ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOYE5

IN SITU PLASMA PROCESSING OF SUPERCONDUCTING CAVITIES AT JLAB*

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 is close to going into 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 is processing C100 cavities by injecting RF power into the HOM coupler ports. The goal will be to improve the operational gradients and the energy margin of the CEBAF linacs by processing cryomodules in situ. Results from processing a cryomodule in the cryomodule test bunker as well as cavity vertical test results will be presented. This work describes the systems and methods used at JLAB for processing cavities using an argon/oxygen gas mixture.

METHODS

Plasma processing [1] is being explored by a number of facilities that work with superconducting cavities [2]. 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 [3, 4]. 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 cavities is done using a mixture noble gas such as argon, neon or helium and oxygen. The discharge is operated at pressures between 50 and 250 mTorr.

Gas Supply and Vacuum Systems.

Process gas was supplied by a mobile cart that had a cylinder of argon, 80% argon / 20% oxygen, and 95% argon / 5% methane. 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. Two gas supply and pumping systems have been fabricated which will allow us to process two cryomodules simultaneously in the CEBAF accelerator.

* Funding provided by SC Nuclear Physics Program through DOE SC Lab funding announcement Lab-20-2310.
† powers@jlab.org

RF System

Two 2-channel and one 1-channel RF systems which is described in [5], have been fabricated. Each RF system is capable of processing one cavity at a time by applying up to 100 W of RF power through a higher order mode (HOM) coupler antenna. The output of two RF sources and network analyzer are combined and after amplification are applied to one of the HOM antennae on a C100 cavity. 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.

Figure 1 is a plot of the relative electric field amplitudes for some of the modes of a C100 cavity. The data was taken using standard bead pull methods and scaled by the real part of S11 [5, 6]. Control over which cell or combination of cells is processed is accomplished by selecting which of the field patterns is applied to the cavity. Using the modes in Fig. 1 as an example if one were to apply RF to the HOM coupler at 1913.24 MHz and increase the RF power a plasma would ignite in the cell with the highest RF fields, which is cell 4. Moving from cell to cell is accomplished by turning on an additional RF source at the frequency that supports a plasma in the new cell then turning off the original cell. It is described in detail in Ref. [5].

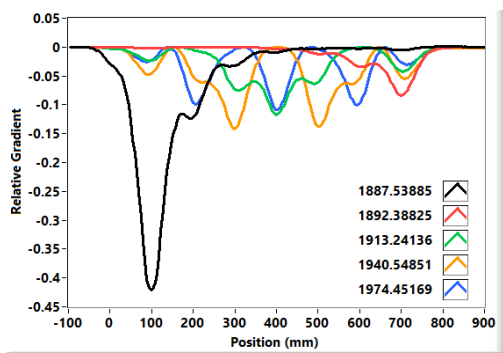

Figure 1: Relative gradient for the 5 modes that are used for plasma processing a C100 cavity. Note: the center of the cells are on even 100 mm intervals between 100 and 700 mm.

Using our off-line system we were able to confirm that by applying two frequencies, we could establish plasma in two adjacent cells. The standard processing combination that was chosen was to process in cell 7, then 5/6, then 3/4, then 1/2. Using this protocol reduced the processing time by 40%.

Cryomodule Issues

One of the issues with processing a C100 cryomodule is that both of the HOM coupler antennas are located on the

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOYE5

same end of the cavity. Because of the geometry there is a relatively strong coupling between the in the HOM frequency band for the TE111 modes. These happen to be the modes that provide a uniform plasma within the cells when the plasma is ignited. Additionally, the HOM cables internal to the cryomodule are built with a specified length of 305 ± 2.5 cm. Thus, when RF is coupled from the driven HOM coupler and is coupled to the unterminated HOM coupler it travels down the cable and is reflected back at an unknown, frequency dependent, fixed phase. These standing waves affect the amount of power that is coupled into the cells and in some cases leads to a discharge in the coupler assemblies. We addressed this issue by placing a motorized phase shifter on the unused port and recorded S11 and S21 of the cavity as a function of phase shifter position. We used this data to determine a phase shifter position that provided a reasonable operating point for all of the different modes [3]. The second issue with the cryomodule is that the beam pipe is not beyond cutoff for the frequencies being used for processing. For this reason, we are limited to processing no more than four C100 cavities simultaneously.

Example Measurements

Figure 2 shows two network analyzer measurements, the red trace is with the plasma off while the second is with the plasma on. When the plasma turns on it reduces the dielectric constant in the volume which contains the plasma. Since this processing creates plasma in discrete cells and since the stored energy profile on a cell by cell basis is frequency dependent, one can determine the plasma location by calculating the frequency shift of the peaks in the S21 measurement on a mode by mode basis.

