COMMISSIONING OF THE ATLAS UPGRADE CRYOMODULE*

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Abstract

The ongoing energy upgrade of the heavy-ion linac ATLAS at ANL includes a new cryomodule containing seven 109 MHz β=0.15 quarter-wave superconducting cavities [1] to provide an additional 15 MV voltage. Several new features have been incorporated into both the cavity and cryomodule design. For example, the cryomodule separates the cavity vacuum space from the insulating vacuum [2-4], a first for TEM cavities. The cavities are designed in order to cancel the beam steering effect due to the RF field [5]. Clean techniques have been applied to achieve low-particulate rf surfaces and are essential for reliable long-term high-gradient operation. The sealed clean subassembly, consisting of cavities, beam spools, beam valves, couplers, vacuum manifold, and support frame, has been attached to the top plate of the cryomodule outside the clean room. Initial commissioning results are presented. The module was designed and built as a prototype for the Facility for Rare Isotope Beams (FRIB) driver linac, however, a similar design can be effectively used in the front-end of SC proton linacs based on TEM-class SC cavities.

INTRODUCTION

Like the Positive Ion Injector at Argonne's ATLAS heavy ion linac, a rectangular cryomodule design has been developed [2-4] that is simple to assembly and maintain. This latest design is also consistent with the requirements for high performance superconducting rf surfaces. Features include separation of the cavity and the cryogenic vacuum systems, and top-loading of the cavity-string subassembly which enables assembly and hermetic sealing of the cavity string in the clean room. The cryomodule assembly includes three stages: (1) clean-room subassembly of the cavity-string, (2) installation of cryogenics, RF and mechanical systems outside of the clean room, (3) installation of the final assembly into the cryostat to form a completed module. The design of the cryomodule and cavities reflects the current state-of-the-art in SRF technology and incorporates several new features with respect to other recently commissioned SC ion linacs [6, 7]. As a result, substantially higher accelerating fields and cavity voltages are possible as compared to other TEM cavity linacs around the world.

The off-line cryogenic and RF commissioning of the cryomodule has been completed and the cryomodule is installed in the ATLAS tunnel. Subsystem testing is being performed in order to start beam commissioning within several weeks.

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CRYOMODULE DESIGN

The ATLAS energy upgrade cryomodule (Table 1) consist of 7 β_G=0.15 QWRs operating at 109.125 MHz and one 9 T SC solenoid. There is presently one empty slot that will accommodate an additional resonator. Primary design and fabrication technology of the cryomodules, cavities and sub-systems have been reported in several papers [8-10].

Table 1: Main Parameters of the Cryomodule

Parameter	Value	Units
Cryomodule dimensions	1.0×2.0×4.62	m
Average acc. gradient	8.4	MV/m
Cavity eff. length	25	cm
Total heat load (4.5K)	<100	W

RF Couplers

Six cavities are equipped with adjustable inductive couplers as reported in ref. [9, 10]. We have also developed an adjustable capacitive coupler which is installed on one of the cavities. This coupler was a simple modification of the other “loop” antennas. In this application as a bottom mounted coupler on QWR cavities, the cold tests show that the capacitive coupler is less susceptible to the RF heating in overcoupled operation than the loop coupler. The cavities will be operated with $Q_{EXT}=2\cdot 10^8$ at average accelerating gradient of roughly 8.4 MV/m determined largely by the maximum VCX switching power.

Slow and Fast Tuners

Large frequency excursions are corrected using a pneumatically actuated mechanical slow tuner which compresses the cavity along the beam axis. The VCX fast tuner is similar to those that is used on existing ATLAS cavities, and was modified slightly to support independent cavity and cryogenic vacuum spaces and to facilitate clean assembly.

