Cryocooler conduction cooling: a review of applications and prospects

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Abstract

Conduction cooling of cryogenic devices and instruments using closed-cycle cryocoolers are fast gaining popularity as a pathway to "invisible" cryogenics. The technique comprises direct mechanical coupling of the device/instrument to the cryocooler and the apparatus enclosed in a high-vacuum environment, without convectively contacting any cryogenic liquid or gas. In this contribution, common applications of cryocooler conduction cooling are reviewed to understand the current state of the technology. Three devices are considered - superconducting magnets, accelerator cavities, and sub-Kelvin refrigerators that use closed-cycle cryocoolers for pre-cooling. Thereafter, basic heat transfer topics are described that require further research for better optimization of the conduction cooling technique. These include thermal contact resistance, cooldown time modeling, and flexible thermal linkages. This contribution is especially helpful for cryocooler developers/researchers who are interested in exploring potential applications of their cryocoolers.

1 Introduction

The process of cooling devices and instruments to cryogenic temperatures involves one of the three methods: (1) convective cooling by circulating a cold liquid (cryogen) or gas around them, (2) radiative cooling by exposing them to a cryogenic ambient, and (3) conduction cooling by mechanically connecting them to cryocoolers, which are refrigerators capable of attaining temperatures below 120 K. The convection cooling technique is widely employed to cool large scale devices such as superconducting magnets and radiofrequency cavities in science-oriented particle accelerators. Devices and instruments deployed in deep space can employ radiative cooling to take advantage of the surrounding cold ambient, typically near 3 K. Cryocooler conduction cooling is particularly attractive for smaller, compact devices and instruments that do not dissipate substantial heat, require reliable operation over long duration with minimal human oversight, or that need to be deployed at locations where an uninterrupted supply of cryogens is difficult to provide.

1.1 Working principle of cryocooler conduction cooling

Cryocoolers are closed-cycle devices that produce cryogenic temperature by utilizing the temperature change associated with compression and expansion processes in real gasses. Helium is the commonly used gas that enables reaching temperatures as low as 2.5 K. An excellent review of cryocoolers, their types, available temperature range and cooling capacities are available in [1].

The conduction-cooling technique involves a mechanical connection of the load (the instrument that is to be cooled) with the cryogenic heat exchanger of a cryocooler. The mechanical connection is established by a thermal link, commonly made of a high thermal conductivity metal such as copper and aluminum. The cryocooler-thermal link-load mechanical connection can be a semi-permanent type such as comprising brazed joints or demountable type realized by pressed or bolted contacts. The thermal link commonly comprises flexible elements such as a strap or braid that compensate for the difference between thermal contraction of the cryocooler body and the instrument body as they cool down from room temperature to the cryogenic operating temperature. The flexible elements also provide vibration isolation between the cryocooler (that typically generates vibration) and the load. With conduction-cooling, the cryocooler-thermal link-load operates in a thermally shielded vacuum space, without any cooling liquid or gas surrounding it.

1.2 Scope of this review

Although different cryocoolers and combinations thereof provides access to the entire sub-ambient temperature range, this review will focus on devices and instruments operating near or below the normal liquid helium temperature of 4.2 K. This temperature range can be reached using multi-stage Gifford McMahon cryocoolers, pulse tube cryocoolers, and Joule Thompson cryocoolers.

1. Low Temperature Superconducting (LTS) magnets - typically made of niobium-titanium (NbTi) or niobium-tin superconductor (Nb_3Sn). Applications include magnetic resonance imaging, nuclear magnetic resonance, particle accelerators (for beam bending and focus/de-focusing), x-ray and neutron diffraction systems, magnetic energy storage systems, and more [2],[3].

2. Superconducting radiofrequency (SRF) cavities - typically made of niobium and niobium-tin. Potential applications include electron-beam irradiation treatment of materials, treatment of flue gas and wastewater, medical device sterilization, and more using conduction-cooled SRF accelerators [4]-[7].

3. Sub-kelvin cryocoolers such as a dilution refrigerator and adiabatic refrigerator that employ 4 K cryocoolers (commonly the pulse tube cryocooler) for precooling. Dry dilution refrigerators have become commonplace in quantum information science, quantum computing development, astrophysics (dark matter search, etc.) and general research at mK temperatures. Cryocooler adiabatic demagnetization refrigerators are routinely used in spaceborne experiments running below 1 Kelvin [8],[9].

