SHIELDING CHARGED PARTICLE BEAMS

- Klaus Dehmelt

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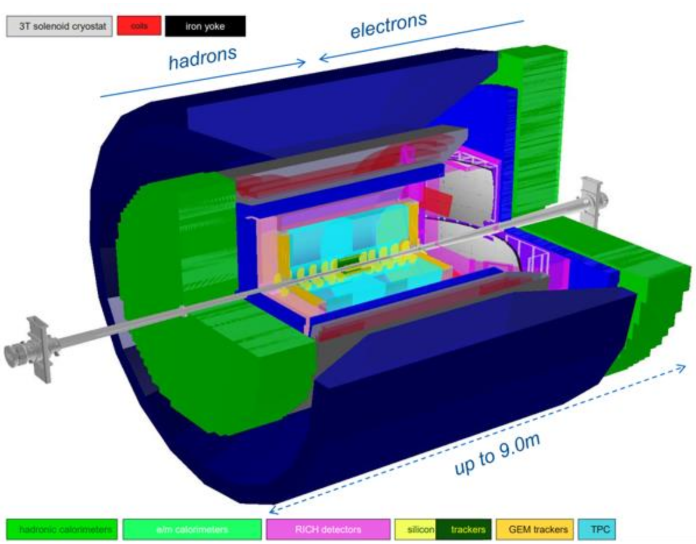
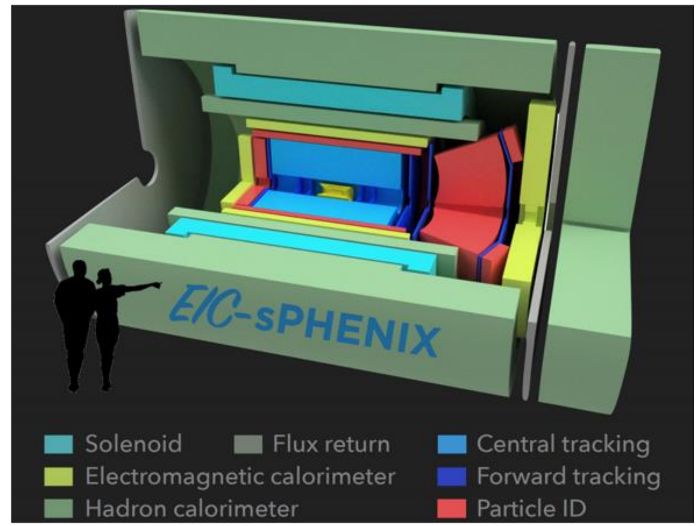
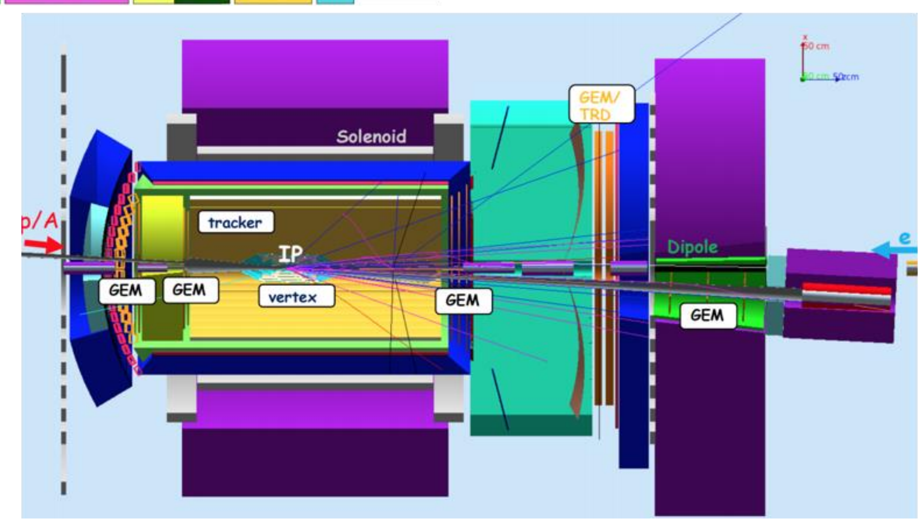
Stony Brook University | The State University of New York

WHY SHIELDING CHARGED PARTICLE BEAMS

All EIC detector concepts based on solenoids







WHY SHIELDING CHARGED PARTICLE BEAMS

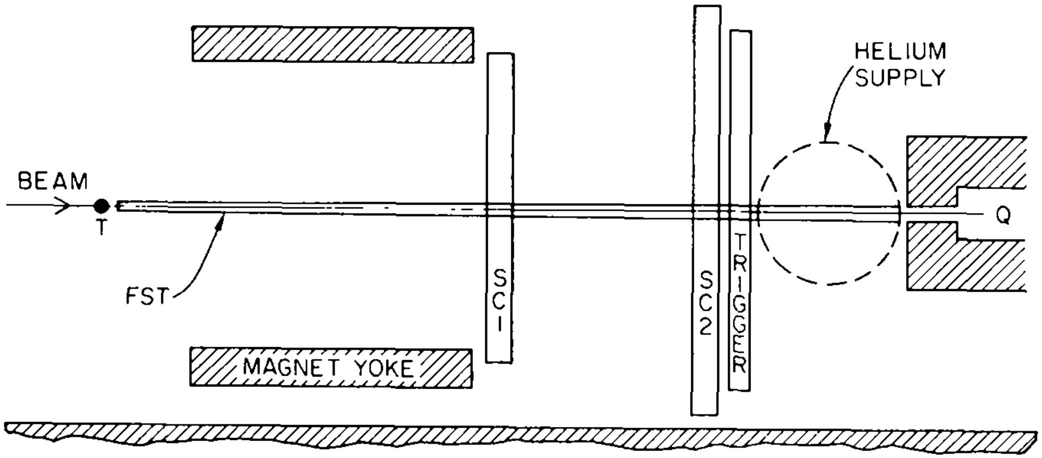
- Momentum measurement → charged final state particles' curvature in magnetic field

$$p_T[GeV] = 0.3 \cdot B[T] \cdot r[m]$$

- $p_T \perp (\vec{B} \parallel \overrightarrow{beam})$, typically solenoid magnets
- Forward measurements loose bending power
- Solution: introduce $\vec{B} \perp \vec{p}$, e.g., dipole magnet
- Drawback: $\vec{B} \perp \overrightarrow{beam}$ → beam deflection
  → beam depolarization
- Shield charged particle beams

SHIELD CHARGED PARTICLE BEAMS

- How to shield?
  - Compensate magnetic field lines in the region of interest
  - E.g., magnetic flux exclusion tube

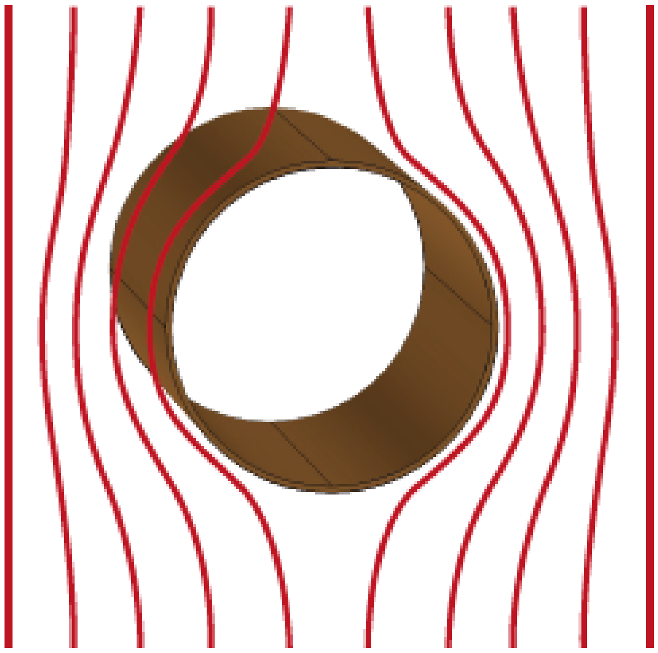


BEAM. $e^{+(-)}$ 2×10^4/pulse.
T: Liquid H_2/D_2 target. 4cms long
FST: Superconducting flux shielding tube
SC1, SC2 Optical spark chambers.
TRIGGER: Lead-lucite shower counters.
Q: Quantameter

F. Martin et al., Nuclear Instruments and Methods Volume 103, Issue 3, 15 September 1972, Pages 503-514

SHIELD CHARGED PARTICLE BEAMS

- How to shield?
  - Compensate magnetic field lines in the region of interest
  - E.g., magnetic flux exclusion tube → superconducting
  - Distorts outside magnetic flux