CRYOMODULE ASSEMBLY

A primary design goal was to minimize the number and complexity of the parts requiring clean assembly. This is achieved by limiting class-100 clean-room assembly to a minimum number of components. These include a pumping manifold to evacuate the cavity rf volume and the seven dressed cavities, each with coupler, VCX fast tuner and rf pickup installed. The cavity string is supported on an anodized aluminum strong-back. A pair of beam-line gate valves (one is visible in Fig. 1) and a large right-angle valve are installed on the pumping manifold to seal the cavity vacuum system before it is removed from the clean room. Following the DESY developments, we have implemented low particulate pump down and venting scheme [11] for the cavity string. Final course tuning adjustments were made by "one-shot" squeezing the cavities along the beam axis, and preliminary alignment of cavities was performed in the clean room prior moving the cavity string (Fig. 1) out of the clean area for further assembly.

Figure 1: The cavity string assembly in the clean area is complete, including complete, sealed cavity vacuum system.

The cavity string is suspended from the box cryostat lid outside the clean room. Installation of liquid nitrogen and helium systems, complete assembly of couplers, local thermal shielding, RF pick-up cables, solenoid current leads, thermometry, etc have been performed outside the clean room. After leak checking of LHe and LN systems, the assembly (Fig. 2) was loaded into the cryostat vacuum-box and sealed. Final leak checks of the insulating vacuum, LN and LHe systems were performed after cool down to LN and LHe temperatures respectively. The cryomodule was cooled down to 77K and warmed up twice due to a cold leak in the LN system, found to be in a commercial flexible metal hose in the cryostat thermal shield circuit.

Figure 2: Cavity string suspended from the lid, with all cryogenic plumbing assembled and leak-checked, ready to drop into the box vacuum vessel.

Figure 3: The main RF rack containing 109 MHz amplifiers and control modules.

RF SYSTEM

The RF system of each resonator includes a 250 W water-cooled solid-state power amplifier, an I&Q type LLRF controller, slow and fast tuner controllers and a stepping motor controller for the variable coupler. The I&Q controller includes amplitude, frequency and phase feedback loops. The amplitude feedback loop regulates RF field amplitude by changing the input drive power of the power amplifier. The frequency feedback loop provides stabilization of the resonator central frequency via a slow tuner control system. The phase stabilization loop controls the phase of the RF field in the resonator by means of VCX. The main RF rack (Fig. 3) includes eight RF power amplifiers with three GEN30-50 (30V, 50A) power supplies, 6U euro crate with eight LLRF controllers, 3U euro crate with eight slow tuner controllers, frequency counter and RF patch panel. The VCX PIN-diode pulsers are located in a separate rack in the accelerator tunnel. The RF control module provides phase scan and RF field amplitude adjustments from the control room. All electronic modules have been developed in the Physics Division and built at ANL.

OFF-LINE COMMISSIONING

We have installed 38 diodes to monitor temperatures in various locations during the cool down. The LHe cool down of the cavities is performed sequentially by manually opening valves in each LHe line of the cavity to provide fast transition through the "Q-disease" temperature range. Fig. 4 shows cool down of the 7 cavities and solenoid as a function of time.

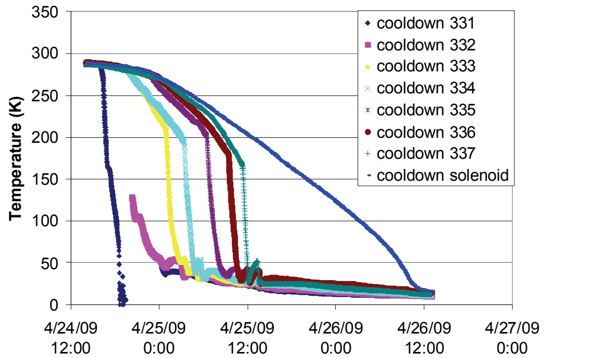

Figure 4: Temperature of the cavities and solenoid as a function of time.

