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CONDUCTION-COOLED SRF CAVITIES: OPPORTUNITIES AND CHALLENGES*

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Abstract

Thanks to improvements in the performance of both commercial cryocoolers and Nb_3Sn-coated superconducting radio-frequency (SRF) cavities, it is now possible to design and build compact, SRF cryomodules without the need for liquid cryogenics. In addition, these systems offer robust, non-expert, turn-key operation, making SRF technology significantly more accessible for smaller-scale applications in fields such as industry, national security, medicine, environmental sustainability, etc. To fully realize these systems, many technical and operational challenges must be overcome. These include properly cooling the SRF cavity via thermal conduction and designing high-power (~100 kW continuous) RF couplers which dissipate minimal heat (~1 W) at 4.2 K. This paper will discuss these challenges and the solutions which have been developed at Cornell University and elsewhere.

INTRODUCTION

Reports from the U.S. Department of Energy have identified a large number of applications which are ideal for small-scale accelerator operations [1,2]. These applications represent a range of fields such as energy and environment (wastewater treatment, soil remediation, flue gas treatment), medicine (isotope production, device sterilization), security and defense (scanning), industry (semiconductor production) and more. One advantage of all of these applications is that they fall within a relatively small beam parameter space with moderate energies but high current and power; see Table 1 [1,2].

Table 1: Typical Beam Parameters

Property	Value	Units
Energy	1 - 10	MeV
Current	100 - 1000	mA
Power	1 - 10	MW

Many of these applications would benefit from the use of SRF technology to increase average power and throughput. However, this would typically require the use of liquid helium for cooling the accelerating cavities. This poses a significant challenge for small operations due to the size and complexity of the infrastructure needed for helium systems.

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This indicates that replacing liquid helium with another cooling source would be a major benefit to the accessibility of SRF technology. This paper explores the use of cryocoolers as a new cooling mechanism for SRF cavities and discusses key aspects of developing new standalone cryomodules in which liquid cryogenics are replaced with cryocoolers.

CONDUCTION COOLED SRF CAVITIES

Two key factors enable SRF cavities to be operated without the use of liquid helium: highly efficient Nb_3Sn cavities and improved commercialized cryocoolers. In recent years, the quality of Nb_3Sn films in SRF cavities has improved dramatically, resulting in cavities which dissipate very low heat even at moderate fields (~10 MV/m) relevant to small-scale operations [3–9]. In addition, commercially available cryocoolers are now able to extract up to 2.5 W at 4.2 K [10]. These developments are represented in Fig. 1, which plots the discussed trends for both Nb_3Sn cavities and cryocooler cooling capacity over time. This highlights how only in the last few years have these technologies matured to the point of enabling the development of conduction-cooled SRF cavities.

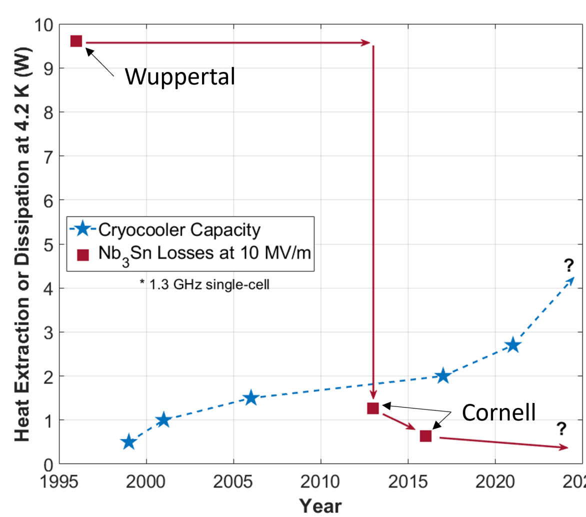

Figure 1: Progress in both Nb_3Sn cavity performance (red squares) and pulse-tube cryocooler capacity at 4.2 K (blue curve) [10].

