CAVITY PROCESSING AND PREPARATION OF 650 MHz ELLIPTICAL CELL CAVITIES FOR PIP-II*

A. M. Rowe[†], S. Chandrasekaran, A. Grassellino, O. Melnychuk, M. Merio, D. Sergatskov
Fermi National Accelerator Laboratory, Batavia, IL, USA
T. Reid, Argonne National Laboratory, Lemont, IL, USA

Abstract

The PIP-II project at Fermilab requires fifteen 650 MHz SRF cryomodules as part of the 800 MeV LINAC that will provide a high intensity proton beam to the Fermilab neutrino program. A total of fifty-seven high-performance SRF cavities will populate the cryomodules and will operate in both pulsed and continuous wave modes. These cavities will be processed and prepared for performance testing utilizing adapted cavity processing infrastructure already in place at Fermilab and Argonne. The processing recipes implemented for these structures will incorporate state-of-the art processing and cleaning techniques developed for 1.3 GHz SRF cavities for the ILC, XFEL, and LCLS-II projects. This paper describes the details of the processing recipes and associated chemistry, heat treatment, and cleanroom processes at the Fermilab and Argonne cavity processing facilities. This paper also presents single and multi-cell cavity test results with quality factors above 5E10 and accelerating gradients above 30 MV/m.

INTRODUCTION

The Fermilab and Argonne SRF cavity processing and testing infrastructure is well-suited to provide superior RF performance for PIP-II R&D and production cavities of all types from the 62.5 MHz half-wave and 325 MHz single spoke to 650 MHz multi-cell elliptical cavities. In particular, the elliptical cavity processing infrastructure originally developed for 1.3 GHz cavities was easily adapted to 650 MHz elliptical cavities. Combining the flexible infrastructure with the experience gained processing and testing 1.3 GHz elliptical cavities for the various R&D programs and LCLS-II, resulted in cavity performance results in single and multi-cell 650 MHz elliptical cavities comparable to typical high Q0 and high gradient 1.3 GHz cavities but without the long R&D path.

This paper describes the major processing details developed for PIP-II 650 MHz elliptical cell cavities at the Fermilab and Argonne facilities. Electropolishing, heat treatment, cleanroom processing, and vertical test data are presented that demonstrate performance well above the required operating gradient E_{acc} = 17.7 MV/m and quality factor > 2.0 E10 at 2 °K for 650 MHz cavities.

ELECTROPOLISHING

Low-Beta EP Tool Adaptation

A second electropolishing (EP) system was commissioned at Argonne in 2011 for the processing of low frequency (72.75 MHz) quarter wave resonators (QWRs) for the ATLAS Intensity Upgrade (AIU) project [1]. Initially built for co-axial low-beta cavities, the tool was based on previous experience with the horizontal processing of 1.3 GHz elliptical cavities for the ILC R&D program which made for a natural transition to larger elliptical cavities, specifically 650 MHz single and five-cell cavities as seen in Figure 1 [2]. Due to the large radius of the 650 MHz cell, consideration was given to the cathode design. A fluted 1100 series aluminum cathode donut was implemented to increase the overall cathode surface area for better electropolishing in the equator region of the cavity. These cathode donuts are clam-shelled to the 1100 series aluminum cathode at the center of each cell.

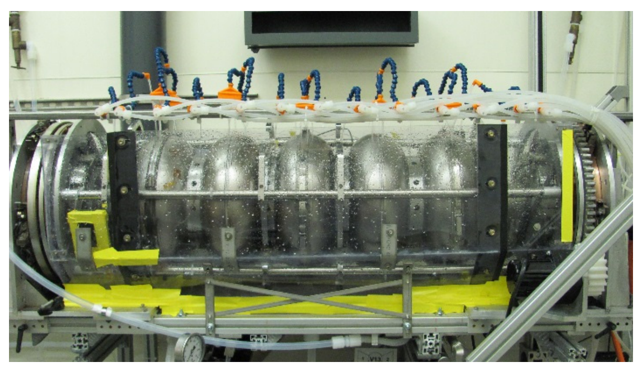

Figure 1: 650 MHz five-cell cavity EP with water cooling.