2 Advantages and limitations

2.1 Advantages

Unique advantages of cryocooler conduction cooling are the following:

1. The advantages of cryocooler conduction cooling result from the basic fact that no cryogenic gas or liquid leaves the cryocooler body during operation. The working fluid is confined to the cryocooler when it is put together as a commercial package at the cryocooler manufacturer. The overpressure safety and electrical safety devices are integrated into the cryocooler package by the manufacturer such that the end user carries no burden of the cryocooler safety aspects.

2. Since no cryogenic fluid leaves the cryocooler package, a conduction-cooled device or its enclosure (known as cryostat) does not make direct contact with a cryogenic fluid. As a result, upset conditions such as a sudden loss of insulating vacuum [10]-[12] or of beamline vacuum [13]-[17] (SRF accelerators) are easier to manage than if cryogens such as supercritical and liquid helium are present in the cryostat.

3. The absence of cryogenic fluid and less severe overpressure condition also simplifies the design of the cryostat. In most cases, the cryostat no longer needs the classification as a pressure vessel because it does not contain cold gas or liquid. Design criteria per codes and standards (example, ASME BPVC) then become relaxed compared to those for a pressure vessel containing cryogenic liquid.

4. Cryocoolers have turnkey operation that enables switching it on and off with the push of a button. As a result, conduction cooled devices do not require complex cooldown and warm up procedures. Conduction cooled systems can be operated by personnel who may not have specialized training or deep experience in cryogenic operations.

5. Modern cryocoolers are highly reliable with mean time between maintenance exceeding 20000 hours. This enables continuous system operation for more than 2 years. For contrast, piston expander-based small-capacity helium liquefiers typically require yearly maintenance.

2.2 Limitations

Some limitations of cryocooler conduction cooling are the following:

1. Cryocoolers that reach liquid helium temperatures (Gifford-McMahon and pulse tube type) use valves to compress and expand the gas in the cold head. These valves introduce high inefficiency in the cryocooler system. As a result, the specific cooling power of currently available most efficient commercial cryocoolers is ~3000 W(electrical)/W(cooling at 4.2 K). This is large compared to ~500

W(electrical)/W(cooling at 4.2 K) for a mid-size helium refrigerator. As a result, 4 K cryocoolers are cost-prohibitive and impractical for cooling large devices that have a heat load of more than ~15-20 W.

2. Cryocooler conduction-cooled devices exhibit long cooldown durations from room temperature to the operating cryogenic temperature. This results from the slow diffusive heat transfer mechanism in the thermal conduction links, large heat capacity of the load, and small unit cooling capacity of commercial cryocoolers (2.5-3 W @ 4.2 K).
3. Due to small unit cryocooler capacity, conduction-cooled devices need to be designed to keep static heat leak to as small as practical. Otherwise, a large fraction of the cryocooler cooling capacity is used up for removing the static heat leak. In general, the static heat leak budget of cryocooler conduction systems is very limited compared to systems using convective heat transfer with super-critical/liquid helium.

3 Conduction cooled superconducting magnets

3.1 Design considerations

Superconducting magnets are dc (direct current) devices that dissipate negligible heat during operation. Dynamic heat load in superconducting magnet systems to 4 K (in case of NbTi magnets) is therefore negligible. Static heat leak through supports to the ambient stage of the cryostat, current leads, and thermal radiation constitute the major sources of heat load. A thermal conduction link then needs to manage the static heat leak, which can be made small by proper optimization of the system. The considerations include using low thermal conductivity supports made of G10, stainless steel, or titanium alloys with optimal thermal interception at warmer temperature (50-70 K), proper design and installation of multilayer insulation to lower thermal radiation, and optimal design and thermal interception of current leads that minimizes heat conduction and Joule heating during current transport (see [18] and references therein).

A superconducting magnet stores substantial energy in its magnetic field when energized. Even a tabletop sized magnet with few-Tesla field can store several tens of kiloJoules. A sudden quench to normal conducting state kills the magnetic field, causing the stored energy to convert into heat, which gets absorbed into the heat capacity of the body of the magnet. Alternatively, a quench protection system can be provided that dissipates the heat in an external resistor or power diode. For smaller magnets, sufficient heat capacity can be provided in the magnet body (by using a larger proportion of stabilizer such as copper with NbTi) that absorbs the stored heat without excessively warming the magnet body. The thermal conduction link also plays a key role in handling such a quench scenario. The link needs to be designed with sufficient thermal conductance so as to enable intimate thermal contact between the cryocooler and the quenched, warm magnet body to prevent a thermal runaway. Additionally, the thermal link should provide sufficient thermal conductance to keep the re-cooldown time of the warm magnet body during quench recovery to as small as practical.

