Overview of the progress of plasma processing

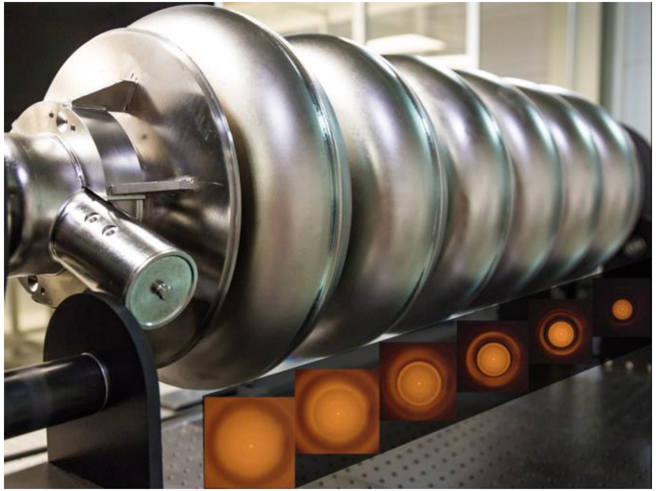
Bianca Giaccone

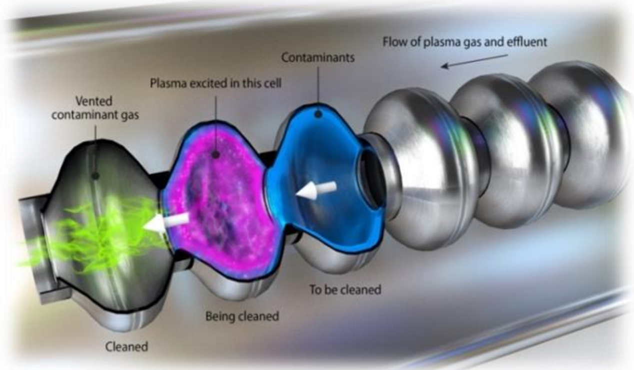
SRF21

June 30th, 2021

Plasma processing at ORNL-SNS

- Cleaning technique uses a neon gas discharge with reactive oxygen for SRF cavities at room-temperature
- Plasma ignited in each cell of a cavity sequentially
- Oxidation of hydrocarbon surface contaminants creates volatile by-products pumped out continuously
- Cleaned surface has increased work function helping mitigating field emission and multipacting





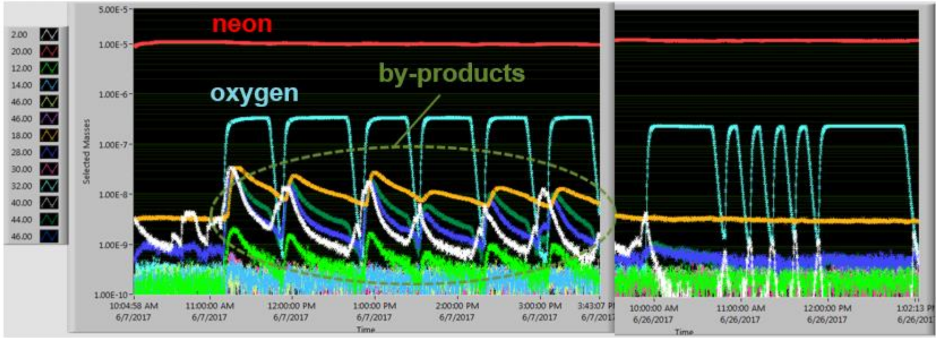
M. Doleans et al., NIMA **812** (2016)
M. Doleans J. Appl. Phys., **120**, 243301 (2016)
P.V. Tyagi et al., Applied Surface Science **369** (2016)

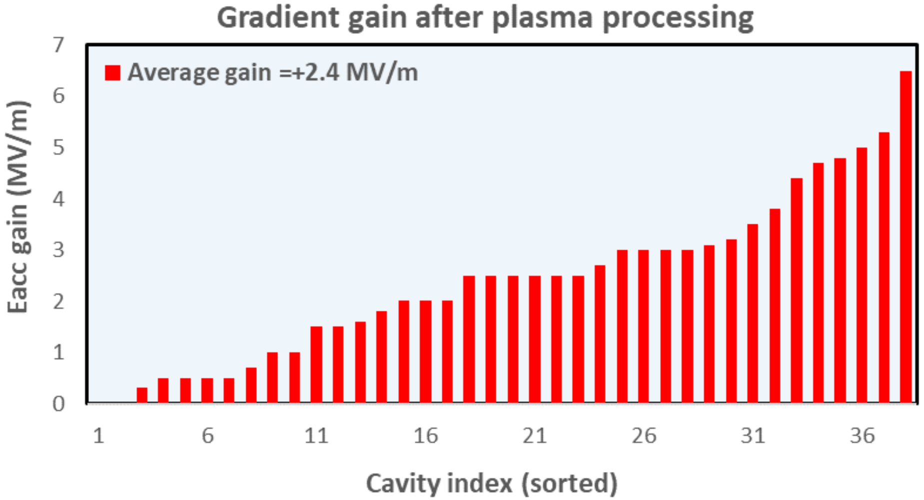
Plasma processing at ORNL-SNS

- Hardware comprises gas injection, RF and pumping systems
- All hardware is packaged in carts that are rolled adjacent to the CM being plasma processed

