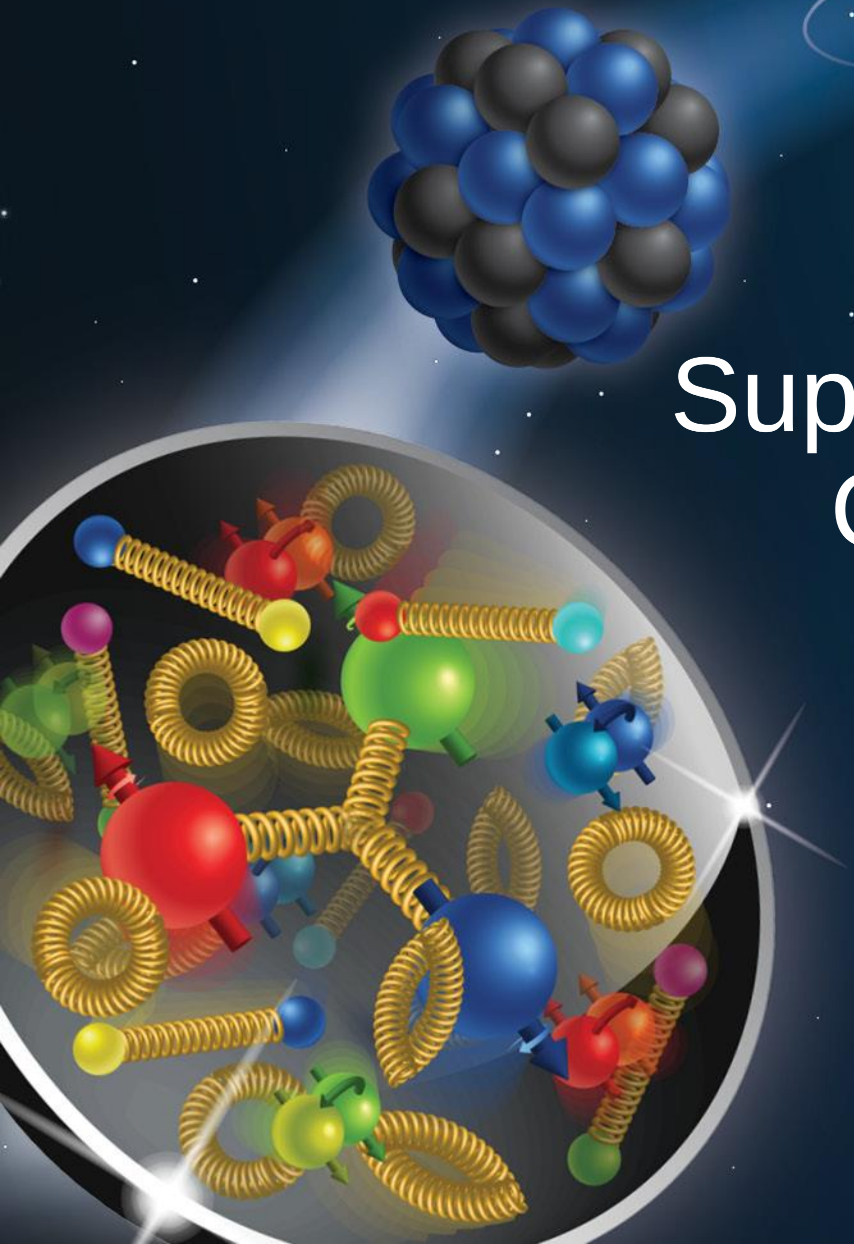

Superconducting Magnet Concepts for Electron Hadron Collider IRs

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Electron Ion Collider – eRHIC

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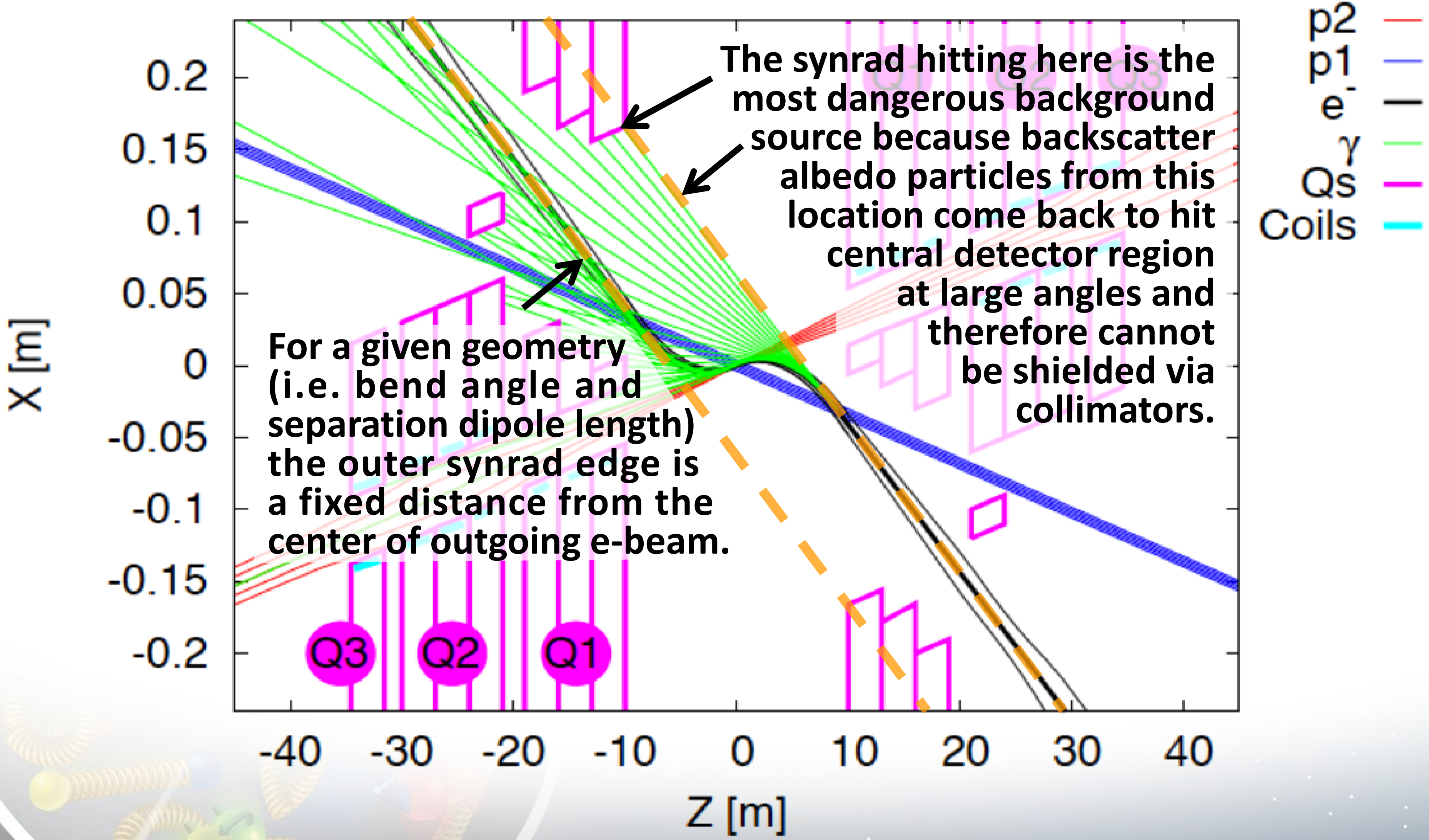
U.S. DEPARTMENT OF ENERGY | Office of Science

Introduction and Outline:

- Review LHeC CDR IR layout challenges.
- Highlight a few Magnetic Septum Quadrupole (MSQ) magnetic design issues.
- Present a thought experiment to show ways that the present Q1 MSQ characteristics might be improved.
- Introduce an alternative MSQ approach based upon above results.
- Briefly review two other approaches to IR beam separation and external field compensation.
- Outline actively shielded quadrupole options for the LHeC IR in context of planned eRHIC magnet R&D.

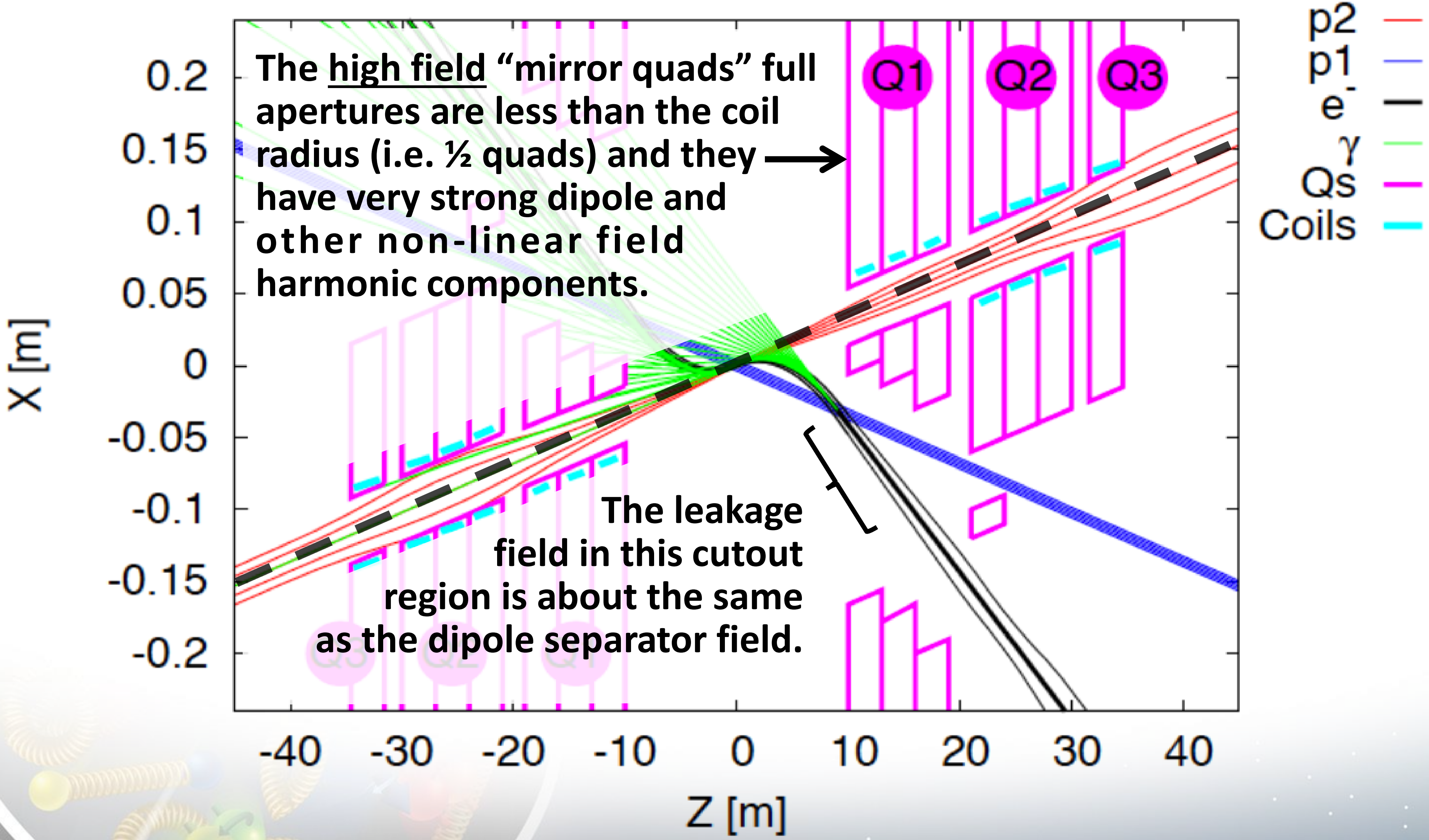
LHeC pCDR IR Layout



The synrad hitting here is the most dangerous background source because backscatter albedo particles from this location come back to hit central detector region at large angles and therefore cannot be shielded via collimators.

For a given geometry (i.e. bend angle and separation dipole length) the outer synrad edge is a fixed distance from the center of outgoing e-beam.

