Methods of speeding up the cool-down of superconducting magnets that are cooled using Small coolers at temperatures below 30 K

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Abstract. The two primary ways of cooling superconducting magnets with small coolers are by conduction from the magnet to one or more the coolers cold heads through high thermal conductivity straps or by fluid flow through a thermal siphon cooling loop. Both methods have been used for cooling down magnets. The thermal siphon cooling loop can also be used to produce liquid helium or liquid hydrogen within the cooling loop. Over 85 percent of the cooldown time is used to cool a magnet coil from 300 K to 80 K. This is also true when a helium refrigerator is used to cool down a magnet. The primary reason for this is the magnet material enthalpy at 80 K is between 4 and 6 percent of the material enthalpy at 300 K. The cooler refrigeration increases with the cold head temperature, but the magnet material enthalpy increases more. If one wants to speed up the cool-down rate, one must remove the heat faster in the temperature range between 80 K and 300 K. Two primary methods for speeding up the cooldown of magnet that is kept cold using coolers will be presented.

1. Introduction
I became involved with cryogenics and superconductivity in 1965. I had a lot to learn before I could be an effective engineer with the Lawrence Radiation Laboratory (LRL) group founded by Louis Alvarez in late 1961. The group had been fabricating superconducting magnets with Nb3Sn, Nb-Zr and Nb-Ti. In the process of working with that group, I learned how to cool-down a magnet with liquid nitrogen and then liquid helium. The key to doing this was not to leaving any nitrogen in the cryostat before starting the cool-down with liquid helium. We put the liquid nitrogen and liquid helium into the bottom of the cryostat and used the sensible cold of the gas to cool down the coil in the cryostat. The technique we used was to monitor the resistance of the coil, and when the coil resistance dropped a factor of six we shut off the liquid nitrogen and let it boil away. With no liquid nitrogen in the cryostat, we could pump the nitrogen gas out the helium space. We backfilled the cryostat with helium gas and finished the cool-down with liquid helium. This technique worked well for small magnets in cryostats filled with liquid helium. Years later I taught this technique to technicians at one of the large aerospace companies.

I was in charge of installing a 500 Incorporated Model 1200 liquefier (one step up from the original Collins machine that had two stages of expansion, a JT valve with heat exchanger between stages and liquid nitrogen precooling [1]. This machine could produce 10 L per hour of liquid helium or 35 W of refrigeration at 4.5 K. This machine could cooldown 1000 kg in ~1.2 days from 300 K to 20 K. The
cold gas from the J-T valve had to be injected into the bottom of the cryostat. The warmed helium gas that came out of the cryostat at the top. During the cool-down the warm gas from the top of the cryostat by-passed the refrigerator cold box and went to the compressor inlet along with the gas that had gone through the expanders and heat exchangers [2]. A general rule here is, “Never force the gas to go in a direction that is counter to natural convection.” Variations of this method have been used to cool-down most superconducting magnets operating on a refrigerator. This method can also be used for cooling down and cooling magnets with coolers with a thermal siphon cooling loop [3].

2. Time-constants that Affect Heat Removal from the Magnet Cold Mass
The energy that is removed from the superconducting magnet cold mass (coil plus cryostat) is the change in enthalpy per unit mass at 300 K $H_m(300)$ minus the enthalpy per unit mass at the operating temperature 4 K $H_m(4)$ times the total cold mass $M_m$. Since the enthalpy of the cold mass at 4 K, is over four orders of magnitude lower than the enthalpy at 300 K, one can approximate the thermal energy removed from the coil $E_m = M_m \cdot H_m (300)$. Thus, the approximate time to cool down the magnet $\tau_{cd} = E_m / (R_{ave})$, where $R_{ave}$ is the average refrigeration applied to the magnet over a time. In most cases, $\tau_{cd}$ is the dominant time constant for the cooling-down of most magnets. Table 1 shows the material enthalpy $H(T)$ and the thermal diffusivity $\alpha(T)$ of various materials that are commonly used to fabricate magnets at temperatures $T$ of 4 K, 20 K, 80 K and 300 K [4], [5], [6].

