COMMISSIONING OF THE 72 MHz QUARTER-WAVE CAVITY CRYOMODULE AT ATLAS*

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Abstract

A cryomodule of seven 72 MHz superconducting (SC) quarter-wave cavities optimized for ions with v/c=0.077 has been commissioned in the ATLAS heavy-ion accelerator at Argonne. The new module, with the new CW RFQ injector [1], provide ATLAS the capability to deliver much higher beam currents with low beam losses for nuclear physics experiments using stable or rare isotope beams or neutron rich beams from the Californium Rare Isotope Breeder. The goal for the cryomodule, to provide a large accelerating voltage of 17.5 MV (2.5 MV/cavity) with no detectable beam losses, was been met during the first month of commissioning. To date, cavities and primary subsystems, including 4 kW nominal RF couplers and pneumatic tuners, are operating as designed with full availability. For V_{ACC}=17.5 MV (ave. E_{PEAK}=40 MV/m) field emission is small and RF losses to 4.5 K helium are 5 Watts/cavity, about half of the planned value. Cavity fields continue to be gradually increased beyond the nominal design values. The limit due to cavity quench is at least V_{ACC}=3.75 MV per cavity. The good RF performance stems primarily from combination of RF design and cavity processing. Effective voltages are 2½ times higher than those of other operational cavities for this v/c. We report here on the recent online test results and important technical features.

INTRODUCTION

SC two-gap quarter-wave cavities, with intrinsic properties of high shunt impedance, large aperture, and wide particle velocity acceptance have been the cavity of choice for heavy-ion linacs with beam velocities near β=0.1 for more than four decades. Rapid advance in SRF cavity performance and new requirements, such as for high-intensity CW ion beams, have not changed these basic considerations. In fact, quarter-wave cavities combined with the latest techniques provide the best means to reduce low-beta linac footprint and cost and, permit high reliability needed for high-intensity/high-power applications [2,3].

Key technical features of the new ATLAS 72 MHz quarter-wave cavity and cryomodule, some of which are known widely but not practically implemented until now, include:

* 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. This research used resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility.
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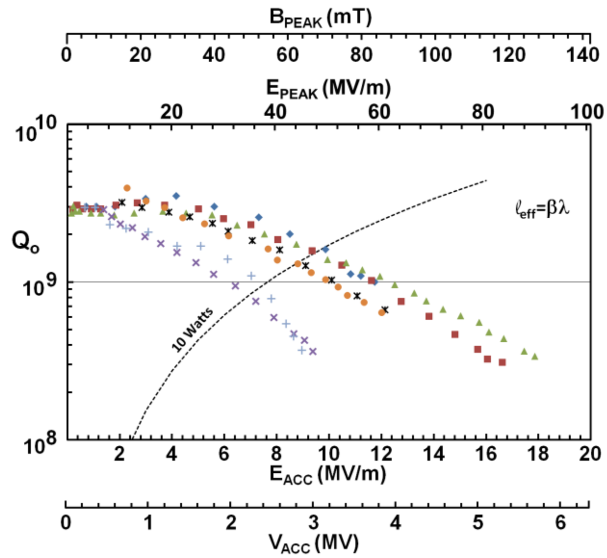

Figure 1: Measured online performance data for seven quarter-wave cavities at T=4.5 Kelvin.

- The first use in any TEM-mode cavity (quarter- or half-wave) of tapered inner and outer conductors [4].
- Electropolishing on the completed quarter-wave cavity with stainless steel helium jacket.
- Tilted drift-tubes formed into the niobium to cancel the beam steering from on-axis magnetic fields over a wide velocity range [5].
- Centering of the central conductor to 100 microns during fabrication to nearly eliminate the effect of resonant, *i.e.* pendulum mode, microphonics.
- 'In-situ' maintenance on the clean cavity string while maintaining performance with E_{PEAK}≥40 MV/m.

RF PERFORMANCE

The approach for ATLAS cavities has never been to design to a gradient 'spec', but to provide the maximum capability to ATLAS with available funding. The 72 MHz cavity, β_{OPT}=0.077, provides at least 60% of the peak voltage over the range 0.05<v/c<0.2. Higher cavity accelerating voltages, therefore, add directly to the list of beam/energy combinations available to the over 400 active ATLAS users. This is particularly important for higher beam intensities (≥100 eμA) where only the new steering-corrected cavities are practical.