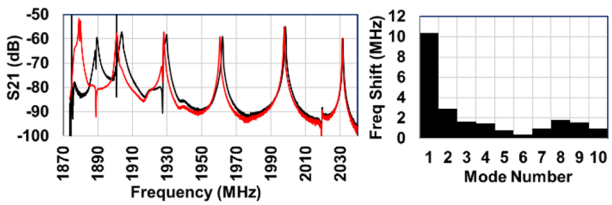

Figure 2: Network analyzer traces showing the first 6 modes with plasma in cell 7 (black) and no plasma (red) and corresponding frequency shift plot.

Where the modes are symmetrical, such as the one at 1940.54 MHz in Fig. 2, the frequency shift pattern only indicates that it is in cells 3 or 5. However, the mode pattern for cell 7 is unique, which is shown in Fig. 2. Thus, the mode pattern can be used to ensure that we are at a good starting point for moving the plasma to cells 6 and 5. The mode pattern for cell 4 is also unique which allows us to know that we are in a good starting point to go to cell 7 or cell 3. Note that the narrow frequency line at 1901 MHz in the plasma-on network analyzer trace is the primary RF signal which is nominally used to excite cell 4 but produces a strong plasma in cell 7 if a plasma is already established in cell 7. The narrow line at 1875 MHz is an image frequency produced by the down converter in the network analyzer.

Figure 3 shows the typical RF power plots and partial pressure of oxygen and the hydrocarbon residuals when processing after intentionally contaminating the cavity surface with the argon/methane gas mixture. The standard processing order of cells 7, 5/6, 3/4, and 1/2 was followed. On the RF plots note that the RF power that actually goes into the system is relatively small. Also, on the RGA plots notice that the dips in the oxygen content occurred when the partial pressure of water, carbon monoxide and carbon dioxide increased. This indicates that the oxygen combined with the hydrocarbon compounds to produce the hydrocarbon residual compounds.

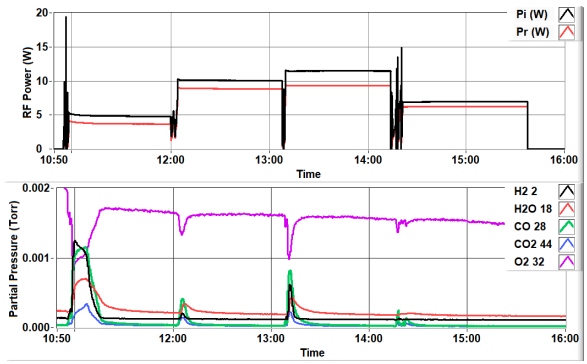

Figure 3: Typical processing cycle in the vertical staging area. The partial pressure values are scaled to the values at the exit port of the cavity.

RESULTS

Two types of results are reported here. The first is vertical test results where a cavity was tested in a vertical cryostat, plasma processed in the vertical staging area and the vertical test was repeated. In these tests the cavity remained on the vertical test stand when it was processed. The second set of results is from processing a cryomodule. This cryomodule was C100-5 which had been in the accelerator for about 10 years and was still producing 75 MeV of accelerating voltage while producing approximately a neutron dose of 15 Rem/hr approximately 1.5 m away from the downstream end of the cryomodule.

Vertical Processing

The vertical testing program made use of a C100 cavity that was mounted on a vertical test stand. The test stand was modified in order to accommodate a second pump-out valve at the bottom of the cavity as well as a gas supply line at the top of the cavity.

In the past year we completed 20 vertical tests and 18 cycles of plasma processing where plasma processing was either two cycles of plasma processing with an argon/oxygen gas mixture or one cycle of processing with an argon/methane gas mixture. The purpose of the latter was to contaminate the inner surface of the cavity in a controlled manner so that we had a uniform starting condition when modifying the processing methods.

Once we had developed the methods we began a series of experiments where we adjusted the amount of oxygen in the gas mixture in order maximize the improvement in the

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOYE5

field emission (FE) properties of the cavity. We determined that a good method was to process the cavity with a 1% oxygen, 99% argon mix followed 24 to 48 hours later with a 20% oxygen, 80% argon mix. Figure 4 shows the improvement after said processing cycle. In this series the FE onset was improved from 9.5 MV/m to 14 MV/m and the radiation at 18 MV/m, which is the nominal operating gradient for a C100 cavity, was reduced from a value in excess of 1 Rem/hr to 0.008 Rem/hr. Also, it should be noted that this cavity came out of the clean room with FE onset of 7.5 MV/m, thus the net improvement was 6.5 MV/m.

