Novel Design for High Field, Large Aperture Quadrupoles for Electron-Ion Collider

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Overview

- Design requirements for EIC quadrupoles
- Efficiency of racetrack coil quadrupoles
- Modular design and modular R&D
- Scope of work in Phase I and initial plan for Phase II

Design Requirements for the Interaction Region Quadrupoles of EIC

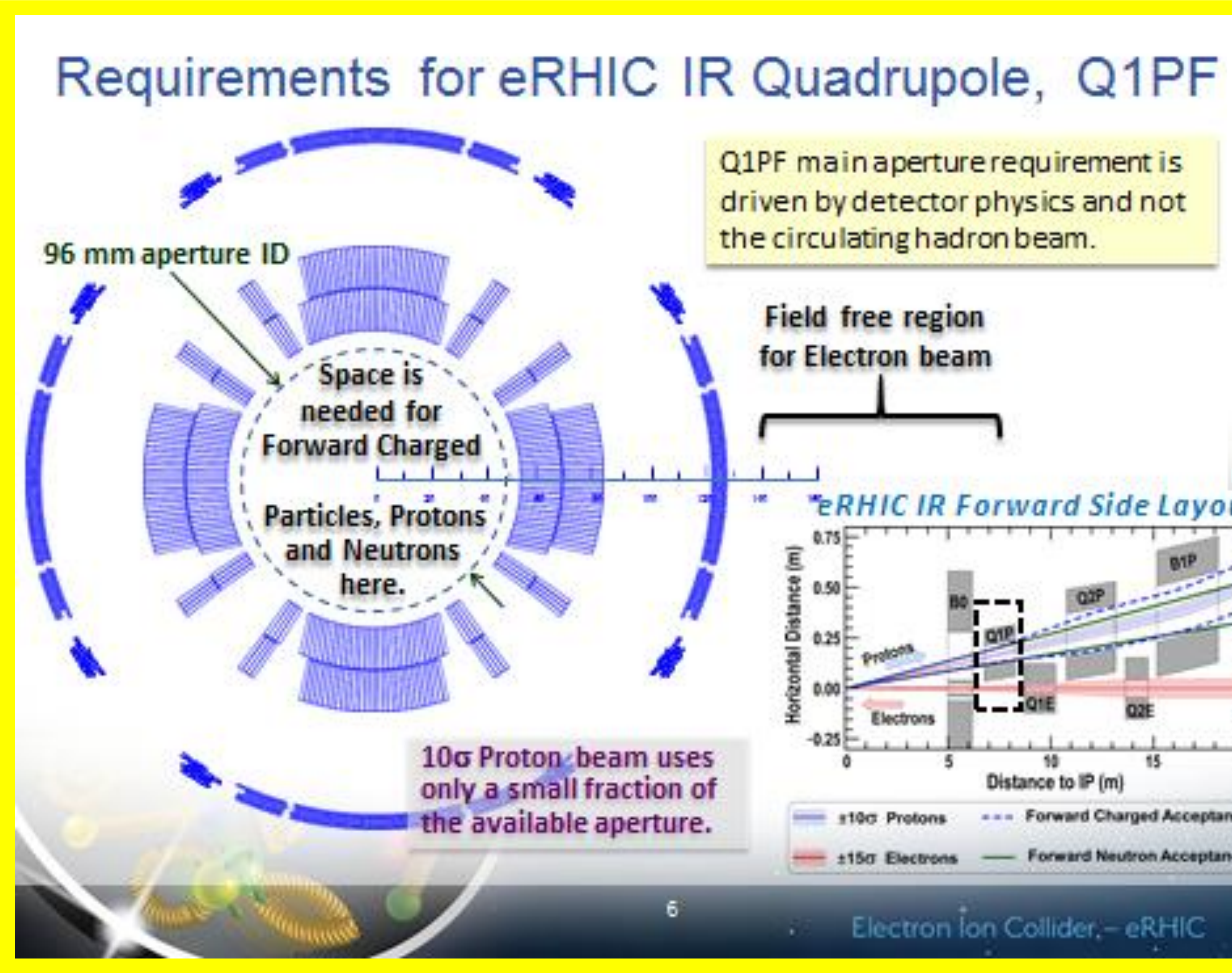
- **Large aperture, high field (several such quads in the JLEIC proposal)**
- **Have a field-free region along the length for electron beam**
- **Able to tolerate high radiation load (specifications?)**
- **Compact in size, with limited space for shielding (specifications?)**

Actual requirements may have evolved overtime

A conceptual approach developed (but never tried) during LARP R&D program over a decade ago, seems to fit well for EIC quad R&D program.

- **This SBIR is based on that approach.**

Brett Parker's Slide at EIC Meeting
Q1PF with Active Shielding



Requirements for eRHIC IR Quadrupole, Q1PF

Q1PF main aperture requirement is driven by detector physics and not the circulating hadron beam.

96 mm aperture ID

Space is needed for Forward Charged Particles, Protons and Neutrons here.

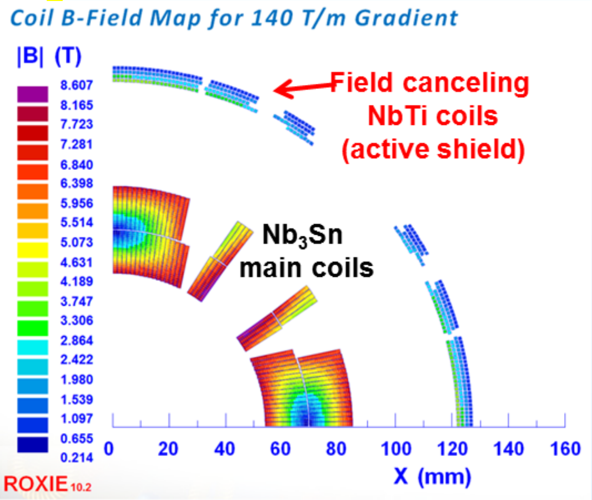
Field free region for Electron beam

10σ Proton beam uses only a small fraction of the available aperture.

eRHIC IR Forward Side Layout

6

Electron Ion Collider – eRHIC

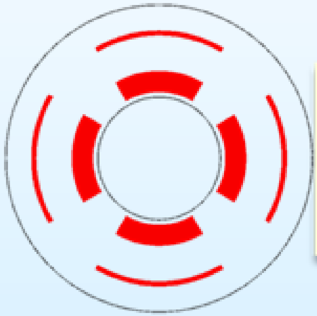


Coil B-Field Map for 140 T/m Gradient

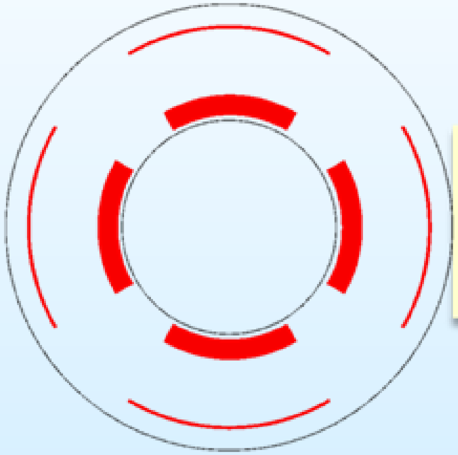
EIC Magnets at JLab JLEIC Design

Design parameters of the JLAB design of the EIC (JLEIC) and a conceptual representation of the conventional cosine two-theta design

JLEIC QFFB2_US
G = 149 T/m
R_{apt} = 40 mm
R_{outer} = 120 mm



JLEIC QFFB1
G = 88 T/m
R_{apt} = 68 mm
R_{outer} = 171 mm



JLEIC QFFB2
G = 51 T/m
R_{apt} = 118 mm
R_{outer} = 247 mm

Project Considerations for the Cost of Magnet Development

- There are two major project costs in the development of high field magnets:
  a) Cost of material, plus cost of labor per magnet
  b) Cost of tooling, cost of engineering, and cost of R&D, etc.
- If the project needs a large number of high field magnets then to minimize project cost, we should focus on (a), i.e. cost of material, etc.
- If the project needs one or a few high field magnets then (a) the cost of material is less important and (b) the cost of tooling, etc. is more
- In addition, if there are a number of "one of a type" magnets, then the developing a strategy for common tooling, R&D etc. would further bring significant savings and reduce risks

Racetrack coil designs seem attractive on the above grounds for EIC high gradient quadrupoles as EIC needs only a few high field magnets

Racetrack Coil Design for High Gradient Quads of EIC

Primary goal:

Develop a racetrack quadrupole design that can generate a field gradient comparable to that created by cosine theta designs

Key design considerations:

For a few key IR magnets, the design should be efficient in creating field gradient; it need not be so efficient in minimizing the conductor usages

Major motivations:

It has been generally observed that the high field Nb_3Sn magnets made with simple racetrack coil tend to perform better in the initial attempts.

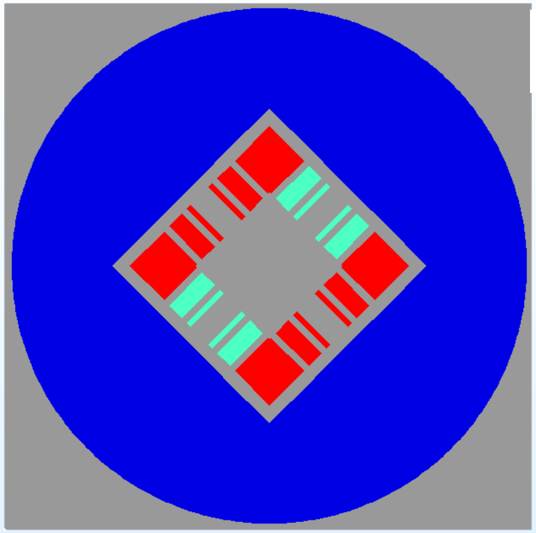
Racetrack coils (and associated tooling) are faster and more economical to build. It allows a modular design and modular R&D program.

Can make program flexible and versatile. One can use the same coils for varying quad aperture or even magnet type (quad or dipole) during the R&D phase.

