The Importance of the Connection between a Cryogenic Cooler and Its Load

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ABSTRACT

Coolers are used to cool and cool down devices of all kinds. These can be anything from small electronic devices [1] to large devices such as superconducting magnets [2, 3]. The two types of connections between the cooler cold head and the load are: 1) thermal conduction through a high thermal conductivity strap from the load to the cooler, and 2) a connection via fluid flow between the cooler and the load such as using a heat pipe [4, 5] or a thermal-siphon cooling loop [6, 7]. In general, small-device detectors are often cooled by conduction from the load to the cooler cold head. Large devices, such as large superconducting magnets that generate a large stray magnetic field, can be cooled down and cooled using some form of cooling loop. This paper discusses both types of thermal connections and where one might choose one type of connection over the other.

INTRODUCTION TO THE COOLER CONNECTION PROBLEM

How coolers are connected to the loads is dependent on a number of factors that includes the following: 1) the distance from the cold head to the load, 2) the physical size of the load, 3) the maximum allowable temperature difference between the hottest place in the load and the cooler cold head, 4) the required operating orientation of the cooler, 5) the need for flexible connections, 6) the effect of cooler vibration and vibration isolation, 7) the magnetic field at the cooler, 8) the required reliable operating time for the device being cooled, and 9) packaging issues associated with the devices being cooled and cooled down.

Two types of coolers are considered here, because these are the coolers that are mass produced by a number of different companies. The two types of commercial coolers are Gifford McMahon (GM) coolers and pulse tube coolers using a GM cycle. Both single-stage and two-stage versions of these coolers are available from more than one manufacturer. Single-stage GM coolers can reach temperatures as low as 11 K. Single-stage pulse tube coolers don't go lower than 20 K. Two-stage GM coolers and pulse tube coolers can reach temperature as low 2.6 K when helium 4 is the working fluid. With helium 3 as a working fluid, temperatures $<$ 1.7 K can be reached [8]. Dilution refrigerators that operate at $<$100 mK use helium 3 and helium 4. These are also commercially available [8]. Both GM and pulse tube of coolers are capable of re-condensing helium, hydrogen, neon or other cryogenic fluids provided the right kind of regenerator and cold heat exchangers are used. Both types of coolers are capable of liquefying the same gasses that they can re-condense provided proper precooling of the gas is done before liquefaction [9].

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Characteristics of the Two Types of Coolers

Most of the commercial coolers being produced today are GM coolers. These coolers have motor driven pistons and a regenerator to produce the cold. In general, these types of coolers are not sensitive to their physical orientation with respect to gravity. If one needs a cooler that must operate at any orientation one should select a GM cooler. These coolers typically operate at 1 to 1.2 Hz. They can be built to operate at higher frequencies, but there is more wear between the pistons and cylinders. Because they have pistons sliding within cylinders, GM coolers are sensitive to magnetic fields > 0.1 T [10, 11]. Magnetic fields cause the piston to press against the cylinder, thus the operating life of the cooler between maintenances is lower. The driving motor of the pistons is also affected by magnetic fields > 0.1 T [10]. Because of the moving piston mass, cooler vibration may be an issue for some applications. Commercial GM coolers have suggested maintenance intervals of ~10000 hours. Cooler maintenance usually requires that the cooler be removed or disassembled in place. Drop-in GM coolers are also possible.

Commercial GM pulse tube coolers are produced by at least two companies. This type of cooler must be oriented with the warm end up and the cold end down. Changing the cooler orientation by 15 degrees affects the cooler performance. Commercial GM pulse tube coolers operate between 1.0 and 1.2 Hz. One can speculate whether higher frequencies are doable with good results. Pulse tube coolers produce much less vibration than GM coolers, because there is no moving mass in the cold head. The only part of a GM pulse tube cooler that is sensitive to magnetic field is the pulsing motor [10], [11]. If the pulsing motor is remote from the cooler, it can be shielded more effectively [10]. In 4 K coolers, regenerator material becomes less effective at fields above 1 T level [10]. This would be true for GM coolers too. High frequency Stirling Cycle coolers are not sensitive to gravity. Commercially available pulse tube coolers have a suggested maintenance interval of 25000 hours. This interval applies more to the compressor than the cold head rotary valve assembly. A remote rotary valve assembly is easy to maintain while the device is cold, provided one puts full flow valves between the rotary valve assembly and the cooler cold head.

