CRYOGENIC PERFORMANCE OF A NEW 72 MHz QUARTER-WAVE RESONATOR CRYOMODULE*

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Abstract

The Argonne National Laboratory ATLAS accelerator's Intensity and Efficiency Upgrade project has been successfully finished [1]. This upgrade substantially increases beam currents for experimenters working with the existing stable and in-flight rare isotope beams and for the neutron rich beams from the Californium Rare Isotope Breeder Upgrade. A major portion of this project involved the replacement of three existing cryomodules, containing 18 superconducting (SC) accelerator cavities and 9 SC solenoids, with a single cryomodule containing 7 SC 72.75 MHz accelerator cavities optimized for ion velocities of 7.7% the speed of light and 4 SC solenoids all operating at 4.5 K. This paper reports the measured thermal load to the 4 K and 80 K coolant streams and compares these results to the pre-upgrade cryogenic system.

INTRODUCTION

A major objective of the ATLAS Intensity and Efficiency Upgrade was replacing three existing split-ring resonator cryomodules with a single Quarter-Wave Resonator (QWR) cryomodule. This intensity upgrade was motivated by experimental needs which require higher currents for both stable and exotic beams to isolate and investigate previously unstudied uncommon-isotopes. The split-ring cryomodules steer the beam and limit the total transmission through the ATLAS linac and must be replaced to achieve the increased intensity goal [1]. The new SC QWRs were built with tilted drift tube and reentrant nose faces, reducing beam steering to negligible levels and improving the overall transmission through this portion of the accelerator [1]. The QWR cryomodule constructed at Argonne National Laboratory (ANL) contains 7 72.75 MHz, $\beta = 0.077$, QWRs and 4 superconducting 9 T solenoids, all of which operate at 4.5 K. The cryomodule occupies 5.2 meters of beam-line and provides a total voltage gain of 17.5 MV (2.5 MV per cavity, roughly twice any other cavity operating in this velocity regime) [2] with a total measured 4.5 K heat load of 33+10/-5 W.

A second upgrade goal was the reduction of the 4.5 K thermal load in the section of the ATLAS linac where the new QWR cryomodule is located. Reducing the 4.5 K load was accomplished through two measures: (1) reducing the number of cryomodules in the ATLAS linac by replacing 3 old cryomodules with a single new one and (2) replacing and installing new, more efficient, liquid helium transfer lines and distribution boxes. This paper reports on the upgraded 4.5 K and 80 K loads present in ATLAS.

In the following the 72.75 MHz QWR cryomodule design, and measured thermal loads are discussed. This is followed by a comparison of the results to the previous split-ring cryomodule performance. The new QWR cryomodule was first cooled to 4.5 K in December 2013 and has been in full-time use supporting ATLAS operations since March 2014. This has given us ample time to characterize the cryomodule performance and the results presented here represent the highest measured thermal-loads; e.g., with all cavities operating at 2.5 MV.

QWR CRYOMODULE

Cryomodule cold-mass hanging from the lid is shown in Figure 1. The intensity upgrade cryomodule is a modified version of our previous box-type cryomodule which has been in operation since 2009 [3]. Argonne box cryomodules implement current state-of-the-art techniques such as separate cavity and insulating vacuum systems, surface processing and clean handling to achieve and preserve record single-cavity test performance [2, 4], and a design which enables the clean assembly to be complete and hermetically sealed prior to installing the "dirty" subsystems of the cryomodule. The cryomodule structure has been described in great detail in [5].

The cryomodule 4.5 K cryogenic system is gravity fed where each of the 7 QWR and 4 solenoids is attached to a common helium distribution manifold. All penetrations through the cryomodule 80 K thermal shield are baffled or covered such that the solid angle for room temperature surfaces viewing 4.5 K surfaces is minimal (a few square inches for the entire cryomodule) and much of the reflective path between room temperature and 4.5 K is coated with high-infrared-emissivity blackened surfaces [6]. Further reducing the 4.5 K heat load are the low-emissivity 80 K and 4.5 K surfaces which are either aluminized mylar or electropolished stainless steel. Finally, all of the connections to 4.5 K are very low-conductivity. This is accomplished by using very thin stainless steel walls (e.g., the beam-line gates valves and the helium manifold safety pressure relief) or by taking advantage of the acoustic impedance mismatch between titanium and stainless steel at low temperature to increase the contact impedance between these materials (e.g., the cold-mass hangers). The calculated 4.5 K static thermal load is 15 W

