US LHC Accelerator Research Program

bnl - fnal- lbnl - slac

Dipole for LHC IR Upgrade

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Overview of the Presentation

- Nb$_3$Sn Magnet R&D Goals for LARP
- Open Midplane Dipole Design : An overview
- Summary of the Design Presented at LAPAC04 :

  > A Proof of Principle Design

- A Preliminary Design with Reduced Aperture and Reduced Field Quality Requirements to Reduce the Magnet Cost
- ***A New & More Attractive Lower Cost Configuration***

Nb_3Sn Magnet R&D Goals for LARP(1)

Since no high field Nb_3Sn accelerator magnet of any significant length has been built yet, our hopes and/or fears are yet to be tested.

In other words, no magnet design and/or technology has been proven to work or has been proven that it can be ruled out.

Therefore, it will be wise to keep technology and design options open.

No one has any experience with challenges associated with long, industrial accelerator magnet construction. It is too early and potentially too dangerous to restrict the development of the future technologies based on the limited experience with short, lab-built magnets.

1 ▹ Continue R&D on both "Wind & React" and "React & Wind" technology.

2 ▹ Continue with both "cosine theta" and "racetrack coil" designs.

Nb_3Sn Magnet R&D Goals for LARP (2)

Our guiding principle in working with machine physicists, specially at this early stage of the game with no LHC operational experience, should be:

Provide options (not limit options).

▹ Need not rule out "Dipole first" yet!

Since this is a more challenging design, it is more important for machine physicists to know whether such a magnet is possible or not? And if yes, what is the cost to benefit ratio.

General Goal (inside or outside LARP):

- **Develop high field magnet technology for future accelerators.**

Recent Magnet Test Result of DCC016

A React & Wind Common Coil Dipole (1)

- The performance of our earlier 10-turn "React & Wind" common coil dipole magnet has been limited to 12-13 kA (a result similar to "Wind & React" magnets).
- It is now widely accepted that these limitations were due to "conductor instability" rather than any thing to do with a particular choice of "technology" or "construction".
- Recently a cable sample was reacted based with a new heat treatment (RRR ~40).
- Earlier Arup Ghosh has successfully tested a single strand (wire) to its short sample based on a similar heat treatment.
- However, the cable test with new heat treatment showed that the performance was still erratic at ~15 kA and was independent of applied field.
- A "React & Wind" magnet (DCC016) made with this cable reached ~17.9 kA (>8 T). This is 80% of the wire short sample and ~90% (estimate) of the cable short sample.
- The performance was still erratic (still instabilities?). All quenches over 17 kA were at high ramp rate (200+ A/s). At 50 A/s most quenches were at ~15.4 kA.

Recent Magnet Test Result of DCC016
A React & Wind Common Coil Dipole (2)

➢ **What do these results (and earlier results from Fermilab Common Coil Program) are telling us about "React & Wind" technology?**

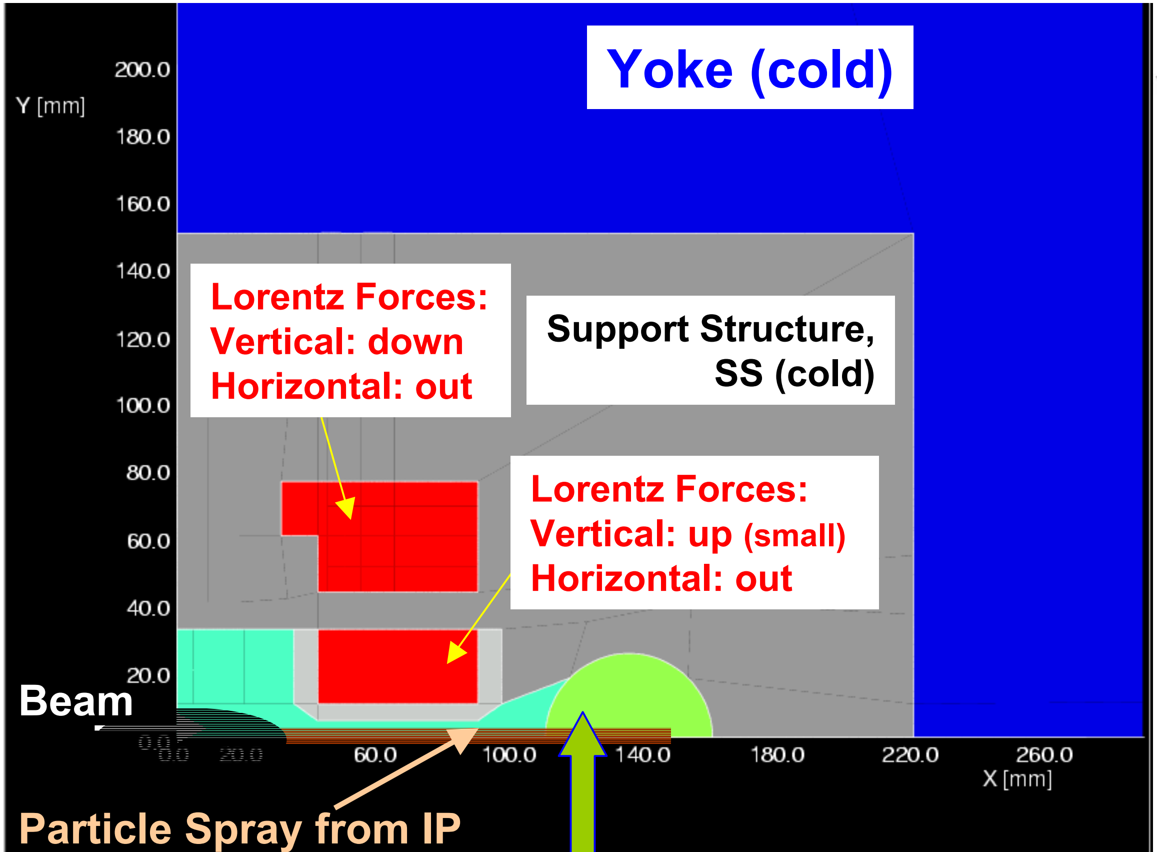
- **A quench at any rate means that the conductor is not degraded/damaged.** Erratic performance is related to the conductor instability or the magnet mechanics.
- This proves that the "React & Wind" Technology is OK, at least to the level tested.
- This means that given the major benefits of the "React & Wind" (scalable to long magnets, significant use of existing magnet technology with small modifications, insulation choices, no need to deal with differential thermal expansion of various materials, etc.), the development of this technology must continue.
- Also recall that the BNL common coil design is intended to present a more sever test of the bending strain. Once we know the limit of it in the magnet environment, we must step back a little for building magnets that are designed for machine. For example, to produce a proof-of-principle "React & Wind" magnet under LARP magnet program, we need not be super aggressive.

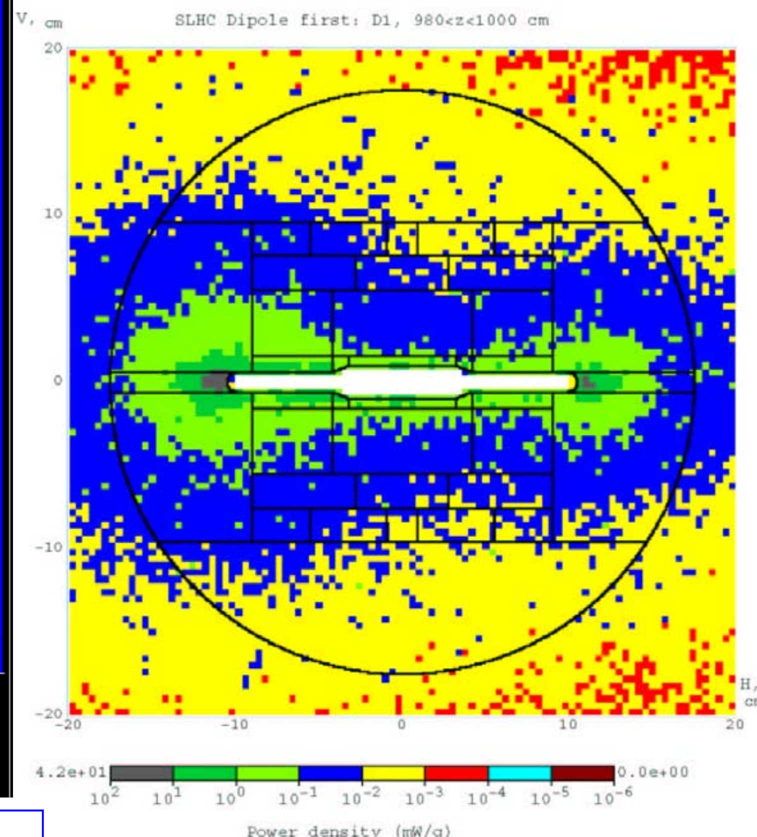
Some Special Considerations for LHC Upgrade Dipole Design in “Dipole First Optics”

