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COMPACT TURN-KEY SRF ACCELERATORS*

N.A. Stilin†, A. Holic, M. Liepe, T. O'Connell, J. Sears, V.D. Shemelin and J. Turco
Cornell Laboratory for Accelerator-Based ScienceS and Education (CLASSE), Ithaca, USA

Abstract

The development of simpler, compact Superconducting RF (SRF) systems represents a new subject of research in accelerator science. These compact accelerators rely on advancements made to both Nb_3Sn SRF cavities and commercial cryocoolers, which together allow for the removal of liquid cryogenics from the system. This approach to SRF cavity operation, based on novel conduction cooling schemes, has the potential to drastically extend the range of application of SRF technology. By offering robust, non-expert, turn-key operation, such systems enable the use of SRF accelerators for industrial, medical, and small-scale science applications. This paper provides an overview of the significant progress being made at Cornell, Jefferson Lab, and Fermilab (FNAL), including stable cavity operation at 10 MV/m. It also introduces the primary challenges of this new field and their potential solutions, along with an overview of the various applications which could benefit the most from this technology.

INTRODUCTION

Various workshops and investigations have shown that numerous applications exist for particle accelerators which could further benefit from the use of SRF technology [1,2]. These applications cover several fields of interest, including: energy and environment, such as wastewater or flue gas treatment; medicine, such as device sterilization and isotope production; security and defense, such as cargo inspection; industry, such as biofuel production. Many of these applications fall within a similar range of beam parameters, requiring only moderate energies but high current and average power; see Table 1 [1,2].

Table 1: Typical Beam Parameters

Property	Value	Units
Energy	1 – 10	MeV
Current	0.1 – 1	A
Power	1 – 10	MW

These applications can benefit from the use of SRF technology, which offers significantly more efficient operation compared to normal conducting cavities. However, the use of SRF cavities has not been possible until the recent improvements made to both Nb_3Sn cavities and cryocoolers. Together, these improvements allow compact accelerators to operate at the energies required while not being reliant on liquid helium for cooling. This shift to conduction-based cooling greatly simplifies the system while also being much cheaper than the extensive infrastructure required for operating with helium. Combined, these developments have brought SRF technology within reach of important small-scale applications such as the ones discussed above.

KEY COMPONENTS

This section will briefly describe the improvements made to both Nb_3Sn cavities and commercial cryocoolers which are essential to the design of new compact accelerators.

Nb_3Sn Cavities

Nb_3Sn is an alternative material for SRF cavities which has seen significant interest and growth over the last couple decades. The main advantage offered by Nb_3Sn is that its critical temperature is 18 K, almost twice that of pure Niobium [3]. This affects the BCS component of the surface resistance, which means Nb_3Sn cavities can operate with lower losses and/or at a higher temperature compared to Niobium cavities.

Since 2013, Nb_3Sn cavities have been improved to the point of operating at 4.2 K at 15 MV/m or higher while still maintaining a high Q_0 of 1 – 2 E10 [**?**, 3–7, 9]. These high Q_0 values correspond to a very small cavity heat load of less than one watt for a single-cell 1.3 GHz cavity; see Fig. 1. This means that we can now achieve highly efficient cavity operation at field levels which are relevant to small-scale operations. Since these achievements have been demonstrated at 4.2 K, these cavities are also capable of using a new cooling scheme which does not require liquid helium.

Cryocoolers

The cryocooler concept was first introduced in the 1960's, but only in the last few years have they reached the cooling capacity required for use with Nb_3Sn cavities. For example, initial models of Cryomech's 4.2 K pulse-tube type cryocoolers, which were released around 2000, could only remove less than 1 W of heat from a system at 4.2 K [10]. By comparison, the most recent models are able to remove more than 2 W [10], which means they are capable of being used as the primary cooling source of current Nb_3Sn cavities operating at medium fields. Figure 1 shows this improvement of cryocooler performance.

