ACHIEVING HIGH PEAK FIELDS AND LOW RESIDUAL RESISTANCE IN HALF-WAVE CAVITIES*

Z.A. Conway#, A. Barcikowski, G.L. Cherry, R.L. Fischer, S.M. Gerbick, C.S. Hopper, M.J. Kedzie, M.P. Kelly, S-h. Kim, S.W.T. MacDonald, B. Mustapha, P.N. Ostroumov, and T.C. Reid
ANL, Argonne, IL 60439, USA

Abstract

We have designed, fabricated and tested two new half-wave resonators following the successful development of a series of niobium superconducting quarter-wave cavities. The half-wave resonators are optimized for beta = 0.11 ions, operate at 162.5 MHz and are intended to provide up to 2 MV effective voltage for particles with the optimal velocity. Testing of the first two half-wave resonators is complete with both reaching accelerating voltages greater than 3.5 MV with low-field residual resistances of 1.7 and 2.3 nΩ respectively. The intention of this paper is to provide insight into how Argonne achieves low-residual resistances and high surface fields in low-beta cavities by describing the cavity design, fabrication, processing and testing.

INTRODUCTION

Fermi National Accelerator Laboratory (FNAL) is building the front-end of a new 800 MeV accelerator as part of the Proton Improvement Project-II (PIP-II) [1, 2]. The first superconducting cryomodule in this front-end is being built at Argonne. It contains 8 162.5 MHz half-wave resonators (HWRs) and 8 solenoids, one in front of each cavity, for the acceleration of an H^- beam from 2.1 to 10.3 MeV. These cavities will operate at 2.0 K and are designed to provide up to 2.0 MV of effect voltage gain for beta = 0.11 H^- ions with less than 2 W of cryogenic heating per cavity. The first two HWRs are now finished and have been cold tested. The aim of the work presented here is to describe the fabrication, processing and test results for two prototype HWRs to highlight the peak fields and low residual resistance achieved in cold testing. In the following we discuss the design, processing and cold test results for two 162.5 MHz HWRs optimized for particle velocities of β ~ 0.11. Figure 1 shows the HWR and Figure 2 shows the cold testing results.

CAVITY SPECIFICS

Design and Fabrication

The HWR design was constrained to provide 2 MV per cavity at 162.5 MHz with an optimum β = 0.11 with a 33 mm aperture. Given these constraints the RF optimization focused on reducing the cryogenic load and the peak electromagnetic surface fields while maximizing the shunt impedance [3]. This was accomplished with an advanced design using 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 [4]. This design is electromagnetically similar to recently commissioned quarter-wave resonators which have excellent online performance [5]. Table 1 gives the RF performance parameters for the HWR.

The RF design described above includes 2 ports on each end of the cavity. These ports are located to ensure that the cavity 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.

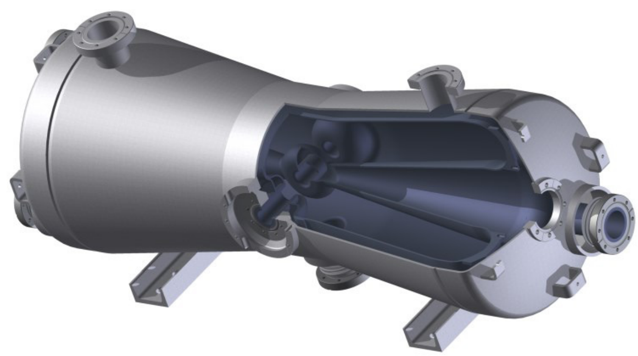

Figure 1: Cut away view of the 162.5 MHz, β = 0.11, niobium half-wave resonator enclosed in an integral stainless-steel helium vessel. The cavity is 125 cm end-to-end.

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

*This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract number DE-AC02-06CH11357, and the Office of High Energy Physics, under contract number DE-AC02-76CH03000. This research used resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility.
zconway@anl.gov

