A Review of BNL Direct-Wind Superconducting IR Magnet Experience

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for the Brookhaven Superconducting Magnet Division

30th Advanced ICFA Beam Dynamics Workshop on High Luminosity e+e- Collisions

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

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"A Review of BNL Direct-Wind Superconducting IR Magnet Experience."

- **Overview of Past and Current Projects.**
  - HERA-II Luminosity Upgrade IR Magnets.
  - NLC Superconducting Final Focus Magnets.
  - BEPC-II Luminosity Upgrade IR Magnets.

- **Winding Technology Overview.**
  - New Types of "Serpentine" Coil Windings.
  - Winding Test of BEPC-II Serpentine Coil.

- **Some Issues Relevant for Super B-Factory.**
  - Cryostat & Warm Bore Allowance.
  - Quadrupole Coil Layout Options.
  - Magnetic Length Vs. Slot Length.
  - Dipole Torque Considerations.

A Summary of HERA-II Luminosity Upgrade Magnet Production.

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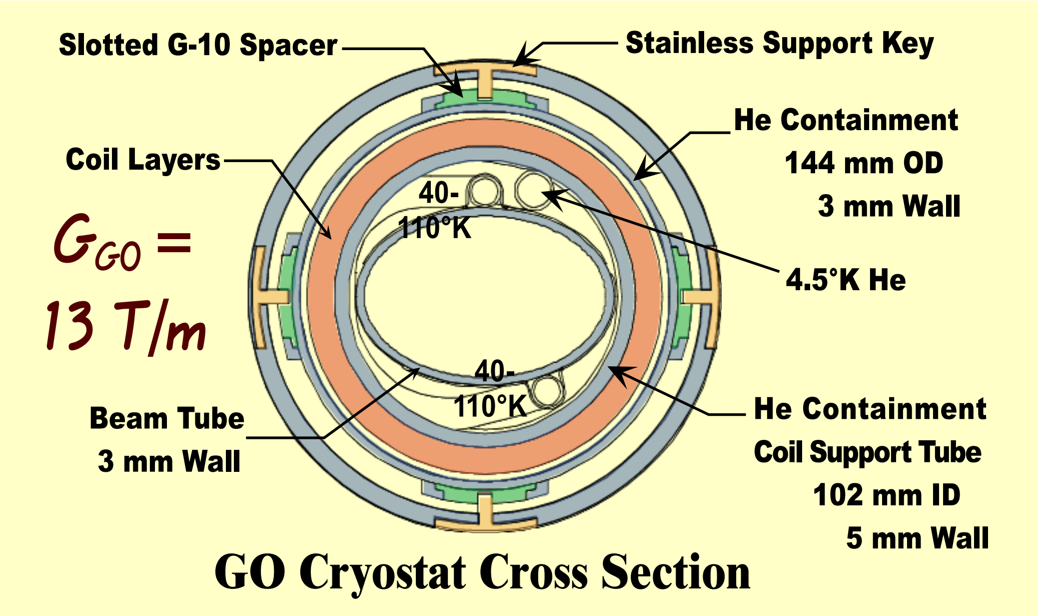
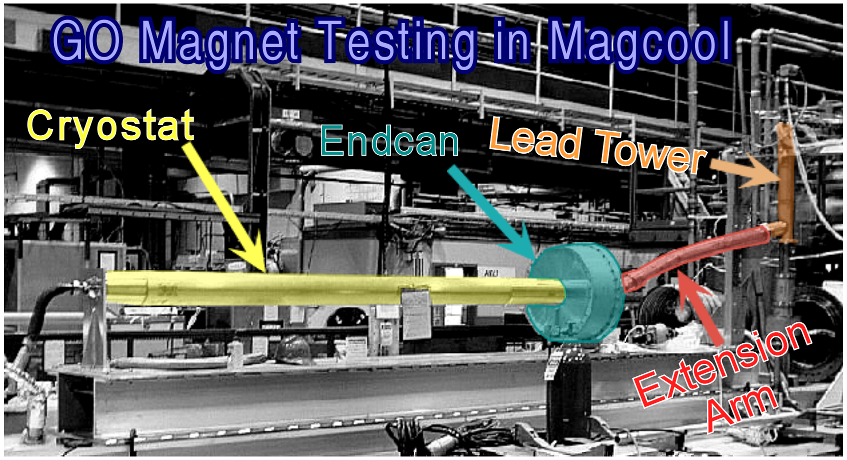


GO Cryostat Cross Section

H-Dipole, Quad, V-Dipole, Skew Quad & Sextupole coils fit inside a very tight radial envelope!



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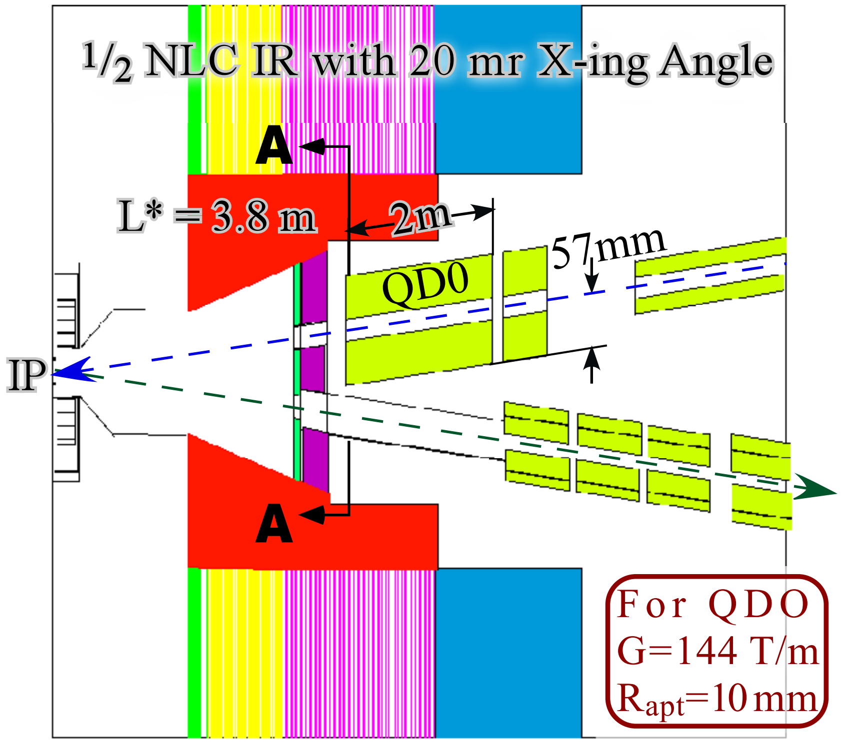
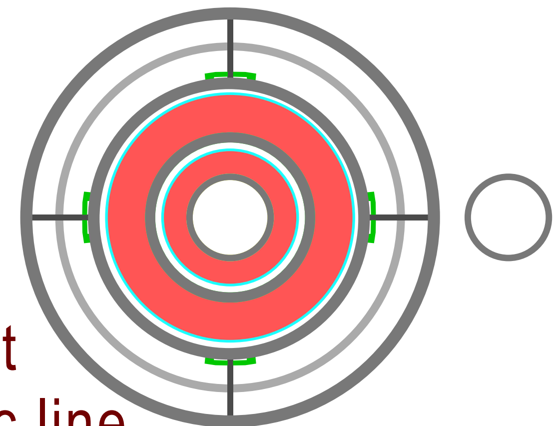
Superconducting Quadrupoles for the NLC Final Focus.



