DESIGN OF SUPERFERRIC MAGNET FOR THE CYCLOTRON GAS STOPPER PROJECT AT THE NSCL*

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Abstract

We present the design of a superferric cyclotron gas stopper magnet that has been proposed for use at the NSCL/ MSU to stop the radioactive ions produced by fragmentation at high energies (~140 MeV/u). The magnet is a split solenoid-dipole with three sectors (B_{ave}~ 2.7 T at the center and 1.7 T at the pole-edge.) The magnet outer diameter is 3.8m, with a pole radius of 1.1m and B*ρ= 1.7 T-m. The field shape is obtained by extensive profiles in the iron. The coil cross-section is 80 mm x 80 mm and peak field induction on the conductor is about 2.05 T. The upper and lower coils are in separate cryostats and have warm electrical connections. We present the coil winding and the protection schemes. The forces are large and the implications on the support structure are presented.

INTRODUCTION

The concept to stop and re-accelerate the radioactive ions produced by fragmentation at high energies (~140 MeV/u) using cyclotron gas stopper magnet and superconducting linear accelerator has been under development at NSCL/MSU for some time. The cyclotron gas stopper is sector-focusing magnet filled with helium gas at low pressure and have static electric field with radiofrequency (RF) carpet to guide and extract stopped ions. This technique has several advantages over present linear gas stopper in operation at NSCL/MSU [1].

A similar concept has been used in the past for the production of antiprotonic, pionic and muonic atoms [2] and also has been discussed for light ions [3].

SUPERCONDUCTING MAGNET

Fig. 1 shows the cross-section of the superconducting cyclotron gas stopper magnet, with the superconducting coil and iron yoke indicated. It's a sector magnet with 120^o symmetry and the iron in both hills and valleys is shaped to provide the required field integral and field index, k (r/B*dB/dr). The other main parameters of the magnet are given in Table I. The superconducting coil with an average current density of 5x10^7 A/m^2 is designed to achieve the required magnetic flux density in the magnet. Simulations with TOSCA [4] were performed to calculate the magnetic field and forces acting on the coils and iron pole. The peak magnetic field induction in the coil area is about 2.05T. The stray field at an axial distance of 1.0 m from the center of magnet system does not exceed 200 gauss. Low stray field is required to avoid interference with extraction of stopped ions through the center of magnet system. A field plot is shown in Fig. 2. The required average field variation with B (T)*ρ (m) along the radial axis is also inducted in Fig. 2; Figure 3 presents field index variation along radius for full excitation. The field index should be different from 0.2 to avoid the walkinshow coupling resonance (γ_r=2γ_z). Since, the stopped ions close to the magnet center begin to be decelerated at the edge of magnet at r=1.0m, k is higher and only decreases as the radius decreases. The k=0.2 point should be as close to the center as possible to mitigate the adverse effects. The field index only approaches zero at the center and crosses k=0.2 at approximately 0.25 m from the center.

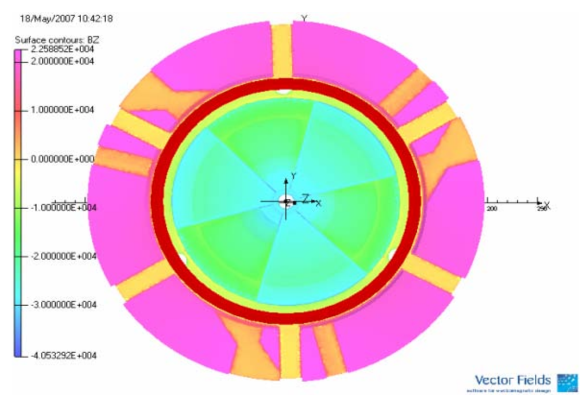

Figure 1: Cyclotron gas stopper magnet cross-section.

SUPERCONDUCTING COIL

The superconducting coil for cyclotron gas stopper is basically a split solenoid with full diameter warm bore and current leads of upper and lower pole solenoid have warm electrical connection; several room temperature penetrations also pass through the coil at the solenoid split, as for an example degrader [1].

Away from the magnet center the field is segmented into focusing hills and valleys, as shown in Fig. 1. The peak field in the gap close to center is 2.7 T. In the coil proper, the maximum field induction is 2.05 T. An important design aspect of the proposed coil and cryostat is compactness; the extent of the weight of the cyclotron gas stopper magnet

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* Supported by DOE Grant DE-FG02-06ER41413, NSF Grant 0606007 and Michigan State University

system is in the portion of the iron yoke (~150 tons) which passes around the outside of the coil and cryostat; minimizing the cross-sectional area of the coil-cryostat assembly has a large impact in reducing the overall weight of the magnet system.