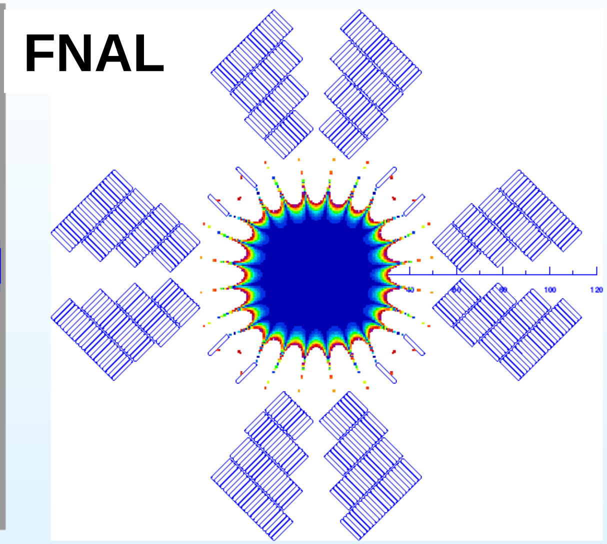
Previous Racetrack Designs

Figure of merit: Highest gradient for the maximum field on the conductor

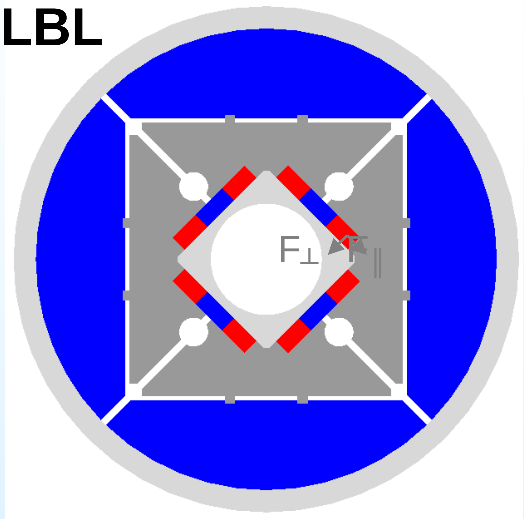
BNL

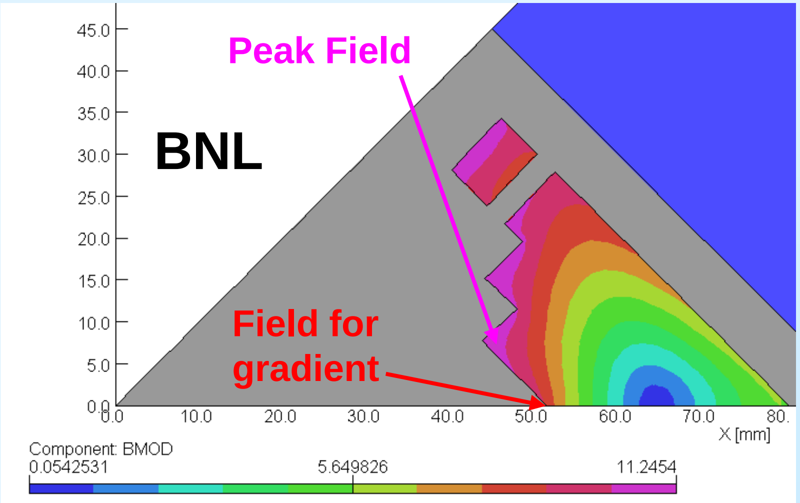


FNAL



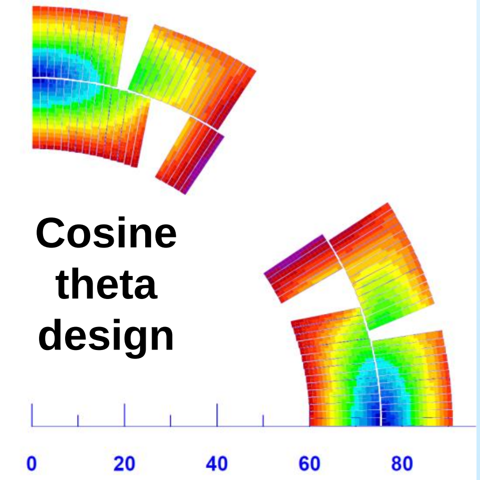
LBL



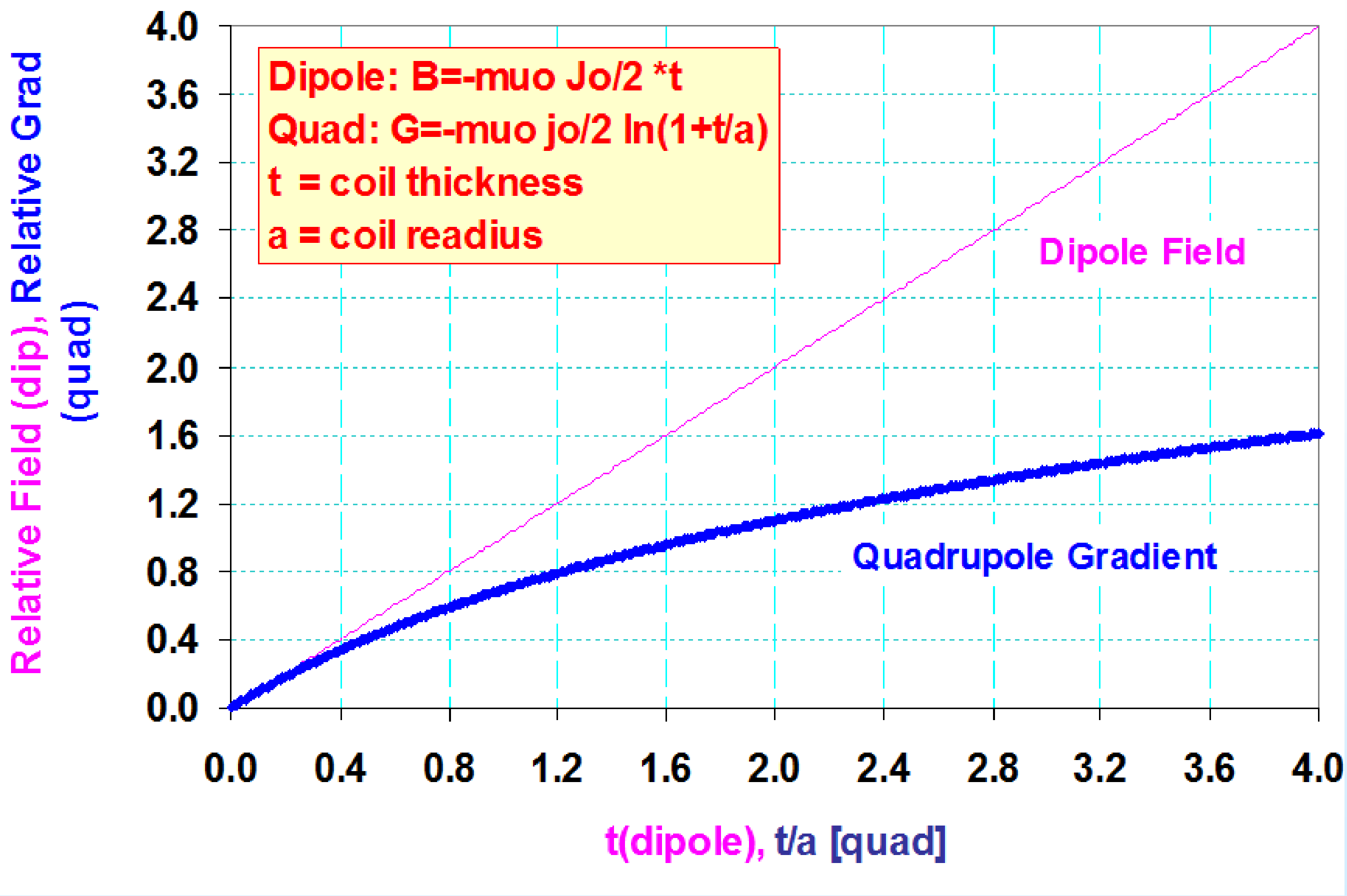


None of these racetrack designs were as good in generating high gradients as the cosine theta designs. That was because of unfavorable conductor configuration at midplane.

(missing conductor, or much higher field elsewhere)



Performance Enhancement in Dipole and Quads with the Thickness of Coil



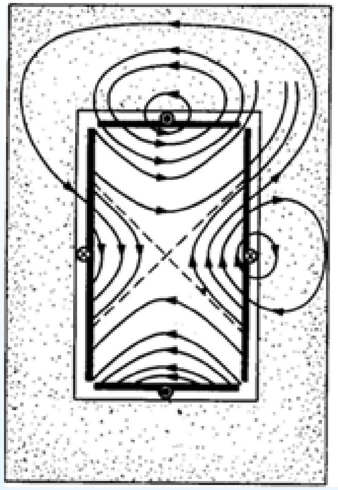
Dipole: B=-muo Jo/2 *t
Quad: G=-muo jo/2 ln(1+t/a)
t = coil thickness
a = coil readius

In quads, one can't get the higher gradient by piling more conductor. The increase in gradients with coil thickness saturates.

One has to be careful in placing the conductor to create higher gradient

***Gradient = B/a*, where "*a*" is the coil radius and "*B*" is the field at the defining radius (midplane defines the field gradient)**

Panofsky Quadrupole
(efficient for generating highest gradient)

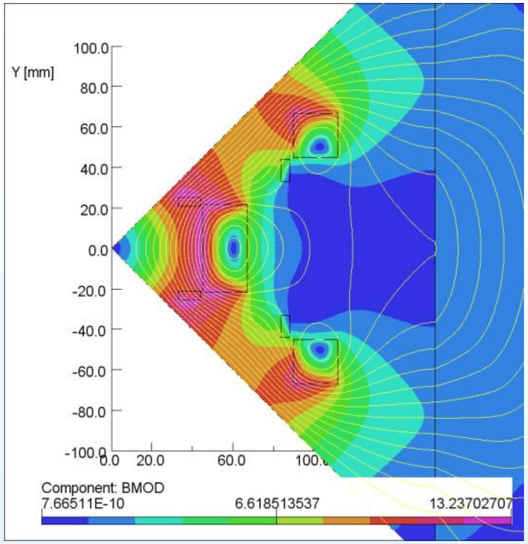


Panfosky, etc. (1959)

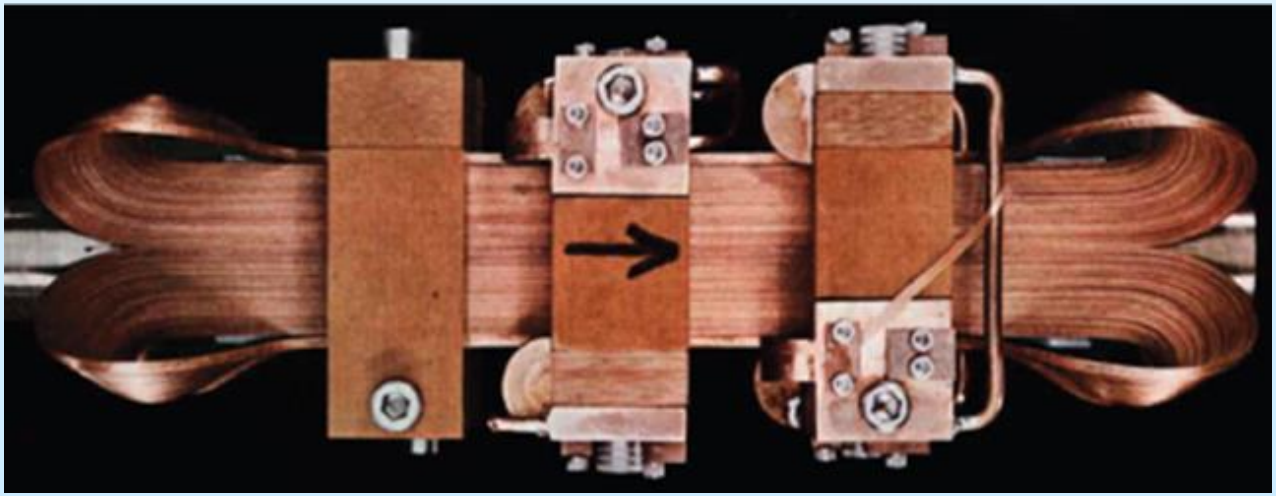
FIG. 2. Field lines of B in an "ideal" rectangular quadrupole consisting of uniform current sheets inside a rectangular iron frame.

Rectangular Aperture Panofsky Quadrupole (field at midplane determines the gradient)

Good design for racetrack coil quadrupoles



Superconducting quadrupole built with Nb_3Sn tapes (Sampson, 1967)



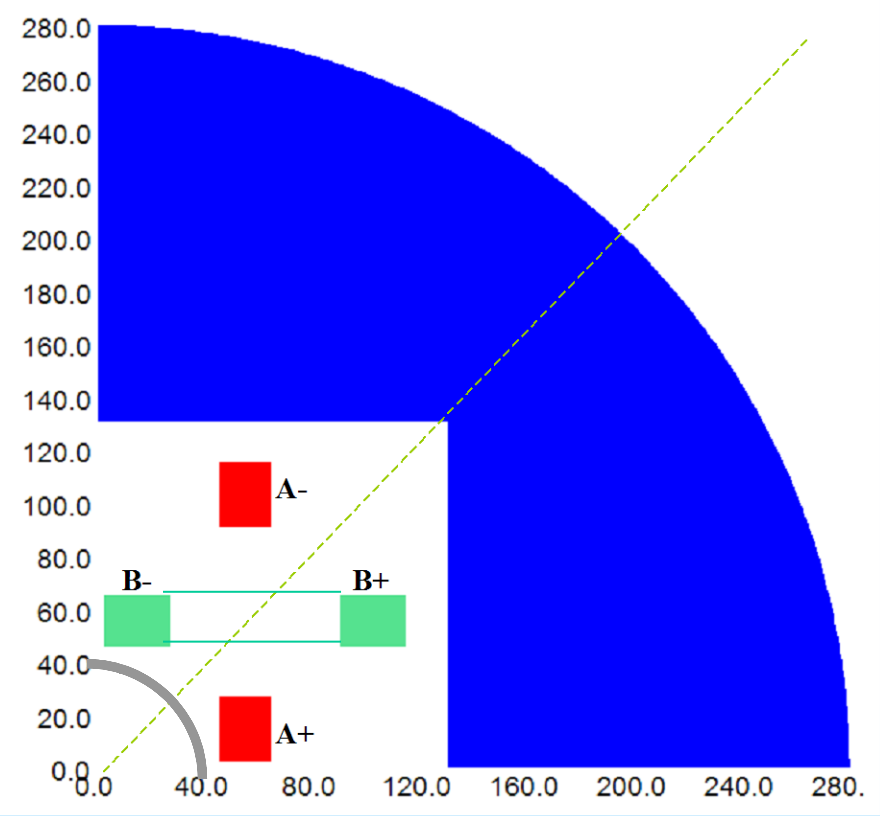
Simple design with interesting ends

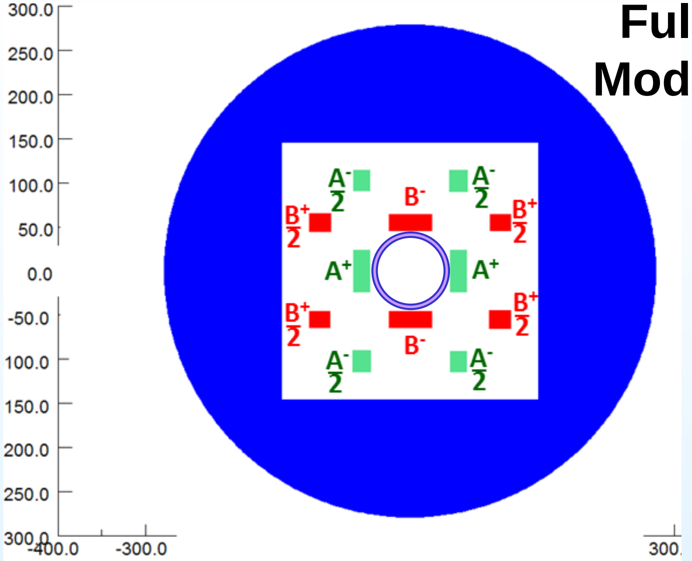
Modular Design for LARP Quadrupole

(taking advantage of Panofsky quad in a simpler geometry)

Cross-section of a Quadrant - made of 2 coils

(ideal eight fold quad symmetry - mirror symmetry at 45°)

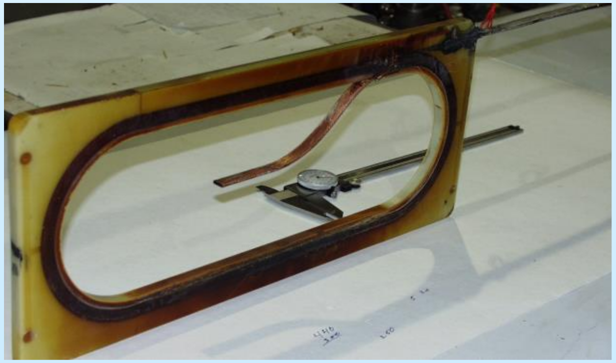




Full Model

Quadrupole with all 8 coils

In this design, horizontal (or vertical) coils must interleave in to other.



