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IN SITU PLASMA PROCESSING OF SUPERCONDUCTING CAVITIES AT JLab, 2023 UPDATE*

T. Powers†, N. Brock, T. Ganey
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

Abstract

Jefferson Lab has an ongoing R&D program in plasma processing which just completed a round of production processing in the CEBAF accelerator. Plasma processing is a common technique for removing hydrocarbons from surfaces, which increases the work function and reduces the secondary emission coefficient. The initial focus of the effort was processing C100 cavities by injecting RF power into the higher order mode (HOM) coupler ports. Results from processing cryomodules in the CEBAF accelerator as well as vertical test results will be presented. The goal of in-situ processing is to improve the operational gradients and the energy margin of the linacs. This work will describe the systems and methods used at JLab for processing cavities using an argon-oxygen gas mixture as well as a helium-oxygen gas mixture. Before and after plasma processing results will also be presented.

METHODS

Plasma processing is being explored by a number of facilities that work with superconducting cavities [1]. 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 [2, 3]. 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. Processing of SRF cavies is done using a mixture 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 99.999% 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 cart 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. The pumping system consisted of two turbo molecular pumps, a 300 L/s primary pump and a 70 L/s secondary pump. The 70 L/s pump was used as part of a differentially pumped RGA system. In addition to monitoring the argon to oxygen ratio, the RGA is used to monitor H_2, CO, CO_2 and H_2O, which are hydrocarbon fragments that are produced when the free oxygen interacts with the hydrocarbons.

RF System

Each channel of the RF system, which is described in [4], is capable of processing up to 2 cells in a cavity simultaneously. Four channels of RF system were prepared for use in the CEBAF tunnel. They were set up in pairs each of which shared a 4-port network analyzer and process control computer. The output of two RF sources and network analyzer are combined and applied to the input of a 100 W amplifier. The output of the amplifier is applied to the cavity via one of the HOM coupler antennas. The system monitors the incident and reflected power and the power that is emitted from the fundamental power coupler. The latter is effectively acting as a field probe for the electric field in the cell furthest away from the HOM couplers. Control over which cell or combination of cells is processed is accomplished by selecting one of the TE111 modes that provided a peak electromagnetic field in the desired cells. Early on we determined through simulation and confirmed with bead pull measurements that there were two modes that were strongly tilted towards cells 1 and 7, where cell 1 is closest to the HOM couplers. There was a mode that had peak fields in cell 4 and two other modes that had peak fields symmetrically in cells 2/6 and 3/5 [5]. Using these 5 modes we were able to predictably establish a plasma in each of the cells by starting furthest away from the HOM couplers then turning on the second source. For example, if we started with cell 7 on and turned on the frequency for cells 2/6 we would establish a plasma in cells 6 and 7. When we turned off the mode for cell 7 the plasma remained in cell 6. The modes and methods are described more fully in Ref. [4, 5]. Figure 1(a) shows an image of an argon/oxygen plasma in each of the 7 cells of a cavity in a C100 cryomodule. Figure 1(b) shows an image of a helium/oxygen plasma in cells 7, 5 and 6, 4 and 3 as well as 2 and 1. The blue shift in the colors in the cell 7 mode is due to a reduction in oxygen content in the process gas coupled with an increase in the hydrocarbon residues.

C100 Cryomodule Issues

One of the issues with processing a C100 cryomodule is that both of the HOM coupler antennas are located on the same end of the cavity. Because of the geometry there is a relatively strong coupling between the antennas in the HOM frequency bands that provide a uniform plasma. Because of this strong coupling, RF power that is applied to one HOM coupler is picked up by the second coupler,

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† powers@jlab.org

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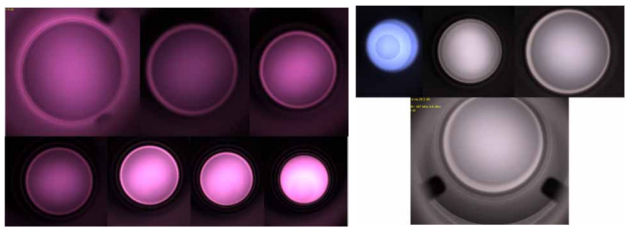