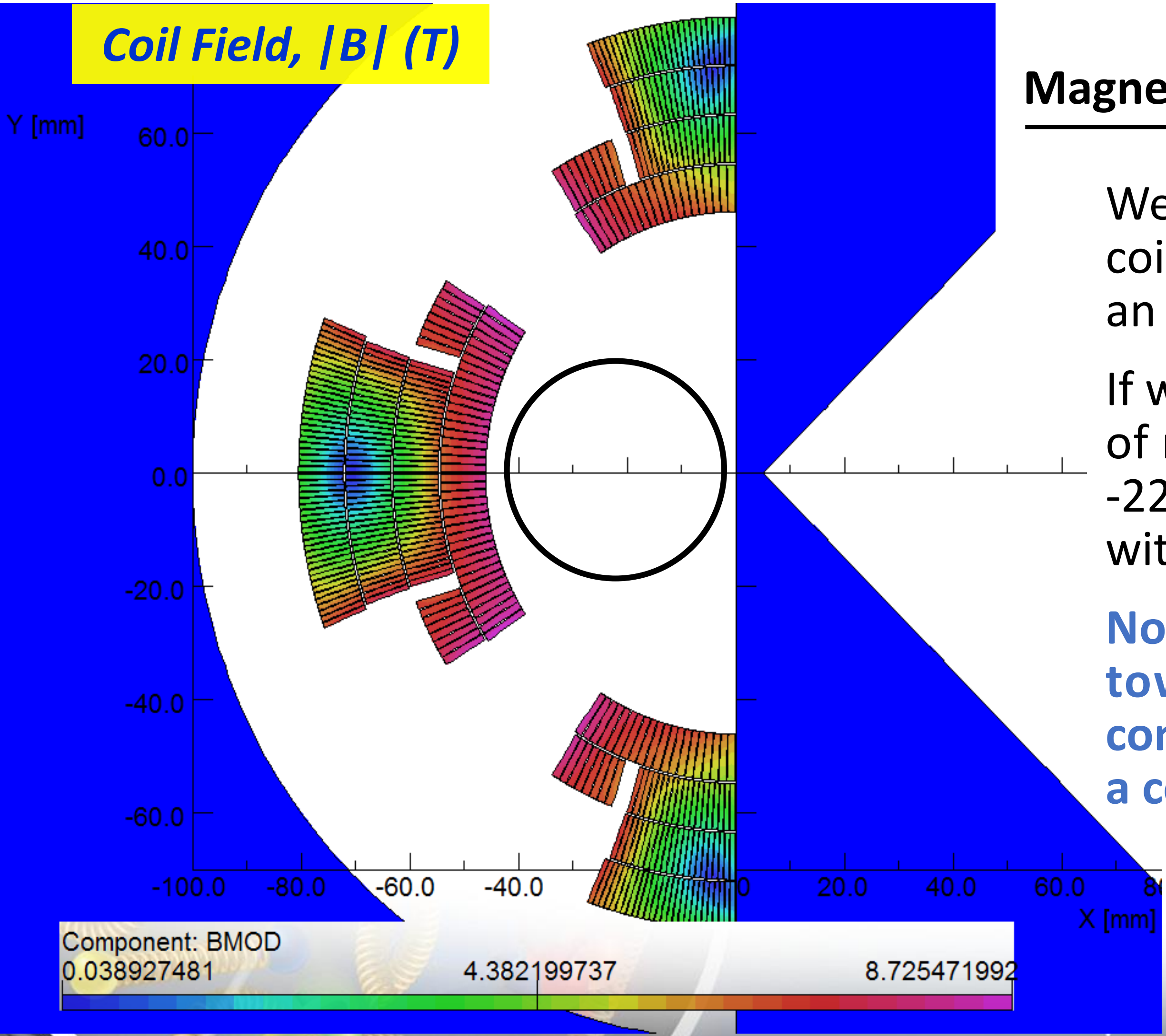
LHeC pCDR IR Layout



The **high field** “mirror quads” full apertures are less than the coil radius (i.e. ½ quads) and they have very strong dipole and other non-linear field harmonic components.

The leakage field in this cutout region is about the same as the dipole separator field.

LHeC Magnetic Septum Quadrupole Details



Magnetic Septum Quadrupole (MSQ)

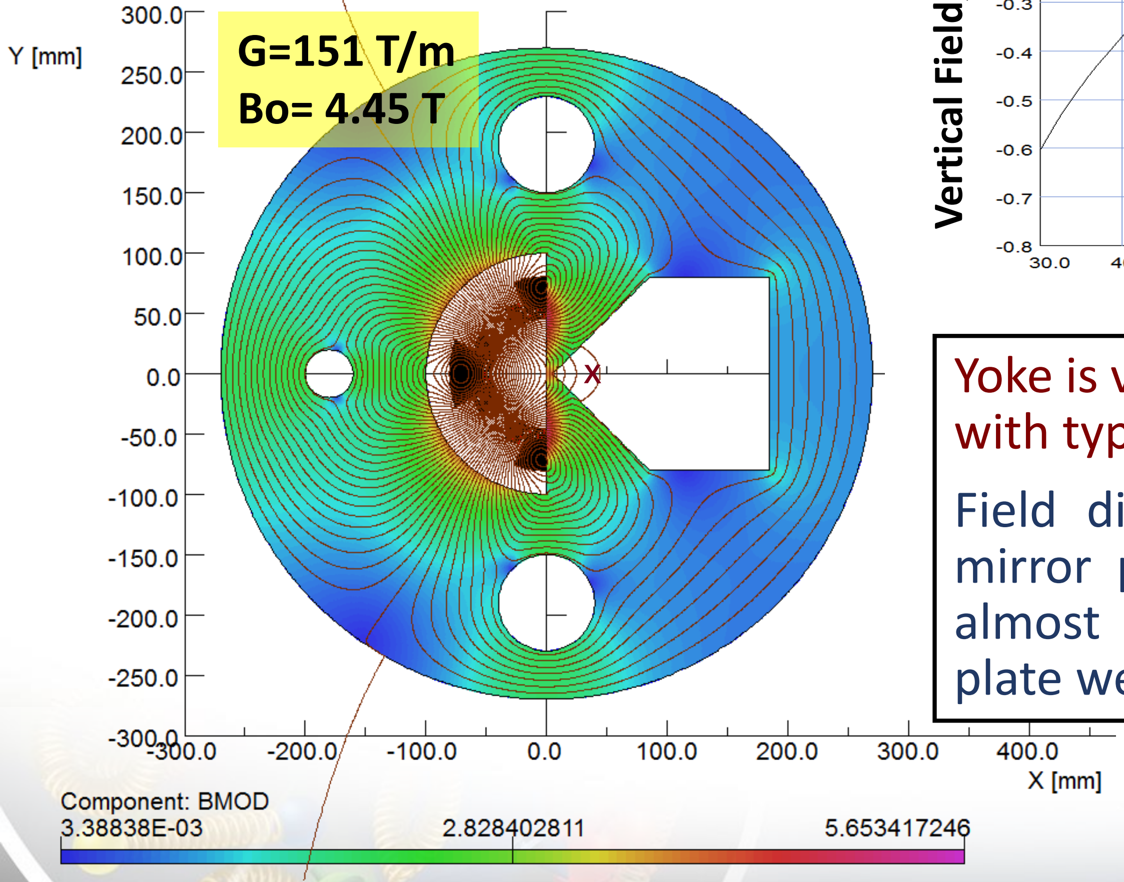
We have a four layer quadrupole coil excited at 4.5 kA that yields an 8.7 T coil peak field.

If we analyze the field on a circle of radius 20 mm and centered at -22 mm, we get **151 T/m gradient** with B(-22 mm) = **4.45 T**.

Note: Much of the coil field goes towards creating a dipole field component (i.e. is fundamentally a combined function magnet).

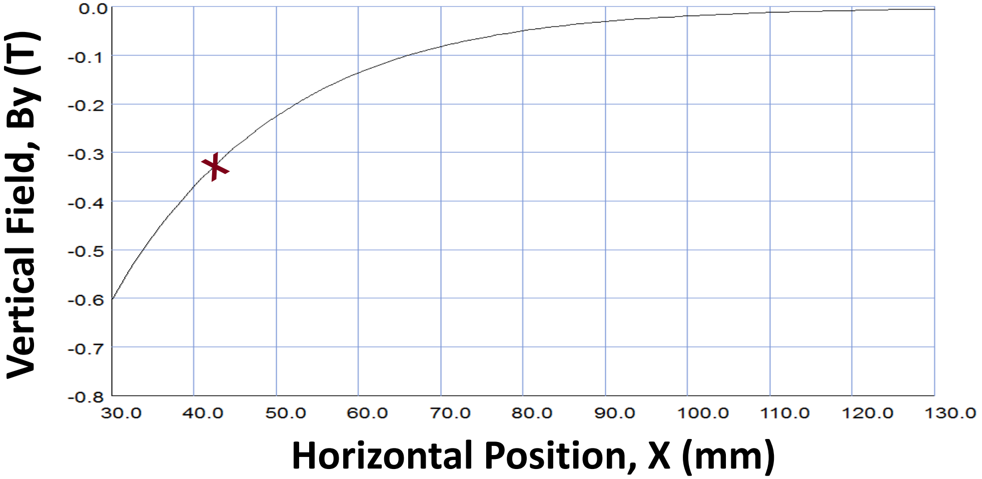
LHeC Magnetic Septum Quadrupole Details

Field Magnitude, |B| (T) Inside the Magnetic Yoke



G=151 T/m
Bo= 4.45 T

Field Profile Inside Cutout Region



Yoke is very saturated with typical μ_ry2.

Field distribution near mirror plate surface is almost same as if the plate were absent!

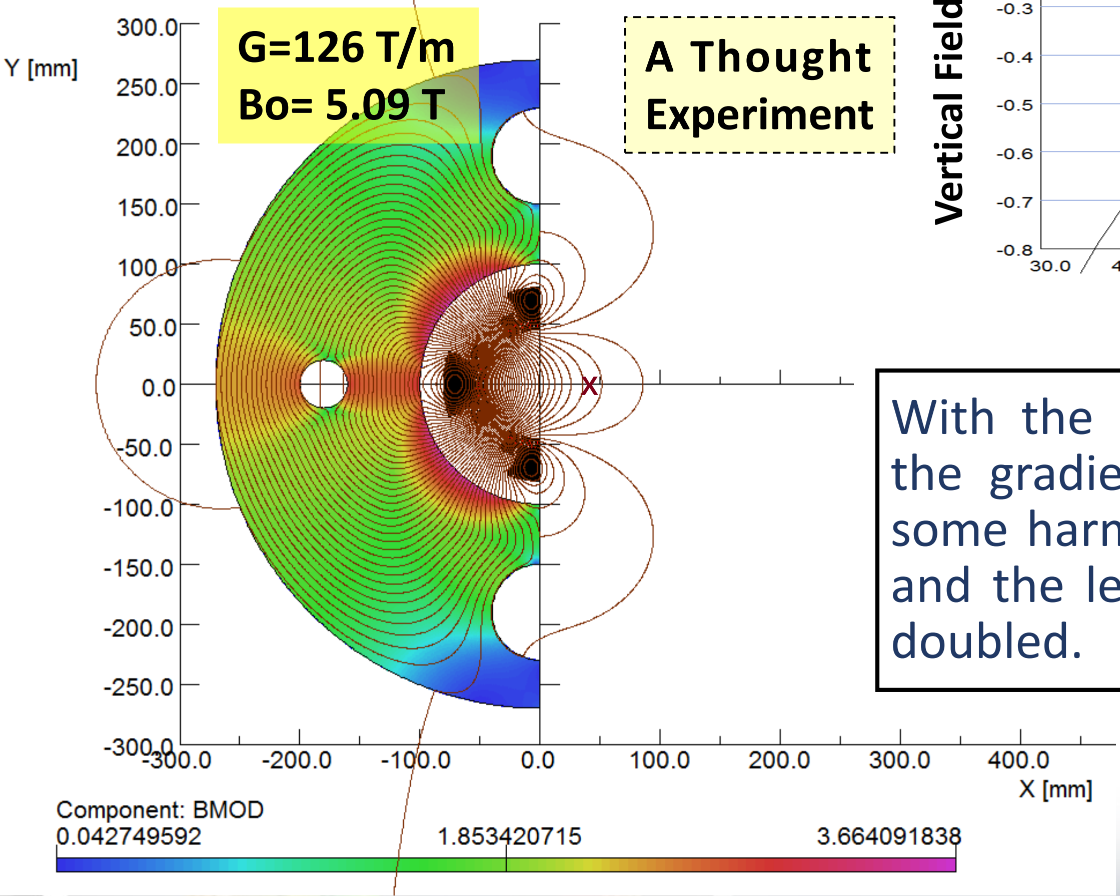
Field Harmonics At R_{ref}=20mm:

1	-14781.
2	10000.
3	-633.
4	-138.
5	-117.
6	-144.
7	-92.
8	-74.
9	-59.
10	-38.

Sum b_3-b_{10} yields 13% nonlinear harmonics

LHeC Magnetic Septum Quadrupole Details

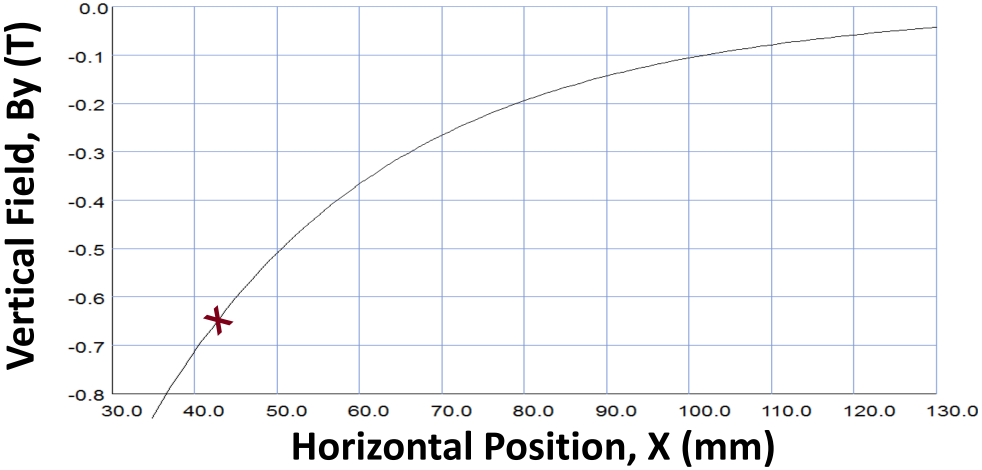
Field Magnitude, |B| (T)
Inside the Magnetic Yoke



G=126 T/m
Bo= 5.09 T

A Thought Experiment

Field Profile Inside Cutout Region



With the right side gone, the gradient is lower but some harmonics improved and the leakage field only doubled.

