AN OVERVIEW OF PLASMA PROCESSING OF SRF CAVITIES AT JLAB*

T. Powers†, T. Ganey, N. Raut, I. H. Senevirathne
Thomas Jefferson National Accelerator Facility Newport News, VA

Abstract

Plasma processing is a common technique where the free oxygen produced in a low-pressure RF plasma breaks down and removes hydrocarbons from surfaces. This increases the work function and reduces the secondary emission coefficient of the treated surfaces. Jefferson Lab has an ongoing R&D program in plasma processing. The experimental program investigated processing using argon/oxygen and helium/oxygen gas mixtures. The initial focus of the effort was processing C100 cavities by injecting RF power into the HOM coupler ports. We also developed the methods for establishing a plasma C75 cavities where the RF power is injected via the fundamental power-coupler. As part of the process development we processed, three C100 cryomodules in our off-line cryomodule test facility. In May 2023 we processed four C100 cryomodules in-situ in the CEBAF accelerator with the cryomodules returning to an operational status in Sept. 2023. The cumulative improvement in field emission free operation, as measured on a cavity by cavity basis, was 59 MeV or 24%. We recently started processing 7 cryomodules in the CEBAF accelerator in August 2024. Methods systems and results from processing cryomodules and individual cavities in the vertical test will be presented. Current status and future plans will also be presented.

METHODS

Plasma processing is being explored by a number of facilities that work with superconducting cavities [1-4]. Between 2015 and 2018 it was used to process 32 cavities in the SNS accelerator at ORNL where they achieved an average improvement in operational gradients of 2.5 MV/m [5]. Unlike helium processing which relies on ion bombardment of the field emitters, plasma processing uses atomic oxygen produced in an RF plasma to break down the hydrocarbons on the surface of the cavity. Removing this layer of dielectric material increases the work function and decrease the secondary emission coefficient [6]. Processing of SRF cavities is done at room temperature using a mixture of noble gas such as argon, neon or helium and oxygen. The discharge is operated at pressures between 50 and 300 mTorr. The current gas mixture used at Jefferson lab is 94% helium and 6% oxygen at 300 mTorr.

Gas Supply and Vacuum Systems

Process gas was supplied by a mobile cart that had a cylinder of helium or argon and a cylinder of 20% oxygen with the remainder of the gas being helium or argon depending on the gas that was being used. The gas supply system used in the vertical test area also has a cylinder of 95% argon and 5% methane which is used to “contaminate” a cavity with hydrocarbons so that we could experiment with different processing techniques. Using a series of valves and flow controllers we were able vary the percentage of oxygen in the process gas as well as to regulate the flow and pressure in the cavities. Two mass flow controllers are used; one to regulate the pressure and one to regulate the percentage oxygen. The outlet pressure of the flow controllers is appropriately 5 Torr. The pumping system contains two turbo pumps and an RGA. In addition to monitoring the oxygen percentages the RGA is used to monitor the hydrocarbon fragments of H_2, CO, CO_2, and H_2O.

Selecting RF Frequencies for Processing

For both C75 and C100 cryomodules the RF-coupling via fundamental power coupler (FPC) is fixed and set up for cryogenic operations of a beam loaded cavity. Thus, when the cavity is at room temperature very little power is coupled to the fundamental mode and pass band modes of the cavities through the FPC. For the warm C100 cavities the ILC style HOM couplers have relatively strong coupling to the TE111 higher order modes, 1870 MHz to 2050 MHz where the power coupled into the cavity is between 20% and 95% of the power that is applied to the HOM coupler.

For the C75 cavities there is moderately good coupling through the fundamental power coupler to the first three TE111 modes. C75 cavities continued to use the glassy ceramic higher order mode loads which use waveguides to couple the HOM power out of the beam line. The cut-off frequency for these waveguides is 1966 MHz. Above this frequency RF power is coupled to the HOM loads and tends to cause a breakdown in the region of the HOM loads. Thus, we are limited to operating at frequencies below that value. The higher order modes below that frequency are coupled out through the fundamental power coupler which makes use of a half-height WR530* waveguide and are damped by a waveguide higher order mode filter. Said filter is replaced by a straight section of waveguide when we perform in situ processing.

