EIC R&D Progress Report

Reporting Period: **July 2014** to **December 2014**

eRD2: A Compact Magnetic Field Cloaking Device

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1 Objectives

We continued the realization and test of a magnetic field cloaking device with dimensions close to those we expect for an experiment like an EIC detector. This included extending our test set-ups, evaluating materials for the prototype construction, and building and testing prototypes for this device.

2 Timeline

Figure 1 shows the timeline for this project as it was laid out in the previous reports (blue) and our overall progress (green).

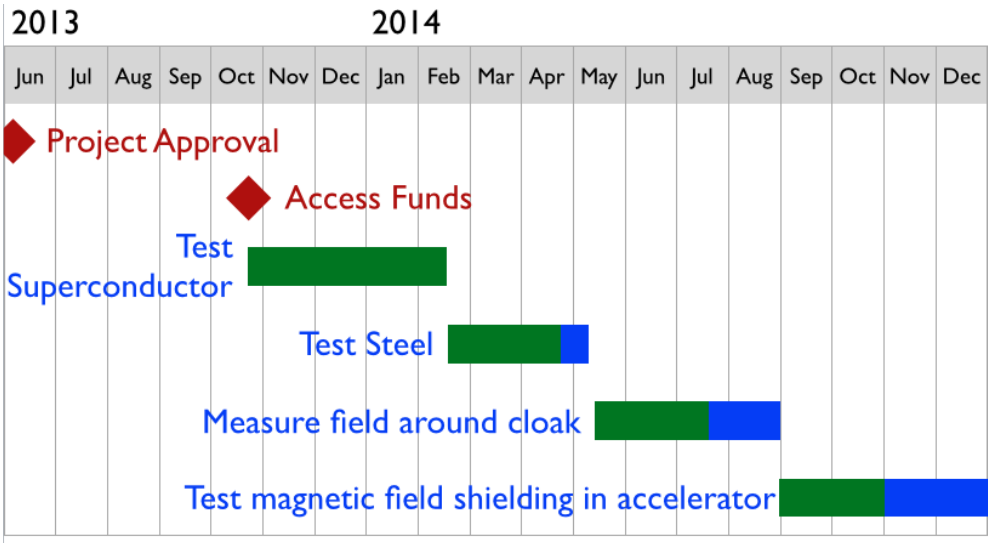


Figure 1: Project timeline.

This report presents updated results from testing the high-temperature superconductor tape we used for our magnetic field cloak prototypes.

Our previous approaches to create a ferromagnetic cylinder of tuned permeability (cold working stainless steel sheets and baking and rolling a mixture of aluminum and stainless steel powder) turned out to be no viable options for us. Therefore, we explored another option: Fabricating a cylinder from epoxy and steel powder.

The big CDS solenoid magnet has been temporarily moved to MIT / Bates and will be commissioned there. We will use this setup to measure the effect of a magnetic cloak prototype on an external field of up to 500 mT (as we had initially planned).

The demonstration of shielding a charged particle beam from a magnetic field (using a long cylinder made from high-temperature superconductor tape in the Van de Graaff accelerator at Stony Brook) takes longer than expected. We had to redesign our superconductor cooling system. In addition, the ion source of the accelerator and the switching magnet are currently under repair. We expect the beam line to become available again in January 2015.

3 Achievements

With five Stony Brook undergraduate students (K. Capobianco-Hogan, B. Coe, T. LaByer, A. Quadri, K. Sharma) and one MSI student (R. Cervantes) we have made continuous progress towards accomplishing our objectives. We successfully:

- tested the shielding performance of up to 20 layers of our superconductor tape from 1 mT to 500 mT external field (Sec. 3.1),
- evaluated different options for wrapping superconductor tape on a core with larger (more realistic for accelerator applications) diameters (Sec. 3.2),
- built and tested a new cryostat for the 1.3 m long prototype for shielding the beam of the Van de Graaf accelerator from a magnetic field and added five superconductor layers to it (Sec. 3.3),
- fabricated a ferromagnetic cylinder of variable magnetic permeability from an epoxy / stainless steel powder mixture and measured the permeability as a function of steel powder concentrations (Sec. 3.4).

