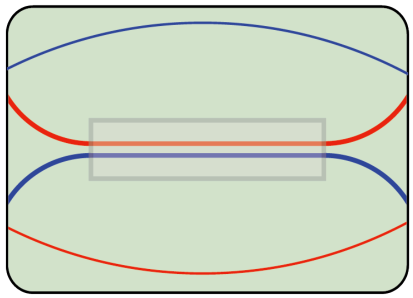

A Compact Magnetic Field Cloaking Device

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Objective: To develop a magnetic field cloaking device which allows to use a forward dipole magnet analyzer at an EIC Detector

Magnetic fields are an integral part of particle accelerators and storage rings. They also play a key role in measuring the momenta of charged particles at experiments. For most experiments, it is desirable to shield the primary beam from magnetic fields to avoid deflecting the beam or affecting its polarization if it is polarized. Two methods have been traditionally used: 1) adding a compensating magnetic field as was tried at HERA [1], [2] and 2) devising clever magnetic flux shielding devices using superconductors [3]. The design and operation of compensator magnets requires a precise matching of the magnetic fields and can therefore be very tricky. A recent example of superconducting shields in an accelerator experiment was the BNL muon g-2 experiment [4], which is now being moved to FNAL. In such experiments, superconducting tubes shield the primary beams from outside magnetic fields because magnetic fields cannot penetrate an ideal superconductor and the fields are effectively bent around the tubes. However, this bending is a strong distortion of the field itself. What if the outside magnetic field needs to be unaffected as well, so that it could be used for momentum analysis as part of a spectrometer system?

We propose a magnetic field cloaking device for accelerator-based experiments to be used in a forward spectrometer for an experiment at the future Electron Ion Collider EIC. A magnetic cloak is a device that creates a field-free region inside a magnetic field without disturbing the field around it. The idea is universal enough that if it succeeds, it may have potential applications in all future high energy physics experiments (collider or fixed target) and also in the muon g-2 experiment at FNAL.

Fig. 1 sketches a possible layout of an EIC experiment. Such an experiment would benefit from measuring the momenta of charged particles very close to the beam pipe, i.e. up to pseudorapidities η[4] of $\eta = 5$. These particles (especially those going in the hadron direction) have a large momentum component along the beam axis and only a small transverse momentum

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[4] $\eta = -\ln(\tan\theta/2)$; θ is the angle between the momentum of a particle and the beam axis

