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CW OPERATION OF CONDUCTION-COOLED NB_3SN SRF CAVITY*

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Abstract

The substantial development of Nb_3Sn for use in SRF cavities has enabled reliable RF operation at 4.2 K rather than 2 K while maintaining comparable cavity performance. This reduction in required cooling power makes novel cooling schemes possible. New studies have examined the use of commercialized cryocoolers in conduction-cooling based test assemblies for Nb_3Sn SRF cavities. Cornell University has developed and tested a 2.6 GHz Nb_3Sn cavity assembly which utilizes such cooling methods. RF tests in early 2020 resulted in the first-ever demonstration of stable CW operation at 10 MV/m for a conduction-cooled cavity. Our studies also revealed the importance of re-cooling the cavity with more controlled methods in order to improve cavity performance. This finding is connected to the reduction of thermal gradients across the cavity during the superconducting transition.

INTRODUCTION

National studies and workshops have found that a wide range of fields benefit from the use of accelerators at different energy scales, some of them around a few MeV. Some notable examples include: radioisotope production for medical imaging and treatment, material processing and e-beam lithography for integrated circuit printing in industry, wastewater treatments for environmental impacts, and cargo scanning for national defense. Such applications, along with many others, are examined in detail in reports from the DOE and national labs [1, 2]. In many cases, switching to SRF technology could pose a significant advantage thanks to the massive increase in cavity efficiency compared to normal conducting cavities. However, the cooling requirements for SRF cavities present a substantial obstacle, as they require complex and expensive cryogenic infrastructure for efficient operation. This makes SRF technology inaccessible to small-scale operations, as they may not have the resources or space needed for such systems.

There are two significant developments in recent years which could enable the widespread use of SRF technology in industry. First is the improvement of Nb_3Sn as a new material for use in SRF cavities. Nb_3Sn has a critical temperature of just over 18 K which allows for efficient cavity operation at temperatures of 4.2 K [3]. This is a marked improvement over pure niobium, which requires temperatures around 2 K for comparable efficiency [4]. Steady improvements in the performance of Nb_3Sn cavities [3, 5–10] have resulted in cavities capable of reliable operation at accelerating gradients relevant to the various applications described above. Second is the recent development of commercial cryocoolers which are capable of dissipating a couple watts of heat at 4.2 K while providing robust, turn-key operation. Thus, the demonstration of stable RF operation using Nb_3Sn cavities cooled by such cryocoolers can play a significant role in making SRF technology more accessible.

We would like to acknowledge that both FermiLab [11] and Jefferson Lab [12] have performed their own studies on conduction cooling setups with commercial cryocoolers. Those studies involved lower-frequency Nb_3Sn cavities which showed limitations at lower accelerating gradients.

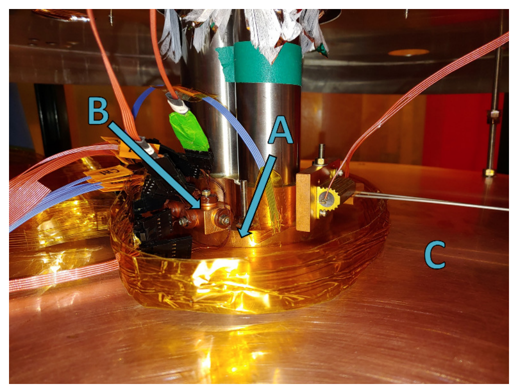

Figure 1: Close-up of the 1st stage cold head portion of the test assembly. (A) indicates the cold head itself. (B) indicates the heat sink used to intercept room-temperature heat loads from the various sensor cabling. (C) indicates the top surface of the copper thermal shield which is used to protect the primary cavity assembly from any room-temperature thermal radiation.

ASSEMBLY

The assembly built at Cornell uses a Cryomech PT420-RM cryocooler, which is capable of dissipating a maximum of 1.8 W at 4.2 K at the 2nd stage cold head. This cooling capacity is maximized when the 1st stage cold head is intercepting 55 W which results in a temperature of 45 K [13]. The 1st stage is primarily used to intercept heat loads from room temperature. This helps reduce static heat at the 4.2 K portion of the assembly, which leaves more room for dynamic heat dissipation during RF operation. Figure 1 shows a close-up image of the 1st stage cold head and surrounding components in our test assembly. The cold head itself is

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located at the bottom of the heat exchange pipes. There is also a thermal anchoring block attached to the 1st stage. This block has several copper bobbins wrapped in wire, which are used to thermally anchor the cable connections coming from the top plate feed-throughs. Lastly, the top surface of a copper thermal shield is connected to the bottom of the cold head. This thermal shield is used to protect the primary cavity assembly from room-temperature thermal radiation. The copper shield is also wrapped in 30 layers of aluminized mylar superinsulation to further reduce any heating from thermal radiation.