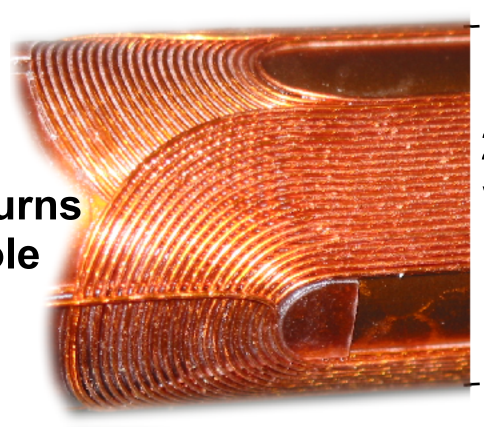
With a compact FF quadrupole, QD0, the NLC crossing angle solution permits the disrupted beam to pass outside the cryostat into a beam diagnostic line that ends at a high-power beam absorber.

Section AA at QD0 Front End

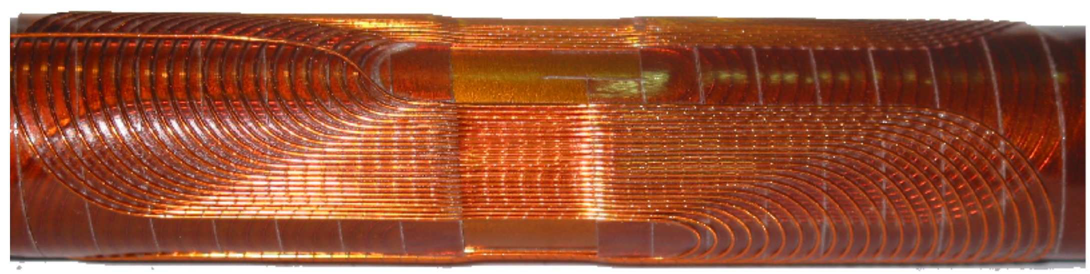


Work is in progress at BNL to produce and test compact, high-gradient, small aperture superconducting quadrupoles.

11½ turns per pole



25 mm coil winding diameter



NLC Nested Serpentine Winding Patterns

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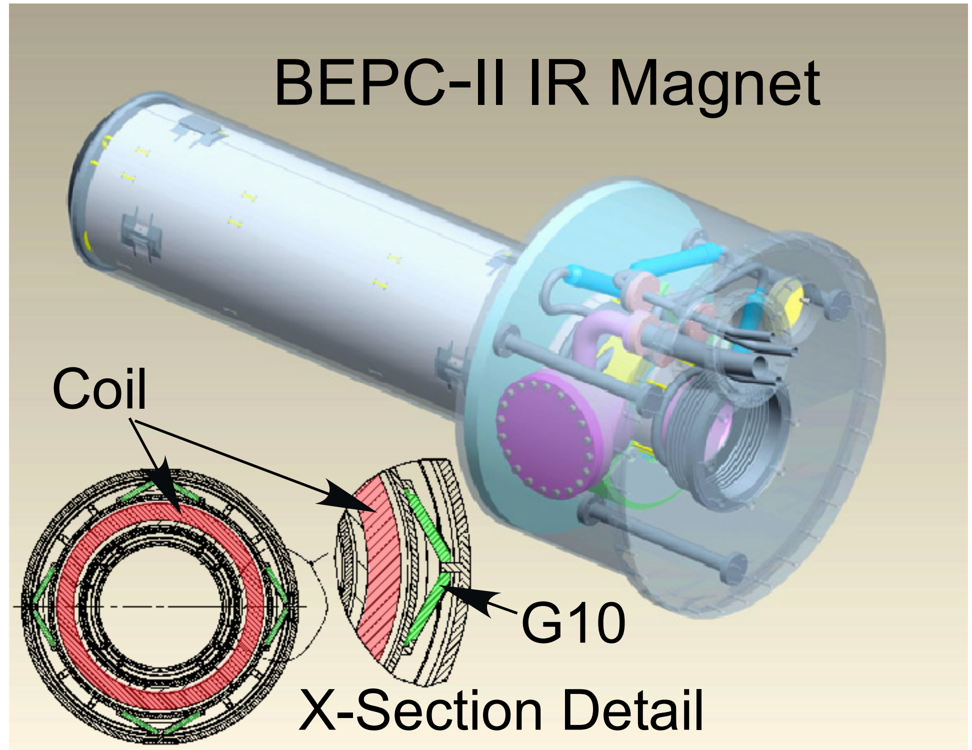
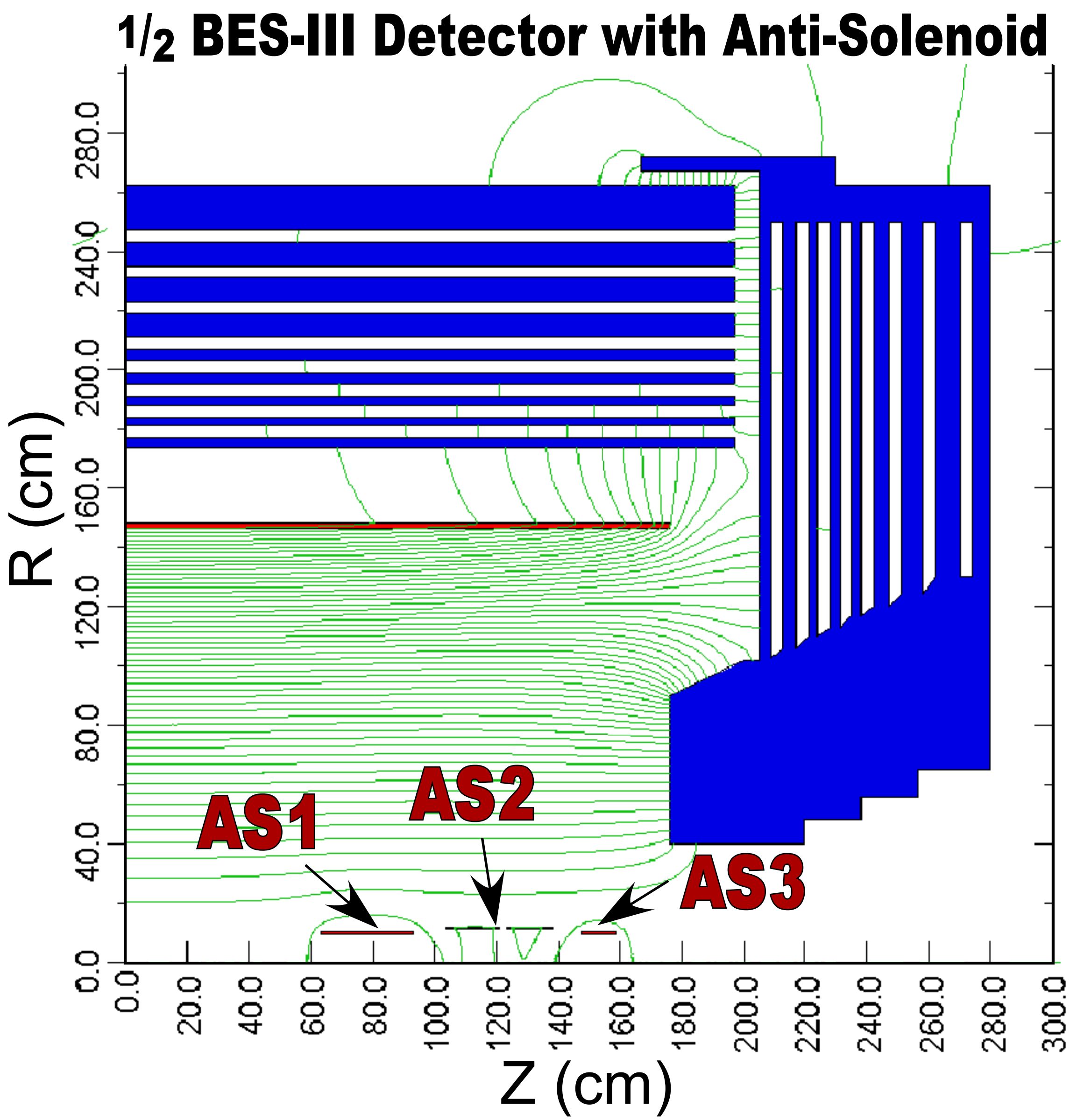
IR Magnets for the BEPC-II Luminosity Upgrade at IHEP, Beijing, P. R. China.