3.1 Superconductor Tape Properties

We measured the magnetic field that multiple layers of high-temperature superconductor tape (12 mm wide type II superconductor tape, SuperPower, 65 μm Cu stabilizer, critical current above 420 A) shield. Setup and procedure were the same as described in the previous progress report[1] and illustrated in Fig. 2.

Figure 3(a) shows B_{shield} as a function of B_0 for up to 20 layers of superconductor tape shielding the Hall sensor. As expected, adding more layers both extends the range where B_{shield} is proportional to B_0 and the field shielded at $B_0 = 500\,\text{mT}$.

Figure 3(b) shows the maximum external field B_{95} for which we observe 95% shielding as a function of the number of superconductor layers. The

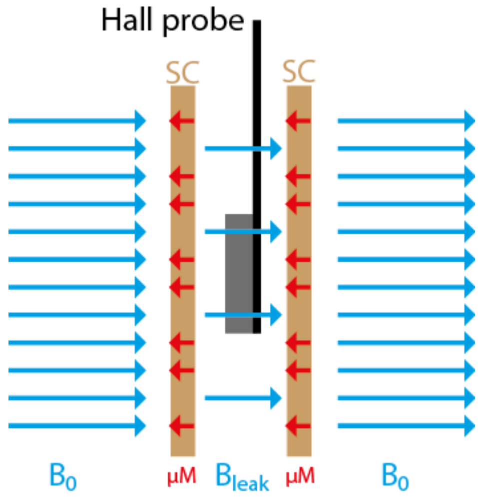


Figure 2: Measuring the magnetic field B_{leak} between small superconductor tape samples (SC, 12 mm long and wide) in a liquid Nitrogen bath inside a dipole magnet of varying field strength B_0. The shielded field B_{shield} is the difference between B_0 and B_{leak}.

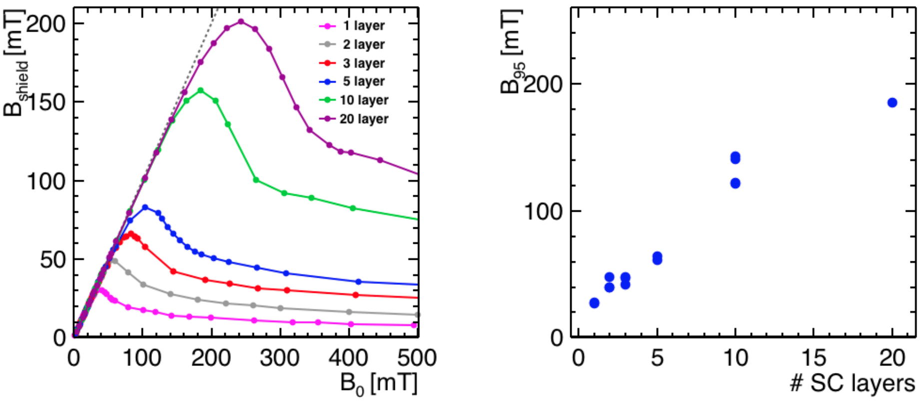
relation appears to be linear up to 10 layers. We are still qualifying the uncertainties on B_{95}, which may explain the spread of the 10 layer measurements and why B_{95} for 20 SC layers is less than twice B_{95} for 10 layers.

We compared B_{shield} for a single layer of tape before and after bending the tape on a 0.5 inch tube to check for possible effects of tape damage caused by bending. We did not observe any change in the shielding performance of the tape.

