COOLING-DOWN AND COOLING OF SUPERCONDUCTING MAGNETS AT 4.5 K WITH VERY LITTLE LIQUID HELIUM USING COOLERS*

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Abstract

Because liquid helium is often in short supply, it can be difficult to get helium for cooling superconducting magnets that are too large to be cryogen free magnets. Grade A helium is often available in high-pressure bottles, but not in large quantities. This report describes how one can cool-down and maintain a constant temperature of ~4.5 K in a superconducting magnet that has < 5 liters of liquid in the cryostat once it has been filled. One can do this with either GM coolers or with pulsed tube coolers. The number of coolers needed to cool the magnet depends to the heat load at 4.5 K and the desired cool-down time for the magnet system. This type of cooling system is suitable for magnets that are away from a conventional large helium refrigeration system. Examples are superconducting insertion devices, spectrometer magnets, and ECR ion source magnets.

THE HELIUM PROBLEM

There was a time when liquid helium could be purchased for \$1.00 to \$1.50 per liquid liter from different companies. Helium was relatively cheap and available for anyone to buy. Several factors have changed both the cost and the availability of helium in liquid or gas form. At the same time the demands for helium for non-cryogenic uses for helium have increased.

The United States had a helium separation and storage program that was shut down during the Clinton administration. Helium that could have been saved has been lost for over 20 years. The US helium reserve is close to depletion. Helium in quantities of 0.1 percent in natural gas can be separated economically, but the efforts to separate helium from natural gas in Qatar, Algeria, and some other places have been stalled.

The community should expect that helium will be in short supply and expensive for some time to come. Helium users should not waste helium and the helium cryogenic systems should be built should strive to minimize the helium volume. This applies to cooling systems using large refrigerators as well. Large system users should have helium re-purification and room temperature He gas storage equal to the amount of liquid He mass.

TO USE 4 K COOLERS OR NOT

The decision to use 4 K coolers to cool and cooldown magnets using small coolers is based on several factors. These factors include; 1) The distance the magnet is from a central helium refrigerator, 2) the number of magnets in a group of magnets being cooled, 3) the speed of the magnet cool-down that is required, 4) the magnet current that enters the cryostat on a continuous basis, 5) the capital and operating cost for the refrigeration, 6) the effect of the cooling method on the capital cost of the magnet, and 7) other factors, such as magnetic field, that affect the cold box and its compressor.

Cooling using coolers is well suited for individual magnets with low current leads such as MRI magnets, superconducting insertion devices (such as wigglers and undulators), and ECR ion sources that are well away from a central refrigerator. Individual bending magnets such as the three 5 T superconducting bending magnets in the 600-m circumference ALS electron storage ring at LBNL is a good example of where coolers should be used to cool superconducting magnets [1].

The cooling of the Muon Ionization Cooling Experiment (MICE) [2] magnets and detectors with coolers was a mistake that the author was partly responsible for making [3]. The reasons were: 1) The decision to use coolers was made before we knew that the 5-meter long pion decay solenoid must be cooled using a refrigerator. Had the pion decay solenoid been considered along with the seven original MICE channel magnets, the decision to use a refrigerator (100 to 150 W at 4.5 K) would have been clear. 2) The number of coolers needed for MICE was underestimated by a factor of ~2. 3) The use of coolers led to complicated magnets that led to the MICE project delay and increased cost. The slow cool-down rate for the MICE magnets using coolers created further delays in the project. The detector magnet design called for 190 L of helium within the cryostat. Today this isn't acceptable.

Once one has made the decision to use coolers for magnet cooling, one must decide how the coolers and the magnet are connected. Will the magnet operate in the cryogen-free mode, or will there be liquid helium within the cryostat to spread the cooling on the magnet surface?

One should also ask the following questions: Will the coolers cool-down the magnet from 300 K to 4 K or will liquid nitrogen be used to speed up the cool-down from 300 K to 80 K? Will there be a separate helium circuit that connects the cooler 4 K cold head to the load? If there is a separate helium cooling circuit, can that circuit be passive with no helium added during a cool-down and no helium lost during a warm up?

CRYOGEN-FREE MAGNETS

Cryogen-free magnets are usually connected to the cooler second-stage (4 K) cold head directly. This connection is made within the cryostat vacuum space and within the 50 K shield that is cooled with the cooler first-stage. There is a temperature drop ΔT of 0.2 to 1.5 K between the highest temperature point within the coil and

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the cold head. It is not unusual for the magnet high temperature point to be close to the high magnetic field point in the coil, which reduces the magnet's operating margin.