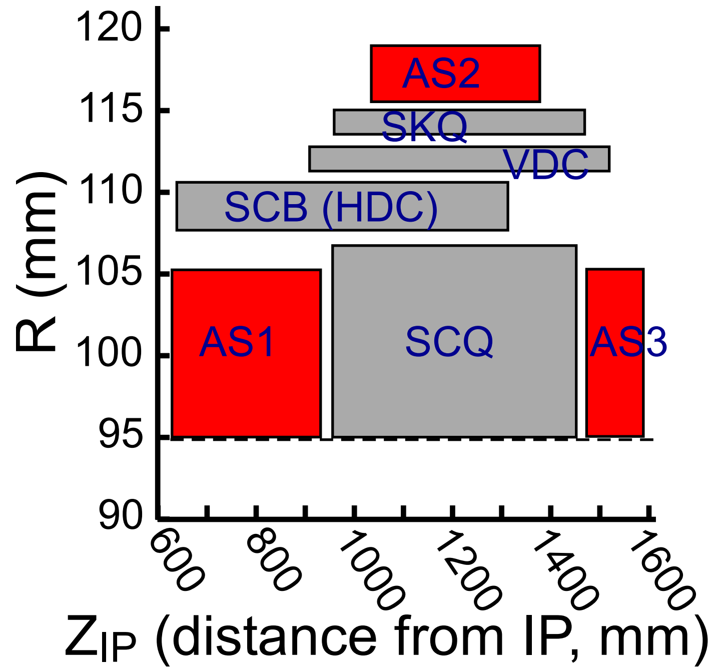
Name	Function	Layers	Conductor
SCQ	Main Quad	8	7 strand cable
SCB (HDC)	Hor. Dipole	2	7 strand cable
VDC	Vert. Dipole	2	1 strand wire
SKQ	Skew Quad	2	1 strand wire
AS1	Anti-Solenoid	6	MRI wire
AS2	Anti-Solenoid	2	MRI wire
AS2	Anti-Solenoid	6	MRI wire

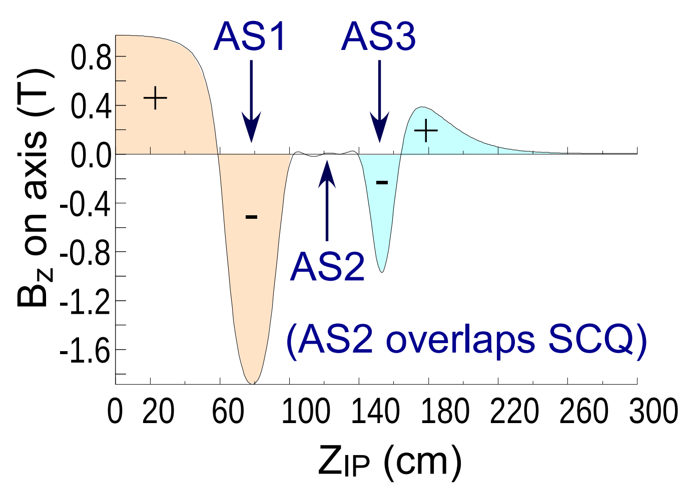


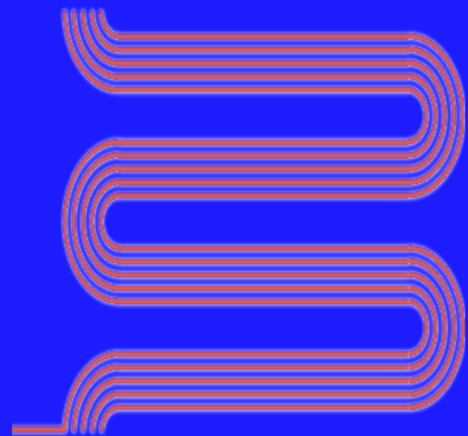
Compared to HERA-II magnets, these have almost double the aperture but only 1/7 the length. The radial budget does give more space for the cryostat (…that is used to provide a warm bore tube, inner and outer heat shields and LHe cooling flow on both sides of a thicker coil pack).

BEPC-II Special Feature: Local BES-III Detector Solenoid Compensation Scheme.