CONDUCTION COOLED CAVITIES

With the current state of Nb_3Sn cavities and commercial cryocoolers, it is possible to design a system which uses an entirely new cooling scheme compared to standard LHe cooling; see Fig. 2. The first possibility is to use direct conduction cooling, in which the cryocooler cold head and

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† nas97@cornell.edu

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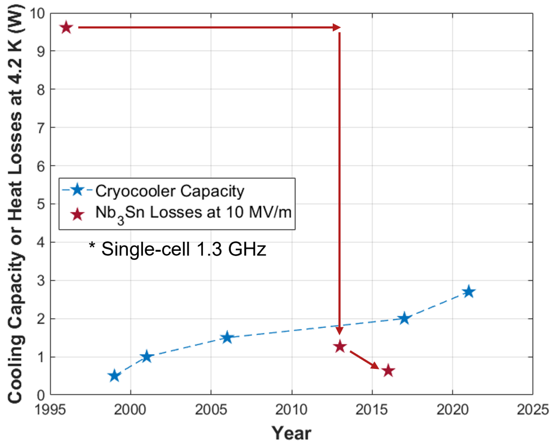

Figure 1: Progress in both Nb_3Sn cavity performance (red stars) and pulse-tube cryocooler capacity at 4.2 K (blue curve) [10].

Nb_3Sn cavity are directly connected by a thermal conduction path, typically including metal foil or braided connections. This choice offers the flexibility needed to accommodate differential thermal contraction while maintaining the high thermal conductivity needed to sufficiently extract the RF heat load from the cavity during operation. Designing a cryomodule using direct conduction cooling offers a relatively simple and low-cost cooling scheme.

The second possibility utilizing cryocoolers is to install a closed helium tank around the Nb_3Sn cavity, where the cryocooler cold head is installed in contact either with the tank exterior or directly in contact with the helium volume. While this option is not cryogen-free, the helium is contained within a closed system and thus does not need to be replenished or cycled through a larger system. While this option may benefit from the cooling capabilities of liquid or gaseous helium, it does involve an added layer of complexity due to the additional vacuum sealed volume. Because of this, most compact SRF cryomodule designs utilizing cryocoolers involve the direct conduction cooling scheme.

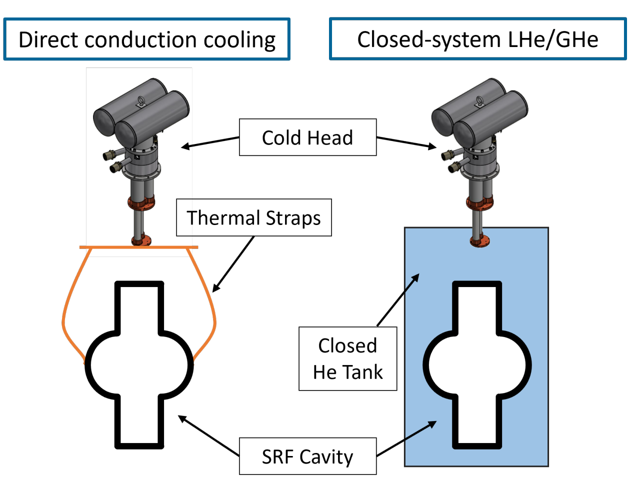

Figure 2: Two new cooling schemes which are possible using crycooolers. Most cryomodule designs proposed today use the direct conduction cooling method.

Proof-of-principle demonstrations of the conduction cooling scheme have been successfully completed at Cornell [11], Fermilab [12, 13] and Jefferson Lab [14]; similar work is ongoing at KEK and IMP. At Cornell, our assembly used a 2.6 GHz cavity with copper beam clamps attached immediately outside of the iris on both sides of the cavity cell. This design was used to get more even cooling across the cavity, both during assembly cooldown and RF operation. Starting with the second test of this assembly, resistive heaters were also added to these beam clamps to offer even more precise control of thermal gradients during cavity cooldown. Minimizing thermal gradients across the cavity as it transitions to superconductivity is crucial for improving RF performance, as these gradients generate thermal currents in the bi-metal structure of Nb_3Sn. These currents in turn generate magnetic flux which can get trapped in the cavity, resulting in a larger residual resistance and degrading performance [6].

With this cavity assembly, we demonstrated the world's first example of a conduction-cooled SRF cavity reaching stable CW operation at 10 MV/m [11]. One key takeaway from this study was the importance of utilizing more controlled cooldowns with cryocoolers. As shown in Fig. 3, the breakthrough RF performance was only obtained after a more controlled cooldown was used, in this case by completing a temperature cycle of the assembly.