The 2nd stage cold head is used primarily to dissipate the dynamic heat loads generated by the cavity during RF operation. However, it must also intercept any remaining static heat loads that reach the 4.2 K portion of the assembly. For example, any temperature or magnetic flux sensors that are in direct contact with the cavity must first be anchored again at the 2nd stage. This is done using the same wrapped bobbin method as on the 1st stage. Figure 2 shows some of the main components of the primary cavity assembly. The 2nd stage cold head is again visible at the bottom of the heat exchange pipes, and there is a copper block mounted below it. This block is used as an anchoring point for the remaining parts. The main thermal pathway is made up of copper thermal straps and beam clamps, which are highlighted in the figure. Finally, there is the 2.6 GHz Nb_3Sn cavity seen in the center of the assembly.

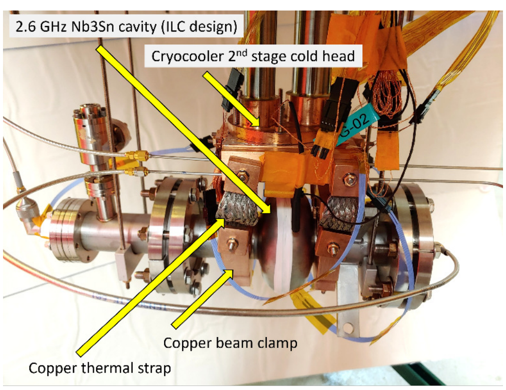

Figure 2: Primary cavity and copper cooling assembly. In the center is the TESLA-shaped 2.6 GHz Nb_3Sn cavity. The cavity is wrapped in Teflon tape to improve the thermal contact of the equator Cernox sensors. Above the cavity is the copper block attached to the 2nd stage cold head of the cryocooler. Surrounding the cavity are copper thermal straps and copper beam clamps which are attached to the cavity beam tubes. These copper components compose the primary thermal path between the cavity and cold head. Also visible are various cable connections for temperature and magnetic flux sensors, as well as the RF power cables.

Throughout several rounds of testing, various changes were made to the assembly in order to improve performance. At one point, high ambient magnetic fields were measured near the cavity before and during cooldown. After examining various components, it was discovered that the inconel Belleville washers had become strongly magnetized. This may have occurred due to the washers being subjected to multiple rounds of temperature cycling while being torqued beyond their listed specs, which caused permanent deformation. In any case, replacing the magnetized washers and properly stacking them resulted in the ambient fields being reduced to <5 mG. Another key change was the addition of resistive heaters to the cavity beam clamps, as seen in Fig. 3. These were used to give precise control of the temperature gradient between the two beam clamps during cooldowns. The motivation for this will be discussed more in the following sections.

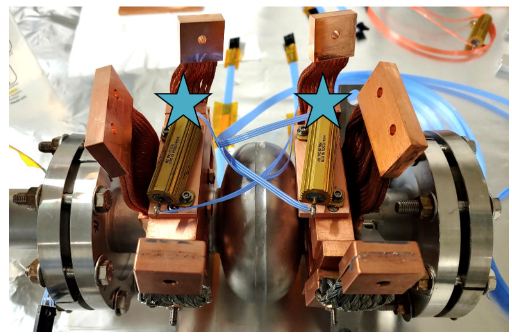

Figure 3: Primary cavity assembly with added resistive heaters. 1 kΩ resistors were attached to the cavity beam clamps in order to heat the cavity above 18 K and then precisely control the temperature gradient between the clamps as the cavity cooled back down.

CAVITY PERFORMANCE AND THERMAL BEHAVIOR

Over the course of a year, multiple rounds of RF testing were performed using the assembly described above. Figure 4 shows the cavity quality factor Q_0 for a few of the most relevant test runs. These results were discussed in detail in previous reports [14, 15], so this section will focus on the primary takeaways. First, there were three different tests (excluding the baseline vertical test) in which the cavity reached an accelerating gradient of 10 MV/m. This was the very first demonstration of a conduction-cooled SRF cavity operating at accelerating gradients relevant to certain industrial applications. In all three cases, the cavity was allowed to reach thermal stability, indicating that these results are representative of reliable CW operation.

The second primary finding is that all three tests which reached 10 MV/m followed rounds of temperature cycling, in which the cryocooler was turned off so that the cavity could warm up above 18 K. Once the cavity reached 20 K, 30 K, and 40 K respectively, the cryocooler was turned back on to cool down the cavity again. This was done in an attempt to reduce the thermal gradients across the cavity during the superconducting transition. Due to the bi-metal structure of the Nb/Nb_3Sn interface, any thermal gradients present across the cavity will generate thermoelectric currents which in turn generate magnetic fields. As the cavity transitions into

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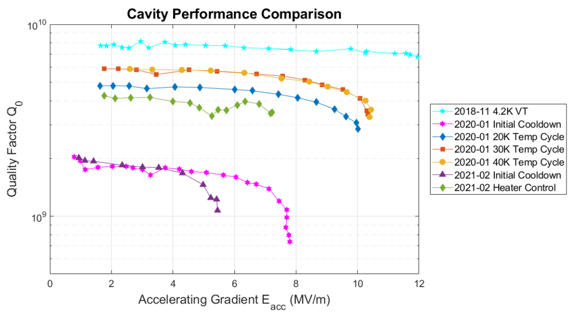

Figure 4: Comparison of various QvE curves for the 2.6 GHz Nb_3Sn cavity used in this study. We see poor performance following an initial cooldown, which is improved by better controlled cooldown methods.