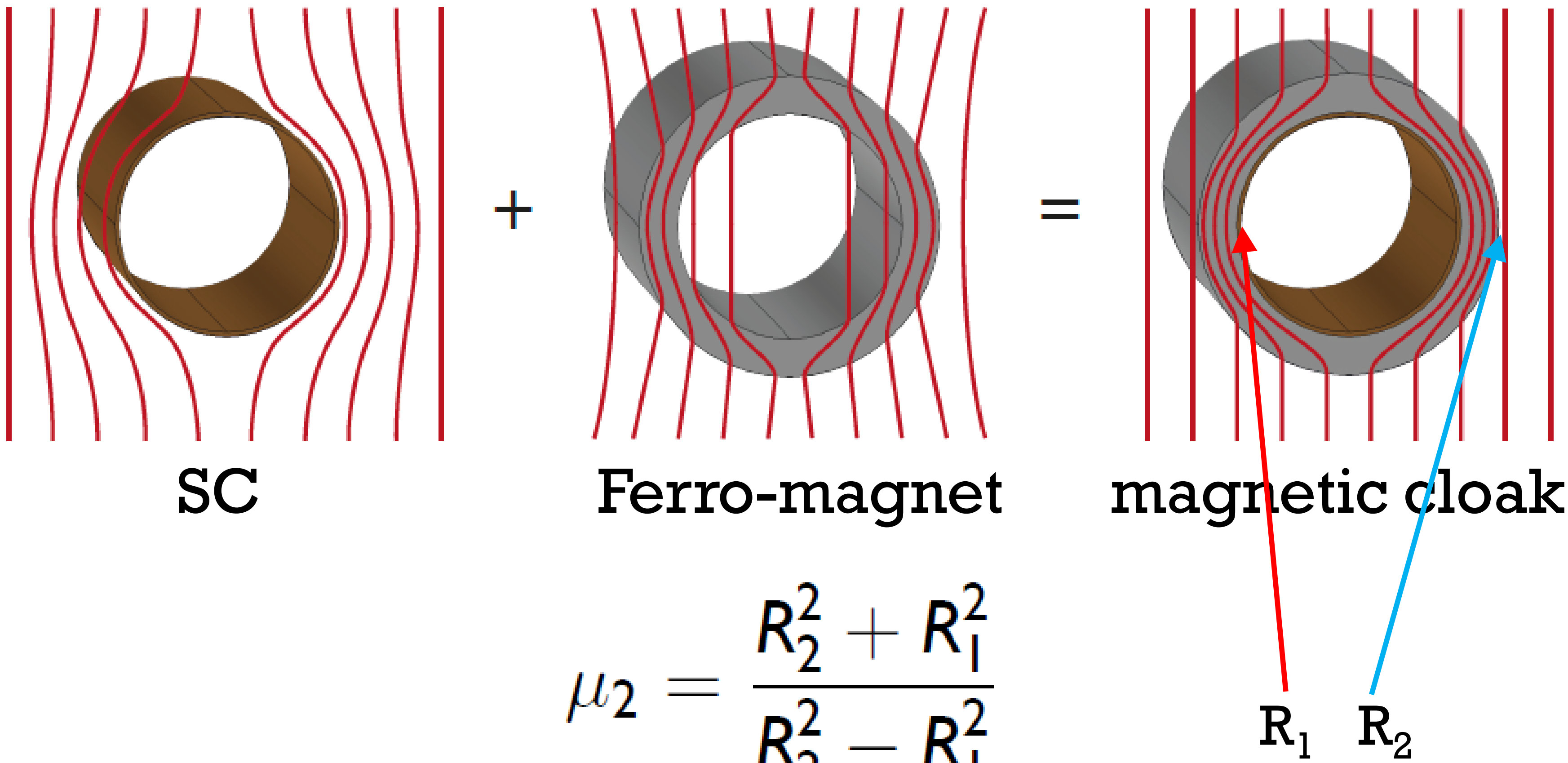


F. Martin et al., Nuclear Instruments and Methods Volume 103, Issue 3, 15 September 1972, Pages 503-514

SHIELD CHARGED PARTICLE BEAMS

- How to shield?
  - Ideal shield: ‘switch off’ magnetic interaction of magnetic material with existing magnetic fields without modifying them
  - Antimagnet: conceals magnetic response of volume under consideration without altering external magnetic fields → magnetic cloaking
  - Superconductors (SC) and isotropic magnetic materials

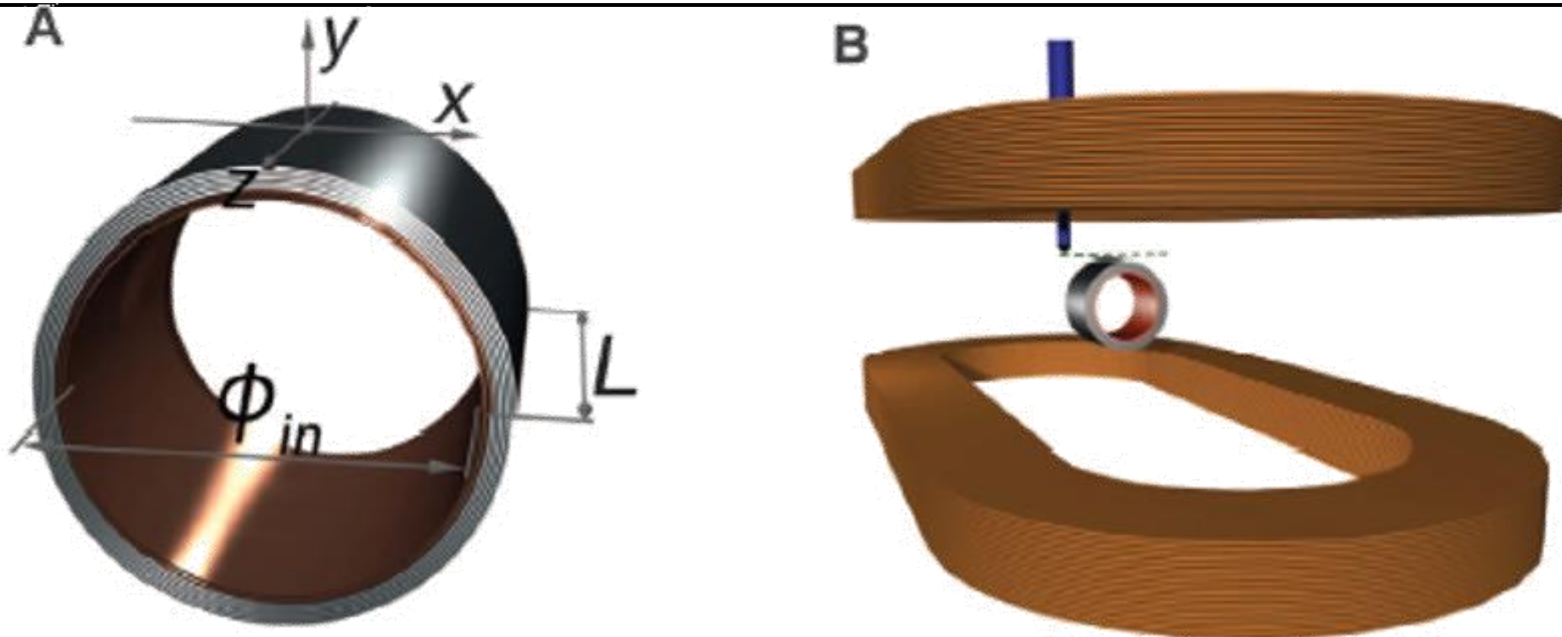
Concept Magnetic Field Cloak



$$\mu_2 = \frac{R_2^2 + R_1^2}{R_2^2 - R_1^2}$$

Fedor Gömöry *et al.*., *Science* **335**, 1466 (2012), DOI: 10.1126/science.1218316

EXPERIMENTAL REALIZATION

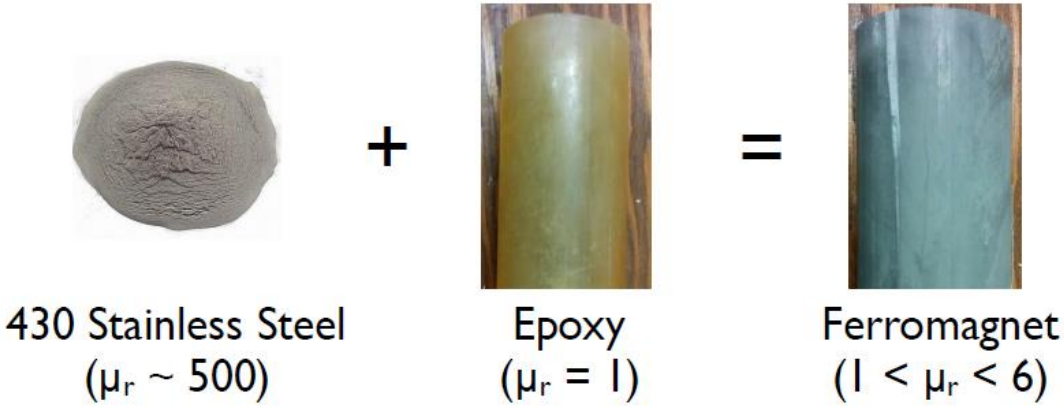


SC tape @ R_1: ReBCO (cuprate HT-SC)

FM-tape @ R_1 to R_2: $Fe_{18}Cr_9Ni$ $\mu_2 = 3.54$

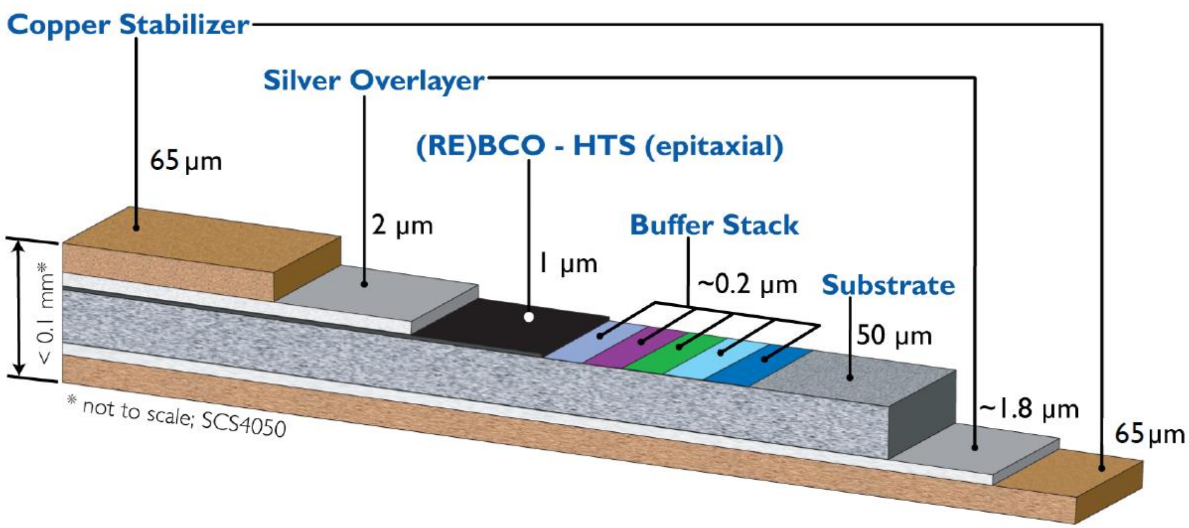
Place cloak cylinder in magnetic field

EXPERIMENTAL REALIZATION



manufacturing FM with customized μ_r dependent on fractional mass f_m

manufacturing SC with ReBCO "tape"