Drop-in Coolers, a Solution to Maintenance and Transport Problems

Fig. 1 shows three configurations for drop-in coolers. Fig. 2 shows a Cryomech PT415 cooler configured as a drop-in cooler with a condensing cold head. Drop-in pulse tube coolers

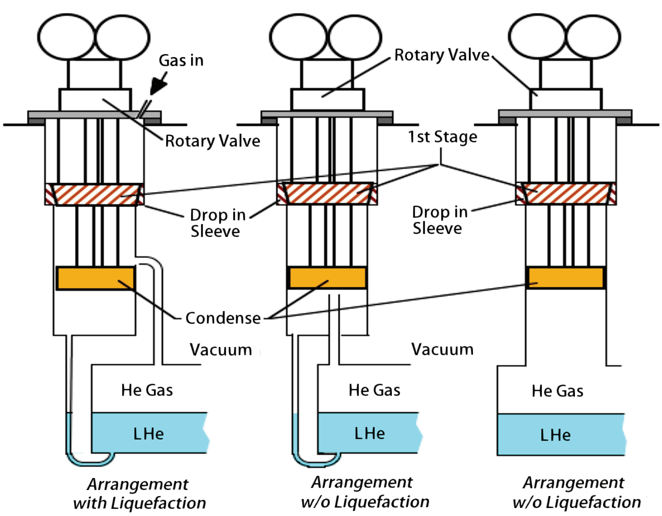


Figure 1. Three configurations of drop-in coolers tested by LBL in 2007. The configuration on the left is the only one that permits liquefaction of helium. The two configurations on the right are only good for re-condensation of helium. The ΔT between the helium and the cold head was less than 0.1 K [9].

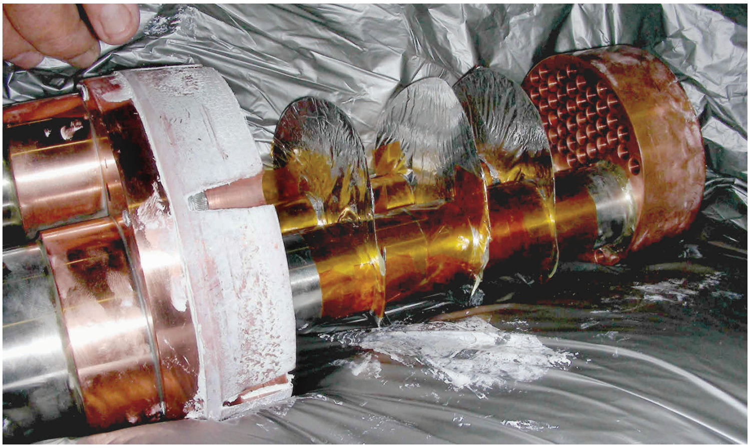


Figure 2. The first and second stages of a Cryomech PT415 cooler. The first stage is tapered to fit into a tapered hole attached to the shield and the stainless steel can around the cooler cold part. The grease on the first stage increases the thermal conductivity between the shield and the first stage. The second stage has a condenser with an area of 0.04 m^2.

have been used to cool and cool down superconducting magnets [12, 13]. When using drop-in coolers, one can easily remove a cooler for maintenance. Another benefit of using drop-in coolers is that the coolers can be shipped separately from the device to which the cooler is attached. The use of drop-in coolers requires that the vacuum around the cold heads be separate from the device vacuum system. It should be noted that GM coolers can also be configured as drop-in coolers. Drop in coolers make cooler maintenance easy, but it is difficult to connect the cooler stages to the load. One can design a single-stage cooler that can be plugged into the load. Plugging in two or more stages into their loads is much more difficult. The separate vacuum vessel for a drop-in cooler produces extra heat leaks into the shields around the device and the device itself.

The extra heat flow from 300 K to 20 K through the separate stainless-steel vacuum vessel to the first-stage cold head is 2 to 4 W. For a two-stage cooler such as a PT415, the heat leak between the cooler first stage to a liquid helium vessel would be from 0.1 to 0.2 W. In the opinion of this author, a two-stage cooler is best connected to the second stage heat load via some sort of heat pipe or cooling loop. Referring again to Figure 1, the configuration on the left is the only configuration that has demonstrated that room temperature helium can be liquefied after the helium tank is cooled down [9, 12]. The two configurations on the right side of Figure 2 re-condense helium, but they don't liquefy warm helium gas.

