Superconducting Solenoid R&D for the Electron Cooler

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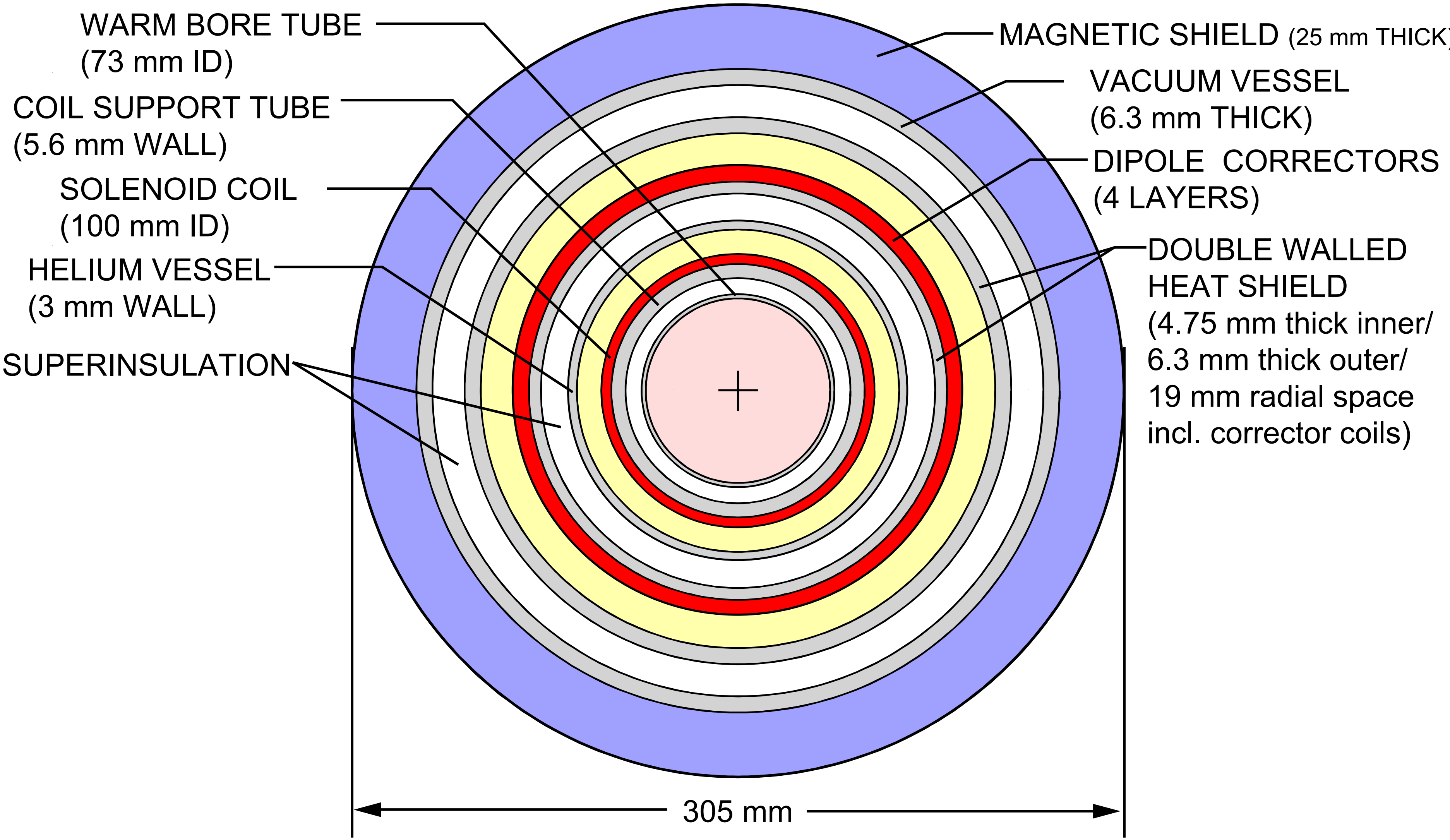
BROOKHAVEN NATIONAL LABORATORY

RHIC

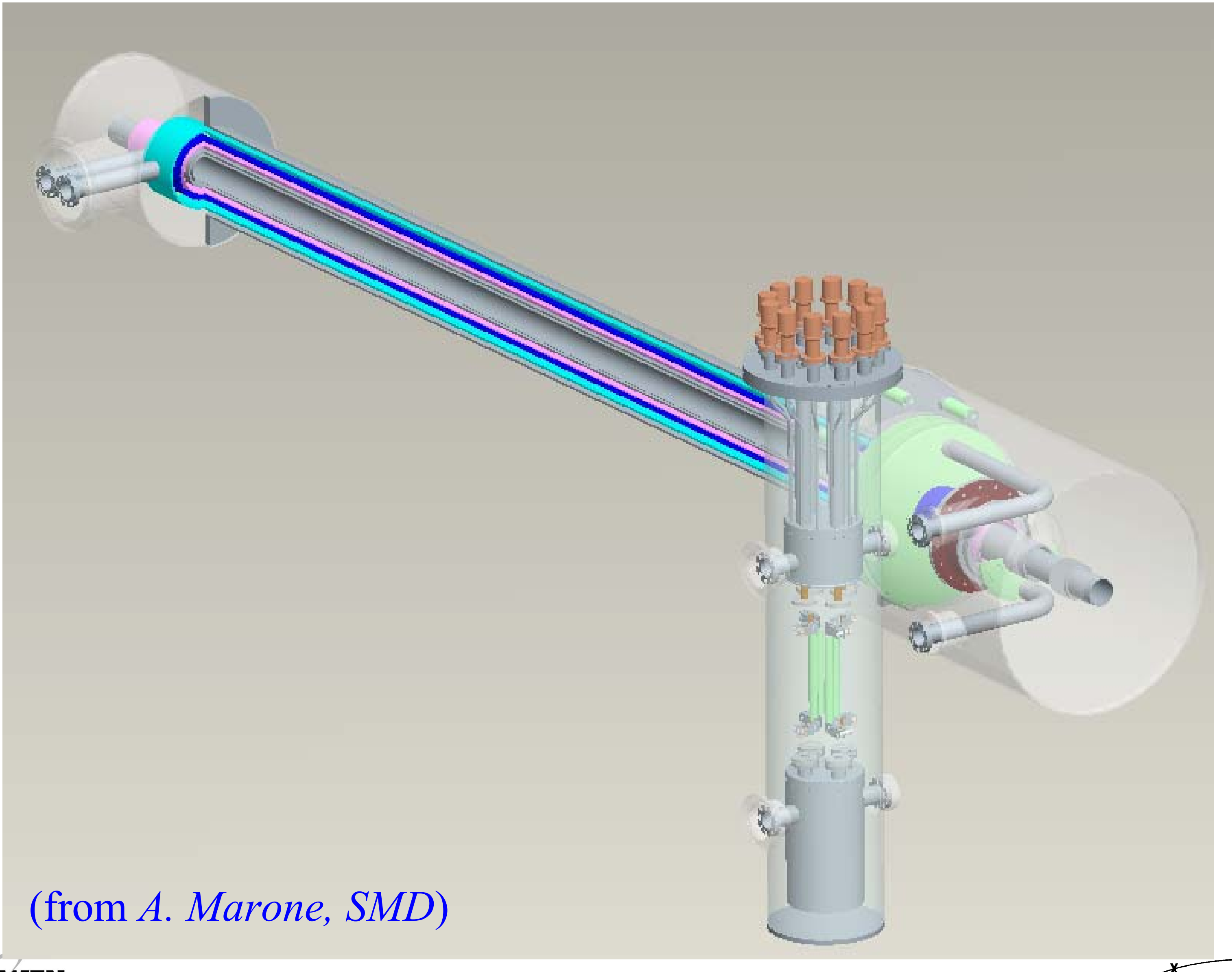
Solenoid Requirements

- 2 Tesla axial field (upgraded from initial 1 T)
- Up to 30-meter total length (in two sections)
- 100 mm coil ID (~89 mm *cold bore* diameter)
- $B_{\perp} / B_{axial} \leq 1 \times 10^{-5}$ (on-axis straightness):
  - ›› implies use of a dipole correction system
  - ›› significantly increases magnet complexity
  - ›› challenging measurement task
- Quadrupole triplets between solenoids

