EIC R&D Progress Report and Proposal

Reporting Period: **January 2015** to **June 2015**

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eRD2: A Compact Magnetic Field Cloaking Device

A. Adhyatman[‡], G. Arrowsmith-Kron[‡], K. Boyle[†], R. Bruce[‡], K. Capobianco-Hogan[‡], R. Cervantes[‡], J. Chang[‡], B. Coe[‡], K. Dehmelt[‡], A. Deshpande[‡*], N. Feege[‡*], Y. Goto[§], R. Gupta[¶], S. Jeffas[‡], T. K. Hemmick[‡], P. Karpov[‡], Y. Ko[‡], T. Krahulik[‡], J. LaBounty[‡], T. LaByer[‡], R. Lefferts[‡], A. Lipski[‡], R. Losacco[‡], S. Mahmud[‡], E. Michael[‡], I. Nakagawa[§], J. Nam[‡], A. Oliveira[‡], B. Parker[¶], V. Ptitsyn[¶], A. Quadri[‡], J. Seele[†], K. Sharma[‡], A. Tishelman-Charny[‡], I. Yoon[‖]

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[*]Project Leaders and Contact Persons
E-mail: Abhay.Deshpande@stonybrook.edu, Nils.Feege@stonybrook.edu

[†]RIKEN BNL Research Center
[‡]Stony Brook University, SUNY
[§]RIKEN
[¶]Brookhaven National Laboratory
[‖]Seoul National University

1 Objectives

We planned to continue the realization and testing of a magnetic field cloaking device with dimensions close to those we expect for an experiment like an EIC detector. Such a device would have to shield a 1 m long cylinder with 2 cm inner diameter from a 500 mT transverse magnetic field. Our objectives included extending our test set-ups, evaluating materials for the prototype construction, and building and testing prototypes.

2 Timeline

Figure 1 shows the timeline for this project as it was laid out in the previous report (blue) and our overall progress (green). This report presents updated results from testing high-temperature superconductor tape. We have placed samples of our superconductor tape in the PHENIX IR to expose it to radiation and will measure its properties after the end of the current RHIC run. This report also covers a more optimized approach to fabricate ferromagnetic cylinders from epoxy and steel powder.

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) is delayed further because of ongoing repair work on the accelerator's ion source. We still expect the beam line to become available again later this year.

In the second half of this year, we plan to start superconductor tests with liquid Helium cooling at the BNL Superconducting Magnet Division. In addition, we will assemble a new magnetic cloak prototype, combining our results from the superconductor and ferromagnetic cylinder tests.

3 Achievements

With 15 Stony Brook undergraduate students and one MSI student we have made continuous progress towards accomplishing our objectives. We successfully:

1. Demonstrated the shielding of 40 mT with cylinders made from high-temperature superconductor tape at liquid Nitrogen temperatures.

2. Established an extrapolation method to predict the shielding performance of multiple layers of high-temperature superconductor tape up to fields of 0.5 T.

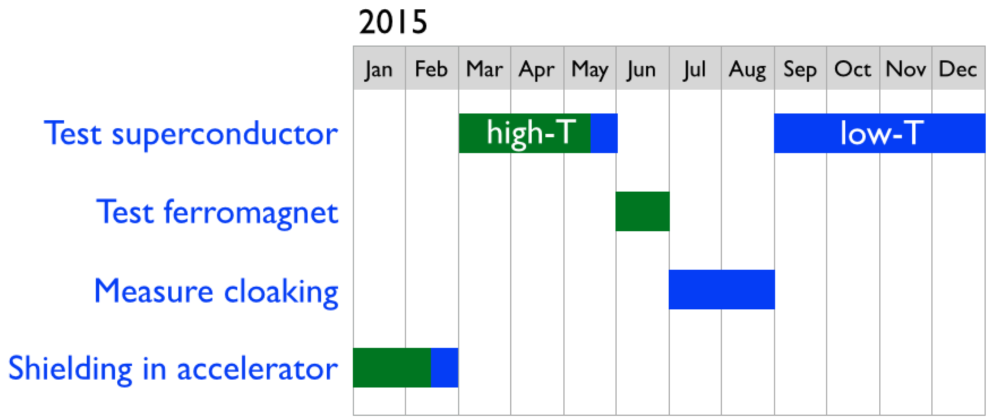


Figure 1: Project timeline.

3. Refined our procedure to manufacture the ferromagnet layer of a magnetic cloak with tunable magnetic permeability.

4. Measured the magnetic field shielding performance of our 1.3 m long prototype (designed for test inside the Van de Graaff accelerator at Stony Brook) inside a beam pipe.