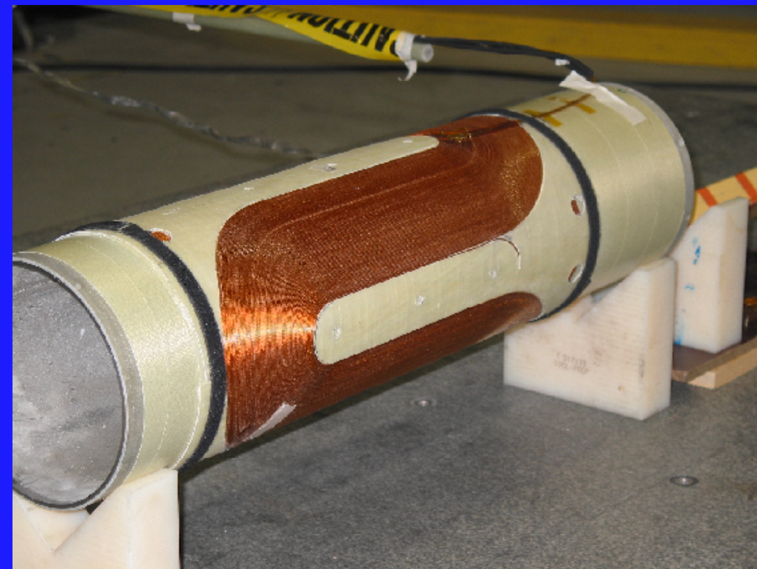








Serpentine Test Winding



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A Demonstration How the BNL Coil Winding Machine Works: Serpentine Coil Example.

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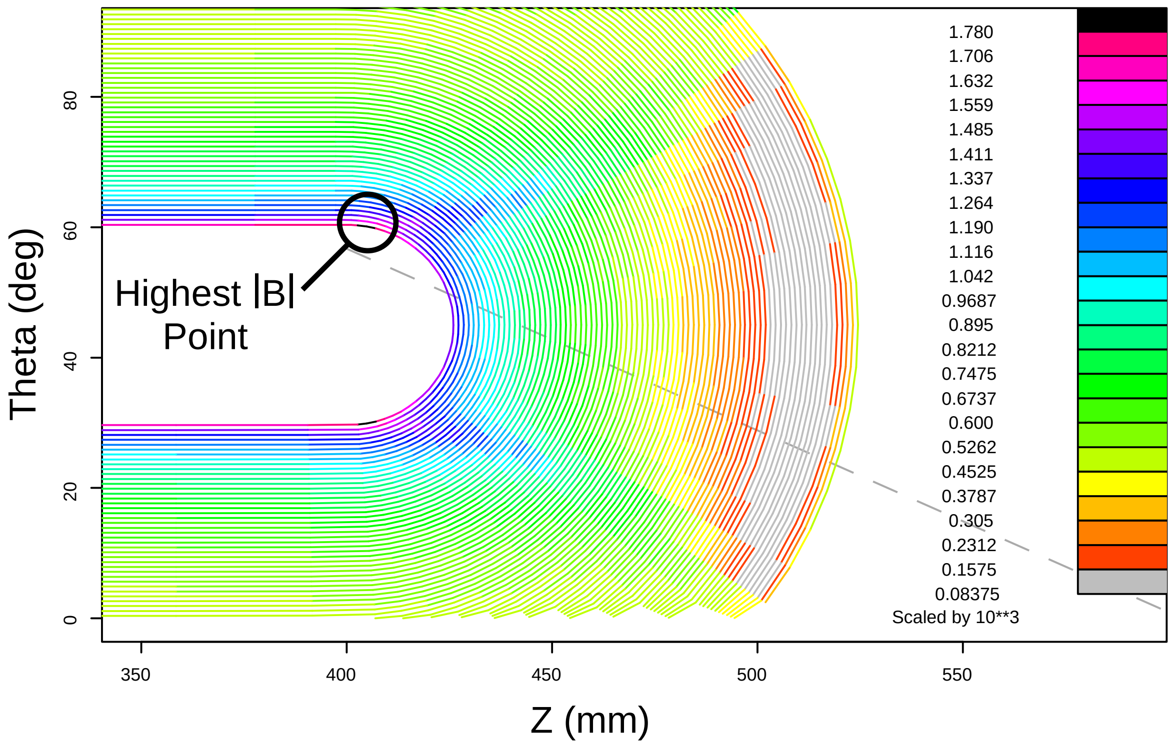
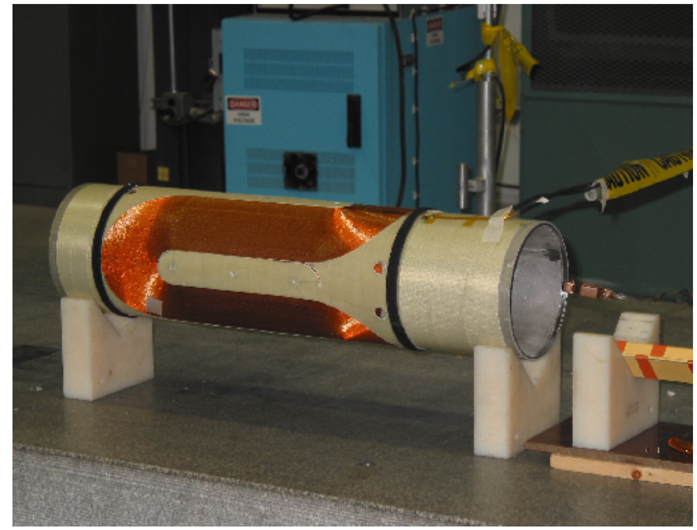
A Test of the New Serpentine-Style BEPC-II SCQ Coil Winding Pattern.

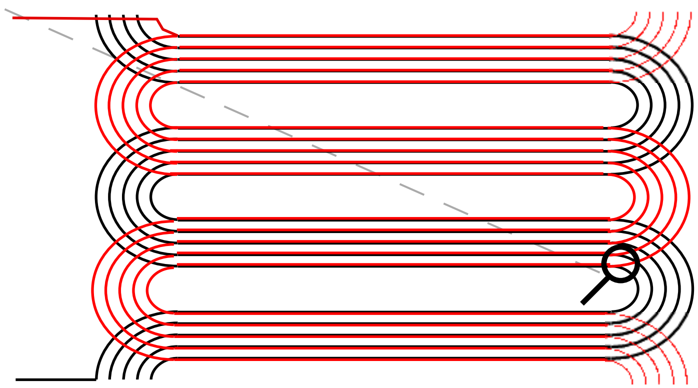
|B| per ampere of excitation current for wire segments in lower coil layer.





Warm coil testing before vacuum impregnation was done and the fiber-glass prestress wrap was added.

Test winding quenched at 911 A which is 90% of cable short sample.



Double-Layer Winding Schematic.