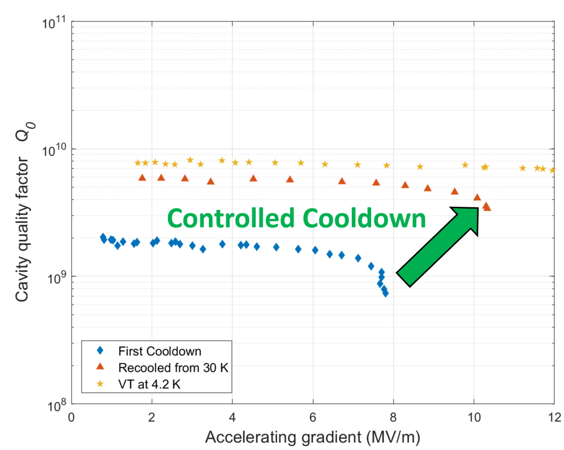

Figure 3: Example RF results from a proof-of-principle demonstration of operating a conduction-cooled Nb_3Sn cavity at Cornell. The curve labeled "VT at 4.2 K" is from a vertical test in a helium bath and represents the baseline performance of this cavity, while the other two are from tests using the conduction cooling assembly. Note that the optimal performance was achieved after a more controlled cooldown, in this case achieved via temperature cycling the system.

Fermilab performed a similar demonstration study using a 650 MHz cavity which had niobium rings welded near the cavity equator to extract the primary cavity heat load. This cavity was also able to reach stable CW operation at 10 MV/m after implementing a more controlled cooldown. This shows again that including some capability of better controlling the assembly cooldown is of utmost importance for obtaining the best possible RF performance. Further

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information on this study can be found in Fermilab's publication [12, 13].

Jefferson Lab performed their conduction cooling tests using a 1.5 GHz cavity which had a 5 mm layer of copper electroplated to the exterior. This was done to obtain better thermal conduction around the cavity in order to apply more uniform cooling across the entire surface. While this cavity did reach moderate field levels, it saw degraded RF performance after the copper electroplating. It was suggested that this poor performance may have been due to strain on the Nb_3Sn layer due to the differences in thermal contraction between niobium and copper; more information can be found in the publication on this study [14].

Information about the work ongoing at KEK and IMP was provided by the contacts listed in the Acknowledgment section.

COMPACT CRYOMODULES

After demonstrating that operating a Nb_3Sn cavity cooled with a cryocooler is indeed possible, the next step is to begin designing and constructing full cryomodules which use this new cooling technology. These cryomodules are intended to be dry cryostats, i.e. containing no liquid cryogenics. By "compact," we mean cryomodules which are only 1 - 2 m in length. By using cryocoolers in place of liquid helium, these designs offer turn-key, non-expertise operation of the cooling system. As mentioned before, this is the main driving factor which makes such cryomodules more accessible to small-scale operation.

At Cornell, we are designing a cryomodule which is primarily R&D focused, and is intended to be usable for a variety of applications. A cross-sectional view of the cryomodule can be seen in Fig. 4, and the beam parameters for the system are listed in Table 2. This system will utilize one PT420 and one PT425 cryocooler from Cryomech, providing total cooling capacities of 4.1 W at 4.2 K and 110 W at 45 K [10]. Beyond adapting the system to be used with cryocoolers, one design focus for this project is to reduce cost and complexity as much as possible.

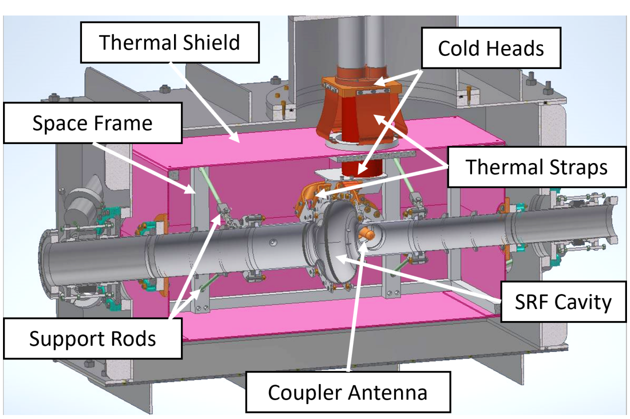

Figure 4: 3D model of the current design iteration of Cornell's conduction cooled cryomodule. Some components of interest are labeled on the figure.

