PROGRESS ON THE MSU SUPERFERRIC CYCLOTRON GAS STOPPER MAGNET QUENCH PROTECTION AND COOLING SYSTEM

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Abstract

The MSU gas cyclotron stopper system is designed to decelerate rare isotope ions from energies from >50 MeV to energies in the 10 keV range. The ions are decelerated in low-pressure helium gas in vertical cyclotron magnet. The magnet and the system for decelerating the ions are mounted on a high voltage platform. The cyclotron gas stopper magnet is a warm iron superconducting cyclotron sector dipole. The maximum field in the gap (0.18 m) is 2.7 T. The outer diameter of magnet yoke is 3.8 m, with a pole radius of 1.1 m and Br = 1.8 T m. The desired field shape is obtained by the pole profile. Each coil of the two halves is in a separate cryostat and connected in series through a warm electrical connection. The entire magnet system will be mounted on a high voltage platform. The magnet coils have been fabricated and installed in their cryostats. The iron poles have been machined and assembled. This paper presents the progress on the magnet system fabrication and assembly.

INTRODUCTION

The fragmentation of fast heavy-ion particles enables fast, chemistry-independent production, separation and delivery of exotic isotope beams. The resulting beams of exotic nuclei have high energies (>50 MeV/u) and large emittances. The range of possible experiments with the fast beams can be extended by slowing down the fast ions. The ReA3 [1] re-accelerator under construction at MSU will re-accelerate the thermalized ions to provide low emittance exotic beams over a range of energies. The thermalization of the fast ions and their extraction using existing techniques are limited by space charge and other limitations.

A proposed solution to thermalize and extract light to medium mass ions and high intensity beams is to apply strong gradient-dipole magnetic field in a large magnetic gap (0.18 m) that forces the fast ion beams to follow spiral trajectory while slowing down in the gas. Concentrated thermalized ions near the central extraction port are then transported in to central extraction orifice via an RF-carpet. These extracted ions will be transformed into low energy beams using a differentially pumped ion-guide. The low energy ion beams can be transported directly to low-energy experiments or to other accelerators for reacceleration. The high performance and high field (2.7 T) super-ferric cyclotron gas stopper sector-magnet at National Superconducting Cyclotron Laboratory (NSCL), Michigan State University (MSU) will enable the capture of short-lived rare isotopes produced in nuclear reactions.

The cyclotron gas-stopper magnet design has evolved since its original design in 2007 [2]. A gradient dipole field is produced in a gap of 180 mm between sector cyclotron iron poles. The peak field in the gap is ~2.7 T. A pair of superconducting solenoid coils produce the field. The warm iron poles can be separated so that the deceleration system can be maintained. Each pole coil has its own helium cryostat and superconducting coil that operate at 4.3 K. The 300 K iron poles are physically connected through the magnet iron flux return path, but the superconducting coils are not physically connected. The forces on the magnet coils are transported to the iron return yoke through the cold mass supports. The magnet is oriented so that the common axis of the solenoid coils is horizontal. Thus the beam plane for the super-ferric cyclotron magnet is vertical. Each of the two magnet superconducting coils will be cooled using three PT-415 pulse-tube 4 K coolers with remote valves.

IRON POLES AND RETURN YOKE

The split iron poles and return yoke are shown in Fig. 1. One of the sector cyclotron pole pieces is shown in Fig. 2. Table 1 presents the parameters for the magnet [3].

Figure 1: The split magnet iron return path and poles.

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Figure 2: The machined sector cyclotron pole pieces on the 2.2-m diameter pole for the magnet. The coil cryostat is in the slot between the pole and the return iron yoke.

Table 1: Cyclotron Gas Stopper Magnet Parameters [3]

Parameter	Value
Number of Magnet Coils	2
Iron Pole Radius (m)	1.10
Iron Return Yoke Outer Radius (m)	~1.90
Average Induction in the Gap (T)	~2.0
Average Pole Half Gap (mm)	~90
Number of Coil Turns per Layer	31
Number of Layers per Coil	57
Coil Cross-section R / Z (mm)	80 / 80
Coil Peak Design Current (A)	200
Peak Coil Current Density (A mm^{-2})	54.9
Peak Magnetic Induction in Coil (T)	2.05
Magnet Self Inductance Assembled (H)	178
Magnet Peak Stored Energy (MJ)	3.56
Coil Cold Mass per Pole (kg)	~370
Magnet Cold Mass per Pole (kg)	~1240
Magnet Iron Mass (metric tons)	~167

MAGNET COILS AND QUENCH PROTECTION

The 1767 turn magnet coils were wet wound and molded to fit into the 80 mm by 80 mm final shape. A 22-turn non-inductive work hardened 6061-Al resistor with a resistance of 2.26 ohms was wound on the outside of the coil as part of the quench protection system [4]. When the magnet quenches, the diodes fire shunting the current into the resistor, which heats the coil from the outside. A quench, which fires the diodes, will cause the full current of the coils to flow in the resistor. It takes ~100 ms, for the outside of the coil to be heated to 10 K. The calculations show that both magnet coils will become fully normal in <4.3 s. At the start of the quench at full current 89 kW of heat will come from the resistor. This will boil the helium in the cryostat as well cause the coil to turn normal. Once the coil has turned normal, the coil rapidly discharges.

