COLD TESTING OF SUPERCONDUCTING 72 MHz QUARTER-WAVE CAVITIES FOR ATLAS

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Abstract

A set of seven 72 MHz β=0.077 superconducting quarter-wave cavities for a beam intensity upgrade of the ATLAS heavy-ion accelerator has been completed. Cavities have been fabricated using lessons learned from the worldwide effort to push the performance limits for niobium cavities close to the fundamental limits. Key developments include the use of electropolishing on the completed cavity. Polishing parameters, including temperature, are better controlled compared to the standard horizontal electropolishing systems for elliptical cavities. Wire EDM, used instead of traditional niobium machining, looks well suited for preparing weld joints that are, with respect to quench, defect free. Hydrogen degassing at 625 C has been performed after electropolishing, removing the need for fast cool down in with 2 K or 4 K operation. Tested cavities have useful accelerating voltages of >3 MV/cavity at 4 K, as for ATLAS, and 5 MV or more per cavity at 2 K with B_{PEAK}>130 mT in 3 of 4 cases.

INTRODUCTION

The essential components of the ATLAS Efficiency and Intensity Upgrade [1] are a new CW radio frequency quadrupole injector and one new cryomodule of 7 SC cavities for β=0.077, scheduled to replace three existing cryomodules of split-ring resonators in the middle portion of the ATLAS SC ion linac. This upgrade follows upon the 2009 β=0.15 ATLAS Energy Upgrade cryomodule, presently the world leading cryomodule for low velocity ions, providing 14.5 MV accelerating voltage over 4.5 meters.

The new cryomodule will nominally provide 17.5 MV of accelerating potential at a lower beta of 0.077 in a 5 meter cavity string (see Figure 1). ATLAS beam transport efficiency for both stable and radioactive ion beams will be improved dramatically by increasing overall acceptance and reducing emittance growth inherent in the split-ring designs.

Figure 1: Initial mock up of the 72 MHz cavity clean room assembly.

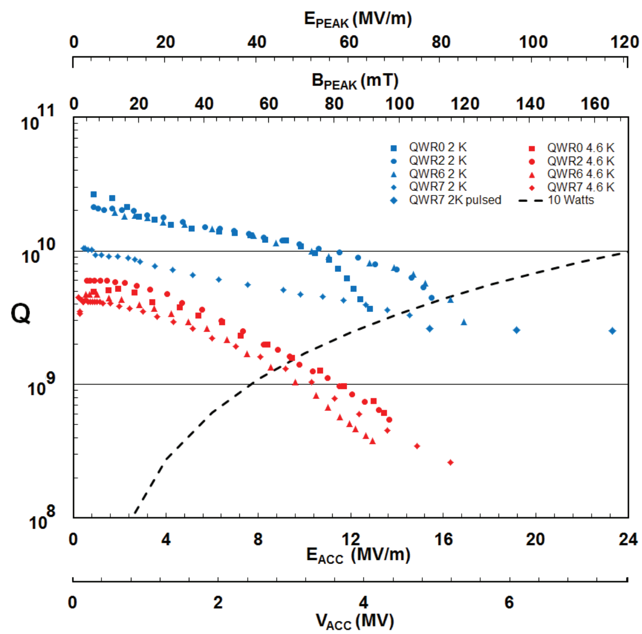

Figure 2: Quality factor versus accelerating gradient, voltage and surface fields at 2 and 4 K (l_{eff}=βλ=0.32m)

The planned cavity operating voltage of V_{ACC}=2.5 MV/cavity is roughly two times higher than for the present state-of-the-art at this beta, however, cavities and subsystems, including power couplers and cryogenics are all designed for operation with at least V_{ACC}~3 MV/cavity. Several improvements have been made since 2009 to achieve this performance, however, the two critical pieces are the improved rf design [2] and the unique capability to electropolish complete quarter-wave cavity/helium jacket assemblies [3].

CAVITY PERFORMANCE

Cold tests at 2 K and 4 K for four out of eight new 72 MHz cavities are complete and test results are shown in Figure 2. Seven of these cavities will be installed into ATLAS as part of the intensity upgrade and the eighth is for R&D and intended to advance the performance for this class of cavity [4]. Of the seven ATLAS cavities, four will be tested individually in the ANL test cryostat while the remaining three will be tested in the full cryomodule before installation into the ATLAS beamline. If a cavity requires a second round of cleaning, it can be removed

Table 1: Measured 72 MHz cavity performance characteristics

Quarter-wave number	0	2	6	7
Quench field (mT)	98	130	153	>165
R_{RES}^{*} (nΩ)	1.0	1.2	1.2	2.5
Field emission onset# (MV/m)	37	74	74	77

*extracted from low field data at 2 K
#value of E_{PEAK}

from the cryomodule string using the previously developed up-to-air system [5].