(a) (b)

Figure 1: (a) Images of argon/oxygen plasma in cells 1 through 7. (b) Images of helium/oxygen plasma in cells 1, 5/6, 3/4, and 1/2.

travels up the cable, is reflected back at a random phase and is applied to the cavity. This had a strong impact on the properties of the modes used to excite cells 1 and 4. In order to mitigate this issue when processing cavities in a cryomodule we connected a motorized phase shifter to the unused coupler and measured S11 and S21 as a function of phase shifter position. We analyzed the data off-line and chose the phase shifter position that provided a more optimal operation point which was not prone to coupler breakdown.

When there is a coupler breakdown there is a change in the amount of RF power that is transmitted from the HOM coupler to the waveguide coupler. If the breakdown is on the tip of the HOM coupler, as it is shown in Fig. 2(a), the change is about 3 dB and it can go up or down. When it is a breakdown of the antenna of the RF feedthrough, as shown in Fig. 2(b), the power that is transmitted to the waveguide is reduced by about 20 dB. We used these values to create an interlock based on the ratio of the incident power and the transmitted power where the nominal set-point was ±1.5 dB.

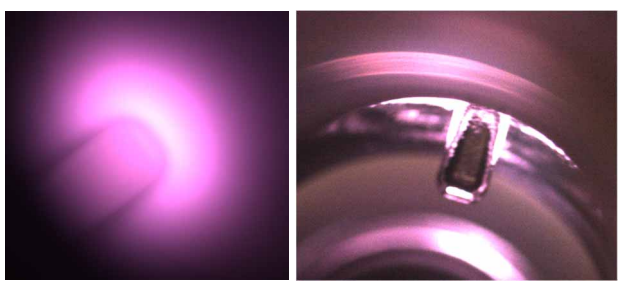

Figure 2: Images of (a) tip glow coupler breakdown, and (b) breakdown at the HOM feedthrough antenna in argon.

Determining Plasma Location

One of the issues with processing a cryomodule in an accelerator is that 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 frequency shifts can be used to determine where the plasma is located. Figure 3 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.

Another example is shown in Fig. 4 where there is a frequency shift when the plasma is in cell 6 but not when it is in cell 2. This subtle change is a good way to confirm that the plasma is in cell 2 rather than cell 6 when applying the frequency for cells 2/6 or 1/2.

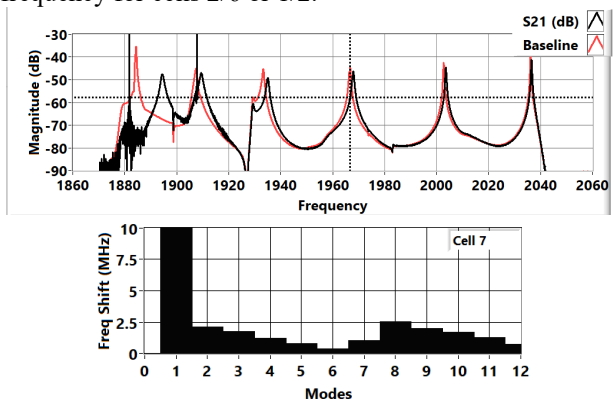

Figure 3: Network analyzer traces showing the first 6 modes with plasma in cell 7 (black) and no plasma (red) and corresponding frequency shift plot.

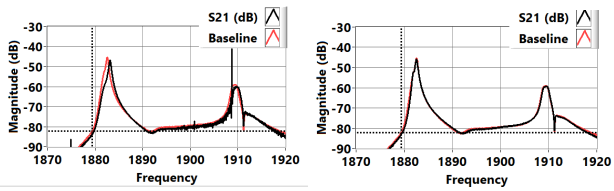

Figure 4: Frequency shift in the "cell 7" mode when the plasma is in cell 6 (left) as compared to when it is in cell 2 (right).

