Modular Program and Modular Design for LARP Quadrupoles

A research program and magnet design based on flat racetrack coil modules

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(Revised June 14, 2005)

Review of A Design Study Performed Soon After The Port Jefferson Meeting

Only basic concepts will be presented.

Design note contains a little more info.

http://www.bnl.gov/magnets/magnet_files/Publications/MDN-641-43.pdf

Basic Considerations

Primary goal (or motivation):

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

Constraints (or liberty):

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

Advantages (or prejudices):

During the reaction process in long magnets, simple flat racetrack coils are less prone to damage or degradation in critical ends and transition regions.

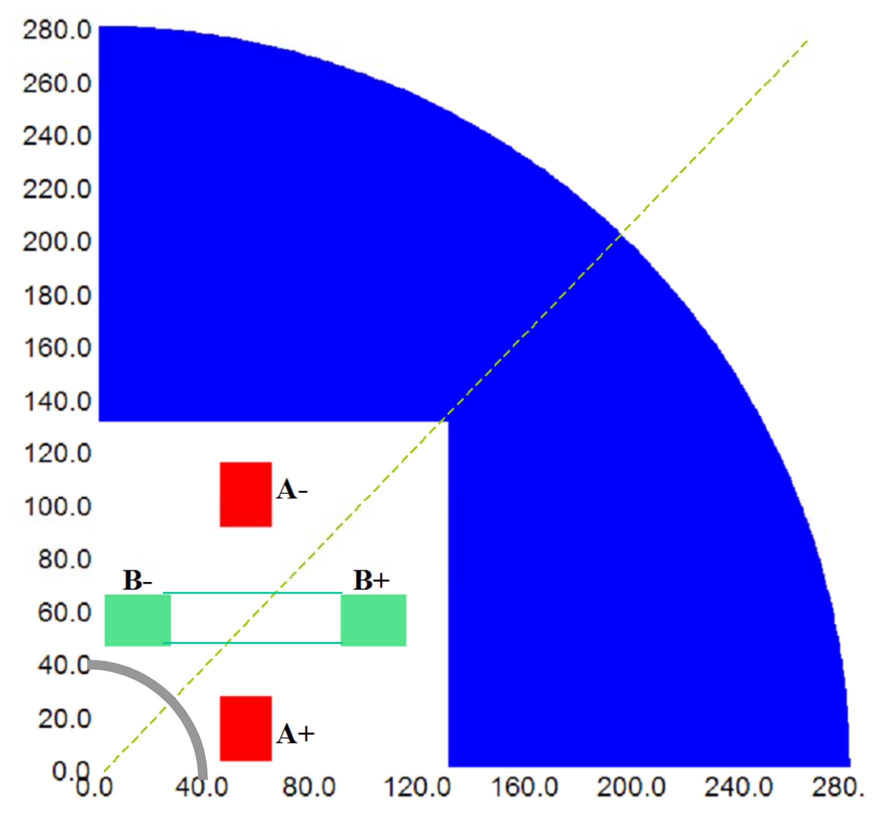
Racetrack coils (and associated tooling) are faster and more economical to build. It allows a modular design and modular R&D program.

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.

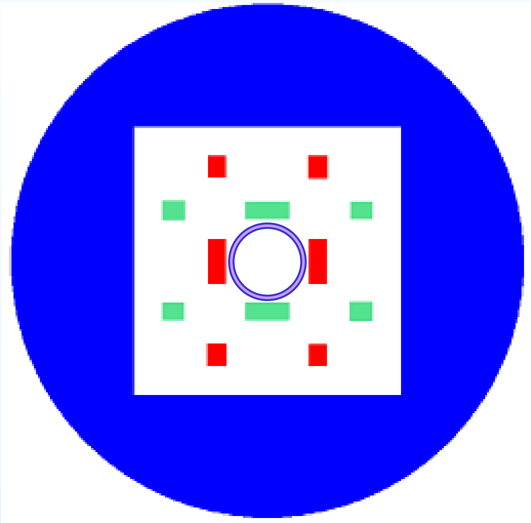
Modular Design for LARP Quadrupole

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.

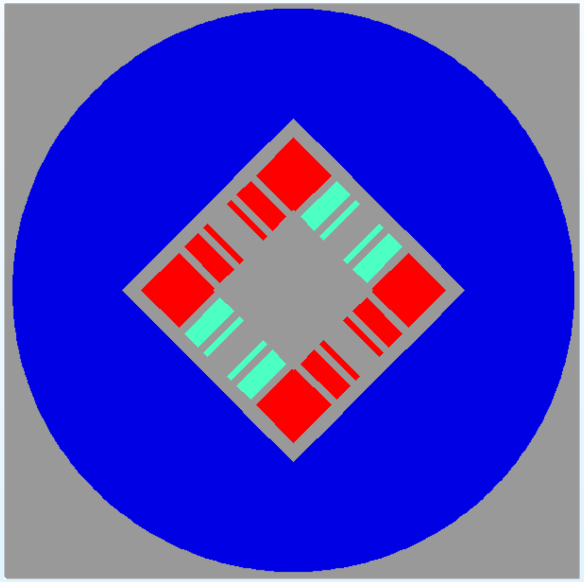
A bobbin-less coil

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!

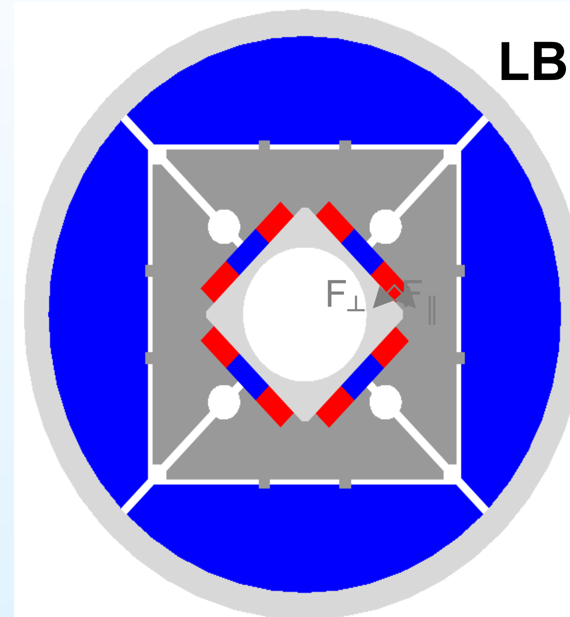
Previous Racetrack Designs
(Considered for LHC upgrade or VLHC)

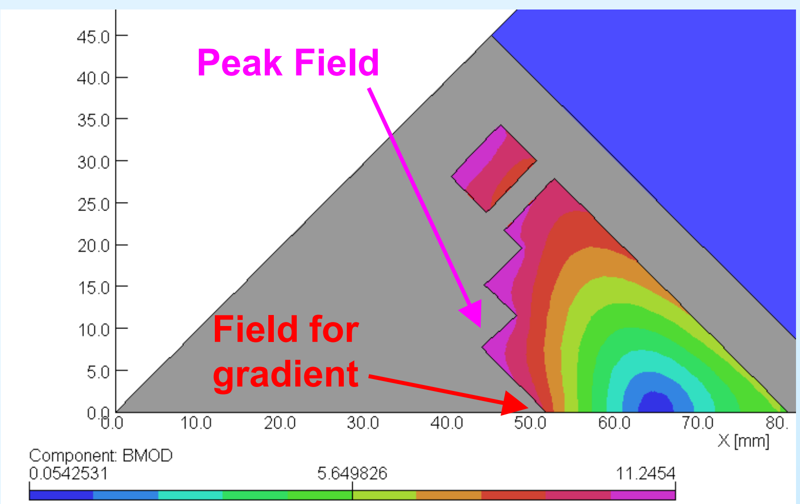
BNL designs for VLHC (ASC'02)



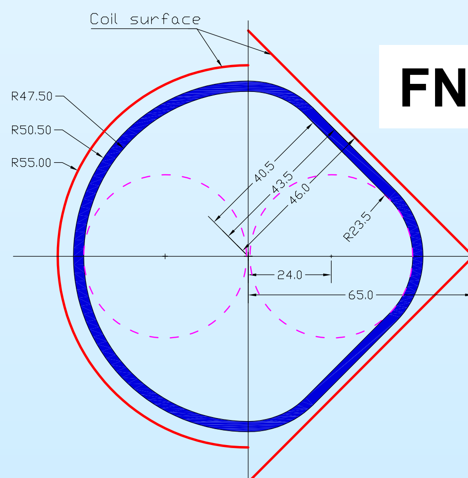
None of these designs were efficient in generating high gradient