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” (some estimates show that the increase is a factor of two)

Open Midplane Design Takes Advantage of the Anisotropy in Energy Distribution (highly peaked at midplane)



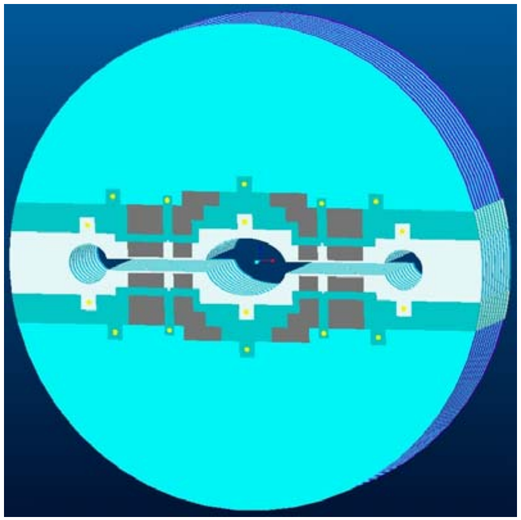


A large amount of particles coming from high luminosity IP deposit energy in a warm (or 80 K) absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.

Calculations from Mokhov proving that the concept works

A True Open Midplane Design

By open midplane, we mean truly open midplane:



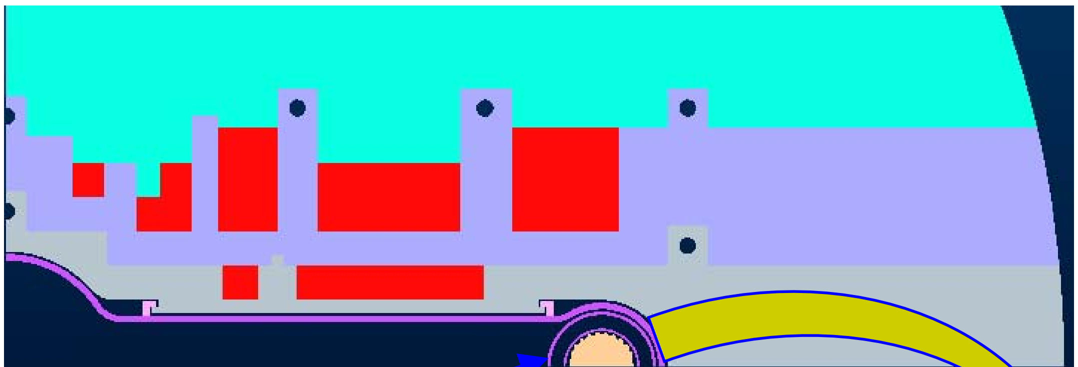
Particle spray from IP (mostly at midplane), pass through an open region to an absorber sufficiently away from the coil without hitting anything at or near superconducting coils.

In earlier "open midplane designs", although though 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 energy on the coils.

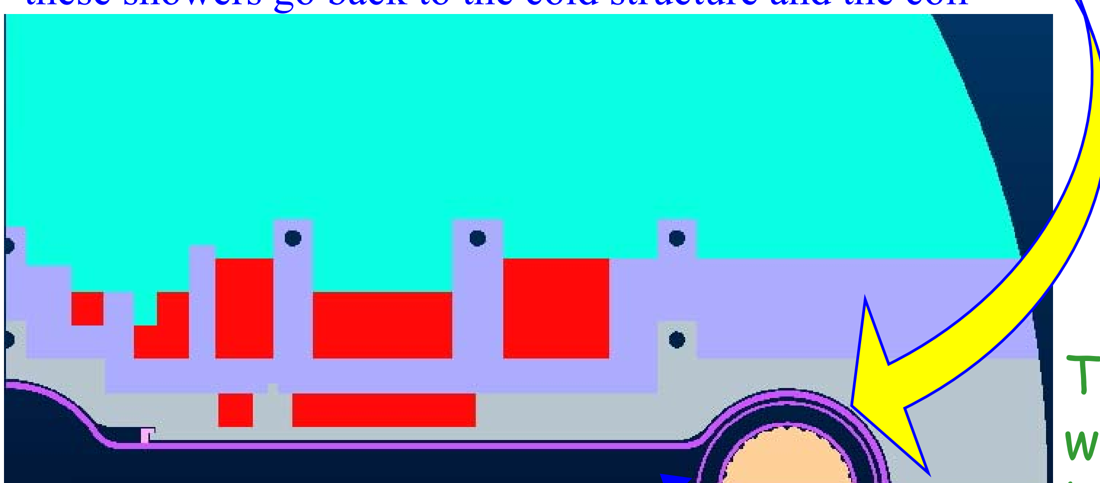
The energy deposited on the superconducting coils by this secondary shower became a serious problem. Therefore, the earlier open midplane designs were not that attractive.

Impact of the Energy Deposition from the Secondary Particles in the Basic Design

An example of how crucial it is to incorporate the impact of the energy deposition from the secondary radiation in the basic open midplane dipole design:



Secondary showers are created from this mass. Some of these showers go back to the cold structure and the coil



Secondary showers are created from this mass.

In an attempt to reduce the size of collar, we put the absorber closer to the center (upper figure). Even though it is was well out side the coils near the midplane, Mokhov's calculations showed that the secondary radiations from the pipe (some travelling backward in magnetic field) were enough to increase energy deposition on the coil above the acceptable limit. **We were forced to move the absorber and cryo-pipe away.**

This study is important to those who wish to put some structure between upper and lower coils.

How Simple Can The Design Be?

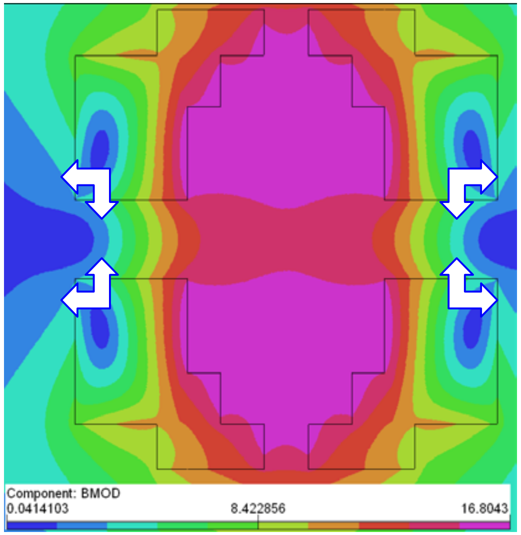
• I am always for a simple design. The design should be as simple as possible as long as it does what it is intended to.

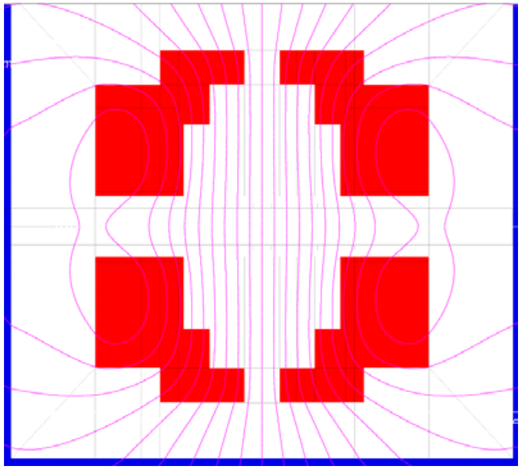
• Examples when things have to be relatively complicated:
- Compare the underground transportation in the tunnel (e.g. English Channel) to the country side road.
- Compare the air travel of local flight to space flight.

• The basic requirements is that "energy deposition on s.c. coils" <u>and</u> "operating and upgrade cost of LHC cryo-system" should be small (acceptable) . Any complete design exercise must meet these minimum requirements.