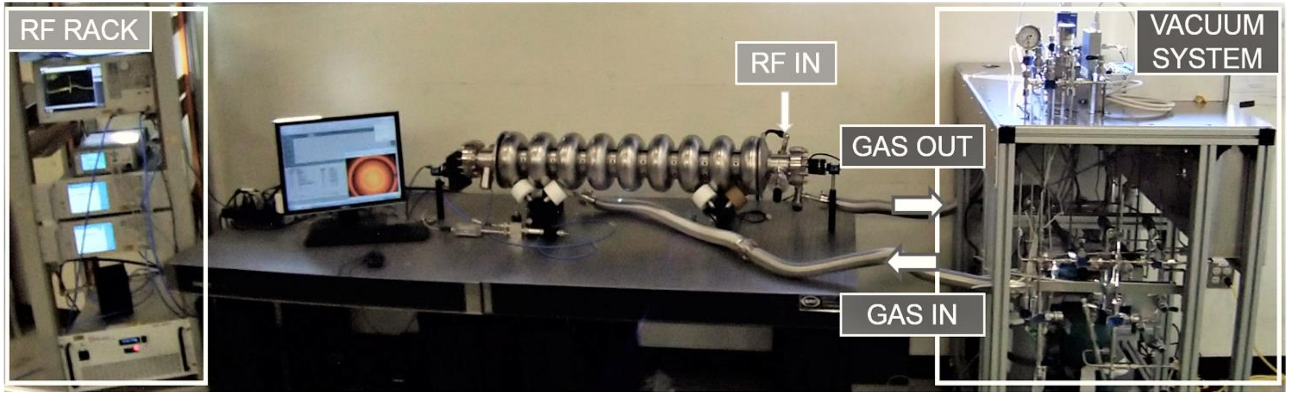
Plasma processing at ORNL-SNS

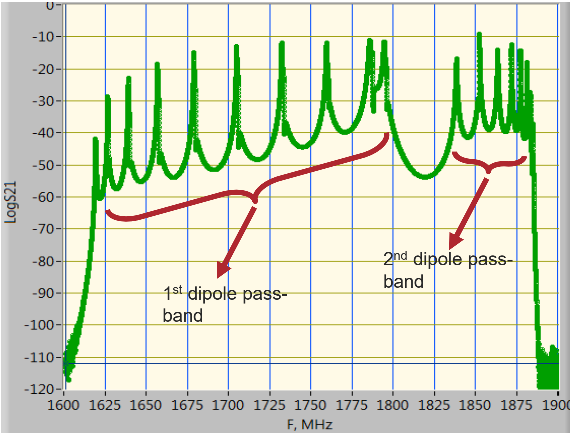
- 10 cryomodules plasma processed at SNS either in offline facilities or directly in the linac tunnel
  - 8 High-beta CMs
  - 2 Medium-beta CMs
- Cleaning of the cavity surfaces revealed by the significant reduction of by-products' partial pressures over time
- 38 cavities plasma processed at SNS with an average E_{acc} increase of 2.4 MV/m

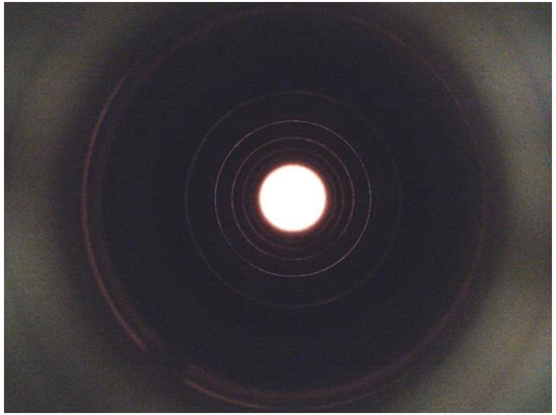




Plasma processing at FNAL for LCLS-II





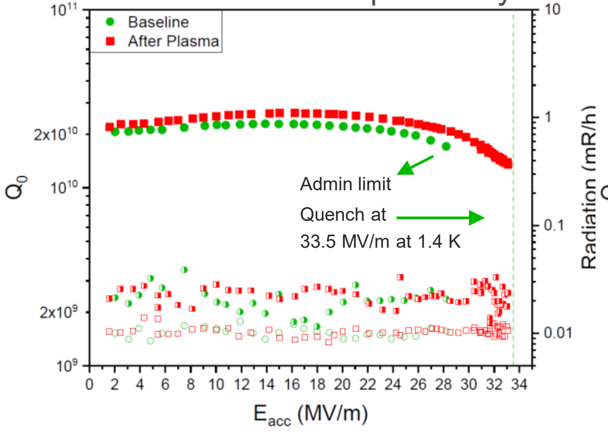


- HOM modes and couplers are used for plasma ignition
- Plasma is ignited in the central cell and transferred to adjacent cells using mode superposition
- Each cell is processed individually
- Gas mixture: 50-150 mTorr, O_2 partial pressure ~ 1-2.5% of Ne
- All the connections between the cavity and the vacuum/gas system are done inside a portable clean room to minimize contaminations