ISBN 978-3-95450-178-6

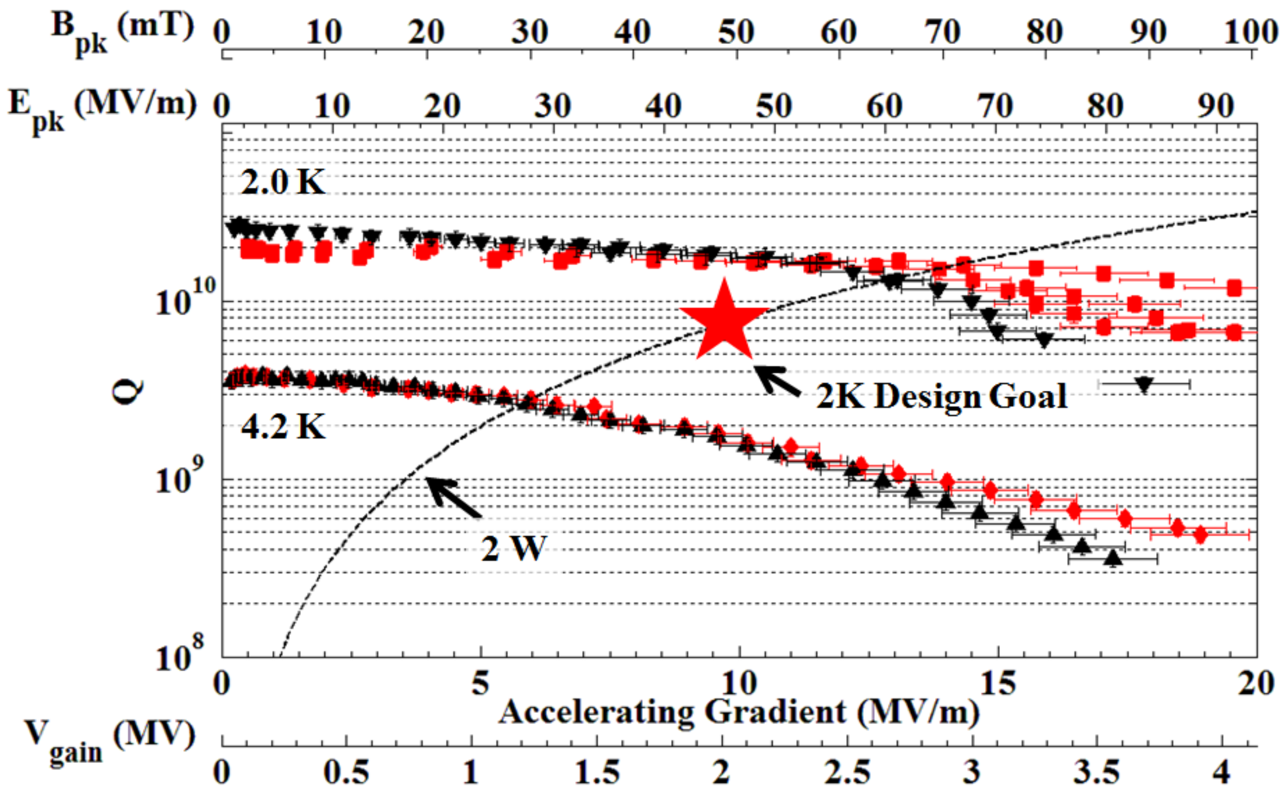

Figure 2: Cavity quality factor, Q, vs the accelerating gradient for the two HWRs are shown for both 2.0 and 4.2 K operation. The red data points are HWR0 and the black data points are HWR1. The peak surface fields and total voltage gain for a synchronous particle are included on separate axes for reference.

The cavities were formed from high purity (RRR 250-280) 1/8 inch thick sheets and rods (beam ports and center conductor drift tube). The only exceptions are the cavity coupling ports located on the ends of the cavity and at 90^0 to the beam ports. This niobium was machined from low-RRR (~25) round bar stock. All of the niobium parts formed from sheet was die formed. The center and outer conductors were formed in halves and seam-welded together. The cavity re-entrant noses and doubler plates were assembled into a single weldment and then welded into the outer conductors. Prior to final closure welding all surfaces are inspected and hand-polished with 120, 240, 400 and then 600 grit sandpaper to remove imperfections.

All parts receive a pre-weld etch in Buffered Chemical Polish (BCP, 1:1:2, 48% HF, 70% nitric acid, and 85% Phosphoric acid, all ACS grade purity) for at least 5 minutes. This is done to not only clean the parts prior to welding but to remove the recast layer left on the parts after electrostatic discharge machining. This etch is done by either submerging the entire part in BCP or by submerging the edges to be welded to a level sufficient to cover the melt and heat-effected zone regions. All welds were electron beam welds performed at pressures below 5e-5 torr, and the welded parts were cooled in vacuum for at least 45 minutes and, subsequently, in a nitrogen atmosphere of 20 torr for an additional 20 minutes prior to venting to atmosphere. The cavity parts were typically 85^0C or less upon removal from the electron beam welder.

External to the niobium cavity is an integral stainless steel helium jacket which was formed from 0.187" thick sheet of joint certified 304/304L material while the portions of the jacket around the beam ports were machined from solid 304 stainless steel and welded into the formed portions of the cavity jacket. The liquid helium coolant is contained within the helium jacket and was designed to be compliant with Section VIII, Division 2, Part 5 of the ASME Boiler and Pressure Vessel Code.

Processing

HWR processing followed the procedure used for the very successful quarter-wave cavities recently produced at Argonne [5]. After the fabrication of the helium jacket was finished, 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 [6], where they were filled 60% with BCP and constantly rotated throughout the procedure. After the BCP the HWRs received a heavy (120 µm) electropolish in the same tool. To degas the hydrogen dissolved in the bulk niobium they were degassed at 625^0C for 10 hours in one of Fermilab's high vacuum furnaces. This bake was followed by a light electropolish (20 µm) in both cases.