Figure 1 shows relative electric fields as determined by a set of bead-pull and S11 measurements for the three modes that are used for processing a C75 cavity. The 1850 MHz mode has a tilt in the field pattern where the strongest field is in the cell furthest away from the fundamental power coupler (cell 5). Fortunately, that mode also had strong enough coupling that we could repeatedly ignite plasma in cell 5. We did find that it was difficult to go from no plasma to plasma on in any of the cells other

---

* Funding provided by SC Nuclear Physics Program through DOE SC Lab funding announcement DE-FOA-0002670
† powers@jlab.org

than cell 5. Thus, we had to always ignite in cell 5 and "walk" the plasma back to cell 1. Once we established plasma in cell 3 with the 1743 MHz mode in the cavity, the Debye shielding reduces the fields in cell 4 due to the 1791 MHz mode and the plasma will ignite in cell 2. When cell 2 has plasma, Debye shielding will reduce the fields in cells 3 and 5 when the mode at 1850 MHz is applied and the plasma will ignite in cell 1. Figure 2 shows the relative electric fields for the modes that are used when processing a C100 cavity.

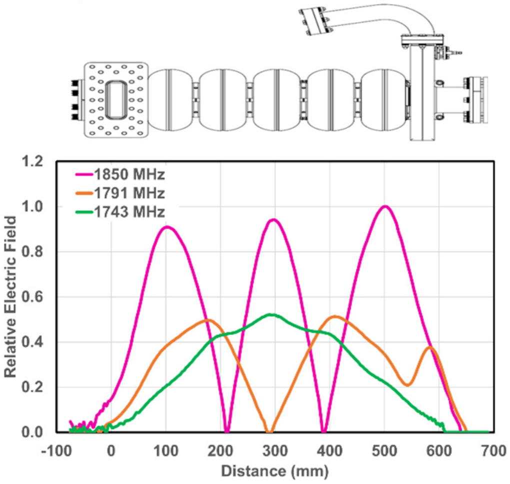

Figure 1: Relative electric field pattern in the center of the cavity as determined using a bead pull measurement for the three modes used for plasma processing a 5-cell, C75 cavity. Note the peak at 580 mm is the center of the HOM waveguide.

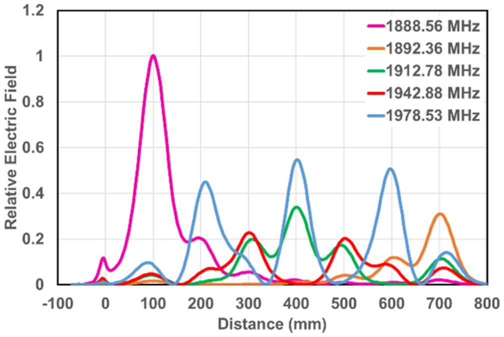

Figure 2: Relative electric field pattern in cavity C100-2 for the modes used to process a C100 cavity.

C100 cavities have two higher order mode couplers which are located adjacent to each other. Unfortunately, there is a relatively strong coupling between the two couplers in the frequency range which includes the TE111 modes. Thus, any signal that is coupled from the driven HOM coupler to the passive HOM coupler travels down the cable and is reflected back with a fixed but random phase and has the potential to affect the fields within the structure. This is especially impactful for the modes that produce strong fields in cell 1. The bead pull measurements that were done in order to help understand this phenomena are described in Ref. [7].

We are limited to RF measurements through the two HOM couplers and the FPC, when preparing to process a C100 cryomodule in-situ. The measurements that we make are S11 and S21 as a function of phase shifter position, where the phase shifter is connected to the HOM coupler that is not driven by the RF system and is not terminated. The primary concern in choosing a phase shifter position is which position will allow us to produce plasma in the cell 1, as well as understanding the frequency of that mode. Once we have the data we review the S11/S21 data and select promising frequencies. Experience has shown us that there are frequent coupler breakd down when we drive the system at a frequency that has substiantial S11 (losses) at frequencies below and close to that of the cell 7 mode frequency. For this reason we choose a phase shifter setting to avoid having those losses. Next we use modal analysis techniques to determine the frequency, loaded-Q and relative magnitude of each of the modes. Figure 3 shows the fits for the cell 7 and cell 1 modes for two different phase shifter settings on the same cavity.

