LOW BETA CAVITY DEVELOPMENT FOR AN ATLAS INTENSITY UPGRADE

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Abstract

Seven new 72 MHz superconducting quarter-wave (QWR) cavities have been completed and are being installed in the ATLAS heavy-ion accelerator at Argonne. The aim is to provide at least 17.5 MV accelerating potential with large acceptance and minimal beam losses for high intensity ion beams. Cavities are being installed into ATLAS in 2013 as part of a larger beam intensity upgrade. The cavity electromagnetic design uses optimizations not used before with quarter-wave cavities, including a taper on both the inner and outer conductors in order to reduce surface fields, while at the same time, spanning no more space along the beam line axis. Electropolishing (EP) on all cavities with integral helium jacket and no demountable rf joints is unique for low beta cavities. The new EP system is an extension of the Argonne system for ILC work. Single cavity cold tests show quench fields between 98-165 mT. Cavity residual resistances at the proposed operating point of ~70 mT are 2-3 n**Ω.** Significant technical details including the use of wire EDM and relatively low heat 'keyhole' welds for niobium fabrication are presented.

INTRODUCTION

The ATLAS Efficiency and Intensity Upgrade [1] includes a fully operational CW radio frequency quadrupole injector and a new cryomodule of 7 SC cavities for β=0.077. The cryomodule is replacing three cryomodules of split-ring resonators in the middle portion of the ATLAS SC ion linac. In fact, the three split-ring cryomodules are the first section of superconducting linac used for ion acceleration and the second superconducting linac anywhere. This follows work on the 2009 ATLAS Energy Upgrade cryomodule. The 2009 cryomodule has been available for full time operations, providing V_{ACC}=14.5 MV over 4.6 meters, the highest gradient for any SC linac for this range of beta. The new 5-meter cryomodule will provide at least 20% more voltage, 17.5 MV, even though cavities have half the beta, β_G=0.077. A number of technical improvements are implemented compared to the previous designs in order to achieve this performance. The improved rf design [2] and the unique capability to electropolish complete quarter-wave cavities [3], the near elimination of resonant micophonics and the relatively uncommon use of wire electron discharge machining (EDM) and lower heat 'keyhole' welds are described here.

Figure 1: Final clean string assembly just before removal from the clean room.

CAVITY PERFORMANCE

Cold tests at 2 K and 4 K for five out of eight new 72 MHz cavities have been performed in the large Argonne single cavity test cryostat. Seven of these cavities, shown in Figures 1 and 2, have been installed into the new ATLAS cryomodule as part of the intensity upgrade. The eighth was intended for R&D to advance the performance for this class of cavity [4]. Three cavities were not tested individually, but instead installed directly into the cryomodule. During a two week commissioning test, all cavities, including the three previously untested cavities, reached at least E_{ACC}=10 MV/m with minimal rf conditioning, and exceeding the nominal design goal of E_{ACC}=8 MV/m **(**ℓ_{EFF}**=** $\beta\lambda$**=0.3175 m).** Curves for quality factor versus accelerating gradient curves will be measured during the next cold test. For commissioning purposes, accelerating gradients were extracted from the previously measured CW Lorentz force detuning coefficient of 1.7±0.2 Hz/(MV/m)^2 and checked for two cases using x-ray end point energies, the product of bremsstrahlung from field emitted electrons.

Figure 2: Cavity cold mass suspended from the cryomodule lid.

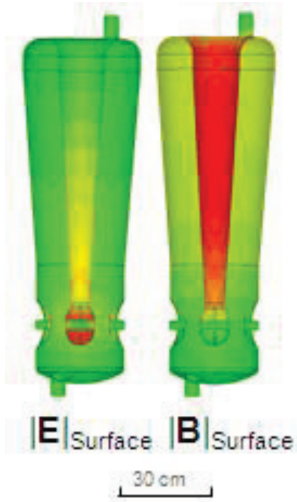

Figure 3: Surface fields (absolute value on a linear scale) for the ANL quarter-wave with the conical outer housing.

DESIGN AND FABRICATION

Electromagnetic Design

The 72.75 MHz cavity electromagnetic (EM) design incorporates two features which are unique to date. One directly improves cavity RF field performance and the second permits loss free transport of high current (≥100 eμA) ion beams. The modifications in the shape of the cavity, primarily in the high magnetic field region and analogous to the adaptation of the standard TESLA 1.3 GHz cell shape to the high gradient shape, are discussed first.

