Dipole Design Status

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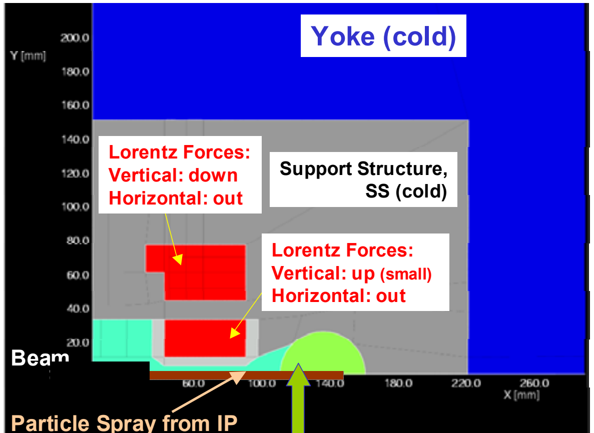
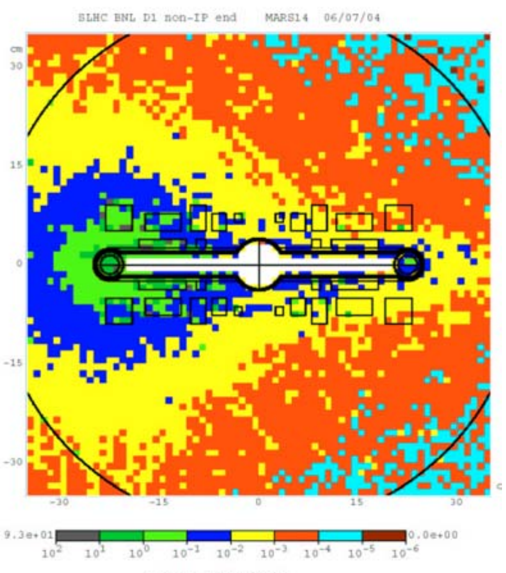
Open Midplane Dipole for LHC Luminosity Upgrade

Basic Design Features and Advantages



A large amount of particles coming from high luminosity IP deposit energy in a warm (or 80 K) absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.



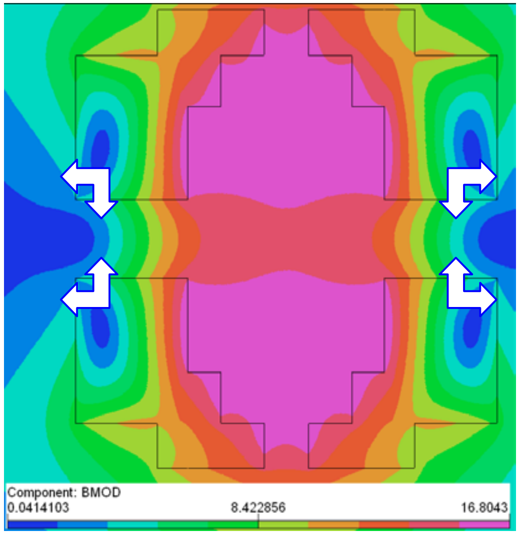
- In the proposed design the particle spray from IP deposits most of its energy in a warm absorber, whereas in the conventional design most of the energy is deposited in coils and other cold structures.

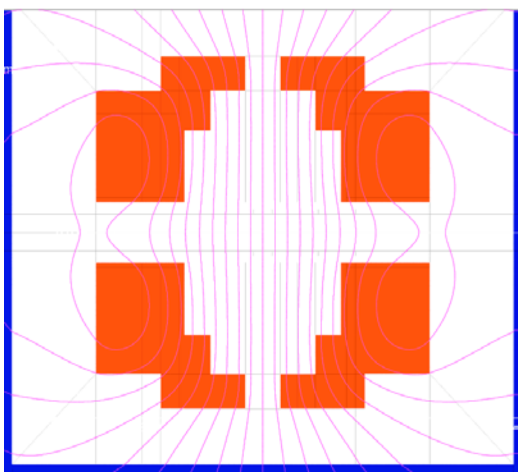
- Calculations for the dipole first optics show that the proposed design can tolerate ~ 9kW/side energy deposited for 10^{35} upgrade in LHC luminosity, whereas in conventional designs it would cause a large reduction in quench field.

- The requirements for increase in CERN cryogenic infrastructure and in annual operating cost would be minimum for the proposed design, whereas in conventional designs it will be enormous.

- The cost & efforts to develop an open midplane dipole must be examined in the context of overall accelerator system rather than just that of various magnet designs.

Open Midplane Dipole Design
Challenges





- Attractive vertical forces between upper and lower coils are large in any high field magnet, but they react against each other. Containing these forces in a magnet with no structure between the upper and lower coils appears to be a big challenge.
- The large gap at midplane appears to make good field quality a challenging task.
- The ratio of peak field in the coil to the field at the center of dipole appears to become large as the midplane gap increases.
- Designs may require us to deal with magnets with large aperture, large stored energy, large forces and large inductance.

♉ With these challenges in place, don't expect the optimum design to necessarily look like what we are used to seeing.

LARP Dipole Design Guidelines

Develop an integrated design of a high field dipole that

- Has an open midplane that is adequate for removing most spray particles from IP.
- Has a support structure that can accommodate large vertical forces in an open midplane design.
- Has desired field quality (10^{-4}) along the beam path.
- Is technology independent ("React & Wind" Vs. "Wind & React") in 2-d magnetic and mechanical design.

The design is being developed in an iterative way, where the "magnetic", "mechanical", "energy removal" and beam physics requirements are being optimized together. The maximum operating field is ~13.6 T with 10% margin (~15 T quench).

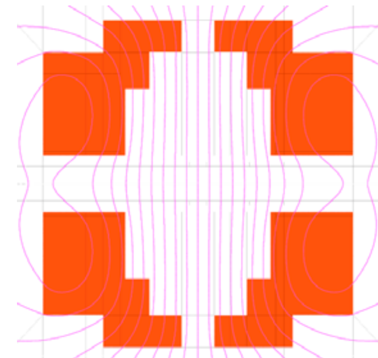
A Few Design Iterations To Help Evolve Basic Design Parameters

Design #1:

Midplane Gap = 33 mm,

Horizontal Coil Spacing = 84 mm

Energy Deposition calculations by Mokhov established the benefits of the design.

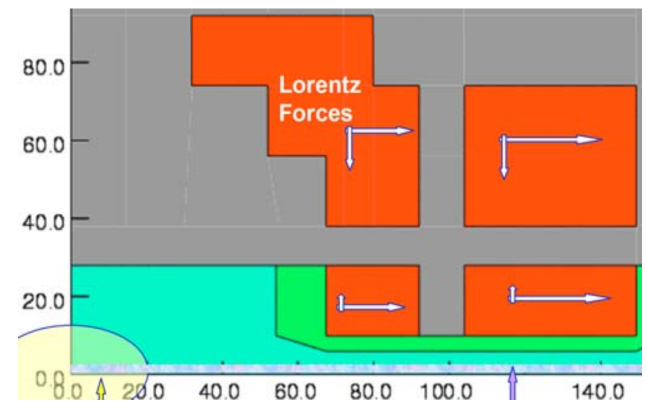


Design #2:

Midplane Gap = 20 mm,

Horizontal Coil Spacing = 135 mm

With the techniques developed along the way, the exercise indicated that a design with a sufficient gap, good field quality and proper structure should be feasible.