3.2 Architectures

The typical configuration of a cryocooler conduction cooled magnet is depicted in figure 1 [19]. This includes a vertically oriented solenoid made of NbTi or Nb_3Sn superconductor, stabilized using a high thermal conductivity metal such as copper. The solenoid has a warm bore that allows insertion of an experimental device in the high magnetic field region. The thermal conduction link (referred to as conduction plate) connects to the 4 K stage of a GM cryocooler on one end and to multiple locations of the solenoid former on the other. The 4 K cold mass including the magnet body, conduction links, and the cryocooler section are enclosed in a multilayer insulation wrapped thermal shield. The thermal shield is also conduction cooled to the cryocooler at its warmer 50 K stage. The thermal shield and the magnet body are hung from a vacuum vessel top plate using G10 supports. This top assembly is then hosted in a vacuum vessel chamber.

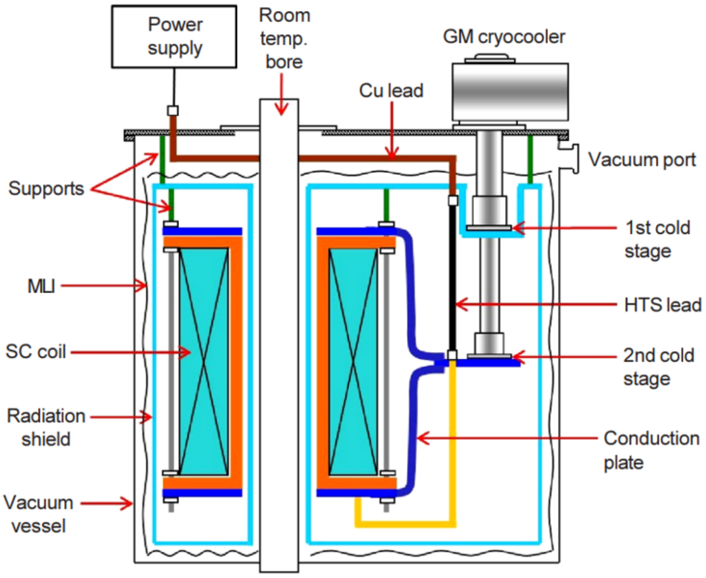

Figure 1: Typical cryocooled conduction cooling architecture for superconducting magnets [19].

The magnet uses hybrid current leads with a copper section between the vacuum vessel (ambient) and the thermal shield (∼50 K intercept) and then a HTS (high temperature superconductor) section between the thermal shield and the solenoid. Slight variants of this configuration include a horizontally laid out solenoid [18] and a split coil that allows hosting of a larger experimental sample in the high magnetic field region. Several low temperature superconducting magnets have been successfully built and operated using cryocooler conduction cooling, see [20], [21] for examples. The recent effort is this area is to develop magnets using intermediate temperature superconductors (namely MgB_2 [22]) and high temperature superconductors (using REBCO) [23] that can be operated at temperatures much higher than 4 K where cryocooler exhibit significantly greater thermodynamic efficiency and cooling capacity.

4 Conduction cooled SRF accelerator cavities

4.1 Design considerations

Unlike superconducting magnets, superconducting RF (SRF) accelerator cavities are heat generating devices. This is because SRF cavities are electromagnetic resonators that work with alternating currents albeit in the superconducting state. SRF cavities thus experience significant dynamic heat load during operation. The thermal conduction link for cooling SRF using cryocoolers must be designed to handle this dynamic heat load. This roughly translates to the requirement of high bulk thermal conductance and low thermal contact resistance in the thermal link.

The most common SRF cavity shape is the elliptical cell made by deep drawing niobium sheets into elliptical half-cells and then welding them together to form the full elliptical cell. Such a cell can be cooled using liquid helium simply by immersion. However, the elliptical surface of the cell does not provide a ready mechanism for attaching a thermal link for conduction cooling. Three techniques have recently been developed that enable connection of a thermal conduction link to elliptical cell niobium cavities.

