Conceptual Design of a Smaller Aperture Open Midplane Dipole

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Some Special Considerations for LHC Upgrade Dipole Design in "Dipole First Optics"

High luminosity (10^{35}) Interaction Regions (IR) present a hostile environment for superconducting magnets by throwing ~9 kW of power from each beam

- This raises two basic challenges :
  - How to design a magnet that can survive these large heat and radiation loads
  - What is the cost of removing these large heat loads both in terms of "new infrastructure" and "operating cost"

Overview of the Presentation (1)

- Basic Design Features and Advantages
  - What are we trying to achieve and why ?
- Inherent Design Challenges
  - What makes this design so challenging ?
- Conceptual Development of the Design
  - What makes this design look so different?
- Design Iterations
  - Summary of designs with various apertures.
  - Latest Design Studies since last meeting in October '04.
- Now is about time to pick one set of parameters and move ahead.

Overview of the Presentation (2)

- Technology Choice
  - ✍ With magnet aperture decreasing and operating field increasing, bending strain degradation associated with "React & Wind" technology becomes an important consideration. Bending strain degradation should be kept within a reasonable limit.
  - ✍"Wind & React" technology becomes relatively more desirable if design parameters drift towards smaller aperture and higher fields.
- Parameters of a Proof of Principle Design
  - ✍ Goal is to build a model magnet within expected budget.
- Discussion and Summary

Desired Goal and Approach

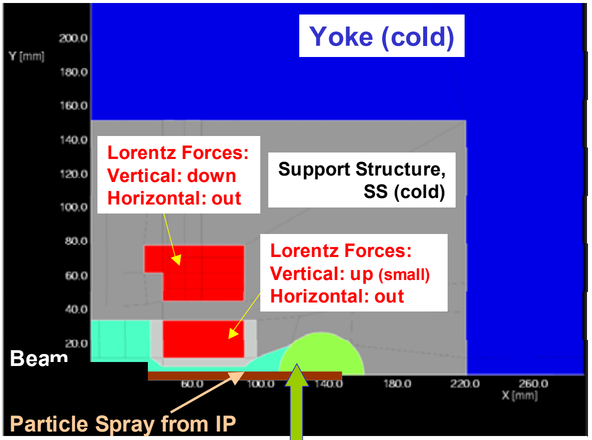
Whether it is LHC upgrade, or any other project, one needs to have an integrated approach, rather than focusing on an individual component.

The magnet technology should be developed, at least at this stage, to minimize the overall system cost (infrastructure & operating) and not just the magnet cost. It should also support good technical options.

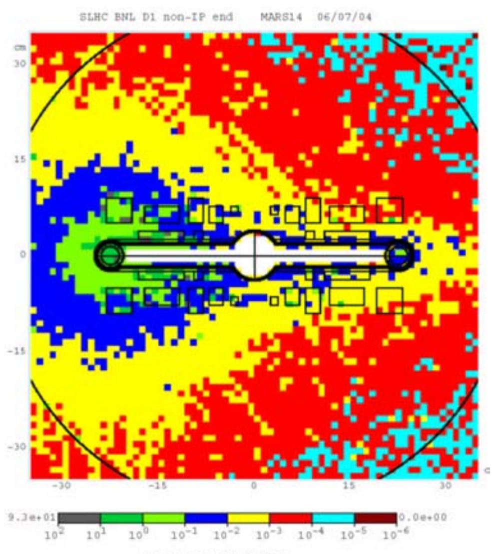
To allow a credible consideration of any option, one needs to know if there will a solution for all critical components. And if yes, then what would be the cost of R&D and of building. This will allow machine physicists to make a more informed decision when the time comes.

If magnet R&D cost appears too high, then the challenge is to find a way to reduce the cost of this R&D. Demonstration of the proposed design & technology must be achieved within the budget allocated.

Open Midplane Dipole for LHC Luminosity Upgrade
Basic Design Features and Advantages

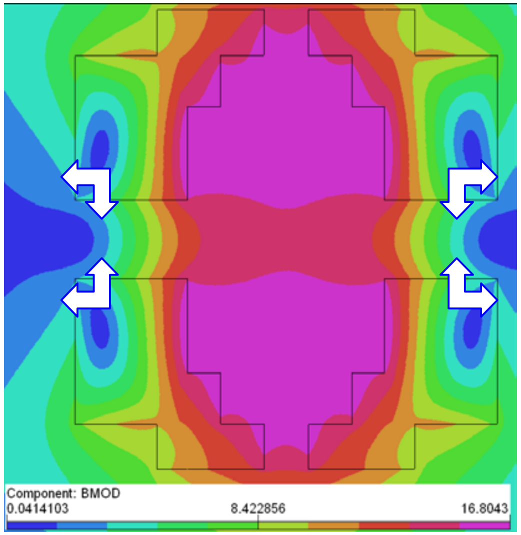


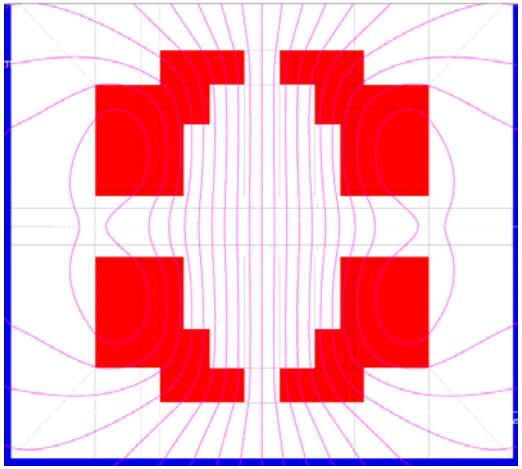
A large amount of particles coming from high luminosity IP deposit energy in a warm (or 80 K) absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.



- 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 than in any high field magnet. Moreover, in conventional designs 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 obtaining 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

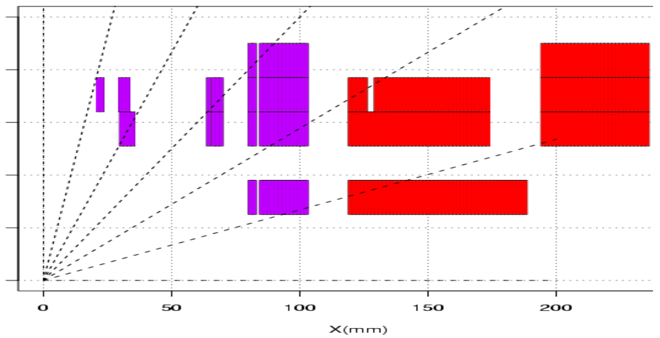
Develop an integrated design of a high field dipole that

- 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 along the beam path.
- Is technology independent ("React & Wind" Vs. "Wind & React") in 2-d magnetic and mechanical design.

Design Iterations in Year 2004
To Help Evolve Basic Design Parameters

Design A (06/04): D1

Angle of midplane block=17.4°



Vertical/Horizontal Gap = 50 mm/160 mm

Design/Quench Field = 13.5 T/15 T

Proof of principle open midplane design. To first order, it met all technical requirements: energy deposition, field quality, and support structure to contain Lorentz forces.

✍ But the magnet became big and expensive.

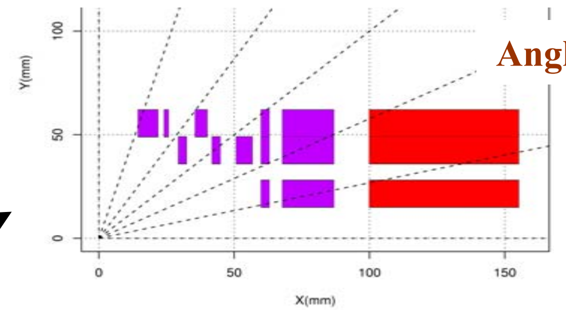
Design B (10/04): D1

Vertical/Horizontal Gap = 30 mm/120 mm

Design/Quench Field = 13.5 T/14.5 T

Smaller magnet.

➢ NOTE: Nikolai has not examined this case.

