

- **Medium-beta cryomodules being plasma processed as part of PPU to increase their accelerating gradients**
  - **First time medium-beta cryomodules are being plasma processed at SNS**
  - **8 high-beta cryomodules have been plasma processed before**
- **The 3 cavities in medium-beta cryomodules plasma processed simultaneously**
- **Cleaning of the cavities' RF surface is observed with an RGA**
- **Cavities in the first plasma processed medium beta cryomodule improved by 2.5 MV/m on average**



Plasma processing RF carts in front of a medium-beta cryomodule



Gas analysis during plasma processing. By-products of hydrocarbon oxidation by the neon-oxygen plasma are observed indicating cleaning of the RF surfaces.

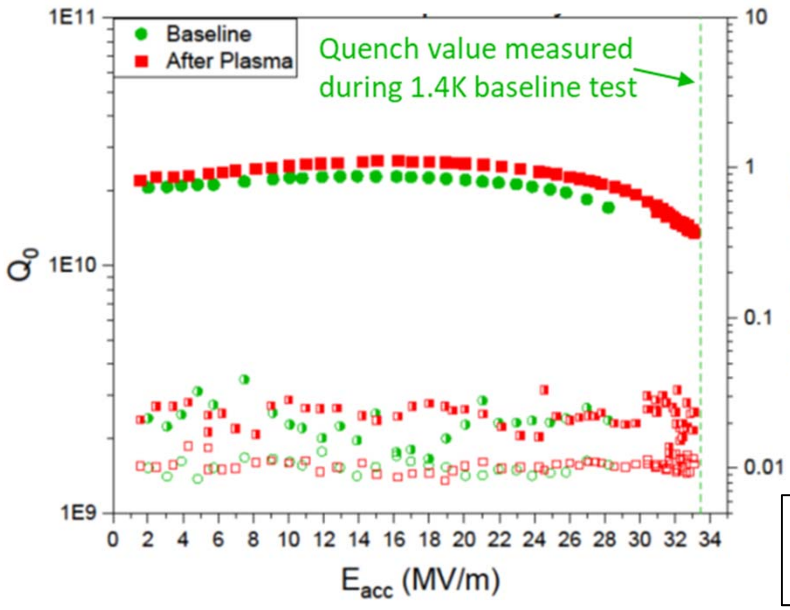
OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR | SPALLATION NEUTRON SOURCE

*Marc Doleans personal communications

Fermilab Plasma Processing for LCLS-II 1.3GHz Cavities*

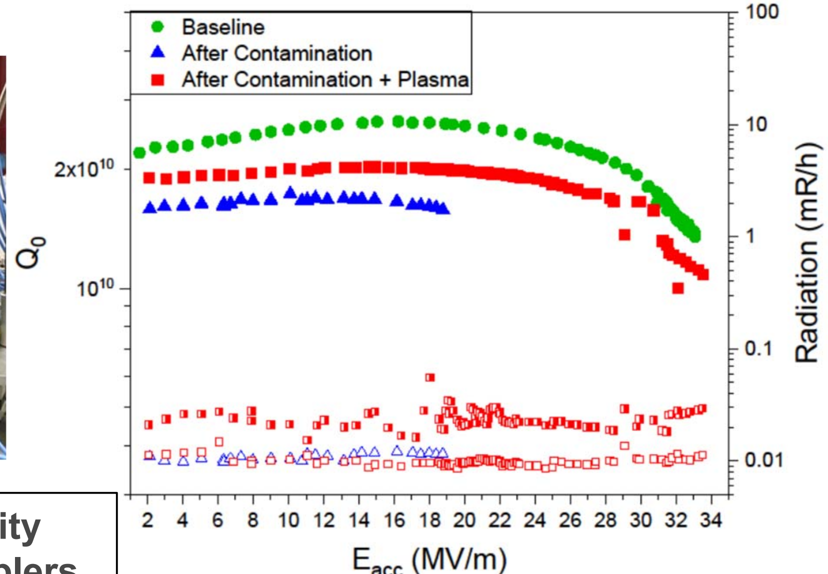
The technique has been applied to single cell and 9-cell cavities with natural FE (FE of unknown source, not introduced artificially) or contaminated with different sources, showing very promising results.

