SRF ADVANCES FOR ATLAS AND OTHER β<1 APPLICATIONS

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Abstract

The primary goal for seven new 72 MHz quarter wave SC cavities at Argonne is to provide the maximum accelerating gradient along the linac with large acceptance and minimal beam losses for the acceleration of high intensity beams. Cavities will be installed into ATLAS in 2012 as part of this intensity upgrade. However, ANL also intends to demonstrate the techniques required for future ion linacs for basic and applied science and technology.   These accelerators would be cost prohibitive with older technology. New cavity electromagnetic design optimizations and improved electropolishing techniques developed at ANL have been applied to the construction of the first prototype. Initial tests show the highest performance achieved to date for this class of cavity designed to cover the velocity range 0.06<β<0.15. The cavity has very low RF losses and the highest useful accelerating gradients ever achieved for a quarter-wave structure. Indeed, the accelerating voltage of 4.3 MV is twice that for cavities installed and operating in ATLAS since 2009, with RF surface fields comparable to those being achieved for the ILC effort.

INTRODUCTION

The ATLAS Efficiency and Intensity Upgrade [1] includes a new high-efficiency CW radio frequency quadrupole injector [2] and one new cryomodule of 7 SC

Figure 1: Prototype 72 MHz quarter-wave cavity with 4 kW power coupler and fast and slow tuners.
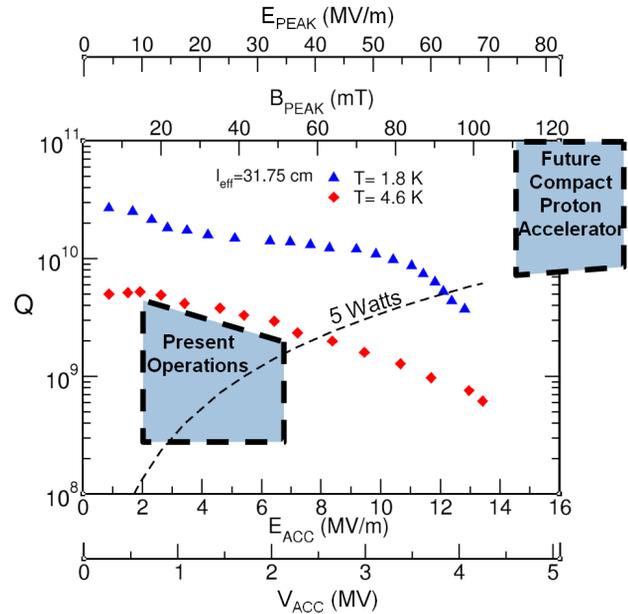

Figure 2: Quality factor versus accelerating gradient, voltage and surface fields at 2 and 4 Kelvin.

cavities to replace three existing cryomodules of split-ring resonators in the middle portion of the ATLAS SC ion linac. The cryomodule will provide 17.5 MV of accelerating potential over 5 meters and dramatically increase beam transport efficiency for both stable and radioactive ion beams by increasing overall acceptance and reducing emittance growth inherent in the earlier cavity designs.

The cavity operating voltage will be V_{ACC}=2.5 MV/cavity at β=0.077, roughly two times higher than for the present state-of-the-art at this beta [3]. To achieve this, a combination of improved rf design [4] and improved cavity processing techniques have been developed.

CAVITY PERFORMANCE

Initial cold test results at both 2 and 4 Kelvin for the prototype 72 MHz cavity are complete. Processing included heavy, 150 μm, electropolishing on the complete cavity (see Figure 1). Work is ongoing, including baking and re-rinsing, however, early results shown in Figure 2. already show the highest accelerating gradients and voltages for any cavity in the region of β~0.1.

4 Kelvin Performance

In ATLAS cavities are operated at 4.5 Kelvin using the ATLAS liquid helium refrigerator. The planned accelerating gradient is 7.9 MV/m (l_{eff}=βλ=31.75 cm)

with a quality factor of $Q=1\times10^9$, corresponding to 10 Watts of rf power per cavity and a surface resistance of 26 nΩ.

The achieved cavity accelerating gradient of $E_{acc}=13.4$ MV/m is almost double that required for ATLAS and was measured following approximately 3 hours of low-level multipacting conditioning and 1-1/2 hours of short pulse conditioning with using 4.5 kW peak power. At 4 Kelvin the measured low-field quality factor of 5×10^9 gives a residual surface resistance of 3.1 nΩ. RF power to reach $E_{ACC}=7.9$ MV/m was only 5 Watts, about half the per cavity value planned for ATLAS. The maximum accelerating potential, 4.3 MV, is easily the largest for any SC cavity in this velocity range.