| Temperature T (K) | 4    | 20   | 80   | 300  |
|------------------|------|------|------|------|
| Copper RRR = 70   | H(T) | 0.13 | 34   | 6020 | 79600|
|                   | $\alpha(T)$ m$^2$/s | $\approx 5 \times 10^{-1}$ | $1.14 \times 10^{-2}$ | $1.07 \times 10^{-3}$ | $1.14 \times 10^{-4}$ |
| 6063 Al RRR = ~5  | H(T) | 0.46 | 48   | 9370 | 170400|
|                   | $\alpha(T)$ m$^2$/s | $\approx 2.2 \times 10^{-2}$ | $3.2 \times 10^{-3}$ | $2.8 \times 10^{-4}$ | $8.5 \times 10^{-5}$ |
| 304 Stainless Steel | H(T) | 0.68 | 32   | 3880 | 80700|
|                   | $\alpha(T)$ m$^2$/s | $\approx 6.6 \times 10^{-5}$ | $6.2 \times 10^{-5}$ | $3.4 \times 10^{-6}$ | $2.4 \times 10^{-6}$ |
| 1020 Steel       | H(T) | 0.74 | 31.6 | 3840 | 81100|
|                   | $\alpha(T)$ m$^2$/s | $\approx 1.3 \times 10^{-3}$ | $5.7 \times 10^{-4}$ | $4.9 \times 10^{-5}$ | $2.0 \times 10^{-5}$ |
| Nb-Ti            | H(T) | ~0.26| 53.0 | 6885 | 80300|
|                   | $\alpha(T)$ m$^2$/s | $\approx 3 \times 10^{-5}$ | $5.4 \times 10^{-6}$ | $9.8 \times 10^{-7}$ | $1.9 \times 10^{-6}$ |
| Glass Epoxy Insulation | H(T) | ~2.3 | 258  | 9674 | 167000|
|                   | $\alpha(T)$ m$^2$/s | $\approx 1 \times 10^{-4}$ | $1.2 \times 10^{-6}$ | $5.2 \times 10^{-7}$ | $2.7 \times 10^{-7}$ |

The enthalpy $H(T)$ given J per kg of the magnet material as a function of temperature $T$ can be calculated as follows:

$$H(T) = \int_0^T c(T) dT,$$  \hspace{1cm} (1)

where $c(T)$ is the specific heat in J per kg K$^{-1}$. Thermal diffusivity $\alpha(T)$ is defined as [7]:

$$\alpha(T) = \frac{k(T)}{c(T)},$$  \hspace{1cm} (2)

where $k(T)$ is thermal conductivity in units W per meter K and $C(T)$ the volume specific heat as a function of T in J m$^{-3}$ per °K. For metals when thermal conductivity was unavailable, but resistivity was available, the thermal conductivity was estimated using the Wiederman and Franz law [8].
Once one has the thermal diffusivity of the materials in the magnet one can estimated the distance \( \lambda(t) \) that the heat to penetrates into the magnet as a function of time \( t \) and temperature \( T \) with the following expression [9]:

\[
\lambda(T, t) = (\alpha(T) t)^{0.5}.
\] (3)

The distance the heat travels through a material depends on both temperature and time. For magnets with large dimensions the thermal diffusion times can be long especially at high temperature when the specific heat is high. The heat will travel along paths where the thermal conductivity is high. In solenoid magnet the heat will travel much faster around the circumference than along the length or through the diameter. In a dipole or quadruple magnet, the preferred heat flow direction is along the magnet length. This suggests that the placement of coolers and cooling pipes and the material they are attached to maximize the heat transfer in the non-preferred directions within the coil package.

There are two primary methods of connecting a cooler to the cold mass being cooled [10]. The first is a direct connection between the cooler cold head and the cold mass using a flexible high thermal conductivity flexible strap that allows for thermal contraction of the cold mass. The second method uses the cold head to condense the gas that is boiled off from the cold mass. This method allows for drop-in coolers that can be removed for maintenance and it allow for coolers to be some distance from a magnet so that the magnet field doesn’t affect the operation of the cooler [11]. An extension of that method was used on the cyclotron gas-stopper magnet at Michigan State University [12], [13]. This magnet can be cooled down to 4.5 K, and helium was condensed from room temperature helium gas.