Test on clean N-doped single cell cavity



Single cell cavity with HOM couplers

Test on Carbon-Contaminated single cell



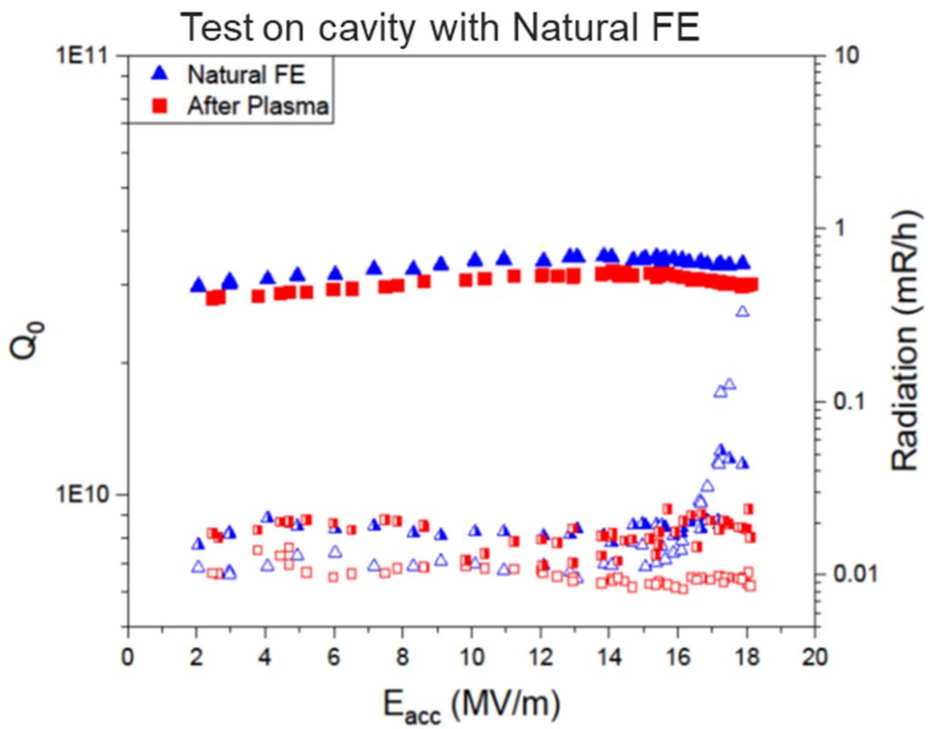
Plasma processing preserves the high Q factor and quench field typical of Nitrogen-doped cavities!

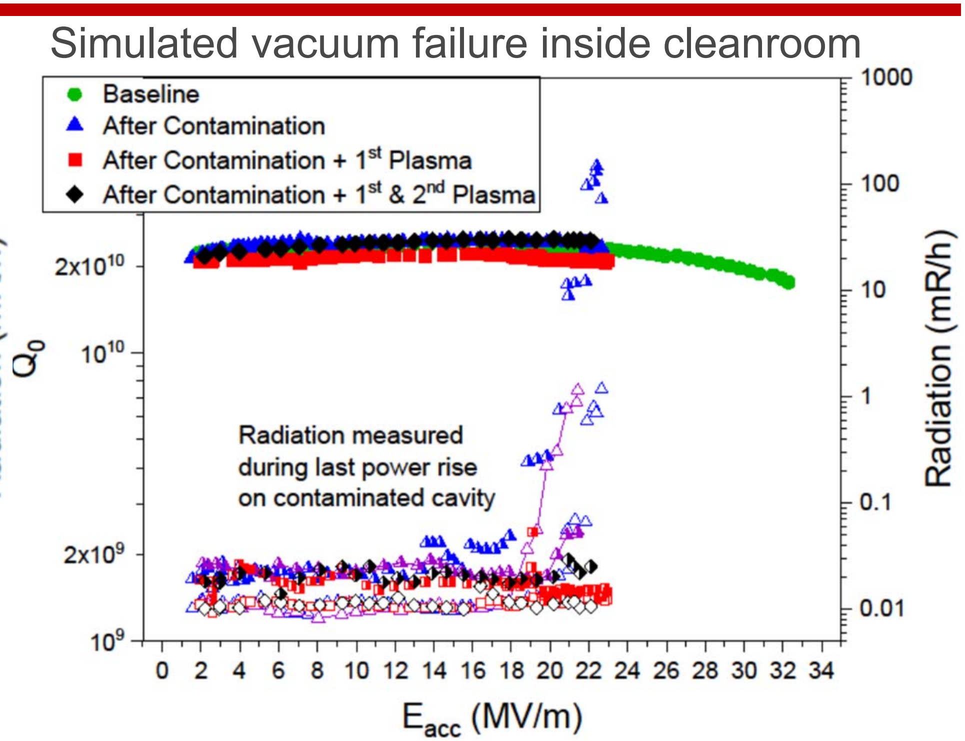
E_{acc} was fully recovered after plasma processing!