Electropolishing

A key processing step for the cavities was the heavy, 150 μm, electropolishing on the complete cavity. Two separate rounds of polishing are performed. First, after fabrication, the cavities were electropolished on consecutive days, removing 65 μm of niobium each day. Total polishing time was about 12 hours. The cavities were then baked under vacuum at Fermilab for 14 hours at 625°C in order to degas hydrogen. Last, the cavities were returned to Argonne for a final light 20 μm electropolish.

Fundamentally, the ANL low-beta cavity electropolishing system and associated polishing parameters are similar to those for horizontal systems used with 1.3 GHz cavities for the global international linear collider effort. There is one major improvement, however. Since quarter-wave cavities do not require field flatness tuning or direct access to the niobium surface after polishing, final heavy electropolishing can be performed with the complete cavity with liquid helium jacket. The helium jacket is used to directly cool the niobium surface with chilled (22+/-0.5 °C) water in order to maintain a stable and uniform temperature over the entire cavity surface. As for elliptical cells, the cavities are rotated during the procedure at a speed of 1 rpm, however unlike with most e-cells, the maximum temperature on the niobium surface never rises above 32°C at any time during the rotation period.

4 Kelvin Performance

In ATLAS cavities are operated with 4.5 K helium from the ATLAS refrigerator. The nominal accelerating gradient is 7.9 MV/m (l_{eff}=βλ=31.75 cm) or 2.5 MV/cavity with a quality factor of $Q=1x10^9$ and a corresponding total surface resistance of 26 nΩ. At least 10 Watts of cryogenic cooling per cavity will be available.

In four cavities tested so far, achieved cw cavity accelerating gradients at 4.6 K range between E_{ACC}=12.4-16.2 MV/m, or double the requirement for ATLAS. Most cavities had approximately 3 hours of low-level (E_{ACC}=0-1.5 MeV) multipacting conditioning and one half to 1 hour of short pulse conditioning with 4 kW peak power in order to achieve the measured performance shown in Figure 2. Based on recent cavity results for Spiral-2 [6], an 'in-situ' bake at 110-120°C for 48 hours was performed for QWR0 by circulating warm helium gas through the cavity helium vessel. In this case, cold testing before and after showed no measureable difference from baking. This is not considered to be definitive since the temperature variations of 10°C both in time and over the cavity surface were larger than desirable.

2 Kelvin Performance

ANL is also pursuing the developments needed in order to demonstrate practical 2 K operation, the likely operating mode for future large SRF linacs. The high practical cavity field gradients possible at 2 K, combined with the compact lattice of the Argonne cryomodule design, can provide 'real-estate' gradients of 7 MV/m (at B_{PEAK}=120 mT), or about 2-3 times higher than for today's state-of-the-art at 4 K. This would make feasible the construction of a compact proton linac that would be extremely attractive for the next generation of high-power accelerators in areas of energy, national security, and medicine.

The four cavities tested to date support this goal. Cavities reach magnetic surface fields in the range B_{PEAK}=98-165 mT. In two of four cases, the thermal magnetic breakdown was extracted from pulsed 5% duty cycle measurements in order to limit x-ray radiation at very high fields. These points are not included on the Q curve for QWR's 2 and 6. The lowest quench at 98 mT for QWR0 is due to breakdown on the central conductor, based on second sound measurements. The location corresponds to that of a known welding defect, where contamination on the center conductor weld preparation is strongly suspected. At the other end, the QWR7 never quenched (B_{PEAK}=165 mT) and was administratively limited due to x-ray emission at the very high field of E_{PEAK}=115 MV/m, a regime that the present test cryostat shielding was not designed for. QWR7 was also fabricated from RRR 300 niobium, rather than RRR 250, and received particularly careful attention during fabrication [4]. Quench locations for the other two QWR's, numbers 2 and 6, were not measured.

Generally, each of the four tested cavities is much more efficient at 2 K, even considering the additional cost of refrigeration. The 2 K residual resistance, ranging from 1-2.5 nΩ comes directly from low field decay time measurements. Values of 5 nΩ for accelerating gradients up to 12 MV/m in three out of four cavities are, indeed, low for any cavity of any type. A goal for future cryomodules of B_{PEAK}=120 mT with R_s=5 nΩ and V_{ACC}=5 MV/cavity at T=2 Kelvin is within reach based on these results.