Multiple labs have already completed proof-of-principle demonstrations of this concept. The cavity assembly used in Cornell's original studies can be seen in Fig. 2a. Key components indicated include the 2.6 GHz Nb_3Sn cavity,

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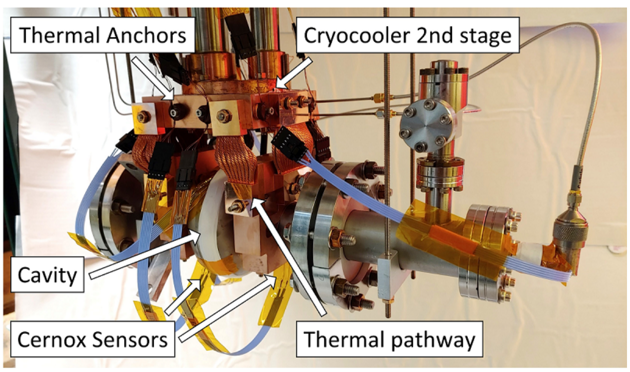
the thermal pathway, thermal anchor points and the cryocooler's 2nd stage cold head. In this study, the conductive pathway between the cavity and the cryocooler was made up of braided copper straps with copper beam tube clamps on each side of the cavity cell. This assembly reached 10 MV/m CW operation, the very first conduction cooled cavity to do so at the time [11, 12]; see Fig. 2b. Further studies using this assembly demonstrated that using independently controlled heaters on both sides of the cavity provided the most reliable way to achieve thermal gradients less than 200 mK/m across the cavity during cooldown. This is required for Nb_3Sn cavities to achieve optimal RF performance by reducing the generation of thermal currents [5]. More detailed results and further analysis of this proof-of-principle experiment can be found in Ref. [12].



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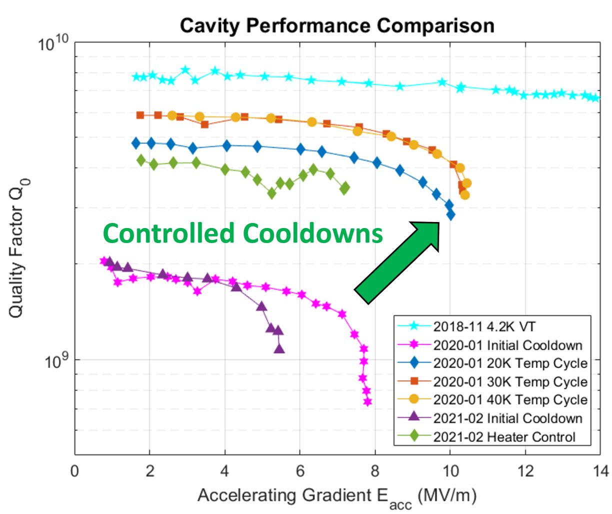

(b)

Figure 2: (a) Cavity assembly used in the original proof-of-principle demonstration at Cornell. (b) RF results from the conduction-cooled assembly. The most successful tests were one which followed a more controlled cooldown.

Fermilab's initial studies involved a single-cell 650 MHz Nb_3Sn cavity with Nb rings welded to both sides of the cavity equator. High-purity (5N) aluminum rings were then bolted on with a thin layer of indium in between, and bent 5N aluminum plates completed the conduction path to the cryocooler cold head. This cavity also reached 10 MV/m after controlled cooldowns; more information can be found in their publications [13, 14].

Jefferson Lab originally investigated a conduction-cooled assembly using a single-cell 1.5 GHz Nb_3Sn cavity which was plated with a 5 mm layer of copper on the cavity exterior. This thick copper layer was added to improve thermal conduction across the entire cavity. An additional copper ring was added to the equator region, which was then connected to the cryocooler via copper thermal straps. This cavity saw promising results which are discussed in Ref. [15].

There are also ongoing proof-of-principle studies in labs around the world such as KEK in Japan and IMP in China. Further details of these studies can be found by contacting the contributors listed in the Acknowledgments section.

KEY CHALLENGES AND SOLUTIONS

With the concept of conduction-cooled SRF cavities successfully proven, the next step to further develop this technology is to design a standalone SRF accelerating cryomodule which only utilizes cryocoolers for heat extraction. The targeted operating specifications of a new system worked on at Cornell are shown in Table 2. This design process faces new challenges which must be considered to find a successful implementation. This section will discuss two key challenges along with the solutions which have been developed at Cornell.