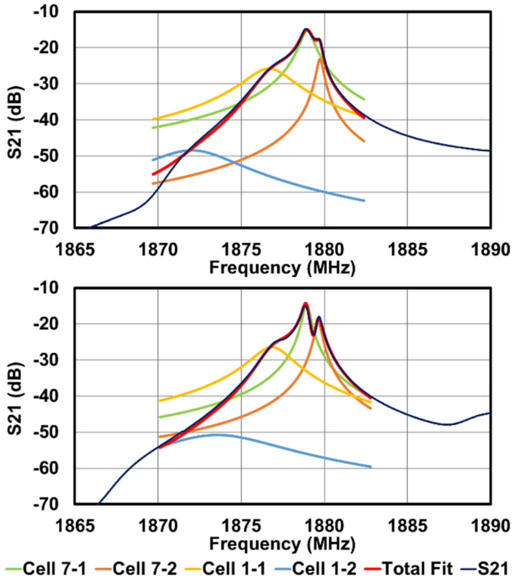

Figure 3: S21 data with modal fits for two different phase shifter settings.

In the offline setup, we can used cameras to determine that we could reliably excite a plasma in two adjacent cells simultaneously. Operating in this mode reduced the time to process a C100 cavity by 40%. We also determined that we could "walk" the plasma from one end of the cavity towards the source of the RF power by applying RF using a second source frequency that excites the next cell, followed by turning off the first source. Details regarding the modes used and issues relating to C100 cryomodules are included in references [8, 9].

RF System

Each channel of the RF systems used for C100 and C75 cavities is capable of processing up to 2 cells in a cavity simultaneously. The system used for processing C100 cavities is described in Ref. [7]. It made use of a single RF amplifier. Two RF sources and a network analyzer were combined and applied to the input of the amplifier. For C100 cavities, where we were able to establish and maintain a plasma using 10 W to 15 W of RF power for each mode, this could easily be done with a 100 W amplifier.

For a C75 cavity each mode requires approximately 30 W of RF power in order to establish and maintain the RF plasma. With this power level and a single 100 W amplifier, when the input power was increased on the second RF source the output power of the first RF frequency was reduced. This reduction, which was due to saturation effects in the amplifier. This reduction was enough to cause a reduction in density of the already established plasma, and thus, the Debye shielding which we relied on to ensure that the plasma would ignite in the upstream cells rather than the down-stream cell when trying to move the plasma from cell 3 to the combined cell 2 and cell 1. To overcome this effect we added a second 100 W amplifier and a combiner network. In addition to providing more RF headroom it meant that applied RF power at the two frequencies were decoupled. A diagram of the C75 RF system is shown in Fig. 4.

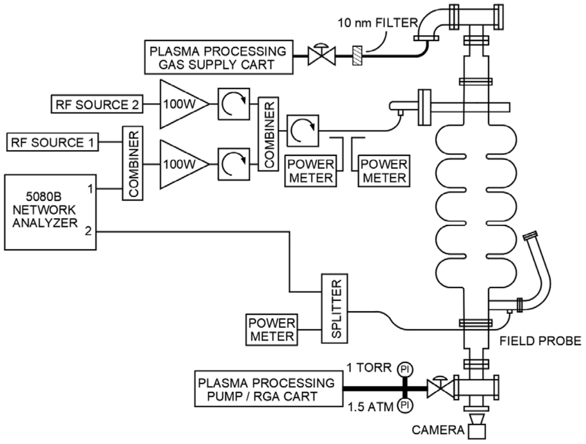

Figure 4: Block diagram of the RF system used for processing C75 cavities.