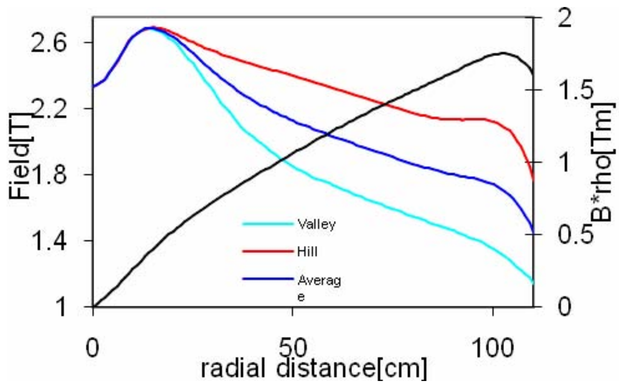

Figure 2: Profile of magnetic field for full excitation current along the radial axis.

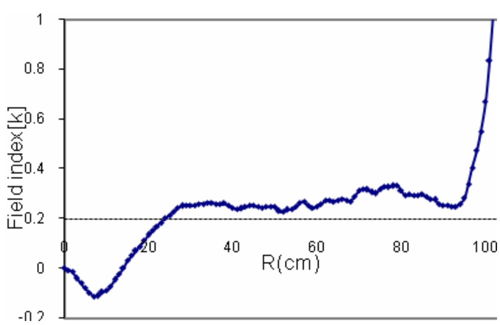

Figure 3: Profile of calculated field index along radial axis.

Table 1: Parameters of the superconducting cyclotron gas stopper magnet

Magnetic field in the gap at the center of the magnet, T	2.7
Ampere-turns of the individual coil, MA	0.32
Nominal operational current, A	450
Stored energy, MJ	2.98
Self inductance, Henry	29.432
Peak field in the superconducting winding at operational current, T	2.05
Mass of iron, Tons	150
Pole diameter, m	2.2
Outer iron diameter, m	3.8

The coil for the cyclotron gas stopper magnet is an epoxy impregnated, ordered winding. The coil and conductor specifications are given in Table 2. The proposed conductor uses large filaments because the conductor is a standard for MRI magnets and readily available. Because the coil operates in a low magnetic field, the filament size (220 µm) is larger than the classical limit for stability against flux jump (80 µm); however, the large amount of copper provides excellent heat transfer. A sample of the wire with the same conductor area was tested at Fermi lab by setting the current to 1000 A (twice the operating current) and ramping the field from 0 to 4 T and back to 0. No instability was seen at the 10 µV/cm level.

Table 2: Conductor specification

Conductor	
Size (mm)	2 x 4
Cu: Superconductor	15:1
Measured I_c @ 6 T (1µV/cm)	952
Insulation	Formvar
Coil	
Turn per layer	20
Layers	36
Size (mm)	80 x 80
Insulation between layers (mm)	0.2

Quench Calculations

QUENCH [5] calculations were done assuming all of the energy is dumped into one coil with no external dump.

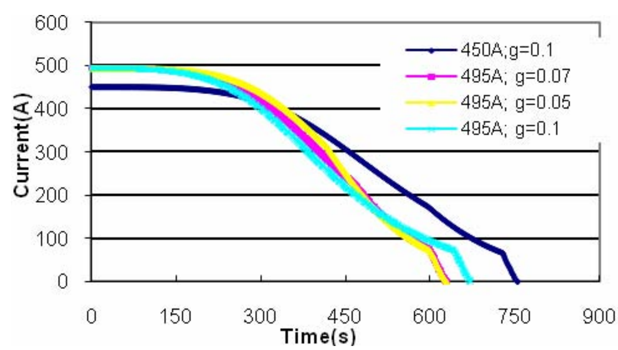

Figure 4: Current decay calculations with different transverse propagation velocities.

The voltages in the coils, rise in temperature and decay of current with respect to time as quench propagates were calculated. The results are shown in Fig. 4-6. The crucial parameter in calculation is transverse quench propagation velocity, expressed as ratio of propagation constant, G, times the velocity along wire. Experimentally [6] we have found that tightly wound and potted coils like these have a rapid transverse quench propagation velocity ratio of 0.05 to 0.1.

The current decay as a function of time is shown in Fig. 4, along with several quench calculations. Three curves are shown for 10% higher current compare to operational current and have been produced by varying the transverse velocity from 5% to 10%.

