Solenoid & Wiggler R&D for the Electron Cooler for RHIC

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BROOKHAVEN NATIONAL LABORATORY

RHIC

Introduction

- A 2 Tesla solenoid was initially foreseen for the electron cooling project, which was later changed to a 5 Tesla field (magnetized cooling).
- A basic magnetic design was completed for both versions.
- A dipole correction scheme was worked out to achieve the required field straightness.
- The present plan calls for a low field wiggler (non-magnetized cooling).
- The work done so far is summarized in this talk.

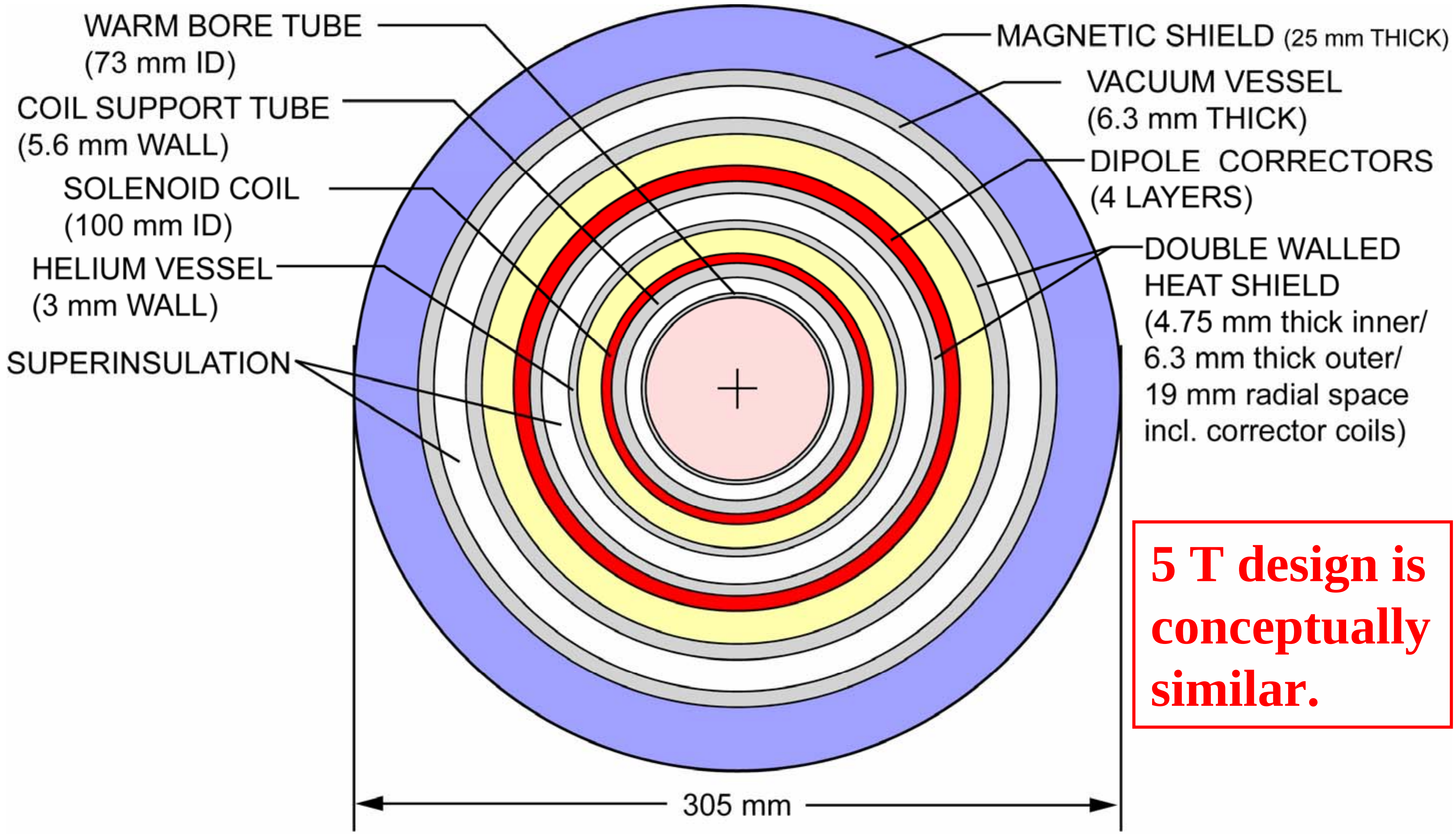
e-Cooling Solenoid Requirements

- 5 Tesla axial field (may change back to 2 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

Major Cost Driver

- End design details were not fully worked out:
  - Available gap between solenoids ?
  - Correction system and diagnostics in the gap ?