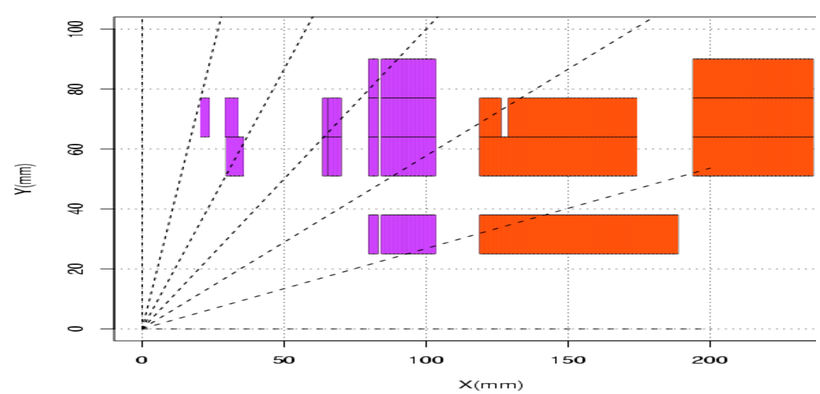


Design #3:

Midplane Gap = 50 mm,

Horizontal Coil Spacing = 160 mm

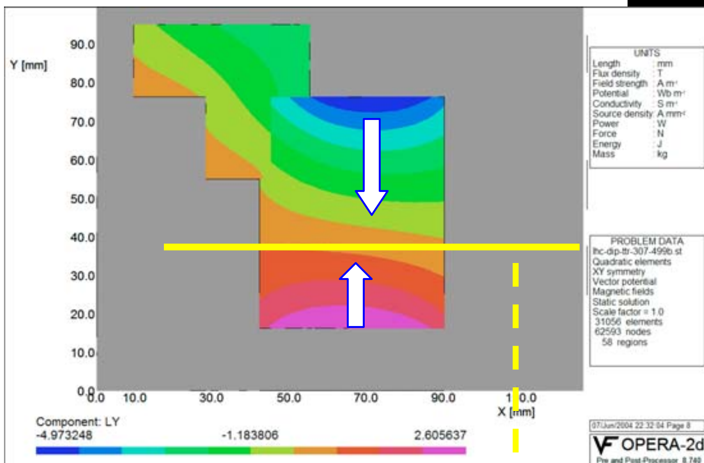
The magnet design seems to meet all basic requirements.



Navigation of Lorentz Forces (1)

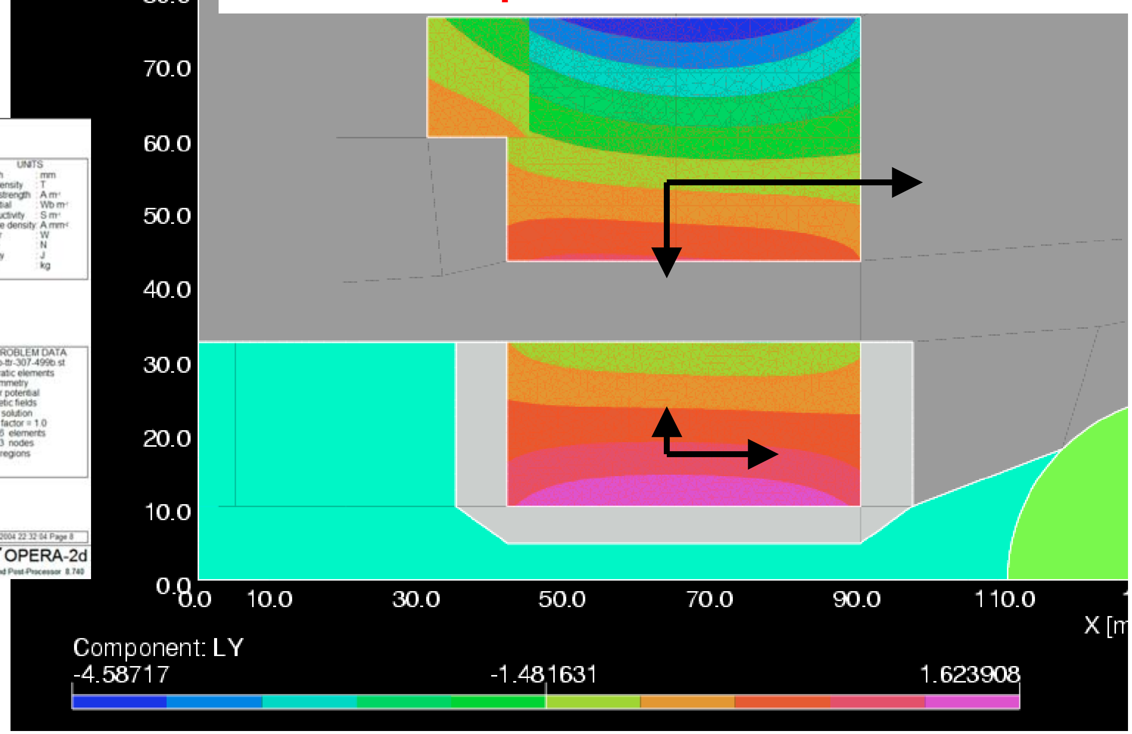
A new and major consideration in design optimization

Vertical Lorentz force density in certain designs



~Zero vertical Lorentz force density line

Vertical Component of the Lorentz Force Density



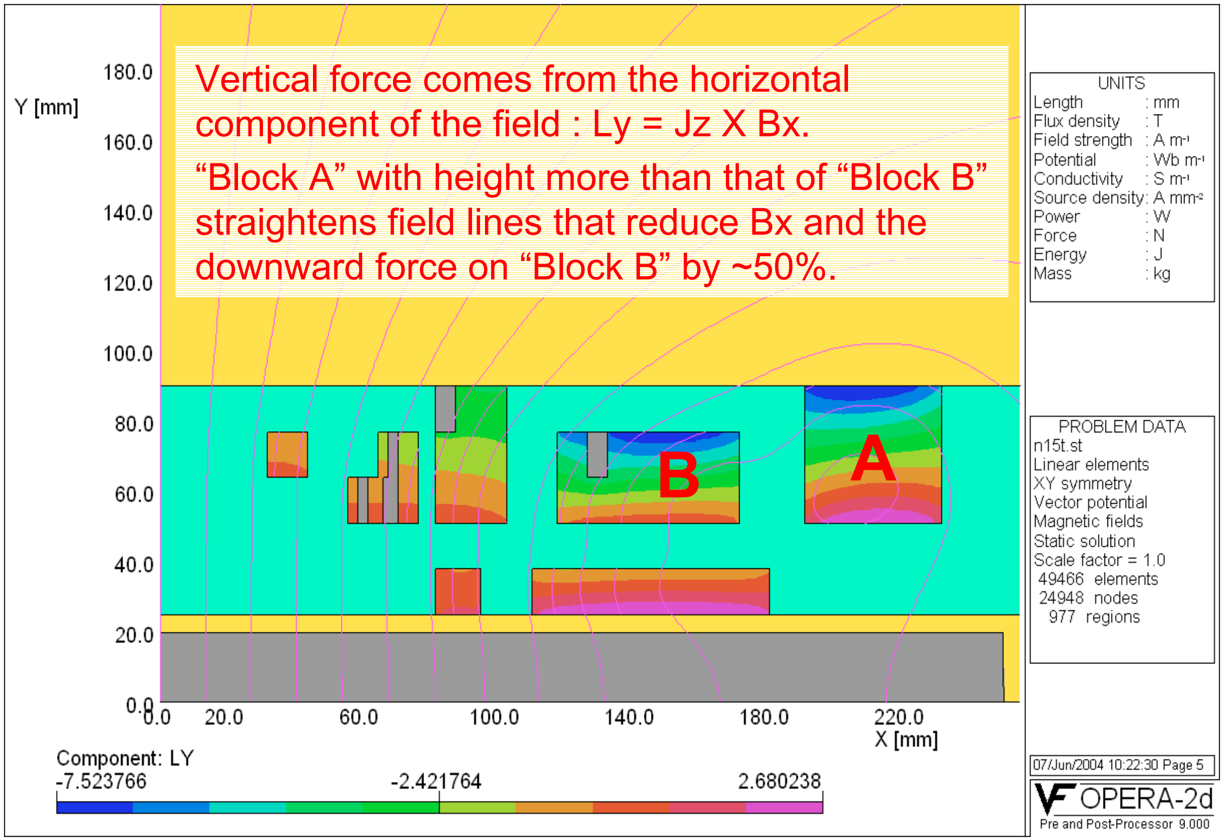
Since there is no downward force on the lower block (there is slight upward force), we do not need much support below it, if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