Other Performance Considerations

Improvements other than electropolishing have been made since the 2009 upgrade. Electromagnetic (EM) optimizations of the 72 MHz QWR accounts for about 20% of the performance increase relative to the previous 109 MHz ATLAS Energy Upgrade cavities. The design has been presented previously [2], however, the most substantial new feature is the conical-shaped outer

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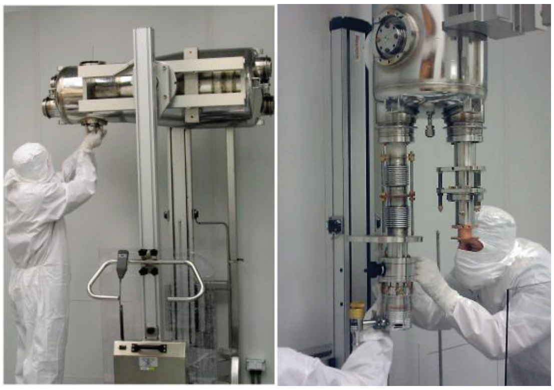

Figure 4: Clean room assembly for the 72 MHz QWR's.

housing which reduces B_{PEAK}/E_{ACC} by 20% compared to a straight cylindrical housing. No additional beam-axis space is needed since the expanded volume occupies the empty space already needed to join cavities together.

High values for E_{PEAK} in Table 1 are possible due to improved clean room fixturing. All of the assembly onto the six cavity ports is performed with the workers located well below the open cavity port (Fig. 4). Final rinsing of the cavities was performed for 1 hour through each of six ports in a class-100 clean room adjacent to the existing 1.3 GHz cavity rinsing area. The sequence for rinsing and assembly, as for e-cell cavities, includes mounting pickup probes, and blanks before the final rinse.

It is noted that wire electric discharge machining (EDM) was used to perform essentially all cutting on niobium subcomponents. The technique should, in principle, give similar results as for traditional mill machining, however, in practice it requires much less fixturing and technical skill with niobium and reduces the likelihood for embedding inclusions. Hydrogen contamination from EDM is not a major drawback since cavities require degassing anyway to achieve optimal performance at either 2 K or 4 K.

MICROPHONICS

Design and fabrication techniques for these quarter-wave cavities that nearly eliminate microphonic detuning include; (1) reduction of pressure sensitivity by EM design, **(2)** mechanical centering of the central conductor during fabrication, and (3) a passive mechanical damper to reduce the intrinsic mechanical Q of cavity vibrations. We show in Figures 5 and 6 early measurements of the effect of mechanical centering of the center conductor. Data is for QWR0 after all mechanical fabrication and electropolishing. Centering is done by inserting a long stainless bar into the center conductor through a 50 mm port in the top of the helium jacket and then inelastically bending the center conductor while monitoring the frequency on a network analyzer. The total bending was approximately 1 mm with a final accuracy of +/- 100 microns. The beneficial effect (Figure 5) is large, with a reduction in the peak-to-peak amplitude by a factor of 7, even before mechanical damper installation.

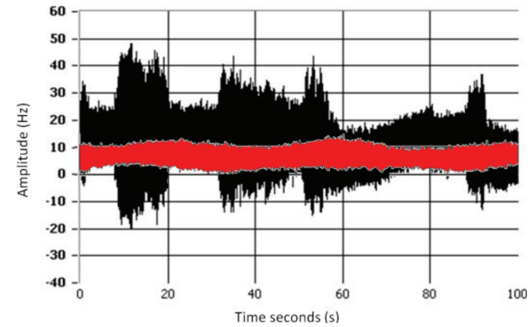

Figure 5: Microphonic amplitude reduction in a quarter-wave cavity due to centering the central conductor

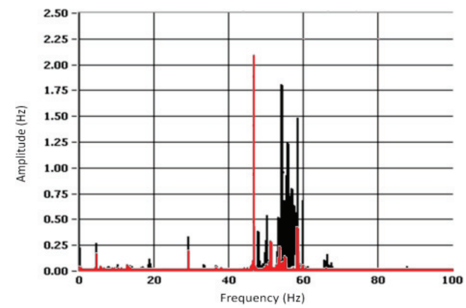

Figure 6: Fourier spectrum for data in previous Figure. Microphonics are lower (red) but the mechanical Q remains high when no mechanical damper is used.

CONCLUSION

The fabrication of eight quarter-wave cavities for β=0.077 and 72.75 MHz is complete and four of these have been tested. Horizontal electropolishing on the completed cavities was performed for the first time. Initial results at both 2 K and 4 K show remarkably good performance, easily exceeding the ATLAS requirements. Performance ranges from B_{PEAK}=98-165 mT, E_{PEAK}=70-120 MV/m, with practical acceleration at V_{ACC}>3 MV/cavity at 4 K and V_{ACC}>5 MV/cavity at 2 K.

ACKNOWLEGDEMENT

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