MAGNETIC CLOAKING OF CHARGED PARTICLE BEAMS*

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Abstract

In order to measure the momentum of particles produced by asymmetric collisions in the proposed Electron Ion Collider, a magnetic field should be introduced perpendicular to the path of the beam to increase momentum resolution without bending or depolarizing it. A magnetic cloak consisting of a superconducting magnetic shield surrounded by a ferromagnetic layer is capable of shielding the interior from a magnetic field – thereby protecting the beam – without distorting the field outside of the cloak – permitting detector coverage at high pseudorapidity.

MOTIVATION

The Electron Ion Collider (EIC) is a proposed upgrade to an existing accelerator at either Brookhaven National Laboratory (BNL) or Jefferson National Laboratory (JLab) that would collide 21 GeV electrons with 250 GeV protons (or other hadron) [1]. The EIC detector built around the BaBar solenoid has been proposed as an upgrade to BNL's sPHENIX experiment if the Relativistic Heavy Ion Collider (RHIC) is upgraded to the eRHIC [2].

The addition of 1 m long 1 T homogeneous dipole fields perpendicular to the beam in the hadron going and electron going regions coupled with three position measurements with $\sigma_x = 60\,\mu\text{m}$ would result in momentum resolution of $\delta p/p = p \cdot 0.2\,\%\,\text{GeV}^{-1}\,c_0$ [3]. Such dipole magnets would deflect and depolarize the electron and hadron beams as they passed through the detector. The beams can be protected from these magnetic fields using 2 m to 3 m long superconductor cylinders with diameters of 4 cm [3]. Use of such superconducting magnetic shields would distort the dipole fields near the beam line, but ferromagnetic cylinders surrounding the superconducting shields can be used to contain these distortions, creating a magnetic cloak as shown in Fig. 1.

MAGNETIC CLOAKING

Superconducting Magnetic Shield

The critical temperatures (T_c) of a superconductor is the temperature at which the superconductor transitions from the normal conducting to the superconducting states in the

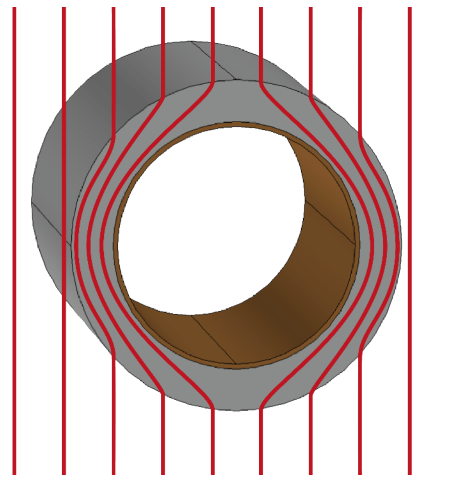

Figure 1: Diagrams the principle of magnetic cloaking, field lines shown in red [4].

when cooled in the absence of applied currents and magnetic fields. When cooled below its T_c, a type I superconductor will expel applied magnetic fields below the critical field (B_c) of the superconductor, which is a function of its temperature. Type II superconductor have two critical fields, the lower critical field (B_{c1}) and the upper critical field (B_{c2}), which are also dependant on the temperature of the superconductor. A type II superconductors can shield the majority of applied magnetic fields less than it's B_{c1}. The small leakage in this field range are due to shield geometry and magnetic flux pinning caused by microscopic impurities common in type II superconductors. Between B_{c1} and B_{c2}, a type II superconductor is in a mixed state where it will shield a portion of the applied magnetic field by allowing partial flux penetration through microscopic regions in the normal conducting state. These normal conducting regions are surrounded by vortex currents that shield the superconducting region from the magnetic field that penetrates the superconductor. Above B_{c2}, a type II superconductor will be in the normal conducting state. The critical fields of both types of superconductor are approximately given by

$$B_c(T) \approx B_c(0)\left(1 - \frac{T^2}{T_c^2}\right), \tag{1}$$

where B_{c1} and B_{c2} can be substituted for B_c.

