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STAND-ALONE ACCELERATOR SYSTEM BASED ON SRF QUARTER-WAVE RESONATORS*

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Abstract

Superconducting accelerators are large and complex systems requiring a central refrigerator and distributed transfer systems to supply 2-4 K liquid helium. Stand-alone, cryocooler-based systems are of interest both to scientific facilities and for industrial applications, as they do not require large cryogenic infrastructure and trained specialists for operation. Presented here is our approach to the challenge of using low-power commercially available cryocoolers to operate niobium superconducting resonators at 4.4 K with high accelerating voltages and several watts of heating. Engineering and design results from RadiaBeam Systems, collaborating with Argonne National Laboratory, for a stand-alone liquid-cooled cryomodule with 10 Watts of 4.4 K cooling capacity housing a 72.75 MHz quarter-wave resonator operating at 2 MV for synchronous ions travelling at 7.7% of speed of light will be discussed.

INTRODUCTION

Typical superconducting RF (SRF) accelerators are relatively large complex systems requiring a central refrigeration system and complex piping to distribute liquid helium and nitrogen to the accelerator. However, in recent years the development of self-contained Gifford-McMahon (GM) and pulse tube refrigerators have continued to improve in both reliability and capacity. Today a number of superconducting magnet designs rely on those systems and have resulted in a significant expansion of the applications for such magnets. The cooling capacity of these systems has become great enough to consider their application for cooling SRF resonators and associated components. As long as the SRF cryomodule heat load is well managed, and attention is carefully paid to the issues of total cooling requirements and vibration, a cryocooled SRF cryomodule is realizable. Such systems are of interest both to scientific facilities and for industrial applications as they do not require massive and extremely expensive cryogenic facilities (4.4 K) and the trained specialists required for their operation. Stand-alone accelerators can be used as bunchers or accelerating sections in large accelerator facilities or as turn-key accelerator systems for industrial applications such as materials processing, semiconductor manufacturing, food irradiation and homeland security.

For example, the Argonne Tandem Linac Accelerator System (ATLAS), a national user facility for stable low-energy nuclear physics, is actively working on the expansion of their scientific capabilities and require additional SRF resonators in experimental areas where no helium cryogenics are available. Examples of the applications of the SRF resonators at ATLAS include the following [1]:

- Multi-User Upgrade (MUU) re-accelerator in the general-purpose beamline.
- De-buncher cavity the Argonne In-flight Rare Isotope Separator (AIRIS).
- A high-performance buncher before a beam switch yard.

ATLAS, however, does not have excess refrigeration capacity in the existing main refrigeration system to support operations in the experimental areas. A stand-alone cryomodule would eliminate the need for additional cryoplants or capacity.

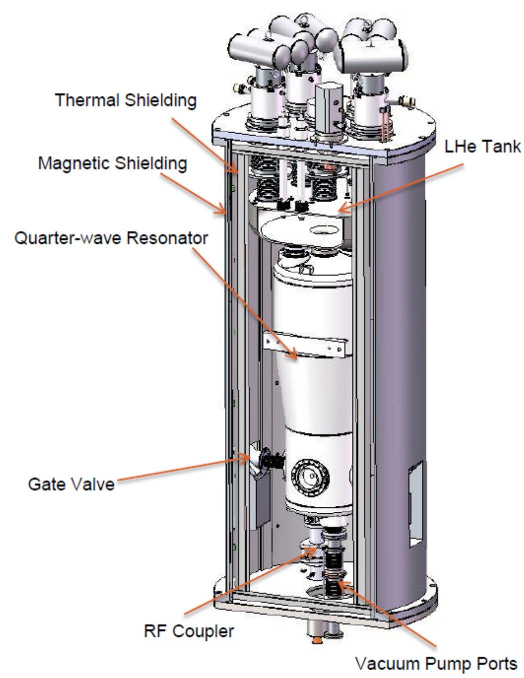

Figure 1: Conceptual engineering design of the stand-alone QWR-based cryomodule.

In response to this need, RadiaBeam Systems in collaboration with Argonne National Laboratory has developed a stand-alone cryomodule, based on a commercially available cryocooler, for the dressed 72.75 MHz quarter-wave resonator (QWR) [2]. QWR was designed and fabricated at Argonne for the ATLAS intensity upgrade project [3], as shown in Figure 1. The dressed cavity, developed by Argonne, can provide up to 2 MV voltage gain for particles

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traveling at 7.7% of the speed of light with 4.5W of dynamic power losses, which makes it a perfect fit for the above-mentioned purposes at ATLAS. The main innovation of this project is the development of a cryocooler/liquid-based cooling system. Prior stand-alone cryomodule designs incorporated conduction cooling [4, 5]. Conduction cooled accelerator resonators are limited by conductive cooling flow and cannot operate at high fields. Helium bath cooled resonators, with their greater cooling capacity, can reach higher fields. The stand-alone system will employ liquid-based cooling where the helium tank is prefilled with liquid helium, and the cryocoolers are used to maintain the liquid state and re-liquefy boil-off. The 40 liters He tank incorporated in our design provides about an hour of protection before the helium evaporates, in case of a short power outage. This is more than enough time for a power changeover to battery backup or a generator.

