THE ATLAS ENERGY UPGRADE CRYOMODULE*

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Abstract

A new cryomodule containing seven drift-tube-loaded quarter-wave resonant cavities has been added to the ATLAS heavy ion linac at Argonne National Laboratory (ANL). Initial operation with beam took place this summer. The module provided a stable 14.5 MV of accelerating potential (2.1 MV/cavity), a record for cavities at this beta. This paper describes cavity, cryomodule, and subsystem performance. A report on the final assembly, commissioning, and operational experience is also given.

INTRODUCTION

The ATLAS Energy Upgrade project is designed to increase ion beam energies by 30-40% in support of the nuclear physics program at ANL. The centerpiece of the upgrade is a group of seven new srf cavities operating at 109 MHz and designed for optimal $\beta = 0.15$. These drift-tube-loaded quarter-wave resonant (QWR) structures are housed in a top-loading box cryomodule which separates the cavity vacuum space from the cryogenic insulating vacuum. This cryomodule (Fig. 1) represents the first successful demonstration of separate cavity and insulating vacuum systems for a low-beta cryomodule. Figure 2 shows a section view of one QWR structure and Table 1 lists cavity parameters. Details of cavity fabrication may be found in Ref. [1].

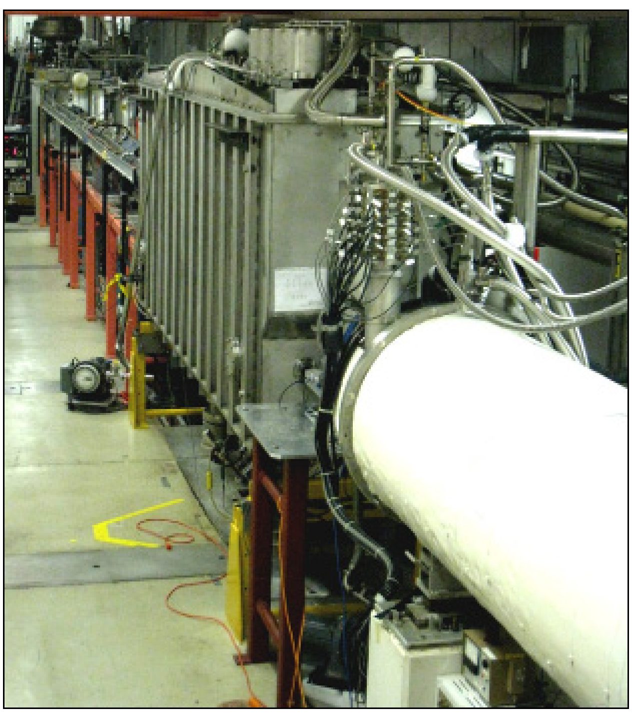

Figure 1: Cryomodule on-line in the ATLAS tunnel.

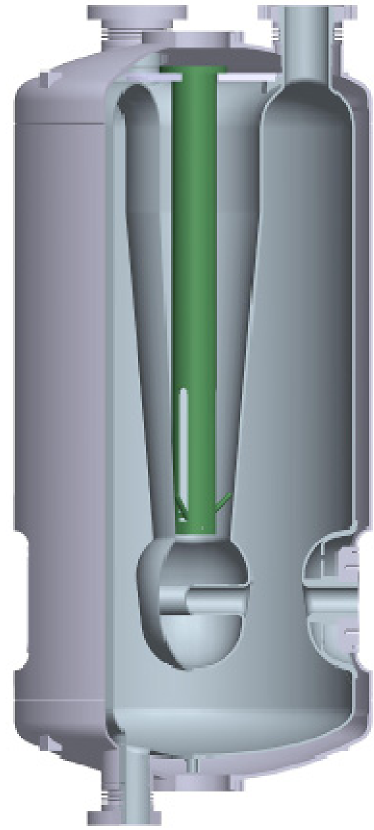

Figure 2: Model of 109 MHz quarter-wave cavity.

PERFORMANCE

The upgrade cryomodule went on-line in late June 2009 and has been available for operations with beam since then. The data come from measurements made on the fully assembled module during initial commissioning and after it was installed in the accelerator. For a discussion of individual cavity performance measured during off-line single cavity tests, see Ref. [2].

Table 1: Cavity Parameters

Frequency	109.125 kHz
β	0.15
U_0	37 J*
Active length	25 cm
E_{PEAK}	48 MV/m*
B_{PEAK}	88 mT*
G	40 Ohm
R_{sh}/Q	548 Ohm

*at 3.75 MV/cavity = 15 MV/m

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Cavity

Figure 3 shows the quench limit for each cavity. The average accelerating gradient is 11.7 MV/m. Two cavities reach 15 MV/m which represents a voltage of 3.75 MV per cavity. For comparison, the state of the art for 2-gap QWR cavities in operation today is slightly over 1 MV per cavity.