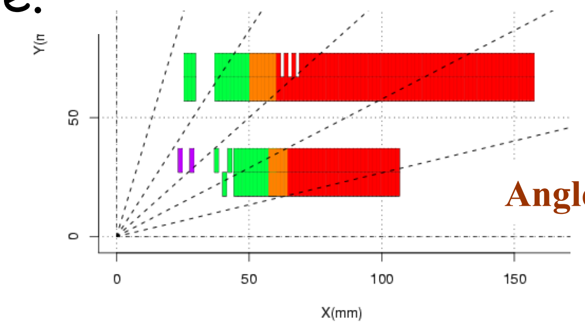


Design C (12/04): D1A

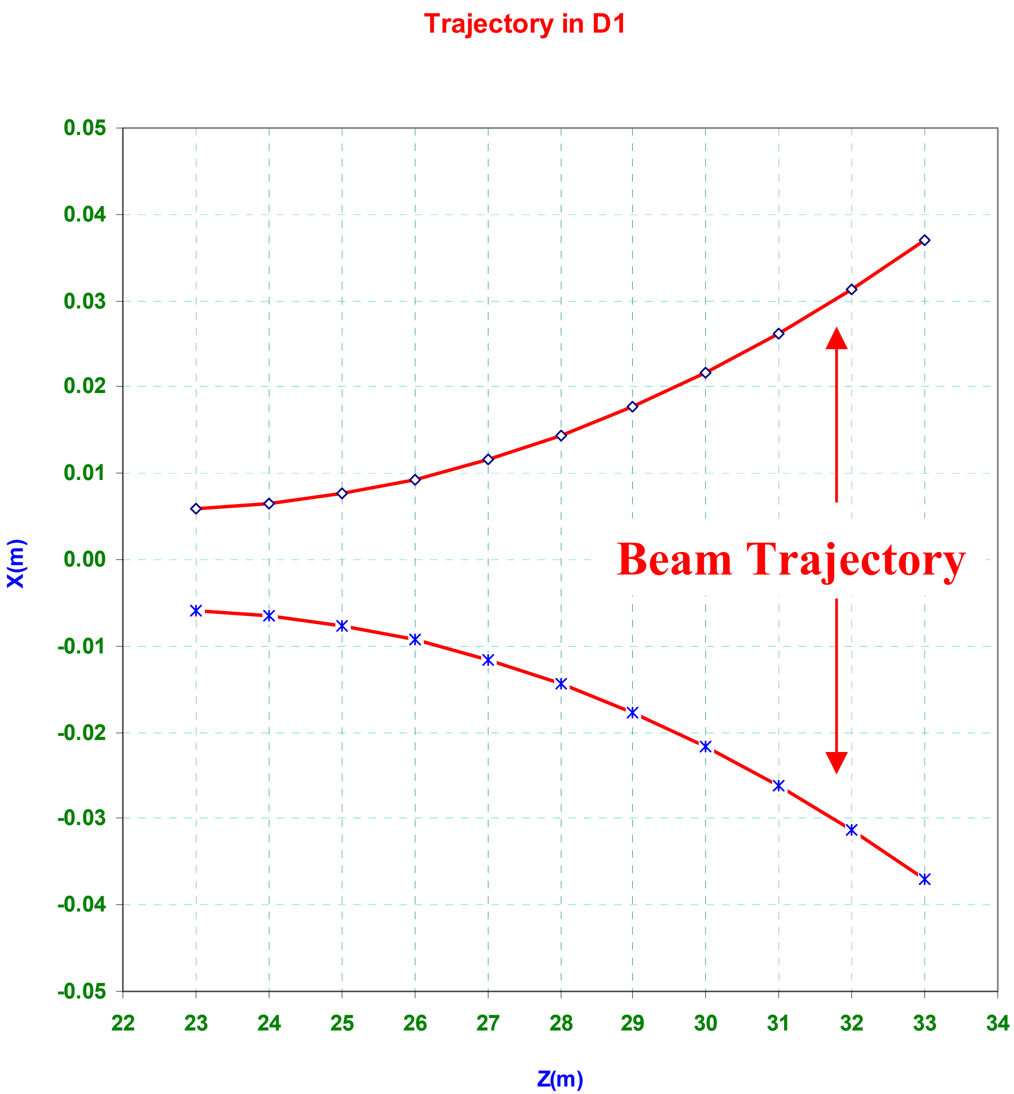
Vertical/Horizontal Gap = 34 mm/80 mm

Design/Quench Field = 15 T/16 T

An aggressive target (large angle for midplane block).



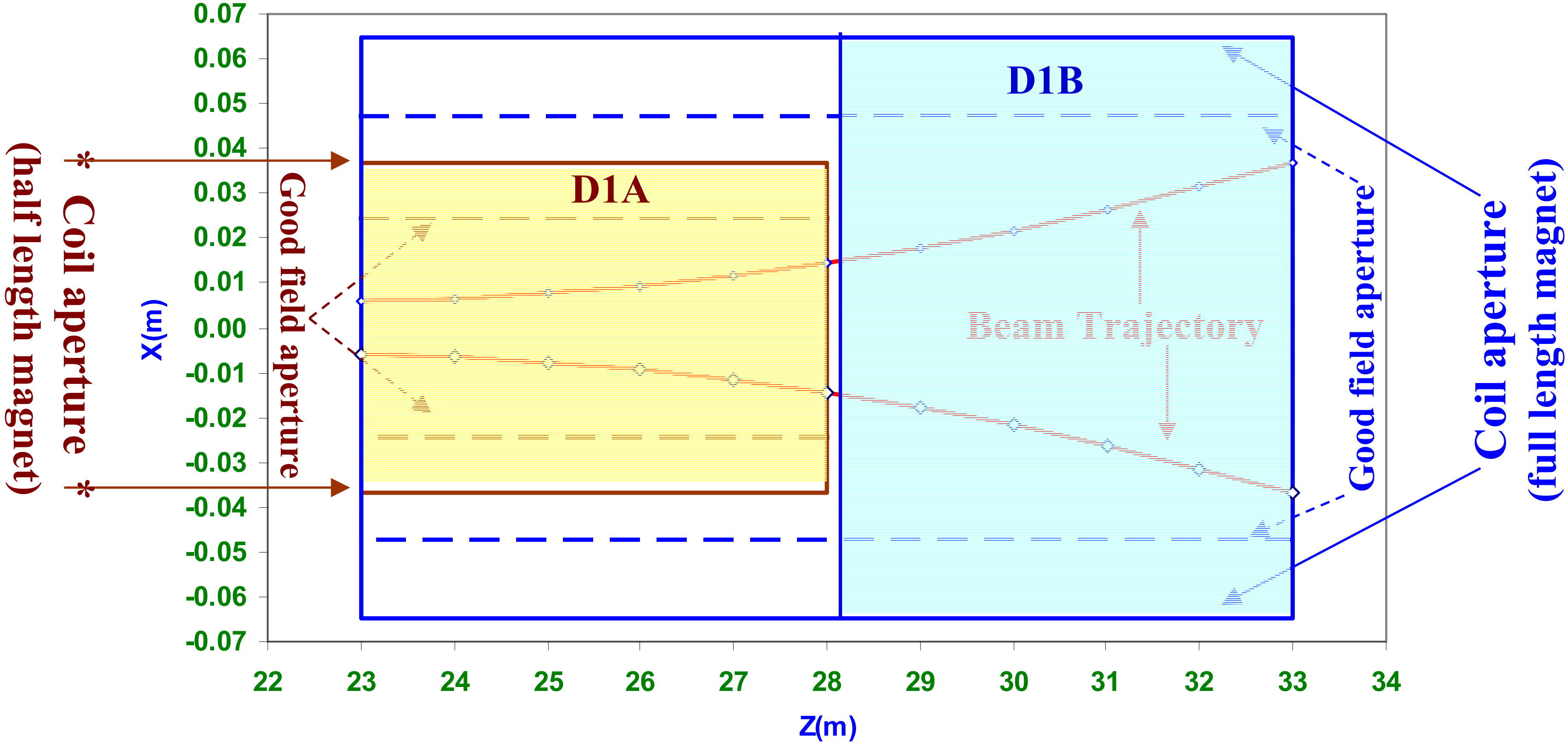
A Lower Cost Open Midplane Dipole Proposal
(A possibility presented during October meeting)



- At present, the aperture of D1 is determined by the requirements at the far end of IP.
- We propose dividing each D1 in two dipoles D1A and D1B. We also propose to develop only D1A under LARP.
- D1A will be shorter and will have lower aperture.
- One can also consider raising field in D1A and reducing in D1B. This will balance Lorentz forces better between D1A (higher field, lower aperture) and D1B (lower field, larger aperture).

Proposal: Build D1A Under LARP Funding

A lower aperture, lower length, lower cost, open midplane racetrack coil dipole that while developing and proving the basic technology, also gets used in LHC IR upgrade



Consider increasing the field in the first D1 (D1A), and also consider using HTS there. HTS has a potential to generate higher fields and can tolerate higher heat loads, as well.

LARP Dipole Design Development

The design is being developed in a comprehensive and iterative way, where

- energy removal
- magnetic
- mechanical
- and beam physics

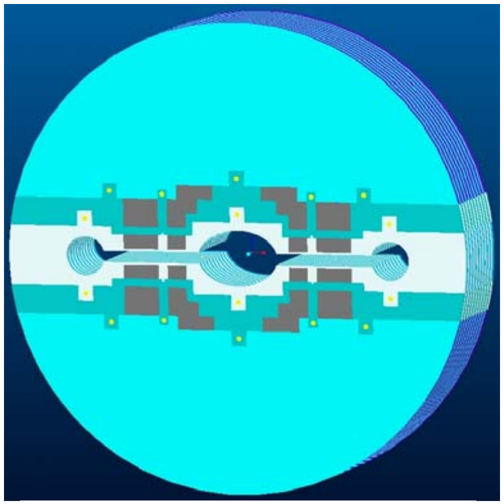
requirements are being (and must be) optimized together.

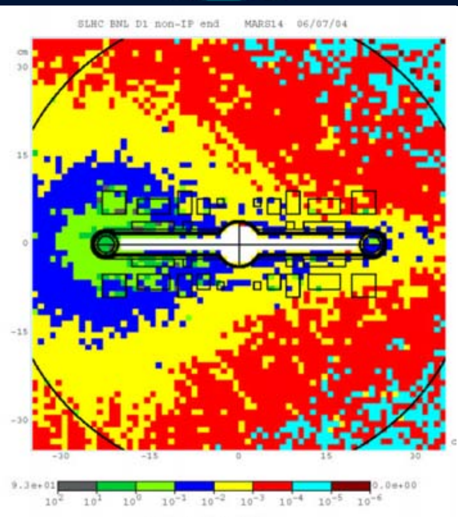
There are no rules, past experience or guidelines to follow. Given that that it's a new type of design, old approaches may not always provide the best or even a working solution. Some time, we are forced to become creative – e.g., when we get stuck. We are trying to do it in an as objective manner as possible.

Constant communications/iterations with Mokhov (energy removal requirements) and Jesse/Mike (support structure requirements). Now time has come to do iterations of the design with input from "beam physicists".

A True Open Midplane Design

By open midplane, we mean truly open midplane:





Particle spray from IP (mostly at midplane), pass through an open region to an absorber sufficiently away from the coil without hitting anything at or near superconducting coils.