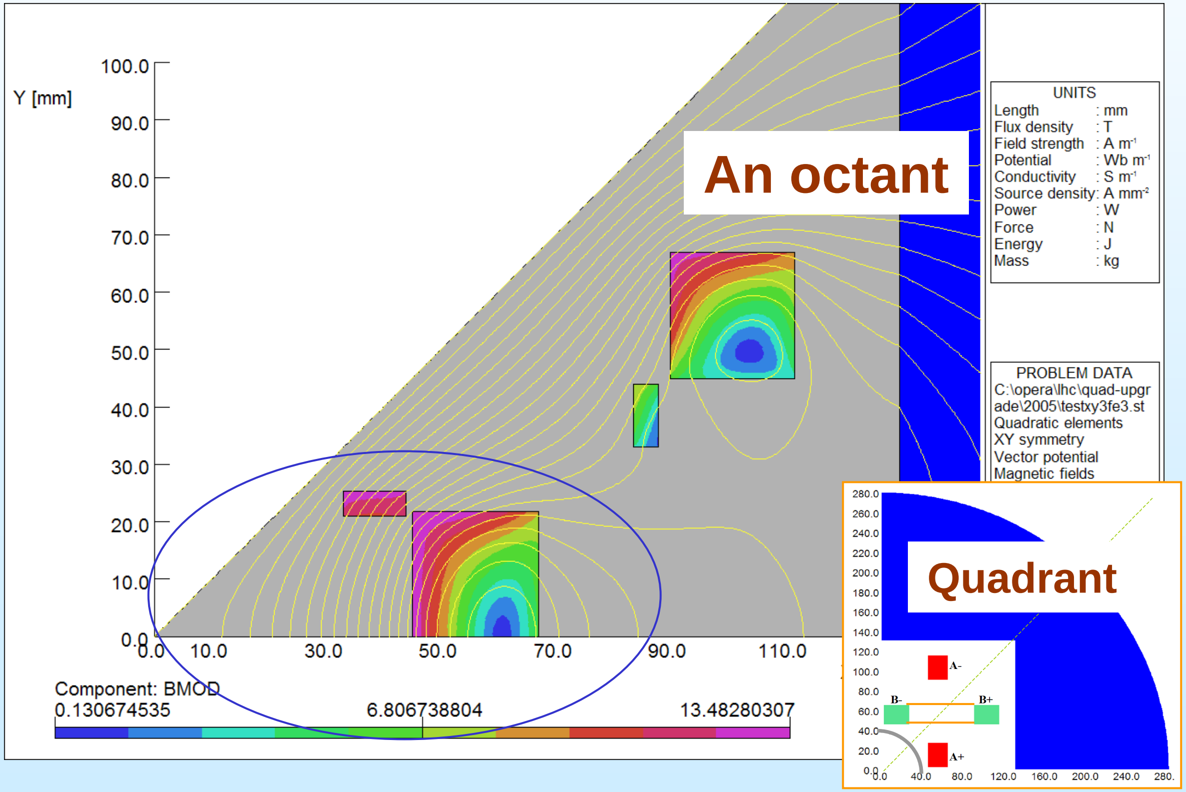
A bobbin-less coil

Most field comes from A+ (return A-) and B-(return B+).
B+ and A- make positive but only a small contribution.

NOTE: The design needs about twice the conductor!

Efficient Design to Create Gradient
(not necessarily to minimize conductor usage)

The key is to have conductor at or near the midplane (@ quad radius)



UNITS

Length	: mm
Flux density	: T
Field strength	: A m^{-1}
Potential	: Wb m^{-1}
Conductivity	: S m^{-1}
Source density	: A mm^{-2}
Power	: W
Force	: N
Energy	: J
Mass	: kg

PROBLEM DATA
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Quadratic elements
XY symmetry
Vector potential
Magnetic fields

OPERA2d model of the octant of a 2 layer, 90 mm aperture LARP "Modular Quadrupole Design".

J_e = 1000 A/mm^2 generates a gradient of ~284 T/m.

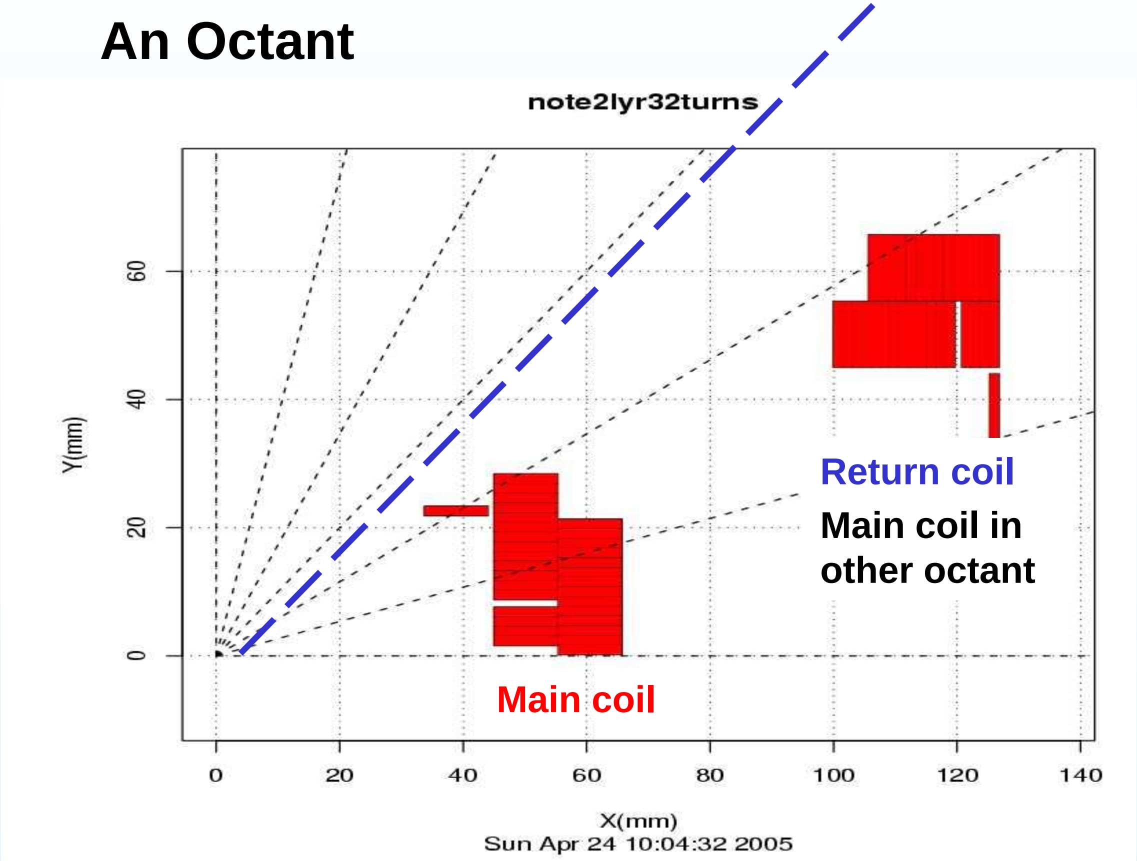
Quench gradient ~258 T/m for J_c = 3000 A/mm^2 (4.2K, 12T).

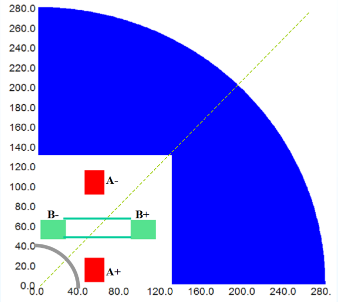
This is similar to what is obtained in competing cosine theta designs.

2-d Magnetic Design

(proof that the design can create a good field quality)

An Octant





Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius, 10^{-4} units).

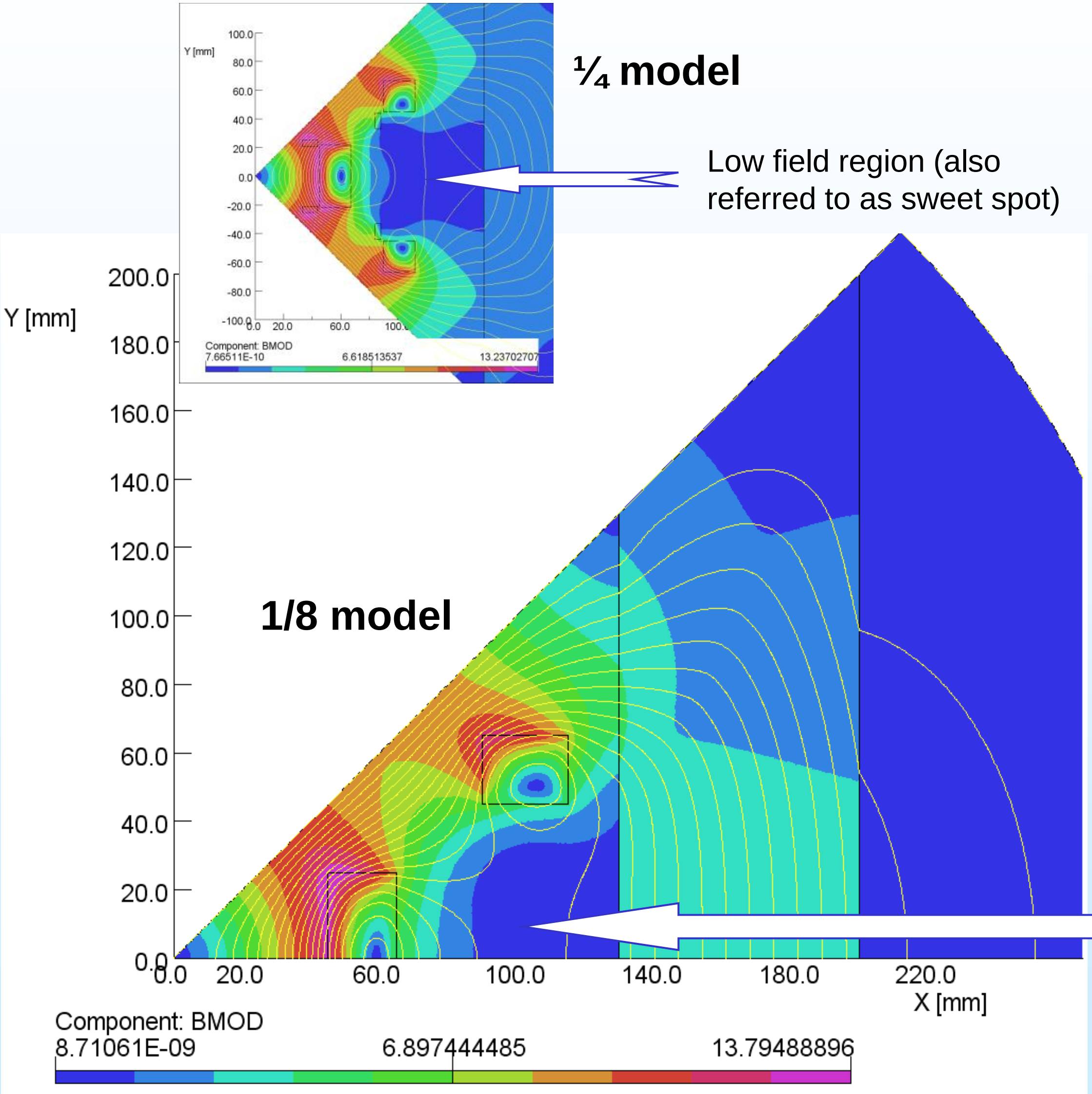
Harmonic	Value
b_6	0.005
b_{10}	-0.004
b_{14}	0.003
b_{18}	0.000

90 mm aperture LARP quadrupole design optimized for field quality with RACE2DOPT

⇨ ***Thank you Pat Thompson for one of many programs.***

NOTE: The 2-d harmonics are essentially zero (within construction errors)