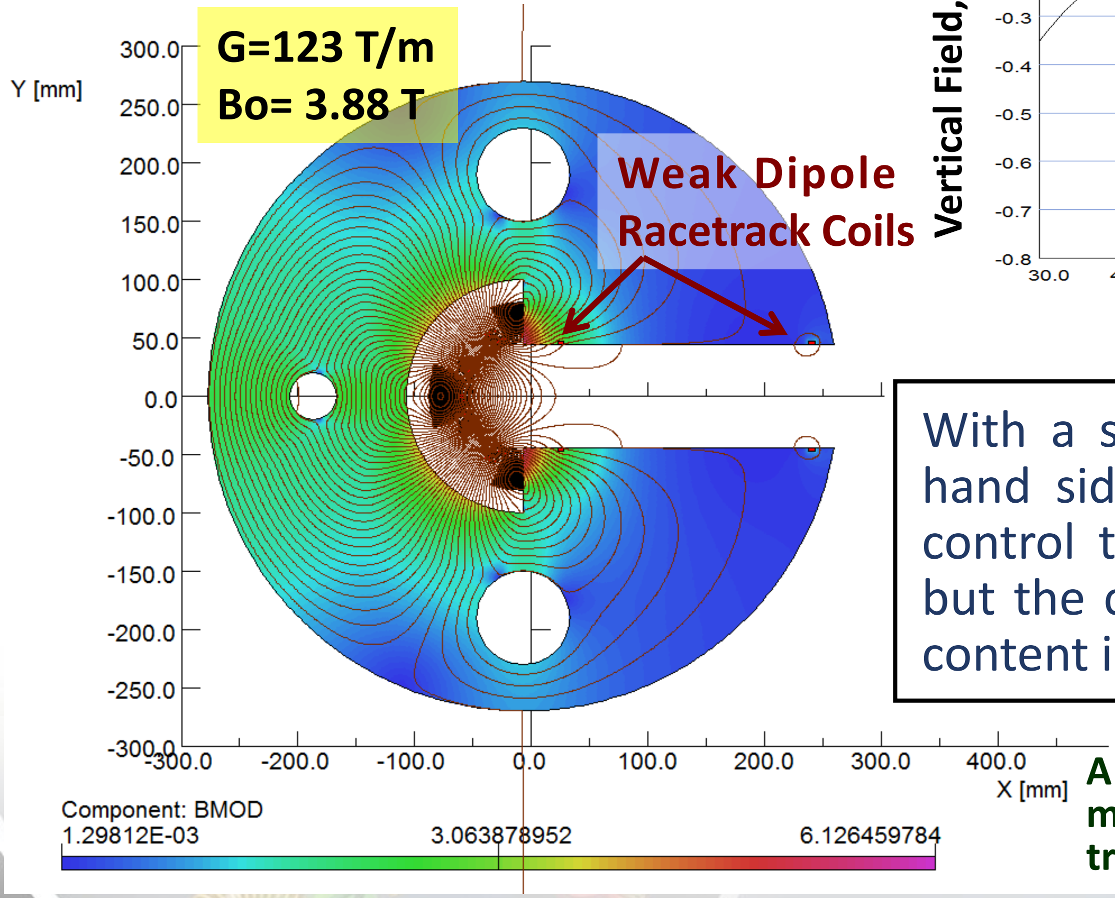
Field Harmonics At R_{ref}=20mm:

1	-20154.
2	10000.
3	-1274.
4	-140.
5	17.
6	-19.
7	14.
8	4.
9	-5.
10	-1.

Some higher order harmonics dropped

LHeC Magnetic Septum Quadrupole Details

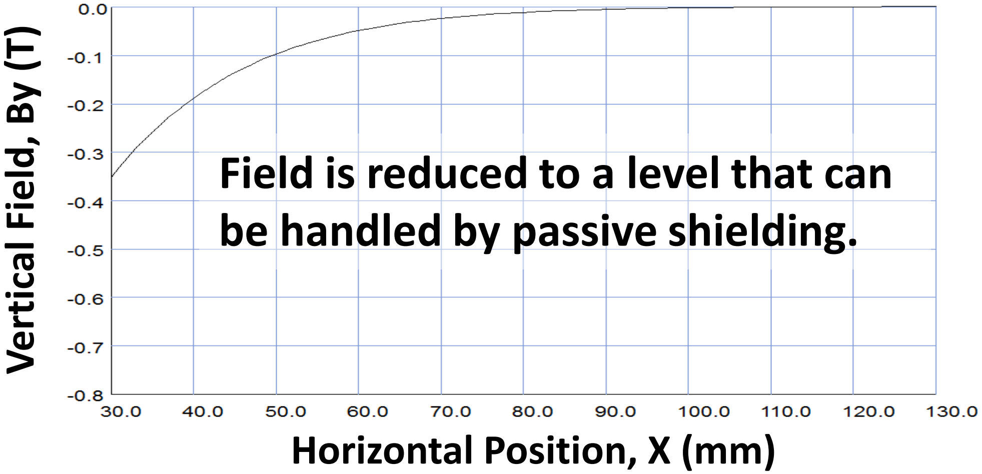
Field Magnitude, |B| (T)
Inside the Magnetic Yoke



G=123 T/m
Bo= 3.88 T

Weak Dipole Racetrack Coils

Field Profile Inside Cutout Region



Field is reduced to a level that can be handled by passive shielding.

With a slot on the right hand side we can easily control the leakage field but the central harmonic content is still fairly poor.

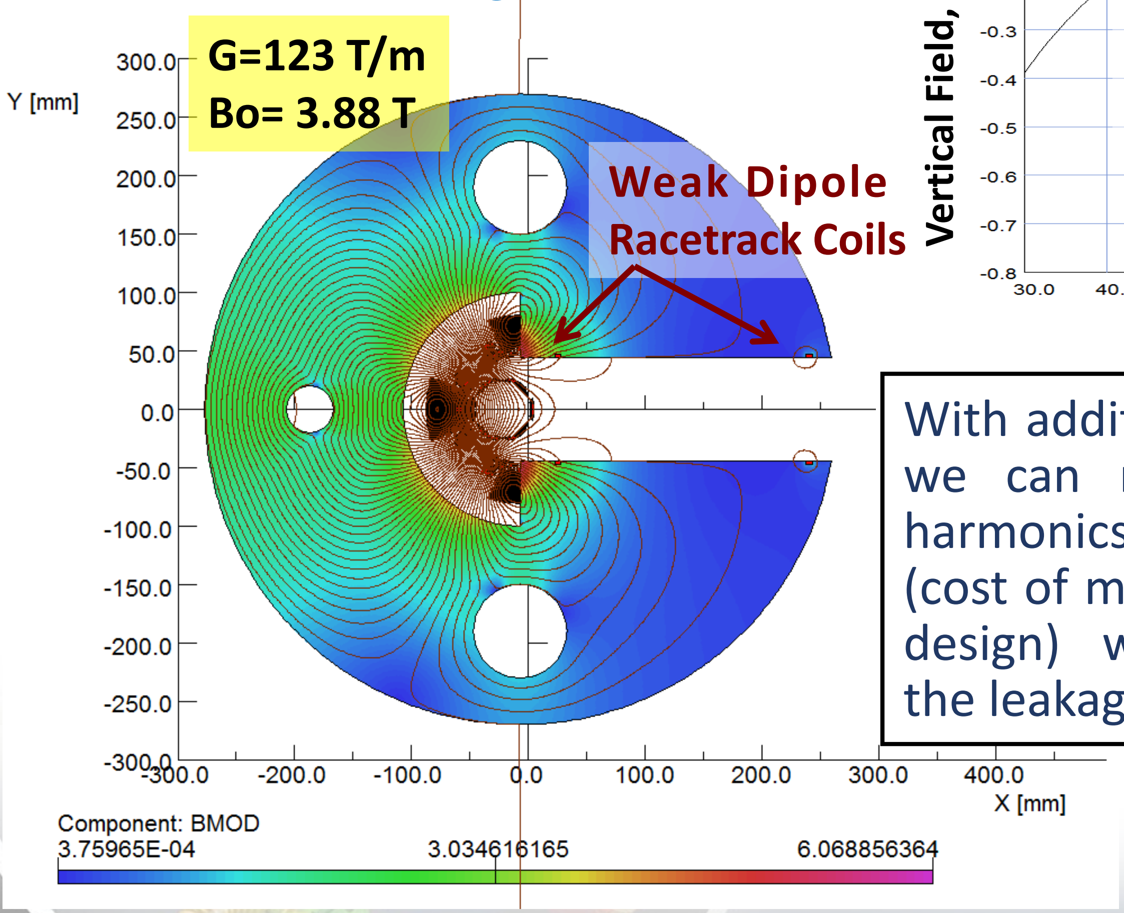
An eRHIC dual aperture magnet uses a similar trick... see backup slides.

Field Harmonics At R_{ref}=20mm:

1	-15834.
2	10000.
3	-1512.
4	-212.
5	0.
6	18.
7	13.
8	-6.
9	-1.
10	1.

LHeC Magnetic Septum Quadrupole Details

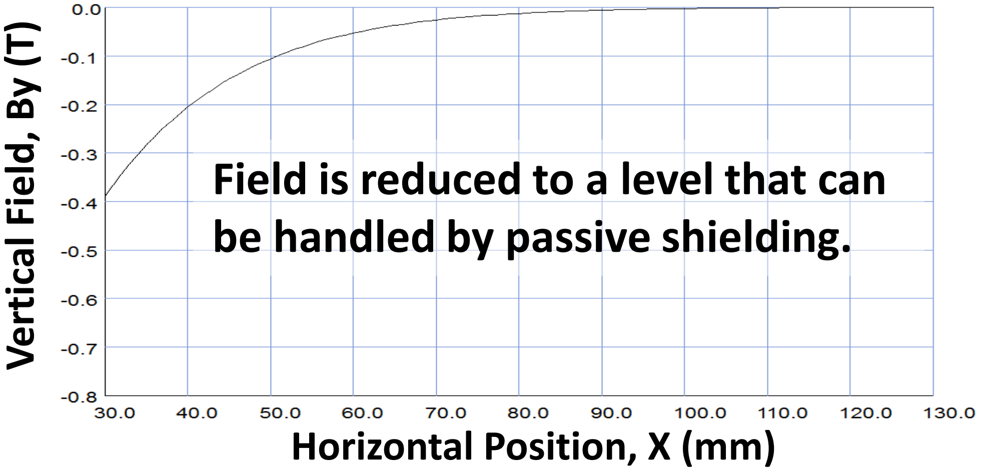
Field Magnitude, |B| (T)
Inside the Magnetic Yoke



G=123 T/m
Bo= 3.88 T

Weak Dipole Racetrack Coils

Field Profile Inside Cutout Region



Field is reduced to a level that can be handled by passive shielding.

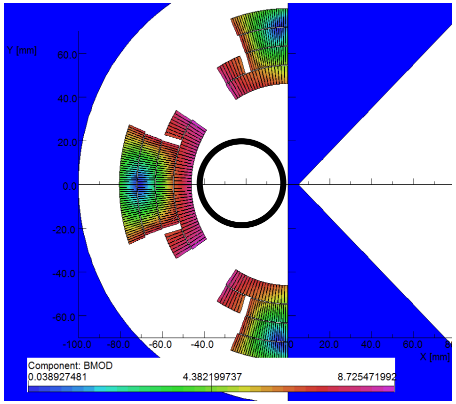
With additional correctors we can make the field harmonics arbitrarily good (cost of more complicated design) without spoiling the leakage field.

Field Harmonics At R_{ref}=20mm:

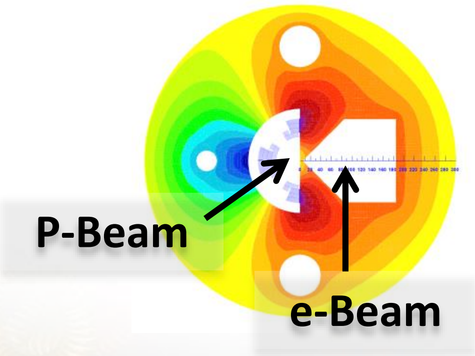
1	-15830.
2	10000.
3	-0.8
4	-1.1
5	0.0
6	18.
7	13.
8	-6.
9	-1.
10	1.

Used sextupole and octupole correctors

Two Takeaways From This Thought Experiment



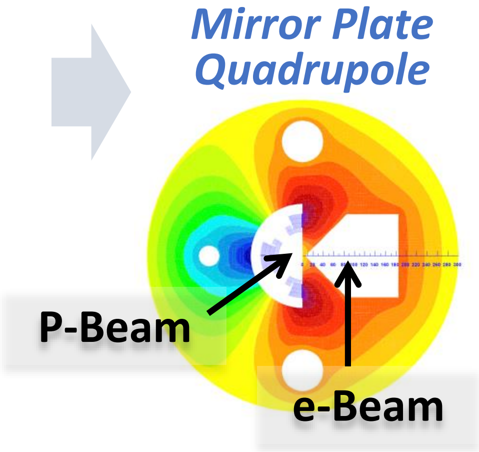
In order to have as much usable aperture as possible with good field quality and the lowest coil peak field, we should look to make coils with full symmetry and reduce the coil radius to the minimum that is required.

