FIRST EXPERIMENTAL RESULTS FOR THE SUPERCONDUCTING HALF-WAVE RESONATORS FOR PXIE*

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Abstract

The first superconducting niobium half-wave resonator operating at 162.5 MHz for the FNAL PIP-II project is complete and this paper reports the cold test results. The half-wave resonator cavities are optimized to accelerate protons/H^- from 2 to 10 MeV and build upon optimized electromagnetic designs and processing techniques developed at Argonne for the Intensity Upgrade of the ATLAS superconducting heavy ion accelerator.

INTRODUCTION

Fermi National Accelerator Laboratory (FNAL) is pursuing an ambitious plan to modernize the on-site accelerator infrastructure to provide high-intensity proton beams of >1.2 MW at 120 GeV [1], with powers approaching 1 MW at energies down to 60 GeV. The first phase of this plan was the recently completed upgrades to the Recycler and Main Injector synchrotrons for the NOνA experiment. The next phase, the Proton Improvement Plan (PIP-II), includes improvements to the existing Linac aimed at supporting higher intensity beam operations by enabling 15 Hz beam operations, a 50% increase in delivered protons per pulse, raising the booster energy from 400 to 800 MeV and requiring that all of the new hardware must be upgradable to continuous-wave operation in the future. These demanding requirements can be met by replacing the existing 400 MeV injector with a new 800 MeV superconducting linear accelerator injecting into the existing Booster synchrotron.

The new 800 MeV accelerator has a superconducting cryomodule containing 8 half-wave resonators (HWRs) and 8 solenoids for the acceleration of an H^- beam from 2.1 to 10 MeV. This cryomodule will be commissioned as part of a prototype front end accelerator demonstration experiment referred to as PXIE, the Project-X Injector Experiment [2]. The aim of the work presented here is to demonstrate the viability of operating HWRs in the first superconducting accelerator cryomodule of PXIE by presenting the cold test results for the first prototype.

For details of the HWR design, see reference [3], which reviews the RF optimization. In the following we discuss the design, processing and cold test results for a 162.5 MHz HWR optimized for particle velocities of $\beta \sim 0.11$.

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CAVITY FABRICATION

Design and Construction

HWR operation is proposed to be 1.7 MV of voltage gain per cavity at 2 K. The design was constrained to provide a 162.5 MHz HWR of optimum $\beta = 0.11$ with a 33 mm aperture. Given these constraints the RF optimization focused on minimizing the cryogenic load and the peak electromagnetic surface fields simultaneously. This was accomplished with an advanced design using conical inner and outer conductors. This design is electromagnetically similar to recently commissioned quarter-wave resonators which have excellent online performance [4]. The cavity is 125 cm from end-to-end and 41 cm in diameter at its largest. Table 1 gives the RF performance parameters for the HWR.

Figure 1: The 162.5 MHz, $\beta = 0.11$, 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
β	0.112
Effective Length ($\beta\lambda$)	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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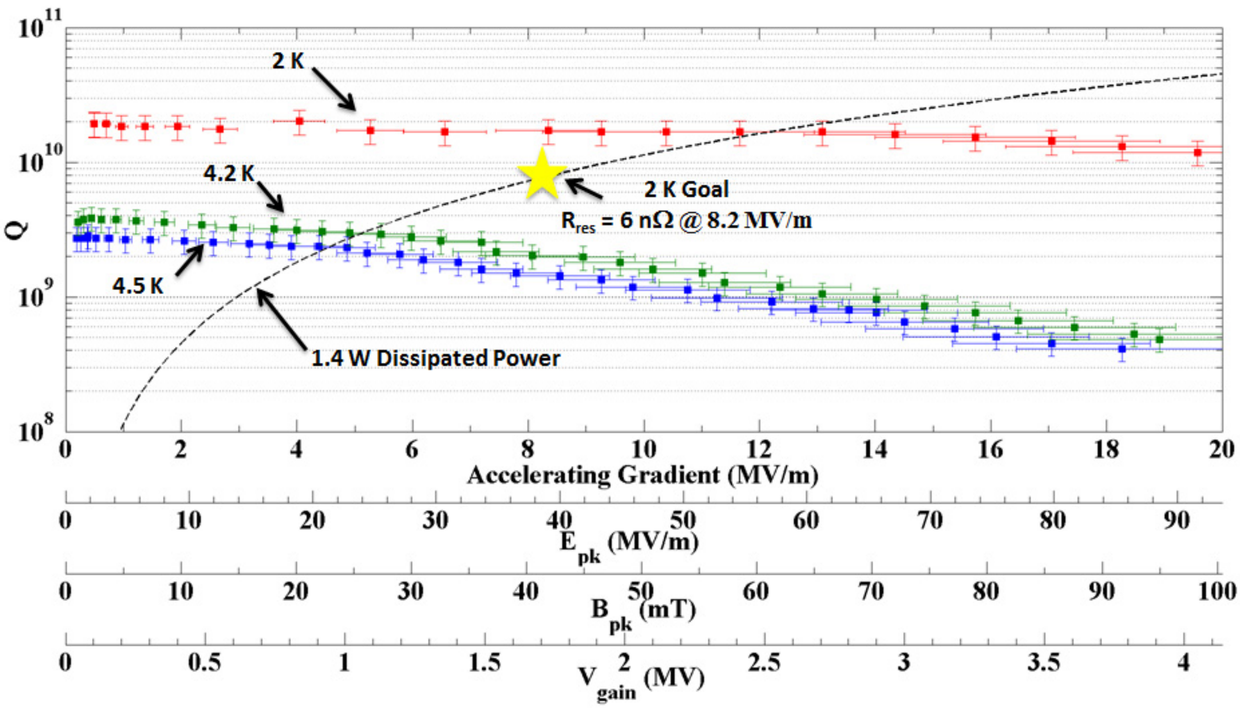

Figure 2: Cavity quality factor, Q, vs the accelerating gradient. The peak surface fields and total voltage gain for a synchronous particle are included for completeness.