Table 2: Cryomodule Operating Specifications

Property	Value	Units
Frequency	1.3	GHz
Energy Gain	1	MeV
Max Current	100	mA
Max Power	100	kW

The first challenge is achieving effective conduction cooling of the cavity assembly. A key factor which makes this difficult is the limited cooling capacity that cryocoolers can provide. As mentioned earlier, currently available cryocoolers are only capable of extracting 2-2.5 W at 4.2 K. The system designed at Cornell uses only two cryocoolers for a total cooling capacity of 4.15 W at 4.2 K. Another factor is that the Nb_3Sn cavity temperature must stay near 4.2 K to maintain a high Q_0, which requires very small thermal gradients across the conductive path between the cavity and cryocooler. Finally, uniform cooling of the cavity is required during operation. While a helium bath would obtain this easily, additional attention must be paid to ensure that the thermal design provides good conduction around the entire cavity. Only high-purity (e.g. 5N) aluminum and copper offer thermal conductivity high enough to satisfy these requirements; see Fig. 3.

Figure 4 shows the new cavity assembly designed at Cornell. The top image shows a CAD model of the cavity and thermal connection to the cryocooler, while the bottom im-

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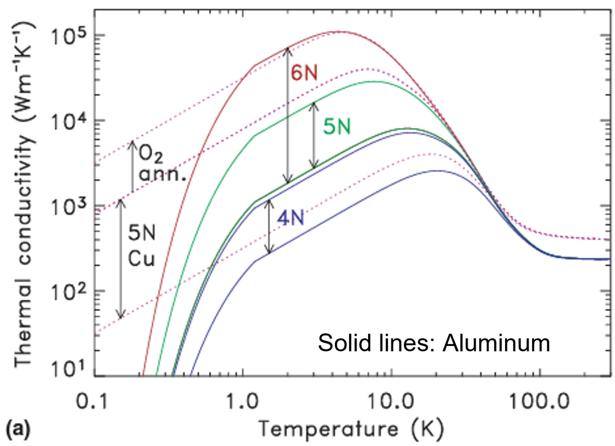


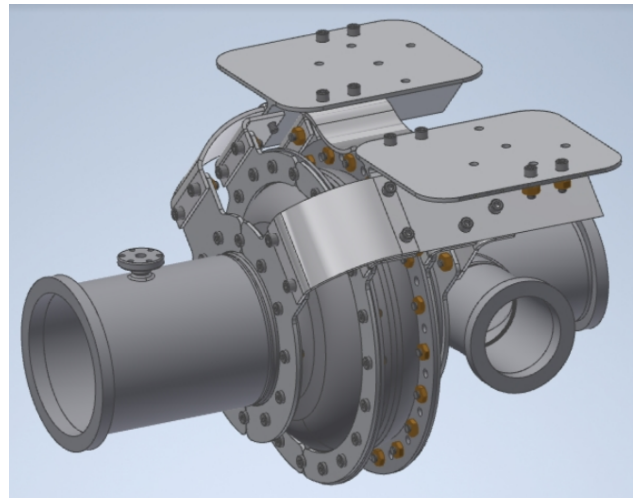
Figure 3: Thermal conductivity values of high purity aluminum and copper at cryogenic temperatures. Solid colored lines represent different aluminum purity while dotted lines represent copper [16].

age shows the cavity itself after completion of welding. This design includes four niobium rings welded to different parts of the cavity: two rings are located 2 cm from the cavity equator while two rings are located near each iris. High-purity (5N) aluminum rings are then bolted to each of the niobium rings, and 5N aluminum foil straps connect the rings to the cryocoolers.

Thermal modeling of the cavity assembly was performed in Ansys; Fig. 5 shows a resulting temperature profile for 10 MV/m operation. The results show small thermal gradients both across the cavity and between the cavity and cryocooler cold heads, which are held at 4.2 K. In addition, the heat load at 4.2 K is 1.65 W for RF losses corresponding to 10 MV/m operation. Together, these results satisfy the restrictions discussed previously, confirming that this design successfully addresses the first major challenge. Further details on the cavity design and modeling, as well as discussion of additional capabilities like thermal gradient control during cooldown, can be found in Ref. [17].

The second major challenge comes from the design of the RF coupler. As stated previously, many small-scale applications require high power on the order of 1 MW. This means that the couplers used for such a system must deliver very high power while also maintaining very low heat leak at 4.2 K. For example, the couplers designed at Cornell had a design goal of dissipating only ~1 W of heat at 4.2 K with 100 kW forward power. This represents a factor of 10^5 difference between the forward power and allowable heat leak. Accomplishing this requires significant RF optimization and re-distribution of heat loads in the coupler.