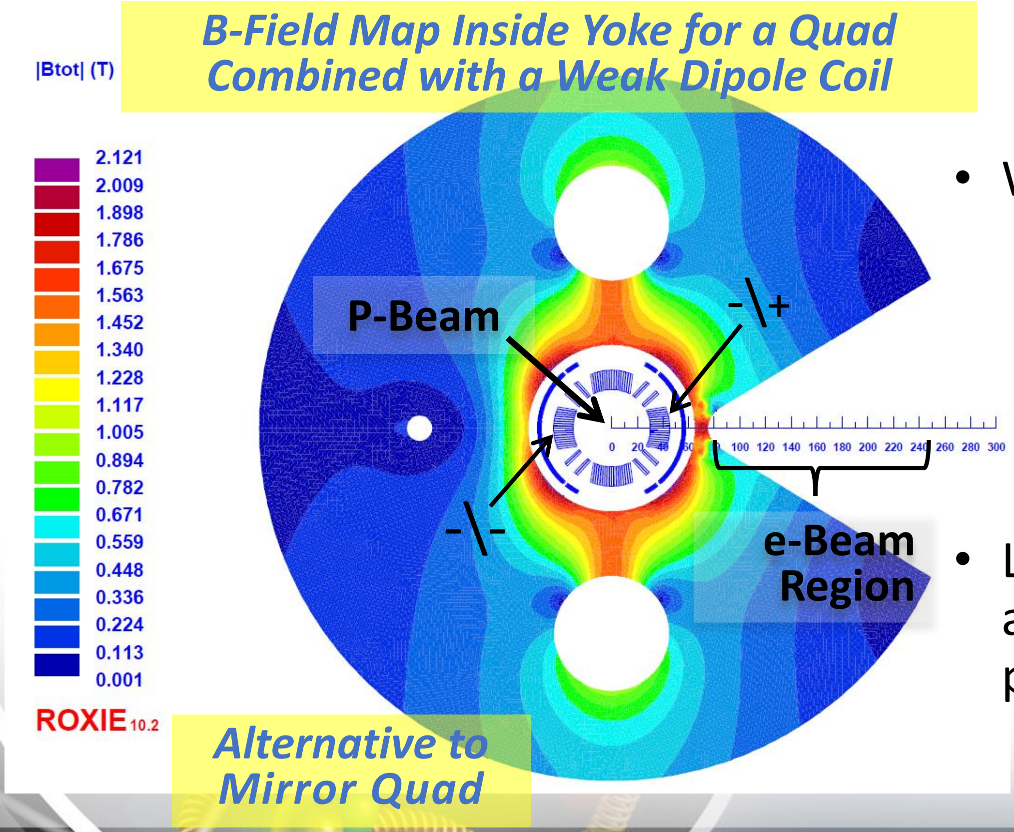


If we need to use a septum or yoke cutout to realize a beam separation as small as possible, it could be useful to provide extra coils to reduce the septum saturation and to control the leakage field in the cutout region.

Alternative LHeC Septum Quadrupole Approach

- When energized beyond 1 T field, the mirror plate concept shown has horrible field quality and a very large leakage field.
- Below is a new concept that adds a weak dipole coil to control the yoke magnetic saturation of the “septum region.”





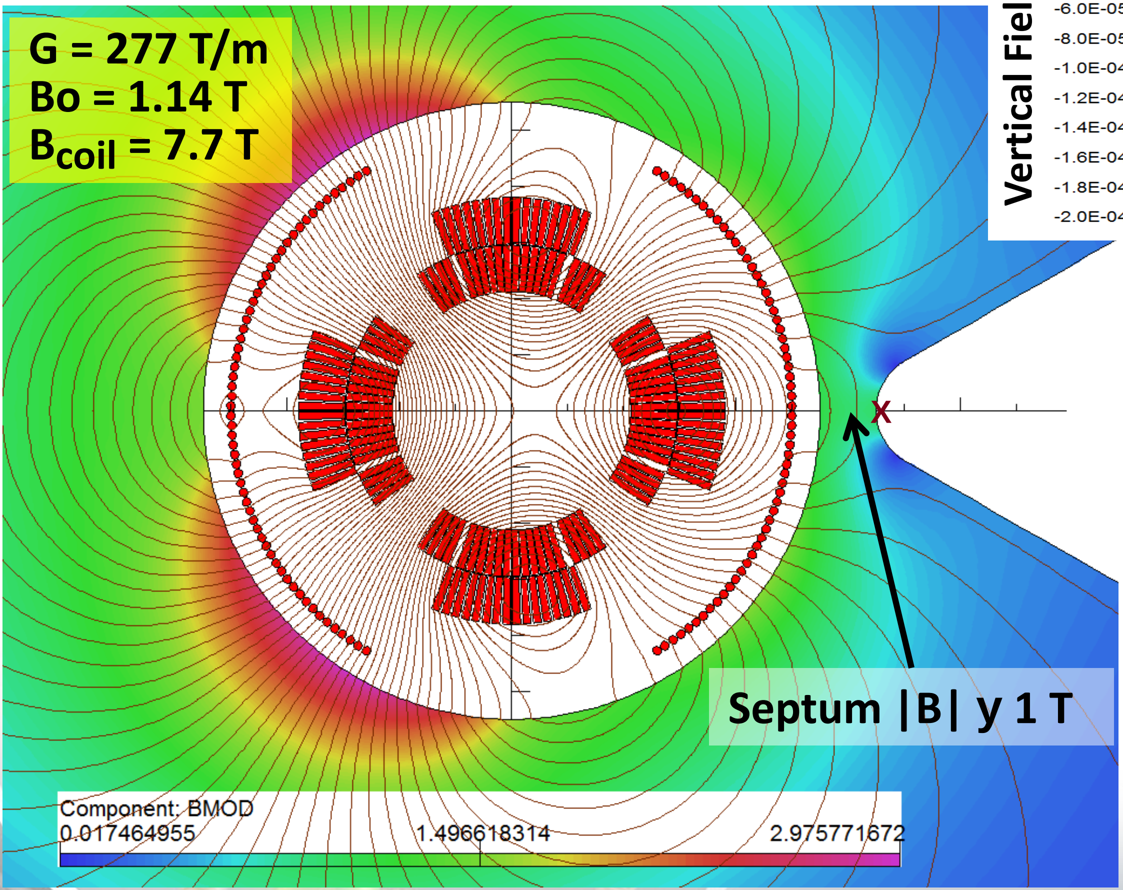
B-Field Map Inside Yoke for a Quad Combined with a Weak Dipole Coil

Alternative to Mirror Quad

- With this new scheme we have:
  - ✓ *Larger gradient for same coil B-peak.*
  - ✓ *Smaller kick to circulating p-beam*
  - ✓ *Good field quality over range of fields*
  - ✓ *Very low leakage field at the e-beam*
  - ✓ *Naturally wide cutout region for e-beam*
- Look to combine a Nb_3Sn inner coil with a NbTi Direct Wind outer coil for the best possible performance.

Alternative LHeC Septum Quadrupole Approach

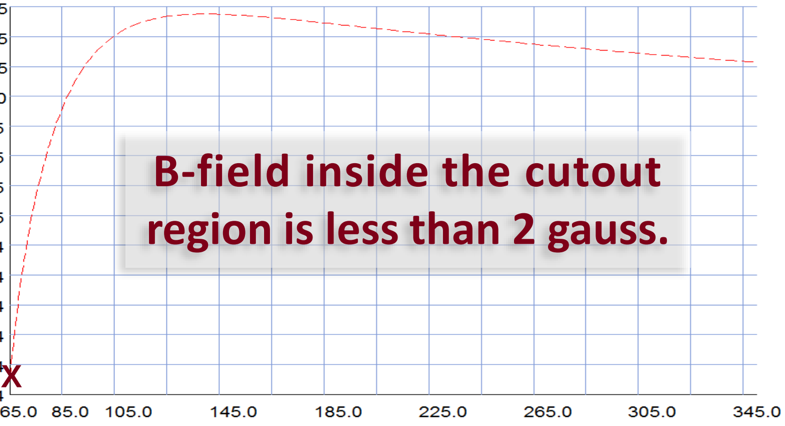
Field Magnitude, |B| (T)
Inside the Magnetic Yoke



G = 277 T/m
Bo = 1.14 T
B_{coil} = 7.7 T

Septum |B| y 1 T

Field Profile Inside Cutout Region

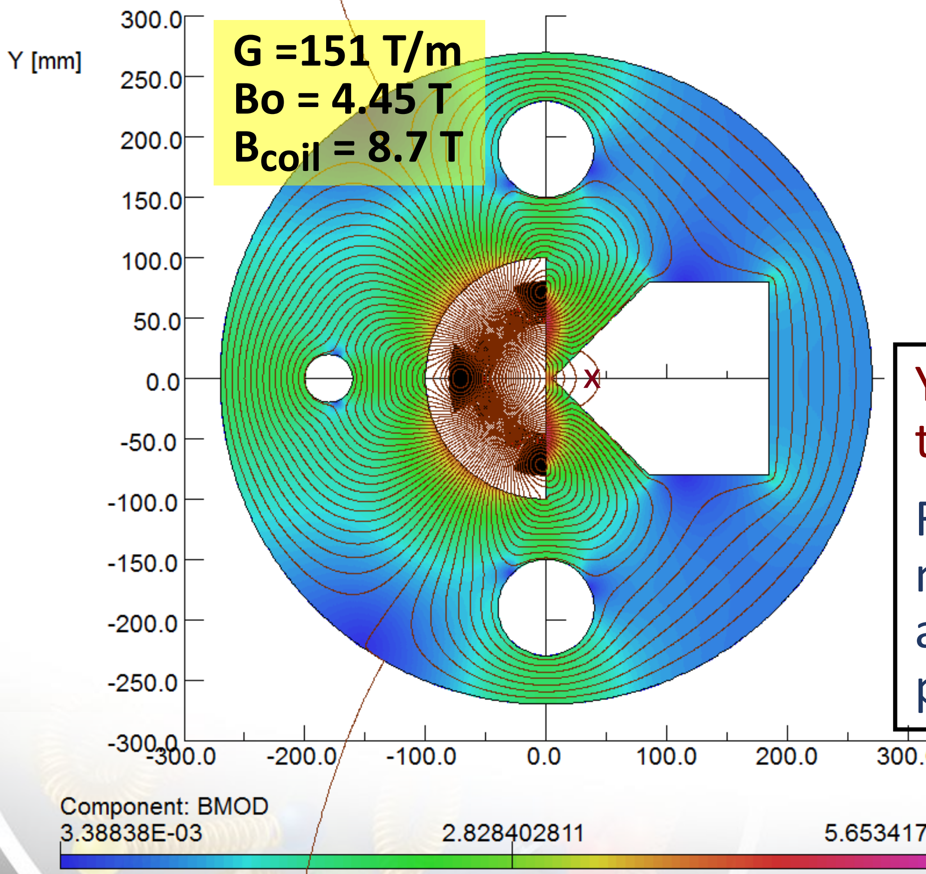


B-field inside the cutout region is less than 2 gauss.

Compared to the original MSQ we have higher gradient for lower coil peak field, reduced dipole kick, good harmonics and low leakage field over a wide region. **Minimum beam separation is almost the same in both cases.**

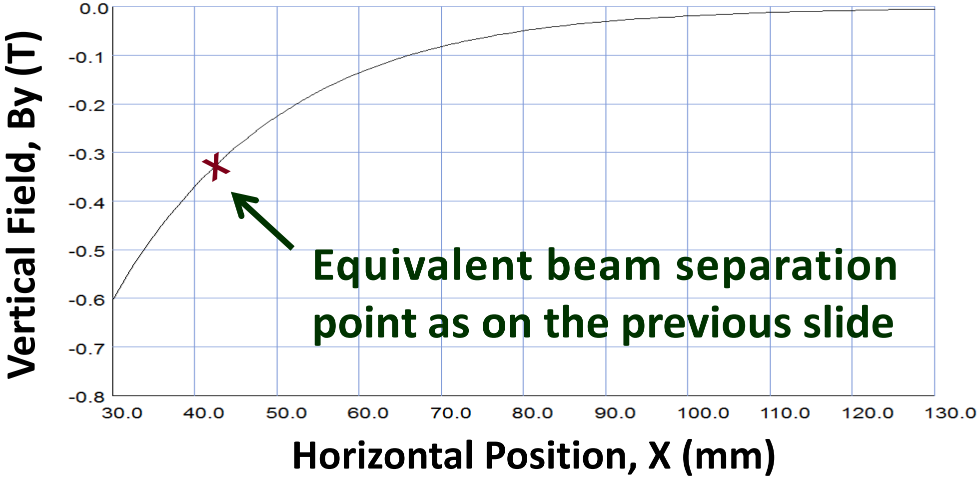
(Repeat Slide 6) LHeC Magnetic Septum Details

Field Magnitude, |B| (T)
Inside the Magnetic Yoke



G =151 T/m
Bo = 4.45 T
B_{coil} = 8.7 T

Field Profile Inside Cutout Region



Equivalent beam separation point as on the previous slide

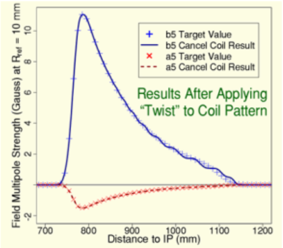
Yoke is very saturated with typical μ_ry2.