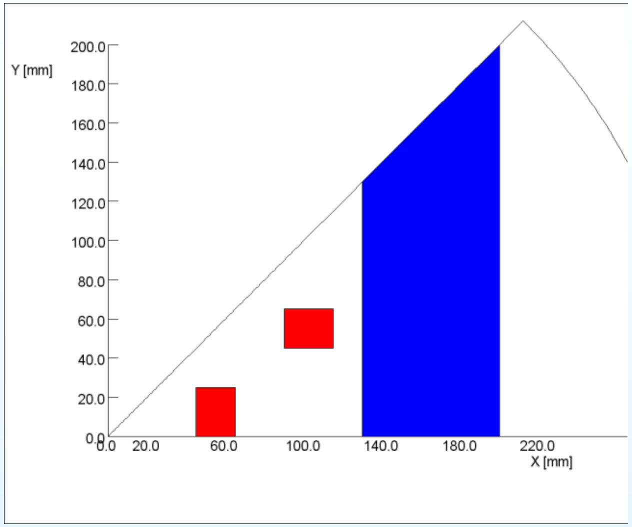
Low Field Region inside the Magnet



¼ model

Low field region (also referred to as sweet spot)

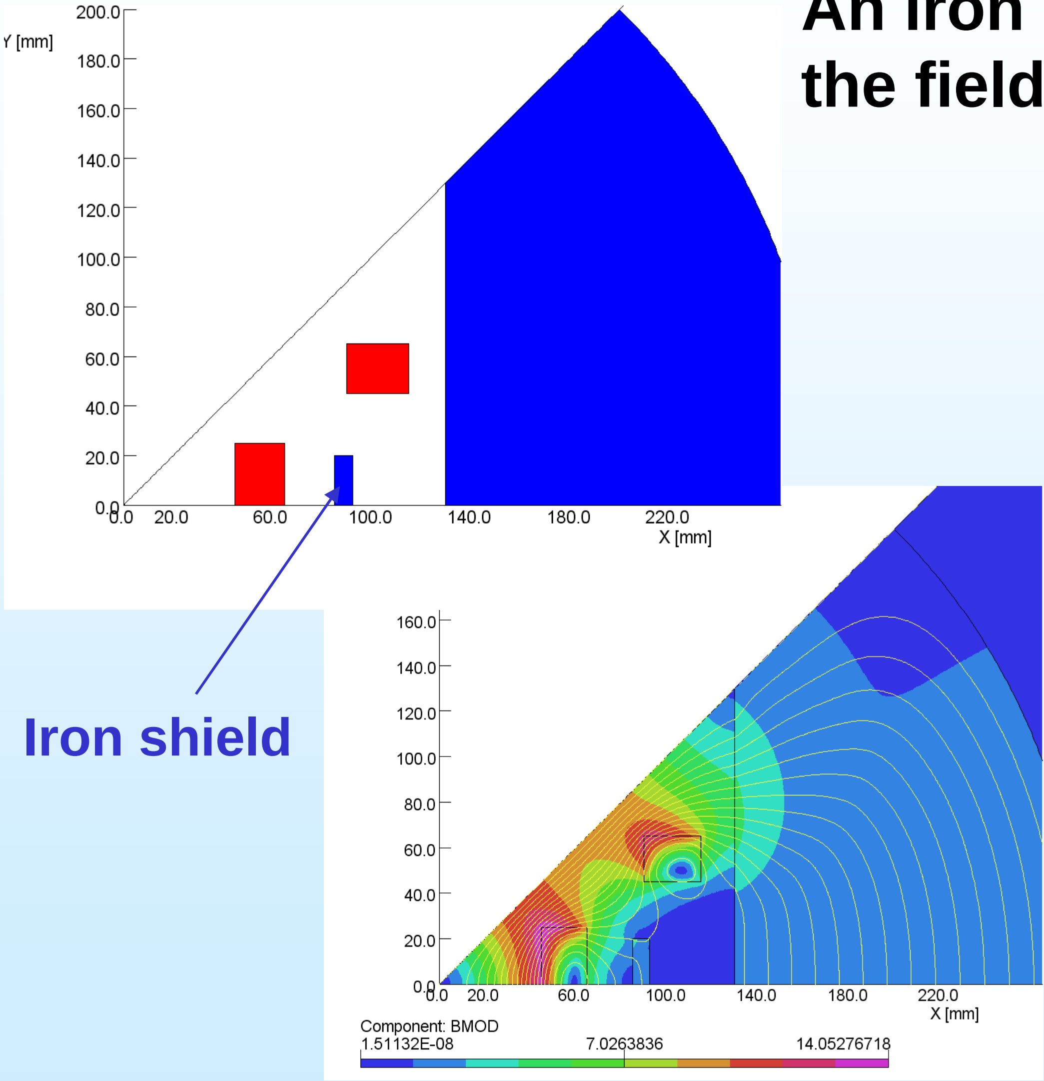
1/8 model



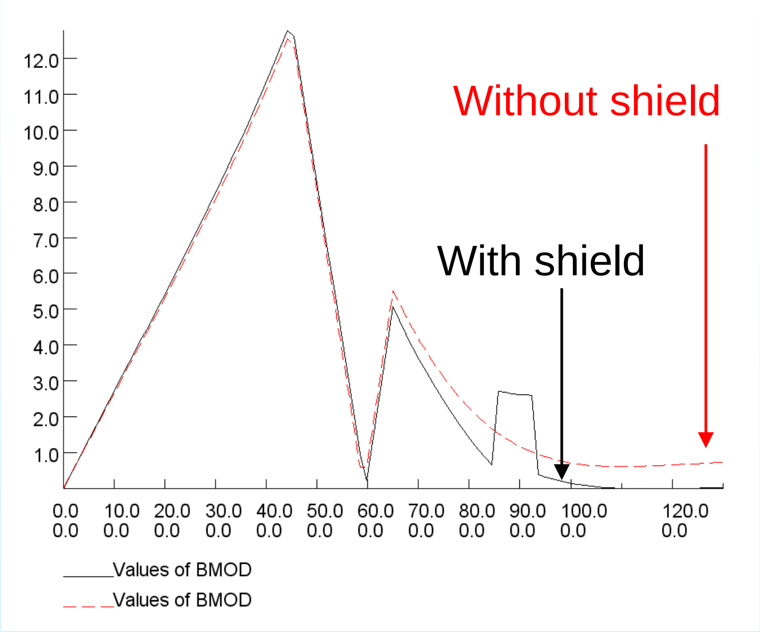
During the LARP work (2005), Steve Peggs noticed that the design naturally leaves a field free space that can be used by another beam in crab cavity optics

Further Reduction in Field in the Region of the Beam Trajectory

An iron shield can further reduce the field in the region of interest



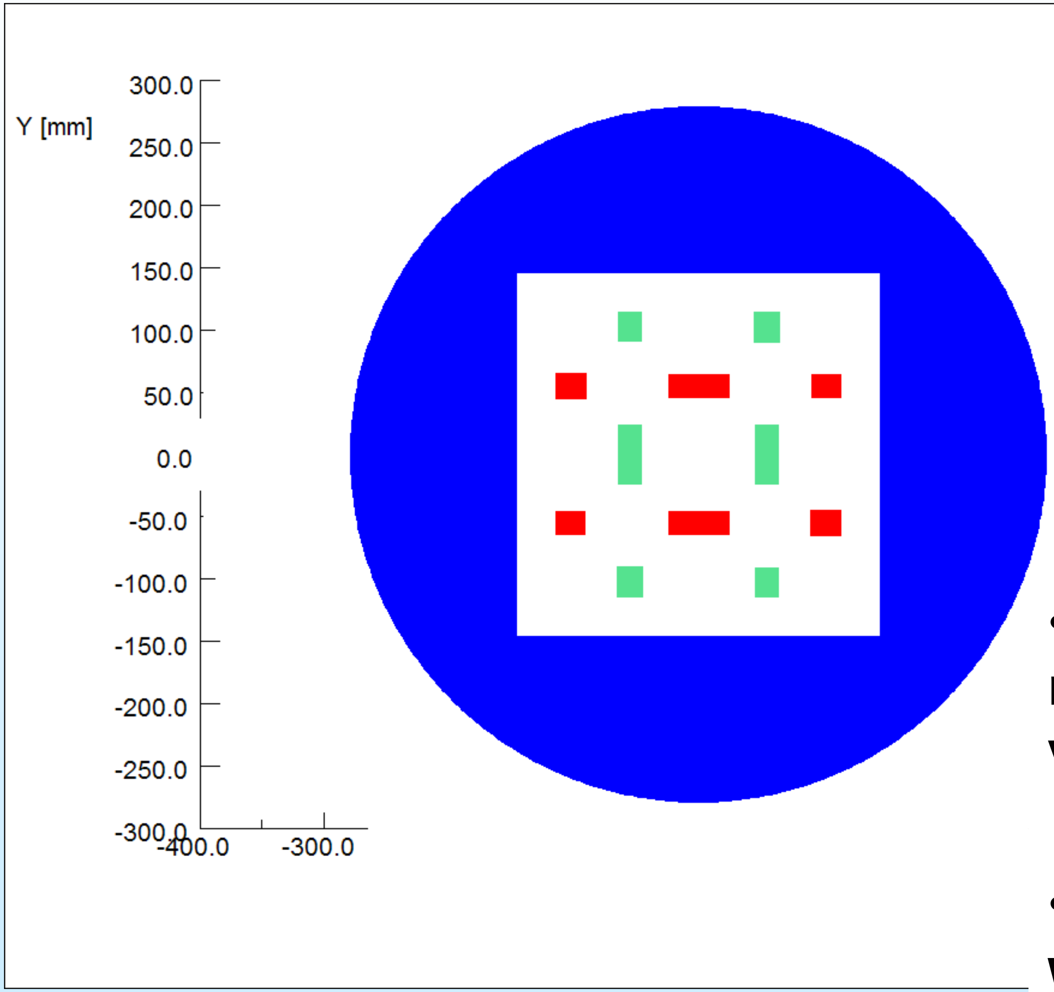
Iron shield

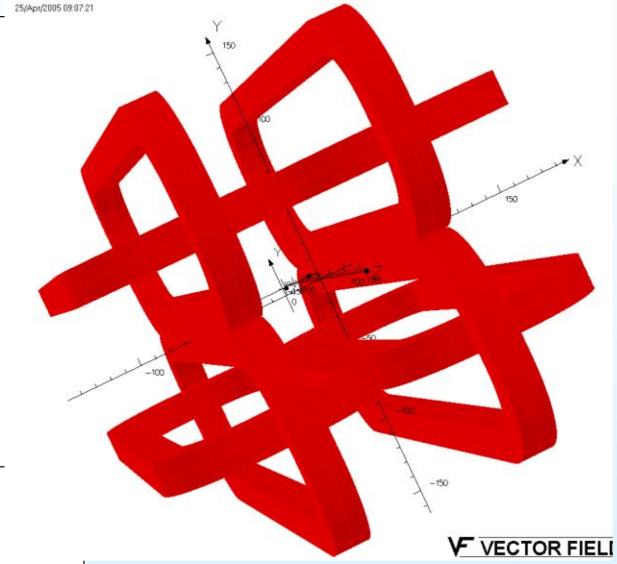


Note: All these calculations are for LARP Quad. As a part of this SBIR, we will optimize the design for various EIC Quads

A Complication in the Design Just Presented

Symmetric Design



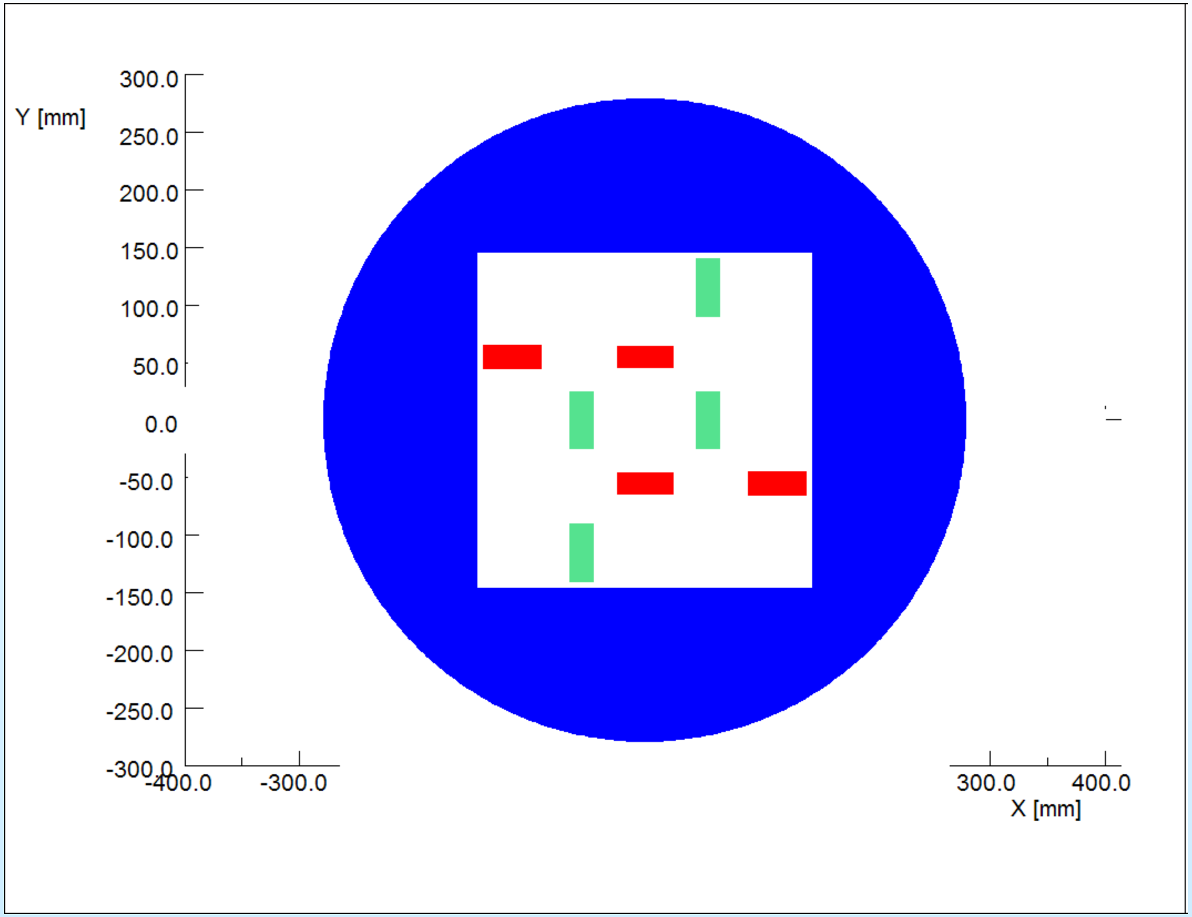


- Coils must interleave (means must have different lengths for vertical and horizontal coils)