Solenoid Cross Section: 2 Tesla Design



5 T design is conceptually similar.

2 Tesla 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 (~3 m long) was planned, but not built.

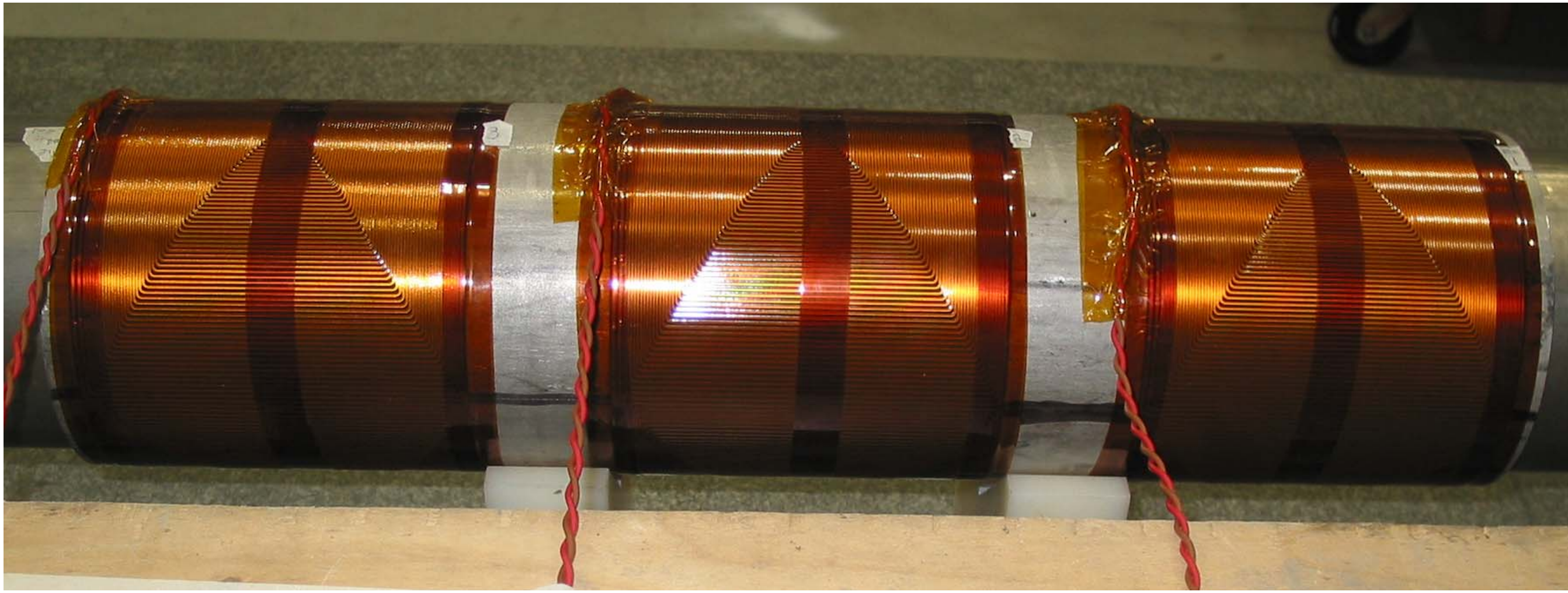
5 T Solenoid Characteristics

- Coil ID = 100 mm; Length ~ 3 meters (prototype)
- 18-strand (or 16-strand) cable from LHC outer wire.
- 6 Layers; 5.0 Tesla field at ~ 5.07 kA.
- Inductance = 7 mH/meter; Energy = 90 kJ/meter (5T)
- Peak hoop stress in the coil = 101 MPa (~ 14.6 kpsi)
- Maximum axial force per turn = 7.2 kN (~ 1600 lbf)
- 4 layers of dipole correction coils, each ~300 mm long (~40 correctors in 3 m) – May be changed to 150 mm long correctors for 2 T operating field, with twice the number.

Dipole Correction Coils

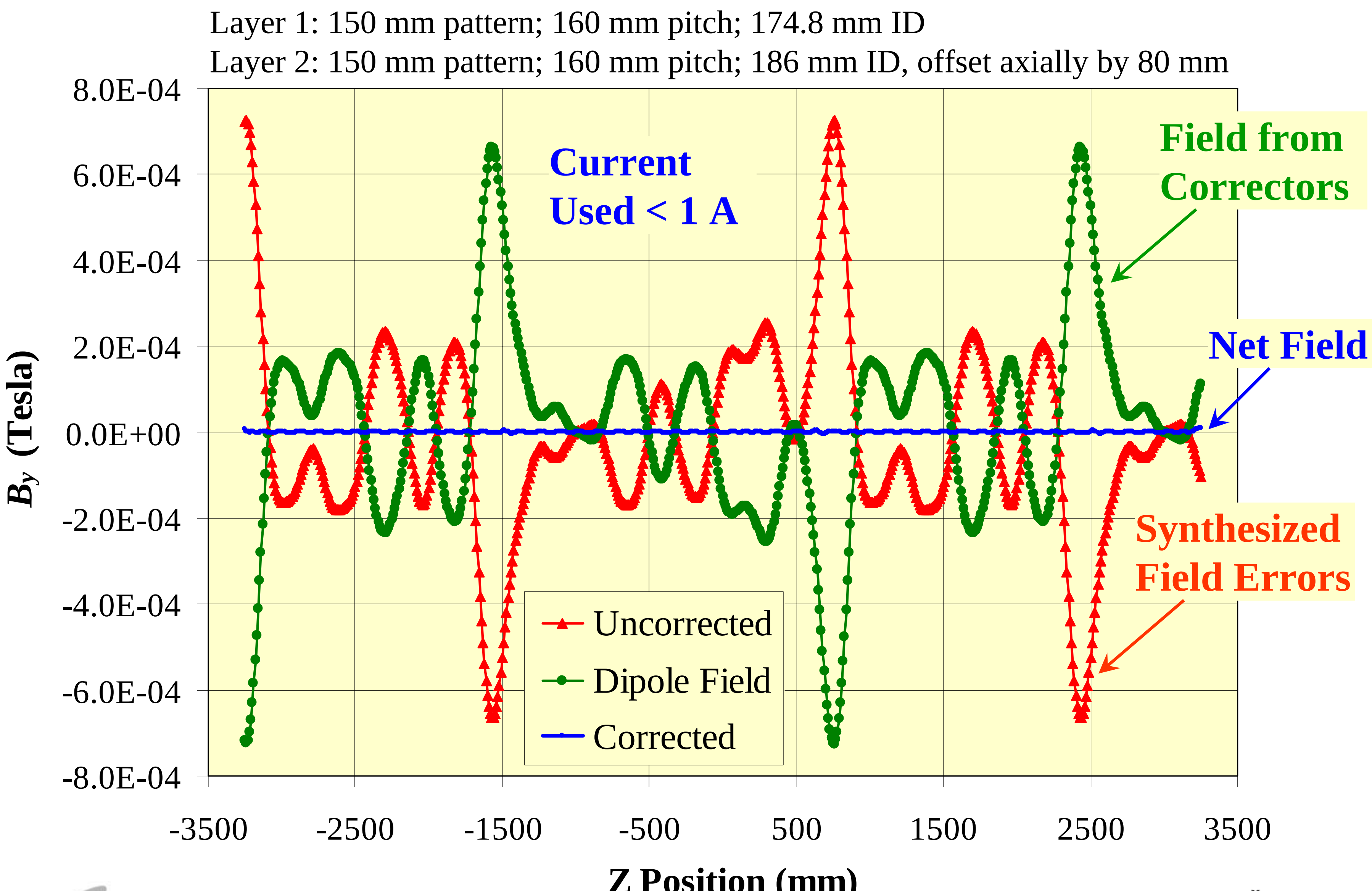
- $B_\perp / B_z < 10^{-5}$ implies a straightness of better than 10 μm over 1 meter length. This may not be achieved with mechanical alignment alone.
- Winding imperfections are also likely to produce transverse fields on-axis.
- Goal is to achieve as close to requirement as possible with construction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