Open Midplane Dipole Design

Challenges Due to Open Midplane

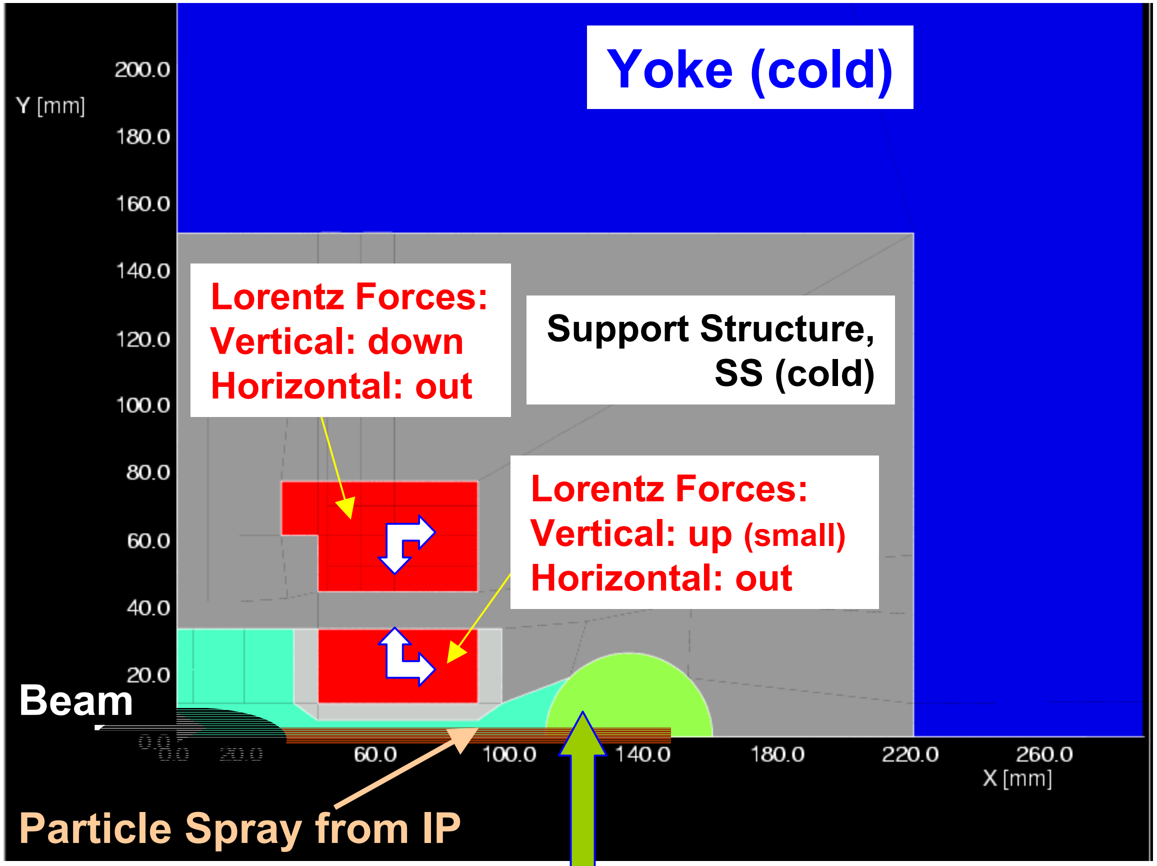




- Attractive vertical forces between upper and lower coils are large in any high field magnet, but they react against each other. Containing these forces in a magnet with no structure between the upper and lower coils appears to be a big challenge.
- The large gap at midplane appears to make good field 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.

Open Midplane Dipole Design Strategies



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.

- Particle spray from IP go through the open midplane and dump most of their energy in a cryo-insulated warm absorber.
- The lower coil block has small upward force and upper coil has large downward force. The large downward force is taken out in a segmented support structure.
- The lower coil block is now brought closer to midplane to produce a good field quality design.

Design Parameters of 15 T Open Midplane Dipole

Presented at LAPAC June'04

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.

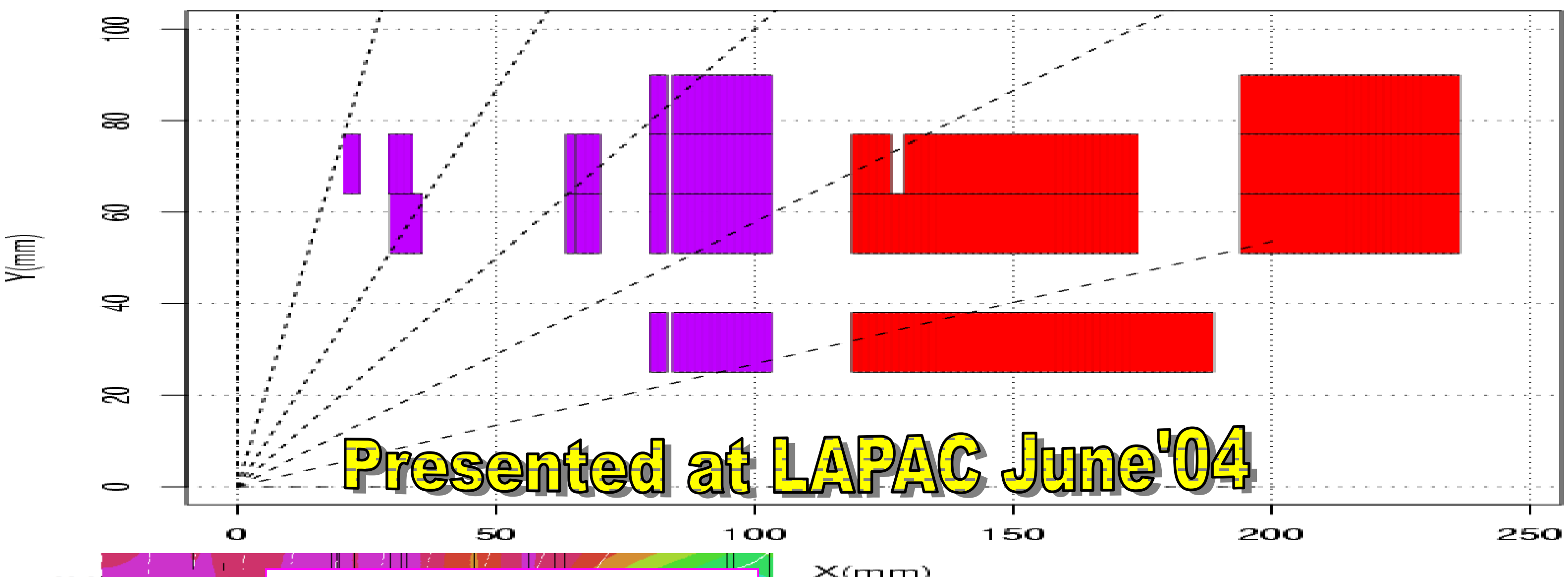
The magnet itself is big and expensive. But these are only a few. If one considers the overall increase in infrastructure and operating cost, and just not the magnet cost, the net savings will be substantial.

Hand Optimized Design =>

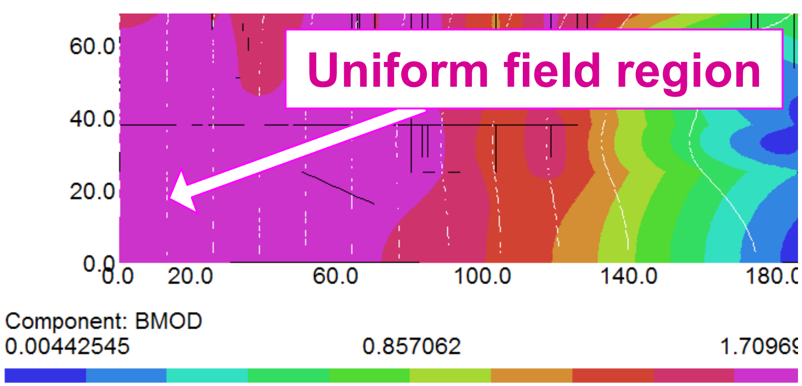
Fine-tuned by RACE2DOPT for Harmonic Minimization