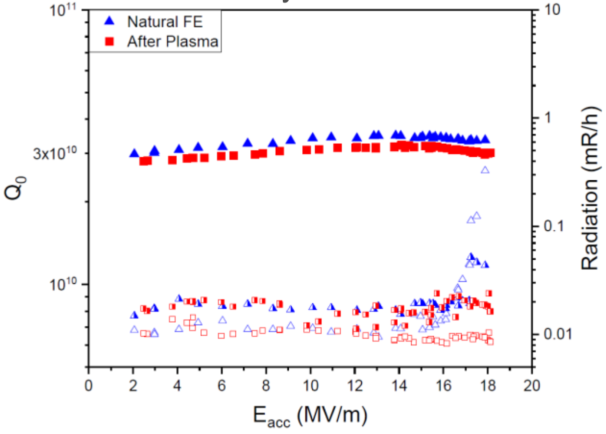
P. Berrutti, B. Giaccone *et al.*, J. Appl. Phys. 126, 023302 (2019)
B. Giaccone *et al.*, Phys. Rev. Accel. Beams 24, 022002

Plasma processing at FNAL for LCLS-II: RF cold tests results

Test on clean N-doped cavity

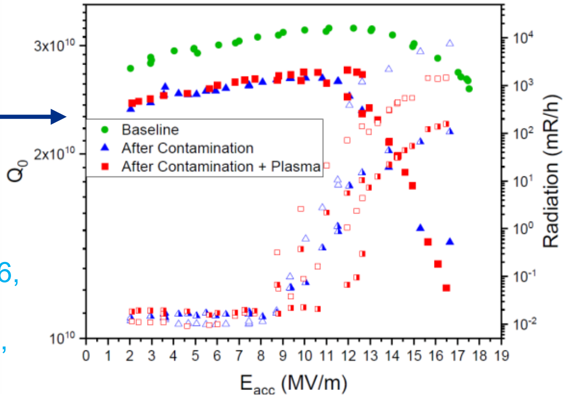


Test on cavity with natural FE



Multiple 1.3GHz cavities have been subjected to plasma processing, showing positive results on FE caused by hydrocarbon contamination. Moderate or no improvement in performance was observed on cavities with FE likely caused by metal particles

Test on cavity subjected to vacuum failure simulation from HV to atmospheric presssure

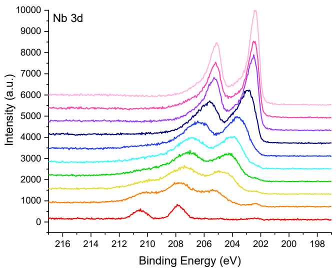


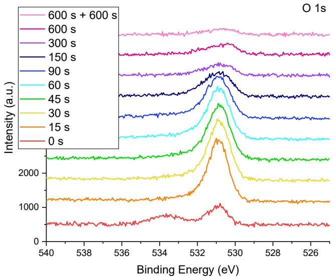
P. Berrutti, B. Giaccone *et al.*, J. Appl. Phys. 126, 023302 (2019)
B. Giaccone *et al.*, Phys. Rev. Accel. Beams 24, 022002

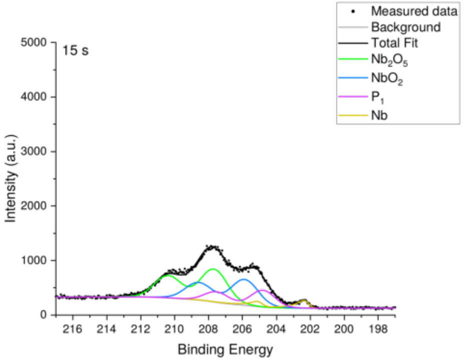
Fermilab

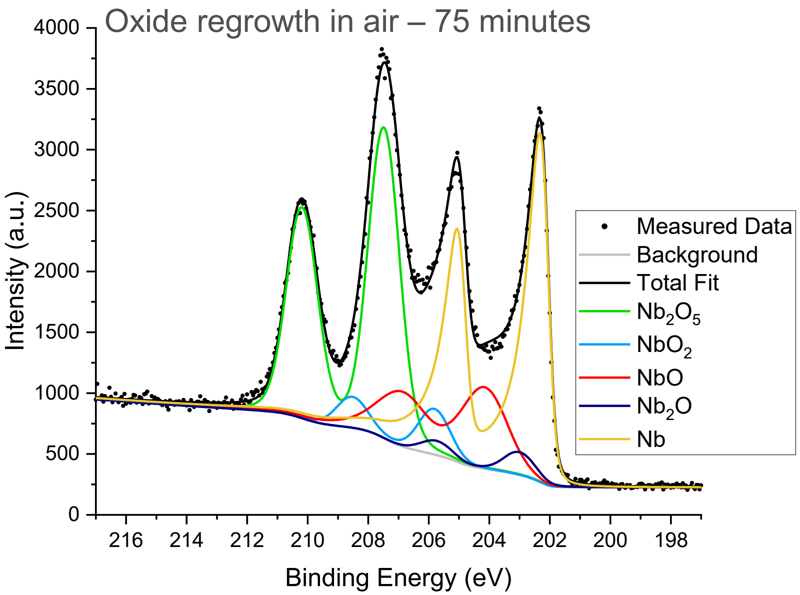
Plasma Processing at FNAL: microscopic study on Nb samples (1)