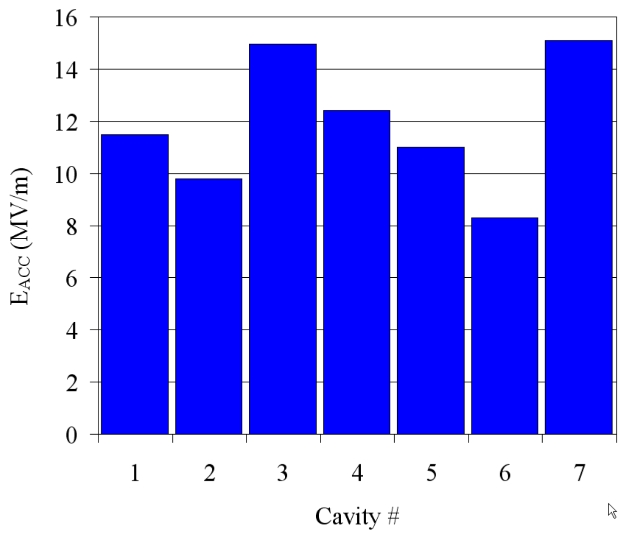

Figure 3: On-line cavity performance.

Accelerating voltages have been measured directly with beam. Table 2 lists beam energy gain per cavity for a Carbon +6 ion beam. Time-of-flight measurements provide beam energy, which are used to derive cavity accelerating voltage via the TRACK analysis code.

Table 2: Beam-Based Performance

Cavity Number	Beam Energy [MeV]	Cavity Voltage [MV]
1	174.0	1.96
2	184.5	1.89
3	196.1	2.13
4	208.5	2.29
5	219.7	2.12
6	229.9	1.92
7	241.5	2.24
Total voltage		**14.5**

For the beam energy in Table 2, the measured dynamic heat load of the cryomodule was 55W. At an average voltage of 2.1 MV (= 8.3 MV/m accelerating gradient), the resulting average Q value is 1.0×10^9.

Coupler/Tuner

Details on the adjustable input coupler design are found in Ref. [1]. The ability to vary the coupling from 10^6 to 10^9 has simplified operations and justified the design vs. fixed coupling.

The mechanical slow tuner range is shown in Figure 4. Tuning steps during fabrication ensured that each cavity achieved the target frequency of 109.125 kHz at the midpoint of the slow tuner range of 30 kHz. The tuners are pneumatically actuated using helium gas at 80K and operate on-line with a slew rate of about 1 kHz/s, limited by the helium gas management system.

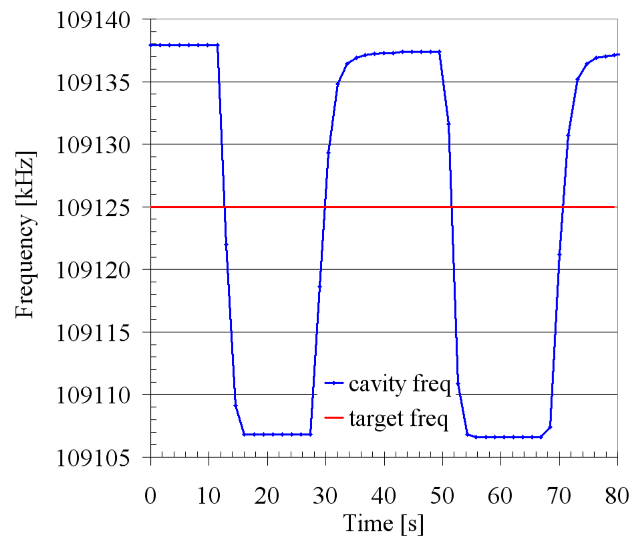

Figure 4: Mechanical slow tuner range.

Fast tuning is accomplished using VCX (Voltage Controlled Reactance) tuners [3]. These reliable units have been in use at ANL for over 30 years, but now represent the limiting component in terms of cryomodule performance. Figure 5 shows measured cavity microphonics during simultaneous operation of all seven cavities at an average voltage of 2 MV/cavity. The rms frequency deviation is 1-2 Hz and the maximum deviations are well within the fast tuner window of 40 Hz [4]. Since operations began at the end of June 2009 none of the cavities in this cryomodule have gone out of lock due to microphonics.