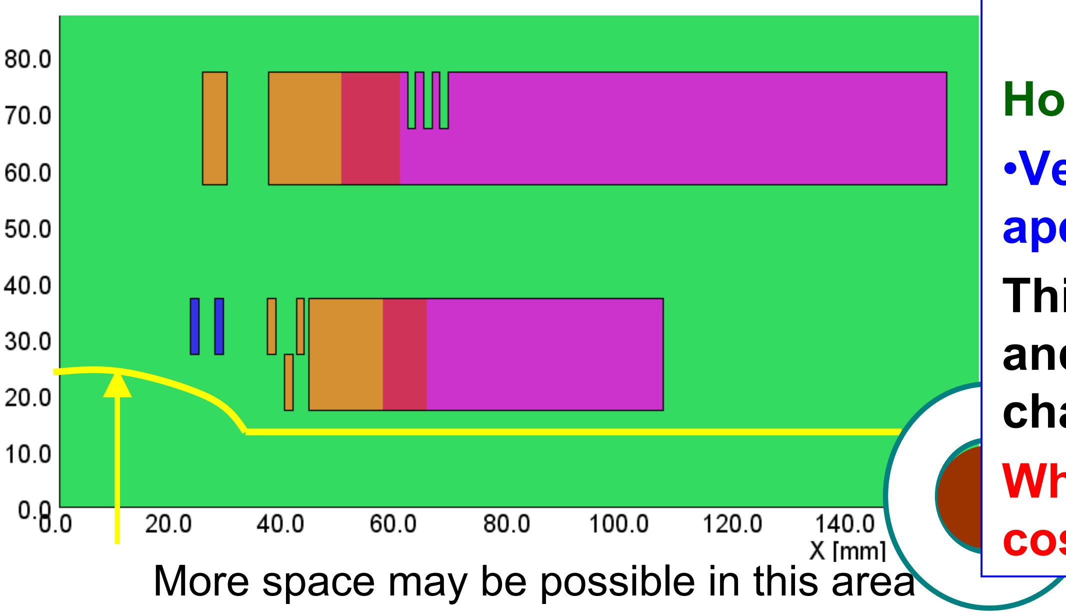
In earlier "open midplane designs", although there was "no conductor" at the midplane, but there was some "other structure" between the upper and lower halves of the coil. Secondary showers from that other structure deposited a large amount of energy on the coils.

The energy deposited on the superconducting coils by this secondary shower became a serious problem. Therefore, the earlier open midplane designs were not that attractive.

Magnetic Design and Field Quality

A **critical constraint** in developing magnetic design of an open midplane dipole **with good field quality** is the size of the **midplane gap for coil**.

The desired goal is that the gap is large enough so that most showers pass through without hitting anything before hitting the warm target.



Coil-to-coil gap in latest design

= 34 mm (17 mm half gap)

Horizontal aperture = 80 mm

- Vertical gap is > 42% of horizontal aperture (midplane angle: 23°)

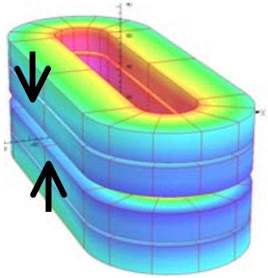
This makes obtaining a high field and a high field quality a kind challenging task !

What part of cosine (θ) is left in that cosine (θ) current distribution now?

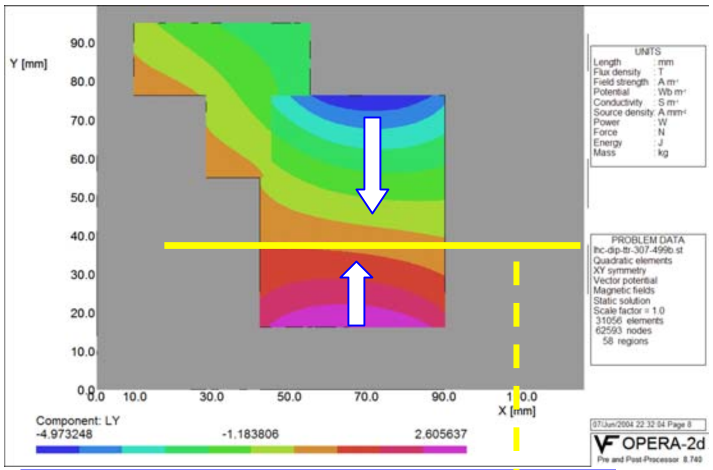
Navigation of Lorentz Forces

A new and major consideration in design optimization

Unlike in conventional designs, in a truly open midplane design the upper and lower coils do not react against each other. As such this would require a large structure and further increase the coil gap. That makes a good field quality solution even more difficult.



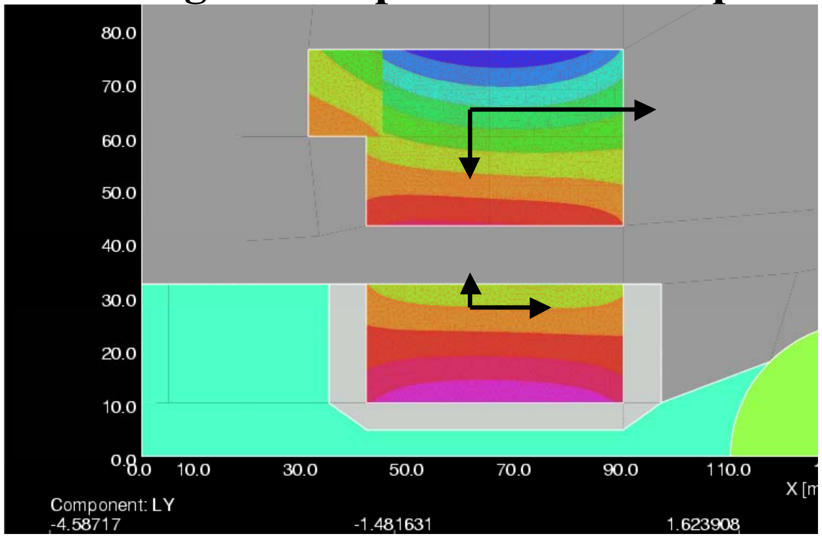
Original Design



Zero vertical force line

Lorentz force density (Vertical)

New Design Concept to reduce midplane gap



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.

A Preliminary 15 T Design for D1A

This is a preliminary (conceptual) design since we have spent a limited time only. We started working on it after the LARP collaboration meeting in October, '04. This study includes some iterations between magnetic & mechanical designs.

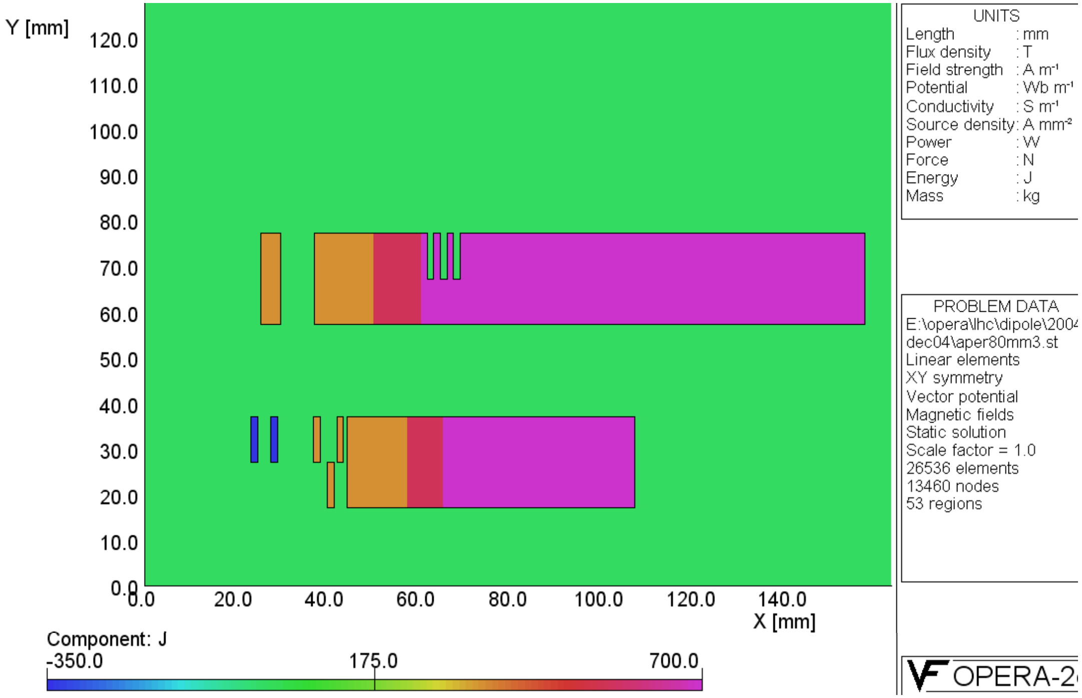
D1A Design guideline from Harrison & Peggs

15 T, 5 meter, Field Quality < 10^{-3}

Horizontal +/-28 mm, Vertical +/-14 mm

A Design with Simple Pancake Coils

The design is based on two simple double pancake coils in each half of the magnet.



Mechanical structure is such that the coil can be as close to midplane as possible while allowing adequate space for transmission of (a) beam in good field region and (b) spray particles to warm region.