CRYOMODULE CONCEPT

The proposed cryomodule design is shown in Figs. 1 and 2. The body is a large cylindrical stainless-steel vacuum chamber with a diameter of 36 inches, 40-inch diameter at the flange, and a flange to flange height of 88.5 inches to house Argonne's 72.75 MHz quarter-wave resonator. A cylindrical design helps to keep the chamber relatively compact and robust. The cylindrical design also lends itself to the easy addition of thermal and magnetic shielding. Two re-entrant style ports allow the QWR to be installed fully dressed. The chamber is designed to be operated at vacuum levels of less than a microbar.

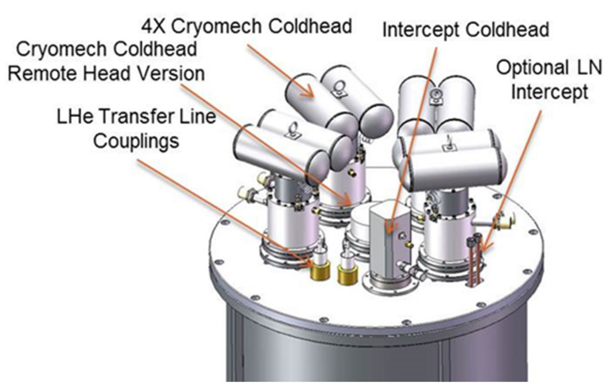

Figure 2: Cryomodule head close-up.

There are four Cryomech pulse tube refrigerators and one remote head cryocooler in the center of the flange. The net cooling power of these five cryocoolers working in parallel should be 9.8W at 4.5K. These cryocoolers hang into the liquid helium tank below, which in turn feeds into the QWR, working to offset static heat leaks and additionally the dynamic heat loading generated during operation. The smaller cryocooler acts to remove heat from the thermal shield and thermal intercepts internal to the system. The liquid helium tank acts as the fill reservoir, approximately 40 liters volume, for the temperature fluctuations the QWR may experience. It is also the natural place for the cryocooler to directly feed into and act as a heat sink for these heat fluctuations. The LHe tank was designed to be suspended from the top flange using three central rod hangers. The QWR is flanged on to the base of the liquid helium tank. Every other connection between the resonator and the chamber occurs with adjustable bellows.

The magnetic shielding was added to protect the SRF cavity from the environmental noise that otherwise exists. The immediate inner wall of the cryomodule chamber and flanges will be lined with high permeability magnetic shield plating utilizing a mu-metal derivative, such as AD-MU-80. The thermal shielding is mounted to welded connection points along the chamber wall. First a thick number of layers of multilayer insulation (MLI), then a copper thermal shield, followed by a much thinner layer of MLI, similar to LCSL-II design [6]. MLI is typically made up of a material that has high emissivity, such as Aluminized Mylar, and a low thermal conductivity spacer material, such as polyester.

HEAT LEAKS

We have performed the analytical and ANSYS numerical thermal analysis of the designed cryomodule to quantify the static heat leaks. One of the major sources of static heat are the heat transition sections that connect the RT environment with any LHe parts. The other heat leak sources include:

- heat diffusion into all solid / surface elements given temperature dependent thermal conductivity;
- surface to surface heat radiation inside the transition given temperature depend on emissivity;
- heat radiated from the vacuum vessel onto the surfaces of the cold to warm transition;
- heat radiated from the thermal shield onto the surfaces of the cold to warm transition.

Table 1: Summary of Components' Static Heat Leaks

Component	# of units	To LN2, W	To LHe, W
He chamber bellow 1	1	4.1	0.97
He chamber bellow 2	4	4.79	0.24
Gate valve	2	0.46	0.03
RF coupler	1	2.14	0.06
Pumping spool bellow	1	4.84	0.6
Magnetic shield	10	1.23	-
Radiative heat transfer	1	13.44	0.07
He transfer line	1	-	0.51
Total heat leak		56.90	2.61

Optimization of the helium chamber bellows was performed to minimize the total flow to 4.5K and thermal intercept. The total heat leak to the liquid helium bath was estimated at the level of 2.6W, which is below the target value of 5W. The heat leak to the thermal intercept, kept at

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the temperature of liquid nitrogen is ~57W, which is equal to the smaller cryocooler capacity at this temperature. The thermal intercept losses can be traded-off with the LHe losses if needed, as shown in Figure 3. This is especially important for the operations in semi-stand-alone regime, when the liquid nitrogen can be supplied from the external cryogenic facility. The Summary of individual components' heat leaks is shown in Table 1.