3.2 Tape Wrapping Options For SC Cylinders

We measured the magnetic field shielding of superconductor cylinders made from superconductor tape wrapped around a copper tube with 1-1/8 inch outer diameter. We compared the two wrapping styles: 'vertical' and 'helix' (see Fig. 4(a)). Figure 4(b) shows the field from a pair of Helmholtz coils (set to 2 mT) measured along the center axis of cylinders made from one and two layers of superconductor tape for both wrapping styles. The second layers were aligned to cover the gaps in the first layers. For one layer, a significant fraction of the field leaks through the gaps. For two layers, the field leaking through the 'helix' style cylinder is significantly smaller than for the 'vertical' style cylinder. We therefore use the 'helix' style for subsequent tests.

In the previous report, we noted that the 'vertical' wrapping performed



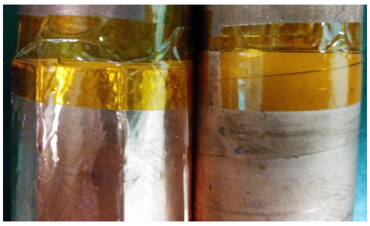
(a) (b)

Figure 3: (a) Shielded field B_{shield} as a function of external field B_0 for up to 20 layers of superconductor tape. The dashed line illustrates $B_{shield} = B_0$. (b) Maximum field B_{95} for which we measured 95% shielding as a function of the number of superconductor layers.

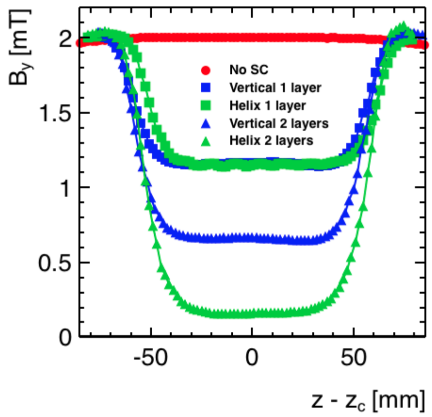
better than the 'helix' for cylinders of 0.5 inch diameters[1]. We attribute the worse performance of the 'vertical' wrapping on larger diameter cylinders to the increased number strips (and therefore gaps) required to cover the full surface.

The superconductor tape we used has a layered structure: A copper stabilizer (65 μm), a substrate (50 μm), the actual superconductor (1 μm), and another copper stabilizer (65 μm). Figure 5(a) illustrates two ways to orient the tape in subsequent layers, 'separate' and 'adjacent', which affects the effective distance between the actual superconductor layers. Fig. 5(b) shows that cylinders made from two and four layers in the 'adjacent' orientation shield slightly more field than the corresponding 'separate' orientation cylinders. We will test superconductor tape without the copper stabilizer to see if further reducing the gap between the superconductor in subsequent layers improves the cylinder performance.

For the large prototype described in Sec. 3.3, we used five layers of superconductor tape wrapped around a 1 inch diameter copper cylinder ('adjacent' 'helix' style). We built a 12 cm long test cylinder of the same style to get an estimate of the performance of the large prototype. Figure 6(a) presents the shielded field in the center of this cylinder as a function of the external field in a pair of Helmholtz coils. The figure also includes the shielding of a single layer of superconductor tape from Fig. 3(a). Apparently the shielding



(a)



(b)

Figure 4: (a) Superconductor tape wrapping styles 'vertical' and 'helix'. (b) Magnetic field measured along the center axis of 'vertical' and 'helix' style cylinders in a pair of Helmholtz coils.

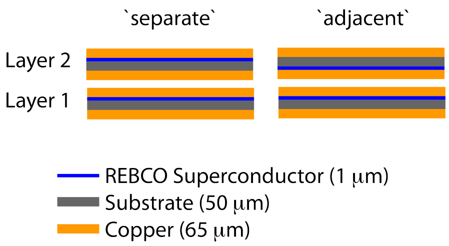
performance of a cylinder made from our superconductor tape is much worse than the shielding performance of the tape itself. We will investigate the origin of this leakage by mapping the field leaking into the cylinder at higher external field strengths and covering one end of the cylinder with additional superconductor. Figure 6(b) shows the field along the center axis of the 5 layer cylinder inside a pair of Helmholtz coils at 2 mT and 9.5 mT.