Field distribution near mirror plate surface is almost same as if the plate were absent!

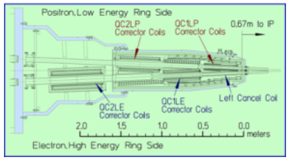
Field Harmonics At R_{ref}=20mm:

1	-14781.
2	10000.
3	-633.
4	-138.
5	-117.
6	-144.
7	-92.
8	-74.
9	-59.
10	-38.

Some Other Design Approaches To Consider

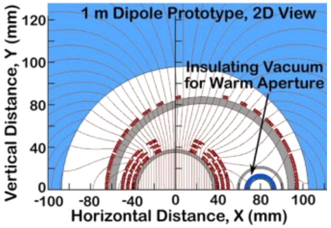


Calculated b5 Normal/Skew Fields Compared to Targets.



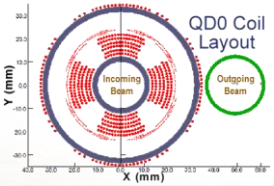
SuperKEKB

Look to make local field cancellation or compensation of the external field outside of a coil structure (**SuperKEKB example**)



eRHIC R&D

Look to make local cancellation of field over a small region inside a coil structure (**eRHIC Sweet Spot example**)



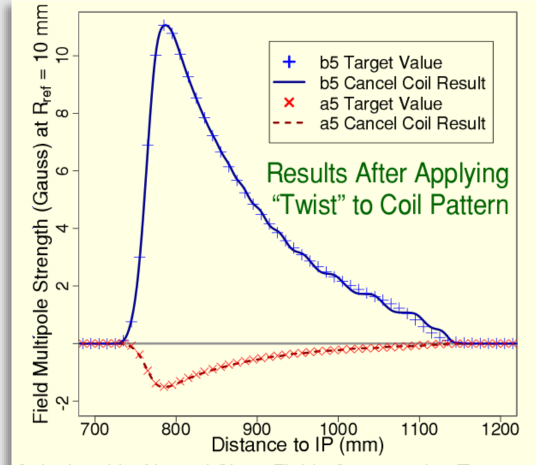
ILC and eRHIC R&D

Use active shielding to cancel the external field everywhere outside of a coil structure (**ILC and eRHIC/JLab EIC examples**).

Cancel Coils and Sweet Spot Magnets

Winding SuperKEKB B5 Cancel Coil

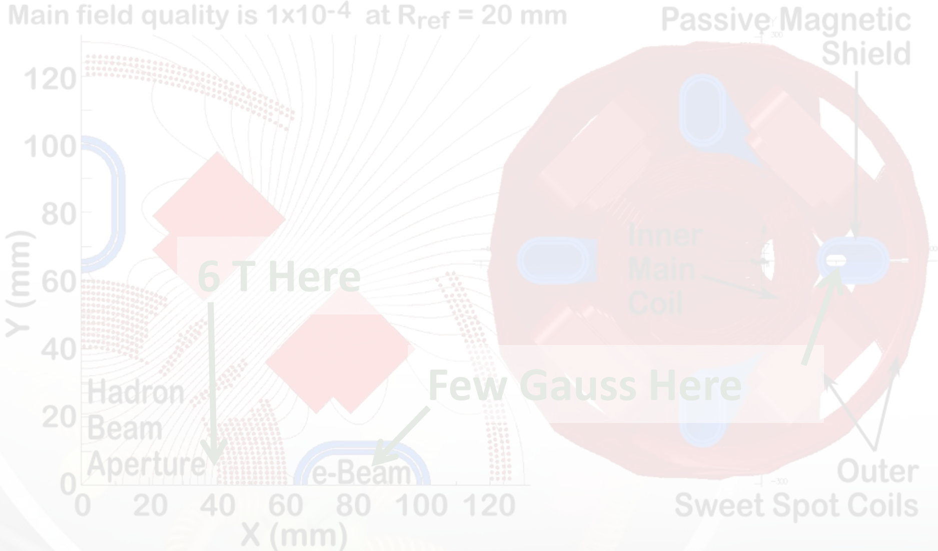
An example of BNL Direct Wind magnet production



Calculated b5 Normal/Skew Fields Compared to Targets.

SuperKEKB takes a brute force approach canceling external field coming from the neighboring IR quads; the linear (dipole & quad) external field components are not cancelled.
(see backup slide)

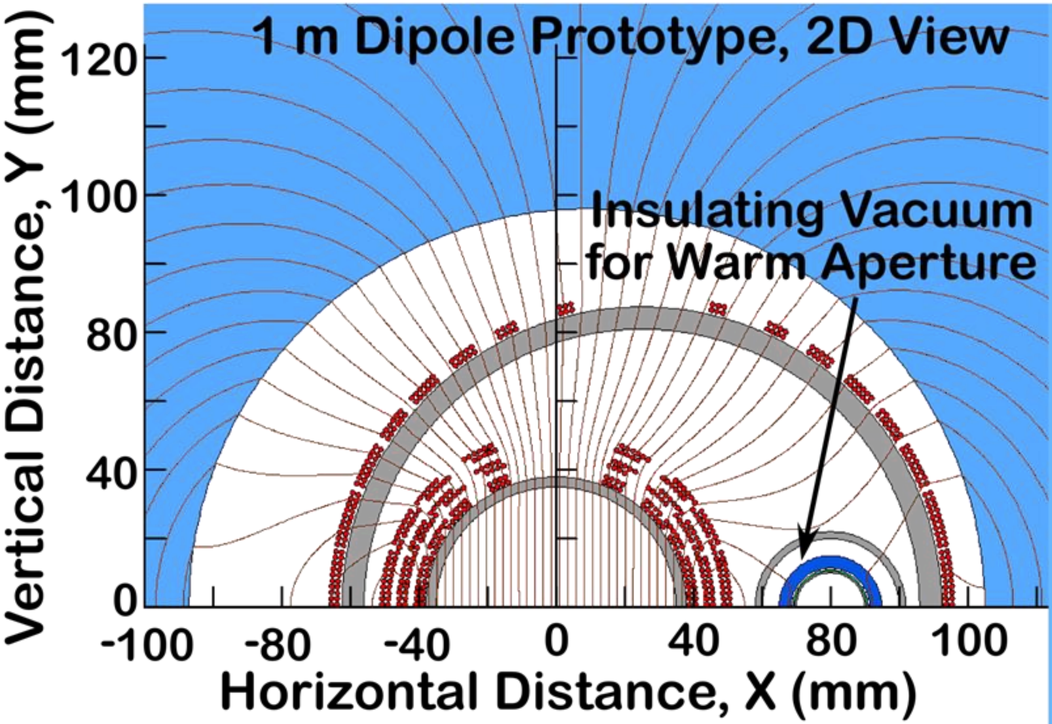
The sweet spot coils contribute 36% of the eRHIC Q1 137 T/m gradient
The e-Beam in the shielded region sees about 1 gauss
Main field quality is 1×10^{-4} at R_{ref} = 20 mm

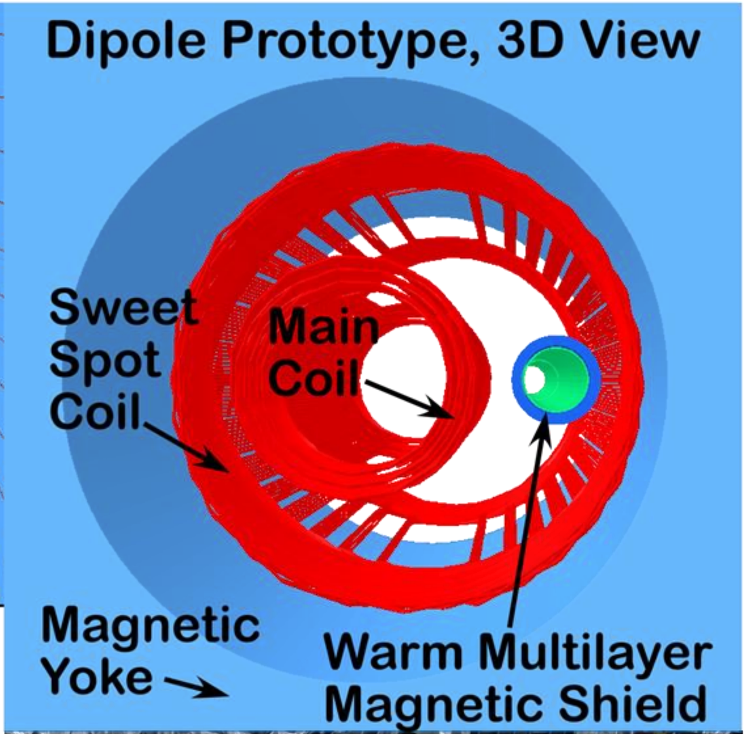


- Invented Sweet Spot concept where e-beam passes through a zero field region inside the coil structure[†].
- Very efficient coil geometry (fields add).
- Accommodates very small beam separations (small crossing angle).
- Yet still can have good field quality.

[†] Brett Parker, "SWEET SPOT DESIGNS FOR INTERACTION REGION SEPTUM MAGNETS," Contribution TUPMB042 to Proceedings of IPAC2016, Busan, Korea, May 2016, pp. 1196-1198.

Sweet Spot R&D at BNL


1 m Dipole Prototype, 2D View

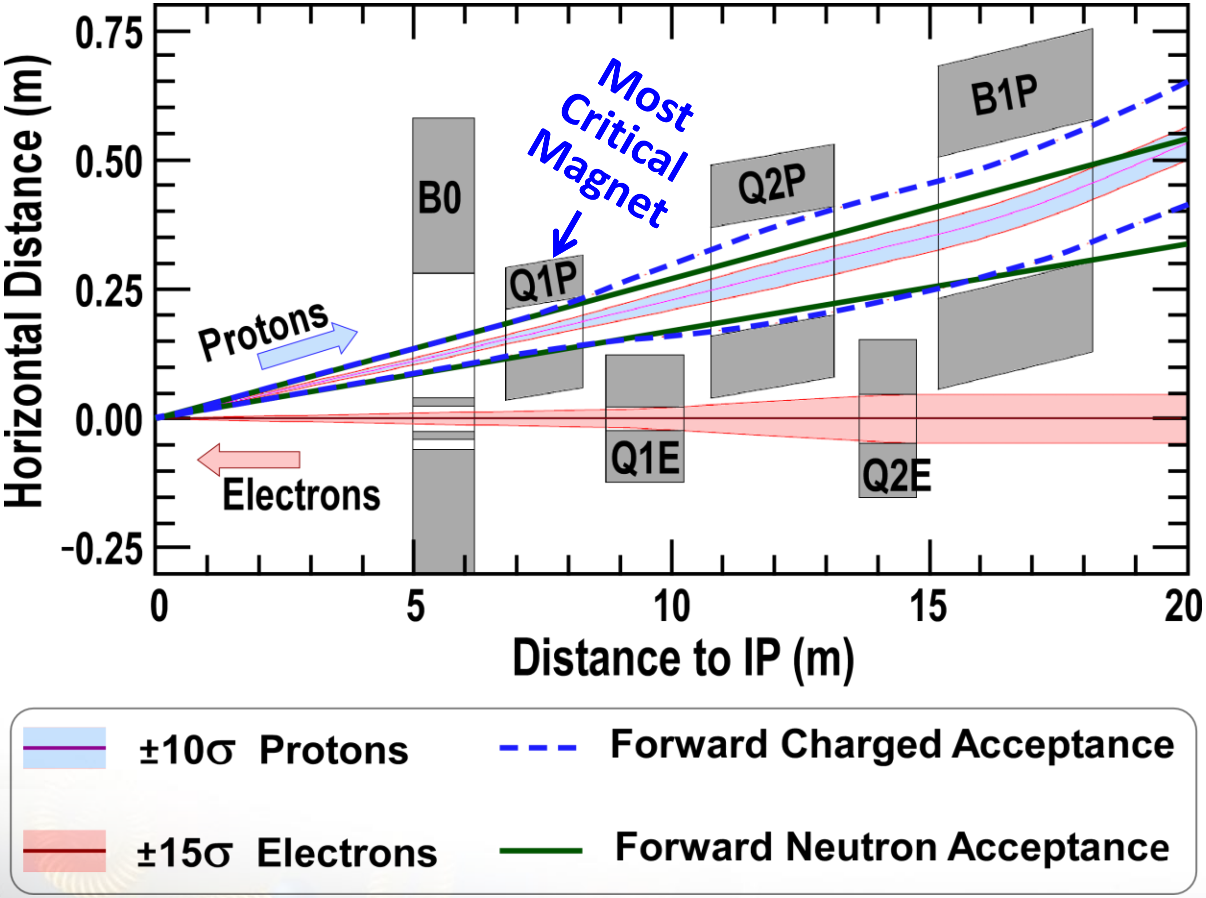

Dipole Prototype, 3D View


Sweet Spot Coil During Production

- Production of dipole Sweet Spot coil is nearly complete.
- Present plan is to test this Sweet Spot coil during FY'18.