Based on recent cavity results for Spiral-2 [5], a controlled 'in-situ' bake at 115°C for 48 hours has been performed and the results of this will be measured following the next cool down.

2 Kelvin Performance

ANL is also pursuing the developments needed in order to demonstrate practical 2 Kelvin operation in the region of performance highlighted in the upper right hand side of Figure 2. These high cavity field gradients combined with the compact lattice of the Argonne cryomodule design would give 'real-estate' gradients of 7 MV/m, or about 2-3 times higher than for today's state-of-the-art. This real-estate gradient would make feasible the construction of a compact proton linac and would be extremely attractive for the next generation of high-power accelerators in areas of energy, national security, and medicine.

Key to the compact layout is the requirement that low- and high-beta cavities, including quarter-wave, half-wave, spoke and/or elliptical cell cavities all operate with peak surface magnetic fields near $B_{PEAK}=120$ mT.

The prototype cavity tested here is reaching a surface field of $B_{PEAK}=105$ mT. The limit, based on second sound measurements, appears to be a quench on the central conductor of the QWR. High-temperature baking to degas

hydrogen, re-electropolishing and additional high-pressure rinsing are planned in an effort to increase 2 Kelvin field performance.

Already, however, this cavity is much more efficient at 2 Kelvin even considering the additional cost of refrigeration. The 2 Kelvin residual resistance of 1 nΩ at low field levels and 5 nΩ up to 12 MV/m accelerating gradient is rarely achieved for any cavity of any type.

Our goal of reaching $B_{peak}\sim120$ mT and $R_s\sim5$ nΩ at T=2 Kelvin would provide a useful CW accelerating potential of $V_{acc}\sim5$ MV. Successful development would provide an attractive option for megawatt-class CW linacs in areas of applied science and technology such as for medical isotope production, national defense, and accelerator driven systems.

DESIGN AND FABRICATION

Electromagnetic Design

Electromagnetic (EM) design and optimization of the 72.75 MHz QWR have been presented previously [4]. The guiding principle has been to provide the maximum accelerating gradient along the linac with large acceptance and minimal beam steering. The design also includes ports specifically for electropolishing and cleaning the cavity, including two ports on the top of the cavity and two on the bottom, in addition to the beam ports. The 72 MHz frequency derives from the 6th multiple of the ATLAS 12.125 MHz master oscillator giving a physical cavity height of 1.3 meters. This was judged to be the largest practical cavity size for fabrication and processing.

The most innovative EM design feature is the conical-shaped outer housing (see Fig. 3) which reduces B_{peak}/E_{acc} by at least 20% compared to a straight cylindrical housing but takes no additional space along the beam axis since some space, ~7 cm, is already required to join adjacent cavities at the beam ports using an inter-cavity spool.

Mechanical Design and Microphonics

The most important mechanical consideration for this thin-walled (3 mm) structure formed from high purity (RRR>250) fine-grained niobium sheet is mechanical stability in the presence of various sources of microphonics. These include helium bubbling at T=4.5 K and mechanical vibrations coupled into the cavity from the accelerator environment. Other important mechanical considerations include the need to tolerate differential pressures of 15 PSIA at room temperature and >25 PSIA at cryogenic temperatures without permanent detuning and to tolerate the application of a slow tuner force at the beam ports of up to 4500 lbs per side. This will also be the first set of ANL cavities to include an ASME code stamp on the helium pressure vessel. Additional design details are provided elsewhere [6].

Cavity Tuning

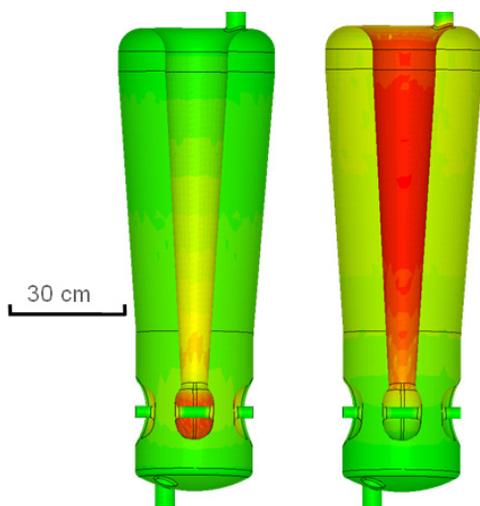For the last decade all ANL low-beta cavities have included a straight section on the center conductor