Printed Circuit Dipole Correctors for 2 T

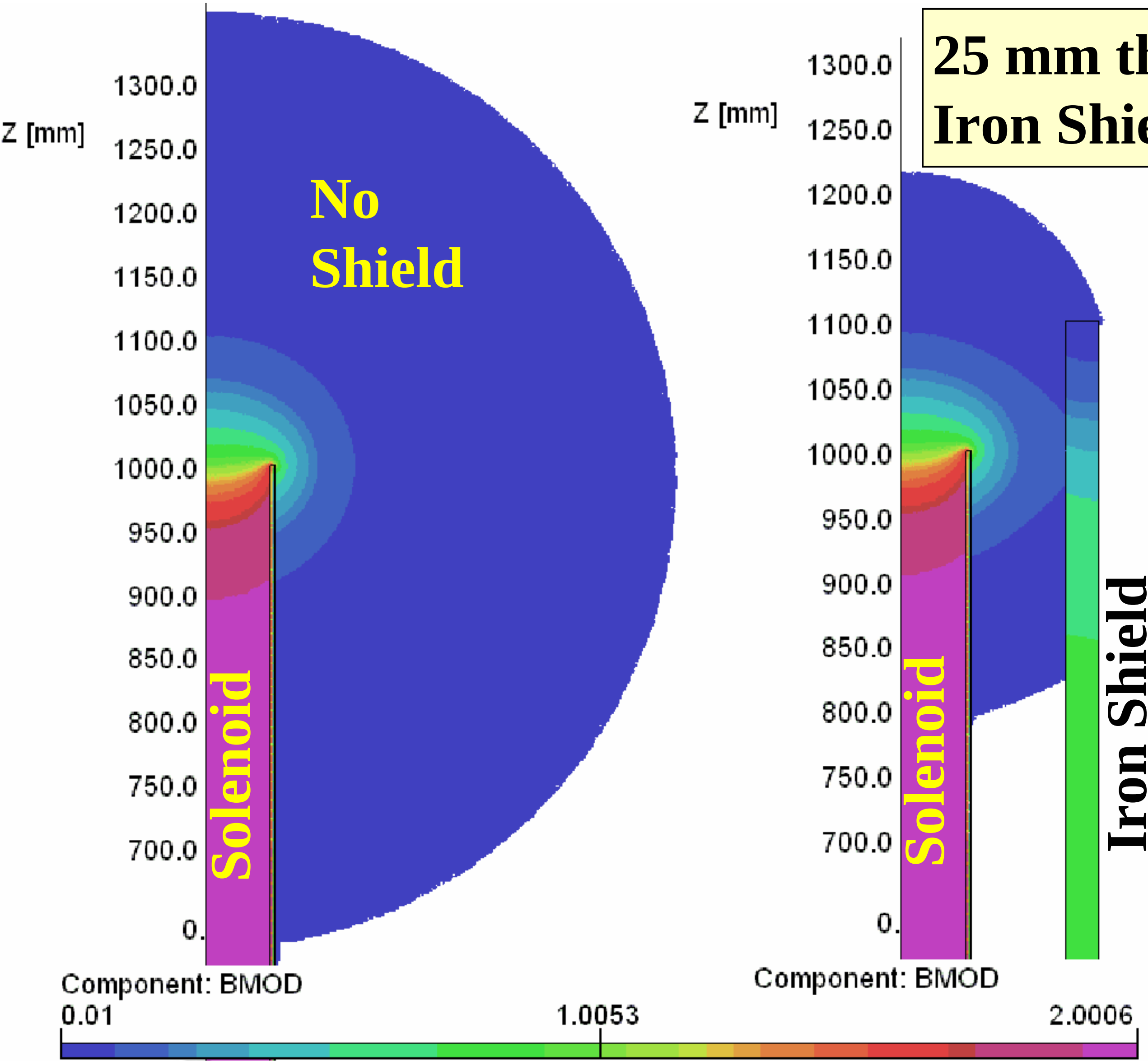


- 2 Layers of 4 oz Copper patterns; 159 mm ID, 150 mm long
- 1.25 $\times 10^{-3}$ Tesla central field at 2 A; $\Delta B/B \sim 10^{-3}$ at 50 mm
- Mounted on cryogenic heat shield to minimize dissipated power (approx. 190 W/m expected at full power).