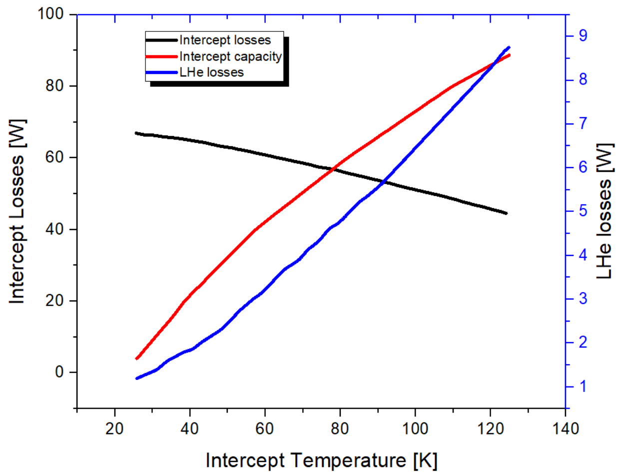

Figure 3: Possible trade-off between intercept and LHe losses.

Dynamic losses are comprised of RF losses is the ATLAS QWR cavity and the RF coupler. The cavity losses to liquid at 2 MV operation are 4.3 W, and the RF coupler adds another 1.34 W at 4 kW input power. The total heat leak during the operation is, therefore, 8.5W, which is below the maximum cryocooler capacity of 10 W.

STRUCTURAL ANALYSIS

Finally, we have performed the structural analysis of the designed cryomodule to ensure basic mechanical stability in its role. First, Von Mises stress was looked at for any sign of loading failure (see Figure 4).

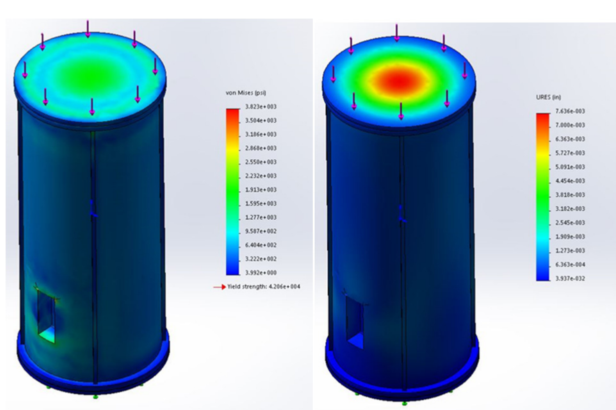

Figure 4: Simulated von Mises stresses (left) and deformations (right) of the cryomodule.

In general, all stresses were so low that it is clear that the chamber design has some flexibility when moving towards manufacture. The next area explored was material deformation or displacement under load. The maximum displacement was on the top, flat, heavily loaded flange at around .008 inches down. This amount of deformation is well within reason and would still not be a concern if the result was a factor of four worse. Buckling analysis was performed to ensure that the chamber would be robust enough to be handled or bumped once it is built. With a load factor of 72, this chamber design has proven to be extremely robust.

As a whole the cryomodule performed excellent in all forms of structural analysis. The current design should allow for good flexibility in fabrication. One of the greatest benefits to this design is its cylindrical shape which adds to its nets strength while saving on manufacturing costs. This is a very simple feature that cannot easily be taken advantage of in the majority of cryomodule designs due to the need for multiple components versus a single resonator.

SUMMARY

The design offers some attractive features:

- The cryomodule has a cylindrical shape, which is much more mechanically stable than the rectangular;
- The cryomodule has five 2W cryocoolers which allow flexibility in the available power, and gives the user an opportunity to upgrade the system from 3 to up to 5 cryoheads later if needed;
- The cost of cryocoolers is comparable to the cost of the stationary cryogenic system;
- The stand-alone system will employ a liquid-based cooling where the helium tank is pre-filled with liquid helium, and the cryocoolers are used to maintain the liquid state and prevent boiling;
- Static heat leaks are minimized to the level of 2.6 W, allowing the cavity operation with up to 2 MV voltage;
- The cryomodule design can be adapted for the other types of cavities;

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