Figure 3: Surface electric (left) field and surface magnetic (right) field distributions for the 72 MHz β=0.077 QWR.

specifically to facilitate tuning during fabrication. Here, coarse tuning for the 72 MHz cavity was performed using wire EDM to cut ~2.2 cm lengths of niobium from (1) the straight section of the center conductor and (2) the top of the cylindrical section on the outer conductor of the cavity. It is noted that both the inner and outer conductors need to be cut in order to keep the beam ports on the same axis. The measured sensitivity for this cutting step is 55 kHz/mm. A final finer tuning step is performed after all components except the bottom dome of the cavity have been welded on. In this case, the dome is trimmed (see Figure 4 - left) with a sensitivity of ~3 kHz/mm in order to bring the frequency to within a few kHz of the desired value. Finally after, electropolishing the cavity can be squeezed or stretched at the beam ports with a sensitivity of 22 kHz/mm to compensate for any differential polishing during final electropolishing. For the prototype cavity after final electropolishing and evacuation (+20 kHz frequency shift) and cool down from room temperature (+90 kHz), the final cavity frequency was 72.755 MHz at T=4.6 K. This is only 5 kHz above the nominal frequency and well within the 30 kHz window of the slow tuner system.

Wire EDM

ANL has developed wire EDM techniques over the last decade together with several industrial partners to perform essentially all of the trimming on niobium cavity subcomponents before electron beam welding. The primary technical benefit is that there is essentially no possibility for foreign material inclusions as compared to traditional machining on an end mill, which requires particular skill and expertise with niobium. Hydrogen contamination from EDM is not a major drawback since ANL cavities typically require degassing anyway to achieve optimal performance at 2 Kelvin.

Figure 4 shows a vertical wire cutting excess niobium material from the bottom dome of the cavity (left) and the center conductor (right). The re-cast layer left over after EDM, a combination of niobium- and brass-oxides, is 5 microns thick. This should be removed using standard buffered chemical polishing for 5-10 minutes prior to electron beam welding or electropolishing.

CAVITY PROCESSING

Electropolishing

A new electropolishing system at ANL for co-axial quarter- and half-wave SC cavities is the first of its kind and similar in concept to that used for 1.3 GHz ILC-type cavities [7]. One major improvement, however, is that the cavity is electropolished after the helium jacket is installed and after all other fabrication steps are complete.

Operation is straightforward based on several years experience with the existing ANL system for elliptical cavities. The system cools the outside of the niobium using circulating water in the liquid helium jacket. The technique provides accurate control of the cavity wall temperature since the rate of acid flow through the cavity

Figure 4: Wire electrical discharge machining (EDM) used to trim niobium cavity subcomponents.

is de-coupled from the requirement to maintain the cavity surface at a fixed temperature (25-30°C).

Mechanically the system is similar to the ILC-cavity system, except that the single aluminium cathode is replaced by four separate cathodes, one through each of the four coupling ports at the ends of the cavity. During EP the cavity rotates at ~1/2 rpm and the anode/cathode voltage is fixed at 18 V. The ratio of surface areas of the anode-to-cathode is ~6:1.

A total surface removal of 150 μm of niobium for the QWR was performed in two separate steps over the course of two days requiring a total electropolishing time of 12 hours. The time required to mount, polish, dismount and ultrasonic clean the cavity is two person-days. This is similar overall to buffered chemical polishing, where the cavity must be dismounted and flipped midway through etching for uniform removal.

For final preparation, the cavity was rinsed in a new vertical high-pressure water rinse stand and assembled in a class 100 clean room adjacent to the existing ILC-cavity clean room area. The measured onset of field emission was between E_{peak}=35-40 MV/m. The quench at E_{peak}~70 MV/m, based on second sound thermometry, is known to be located on the cavity center conductor, however, other details such as the location with respect to the weld and the nature of the defect are still under study.

CONCLUSION

The fabrication of an advanced quarter-wave resonator design for β=0.077 at 72.75 MHz has been completed. Horizontal electropolishing on the completed cavity was performed for the first time. Initial cold test results at both 2 and 4 Kelvin show remarkably good performance, easily exceeding the ATLAS requirements. Maximum performance parameters are E_{acc}=13.4 MV/m (l_{eff}=βλ), E_{peak}=69 MV/m, B_{peak}= 102 mT and V_{acc}=4.3 MV. Further work including low temperature baking, second sound studies, optical inspection and re-rinsing will be performed.

ACKNOWLEGDEMENT

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