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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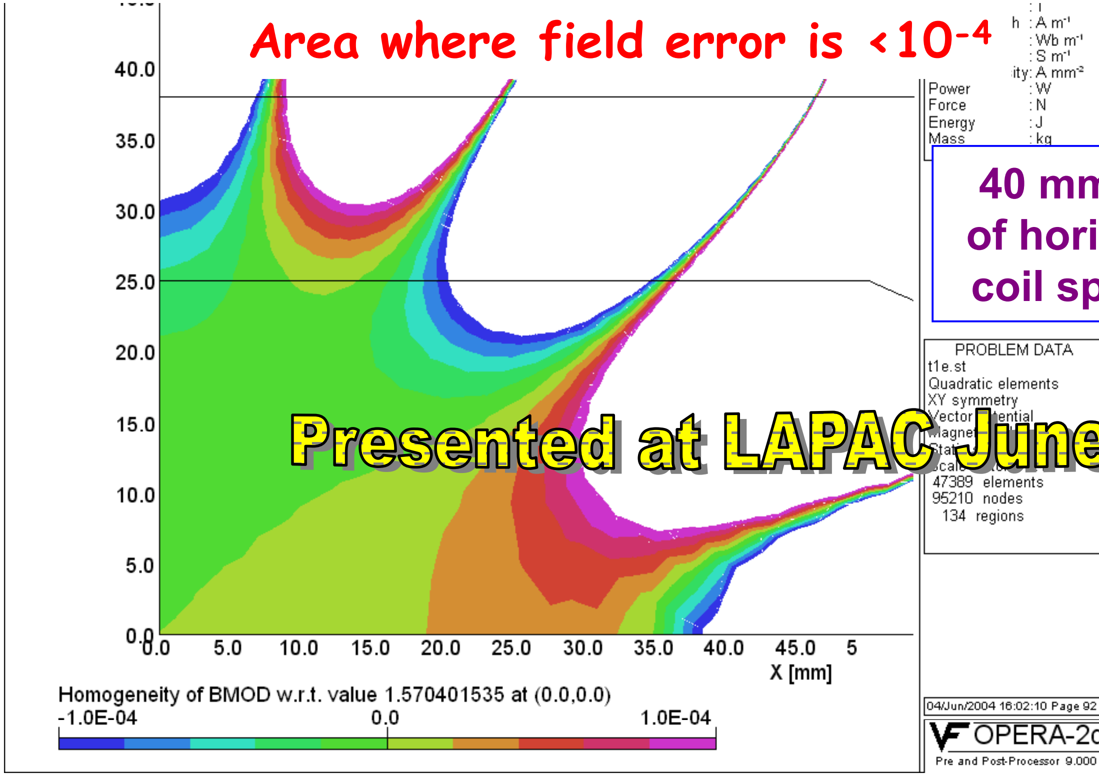
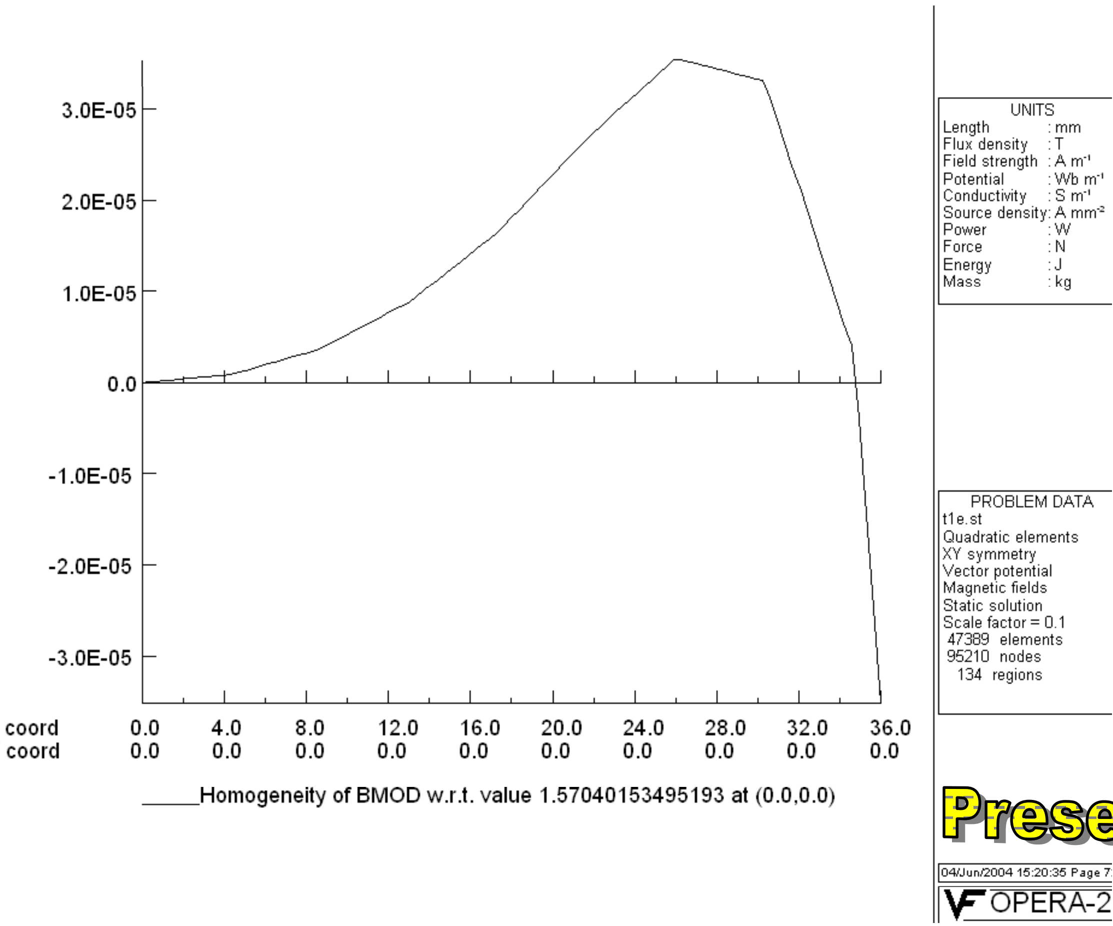
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00



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.

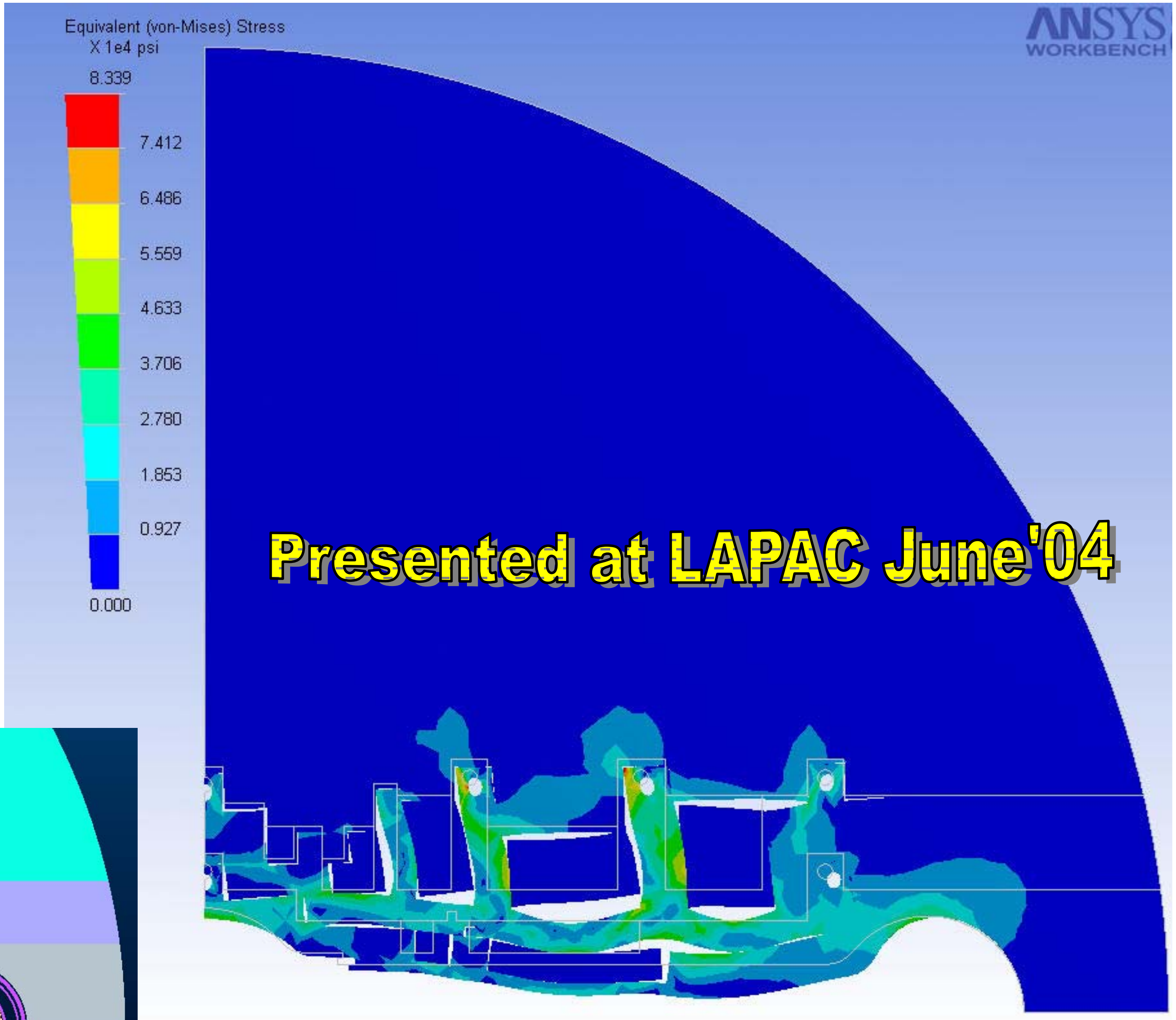
The actual field errors in these magnets will now be determined by construction, persistent currents, etc.