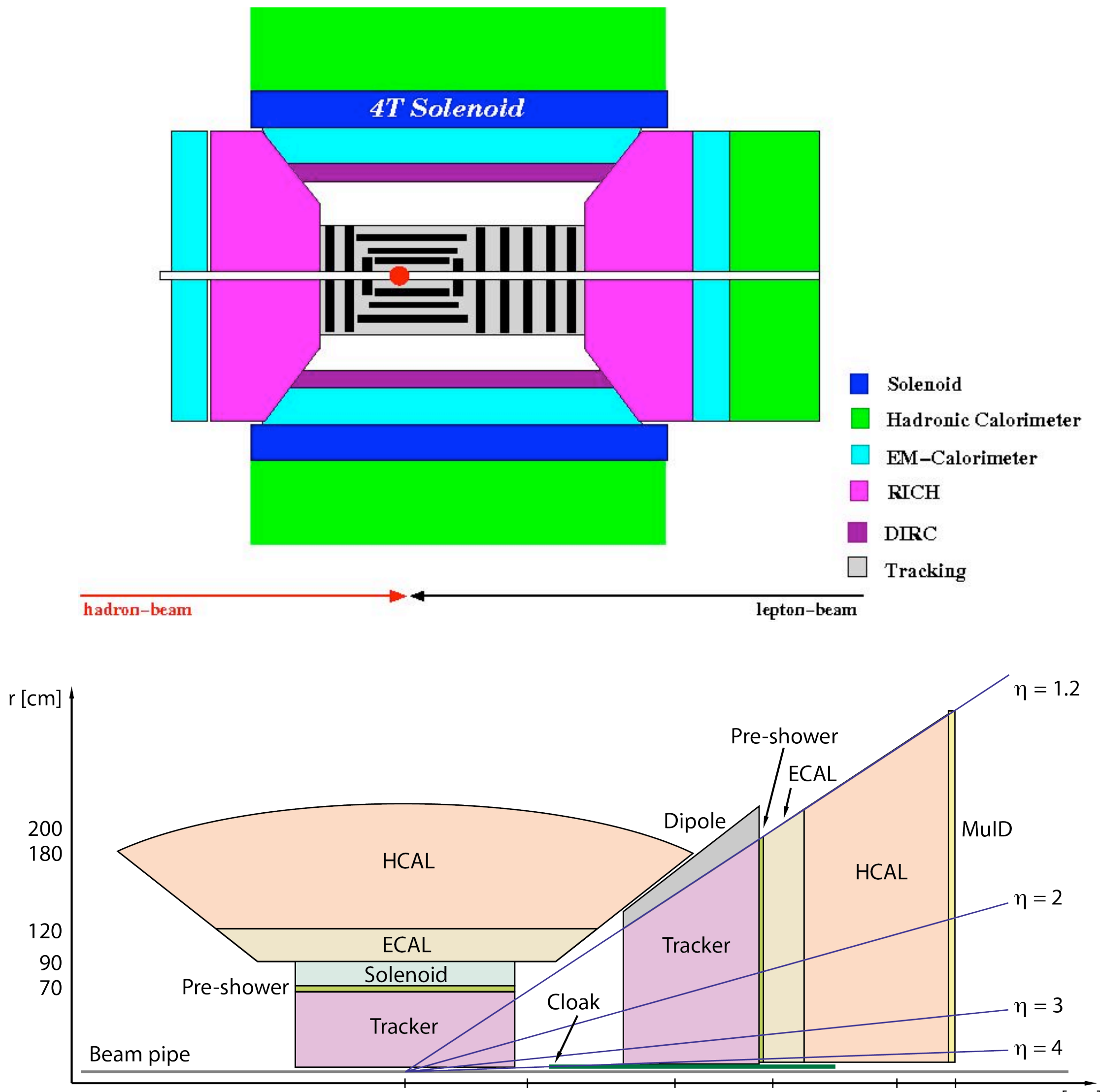

Figure 1: Two possible designs for an EIC detector with the capability to measure the momenta of charged particles close to the beam pipe (high η). Top: An EIC dedicated detector [5]. Bottom: A design for an upgrade of the PHENIX detector to ePHENIX which includes a dipole field in the forward direction and a magnetic cloak to shield the primary beams from this field without distorting the field itself.

component. All current designs use either the fringe field of the central solenoidal magnet or complicated toroidal geometries of magnetic fields as currently used in PHENIX. However, a magnetic field orthogonal to the beam axis (e.g. a dipole field) is best suited to bend these particles and measure their momenta. A magnetic cloak in this region would allow such a field design. A dipole field of B = 1 T over a length of L = 1 m combined with three position measurements (one before the field, one in the center, and one after) with σ_x = 60 μm precision would yield a momentum resolution[5] of $\delta p/p = 0.2\% \cdot p$ (not taking into account multiple scattering effects), which is more than sufficient for an EIC detector in this pseudorapidity range [5]-[7].

Our magnetic cloak would create a field-free tunnel for the primary electron and proton beams through such a dipole field while minimizing the disturbance of the field outside it (and therefore facilitating the momentum measurement with this field). This device could be realized in form of a thin layer of material around the beam pipe or be inside the beam pipe. In an extremely ambitious design the device could even become the beam pipe itself. The small radius of either of these options allows experimenters to maximize the pseudorapidity coverage for charged particle momentum measurements.

Basis: Experimental realization of a magnetic cloak

A recent article in Science presents the successful experimental realization of a dual-layer cylindric cloak for magnetic fields [8]. Such a device creates a field-free region inside and no interferences outside a cylindrical volume, which is exactly the field configuration we want to achieve. This section summarizes the basis of this experiment and its results.