4.2 Architectures

One technique involves high purity copper on the outer surface of the niobium elliptical cell. As niobium and copper cannot be joined by brazing or welding, the first step in this process is to grow a thin “seed” layer of copper onto niobium by cold spray. Herein, copper powder is impinged on the niobium surface with extremely high velocity such that the powder mechanically bonds to the niobium. Thereafter, a thicker layer of copper is electro-deposited on the copper seed layer. Finally, this thick copper layer is machined to create features such as a ring with holes that allow bolting a thermal conduction link. Figure 2 shows a cavity prepared for cryocooler conduction cooling following this technique [24]. This cavity was connected to a 1.5 W @ 4.2 K Gifford-McMahon cryocooler using a copper plate shaped thermal link as depicted in figure 3. RF tests showed that his 1.495 GHz cavity produced 6.5 MV/m continuous-wave average accelerating gradient at a quality factor of $2\text{x}10^9$.

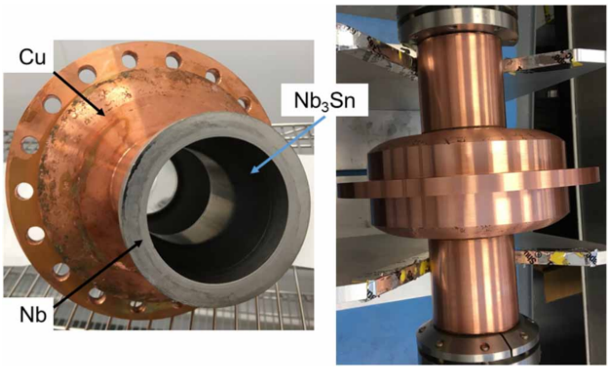

Figure 2: Conduction cooled SRF cavity prepared by electro-deposition of copper on the outer cavity surface [24].

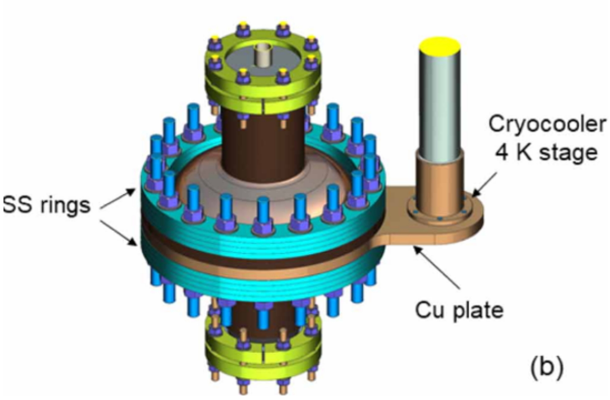

Figure 3: SRF cavity electro-deposited with copper as connected to 4 K stage of a Gifford-McMahon cryocooler [24].

Another technique that has shown to work, especially for smaller cavities (>2.5 GHz) is depicted below in figure 4. Herein, the thermal link clamps onto the two cavity beam pipes. RF tests on this 2.6 GHz SRF cavity showed cw average accelerating gradient of 12 MV/m at a quality factor of $7\text{x}10^9$ [25].

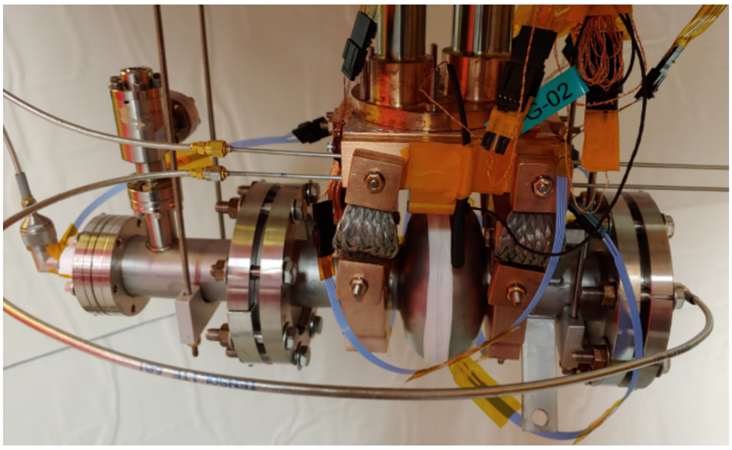

Figure 4: Conduction cooled SRF cavity prepared by clamping thermal straps on the cavity beam pipes [25].