The Effect of the Cooler Distance from the Load and the Size of the device

This section applies to devices such as superconducting magnets that produce large stray magnetic fields, or they are in ionizing radiation that could damage the coolers. The upper ends of HTS leads are usually connected to a two-stage cooler's first-stage cold head, but such leads can also be connected to a liquid nitrogen shield. The performance of HTS leads are affected by magnetic fields [10, 14]. This effect is worst when the field is perpendicular to a tape conductor. When a device is conduction cooled, the cross-sectional area of the connector is proportional to the connector length. Longer connector lengths require more flexibility due to thermal contraction. More heat can be transferred by fluid flow for a given cross-section provided the cooler is above the load [7]. Long distances favor using a cooling loop for cooling.

Large devices are usually cooled using multiple coolers. If a device is long compared to its other dimensions, the coolers should be distributed along the length of the device [14]. The shield should be made of a material that has a *higher* thermal conductivity as the temperature goes down from 80 K to 40 K [15]. A high RRR copper shield (RRR > 50) or an annealed 1100-O (RRR > 20) aluminum shield are good choices. The aluminum shield is three times thicker and much stiffer for a given shield mass. The upper end of the HTS leads must be near the lowest temperature cooler [16]. If the device is large in diameter and short in length, the coolers must be distributed around the device if the device is cooled by conduction [17]. In the case of a short device with a large diameter, connecting the coolers with a fluid cooling loop permits the coolers to be mounted in one place; however, the shield around the device must be cooled using liquid nitrogen [17]. A liquid nitrogen shield must have a low emissivity coating on the inside of the shield and there must be several layers of MLI between the shield and device being cooled by the coolers [18]. The insulation between the shield and the cold device also reduces the heat leak from the shield when the cryostat vacuum is marginally too high.

COOLER CONNECTION TO THE LOAD VIA THERMAL CONDUCTION

The most common way to cool a small device is to connect the device directly to the cooler cold head. If that device is an array of detectors on a chip as described in [1], the device must be in the correct location so that the image is fully in focus across the detector array on the chip surface. The effects of cooler head vibration may also have to be considered. A flexible connection between the cooler cold head allows the location of the device to be set separate from the cooler, and a flexible connection may also reduce vibration at the device.

Ordinary copper cables are not the answer. The copper in an ordinary copper cable is too cold-worked to have high thermal conductivity below 40 K. The material that should be in the connection between the cold head and the load should be made from a high resistance ratio (RRR) copper or aluminum. A typical metal follows the Wiedeman-Franz law. This means that a low resistivity metal has a higher thermal conductivity. For copper and aluminum with an RRR > 100, the resistivity of the metal ceases to change as one goes down in temperature at some temperature below 25 K. The higher the RRR the lower the temperature where the resistivity ceases to change. At temperatures below 5 to 10 K, the thermal conductivity of the metal is often proportional to the absolute temperature and the RRR [19]. Magnetic field decreases the thermal conductivity of copper and aluminum at temperatures below ~80 K [20]. Since the cooler cold heads should be kept at low magnetic inductions the increase in magneto-thermal conductivity is most likely to be seen close to the device. The magnetic field effects on the strap thermal conductivity are less for an aluminum strap than for a copper strap [20]. Very pure aluminums can have a thermal conductivity greater than copper [21]. The strap RRR doesn't affect device cooldown time very much [22], because the benefit of having a high RRR occurs when the device specific heat is low. For a given cable mass, an aluminum cable will have over three times the cross-section of a copper cable. When an electrical insulator is needed between the device and the strap, sapphire is a good material to use because of its high thermal conductivity from 7 to 100 K [21].

With all high RRR materials, one must control the conductor strain. The low resistivity material must be near the neutral axis in any bend and the bends should be gentle. Aluminum has a number of issues. It is difficult to solder to copper because of the oxide that forms on the surface of aluminums of all types. Very pure aluminum has a much lower yield stress than pure copper. The final issue with aluminum is that the total contraction coefficient from 300 K to 4 K is a third larger than copper or stainless steel. Good references for the thermal conductivity of various materials including solders can be found in Eiken's book [21] and in NBS Monograph 131 [23].

Conducting straps or cables should not be used to transfer heat to a cooler under the following circumstances: 1) when the heat from the device to the cold head must be transferred long distances (say > 1 m) [7], 2) when the temperature difference within superconducting device is too large (an example of this is when the internal temperature drop is greater than 20 percent of the critical temperature at the peak magnetic induction in an HTS superconducting device when the field orientation is most unfavorable), and 3) in many cases when two-stage drop-in coolers are used.

