PROGRESS ON THE CRYOGENIC AND CURRENT TESTS OF THE MSU CYCLOTRON GAS-STOPPER SUPERCONDUCTING MAGNET*

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Abstract

The Michigan State University (MSU) cyclotron gas stopper magnet is a warm iron superconducting cyclotron dipole. The desired field shape is obtained by the pole iron profile. Each coil of the two halves is in a separate cryostat and connected in series through a warm electrical connection. The entire system is mounted on a high voltage platform, and is cooled using six two-stage 4.2 K pulse tube coolers. This paper presents the progress on the magnet fabrication, cooling, and current testing.

INTRODUCTION

The fragmentation of fast heavy-ion particles enables fast chemistry-independent production, separation and delivery of exotic isotope beams. The resulting beams have high energies (<100 MeV/A) and large emittances. The range of experiments can be extended by slowing the fast ions, extracting them, and then re-accelerating them. The ReA3 [1] re-accelerator under construction at MSU will reaccelerate thermalized ions (~10 keV) to provide low emittance exotic ion beams over a range of energies.

A solution to thermalize and extract light to medium mass beams is to apply a strong gradient dipole magnetic field in a large magnetic gap that forces the ions into a spiral path while slowing them down in He gas at 80 K. Low energy ions near the extraction port are transported in a central extraction orifice by an RF carpet [2], [3]. The ions are transformed into low-energy beams using a differentially pumped ion guide. The low-energy low-emittance beams are transported directly to experiments or to other accelerators for reacceleration. The super-ferric cyclotron gas-stopper magnet at MSU will enable the capture of short-lived rare isotopes.

THE GAS-STOPPER MAGNET

The cyclotron gas-stopper magnet has evolved since it was first proposed in 2007 [4]. The gradient dipole field is produced in a gap of 180 mm between sector cyclotron poles. The peak field in the gap is ~2.6 T. A pair of superconducting solenoid coils produce the field. The warm iron poles and flux return can be separated so that the deceleration system can be maintained. Each pole has its own coil and liquid helium cryostat. The two 300 K magnet poles are connected through the iron return path. The coils are not connected at 4 K. Forces to the yoke are transmitted by the cold mass supports. The common axis of the magnet coils is horizontal.

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The space between the poles is evacuated to provide an insulating vacuum for the 80 K magnet beam chamber. Figure 1 shows the assembled magnet with the iron poles closed. Figure 2 shows the magnet poles open. The magnet cryostat on the right has the cylindrical part of the beam chamber vacuum vessel attached. There is a double o-ring seal between the cylindrical portion of the vacuum vessel and the magnet cryostat installed in the left pole piece. One can see the shaped face of the shaped sector cyclotron pole on the pole to the right of Fig. 2.

Figure 1: The assembled magnet is shown fully closed.

Figure 2: The magnet is shown with poles separated. The beam chamber insulating vacuum chamber is visible along with one of the shaped cyclotron poles.

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The nominal design current for the magnet is 200 A. The operating current is expected to be ≤180 A. Table 1 shows the cycltron gas-stopper magnet parameters [5-8]. At both the design current the magnet pole pieces may be somewhat saturated. When the shapped iron poles are not saturated (relative permiability <100), the magnet self-inductance is nearly constant and lower than when it is with the poles saturated. The self inductance in Table 1 is based on the stored magnetic energy at the magnet design current I_D of 200 A.

Table 1: Cyclotron Gas-stopper Magnet Parameters

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

Figure 3: The 80 K beam chamber that will be filled with low pressure He gas. (The chamber cover is not shown.)

Figure 3 shows the helium gas filled beam chamber that is cooled to 80 K with liquid nitrogen. The gas slows the ion beam causing it to spiral inward in the gradient dipole field to the center of the chamber.

The magnet cold mass supports are of two types. There are six compression supports that take coil axial forces into the iron. The there three radial supports the carry gravitational loading and de-centering forces caused by the magnet coil current axis not being the same as the axis of the magnet poles. The cold mass supports are adjustable and their forces are measured during charging.

Even at its design current, the magnet stored-energy is low and the current density in the conductor is low. As a result, the magnet is self quench-protected with long time constant current decays. There is a quench protection system that quenches the magnet in the event of a failure of a lead [9] or when certain system interlocks are triggered. When an event that triggers a rapid discharge is measured, the power supply is disconnected causing the coils to be discharged across a number of 300 K diodes in series. This causes the 4 K diodes [10] across the coils to fire directing the coil current to a resistor wound on the outsides of the coils [6]. When the coil current is 200 A, the coil becomes fully normal within 5 seconds [11].

Each magnet coil is cooled-down and cooled with three Crymech PT415-RM pulse tube coolers with remote valves and tanks. The helium from the compressors goes through the rotary valves. The rotary valves and the compressors are at ground potential while the coolers and the rest of the magnet may be at ±50 kV with respect to ground. Figure 4 shows the two magnet cryostats with their coolers. Figure 5 shows the rotary valves and the insulators between the remote valves and the cooler cold heads.

Figure 4: The 4 K cryogenic system for the two cryostats.

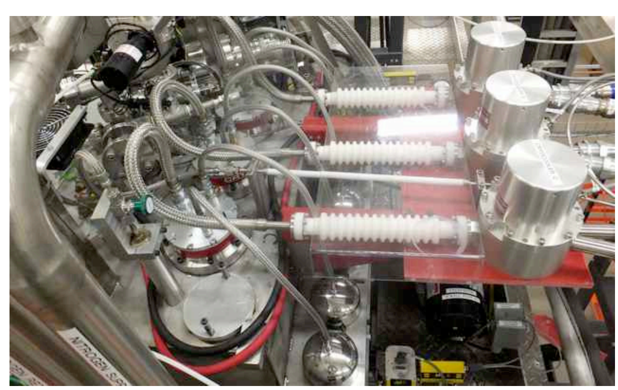

Figure 5: Three cooler cold heads, three 50 kV insulators and three remote valves connected to the compressors.