- Study of the Nb near surface region and the microscopic effect that plasma processing has on the cavity surface
- Started with argon ions sputtering on Nb sample and subsequent growth of the oxide in air





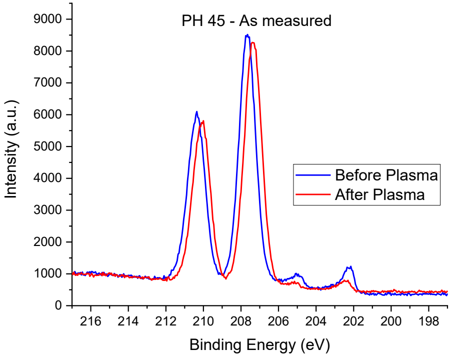


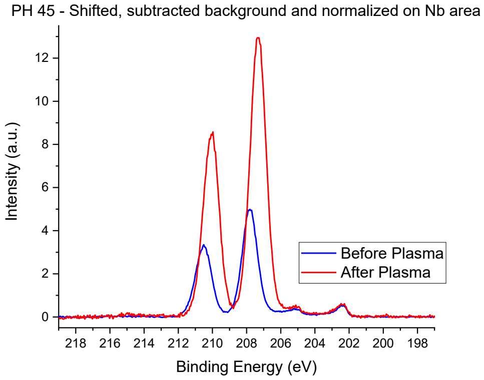


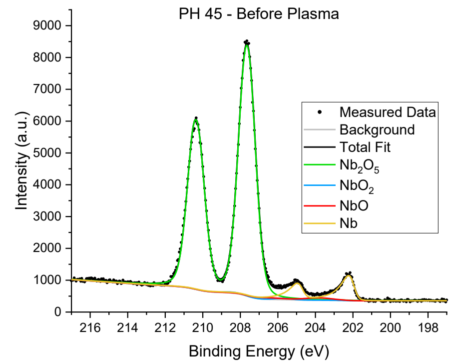
More details in poster WEPCAV001

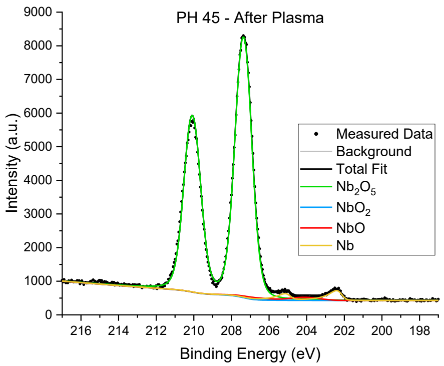
Plasma Processing at FNAL: microscopic study on Nb samples (2)

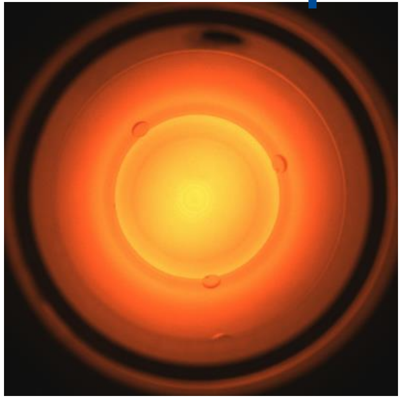
Samples were plasma processed for 6h while positioned on cavity iris











- Increase in the relative area of the Nb_2O_5 peak compared to the Nb metal signal
  - Possible increase in the oxide thickness. No effect on the cavity performance
- No particular differences in the suboxide spectra before and after plasma processing

More details in poster WEPCAV001

Plasma Processing at FNAL: next steps

We are preparing for processing the LCLS-II-HE vCM in a couple of weeks!

In preparation for this test: we built a new vacuum system, we tested the HOM CM cables for heat dissipation and installed a variable FPC coupler analogous to the CM FPC on a 9-cell cavity and subjected it to plasma processing.

Fermilab

In-situ plasma processing at JLAB (1)

Jefferson Lab

- JLAB has developed procedures and equipment for in-situ plasma processing to help mitigate CEBAF linac energy degradation for just over 2 years.
- They built up to 5 channels of RF systems, 2 gas supply systems and 2 pumping systems.
- Initial effort focuses on C100 cryomodules with follow-on effort towards processing the other cryomodule types used in CEBAF.