PLASMA PROCESSING ACTIVITIES

Since 2020 we completed 35 cycles of vertical test, plasma process, and post-processing vertical test of a C100 cavity. 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. Initially, we focused our efforts on argon/oxygen gas mixtures and had good results when processing with 2% oxygen followed by processing with 20% oxygen. In the summer of 2022 after processing a cavity with argon/oxygen to the point where it stopped improving, we processed it with a helium/oxygen gas mixture. As shown in Fig. 5, it improved by an additional 2.5 MV/m. Following this we did a series of experiments using different gas pressures and mixtures of helium and oxygen. Finally determining that a good gas mixture was 94% helium and 6% oxygen.

In June 2021, we processed cryomodule C100-10 in the off-line test bunker. It was severely degraded due to the catastrophic failure of a Viton seal on a beam line gate valve [4]. While a very useful exercise in training and process development, the resulting improvement of field emission free operation from 36.3 MeV to 37.9 MeV was a demonstration that plasma processing may not be that effective for severely contaminated cavities. In June of 2022

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we processed cryomodule C100-5, in the off-line test bunker. Prior to removal from the accelerator the cavities this cryomodule had been operating 75 MeV. At the time we

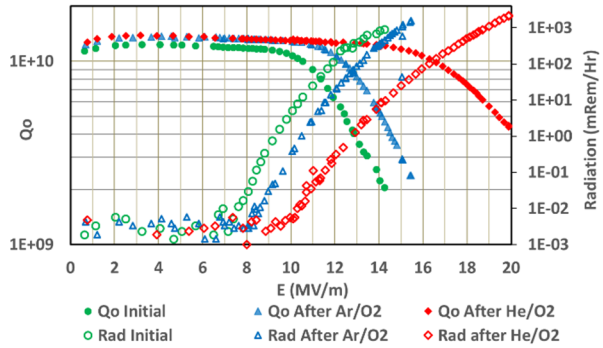

Figure 5: Improvement after processing with a gas mixture of argon/oxygen followed by a mixture of helium and 8.5% oxygen.

were using a processing protocol of one hour per cell or combination of cells with a 2% argon/oxygen gas mixture followed by a second processing cycle using a 20% argon/oxygen gas mixture.

In January 2023 we processed 4 cavities in the recently reassembled C100-10R cryomodule. The 4 cavities that we processed were exhibiting field emission. By this time we had changed our processing protocol and were using a helium/oxygen gas mixture with 6% oxygen.

In May 2023 we processed 4 cryomodules in-situ in the CEBAF accelerator. Field emission onset measurements were made prior to processing. These will be compared to measurements which will be taken as soon as the accelerator is restored to 2 K. By using the 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. Since we had two vacuum carts and two sets of waveguide hardware we were able to prepare the next cryomodule for processing while we were actively processing the current cryomodule. Figure 6 is an image of the equipment setup in the tunnel.

Figure 6: Image of the two of the channels of the RF system set up in the CEBAF accelerator. In the background is the portable clean room which was used in order to make beam line connections.

On day one of the four day cycle we would move the 4 RF systems and gas supply system from the previous zone to the current zone. We would then make low power S11 and S21 measurements as a function of phase shifter position where the phase shifter was connected, open circuit, to the unused HOM port. We set the phase shifters and connected the RF systems to the first 4 cavities. If time permitted we would process one or two cell combinations on the first 4 cavities. On day two we would process all 8 cavities once. The third day was an off day, which allowed any remaining hydrocarbons to redistribute themselves. On day four we would process the cavities a second time. After we were done processing we would close the gas supply valve and begin pumping on the beam line overnight using he plasma pumping system. Then next day, in parallel with moving the equipment to the next zone we would re-establish ion pump operation and isolate the plasma pumping system from the beam line.

Figure 7 shows plots of the RF power for cavities 7 and 8, the percentage oxygen while we were processing and the partial pressure of the hydrocarbon residues as a function of time. Figure 8 are the same data plots for the second round of processing which occurred two days later. Note that while there were still transient peaks in the partial pressure of the hydrocarbon residues when we changed cells, there was a significant reduction during the second round of processing.