Beam acceleration is done by a single-cell 1.3 GHz Nb_3Sn cavity. This cavity has Nb rings welded both at the cavity equator and the cavity irises. Similar to Fermilab's design described previously, the rings at the equator are used to extract the primary heat load from the cavity, while the additional rings at the irises will enable very precise thermal gradient control during cooldown via mounted resistive heaters. Thermal modeling of the cavity and full beamline was performed in Ansys, resulting in total heat loads of 21.3 W at 45 K and 1.65 W at 4.2 K. The heat load at 45 K is entirely a static heat load from the room temperature ends of the beam pipes, while the heat load at 4.2 K is almost entirely dynamic loads from RF dissipation in the cavity.

Table 2: Beam Parameters of Cornell's Conduction-Cooled Cryomodule.

Property	Value	Units
Energy	1	MeV
Current	100	mA
Power	100	kW

Creating a high-power coupler which can be sufficiently cooled with a cryocooler poses a significant challenge in designing a conduction-cooled cryomodule. At Cornell, the primary goals for the design process were to re-optimize the heat load distribution while also greatly simplifying the coupler design. Some of the key choices to achieving the design goals were using a warm RF window only, utilizing an "RF shield" design inspired by Fermilab [15] to reduce the RF heat load at 4.2 K, and inserting an optimized quarter-wave transformer around the inner bellows to significantly reduce reflections at the operational frequency of 1.3 GHz. Each of these components, along with a few others, can be seen in the design model in Fig. 5. Thermal modeling has also been completed for the coupler assuming 50 kW operation (two twin coaxial couplers for a total of 100 kW). This resulted in heat loads of 0.16 W at 4.2 K and 17.5 W at 45 K (per coupler). Total heat loads in the system are listed in Table 3.

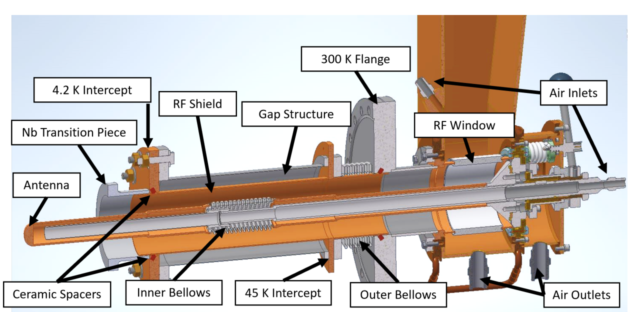

Figure 5: CAD model of the high-power input coupler for Cornell's conduction-cooled cryomodule. Several key components are labeled on the figure.

Many other projects are ongoing at other labs and industry partners, which will now be given a brief overview. More

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Table 3: Total Heat Loads in Cornell's Conduction-Cooled 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

details on the main examples given can be found in the cited publications. The team at the Illinois Accelerator Research Center (IARC) at Fermilab are designing a wastewater treatment system with beam parameters listed in Table 4. The full system includes components for beam generation, acceleration, and delivery. Their compact accelerating cryomodule uses a 5-cell 650 MHz Nb_3Sn cavity which has Nb rings welded at the equators of each cell. This system requires 8 cryocoolers for a total heat capacity of about 17 W at 4.2 K. The cryomodule is shown in Fig. 6. The final design goal of this project is to eventually treat up to 12 million gallons of wastewater per day at a treatment facility outside of Chicago [15].

Table 4: Beam Parameters of Fermilab's Conduction-Cooled Cryomodule [15]

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

Two additional projects are being proposed by the IARC, one intended for medical device sterilization and one for impoved pavement processing. The former is designed for a lower power of just 20 kW and uses a 1.5-cell 650 MHz cavity, while the latter is designed for 200 kW using a 9-cell 1.3 GHz cavity. These projects are in early development, and more information can be found by contacting the IARC team (members can be found listed with Fermilab in the Acknowledgment section).

Jefferson Lab is developing a system to be used for environmental remediation, such as flue gas or wastewater treatment. The beam parameters can be found in Table 5. The main cryomodule will contain a single-cell 750 MHz Nb_3Sn cavity which will have a copper layer electroplated to the cavity exterior. Four Gifford-McMahon type cryocoolers will be used, offering a total cooling capacity of 6 W at 4.2 K. This cryomodule is shown in Fig. 7. The full system design also includes components required for beam generation and delivery [16].