In-situ plasma processing at JLAB (2)

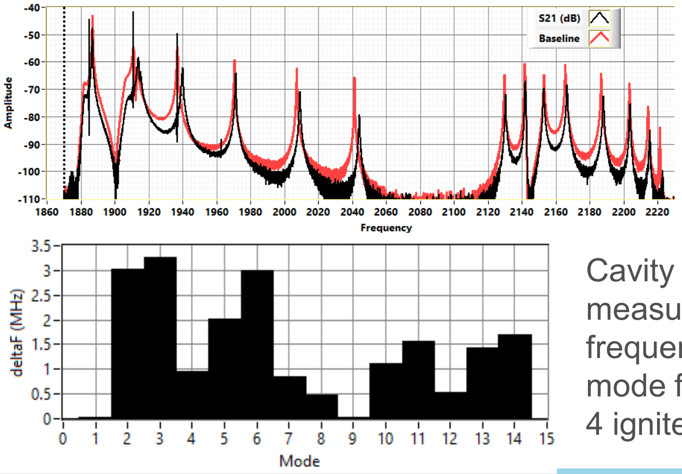
Jefferson Lab

- Their “standard” technique for C100 cavities is to process 2 cells at the same time by applying RF power to one of the HOM ports. The cell furthest from the HOM ports is processed individually.
- By simultaneously processing two cavities they are able to process a cryomodule one time in two 9 hour shifts. This was demonstrated in their cryomodule test facility three weeks ago.
- They have processed a cavity several times in the vertical staging area and a C100 cryomodule in the cryomodule test facility.

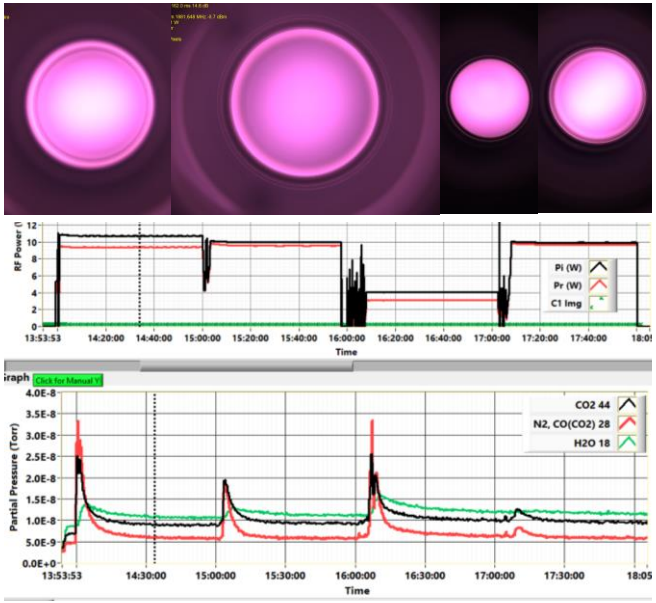
Processing Methods in JLAB Vertical Test Area

Jefferson Lab

- Processing done in the vertical staging area with the cavity is mounted on a vertical test stand in order to reduce cleanroom labor and improve throughput.
- Argon with 1% to 3% oxygen at a pressure between 80 mTorr and 250 mTorr.
- Two cells are processed at the same time by using two different frequencies. This reduces processing time by about 40%
- Exhaust gas monitored using an RGA.



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

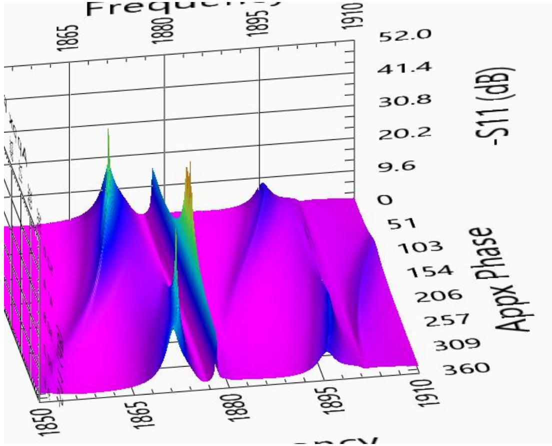


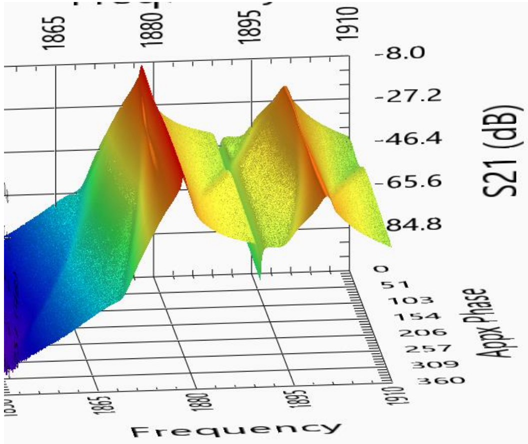
Plasma image, RF Power and partial pressure of CO_2, CO and H_2O during processing

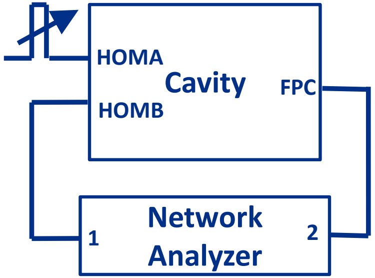
Fermilab

The Effects of Varying Cable Length on Second HOM Cable

-S11 (Left) and S21 (right) as a function of phase and frequency.