The temperature drop ΔT is in two parts. The first ΔT is in the flexible strap and fixtures that connect the cold head to the magnet. The second ΔT is between the place on the magnet surface to the magnet hot spot. The magnitude of the total ΔT is inversely proportional to the material average thermal conductivity and directly proportional to the length over which the each ΔT spans. In general, successful cryogen-free magnets are relatively small with low heat leaks per unit area and the material that carries the heat by conduction is a good conductor of heat. The MICE magnets were large enough to make cryogen-free cooling unattractive [4].

If a magnet is long and multiple coolers are used to cool and cool-down the magnet, even spacing the coolers along the magnet length is a good idea because it reduces the total ΔT and it reduces the ΔT between the cooler first-stage and the highest temperature point on the shield. The shield for any magnet cooled with coolers should be made of a material that has a thermal conductivity that increases as the temperature goes down in the range from 30 K to 80 K [5]. From the standpoint of shield mass and shield rigidity, 1100-O aluminium is an excellent material to use for shields. With any thermal shield, eddy current forces during a quench may be a problem [6].

MAGNETS WITH A THERMAL-SIPHON COOLING LOOP

When the temperature drop is too large for cryogen-free magnet operation, one can put the magnet in a tank of liquid helium with a re-condenser attached to the cooler second-stage. Figure 1 shows a condenser on a drop-in Cryomech PT415 cooler 2nd-stage [7]. LBL has used drop-in PT415 coolers that can be easily removed for shipping and cooler maintenance. Drop-in coolers reduce the net cooling on both stages by 10 to 15 percent. Using re-condenser is straight forward if the magnet is in liquid helium bath. MRI magnets are often kept cold this way. However, today, one should minimize the cryostat liquid helium volume.

A magnet cool-down with coolers is difficult if one doesn't use a thermal-siphon cooling loop [8]. Coolers used for helium liquefaction must have pre-cooled helium gas using the cooler 1st-stage [9]. Cooling from the tubes between the two stages is also desirable. The pre-cooled gas must enter the condenser from the top [7].

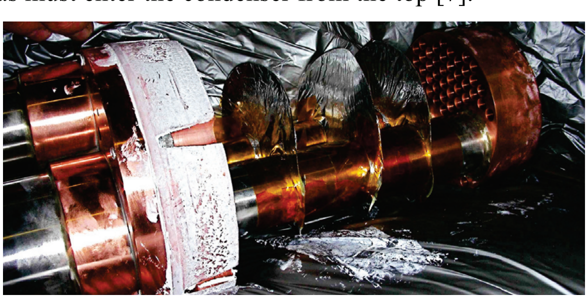

Figure 1: Drop-in cooler with a 2nd-stage condenser [7].

Since it is desirable to limit the amount of liquid helium in the magnet cryostat, one should cool the magnet with helium in tubes or one must have the liquid helium vessel close to the magnet coil. The cyclotron gas-stopper magnet at Michigan State University (MSU) is a successful example of the second approach to cooling using a gravity driven thermal-siphon cooling loop [10]. The magnet at MSU was originally designed to be cooled using a large refrigerator located ~200 m from the magnet. The cyclotron gas stopper magnet has two separate coil cryostats that must be separable with the magnet cold. In 2012, the design was changed so that the magnet could be kept cold with a liquid helium filled thermal-siphon cooling loop. In addition, each magnet coil and cryostat with a cold mass of 1250 kg can be cooled-down and filled with 12 L of liquid helium was liquefied from 300 K gas using three Cryomech PT415 pulse tube coolers in ~14 days. When the cryostat was cold and filled with liquid helium, one cooler on each cryostat was turned off so that the two magnet coils were operating at temperatures <4.6 K [11]. Figure 2 shows the MSU cyclotron gas-stopper magnet with the coil cryostats installed and two iron poles separated.

Figure 2. The MSU cyclotron gas-stopper magnet with the iron yoke open and the two coil cryostats installed in the iron pole pieces. The magnet height is ~5 meters.

A gravity driven thermal-siphon loop is driven by natural convection. The cold cooler condenser heat exchangers are above the magnet that is being cooled. The temperature difference between the cold heads and the magnet coils can be as large 250 K during a cool-down, but when the magnet has been cooled-down and the cryostat has been filled with liquid helium, the temperature differences is as low as 0.1 K.