- Support structure must deal with this

A Simpler Modular Design (no need for coils to interleave)

The design does not have mirror symmetry but 4-fold quadrupole symmetry is still present



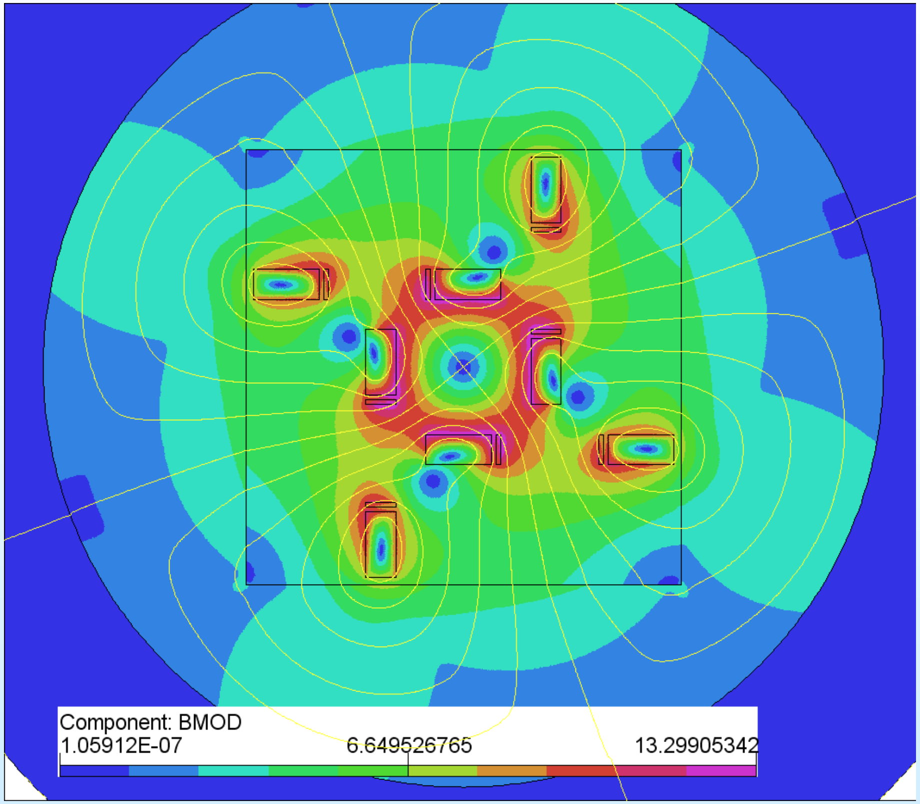
- **No interleaving of coils needed**
- **All coils have the same length**
- **Support structure may be simpler**

But magnetic design becomes more complicated.

In addition to b_6, b_{10}, b_{14} , ... one also gets a_6, a_{10}, a_{14} ,...

Magnetic Modelling

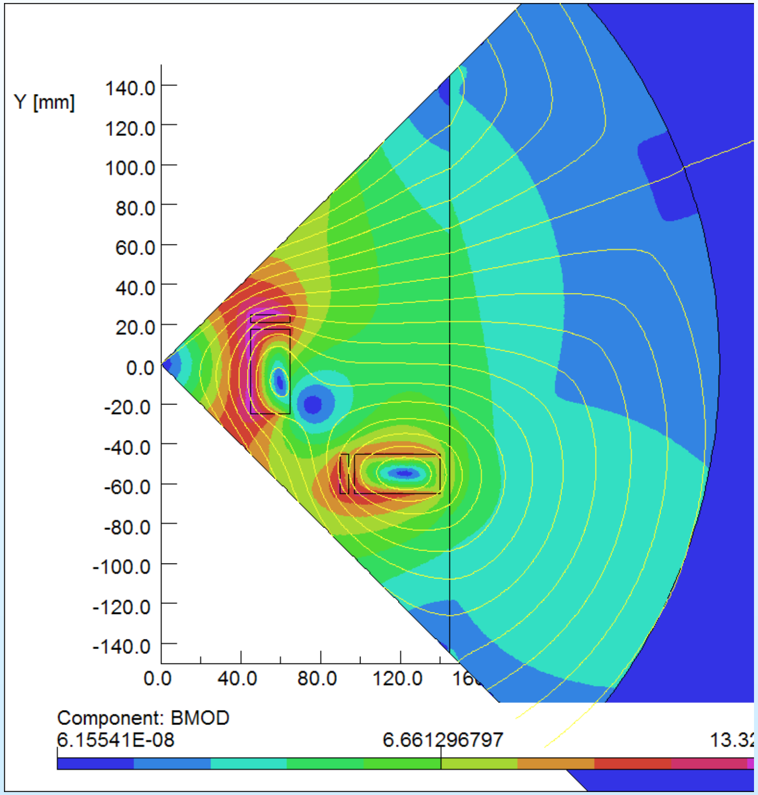
Complete Model



Magnetic Midplane need not be at the conventional location (may need a rotation)

Need only 1/4 model

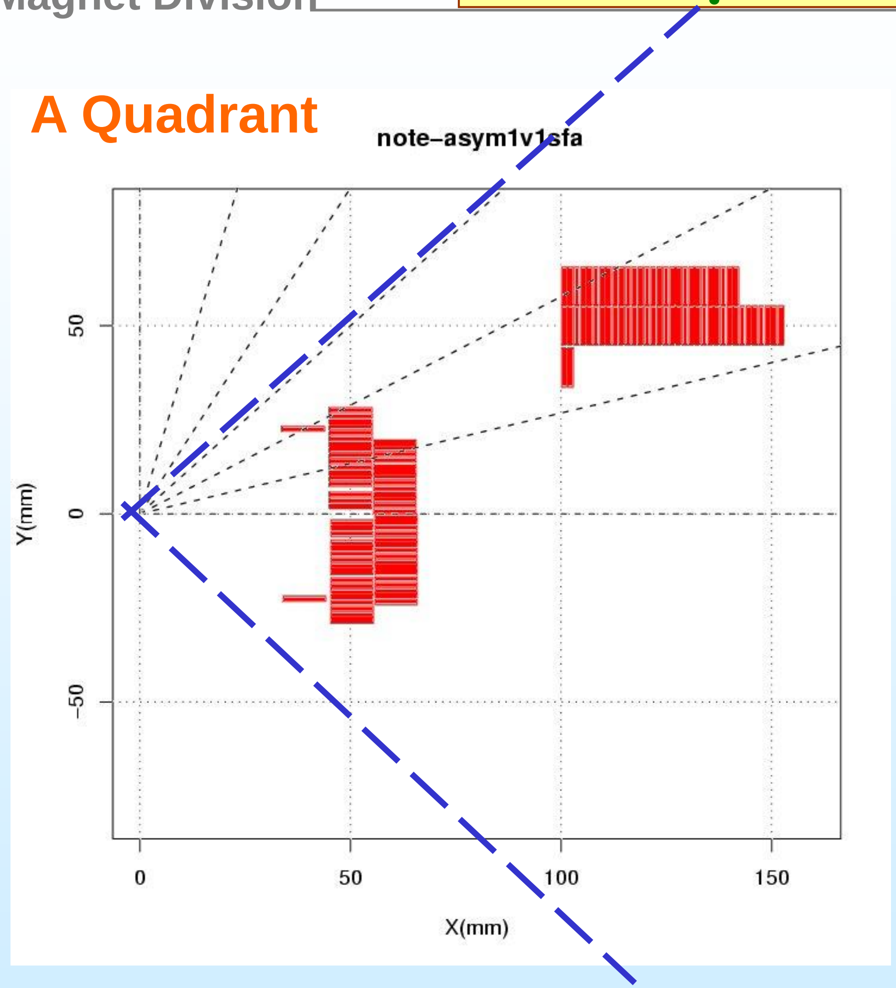
(with proper boundary conditions)



Question: Is it possible to develop a good magnetic design?

2-d Magnetic Design (simpler but asymmetric design)

A Quadrant



Proof that the design can create a good field quality

Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius, 10^{-4} units).

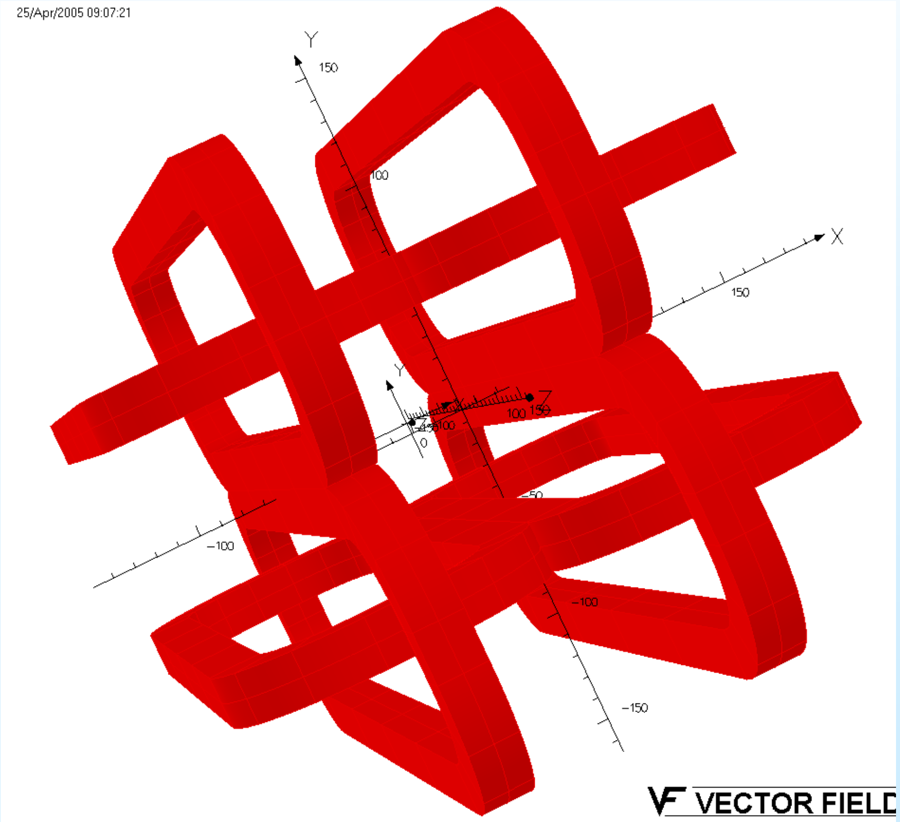
n	a_n	b_n
6	-0.0007	0.0000
10	0.0016	-0.0010
14	-0.0020	-0.0006
18	0.0000	0.0000

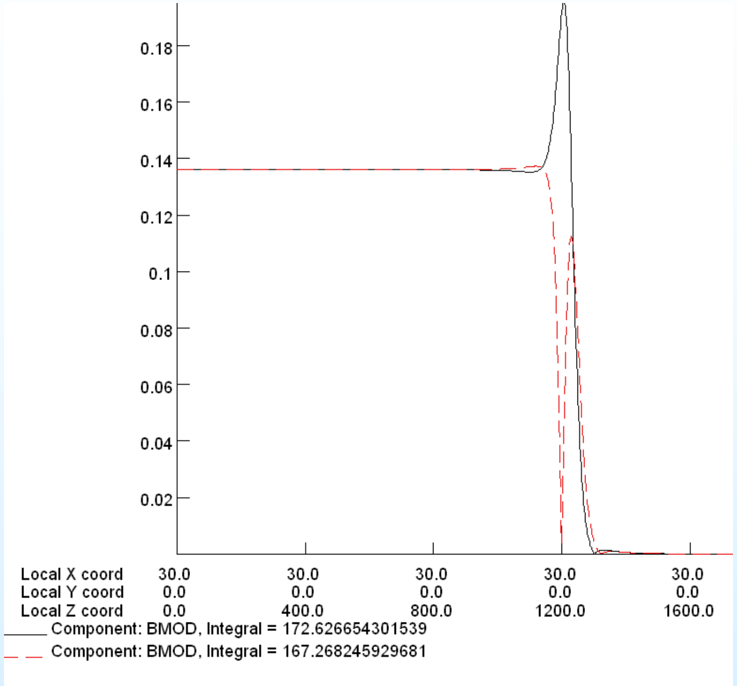
Non-symmetric 2-layer design. Number of turns, transfer function, etc. are similar to that in the symmetric design.