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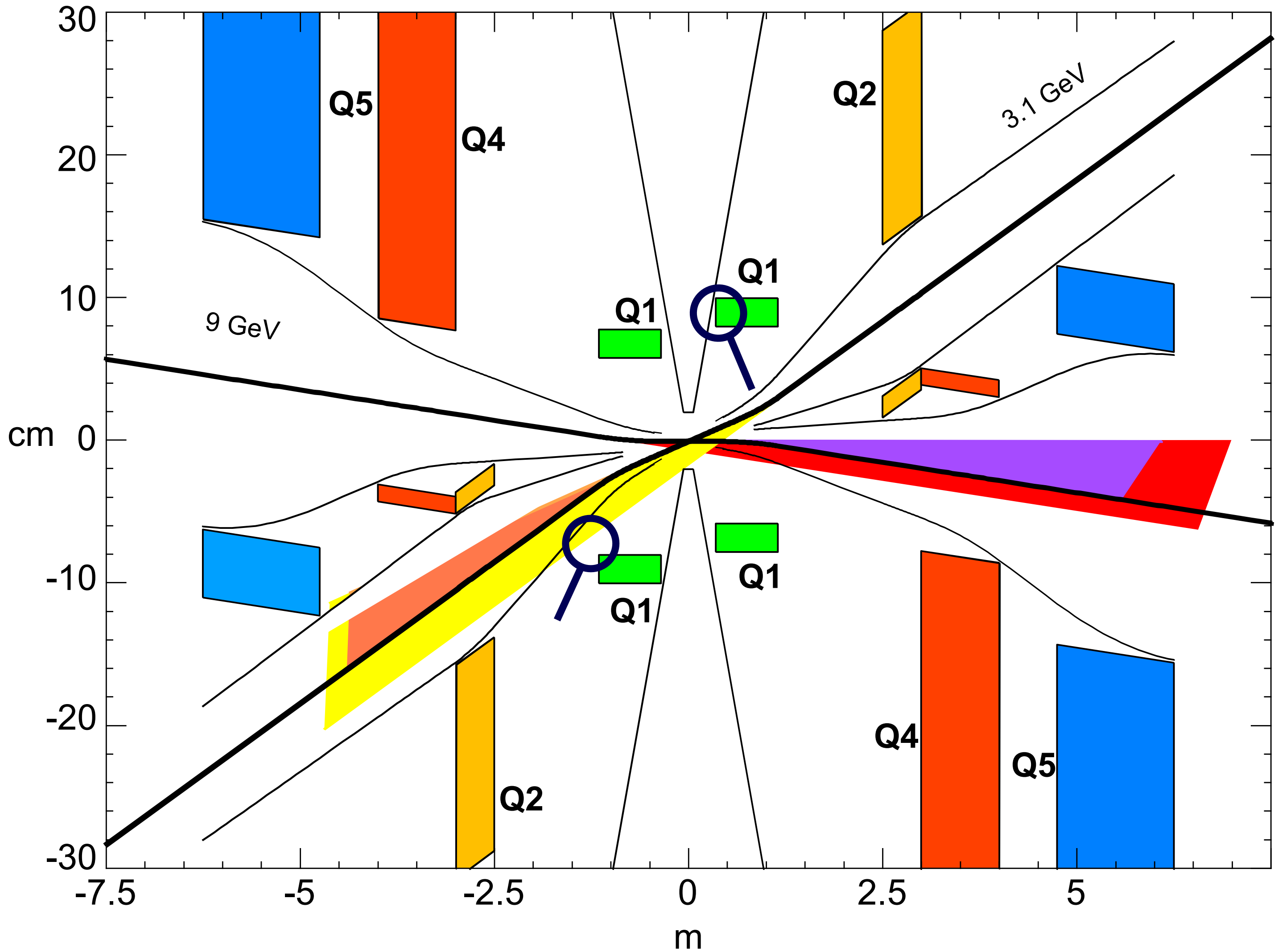
Summary of IR Magnet Parameters for a Proposed $\mathcal{L} = 10^{36}$ Super B-Factory Scenario.

E36 B-Factory +/- 12 mrad xing angle Q2 septum at 2.5 m



Q1 Design Parameters†:

$L^* = 350$ mm

$L_{mag} = 800$ mm

$B = 0.3$ T

$G = 26.6$ T/m

$R_{warm\ bore} \approx 60$ mm

$R_{outer\ cryostat} \approx 100$ mm

Must use care at critical areas to keep Q1 coil radius as small as possible!

†Vertical Dipole, Skew Quad and Anti-Solenoid coils also requested.

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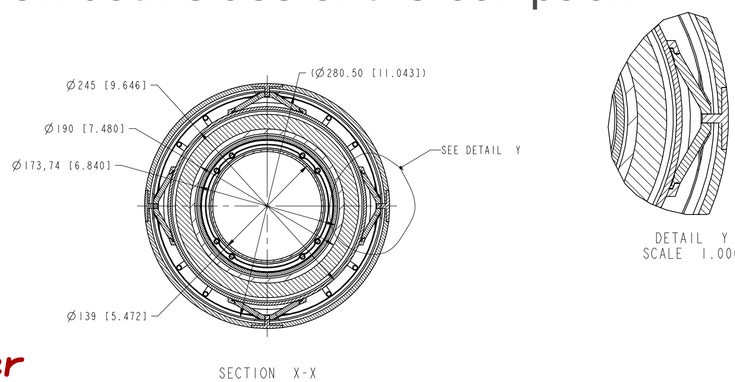
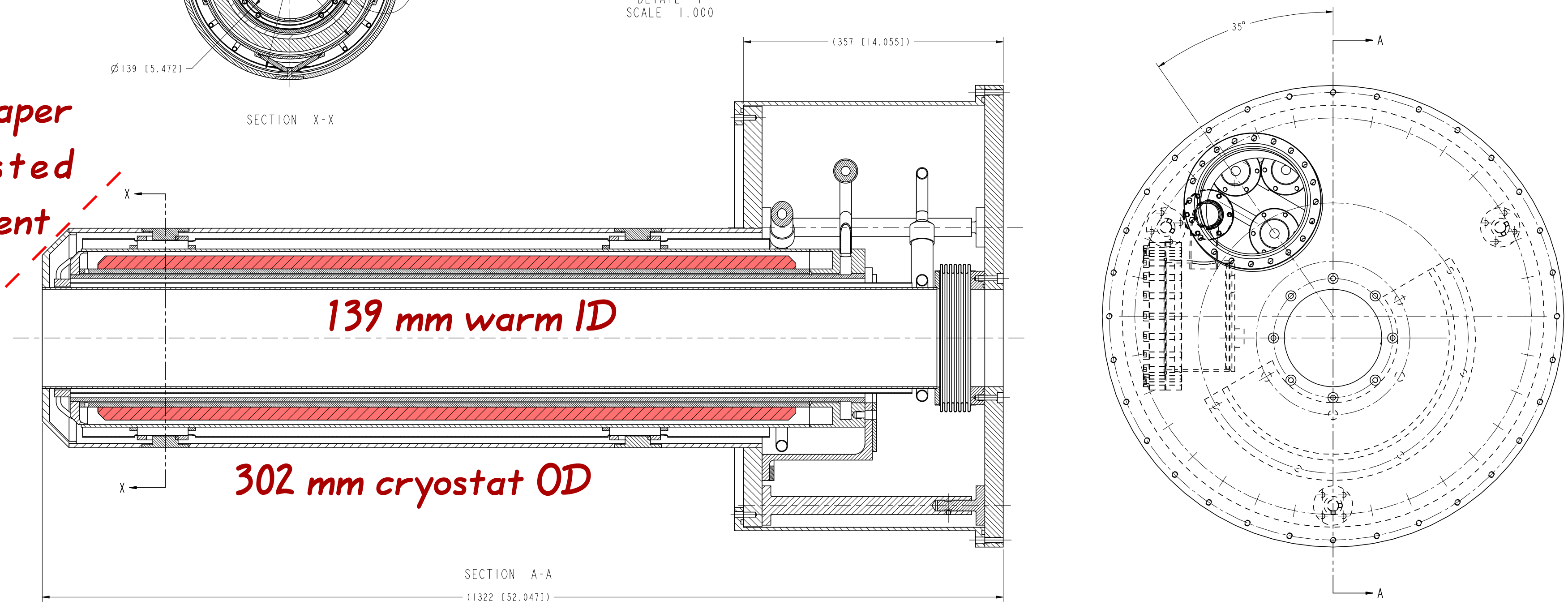
First Pass at Super-B IR Magnet Cryostat Radial Buildup: Assume Same As BEPC-II.