3.3 Large Prototype Tests

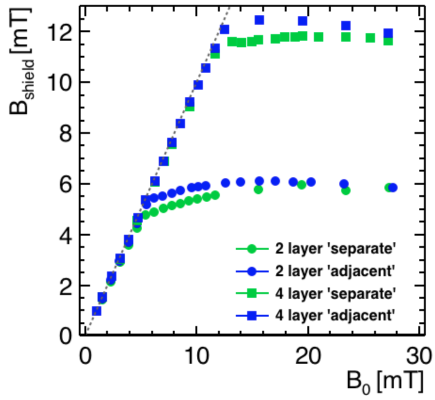
We assembled a test stand to commission the large prototype (for demonstrating the shielding of a charged particle beam from a magnetic field in the Van de Graaff accelerator) before installing it in the actual beam line. The test stand consists of a 2 m section of 4 inch beam pipe connected to a roughing pump and turbo pump, vacuum gauges, liquid Nitrogen feedthroughs, and electrical feedthroughs for temperature sensors and a Hall sensor (See Fig. 7(a)).

We wrapped five layers of superconductor tape covering a length of 1.3 m around a re-designed cryostat (see Fig. 7(c)). The new cryostat is a 1 inch diameter liquid Nitrogen reservoir made from two connected copper tubes (see Fig. 7(b)). The center is hollow and allows a beam to pass through. The cryostat has two 1/4 inch tube connections on both ends with a distance of 1.3 m.

To ensure a steady flow of liquid Nitrogen in the cryostat, we connected

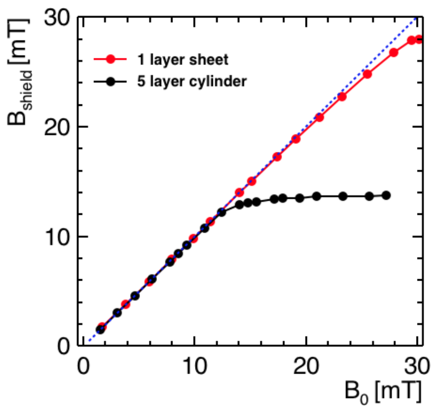


(a)

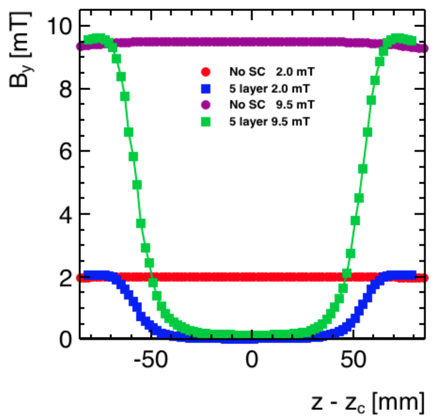


(b)

Figure 5: (a) Layered structure of superconductor tape and ’separate’ and ’adjacent’ orientation for subsequent layers of tape. (b) Shielded field as a function of external field in the center of the cylinder for two and four layers of ’helix’ wrapping with ’separate’ and ’adjacent’ orientation.