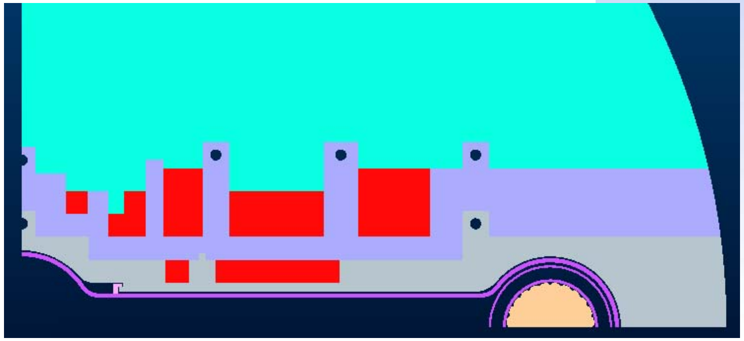
Presented at LAPAC June'04

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.





Conclusions from LAPAC04 Design Studies

- The challenging requirements of the design appear to have been met:
  - ➢ A design that can accommodate a large gap between upper and lower coils with no structure in between.
  - ➢ 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.

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

- However, in an attempt to satisfy all requirements, the magnet has become larger. We still believe that it saves money in the sense of complete system (including cryogenics), but to build one within the resources allocated is a difficult proposition.

Guidelines for A Lower Cost (Reduced Aperture) Magnet

The design presented at LAPAC04 satisfied most requirements, but it was too big.

It was a proof of principle design to show that most severe requirements (field quality, downward Lorentz forces) can be met despite a large unsupported gap at the midplane (~1/3 of horizontal aperture).

Design Parameters of 15 T Open Midplane Dipole

Presented at LAPAC June'04

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
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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.

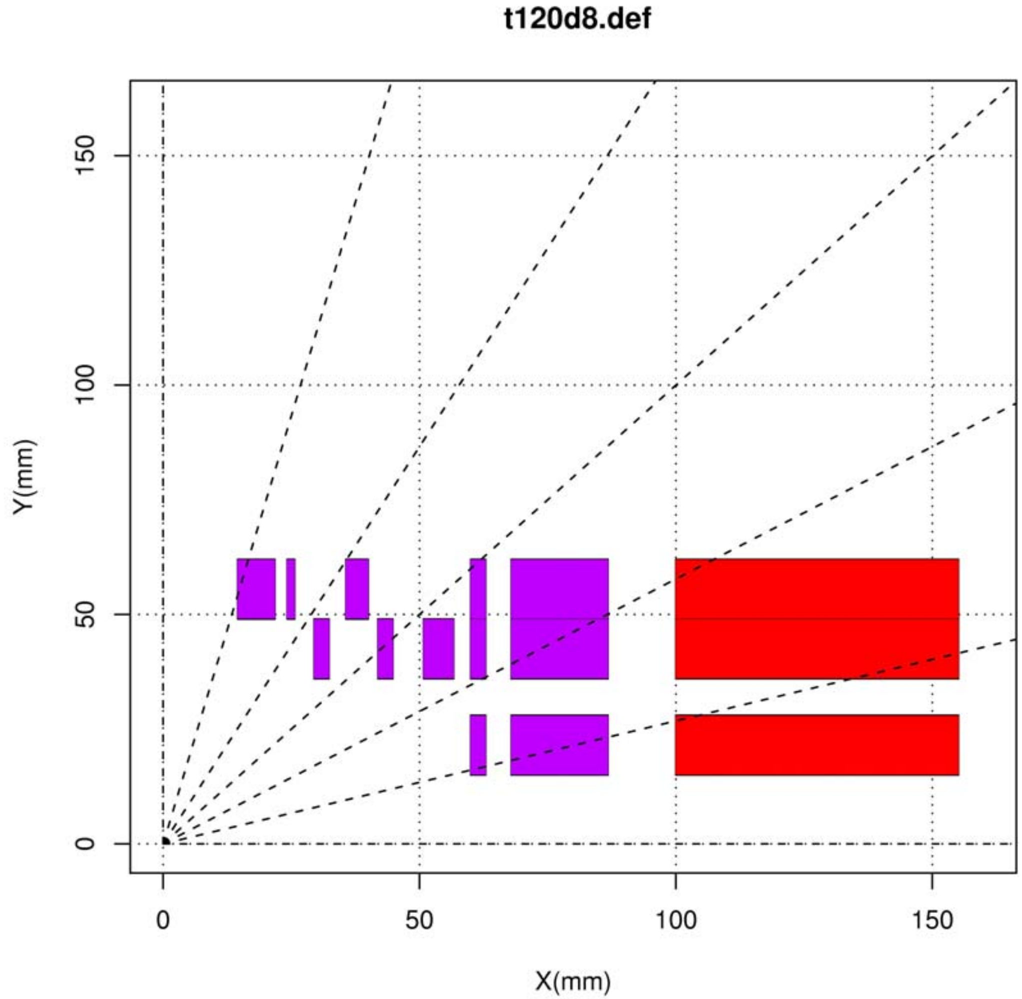
The magnet itself is big and expensive. But these are only a few. If one considers the overall increase in infrastructure and operating cost, and just not the magnet cost, the net savings will be substantial.

New design guidelines from Mike Harrison to reduce magnet cost:

dB/B : ~ 10^{-3} to +/- 47 mm

Coil Optimization with RACE2DOPT

To get the desired field quality (relative field errors ~10^{-3} at +/- 47 mm), we attempted coils with horizontal aperture in the range of 120 mm to 130 mm.

