Lessons learned from the cool down of a superconducting magnet using a thermal-siphon cooling-loop

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Abstract. The two Michigan State University (MSU) cyclotron gas-stopper magnet superconducting-coils were designed to be cooled down and to be kept cold using three pulse-tube coolers per coil cryostat. These coolers are designed to produce from 1.3 to 1.7 W per cooler when the cooler first-stage is at 40 K. The cyclotron gas stopper coils can be separated while cold, but unpowered. The two coil cryostats were cooled down separately in 2014, and room temperature helium gas was liquefied into the coil cryostats. The magnet temperature at the end of the cool-down was 4.55 K for one coil and 4.25 K for the other with an added 1.6 W of heat. The coil-down time for the coils was three and a half times longer than expected. The time to liquefy the helium was also much longer. The reasons for the disparity between the calculated cool-down time and measured cool-down time are discussed in the paper.

1. Introduction

The cyclotron gas stopper magnet at MSU is part of a system that decelerates higher energy medium mass ion beams (<100 MeV/u) to energies in the 10 keV range [1], [2]. The beam chamber contains low-pressure helium gas at 80 K used to decelerate the ions traveling in a spiral path in the magnetic field of a 2 T strong-focusing cyclotron magnet. Reduced emittance low energy beams near the extraction port are transported out of the magnet by an RF carpet [2], [3]. Once the low energy ions have been extracted and transported to a high vacuum region, they can be used in low-energy experiments or reaccelerated to higher energies.

The cyclotron gas stopper magnet is a cyclotron-style dipole magnet that has the direction of the dipole field parallel to the ground [4], [5], and [6]. The magnet consists of two superconducting coils each in its own cryostat. The coil cryostats are mounted within 4-meter diameter room temperature iron return yoke and pole pieces. The iron poles and the vacuum chambers between the poles are designed to be separated so that the 80 K beam chamber can be installed between the poles. Each coil is contained within its helium vessel. Each helium vessel is supported within each part of the split iron return yoke and pole. Each coil cryostat is supported by six axial supports and three radial supports. Figure 1 shows the assembled cyclotron gas stopper magnet and cryogenic system. Table 1 presents the design parameters of the magnet [5], [7].
2. The Cyclotron Gas Stopper Magnet 4 K Cryogenics System

The magnet cryostats are imbedded in the warm iron poles and return yoke. The cryostats and the cryogenic system are fixed to a magnet pole and half of the iron return-yoke. Each coil cryostat and its cryogenic cooling system move with that half of the magnet iron return-yoke. Figure 2 shows the cryogenic system on the tops of the two coil cryostats.

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Table 1. Cyclotron gas-stopper magnet physical and electrical parameters.

| Parameter                        | Value |
|----------------------------------|-------|
| Iron Pole Radius (m)             | 1.10  |
| Return Iron Outer Radius (m)     | 2.00  |
| Average Pole Gap (mm)            | 180   |
| Magnet Iron Mass (tons)          | ~167  |
| Magnet Cold Mass per Coil (kg)   | ~1240 |
| Number of coil turns             | 1767  |
| Coil Cross-section R/Z (mm)      | 80/80 |
| Coil Design Peak Current $I_D$ (A)* | 200   |
| Coil Current Density at $I_D$ (A mm$^{-2}$) | 54.9 |
| Peak Induction in Coil at $I_D$ (T) | 2.05 |
| Magnet Stored Energy $E_D$ at $I_D$ (MJ) | 3.56 |
| Self Inductance based on $E_D$ (H) | 178   |

* The magnet operating current is 180 A.
Each cryostat is cooled down and kept cold at 4.25 to 4.6 K using three Cryomech PT415RM coolers that each produces 1.35 W at 4.2 K while producing ~36 W at 40 K. The rotary valve and the compressors are at ground potential. The cooler body is connected to the rotary valve by an insulated pipe that can hold off at least 60 kV. The high voltages are needed for beam manipulation and extraction. The magnet iron and the magnet cryostats float with respect to ground. Figure 2 shows the three rotary valve motors and the hoses from the compressors on the left side of the picture. The cooler bodies are in the cryostat to the right of the white insulators. The insulated pipe is between the rotary valves and the cooler bodies and ballast tanks, which are not visible in Figure 2.