NOTE: The 2-d harmonics are essentially zero (within construction errors)

3-d Magnetic Design
(symmetric cross-section)

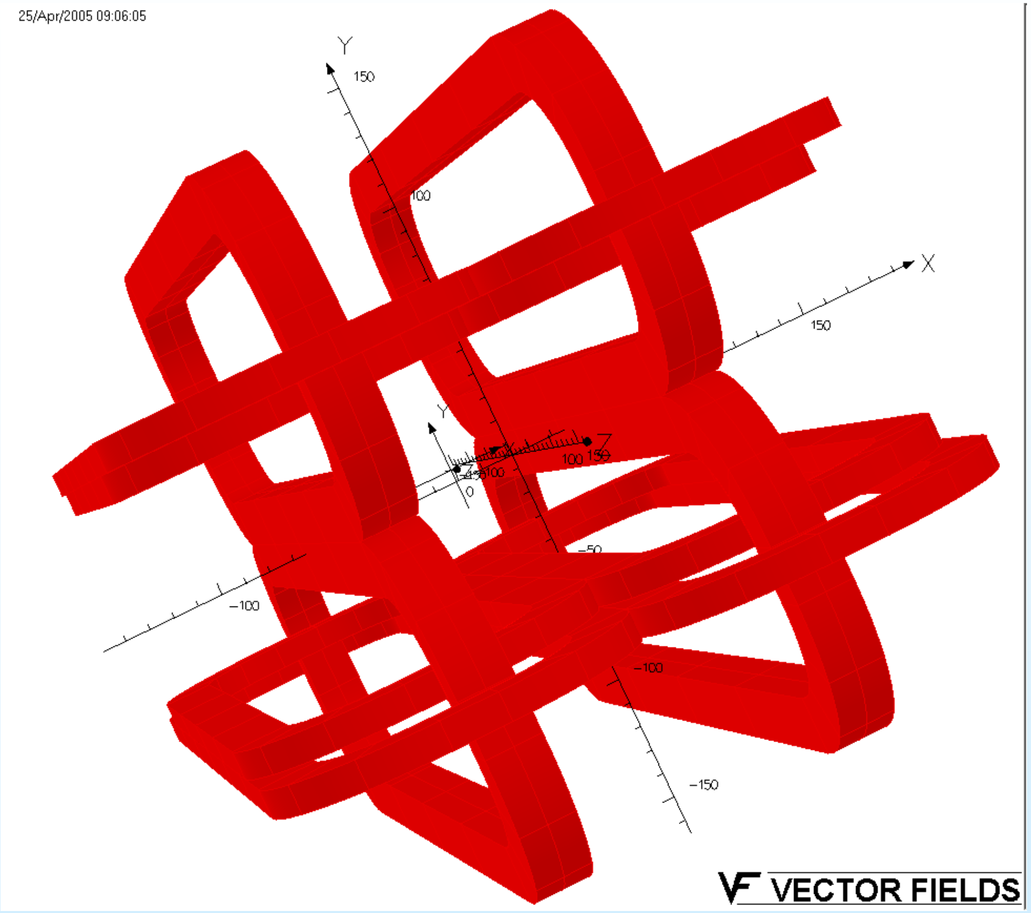
Coils of modular design in a short magnet. The simplest way of interleaving coils creates a magnetic asymmetry in the ends between the horizontal and vertical planes and generates a non-zero octupole harmonic.

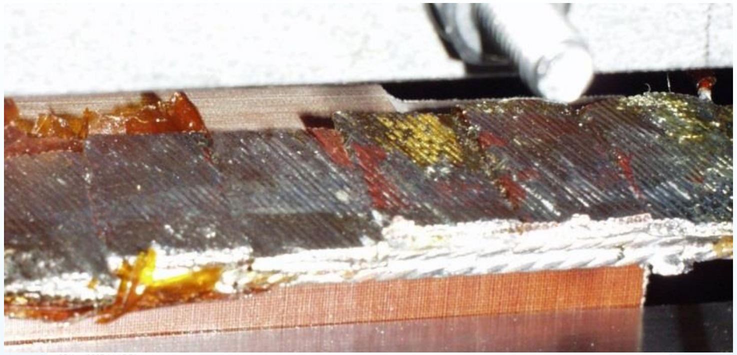


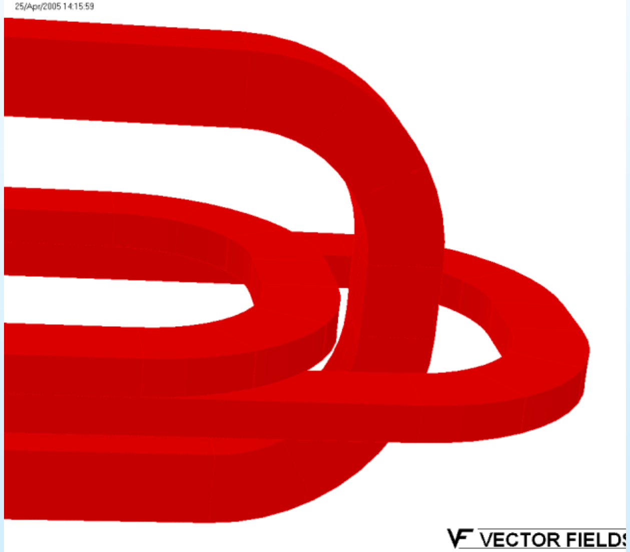


The magnitude of the field as a function of axial position on the horizontal axis (black full line) and vertical axis mm (dashed red line) at a distance of 30 mm from the origin. The integral value is listed at the bottom of the picture.
The difference between the two integrals is the measure of integral asymmetry.

Conceptual 3-d Optimization in Magnetic Design (symmetric cross-section)





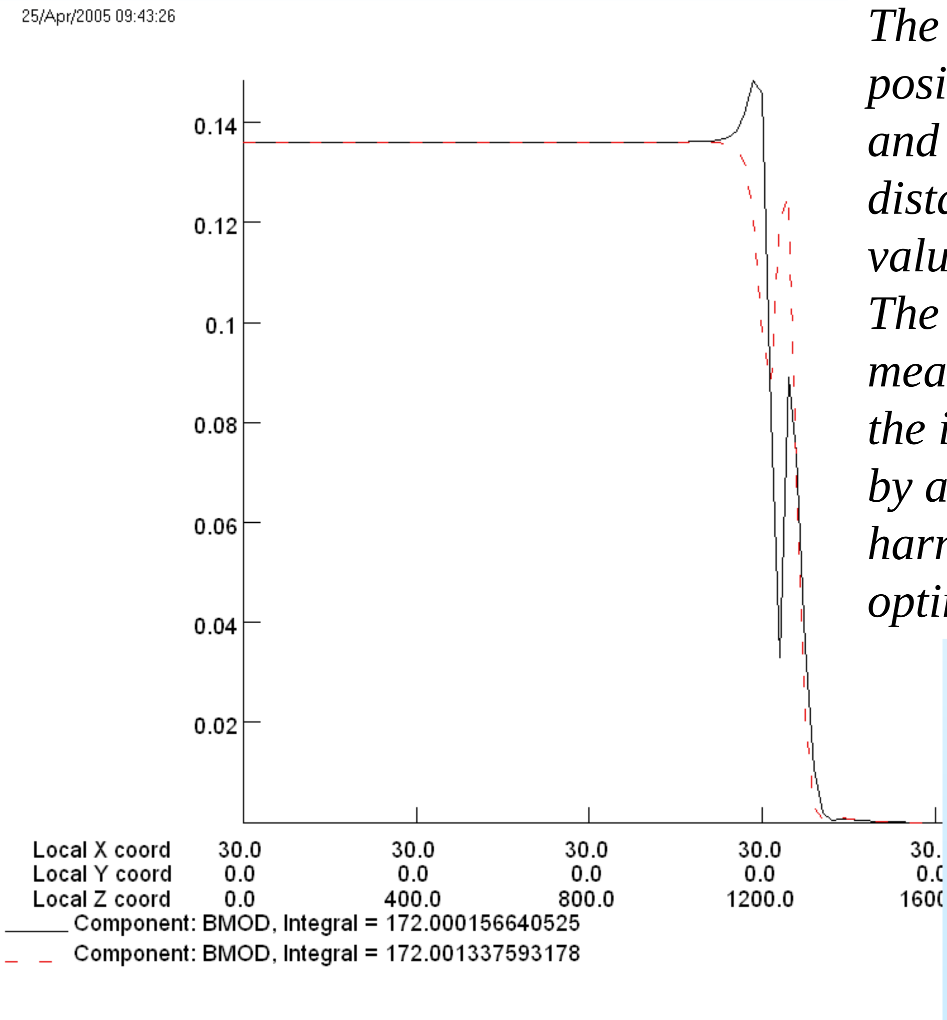


Try to match average coil lengths for horizontal and vertical coils.

(Other option: additional small coils in the end).

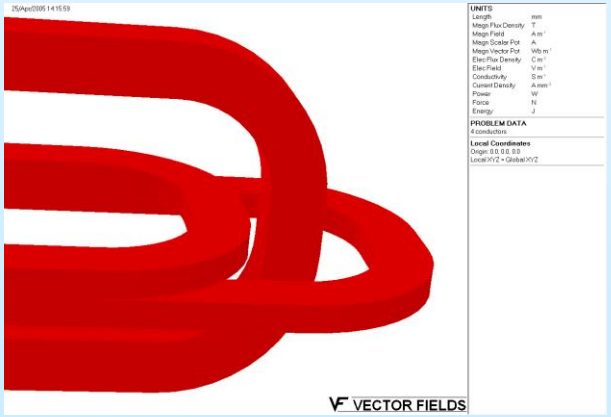
Final choice to depend on the mechanical design and assembly considerations.

Conceptual 3-d Optimization in Magnetic Design (symmetric cross-section)

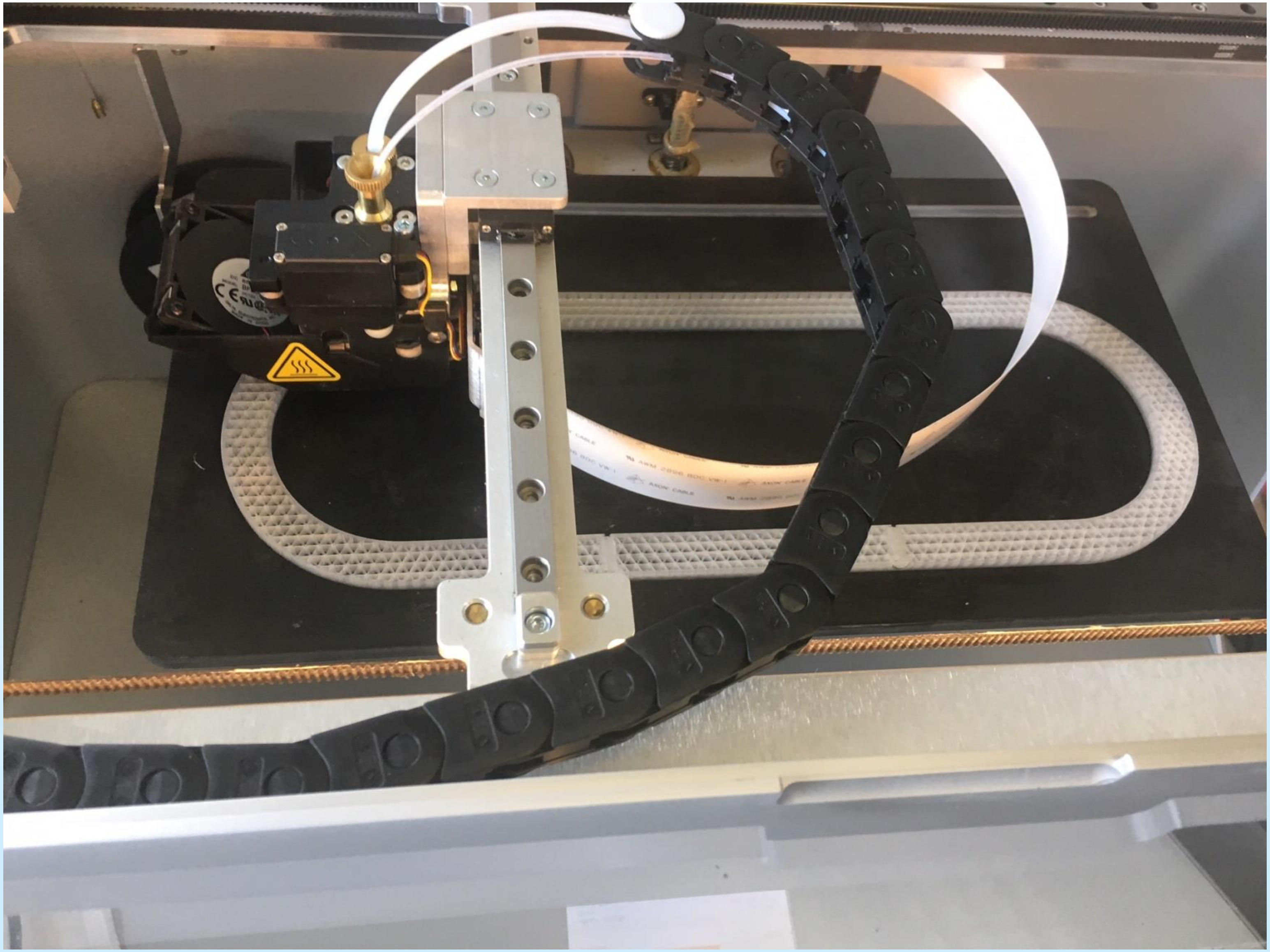


The magnitude of the field as a function of axial position on the horizontal axis (black full line) and vertical axis mm (dashed red line) at a distance of 30 mm from the origin. The integral value is listed at the bottom of picture.