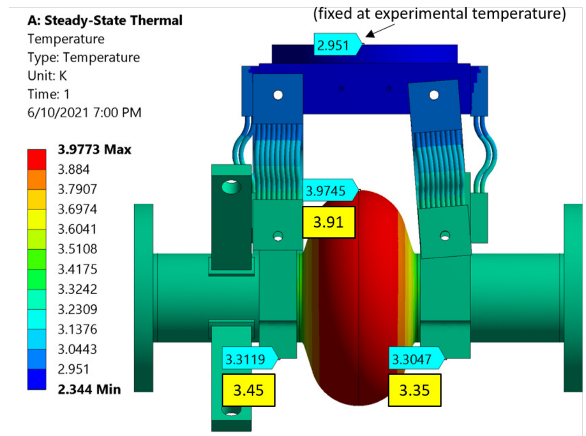

Figure 5: Thermal results for the cavity assembly from an ANSYS simulation (upper cyan blocks) compared to experimental measurements (lower yellow blocks). To run the simulation, the cavity heat load and 2nd stage cold head temperature were set to match what was measured at 10 MV/m from the 30 K temperature cycle test. This allowed us to compare the resulting temperatures for the beam clamps and cavity equator.

the superconducting state, any such fields that are present can get trapped in the cavity and result in a higher residual resistance [4]. The results of our studies clearly demonstrate the importance of minimizing these temperature gradients through better-controlled cooldowns, either via temperature cycling, the use of beam clamp heaters, or some other method.

Another finding, discussed further in [16], relates to the use of ANSYS simulations for modeling the assembly's thermal behavior, which can be compared to experimental measurements. An example of such a comparison is shown in Fig. 5. We see good agreement between the simulated and experimental results, confirming that the numerical simulations provide accurate predictions which can be used reliably in future iterations. These ANSYS simulations can also be used for more detailed analysis of the thermal gradients seen during RF operation, which can in turn be used to extract static heat loads across the assembly. More details regarding such calculations can again be found in [16].

FUTURE WORK

To continue development of the conduction cooling concept, we will begin designing and constructing components for a new standalone cryomodule which makes use of cryocoolers in place of liquid cryogens. This cryomodule will use a single-cell 1.3 GHz cavity based on the Cornell ERL design. Modifications will be made to optimize the cavity for efficient 4.2 K operation while sustaining high beam currents on the order of 100 mA. A 1.3 GHz cavity can expect a quality factor of 1 to 2×10^{10} which corresponds to 0.5 to 1 W of dissipated heat.

An important focus for the rest of the project is reducing static heat loads at 4.2 K, since a single cryocooler can only dissipate a couple watts of heat at that temperature. Most cryomodule components are currently optimized for 2 K performance, since that is the standard operating temperature of niobium cavities. Fortunately, the 1st stage cold head of a cryocooler can intercept about 55 W at 45 K. This means that we can divert as much static heat as possible to the 1st stage in order to minimize the amount of heat reaching the 2nd stage. This process will require making adjustments to key cryomodule components such as the RF input coupler and various support structures.

Other design considerations will be guided by dynamic effects from RF operation. For example, implementing a high-power RF input coupler capable of delivering above 50 kW beam power will generate significant dynamic heat loads in the system. Our designs will need to ensure that this dynamic heating is intercepted by the 1st and 2nd stages of the cryocooler such that it does not reach the cavity itself. Another important dynamic effect is microphonics, which can be more severe when using cryocoolers. Though operating a cryocooler is much simpler than using liquid helium, the mechanical processes occurring inside the cryocooler, including the heat exchange pipes which connect directly to the cold heads, present a notable source of microphonics. Therefore, the cryomodule design must examine viable methods for dampening the effects of this additional microphonics source.

CONCLUSION

At Cornell University, we have developed a new cryocooler testing assembly which utilizes a 2.6 GHz Nb_3Sn cavity to examine the effectiveness of cryocoolers as a cooling method for SRF operation. Through various sets of RF tests, we have found that commercial cryocoolers indeed provide a viable alternative to liquid helium when using Nb_3Sn-coated cavities. We achieved the first demonstration of stable RF operation of a conduction cooled cavity at 10 MV/m, reaching accelerating gradients relevant to many important industrial applications. Our tests also revealed the key importance of using controlled cooldowns to in-

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crease cavity performance. By reducing thermal gradients across the cavity during the superconducting transition, the magnetic fields produced via the thermoelectric effect are minimized. This in turn reduces the amount of trapped flux in the cavity, leading to improved performance.

As the next step in our studies, we plan to begin the design and development of a standalone SRF cryomodule which operates using two commercial cryocoolers. This cryomodule will contain a 1.3 GHz Nb_3Sn cavity based on the Cornell ERL design. This will allow the cavity to sustain high beam currents on the order of 100 mA. The high-power input coupler and other key components of the cryomodule will be modified in order to optimize 4.2 K performance and minimize static heat loads.

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