External Water Cooling

The addition of external water cooling improves process control and stability and minimizes temperature gradients across the cavity that result in non-uniform material removal. A 10 kW chiller is used to spray water through up to thirteen independently controlled spray heads made from standard machine coolant hoses. The total flow rate is up to 40 l/min for five-cell cavities. Each cooling line has its own throttle valve that allows for in-situ changes to the amount of cooling water flow needed at individual beam tubes, irises, and equators. Shields made of polycarbonate minimize splashing and protect the rotary bearings. A stainless steel drip tray underneath the cavity directs the water where it is pumped back to the chiller.

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† arowe@fnal.gov

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Process Measurement and Control

The EP parameters used on the 650 MHz cavities were developed from extensive experience on 1.3 GHz elliptical cell cavities. Using a constant voltage of 18 V, the cavities are rotated at 0.5 rpm with niobium surface temperatures controlled to <35 °C for bulk polishing and <30 °C for final light polishes [3]. The cavity surface temperatures are measured using K-type thermocouples connected to a waterproof enclosure that houses a wireless data acquisition transmitter powered by a battery backup. A Labview GUI monitors the cavity surface temperatures, voltage, current, electrolyte temperatures and flow. Labview also allows for direct control of chillers and power supply limits. Cavity surface temperatures are driven by the temperature of the acid inside the cavity, the external cooling water on the outside, and the electropolishing reaction heat generation. Typically, the acid entering the cavity is kept to <20°C and the external cooling water is used to drive the cavity surface temperature to the desired polishing temperature.

HEAT TREATMENT

The 650 MHz cavities are heat treated at 800 °C for 3 h, in ultrahigh vacuum (UHV), using a T-M Vacuum furnace. This furnace has the capability to nitrogen dope cavities [4]. The heat treatments are aimed at degassing hydrogen from the Nb bulk of the cavities. Although nitrogen doping is not yet the specification for PIP-II cavities, several cavities have been doped with nitrogen to examine the benefits. The process parameters from one such heat treatment of a 650 MHz 5-cell cavity with nitrogen doping at 800 °C is illustrated in Figure 2. The doping is done after 3 h have elapsed at 800 °C, by injecting nitrogen at 25 mTorr for 2 min, followed by a 6 min soak at 800 °C in UHV. The partial pressures of the residual gases in the furnace during the heat treatment indicate a large volume of hydrogen being outgassed during the heating.

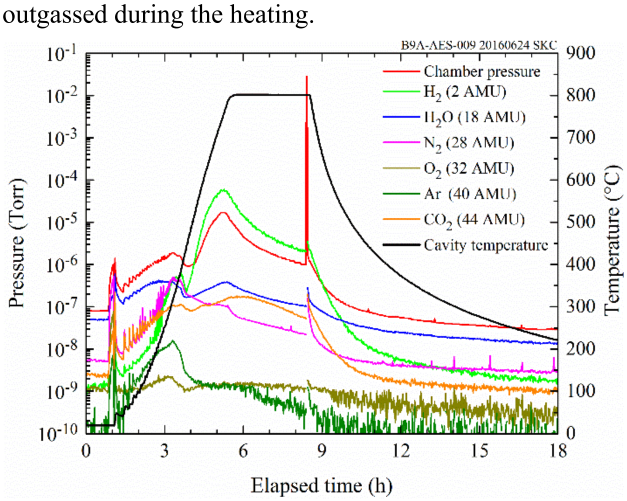

Figure 2: RGA plot of an 800 °C heat treatment with nitrogen doping of a 650 MHz 5-cell cavity.

CLEANROOM PROCESSING

Surface preparation activities in the cleanroom both for elliptical cavities and components, are tailored to minimize particulate contamination. The large elliptical 650 MHz cavities are cleaned and high pressure rinsed (HPR) using modified but similar processes employed for 1.3 GHz cavities. Components used for PIP-II 650 MHz cavities are constructed of the same materials and to the same specifications as for the 1.3 GHz cavities and so are prepared with the same care and similar procedures.