An Opportunity to Improve the eRHIC Forward Acceptance Via High-Field Magnet R&D

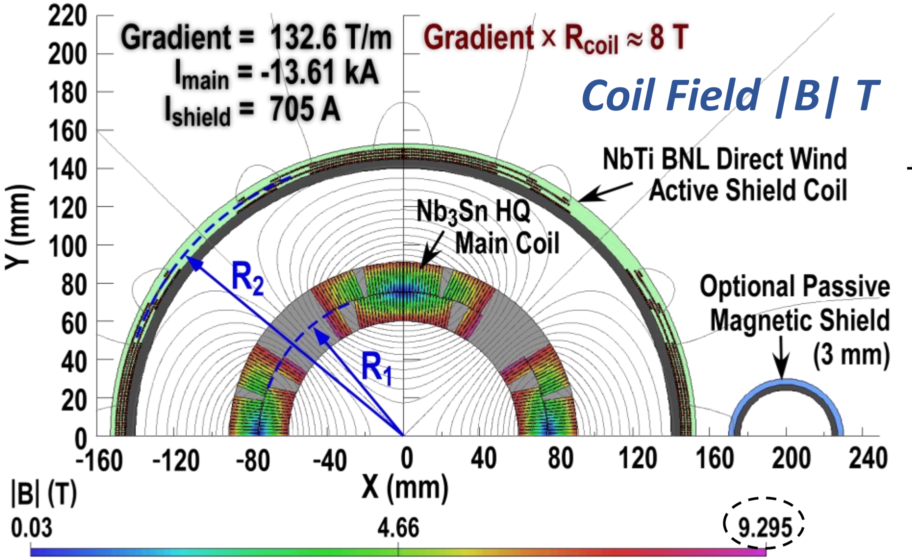
eRHIC IR Forward Side Magnet Layout



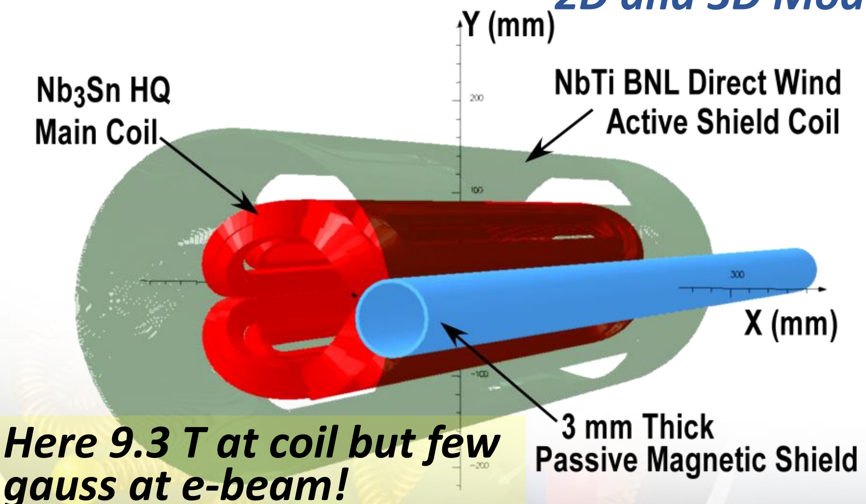
- An eRHIC IR design exists with a maximum coil peak fields of 4.5T (R_{apt}*Gradient).[†]
- **For critical magnets it can be worthwhile to be more aggressive (ie. use Nb_3Sn or 1.9K cooling).**
- The first proton quadrupole, Q1PF, is actively shielded.
- **Pushing Q1PF's field to 6.8 T allows increasing the forward acceptance and leads to a more compact IR layout.[†]**

[†] **Here we Use Bob Palmer's criteria (Gradient*Aperture Radius) to define a "pole tip field." The actual peak field found in the superconducting coil will be somewhat greater.**

Active Shielding Example from eRHIC R&D



2D and 3D Models



Here 9.3 T at coil but few gauss at e-beam!

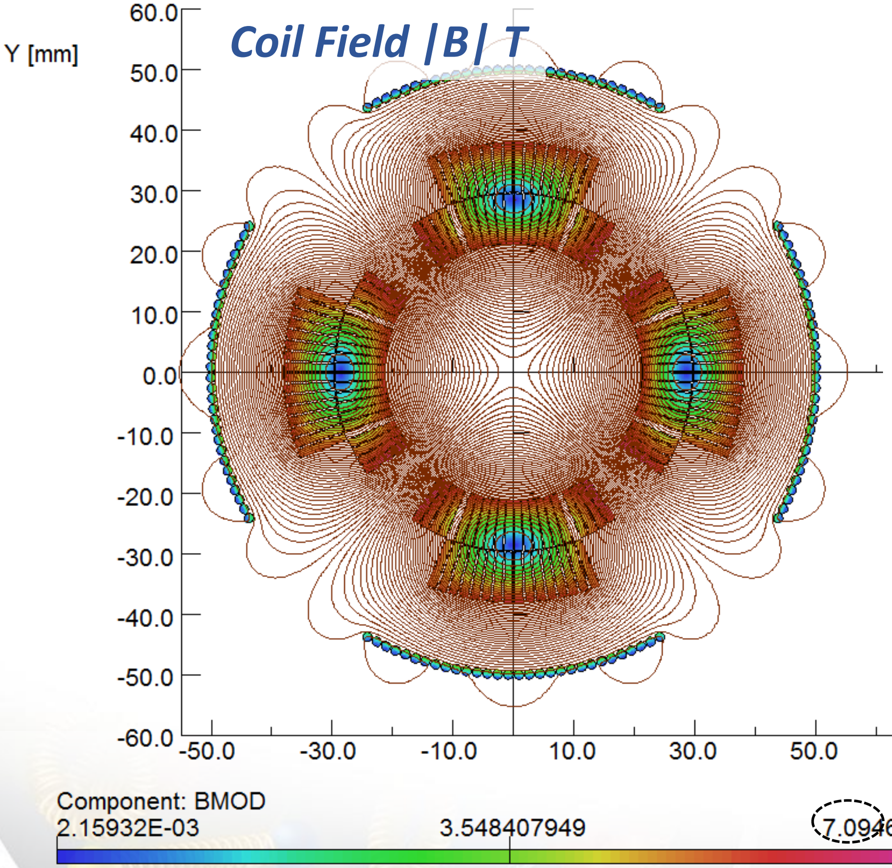
Actively Shielded Coil Designs

- As with the ILC QD0 we can use an Active Shield (here an anti-quad) to eliminate the external field.
- Active shield geometries are not as efficient as Sweet Spot geometries.
- But an Active Shield is useful for a large crossing angle since it can null the external field over a very large region.
- Active Shield magnets are of interest for both the BNL and JLAB EIC IR designs and thus represent an area of common R&D interest.

Models correspond to "Fast Track" R&D quad described on a later slide.

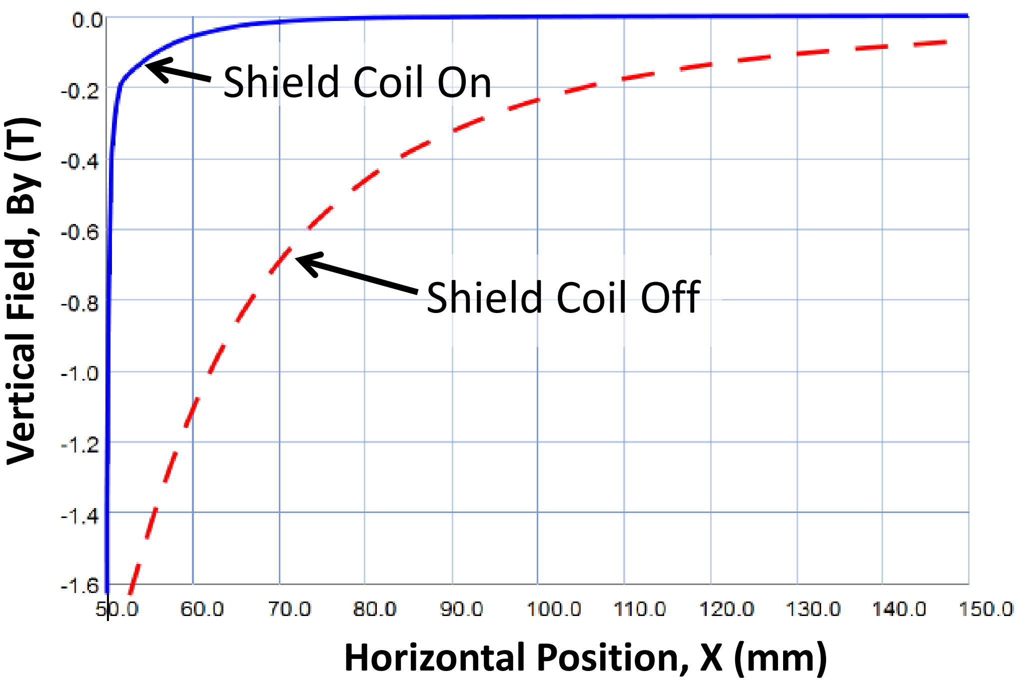
Active Shield Configuration for LHeC IR

Gradient is 284 T/m with the shield on
Gradient is 322 T/m with the shield off
$1-(29.3/50)^4 = 0.882$ agrees with above



Active Shield Coil for an LHeC IR Quad

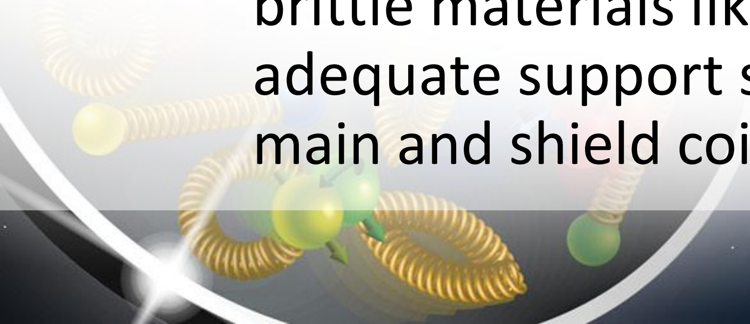
Field Profile Outside Shield Coil



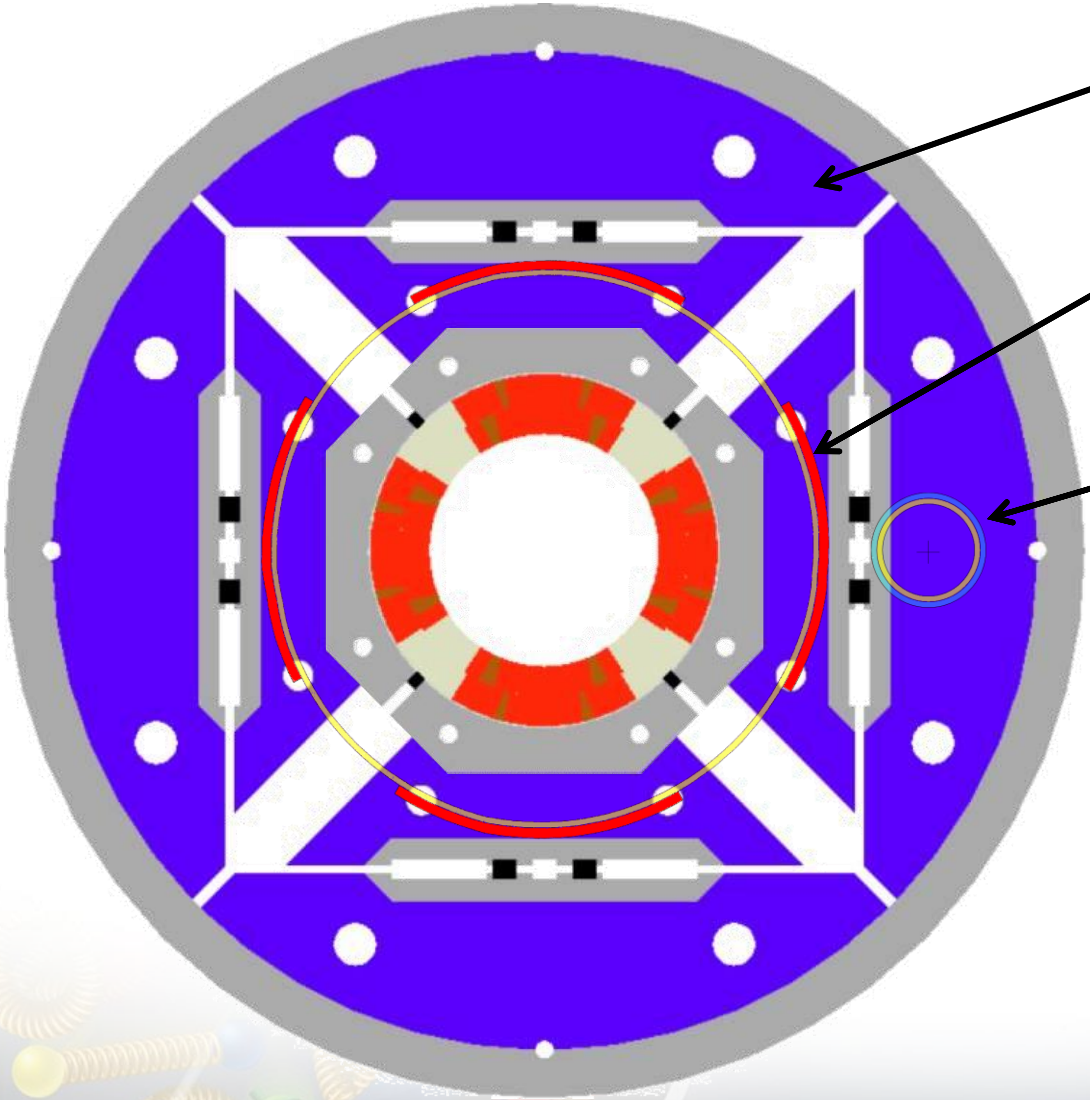
Active shield reduces the gradient and we need a very compact structure to hold the coil together and provide pre-stress. **But the external B-field is now very low everywhere outside the shield.**

Active Shield Magnet Design Process

- **"Magnetic Design Process" for active shielding can be relatively easy and straightforward.**
  - With no (interior) magnetic materials, only simple, linear, field calculation and optimization is required.
  - But do need to take care to match different end field falloffs.
- **"Mechanical Design Process" for active shielding can be relatively difficult.**
  - With a self supporting coil structure, such as the Direct Wind process (à la ILC QD0), the main and the shield coils can be mounted via independent support tubes for easy integration.
  - But for very high field main coils, especially those wound using brittle materials like Nb_3Sn, it can be challenging to design an adequate support structure in the limited space between the main and shield coils.