EXPERIMENTAL REALIZATION

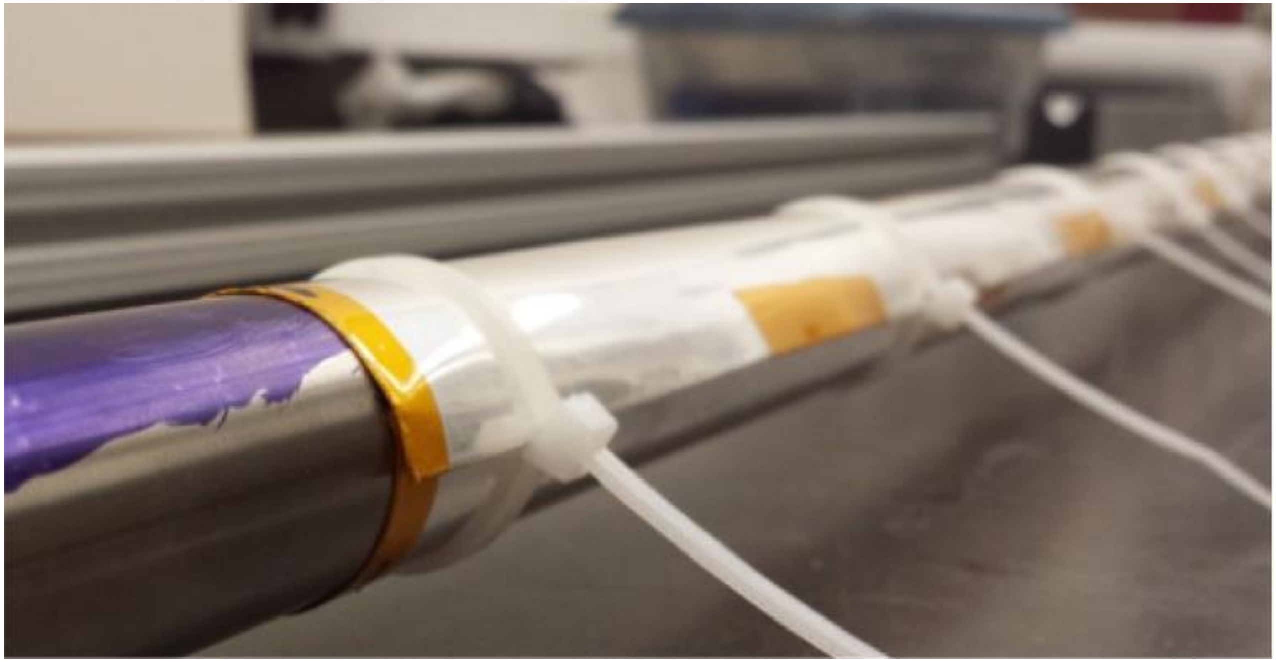
- Test setups with prototypes
  - Tandem Van de Graaf Facility (BNL) → shielding ion beams from magnetic dipole field
  - Helmholtz coil → measure permeability of FM cylinder + test cloaking at low magnetic fields
  - ANL-MRI up to 4 T → measure permeability of FM cylinder + test cloaking at magnetic fields up to 0.5 T

EXPERIMENTAL REALIZATION

- Test setups with prototype constructions
  - 1 m long -- 2-layer HTS shield
  - 4.5 inches long -- 4-layer HTS shield
  - 4.5 inches long -- 45-layer HTS shield
  - 4.5 inches long -- 4-layer HTS cloak
  - 4.5 inches long -- 45-layer HTS cloak

EXPERIMENTAL REALIZATION

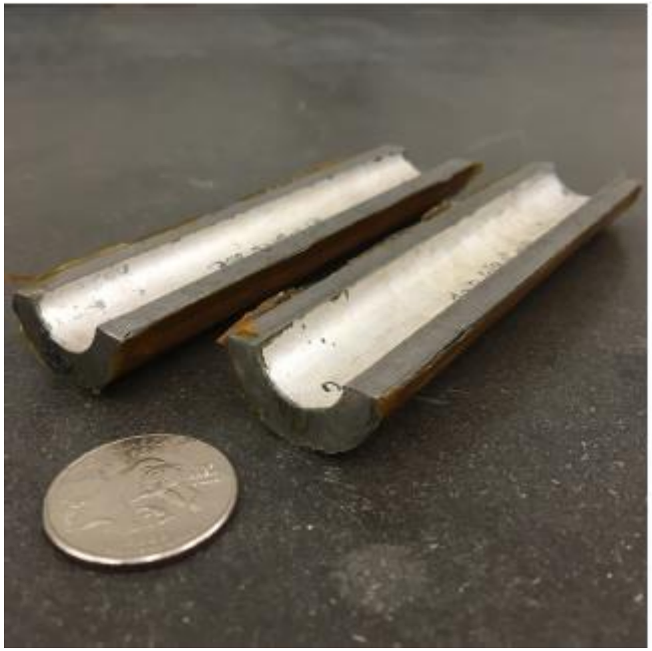
- Test setups with prototype constructions
  - 1 m long -- 2-layer HTS shield



Two double layer HTS wrapped around top/bottom of SS-tube

EXPERIMENTAL REALIZATION

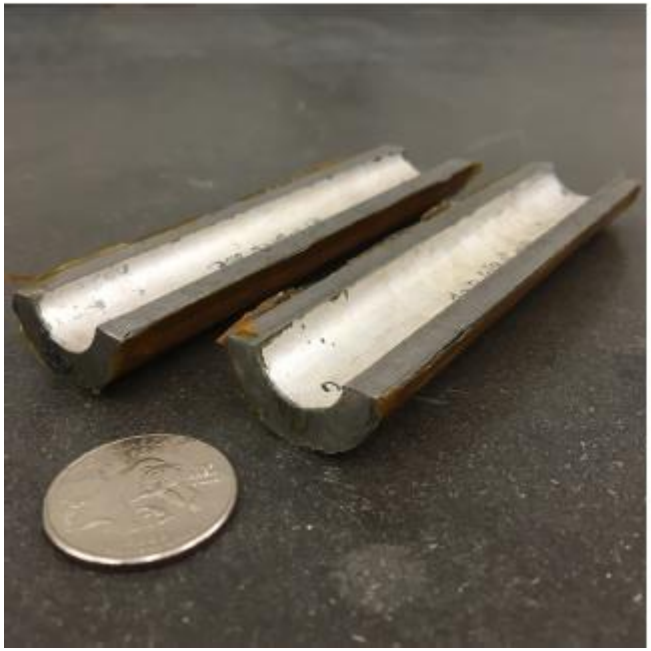
- Test setups with prototype constructions
  - 4.5 inches long -- 45-layer HTS shield

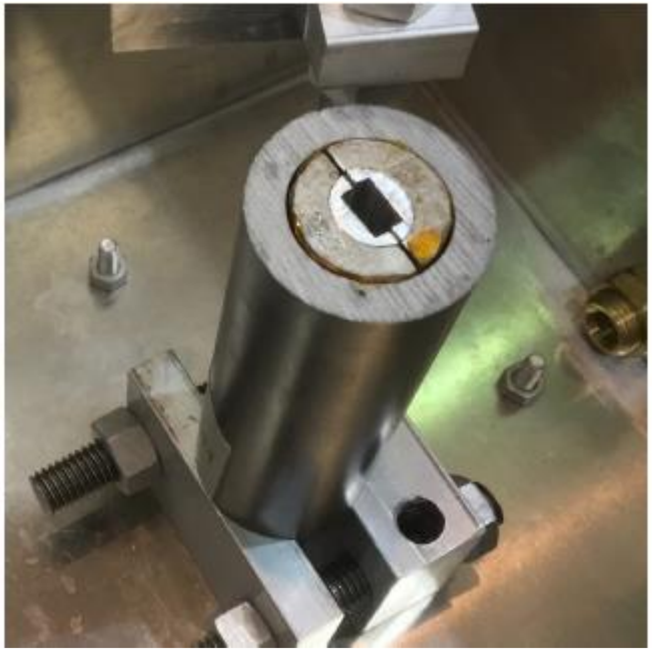


Lamination: die-and-mandrel setup in oven

EXPERIMENTAL REALIZATION

- Test setups with prototype constructions
  - 4.5 inches long -- 45-layer HTS cloak