Solenoid Cross Section



Conceptual Design of Solenoid



(from *A. Marone, SMD*)

Solenoid Coil Characteristics

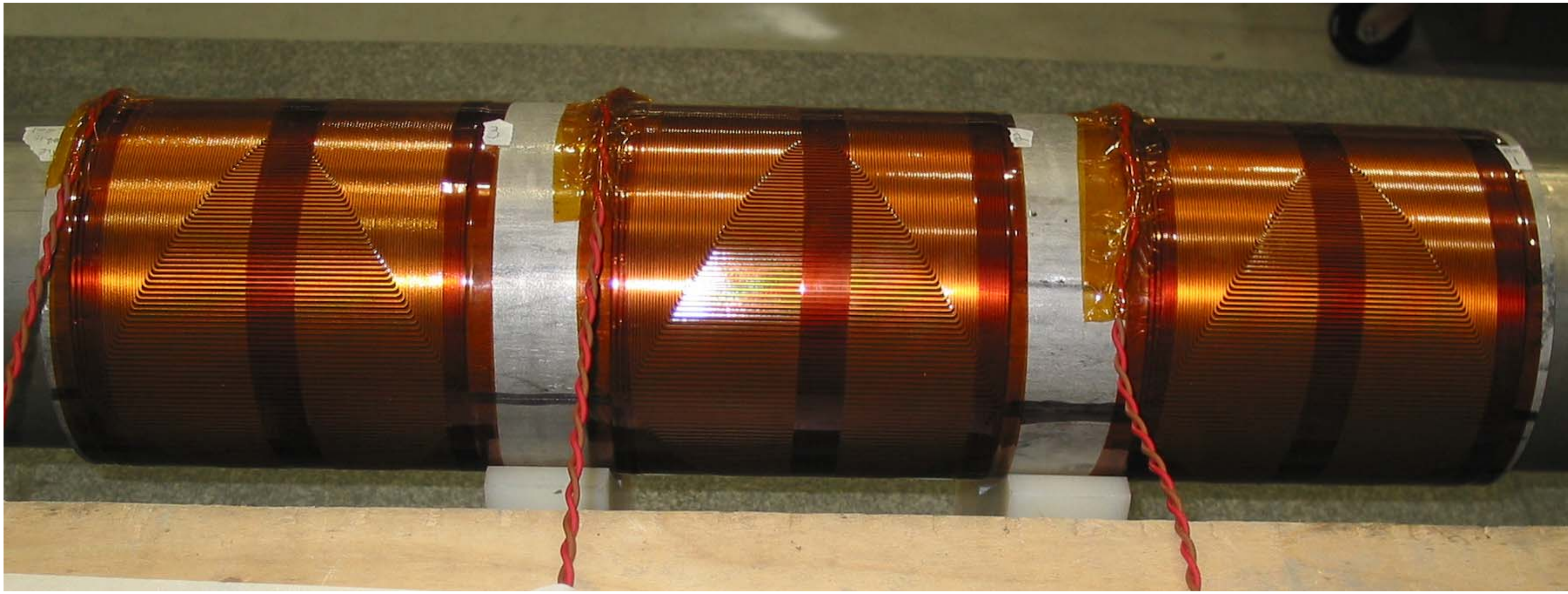
- 2.29 mm × 1.52 mm superconductor; Cu:SC = 6.88
- 4 Layers, ~ 390 turns/meter in each layer
- 2.0 Tesla at 1020 A; Conductor limit 1500A (2.9 T)
- Coil ID = 100 mm; Coil OD = 116 mm
- Inductance = 26 mH/meter; Energy = 13.5 kJ/m (2T)
- Peak hoop stress in the coil = 25.3 MPa (~ 3700 psi)
- Maximum axial force per turn = 400 N (~ 90 lbf)

A prototype coil (~2.5 m long) will be built & tested.

Dipole Correction Coils

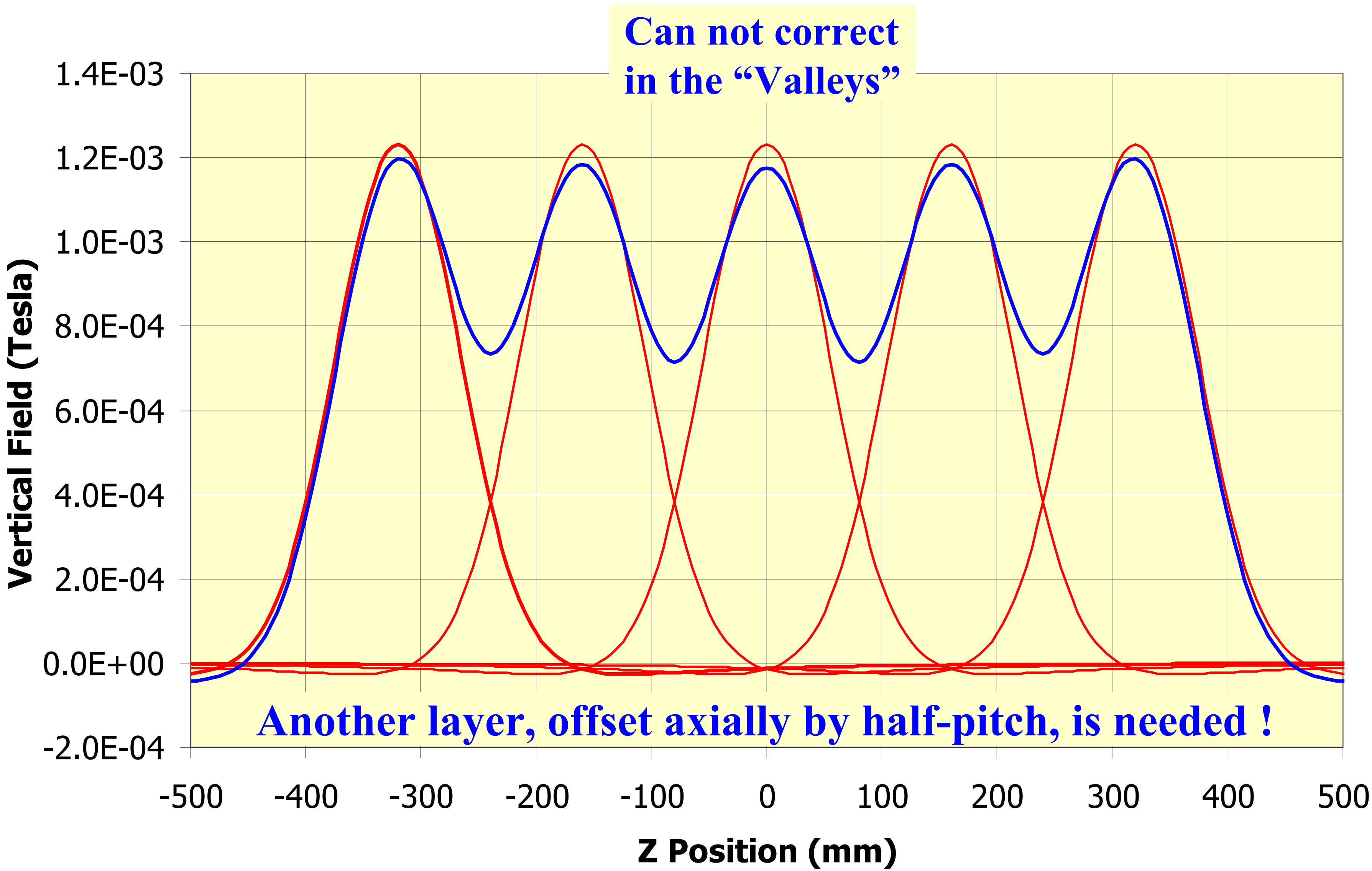
- $B_\perp / B_z \sim 10^{-5}$ implies a straightness of 10 μm over 1 meter length. This may not be achieved with mechanical alignment alone.
- Winding imperfections are also likely to produce transverse fields on-axis.
- Goal is to achieve as close to 1×10^{-5} as possible with construction tolerances and mechanical adjustment (expect ~ a few $\times 10^{-4}$)
- Correct the remaining errors with an array of ~ 150 mm long, printed circuit dipole correctors.
- **Two sets of correctors *per axis* are required.**