3.1 Magnetic Field Shielding Performance of High-temperature Superconductor

In our previous report, we showed that the 12 mm wide superconductor tape is not a viable option to create cylinders to shield transverse magnetic fields: 5 layers of helically wound tape (figure: 2a) only shield 12 mT, which leads to an unwieldily large number of layers required to shield 0.5 T. Thus, we are exploring three other options

1. Low-temperature superconductor with Niobium-Titanium: NbTi/Nb/Cu sheets have been demonstrated to shield magnetic fields of 1 T and above. However, NbTi has critical temperature of $\approx$ 9K, and therefore requires liquid helium cooling. We do not have the required infrastructure at Stony Brook, so we need to cooperate with BNL's Superconducting Magnet Division to use this material. Another caveat is that these sheets are also no longer being produced and only a few remaining sheets are available from the supplier.

2. Medium-temperature superconductor with Magnesium Bromide: A recent paper showed that 10 cm MgB_2 tube can shield up to 2 T at a

temperature of 4.2 K [2]. Because the critical temperature of this material is 39 K, the requirements to the cryogenic cooling system are less stringent than for NbTi. To obtain cylinders made from this superconductor, we would have to sinter it in-house. Obtaining the raw materials and sintering a 10 cm prototype is feasible. However, we do not have a furnace long enough to produce a 0.5 m prototype.

3. Wider high-temperature superconductor tape: We obtained a sample of 46 mm wide superconductor tape from American Superconductors. This width is not commercially available at the moment- it is an intermediate state of the tape on their production line. This tape allows us to wrap two half-tubes around a 1 inch core. This configuration allows the supercurrents to act like a cos-theta magnet and is therefore very effective for shielding transverse magnetic fields. Also, forming a long superconducting cylinder using shells from 46 mm wide tape is far easier to do and less error prone than wrapping 12 mm tape helixes. However, this configuration limits the maximum diameter of the cylinder that two strips of this tape can cover.

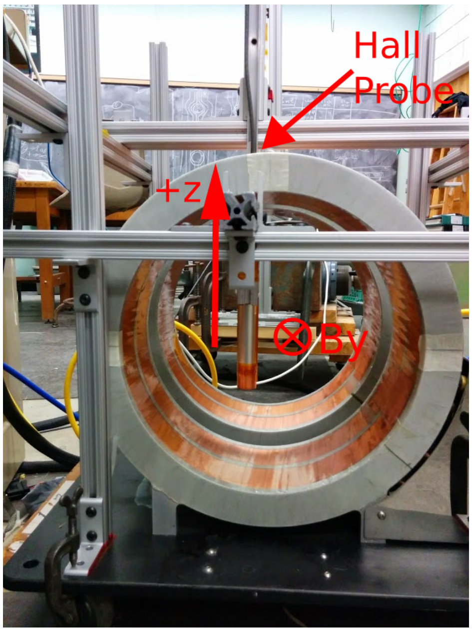
We compared the shielding performance of 46 mm wide tape from American Superconductors to that of 12 mm wide tape from Superpower. We wrapped the superconducting tape around a 1 inch copper core to make a superconducting tube (figure: 2a). For the 46 mm wide tape, we only needed to use two strips of superconductor to cover both sides of the core. We left an overlap where the two strips meet to cover any superconducting gaps. For the 12 mm tape, we could not cover half the core, so we wrapped it helically. We covered the superconducting gaps of one layer with the layer on top.

We then placed each superconducting tube in a Helmholtz coil and measured the amount of the transverse field that leaks through as a function of the applied field (figures: 2b, 2c).

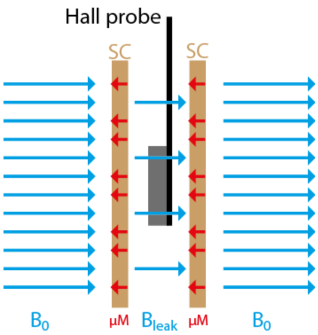
We also measured the intrinsic shielding properties of the 12 mm wide tape, without the effects of superconducting gaps. To accomplish this, we sandwiched the hall probe in between to superconducting strips to form a superconducting sheath (figure: 2d. To the hall probe, this effectively is a nearly infinite plane.