In another technique, one niobium conduction ring is first welded to each elliptical niobium halfcell. The weld is located near the equator of the cavity cell where most heat is dissipated during cavity RF operation. The niobium conduction rings have flat surfaces with several holes to which a thermal conduction link can be bolted to. Thereafter, thermal link made of high purity aluminum is made by bolting flat panes cut out of a larger sheet. This thermal link is bolted to the niobium conduction rings on one end and to the cryocooler 4 K stage on the other end. All of the bolted contacts are interposed with thin film indium to reduce thermal contact resistance. A cavity setup developed using this technique is shown in figure 5 and further construction details are available in [26]-[30]. This 650 MHz cavity when cooled using a Cryomech PT420 (2 W @ 4.2 K) pulse tube cryocooler in a thermally and magnetically shielded cryostat produced 10 MV/m continuous-wave average accelerating gradient at a quality factor of 2x10^{1}0. Figure 6 shows the experimental setup.

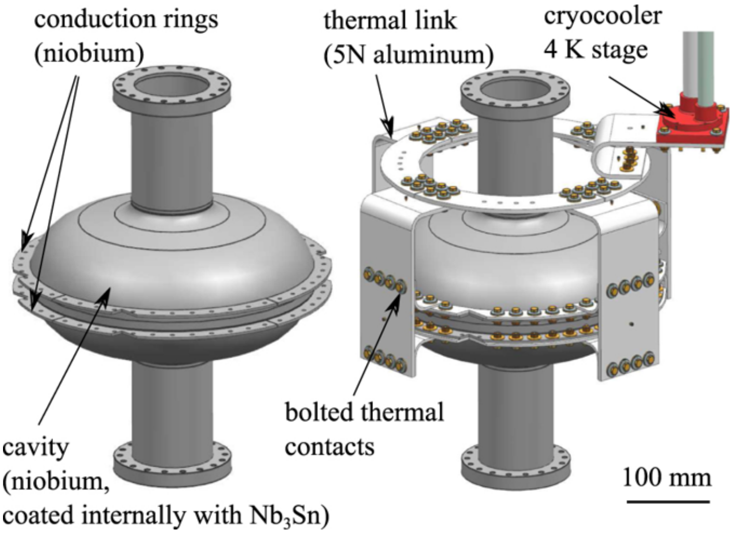

Figure 5: Conduction cooled SRF cavity prepared by welding niobium rings on the elliptical half-cells (left) and bolted to a pulse tube cryocooler using high-purity aluminum thermal link [26]-[30].

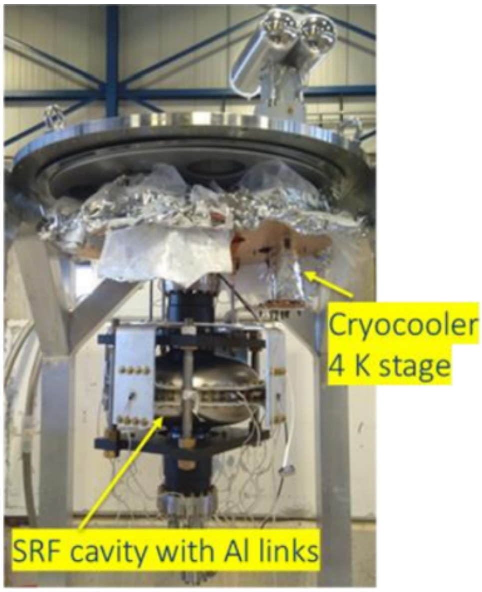

Figure 6: Experimental setup showing the aluminum thermal link conduction cooled cryocooler connected to the cryostat top plate [26]-[30].