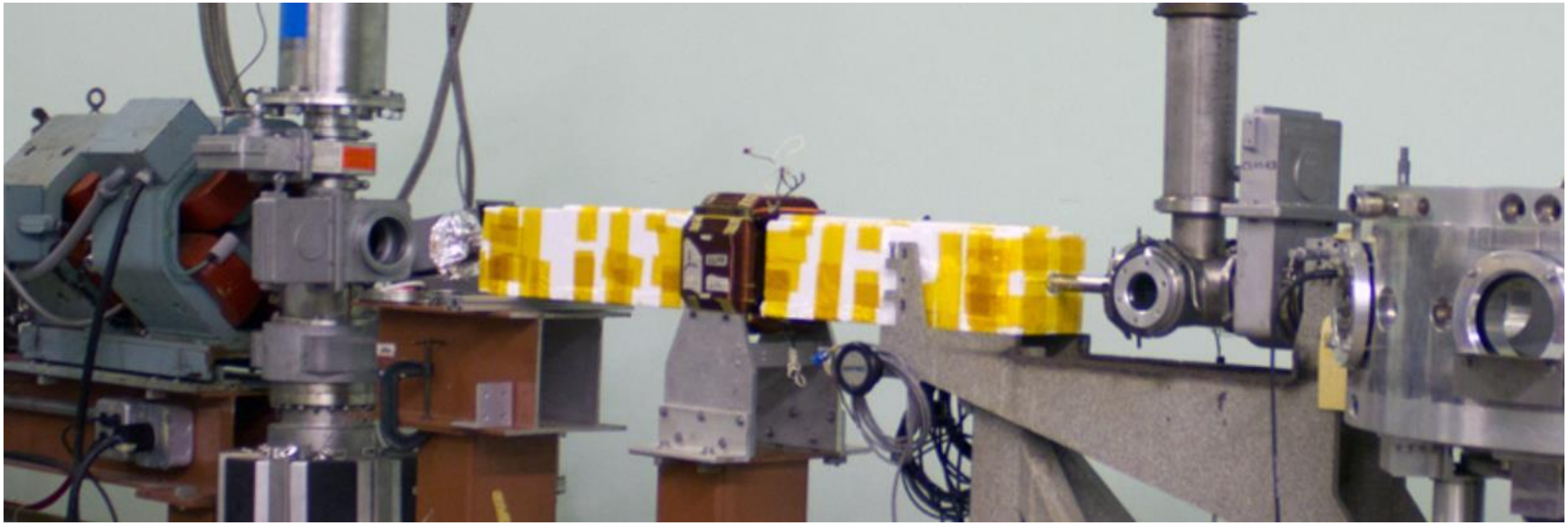




Manufactured FM shell and assembly around SC

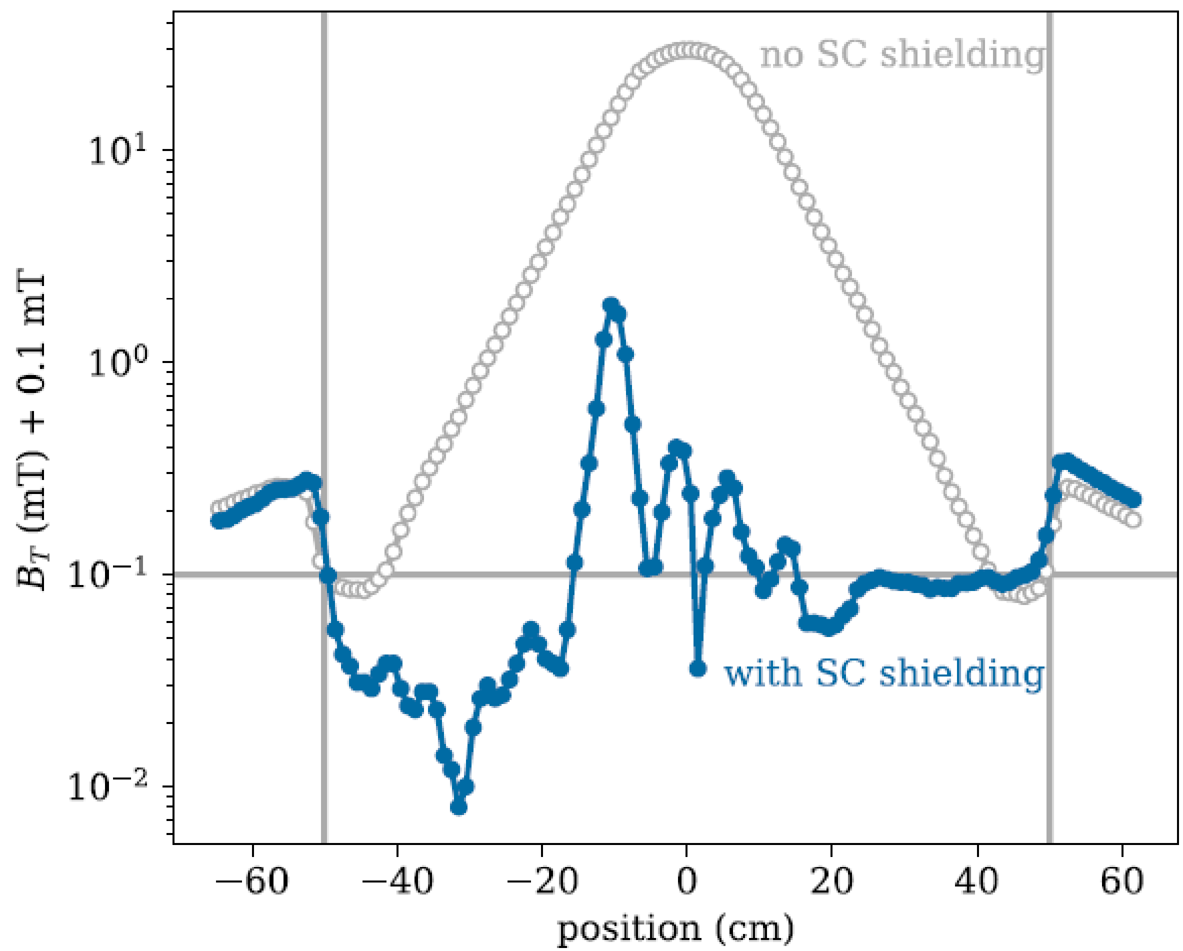
TANDEM VAN DE GRAAF FACILITY

1 m long -- 2-layer HTS shield → extends magnet



TANDEM VAN DE GRAAF FACILITY

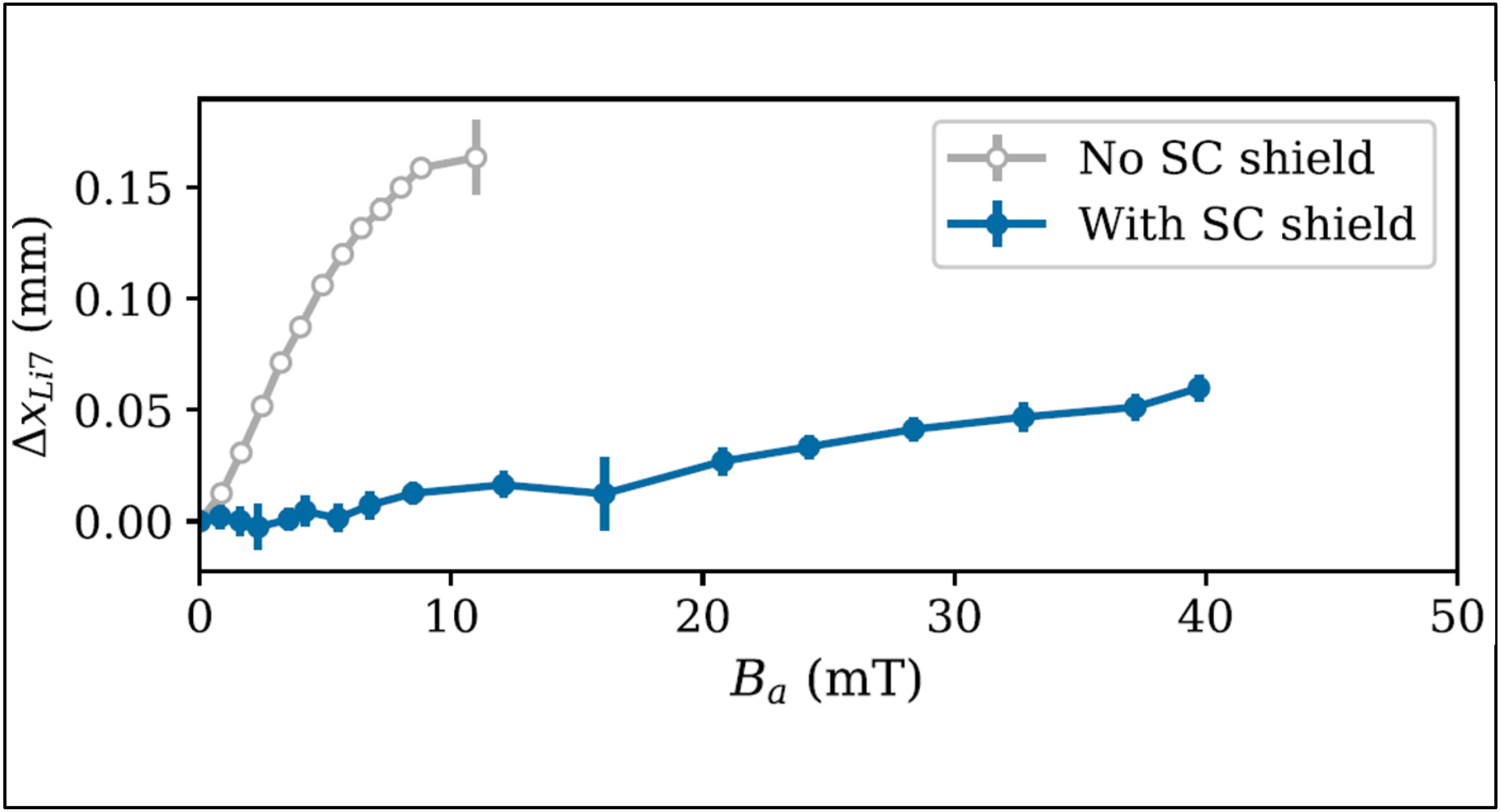
Structural imperfections + trapped background fields