Printed Circuit Dipole Correctors

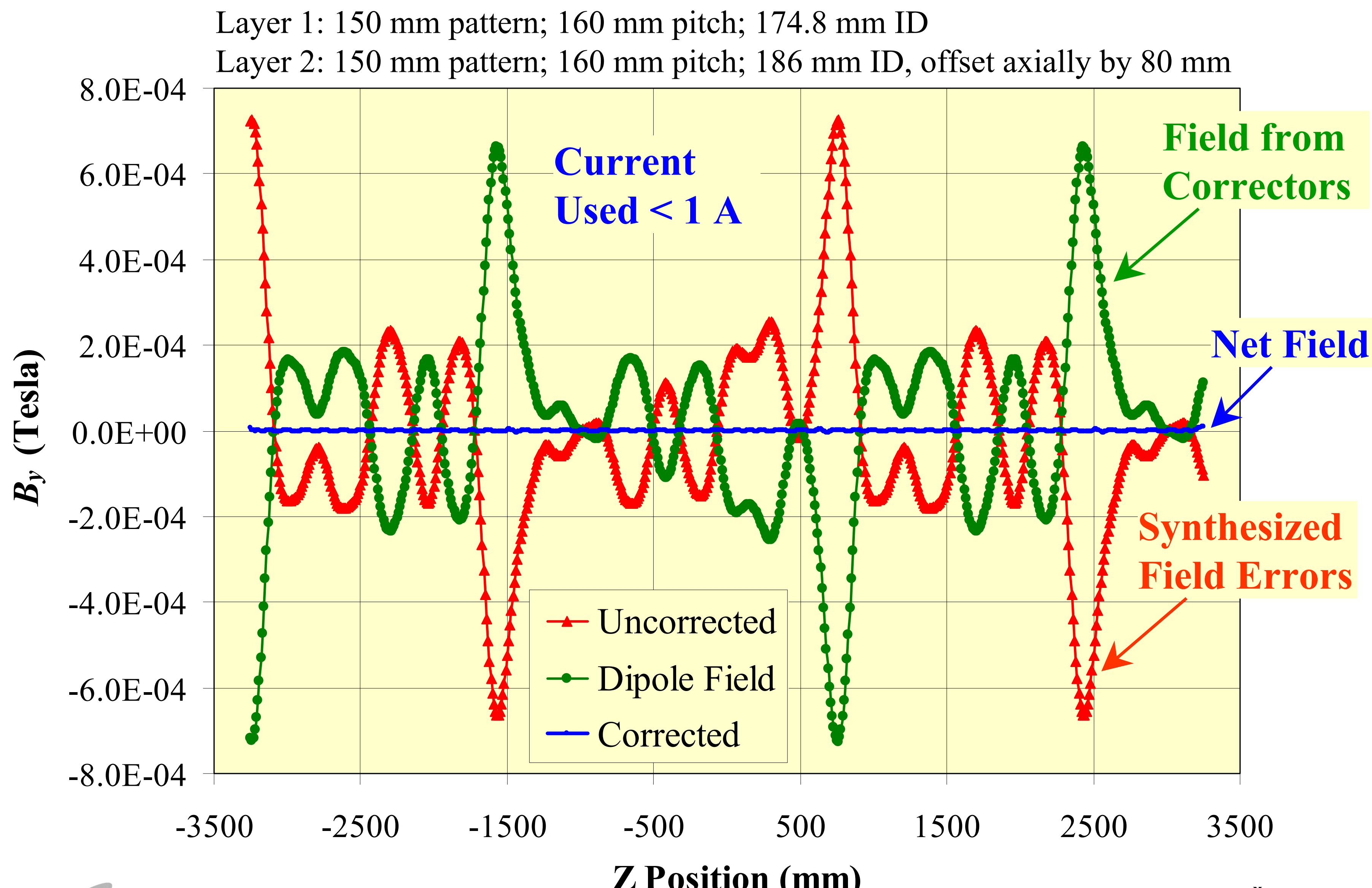


- 2 Layers of 4 oz Copper patterns; 159 mm ID, 150 mm long
- 1.25×10^{-3} Tesla central field at 2 A; $\Delta B/B \sim 10^{-3}$ at 50 mm
- Mounted on cryogenic heat shield to minimize dissipated power (approx. 190 W/m expected at full power).

Array of 150 mm long Correctors, 160 mm apart



Simulation to Check Correction Algorithm



Simulation to Check Correction Algorithm

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B_y Error data;20 harmonics; Lambda=100mm to 2 meters; 6.5m long solenoid; ~6.6m long corrector
2 families; Dipole06a;b; 150mm patterns. 160mm spacing; 80mm offset for second layer; No extra gaps.