Simulation to Check Correction Algorithm



Shielding: 100 Gauss Boundary at 2 T

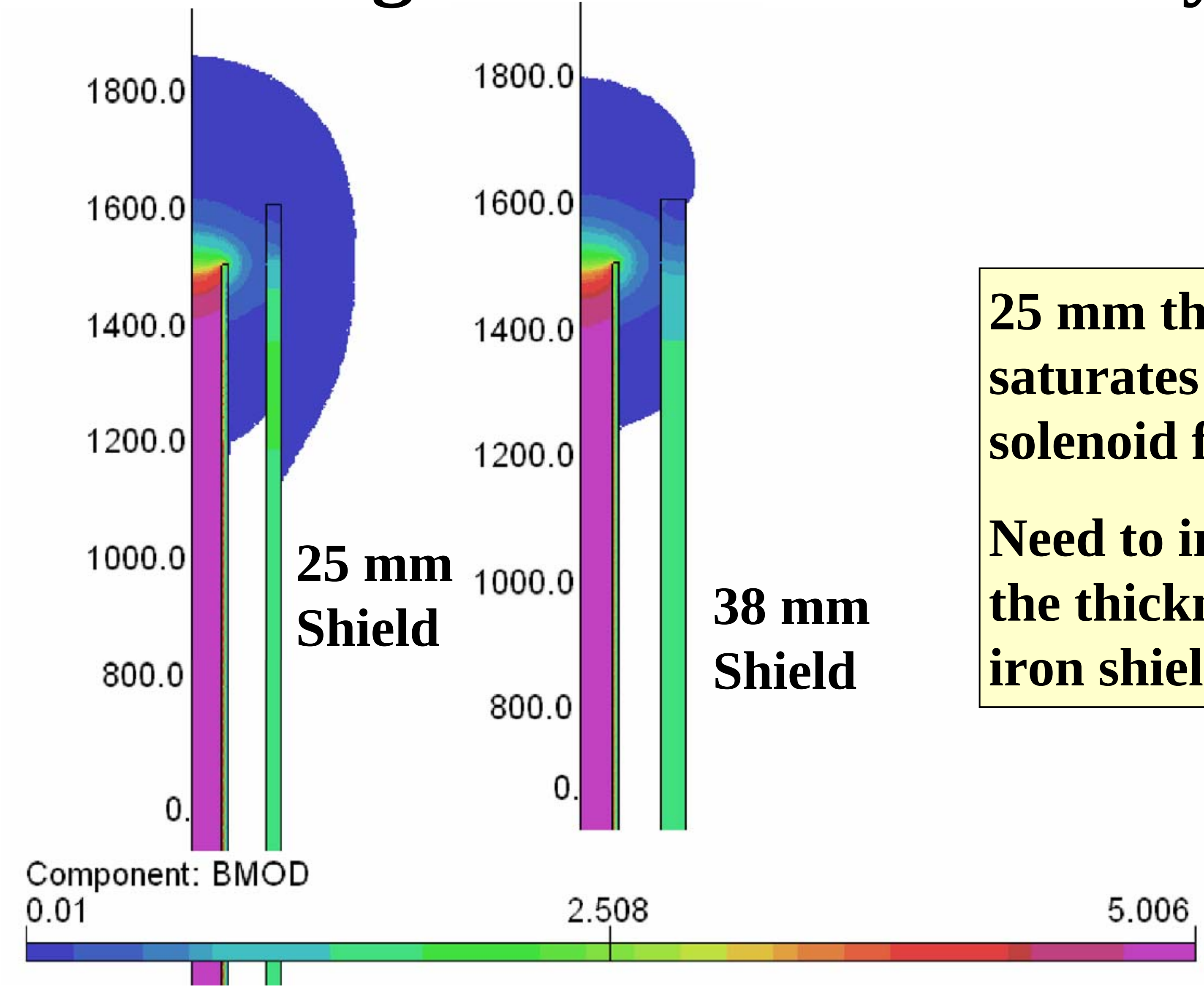


25 mm thick Iron Shield

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: 100 Gauss Boundary at 5 T

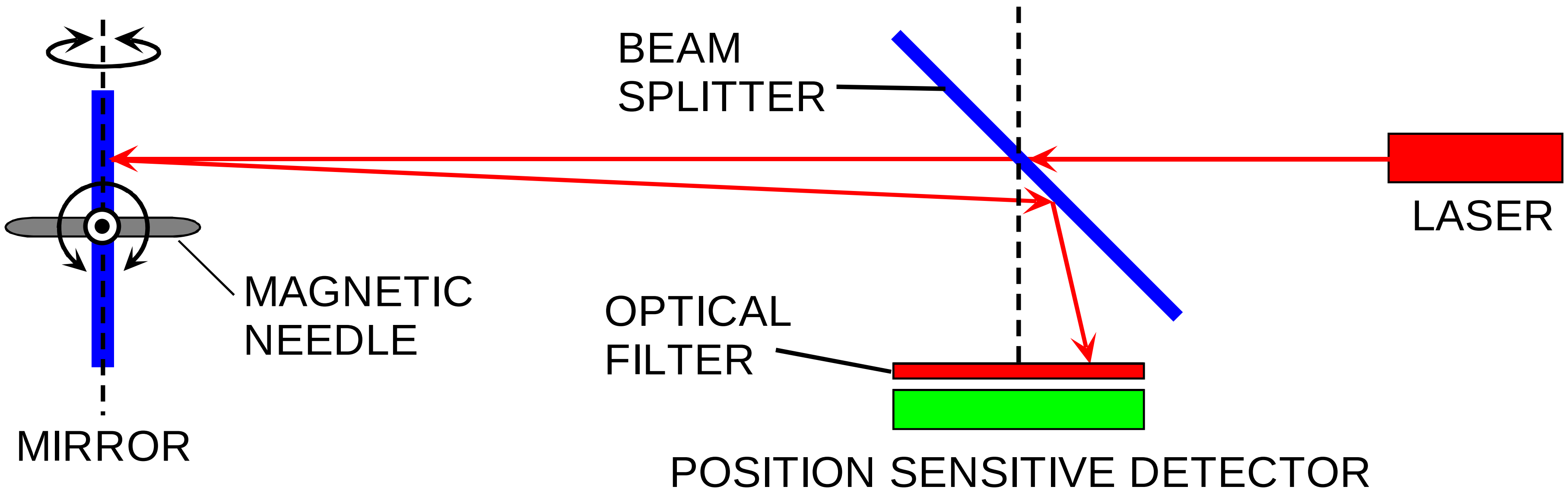


25 mm thick iron saturates for 5 T solenoid field.

Need to increase the thickness of iron shield.

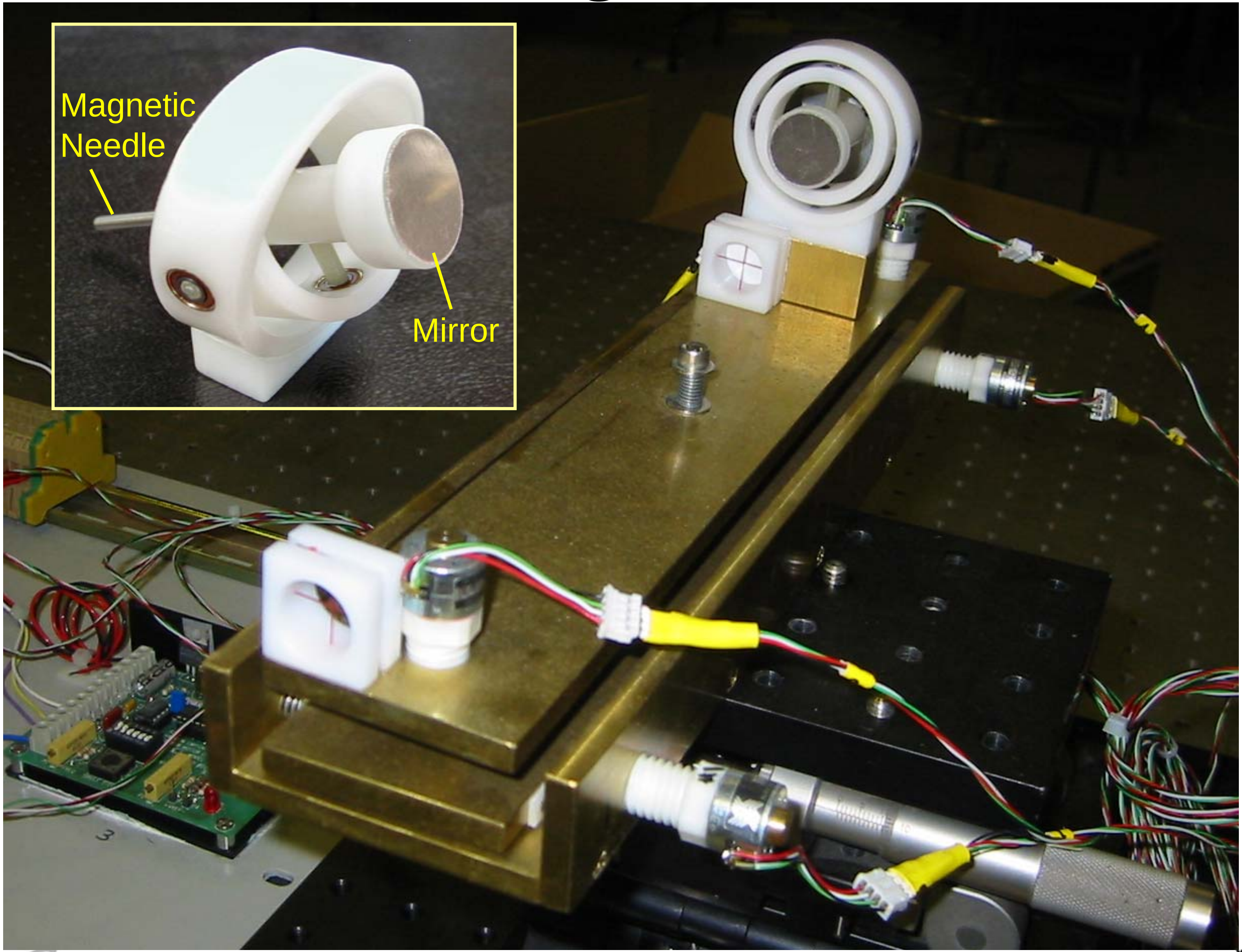
e-Cooler Solenoid Measurement System

- 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*)