- Modes shown are for Cell 1 (1874.5 MHz), Cell 7 (1878.1 MHz) and Cell 4 (1889.6 MHz) as well as other as, yet understood, losses.
- In a cryomodule the HOM cables are +/-2.5 cm in length for an open cable this represents +/- 160° in phase shift on the reflected signal.
- There are phase settings where it is difficult to establish a plasma in given cells without getting coupler breakdown events.

- Data indicates that splitting the two signals and applying a phase shift to one HOM coupler would require that each cell would have to have a different phase shifter setting.

Cryomodule Results and What Is Next for JLAB

Jefferson Lab

Cryomodule:

- C100-10 had severely reduced operating gradients probably due to a catastrophic gate valve o-ring failure on the cavity 1 end of the cryomodule.
- The goal of the test was to train staff and validate procedures.
- Baseline measurements were made in the cryomodule test facility, all cavities except cavity 1 were plasma processed twice. Cavity 1 was processed 6 times.
- With two 1-channel systems they were able to process 4 cavities per shift.
- Post plasma processing data was still being taken when this talk was being completed. Visit the poster TUPEV004 to discuss results with the author.

Future Plans:

- Develop ways to process C50 and C75 cavities.
- Start to investigate novel ways to ignite the plasma in C100, C50 and C75 cavities as well as novel processing techniques.
- Prepare to process cryomodules in the CEBAF tunnel during an upcoming maintenance periods.

More details in Poster TUPEV004 "In Situ Plasma Processing of Superconducting Cavities at JLAB"

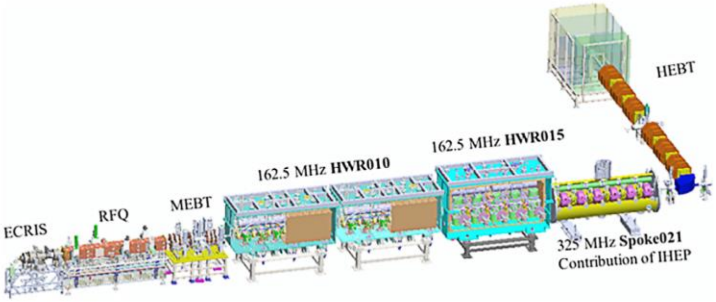
Plasma processing for CiADS

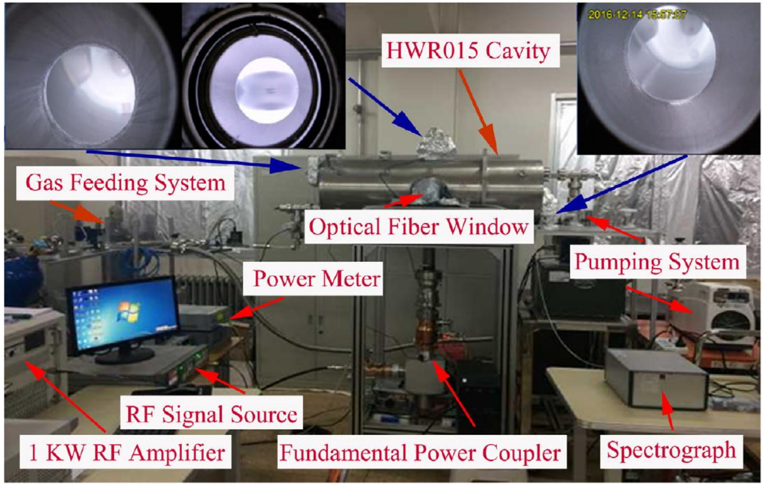
CiADS (China initiative Accelerator Driven System) aims at demonstrating nuclear waste transmutation using a 5 mA/500 MeV proton linac

Successful commissioning of the linac up to 25 MeV has been achieved

Field emission in SC cavities has been a limiting factor:

- Plasma and Helium processing are being explored as complementary in-situ techniques to mitigate field emission in CiADS