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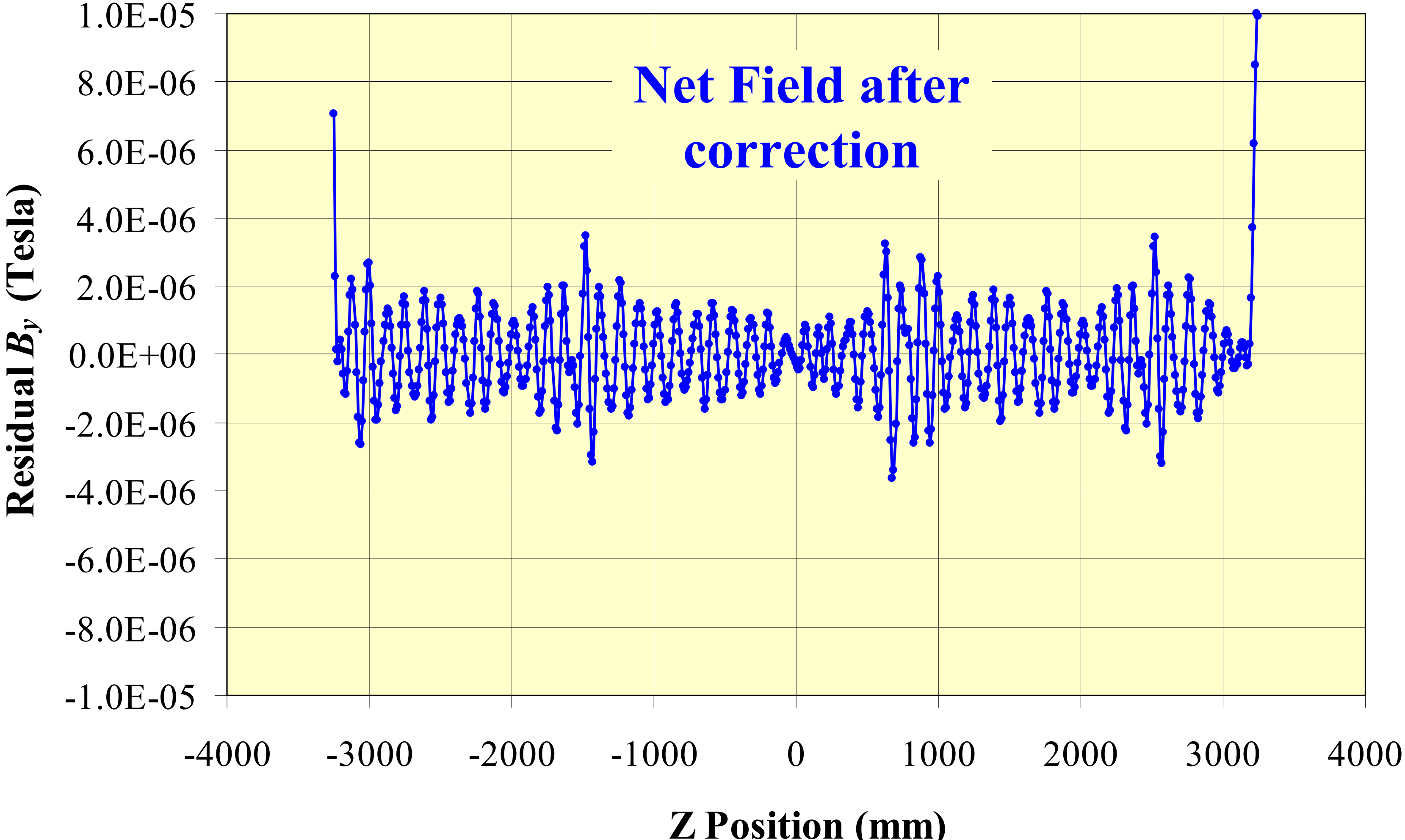
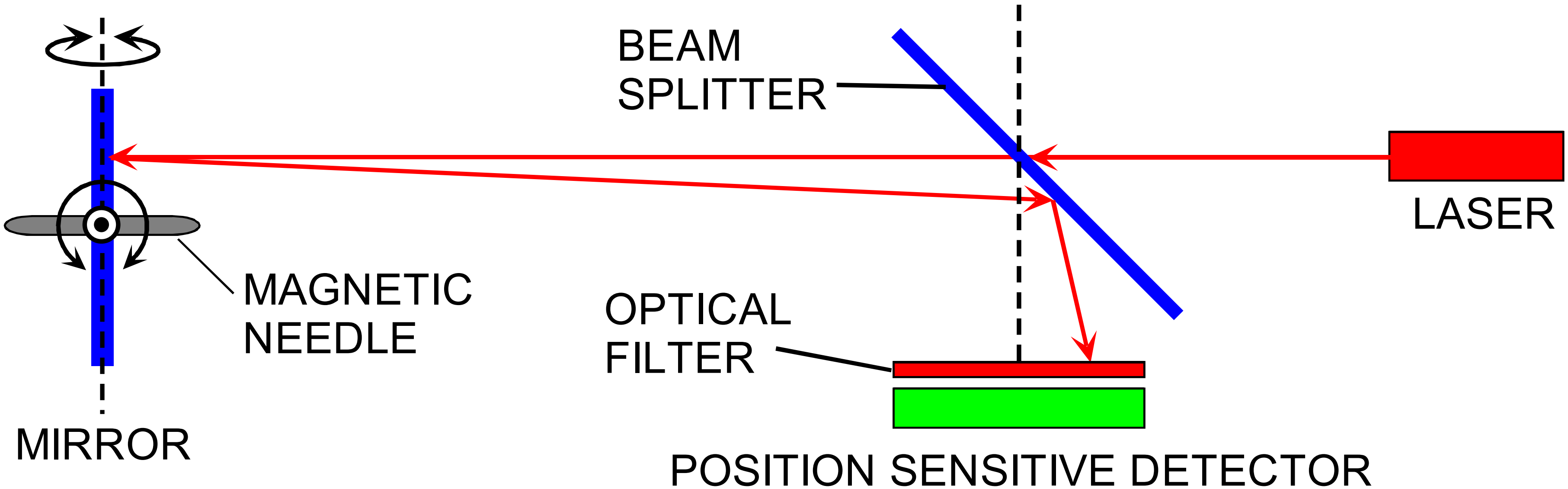


e-Cooler Solenoid Measurement System

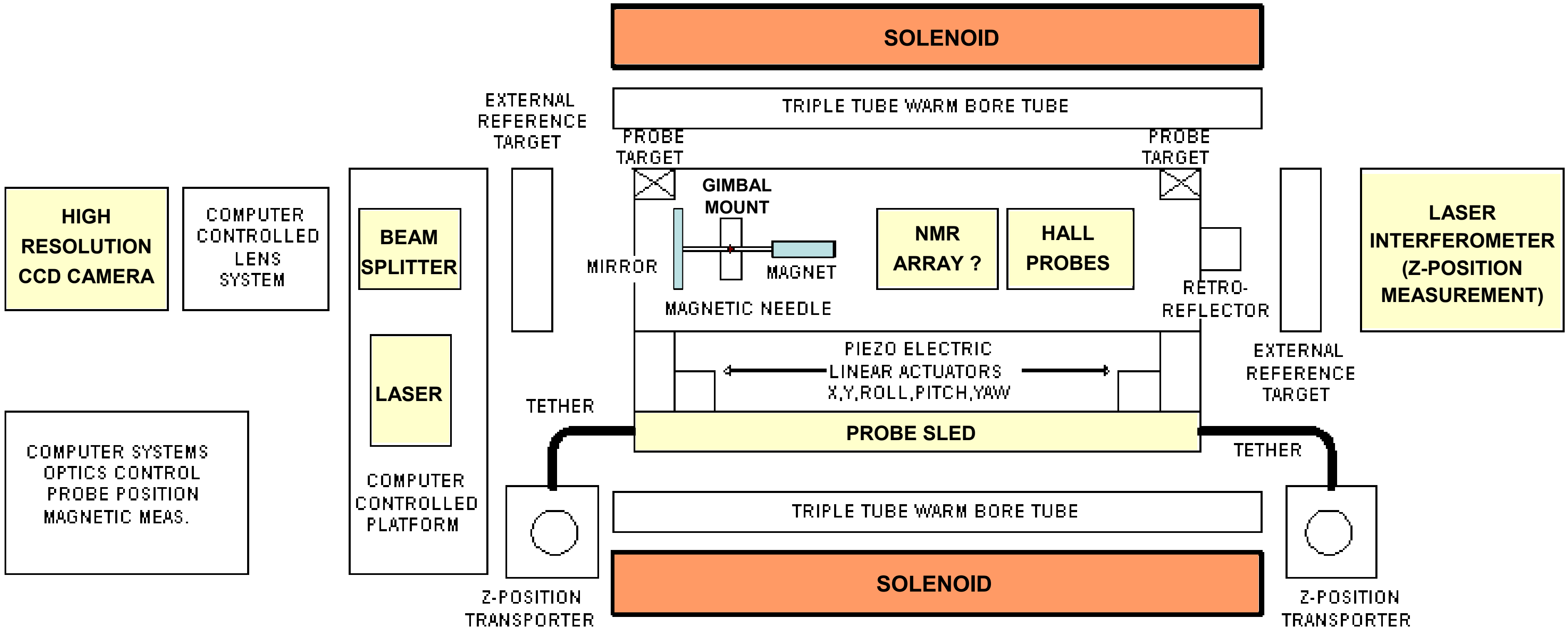
- 3-D Hall probe system (expected resolution of ~10^{-3} radian)
- Magnetic needle and mirror system (expected resolution of ~10^{-5} radian; used at BINP, IUCF, Fermilab)



(Based on *C. Crawford et al., FNAL and BINP, Proc. PAC'99, p. 3321-3*)