Type II superconductors have several advantages over type I superconductors for shielding applications. Firstly, all

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type I superconductors are low temperature superconductors whereas type II superconductors can be low temperature or high temperature superconductors. Since B_{c2} of type II superconductors can be orders of magnitude higher than B_c of type I superconductors, multilayer shields made of type II superconductor have be used to shield fields of several tesla while type I superconductors are limited to applications that require shielding on the order of microtesla [5]. Multilayer shields function by using the outer layers in the mixed state to partially shield the applied field so that each layer is exposed to a successively lower fields. After passing through enough layers, the applied field is reduced to below B_{c1} and is then shielded by a layer in the fully superconducting state. Additional inner layers may be used to reduce the effects of flux pinning and geometric factors.

We have investigated the use yttrium barium copper oxide (YBCO) superconductor as a candidate superconductor for use in a 1 m long magnetic cloaks capable of shielding charged particle beams from fields of 0.5 T from detector dipoles[1]. To study the viability of long superconducting shields, a 1 m long, 25 mm diameter magnetic shield prototype consisting of two layers of 46 mm wide YBCO wire on the top and bottom was constructed for a proof of concept test of charged particle beam shielding capabilities. This prototype was installed on the beam line of the BNL Tandem Van de Graaff Facility to perform said proof of concept measurements.

Ferromagnet

Confinement of the magnetic field distortions caused by the superconductor to within the ferromagnetic layer and thereby achieving the magnetic cloaking phenomena requires the permeability of the ferromagnetic layer be matched to its inner and outer radii (R_1 and R_2 respectively) according to the equation

$$\mu = \frac{R_2^2 + R_1^2}{R_2^2 - R_1^2}\mu_0 \tag{2}$$

when it surrounds an ideal superconductor [3].

BEAM TEST OF SUPERCONDUCTING MAGNETIC SHIELD

The beam test of the 1 m superconducting magnetic shield prototype was performed at Brookhaven National Laboratory's Tandem Van de Graaff Facility. A 15.2 cm long steering dipole was used to apply magnetic field of up to ±40 mT at the center of the magnetic shield. The beam position was measured using a phosphor screens (Fig. 2) in conjunction with a DSLR camera. The phosphor screens were mounted on a stage along with a piece of 0.05 in ruled graph paper for calibration of the DSLR camera pixel to deflection distance. The stage was mounted 2.43 m past the center of the 1 m long shield prototype within a target chamber and rotated so that its normal was 45° from the nominal beam path and 45° from the DSLR camera.

[1] Somewhat smaller than originally described in [3].

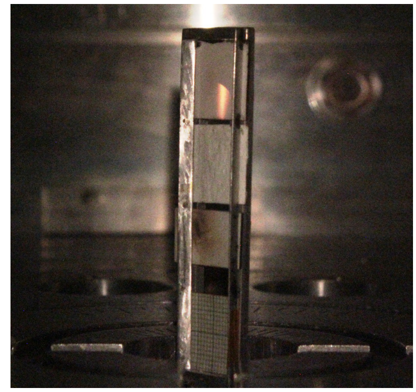

Figure 2: Phosphor screens and calibration grid. From top to bottom: screen made using light-bulb phosphor, screen made zinc sulfide and silver, commercial phosphor screen, calibration grid with 0.1 in interval.

Superconducting Magnetic Shield Prototype

The 1 m long superconducting shield prototype used in the proof of concept beam test consisted of four pieces of 46 mm wide YBCO wire wrapped around a 25.4 mm outer diameter beam pipe with two wires on the top of the beam pipe and two wires on the bottom of the beam pipe. The YBCO wires were secured to the beam pipe using Kapton tape and zip ties. The dipole field used in the beam test was applied vertically.

Cryostat

The magnetic shield prototype was cooled by submerging it in liquid nitrogen contained in an aluminum box insulated with Styrofoam around its exterior. A spray foam insulation was used to seal the ends of the box where the beam pipe passed through.

Beam Species and Properties

Two beam species were used for the tests, the first was a lithium-7 beam with a kinetic energy of 8.14 MeV and the second was an oxygen-16 beam with a kinetic energy of 20.0 MeV, both beams had a charge state of +3 (see Table 1).