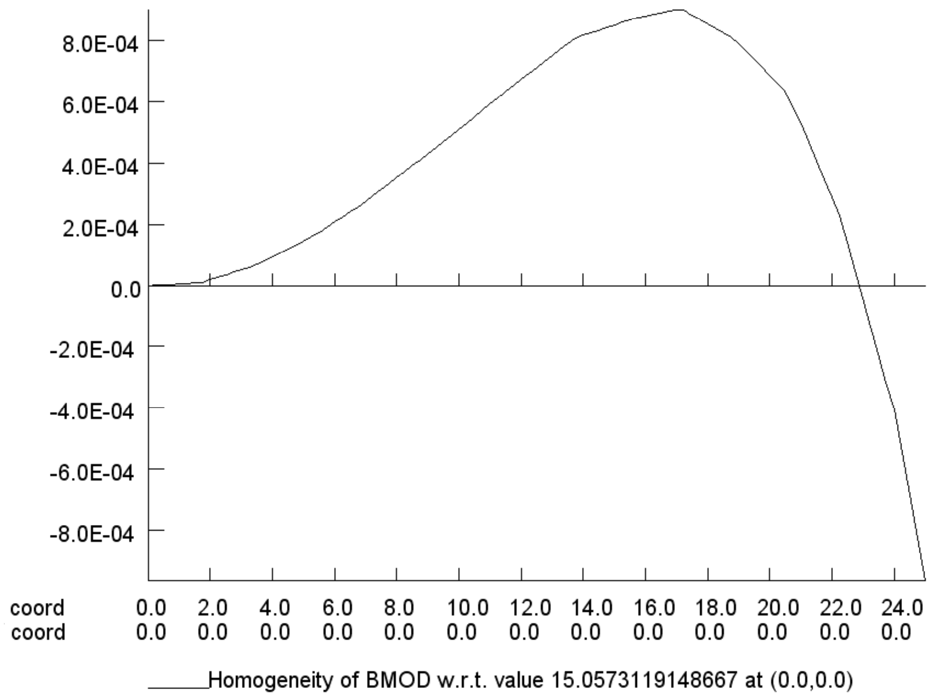
Vertical Lorentz force on lower double pancake is upward. Space between upper and lower double pancake is just adequate to contain downward Lorentz forces.

- Grading is done through varying current density (power supply) rather than through varying conductor (a more cost effective and more flexible approach for R&D magnets). The model above has three current densities: 350, 550, 700 A/mm^2.
- Also used: -350 A/mm^2. A negative current may look counter-intuitive at first, but it works like a magic for such an extreme optimization (now it looks obvious, why?).

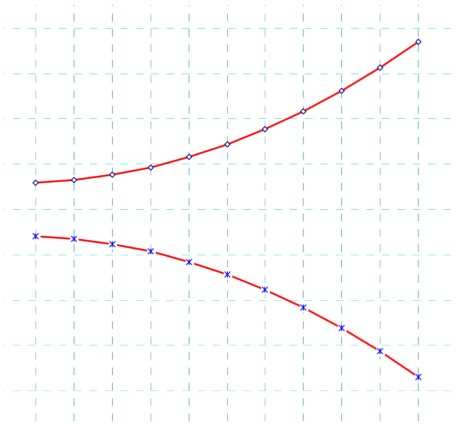
Relative Field Errors

Obtaining a good field quality in a magnet with a large ratio of vertical gap (34 mm) to horizontal aperture (80 mm) is a major challenge.

Demonstration of a ball-park or proof-of-principle solution.



Beam goes to larger excursions only near the end. Field quality is messy in the end region anyway.



Final design may require certain trade-offs between various requirements.

We are waiting for further input from beam physicists to iterate for a more optimal solution.

Design Parameters of a 15 T (~16 T Quench) 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 (or 1.0)
Strand diameter	0.7 mm
No. of strands in cable	26
Cable width (bare)	9. 5 mm
Cable thickness (bare)	1.25 mm
Insulation	Nomex /Fiberglass
Cable width (insulated)	10 mm
Cable thickness (insulated)	1.45 mm
Max. J_{cu} (@quench)	~ 2kA/mm^2

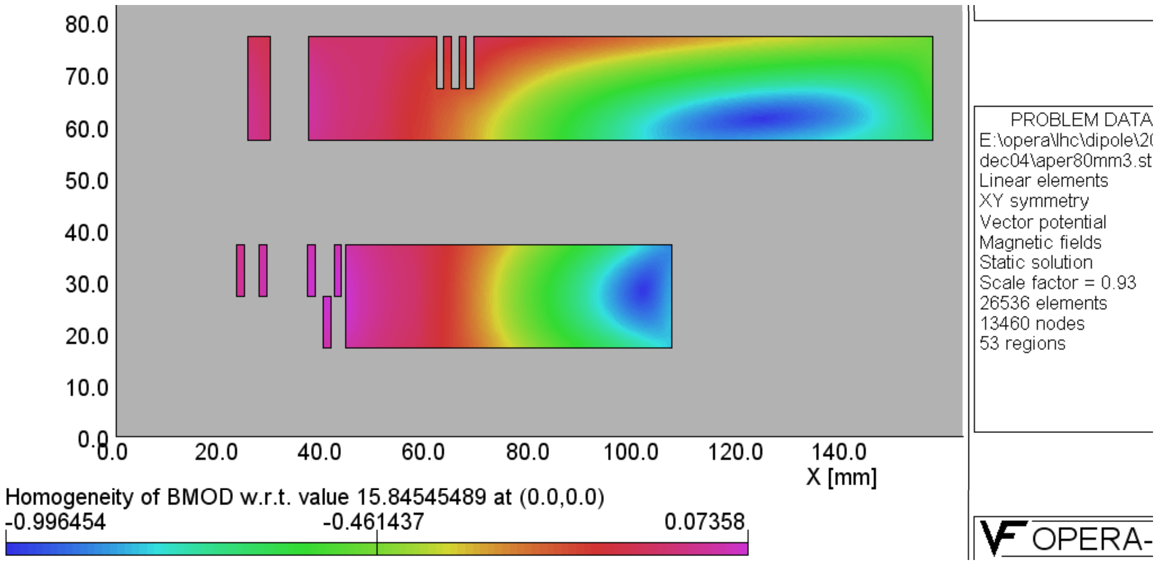
Magnet parameters:

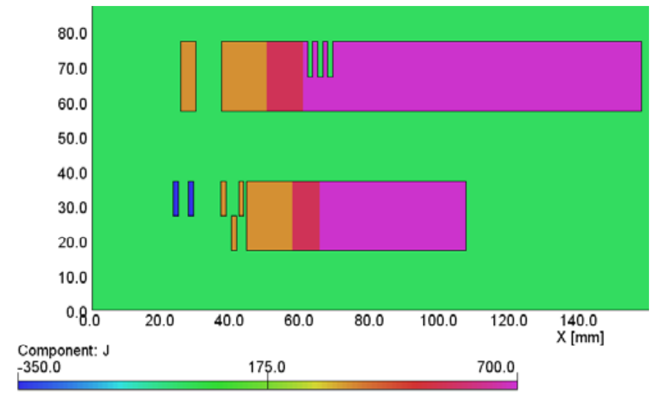
Quench Field	~16 T
Quench Current*	4.7, 7.4, 9.4 kA
Horizontal Spacing	80 mm
Coil Midplane Gap	34 mm
Collar Outer Radius	300 mm
Yoke Outer Radius	700 mm
Stored Energy@Quench	4.8 MJ/meter
Inductance*	.43, .17, .11 H/m

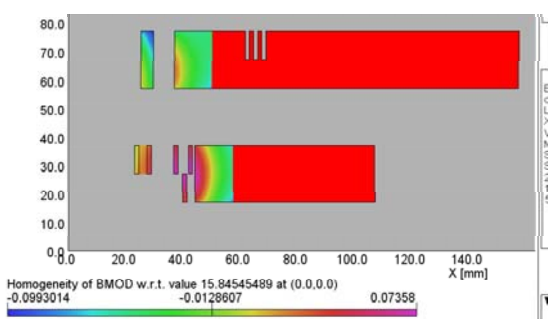
*Three values, since current grading, rather than the cable grading is used. Minimizes the conductor development cost in R&D magnets.

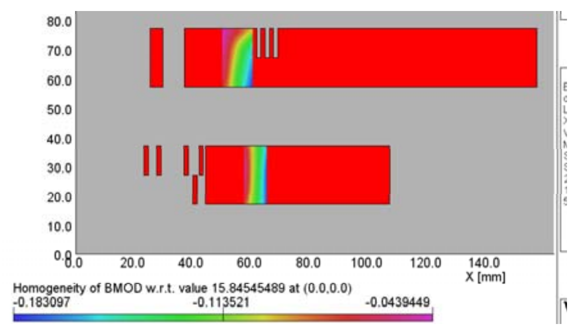
Quench Field will be ~15.8 T if Cu/Non-Cu is 1.