Fig. 2 (top) illustrates the basic idea: A ferromagnetic cylinder placed in a magnetic field (A) pulls in fields lines and reduces the flux inside the cylinder while distorting the field homogeneity. On the other hand, a superconducting cylinder (B) creates a field-free region inside the cylinder by pushing out the magnetic field lines and distorts the field homogeneity around the cylinder in the opposite way. For ideally homogeneous magnetic fields, the combination of a superconducting inner cylinder with a ferromagnetic outer cylinder of the right radius, thickness, and permeability

5 $\delta p/p = \sqrt{3/2} \cdot \sigma_x \cdot 8/(0.3 \cdot B \cdot L^2) \cdot p$

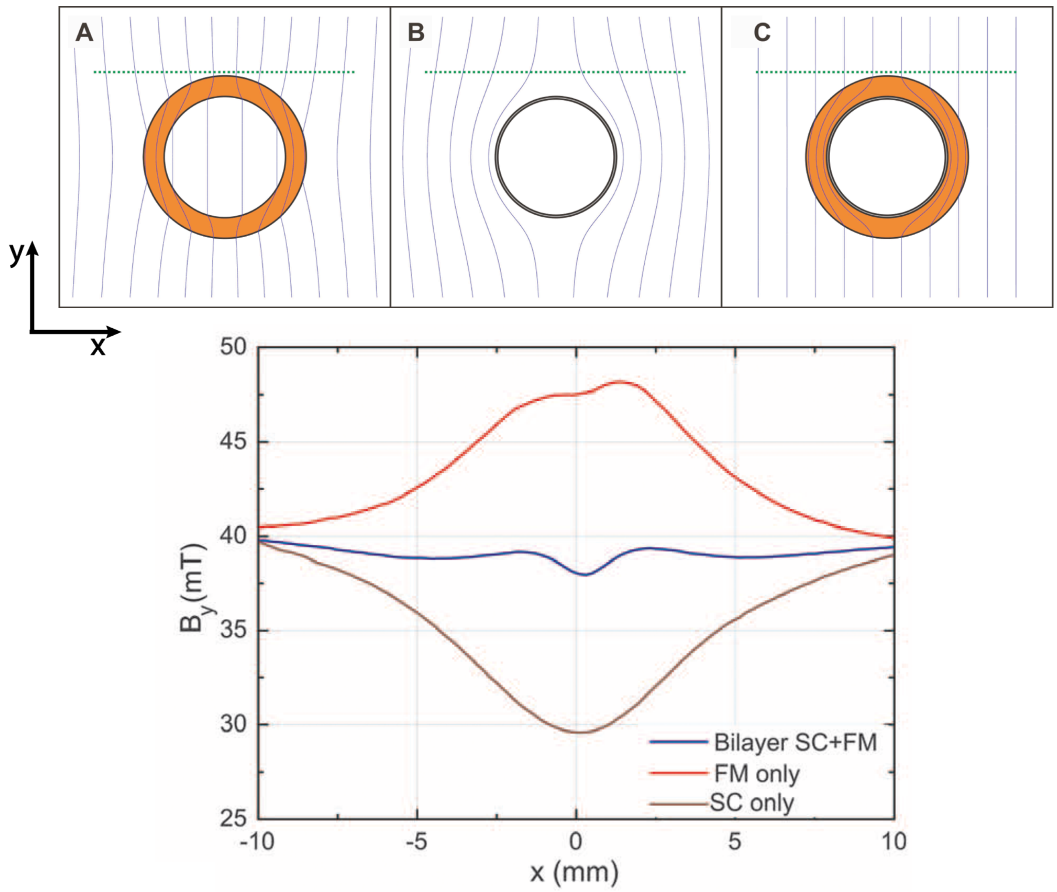

Figure 2: Top: Cross section of a ferromagnetic (A), a superconducting (B), and a combined cylinder (C) in a homogeneous magnetic field. Dotted lines denote the measuring lines in the experiment. Bottom: Component of the magnetic flux in y-direction for the three cylinders from the top figure measured along the dotted lines in a magnetic field of 40 mT. [8]

(C) creates a field-free region inside and no interferences outside the cylinders. Based on Maxwell's equations, the permeability and radii of the ferromagnetic layer have to relate according to

$$\mu_2 = \frac{R_2^2+R_1^2}{R_2^2-R_1^2} \qquad (1)$$

to achieve this perfect cloak. R_1 and R_2 are the inner and outer radius of the ferromagnetic layer and μ_2 is the magnetic permeability of this layer. The superconducting layer does not need to have a specific thickness.

