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STATUS UPDATE ON CORNELL'S SRF COMPACT CONDUCTION COOLED CRYOMODULE*

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Abstract

A new frontier in Superconducting RF (SRF) development is increasing the accessibility of SRF technology to small-scale accelerator operations which are used in various industrial or research applications. This is made possible by using commercial cryocoolers as a cooling source, which removes the need for expensive liquid cryogenics and their supporting infrastructure. In addition, the use of Nb_3Sn-coated cavities allows for efficient operation at 4.2 K. Cornell University is currently developing a new cryomodule based on a conduction cooling scheme. This cryomodule will use two pulse tube cryocoolers in place of liquid cryogenics in order to cool the system. A new 1.3 GHz cavity has been designed with a set of four niobium rings welded at the equator and irises which allow for a direct thermal link between the cavity and cryocooler cold heads. The cavity will use two coaxial RF input couplers capable of delivering up to 100 kW total RF power for high-current beam operation. This coupler design was modified from the Cornell ERL injector couplers, including simplifications such as removing the cold RF window and most outer bellows, while retaining inner bellows for adjustable coupling.

INTRODUCTION

Reports from the U.S. DOE and national labs indicate that small-scale accelerators producing beams of a few MeV can be used for important applications in various fields such as medicine, environmental progress, national security and more [1, 2]. Although these operations would benefit from the vastly improved efficiency of SRF technology, the complexity and cost of the required liquid helium infrastructure quickly becomes prohibitive. However, the combination of current cryocooler technology and Nb_3Sn-coated cavities has opened a new path to utilizing SRF technology. Today's cryocoolers are capable of removing a couple watts of heat at 4 K [3], while steady improvements to Nb_3Sn coatings have produced cavities which operate reliably and efficiently at 4.2 K with accelerating fields relevant to the applications mentioned [4–10]. Therefore, demonstrating that Nb_3Sn cavities can successfully operate while being cooled with cryocoolers in place of liquid helium will represent a major step forward in making SRF technology accessible to small-scale industry applications.

Previous studies conducted at Cornell demonstrated the feasibility of this concept. These studies achieved the first-ever demonstration of a conduction-cooled SRF cavity operating continuously at 10 MV/m [11]. In addition, it was found that if the cryocooler is allowed to cool the system down freely, significant thermal gradients will be created across the cavity, leading to poor performance [12]. Therefore, controlling the cooldown is a requirement when using crycoolers for SRF applications. These studies also showed that placing heaters on the cavity irises provided the most precise and repeatable control of thermal gradients during cooldown [12]. We would like to acknowledge that important progress has also been made at Fermilab [13] and Jefferson Lab [14], in which different implementations of conduction cooling assemblies were examined.

Cornell is now designing a new compact cryomodule which will use two cryocoolers in place of liquid cryogenics. The system will have a single-cell 1.3 GHz Nb_3Sn-coated cavity powered by two coaxial couplers. The couplers will deliver a total of 100 kW RF power to a 100 mA beam with the cavity operating at 10 MV/m; see Table 1.

Table 1: Cryomodule Operating Specifications

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

ACCELERATING CAVITY

The SRF cavity used in our cryomodule is based on the design for the 1.3 GHz 2-cell injector cavities from Cornell's ERL [15]. For the new cryomodule, the cavity has been modified to a single-cell design (see Fig. 1) and will be coated with Nb_3Sn to enable efficient 4.2 K operation. The primary additions to the cavity design are the Nb thermal intercept rings located outside of the cavity equator and irises. The equator ring design is inspired by Fermilab's study on a 650 MHz cavity [13]. The equator rings extract the cavity's primary heat load, while the newly-designed iris rings extract smaller heat loads and serve as mounting locations for heaters. All four rings can be seen attached to the cavity in the bottom-right image of Figure 1.

Thermal modelling was performed in Ansys to study the effectiveness of this design. This modelling includes the full beam line extending out to the vacuum vessel walls at

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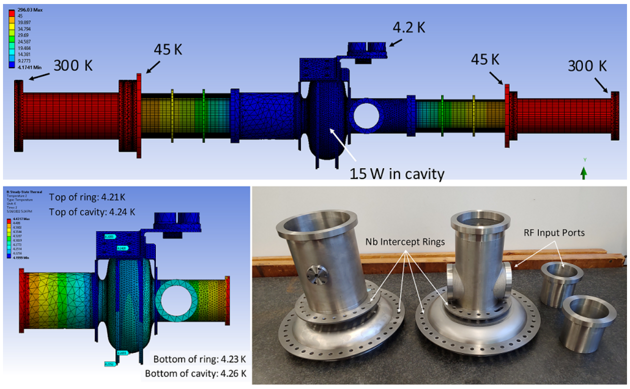