Figure 1 shows measured online performance curves from June 2014, after five months of operation in the ATLAS tunnel. Performance has not changed measurably during this time. The measured accelerating gradient,

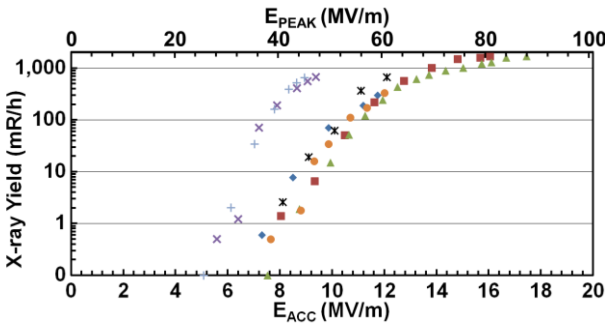

Figure 2: Measured x-ray yield from field emission at 1 meter from the vacuum vessel

determined using power transmitted to the cavity and a calibrated cavity RF field probe, have been cross checked against beam energy gain measured in a silicon surface barrier detector located downstream of the module. The techniques generally agree to within 1-3%. The quality factor, Q_0, in Figure 1, is based on the critically coupled energy decay time and has an uncertainty of less than 5%. This has been cross checked against measured current changes in a load levelling heater, a measure of the dynamic load to the 4.5 K helium refrigerator. The heater data indicates a 30 Watts dynamic load for the cryomodule running at 95% of the nominal 17.5 MV. This scales to 33 Watts at 17.5 MV and, within the accuracy of the heater measurements, is in agreement with the data in Figure 1.

Overall cavity performance relative to the four horizontal axes, E_{ACC}, V_{ACC}, E_{PEAK} and B_{PEAK}, is higher than has been achieved to date for any stable, operational cryomodule near β=0.1. The important parameter, V_{ACC}, is also larger compared to E_{PEAK} and B_{PEAK} than for other quarter-wave cavities due to the shape, mostly the tapered inner and outer conductors [4]. This reduces peak surface electric and magnetic fields (by 10% and 20% respectively) but increases the shunt impedance and geometry factor (by 10% and at least 40%) with respect to co-axial cylinders. It appears obvious that modest increase in project cost due to the tapered shape is a beneficial trade-off when the additional performance is considered.

Figure 2 shows data for measured x-rays collected simultaneously with the Q versus E measurements. The detector is a Ludlum 375 area monitor located 1 meter to the side of the cryomodule vacuum vessel. The initial onset of x-rays from field-emitted electrons ranges from E_{PEAK}=30 MV/m to 40 MV/m. At the average cavity gradient of 8 MV/m (V_{ACC}=2.5 MV), the total x-ray yield from all cavities is about 60 mR/h, and is a negligible contribution to the total cryogenic heat load.

Two critical repair and maintenance operations were required on the clean cavity string assembly after removal from the large clean assembly area. The first was the replacement of one of the two beamline gate valves, which is visible on the left side of Figure 3. The second was the replacement of all of the cavity field probes located on ports at the top of each cavity. Both operations required careful venting, purging and pumping of the cavity string volume using the ATLAS up to-air-system [6]. Local clean rooms were constructed where the work was performed. Resulting field emission is small in terms of operational effects, but it does begin at lower fields than was observed during single cavity testing, where the onset ranged from 40-70 MV/m. In particular, the first cavity in the cryostat has the lowest onset and is located next to the gate valve that was replaced. We believe this is an important demonstration of what can be achieved for 'in the field maintenance' with common hardware (*e.g.* bolted flanges) and careful techniques.

MICROPHONICS AND STABILITY

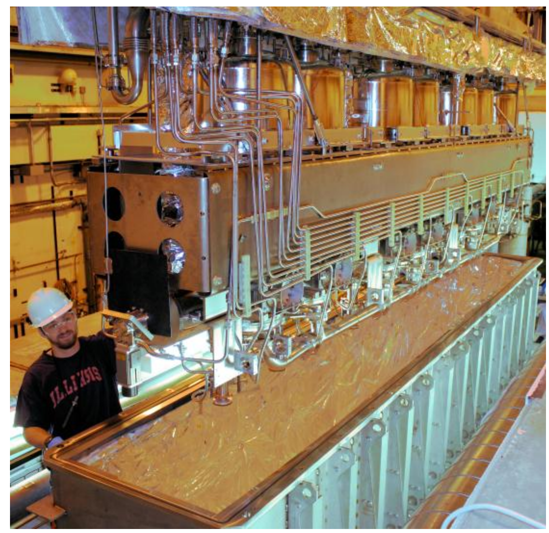

Figure 3: Test fitting the cavity string assembly in the cryostat vacuum vessel

Figure 4: The new Intensity Upgrade cryostat (the rectangular vessel) in the ATLAS tunnel