3. **Free convection cooling and cool-down of large superconducting magnets**

![Figure 1](image-url)

Figure 1. The free convection cooling circuit design [13] for a cyclotron gas-stopper magnet coil cryostat. (Note the magnet and the cooling system are not drawn to the same scale.) The neck shield is cooled to <40 K by the three PT415-RM cooler 1st-stages. The magnet shield, the cold mass intercepts and the leads are cooled using LN\(_2\) at 80 K from an external source. **Cond-1, Cond-2, and Cond-3** are the condenser heat exchangers that are attached to the cooler 2nd-stages. The circuit as shown allows liquid He to be added to the cold cryostat when it is <30 K. Helium liquefaction at 293 K was demonstrated. During the liquefaction, the 293 K make-up gas He enters the cryostat at the top. When full, there will be ~12 L in the cryostat [14].
The Michigan State University cyclotron gas-stopper magnet is a sector focus cyclotron on its side so the axis of the center of the two poles is horizontal. The heavy ion beam is decelerated by low pressure helium gas at 80 K. This allows the two poles to be separated for maintenance. Each magnet pole has its own superconducting coil and cryostat around the return iron pole. Each of the two coils is supported to its pole iron in the axial and radial direction.

The free convection cooling used to cool several detector magnets was used on the Michigan State University the cyclotron gas stopper magnet coil cryostats (see Figure 1) [13]. Each coil is cooled-down and cooled with three Cryomech PT415-RM pulse tube coolers [14]. These three coolers cool-down 1240 kg of cold mass, liquefy 12 L of helium gas and keep the coils at ~4 K. At 4.2 K, PT415-RM coolers with remote motors produce ninety percent of the cooling of three standard PT415 coolers [15]. Two of the three coolers are adequate to keep the magnet coils at 4.5 to 4.6 K, once the cryostat has been filled with liquid helium [16]. The heat leak from the shut-off third cooler was taken up by the first stages of the remaining two coolers. Lead cooling from copper leads from room temperature was taken up by the active cooler first stages.

![Figure 2](image1.png)

**Figure 2.** Temperature of a MSU magnet coil as a function of time [14].

![Figure 3](image2.png)

**Figure 3.** Total Refrigeration from three PT415-RM Coolers as a function of time [14].
Figure 2 shows the temperature of one of the coils as a function of time during the first cooldown of the magnet. The temperature that were recorded were at the cryostat bottom and half way up the magnet sides. The top sensor wasn’t functional. Figure 3 shows the total refrigeration from all three coolers as a function of time in the cool-down cycle.

The cool-down of the cyclotron gas-stopper coil in Fig. 1 appears to be limited by choked flow in the natural convection flow circuit. The as-built cryostat has small channels with ribs that produce extra pressure drop. Cooling between the coolers is unevenly distributed [14]. Increasing the circuit pressure in a factor of four can reduce the cool-down time by a factor of ~1.8 [17], but the cooling system bellows limit the charging pressure during the cool-down. Minor changes in the routing of the make-up helium and increasing the pressure in the circuit to 0.21 MPa reduced the cooldown time and helium liquefaction time by >2 days. For this experiment the cool-down time is not much a problem.

This author has looked at using He, H₂, Ne, and N₂ as working gasses within cooling loops. To minimize the circuit mass flow, the gas specific heat should be high; to minimize channel friction, the gas viscosity should be low; and the gas thermal conductivity should be high to improve heat transfer. Hydrogen was a little better than helium and much better than neon or nitrogen [17], [18].