offset of 0.1 mT

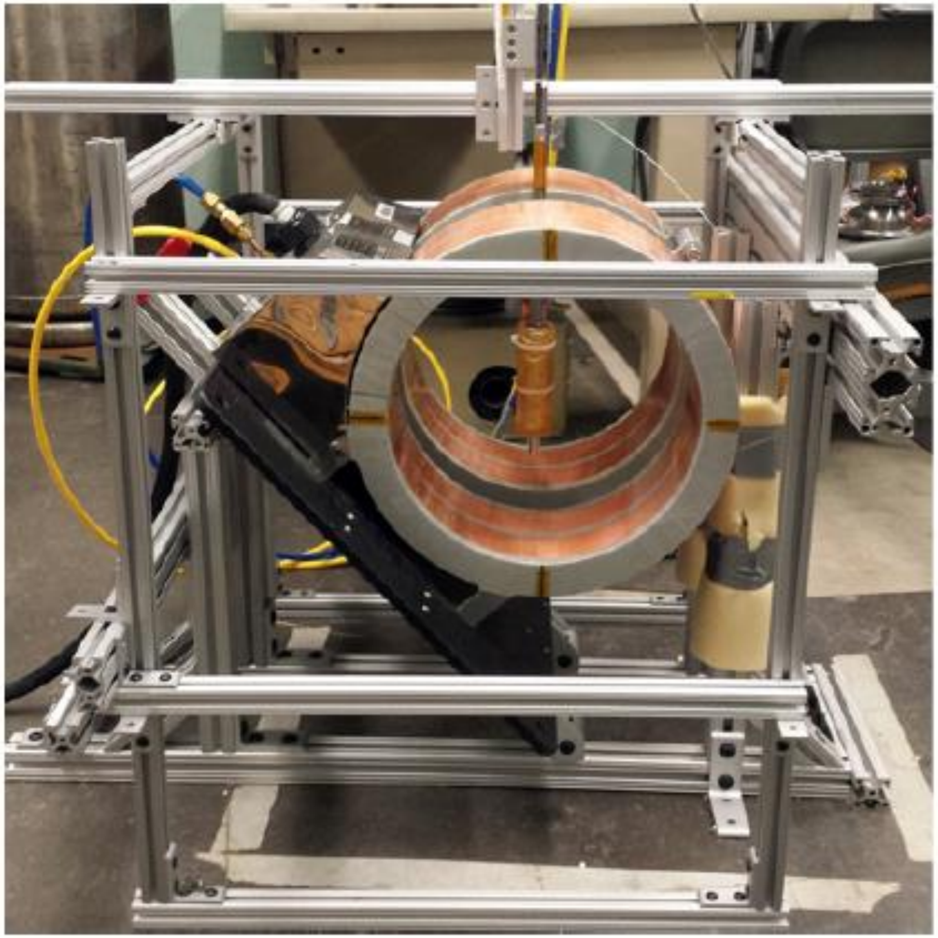
TANDEM VAN DE GRAAF FACILITY

Beam ($^{7}_{3}Li^{3+}$)deflection



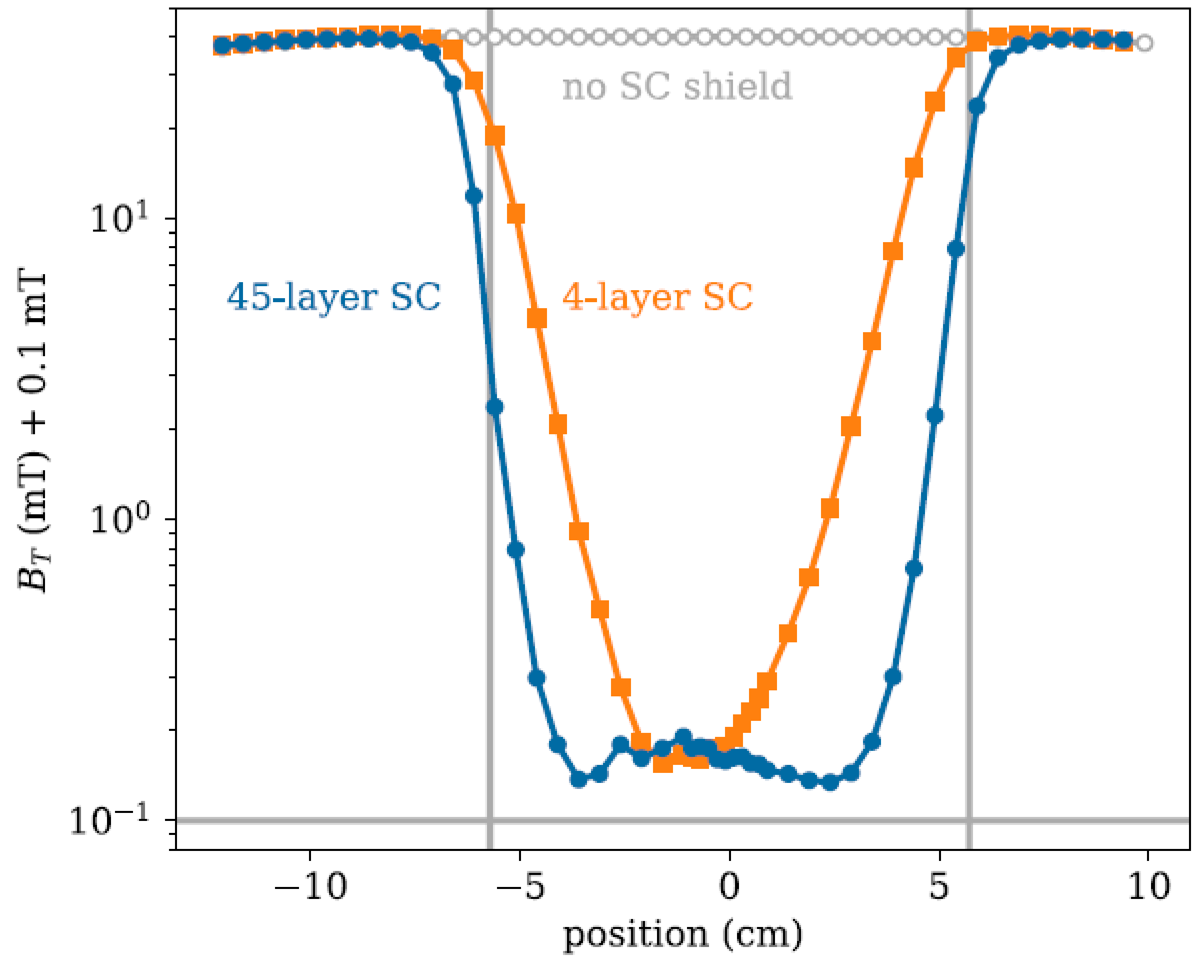
HELMHOLTZ COIL SETUP

High field stability – up to 50 mT



HELMHOLTZ COIL SETUP

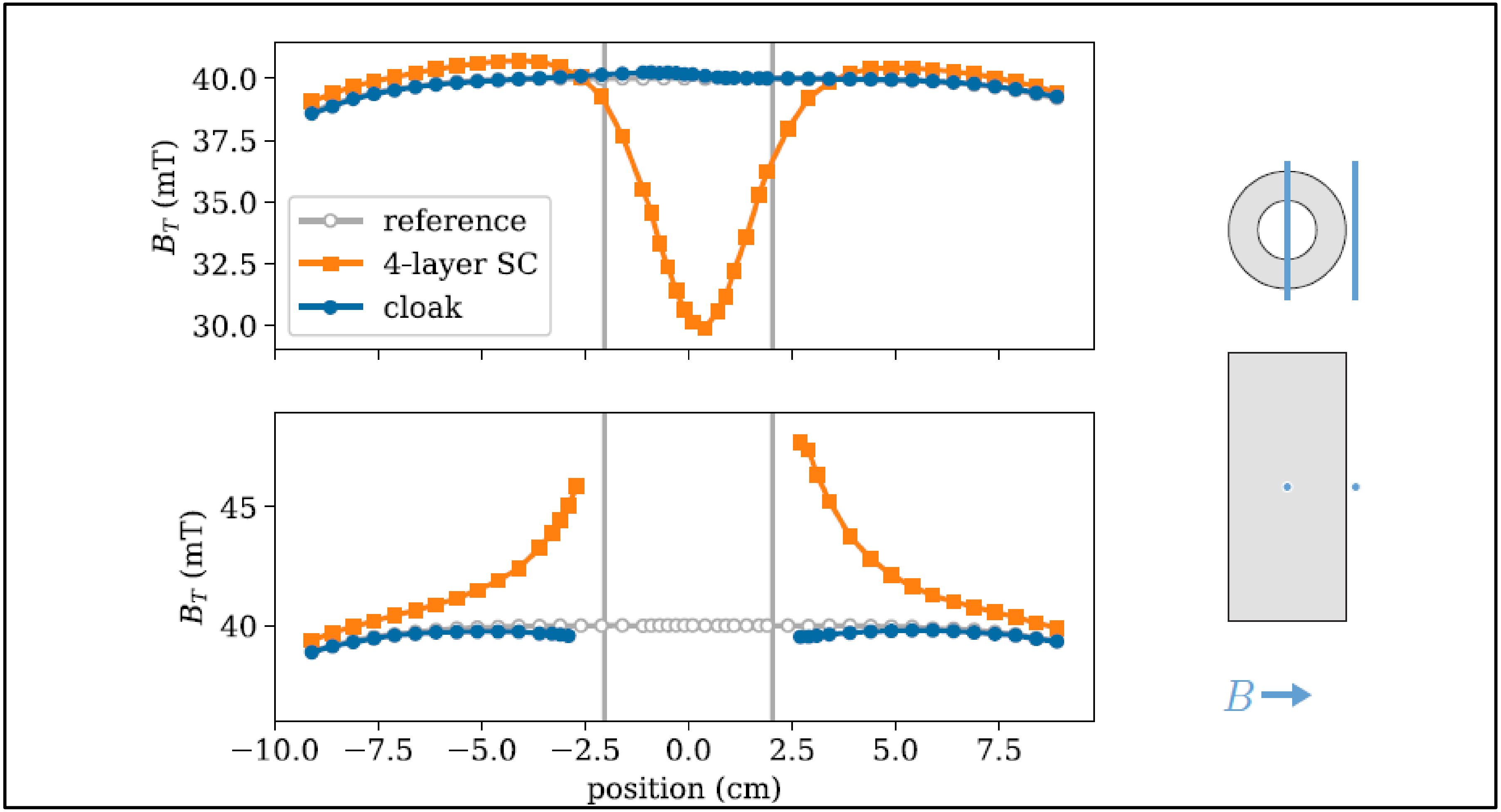
4.5 inches long -- 4-/45-layer SC shield