Two key features contributed significantly to meeting this goal: (1) the addition of quarter-wave transformers to both sides of the inner conductor bellows; (2) the addition of an "RF shield" to intercept RF losses at the cold end of the coupler and redirect them to the 45 K intercept. In the end, the optimization of these and other coupler components result in a heat load of only 1.1 W at 4.2 K for 100 kW forward power.



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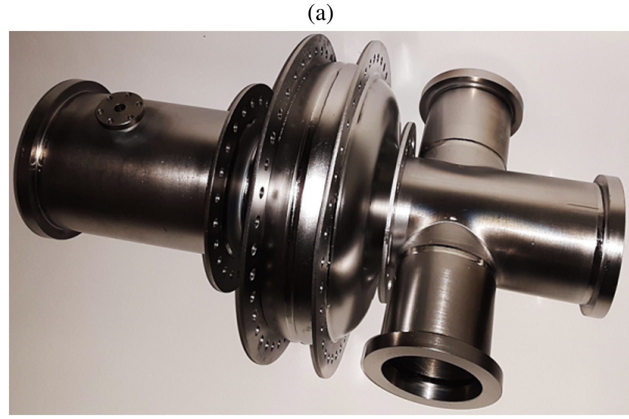

(b)

Figure 4: (a) CAD model of the cavity assembly designed for the new cryocooler-based cryomodule. The model includes both the cavity itself and the thermal strap connections to the cryocooler cold heads. (b) Image of the physical cavity with all welding completed.

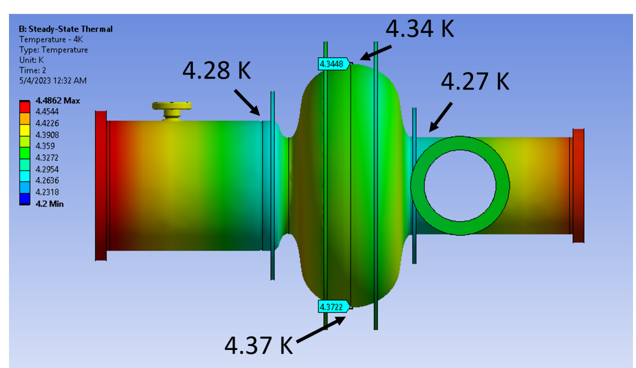

Figure 5: Temperature profile of the cavity obtained from thermal modeling in Ansys.

This again confirms that the design meets the primary requirement described previously. Detailed discussion of the coupler design and optimization can be found in Ref. [18].

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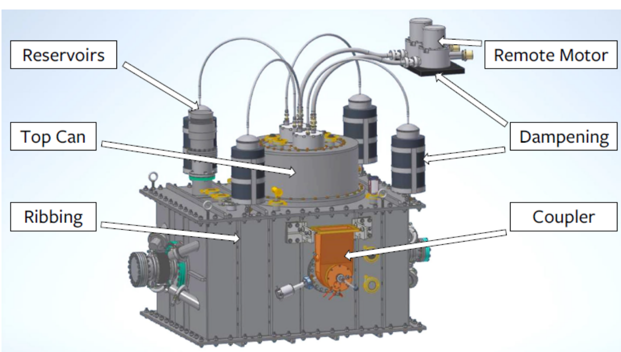
CRYOSTAT DESIGN

Design of the cryostat components was guided by the following considerations:

1. After taking into account the heat loads of the cavity and couplers, only ~0.5 W remains at 4.2 K for the remaining components.
2. Overall size and complexity should be minimized to reduce weight and cost.
3. Components must accommodate thermal contraction and mitigate vibrations.

The resulting design is shown in Fig. 6. The use of a space frame was chosen to reduce the weight on the cryocooler and improve cooling of the thermal shield, while G10 rods are used to support both the frame and cavity assembly while minimizing heat leak. Large copper disks are used for heat intercepts where the couplers and beam tubes intersect the thermal shield in order to minimize the length of the thermal straps, as this increases thermal conduction across these connections. A top "can" which houses the cryocooler units allows for a smaller volume and better access during assembly, while supportive ribs are added to the cryostat walls to increase stability under vacuum.