As soon as temperature stabilized near 4.5K, resonant frequencies of all 7 cavities were measured. The operational frequency is 109.125 MHz with the slow tuner at its middle position or 109.135 MHz before activation of the slow tuner. As discussed in ref. [12] all cavities have very similar frequencies and warm-to-cold frequency shift. Slow tuners were cold tested in the pressure range from 0 to 24 psi. The tuning range is 36 kHz for the six production cavities and 55 kHz for the prototype cavity due to the geometry difference. Fast tuners have been tested by manually switching bias voltage on the pin-diodes. The fast tuner frequency window is 35-45 Hz depending from the cavity number [12]. Microphonics measurements have been made and one sigma rms frequency shifts are ~1 Hz for all cavities.

Cold Test of Cavities

The fast tuning of the cavity is provided by a VCX. The latter consumes considerable RF power (about 60 W at 8.4 MV/m accelerating gradient) that dissipates into the LN system. Therefore, the Q of the cavity system in normal operation mode is much lower than with a bare cavity without VCX as shown in the Q-curves in Fig. 5 for the prototype cavity.

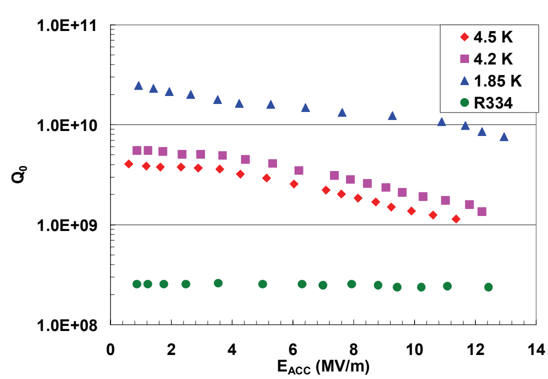

Figure 5: Q-curves measured for the prototype cavity before the installation of the VCX at 4.2K, 4.5K and 1.85K. The green dots show recent measurements with the VCX diodes are on.

The latter has been tested several times in the test cryostat [1] before the installation of the VCX. Measured maximum accelerating gradients for all cavities are shown in Fig. 6. Due to the project schedule constraints we had a limited time for the RF conditioning of the cavities (3-4 hours per cavity). Despite of this, all cavities tested in the cryomodule have shown as good or better performance than in the test cryostat. This fact can be explained by the superior handling techniques and low-particulate pumping system available for the full cavity string assembly. The RF conditioning results of fully-dressed cavities are discussed in detail in ref. [12]. The operational accelerating gradients will be limited by the VCX to an average of 9.38 MV/m .

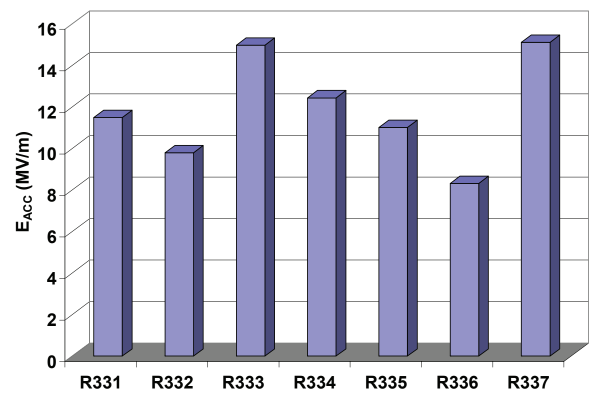

Figure 6: Measured maximum accelerating gradients (L_{EFF} = 0.25 cm).

Static Cryogenics Losses

The static heat leak of the box cryomodule has been measured by the boil-off rate of gaseous helium. The static load is (17 ± 2) W. In addition, the liquid nitrogen static load is 100 W.