Cavity Cleaning and HPR

The 650 MHz multi-cell cavities for PIP-II are physically large (1.4 m long, 0.5 m diameter) and heavy (75 kg bare, 160 kg fully dressed). The goal of cleaning these 1.9 m^2 surface area cavities for PIP-II is to achieve similar surface fields (E_{acc} > 25 MV/m) achieved on 1.3 GHz cavities without field emission.

Cleaning cavities prior to high pressure rinsing includes ultrasonic cleaning in a 2% Liquinox bath in a high-power 44 W/l cleaning tank at a temperature 50 deg C for one hour. Following ultrasonic cleaning, the cavity is thoroughly rinsed by hand with low pressure deionized water. After hand rinsing, the exterior of the cavity is high pressure rinsed in an ISO5 cleanroom with a hand-held wand to help minimize particulate migration into the ISO4 area. The cavity is high pressure rinsed following electropolishing and before heat treatment or vertical test preparation.

HPR is performed using filtered (0.05 µm) deionized water at a pressure of 85 Bar (1250 psi). The quality of the deionized water is kept above a resistance of 18 MOhm/cm and a total organic carbon count below 10 ppb.

The HPR tool has a rotating wand (2 rpm) and translates the cavity vertically at a rate of 6 mm/min. Rinse heads were designed incorporate three 40 degree 4.2 l/min fan-jet nozzles angled to increase the water impact force on the shallow wall angled cells. The integrated spray dwell time at the iris surface is approximately 23.5 seconds for a complete five pass HPR cycle.

Component Cleaning

The level of care taken to clean the inside of the cavity is also taken with components attached to the cavity. Particulate cross contamination from flanges, seals, valves, or RF feethroughs to the cavity interior surface is likely if these components are not properly prepared.

The component cleaning process consists of the following steps: hot ultrasonic degreasing in a 2% Liquinox bath; deionized water rinsing; high-pressure hand deionized water rinsing; part drying in a ISO 4 environment; ionized high velocity nitrogen gas particle blow-off; component staging.

Ultrasonic cleaning of cavity peripherals should be performed with care, especially on components sensitive to certain detergents or the potentially damaging ultrasonic cavitation. For stainless steel, niobium, and niobium/titanium, 2% Liquinox detergent in a 50 °C US cleaning bath with a cleaning duration of a minimum of 15 minutes is used. Components made of other materials like copper (RF probe tips) and silicon bronze are cleaned using a 2% Citranox solution at 60 °C. The US cleaning process for sensitive components occurs in low-energy cleaners and only for a few minutes at a time. Vacuum seals, whether the typical ¼ hard copper conflat flange gaskets or AlMg diamond cross section seals, are cleaned by hand rather than in an ultrasonic cleaner or with manual HPR.

Hand high pressure rinsing of vacuum components, cavity exterior surfaces, and other objects introduced in the ISO4 cleanroom environment with filtered deionized water reduces the particle blow-off process after the components are dry. Immediately following hand HPR, the components are moved to the ISO4 area for drying.

The final particulate cleaning for each component occurs with ionized high velocity boil-off nitrogen gas. A 0.01 u µm membrane filter is installed before the ionized gas gun fed with a supply gas pressure of 5.5 Bar (80 psi) and a flow rate of 170 l/min (6 SCFM). Each component is blown off above an isokinetic sampling probe to a zero particle count of 0.5 µm size at a sampling rate of 75 l/min and a sample size of 10 liters. After each component is cleaned, the parts are carefully arranged on an assembly table in a way that minimizes operator movement during assembly.

Cavity Assembly and Evacuation

Mounting the components to the cavity occurs in two steps. The first assembly occurs after the first three-pass high pressure rinsing cycle is complete and the cavity has dried in the ISO4 environment on the high pressure rinsing tool for at least 12 hours. Each flange is mounted from the bottom, utilizing the top-to-bottom cleanroom air flow and gravity to move particles away from the open cavity. All components are assembled to the cavity with the exception of the bottom beamline flange and isolation valve. After the last two pass rinse, the bottom flange assembly is installed.