One of the issues relating to plasma processing is breakdown of the input coupler which in the case of an HOM coupler can damage the input antenna of an HOM coupler and in the case of a waveguide coupler can damage the ceramic window of the waveguide coupler. When such a breakdown occurs coupling between the input and output of the system is changed dramatically. This change in coupling can easily be observed as a change in S21 trace as compared to a baseline measurement when the RF is off. A coupler breakdown also causes a change in the ratio of the transmitted power as compared by the input RF power as measured with RF power meters. When establishing plasma in a cavity the operator monitors the S21 data looking for a sudden change. Once a stable plasma is established an interlock of the ratio of the transmitted power divided by incident power, in dB, is used as an interlock. A ±1.5 dB range is considered acceptable.

Four channels of C100 RF systems and two channels of C75 RF systems were prepared for use in the CEBAF tunnel. The channels were set up in pairs where each pair shares a network analyzer and process control computer. Using these systems, we were able process up to 4 cavities per C100 cryomodule and 2 cavities per C75 cryomodule simultaneously.

Determining Plasma Location

In the vertical test setup which is shown in Fig. 4 we were able to use a camera located at one end of the cavity to determine which cell contains the plasma. In the offline setup, we can use two cameras to determine that we could reliably excite a plasma in two adjacent cells simultaneously. Processing two cells at once reduced the time to process a C100 cavity by 40%. We also determined that we could “walk” the plasma from one end of the cavity towards the source of the RF power by turning on the second source in at a mode frequency that excites the next cell, followed by turning off the first source. Details regarding the modes used and issues relating to C100 cryomodules are included in references [7-9].

When processing cavities in a cryomodule one cannot use a camera in order to identify the location of the plasma. Fortunately, when a plasma is ignited it reduces the dielectric constant of the volume where the plasma exists. In an RF cavity this will cause a shift in the resonant frequency. Because different modes of the cavity have different stored energy in each cell, the pattern of the mode by mode frequency shifts can be used to determine where the plasma is located. Figure 5 is an example of the frequency shift pattern for a plasma located in cell 7 of a C100 cavity. This mode is at approximately 1875 MHz for this cavity. Additionally, the magnitude to of the frequency shift is a metric of the plasma density, where higher density is better.

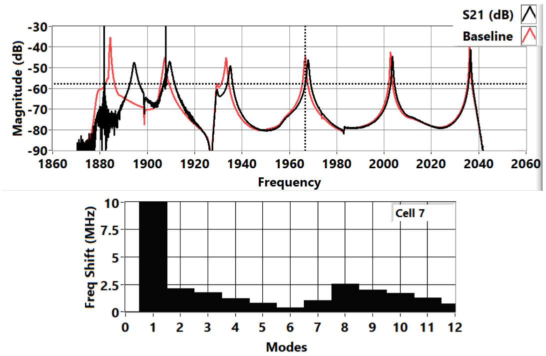

Figure 5: Network analyzer traces showing the first 6 modes of a C100 cavity with plasma in cell 7 (black) and no plasma (red) and corresponding frequency shift pattern.

One useful method for understanding if the plasma is in cell 2 as compared to cell 6 on a C100 cavities is to observe the frequency shift in the Cell 7 mode, 1881.86 MHz, when the plasma is excited by the cell 2/6 mode. Figure 6 shows the difference in the phase shift in the cell 7 mode when the plasma is located in cell 5/6 as compared to when it is located in cell 1/2. The frequency shift in the cell 7 mode when the plasma is in cell 5/6 is due to diffusion of the plasma from cell 6 into cell 7. Such a frequency shift is not observed when the plasma is in cell 2.

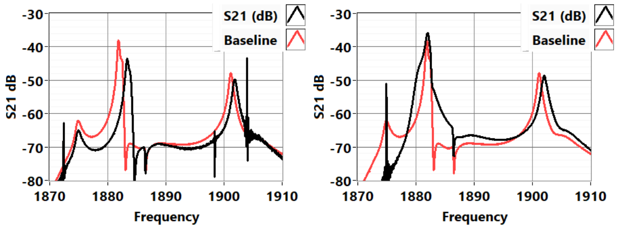

Figure 6: Frequency shift of the cell 7 mode (1881 MHz) and cell 4 mode (1911 MHz) when plasma is present in cells 5/6 (left) and cells 1/2 (right).