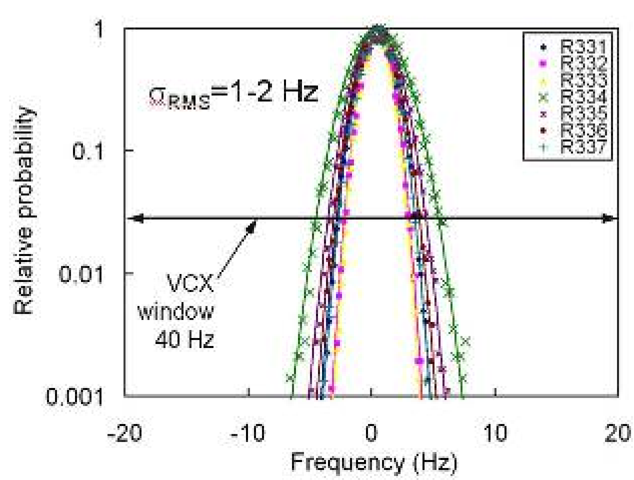

Figure 5: On-line microphonics for all seven cavities.

The accelerating voltages listed in Table 2 are limited by VCX performance, in particular the finite power handling capability of the PIN diodes. All cavities but one are capable of gradients in excess of stable VCX operation. Table 3 shows measured cavity performance with the VCX off. This level of performance can be reached if new mechanical fast tuner technology is used in place of the VCX. Some fraction of the gains shown in Table 3 can also be realized by reducing the tuning window of the existing VCX units. This is a real possibility given the low microphonics signature of the cryomodule.

Table 3: Performance without VCX Limitation

Cavity Number	Cavity Voltage [MV]
1	2.88
2	2.75
3	3.75
4	3.13
5	2.75
6	2.08
7	3.75
Total voltage	**21.1**

RF System

Except for the VCX PIN diode pulsers located next to the module, all the rf systems needed to support eight cavities are contained in a single full-height relay rack. The amplifiers occupy the lower half and consist of 250W solid-state water cooled units. I&Q type LLRF controllers occupy the upper half of the rack and include feedback loops for frequency (slow tuner control), phase (VCX control) and amplitude (input drive power control). The system was assembled in-house and has operated without major incident, allowing all seven cavities to be phase locked on day one of on-line operations.

Cryomodule

Cryomodule performance is described in detail in Ref. [5]. The measured static heat load to liquid helium is 15 W while the load to liquid nitrogen measured 200 W.

Cooldown data are shown in Figure 6. Each cavity together with the focussing solenoid and the cavity support frame is equipped with an independent cooldown circuit. This allows the full cooling power of the refrigerator to be applied to each cavity, providing a fast cooldown to avoid Q-disease (cavities have not received any form of bakeout).

ASSEMBLY

Inside Cleanroom

A model of the clean string assembly is shown in Figure 7. Only those components associated with the cavity vacuum space are involved in the cleanroom phase of assembly. This minimizes the required assembly effort and reduces the particulate contamination risk.

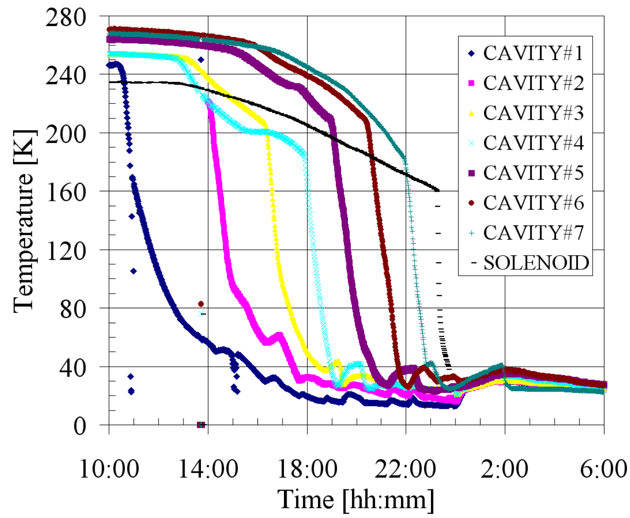

Figure 6: Cooldown rates for cavities and solenoid.