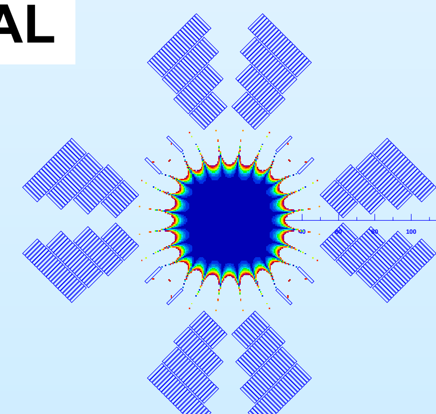
LBL





FNAL

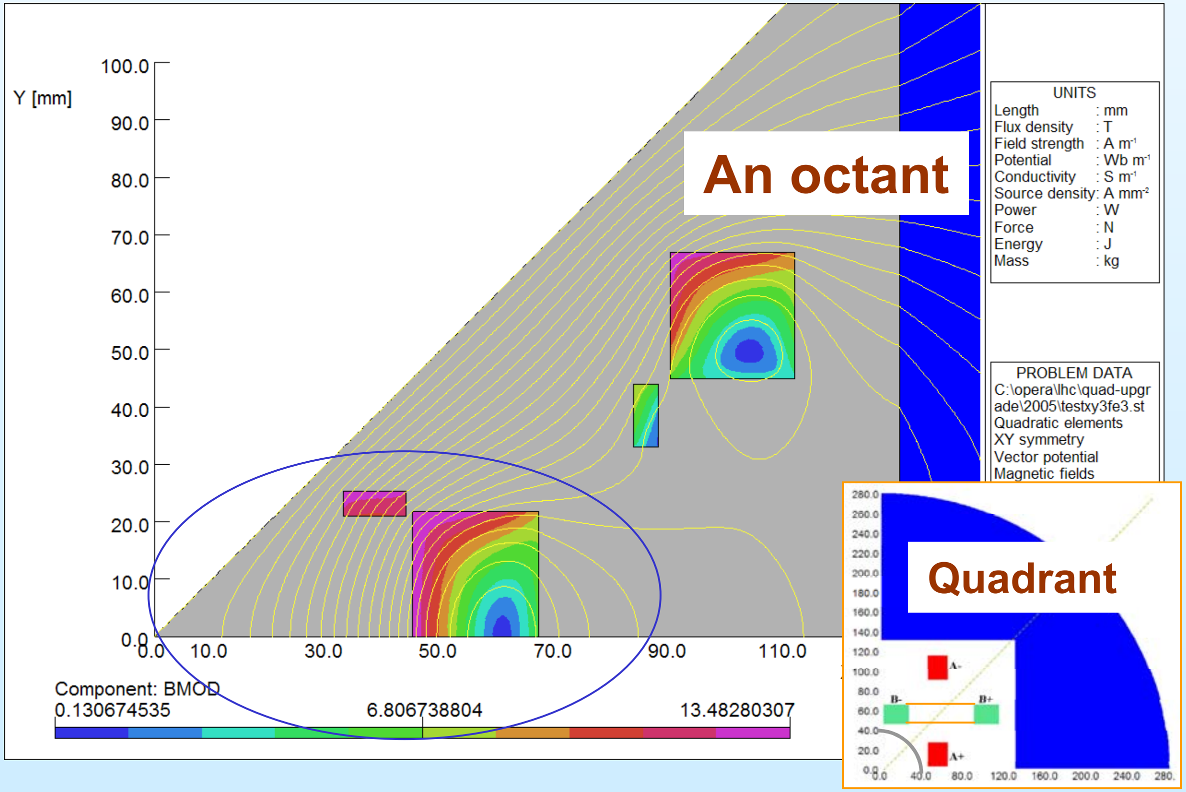




Efficient Design to Create Gradient (not necessarily to minimize conductor usage)

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

Quadrupole is different from dipole. Gradient implies increasing field on coil as one moves outward within the aperture. We loose substantially if conductor at midplane does not determine the field gradient.



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

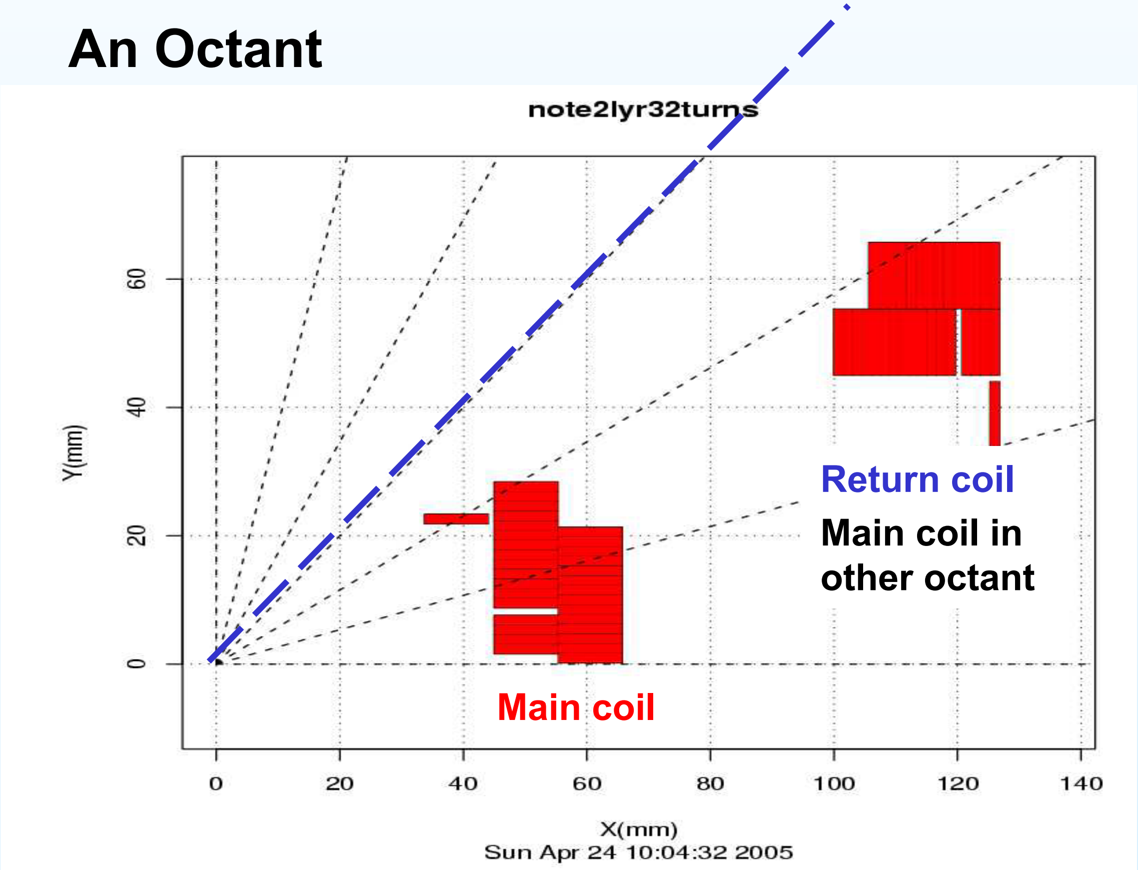
J_e = 1000 A/mm^2 generates a gradient of ~284 T/m.

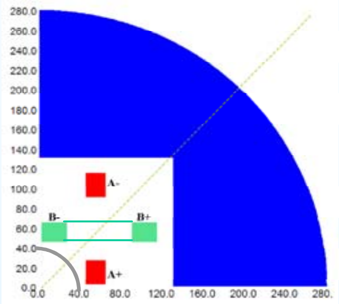
Quench gradient ~258 T/m for J_c = 3000 A/mm^2 (4.2K, 12T).

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

2-d Magnetic Design

An Octant





Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius).

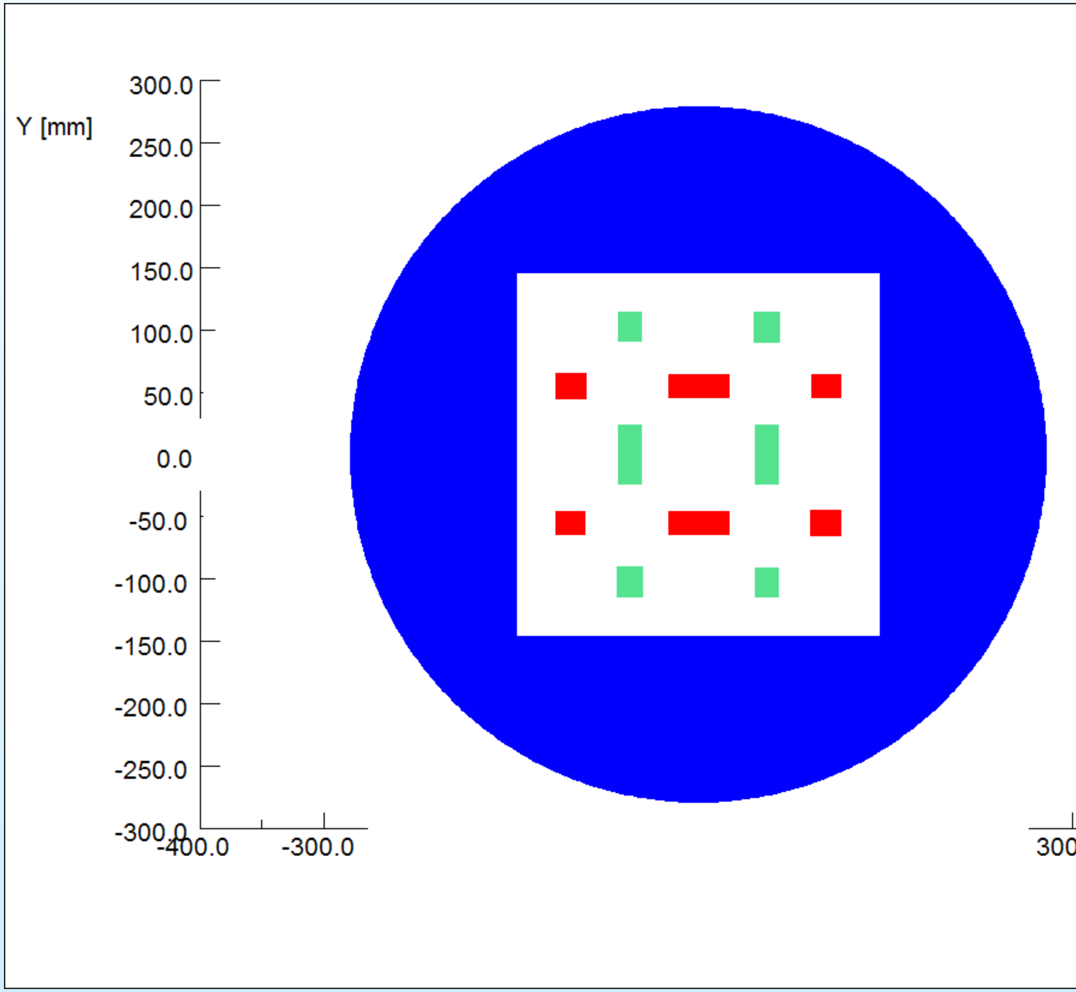
Harmonic	Value
b_6	0.005
b_{10}	-0.004
b_{14}	0.003
b_{18}	0.000