From figure: 3a, we see that 1 layer of the 46 mm wide tape performs better than 5 layers of the 12 mm wide tape at an applied magnetic field of $B_o > 15$ mT, despite the better intrinsic shielding properties of the 12 mm wide tape, as derived from the sheath geometry measurement. This suggests that the 12 mm wide tape has a higher critical current than the 46 mm wide tape. But a higher critical current is not enough to shield higher fields, we

(a) 5 layer helical wrapping using 12 mm wide Superpower tape (Ic: 368 A) and 1 layer of 46 mm wide tape from American Superconductors tape (Unknown Ic).



(b) Experimental setup for measuring magnetic shielding performance. We place the superconducting tube inside of a Helmholtz coil and submerge it in a liquid nitrogen bath (not shown).

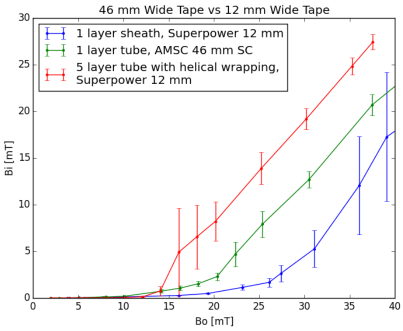


(c) We measure the field leakage with varying external fields and z position.

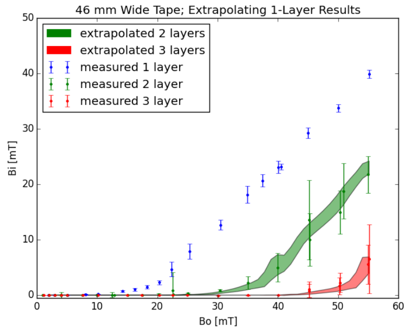
(d) We test the shielding properties of 12 mm tape by placing the hall sensor in between two strips.

(e) Sheath setup to measure magnetic shielding up to 0.5 T with dipole magnet

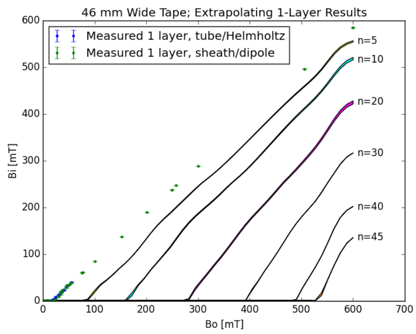
Figure 2



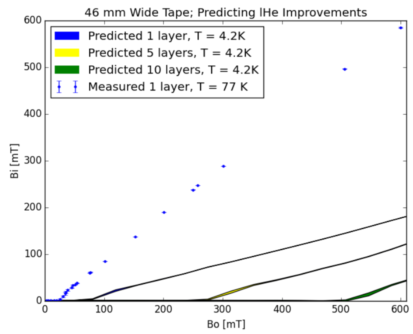
(a) The wide tape is intrinsically better at shielding a 1in diameter tube than the 12 mm tape, despite the 12 mm tape being of superior quality.



(b) From 1 layer shielding measurements, we are able to predict the shielding measurements of an arbitrary number of layers.



(c) Shielding measurements with 1 layer sheath in dipole magnet.



(d) Predicted shielding improvements by using liquid He temperatures.

Figure 3

must also allow the supercurrents to flow in a path that allows for shielding of the applied field. Thus, the 46 mm wide tape performs better due to its geometry rather than its critical current.

From the 1 layer measurement, we extrapolate the shielding capabilities of an arbitrary number of layers, up to the maximum field measured by the first layer. We perform this extrapolation by stating that the applied field on the 2nd layer is the leaked field from the 1st layer. We can iterate this procedure to obtain the shielding performance of an arbitrary number of layers. Figure 3b shows that our measurements are in great agreement with the extrapolated predictions.

The Helmholtz coil can only reach about 55 mT, so we use a dipole magnet to characterize the superconductor at higher fields. The dipole magnet is not ideal due to its inhomogeneity, but is good enough to characterize 1 layer.

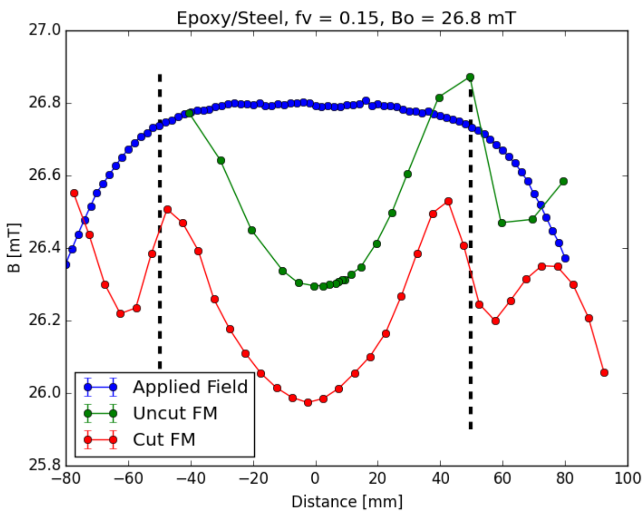
We measure the shielding of 1 layer, and extrapolate to an arbitrary number of layers. We see from figure 3c that we can shield 0.5 T with about 40 layers of superconductor. While this number seems high, it's comparable to the number of layers in a commercial NbTi sheet [1].