Unlike HERA-II, the BEPC-II magnets have inner/outer gas cooled heat shields plus LHe cooling on both sides of the coil pack.

For BEPC-II we have just over 25 mm radial space between the inner coil and warm bore and just over 30 mm radial space between the outer coil radius and the outside of the cryostat.*



Note 45° taper as requested by experiment



*But 60 + 25 + 16 > 100 mm, even without other coils and 30 mm for outer cryostat! Problem?

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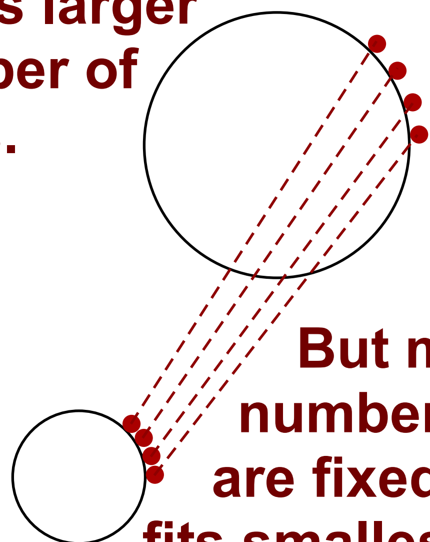
Recommendation: Try to Avoid Tapering Coil Support Tube as Done for HERA-II*.

Larger radius needs larger number of turns.



But maximum number of turns are fixed by what fits smallest radius.

For HERA-II upgrade GG magnet coil radius was tapered from 65 to 70 mm in order for cryostat nose to fit inside existing H1 "SpaCal" detector. These magnets met demanding field quality goals.

While our winding machine and coil design software are flexible enough to allow us to wind coils on tapered support tubes, such tapering does add to production complexity (especially coil curing) and results in magnets that are relatively inefficient.

*GG coil tapering was lesser of two evils. Splitting 1.5 m coil in two parts deemed worse ("two magnets… all ends").

Example of Coil Layout & Cryostat Tricks: Getting eRHIC Electron Triplet Closer to IP.

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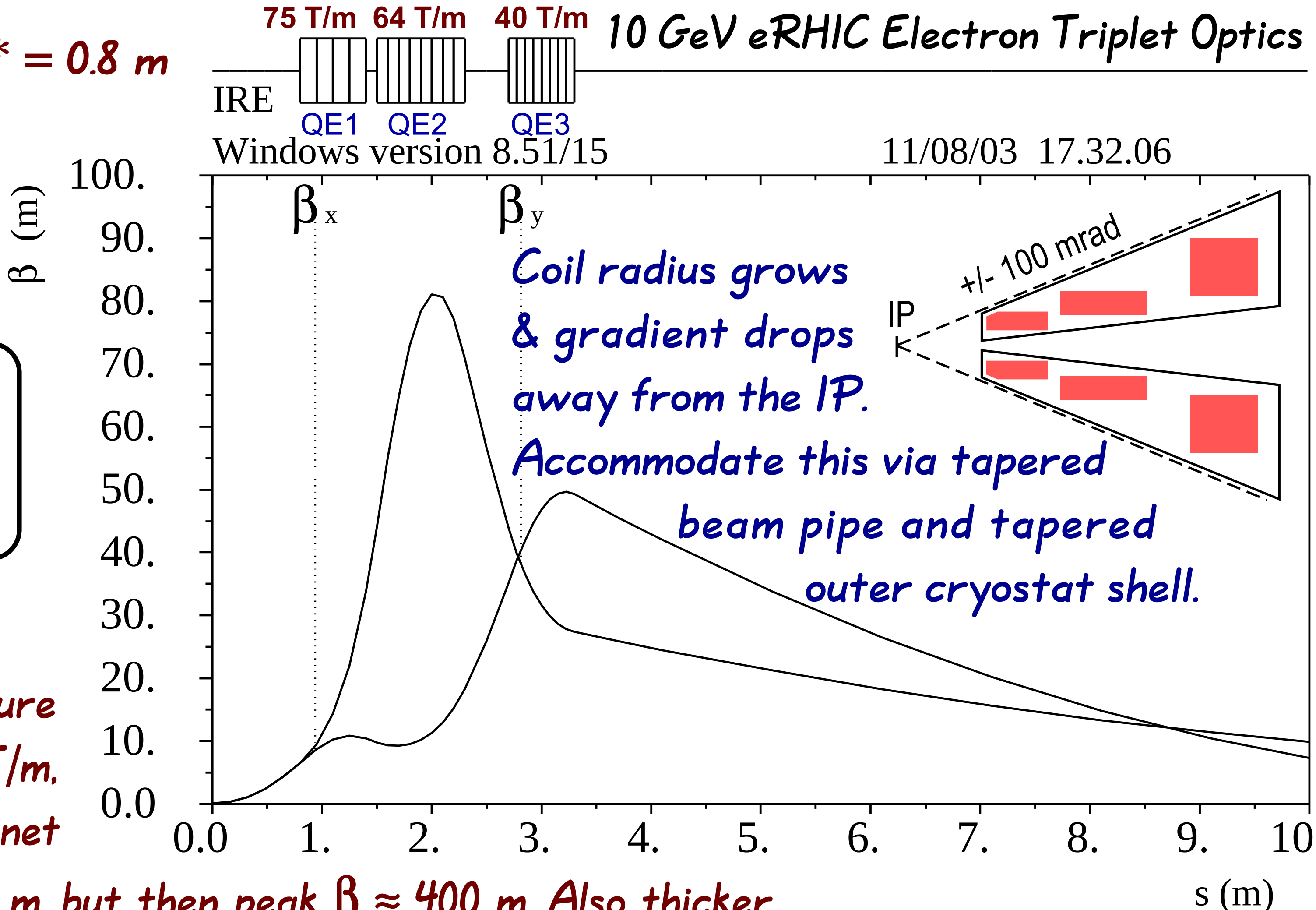
L = 0.8 m*

10 GeV eRHIC Electron Triplet Optics



For more eRHIC details see talk by Christoph Montag.