ALIGNMENT

The cryomodule box, lid and strongback have been fiducialized to establish fit and repeatability of the cryomodule assembly and to facilitate final alignment of the cryomodule in the beamline. The resonators and solenoid have been preliminarily aligned in the clean room with respect to the strongback. The small welded blocks located at the top and bottom of the resonators serve as fiducial reference points. Fixtures have been built and installed to transfer the cavity aperture center to the resonator fiducial points. More accurate alignment of the cavities and solenoid have been performed outside the clean room using optical tooling instruments. At this stage, the ±100 µm accuracy of beam port alignment in both lateral and vertical directions with respect to the stongback has been achieved. However, measurements taken after the resonator flange connections and loading cavity string into the cryostat, indicate the final positions of the beam ports were closer to ±0.5 mm. The aperture diameter of the cavities is 30 mm and it is larger by 5 mm than the aperture of any accelerating and focusing devices in the existing ATLAS. Therefore, we have decided to accept present ±0.5 mm alignment results and proceed with the installation of the cryomodule in the tunnel.

To monitor movement of the cavities and solenoids during the cooldown and pumping out, we have installed 6 cross-hair targets attached to the solenoids and cavities. Targets are visible through optical viewports on the ends of the cryomodule. Up cooldown shift of (1.58±0.25) mm in vertical position of the targets was measured and is very close to the calculated value of 1.5 mm.

Final alignment of the entire cryomodule will be performed in the tunnel. We plan to verify the alignment procedures by turning on each resonator sequentially and measuring beam center.

BEAM DYNAMICS

The new 7-cavity cryomodule contains only one 9 T SC solenoid. However, beam optics calculations show that an additional SC solenoid is required between the existing F-cryostat of ATLAS and new cryomodule for the focusing of ion beams with lowest q/A ≈1/7. Therefore we have decided to develop and build a new cryostat to house 9 T SC solenoid which was available as an ATLAS spare. Fig. 7 shows assembled cryostat with the SC solenoid inside.

Figure 7: New solenoid in an individual cryostat.

The new cryomodule will routinely provide 14.8 MV accelerating voltage which is calculated assuming 90% of the demonstrated maximum accelerating voltage with VCXs in operation. Energies of all ion beams available at the ATLAS facility will be increased as is shown in Table 2. The simulation of the energy gain of each ion beam has been performed with the code TRACK taking into account available voltages from the existing cavities and new cryomodule.

Table 2: Ion Beam Energies in the upgraded ATLAS

Ion	Q1*	W (MeV/u)	Q1/Q2*	W (MeV/u)
^{12}C	4	19.3	4/6	23.9
^{16}O	6	20.9	6/8	24.3
^{28}Si	9	18.8	7/14	23.1
^{50}Ti	13	16.2	12/21	20.8
^{64}Ni	14	14.3	14/25	19.7
^{84}Kr	15	12.2	15/31	18.5
^{92}Mo	21	14.7	21/34	19.2
^{127}Xe	25	13.2	25/40	17.1
^{178}Hf	31	12.0	31/50	15.7
^{208}Pb	36	11.9	36/55	15.1
^{238}U	34	10.0		

*Q1 is the charge state selected after the ECR, Q2 is the charge state after the stripping downstream of the Booster.

INSTALLATION

After high-power RF testing of all cavities, the box cryomodule was moved into the ATLAS tunnel. The new SC 9 T solenoid in the individual cryostat will be installed upstream of the cryomodule. A cold trap with the total length of ~60 cm was built and will be installed downstream of the cryomodule. Both the cold trap and solenoid cryostat will help to isolate the cavity space in the upgrade cryomodule from the rest of ATLAS vacuum space which is not maintained as a clean, oil free and low particle environment. A photograph of the cryomodule installed and roughly aligned to the ATLAS beamline is shown in Fig. 8.

Figure 8: Photo of the cryomodule in the tunnel.

CONCLUSION

A new state-of-the-art cryomodule for TEM-class SC cavities has been successfully assembled and commissioned. The initial performance of SC cavities exceeds the design goal of E_{ACC}=8.4 MV/m. The cryomodule was installed into the ATLAS tunnel and beam commissioning will be started in several weeks.

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