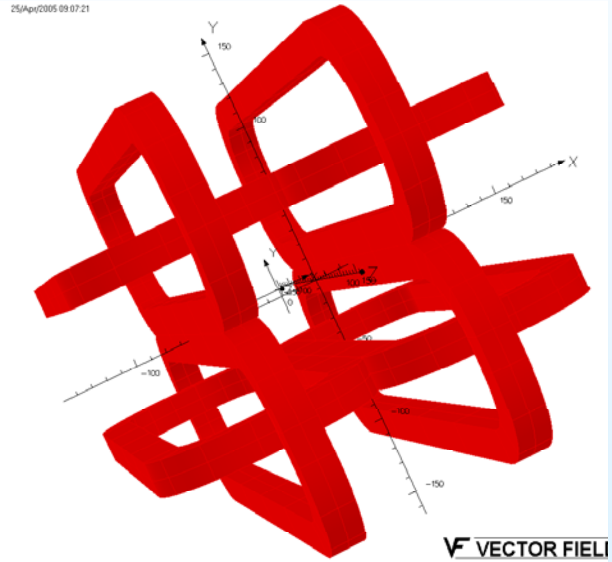
90 mm aperture LARP quadrupole design optimized for field quality with RACE2DOPT
(Thank you Pat Thompson for this program).

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

A Complication in the Design Just Presented

Symmetric Design

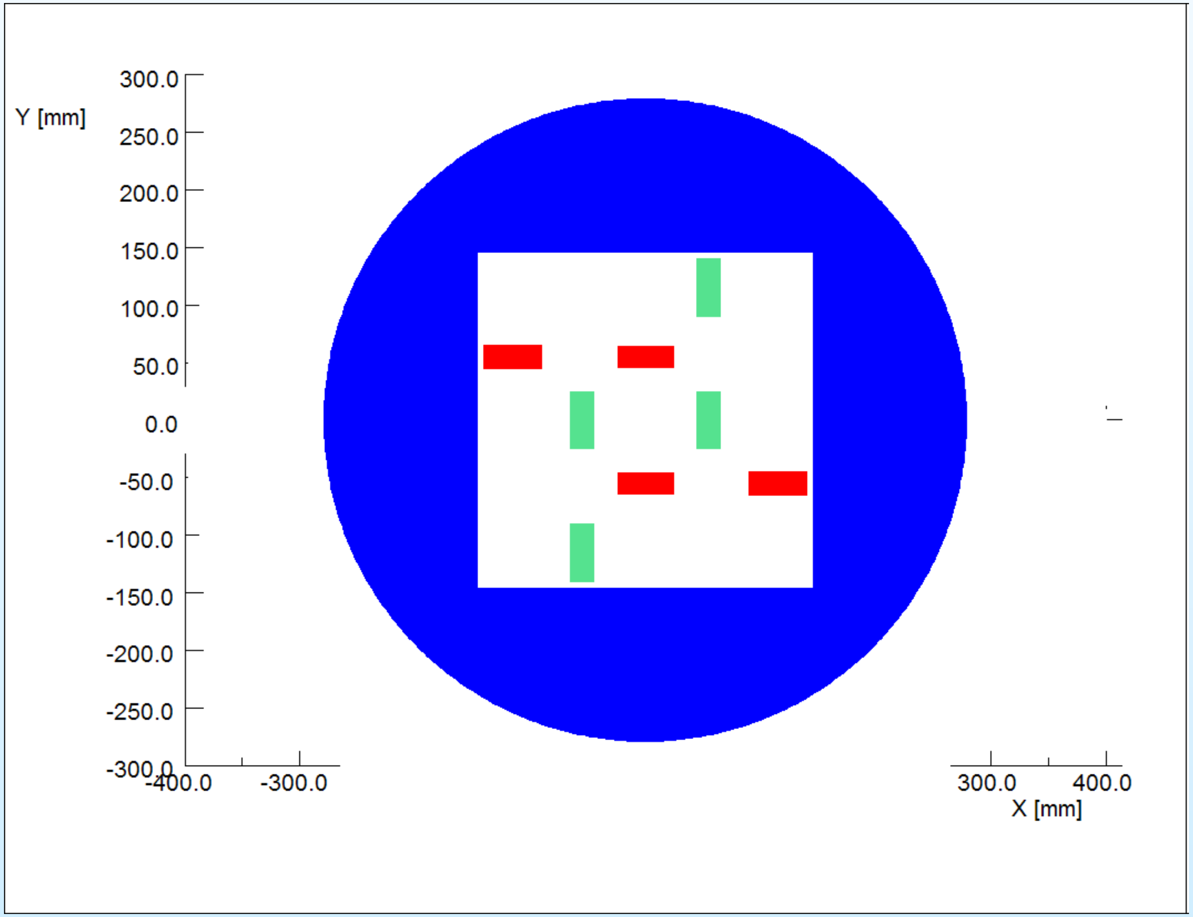




- Coils must interleave (different lengths for vertical and horizontal coils)
- Support structure must deal with this

A Simpler Modular Design

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

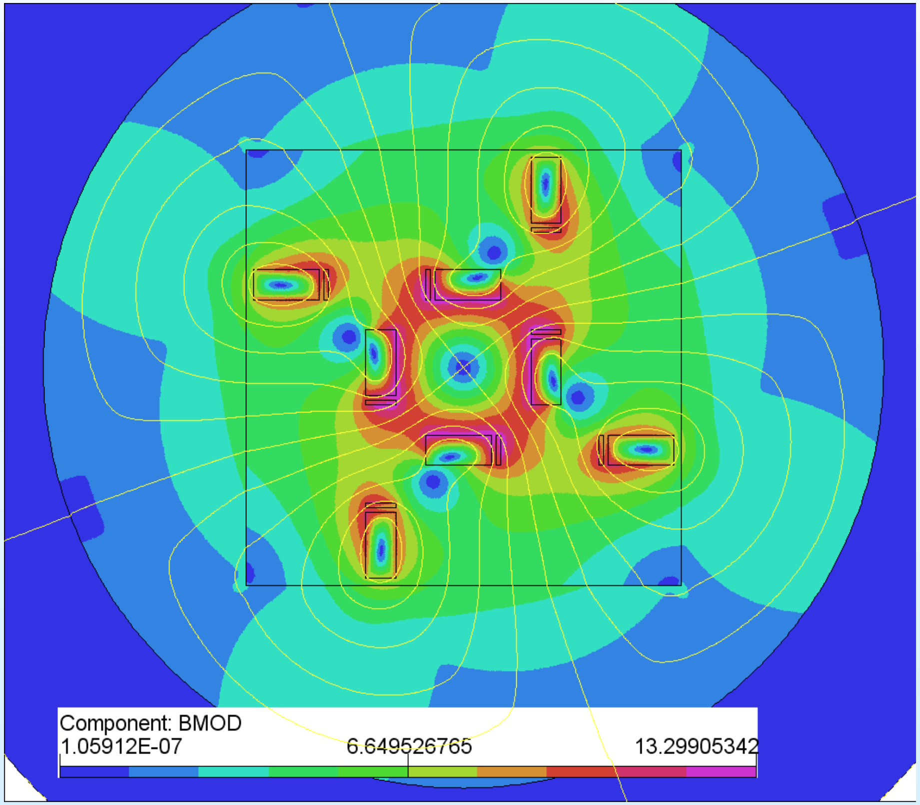
But magnetic design becomes more complicated.