We can reduce the number of layers needed by going to liquid Helium temperatures. We estimate that a temperature of 4.2 K allows us to shield 0.5 T with only 10 layers, as shown in figure 3d. This estimate assumes that the shielding performance scales with the increase in critical field at lower temperatures, such that $B_i(B_o, T = 4.2K) = B_i(\frac{B_c(T=77K)}{B_c(T=4.2K)} \times B_o, T = 77K)$. We would have to do a measurement to confirm this prediction.

We are excited to demonstrate the feasibility of shielding a 0.5 T magnetic field with high temperature superconductors. Such a feat is unprecedented to our knowledge, especially at liquid Nitrogen temperatures.

3.2 Ferromagnet Progress

(a)



(b)

Figure 4: Having maximum ferromagnetic shielding in the middle of the steel/epoxy mixture, i.e., reaching a minimum field near z = 0 mm, demonstrates the uniformity of the steel powder in the epoxy. Having maximum shielding near z = 0 mm even after cutting the ferromagnet in half demonstrates that we can stitch two ferromagnetic tubes to make a longer tube.

Our strategy for fine tuning the permeability to achieve cloaking is to mix ferromagnetic and non-ferromagnetic material to dilute the permeability in a precise manner. We opted to mix ferretic powder (430 stainless steel from Alfa Aesar) with a non-magnetic polymer (commercial epoxy). To produce these ferretic tubes, we mix the epoxy resin/hardener with the stainless steel powder and pour it into a tubular mold. The end result can be seen in figure 4a.

The differing densities of stainless steel and epoxy initially created a problem. Because stainless steel is much denser than epoxy, the stainless steel wanted to settle towards the bottom during the curing process. This created a gradient of fractional volume of epoxy along the length, leading to a permeability gradient. To remove such gradients, we rotated the epoxy constantly (by hand) while it was curing. We also replaced the slow hardener (pot life = 25 min) with fast hardener (pot life = 12 min). Figure 4b shows that we are able to achieve a uniform powder distribution for a steel/epoxy mixture with steel fractional volume of 15 percent.

We also considered whether or not our method could scale up to develop 1 m a prototype. It would be impractical to pour epoxy into a 1 m mold, so we considered whether or not we can stitch together smaller tubes and achieve the same magnetic properties. We tested this stitching method by cutting the ferretic epoxy tube in half and measuring its shielding profile after putting the two pieces back together. Figure 4b shows that making this cut made no difference in the position in the shielding profile's minimum. The offset between the cut and uncut profiles likely results from hysteresis. Regardless, the fact that the profile shape doesn't change shows that we can scale the length merely by stitching smaller tubes together.

Our next step is to characterize these ferromagnetic cylinders at high fields, up to 0.5 T, so we can tune the ferromagnet's permeability to achieve cloaking at such high fields. We do not have a suitable magnet at Stony Brook and plan to collaborate with the Superconducting Magnet Division at BNL to get access to one.

3.3 Prototype for Test in Van de Graaff Accelerator

We extended our table-top test setup (presented in the previous report) for the 1.3 m superconductor shield prototype by adding five dipole magnets in series (Fig. 5). We attached a Hall sensor to a 6 foot aluminum rod. The end of the rod exits the beam pipe section through a feedthrough, so that we can move the Hall probe while the beam tube remains evacuated. This setup allows us to characterize the magnetic field shielding of this prototype along its length.

Figure 6 shows a measurement of the magnetic field shielding performance of this prototype. The prototype shields the applied external field of 5 mT to

Figure 5: Five dipole magnet extend our cryostat test setup (presented in the last report).

7 mT over 40 cm of the measured length, while the other section shows is a significant leakage of magnetic field though the superconductor. We are still investigating the source of this leakage. Possible reasons are a temperature gradient along the cryostat which brings the right end of the superconductor closer to the critical temperature then the left end, or gaps in the helix wrapping of the superconductor tape layers.