Measurements along axis of shields

HELMHOLTZ COIL SETUP

4.5 inches long -- 4-layer SC shield/cloak(μ_r=2.43)



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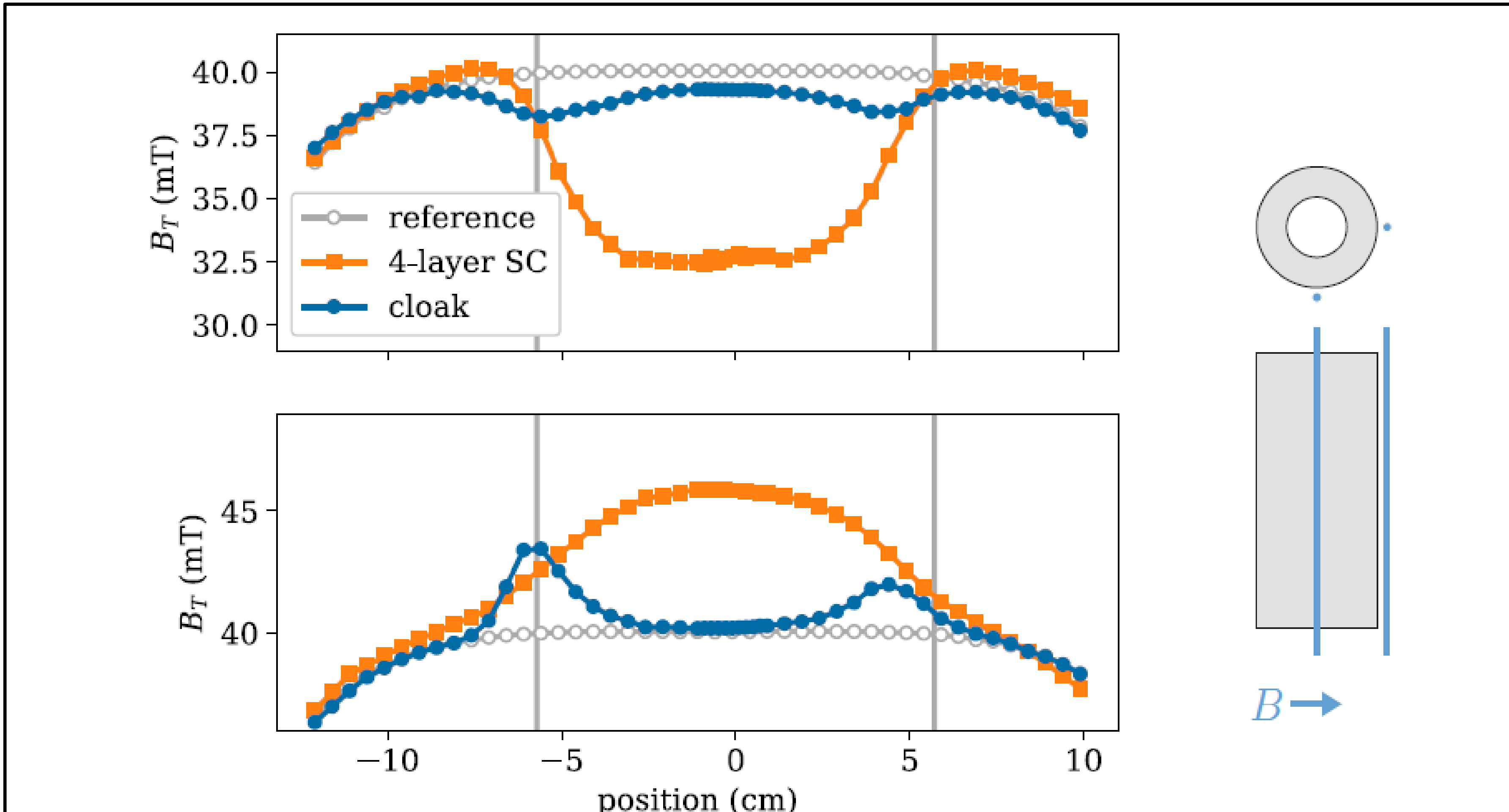
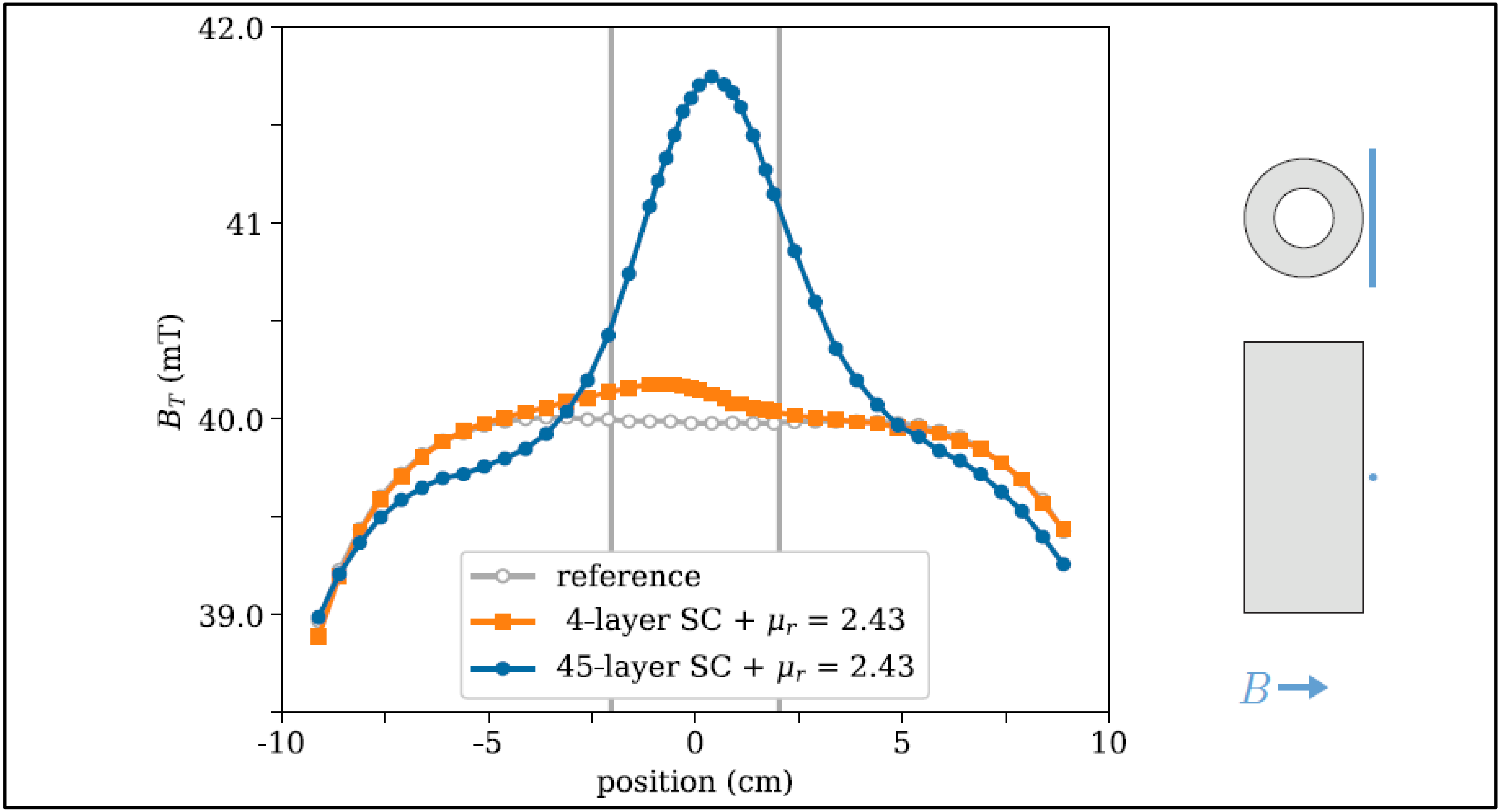