PLASMA PROCESSING ACTIVITIES

Since 2020 we completed 37 cycles of vertical test, plasma process, and post-processing vertical test of C100 and C75 cavities. The normal experimental cycle was to contaminate the cavity with a methane/argon plasma, confirm that it was degraded then process it with a gas-mixtures that contained oxygen in order to improve the results. The results of this effort are described in references [7-9]. After we did a short series of a vertical test cycles of a C75 cavity and two C75 cavity pairs. We incorporated processing C75 cavity pair into the production cycle. The pairs are processed while they are in the clean room and the plasma processing systems are outside of the clean room. It is possible to process C75 cavity pairs as part of the production cycle because they are kept under vacuum during the rest of the production process. Figure 7 shows the before and after results of processing one of these pairs. All three of the pairs that were processed in this manner were progressed to assembly in the cryomodule after processing.

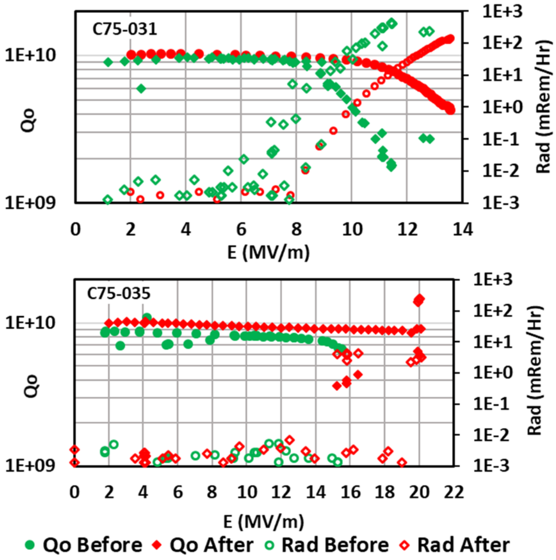

Figure 7: Before Qo as a function of gradient and radiation for two C75 cavities before and after plasma processing in the clean room after being assembled into a pair.

Plasma Processing of Cryomodules

In June of 2022 we processed cryomodule C100-5, in the cryomodule test facility (CMTF) prior to it being disassembled, reprocessed and reassembled. Prior to removal from the accelerator the cavities this cryomodule had been operating at 75 MeV. At the time we were using a processing protocol of one hour per cell or combination of cells with a 2% oxygen/argon gas mixture followed by a second cycle using a 20% oxygen/argon gas mixture. The FE properties of the cryomodule were measured in the CMTF before and after processing. The results were that processing improved cavity by cavity field emission (FE) onset by 11.6 MeV. Although that improvement was sufficient to justify processing cavities in production cryomodules, it was determined that C100-5 would be refurbished with the goal of a FE free 100 MeV cryomodule.

In January 2023 we processed 4 cavities in C100-10R, which had FE at low to moderate gradients. This cryomodule was processed using a mixture of 6% oxygen and 94% helium. The change in gas mixture was based on results of the vertical testing program [9]. The cryomodule was characterized before and after processing. There was a net improvement in FE free operation of the cryomodule of 9.8 MeV.

In the early spring 2023, in preparation for plasma processing during the upcoming accelerator maintenance period, we opportunistically measured the FE properties of the cryomodules 2L22, 2L23, 2L24 and 2L25 in the CEBAF accelerator. The cryomodules were brought to room temperature in April 2023 and, as a regular maintenance activity, the beam line gate valves were replaced. These cryomodules were processed in situ in the CEBAF accelerator over a 3-week period in May 2023. By using 4 RF systems to process 4 cavities in parallel and processing two cells at a time we were able to process 8 cavities in 10 hours. Details on the processing protocols with example plots of the RF power and they hydrocarbon residue plots are were presented in reference [9]. In July 2023 we did post processing FE onset measurements. In June 2024 we processed the cryomodule C75-03 in the test lab after acceptance testing prior to it being installed in CEBAF.