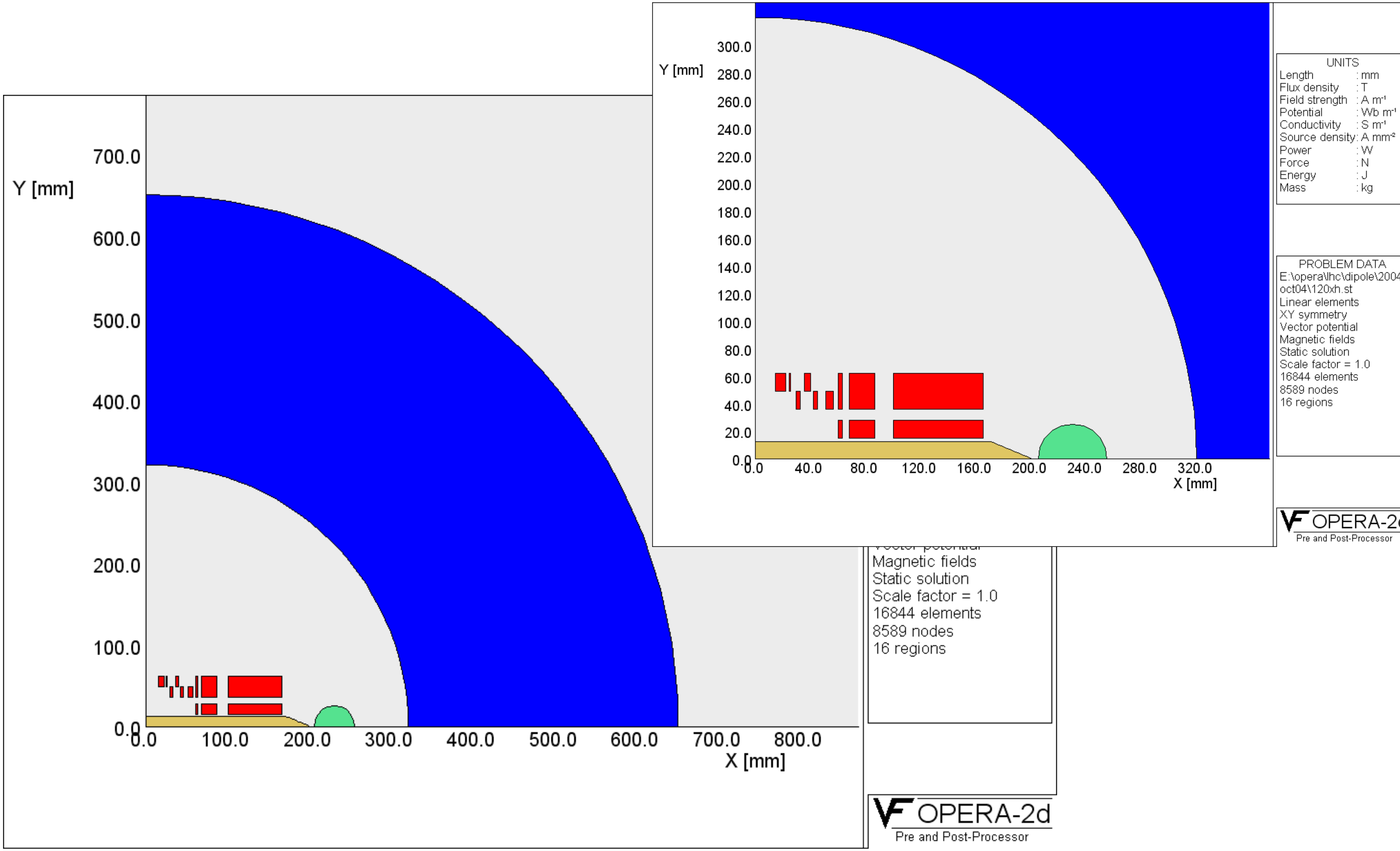


A preliminary study to determine the size of the magnet

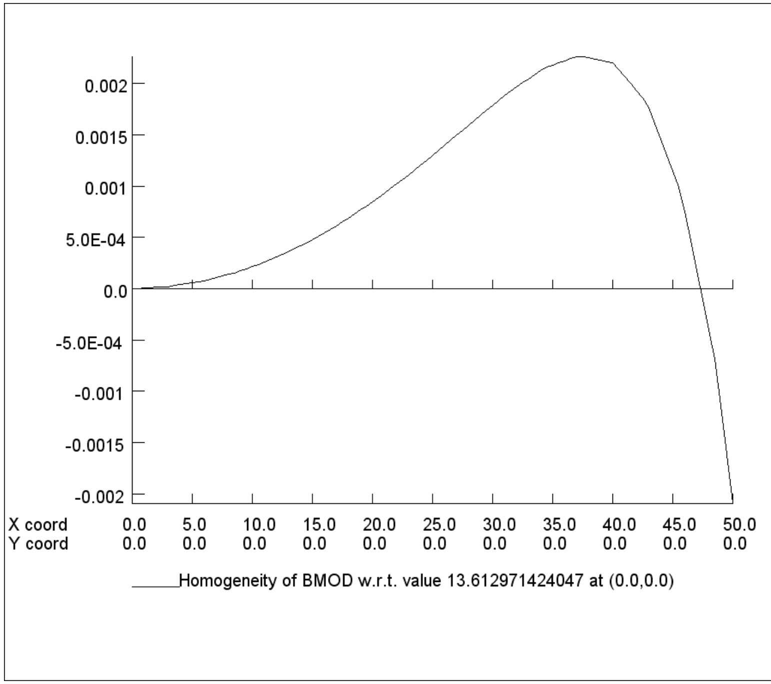
```
 t120d8.def
Rref=    40.000 mm Last Turn    15.901
Transfer Function =      170.1E-05 T,m
794.4E-01
```

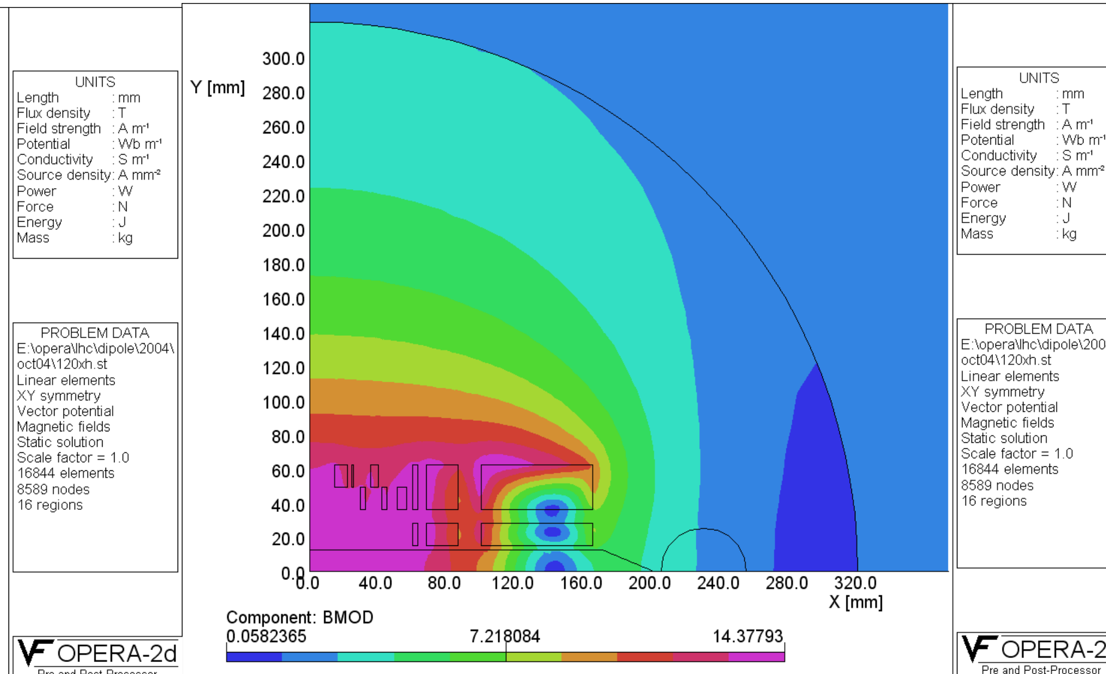
n	bn	bnDesign
1	10000.0000	10000.0000
2	0.0000	0.0000
3	-0.0374	0.0000
4	0.0000	0.0000
5	-0.6137	0.0000
6	0.0000	0.0000
7	-3.2852	0.0000
8	0.0000	0.0000
9	-4.9094	0.0000
10	0.0000	0.0000
11	-6.5599	0.0000
12	0.0000	0.0000
13	0.0451	0.0000
14	0.0000	0.0000
15	0.0000	0.0000
16	0.0000	0.0000
17	0.0000	0.0000
18	0.0000	0.0000
19	0.0000	0.0000
20	0.0000	0.0000

OPERA-2d Model of Reduced Aperture Open Midplane Dipole (Preliminary Design)

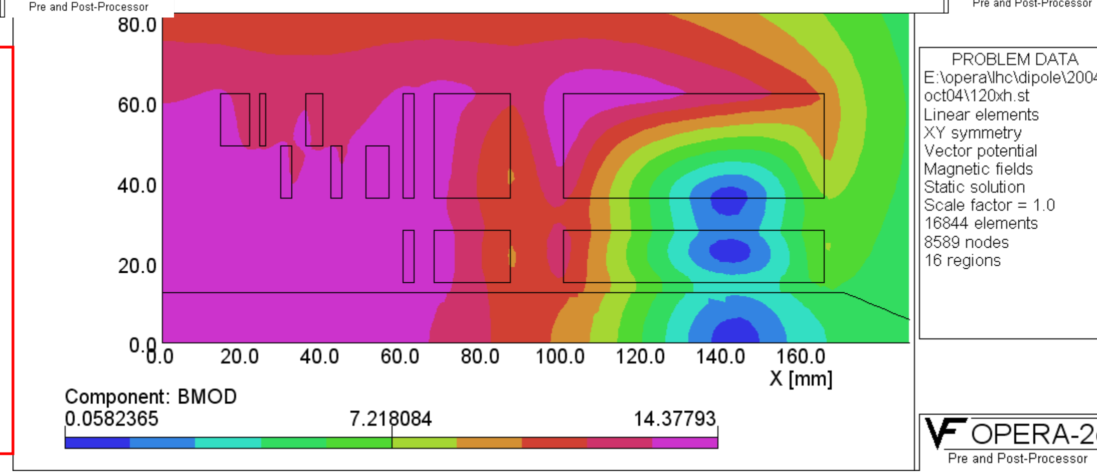


Field Quality in the Reduced Aperture Open Midplane Dipole (Preliminary Design)





Proof that the desired field quality (relative field errors ~10^{-3} at +/- 47 mm) can be obtained. With a little bit more optimization, we should be able to get < 10^{-3} (or may be even 5.10^{-4}).