COOLER CONNECTION TO THE LOAD VIA A COOLING LOOP

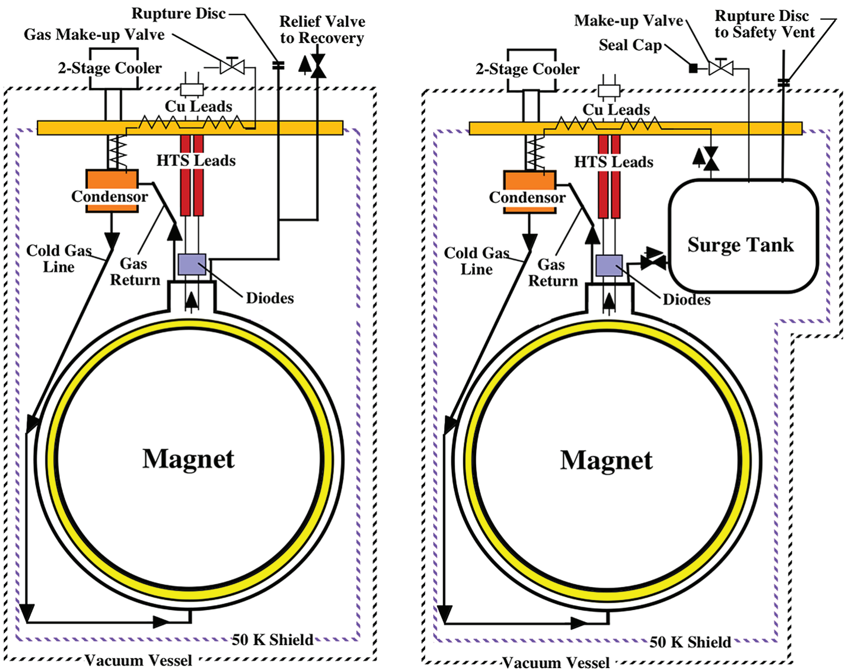
Cooling down a superconducting magnet from 300 to 80 K without putting liquid nitrogen into the magnet cryostat can be as simple as having a closed stainless-steel pipe that is filled with pressurized nitrogen gas that is connected from an insulated container that is outside of the magnet cryostat above the magnet. When the container outside of the container is filled with liquid nitrogen, some of the nitrogen in the pipe will be liquefied. The liquid nitrogen will run down the pipe and cool the pipe and the magnet down. The nitrogen boil-off gas will go back up the pipe to be re-liquefied. When the magnet reaches 80 K, liquid helium can be injected into the magnet cryostat below the magnet thus removing the last ten percent of the thermal energy as the magnet is cooled to 4 K. When the magnet temperature drops below the triple point temperature of nitrogen, the nitrogen freezes. As the temperature drops to 4 K, the partial pressure is so low that very little heat is transferred down the pipe. This is an example of a simple free convection cooling pipe that acts like a heat diode when the magnet temperature drops below 40 K.

During the 1960's there were many heat pipe papers. Many of these papers were for NASA projects. Heat pipes can use free convection that implies that there is gravity [5], or circulation can be achieved using surface tension forces [4]. Many of the heat pipe papers use two-phase fluids that are circulated. Most of the large detector magnets for high energy physics have been cooled using forced two-phase helium cooling, but there some that are cooled using natural-convection two-phase flow helium cooling. These are the 4.96-m diameter ALEPH magnet at CERN [24], the 2.90-m diameter CLEO-2 magnet at Cornell [25], and the 2.76-m diameter BaBar magnet at SLAC [26]. For all three of these magnets the liquid helium is fed from the bottom of a helium storage tank above the magnet coil and the two-phase helium is returned to the top of the tank where phase separation occurs. The tank is kept full using a large helium refrigerator. The magnets were cooled down using a separate cooldown circuit from the refrigerator. Two-phase cooling by natural convection can remove hundreds of watts of heat from a large magnet [27].

In late 2012, Michigan State University (MSU) decided to cool down and cool the Cyclotron Gas-stopper Magnet using six PT415 coolers with remote motors connected to the two magnet coils that are housed in separate cryostats [28]. At the time, we knew about the work at Cryomech and other places to design cooler systems that would liquefy helium from warm gas [29]. LBL demonstrated that this could be done in a cooling loop in 2007 [12], so it seemed straight forward to do the helium liquefaction within the loop heat exchangers after the cool-down. We made calculations of the pressure drops and the helium flow rate during a magnet cooldown based on the original design drawings for the magnet. The calculations suggested that the two magnet coils could be cooled down from 300 K to 5 K to remove 102 MJ of thermal energy in four days [30]. This estimate turned out to be wrong by over a factor of 3.5. The liquefaction time for 15 L of helium gas was also much longer than expected.

