The Superferric Cyclotron Gas Stopper Magnet Design and Fabrication

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Abstract—The Facility for Rare Isotope Beams (FRIB) under construction and the existing National Superconducting Cyclotron Laboratory at Michigan State University (MSU) will provide exotic low energy rare isotope beams (KeV-MeV) by stopping relativistic fragments produced by projectile fragmentation at high energies (<50 MeV/u). The stopped radioactive ions using the cyclotron gas stopper magnet system will feed the existing program centered on precision mass measurements of exotic nuclei and laser spectroscopy. Later on stopped radioactive ions will be available as reaccelerated low energy beams (<15 MeV/u) using compact linear accelerator currently under construction. The cyclotron gas stopper magnet is a warm iron superconducting cyclotron sector dipole. The maximum field in the gap (0.18 m) is 2.75 T. The outer diameter of magnet yoke is 4.0 m, with a pole radius of 1.1 m and Br = 1.8 T m. The desired field shape is obtained by a pole 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 will be cooled by six cryocoolers. This paper presents the magnet design and discusses various design aspects of the magnet.

Index Terms—Cyclotron Magnet, Natural Convection Helium Cooling, Superconducting Coils, and Warm Iron Return Path.

I. Introduction

THE fragmentation of fast heavy-ion projectiles enables fast, chemistry-independent production, separation and delivery of exotic isotopes. The resulting beams of exotic nuclei have high energies (~10 MeV / u) and large emittances due to the production process. The range of possible experiments with the fast beams is extended by slowing down the fast ions in solid degraders, stopping them in helium gas, and then extracting the exotic ions from the buffer gas with a differentially pumped radio frequency (RF) ion-guide [1]. The ReA3 [2] re-accelerator is under construction at MSU to re-accelerate the thermalized ions to provide low emittance exotic beams over a range of energies. The thermalization of

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the fast ions and their extraction with the existing techniques such as linear gas cells are limited due to the large range straggling accompanied by low stopping power of gas, and the space charge created in the buffer gas by slowing down process of ions. All of which obstruct efficient collection of fast heavy ions and results in a low efficiencies.

An alternate proposal to efficiently thermalize and extract light to medium mass, high intensity secondary beams is to apply a strong gradient-dipole magnetic field in a large magnetic gap (0.18 m) that forces the fast ions to follow spiral trajectories while being slowed down in a buffer gas. The thermalized ions stop near the central region of the magnet and are then transported into the central extraction orifice of the magnet. Afterward these extracted ions will be transformed into low energy beams using a differentially pumped ion-guide system and transported to either low energy experiments or to the reaccelerator. The high performance and high field (2.7 T) superferric cyclotron gas stopper sector-magnet at National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) will enable the capture of short-lived rare isotopes produced in nuclear reactions.

II. General Description of the Magnet

The cyclotron gas-stopper magnet design has evolved substantially since the original proposed design [3]. Focusing from the gradient dipole field with a large magnetic gap (0.18 m) provide a larger acceptance than the original flat dipole field and helps to mitigate losses due to angular straggling. The modified pole profile of the magnet specifically avoids ion losses due to a resonant coupling of axial and radial motions, the so-called Walkinshaw resonance [4]. Therefore, the field index, defined as k=r/B*dB/dr where r is the radial co-ordinate and B is the average magnetic field strength, is kept below the critical value k= -0.2, having only a single rapid crossing of the resonance at small radius. The warm iron, superferric cyclotron gas stopper magnet will be fabricated in two halves.

Each magnet section consists of the following parts: 1) a 300 K magnet pole and half of the magnet return yoke, 2) a single superconducting coil fitted in a stainless steel shell, 3) a 80 K liquid nitrogen shield, 4) three cold mass supports to carry radial forces and six cold mass supports to carry forces between the coil and the warm iron, 5) three Cryomech PT-415 two stage pulse tube coolers, 6) second stage heat exchangers that transfer cooling to the helium that circulates through the magnet, 7) a 40 K neck shield and connection