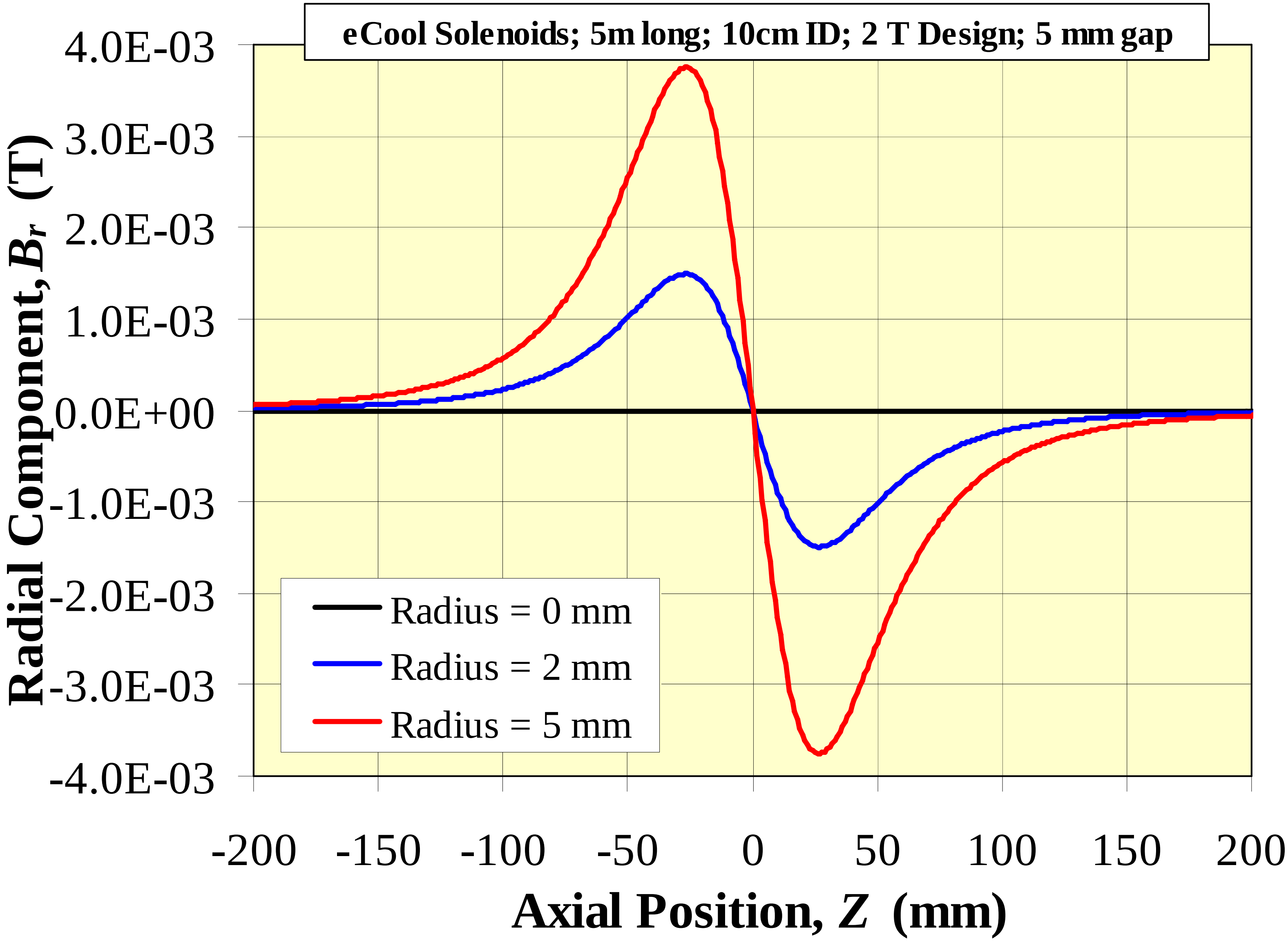
Gimbal mount for magnetic needle and mirror



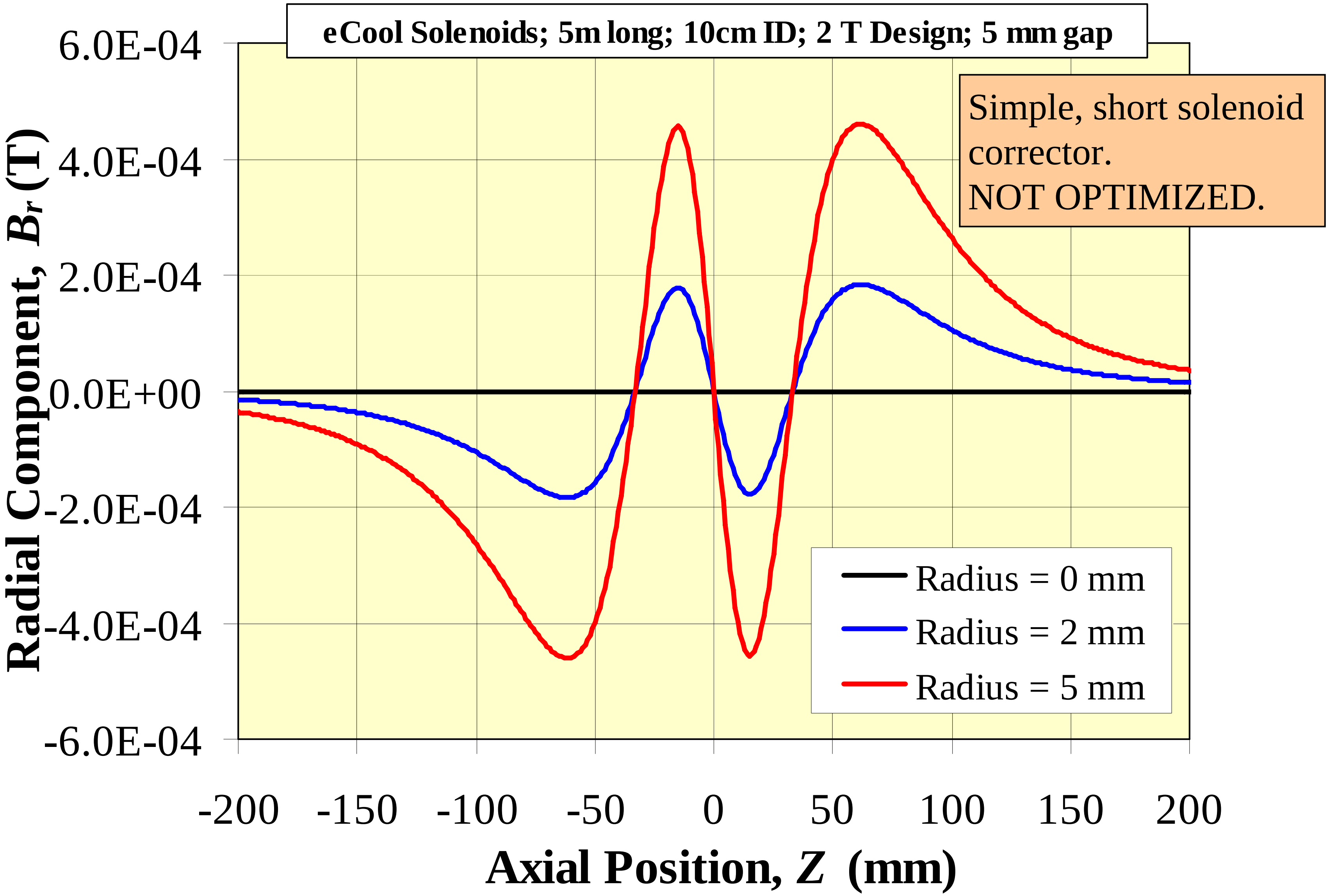
Connecting Solenoids with "Zero Gap"

- It is desirable to produce the solenoid as a single 30 meter long unit from the point of view of cooling.
- Such a length presents formidable manufacturing and testing difficulties.
- Could one connect two solenoids with a minimal gap, so that the system may appear as close to a continuous solenoid as possible?
- It may be possible to achieve a gap of as little as ~5 mm. However, even this may have significant impact on the field quality at the joint.