The following components are included in clean assembly:

- Cavities with mounting hardware
- Input couplers
- VCX fast tuners
- Vacuum manifold with pickup loops
- Evacuation/vent system
- Cavity-to-cavity bellows
- Beam valve assemblies
- Support frame with temporary stands

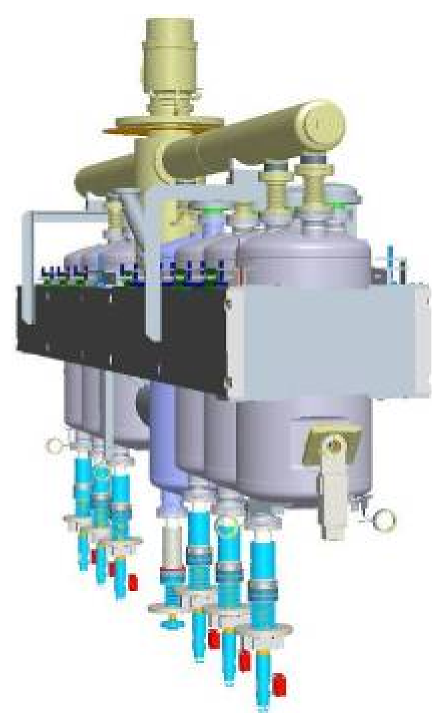

Figure 7: Model of the clean string assembly.

Figure 8: Clean assembly in progress.

The clean assembly task required one month of effort from two workers, not including the up-front component preparation and cleaning. The success of the clean assembly is seen in the performance of the cavities. Figure 8 shows the assembled string in the clean room.

Outside Cleanroom

After clean assembly, evacuation, and leak checking, the string was removed from the clean room and brought to the final assembly area. The string was suspended from the cyromodule lid (Fig. 9) and the remaining subsystems not associated with the cavity vacuum space (slow tuners, coupler drives, instrumentation, cryogenic plumbing) were installed.

Final box closure followed leak checking and subsystem checkout. Figure 10 shows the lid/string assembly being lowered into the box. The box's top-loading geometry is reconciled with the separate cavity and insulating vacuum spaces by passing the beam valves on either end of the string assembly through holes in the angled end walls of the vessel. This design provides straightforward access to module internals to conduct repairs or to replace a cavity. An up-to-air venting system has been developed and tested for this purpose [6].

Figure 9: Dressed string suspended from cryomodule lid.

Figure 10: The lid/string subassembly is loaded into the cryomodule.

Alignment

During clean assembly the cavities and solenoid are rough-aligned automatically by virtue of the inter-cavity bellows assemblies. Once the string emerges from the clean room, the cavities and solenoid are aligned with respect to the support frame to within 0.1 mm of the reference axis. Compliance in the inter-cavity and vacuum manifold bellows is more than sufficient to allow the required adjustment.

Alignment crosshairs are mounted to the solenoid and cavities at outboard locations which are visible through viewports on the end walls of the cryomodule. The crosshairs are referenced to the beam line axis and allow the component positions to be checked after module closure and cooldown. Figure 11 shows the alignment crosshairs and viewports.

COMMISSIONING

The finished cryomodule was cooled down off-line using test ports on the ATLAS refrigeration system. Thermal performance was verified and a temporary rf system was connected for cavity-by-cavity checkout. Subsystems including couplers, slow tuners, and VCX fast tuners were tested. Low level rf checkouts were performed and cavities were conditioned both cw and with 2 kW pulsed rf.

The cryomodule was warmed to room temperature, rolled into the ATLAS tunnel, and rigged into position. The beam line includes liquid nitrogen cold traps immediately upstream and downstream of the cryomodule to avoid particulate contamination of the cavities. In addition, all beam line components in the vicinity of the cryomodule were cleaned prior to re-installation. After 10-15 hours of additional conditioning, the on-line cavity performance matched that achieved off-line.

Figure 11: Alignment crosshair mounted on cavity (top) and cryomodule endwall viewport (bottom).

OPERATIONAL EXPERIENCE

Operations with beam have been underway since late June 2009 with a variety of ion species. Although beam intensities are relatively low, no observable losses have been detected downstream of the cryomodule. Beam-based alignment data suggest some steering effect due to solenoid misalignment, but no steering due to cavity operation has been measured after performing independent checks on each cavity. The solenoid steering is correctable by a straightforward re-alignment of the entire cryomodule.

Subsystems including input couplers, slow tuners, VCX fast tuners, rf systems, and cryogenics have operated without incident.

CONCLUSIONS

The ATLAS Energy Upgrade cryomodule is operating with beam, providing 14.5 MV of accelerating voltage in 4.5 meters. This is a record for this beta range and represents a factor of three performance gain over existing ATLAS technology. An additional 40% performance gain could be realized if the VCX fast tuners were replaced with newer technology.

This cryomodule represents the first full demonstration of clean techniques for low-β srf cavities. All subsystems including adjustable input couplers, mechanical slow tuners, VCX fast tuners, low level and high level rf systems are operating according to specification. Microphonics are very low and have not been an operational issue.

ACKNOWLEDGEMENTS

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