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PROGRESS TOWARD 2 K HIGH PERFORMANCE HALF-WAVE RESONATORS AND CRYOMODULE*

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Abstract

Argonne National Laboratory is implementing a novel 2.0 K superconducting cavity cryomodule operating at 162.5 MHz. This cryomodule is designed for the acceleration of 2 mA H^-/proton beams from 2.1 to 10.3 MeV as part of the Fermilab Proton Improvement Project-II (PIP-II). The 2.0 K cryomodule is comprised of 8 half-wave cavities operated in the continuous wave mode with 8 superconducting magnets, one in front of each cavity. In this paper we will review recent cavity results which demonstrate continuous-wave operated cavities with low-field residual resistances of 2.5 nΩ which achieve peak surface fields up to 134 MV/m and 144 mT, electric and magnetic respectively, with field emission onset fields greater than 70 MV/m in the production cavities following the prototyping effort.

INTRODUCTION

Argonne National Laboratory is building a superconducting half-wave accelerator cryomodule for the Proton Improvement Project-II (PIP-II) at Fermi National Accelerator Laboratory (FNAL). This cryomodule will accelerate a 2 mA H^- beam from 2.1 to 10.3 MeV for a new 800 MeV linac which will replace the existing 400 MeV machine [1, 2]. The cryomodule houses 8 162.5 MHz half-wave resonators (HWRs) and 8 superconducting solenoids, one in front of each resonator. The entire cold-mass will operate at 2.0 K and each of the HWRs is designed to provide up to 2.0 MV of effective voltage gain for beta = 0.11 H^- ions with less than 2 W of dynamic cryogenic load. In 2015 the cold test results of two prototype HWRs were presented showing low-field residual resistances of 2.5 nΩ with peak surface fields reaching 90 MV/m and 95 mT [3]. Since then the fabrication and processing of an additional 7 HWRs, referred to as production HWRs, ha been finished. 5 of the 7 production HWRs have been cold tested and 4 of those have exceeded the prototype HWR peak field performance. In this paper the production HWR RF performance parameters, results of cold testing and future plans will be discussed.

HALF-WAVE RESONATOR PROPERTIES

The need to couple 2 MV per resonator to an H^- beam with β=0.11 resonators operating at 162.5 MHz while reducing the peak surface fields and cryogenic losses (< 2 W) simultaneously and maximizing the shunt impedance determined the HWR design [4]. This was accomplished with an advanced geometry based on conical inner and outer conductors. The conical shape increases the volume over which the magnetic energy is stored decreasing the peak surface magnetic field and increasing the shunt impedance in a manner analogous to re-entrant elliptical-cell resonators [5]. This design is electromagnetically similar to recently commissioned quarter-wave resonators which have excellent online performance [6]. Table 1 gives the RF performance parameters for the HWRs. Figure 1 shows a finished HWR with an integral 304L stainless steel helium jacket.

The RF design described above includes 2 ports on each end of the resonator. These ports ensure that the aluminium electropolishing cathodes remove material from the cavity surface as evenly as practical and also provide good drainage with sufficient high pressure water rinse wand access for thorough low-particulate cleaning.

Figure 1: A 162.5 MHz, β = 0.11, niobium half-wave resonator enclosed in an integral stainless-steel helium vessel. The cavity is 125 cm end-to-end.

Table 1: HWR RF Parameters

Parameter	Value
Frequency	162.5 MHz
Beam Aperture	33 mm
β	0.112
Effective Length (βλ)	20.7 cm
E_{peak}/E_{acc}	4.68
B_{peak}/E_{acc}	5.02 mT/(MV/m)
$G = R_sQ$	48.2 Ω
R_{sh}/Q	271.7 Ω