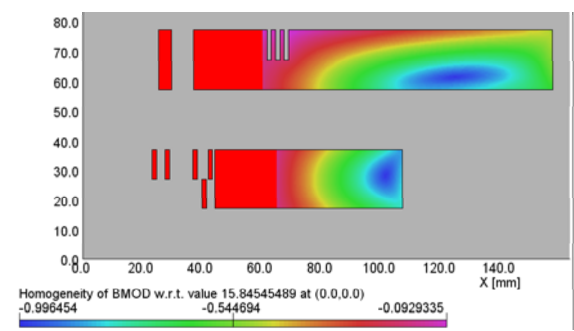
Peak Fields in Coil Blocks











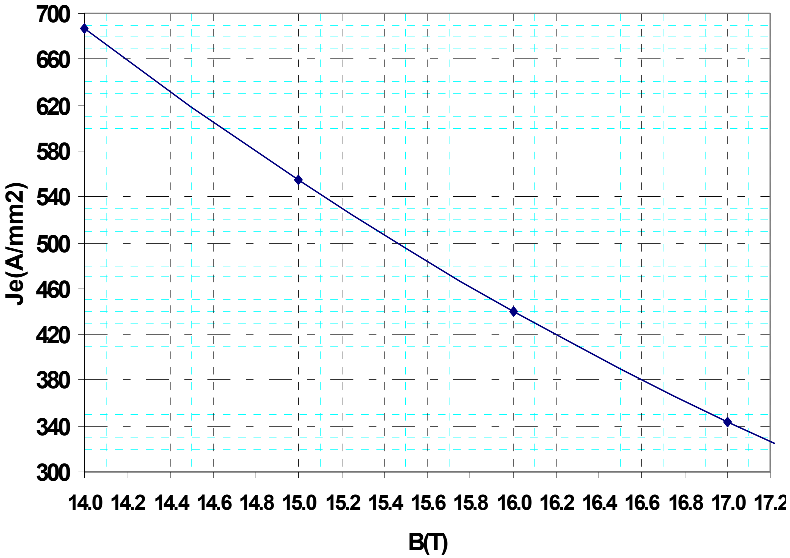
Quench Field: ~16 T with J_c = 3000 A/mm^2, Cu/Non-cu = 0.85

Quench Field: ~15.8 T with J_c = 3000 A/mm^2, Cu/Non-cu = 1.0

Quench Field Calculations

Cu/Sc	Wire Dia	Strands	Bare width	Bare Thic	Degrad	Ins width	Ins Thic	
0.85	0.7	26	9.6	1.25	10	10	1.45	
Field	Fit Jc	Wire Je	Wire Ic	Cable Ic	Ic(degrad)	Cable Jc	Cable Je	Jcu
10	4373	2364	910	23651	21286	1774	1468	4677
11	3653	1975	760	19757	17781	1482	1226	3907
12	3035	1641	631	16415	14773	1231	1019	3246
13	2504	1354	521	13543	12189	1016	841	2678
14	2046	1106	426	11066	9959	830	687	2188
15	1651	892	343	8929	8036	670	554	1766
16	1312	709	273	7096	6386	532	440	1403
17	1022	552	213	5527	4975	415	343	1093
18	776	419	161	4197	3777	315	261	830

		350	550	700	700
	17.2	18.4	16.4	15.8	15.3
		0.068	-0.048	-0.084	-0.110
0.9185	15.80	16.87	15.04	14.47	14.06
		321	505	643	643



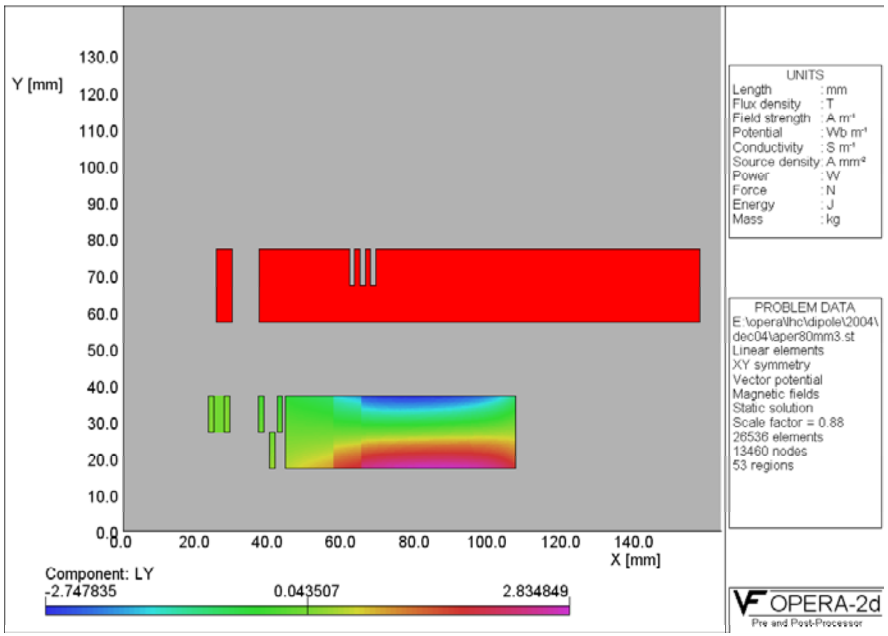
Quench Field: ~16 T with J_c = 3000 A/mm^2, Cu/Non-cu = 0.85

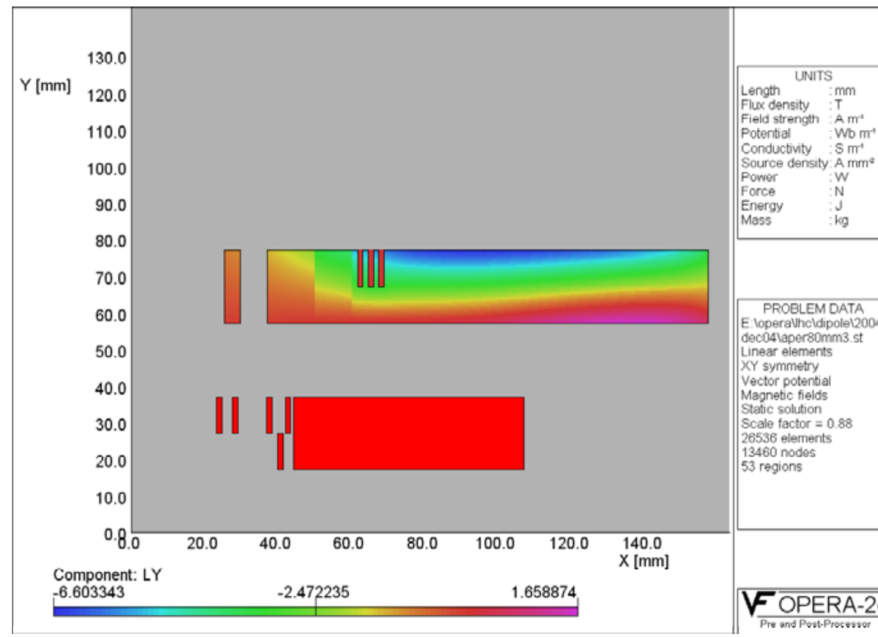
Quench Field: ~15.8 T with J_c = 3000 A/mm^2, Cu/Non-cu = 1.0

Vertical Forces at 15 T

Net upward vertical force on lower double pancake coil

Downward vertical force on upper double pancake coil is taken by the support structure between two double pancake coils

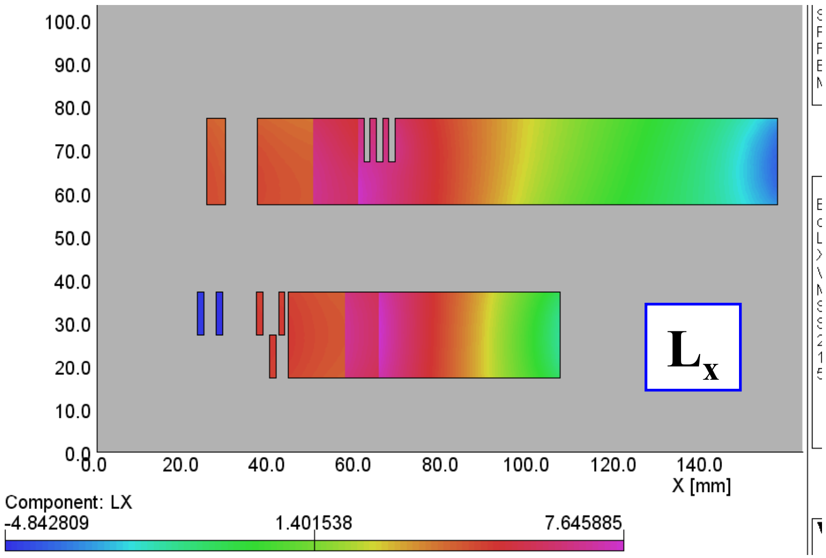


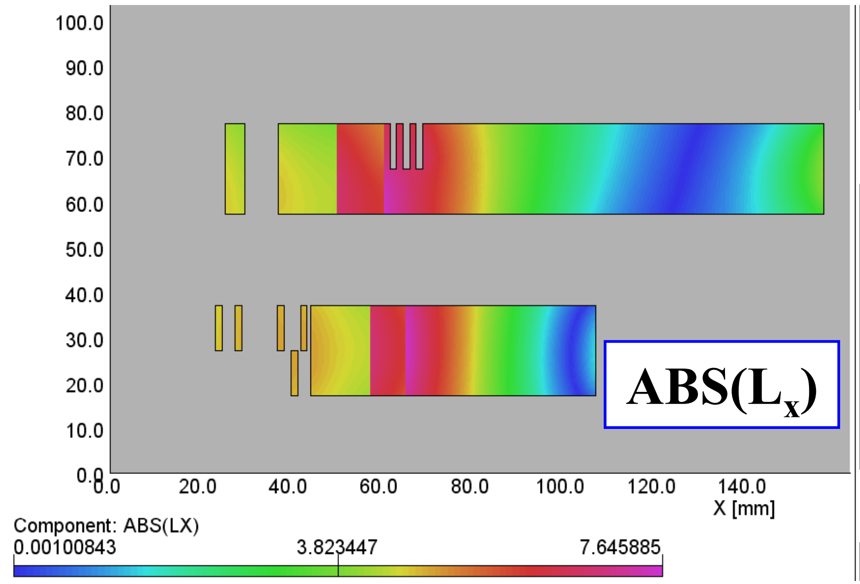


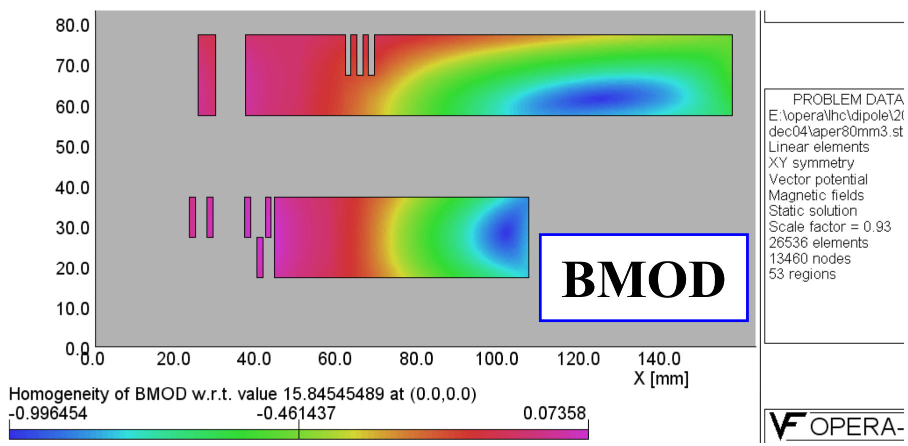
Net Force per quadrant:

Horizontal = 11 MN/m; Vertical –5.4 MN/m

Horizontal Forces at 15 T







Comparison Between 80 mm Aperture and 120 mm Aperture Designs

Design B (10/04):

Horizontal Coil Aperture = 120 mm

Coil Midplane Gap = 30 mm

Design Field = 13.5 T

Quench Field = 14.5 T

Design C (10/04):

Horizontal Coil Aperture = 80 mm

Coil Midplane Gap = 34 mm

Design Field = 15 T

Quench Field = 16 T

Whereas on the one side, the conductor, support structure and over-all magnet size decreases as aperture decreases.