➢ **This allows the lower block to move closer to midplane to improve field quality.**

Navigation of Lorentz Forces (2)

(Transferring vertical forces between blocks)

Design with 50 mm midplane gap:



Blocks must be strategically segmented to minimize maximum stress build-up, navigate Lorentz forces, minimize peak fields and optimize field quality.

The task is to demonstrate that it is possible to satisfy all of the above requirements at the same time.

Note: There is a plenty of space for support structure below "Block A"

Moving Block A upward also minimizes the secondary energy deposition from target.

Guidelines for Developing an Initial Mechanical Design

- Relative deflections in coils remain below 100 micron.
- Absolute deflections in coils remain below 200 micron.
- Simplest possible structure with no pre-stress on coils.

Find out experimentally (tech models), whether acceptable performance can be obtained with the above guidelines.

Otherwise make support structure more robust (and more complicated) to:

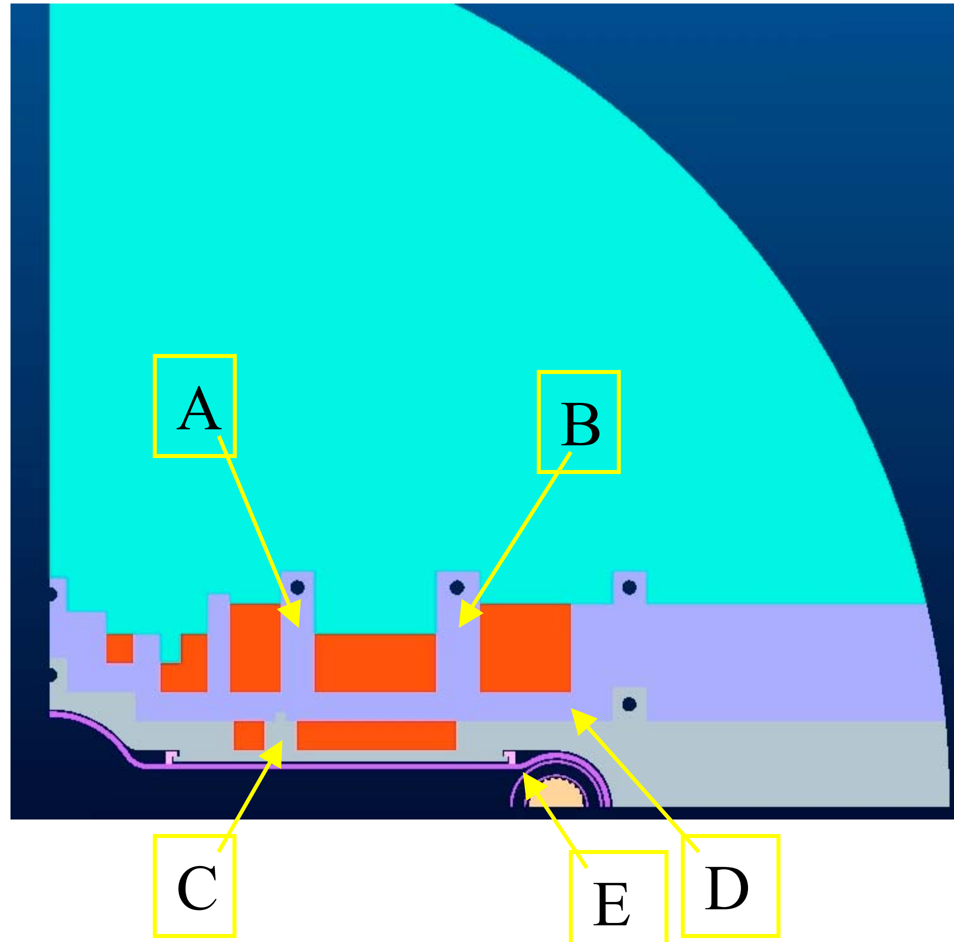
- Reduce deflections
- Apply full/partial pre-stress to counter Lorentz forces on coils

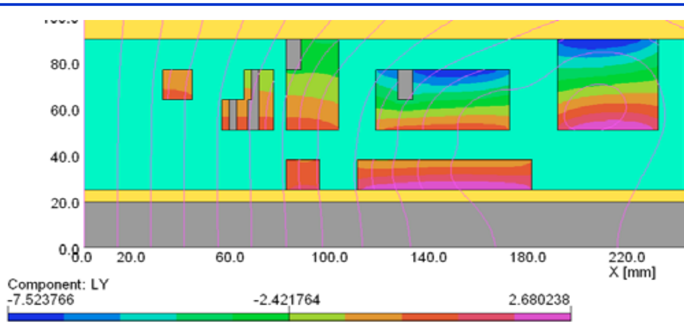
LARP Dipole – Mechanical Analysis
(A systematic study of design parameters)

Basic Structure Analysis

Several coil cross sections analyzed.