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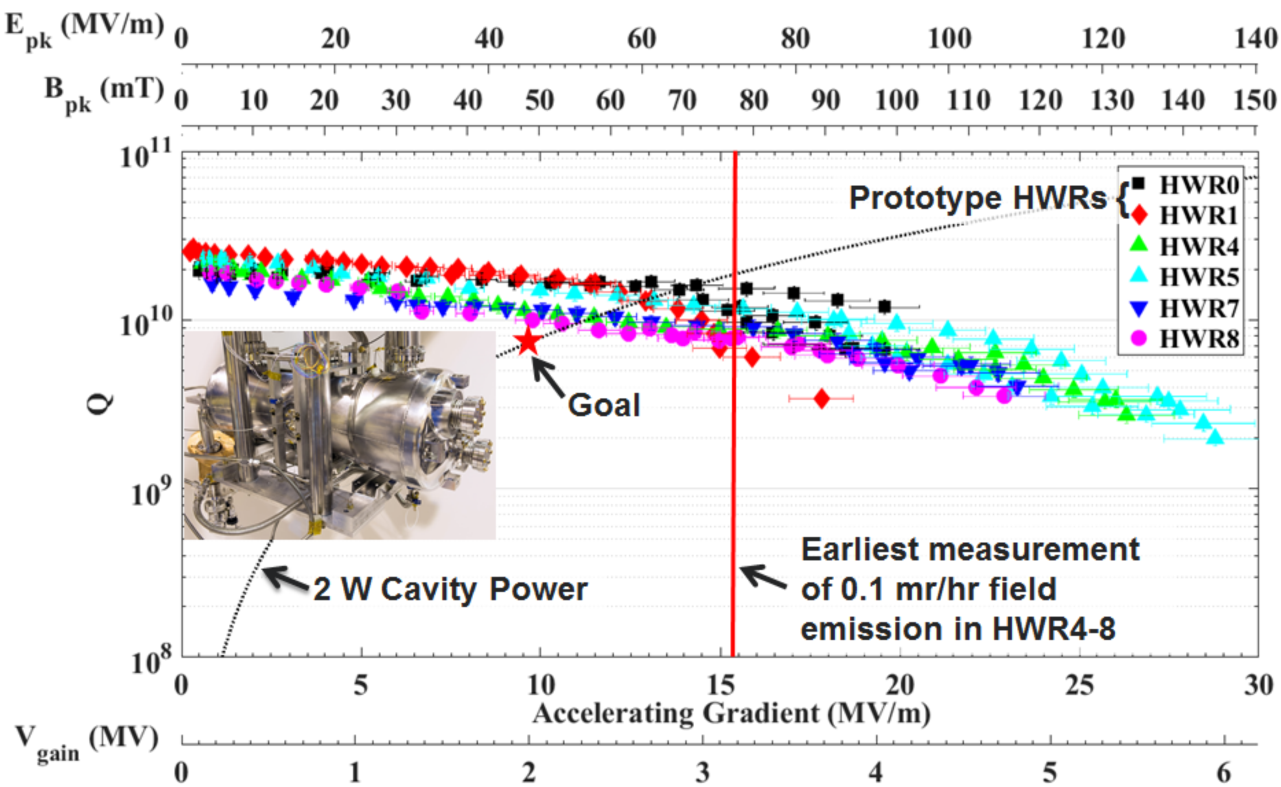

Figure 2: The cavity quality factor's dependence on operating gradient at 2.0 K for 6 of the 9 HWRs. The two prototype cavity results from [3] are included. The peak surface fields and total voltage gain for a β =0.11 synchronous particle are included on separate axes for reference.

2.0 K TEST RESULTS

Figure 2 shows the 2.0 K RF performance measured for the 2 prototype [3] and 4 production HWRs. The HWR processing was performed after all fabrication was finished and followed the procedure used for the very successful ANL 72.75 MHz quarter-wave resonators [6]. After the installation of the helium jacket, the inside of the niobium cavities were given a light BCP (20 µm). The BCP was performed by installing the HWRs in the Argonne low-β EP tool [7] located in the joint ANL/FNAL Superconducting Cavity Surface Processing Facility at ANL, where they were filled 60% in the horizontal orientation with BCP and constantly rotated at 1/2 RPM throughout the procedure. After the BCP the HWRs received a heavy (120 µm) electropolish using the same tool.

To degas the interstitial hydrogen from the bulk niobium, the HWRs were baked at 625^{0}C for 10 hours in one of either Fermilab's or Brookhaven National Laboratory's high vacuum furnaces. All bake cycles finished with the partial pressure of hydrogen less than 5e-7 torr at 625^{0}C. In all cases the hydrogen degassing was followed by a light electropolish (20 µm).

One of the HWRs suffered from an electrical arc during the initial bulk EP and is currently awaiting cryogenic testing with second sound defect location hardware to determine the best course of action for resonator repair.

Prior to testing and after polishing the cavities were ultrasonically cleaned in a 2% Alconox and 98% high-purity water solution for 1 hour and rinsed thoroughly. High-pressure high-purity water rinsing was performed through all ports of the cavities and on all of the parts used in the low-particulate assembly of the cavities for testing [8]. After assembly the cavities were evacuated and kept under vacuum for the remainder of the testing. No 120^{0}C bake was performed after the final 20 µm electropolish.