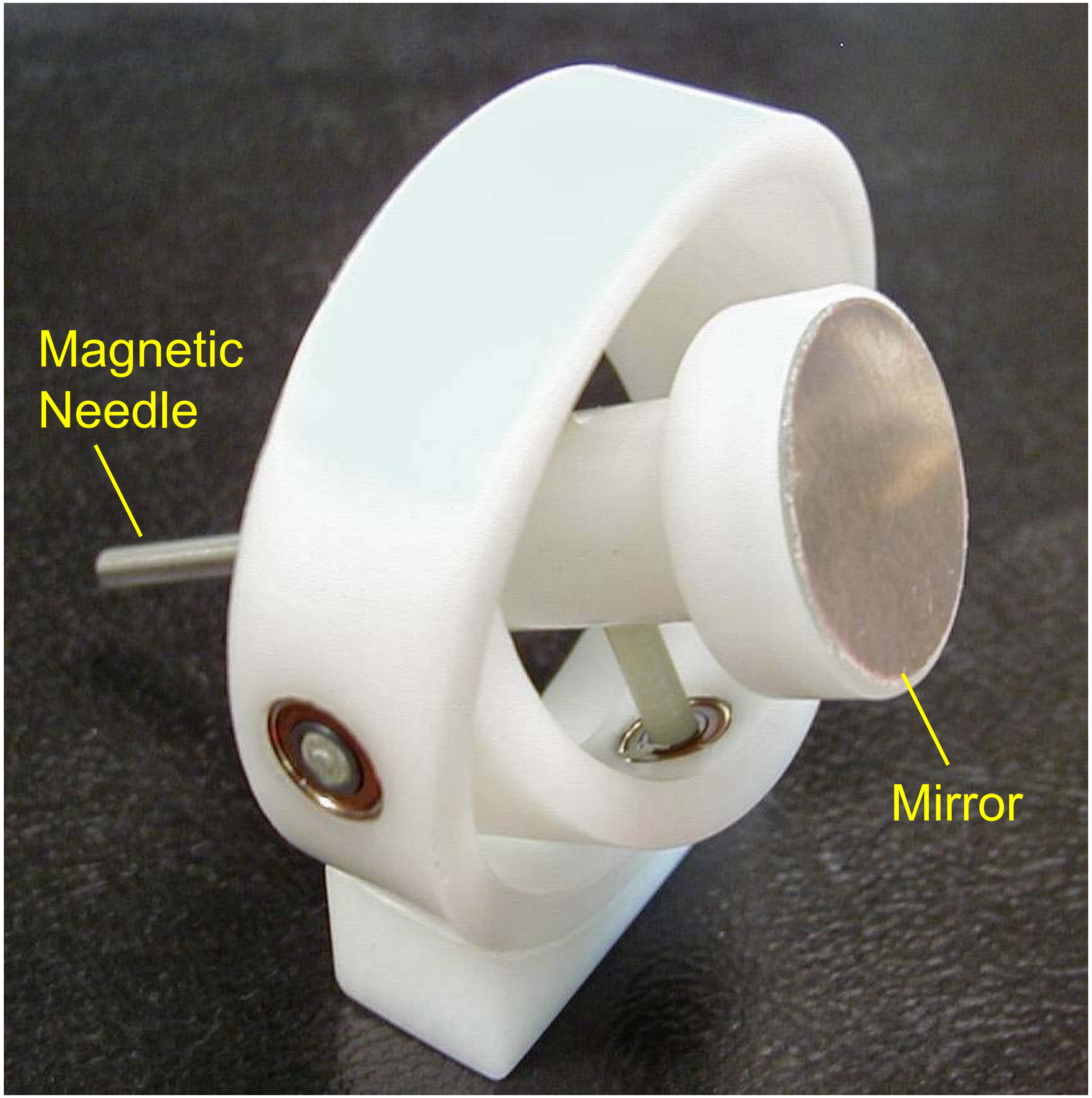
- Array of NMR probes(?) (< 10^{-5} rad.; development needed)

Measurement System Schematic

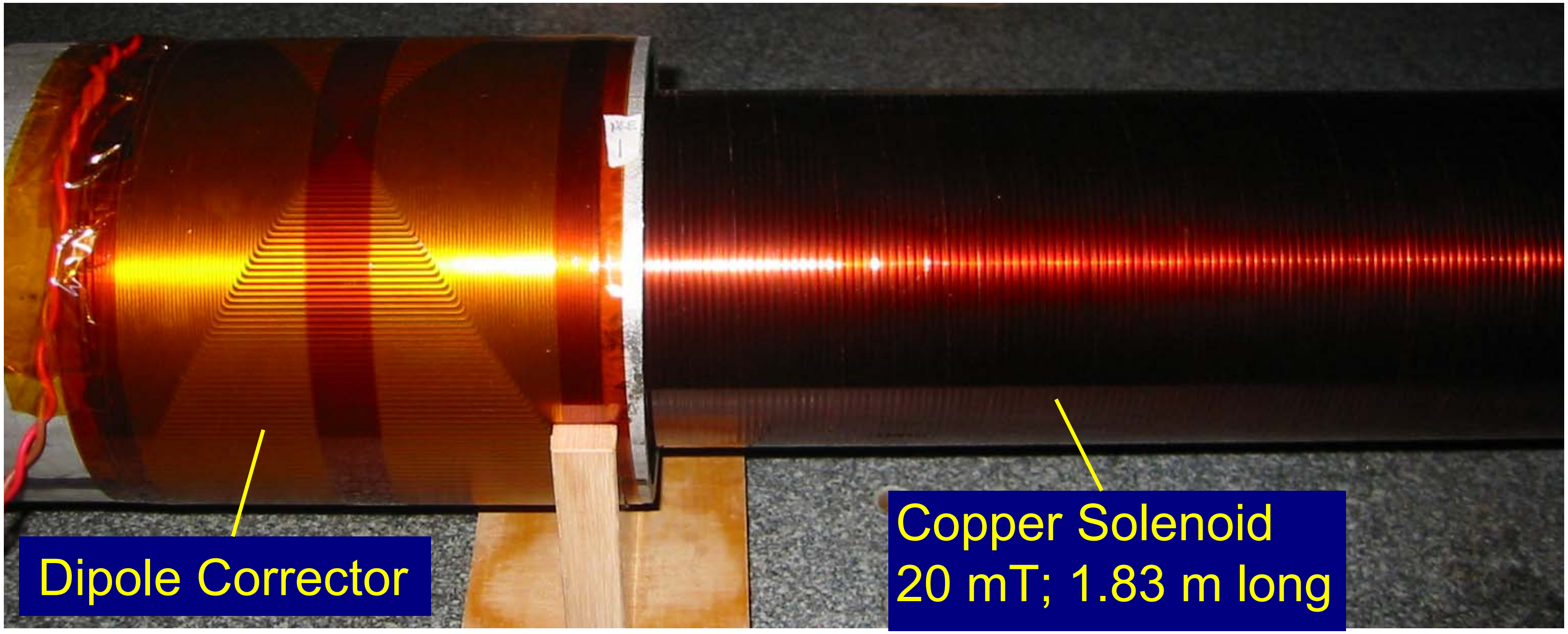


(from *George Ganetis, SMD*)