points for the upper end of a pair of HTS leads, 8) a pair of HTS leads that carry the full magnet current, 9) a pair of copper leads that are conduction cooled, and 10) a 304-stainless steel cryostat vacuum vessel. Fig. 1 shows the magnet halves separated and its vertical orientation. The magnet is cooled-down and kept cold using a thermal siphon circulation and gas circulation.
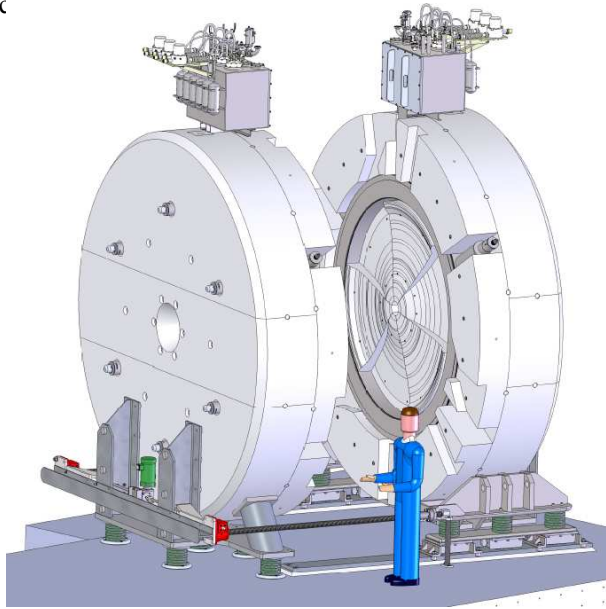

Fig.1. The two halves of the cyclotron gas-stopper magnet open (shown without the beam chamber).

The cyclotron gas-stopper magnet will be cooled using the six cryo-coolers and electrically the two magnet halves will be connected in series at room temperature and operated by a single 200 A power supply.

The thermal connection between the magnet coils and the second (4.2 K) stages of the six coolers will be made through a pair of thermal-siphon cooling loops that provide cooling to operate the magnet at temperatures between 4.3 and 4.6 K. The liquid inventory in each half is about 16 liters.

III. THE COIL AND THE COLD MASS PACKAGE

The magnet cold mass consists of a superconducting coil, a 304L stainless steel helium vessel and support structure, and a stainless steel helium vessel neck assembly that is connected to the coolers and their heat exchangers (condensers).

The conductor for the coil is a standard MRI conductor with Nb-Ti in a copper matrix. The bare conductor dimensions are 1.16 mm by 2.401 mm. The conductor is insulated with a layer of Formvar ~0.025 mm thick. The copper to superconductor ratio is ~4.5 to 1. The conductor critical current is ~2200 A at 4.2 K and 2 T. The operating current corresponds to ~10% of the critical current. The current sharing temperature at 2 T field is T_{cs} = 7.9 K, so the temperature safety margin of this coil is 3.7 K.

Fig. 2 shows a cross-section of the superconducting coil, the helium vessel, the 80 K copper shield and the cryostat vacuum vessel. The quench protection resistors, which are bifilar 6061-aluminum wires, are wound on the outside radius of the

coils. The helium vessel neck contains the superconducting leads, two quench protection diodes, the feed-through for the superconducting power leads at 4 K and ~5 liters of liquid helium, all of which are above the coils. The cyclotron gas-stopper magnet design parameters are given in Table I.
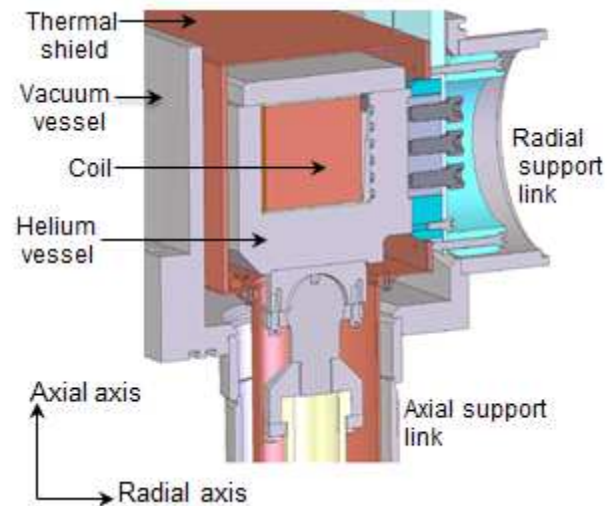

Fig. 2. A cross-section of a cyclotron gas-stopper magnet coil showing the helium vessel (support structure), the 80 K shield and the cryostat vacuum vessel.

IV. MAGNET QUENCH PROTECTION

The magnet has been designed to be passively quench-protected. The calculated current decay time constant that results in a hot spot temperature of 300 K is ~46 s [5]. When the magnet goes normal at its full design current a single coil will become full resistive in ~12 s. The magnet is thus self-protected and should not need a quench protection circuit. However, we have decided to put diodes and a resistor across the coil to provide more quench protection system for the coils [6].

