SUPERCONDUCTING CAVITY CRYOMODULES FOR HEAVY-ION ACCELERATORS AT ARGONNE*

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Abstract

Over one year ago the ATLAS Efficiency and Intensity Upgrade (EIU) was finished. A major portion of this upgrade was the installation of a new superconducting cryomodule for the acceleration of β = 0.077 heavy-ion beams. The EIU cryomodule is capable of supplying a voltage gain greater than 17.5 MV with a total cryogenic load of 45 W to 4.5 K, 12 W static and 33 W dynamic. This unit is comprised of seven 72.75 MHz quarter-wave resonators and four 9 T solenoids. This presentation will review the technology advances that resulted in exceptional operational performance of the EIU cryomodule and the ongoing development work for a new eight-cavity beta = 0.11 half-wave cryomodule.

INTRODUCTION

Low-beta (β = v/c < 0.5) cryomodules occupy a significant portion of the length of proton/heavy ion accelerators. Two recent examples of this are: (1) The proposed 800 MeV booster linac for the Fermilab Proton Improvement Project-II (PIP-II) with low-beta cryomodules occupying 30% of its length which house 59 of the 116 SC cavities [1]. (2) The Michigan State University 200 MeV/u Facility for Rare Isotope Beams (FRIB) ~300 m driver linac where 100% of the cryomodules house low-beta co-axially loaded SC cavities [2]. The accelerator real-estate length occupied by the low-β cryomodules is a strong incentive to make them efficient and high performance.

At Argonne we installed a heavy-ion cryomodule capable of achieving high accelerating voltages with small cryogenic loads which has been in operation for over a year [3]. This cryomodule houses 7 72.75 MHz quarter-wave resonators (QWRs) optimized for the acceleration of beta = 0.077 ions and 4 9 T solenoids. In this paper we first discuss the measured thermal loads. This is followed by a comparison of the results to the previous split-ring cryomodule performance. Finally, a few concluding remarks are made.

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-load; 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 EIU cryomodule is a modified version of our previous box-type cryomodule which has been in operation since 2009 [4]. Argonne box cryomodules implement current state-of-the-art techniques developed for electron accelerators such as separate cavity and insulating vacuum systems, surface processing and clean handling to achieve and preserve record single-cavity test performance [3, 5], 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 [6].

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 [7]. 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 mis-match 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 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

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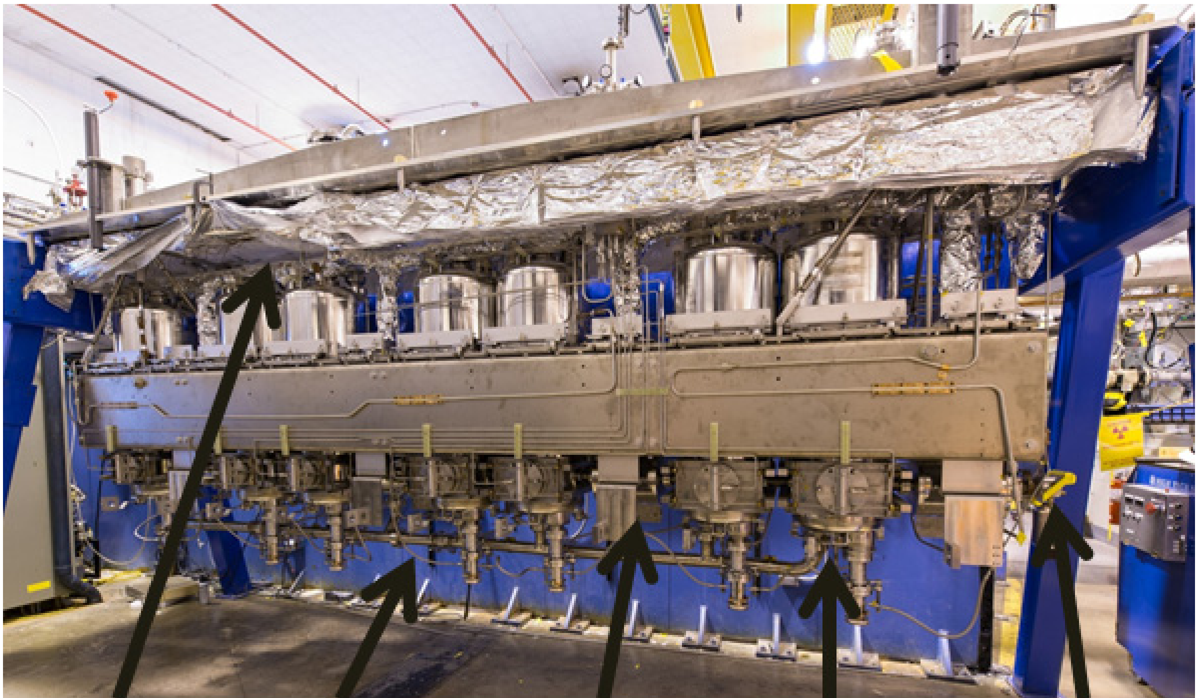

Figure 1: The cryomodule cold-mass hanging from the lid. Not shown are the solenoid gas purged lead feedthrough, the helium manifold relief port and the cold-mass hanger supports.

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 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 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

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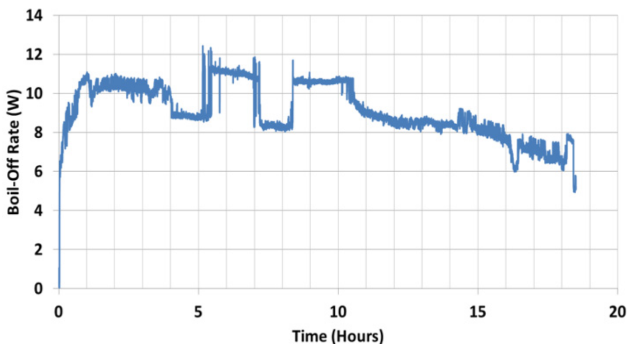

Figure 2: The helium mass-flow meter monitoring the helium boil-off after venting the cryomodule. The venting was done through a single port with all other ports sealed. The steps in the response correspond to the decreasing helium level dropping below the level of the helium manifold dam (a piece of 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.

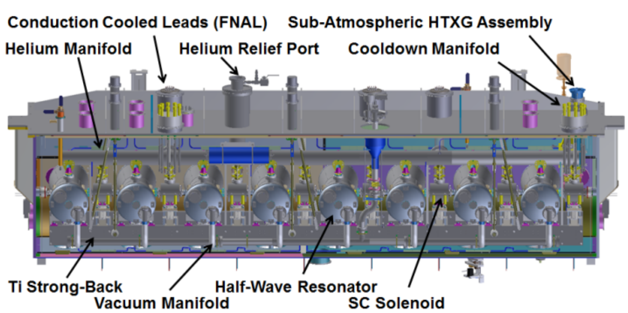

Figure 3: Cross section of the new HWR cryomodule.

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.

PREVIOUS ATLAS 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 [8], 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.

CONCLUDING REMARKS

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, equal to 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.

This work is now serving as the baseline for a new 2 Kelvin half-wave resonator (HWR) cryomodule being built as part of the FNAL PIP-II project. This cryomodule houses 8 HWRs and 8 superconducting solenoids, one in front of each cavity. Figure 3 shows a cross section view of the module. Two HWRs have been tested so far with exceptional results [9].

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