Coil radius grows & gradient drops away from the IP. Accommodate this via tapered beam pipe and tapered outer cryostat shell.

Larger (fixed) aperture alternative had 13 T/m, and a permanent magnet dipole with L = 1.2 m, but then peak β ≈ 400 m. Also thicker coils plus outer cryostat meant that +/-200 mrad was blocked!*

A Super-B Q1 Scenario: Staggered Coil Starts and Lengths That Permit Smaller Coil Radius.

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With L_{coil} = 800 mm we have L_{mag} = 640 mm

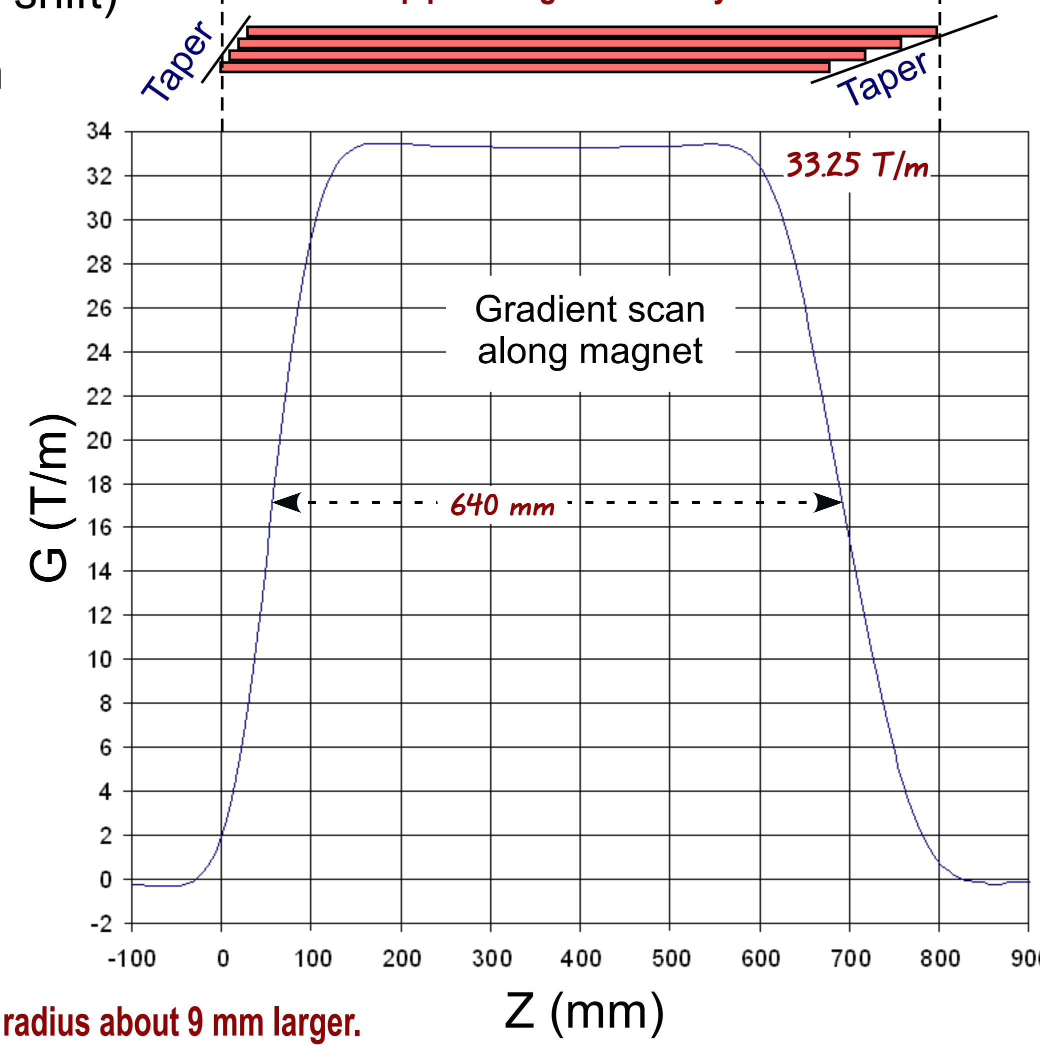
Center is about 375 mm (i.e. 25 mm shift)

Then I_{op} = 648 A for G = 33.25 T/m

At 0 mm, $R_{warm\ bore}$ = 45 mm

& 800 mm, $R_{warm\ bore}$ = 60 mm

Use 4 quadrupole double-layer coils that are staggered to allow cryostat taper on IP side and beam pipe flaring at end away from IP.



Even for untapered coil, magnetic length < 800 mm. Here gradient is increased 25% above 26.6 T/m to compensate for short 640 mm L_{mag}.

Note with 1.5 T solenoid and 0.3 T dipole fields added to quadrupole self-field, the peak field reaches almost 3.5 T (or 90% short sample).

*BEPC-II has 18.7 T/m in 1.0 T detector solenoid and a warm bore radius about 9 mm larger.

Comparison of Coil Length and Magnetic Length for Super-B Dipole Windings.

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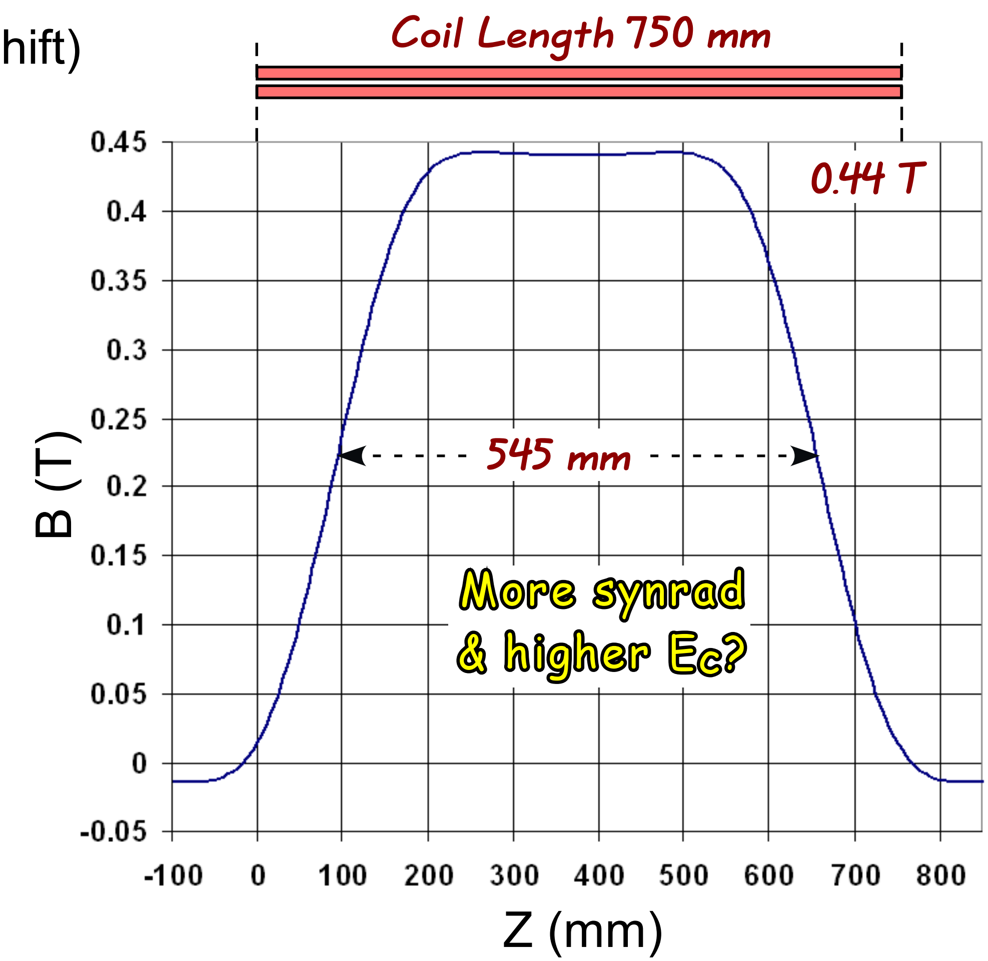
With L_{coil} = 750 mm we have L_{mag} = 545 mm