Overall Parameters of the Reduced Aperture Open Midplane Dipole Preliminary Design

Outer Yoke Radius : 600 mm to 700 mm (old value 1 meter)

Horizontal Coil Spacing : 120 mm (old value 160 mm)

Vertical Coil Spacing : 30 mm (old value 50 mm)

Field errors: 2.10^{-3}, projected to be 5.10^{-4} with more optimization at +/- 50 mm

(old value 5.10^{-5} at +/- 36 mm)

Quench Field: ~14.5 T (old value ~15 T)

- **Conductor requirements: ~60% of previous design**

The above magnet is much smaller than before.
However, it still has a significant size.

Comparing Magnet Size from the First Principle

The size of a dipole is always going to be significantly larger than a quadrupole.

- For the same peak field, the amount of flux in dipole is twice that of quadrupole and hence it needs twice the yoke to contain fringe fields.

- The outward force in dipole is significantly more than dipole so it needs bigger collars to contain Lorentz forces.

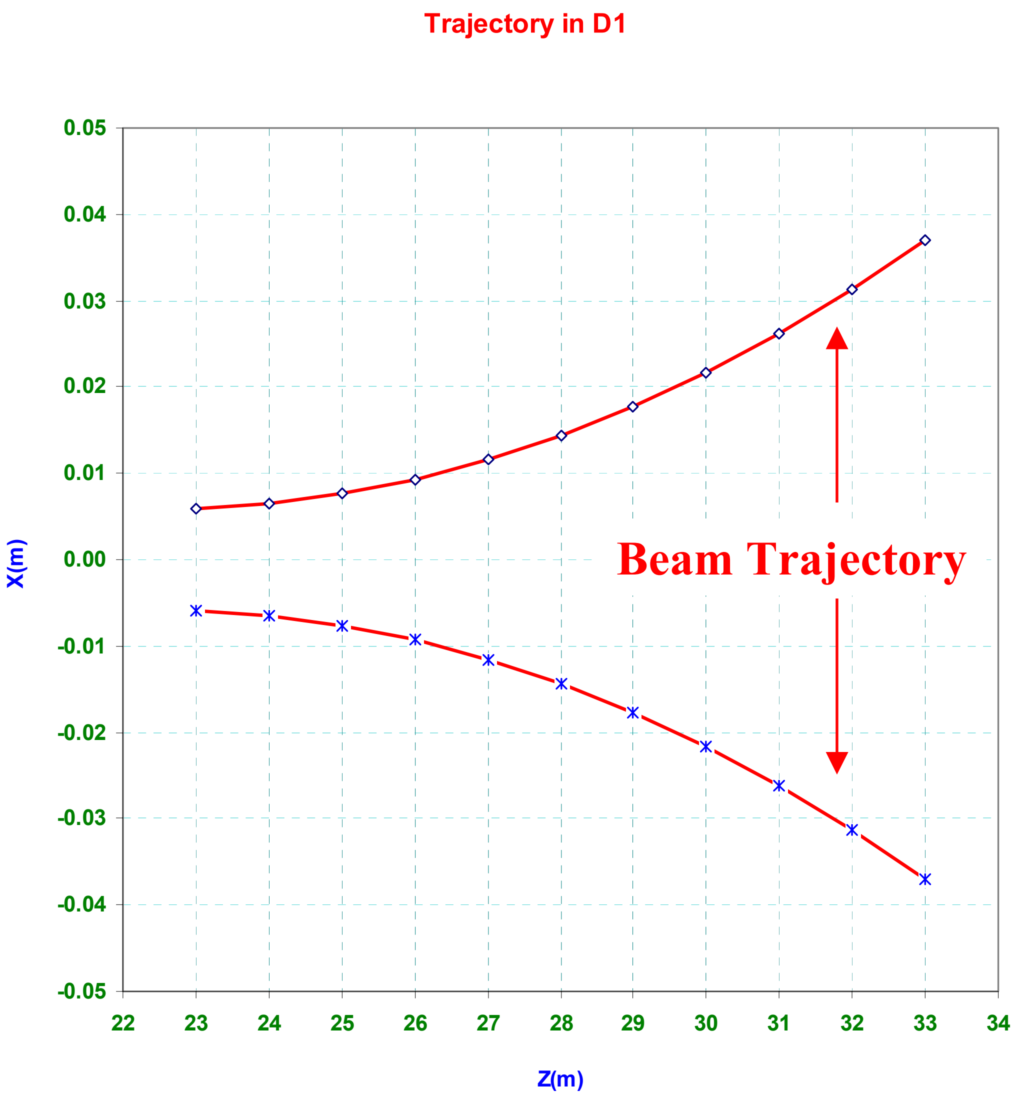
- Taking advantage of the open midplane design, we want to dump heat in a relatively warmer structure (a cryo-insulated absorber within the collars). This increases the size of the collar (and of the magnet). However, the proportionate benefits of this increased size are not only well worth it, but are even perhaps essential.

Still compare to 130 mm cosine theta dipole (yoke radius in Fermilab design 500 mm), the open midplane dipole presented here with a coil aperture of 120 mm is not too large (radius ~650 mm). Rectangular yoke may further reduce the size.

Coming In Next Few Slides

A proposal to build a significantly lower cost open midplane dipole magnet that, while hopefully satisfying, both technical and budgetary requirements, also brings a variety in Nb3Sn magnet technology development and keeps options open.

A Lower Cost Open Midplane Dipole Proposal



- At present, the aperture of D1 is determined by the requirements at the far end of IP.

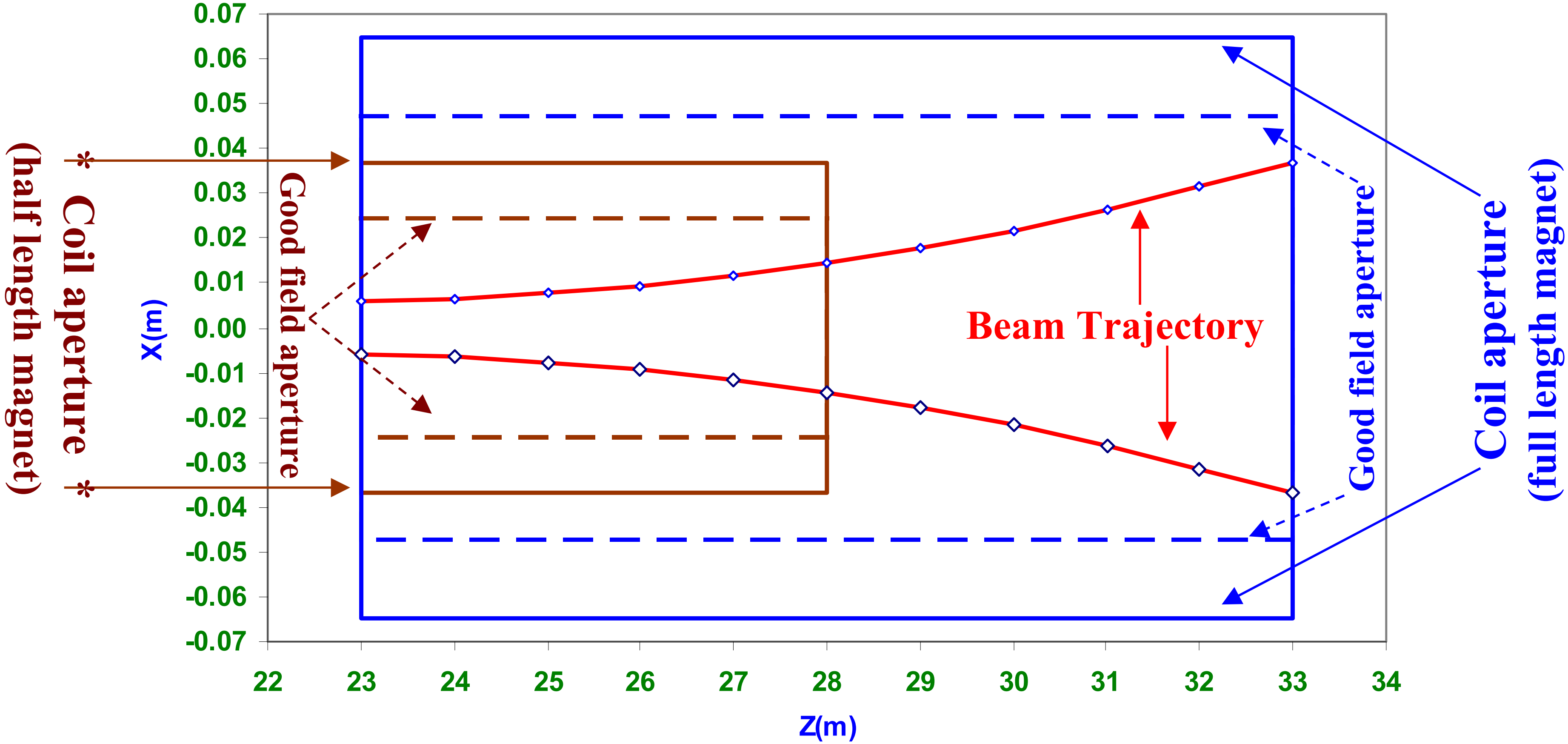
- We propose dividing each D1 in two dipoles D1A and D1B. We also propose to develop only D1A under LARP.