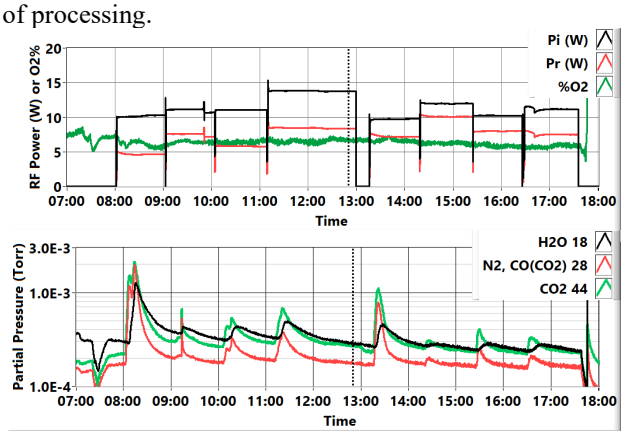

Figure 7: Plots of the forward and reflected power at the HOM connector on the cavity and the partial pressure of the hydrocarbon residues of water, carbon monoxide and carbon dioxide for the first cycle on cavities 2L22-7and 2L23-8.

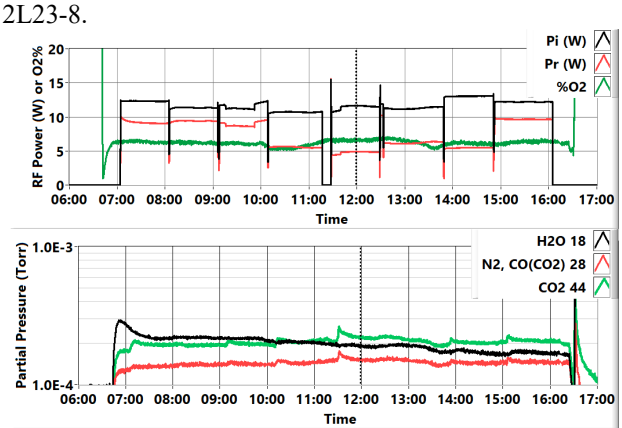

Figure 8: Plots of the same data for the second round of processing.

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It should be noted that we were processing four cavities at the same time. Thus, the added peaks in the hydrocarbon residues were due to the other cavities being turned on a few minutes later. In these plots the partial pressures recorded by the RGA were multiplied by the ratio of the total pressure (300 mTorr) divided sum of the partial pressures of masses 2, 16 and 32.

RESULTS

On a cavity by cavity basis the field emission free gradients on cryomodule C100-5 improved by 0.8 MV/m to 5.4 MV/m, with a total field emission free improvement of 11.8 MeV. The results of processing cryomodule C100-10R are shown in Table 1. Four of the cavities were processed. Three improved by gradients between 1.6 and 8.2 MV/m. Two cavities ended up being degraded. Cavity 1 which was processed, started out with FE onset of 7.5 MV/m and degraded to 6.3 MV/m. Cavity 4, which was not processed, was operated at 24 MV/m field emission free for about 30 minutes before it blew up a field emitter. Afterwards the field emission onset was reduced to 17 MV/m. Cavity 3, which was adjacent to one of the cavities that was processed also improved. The average increase in FE onset for the 4 cavities that were processed was 3.5 MV/m with an overall field emission free energy gain of 9.8 MeV.

Table 1: C100-10R cavity gradients and cryomodule energy before and after processing. Cavities shaded green were processed.

Cavity	FE Free Before	FE Free After	Delta	FE <100 mR/hr Before	FE <100 mR/hr After	Delta
1	7.5	6.3	-1.2	8	7.4	-0.6
2	15.8	24	8.2	19.4	24	4.6
3	16.8	23	6.2	22.3	23	0.7
4	23.3	17	-6.3	23.3	21	-2.3
5	16.8	17	0.2	16.8	17	0.2
6	17.8	19.4	1.6	20.8	23.8	3
7	24	24	0	24	24	0
8	14.5	19.8	5.3	17.2	23.8	6.6
Energy MV/m	95.5	105.4	9.8	106.3	114.8	8.5

Figure 9 shows the before and after field emission free gradients on a cavity-by-cavity basis for all of the cryomodules that were processed to in cryomodules C100-10 and C100-5R.