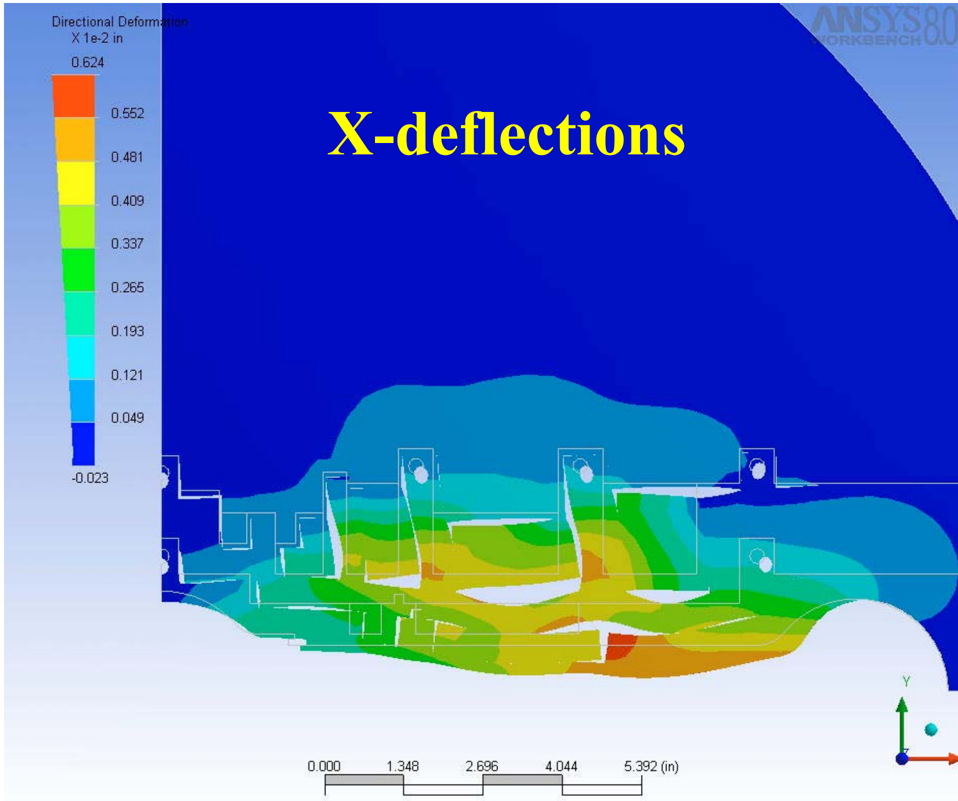
- Many iterations to optimize the thickness of the webs between the coil blocks by varying:
  - Web A 10, 15, 20 mm
  - Web B 10, 15, 20 mm
  - Web C 10, 15 mm
  - Web D 13, 18 mm
  - Cutout Radius E for absorber
  - Position of Absorber

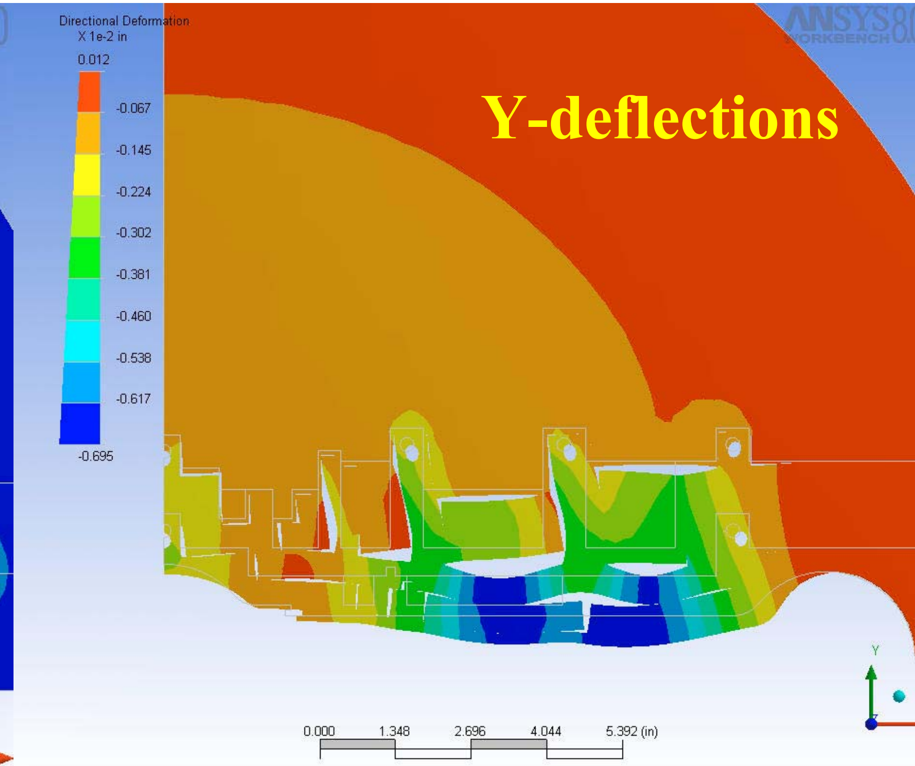




<== These requirements are then fed into the magnetic design

Mechanical Analysis





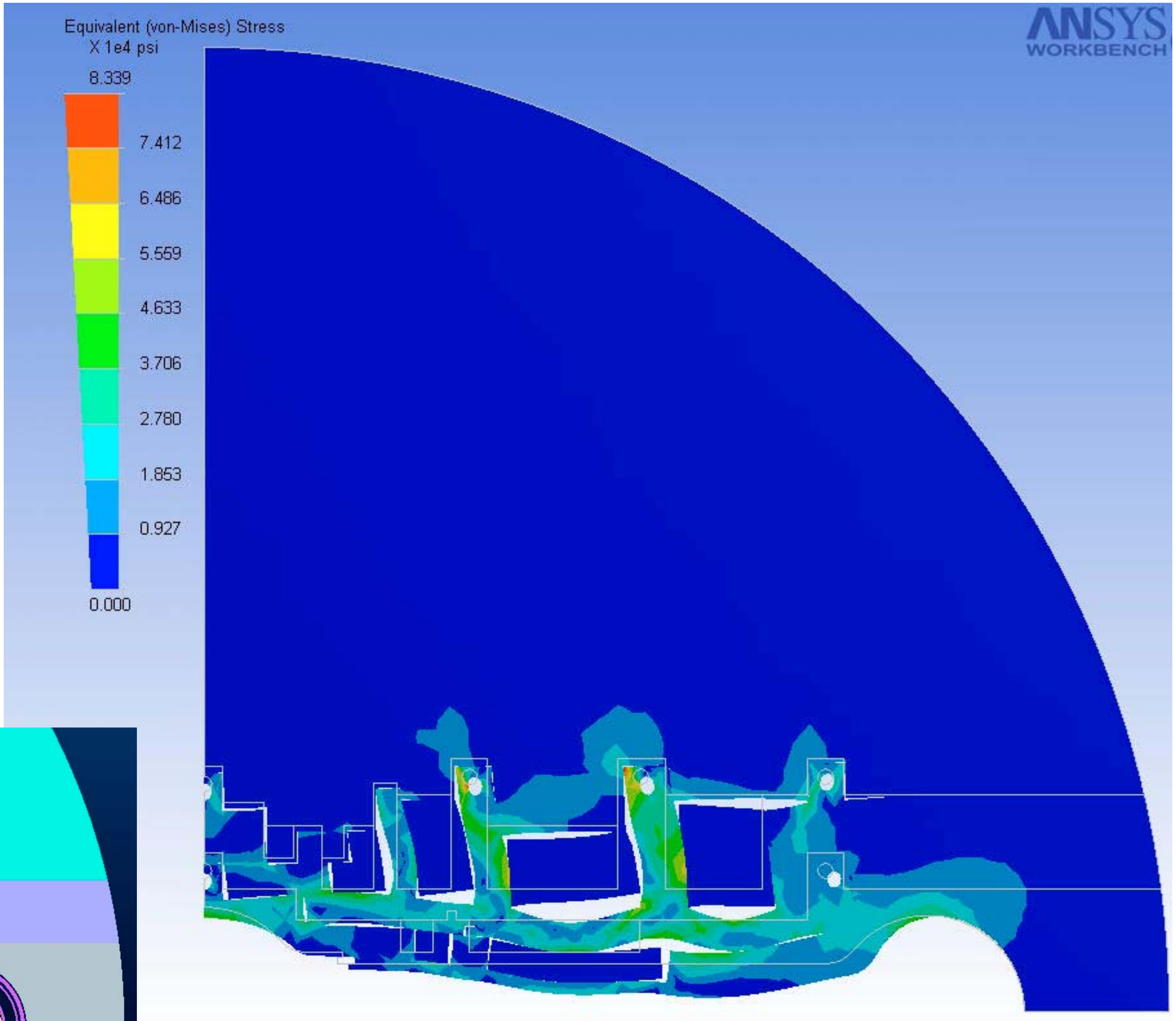
In the present design the relative values of the x and y deflections are 3-4 mil (100 micron) and the maximum value is 6-7 mil (170 micron).

