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A magnetic field cloak for charged particle beams

K.G. Capobianco-Hogan [a,b], R. Cervantes [a,c], A. Deshpande [a,d], N. Feege [a,*], T. Krahulik [a,e], J. LaBounty [a,c], R. Sekelsky [a], A. Adhyatman [a], G. Arrowsmith-Kron [a], B. Coe [a,f], K. Dehmelt [a], T.K. Hemmick [a], S. Jeffas [a], T. LaByer [a], S. Mahmud [a], A. Oliveira [a], A. Quadri [a], K. Sharma [a], A. Tishelman-Charny [a,g]

[a] Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA
[b] Superconducting Magnet Division, Brookhaven National Laboratory, Upton, NY 11973, USA
[c] Department of Physics, University of Washington, Seattle, WA 98195, USA
[d] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[e] Department of Physics, University of Virginia, Charlottesville, VA 22904, USA
[f] Collider Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[g] Physics Department, Northeastern University, Boston, MA 02115, USA

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ABSTRACT

Shielding charged particle beams from transverse magnetic fields is a common challenge for particle accelerators and experiments. We demonstrate that a magnetic field cloak is a viable solution. It allows for the use of dipole magnets in the forward regions of experiments at an Electron Ion Collider (EIC) and other facilities without interfering with the incoming beams. The dipoles can improve the momentum measurements of charged final state particles at angles close to the beam line and therefore increase the physics reach of these experiments. In contrast to other magnetic shielding options (such as active coils), a cloak requires no external powering. We discuss the design parameters, fabrication, and limitations of a magnetic field cloak and demonstrate that cylinders made from 45 layers of YBCO high-temperature superconductor, combined with a ferromagnetic shell made from epoxy and stainless steel powder, shield more than 99% of a transverse magnetic field of up to 0.45 T (95% shielding at 0.5 T) at liquid nitrogen temperature. The ferromagnetic shell reduces field distortions caused by the superconductor alone by 90% at 0.45 T.

1. Introduction

Magnetic fields are routinely used to steer charged particle beams and to analyze the momenta of charged particles produced in fixed-target and collider experiments. The field component transverse to the trajectory of a charged particle deflects it and, in the case of a polarized beam crossing a field gradient, depolarizes it. Beams at particle collider facilities need adequate shielding from fields that would cause disturbances. Established designs of magnetic field shields use cylinders made from low-temperature superconductors [1]. Magnetic flux lines incident on a superconducting cylinder induce screening currents, and the magnetic fields generated by these currents counteract the external field. As a result, the inside of the cylinder remains field-free, while the field on the outside is distorted. This distortion can be corrected by adding a ferromagnetic shell around the superconductor. Unlike the superconductor, a ferromagnetic shell pulls in magnetic flux lines. The combination of superconductor and ferromagnet forms a magnetic field cloak (see Fig. 1). The ferromagnet of a superconductor–ferromagnet bilayer effectively contains all field distortions caused by the superconductor if its magnetic permeability μ_r is tuned to

$$\mu_r = \frac{R_2^2 + R_1^2}{R_2^2 - R_1^2}, \tag{1}$$

where R_1 and R_2 are the inner and outer radius of the ferromagnet (R_1 is also the outer radius of the superconductor) [2]. Thus, a cloak can provide a field-free tunnel without disturbing the external field.

Magnetic field cloaks are topics of active research [3,4]. We want to demonstrate that our design, which uses high-temperature superconductor (HTS) cylinders, is a viable solution to cloak charged particle beams

* Corresponding author.
E-mail address: nils.feege@stonybrook.edu (N. Feege).

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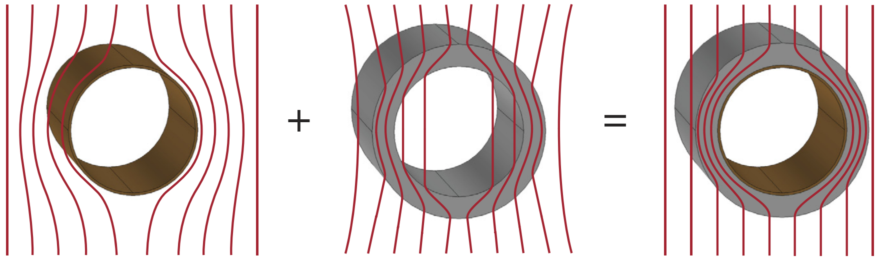

Fig. 1. Concept of a magnetic field cloak. From left to right: A superconducting cylinder pushes out magnetic field lines, a ferromagnetic cylinder pulls in magnetic field lines, and the combination of both forms a cloak (given the correct thickness and magnetic permeability of the ferromagnet).

at future particle accelerator facilities such as the Electron Ion Collider (EIC). Such a facility would require a cloak that shields a magnetic field of at least 0.5 T over a length of 1 m. Section 2 briefly summarizes the basics of shielding magnetic fields with superconductors, Section 3 explains the fabrication of our superconductor shields and cloak prototypes, Section 4 describes our test setups, Section 5 presents the results of magnetic field shielding and cloaking measurements with our prototypes, and Section 6 gives our conclusions.