5 Cryocooler pre-cooled dilution refrigerators

Dilution refrigerators are a special class of cryogenic refrigerators that can attain temperatures as low as a few milliKelvins. They use a mixture of ^{3}He and ^{4}He to produce such cold temperatures. Figure 7 shows the working schematic of a traditional 'wet' dilution refrigerator. The ^{3}He-^{4}He mixture is first compressed and progressively cooled from room temperature to nearly 1-2 K using first a bath of saturated liquid helium and then via convective heat exchange with a pumped helium bath at $\sim$1 K. The mixture is further cooled at the refrigerator stage called 'still' whose temperature is maintained below 1 K by pumping on the returning path of the same mixture. After this, the mixture flows through multiple counterflow heat exchangers losing heat to the colder returning flow. At the lowest thermal stage of the refrigerator the mixture splits into two distinct fluid phases: (1) concentrated phase that is mostly 3He and (2) dilute phase that is a still mixture of ^{3}He and 4He but with more ^{4}He. This phase separation process results from finite solubility of ^{3}He in ^{4}He even at absolute zero temperature. The phase separation process is endothermic (heat absorbing) and the entropy change associated with the process is what provides the cooling power of the dilution refrigerator.

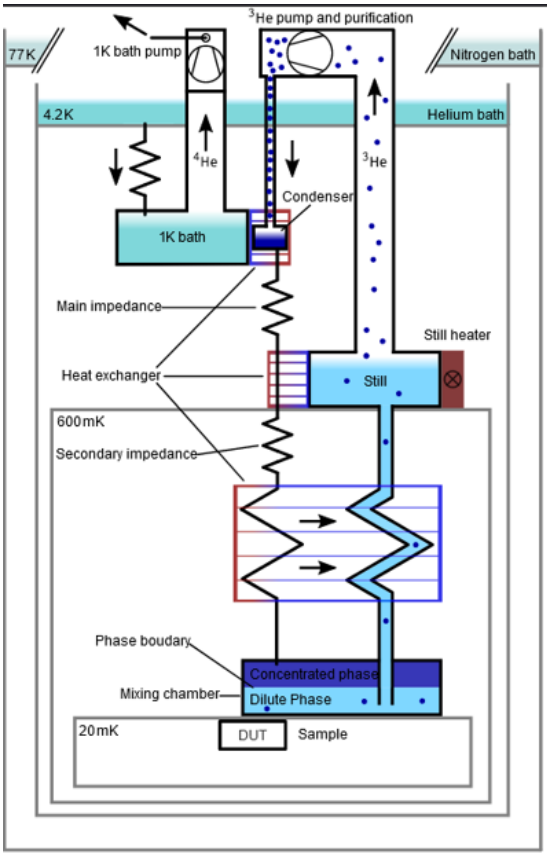

Figure 7: Working schematic of a liquid helium cooled 'wet' dilution refrigerator.

The traditional 'wet' dilution refrigerators use baths of saturated liquid helium as well as a pumped bath of 1 K liquid helium. The use of liquid helium makes the wet dilution refrigerator somewhat unreliable and cumbersome to use. In modern day dilution refrigerators, the liquid helium baths are replaced by two-stage pulse tube cryocoolers. The ^{3}He-^{4}He mixture is cooled by convectively coupling to the two thermal stages of the cryocooler as well as to the second stage regenerator that has non-zero enthalpy flow. The mixture is cooled to nearly 2.5 K by the time it flows past the pulse tube cryocooler. The subsequent cooling stages are much similar to those of the wet dilution refrigerator. The absence of liquid helium baths enables 'dry' operation and hence these cryocooler cooled units are called 'dry' dilution refrigerators. A working schematic of a dry dilution refrigerator is shown in figure 8.

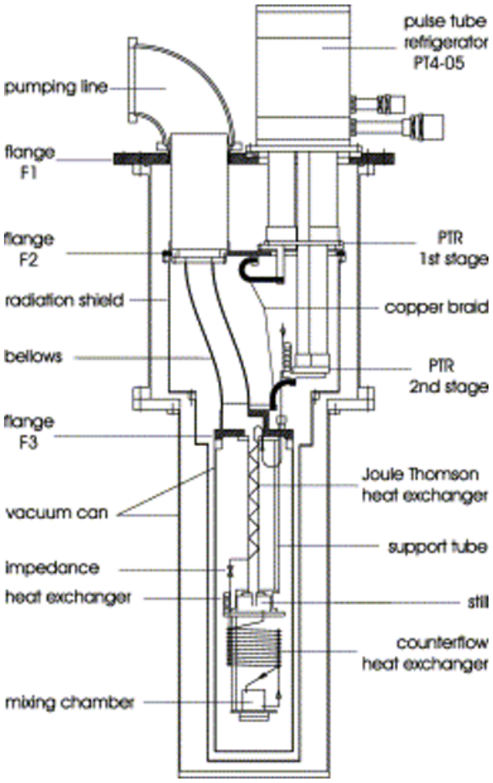

Figure 8: Construction schematic of a cryocooler pre-cooled 'dry' dilution refrigerator [31].