Table 1: Beam Species

	Run 1	**Run 2**
Isotope	lithium-7	oxygen-16
Mass	6.54 GeV c_0^{-2}	14.9 GeV c_0^{-2}
Charge State	3 e	3 e
Kinetic Energy	8.14 MeV	20.0 MeV
Momentum	0.326 GeV c_0^{-1}	0.772 GeV c_0^{-1}
Rigidity	0.363 T m	0.859 T m

RESULTS AND CONCLUSION

Since the phosphor screens spanned 16 mm horizontally and were positioned 2.43 m from the center of the magnet, the beam could not be observed if it was bent by more than

0.006 rad (0.4°). Therefore, the deflection of the beam can be treated as a linear function of the applied field. Multiple photos were taken of the beam spot for each current value. The mean and standard deviation of the first statistical moment of the horizontal beam profile extracted from the photos at each current setting were used for analysis of beam deflection. Applied fields that deflected the beam sufficiently to cause part of the beam to miss the phosphor screen being used were excluded from subsequent analysis as the first statistical moments of their horizontal profiles were skewed by the partial loss of the beam. The displacement (x) of the beam from its position with no applied field was fit with the formula $x = f(B) = a_1 B$. Fitting results are given in Table 2. The reduced chi square values of the fits differ notably from unity suggesting poorly defined uncertainties, which we attribute to low sample numbers. The 1 m superconducting magnetic shield was was able to shield the lithium and oxygen beams from 93.64(31) % of the applied magnetic field. Figure 3 shows the preliminary results from run 1 and Fig. 4 shows the preliminary results from run 2.

Table 2: Summary of Fit Results

	Run 1	**Run 2**
Isotope	lithium-7	oxygen-16
Rigidity	0.363 T m	0.859 T m
Room Temperature Fit		
a_1	21.5(4) μm mT^{-1}	10.74(23) μm mT^{-1}
χ^2_{red}	1.51	3.46
Cryogenic Fit		
a_1	1.41(7) μm mT^{-1}	0.63(6) μm mT^{-1}
χ^2_{red}	0.253	0.543

While this test did not demonstrate complete shielding of the charged particle beam, it is an important step toward a practical application of a magnetic cloak. 114.3 mm long, ten and forty-five layer prototypes have been constructed using methods described in [5]. They are expected to shield a greater percentage of the applied field in their operational field range – which is expected to reach 0.5 T in the case of the forty-five layer prototype – than the 1 m prototype as a result of sturdier mechanical assembly.

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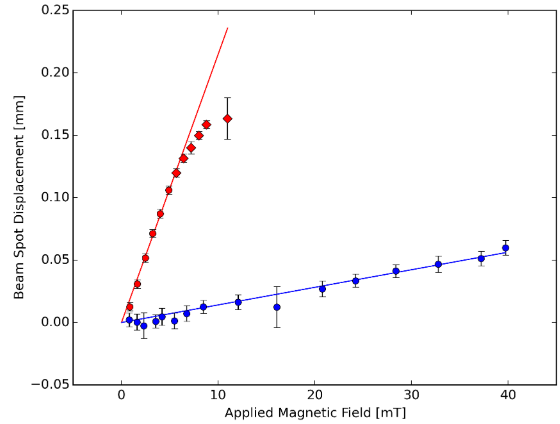

Figure 3: Preliminary results from run 1 (lithium-7 run). Room temperature beam deflection measurements shown in red; cryogenic measurements shown in blue. Diamonds indicate data points that were excluded from linear fit calculations as part of the beam had been deflected from the screen, resulting in the downward skewing of the displacement measurements. Fits are shown in the same color as their respective data sets.

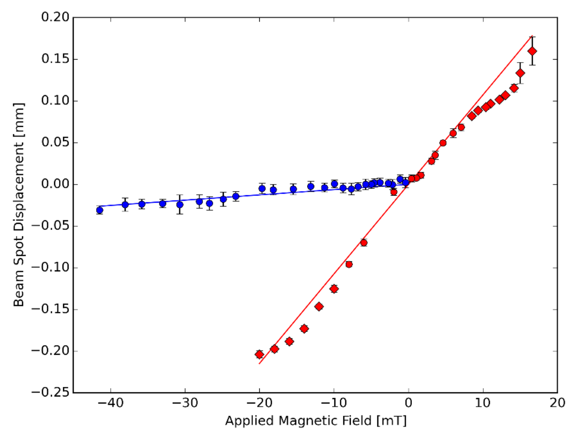

Figure 4: Preliminary results from run 2 (oxygen-16 run). Room temperature beam deflection measurements shown in red; cryogenic measurements shown in blue. Diamonds indicate data points that were excluded from linear fit calculations as part of the beam had been deflected from the screen, resulting in the downward skewing of the displacement measurements. Fits are shown in the same color as their respective data sets.

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