2. Shielding magnetic fields with high temperature superconductors

The response of a type-II superconductor to magnetic fields is characterized by two critical fields: B_{c1} and B_{c2}. If a cylinder made from such a material is exposed to a transverse magnetic field below B_{c1}, the flux lines are bent around the cylinder. Above a certain threshold field, the field penetrating the superconductor has an approximately logarithmic time dependence [5]. Between B_{c1} and B_{c2}, flux vortices form and allow the field to partially seep through the superconductor. In this field range, stacking multiple layers of superconductor improves the overall magnetic field shielding. Above B_{c2}, the superconductivity is destroyed and the field passes through the shield. The critical fields of a superconductor become larger the lower the superconductor's temperature falls below its critical temperature.

High-temperature superconductors (HTS) are especially convenient because they can be cooled below their critical temperature with liquid nitrogen (rather than liquid helium), resulting in relatively modest cryogenic costs and fast prototyping. Although various experiments have characterized HTS shields [6–11], we are not aware of any substantial shielding past 10 mT with such materials, especially for transverse fields. Ref. [11] comes closest, but the authors only shield approximately 60% of the field with an applied field of amplitude 50 mT and frequency 10 Hz. If HTS can be demonstrated to shield fields above 0.5 T, they can replace low temperature superconductor shields (such as NbTi sheets [12]).

3. Prototype construction

3.1. 1 m long/2-layer and a 4.5 inch long/4-layer HTS shield

We use 46 mm wide superconductor wire insert manufactured by American Superconductor Inc (www.amsc.com) to fabricate superconducting cylinders. This width is an intermediate stage on their production line and, due to low demand, not currently supported as a product [13]. The insert is made from a YBCO ceramic with a critical temperature of about 90 K. The ceramic is deposited on an oxide-buffered Ni–W alloy substrate and coated with silver. The width and flexibility of this superconductor allow us to combine two strips to a cylinder of up to approximately 1 inch diameter. The orientation of the strips along the cylinder axis facilitates the induction of supercurrents that generate a magnetic dipole field. Therefore, it is most effective for shielding transverse magnetic fields [14]. The maximum field that a cylinder can shield increases with the number of layers as long as the field does not exceed the second critical field of the superconductor [15]. Fig. 2 shows our HTS shield prototype consisting of four 1 m long superconductor strips attached to a 60 inch long stainless steel tube with 1 inch outer diameter. The superconductor strips form a double layer on the top and the bottom of the pipe and overlap at the connecting sides. We use Kapton® tape and zip ties to hold the superconductor strips in place. In addition, we test a 4.5 inch long HTS shield prototype with four layers of superconductor strips attached to an aluminum tube.

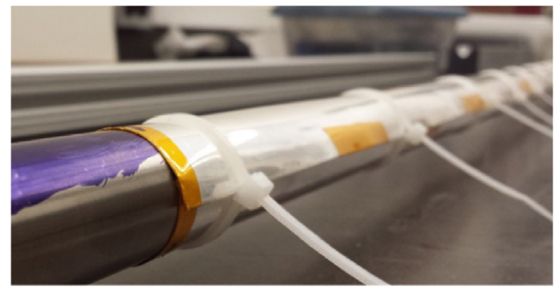

Fig. 2. 2-layer HTS shield made from four 1 m long layers of 46 mm wide superconductor strips attached to a 60 inch stainless steel tube with 1 inch outer diameter. The strips form a double layer around the top and the bottom of the tube.

3.2. 4.5 inch long/45-layer HTS shield

Using a fabrication process based on [1], we build a HTS shield with 45 layers of 46 mm wide American Superconductor HTS wire insert. The process uses a die-and-mandrel setup heated in an oven to laminate multiple layers of superconductor wire and solder. Removing excess superconductor and solder on the sides with a milling machine creates half-cylinders. We combine two of these half cylinders to form a full shielding tube. The left panel of Fig. 3 shows the two halves of our 4.5 inch long, 1 inch outer diameter HTS shield with 45 layers. The thickness of this shield varies between 0.22 inch and 0.26 inch along its circumference. Based on an extrapolation method described in [15] and measurements for single layer shielding, we expect this 45-layer prototype to shield more than 99% of a transverse magnetic field up to 0.5 T.

3.3. 4.5 inch long/4-layer and 4.5 inch long/45-layer HTS cloak

To fabricate a ferromagnetic shell, we mix 430 stainless steel powder (magnetic permeability $\mu \approx 1000$ [16]) with commercial epoxy and pour the mixture into a tubular mold. We keep the mold upright to help air bubbles accumulate at the top and invert it every minute for 30 min to prevent the steel powder from setting while the epoxy is hardening. When placing the hardened cylinder in a 30 mT homogeneous magnetic field perpendicular to its axis, we observe maximum field shielding at the center of the cylinder and a symmetric shielding profile around it (Fig. 8 illustrates the same kind of shielding measurement performed on superconducting cylinders). This confirms the uniform distribution