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. 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.

CAVITY TEST RESULTS

Upon cooling to liquid helium temperatures and with less than 5 minutes of conditioning low-level multipacting, the performance shown in Figure 2 was measured for both cavities. Both cavities were operated continuous wave at all accelerating gradients shown. 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 the first cavity (HWR0) and up to 12 MV/m for the second cavity (HWR1). At the nominal design voltage of 2 MV at 2.0 K the measured RF losses were 0.8 and 0.9 watts respectively. While the residual RF surface resistance was 3 nΩ and less prior to the onset of field emission for both cavities, Figure 3.

HWR0 was stable at 2 K with a peak surface electric field of up to 91 MV/m. At this level an emitter processed and the cavity Q dropped from 1.2×10^{10} to 6.7×10^{9} at E_{peak} = 91 MV/m. Following this event the field emission onset level was 11 MV/m. Processing the cavity with 100 W of RF power for less than 5 minutes recovered the Q up to fields of 15 MV/m to pre-emitter-processing levels but did not improve higher field performance.

Neither cavity was limited by quench during these cold tests. A 200 W RF amplifier was used for testing and this power was insufficient to condition either cavity to operating levels above those shown in Figure 2. In the future, it will be good to try high power conditioning to determine what, if any, defect limits there may be in these cavities.

SUMMARY

The linac development group at Argonne National Laboratory has developed and tested the first two half-wave resonators for the PIP-II project at FNAL. The HWRs operate at 162.5 MHz, have an optimal β = 0.11 and a beam aperture of 33 mm. This builds upon earlier work on quarter-wave resonators at Argonne which exhibit excellent online performance in a cryomodule in the ATLAS accelerator at Argonne [5]. The HWR cold test results show state-of-the-art high-field performance with low residual surface resistance, 4 nΩ, at peak surface fields of 91 MV/m electric and 98 mT magnetic for the first cavity tested. Both HWRs operate field emission free up to accelerating gradients of 12 MV/m and operates with RF losses of less than 0.9 W at the design voltage of 2.0 MV, much less than the 2 W budgeted for online operation. This work constitutes a successful demonstration of the fabrication, processing and cleaning of HWRs.

Eight more half-wave resonators are in various stages of production. The first two of these cavities are being prepared for testing in late 2015. Results here will be shared when available.

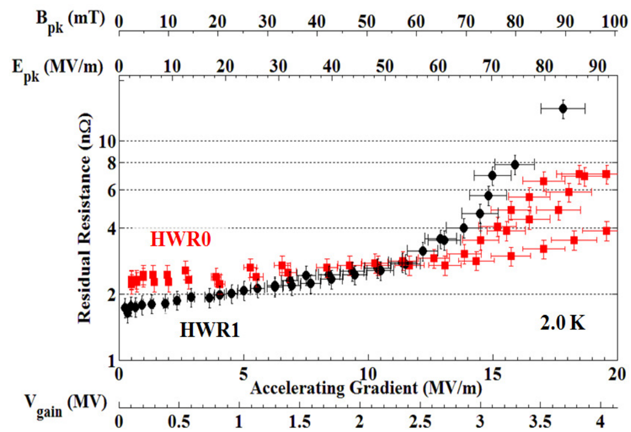

Figure 3: Residual resistance measured for both HWRs.

ACKNOWLEDGMENT

We acknowledge the contributions of Advanced Energy Systems who was responsible for the niobium forming techniques, tooling and much of the machining which was extensive. Also, thanks to Ted Hejna of Sciaky, Inc., for performing the electron beam welding.

A. Rowe and M. Merio of FNAL provided much help with the hydrogen degassing of these cavities prior to cold testing.

REFERENCES

[1] S. Holmes ed, “Proton Improvement Plan-II,” projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232, December 2013.

[2] V.P. Yakovlev, “SRF Development for PIP-II: Status and Challenges,” TUAA05, these proceedings.

[3] B. Mustapha et al, “A Ring-shaped Center Conductor Geometry for a Half-wave Resonator,” in the Proceedings of IPAC 2012, New Orleans, Louisiana, Pg. 2289 (2012).

[4] V.Shemelin, H.S. Padamsee and R.L. Geng, “Optimal Cells for TESLA Accelerating Structure,” NIMA, **496**, p. 1-7 (2003).

[5] M. Kelly et al, “Commissioning of the 72 MHz Quarter-wave Cavity Cryomodule at ATLAS,” TUPP002, these proceedings, LINAC 2014, Geneva, Switzerland (2014).

[5] M. Kelly et al, “Low Beta Cavity Development for an ATLAS Intensity Upgrade,” in the Proceedings of SRF 2013, Paris, France, Pg. 850 (2013).

[6] S. Gerbick et al, “A New Electropolishing System for Low-Beta SC Cavities,” in the Proceedings of SRF 2011, Chicago, Illinois, Pg. 576 (2011).

ISBN 978-3-95450-178-6