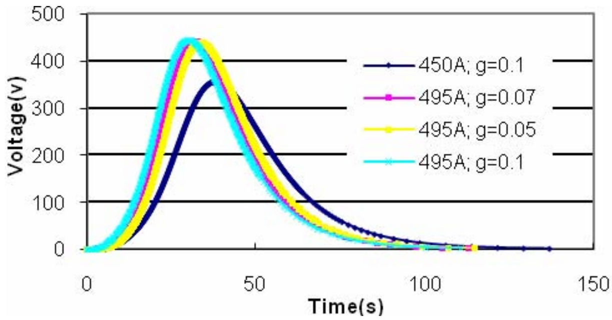

Figure 5: Quench voltage calculations with varying transverse propagation velocity.

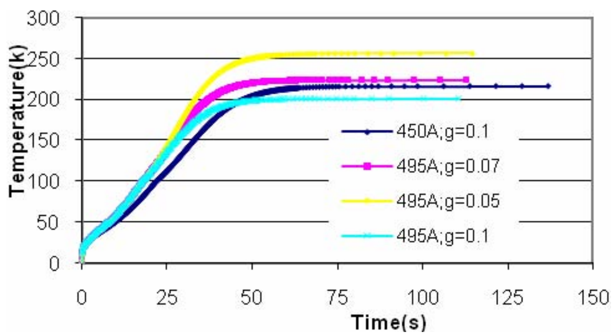

Figure 6: Temperature calculations with varying transverse propagation velocity.

The voltage in the coils during a quench is shown in Fig. 5. Each coil will have 36 layers, so the maximum voltage is very low. The temperature rise as quench propagates is shown in Fig. 6. Three curves are shown for 10% higher current along with curve for operational current and have been produced by changing the transverse quench propagation velocity from 5% to 10%. The worst-case hot spot temperature is only 250 K. This is also the calculated temperature rise for the A1900 dipoles that have been surviving quenches since 1998 [7].

FORCE AND COIL SUPPORTS

Simulations with TOSCA were performed to calculate magnetic forces acting on the coils and iron yoke. The axial and radial magnetic forces on the coil are 6.78×10^5 N and 1.33×10^6 N respectively. The peak field induction in the coil area is 2.05 T and its variation in the coil area close to hill and valley sector is less then 10%, so the forces are essentially the same. Thus irrespective of hill or valley each solenoid coil has suspension system consists of twelve support (6 vertical and 6 radial) links.

A deviation of axial (radial) force 75kN/cm (31 kN/cm) corresponds to a shift of coil axial (radial) position by 10 mm. Axial and radial forces acting on the coil versus coil displacement in that particular direction are shown in Fig. 7 and Fig. 8.

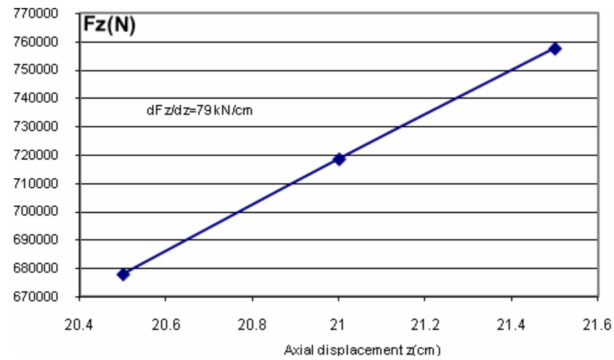

Figure 7: Axial force F_z versus coil axial displacement ΔZ (cm).

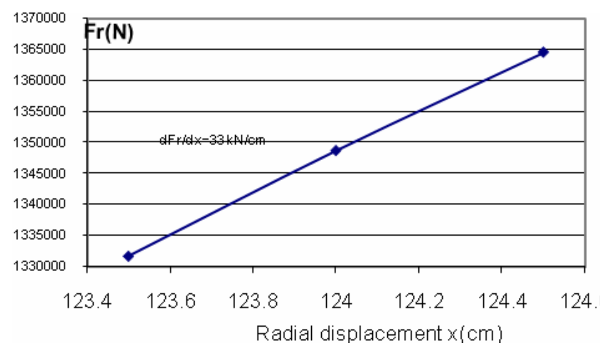

Figure 8: Radial force F_r versus coil axial displacement ΔX (cm).

SUMMARY

Through appropriate shaping of the iron, a superferric cyclotron gas stopper magnet has been designed. The magnet is self-protecting and operates at under 500 A. The beam optics is presently being reviewed before starting construction.

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