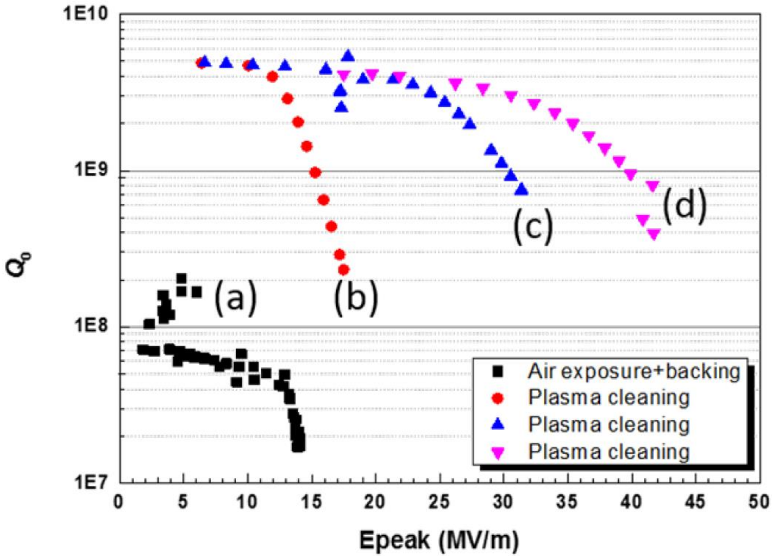


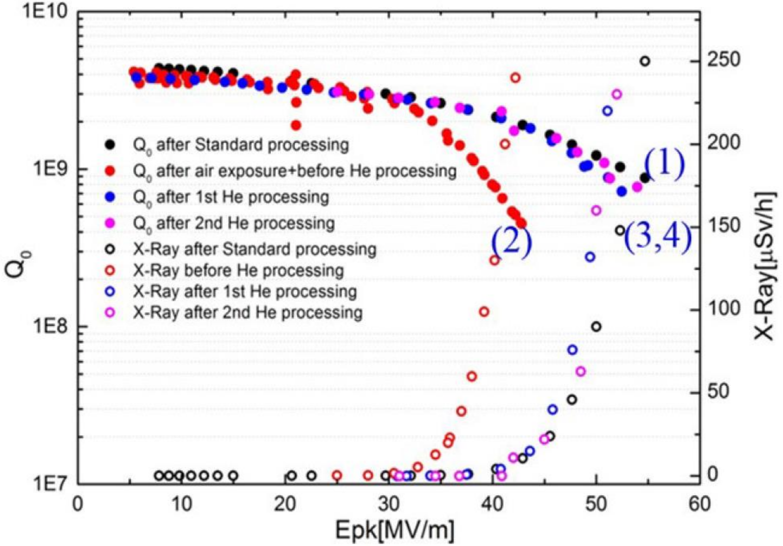


Slides adapted from Marc Doleans ''Overview of Plasma Processing programs in the SRF community'' presented at LINAC2020
Information about CiADS: Z. J. Wang et al. IPAC2019, Melbourne, Australia. JACoW Publishing. doi:10.18429/JACoW-IPAC2019-MOPTS059
Illustrations from A. Wu et al., NIMA **905** (2018) 61–70

Plasma and He processing combination study at IMP

- Half-wave cavity exposed to air (3um filtering) leading to severe performance degradation
- Combination of plasma processing using Ar/O_2 mixture, Helium processing and RF conditioning led to near full recovery of performance



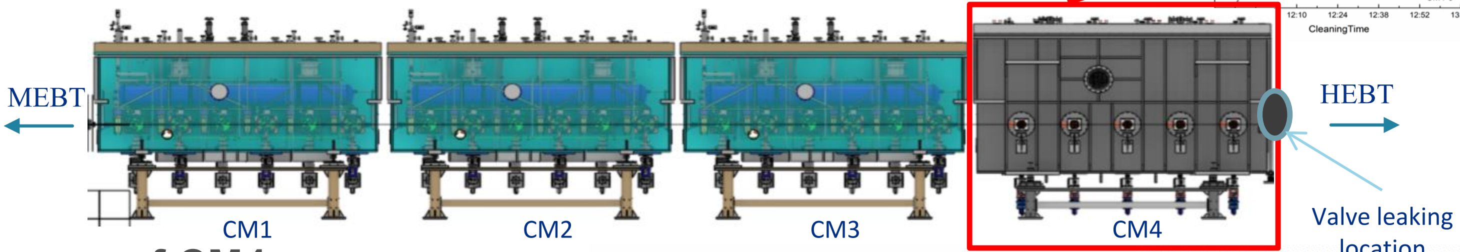


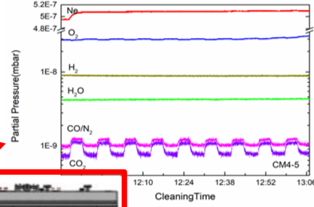
Slides adapted from Marc Doleans ‘’Overview of Plasma Processing programs in the SRF community’’ presented at LINAC2020
Illustrations from S. Huang et al., FRCAB6 - SRF2019, Dresden, Germany, JACoW Publishing, doi:10.18429/JACoW-SRF2019-FRCAB6

Plasma processing online for CAFe facility (1)