Gimbal mount for magnetic needle and mirror



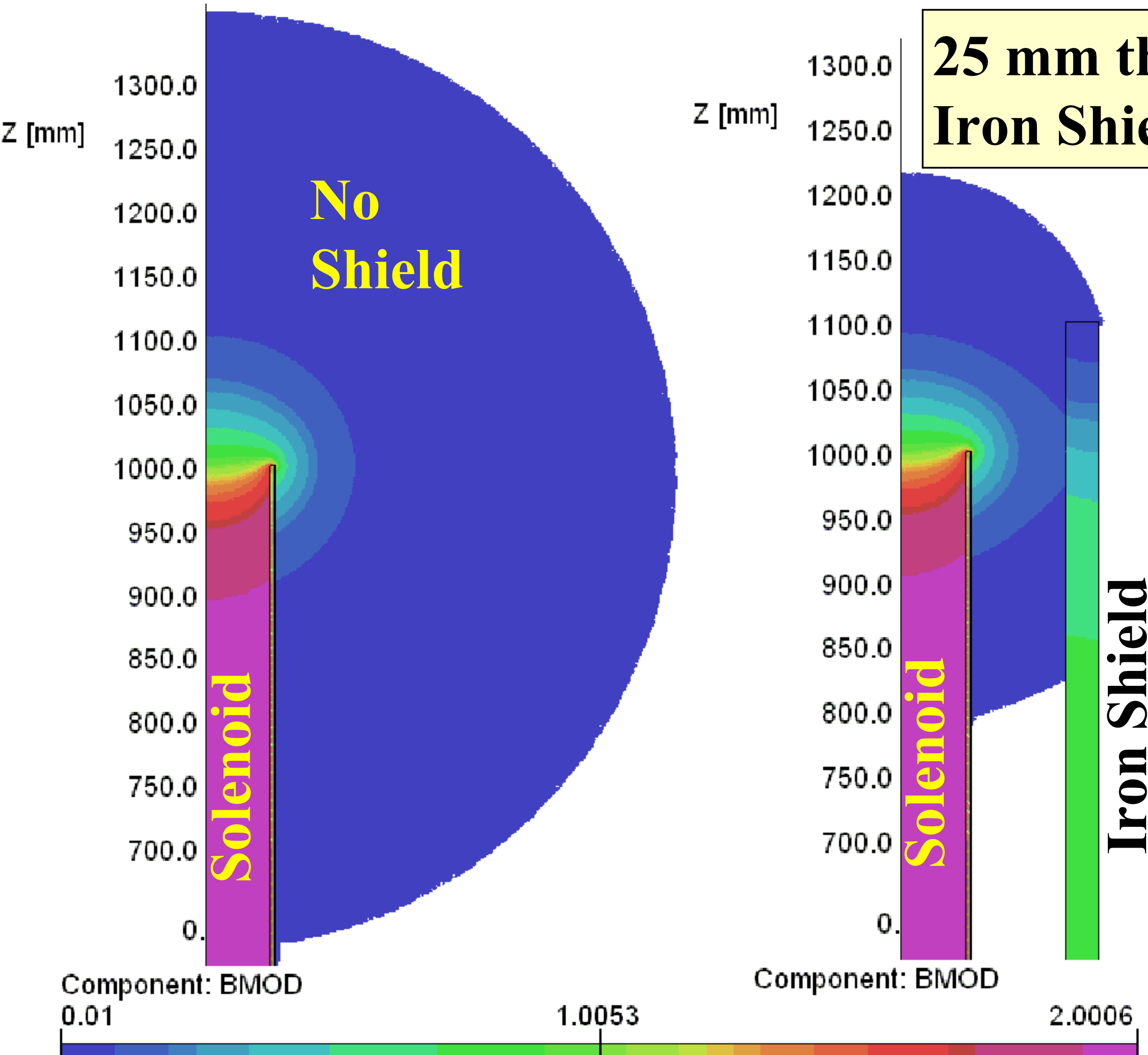
Setup for testing the measurement system



By exciting the dipole correctors at a known strength, the deflection of laser spot can be compared with the expected change in the solenoidal field direction.

The complete measurement system is currently under development.