The cryomodule cavities are gravity fed from the 4.5 Kelvin liquid helium supply of the ATLAS refrigerator. The helium distribution line and valve box are visible to the right of the cryomodule in Figure 4. Helium pressure fluctuations both fast (up to 20 Hz) and slow are known to be the primary source of cavity frequency fluctuations during operation. As such, the cavity design was focussed on reducing microphonics by; (1) reduction of pressure sensitivity in the electromagnetic design, the so called df/dP, (2) centering of the central conductor during fabrication, and (3) installation of a passive mechanical

ISBN 978-3-95450-142-7

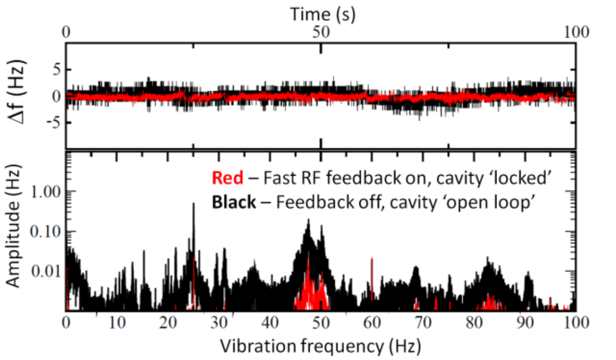

Figure 5: Online microphonics levels in cavity #7 with E_{ACC}=8.5 MV/m. Frequency deviations versus time (top) and Fourier transform (bottom)

damper in each cavity to reduce the mechanical Q for the 'pendulum' mode.

Cavity microphonics in the upgrade cryomodule are being characterized during short periods in between scheduled experimental runs on ATLAS, when the cavities can be unlocked from the master oscillator and measured in the open loop operation.

An example for both open loop and 'locked' conditions is shown in Figure 5. The cavity frequency is measured with a cavity resonance monitor [7] circuit and a low noise external signal generator. The data is for the last cavity in the module, running at 8.5 MV/m with 9 Watts of RF power into the helium bath. The black curves show the residual frequency jitter on the cavity RF pickup in the open loop case. The Fourier decomposition of the frequency jitter shows a small peak at the known pendulum oscillation mode of ~48 Hz, however, the amplitude is less than 1 Hz. The large width of the 48 Hz resonance is evidence that the passive mechanical damper is functioning. In the phase-locked condition, represented by the red curves, the residual deviations are near the limits of the measurement hardware. The total forward RF power required to phase-lock was 1.45 kW (9 Watts to helium with the remainder returned through an RF circulator into a water cooled dummy load). The Q_{EXT}, fully adjustable over a range of more than 50 dB, is set for a value of about $4x10^6$. The high power RF amplifiers and the RF power couplers, as shown in Figure 6, are all tested for 4 kW operation and provide significant room to further increase the operational gradient.

Figure 6: ATLAS 4 kW RF power couplers

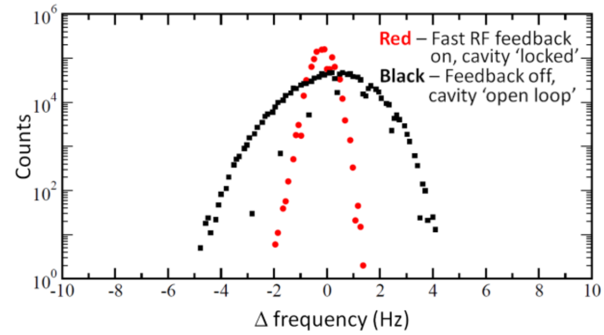

Figure 7: Probability density (normalized to 'counts') for cavity frequency excursions.

Figure 7 shows a projection of the frequency jitter signal onto the vertical axis and is a measure of the (relative) probability distribution for eigenfrequency excursions spanning about 5 orders of magnitude. The behaviour is nearly Gaussian and the full width falls well within the available 40 Hz fast tuning window.

SUMMARY

A cryomodule of seven 72 MHz SC quarter-wave cavities optimized for ions with v/c=0.077 has been commissioned in the ATLAS heavy-ion accelerator. Cavities operate next to four 9-Tesla SC solenoids, with no measurable decrease in surface resistance. Operational goals for stable gradient, E_{ACC}=8 MV/m, and total voltage, V_{ACC}=17.5 MV have been met with large margins in available gradient, refrigeration and RF control power. Gradients will continue to be increased in order to determine the limits of the system.

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