The cloak described in [8] is 12 mm long and has an inner diameter of 12.5 mm and an outer diameter of 17.5 mm. It consists of multiple layers of $Fe_{18}Cr_9Ni$ alloy sheets for the outer (ferromagnetic) layer and a high-temperature superconductor (ReBCO) on the inside. Both materials are commonly available, which allows for the construction of such a device at relatively low cost end effort.

Fig. 2 (bottom) shows the result of measuring the magnetic flux along a line 3 mm above the cloak in a homogeneous magnetic field of 40 mT. The presence of the cloak practically has no effect on the field homogeneity outside, which confirms the viability of this magnetic cloak design [8].

Progress: Scaling the dimensions of a magnetic field cloak in simulations

We confirmed in simulations that a magnetic cloak (based on the idea and proof-of-principle measurement summarized in the previous section) is a viable option for effective and minimal interference magnetic shielding at experiments like an EIC forward spectrometer. Compared to the proof-of-principle measurement, such an application would require a longer cloak (2-3 m) with a larger diameter (4 cm) that is capable of shielding a stronger magnetic field (up to 1 T). In addition, this cloak would have to shield the fringe fields at the ends of a magnetic field to provide a completely field-free passage for the primary beam instead of shielding only an ideally homogeneous part of the field.

We used the COMSOL Multiphysics simulation software [9] to explore the scalability of a dual-layer magnetic cloak. We built a model of the cloak with a permeability of 10^{-25} for the superconducting layer to approximate the behavior of an ideal superconductor. Because of this approximation, our simulation does not account for effects of high magnetic field strengths on the superconductor, like the formation of vortices (which are local normal conducting areas