Radial Field with 5 mm Gap



Radial Field with 5 mm Gap & Corrector



Solenoid Summary

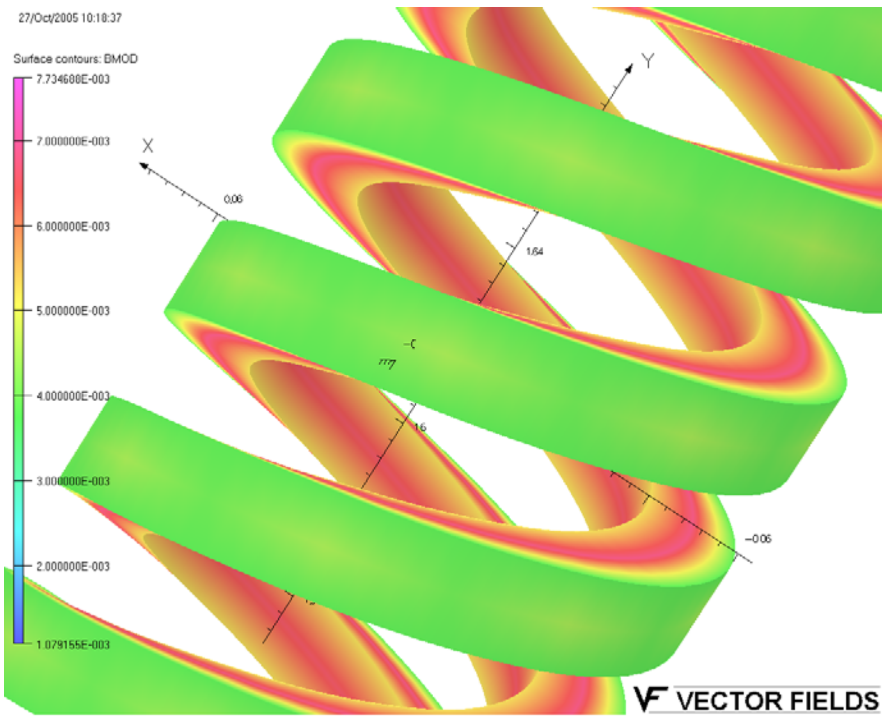
- Conceptual designs for both 2 T and 5 T exist.
- Dipole correction scheme is worked out.
- Corrector length: 150 mm for 2 T; 300 mm for 5 T.
- Large number of correctors introduces complexity.
- Two solenoid ends may be as close as 5 mm, but field perturbation may still require correction.
- Measurement of field straightness is challenging, and system development is required.
- A beam based alignment scheme has been studied, and appears feasible (Peter Cameron: PAC'05).

Wiggler for Non-magnetized Cooling

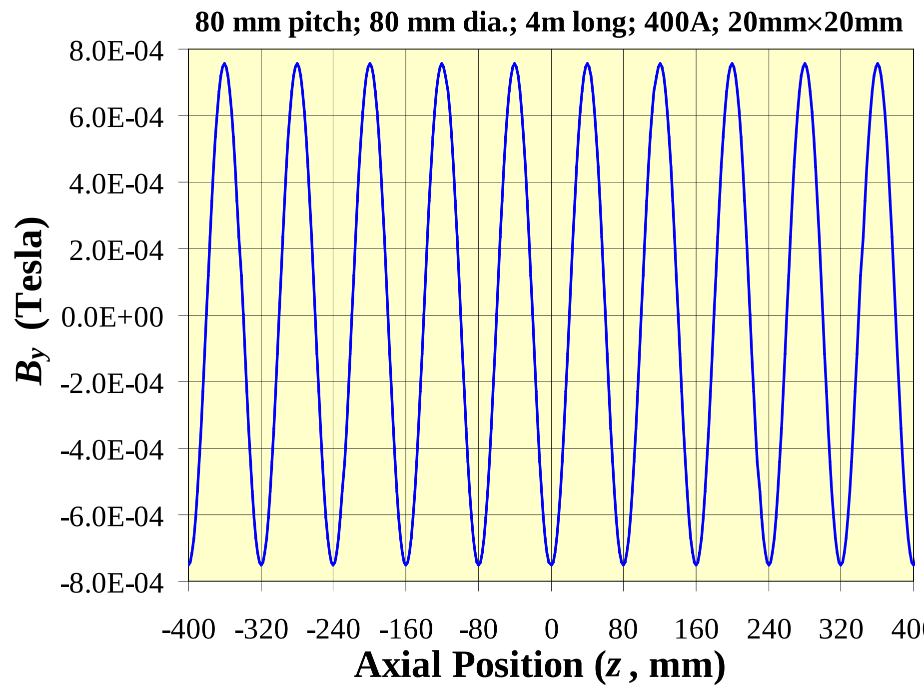
- Non-magnetized cooling requires a low field wiggler with a period of several cm.
- Parameter set presently being considered:
  80 mm diameter; 80 mm pitch; ~ 1 mT field
  - Current density required is too high for air cooled coils.
  - Could be done with water cooled coils.
  - Easy to do with HTS coils at 77 K, with a lot of margin.

Air Cooled Coils: 20 mm × 20 mm

Pitch = 80 mm, diameter = 80 mm, required field = 1 mT.



(Opera model from *Ramesh Gupta, SMD*)