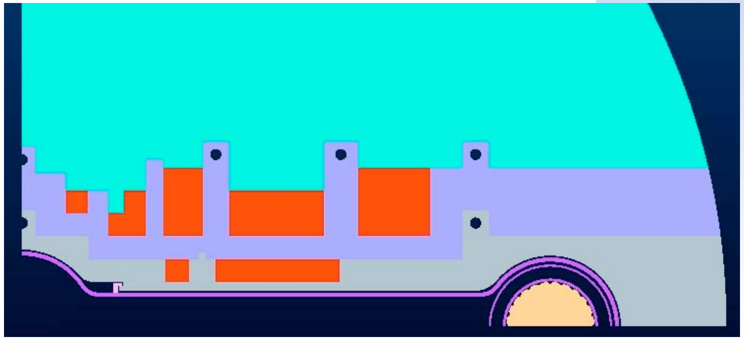
Above deflections are at design field (13.6 T). They are ~1-2 mil higher at quench field.

Mechanical Analysis – Stress in SS Collar

Stresses in stainless steel collar (external support structure) are well within the acceptable limit.

Next step is to examine internal stresses in coil blocks. Adjust/move webs, if necessary.

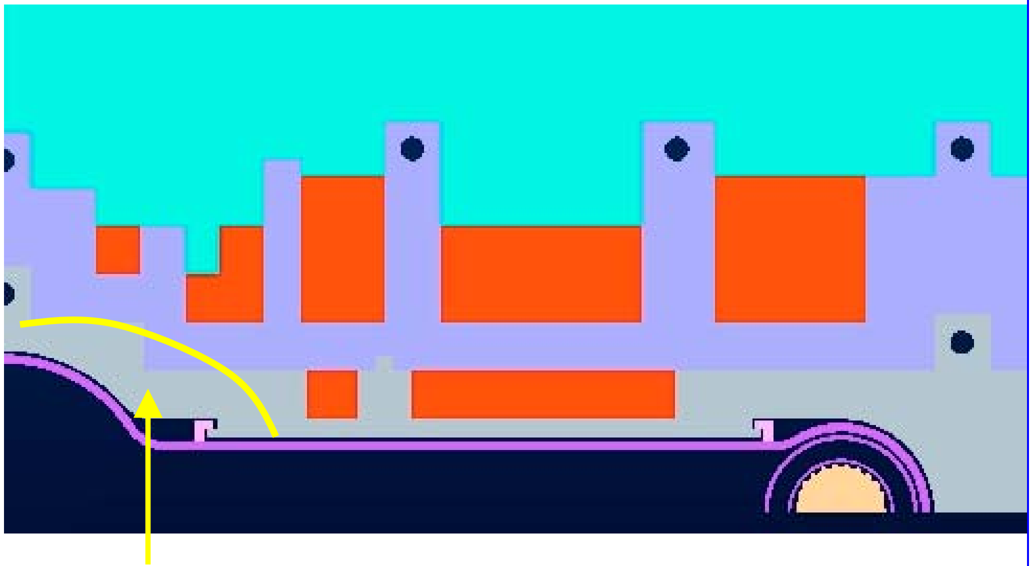




Magnetic Design and Field Quality

A **critical constraint** in developing the magnetic design of the open midplane dipole for obtaining good field quality and for determining the overall parameter set is the size of the **coil midplane gap**.

The gap must be large enough to obtain the stated benefits. It should minimize the energy deposition in the cold structure while allowing for various orbit and misalignment errors.



More space may be possible in this area

We choose a 50 mm coil-to-coil gap (25 mm half gap)

- Incidentally same as SSC aperture
- 1/3 of horizontal aperture.

Gap may be generous: chosen to prove that the concept will work, even if it has to be this much.

However, it also makes the field quality and magnetic design more challenging.

Design Parameters of 15 T Open Midplane Dipole

US LARP

Nb_3Sn wire and cable parameters:

J_{sc}(12T,4.2K)	3000 A/mm^2
Cu/Non-Cu ratio	0.85
Strand diameter	0.7 mm
No. of strands in cable	34
Cable width (bare)	12. 5 mm
Cable thickness (bare)	1.25 mm
Insulation	Nomex
Cable width (insulated)	13 mm
Cable thickness (insulated)	1.45 mm
J_{cu} (@quench)	~ 1800 A/mm^2

Magnet parameters:

Quench Field	~15 T
Quench Current*	11.6 (7.7) kA
Horizontal Spacing	160 mm
Coil Midplane Gap	50 mm
Collar Outer Radius	400 mm
Yoke Outer Radius	1 meter
Stored Energy	11 MJ/meter
Inductance*	0.16 (0.4) H/m

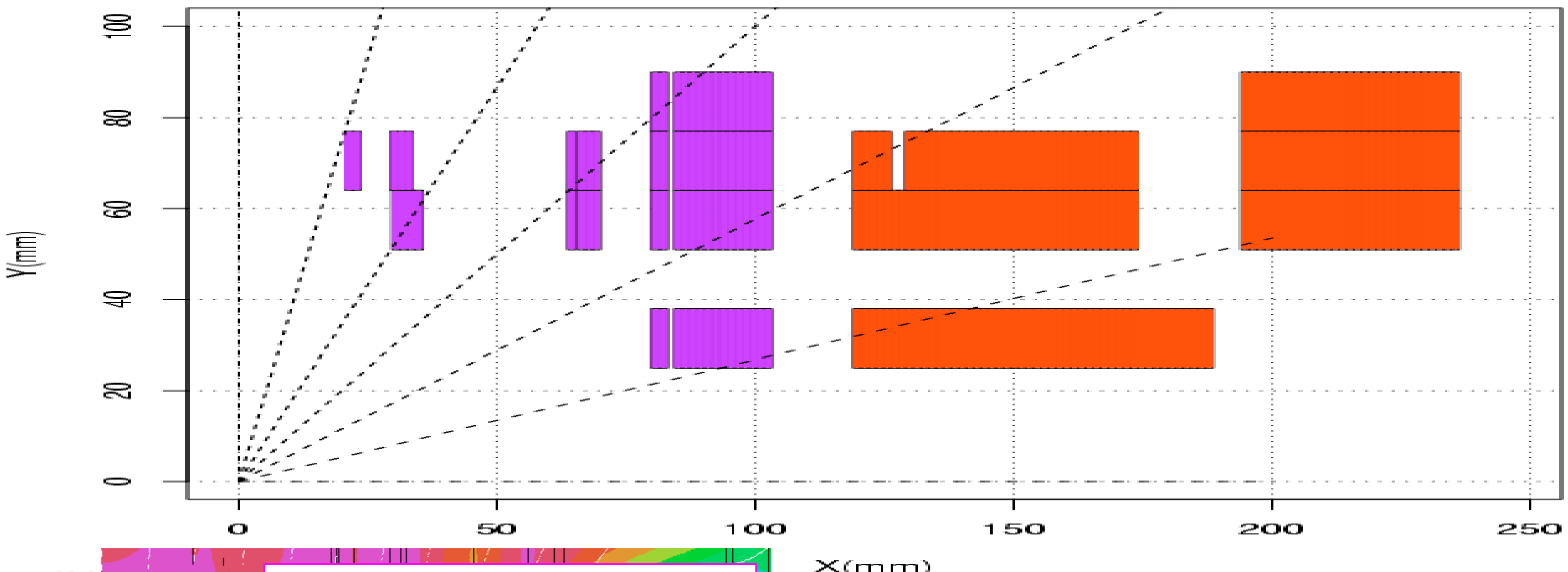
*Two values if current grading, rather than cable grading is used, in R&D magnets.