The dry dilution refrigerator was first developed in 2002 using precooling with Cryomech PT405 two-stage pulse tube cryocooler [31]. Since this inception, several designs have been proposed for dry dilution refrigerators including for tabletop laboratory scale as well as large ones [32]-[33]. Today, dry dilution refrigerators have become a workhorse for quantum computing and information science based on superconducting qubits [8], research in the quantum regime [34], and ultra-low temperature detectors for dark matter searches [9],[35].

6 Domains of further research

6.1 Contact resistance modeling and characterization

Mechanically pressed contacts are ubiquitous to cryocooler conduction-cooled systems because they comprise components of the cooling link bolted to each other, the device, and the cryocooler cold head. Bolted pressed contacts can become a source of large thermal resistance between the device and the cryocooler because of the small area available for heat transfer across them. This is because heat transfer across pressed contacts occurs at the contacting microscopic asperities and not over the entire apparent contact area (real contact area is typically ¡1% of apparent contact area). The design of pressed contacts for conduction cooling, especially at the lowest temperatures, therefore requires special attention. Some methods to minimize pressure contact resistance is the application of a thin layer of cryogenic thermal grease such as Apeizon N, interposing the contact with thin foil indium, and gold plating the surfaces that constitute the pressure contact. Noteworthy and outstanding reviews on contact thermal resistance are given by Gmelin et al. [36] and by Dhuley [37]. The review by Dhuley [37] represents a breakthrough in the topic of thermal contact resistance because it presents a theoretical model for the calculation of contact thermal resistance of copper-copper and gold-plated copper-copper contacts at temperature below 4 K along with a thorough compilation of the data for these generated over the past fifty years.

6.2 Modeling of the cooldown time

One drawback of cryocooler conduction cooling is the long cooldown time from room temperature to the operating cryogenic temperature of the system. As mentioned earlier, the long cooldown results from the slow thermal diffusion process (compared with convection heat transfer) and low unit cooling capacity of cryocoolers (compared with a pool of cryogen). As a result, it is imperative to design the thermal conduction link from the point of view of keeping the cooldown time as small as practical. Calculation of the cooldown time requires a numerical solution of first order partial differential equations loaded heavily with strongly temperature dependent material properties namely thermal conductivity, specific heat capacity, thermal contact resistance, and unit cryocooler capacity. A simplified framework for estimating cooldown time of cryocooler conduction cooled devices is available in [18].

6.3 Flexibility in the thermal conduction link

The primary purpose of a thermal conduction link is to provide a high thermal conductance path for heat flow between the device and the cryocooler. This can be achieved by using a high thermal conductivity metal such as pure copper or aluminum, shortening the link length, and maximizing the cross section area. A short and large cross section thermal link can, however, result in a rigid connection between the device and the cryocooler. Consequently, the vibrations generated by the cryocooler will seamlessly transmit to the device, which can deteriorate the device performance (unstable or noisy signal). To minimize the transmittal of vibrations, a conduction cooling link is routinely equipped with a flexible element. The flexibility is provided using metallic straps or braids. Flexible straps and braids have woven ropes or stacked foils either mechanically pressed or soldered/brazed/welded to solid end-connectors. The strap material is primarily copper while aluminum is used for applications that demand light weight in addition to flexibility with high thermal conductance. Non-metallic graphite or carbon fiber straps have also been constructed but these materials possess far less thermal conductivity at the lower temperatures (below 20-30 K) and hence are not as attractive as copper or aluminum for devices working at liquid helium temperatures. An overview of flexible link construction techniques is available in [40],[41] including those for space and ground based applications, reaching cryogenic temperatures as low as 100 mK.

7 Summary

The review presented in this paper reveals several applications of cryocooler conduction cooling - superconducting magnets, accelerator cavities, and sub-Kelvin refrigerators. Common techniques of thermally linking these devices to cryocoolers have been summarized. While the cryocooler conduction cooling technology appears mature, several areas still exist that need to be researched for further betterment of the technology. Some of these include characterization and modeling of thermal contact resistance, numerical modeling of cooldown time, and design of high thermal conductivity flexible linkages.

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