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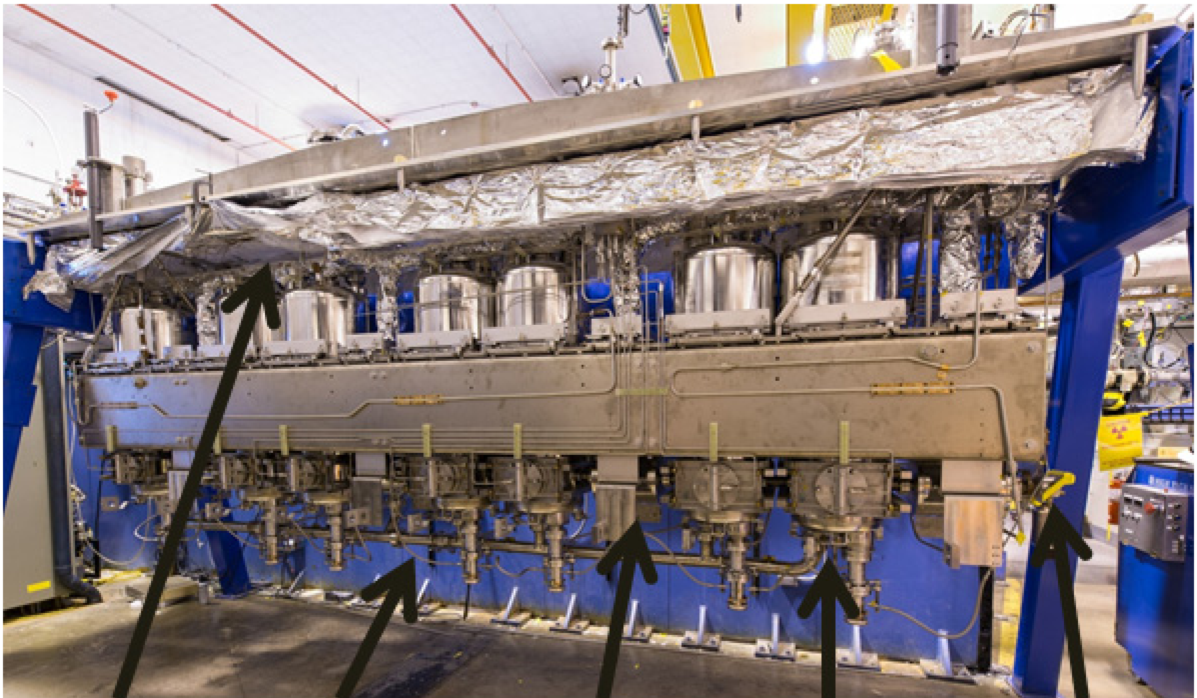

Figure 1: The cryomodule cold-mass hanging from the lid. Not shown are the solenoid gas purged lead feedthrough, the helium manifold relief port and the cold-mass hanger supports.

where the major contributors are: 5 W from 80 K to 4.5 K radiation; 4 W from the helium manifold (with 1.5 W from the solenoid current lead feedthrough and 1 W from the safety pressure relief port); 3 W from the power couplers; and the remainder comes from several <1 W sources which are the beam-line gates valves, the cold-mass hangers, the cavity cool-down lines and the slow-tuner gas lines. We measured the 4.5 K static thermal load with two different methods: (1) The cryomodule helium system was sealed and the rate of pressure rise was measured with two distinct heat loads. First, the pressure rise was observed with only the static thermal load warming the cryomodule. Next, the pressure rise was measured with several different known power levels applied to the helium bath through resistance heaters. For small ΔP, the rise in pressure observed for ~5 minutes was almost linear and the static heat load was extrapolated from comparing the pressure rise for heater powers of 5 W and 10 W to the no-heater case. (2) The cryomodule was vented to atmosphere and all of the venting boil-off gas was passed through a helium mass-flow meter. Figure 2 shows the reading from the mass-flow meter. The initial venting of the cryomodule was done through a different port and the initial mass-flow readings increase from 0 as this valve was closed. The maximum measured value was 12 W and this is used as the static heat load. It is not surprising that the measured value is less than the calculated value. The calculated values all assume shorter conduction paths and neglect thermal contact impedances.