Figure 3 shows the flow circuit for one of the cyclotron gas-stopper magnet coils [8]. The second magnet coil flow circuit is identical to the first. The cryostat cooling system evolved so that magnet could be cooled down using coolers. Each condenser heat exchanger has a heat transfer area of about 0.055 m². Eighty percent of the liquid helium in the cryostat (16 liters) is in the cryostat neck. The liquid level in the neck regions is set so that the quench protection diodes [9], [10] are immersed under >150 mm liquid helium. In the diagram above the helium is cooled (or liquefied) by the condenser heat exchangers. The cold helium flows down from the condenser to the bottom of the magnet cryostat through two ducts (ID = 10.9 mm) over a length of 4.5 m. Within the cryostat the helium stream is split between the inner and outer parts of the magnet cryostat helium vessel. The original design called for 68 percent of the helium to flow in the two inner channels and 32 percent to flow in twelve outer channels. The duct from the top of the magnet cryostat to where the flow separates to go to the condensers had a design ID of 25.4 mm and length of 0.15 m. The pipes connecting to the tops of the condenser were supposed to be 25.4 mm in diameter and 0.15 m long. The whole cryogenic system was supposed to be pressurized to ~0.5 MPa absolute during the cool-down.
3. The Cool-down of the Magnet Cryostats using three PT415-RM Coolers

The two sides of the cyclotron gas-stopper (CGS) magnet are cooled down separately. The fixed side of the magnet was cooled-down in July 2014. The cooler cold heads, the condenser heat exchangers, and the helium gas in the condenser were cooled-down quite rapidly. As the coolers and condensers cooled, helium gas flowed into the cryostat from the bottles. We observed that all of the cooler cold head temperatures dipped and then went back up before leveling off (see Figure 4). We surmised that the dip in the cold-head temperature was an indication that helium wasn’t flowing in the cooling loop. The increased density of the helium in the condenser caused the cooling loop to start flowing. The rise in the cold head temperature was an indication that the coolers were providing cooling to flowing helium gas, which in turn provided cooling to the magnet coil and cryostat.

![Figure 4](image.png)

Figure 4. A screen shot of the cooler 2nd stage temperature versus time for the three cooler cold-heads a little over an hour after the cool-down of the fixed coil starts in July of 2014. The 2nd-stage cold head temperature dips and rises. After the temperature dip the three coolers are not producing the same amount of cooling. The major ticks in the diagram x-axis are hours.

The rate of cooling provided to the magnet is determined by helium mass flow through the magnet. The helium mass flow through the magnet is limited by the pressure drop in the magnet and the piping. Since the cold helium enters the magnet cryostat at the bottom of the magnet and exits at the top of the magnet, the helium flow in the magnet cryostat was assumed to take fourteen parallel paths. Two paths take the helium through nearly identical channels past the inside the coil. Two paths of six identical channels each take helium past the outside of the coil. In series with the magnet cooling channels there is the flow circuit piping. Two pipes carry helium to the bottom of the magnet. The helium entering those two pipes comes from the pipes coming from the bottom of the three condenser heat exchangers. The helium leaving the magnet goes into the neck region in the cryostat. A pipe from the cryostat neck connects to the three pipes that enter the condenser heat exchangers at the top. The design called for the flow around the inside of the magnet cryostat was 68 percent of the total. This was far from being the case in the magnet as built. The three flow-circuits through the condenser heat exchanger were assumed to be identical; they weren’t identical.

Figure 5 shows the temperature at the fixed magnet coil surface at the bottom and at the two sides. The temperature sensor on the top of the magnet coil had failed. Only the temperature sensor at the magnet bottom was properly calibrated. The sensors mounted on the coil were strongly affected by the helium around the coil. As a result, the sensor at the bottom of the coil started out reading colder, because this was where the cold helium enters the system. The cryostat pressure was 0.2 MPa absolute. The magnet cool-down took about fourteen days, which was much longer than expected [7]. The rolling side coil took about the same amount of time to cool-down as the fixed side coil. The reasons for the longer cool-down time for the coils will be discussed in the next section. Added to the cool-down was the time needed for the liquefaction of 12 liters of helium into the cryostat.