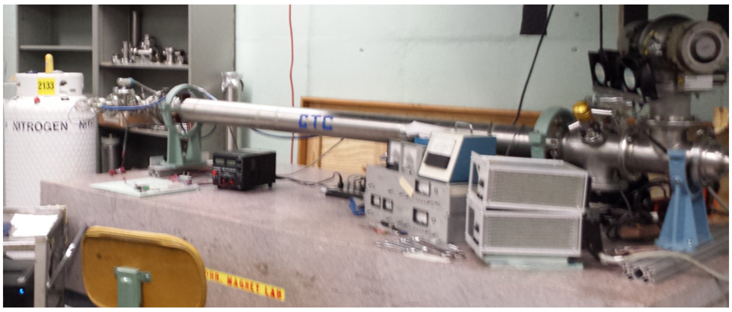


(a)

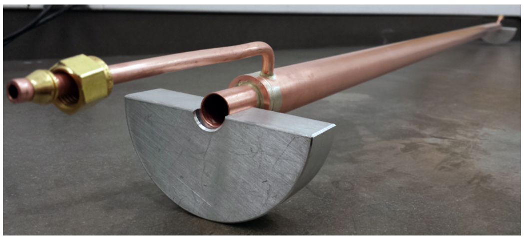


(b)

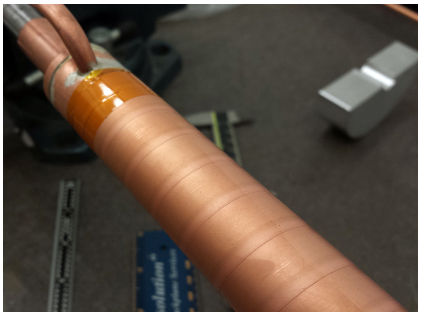
Figure 6: Superconductor cylinder made from five layers of ’adjacent’ ’helix’ style wrapped superconductor tape: (a) Shielded field as a function of external field in the center of the 5-layer cylinder and for a single flat layer of the tape. (b) Magnetic field measured along the center axis of the cylider in a pair of Helmholtz coils at 2 mT and 9.5 mT.



(a)



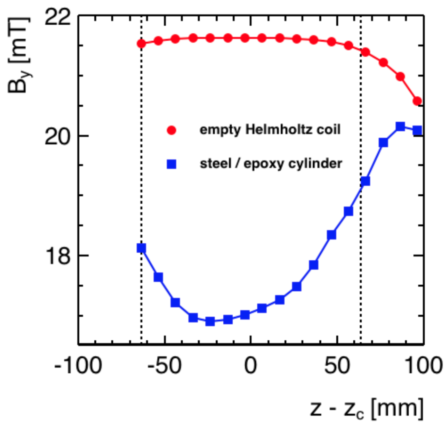
(b)



(c)

Figure 7: (a) The stand-alone test chamber for the large cloak prototype for the van de Graaf accelerator tests. (b) The new cryostat for the large prototype. The inside tube has an inner diameter of 0.561 inch, the outer tube has an outer diameter of 1 inch. (c) Superconductor tape wrapped in a helix around the cryostat.

(a)



(b)

Figure 8: (a) A ferromagnetic cylinder made from an epoxy and steel powder mixture. (b) Magnetic field measured along the center axis of a cylinder made with an epoxy / steel mixture of 50 / 50 volume fraction. The dashed lines indicate the beginning and end of the cylinder.

an open reservoir filled with liquid Nitrogen to one end of the cryostat and let the evaporating liquid Nitrogen gas flow out of the connection on the other end of the cryostat. At a a vacuum of 3e-6 Torr in the test stand and using only a single layer of aluminum foil as heat radiation shield, the outside of the cryostat (measured at the end where the liquid Nitrogen gas left the cryostat) cooled down to 79 K after 1 h and 78.4 K after 4 h. We will verify sufficient cooling of the superconductor layers before proceeding with the tests of the magnetic field shielding performance of this prototype.

3.4 Ferromagnetic Layer Options

We fabricated a ferromagnetic cylinder (inner diameter 1 1/4 inch, wall thickness 1/8 inch, length 12 cm) from epoxy and 430 stainless steel powder (see Fig. 8(a)) using a mold made from two aluminum cylinders. Varying the amount of steel in the mixture allows for tuning the effective magnetic permeability of the cylinder. Figure 8(b) shows the magnetic field of a pair of Helmholtz coils measured along the center axis of a steel / epoxy cylinder with a 50% volume fraction of stainless steel. The shift of the minimum of the measured field below the center of the cylinder indicates an inhomogeneous distribution of the steel powder. We expect to improve the homogeneity by rotating the cylinder during drying to prevent the steel powder from sinking.