Shielding: 100 Gauss Boundary at 2 T

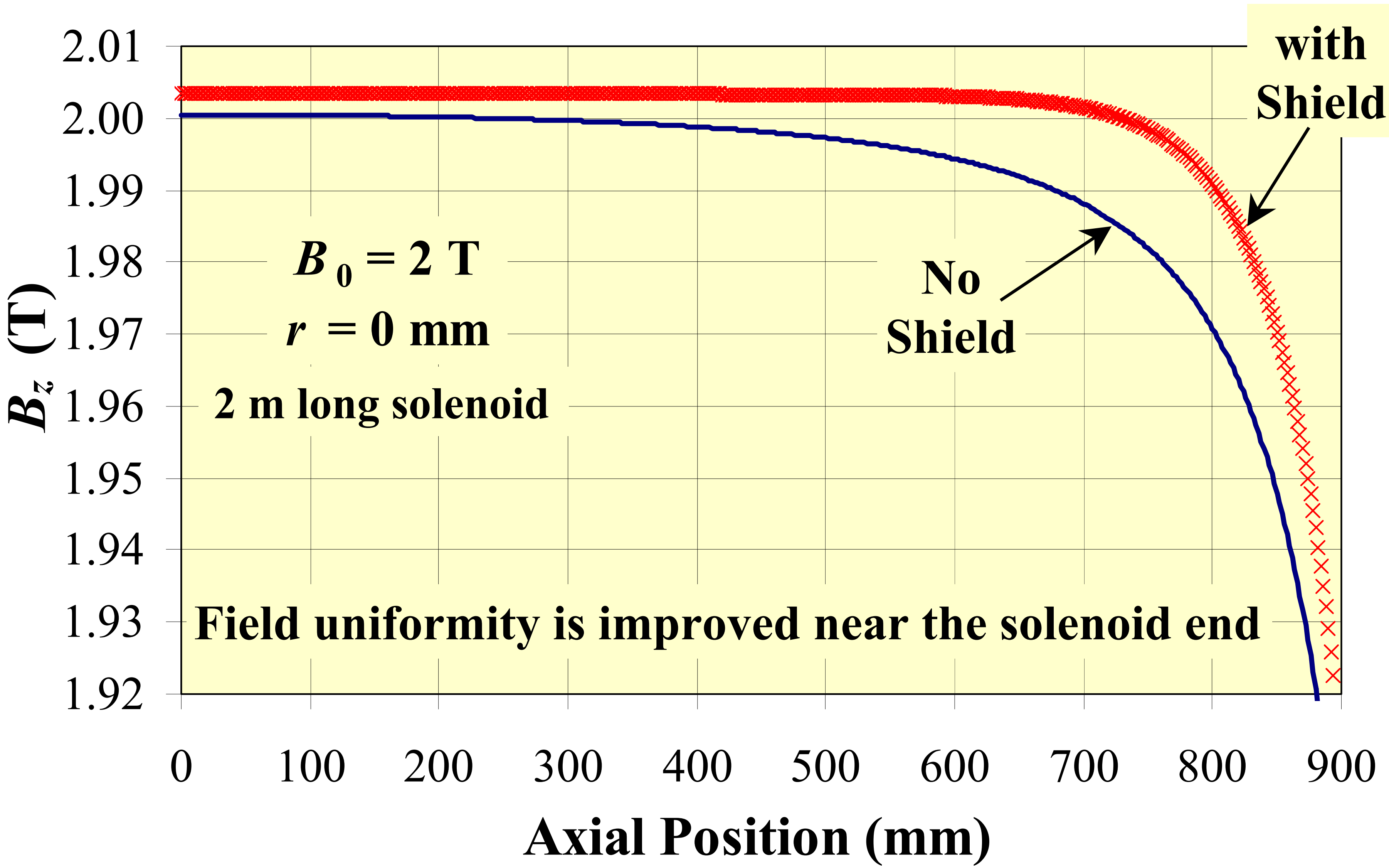


25 mm thick Iron Shield

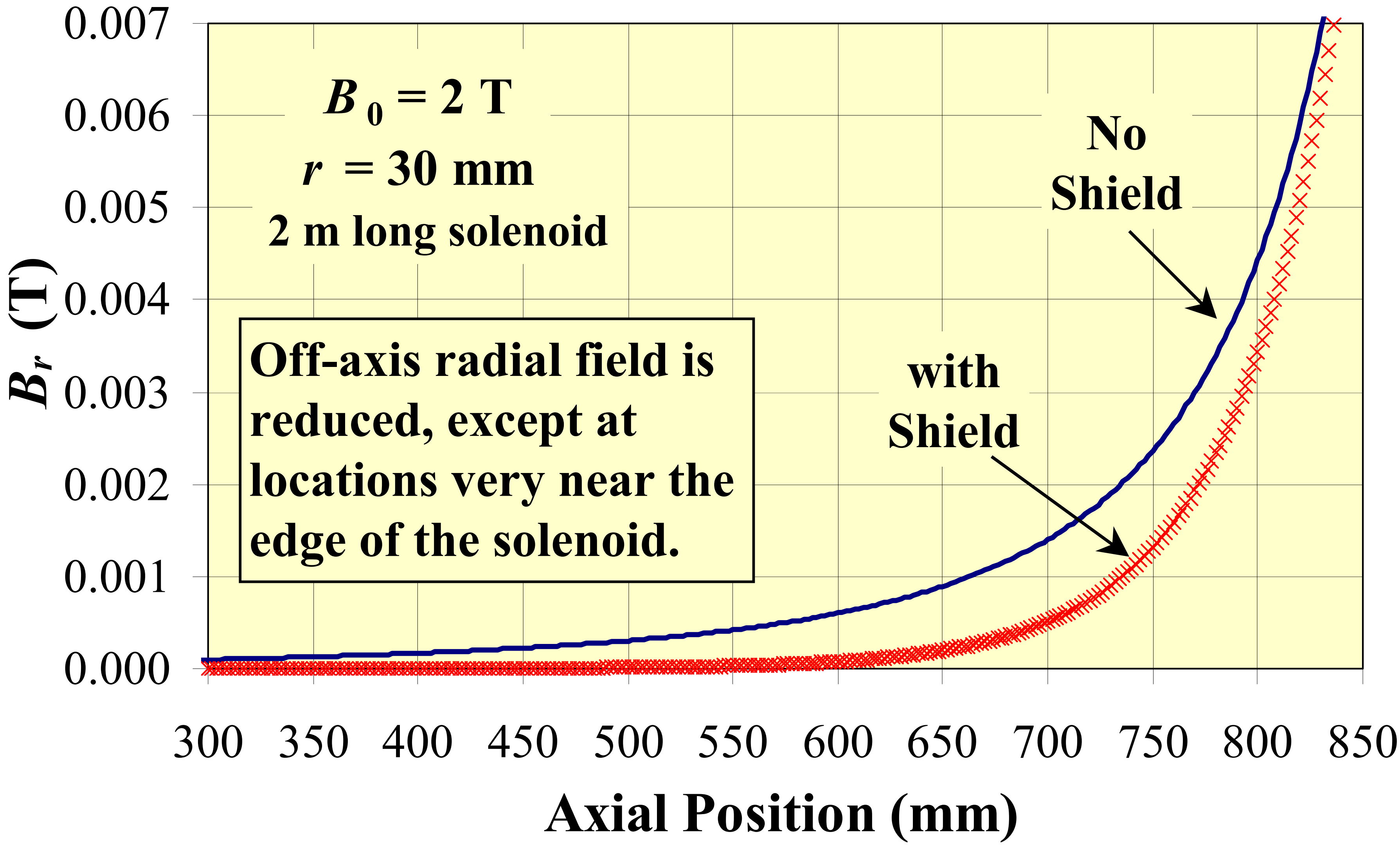
Significant amount of field leaks out of the solenoid ends.

An iron shield prevents field leakage, as well as protects the solenoid field from stray fields.

Shielding: Effect on Solenoid Field Profile



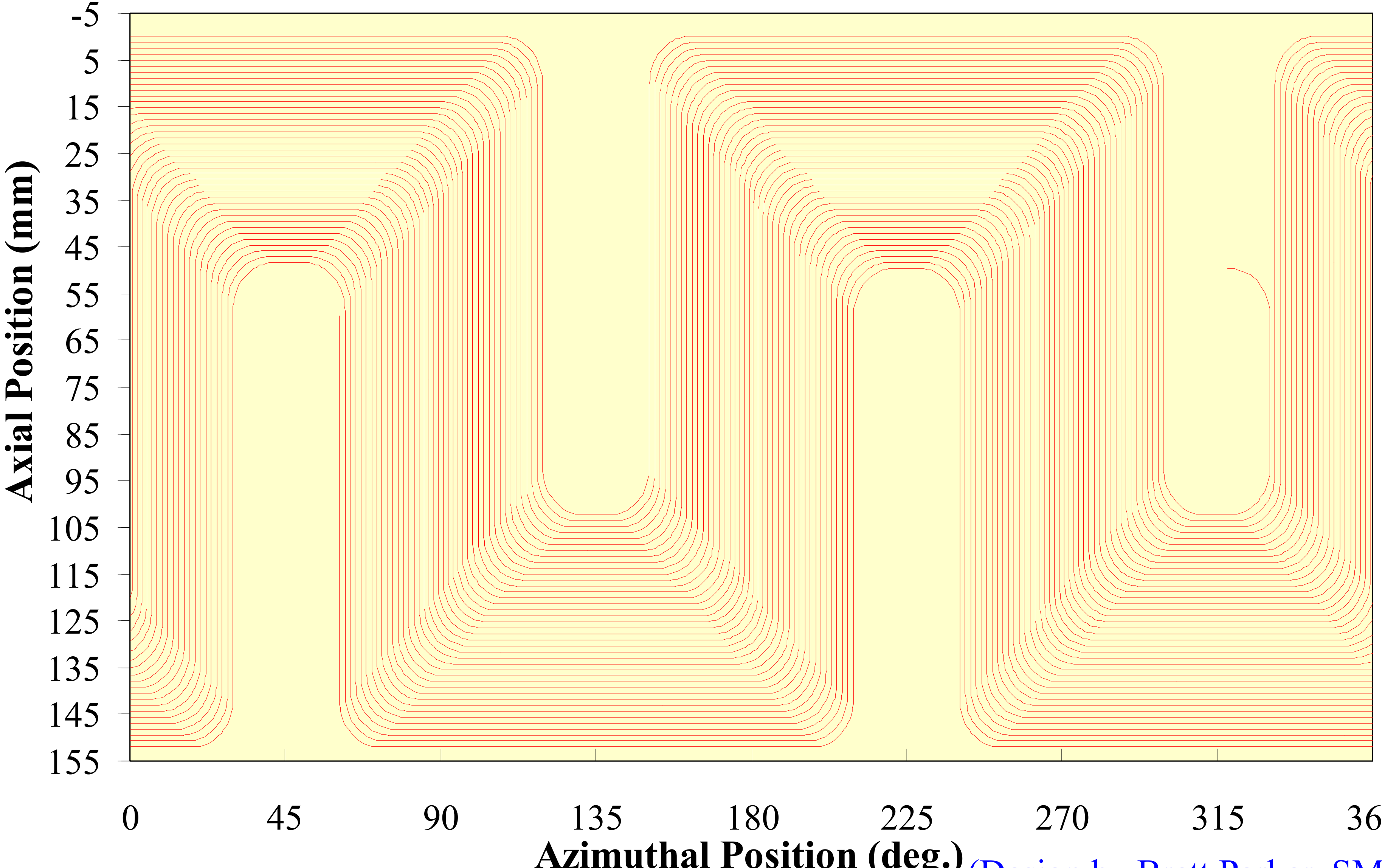
Shielding: Effect on Solenoid Field Profile