A Fast Track R&D Quadrupole Magnet Concept



HQ Yoke

Active Shield Coil

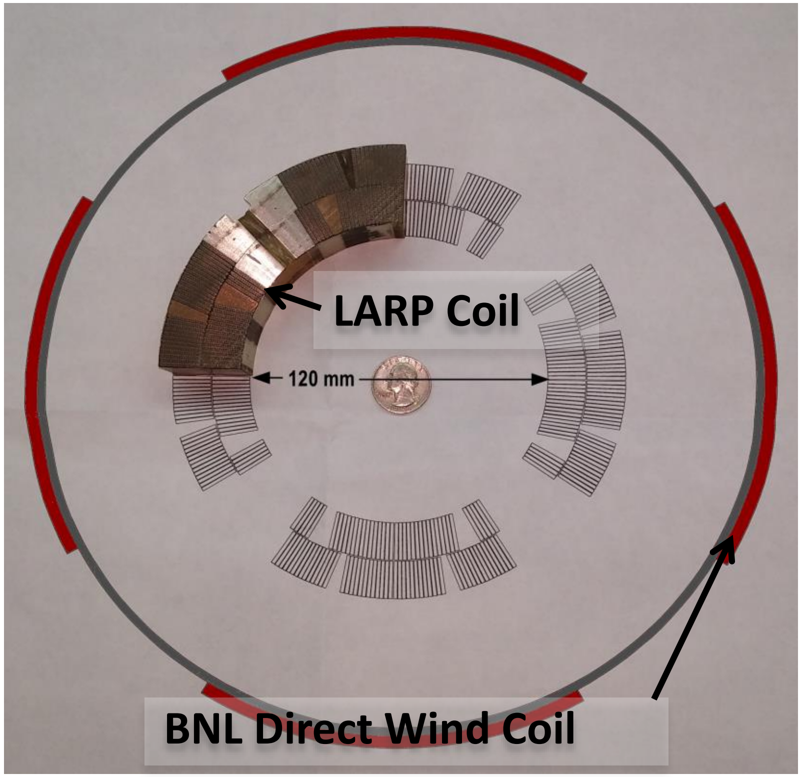
Passive Shield

Designing very compact mechanical structure is the main challenge!

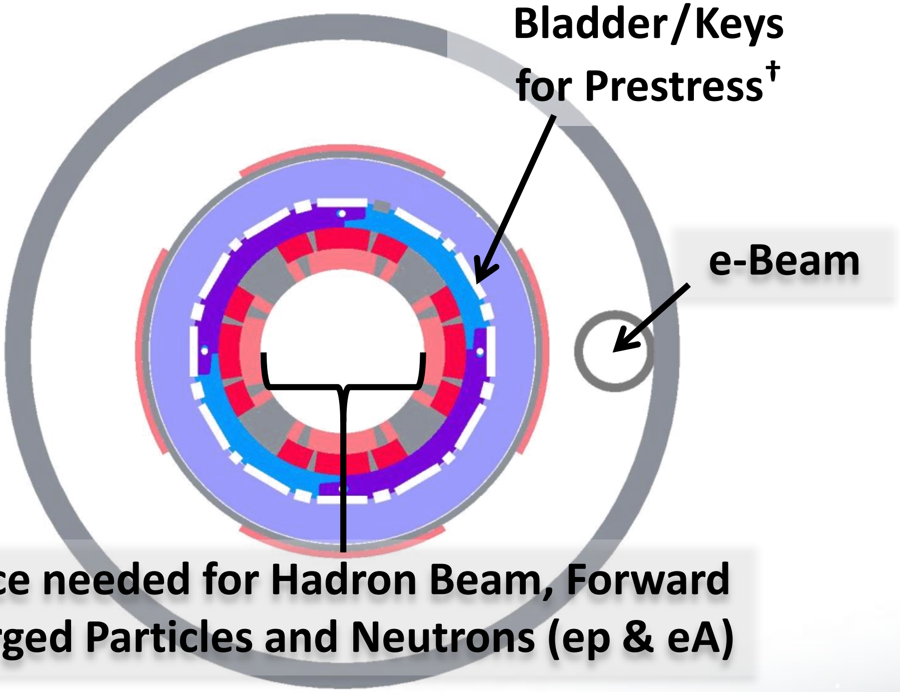
HQ Vs. Active Shield Size Comparison

A Fast Track R&D Quadrupole Magnet Concept

R&D Proposal for a “Fast Track” High Field Nb_3Sn Actively Shielded Quadrupole



A compact structure is needed to provide Nb_3Sn coil prestress. Our preliminary modeling results are very encouraging.



Space needed for Hadron Beam, Forward Charged Particles and Neutrons (ep & eA)

Idea is to add active shield around existing Nb_3Sn coil.

Again 9.3 T at coil but few gauss at e-beam!

[†] Received funding from “BNL/JLab eRHIC R&D” budget to design, build and test a 15 cm long mechanical model of this compact structure.

Conclusions:

- **The MSQ design for Q1 given in the LHeC CDR is really not suitable for its intended usage.**
- **But some variations of the MSQ theme might still be viable and could be considered as Q1 replacements.**
- **However, of the design options presented today, the use of actively shielding is arguably the most promising.**
- **LHeC IR magnet design work can profit from ongoing common R&D for the eRHIC and Jlab EIC IR magnets.**
- **This LHeC design work is also quite relevant to the even more challenging FCC-he IR magnet design requirements.**

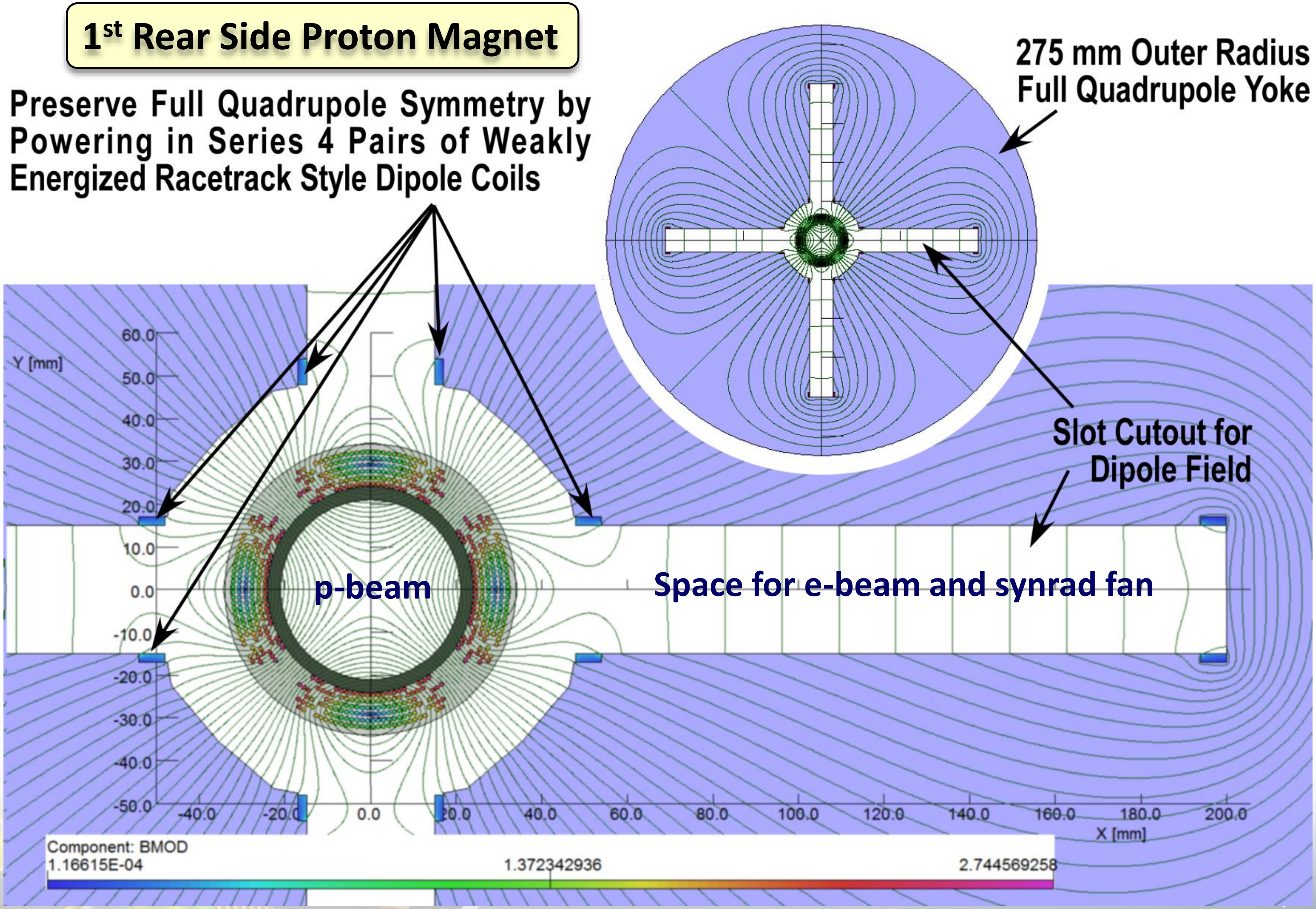
Backup Slides

eRHIC Dual Aperture Magnet Concept

- eRHIC IR layout has 22 mrad crossing angle and avoids bends upstream of the IP that would generate synrad (background).
- Nevertheless some synrad is generated in the IR quadrupoles that must be passed on to absorbers far away from detector.
- Downstream of the detector we use a weak dipole chicane to separate the circulating beam from photons coming from the IP (for the luminosity monitor) and to momentum analyze off-momentum scattered electrons (for physics tagging).
- But we also want the first hadron quadrupole to be as close as possible (i.e. minimize beta peaks and hadron chromaticity).
- Solution is to use a dual aperture magnet with strong focusing for the incoming hadrons and a weak dipole field, over a wide horizontal aperture, for the outgoing e-beam.

eRHIC Dual Aperture Magnet Concept

1st Rear Side Proton Magnet



Preserve Full Quadrupole Symmetry by Powering in Series 4 Pairs of Weakly Energized Racetrack Style Dipole Coils