The cavity was 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. 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. 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. Figure 1 shows the helium jacketed HWR.

Tuning and Processing

Tuning was performed when four major subassemblies of the cavity were complete: the two toroid end groups, the center conductor and the outer conductor. Tuning was accomplished by clamping the four sections together, using a thin layer of high purity indium wire in the seams between each of the major subassemblies, and the RF eigenfrequency was measured. The frequency was then brought to the design value by symmetrically machining the ends of the inner and outer conductors to reduce the length of the half-wave resonant cavity. It is important to note that the cavity was initially fabricated to be longer than the design by 0.110 inches per side and 0.100 inches were actually removed in tuning.

Prior to all welding the niobium parts were etched 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 up but to remove the recast layer left on the parts after electrostatic discharge machining (EDM).

HWR processing followed the procedure used for the very successful quarter-wave cavities recently produced at Argonne [5]. After the fabrication of the entire cavity, the inside of the niobium cavity was given a light BCP (~20 micrometer). The BCP was performed by installing the HWR in the Argonne low-β EP tool [6] and was constantly rotated throughout the procedure. After the BCP the HWR received a heavy (~120 micrometer) electropolish in the same tool, To degas the hydrogen dissolved in the bulk niobium the cavity was degassed at 625^0C for 10 hours in one of Fermilab's high vacuum furnaces. This bake was followed by a light electropolish (~20 micrometers).

After polishing the cavity was 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 cavity and on all of the parts used in the low-particulate

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assembly of the cavity. After assembly the cavity was evacuated and kept under vacuum for the remainder of the testing. No 120^0C bake was performed after the electropolishing of this cavity.

CAVITY TEST RESULTS

Cavity Quality Factor

Upon cooling to liquid helium temperatures and a few minutes of conditioning low-level multipacting, the performance shown in Figure 2 was measured. The cavity was 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. At the nominal design gradient of 8.2 MV/m at 2 K the measured RF losses were 0.68 watts, corresponding to 0.4 watts per MV of accelerating potential.

The cavity 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 began at 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.

The cavity was not limited by quench during this cold test. An ~200 W RF amplifier was used in the testing of this cavity and this power was insufficient to excite the cavity further after the emitter conditioning described above. In the future, it will be good to try high power conditioning to determine what, if any, defect limits there may be in this cavity.

Mechanical Properties

The Lorentz detuning was measured to be – 1.8 Hz per $(MV/m)^2$. Measurements of the cavity frequency, averaged for 2 seconds, were measured at several different field levels. Figure 3 shows the data points used for calculating the Lorentz detuning factor.

The shift of RF frequency caused by changing the pressure of helium in the integral stainless steel jacket was found to be +10.2 Hz/torr, very close to the value of +5.4 Hz/mbar simulated with ANSYS Multiphysics [7].

SUMMARY

The linac development group at Argonne National Laboratory has developed and tested the first production quality prototype half-wave resonator. This cavity operates at 162.5 MHz, has a β = 0.11 and a beam aperture of 33 mm. This builds upon earlier work on quarter-wave resonators at Argonne and has led to the development of new tuning, fabrication and processing techniques which exhibit excellent online performance in a cryomodule in the ATLAS accelerator at Argonne. The cold test results show state-of-the-art high-field performance with low residual surface resistance, 4 nΩ, at the highest fields: 91 MV/m peak surface electric and 98 mT peak surface magnetic fields. The cavity operates field emission free up to an accelerating gradient of 15 MV/m and operates with RF losses of 0.68 W at the design voltage of 1.7 MV, much less than the 1.4 W budgeted for online operation. This half-wave resonator work constitutes a successful demonstration of the work which goes into the fabrication, processing and assembly of this cavity. Eight more half-wave resonators are in various stages of production and test results will be presented when available.

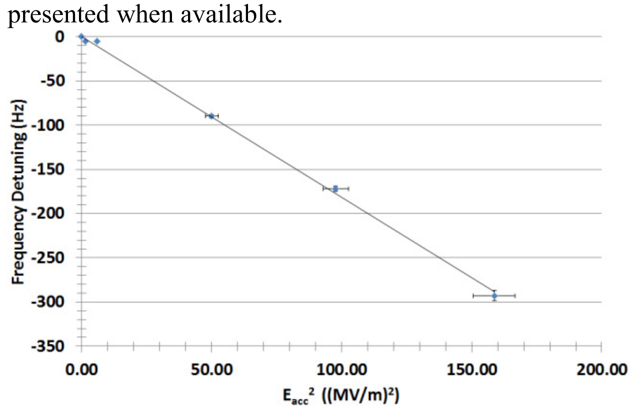

Figure 3: Measured detuning of the HWR verse the square of the accelerating gradient. The Lorentz detuning coefficient is -1.8 Hz/$(MV/m)^2$.

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