*Bianca Giaccone personal communications

B. Giaccone et al., Physical Review Accelerators and Beams 24.2 (2021): 022002.

Fermilab Plasma Processing for LCLS-II 1.3GHz Cavities*





No radiation was detected after plasma processing!

Plasma processing completely removed field emission!

- **No significant improvement were observed in cavities with artificial vacuum failure simulated outside cleanroom, which resulted in a very low field emission onset.**
- **Particle analysis indicated the presence of metal flakes.**
- **These results not shown here.**

B. Giaccone et al., Physical Review Accelerators and Beams 24.2 (2021): 022002.

Upcoming Efforts

JLAB

- Continue off line and vertical test programs as much as permitted with reduced staffing due to the pandemic.
- Continue to develop processing, procedures, travelers and automated software.
- Plan on processing a C100 cryomodule prior to it being disassembled for rebuild late in the spring or early in the summer. Timing dependent on facilities availability.
- Start looking at C50 cavities as well as novel techniques.

SNS / ORNL

- Continue to process medium beta cryomodules.
- Provide a moderate amount of support to the JLAB plasma processing program.

Fermilab / SLAC

- Upgrading gas supply and vacuum carts for remote operations as well as building a second setup (both RF system and gas/pumping cart) for use at SLAC.
- Implementing a LabVIEW program to remotely control and monitor plasma ignition and RF parameters.
- Optimize plasma processing parameters
- Continue Vertical test program at Fermilab to acquire statistics on plasma processing efficacy
- Plan on processing the verification cryomodule for LCLS-II high energy upgrade at Fermilab in the early summer.

Conclusion

Plasma processing using a gas mix of neon/oxygen or argon/oxygen is proving to be an effective method to improve the field emission properties of SRF cavities.

While there is limited results that indicate elimination of field emission, the expected results is to improve field emission onset and reduce field emission radiation at higher fields.

The work at Oak Ridge and University of Wisconsin has shown that it is an effective method for improving the field emission properties of installed cavities.

Acknowledgements

None of the progress at JLAB would be possible without the support of the 30% to 40% of the staff who are permitted on site during the pandemic. I would like to especially thank Tiffany Ganey, Kurt Macha and Roland Overton for the support that they provided to the program.

Backup Slides

In-situ plasma processing at JLAB Detailed Status

- The program had a modest start in the spring of 2019 using internal R&D funds.
- Dedicated funding obtained in Sept. 2019 with follow-up funding in 2020.
- We have two production systems and one RF system for processing cavities off line.
- The two production RF systems can process two cavities simultaneously.
- Automatic software developed to ignite plasma in each of the 7 cells of a C100 cavity.
- Software developed that tracks the frequency shift.
  - Higher plasma density leads to larger frequency shift.
  - Pattern of shifts for different modes can be used to confirm plasma location independent of using a camera which is necessary as cameras are not effective when processing a 10 m long cryomodule.
- Procedures developed for processing C100 cavities in the JLAB vertical test area as well as in an off-line laboratory setting.
- We completed our first C100 cavity vertical test cycle of 2 K RF test, plasma process, 2K RF test, process, 2K RF test.
- Obtained a 1.4 MV/m improvement in operating gradient.
- The cavity was reprocessed in the clean room and we vertically tested it last Friday.
- We will be plasma processing again this week.