The difference between the two integrals is the measure of integral asymmetry. One can see that the integral asymmetry is practically eliminated by adjusting the length of the coils. Integral harmonics will be optimized by 3-d coil optimization codes.



Demo of a Quadrant with 3-d Printer



Benefits of Modular Design

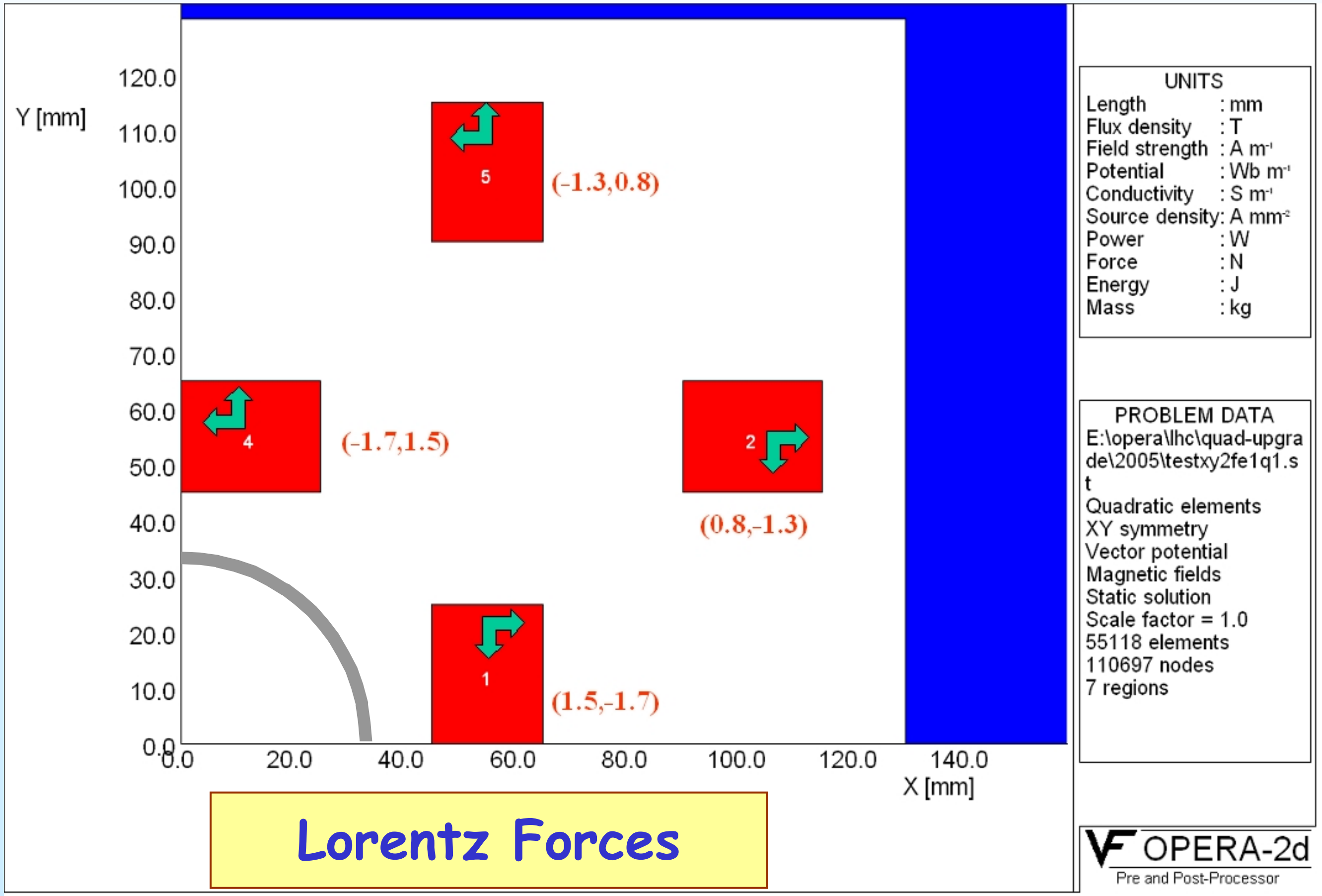
Simple, Fast, Flexible & Cost-effective

- Design is consisted of simple, flat, stackable, racetrack coil modules
  - Positive experience with common coil program
  - Fast and cost effective to start and to carry out systematic R&D
  - Large variations in cable and coil and magnet parameters can be accommodated
- Unique magnet R&D features
  - To increase field gradient add more coil modules
  - Depending on the coil geometry, coils modules can be switched in and out (one may do so based on performance - put better coils in)
  - Allows broad-based magnet R&D as proof-of-principle dipoles can as well be built and tested with these quad coils (small added cost)
- Of course, the support structure needs to be designed properly to accommodate such provisions. One may not be able to design a super structure to do all of above; some intermediate structure on coil(s) plus additional structure enclosing those coils may work better.

Support Structure

Support structure and assembly

Concepts need to evolve - A part of this SBIR program



UNITS
Length : mm
Flux density : T
Field strength : A m^{-1}
Potential : Wb m^{-1}
Conductivity : S m^{-1}
Source density: A mm^{-2}
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
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Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 1.0
55118 elements
110697 nodes
7 regions

Lorentz Forces

More Unique Features Relevant to EIC
Different Aperture With the Same Coils

One can study different aperture using the same coils in R&D magnets.

Final magnet design will be optimized for each aperture, but this strategy offers a cost-effective and rapid R&D approach to demonstrate many *"Proof-of-Principle"* quads having different aperture (can't do with cos θ).

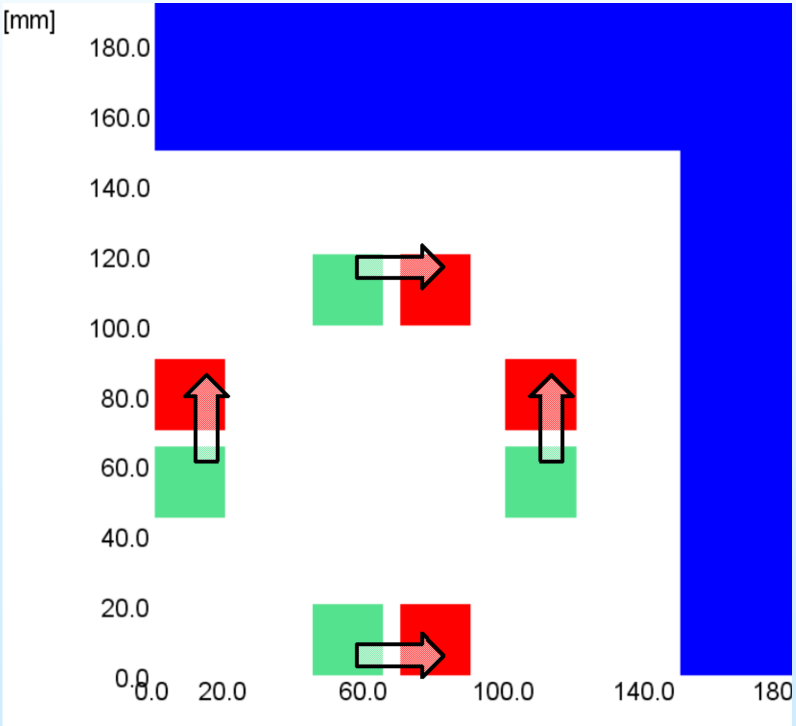
Coils are moved away from the center in going from

green aperture (90 mm)

to red aperture (140 mm).

A flexible and economical design/method to study various aperture and field gradient combinations is useful at this stage, as the magnet parameters can not be fixed yet.

In fact, this feed back should help machine physicist to choose a set of parameters that represents an overall optimum from both magnet and beam optics point of view.



Phase II Demo Magnet

What can be done in the limited budget of Phase II?

- Use iron mirror design so we need to make only a quadrant of the symmetric quadrupole design. However, it must conatin a low field region.

- Examine if we have sufficient funds in Phase II to build a mirror Nb_3Sn quad – even if it is a scaled version
  - ➢ Nb_3Sn requires, reaction and impregnation tooling.

- Or do we have to suffice with NbTi demo design only?
  - ➢ Need to carry out cost studies with engineers.

- Or can we use existing Nb_3Sn racetrack coils from some other program?

Cable Choices for Phase II (Lower current)

- **BNL test facility is heavily booked with LARP work and furthermore the cost of carrying out test in the main facility is expensive.**
- **Lower current cable will allow us to use secondary test facilities.**
- **What are options for low current cable?**
- **Existing supply of conductor?**
- **Nb_3Sn or NbTi?**
- **6-round-1?**

Task List

Task 1: Perform a magnetic design for the Q1PF quadrupole

Task 2: Perform mechanical analysis of the optimized Q1PF quadrupole design

Task 3: Develop a mechanical structure design for the Q1PF modular quadrupole

Task 4: Develop a Proof-of-Principle modular design that can be built and tested in Phase II

Task 5: Design mechanical structure for the Proof-of-Principle modular quadrupole design

Task 6: Design flexible structure concepts for modular R&D with modular design where the magnet aperture and individual racetrack coils can be changed

Task 7: Write project summary and prepare the Phase II proposal

SUMMARY

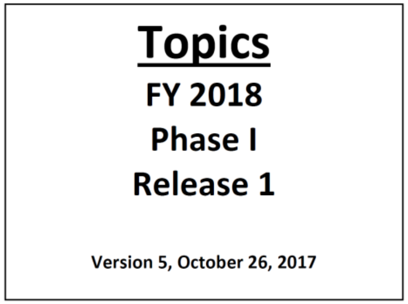
- This SBIR offers an excellent opportunity to develop high gradient quadrupoles based on simple racetrack coils.
- There are several benefits of a modular design and a modular R&D program based on racetrack coils.
- The modular design offers a unique opportunity to demonstrate several "Proof-of-Principle" high gradient quadrupoles having different radii in a cost-effective, rapid-turn-around approach basically using the same coils.
- The design naturally creates a low field region. Optimize design to satisfy requirements of various EIC quads.

Extra Slides

Summary of Proposal

The proposed Electron-Ion Collider (EIC) needs several high-field, large-aperture quadrupole magnets in the interaction region for the ion or proton beams. These magnets should (a) be able to tolerate high radiation loads, (b) be compact in size, with limited space for iron shielding, and (c) have a field-free region along the length of the magnet for the passage of electron beams. We propose to develop designs for EIC quadrupoles in Phase I based on racetrack coils satisfying the above requirements. In particular, we will examine a novel "modular design" concept. The modular design is based on simple racetrack coils, which require less expensive tooling to build the magnets. However, unlike in many racetrack coil quadrupole designs, the modular design is similar to the Panofsky quadrupole design, which allows conductor at the mid-plane to be placed at a radius similar to that in conventional cosine two- theta quadrupoles. This difference in configuration is crucial to creating high field gradient. Moreover, the "modular design" also enables a "modular R&D program" in which the same coils can be used in "proof-of-principle" magnets of different aperture. Such a "modular program" should significantly reduce the cost of R&D, which is a significant part of the overall cost of developing the small number of Nb_3Sn magnets with different apertures. We propose to build a Proof-of-Principle demonstration magnet in Phase II.