4 Future

Our next steps are to:

1. shield fields up to 100 mT using commercially available high-temperature superconductor tape (at liquid Nitrogen temperature) and publish results,

2. measure the properties of our superconductor tape after several weeks of exposure to radiation in PHENIX IR,

3. run a charged proton beam (Van de Graaf beam line at Stony Brook) through our 1.3 m prototype and demonstrate shielding of the beam from external fields,

4. collaborate with BNL SMD to test our tape at liquid Helium temperature and also test low-temperature superconductor sheets (demonstrating shielding up to 0.5 T),

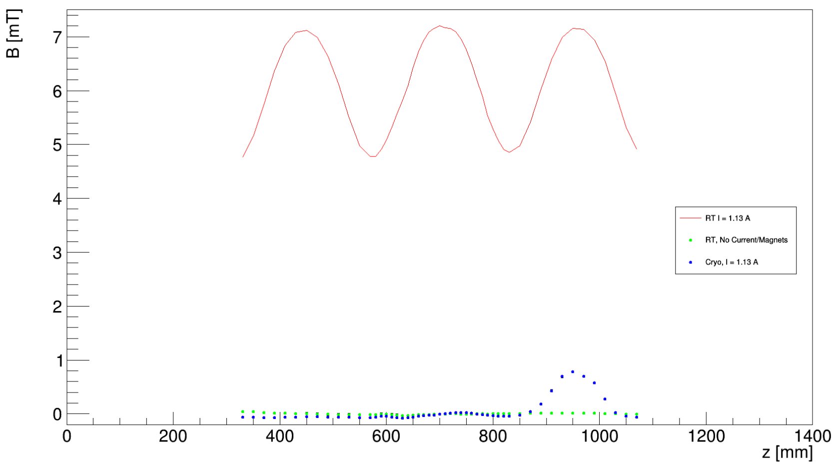


Figure 6: Measurement of the magnetic field B transverse to the center axis of our long prototype inside the beam pipe segment as a function of the position z along this axis. The red line shows the magnetic field of the five magnets at the chosen operating current (no superconductor shielding, room temperature). The green markers show the measurement of the magnetic field along the same line at room temperature when no external magnetic field is applied. The blue markers represent the measurement of the magnetic field after cooling the superconductor shield to liquid Nitrogen temperatures and switching on all five dipole magnets.

5. measure the relation between the magnetic permeability of epoxy / steel powder ferromagnetic cylinders and the fractional volume of the stainless steel powder in the mixture,
6. characterize our ferromagnetic cylinders at magnetic fields up to 0.5 T,
7. demonstrate magnetic field cloaking with our cylinder (superconductor and ferromagnet combined) up to 50 mT and publish results,
8. explore possible collaboration with BNL CAD for beam line integration of a magnetic cloak prototype.

Table 1: Budget request FY 2016

Item	**Cost [$]**
Salaries and Benefits	
Post-doc (100% for 3 months)	12,500
+ Benefits	5,438
Graduate Student (100% for 12 months)	25,000
+ Benefits	3,500
+ Tuition	4,188
3 Undergraduate students (8 weeks during summer)	4,800
+ Benefits	240
Travel	
Domestic, Conferences	3,000
Supplies and Equipment	
Liquid Helium, Liquid Nitrogen	5,000
Superconductor Materials	9,000
Other	
BNL SMD (expert advice, magnets, infrastructure)	10,000
Total Direct Cost	82,700
Total Indirect Cost (Overhead)	40,300
Total Request	**123,000**

5 Budget Request for FY 2016

Table 1 summarizes our budget request for FY 2016. This project is primarily carried out by students and provides an excellent opportunity for them to collect laboratory experience. Therefore, we ask for the salary for one graduate student for one year and for three undergraduate students for eight weeks during summer. We would also like to use travel funds to allow these students to present their research at domestic conferences. In addition, we are asking for a quarter of an annual post-doc salary.

To continue our measurements with liquid Nitrogen and to extend them to liquid Helium temperatures, we need $5,000 to procure supplies of both liquids. The measurements with liquid Helium also require close cooperation with the BNL magnet division to benefit from their expert advice and infrastructure, for which we are requesting $10,000 for initial tests and measurements. In addition, we are asking for funds to procure additional superconductor materials.

References

[1] I. Itoh, T. Sasaki, S. Minamino, and T. Shimizu. Magnetic shielding properties of nbti/nb/cu multilayer composite tubes. *Applied Superconductivity, IEEE Transactions on*, 3, March 1993.

[2] J.J. Rabbers, M.P. Oomen, G. Riparmonti, and G. Giunchi. Magnetic shielding capability of mgb2 cylinders. *Superconductor Science and Technology*, 23, Dec 2010.