Quadrupole Triplets Between Solenoids

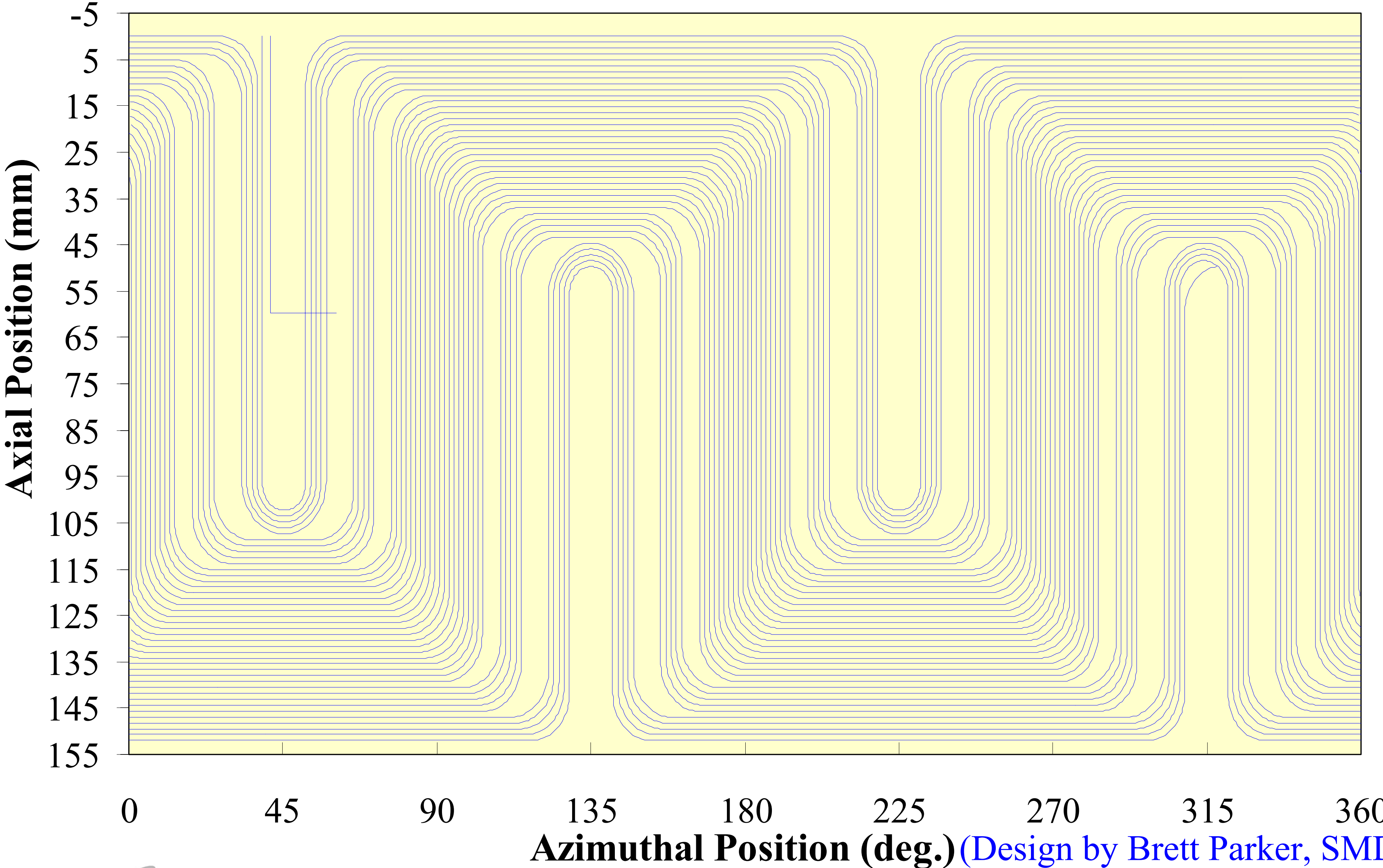
- A pair of quadrupole triplets is needed in the gaps:
  - ›› to prevent electron temperature rise
  - ›› to flip magnetization, so that opposing solenoids can be used to avoid x-y coupling
- Typical parameters assumed:
  - ›› 100 mm magnetic length (same as diameter !)
  - ›› 10 T/m gradient (1 Tesla integrated gradient)
- Will be produced by direct winding a 6-around-1 superconductor. Operating current ~ 530 A.
- 20 turns/pole, dual layer "Serpentine winding" patterns (recently developed by Brett Parker, BNL).

Quadrupole Corrector Pattern: Layer 1



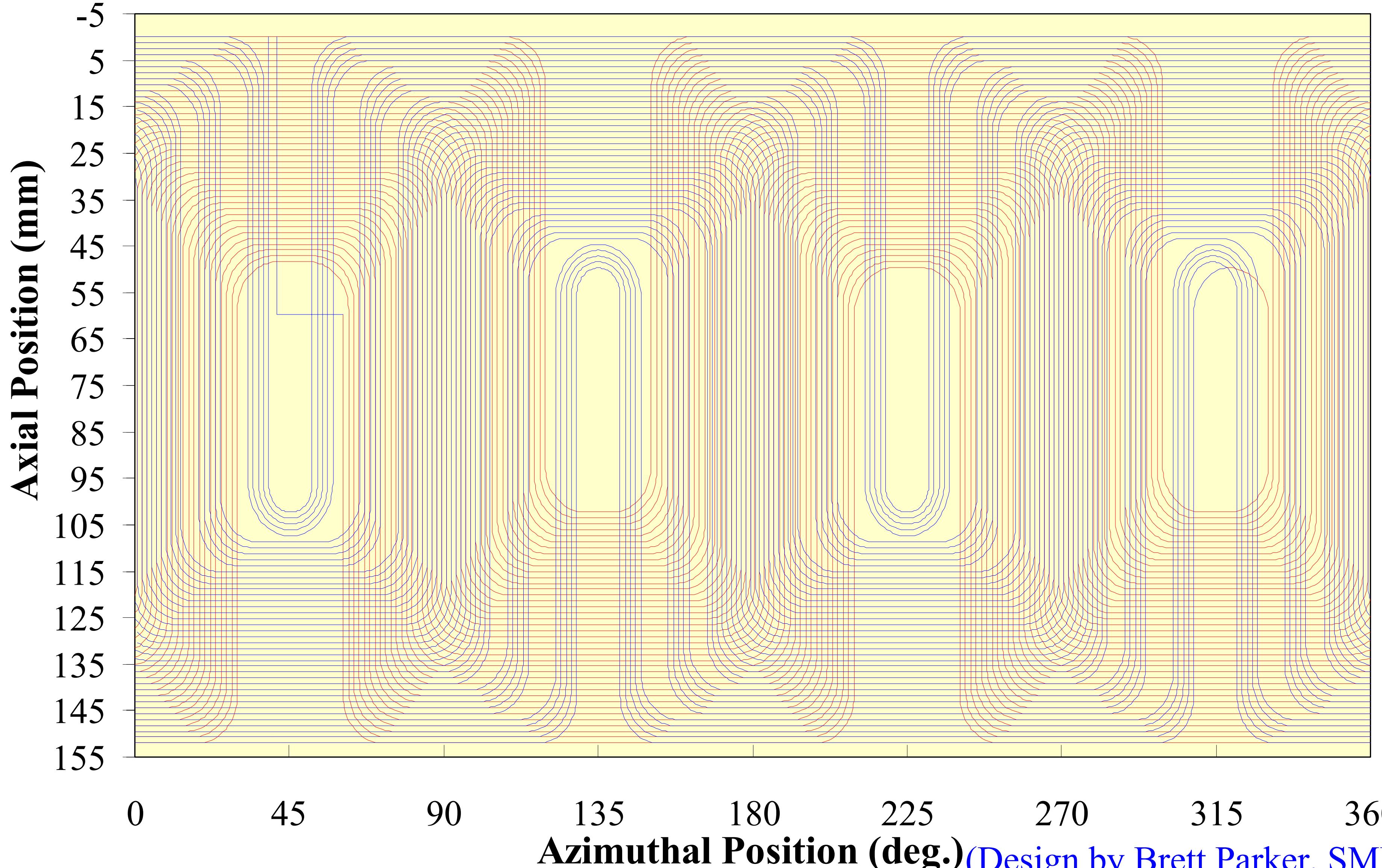
(Design by Brett Parker, SMD)

Quadrupole Corrector Pattern: Layer 2



(Design by Brett Parker, SMD)

Quadrupole Corrector: Layers 1 & 2



(Design by Brett Parker, SMD)

Technical Issues

- Field measurements appear most challenging
  - ›› ~ 1 μ rad resolution required, needs development
  - ›› Temperature gradients in the warm bore tube
  - ›› Techniques other than “mirror & needle” ?
- Simple solenoid, but complex overall system
  - ›› Significant engineering task
  - ›› Prototype experience will be very valuable
- Quench protection (appears manageable)
  - ›› Detailed analysis is needed. Work is in progress
- Layout of the quadrupole matching section
  - ›› Tracking with realistic field profiles
  - ›› Control field leakage from solenoid into quads?
  - ›› Work is in progress

Summary

- A conceptual design of the solenoid, and associated correctors, is completed.
- Engineering design of a short prototype is in progress.
- Prototype dipole correctors have been fabricated
- The correction scheme is shown to work using synthetic data.
- Quadrupole correctors will use winding techniques already well developed at BNL.
- Field direction measurement system is under development.