However on the other side, the conductor, support structure and over-all magnet size increases as the design field increases.

When we compare the overall requirements of two design, it's a wash. The two are similar in requirements within 10%.

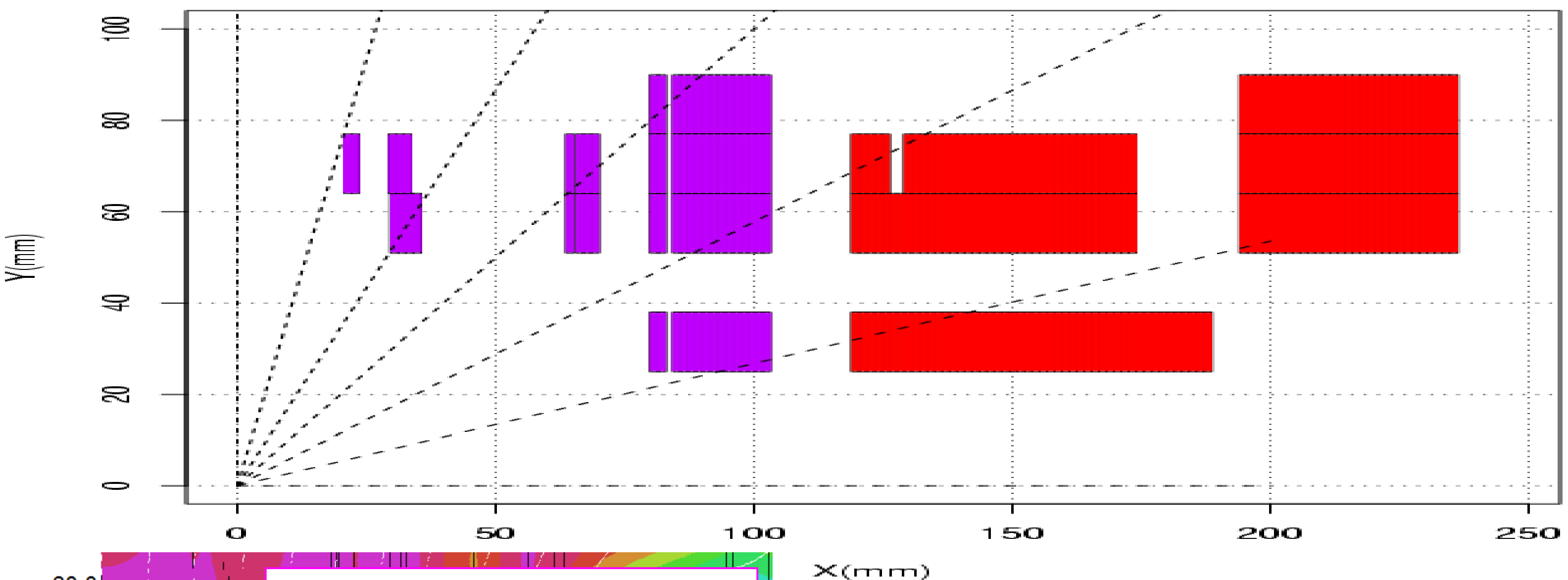
Brief Overview of a More Complete and A Comprehensively Optimized Proof-of-Principle Design

Just to show that a hand optimized design
(such as the one presented just now)
can be further optimized to the next level.

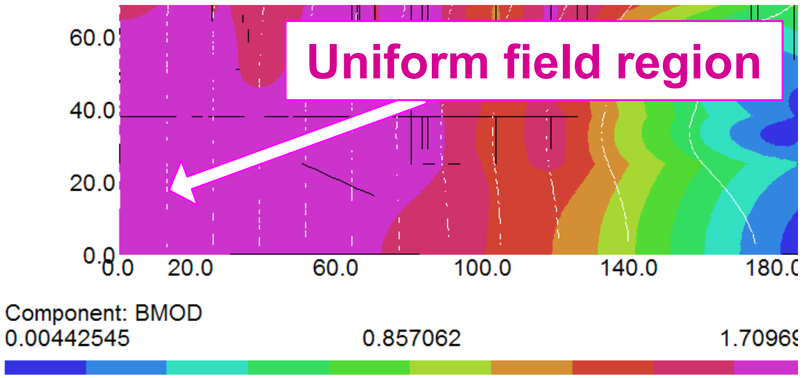
Hand Optimized Design =>
Fine-tuned by RACE2DOPT for Harmonic Minimization

The design is first navigated by hand for "Lorentz Forces", "Support Structure", "Energy Deposition", "Low Peak Field" and better than 10^{-3} "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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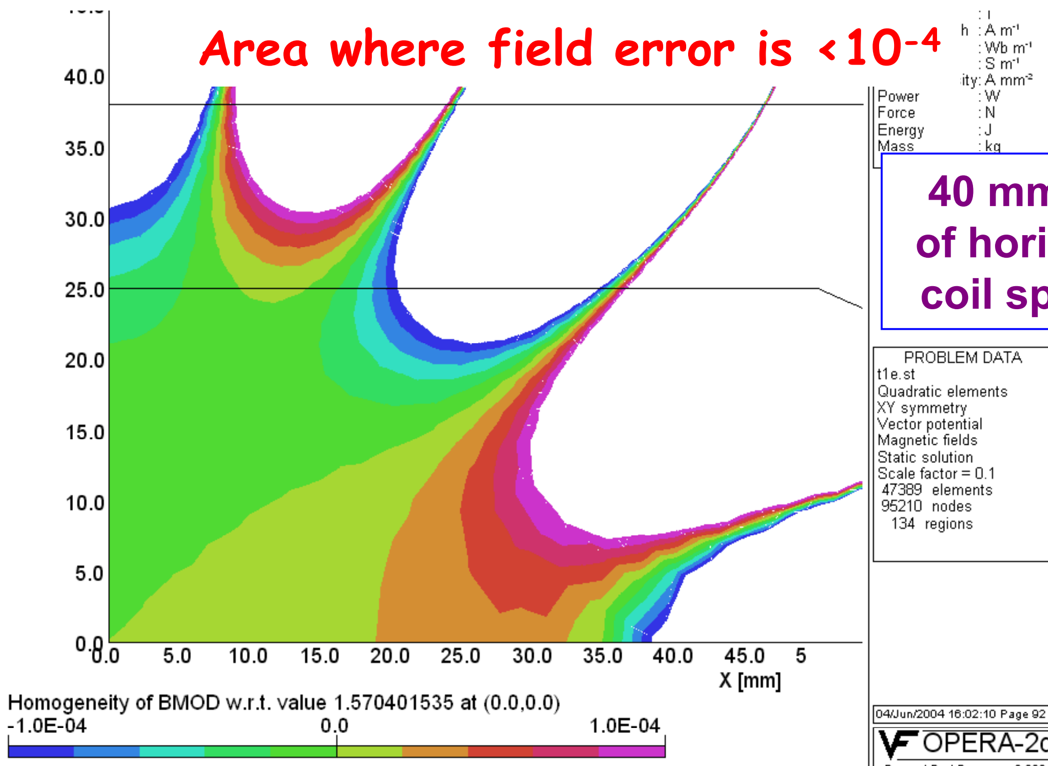
17	0.01	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00