Table 1 is a summary of the before and after in FE free operating voltages for the six cryomodules that were processed in the CMTF and the CEBAF accelerator between June 2022 and May 2023. The average gain in FE free accelerating voltage for the cryomodules that were processed in situ (2L22 – 2L24) was 14.8 MeV or a total of 59.1 MeV. After processing the four C100 cryomodules in the south linac and replacing the cryomodule located in slot 2L26 with cryomodule C100-10R the C100 cryomodules in the south linac improved from 427 MeV to 488 MeV, which is the highest that the ensemble of cryomodules has been operated since 2014.

The results of the pre and post processing FE data is shown in Fig. 8. Five of the processed cavities were FE free after processing. Cavity in slot 2L25-1 degraded by 5 MV/m after the valve change followed by plasma processing. Four cavities had minor degradation and the remainder were improved. Figure 9 shows the distribution of the improvement in the FE free gradients for the 44 cavities that were processed in the CMTF or in CEBAF.

The average improvement in the gradients was 2.7 MV/m, which compares favourably to the 1.4 MV/m average improvement that was achieved when we helium processed 90 cavities in 1997.

Table 1: Field Emission Free Accelerating Voltages for the Cryomodules, Processed in 2022 and 2023

	FE Free Before (MeV)	**FE Free After (MeV)**	**Delta (MeV)**
C100-5	59.7	71.5	11.8
C100-10R	95.6	105.4	9.8
2L22	54.2	72.4	18.2
2L23	71.8	83.1	11.3
2L24	54.6	66.4	11.8
2L25	62.7	90.6	27.9

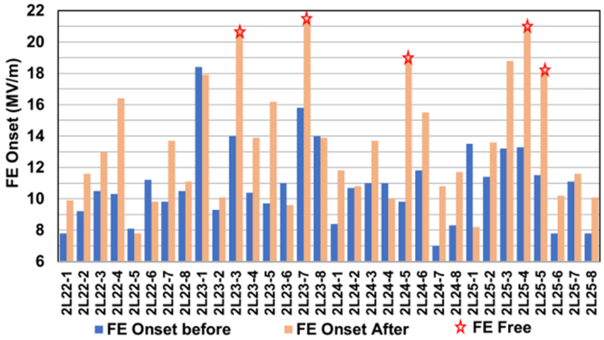

Figure 8: Field emission onset before and after in situ plasma processing in the CEBAF accelerator.

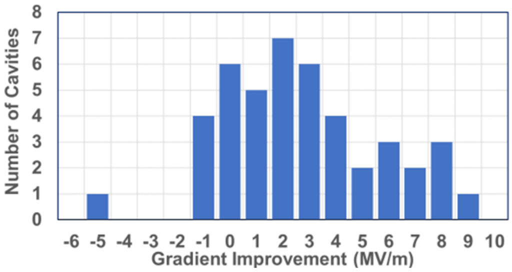

Figure 9: Distribution of the improvement in FE free operation for the 44 cavities that were processed in cryomodules in 2022 and 2023.

In May of 2024, in preparation for next round of plasma processing, we had operations staff re-measure the FE onset properties of twelve C100 and C75 cryomodules that are installed in CEBAF. Four of those cryomodules were the ones that were processed in May of 2023 and subsequently characterized in July 2023. The results of those measurements along with the FE onset properties prior to plasma processing are shown in Fig. 10. The overall degradation of the cryomodules was about 2%. Combined with the newly refurbished cryomodule that was installed in position 2L26 in the summer of 2023 these cryomodules reliably delivered between 485 MeV and 490 MeV throughout the physic run.

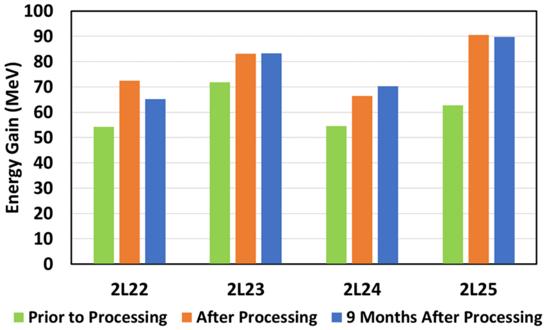

Figure 10: Field emission free energy gain before processing, after processing and after 9 months of operation in CEBAF.