Evacuation is performed with a clean oil-free pumping system at a flow rate < 1 l/min to prevent particle migration in turbulent flow from the isolation valve back into the cavity. Though particles resident in the isolation valve will tend to move away from the cavity volume, slow pumping is still employed as a precaution. Once the cavity reaches a vacuum pressure of < 1e-06 mBar, a helium leak check and RGA scan are performed.

CAVITY PERFORMANCE

The efforts to implement the best SRF elliptical cavity preparation practices for 650 MHz cavities have yielded good early results. R&D and vendor qualification processing and testing on single cells resulted in accelerating gradients above 30 MV/m for both nitrogen doped and standard degassed and electropolished B=0.90 and B=0.61 cavities. Quality factors at 17.7 MV/m of nearly 7E10 were achieved in nitrogen doped cavities [5]. Single cell results are shown in Figure 3.

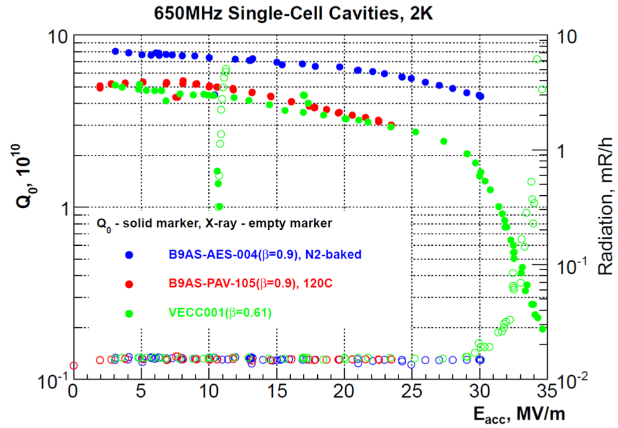

Figure 3: Single-cell 650 MHz cavity vertical test results.

Multi-cell processing and testing developed quickly following the successful single-cell results. Though quality factor and gradient optimization studies and final recipe development are not yet complete, five-cell test results to date are encouraging. The PIP-II specification for both accelerating gradient (17.7 MV/m) and quality factor (2.0E10) are well exceeded as shown in Figure 4.

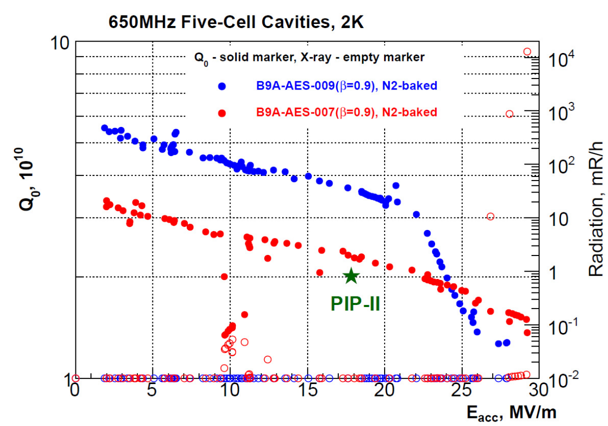

Figure 4: Five-cell B=0.90 650 MHz cavity test results.

CONCLUSION

Cavity processing development for the PIP-II project at Fermilab and Argonne for 650 MHz elliptical cavities has proceeded successfully. Single-cell 650 MHz cavities have achieved quality factors at 2 °K approaching 7E10 at operating gradient E_{acc} = 17.7 MV/m and are field emission free above 30 MV/m. Five-cell B=0.90 cavities have achieved quality factors above 3.5 E10 at operating gradient and are field-emission free above 25 MV/m. A continued effort is expected to finalize the PIP-II processing and testing recipes in the next twelve to eighteen months once additional testing statistics are obtained.

ACKNOWLEDGMENT

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