Small Business Innovation Research (SBIR) and
Small Business Technology Transfer (STTR) Program



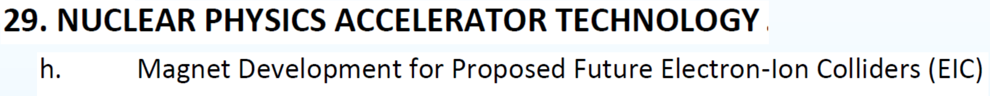
Topics

FY 2018

Phase I

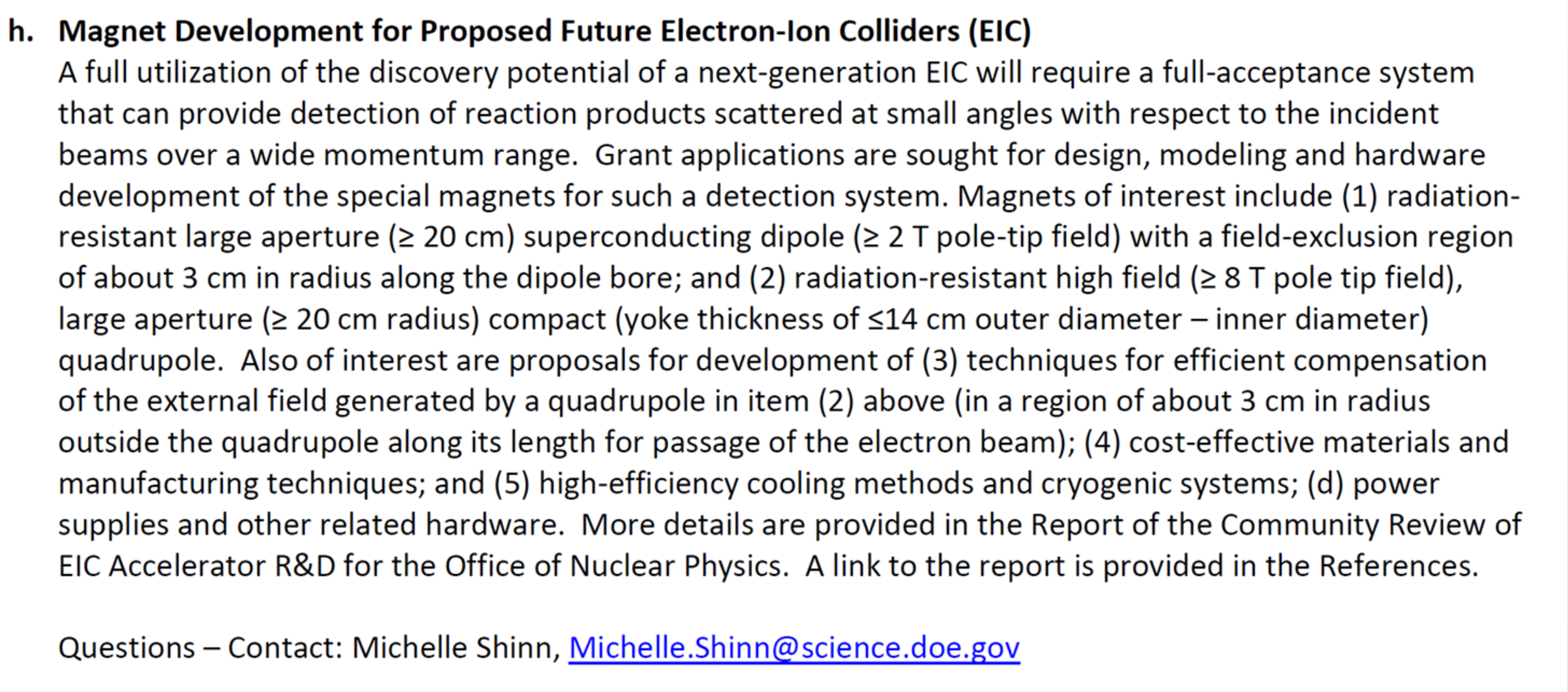
Release 1

Version 5, October 26, 2017



29. NUCLEAR PHYSICS ACCELERATOR TECHNOLOGY

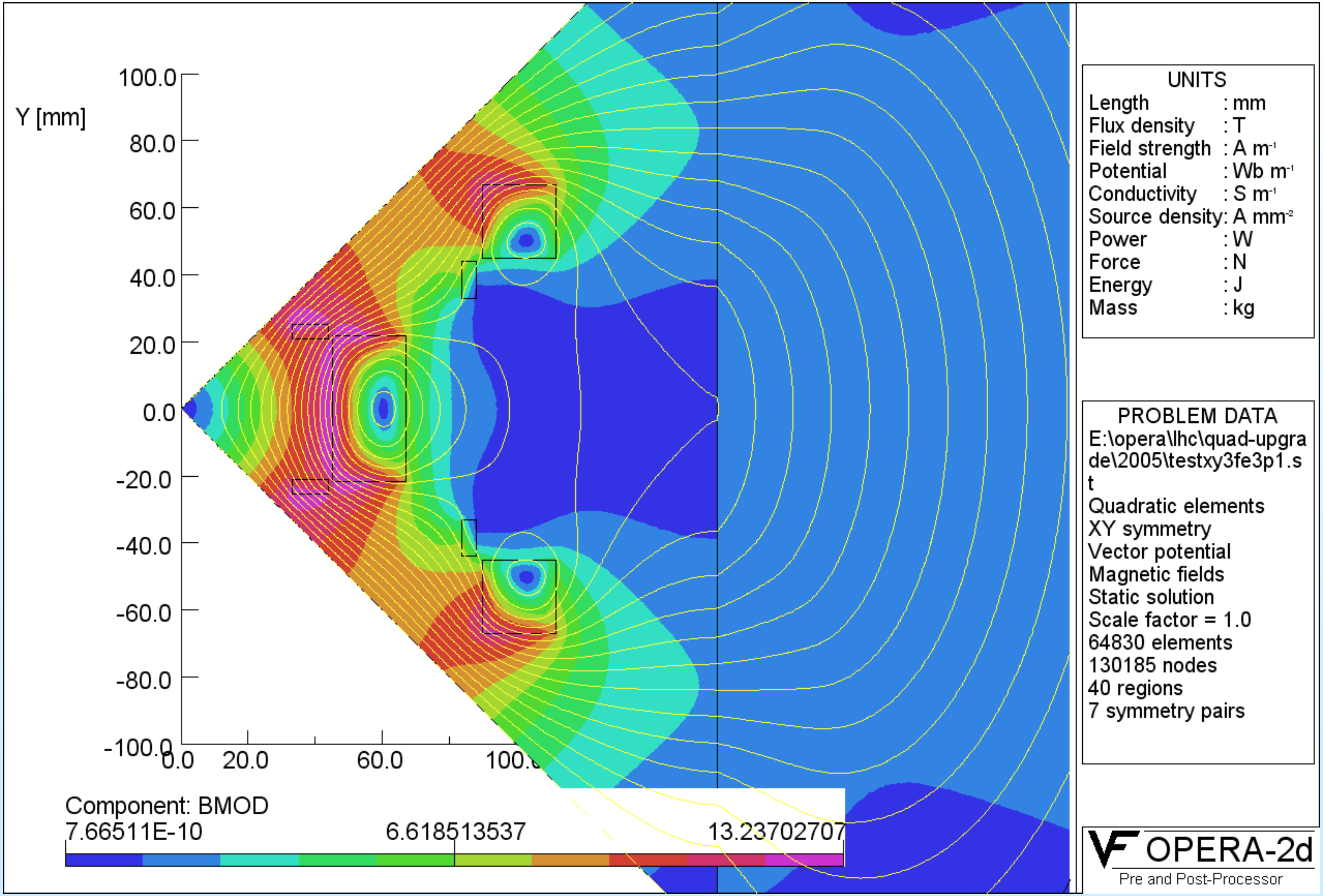
h. Magnet Development for Proposed Future Electron-Ion Colliders (EIC)



h. Magnet Development for Proposed Future Electron-Ion Colliders (EIC)

A full utilization of the discovery potential of a next-generation EIC will require a full-acceptance system that can provide detection of reaction products scattered at small angles with respect to the incident beams over a wide momentum range. Grant applications are sought for design, modeling and hardware development of the special magnets for such a detection system. Magnets of interest include (1) radiation-resistant large aperture (≥ 20 cm) superconducting dipole (≥ 2 T pole-tip field) with a field-exclusion region of about 3 cm in radius along the dipole bore; and (2) radiation-resistant high field (≥ 8 T pole tip field), large aperture (≥ 20 cm radius) compact (yoke thickness of ≤14 cm outer diameter – inner diameter) quadrupole. Also of interest are proposals for development of (3) techniques for efficient compensation of the external field generated by a quadrupole in item (2) above (in a region of about 3 cm in radius outside the quadrupole along its length for passage of the electron beam); (4) cost-effective materials and manufacturing techniques; and (5) high-efficiency cooling methods and cryogenic systems; (d) power supplies and other related hardware. More details are provided in the Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics. A link to the report is provided in the References.

Questions – Contact: Michelle Shinn, Michelle.Shinn@science.doe.gov



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UNITS
Length          : mm
Flux density    : T
Field strength  : A m-1
Potential       : Wb m-1
Conductivity    : S m-1
Source density: A mm-2
Power           : W
Force           : N
Energy          : J
Mass            : kg
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Vector potential
Magnetic fields
Static solution
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130185 nodes
40 regions
7 symmetry pairs
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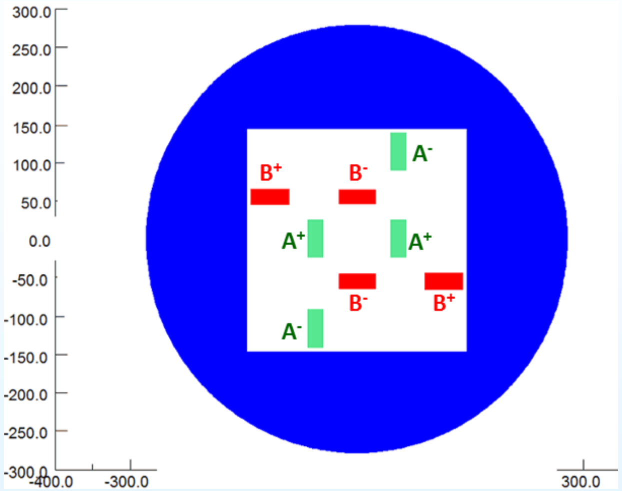
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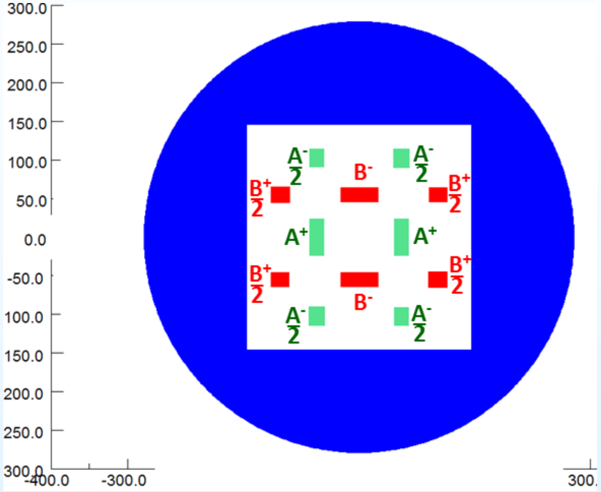
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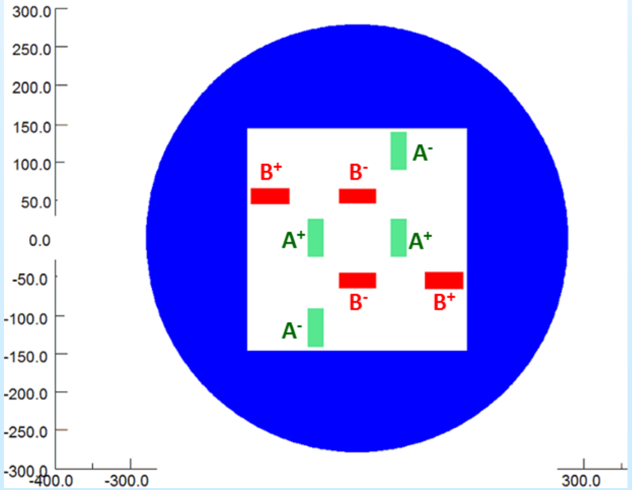
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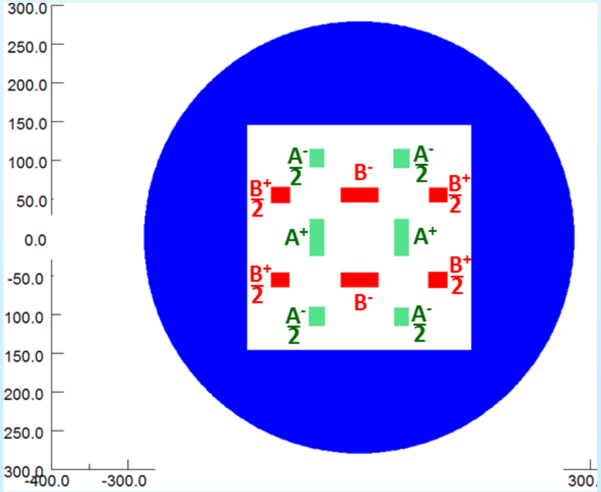
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