HELMHOLTZ COIL SETUP

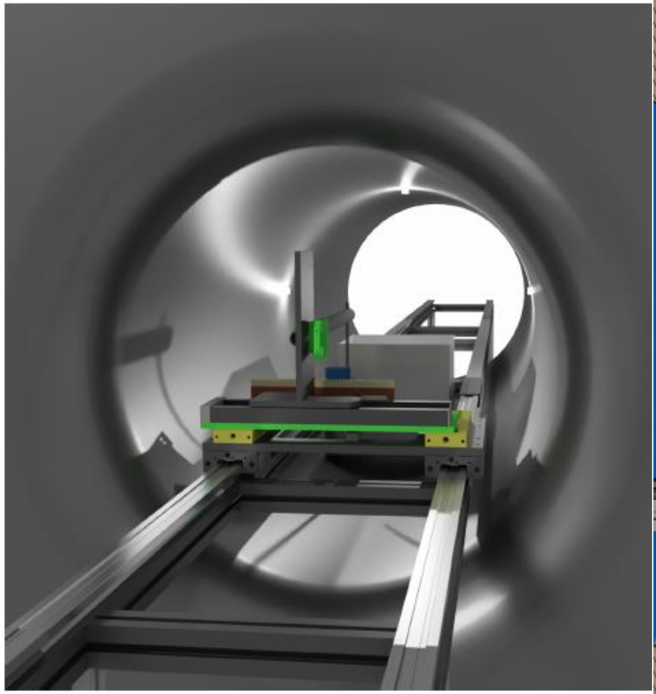
4.5 inches long -- 4-/45-layer SC shield/cloak(μ_r=2.43)