The MSU cyclotron gas stopper magnet was a learning tool concerning cooling-down a magnet with multiple 4 K coolers [12]. We learned the following: 1) Tight flow passages increase the cool-down time greatly. The MSU flow passages where much tighter than the model we used to estimate the cool-down time, so the actual cool-down time was over two times longer. 2) Increasing the cryostat pressure decreases the cool-down time. In the gas-stopper magnet, the maximum cryostat pressure was based on the bellows failure pressure. 3) The flow circuit resistances to and from the three coolers was not the

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same. As a result, two coolers did 90 percent of the cooling and the third cooler did only 10 percent of the cooling. 4) The location of the helium make-up changes the cool-down time. Make-up helium should enter the manifold that delivers warm helium from the magnet back to the three condenser heat exchangers. This has 15 percent effect on the cool-down time and it can reduce the liquid helium fill time by a factor of 3. Having a nitrogen shield and lead intercept from 300 K permitted us to turn off one coolers once the cryostat was filled with helium.

OPEN OR CLOSED COOLING LOOPS

The MSU cyclotron magnet is cooled using two open thermal-siphon cooling loops. Helium gas was fed to the cooling loop from compressed gas cylinders. When the magnet is warmed to the gas is sent to the MSU recovery system. At 4.2 K, the MSU magnet holds 3.3 kg of helium with 90 percent in liquid form. Given the pressure limits imposed on the cryostat pressure by the system bellows (0.3 MPa), this helium could be stored in a 1.2 m^3 tank at 0.3 MPa. Figure 3 compares an open and closed loop cooling system [13]. In the closed loop system, all the loop cryogen is stored within a surge tank that is connected the loop in a way that the cryogen gas enters the cooling loop only through the condenser heat exchanger. The closed loop the surge tank can be located anywhere.

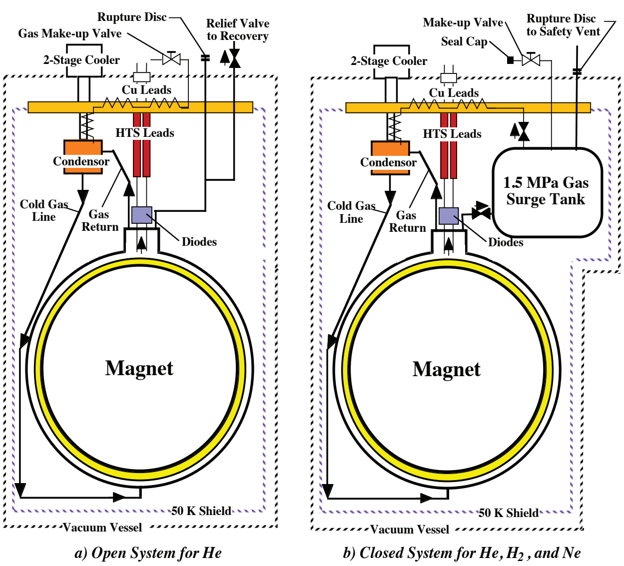

Figure 3: A comparison of open and closed cooling loops.

The closed loop system shown in the right half of Fig. 3 can be used for H_2 or Ne for HTS magnets. A H_2 closed loop is needed for safety. A Ne closed loop is needed because neon is expensive. From the standpoint of magnet cool-down time, H_2 is 15 percent better than to He and a factor of two better than Ne for a given geometry.

When one restricts the amount of liquid in a magnet, things such as cold diodes that might be in the magnet cryostat may have to be attached to the cryostat and be cooled by conduction. The design of leads must be very conservative, when there is only conduction cooling.

CONCLUDING COMMENTS

The use of small coolers to cool and cool-down superconducting magnets is appropriate for isolated magnets. There are times when small coolers shouldn't be used. There times when cryogen free magnets are the best cooling solution. When the temperature rise in a magnet is too high, using a thermal-siphon cooling loop is the best way to cool a magnet with coolers. In all cases one should avoid a large amount of liquid helium in a magnet cryostat. Liquid helium cooling loops can cool-down a magnet given good engineering. Where helium is unavailable and expensive, the cooling loop should be closed so that no helium is needed for the cool-down and no helium is lost when the magnet is warmed up to 300 K.

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