The coils were inserted in 304-stainless steel helium vessels so that there is space between the coil and the helium vessel to circulate helium in a thermal-siphon cooling loop used to cool and cool-down the magnet coils. The helium vessel is stiff to prevent deflection of the cold mass when the magnet sees unbalanced magnetic loads while in the iron. The helium vessel necks contain the quench protection [4] diodes (see Fig. 3), the LTS leads that connect of the bottom of the HTS leads through a vacuum tight feed-through between the helium vessel and the cryostat vacuum vessel, and 5 L of liquid helium out of the total of 7.4 L per coil. The LTS leads are designed so that their length is less than a minimum propagation zone length at the full design current of the magnet. In addition, the LTS leads within the helium vessel are designed to be cryogenically stable in helium gas.

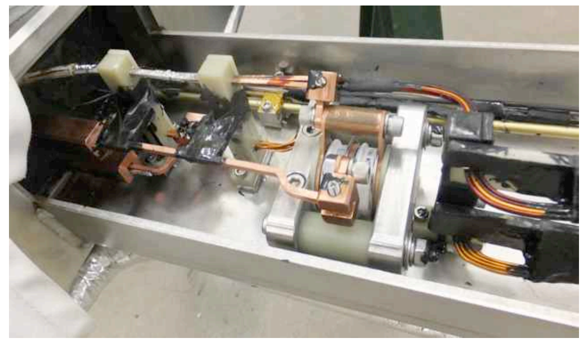

Figure 3: Quench Si diode assembly in the cryostat neck.

MAGNET COOLING SYSTEM

The tops of the HTS leads are connected thermally to the first stages of the coolers. Electrically the leads are insulated from the first-stages. The heat from 293 K to the top of the HTS leads at 45 to 50 K is conducted through the electrical insulation to the cooler first-stages at a temperature <40 K. The heat conducted down the leads to the cooler first-stages is ~20 W all other sources of heat to the cooler first stages amount to < 10 W. The projected cooler first-stage heat load is 10 W per cooler.

Each coil of the cyclotron gas stopper magnet is cooled and cooled-down using three PT-415 two-stage pulse tube coolers with remote rotary valves and ballast tanks. These coolers produce 1.35 W at 4.2 K while procucing 36 W at 40 K. The cooler cold heads mounted in the top of the turret are shown in Fig. 4.

Figure 4: The top of the coil 1 turret cryobox showing the cooler cold heads (labled A, B, and C), the current leads, the instrumentation plugs, and the safety vent tubes.

The cooler cold heads and the ballast tanks, which are mounted on the cryostat turret, are at a high voltage (up to 60 kV) with respect to ground. The rotary valves and the hoses to the compressors are at ground potential. The helium pipes between the rotary valves and the cooler cold heads are insulators that hold off up to 60 kV. Figure 5 shows a mockup of the coolers on the cryostat turret.

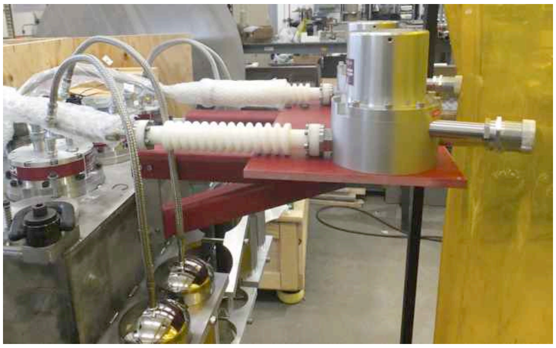

Figure 5: The coolers mounted on the coil turrent.

During a cool-down, the three coolers on each coil cryostat operate in parallel [5]. Helium gas from the magnet enters the three condenser heat exchangers from the top. The gas is cooled in the condenser boxes and is sent to the bottom of the magnet cryostat. Figure 6 shows two of the three condenser boxes. After entering the magnet cryostat, the cold helium goes up past the magnet coil along the inside and the outside of the coil. The helium leaving the top of the coil returns to the condenser boxes to be re-cooled. The thermal siphon circuit flow is by natural convection. The projected cool-down time for the magnet cold mass of 2480 kg from 293 K to 4.3 K is ~4 days using six coolers. The time to fill the helium vessels with 16 L of helium by liquefaction of 293 K gas is an additional day.

Figure 6: The condenser heat excahngers for two of the three coolers. Warm gas from the magnet enters the condenser from the top. Cold gas leaves from the condenser bottom.

CONCLUDING COMMENTS

Both magnet coil cryostats were leak checked and pumped out in preparation for the first test of the cryogenic system. Since the thermal siphon cryogenic cooling system only works when the axis of the magnet is horizontal (so that the condenser is ~3 meters higher than the bottom of the coil cryostat), the cooling-down and the testing of the cryogenic system can only be done with the magnet coil cryostats mounted on the iron poles. The magnet coils were mounted in the iron during September of 2013 in preparation for a magnet cool-down using all six of the PT-415 pulse tube coolers (see Fig. 7). During the fall of 2013, the magnet instrumentation will be connected and the high voltage system will be installed on the magnet. The first magnet cool-down using helium from gas bottles is expected in the winter of 2014. With luck, cryogenic testing and magnet coil training is expected to occur in the first half of 2014.

Figure 7: The magnet coil mounted in the cyclotron gas stopper magnet iron return yoke.

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