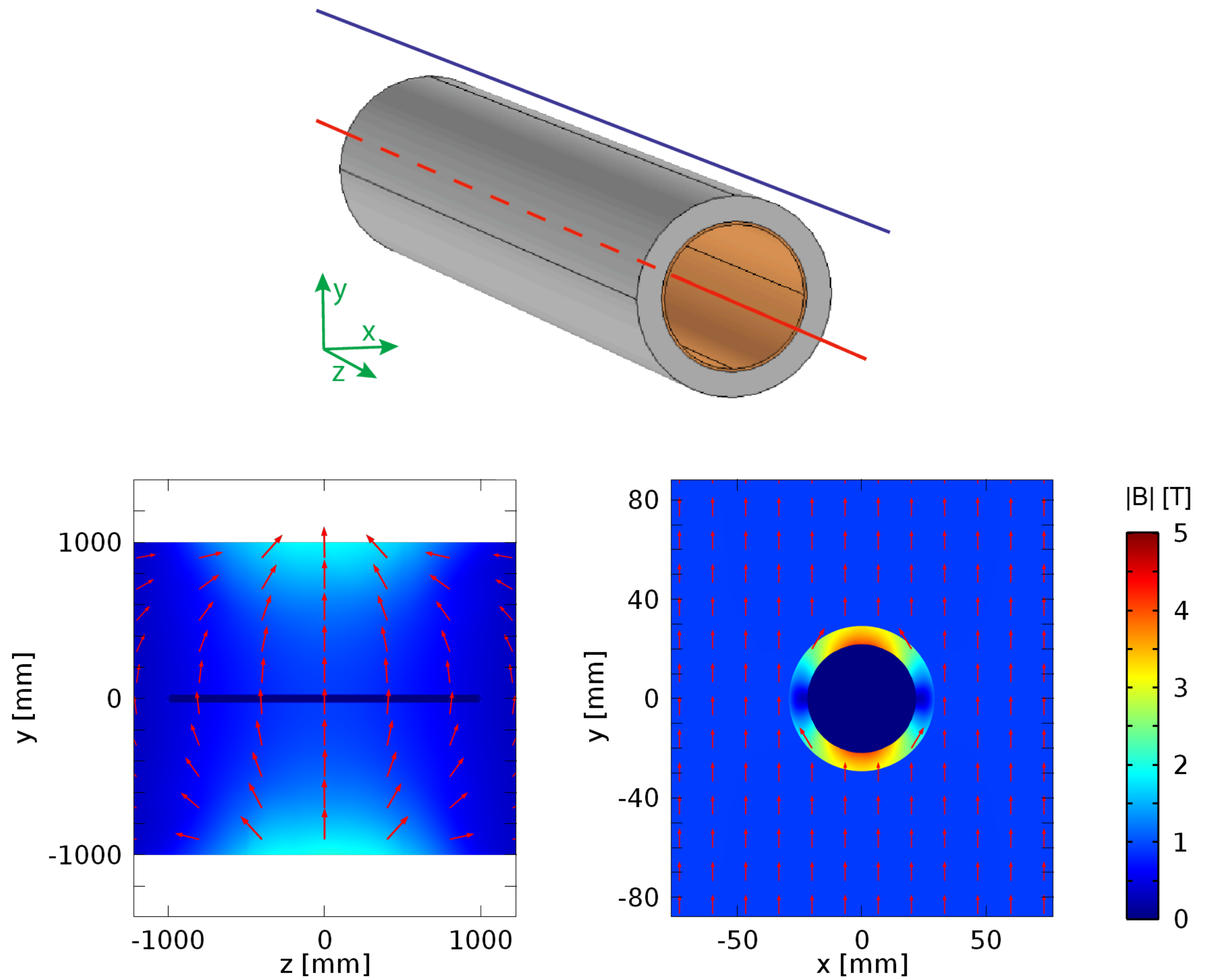

Figure 3: Top: Illustration of our magnetic field cloak in COMSOL. Measurement lines: Along the z axis inside the cloak (red) and 3 mm above the cloak (blue). Bottom: COMSOL simulation of the cloak in a dipole-like field for x = 0 (left) and z = 0 (right). The colors reflect the absolute value of the magnetic flux and the arrows indicate the direction of the magnetic flux in the plane shown. The magnetic flux inside the cloak (dark blue area) is 0 T.

allowing the field to penetrate the superconductor) or the breakdown of superconductivity. Furthermore, our simulation does not yet consider saturation effects in the ferromagnetic material at high magnetic flux densities. The results from our simulation (for the same cloak dimensions, the same permeability of the ferromagnetic layer, and an ideally homogeneous magnetic field of 40 mT) agree with the simulation and measurements from [8].