The magnet itself is big and expensive. But these are only a few. If one considers the overall increase in infrastructure and operating cost, and just not the magnet cost, the net savings will be substantial.

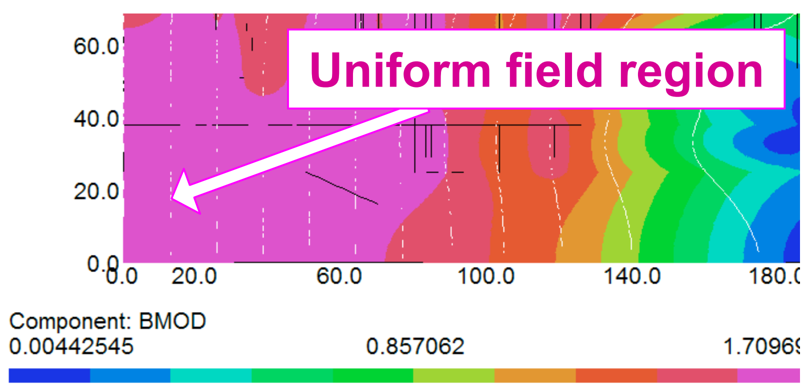
Hand Optimized Design =>
Fine-tuned by RACE2DOPT for Harmonic Minimization

The design is first navigated by hand for "Lorentz Forces", "Support Structure", "Energy Deposition", "Low Peak Field" and not too lousy "Field Quality".

Then a few select cases are optimized for field harmonics with RACE2DOPT (local code).



Red blocks have 50% higher J_e as compared to the purple blocks.



With several new criteria in optimization, and with no prejudice on how ultimate geometry should look like, we reached a vastly different looking solution.

- **Does it look like simulating cosine theta any more?**

Field Harmonics and Relative Field Errors In An Optimized Design

Proof: Good field quality design can be obtained in such a challenging design:

(Beam @ x=+/- 36 mm at far end)
(Max. radial beam size: 23 mm)

Geometric Field Harmonics:

	Ref(mm)	Ref(mm)
n	36	23
1	10000	10000
2	0.00	0.00
3	0.62	0.25
4	0.00	0.00
5	0.47	0.08
6	0.00	0.00
7	0.31	0.02
8	0.00	0.00
9	-2.11	-0.06
10	0.00	0.00
11	0.39	0.00
12	0.00	0.00
13	0.06	0.00
14	0.00	0.00
15	-0.05	0.00
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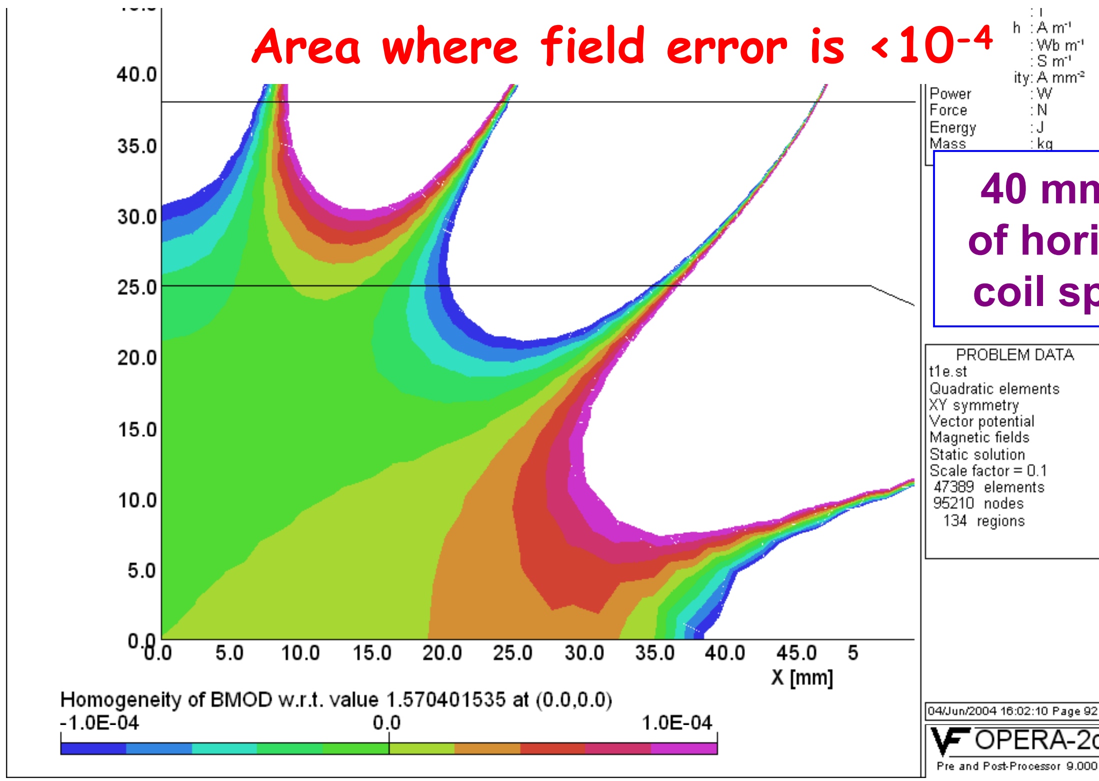
17	0.01	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00