Fig. 3 shows the circuit designed to power and protect the magnet. The arguments for putting cold diodes and a resistor across each coil are as follows: 1) The coil is protected from a failure of any lead between the power supply and the point where the diodes and resistor are connected to the coil [7]. This protects from an HTS lead failure or an LTS bus failure or a break in the leads between the power supply and the tops of the HTS leads. 2) The coil can be quenched by an external resistor across the coil if the power supply is disconnected from the magnet by the switch, provided the heat from the cold resistor can be conducted to the coil to quench the coil. This is a form of quench back from the resistor [8]. The cold resistor is well insulated electrically from the coil. 3) The resistor will reduce the coil hot-spot temperature, because the coil will quench faster. The magnet should have a rapid discharge circuit to discharge the magnet in the event of a power failure. [9]. If the tops of the HTS leads become too warm (70 K), the magnet should be quenched to keep the HTS leads from failing.

The resistor is wound on the outside of the coil so, it must have a low self-inductance and it must not be well coupled to

the coil. In the present case this resistor is a bifilar winding made from a work-hardened Kapton-wrapped 6061 aluminum wire that has dimensions of 1 mm by 3 mm.

TABLE I. BASIC PARAMETERS FOR THE CYCLOTRON GAS-STOPPER MAGNET

Parameter	Value
Iron Pole Radius (m)	1.10
Iron Return Outer Radius (m)	2.00
Average Induction on the Pole (T)	~2
Average Pole Half Gap (mm)	90
Number of Turns per Layer	31
Number of Layers per Coil	57
Coil Cross-section R/Z (mm)	80/80
Peak Design Coil Current Density (A mm^{-2})	54.9
Coil Peak Design Current (A)	200
Peak Design Induction in Coil (T)	2.05
Magnet Self Inductance (H)	178
Magnet Peak Stored Energy (MJ)	3.56
Coil Mass per Coil (kg)	~370
Magnet Iron Mass (metric tons)	~167

V. COOLING THE MAGNET

The magnet will be kept cold by six Cryomech PT-415 two-stage pulse tube coolers. Three coolers are mounted on each coil. The cooling system is designed to keep the coils cold when the halves are separated. Since the cyclotron gas-stopper magnet will be operated at about 60 kV above ground to extract the thermal ion, the connection between the cooler cold heads and the ballast tank and rotary valve assembly must be an in-line electrically insulated tube. This permits the use of flexible metal hoses between the cooler ballast tanks and the compressors, which are electrically grounded.

The PT-415 coolers with separated ballast tanks and remote valves will produce ~1.35 W at 4 K while producing ~38 W at 40 K [10]. Each cooler will produce about 1.75 W at 4.6 K. The three coolers should produce about 5.2 W at 4.6 K while producing a total of 114 W at 40 K. The calculated heats loads at 4.2 and 80 K are 1.93 W and 42 W. The total heat on the first stages of the cooler, with an 80 K shield around them is 40 W and is divided between three coolers.

The connection between the coolers and the coil vessel is through a thermal-siphon cooling loop [11], as shown in Fig. 4. The cold liquid from the condenser enters the magnet cryostat at the bottom and the boil-off gas leaves the magnet cryostat at the top and goes back to the condenser heat exchanger attached to the second-stage cold heads.

The coil can be cooled down from room temperature to 4.5 K using either the MSU central refrigerator system or the six coolers. When the central refrigerator is used to cool down the magnet, the two coils would be connected in series. The rate of cool-down using the central refrigerator depends on a number of factors, such as the helium mass flow available

from the refrigerator and limitations that might be imposed by stress in the helium vessel during the cool-down. When the MSU refrigerator is used to cool down the cryo-stopper magnet at a constant mass flow of 1 g s^{-1}, the cool-down time is expected to be about 90 hours.

In order to cool-down the magnet using a thermal siphon loop the condenser acts like a heat exchanger with the helium entering the heat exchanger from the top. The make-up helium entering the system must be pre-cooled using the 80 K shield and the cooler first-stages [12]. At the start of cool-down the helium pressure in the cryostat will be about 0.3 MPa. The entire magnet will cool-down using six coolers in about ~96 hrs. It will take an additional ~12 hrs to liquefy ~16 liters of helium to fill the magnet cryostat once the coil is cold. Since frequent cooling isn't expected, this is sufficient.
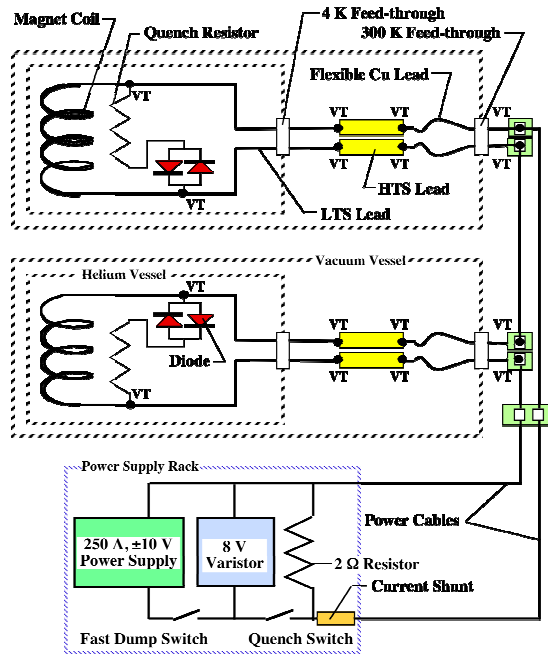

Fig. 3. The schematic quench protection circuit for the cyclotron gas-stopper magnet.