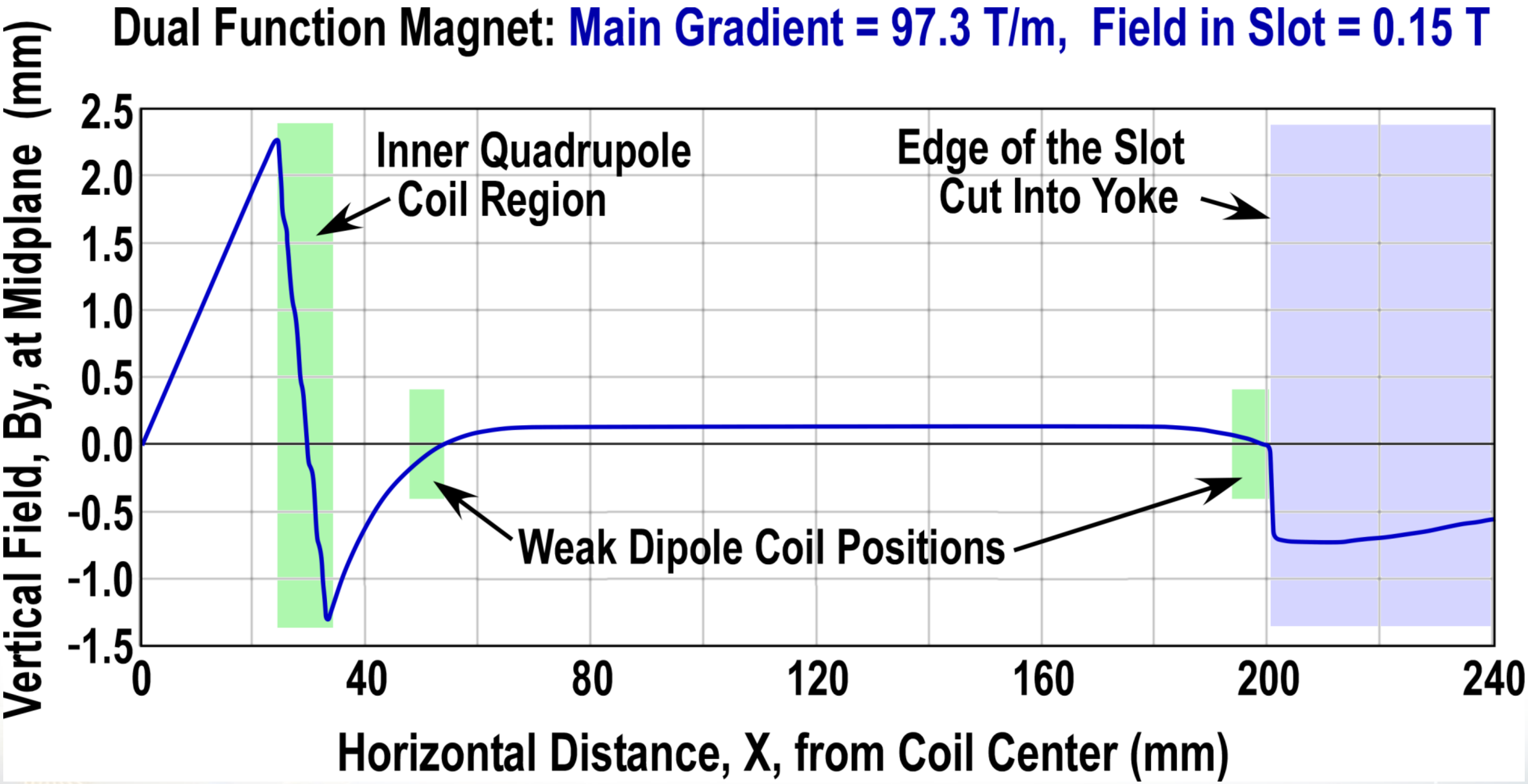
275 mm Outer Radius Full Quadrupole Yoke

Slot Cutout for Dipole Field

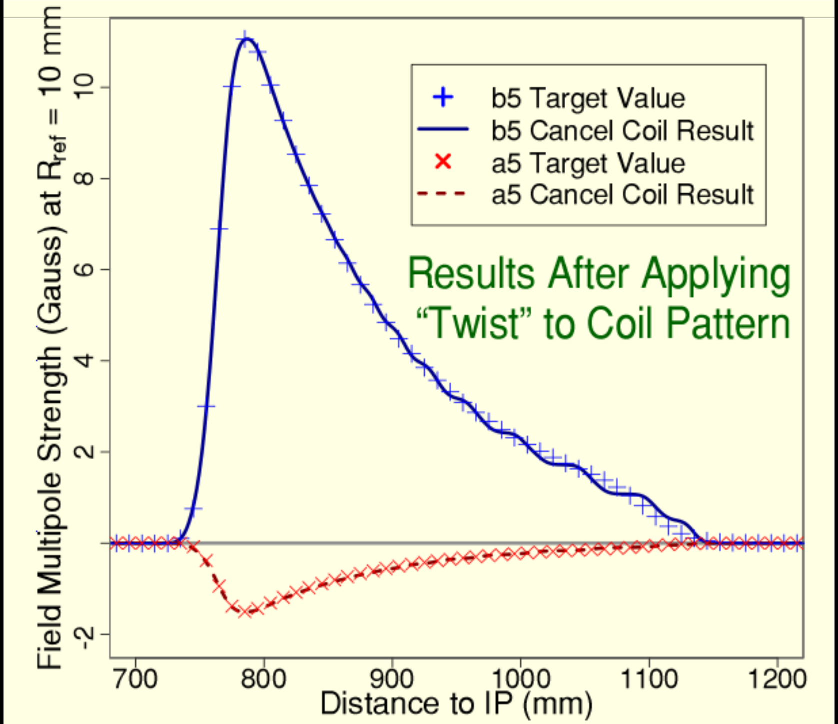
p-beam

Space for e-beam and synrad fan

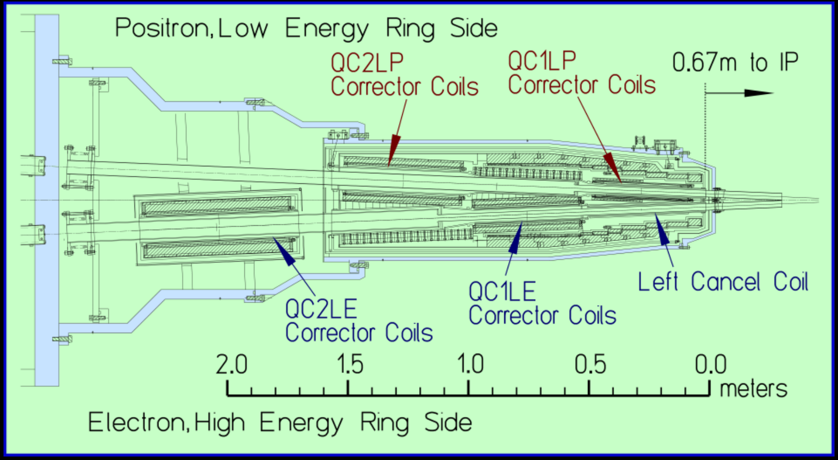
eRHIC Dual Aperture Magnet Concept



SuperKEKB Interaction Region Corrector Magnets



Calculated b5 Normal/Skew Fields Compared to Targets.



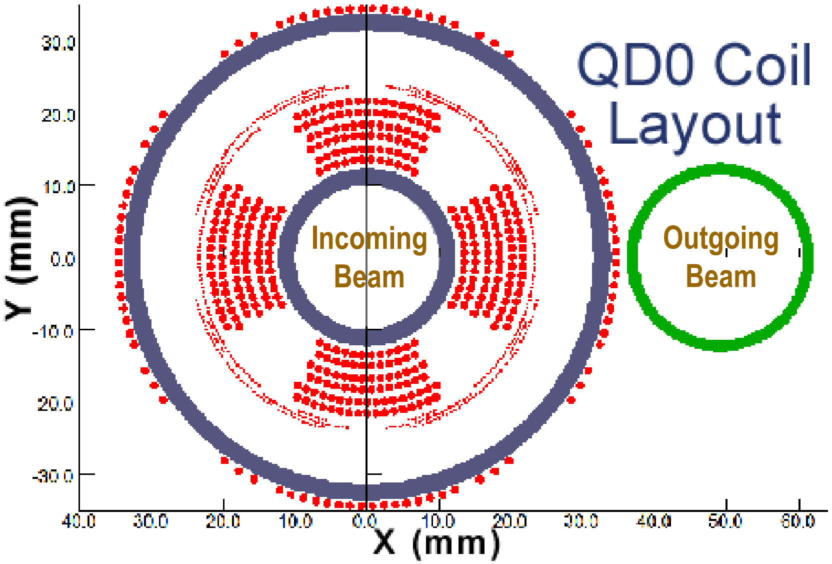
35 correction coils and 8 cancel coils are integrated with the main IR quadrupole and must fit within very limited available space.

The first IR quadrupoles have no magnetic yoke and create external field at nearby beam.

The cancel coil shown during winding on an earlier slide has to match a rapidly changing non-linear field in order to cancel it out.

All of the SuperKEKB corrector coils were wound for KEK using the computer controlled Direct Wind technology developed at BNL.

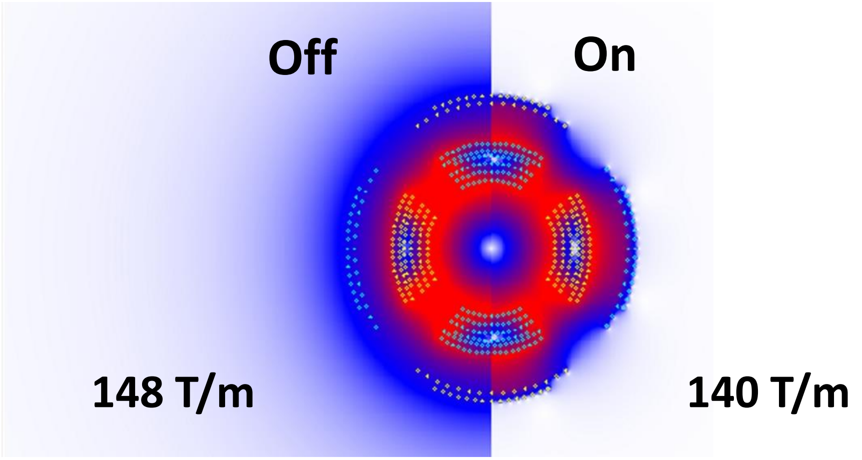
Design for Compact Superconducting Magnet Used in the ILC 14 mr Layout.



- 14 mr crossing angle via compact self-shielded QD0 coil windings.
- Extracted beam passes just outside coil into separate focusing channel.
- Cryostat to fit within limited space inside detector at L* = 4.1 m.

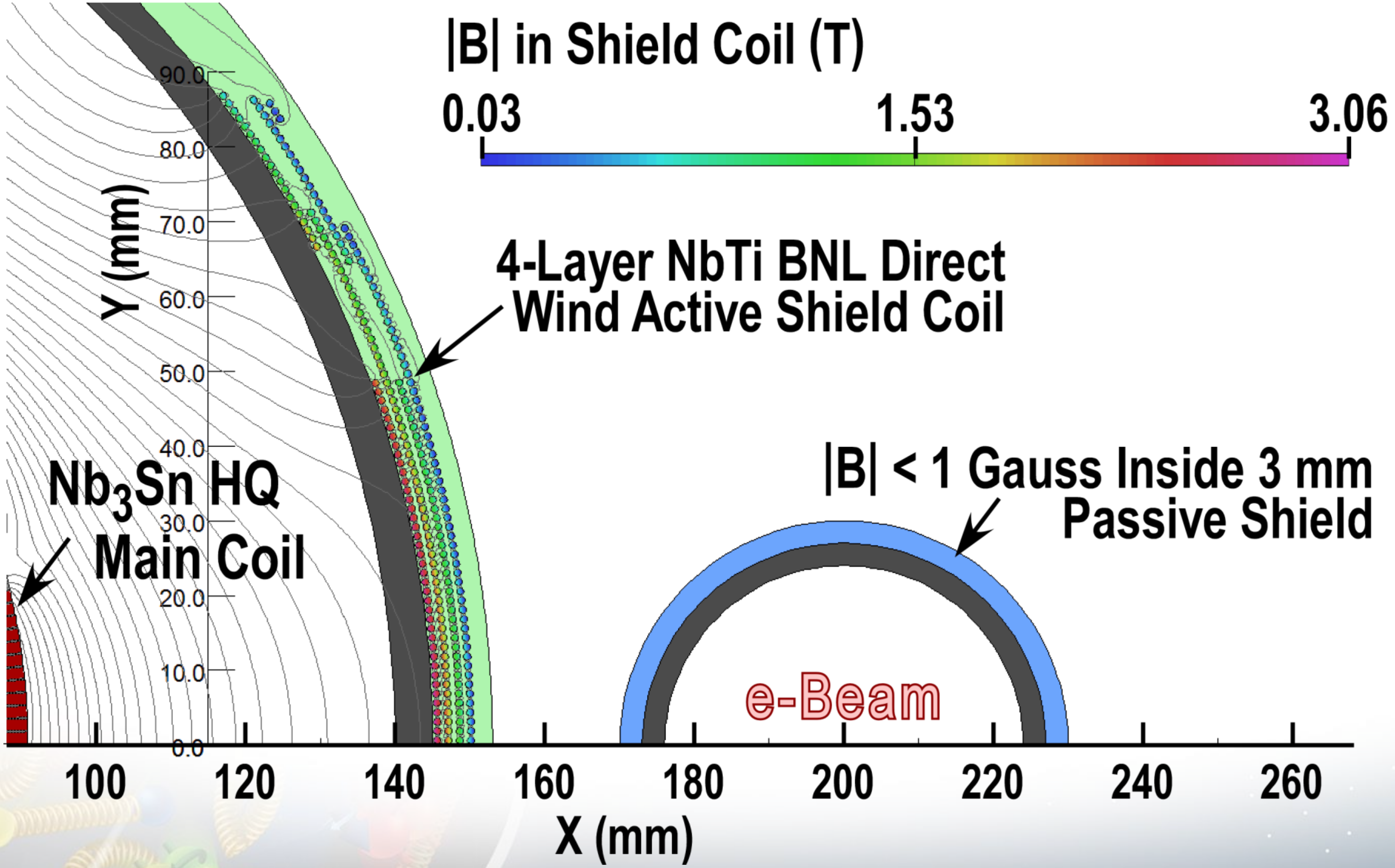
All magnets are variations of same basic design.

QD0 prototype with its outer active shield



QD0 with active shield off/on

A Fast Track R&D Quadrupole Magnet Concept



A Fast Track R&D Quadrupole Magnet Concept