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

Thanks to the suggestion of John Escallier

Magnetic Modelling

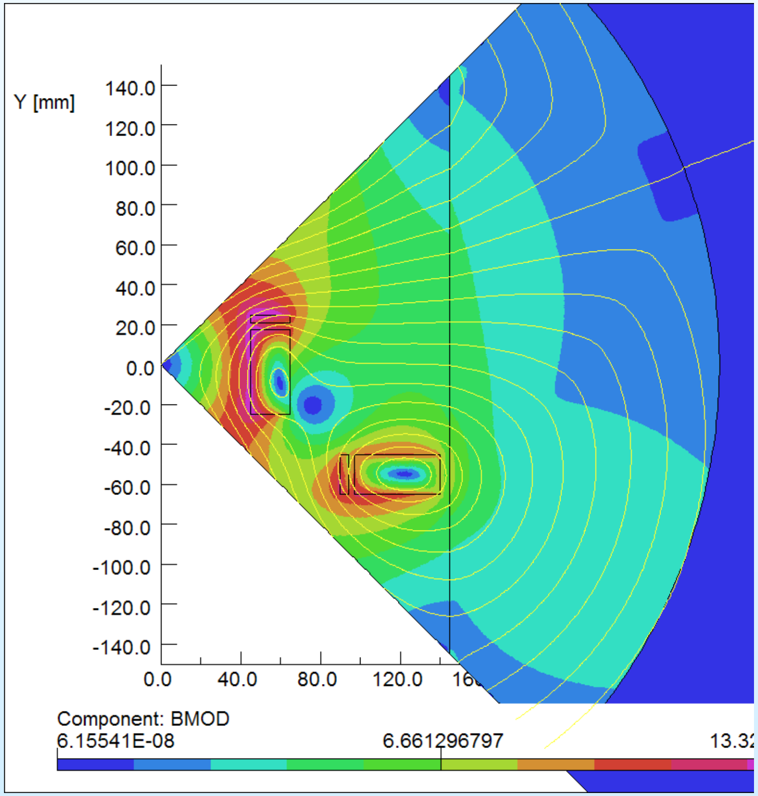
Complete Model



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

Need only 1/4 model

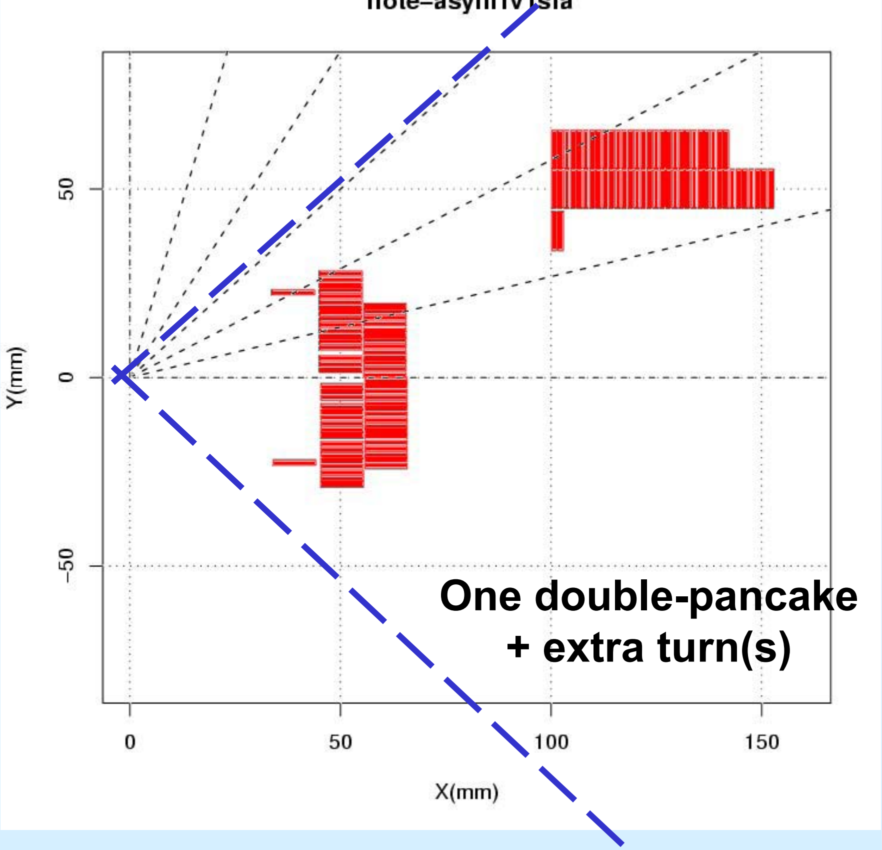
(with proper boundary conditions)



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

2-d Magnetic Design (simpler but asymmetric design)

A Quadrant



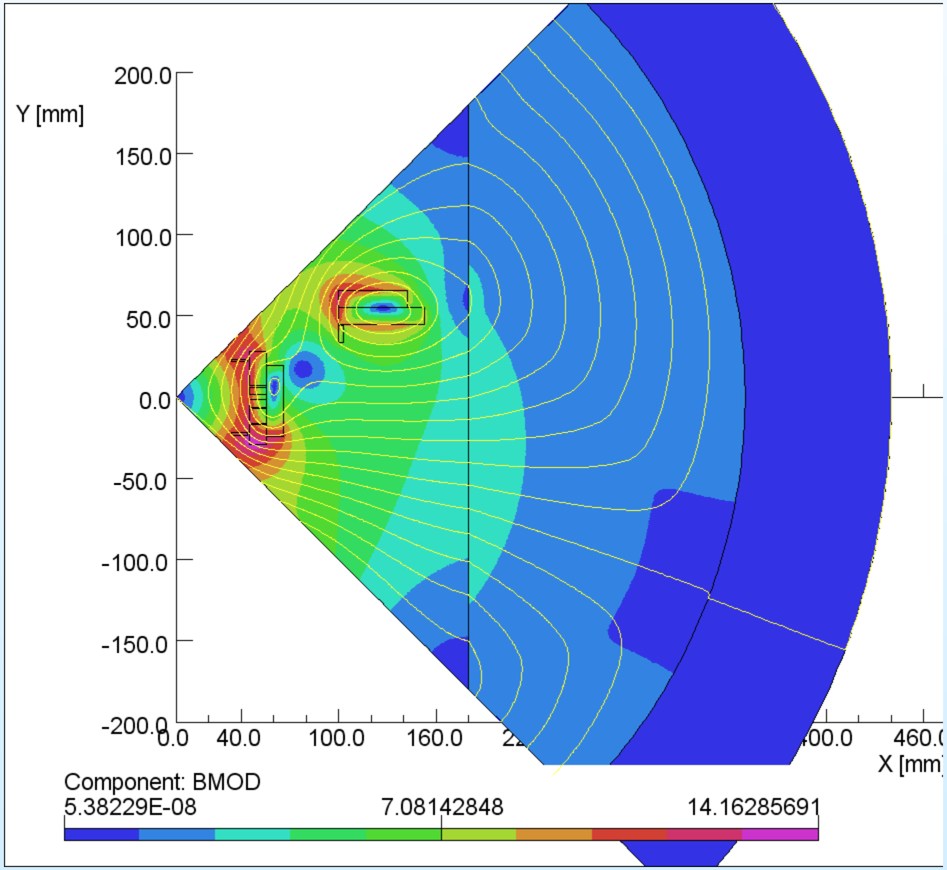
Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius).

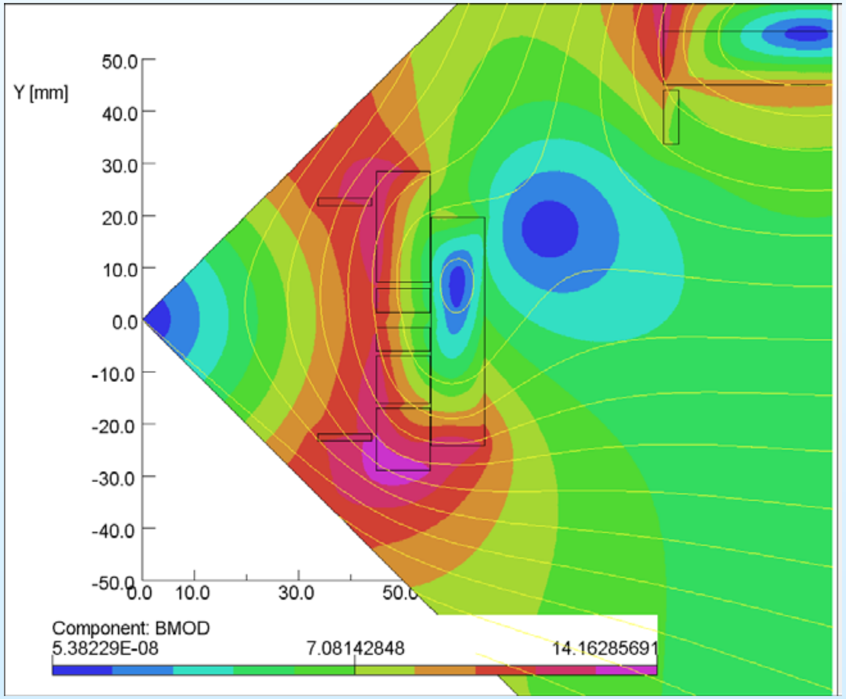
n	a_n	b_n
6	-0.0007	0.0000
10	0.0016	-0.0010
14	-0.0020	-0.0006
18	0.0000	0.0000

Asymmetric 2-layer design. Number of turns, transfer function, etc. are similar to symmetric design.
(Peak field found higher in this particular design)

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

OPERA 2-d model

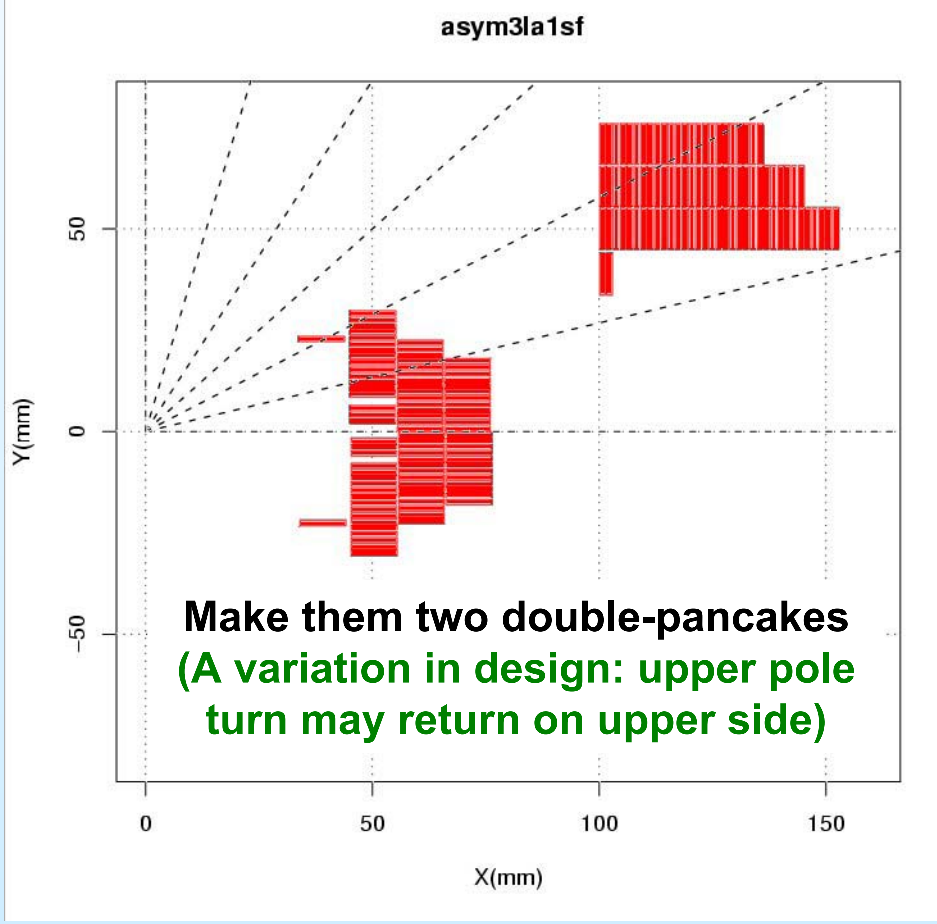




Need to reduce peak field

3-Layer Design for Higher Gradient

Relative increase in transfer function (in 3 layer design, as compared to in 2 layer) : ~28%



Make them two double-pancakes

(A variation in design: upper pole turn may return on upper side)

Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius).