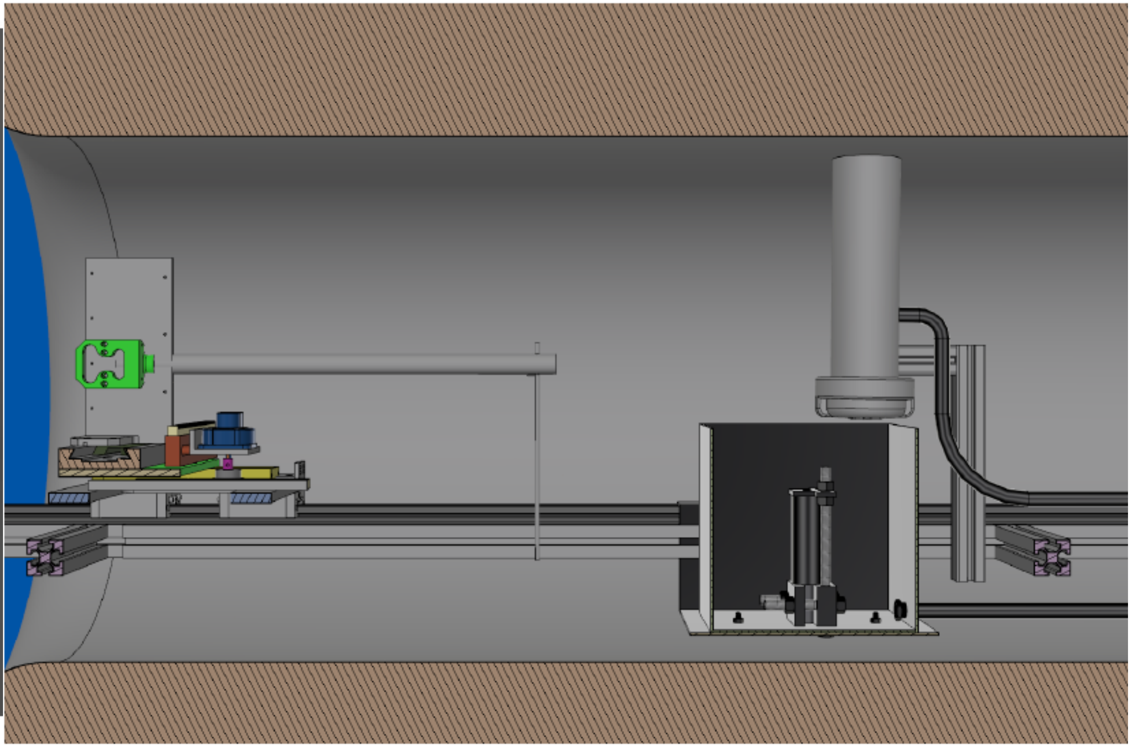


45-layer SC + cloak → imperfections

Commercial MRI magnet, B_{max} =4 T, operated up to 0.5 T

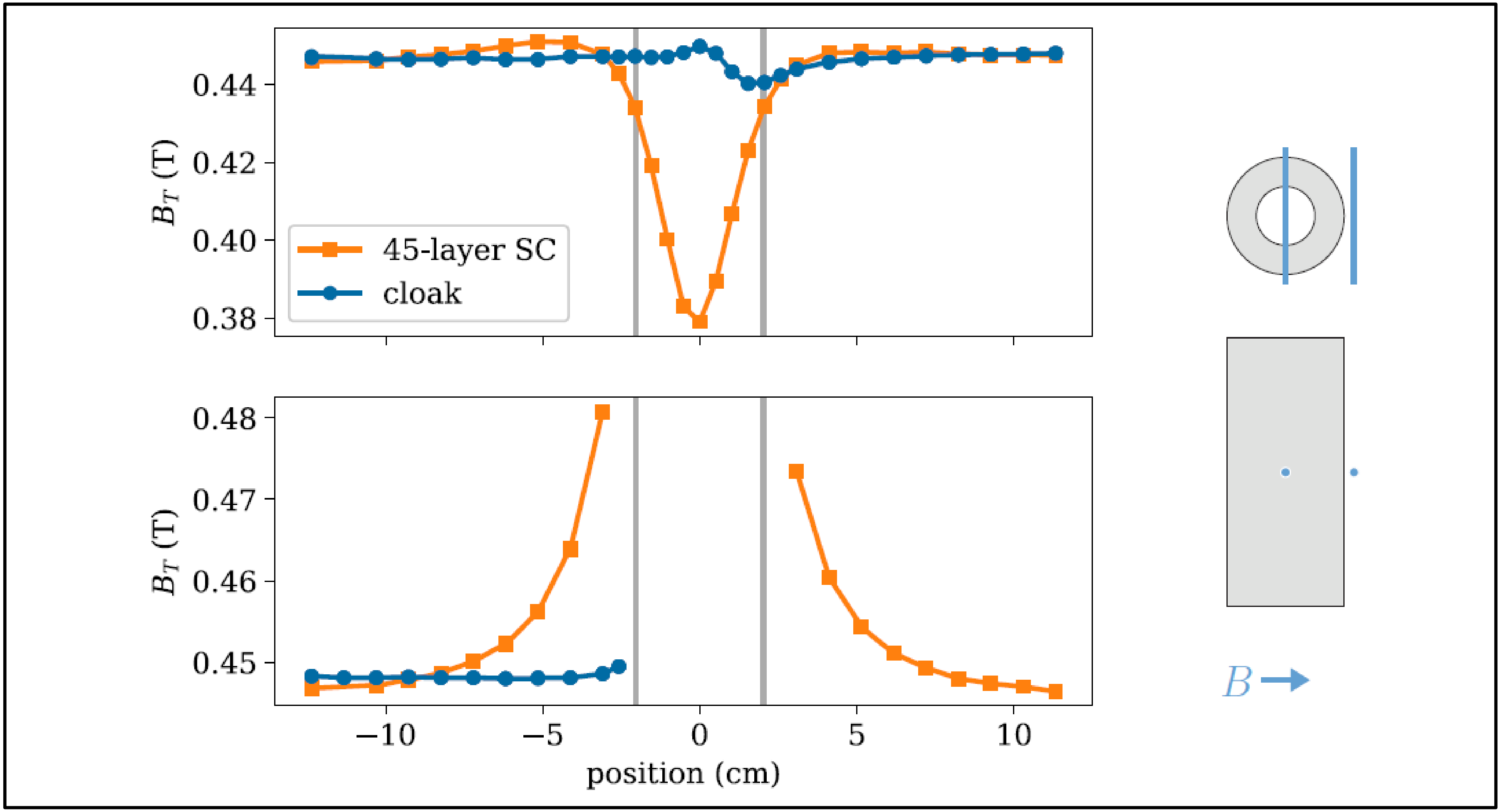
Hall probe table





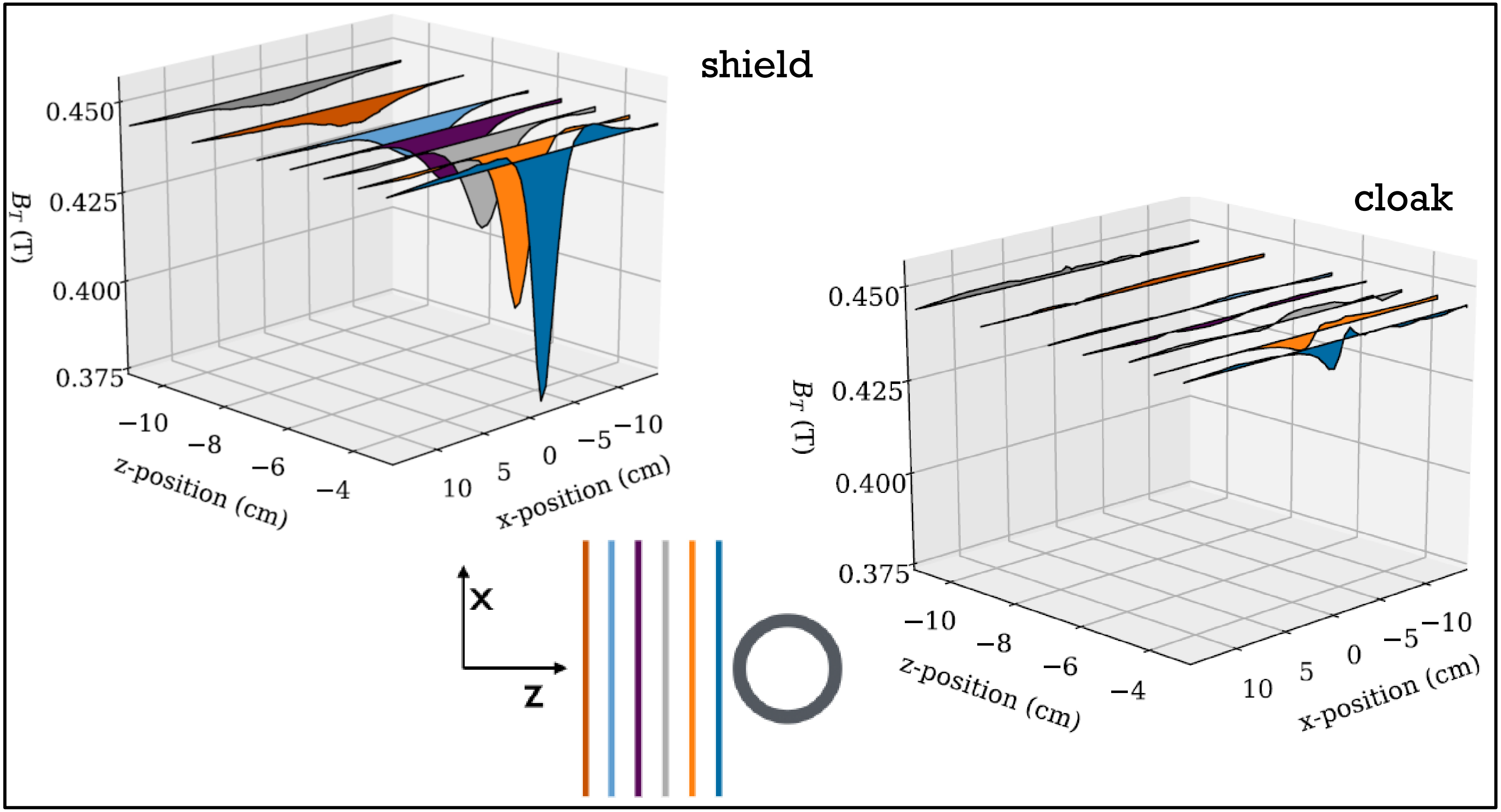
Cloak box in LN2-bath

4.5 inches long -- 45-layer SC shield/cloak(μ_r=2.43)



μ_r effectively reduced due to higher fields

4.5 inches long -- 45-layer SC shield/cloak(μ_r=2.43)



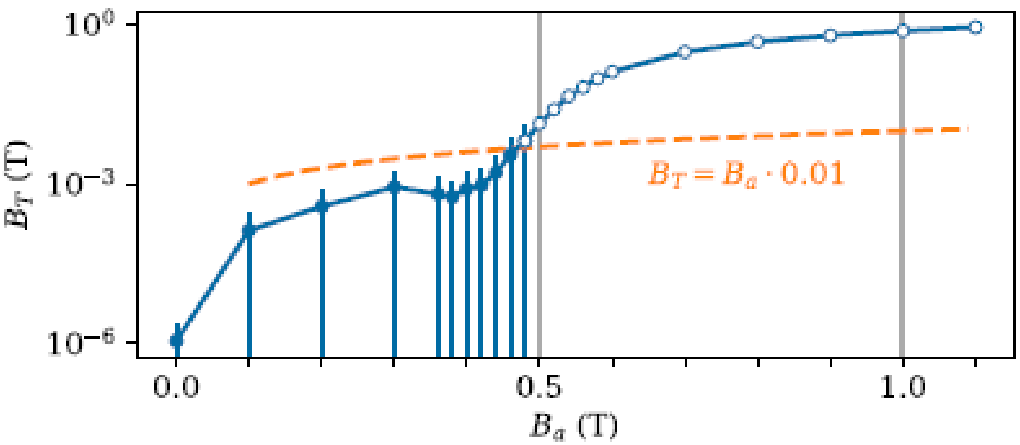
CONCLUSION

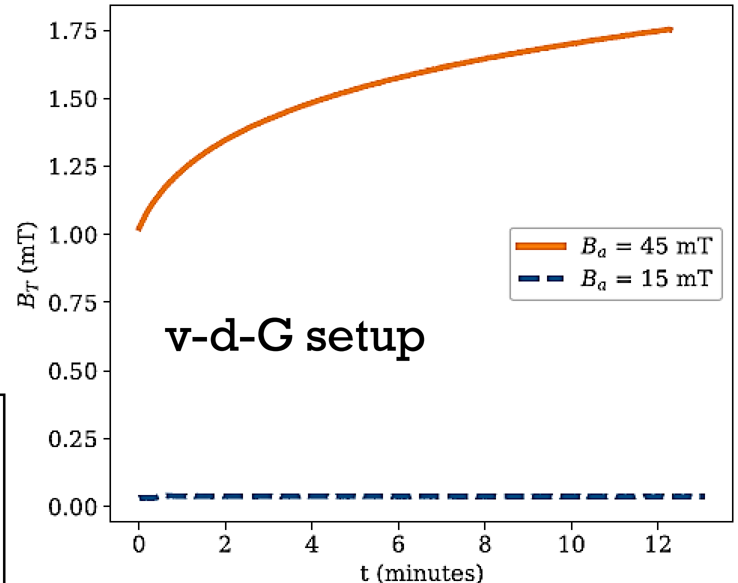
- Demonstrated that B_T can be cloaked up to 0.5 T
- Promising device for shielding charged particle beams
- Need to optimize manufacturing processes
- Need careful study for optimal parameters
- Reconsider SC at LHe temperature → extend to higher B_T cloaking
- Perform transformation optics and maybe use only room-temperature materials → meta-materials

SUPPORTING SLIDES

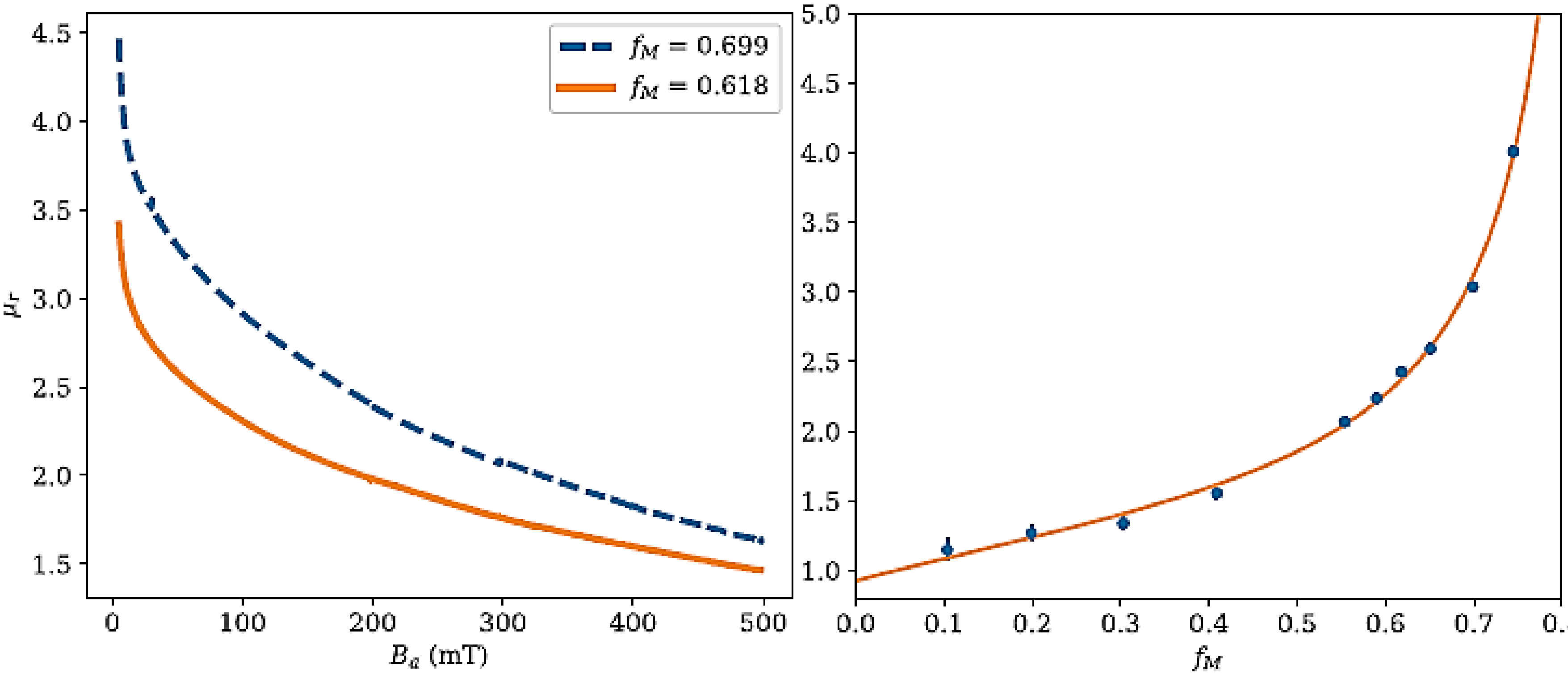
- SC critical fields B_{c1} / B_{c2} : development of flux vortices → shielding time dependent

ANL-MRI





Magnetic permeability (μ_r): influential factors



$$B_T(r < R_1) = \frac{4\mu_r R_2^2}{(\mu_r + 1)^2 R_2^2 - (\mu_r - 1)^2 R_1^2} B_a$$

Fill factor, empirical solution