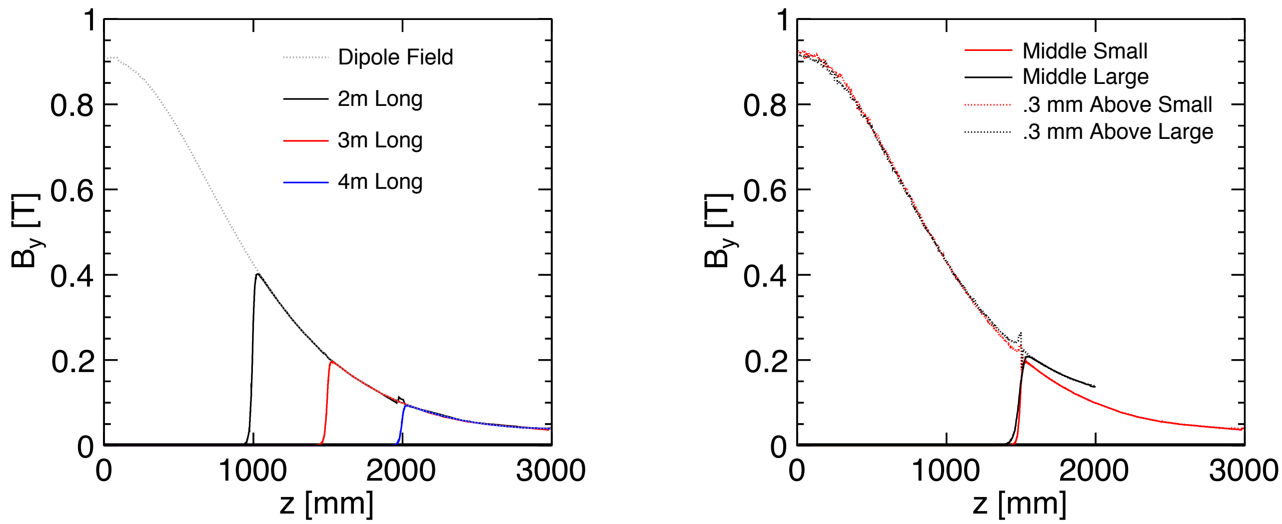

Figure 4: Left: The y-component of the magnetic flux along the z-axis without a cloak and with a cloak of three different lengths. Right: The y-component of the magnetic flux along the middle of the cloak and 3 mm above the cloak for different cloak diameters (small = 12.5 mm inner diameter, large = 42 mm inner diameter).

We created a dipole-like magnetic field in COMSOL by defining a magnetic flux of 1 T through a rectangular plane above and below the cloak. The planes are 1 m long (in z), 2 m wide (in x) and 2 m apart (in y). Fig. 3 (top) illustrates the geometry of the cloak (with its inner superconducting cylinder and its outer ferromagnetic cylinder) in our COMSOL simulation. The lines in this figure indicate the lines along which we measure the y component of the magnetic flux. The bottom part of Fig. 3 shows the absolute value and the direction of the magnetic flux from our simulation. As expected, the inner of the magnetic cloak is field free while the outside field appears undistorted.

Fig. 4 (left) shows the y-component of the magnetic field along the z axis in the center of the cloak for no cloak present and for a cloak of three different lengths. For each length, the inside of the cloak is completely field free. Outside the cloak, the fields with and without the presence of a cloak agree. On the edges of the cloak, the field quickly raises to the value outside the cloak. This transition creates small field disturbances. These disturbances become smaller if the field strength at the edge of the cloak is lower. The change of the magnetic field strength along z does not affect the cloak behavior. Therefore, if the cloak is long enough to extend beyond the end of the magnetic field, it creates the field-free tunnel for a primary beam we want to achieve.

This figure suggests that for a cloak length of 4 m a primary beam along the z axis would still see 10% of the dipole field simulated outside the cloak. This field extends far beyond the planes defining our dipole dimensions. Implementing a more realistic dipole with an iron yoke would make the field strength drop much faster beyond the end of the dipole so that the cloak length needed to get out of the field becomes shorter than in the study presented here. The effects of residual fields at the edge of the cloak could be canceled with a small compensator magnet.

Fig. 4 (right) shows the y-component of the magnetic field along the z axis in the center of the cloak (solid) and 3 mm above (dashed) for two different inner radii of the cloak and a cloak length of 3 m. The outer radius is scaled according to Eq. 1, which increases the thickness of the ferromagnetic layer. Scaling the size of the cloak does not affect its behavior. There is no magnetic field inside the cloak. Keeping the thickness of the outer layer fixed and adjusting the permeability of the outer material according to Eq. 1 would give the same result.

We also quantified that an elliptic cross section of the cloak with an eccentricity of 0.6 changes the field above the cloak by about 10%. Therefore, having a circular cross section is more desirable.

In summary, our simulations demonstrate that a magnetic cloak designed this way could create the field geometry we desire and that we can scale the dimensions of such a cloak to meet the requirements of an accelerator-based experiment like a forward spectrometer at an EIC detector.

Next Milestone: To construct and test a large magnetic cloak prototype

A small magnetic cloak has been successfully realized [8] and we have demonstrated with simulations that we can scale-up the dimensions of such a cloak to use it for a forward dipole magnet analyzer at an EIC detector. Our next goal is to construct and test a prototype of a