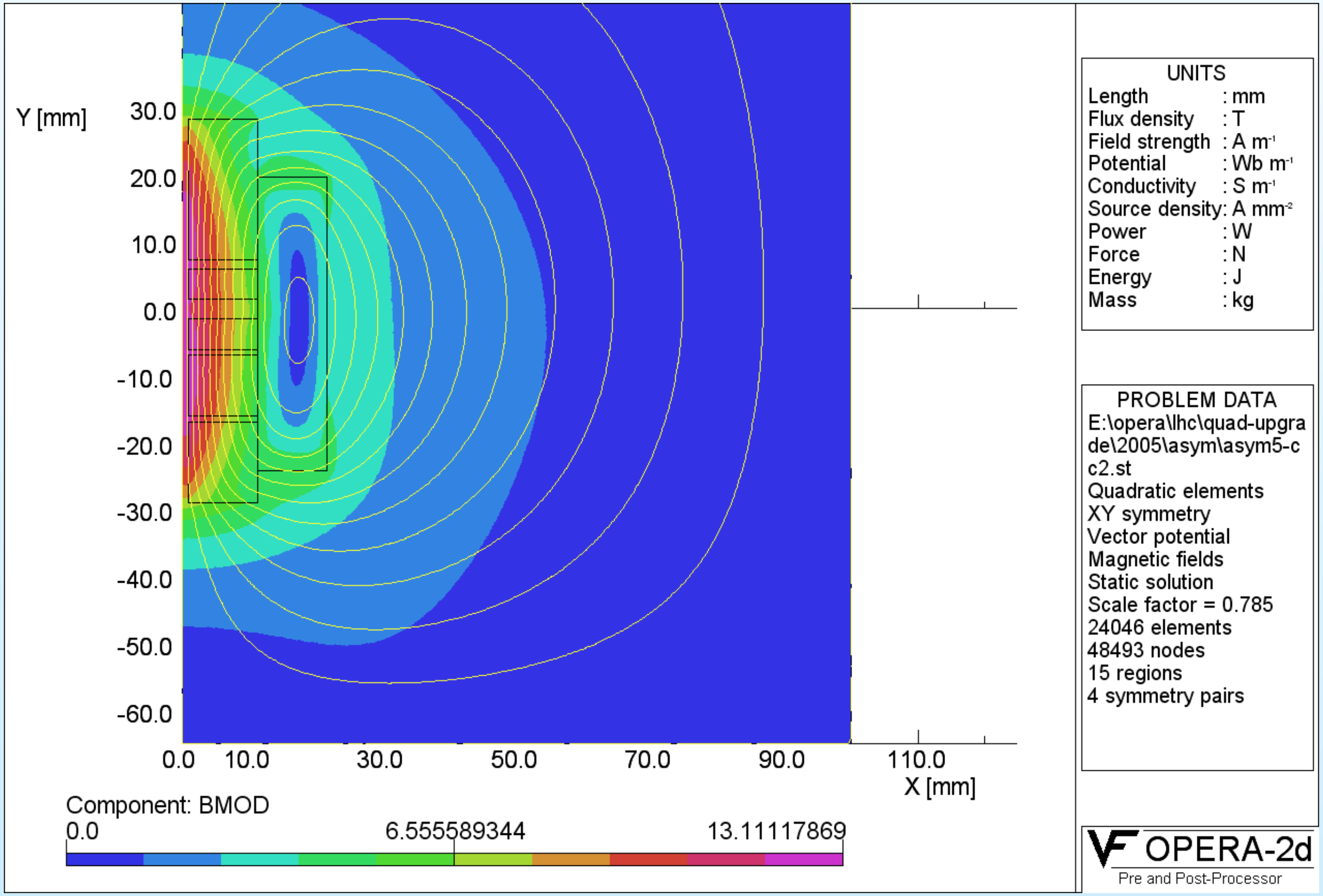
n	a_n	b_n
6	-0.0049	-0.0015
10	0.0006	0.0075
14	0.0018	0.0231
18	0.0000	0.0000

The 2-d harmonics are small

Case Study: Common Coil Dipole Test Scenario of Long Quad Coils

A pair of double pancake coil of LARP quad makes a 13.1 T long dipole.

Note: A long Nb_3Sn R&D dipole program is created out of quadrupole coils with only a modest additional resources.



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.

More Unique Features
Different Aperture With the Same Coils

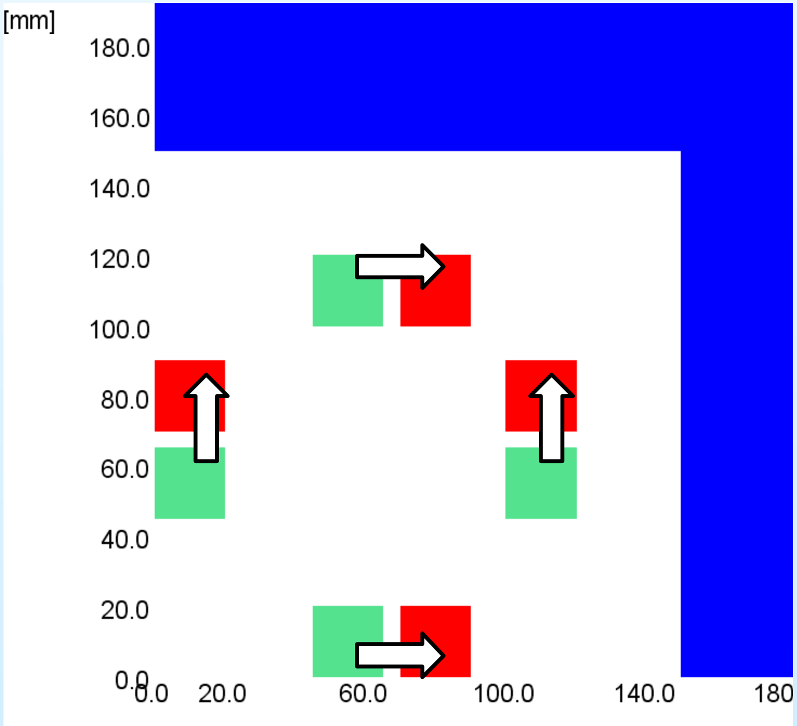
One can study different aperture using the same coils in R&D magnets.

Final magnet design will be more optimized for a particular aperture, but this concept offers a cost-effective and fast turn around method to study most technical issues.

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.