Figure 9(a) presents the relative magnetic permeability of the same epoxy

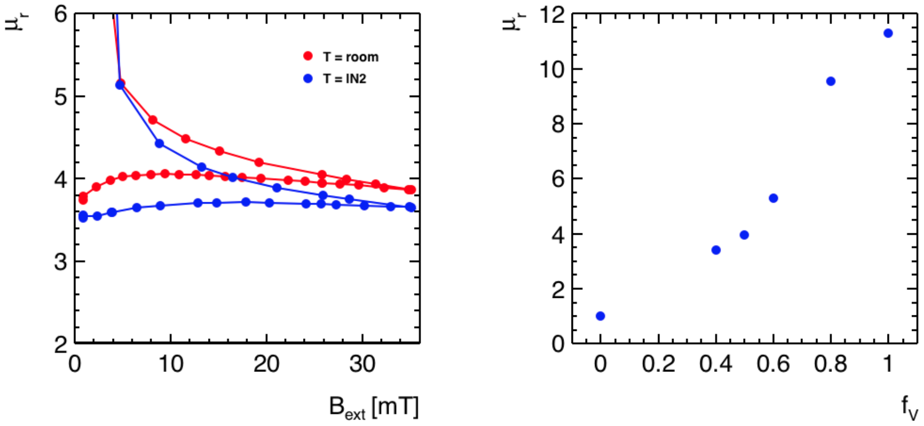


Figure 9: (a) The relative magnetic permeability of an epoxy / steel cylinder with a 50 / 50 volume fraction at room temperature and at liquid Nitrogen temperature as a function of an external field B_{ext}. (b) Relative permeability at room temperature and an external field of 25 mT for different volume fraction f_V of steel powder in a steel / filler material mixture.

/ steel cylinder as a function of external field B_{ext} at room temperature and a liquid Nitrogen temperature. The permeability is about 6% smaller at liquid Nitrogen temperature, which we will take into account for designing a magnetic field cloaking device. We plan to extend these measurements to 500 mT external field, which is the intended application range for the magnetic field cloak.

Figure 9(b) summarizes the relative magnetic permeability measured at room temperature and an external field of 25 mT for various volume fractions of stainless steel powder and filler material.

4 Future

Our next steps are to:

- continue our tests as planned, in particular to add the ferromagnetic layer made from epoxy and steel powder to the cloak prototype, investigate the origin of leakage in cylinders wrapped from superconductor tape, and test the 1.3 m prototype in the Van de Graaff beam line,
- add more layers to the Van de Graaff prototype to improve its shielding performance,

- measure the effects of radiation on the superconductor tape performance,
- measure the field around a magnetic field cloak prototype at 500 mT using the CDS magnet commissioned at MIT/Bates,
- collaborate with BNL SMD to test our tape at liquid Helium temperature and also test low-temperature superconductor sheets,
- explore possible collaboration with BNL CAD for beam line integration of a magnetic cloak prototype.

5 Preliminary Budget Estimate for FY 2016

For FY 2016, we currently plan to request a total budget of $95,000: We expect the costs of initial tests at BNL using low-temperature superconductor sheets to be $15,000 for procuring superconductor sheets (niobium-titanium, 130 mm (W) x 2000 mm (L) x 0.2 mm (T), $5000 each) and liquid Helium supplies. In addition, we plan to request $80,000 for the salaries of a graduate student (one year) and a post-doc (three months).

References

[1] EIC R&D Project eRD2, *Progress Report RD2013-2: A Compact Magnetic Field Cloaking Device*. Reporting Period: July 2014 to December 2014.