4. Connection of added Refrigeration to the Cold Mass during a Cooldown

The connection of extra cooling to the cold mass during a cooldown falls into the following categories; 1) cooling-down with liquid nitrogen and liquid helium in a bath cryostat, 2) cooling-down with liquid nitrogen from an external source via forced flow from a pump or from a pressurized liquid nitrogen tank, 3) cooling with helium gas circulated by a room temperature compressor though a heat exchanger in boiling liquid nitrogen, and 4) cooling-down with high capacity coolers such as the Cryomech AL-600 and AL-630 single stage GM coolers or equivalent.

4.1 Rapid cooldown of bath cooled magnets with liquid nitrogen and liquid helium

The first approach, pre-cooling of magnet in a bath of LN₂ has been done since the discovery of superconductivity. The Collins liquefier made it possible for helium to be produced and used in a separate cryostat by researchers at universities and small companies [6]. One kg (~1.25 L) of liquid nitrogen can cool-down from 293 K to 80 K from about 2.2 to 5.7 kg of cold mass depending on how much of the sensible heat of the nitrogen is used for cooling and whether any liquid nitrogen comes off with the gas. It takes from 220 to 570 L of liquid nitrogen to cool-down 1000 kg of cold mass from 293 K to 80 K. The liquid nitrogen must be put into the bottom of the cryostat and the gas must be taken off the top of the cryostat.

One kg (~8.0 L) of liquid helium can cool-down from 80 K to 4.5 K from about 3.5 kg to 69 kg of cold mass depending on how much of the sensible heat from the helium gas is used for the cool-down. When cooling down with liquid helium, slow cooling rates use far less liquid helium than rapid cooling rates. The cooling of the cold mass is usually by natural convection as the helium flows upward around the cold mass to the helium vent to the top of the cryostat. Many magnets that are cooled with coolers don’t require very much liquid helium in the cryostat, if any at all.

Many MRI magnets have a liquid helium in the cryostat as reserve cooling during a power failure. The three Superbend dipoles at the Advanced light source at the Lawrence Berkeley Laboratory required liquid helium and liquid nitrogen reservoirs to ensure 24 hours of operating time without any cooling from the coolers [19]. Eighty percent of the 1680 kg cold mass for this magnet is the iron used to return the magnetic flux in the magnet gap. The problem with this method of fast cooling down to 80 or 90 K is getting rid of all of the nitrogen before turning on the 4.5 K coolers and adding helium to the helium tank. In this case it is better to have the cooler attached to the tank or magnet or have the coolers acting as re-condensers in the helium tank volume. The condenser must not be in the liquid helium. When the condenser is immersed in liquid helium, the cooling to the helium is poor. At LBL we had a condenser immersed in liquid helium in the tank. The liquid level in the cryostat was rising and so was the magnet temperature. Liquid helium expands over 20 percent per degree at 4 K and it is a poor conductor of heat [20]. It is much better to use a cooling loop to condense the helium gas [21].
4.2 Rapid cool-down of a non-bath-cooled magnet with liquid nitrogen in tubes
The second approach gets rid of the nitrogen contamination problem at the cooler cold heads. This method uses liquid nitrogen in tubes to do the first part of the cool-down. Pumped liquid nitrogen or LN₂ flow from a tank can be used. A positive displacement pump can easily pump to pressures up to 0.4 MPa. This type of pump can pump liquid helium too. The pump built at LBL [22] can pump helium at a rate up to 50 g per second. The liquid nitrogen the pumping rate is larger. The average flow rate of liquid nitrogen needed to cool-down 1000 kg of cold mass to 80 K in 24 hours is ~5 g/s. The liquid nitrogen must be removed from the separate cool-down cooling tubes before the 4.5 K coolers can be turned on. The nitrogen tube must be evacuated to prevent thermal acoustic oscillation heating of the magnet is cold. Figure 4 shows the liquid nitrogen flow pre-cooling system.

Figure 4. Precooling with LN₂ from a dewar with phase separation of the nitrogen in a tank.

Figure 5. Circulating pumped He cooled in a heat exchanger within a tank filled with LN₂.