Figure 1: Top: temperature profile of the full beam line with locations of thermal boundary conditions indicated. The 1.5 W value was calculated based on benchmark operation of 10 MV/m at 4.2 K. Bottom-left: detailed view of cavity and thermal link temperature profile. Bottom-right: all cavity parts have been fabricated.

room temperature. The section of beam line between the cavity and 45 K intercepts has a wall thickness of 0.5 mm to minimize the heat load at 4.2 K. A preliminary design for a 5N aluminum thermal link between the cryocooler 2nd stage cold heads and the cavity is included. The top image of Fig. 1 shows the locations of the thermal boundary conditions.

The full beam line temperature profile and a detailed profile of the cavity and thermal link can also be seen in the top and bottom-left images of Fig. 1, respectively. The modelling shows that there is only a 0.02 K thermal gradient across the cavity equator and thermal intercept rings, which indicates that this design successfully achieves even cooling across the cavity. The resulting heat loads at 45 K and 4.2 K are well within the limits of the two cryocoolers. The load at 45 K is entirely due to static heat leak from room temperature, while most of the load at 4.2 K comes from RF losses; Table 2 lists specific values.

RF INPUT COUPLER

As with the cavity, the base design of the RF input coupler was taken from the twin coaxial input coupler design from Cornell's ERL injector cryomodules [16]. Changes to this design were made to enable conduction cooling, as well as making the coupler simpler and more compact.

One major change which addresses both goals is the removal of the cold RF window. This reduces the heat load at 45 K by removing a significant source of heating while also greatly simplifying the overall design. Next, we implemented an "RF shield" design which was inspired by the input couplers recently designed at Fermilab [17]. This shield is anchored at 45 K and protects most of the stainless steel outer conductor from RF power during operation. This removes the need for copper plating, which in turn reduces the amount of heat transferred to 4.2 K. In our design, the shield is also extended towards the warm end in order to protect the outer bellows. Various other modifications, such as the removal of all liquid cryogenic heat intercepts, were made to simplify and shorten the design as well as minimize reflections in the coupler.

A quarter-wave transformer was inserted at the inner bellows, resulting in an S11 parameter below −60 dB across the full extension range of the bellows. Figure 2 shows the S11 parameter when the inner bellows are set to their nominal extension. The antenna geometry was reoptimized to achieve a Q_{ext} of 2×10^5 for optimal beam loading when the coupler is maximally extended. At minimal extension we have a Q_{ext} of 1.77×10^6, which provides variation in the coupling strength by a factor of 9. Many of the core components discussed are shown in Figure 3.

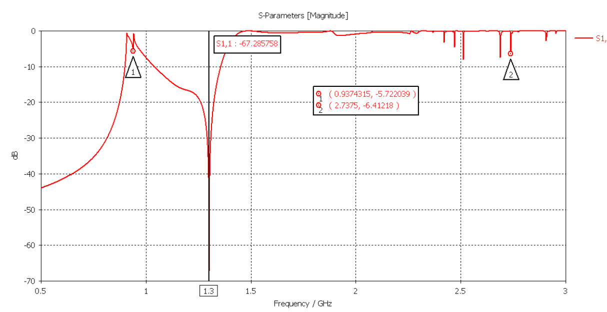

Figure 2: S11 parameter for the optimized coupler across a frequency range of 0.5 to 3 GHz. The minimum of −67 dB occurs at the operational frequency of 1.3 GHz.

Thermal modelling was performed in Ansys to ensure the validity of the new coupler design. Dynamic heat loads due to RF power were first calculated in CST Microwave Studios and then applied to the Ansys model. Radiative heat loads were added to the relevant surfaces of the inner and outer conductors, while a convective heat flow was added to the inside of the inner conductor in order to simulate air cooling.

The resulting temperature profile can be seen in Figure 3. The maximum temperatures reached are 311 K on the outer bellows and 335 K on the end of the antenna. There is a clear temperature difference between the RF shield and the outer conductor at the warm and cold end, indicating that good thermal isolation is maintained. As before, the heat loads at 45 K and 4.2 K are easily manageable, with the most significant contribution being the dynamic load at 45 K due to RF losses; see Table 2.