Support Structure

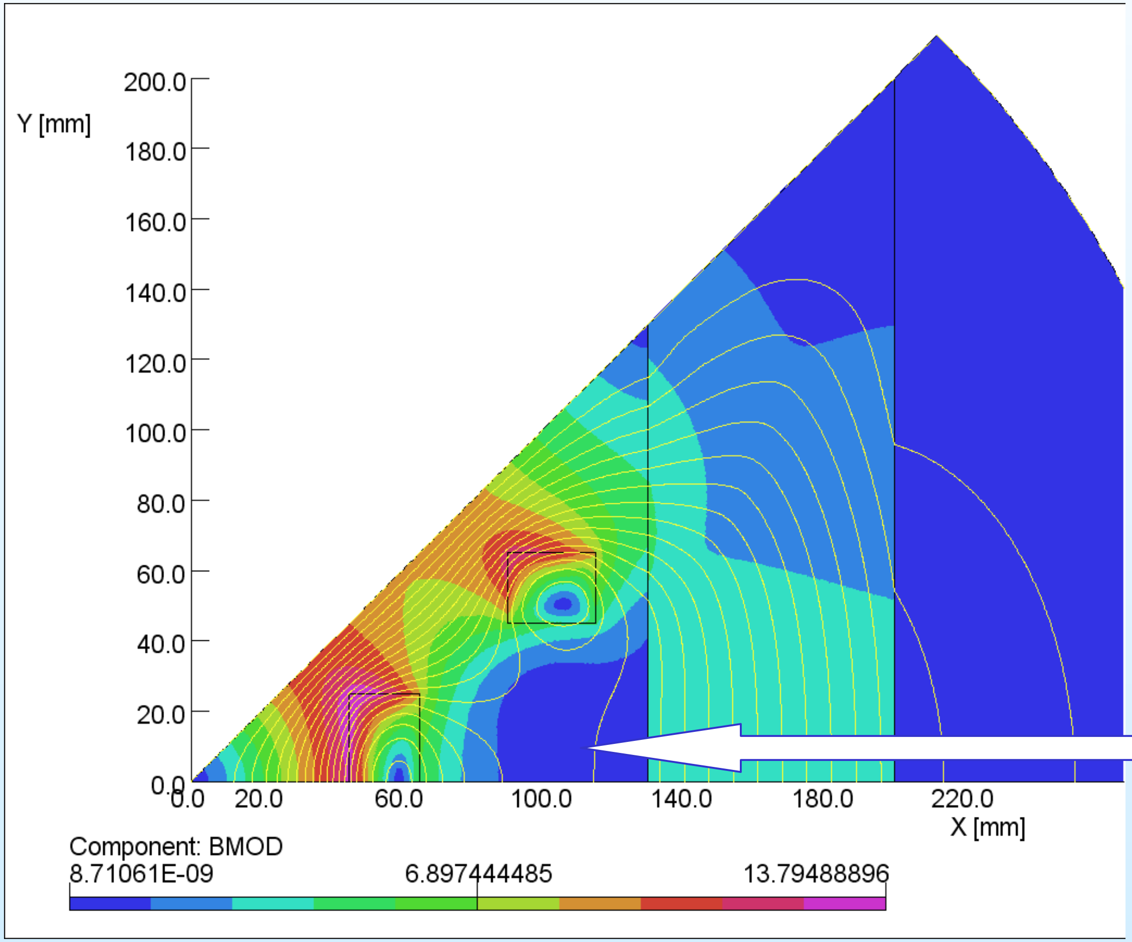
Support structure and assembly

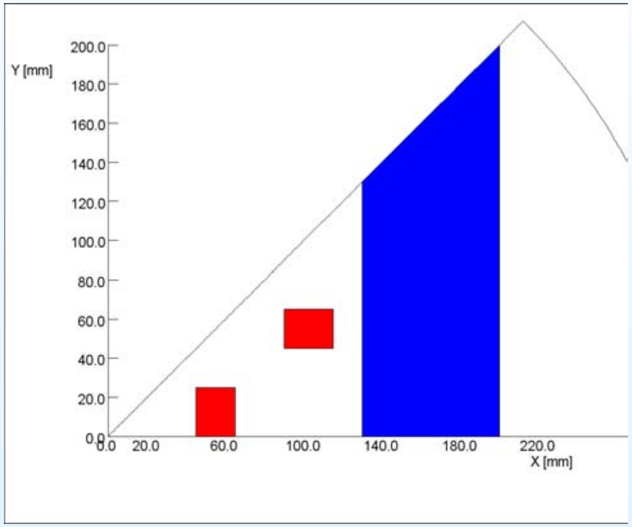
Concepts need to evolve

(start with a few structures before selecting one)

- One can be creative here.
- Think geometry --- it's different!

Possible Use in Crab Cavity Optics (1)

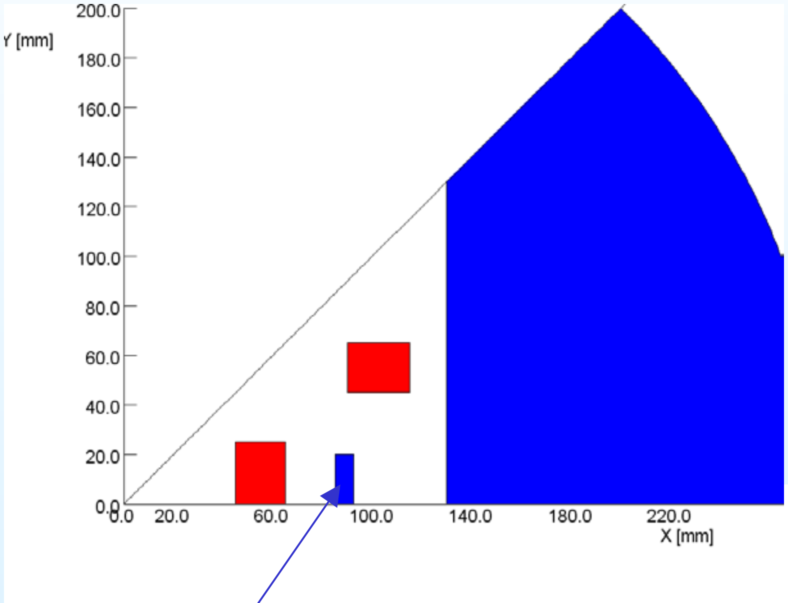




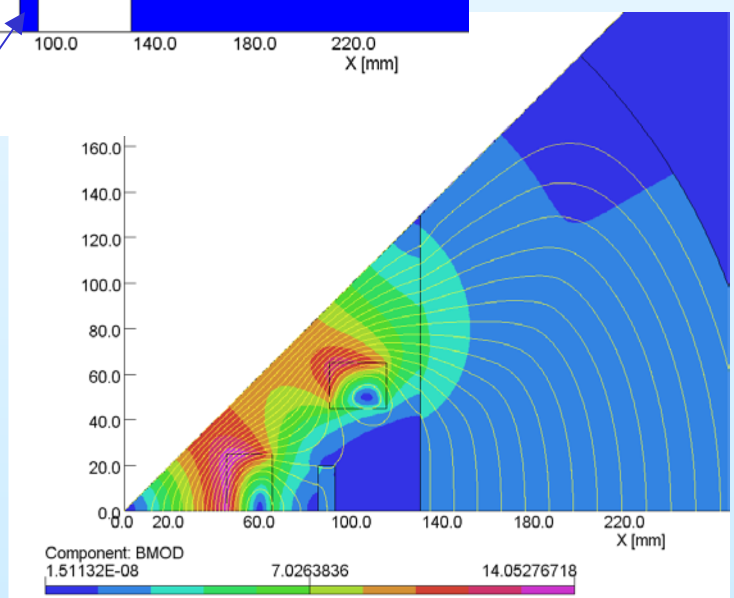
Steve Peggs noticed that the design naturally leaves a field free space that can be used by another beam in crab cavity optics.

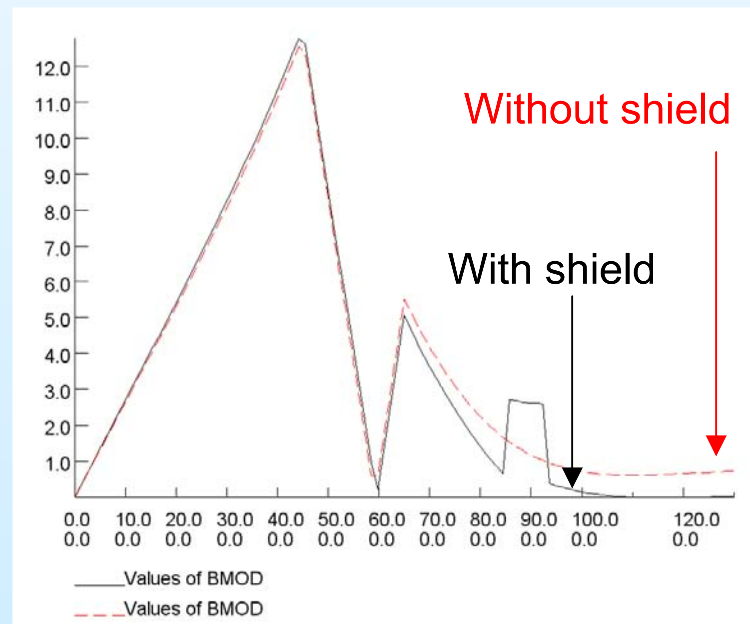
Possible Use in Crab Cavity Optics (2)