The conical shaped inner and outer conductors, shown in Figure 3, have not yet been used on any coaxial TEM cavity. The peak electric and peak magnetic surface fields are calculated in CST MWS. Color coding is on a linear scale. In general terms, the larger volume in the magnetic field region, due to conical shape, results in a lower surface current over the entire center conductor. The reduction of B_{PEAK} is 25% as compared to a cavity at the same frequency and beta that is constructed only from right cylinders.

The other EM parameters, including the R/Q and geometry factor are also improved as indicated in Table 1. The increase in the R/Q is expected due to the reduction in the average magnetic field (squared) over most of the central conductor for a given value of accelerating field. The geometry factor, proportional to the stored energy divided by an integral of surface magnetic field squared, also tends to increase as the shape becomes more 'spherical'. Finally, even though the shape in the beam aperture region is unchanged, the normalized E_{PEAK} is reduced by 10% due to the more efficient geometry.

The improvement in EM parameters is achieved at the cost of an increase in fabrication complexity. Specifically, rather than rolled and seam welded niobium cylinders for

Table 1: Calculated 72 MHz Cavity EM Parameters

Parameter	Right Cylinder	Conical Shapes	Units
E_{PEAK}^{*}	5.9	5.1	MV/m
B_{PEAK}^{*}	10.2	7.6	mT/(MV/m)
Geometry Factor	16.8	26.4	Ω
R_{SH}/Q	515	575	Ω

*normalized to E_{ACC}=1 MV/m, $l_{eff}=\beta\lambda$

the outer housing, the outer conductors were formed from three 120^{o} sections of a cone. However, this was judged to be a reasonable trade off due to the B_{PEAK} reduction and the observation that performance for ANL cavities has been limited by magnetic field (quench or Q-slope). The improved EM parameters could, in principle, provide an additional accelerating voltage equivalent of two additional cavities for a seven cavity cryomodule.

An EM design technique, introduced more than a decade ago, but used in practice only once previously, is the correction of the intrinsic steering in the quarter-wave cavity by means of an electric field intentionally introduced in the direction transverse to the beam axis. The unwanted steering is caused by a non-zero magnetic field on the beam axis due to the 'top-to-bottom' asymmetry in the quarter-wave geometry and the correcting electric field comes from an intentional tilt built into the surfaces of the beam aperture region. For this case (f_0=72.75 MHz and β_G=0.077), the tilted angle of the cavity faces is 2.2^{o} and the resultant reduction in the beam steering angle is a factor of 10 or more over the full useful velocity range (0.07<β<0.2). The absolute value of the steering angle is less than 0.1 mrad with the correction. It is noted that this method of correction has a weaker beta dependence than a correction performed by vertically offsetting the cavity. In the former there is also no sacrifice of beam aperture. Finally, here there is no additional fabrication cost since the angle is built into the NC machined dies used for niobium forming

Fabrication Details

Assembly of the cavity parts from RRR 250 niobium sheet metal formed is performed by electron beam welding in a high vacuum chamber. The geometry requires roughly seven linear meters of electron beam welding, with almost one third of the distance in regions where the magnetic field, B ≥ 0.8 B_{PEAK}.

For the present set of quarter-waves, all welds in the high magnetic field regions are of a so called 'keyhole' type, where the beam necessarily strikes the niobium from the direction of the rf surface. This type of welding is qualitatively different from the standard through weld, but is little known in the SRF cavity community since most elliptical cell geometries can only be assembled using through welds in the high B-field region. In this case the electron beam impinges the surface from the liquid helium side. However, for TEM structures there is direct

ISBN 978-3-95450-143-4

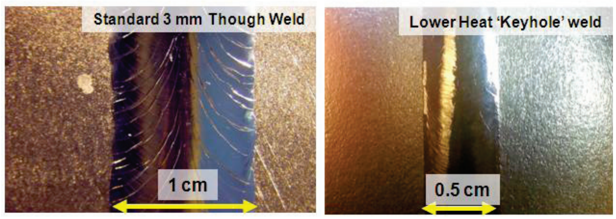

Figure 4: Two weld types used to assemble quarter-wave cavities.

line-of-sight to the high B-field portion of the rf surface until the later stages of assembly, so that the keyhole technique is possible. Examples of the visual appearance for a good quality standard through weld and a keyhole weld are shown in Figure 4.