CRYOMODULE

The primary design goals for the new cryomodule structure are simplicity, compactness, and minimized static heat loads to the cold mass. In general, a significant amount of simplification comes from the removal of typical cryogenic systems in favor of the cryocoolers. We chose to implement a rectangular space frame with G10 support rods between the vacuum vessel and frame as well as between the frame and the cavity, Springs attached to the rods offer flexibility for thermal contraction, while G10 offers very low thermal conductivity; in the current design, the G10 rods only transmit

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Table 2: Total Heat Loads in the Cryomodule

Source	45 K Static/Dynamic/Total (W)	4.2 K Static/Dynamic/Total (W)
Cavity + Beam Tubes	21.30 / 0.00 / 21.30	0.16 / 1.49 / 1.65
Coupler	1.44 / 16.05 / 17.49	0.14 / 0.02 / 0.16
G10 Support Rods	0.34 / N/A / 0.34	0.02 / N/A / 0.02
All sources (incl. 2x coupler)	56.6	1.99
Cryocooler Limits (PT420 + PT425)	110	4.1

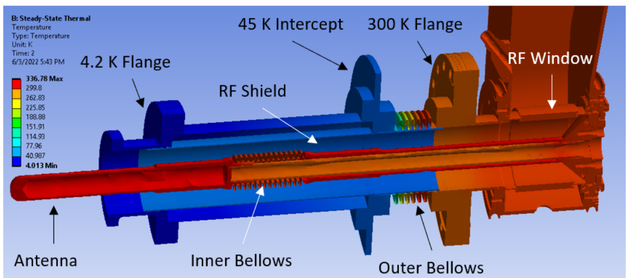

Figure 3: Temperature profile of the input coupler with 50 kW RF power. Locations of thermal anchors and intercepts, as well as core design components, are indicated.

0.34 W of heat from room temperature to the space frame and 0.02 W from the space frame to the cavity.

The space frame will be encased by thin (~1/8") panels which provide thermal shielding from room-temperature radiation; both the space frame and thermal shield panels will be made of 5N aluminum and anchored to the first stage of the cryocoolers at 45 K. The thermal links at both 45 K and 4.2 K will include flexible foil straps which are also made of 5N aluminum. The use of foil straps allows for differential thermal contraction between different components connected to the cryocoolers. Figure 4 shows a CAD model of the current iteration of the cryomodule design. The 4.2 K thermal link is not shown for clarity purposes.

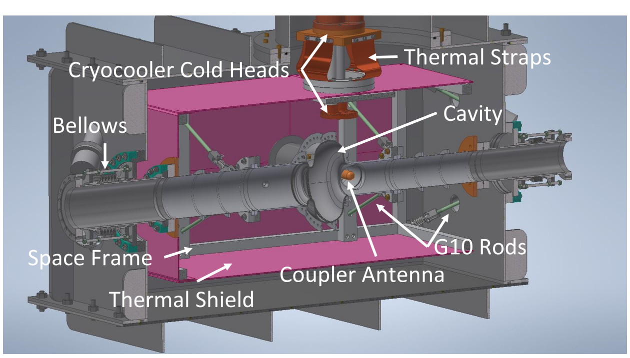

Figure 4: CAD model of the current version of the cryomodule design. Key components of the assembly are highlighted and discussed further in the text.

TOTAL HEAT LOADS

Table 2 shows all of the heat loads that have been calculated for the components discussed previously, as well as the combined cooling capacity of the Cryomech PT420 and PT425 units which will be used [3]. Some sources of heat, such as radiation and instrumentation, have not been calculated yet as many designs are still in progress.

FUTURE STEPS

The fabrication of all the cavity parts has been completed, and electron beam welding has started. Once the cavity is welded, it will receive baseline chemical treatments and be prepared for a vertical test in a helium bath later this summer. The core features of the input coupler design are complete and the final details are in progress. Once finished, the designs will be sent to an outside vendor for manufacturing; this is scheduled to occur by September 2022. Lastly, the design of the remaining cryomodule components will continue to be revised and improved. We aim to begin fabricating parts as they are ready in late 2022.

CONCLUSION

Significant progress has been made in the design and initial construction of the core components for a new cryocooler-based cryomodule. The 1.3 GHz Nb_3Sn-coated cavity design was successfully modified from the 2-cell injector cavities from Cornell's ERL in order to accommodate the replacement of liquid cyrogenics with conduction cooling. A similar process was performed to create the design for the new high-power RF input coupler. Thermal modelling on both components result in heat loads within the limits of the cryocoolers. Design work has also begun on the cryomodule and several core structural components such as the space frame, thermal shield, and G10 support rods.