Future Plans

We are currently in the middle of processing between 6 and 8 cryomodules as part of a scheduled accelerator down. Six of the cryomodules are C100 cryomodules. Five will be done in situ in the CEBAF accelerator and one will be done in the test lab after final assembly prior to any testing. If time permits we will also process two C75 cryomodules in situ. We were just awarded the final two years of funding for a dedicated R&D program, We will use these funds to continue to develop and improve the processing techniques in the offline facilities, investigating different gas mixtures, develop protocols for processing C50 cavities and continue to do plasma simulations [10]. We will also investigate different gas mixtures and other plasma-like processes.

SUMMARY

Jefferson Lab continues to have a robust plasma processing program. Our current gas mixture is 6% oxygen and 94% helium. We built systems to in situ process two cryomodules simultaneously in the CEBAF accelerator. We are currently using machine operators and to supplement SRF staff while processing cryomodules. In total we have processed 10 cryomodules. Four of the cryomodules were processed in the SRF test lab facilities and six were processed in situ in the CEBAF accelerator. The four cryomodules that were processed in CEBAF in 2023 had a 59 MeV increase in energy gain with no FE, which was a 24% improvement. In addition to operating for 9 months at the highest energy since 2014, those cryomodules have only seen minor degradation in FE onset energy since they were processed.

REFERENCES

[1] M. Martinello *et al.*, “Plasma Processing for in situ field emission mitigation of superconducting radiofrequency (SRF) Cryomodules,” in *Proc. Snowmass*, 2021. `https://arxiv.org/abs/2203.12442`

[2] S.-H. Kim *et al.*, “Evolution of the Superconducting Linac Output Energy at the Spallation Neutron Source,” in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 73-75. `doi:10.18429/JACoW-IPAC2018-MOZGBF4`

[3] W. Hartung *et al.*, “Investigation of Plasma Processing for Coaxial Resonators,” in *Proc. 21th Int. Conf. RF Supercond.*

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-THXA005

(SRF'23), Grand Rapids, MI, USA, Jun. 2023, pp. 960-967. `doi:10.18429/JACoW-SRF2023-THIXA01`

[4] M.E. McIntyre *et al.*, "Plasma Processing: Ignition Testing and Simulation Models for a 172 MHz HWR Cavity," in *Proc. 21th Int. Conf. RF Supercond. (SRF'23)*, Grand Rapids, MI, USA, Jun. 2023, pp. 219-223. `doi:10.18429/JACoW-SRF2023-MOPMB049`

[5] M. Doleans, ORNL, private communication, July 2019.

[6] P. V. Tyagi *et al.*, "Improving the work function of the niobium surface of SRF cavities by plasma processing," *Appl. Surf. Sci.*, vol. 369, pp. 29–35, Apr. 2016. `doi:10.1016/j.apsusc.2016.02.030`

[7] T. Powers, N. C. Brock, and T. D. Ganey, "In Situ Plasma Processing of Superconducting Cavities at Jefferson Lab," in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 485-489. `doi:10.18429/JACoW-SRF2021-TUPTEV004`

[8] T. Powers, N. C. Brock, and T. D. Ganey, "In Situ Plasma Processing of Superconducting Cavities at JLab," in *Proc. NAPAC'22*, Albuquerque, NM, USA, Aug. 2022, pp. 22-25. `doi:10.18429/JACoW-NAPAC2022-MOYE5`

[9] T. Powers, N. C. Brock, and T. D. Ganey, "In Situ Plasma Processing of Superconducting Cavities at JLab, 2023 Update," in *Proc. SRF'23*, Grand Rapids, MI, USA, Jun. 2023, paper WEPWB054, pp. 701-705. `doi:10.18429/JACoW-SRF2023-WEPWB054`

[10] N. K. Raut, P. Dhakal, T. D. Ganey, and T. Powers, "Simulation of the Dynamics of Gas Mixtures during Plasma Processing in the C75 Cavity," in *Proc. SRF'23*, Grand Rapids, MI, USA, Jun. 2023, paper WEPWB053, pp. 696-700. `doi.org/10.18429/JACoW-SRF2023-WEPWB053`