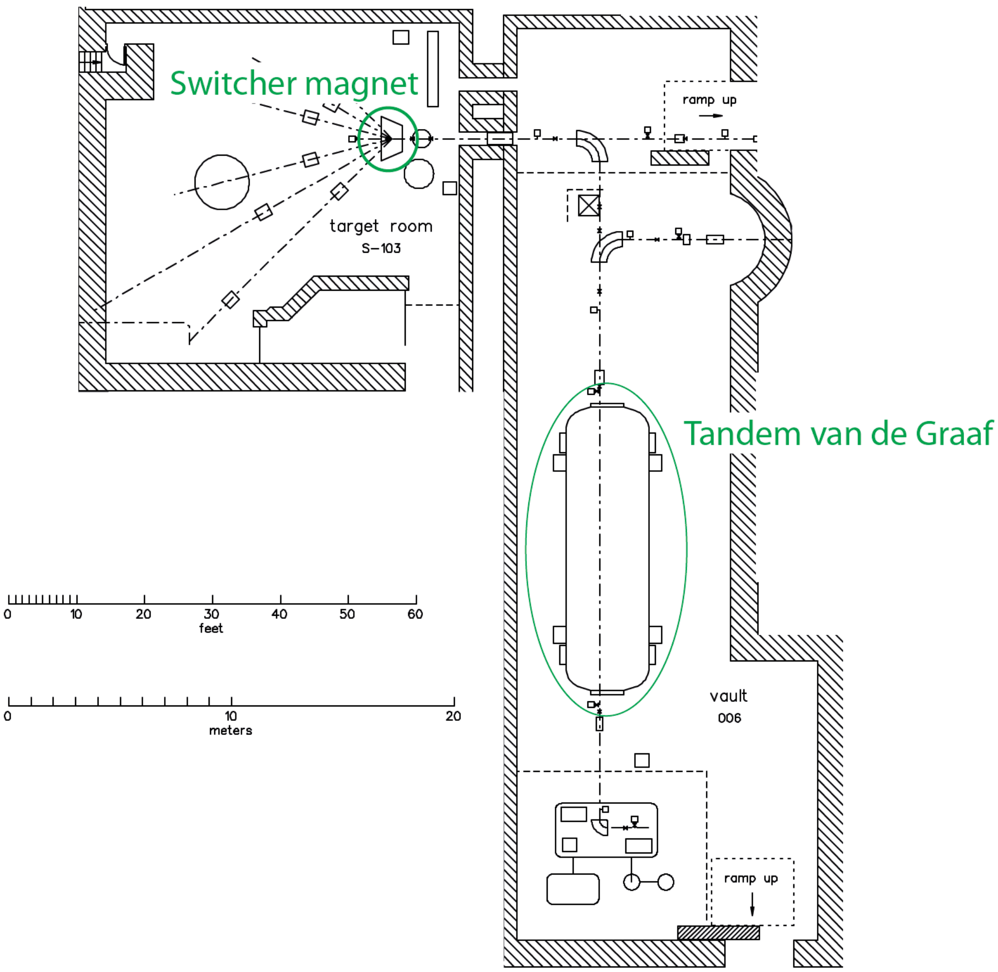

Figure 5: Schematic of the laboratory at Stony Brook University where the tandem van de Graaf accelerator resides. The switcher magnet where we plan to test the magnetic cloaking device is located at the point where the beam enters the target room.

cloaking device for this application with realistic geometries, i.e. 1-2 m length and 4 cm inner diameter.

The construction of the prototype is straight forward. All necessary materials are commonly available and the parameters are known. We need to consider the tensile strength of the cloak and the magnetic forces acting on it and will use a plastic or stainless steel tube as a core for the cloak to ensure its mechanical stability. We intend to build two versions of the cloak, one using a high-temperature superconductor (ReBCO) with liquid nitrogen cooling and one with a low-