REFERENCES

[1] U.S. DOE Report, "Accelerators for America's Future", June 2010. https://www.odu.edu/content/dam/odu/col-dept/physics/docs/report-future-cas.pdf

[2] U.S. DOE Report, "Workshop on Energy and Environmental Applications of Accelerators", Argonne, IL, USA, June 2015. doi:10.2172/1358082

[3] Cryomech, https://www.cryomech.com/products/

[4] S. Posen and M. Liepe, "Advances in development of Nb_3Sn

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superconducting radio-frequency cavities", *Phys. Rev. ST Accel. Beams*, vol. 17, p. 112001, Nov. 2014. doi:10.1103/PhysRevSTAB.17.112001

[5] S. Posen, "Understanding and Overcoming Limitation Mechanisms in Nb_3Sn Superconducting RF Cavities", Ph.D. dissertation, Phys. Dept., Cornell University, Ithaca, NY, USA, 2014.

[6] D. L. Hall, "New Insights into the Limitations on the Efficiency and Achievable Gradients in Nb_3Sn SRF Cavities", Ph.D. dissertation, Phys. Dept., Cornell University, Ithaca, NY, USA, 2017.

[7] S. Posen, M. Liepe, and D. L. Hall, "Proof-of-principle demonstration of Nb_3Sn superconducting radiofrequency cavities for high Q_0 applications", *App. Phys. Lett.*, vol. 106, p. 082601, 2015. doi:10.1063/1.4913247

[8] S. Posen and D. L. Hall, "Nb_3Sn Supercondcution Radiofrequency Cavities: Fabrication, Results, Properties, and Prospects", *Superconductor Science and Technology*, vol. 30, no. 3, p. 33004, Jan. 2017. doi:10.1088/1361-6668/30/3/033004

[9] S. Posen *et al.*, "Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications", *Supercond. Sci. Technol.*, vol. 34, no. 2, p. 025007, Jan. 2021. doi:10.1088/1361-6668/abc7f7

[10] U. Pudasaini *et al.*, "Recent Results From Nb_3Sn Single Cell Cavities Coated at Jefferson Lab", in *Proc. SRF'19*, Dresden, Germany, July 2019, paper MOP018, pp. 65–70. doi:10.18429/JACoW-SRF2019-MOP018

[11] N.A. Stilin, A. Holic, M. Liepe, R.D. Porter and J. Sears, "Stable CW Operation of Nb_3Sn SRF Cavity at 10 MV/m using Conduction Cooling", doi:10.48550/arXiv.2002.11755

[12] N.A. Stilin, A. Holic, M. Liepe, R.D. Porter, J. Sears and Z. Sun, "RF and Thermal Studies on Conduction Cooled Nb_3Sn SRF Cavity", submitted for publication.

[13] R. C. Dhuley, S. Posen, M. I. Geelhoed, O. Prokofiev, and J. C. T. Thangaraj, "First demonstration of a cryocooler conduction cooled superconducting radiofrequency cavity operating at practical cw accelerating gradients", *Super-cond. Sci. Technol.*, vol. 33, no. 6 p. 06LT01, Apr. 2020. doi:10.1088/1361-6668/ab82f0

[14] G. Ciovati, G. Chen, U. Pudasaini, and R. A. Rimmer, "Multi-metallic conduction cooled superconducting radio-frequency cavity with high thermal stability", *Supercond. Sci. Tech-nol.*, vol. 33, no. 7 p. 07LT01, May 2020. doi:10.1088/ 1361-6668/ab8d98

[15] V. Shemelin, S. Belomestnykh, R. L. Geng, M. Liepe, and H. Padamsee, "Dipole-Mode-Free and Kick-Free 2-Cell Cavity for the SC ERL Injector", in *Proc. PAC'03*, Portland, OR, USA, May 2003, paper WPAB012, pp. 2059–2061.

[16] V. Veshcherevich, I. Bazarov, S. Belomestnykh, M. Liepe, H. Padamsee, and V. Shemelin, "Input Coupler for ERL Injector Cavities", in *Proc. PAC'03*, Portland, OR, USA, May 2003, paper TPAB009, pp. 1201–1203.

[17] R.C. Dhuley, *et al.*, "Design of a 10 MeV, 1000 kW average power electron-beam accelerator for wastewater treatment applications", *Phys. Rev. Accel. Beams*, vol. 24, no. 4, p. 041601, April 2022. doi:10.1103/PhysRevAccelBeams. 25.041601