Finally, there are a few additional projects with significant contributions from industry partners which will be briefly described here. Euclid Labs is working on a cryomodule containing a conduction-cooled SRF photogun to be used for Ultrafast Electron Diffraction or Microscopy (UED/M). This system uses a 1.5-cell 1.3 GHz cavity cooled by a single cryocooler. The end goal is for this cryomodule to be installed at a user facility at BNL [17, 18]. RadiaBeam has a couple ongoing projects collaborating with both Fermilab and Argonne. One involves a compact, conduction-cooled cryomodule which is meant to be mobile and will contain a 4.5-cell 650 MHz cavity cooled by four cryocoolers. The second project is focused on using cryocoolers to cool Nb_3Sn-coated quarter-wave resonators to be used in various upgrades at ATLAS. More information about these projects can be found by contacting the members from RadiaBeam and Argonne listed in the Acknowledgment section.

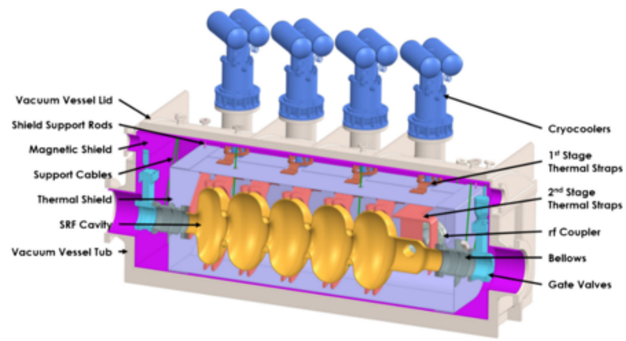

Figure 6: CAD model of the accelerating cryomodule used in Fermilab's wastewater treatment design [15]. Some key components include 8 total crycoolers (4 being visible), the 5-cell 650 MHz cavity, and the 4.2 K conduction path (visible above the cavity).

Table 5: Beam Parameters of Jefferson Lab's Conduction-Cooled Cryomodule [16]

Property	**Value**	**Units**
Energy	1	MeV
Current	1	A
Power	1	MW

CONCLUSION

Several labs and industry partners have proposed various compact conduction-cooled cryomodule designs utilizing cryocoolers as the sole cooling source. These designs address a wide range of unique applications, and represent a remarkable start to this new topic of R&D. There is still more room for significant growth in this field, as more labs begin their own work on developing conduction-cooled systems using cryocoolers. Looking forward, it is clear that this line

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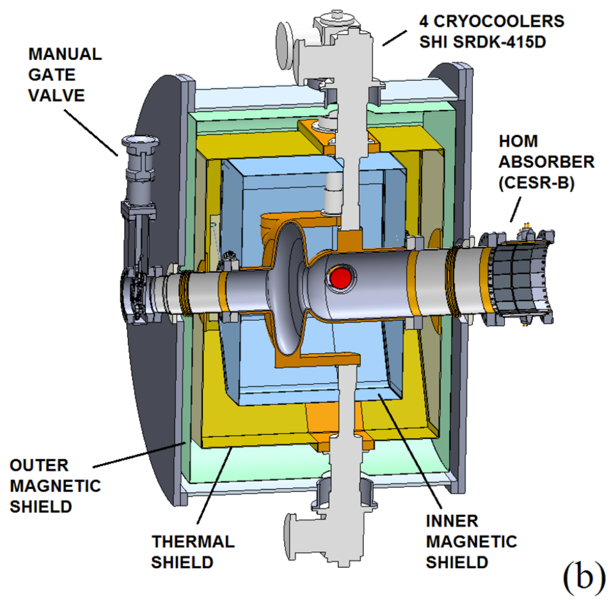

Figure 7: CAD model of the accelerating cryomodule used in Jefferson Lab's environmental remediation design [16]. Some key components include 4 total crycoolers (3 being visible), the single-cell 750 MHz cavity with an electroplated exterior copper layer, and the 4.2 K conduction path (visible above and below he cavity).

of work can play a critical role in bridging the gap between SRF technology and the applications which can benefit from it, as we have already seen several projects developed in the short time since conduction-cooled Nb_3Sn cavities were first possible.

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