A shield can further reduce the field in the region of interest



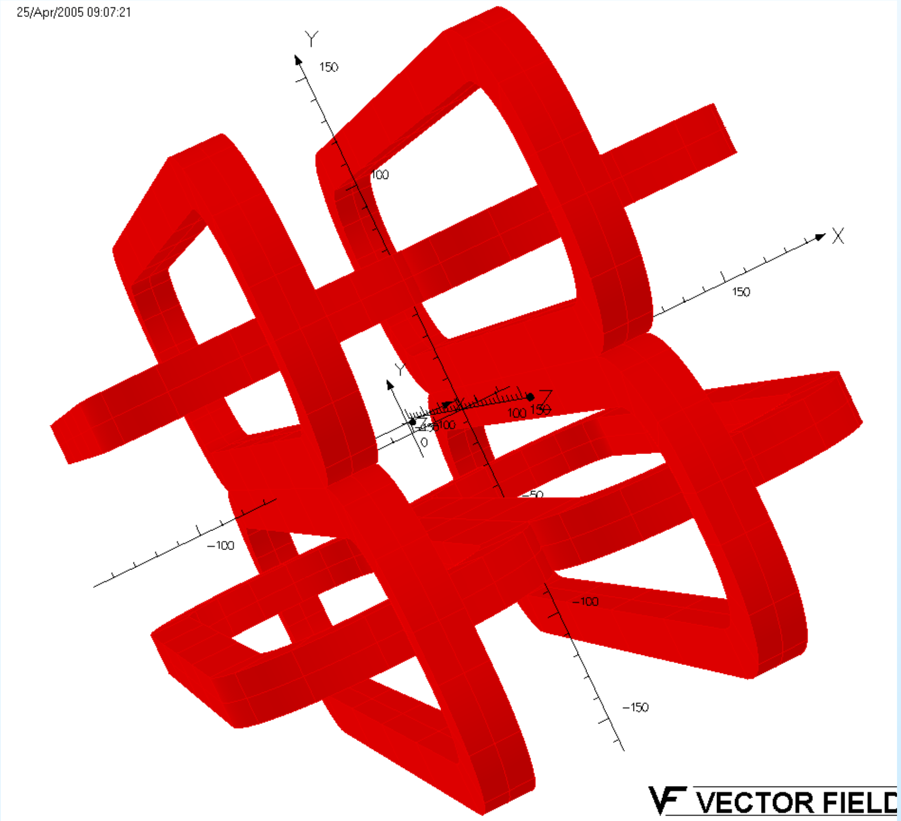
Iron shield

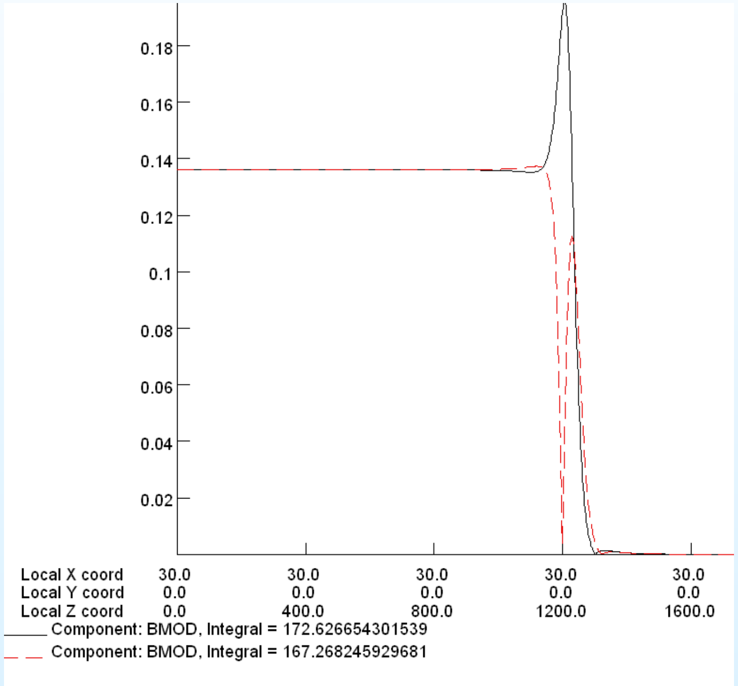




3-d Magnetic Design (symmetric cross-section)

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.

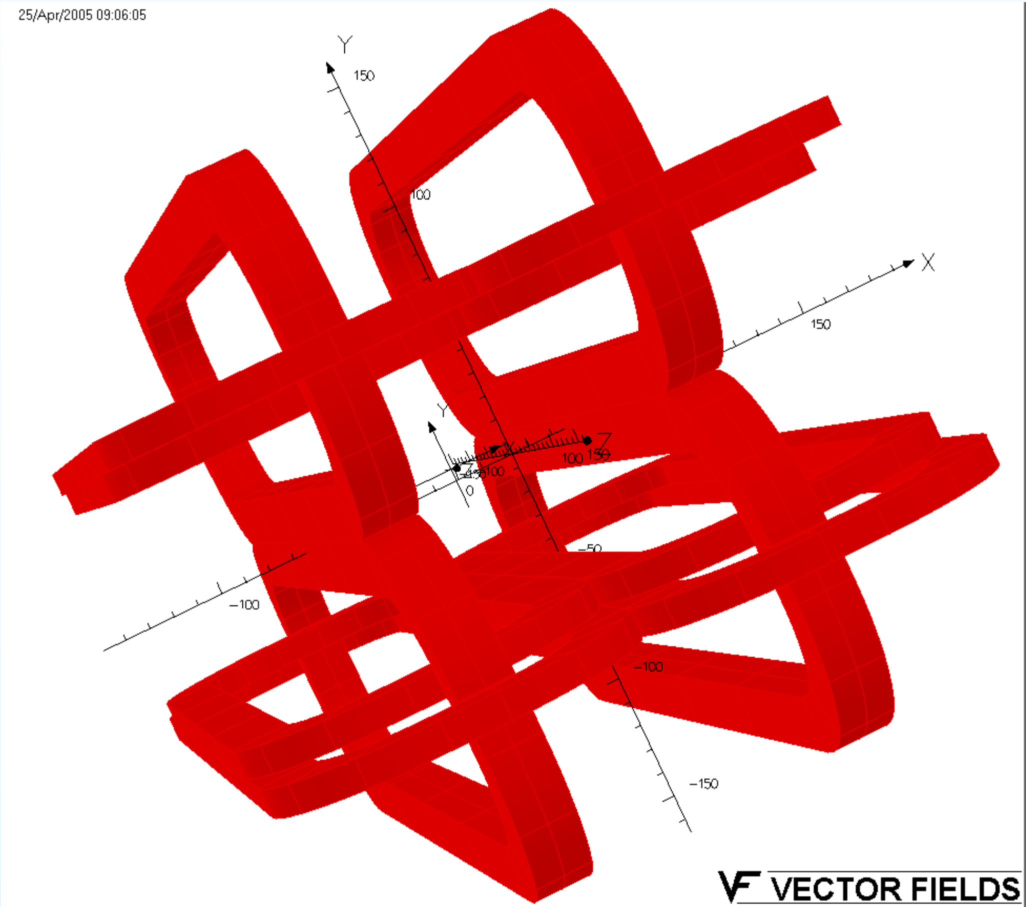


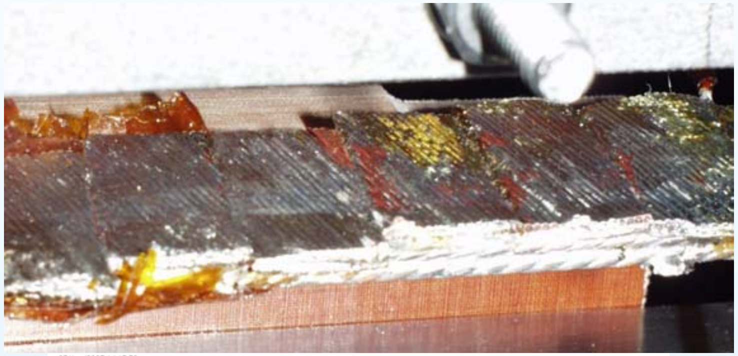


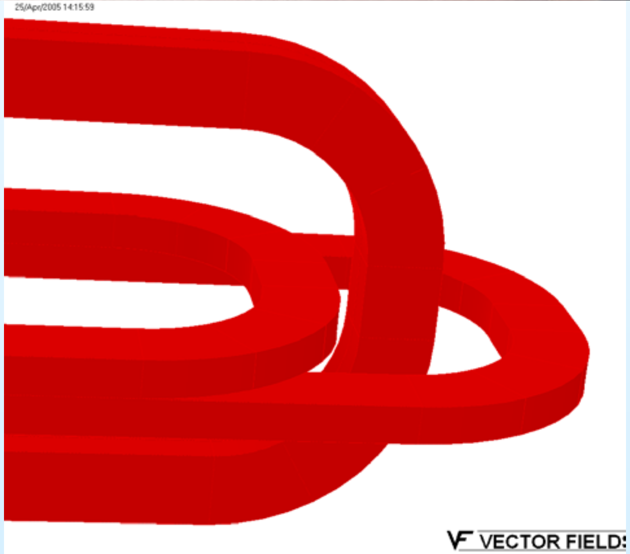
The magnitude of the field as a function of axial position on the horizontal axis (black full line) and vertical axis mm (dashed red line) at a distance of 30 mm from the origin. The integral value is listed at the bottom of the picture.

The difference between the two integrals is the measure of integral asymmetry.

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





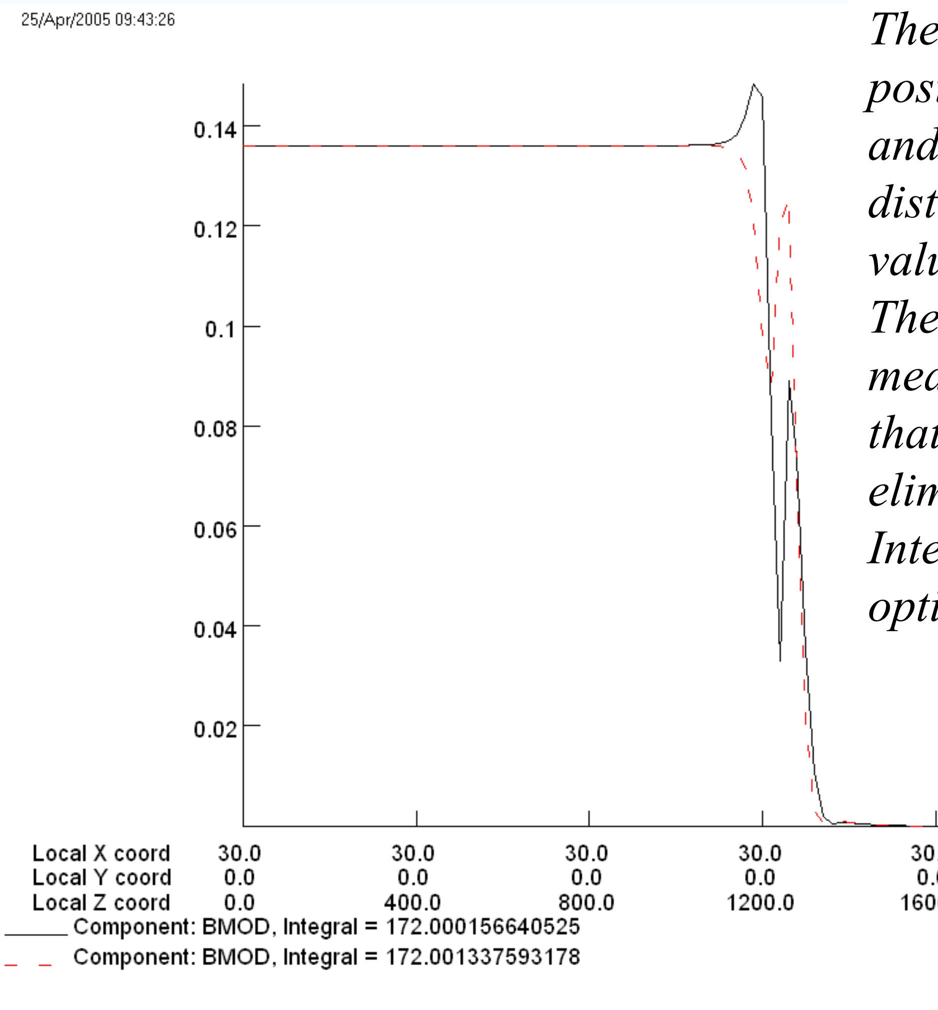


Try to match average coil lengths for horizontal and vertical coils.