The reasons for the discrepancy in the actual cooldown time compared to the initial calculated cooldown time are as follows [31]:

1) The actual cold mass was ~10 percent higher than originally calculated.
2) The flow space on the outside of the coils was smaller by a factor of two than the original design; there was almost no flow space on the inside of the coil. The total area of all of the flow channels should have been a factor of three larger and it should have been split between the inside and the outside of the coil.
3) The magnet shims on the outside of the coil produced large momentum jumps in the flow, which reduced the helium mass flow rate.



a) Open System for He *b) Closed System for He, H_2, and Ne*

Figure 3. Open and closed two-phase, free-convection thermal-siphon cooling loops for use with cryogens such as helium, hydrogen or neon. Helium can be used in either an open loop or a closed loop. Hydrogen, a highly flammable gas is best used in a closed loop with the loop pre-charged and sealed. The size of the tank is dependent on the tank and cooling system design pressure and mass of the gas in the tank. A loop with no liquid in it requires a smaller surge tank.

4) The actual pressure in the helium vessel was 0.16 MPa; the pressure used for the calculation was 0.40 MPa. The working pressure was limited by the bellows in the system.
5) The flow circuit resistance was different for each cooler, so the total cooling available from all three coolers was reduced by one third.
6) The model for the maximum available cooling from the coolers was optimistic. The measured cooler performance [32] was less than predicted.
7) The heat exchanger attached to the cooler cold head could have been more efficient. The heat transfer coefficient multiplied by the heat transfer area could have been increased by a factor of five. In subsequent tests, the helium liquefaction time was reduced a factor of four by changing the injection point for makeup helium coming from the cooler first stage [33].

Figure 3 shows an open loop cooling system for use with helium or nitrogen and a closed loop system that one would use for hydrogen or neon [22].

Table 1 shows the effect of the cooler to device connector length, and heat transmitted per unit area on the temperature drop between the load and the cooler ΔT. Increasing the Cu RRR will reduce the ΔT for the case with the Cu strap. The cross-section area used for the loop cases is the ID cross-section area of the input pipe to the load plus the ID cross-section area of the outlet pipe from the load.

A neon loop was not included in Table 1 because the cooldown time for the neon loop is much longer. If one compares a loop with hydrogen gas with a loop with helium gas (no liquid in either case), hydrogen gas will remove the heat with a lower ΔT in the loop, for the same reason that the cooldown time for a hydrogen loop is shorter [22]. The gain from the use of hydrogen gas in the loop may not be worth the extra steps required for hydrogen safety. From the studies

Table 1. Temperature drops for cooling transmission as a function of temperature, heat flow per unit Area, and length for copper straps or liquid helium and liquid hydrogen cooling loops [7].

Heat Transfer Method	T (K)	Q/A (W m^{-2})	Length (m)	ΔT (K)
RRR = 130 Copper Strap	4.2	2600	0.15	~0.5
RRR = 130 Copper Strap	4.2	2600	1.00	~3.0
RRR = 130 Copper Strap	4.2	2600	6.00	~10
LHe Cooling Loop	4.2	25000	0.15	< 0.1
LHe Cooling Loop	4.2	16800	1.00	< 0.1
LHe Cooling Loop	4.2	11800	6.0	< 0.1
RRR = 130 Copper Strap	20.3	2600	0.15	~0.2
RRR = 130 Copper Strap	20.3	2600	1.00	~1.0
RRR = 130 Copper Strap	20.3	2600	6.00	~7.0
LH_2 Cooling Loop	20.3	89000	0.15	< 0.2
LH_2 Cooling Loop	20.3	60000	1.00	< 0.2
LH_2 Cooling Loop	20.3	42000	6.00	< 0.2

done by this author, it appears that helium gas is a reasonably good coolant for applications such as HTS magnets. The ΔT for a gas loop will be larger than for a liquid helium (or hydrogen) cooling loop. An advantage of a helium gas loop is that one doesn't have to worry about freezing the coolant. This author hasn't looked as using mixtures of hydrogen and helium for temperatures in the range from 15 K to 30 K.

CONCLUDING COMMENTS

The decision on the type of connection from the cooler to the cold head is dependent on many factors. For small devices, it is usually better to connect the cooler cold head to the device through a high thermal conductivity strap. When the device (say a large superconducting magnet) is large, there is a lot to gain from using a two-phase thermal siphon cooling loop. If the cooler has to be moved away from the device being cooled, there are good reasons for using a natural convection cooling loop to connect the cooler to the heat load. The cooler must be physically above the load being cooled, so that natural convection can be used.

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