Figure 6 shows the sum of cooling provided by the three coolers during the fixed side cool-down. The cooling provided by each cooler was based on the measured cold head temperature. When one integrates the cooling over time, one finds that only 81 percent of the coil and cryostat thermal energy was removed. Some of the difference may be accounted for by cooling from the liquid nitrogen shield through the inner cold mass supports. The calibration of the temperature sensor on condenser 2 is the primary cause of the discrepancy. This will be discussed later.
4. The Reasons Why the Cool-down took much Longer than Expected

The reasons for a much longer cyclotron gas-stopper magnet cool-down are as follows: 1) channels within the magnet are much tighter than the original drawings indicated (see Figure 7). The cross-section in Figure 7 doesn’t show the thirty-six 19-mm-wide and 3.2 mm-thick shims on the inner and outer surfaces of the coil that are needed to center the coil. The inner shims block helium passage inside the coil except for two grooves in the shims 12.7 mm wide and 0.8 mm thick. As a result, the flow on the outside of the coil is much larger than the flow on the inside of the coil. 2) The flow circuits connected to the condenser heat exchanger are different for each cooler (see figure 8). The piping entering condenser 1 is smaller because there is a liquid helium input port in that line. Flow to condenser 2 is the least constricted. Thus each cooler removes a different amount of heat during the cool-down. 3) The cooler model used to estimate the maximum available cooling from the magnet coolers was optimistic. The original cooling model was based on the PT410 cooler [11]. At the time, we didn’t have sufficient information about the PT415-RM coolers that are used on the magnet [12]. (See Figures 9 and 10 show the cooling from a PT415-RM cooler.) 4) The cryostat pressure was too low. The cryostat pressure could not be higher than 0.2 MPa because the pipe bellows might fail.
Both coils were cooled down to 4 K and liquid helium was produced in the cryostat, despite the fact that the shield and cold mass support intercepts were above 80 K [13]. The fixed coil cryostat came to an equilibrium temperature of 4.55 K. The rolling side cryostat equilibrium temperature was below 4.2 K. An extra 1.6 W was put into the cryostat to ensure that rolling side cryostat was kept above 4.25 K. The liquefaction rate into the fixed side coil cryostat was lower than for the rolling side cryostat. Both cryostats had a liquefaction time for 12 L of helium that was much longer than expected. It is clear that the excess refrigeration for the liquefaction of helium was higher for the rolling side than for the fixed side. The room temperature helium gas coming into the cryostats was pre-cooled by the first-stage cold head attached to condenser two. There was no further pre-cooling between the first and second stages, which reduced the helium liquefaction rate into both cryostats.
5. The Magnet Cool-down Model: the Effect of Pipe Constrictions and Cryostat Pressure

Figure 11 is a plot of available refrigeration from three PT415-RM coolers versus magnet temperature. Figure 12 is the magnet temperature as a function of time from the start of the cool-down. Three cases considered in Figures 11 and 12 are: 1) a case with two pipe constrictions like the one in Figure 8, 2) a case with the single pipe constriction (see Figure 8), and 3) a case where the flow passages for all condensers are equalized by using manifolds. The absolute cryostat pressure is 0.2 MPa in all cases.

**Figure 11.** The available refrigeration from three coolers as a function of temperature and number of pipe constrictions. (Zero is the manifold case.)

**Figure 12.** The magnet temperature versus time from the cool-down start as a function of number of pipe constrictions.

**Figure 13.** The available refrigeration from three coolers as a function of temperature and cryostat pressure for no pipe constrictions (manifold case).

**Figure 14.** The magnet temperature versus time from the cool-down start as a function of the cryostat pressure for no pipe constrictions.
Figure 13 is a plot of available refrigeration from three PT415-RM coolers versus temperature. Figure 14 is the magnet temperature as a function of time from the start of the magnet cool-down. The three cases Figures 13 and 14 are the manifold case in Figures 11 and 12 with cryostat absolute pressures during the cool-down of 0.2 MPa, 0.4 MPa, and 0.6 MPa.

It is clear that the only real pipe constriction is the one shown in Figure 8. The difference between a cool-down of 14.6 days and the 13.9 day cool-down observed is most likely the added heat flow from the liquid nitrogen shield to the magnet at temperatures >150 K. At 300 K, the added heat flow from the liquid nitrogen shield into the helium vessel can be as much as 4 W. The temperature discrepancy on condenser 2 in Figure 4 appears to be due to temperature sensor calibration error.

6. Some Concluding Comments
The primary cause of the long cool-down time for the cyclotron gas-stopper magnet is the fact that helium flows along both the inside and the outside of the coil is constricted by shims in the flow passages. The flow inside of the coil is 0.6 percent of the total at the start of the cool-down. The rest of the flow is on the outside of the coil. As the cool-down progresses the flow inside of the coil increases to 3 percent. One of the coolers contributes only 10 percent of the cooling to the cool-down process, because of constrictions in the piping. Finally, there isn’t enough available cooling from three PT415-RM coolers to cool down the magnet in four days under any circumstance.

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