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

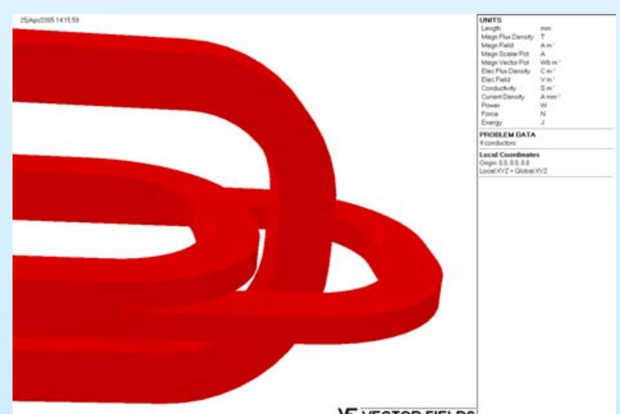
Final choice to depend on the mechanical design and assembly considerations.

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.



Splice Location

As in common coil design, splices can take place in a low field region since there is naturally one inside the coil. We can make "perpendicular splice", as successfully developed in common coil design.

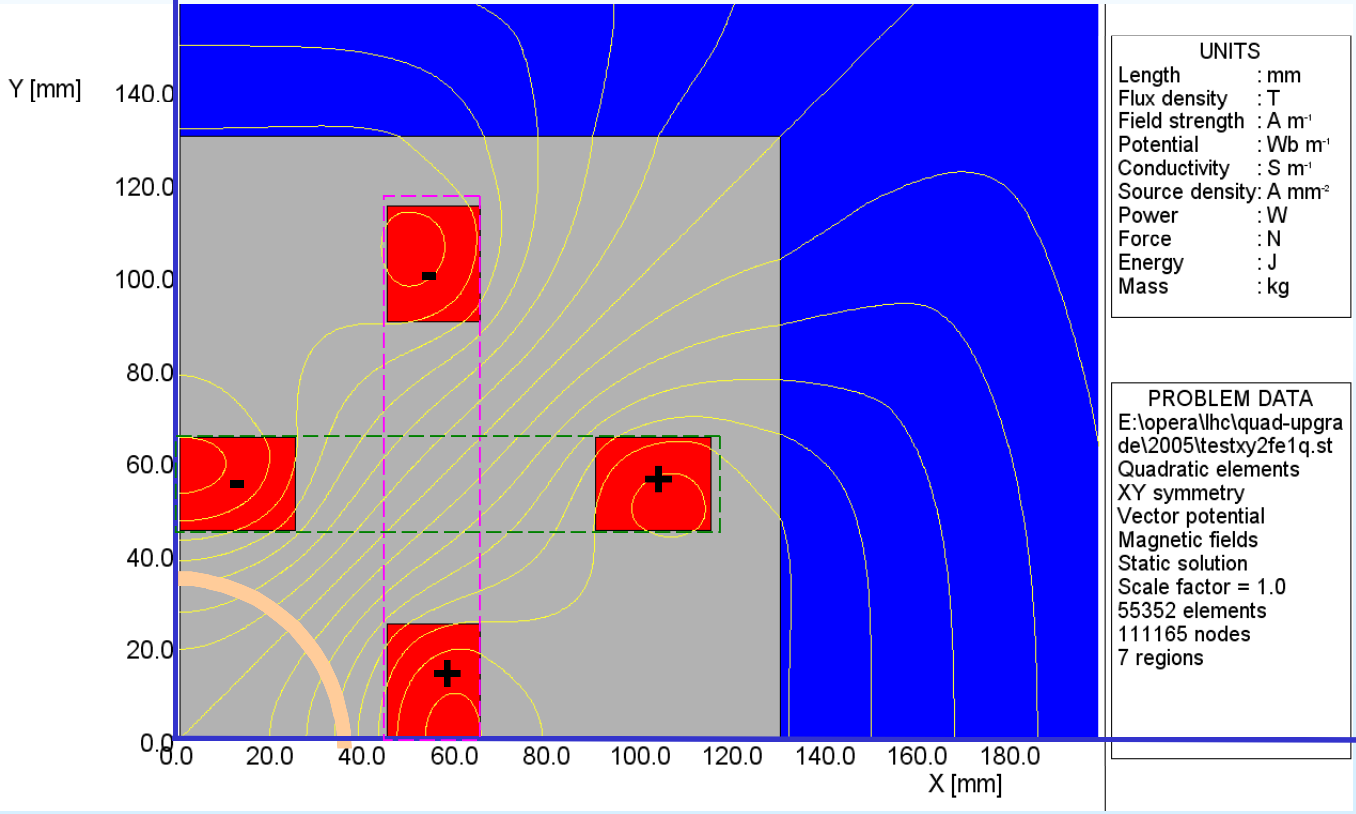
Double pancake coils reduces number of splices significantly, but then we have to always make two coils at a time and be slightly careful in transition region between the two coils.

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

First Model: A Magnetic Mirror (with two 15 turn double pancake coils)

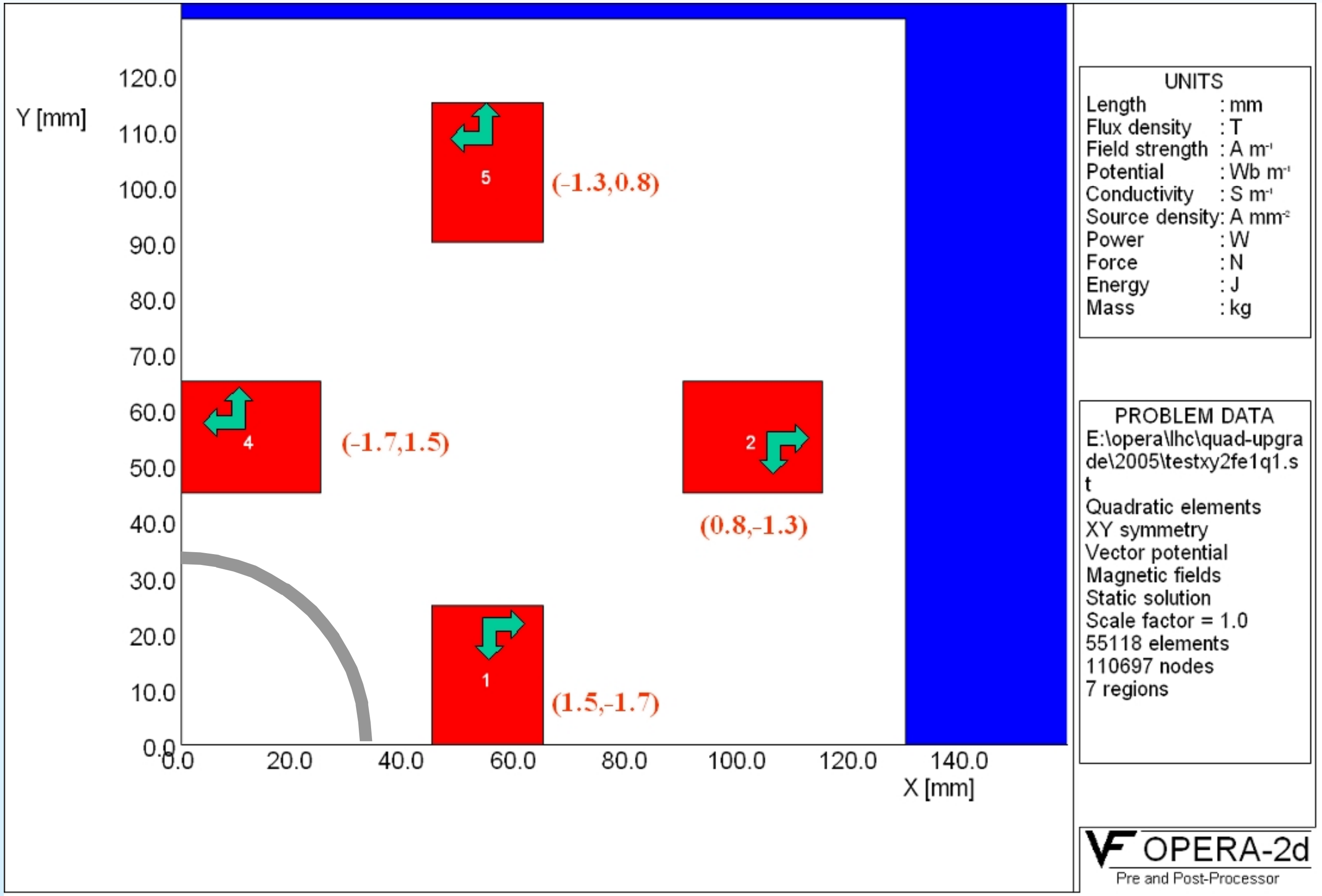
Magnetic mirror plane



Magnetic mirror plane

Field lines in the first quadrant of modular design.
Mirror iron can be placed on the X-axis and the Y-axis as the field lines are perpendicular there.

Lorentz Forces



Discuss Lorentz forces and support structure before the summary slide.

SUMMARY

- The proposed modular design seems to offer an alternate design for generating a high (required) gradient LARP quad.

- The design offers a way to use the racetrack coils, now under development, to be tested in a quadrupole structure under right field and forces

  (if one gets serious, then coil parameters need to be defined properly so that they are consistent with a reasonable design).

- There are several benefits of a modular design and a modular R&D program based on racetrack coils.

- But, is there any interest?