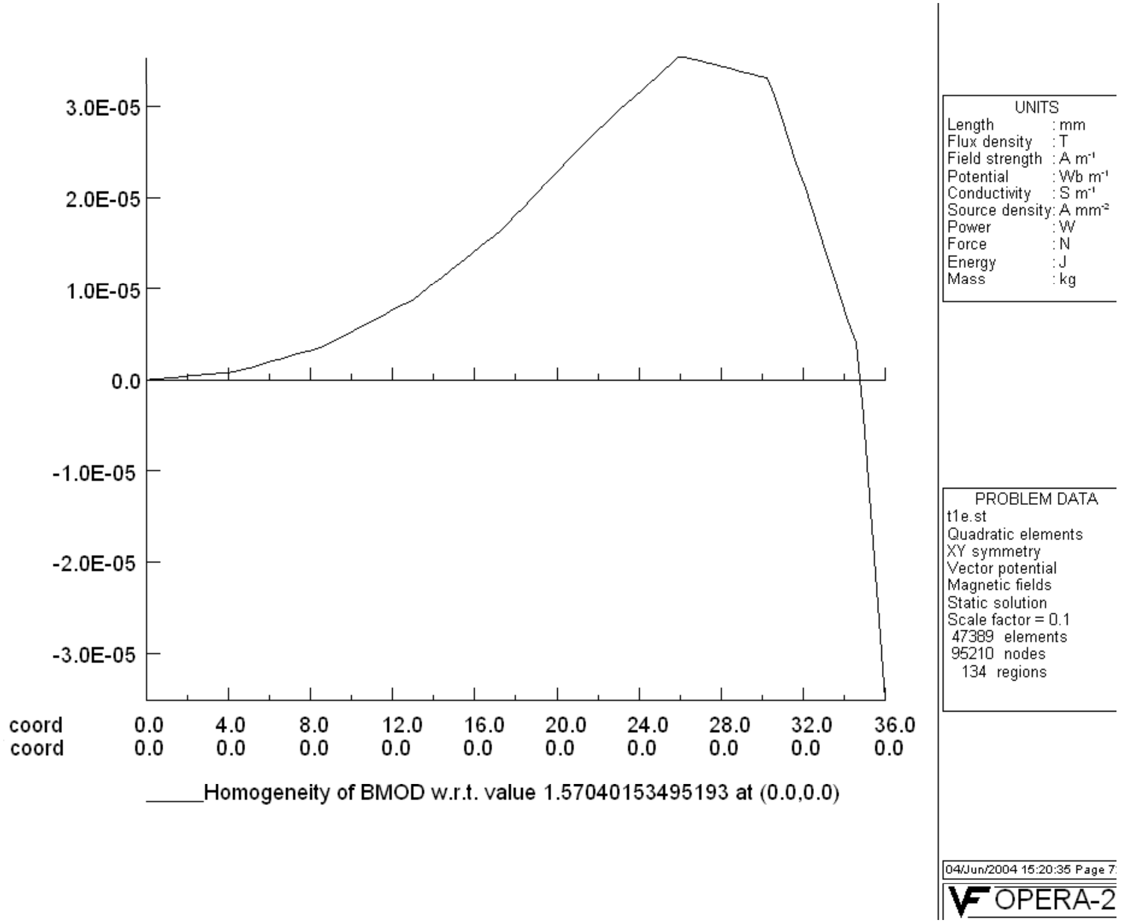


40 mm is ½ of horizontal coil spacing

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.

Design Parameters of 15 T Open Midplane Dipole

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

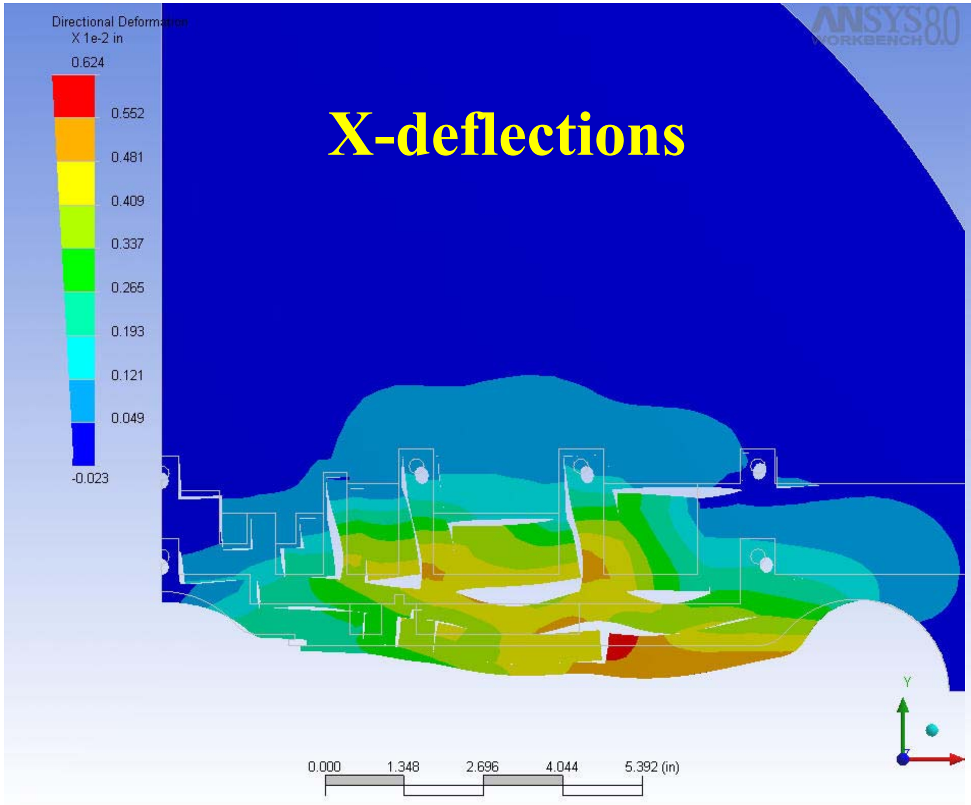
Magnet parameters:

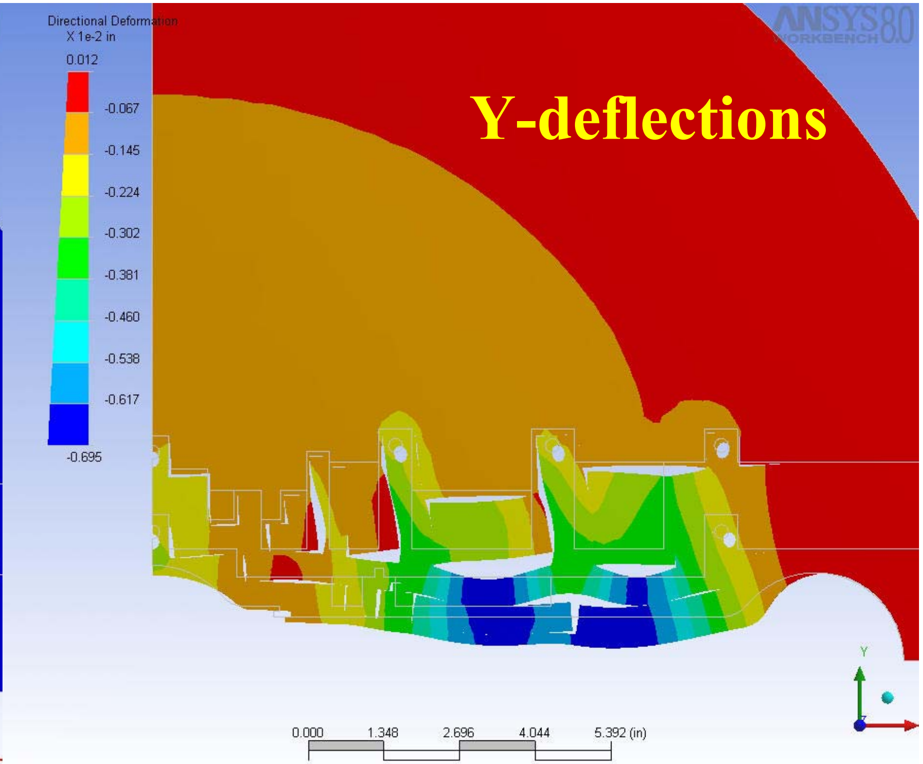
Quench Field	~15 T
Quench Current*	11.6 (7.7) kA
Horizontal Spacing	160 mm
Coil Midplane Gap	50 mm
Collar Outer Radius	400 mm
Yoke Outer Radius	1 meter
Stored Energy	11 MJ/meter
Inductance*	0.16 (0.4) H/m

*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.

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.

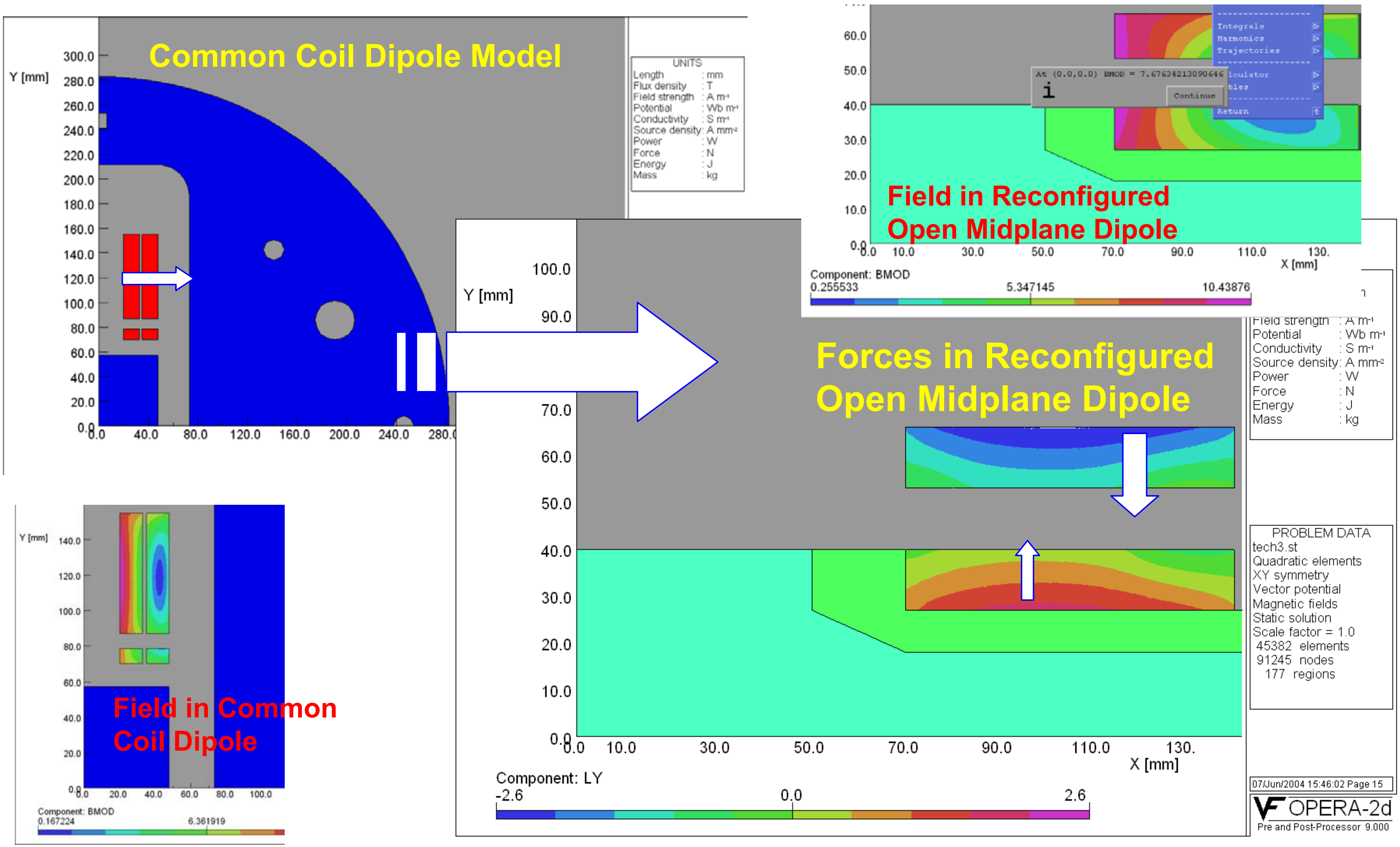
Energy Deposition Calculations From Mokhov