CAFe at IMP for ADS research

Superconducting section of CAFe facility consisted with 4 HWRs' cryomodules

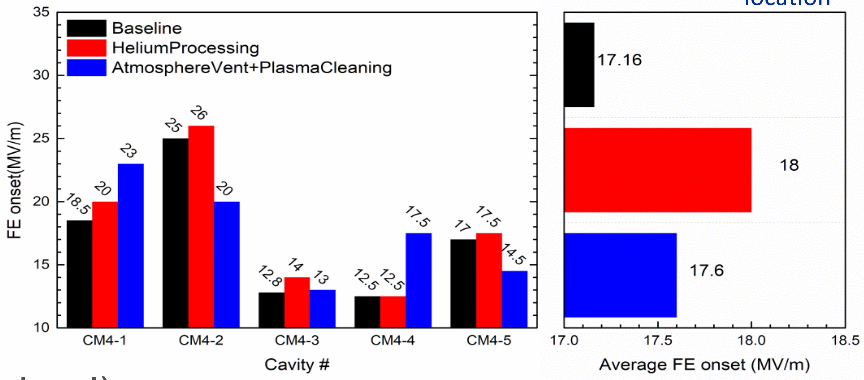




The accident and recovery of CM4

- 2020.6.21 **Baseline** acquisition.
- 2020.7.03 **Helium Processing** at 4 K.
- 2020.8~9 Mistake during the upgrade for the commission of 200 kW: venting to atmosphere induced by valve leaking at 300K.

(The performance degradation due to this vacuum accident was not tested due to cryogenic system overhaul)



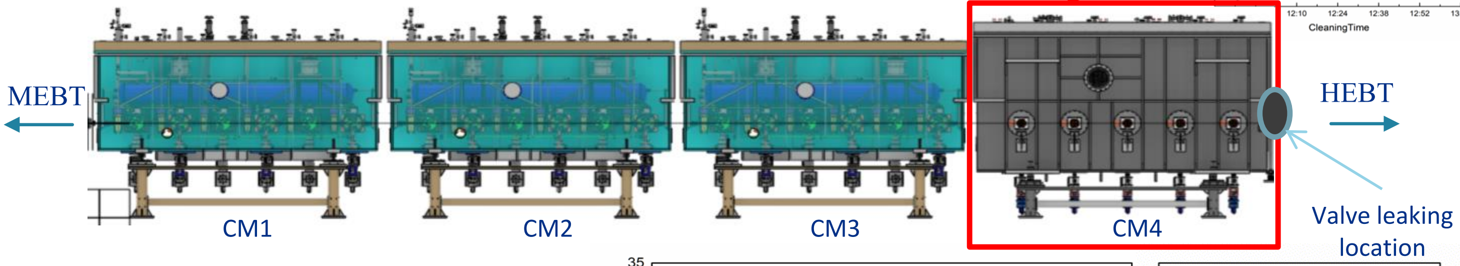
- 2020.10.16 **Plasma cleaning** (Ne/O_2) to remove possible contaminations on inner surface of CM4.
- 2021.1~3 CAFe's successful commissioning of a 10 mA, 205 kW CW proton beam at an energy of 20 MeV.

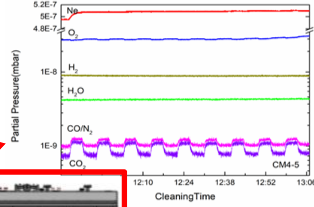
Fermilab

Plasma processing online for CAFe facility (2)

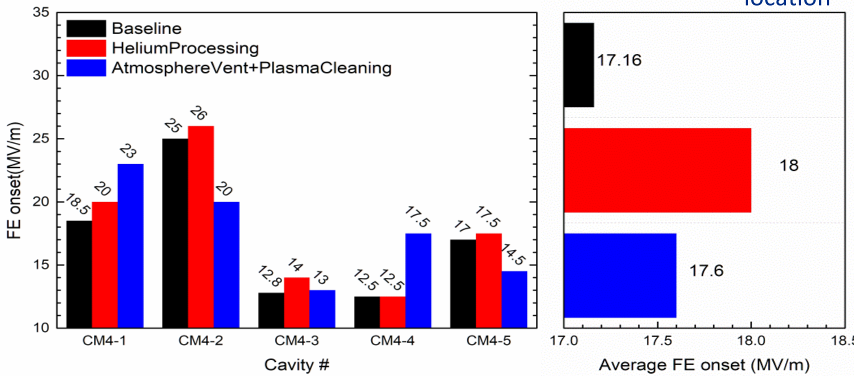
CAFe at IMP for ADS research

Superconducting section of CAFe facility consisted with 4 HWRs’ cryomodules





- The performance CM4-1, CM4-3, CM4-4 were fully recovered after oxygen active plasma cleaning (CM4-1 and CM4-4 performance increased!). The performance of CM4-2 and CM4-5 did not recover to the initial level, additional helium processing might be effective for full recovery.



- Oxygen reactive plasma processing effectively cured FE induced by carbon contamination, but not effective on FE caused by physical particles (such as dust and metal flakes). Thus, the combined use of plasma cleaning and helium processing may provide a complete method to overcome the performance degradation for SRF operation online.

Conclusions

- Starting from SNS successful experience, plasma processing has been developed for multiple types of SRF cavities
- ORNL-SNS and IMP processed cryomodules, showing positive results in FE mitigation and performance recovery
- IMP is studying the use of plasma processing and helium processing as complimentary *in-situ* techniques for FE mitigation
- JLAB developed a method to process C100 cavities and already processed CM C100-10 as a test to train the staff and validate the procedure
- FNAL showed successful results in FE mitigation on LCLS-II cavities and is ready to process LCLS-II-HE vCM in a couple of weeks