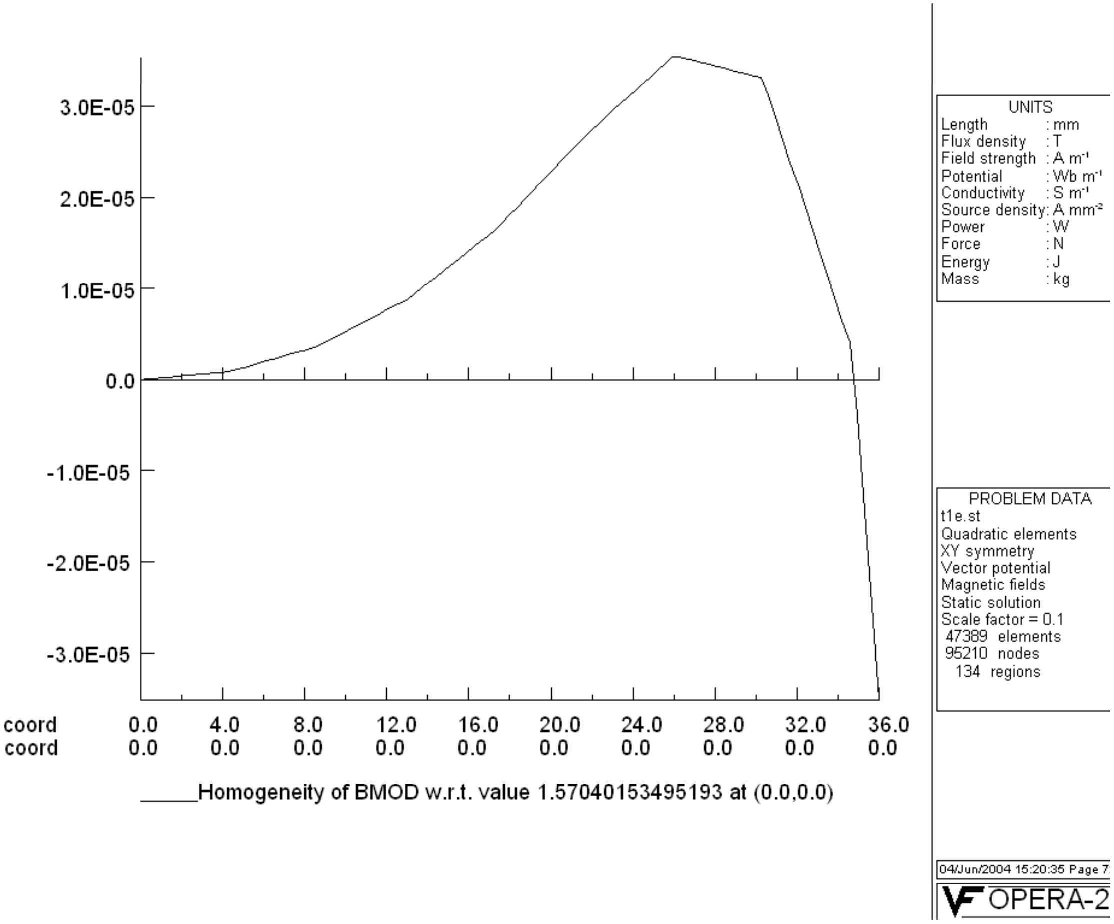


40 mm is ½ of horizontal coil spacing

Field errors should be minimized for actual beam trajectory & beam size.
It was sort of done when the design concept was being optimized by hand.
Optimization programs are being modified to include various scenarios.
Waiting for feed back from Beam Physicists on how best to optimize.
However, the design as such looks good and should be adequate.

Field Uniformity in An Optimized 15 T Open Midplane Dipole Design

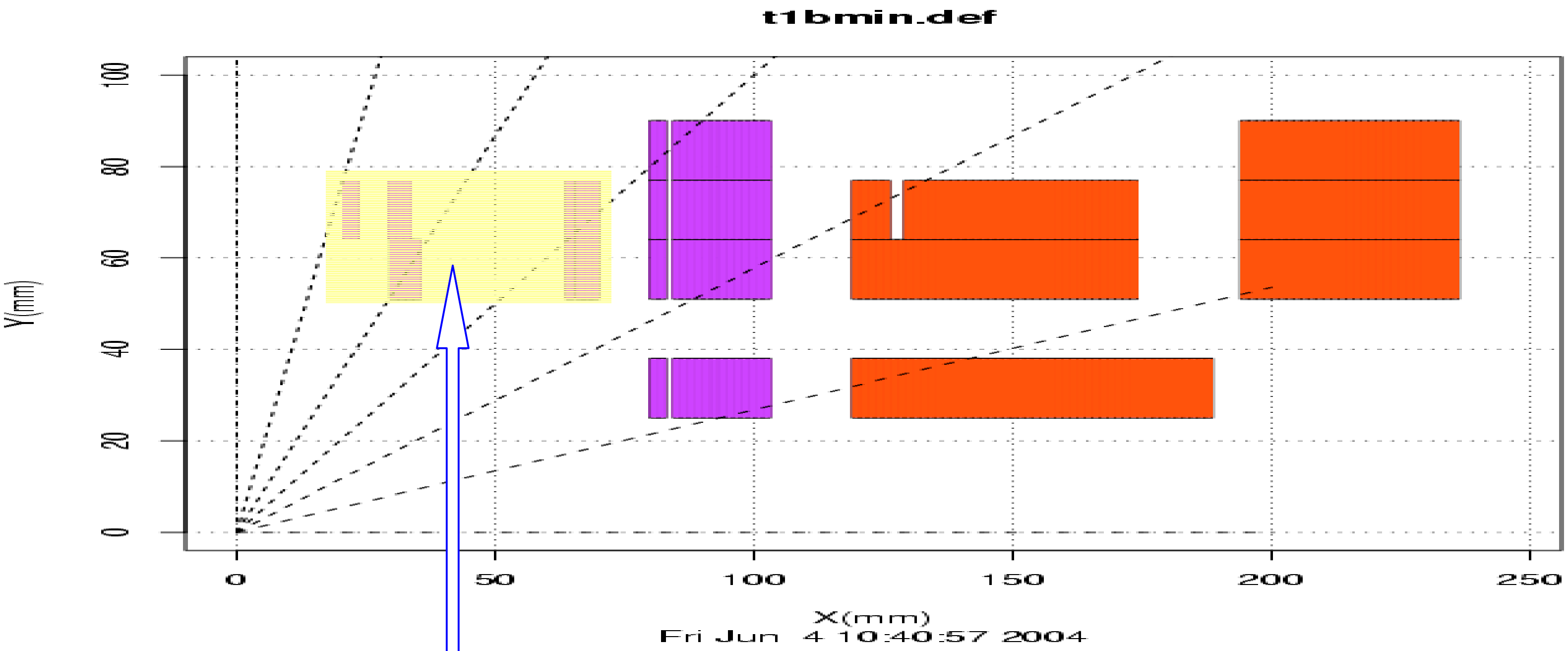
Proof that good field quality can be obtained in such a wide open midplane dipole design (~1/2 of vertical and ~1/3 of horizontal aperture):



The maximum horizontal displacement of the beam at the far end of IP is +/- 36 mm.

The actual field errors in these magnets will now be determined by construction, persistent currents, etc.

Construction Plans



These field shaping coils will not be built in the 1st phase.

The design is being developed so that these coils can be added later.

One may also consider building only the red coils first.

Field shaping coils would either have flared ends or could be made using "Wind & React" technology.