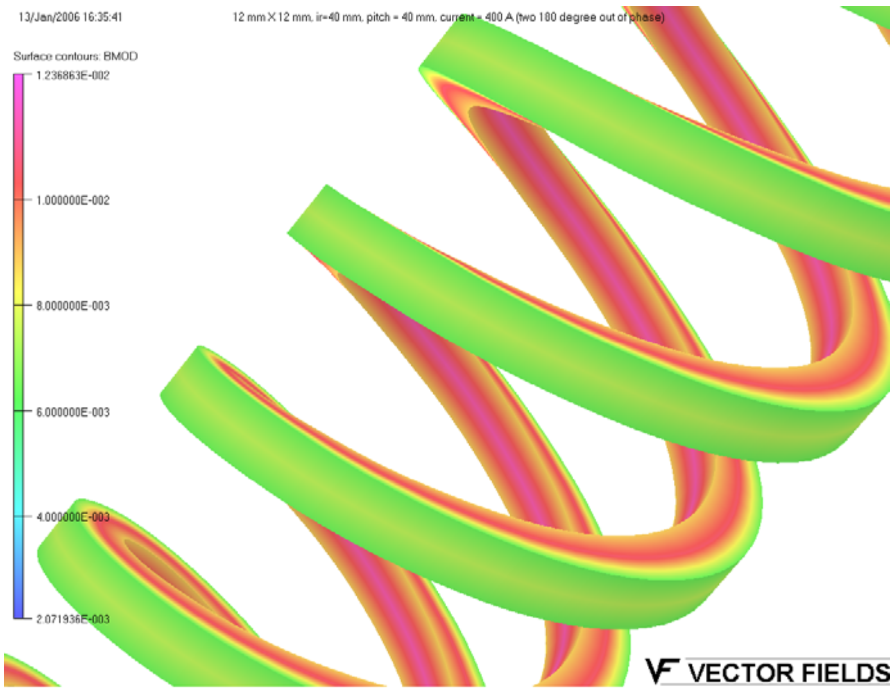
1 A/mm² creates only ~ 0.75 mT

~ 1.35 A/mm² needed for 1 mT

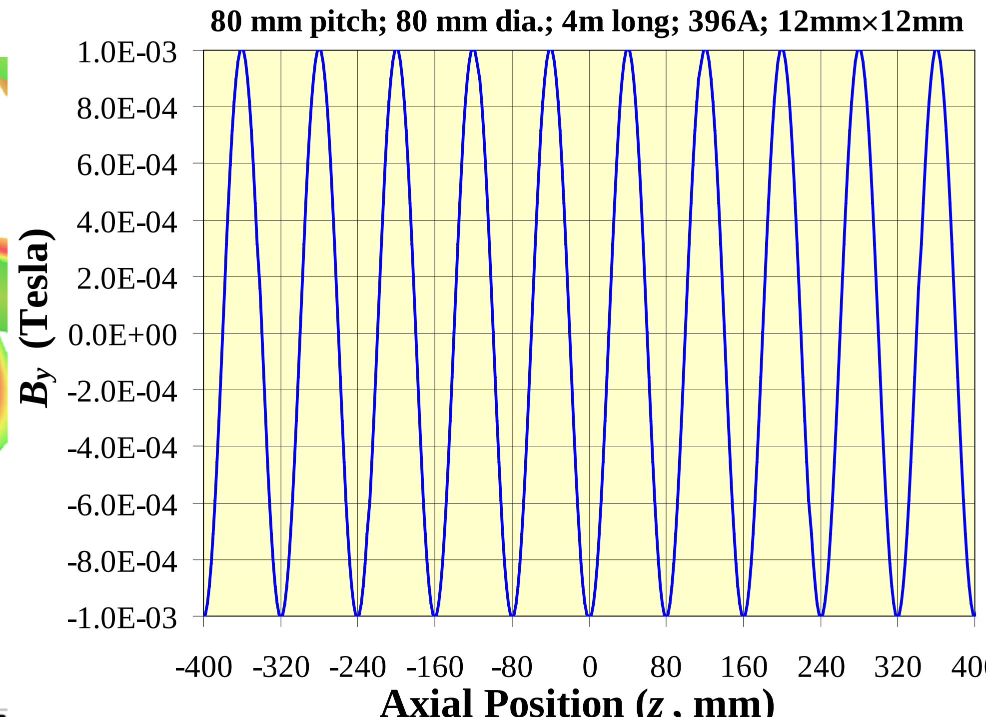
~ 35% more than typical limit of 1 A/mm² for air-cooled coils

Water Cooled Coils: 12 mm×12 mm

Pitch = 80 mm, diameter = 80 mm, required field = 1 mT.



(Opera model from *Ramesh Gupta, SMD*)

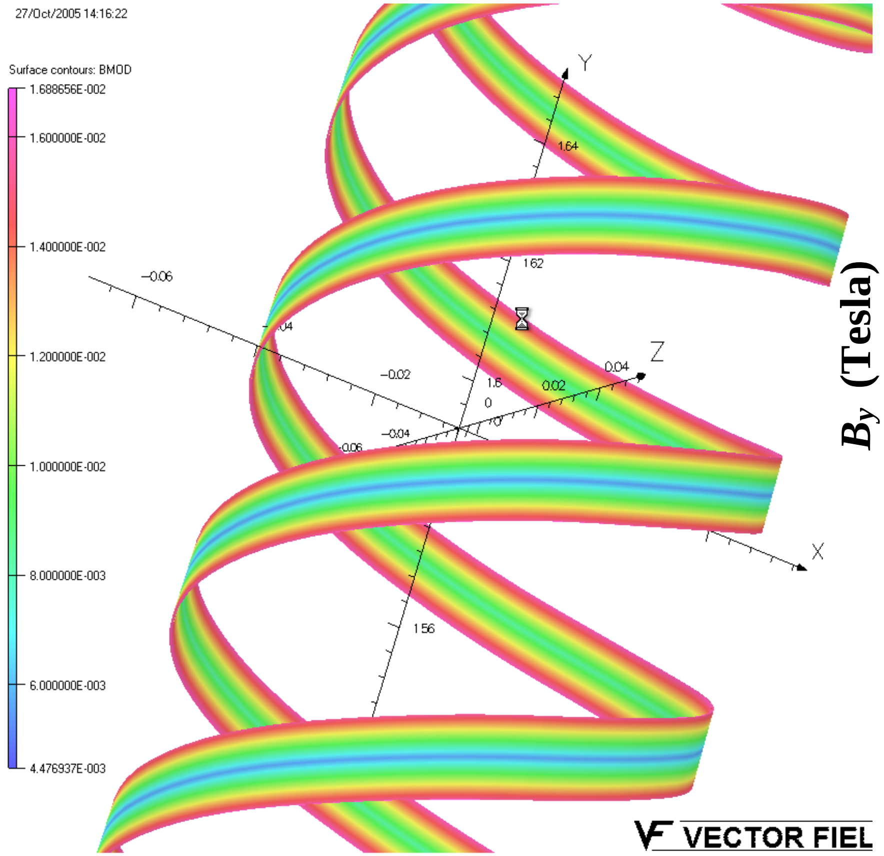


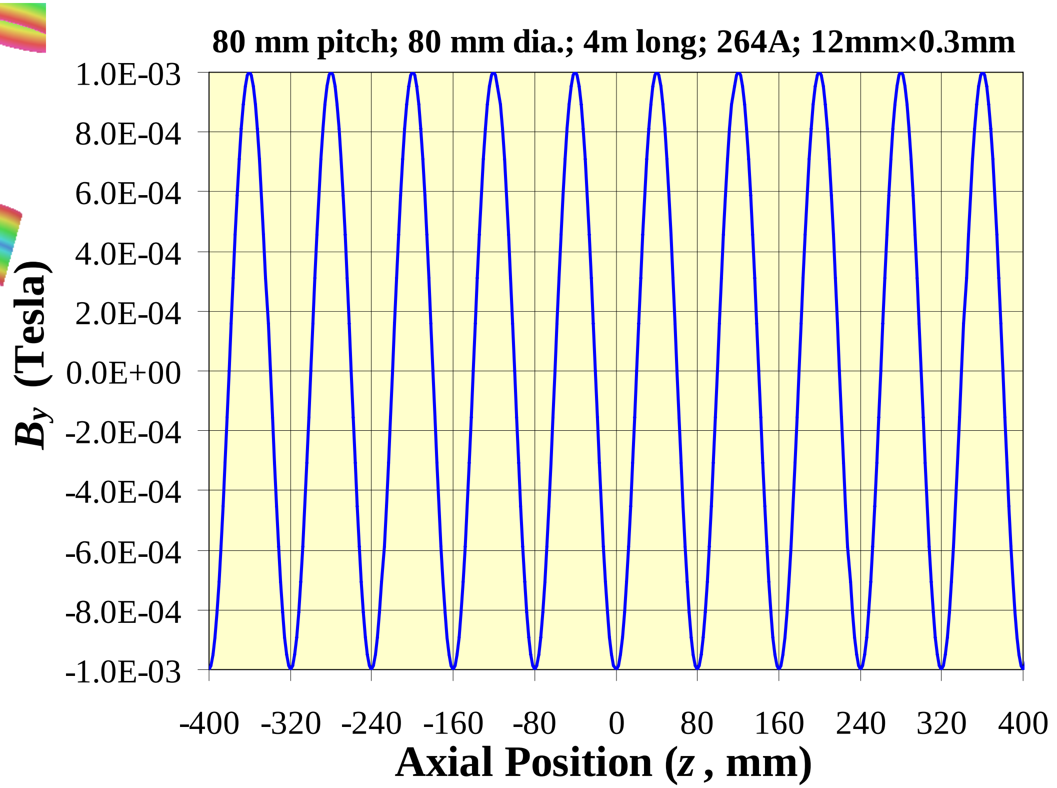
396 A gives 1 mT (2.75 A/mm^2)

With a 7 mm diameter cooling channel, current density in copper is ~ 3.8 A/mm^2: should be OK

HTS Coils at 77K: 12 mm × 0.3 mm

Pitch = 80 mm, diameter = 80 mm, required field = 1 mT.