Nikolai Mokhov's calculations showed that only a small fraction of energy is deposited in superconducting coils and that the magnet life due to this is not limited for at least 10 years.

It also showed a significant reduction in 4 K heat load.

Partial Magnet Technology Test of Open Midplane Design Concept with LBL Sub-scale Coils

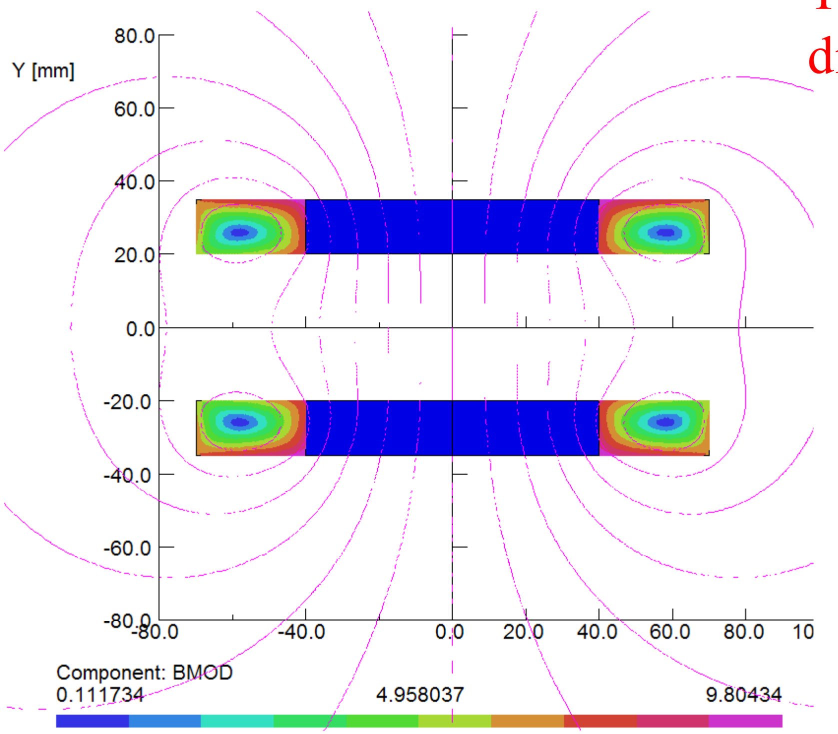
Re-configuration of Common Coil Dipole Coils (or Other Magnet Coils) for High Field Technology Test



Technology Development Tests

Sub-scale Coils in Open Midplane Structure

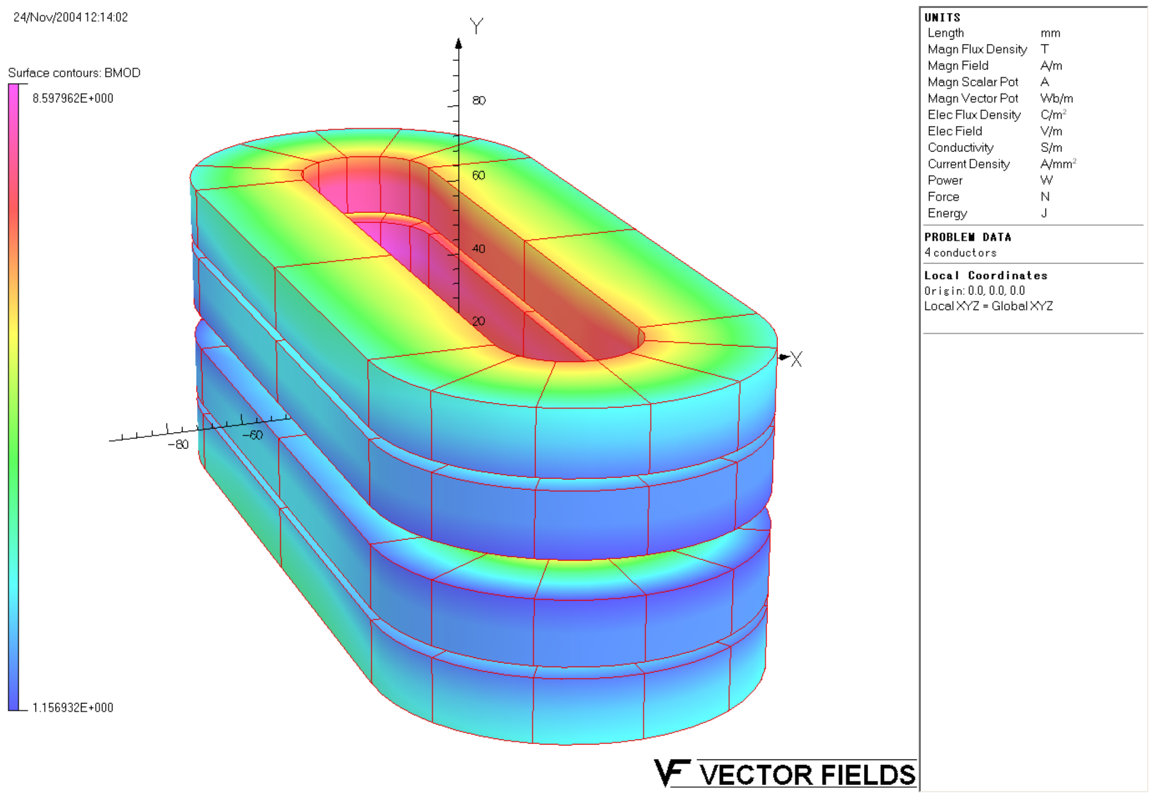
Short coils made and pre-tested for other applications can be used in an open midplane configuration to examine the basic technological issues. (A possible BNL/LBL collaboration).



The support structure for this open midplane dipole test may 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

Lorentz Forces for LBL Sub-scale Coils



See Jesse Schmalze's Presentation for more on testing LBL coils in BNL structure for initial simulation of open midplane design.

	ABS(FX)	ABS(FY)	ABS(FZ)
Total(MN)	0.86	0.46	0.28

A Possible R&D Path to
1st 15 T Open Midplane Model Magnet

Note: All coils are double pancake
(complete magnet requires four double pancake coils).

In "Wind & React" approach, one would build the complete double pancake coil in one go.

A prudent approach may be to first build and test a pair of coils without midplane gap (one pair at a time even one coil).

Before testing the complete magnet, we should also evaluate the benefits/added complications of a mirror test configuration.

The above scenario (testing components in stages) minimizes the cumulative risk to the magnet as a whole.

Conductor Requirements in the Present Design

The coil design has ~260 turns of ~10 mm X 1.45 mm cable.

The cable uses 26 strands of 0.7 diameter.

The estimated conductor cost for a 0.5 meter long model magnet is <100 k$.

We can afford the purchase of this (plus spare conductor) in our next year budget.

A Strategic Comparison of "D1" Vs. "D1A+D1B" Options

D1	D1A
Single magnet	Two magnets (D1A + D1B)
High field large aperture	Very high field smaller aperture + Higher field larger aperture
Very large Lorentz forces	Large Lorentz forces
Required field : ~13.5 T	Required Field : ~15 T
Quench field : ~14.5 T	Quench Field : ~16 T
Collar o.d. : ~600 mm	Collar o.d. : ~600 mm
Yoke o.d. : ~1400 mm	Yoke o.d. : ~1400 mm

• Conductor requirements, overall magnet size, etc. are similar in D1 and D1A. D1, due to its larger aperture, may be better from energy deposition point of view.

• If it was a magnet based on known technology, with parameters that can be fixed at this stage, then perhaps first solution (D1) would be preferred.

• If one of the goal of the LARP is to develop higher field magnet technology, and the magnet parameters can not be defined at this stage, then perhaps R&D magnet based on D1A parameters should be preferred.

• After having developed a very high field R&D magnet, one can step back a bit in specifying parameters for a machine magnet, if so desired.

SUMMARY

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

- To first order, the challenging requirements associated with the open midplane design appears to have been met in a proof of principle design.

- With the design and R&D program presented, it is possible to carry out model magnet R&D within the budget allocated (see Peter Wanderer's) presentation for more specific numbers.

- "D1" and "D1A+D1B" options have been compared.

- Open midplane design brings a significant addition to magnet technology.