4.3 Rapid cool-down of a non-bath-cooled magnet with 80 K helium in tubes
The third approach involves using helium gas at liquid nitrogen temperatures to cool the magnet in place of liquid nitrogen. Helium at >25 K has a constant specific heat of ~5.2 J g⁻¹ K⁻¹ at pressures of <1 MPa. If one can pump on the liquid nitrogen in the tank to pressures < 0.02 MPa near the end of the high temperature phase of the cooldown, magnet temperatures of <70 K could be reached. The cooling method can be using in conjunction with the cool-down using coolers that are supposed to keep the magnet cold. When any portion of the magnet is at 298 K, up to 1.1 kW of cooling per gram per second of helium flow can be applied to the coil cooling when the cold helium gas enters the cooling circuit at 80 K. Figure 5 shows the 80 K helium gas cooling pre-cooling system.

The heat exchanger that is used to cool the helium gas in tubes must be designed so that all of the boiling in in the nucleate boiling range for tubes >10 mm in diameter. The spacing between the tubes should be at least 10 mm. I suggest that the heat transfer rate on the active parts of the heat exchanger be at the minimum film boiling point [23], which is about 7500 W per m² for liquid nitrogen [24]. As in the previous case, the helium cooling tube must be evacuated to prevent thermal acoustic oscillation heating of the magnet. Figure 5 shows a flow system with helium gas at 80 K entering the
magnet cooling tubes, with the gas being cooled using a liquid nitrogen heat exchanger. Figure 5 also shows a three-pass heat exchanger between the helium compressor and the liquid nitrogen tank to minimize the usage of liquid nitrogen. The extra heat exchanger isn’t necessary, but it reduces the consumption of liquid nitrogen during the cooldown. If the cold mass is large, the extra heat exchanger is useful. Finally, the output pressure of the compressor is low because the pressure drops in the system are low. As a result, there may be more options for circulating the helium gas through the extra helium circuit that may be less costly than the compressor that one normally thinks about.

4.4 Rapid cooldown of a non-bath-cooled magnet with high capacity coolers
The fourth approach is to use high capacity single stage GM coolers that produce >240 W of cooling at temperatures above 40 K to cool-down the cold mass from 300 K. This approach could permit one to cool-down the magnet in conjunction with the coolers that keep the magnet cold at 4.5 K. Realistically this method works best when the magnet design operating temperatures are between 25 K and 40 K. For 4.5 K magnet operation, the major problem with this approach is detaching the high capacity cooler from the magnet so that the coolers don’t contribute to the magnet heat load at 4.5 K.

Cryomech and several other companies produce coolers that can produce cooling from 300 W to about 1 kW at 80 K. For example, Cryomech’s AL-600 cooler [23] is optimized to be most efficient in the temperature range from 40 to 70 K, with a base temperature of ~25 K. At 35 K, 50 K, 65 K, and 80 K, the refrigeration is ~150 W, 350 W, 470 W, and 600 W respectively. The peak efficiency of the AL-600 is ~14.2 percent of Carnot at ~55 K. The Cryomech AL-630 cooler [25] is optimized to be most efficient in the temperature range from 25 to 45 K, with a base temperature of ~12 K. At 20 K, 35 K, 50 K, 65 K, and 80 K, the refrigeration is 100 W, 235 W, 320 W, 380 W, and 440 W respectively. The peak efficiency of the AL-630 is ~14.2 percent of Carnot at ~35 K. The compressor power consumption is 12.5 kW on 60 Hz power. Magnets cooled with these coolers can be precooled with liquid nitrogen (sub-section 4.2) or with helium gas at 80 K (sub-section 4.3).

5. Concluding Comments
Four methods of pre-cooling have been presented. The methods presented in sections 4.2 and 4.3 make the most economic sense. The option of for a faster cool-down must be built into the magnet cryostat from the beginning. One must also decrease the internal time constants related to magnet material thermal diffusivity as much as possible. For most magnets cooled using coolers to keep them cold at 4.5 K, the best cooling method of rapid cooldown is circulating helium gas at liquid nitrogen temperature in tubes around the cold mass. When the cold mass is kept cold at 20 K to 40 K using single stage GM coolers, these are two viable methods for speeding up the cool-down.

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