Upon cooling to liquid helium temperatures and with very little low-level multipacting conditioning, typically less than 10 minutes, the performance shown in Figure 2 was measured for all resonators. All data points shown were measured in the continuous wave mode. There was no observable field emission, next to the test cryostat on the inside of the test cave, up to an accelerating gradient of 15 MV/m for HWR0 and up to 12 MV/m for HWR1, the two prototypes. The production HWRs showed reduced levels of field emission with the earliest detection of field emission occurring at a peak surface electric field of 72 MV/m. Figure 3 shows the results for HWR5 with the measured field emission overlaid. These results are typical for HWR4-8 and high field cw conditioning with 200 W did not change the resonator performance in all cases. All HWRs have exceeded the design goal of < 2 W of dynamic 2.0 K cryogenic load at 2 MV per resonator, giving the end user, FNAL, ample margin in operation.

Figure 4 shows the performance history for HWR4 which required additional chemical processing after a

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discharge in the coupler during the first test contaminated the inside RF surface with either indium or copper. After this test the resonator was tested again after additional ultrasonic cleaning and HPR, which did not improve performance to the design goal. Only after performing an additional 20 µm BCP did the resonator exceed the design goal. It is important to note that the final process was BCP and not EP, and still HWR4 performs at the level of the other resonators which received final light EP.

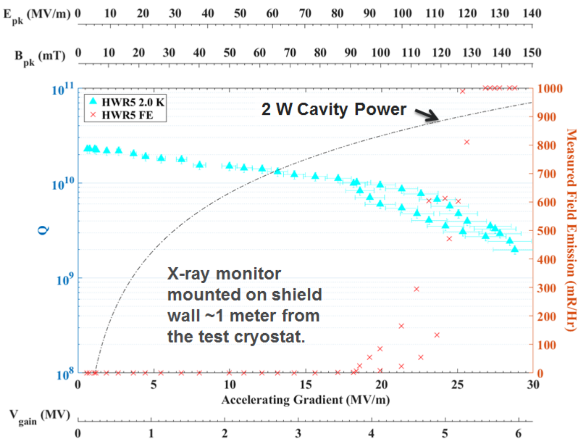

Figure 3: HWR5 2.0 K performance with measured X-ray intensities charactering the resonators field emission.

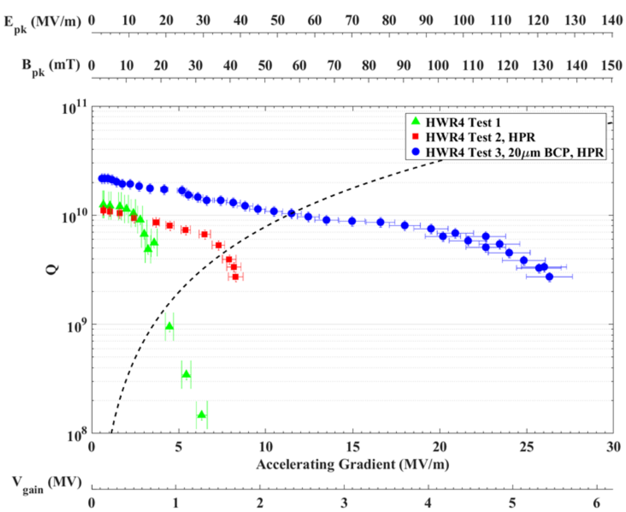

Figure 4: HWR4 2.0 K performance measured at three points throughout processing. During the first test the coupler had a discharge which contaminated the inside surface of the resonator.

CLOSING REMARKS

All 9 of the HWRs have been fully processed. 2 HWRs remain to be tested at 2.0 K, which will be finished in the upcoming months. After successfully testing the last 2 HWRs the cryomodule assembly will begin. Preliminary assembly of the cryomodule finished in 2017 with the successful demonstration of the cryogenic alignment system and measurement of < 60 W cryogenic load to the 70 K radiation shield of the cryomodule. Figure 5 shows the test assembly of the accelerator cold-mass hanging from the lid of the cryomodule prior to installing the lid on the cryomodule box.

Figure 5: The HWR cold-mass hanging from the lid prior to installing on the lower vacuum vessel. This was a “mock” assembly to practice for the final assembly and to verify that the components go together.

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