Each coil has three PT415-RM coolers that each develops ~1.35 W of cooling on the second-stage cold head while developing ~36 W at 40 K on the first-stage cold head [12]. The first-stage cold heads cool the top of the HTS magnet leads and the 35 K shield around the upper part of the cryostat. The shields around the coils are cooled using liquid nitrogen [13]. Each second-stage cold head has a condenser heat exchanger attached to it.

The three condenser heat exchangers are connected in parallel to a pair of pipes going to the bottom of the magnet coil cryostat and a single pipe coming from the top of the helium reservoir at the top of the cryostat. During 4 K operation there is ~12 L of liquid helium in each coil cryostat. The whole circuit is a thermal-siphon cooling loop [14], [15] that can cool-down the 1240 kg magnet cold mass as well as keep it at 4.3 to 4.7 K.

THE MAGNET COOL-DOWN AND POWERING TO 180 A

Magnet Cool-down

The first cool-down of the fixed-side of the magnet started in February of 2014. During the first cool-down a number of problems were uncovered as would be expected the first time a cryogenic system is operated. The insulated pipes bringing helium to the cryostats from the bottles out-gassed clogging the pure helium gas line entering the cryostats. There was some sort of organic crud that froze at ~100 K. The insulated pipe was replaced with a pipe that didn't out-gas. Cryostat vacuum problems were also uncovered. The fixed-coil cold mass was cooled to 4 K using three coolers, but it took 3.5 times longer than predicted [16], [17]. The system liquefied helium into the cryostat from warm gas from the high-pressure pure helium gas bottles. Fig. 6 is plot of the temperature in three places on the fixed side coil versus time from the three coolers starting.

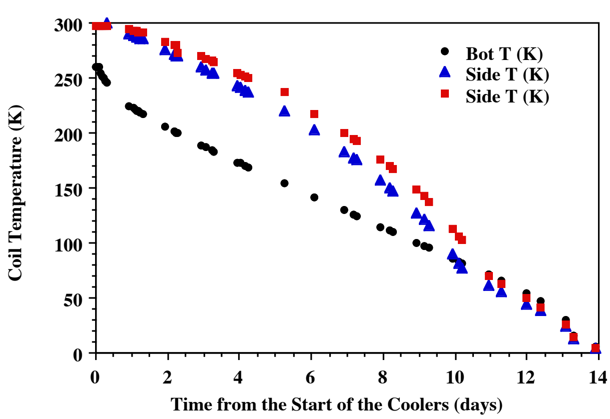

Figure 6: Fixed-coil temperature in three locations as a function of time after the start of the three coolers.

Figure 6 shows that the cool-down time from ~297 K to ~4 K is about fourteen days once the nitrogen cooled shields are at 80 K. The shields took less than one day to cool-down. There is some cooling of the helium vessel from the shield through the cold mass supports. The reduced temperature at the bottom of the magnet is due cooling at that point from two of the nine cold mass supports. During the first eight days the three PT415RM coolers provided 75 and 85 W of cooling to the 1240 kg coil cold mass. In terms of the time needed to cool-down the magnet coils, there isn't much difference between the fixed-coils and rolling-coils. The actual cool-down time for both coils was longer than was expected.

The primary reasons for the longer cool-down time for the coils are: 1) the flow passages within the cryostat are smaller than design. 2) There are many more momentum changes within the flow streams. 3) The cryostat helium vessel and flow circuits could not be pressurized above 0.2 MPa. 4) There are unbalanced flows within the flow circuits. 5) The cold mass of each cooing system was larger than 1240 kg. All of these factors will be discussed in a future paper.

Once the magnet was cold and filled, it was clear that the two coil cryostats had very different heat leaks. The fixed-side cryostat has a heat leak of ~4.9 W while the rolling-side cryostat has a heat leak of ~2.7 W. This will be a topic of a future paper. Both cryostats are at 4.3 to 4.7 K despite having shields at ~85 K [13], [18].

Magnet Charging to Full Current

The magnet iron was closed and the two magnet coils were connected in series. The magnet was charged and the forces on the cold mass supports were measured. The cold mass supports were adjusted to balance the magnetic forces on the coils. The magnet quenched a number of times, but there was no quench that originated in either of the coils. All quenches except the last one were caused by interlocks that put warm external diodes across both coils, causing both coils to quench. The final quench at the magnet operating current 180 A was deliberately triggered by putting the warm diodes across the magnet coils. The 180-A quench was like the quench model predicted [11]. It took two days for the two helium vessels to re-fill with liquid helium after the 180-A quench. We have demonstrated that the magnet can operate for long periods of time without quenching.

CONCLUSION

Between late 2013 and mid 2014, the assembly of the MSU cyclotron gas-stopper magnet and its cryogenic system was completed. The magnet coils were cooled down and filled with liquid helium that was liquefied by the coolers from room temperature gas. While the heat load to one cryostat is greater than the heat load to the other, the cooling for both magnet cryostats is acceptable.

The magnet was charged its operating current of 180 A with the iron closed (see Fig. 1). As the magnet was powered, the cold mass supports were adjusted to minimize the unbalanced forces on the magnet cold mass supports. We are nearing off-line beam transport tests (see Fig. 3) now that the magnet is operating routinely.

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