(Opera model from *Ramesh Gupta, SMD*)

Three 4 mm wide tapes, side by side

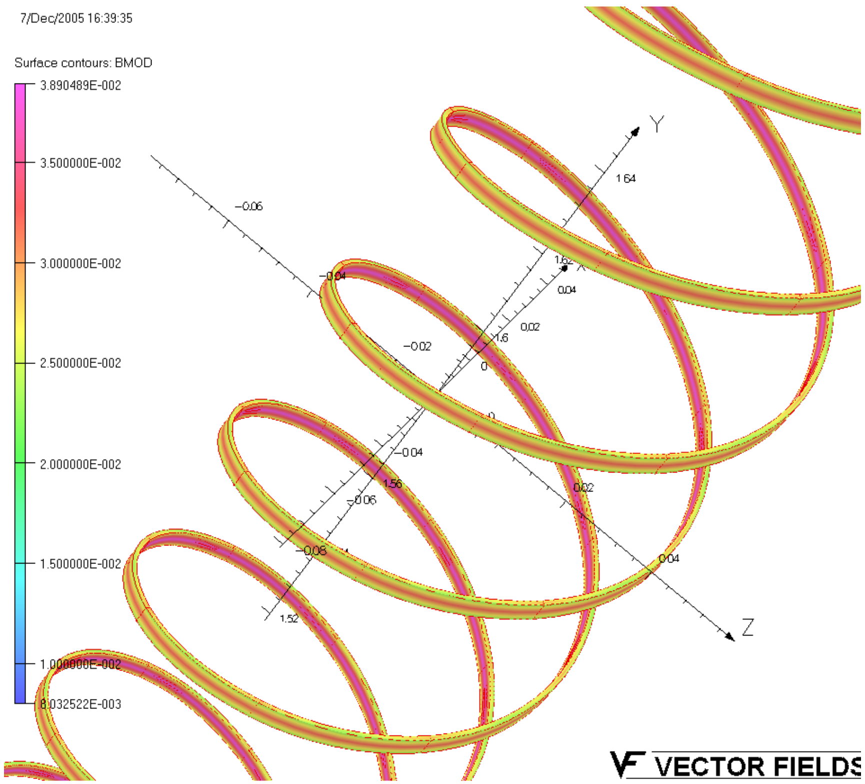
264 A gives 1 mT

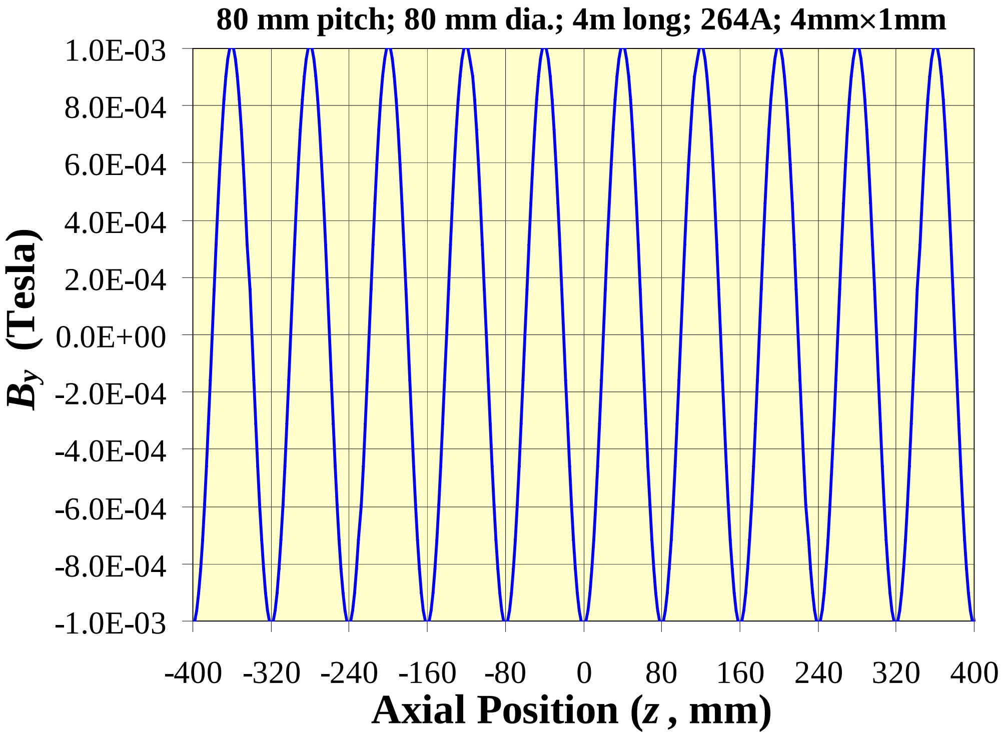
Current density is < 75 A/mm^2

Conductor has >100% margin.

HTS Coils at 77K: 4 mm × 1 mm

Pitch = 80 mm, diameter = 80 mm, required field = 1 mT.





(Opera model from *Ramesh Gupta, SMD*)

Three layers of 4 mm wide tapes

264 A gives 1 mT

Current density is < 75 A/mm²

Conductor has >100% margin.

Wiggler Issues

- Low field device – field quality and alignment should be less critical, but easily affected by stray fields.
- What measurements are needed? (Measurements with a short rotating coil are planned.)
- BPMs to monitor alignment of the electrons and ions.
- Some dipole correctors may be needed.
- Power dissipation for the 12 mm × 12 mm conductor design is estimated to be ~2.3 KW for a 10 m long module. A cooling analysis is needed.
- Manufacturing details have not been worked out yet. Need to establish tolerances.

Wiggler Summary

- Wiggler parameters are not finalized yet.
- Multiple coil solutions are studied for a period of 80 mm, and a diameter of 80 mm.
- 1 mT field is ~35% above what typical 1 A/mm^2 in an air-cooled coil would provide.
- Water cooled coils (12 mm x 12 mm) may do the job, but cooling analysis is needed.
- HTS coils may also provide practical solutions, particularly if wavelengths shorter than 80 mm, or fields stronger than 1 mT are required.
- Optimal design would depend on final parameters.