Center is about 350 mm (i.e. 50 mm shift)

Then I_{op} = 206 A* for B = 0.44 T

(Note: 0.30 x 800 / 545 = 0.44 T)

- *Lose more magnetic length from dipole ends than from quadrupole ends (more turns per pole & larger coil radius).*
- *Dipole coil also shortened to match quad taper. Net result is to significantly increase B-field!*



*Original calculation done for 0.98 T instead of 0.3 T had required 673 A excitation.

Dipoles Cause Cold Mass Torques, Even When Inside Anti-Solenoids (Quads Don't).

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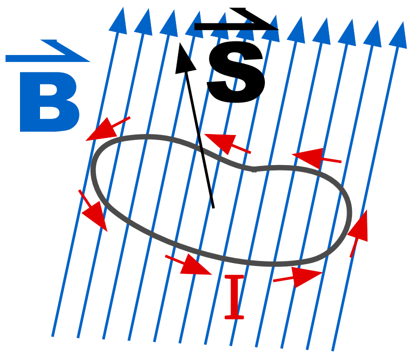
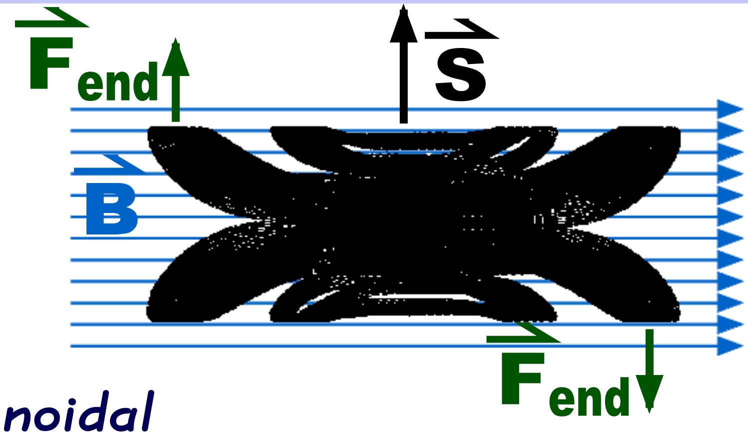


Torque on Current Loop

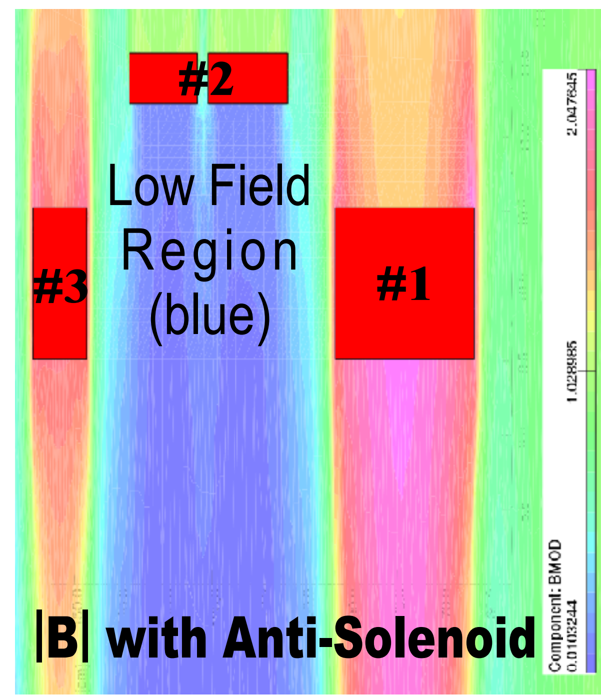
$$\vec{\tau} = I\,\vec{S} \times \vec{B}$$



- *There is a net torque on a dipole in a solenoidal field (but not on quadrupole due to symmetry).*
- *Magnitude of torque is $I_{Dipole} \cdot S_{Proj} \cdot B_{BES\text{-}III}$.*
- *Even though anti-solenoid changes the field seen by the dipole, a net torque remains on cold mass!*

$$\vec{\tau}_{Dipole} = \vec{\tau}_{BES\text{-}III} + \vec{\tau}_{Anti} = 0 \text{ means that}$$

$$\vec{\tau}_{Anti} = -\vec{\tau}_{BES\text{-}III}$$



Max. $\tau_{BES\text{-}III+HDC}$ = 1330 N·m (980 ft·lbs).

Large Torque is Generated By Super-B Dipole as Specified: Can This Torque be Reduced?

- *When placed in a 1.5 T solenoidal field and the dipole is energized at 206 A (0.24 T·m), each Super-B cold mass will experience 15. kN·m (11. kft·lbs) torque in the vertical plane (compared to 1.3 kN·m for BEPC-II).*

With small vertical IP spot size, Super-B luminosity must be quite sensitive to vertical offsets….

Can correct center shift with vertical corrector, but then have extra horizontal torque!

- **Given that the quadrupole coil does not experience a torque in a solenoidal field and that 30 T/m × 0.010 m => 0.30 T, we recommend generating the dipole field at beam position via transverse offsets as much as possible*.**

***But only if such movement is "natural," i.e. should not increase quadrupole radius too much!**

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"A Review of BNL Direct-Wind Superconducting IR Magnet Experience."

Summary:

- *From previous IR design work, we see that the Super B-Factory magnets look to be (just) doable via BNL direct-wind technology.*

- *However very close collaboration & careful optimization is needed to develop a prudent design.*

Thank you for your attention.