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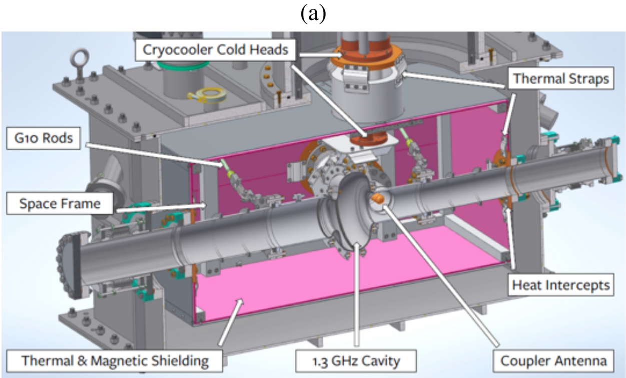

(b)

Figure 6: (a) CAD model of the full cryostat showing two cryocoolers attached. (b) Cross-sectional view of the cryostat with key components indicated.

Thermal modeling was performed on the thermal shield to determine the expected temperature profile and heat loads at 45 K. Materials used in the model include Al-1100 (space frame, side and bottom thermal shield panels), OFHC 150 RRR Cu (heat intercepts, thermal straps, top thermal shield panels), and 316 stainless steel (beam tubes, outer flanges, bellows). Temperature-dependent thermal conductivities were defined for each material. To represent heat loads at 100 kW forward power per coupler, 37.9 W were applied to each coupler intercept [18]. The cryocooler cold heads were held at 45 K while the warm and cold ends of the beam tubes were held at 300 K and 4.5 K (see Fig. 5), respectively. Finally, a radiative heat flux of 1.5 W/m^2 was applied to all exterior surfaces; this value is expected based on the use of MLI surrounding the thermal shield assembly.

Figure 7 shows a temperature profile of the thermal shield assembly calculated from this thermal model. The results show relatively small thermal gradients across the thermal straps due to their short lengths. The average temperature of the thermal shield is 53.7 K, with a total heat load of 92.5 W at 45 K.

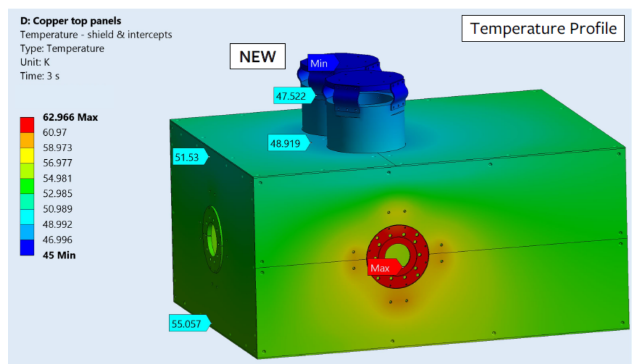

Figure 7: Temperature profile of the thermal shield assembly obtained from thermal modeling in Ansys.

Combined with an estimated 0.34 W from the G10 rods, the total heat load of our system at 45 K is 92.84 W out of a total cooling capacity of 100 W from the two cryocoolers. At 4.2 K, the heat load contributions are 1.65 W (cavity), 2*1.11 W (couplers), 0.02 W (G10 rods) and 0.1 W (radiation) for a total of 3.99 W. The total cooling capacity available at 4.2 K is 4.15 W. This confirms that our system is able to operate at spec within the limits set by the cryocoolers. The total heat load comparisons are summarized in Table 3.

Table 3: Total System Heat Loads

	45 K	4.2 K
System Heat Loads	92.84 W	3.99 W
Cryocooler Limits	100 W	4.15 W

For details on a variety of other projects which develop the cryocooler-based SRF cryomodule concept for a variety of applications, please refer to project updates from Fermilab [19] and Jefferson Lab [20].

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CONCLUSION

The continued improvement of both Nb_3Sn-coated SRF cavities and commercialized cryocoolers has opened the door to the design and fabrication of compact SRF cryomodules which only use cryocoolers for extracting heat from the system. Several proof-of-principle demonstrations of the concept have been completed at various labs, showing successful implementations of different cooling schemes. These studies have since led to the development of standalone cryomodules designed to for use in a wide range of applications in fields such as environmental sustainability and medicine. At Cornell, we have completed the design of such a system and modeling shows that it will be able to operate with the targeted parameters while remaining within the cooling limits set by the use of two cryocoolers. Now that the design stage is complete, fabrication of the various components has begun and we intend to begin assembly and testing of the cryomodule at the end of this year.

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