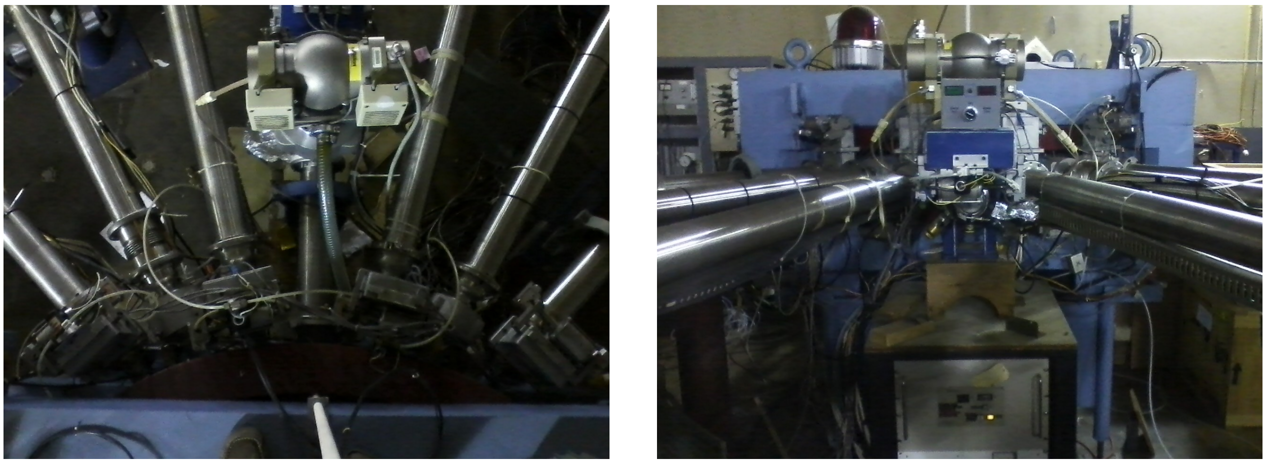

Figure 6: Photos of the switcher magnet in the tandem van de Graaf accelerator at Stony Brook where we intend to test the magnetic cloaking device. Right: The zero degree (non-bend) port of the magnet with space for the installation of the cloak.

temperature superconductor (niobium-titanium) with liquid helium cooling. This allows us to directly compare the shielding efficiency and the interference with the external magnetic field of both options.

We plan to install the prototype in a non-bend port of the switcher dipole magnet in the tandem van de Graaf accelerator in the nuclear structure laboratory at Stony Brook University. This accelerator provides carbon isotope beams in the MeV energy range. Fig. 5 illustrates the accelerator beam line and Fig. 6 shows two photographs of the switcher magnet. This magnet is a dipole of tunable strength between 0 T and about 0.5 T which usually bends the beam to different end stations. We will measure the beam position downstream the magnet for 0 T and for increasing field strength. The deflection of the beam we observe (or the absence of any bending) will be a measure of the shielding capabilities of the cloak.

In addition, we intend to place the cloak in a stand-alone solenoid magnet which is also available at Stony Brook University. Measuring the field inside and outside the cloak with Hall probes for different orientations of the cloak with respect to the field lines will give us a better understanding of the cloak behavior, the shielding and in particular the effect of the cloak on the external magnetic field.

Budget Request (Preliminary)

Table 1 summarizes our current estimate of the funds we will need to build, commission and test a magnetic field cloak with dimensions close to those proposed for a forward spectrometer for an EIC experiment. These numbers are still preliminary and may be revised soon.

We need to buy the materials for the two layers of the cloak from commercial companies providing ferromagnetic alloys and superconductors (e.g. American Superconductors). Because all required materials are commonly available, we can construct the cloak prototype at relatively low cost.

We plan to use the tandem van de Graaf accelerator, the switcher dipole magnet and a solenoid magnet at Stony Brook University for testing the cloak. This eliminates the costs of buying a magnet. However, we need funds to set up a structure to hold the cloak inside the switcher magnet and to provide a cooling system for the superconductor. The commissioning and operation of the solenoid requires additional funds. In addition, we need to buy measurement devices for the evaluation of the cloak performance.

We plan to hire a student to help building the prototype, setting up the experiment and conducting the measurements.

We expect RIKEN to provide funds ($15,000) towards the low-temperature superconductor and infrastructure.

Item	Cost estimate [$]
Superconducting layers (high- and low- temperature superconductor)	10,000
Superconductor cooling (liquid nitrogen and helium)	10,000
Ferromagnetic layer	5,000
Test set-up, including machine shop (cloak support, hall probes, beam position monitor, temperature probes)	15,000
Solenoid magnet commissioning and operation	10,000
Student salary (2 UG summer salaries)	11,000
RIKEN contribution	-15,000
Total	46,000
Overhead (57%)	26,220
Total Budget Request	**72,220**

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