Differences in the main beam parameters include a higher travel speed, a tighter focus and a four times lower total deposited power for the keyhole approach. The weld bead structures are very different. Whereas the 3 mm though weld (Figure 3 left) produces a large grained, 1 cm wide bead through the bulk, and large grain steps on the rf surface, the keyhole weld (right) produces a smooth narrow bead with small grain steps. The smoothness is produced during a final low (~40% of full) power welding step referred to as the 'cosmetic pass'. This final step is not possible for through welds. These cavities don't provide a chance to isolate the impact of this technique alone on rf performance; however, they do provide proof of principle that the keyhole technique is compatible with high (~165 mT) surface fields.

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.

Electropolishing

The ANL low-beta cavity electropolishing system provides a unique and practical capability to perform electropolishing on the complete niobium cavity with helium jacket. This is possible because TEM-mode cavities do not require field flatness tuning or access to the niobium surface after polishing. The 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. For co-axial TEM cavities, the helium jacket has been used to directly cool the niobium surface with chilled (22+/-0.5°C) water and the niobium temperature has been measured to be stable and uniform to within ≤ 5 °C over the cavity surface. As with 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.

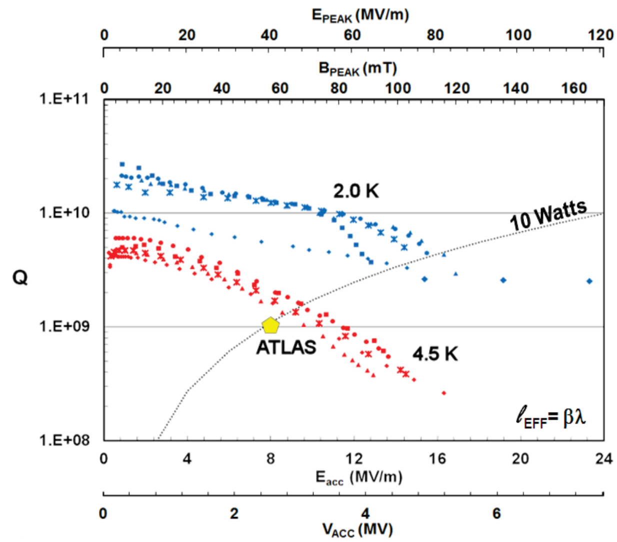

Figure 5: Q versus E_{ACC}, V_{ACC}, B_{PEAK} and E_{PEAK} for 5 of quarter-wave cavities.

The total removal for all cavities was close to 150 µm. Two separate rounds of polishing were 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. Possible contamination from the Fermilab furnace, a known issue for some bare niobium elliptical cavities, appears to have had no negative impact here, possibly because of the relatively small 50 mm cavity access ports which make an effective baffle to the rf surface.

PERFORMANCE

Four out of seven new 72 MHz cavities and one R&D cavity were tested at both 2.0 and 4.5 Kelvin and results are shown in Figure 5. In ATLAS, cavities will be operated at 4.5 K with a nominal accelerating gradient of 7.9 MV/m (l_{eff}=βλ=31.75 cm) or 2.5 MV/cavity. The assumed quality factor was Q=1x10^9 with a corresponding surface resistance of 26 nΩ. In practice, as much as 15-20 Watts of cryogenic cooling per cavity should be available, allowing cavities to operate at or above E_{ACC}~10 MV/m.

The five tested cavities achieved CW accelerating gradients at 4.5 K ranging between E_{ACC}=12.4-16.2 MV/m, or up to double the originally planned values. Most cavities had approximately 3 hours of low-level (E_{ACC}=0-1.5 MV/m) multipacting conditioning and one half to 1 hour of short pulse conditioning with 4 kW peak