VI. FORCES AND COLD MASS SUPPORT SYSTEM

Each coil vessel support system consists of six axial supports 60 degrees apart and three radial supports, 120 degrees apart. For the optimized magnetic design, the hoop force is 1310 kN and axial forces are 630 kN being attractive towards the yoke steel. Because the coils are in two independent sections, the axial forces are carried by 6 composite tubes in compression on each half.

The radial supports are arranged such that two supports are at +/- 60 degrees from the top and the third support is at the bottom. The total weight of each cold mass supported is about 1588 kN. The radial forces from the coil on the bobbin vary circumferentially depending on whether you are in hill or valley region of the pole steel. This present no problem when the bobbin is centered since there is symmetry of the support system with the loads. If the bobbin is off center then these forces become non-symmetric. This causes the bobbin to

become oval which further increases the radial forces. This condition could be better supported if six radial links could be used; however, the penetration design does not allow this. The coil bobbin design was changed to provide greater stiffness. TOSCA [13] calculations were also performed to find load distribution with offsets at various angles to the link symmetry. FEA calculations of the bobbin and support system were done giving a design that safely handles up to 1 mm off center radial displacement with the worst load distribution. The link material is Ti 6Al4V ELI because the spring constant needed to handle these load conditions with only 3 links was 60% larger than what can be handled through glass composite tension staps. Typical tension loads are 5000 kN for the two links also supporting the mass and 3200 kN for the bottom link.
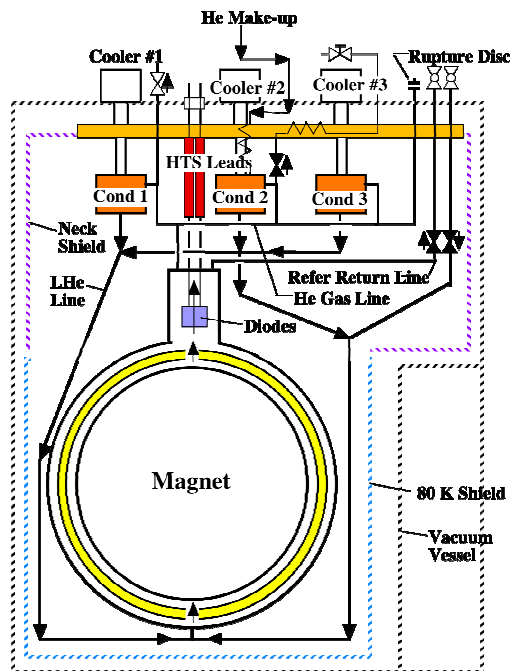

Fig. 4. The thermal-siphon cooling circuit for half of the cyclotron gas-stopper magnet. The circuit as shown can be used to cool down the magnet as well.

Bobbin stresses are relatively low for the centered condition: around 30 MPa but can rise to 110 MPa for a condition of 1 mm radial offset.

Fig. 5.   A single cyclotron gas-stopper magnet coil that has an average diameter of 2470 mm and a cross-section of 80 by 80 mm.

VII. FABRICATION

Three cyclotron gas-stopper magnet coils have been fabricated. Two of these coils will be used for the magnet; the third coil will become a spare. One of the coils is shown in Fig. 5. Fabrication of the iron return yoke has started and the pole pieces are finished as can be seen in Fig. 6.

Fig. 6. The machined pole-piece sectors for the magnet. The outside diameter of the pole is 2200 mm.

The planned operating temperature for the magnet is 4.3 K. The lower limit of the operating temperature is set because one does not want the magnet cryostat to operate at pressures less than less that 0.11 MPa absolute to prevent air from entering through any leaks. Testing of the magnet half at the full operating stress and force conditions can only occur when both halves of the magnet have been assembled so that the forces can be balanced.

VIII. CONCLUSIONS

Construction of the cyclotron gas stopping magnet is well advanced. The design presented here provides for a cryocooler-based cooling system with a very conservative coil and protection design. The system will be in operation in 2013.

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