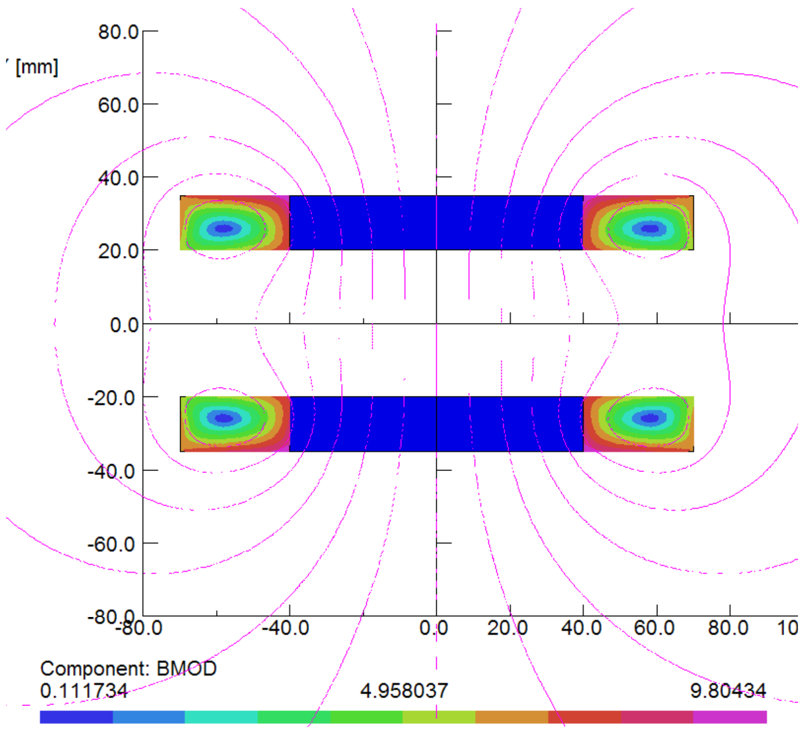
Technology Development Tests

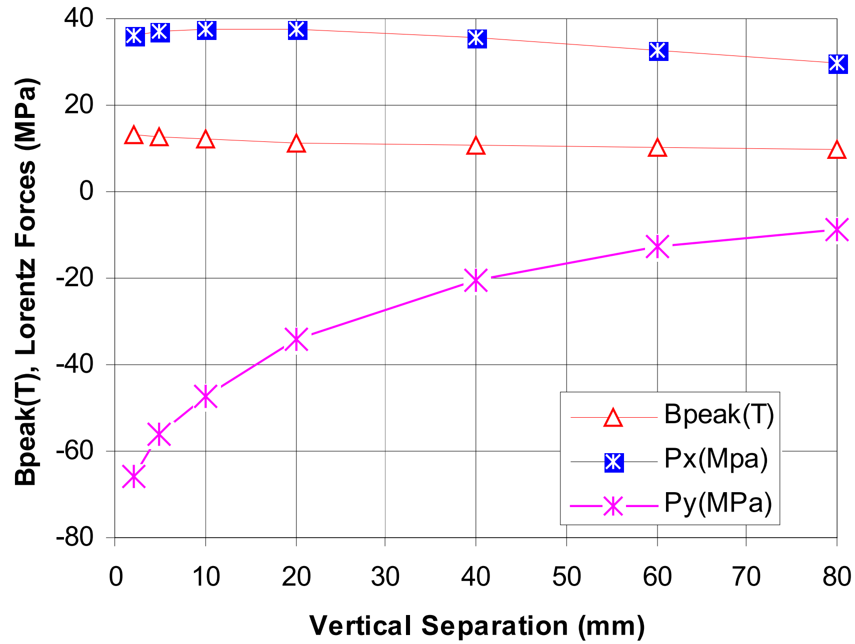
Sub-scale Coils in Open Midplane Structure

Short coils made and pre-tested for other applications can be used in an open midplane configuration to examine the basic technological issues. (A possible BNL/LBL collaboration).

The support structure for this open midplane dipole test will be designed such that it:

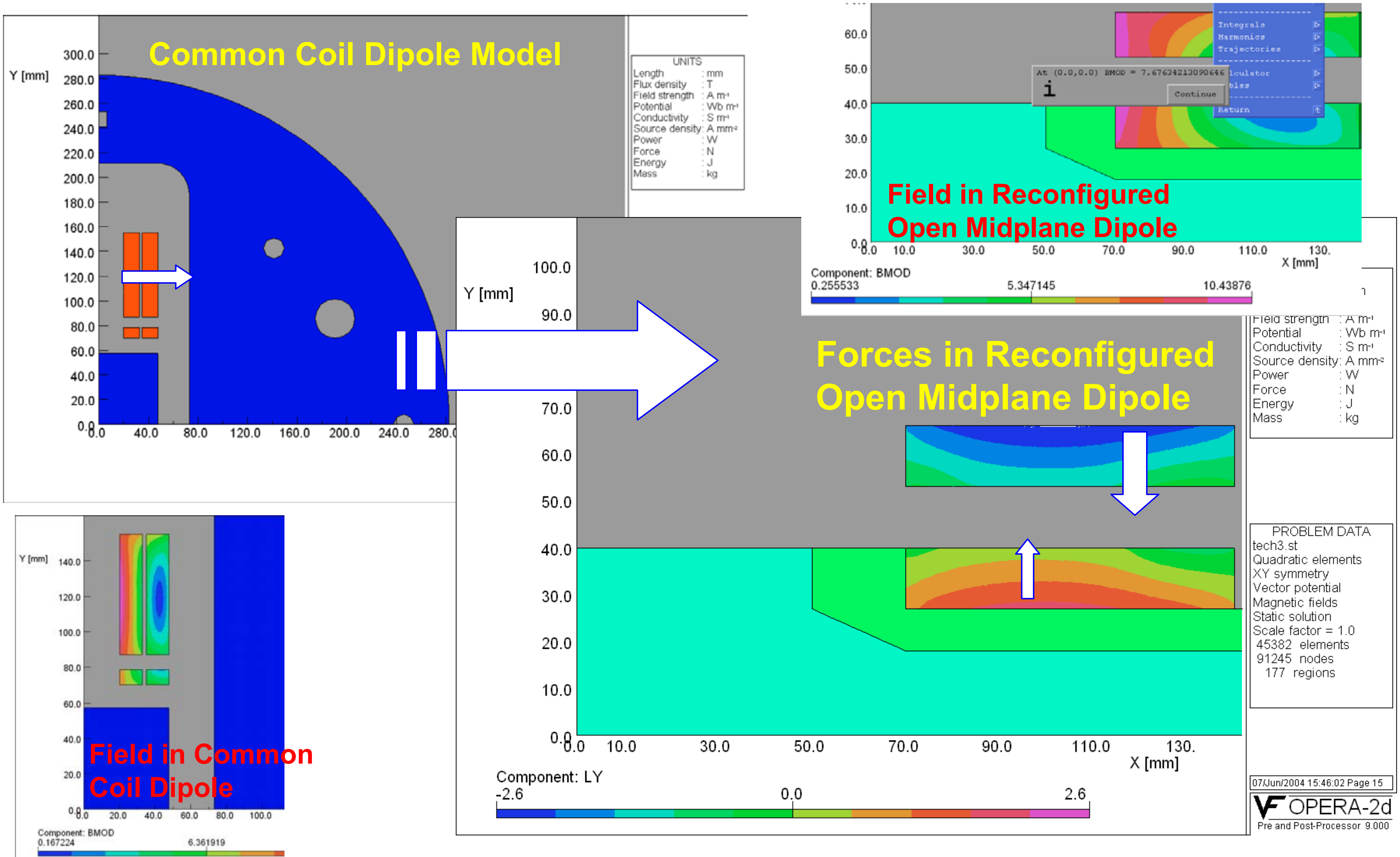
- Produces similar deflections (after the 1st test with ~zero deflection)
- Allows variation in pre-stress
- Allows variation in vertical separation





Max. stress in actual magnet:
Horizontal = 150-200 MPa
Vertical = 90-100 MPa

Re-configuration of Common Coil Dipole Coils (or Other Magnet Coils) for High Field Technology Test



SUMMARY

• The "Open Midplane Dipole Design" seems to offer a good technical and an economical option for LHC luminosity upgrade

•The challenging requirements of the design appear to have been met:

- Have presented a design that can accommodate a large gap between upper and lower coils with no structure in between.
- Have obtained a design with good field quality design despite a large midplane gap.
- Ongoing calculations and analysis indicate that the energy deposition on the s.c. coils can be kept below quench limit and that the heat can be removed at a higher temperature with a warm absorber within coldmass.

• A proof of principle design has been developed in a short period of time and with limited resources. However, phased magnet R&D (both models & experiments) is now required to demonstrate the design in a working magnet.

• The design brings a significant new addition to magnet technology.