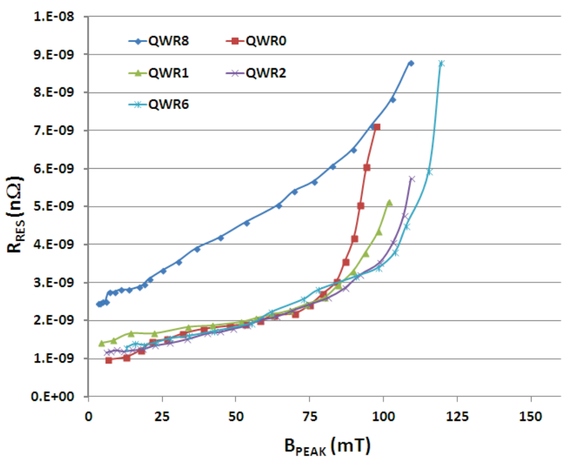

Figure 6: Averaged surface resistance extracted from the cavity geometry factor and the measured Q_o at 2 K. (R_{BCS}~0).

power in order to achieve the measured performance shown in Figure 2. High-field multipacting (E_{ACC}>2 MV/m), observed briefly in most cavities, was easily conditioned in minutes by adjusting the coupler for the matched condition and transmitting a few 10's of Watts into the multipactor barrier.

Only the prototype cavity received an 'in-situ' 120 °C bake. For this case, cold testing before and after showed no measureable difference from baking. This is not considered to be a definitive test of the technique since unwanted temperature variations of ±10°C both in time and over the cavity surface were observed.

2 Kelvin Performance

ANL is also pursuing R&D needed in 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 ion linac that might be attractive for the next generation of high-power accelerators.

The five cavities tested individually already move close to this goal, reaching magnetic surface fields in the range B_{PEAK}=98-165 mT. In two of five cases, the thermal-magnetic breakdown was extracted from pulsed, 5% duty cycle, measurements in order to limit x-ray production at very high fields. These points are not included on Figure 6. The lowest quench at 98 mT for the first prototype is due to breakdown on the central conductor as determined from second sound measurements. The location corresponds to that of a known welding defect, where contamination on the center conductor weld preparation is known to have occurred.

At the other extreme of performance, the R&D quarter-wave cavity was never driven to quench (maximum B_{PEAK}=165 mT), but was finally administratively limited due to copious x-ray emission at E_{PEAK}=115 MV/m, producing x-rays for which the existing shielding was never designed. In addition to the high quench field, the R&D cavity also has a slightly higher surface resistance than for the other four cavities. It is unknown whether this is related to the longer 625 °C hydrogen degassing time, the different niobium supplier, or some other effect.

Four of the cavities have a 2 K residual resistance, ranging from 1-2 nΩ at low fields, a value that has been very difficult to achieve in higher frequency elliptical cell cavities. The curves in Figure 5 show a measure of residual resistivity as a function of magnetic field. We note that with the 7 cm variable coupler used for these tests, Qo comes directly from low field weekly coupled decay time measurements. Errors on both Qo and 'R_{RES}' are, therefore, much smaller than is common with fixed couplers. The estimated Qo error is ±2.5% coming mostly from extraction of the weakly coupled energy decay time from the voltage decay curve as measured on a digital oscilloscope.

MICROPHONICS

Design features and fabrication techniques for new quarter-wave cavities nearly eliminate microphonics. These include; (1) reduction of pressure sensitivity by mechanical and 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.

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 about +/- 100 microns, however, we note it is unnecessary to make dimensional measurements in order to perform the centering. Only frequency is required. The benefit is large, with a reduction in the peak-to-peak amplitude for resonant 'pendulum' mode microphonics by an order of magnitude, even before mechanical damper installation. Peak-to-peak microphonics amplitude for all cavities installed inside the cryomodule was measured to by ±2 Hz over periods of minutes to days during the commissioning cool down, or only about 5% the maximum planned fast tuning window.

CONCLUSION

The fabrication and assembly of a seven cavity ATLAS cryomodule of quarter-wave cavities and one R&D cavity for β=0.077 and f_0=72.75 MHz is complete. Horizontal electropolishing on the completed cavities was performed for the first time. Initial results at both 2 K and 4 K show performance ranging from B_{PEAK}=98-165 mT, E_{PEAK}=70-120 MV/m, and practical acceleration at V_{ACC}>3 MV/cavity at 4.5 K and V_{ACC}>5 MV/cavity at 2 K. In the commissioning cool down of the cryomodule all cavities where operated with E_{ACC}≥10 MV/m. Levels for fast

ISBN 978-3-95450-143-4

microphonics were measured to be ±2 Hz peak-to-peak demonstrating the effectiveness of EM and mechanical techniques presented here.

ACKNOWLEGDEMENT

This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

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