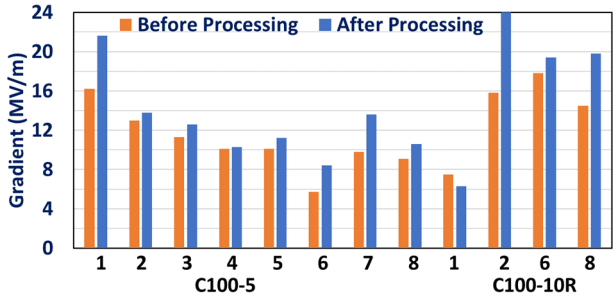

Figure 9: Field emission onset before and after processing 8 cavities in C100-5 with argon/oxygen and 4 cavities in C100-10R with helium/oxygen.

Another metric for operational improvement is the amount of radiation produced by each cavity at the nominal operating gradient of 18 MV/m. An ionization chamber that is part of the radiation protection system was used for this measurement. This was done because the Geiger-Muller tubes that are normally used for determining field emission onset saturated well before 18 MV/m on most cavities. Of the cavities that were processed, we were able to operate 6 cavities in C100-5 and 3 cavities C100-10R at 18 MV/m before and after processing. This is the nominal operating gradient required to reach 100 MeV. Table 2 shows the reduction in radiation production for those six cavities. All of the field emission levels at 18 MV/m were reduced substantially. The three cavities were processed with helium/oxygen were field emission free at 18 MV/m after processing.

Table 2: Improvement in FE Radiation at 18 MV/m

Cavity	Before Radiation (mR/hr)	After Radiation (mR/hr)	Percentage Reduction
C100-5-1	9	0.04	99%
C100-5-2	50	25	50%
C100-5-3	1300	200	85%
C100-5-5	2000	300	85%
C100-5-7	4000	60	98%
C100-5-8	150	13	91%
C100-10R-2	27	<0.02	>99%
C100-10R-6	3	<0.02	>99%
C100-10R-8	190	<0.02	>99%

PLANS MOVING FORWARD

We will be remeasuring the field emission onset and determining Qo values in early July 2023. These results will be compared to the field emission radiation data that was acquired in March 2023 so as to evaluate the effects of plasma processing of the 32 cavities. We are currently in the middle of the process of determining how we might ignite and control a plasma in C75 cavities. We will follow this by using the plasma processing vertical test stand and determine that it is an effective means of mitigating [6] the multipactor problem [7]. Based on these results we will modify a C75 production test-stand so that plasma processing can be implemented prior to the vertical test. Since

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C75 cavities are handled hermetic pairs during the production process this should insure that they are free of multipactors once they are assembled into a cryomodule. The plan is to continue to process multiple cryomodules in-situ during the next extended accelerator maintenance period which is currently scheduled for the spring of 2024.

CONCLUSION

Plasma processing of SRF cavities continues to be an active program at Jefferson Lab. There is a robust vertical test program that will continue for at least the next year. The protocols and processes that were developed in the vertical test program have been adapted and used for processing C100 cryomodules. To date we have processed 6-1/2 C100-style cryomodules. 2-1/2 were processed in the offline cryomodule test facility as part of a process development and validation program. Four were processed in-situ in the CEBAF accelerator. Cryomodule C100-5 was processed using an argon/oxygen gas mixture. The average improvement in field emission free gradients in this cryomodule was 1.5 MV/m. Four of the cavities in cryomodule C100-10R were processed with a helium/oxygen gas mixture. The average improvement in field emission free gradients for those cavities was 3.5 MV/m. The results for the 32 cavities that were processed in-situ in the CEBAF accelerator will be available in the summer of 2023. The current plan is to determine methods to process C75 cavities which have waveguide coupled lossy ceramic HOM loads and to develop processing protocols in the vertical test area. This will be followed by more in-situ processing of C100 and C75 cryomodules in the spring of 2024.

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