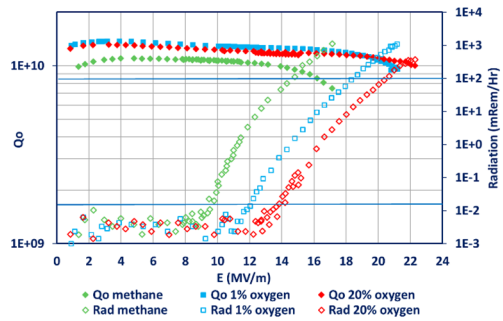

Figure 4: Improvement in a C100 cavity that had been contaminated with a methane plasma after processing with 1% oxygen/argon, vertically tested then processed with 20% oxygen/argon.

Cryomodule Processing

The cryomodule C100-5 was removed from the CEBAF accelerator with a plan of reprocessing the cavities and rebuilding the cryomodule. Prior to that, we moved it into the cryomodule test bunker for characterization, plasma processing and recharacterization. Part of the goal of the work was to continue to develop the procedures, software, and protocols for processing cryomodules in situ in the CEBAF accelerator. The other goal was to demonstrate the value of plasma processing a cryomodule, in situ.

Table 1: Accelerating Gradients Before and After Plasma Processing

Cav	E (MV/m) at 10 mR/hr			E (MV/m) at 100 mR/hr		
	Before	After	Delta	Before	After	Delta
1	16.2	21.6	5.4	18.4	23.8	5.4
2	13.0	13.8	0.8	14.4	15.3	0.9
3	11.3	12.6	1.8	12.3	14.1	1.8
4	10.1	10.3	0.2	11.0	11.6	0.6
5	10.1	11.2	1.1	11.0	12.3	1.3
6	5.7	8.4	2.7	6.3	9.3	3.0
7	9.8	13.6	3.8	10.7	14.8	4.1
8	9.1	10.6	1.5	10.7	11.7	1.0
Energy Gain (MeV)						
	59.7	71.5	11.8	66.3	79.0	12.7

Table 1 shows the before and after accelerating gradient values at the onset of FE (10 mR/hr) and at a dose rate of 100 mR/hr. The dose rate was measured with 10 Geiger Muller tubes located adjacent to the insulating vacuum vessel with one at each of the 7 waveguide ports, on top of the cryomodule in the center and one on each end of the cryomodule, next to the beam line. For all of the data the location which had the earliest field emission onset was used. The improvements ranged from 0.2 MV/m to 5.4 MV/m with a total energy improvement of 11.6 MeV for field emission onset and 12.6 MeV for operation at a dose rate of 100 mR/hr.

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. Out of the 8 cavities in the cryomodule 6 were able to operate at 18 MV/m before and after processing. Table 2 shows the reduction in radiation production for those six cavities. The average reduction on a cavity by cavity basis was a factor of 6.6.

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

Cav	Before Radiation (mR/hr)	After Radiation (mR/hr)	Reduction
1	9	0.04	0.4%
2	50	25	50%
3	1300	200	15.4%
5	2000	300	15%
7	4000	60	1.5%
8	150	13	8.7%
		Average	15.2%

SUMMARY

The status of the plasma processing program has been presented. We have a robust vertical testing program which makes use of an argon/methane plasma discharge in order to contaminate a cavity in a predictable manner. We are able to use this contaminated cavity to do experimental studies relating to processing recipes. Using these methods and keeping the cavity on the vertical test stand when we process it, we are able to complete a plasma process vertical test cycle per week. We were able to repeatably achieve a 4.5 MV/m improvement in field emission onset. We processed a cryomodule after it was removed from the accelerator and prior to it being rebuilt. We were able to achieve a 12.7 MeV improvement on that cryomodule. On a cavity by cavity basis this was an average improvement of 2.3 MV/m. We will be continuing to have an experimental program in the vertical test area as well as in our off-line system with the goal of improving the processing results. We are developing detailed plans for processing 3 cryomodules in situ in the CEBAF accelerator in the Spring of 2023.

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOYE5

REFERENCES

[1] 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, 2016. doi:10.1016/j.apsusc.2016.02.030

[2] M. Martinello *et al.*, "Plasma Processing for in-Situ field emission mitigation of superconducting radiofrequency (SRF) Cryomodules", Snowmass, 2021. doi:10.48550/arXiv.2203.12442

[3] 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

[4] M. Doleans, ORNL, personal communication, Jul. 2019.

[5] T. Powers, N. C. Brock, and T. D. Ganey, "In Situ Plasma Processing of Superconducting Cavities at JLAB", in *Proc. Of SRF'21,* East Lansing, MI, USA, Jun.-Jul. 2021, paper TUPTEV004. doi:10.18429/JACoW-SRF2021-TUPTEV004

[6] H. Padamsee, J. Knobloch, and T. Hayes, "Multicell field flatness", *RF Superconductivity for Accelerators*, New York, NY, USA, Wiley, 1999, pp 129-144.