The static 80 K load was measured by passing the nitrogen boil-off gas through a flow meter which was calibrated for room-temperature nitrogen gas flow. After the cryomodule came to thermal equilibrium the measured 80 K boil-off rate was measured to be 60 W. 5 days were required to reach thermal equilibrium. The 5 day cooldown is due to the poorly cooled titanium strong-back. The titanium strong-back is conductively cooled through the cavity and solenoid kinematic mounts [7] which are very low-conductivity. We installed an active He cool-down circuit on the strong-back and will use it to pre-cool more in the future.

Dominating the total 4.5 K thermal load are the dynamic RF losses from the QWRs and couplers. Measuring the dynamic cryomodule losses was possible when the entire cryomodule was cooled with the upgraded ATLAS 4.5 K distribution system. First, the ATLAS 4.5 K refrigerator was operated at constant load. The load was kept constant through the operation of a load levelling resistive heater. The heater power was operated in a feedback loop to stabilize the entire system load such that it varied by 5 W peak-to-peak over the span of an hour prior to the measurements. The load levelling resistor was calibrated by energizing heaters internal to the QWR cryomodule. These heaters are rigidly attached to the helium manifold with hose clamps and there is indium wire between the

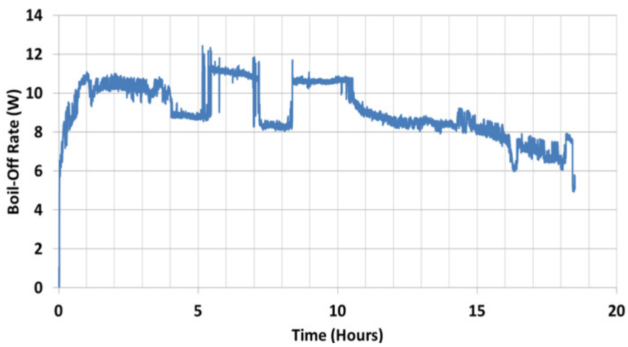

Figure 2: The helium mass-flow meter monitoring the helium boil-off after venting the cryomodule. The venting was done through a single port with all other ports sealed. The steps in the response correspond to the decreasing helium level dropping below the level of the helium manifold dam (a piece of metal welded into the pipe to regulate the maximum liquid level), the helium manifold, the top of the cavities, and the top of the solenoids. A 12 W load was largest reading observed.

heaters and the manifold to ensure good thermal contact. The cryomodule heaters were operated at 5 W, 10 W, 20 W 30 W and 40 W. Measureable changes in the 4.5 K helium system load levelling heater occurred for heater powers of 10 W and greater. Above 30 W the 4.5 K system pressure started to increase leading to a larger measurement error as reflected in the error bars. The day after the load levelling heater was calibrated the cryomodule QWRs were all energized to an average voltage gain of 2.5 MV per cavity. After the last cavity was excited and the 4.5 K helium system came to equilibrium the load levelling resistor power was measured to be 33 +10/-5 W. The helium system pressure was constantly rising during this time indicating that the cryogenic load was somewhat higher giving the larger upper error bar.

COMPARISON TO PREVIOUS PERFORMANCE

The 3 split-ring cryomodules which were removed consisted of a 4-cavity, an 8-cavity and a 6-cavity cryomodule. These cryomodules each had static 4.5 K thermal loads of 25 W static and the dynamic cavity loads were ~5 W per cavity. With the total 4.5 K load for all split-ring cryomodules being 165 W, 75 W static and 90 W dynamic. The new QWR cryomodule has a measured total 4.5 K load of 45 W, 12 W static and 33 W dynamic. This saves roughly 120 W of 4.5 K capacity relative to the older split-ring cryomodules. More importantly, this demonstrates the cryogenic savings gained by using fewer higher-performing superconducting cavities in a compact linear accelerator.

SUMMARY

The installation and commissioning of a new QWR cryomodule for ATLAS is complete. The new cryomodule has a measured 4.5 K thermal load of 45 W, 12 W static and 33 W dynamic. The 80 K load was observed to be 60 W. This has resulted in considerable saving for the ATLAS cryogenic system, 120 W. Extra cryogenic capacity is now available for other liquid helium cooled devices and some of this is already being used. The reduced cryogenic loads clearly demonstrate the utility of using high-performance superconducting resonators to shrink the cryoplant size for new accelerators and the cost of future projects.

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