- 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).

A Proposal to Build D1A Under LARP

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.

A Similar Layout Was Considered for VLHC

Beam optics reasons were different, but magnet design reasons were partly similar.

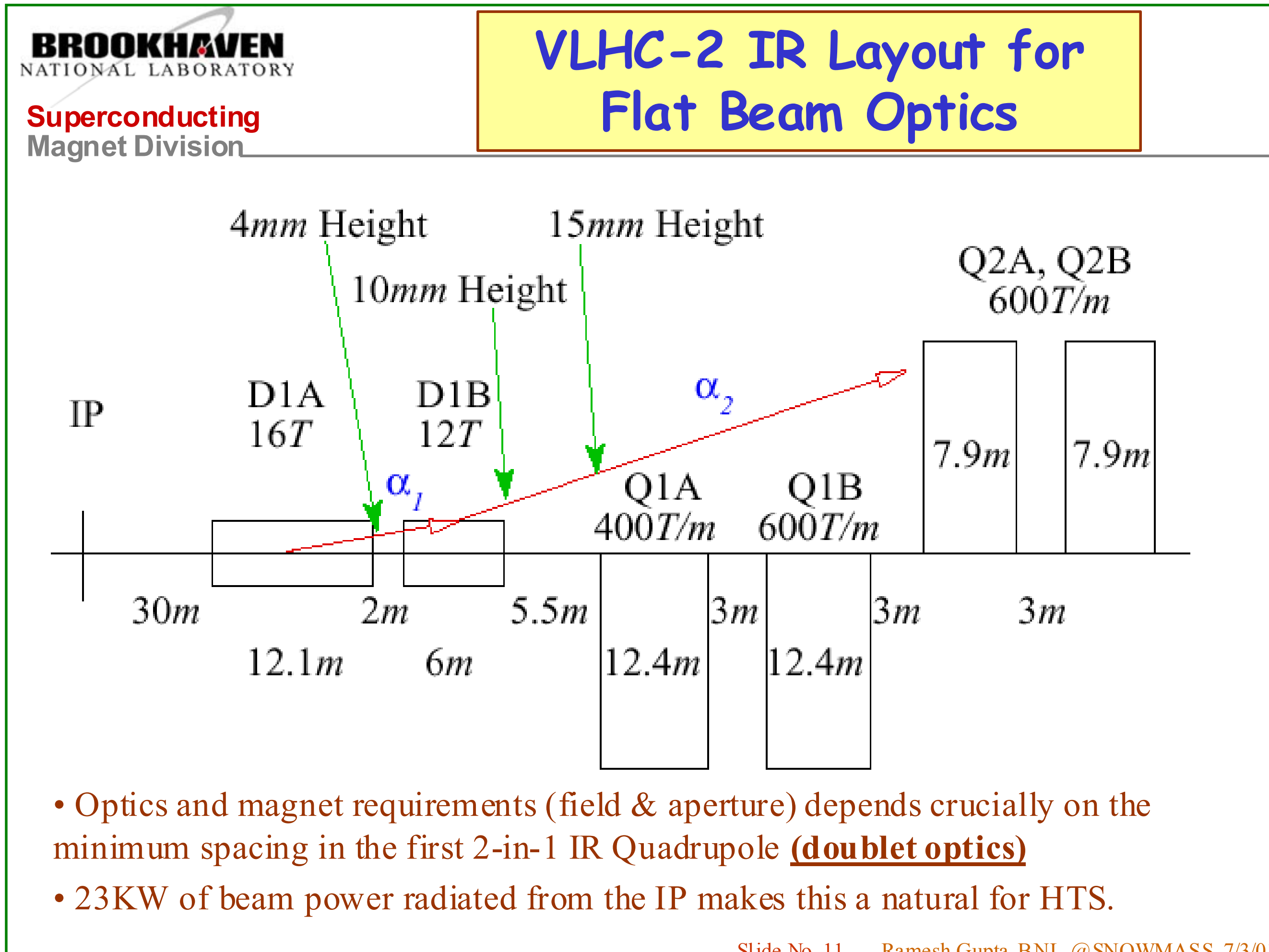
First Magnet (D1A):

Higher field, lower aperture, taking help of HTS.

Second Magnet (D1B):

Lower field, larger aperture, based entirely on Nb_3Sn.

Given the time frame of LHC IR Upgrade, we would consider HTS. However, we won't make the design contingent on that.



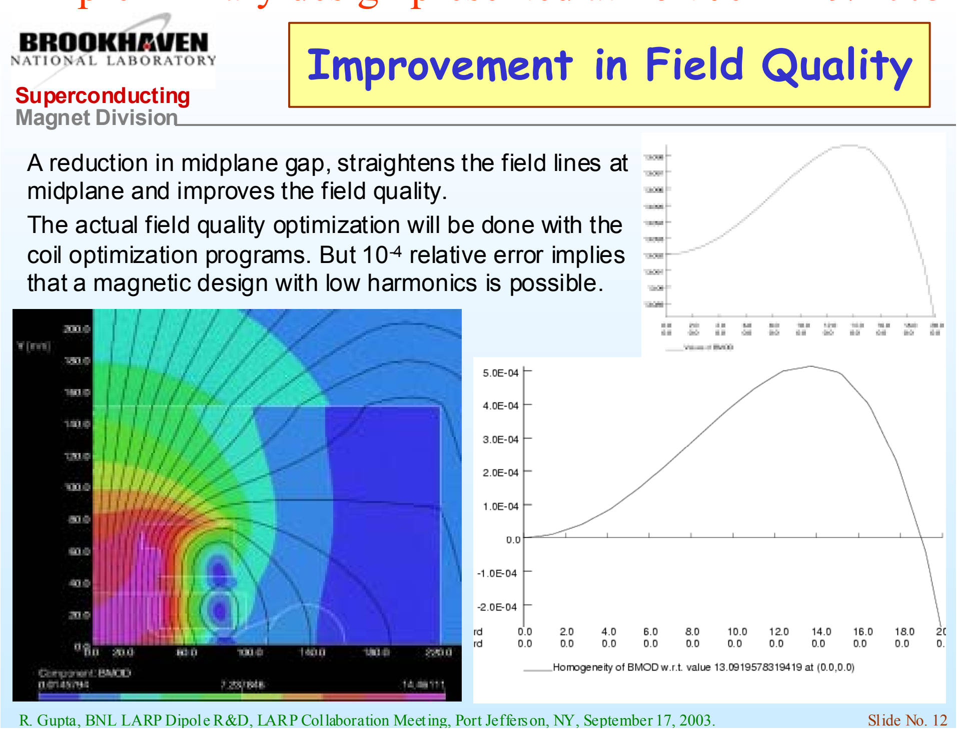
Starting Point and some estimates on D1A Parameters (to be iterated)

Design Goal: An open Midplane design with large horizontal and small vertical aperture that includes a warm absorber inside the cold-mass to avoid a major upgrade in CERN cryogenic facility and to remove ~9KW at an affordable cost.

D1A (to be developed under LARP):

Horizontal Aperture : ~70 mm
Magnet Length : ~ 5 meter
Quench Field : 15+T
Yoke outer radius: ~400 mm
(or a rectangular yoke with smaller vertical size?)

A preliminary design presented at Port Jeff in 9/2003



D1B (NOT to be developed under LARP):

Horizontal Aperture : ~140 mm
Magnet Length : ~ 5 meter
Quench Field : ~13T
Yoke outer radius: ~600 mm
Note: D1B may have similar Lorentz forces as D1A

SUMMARY

Given that there is <u>NO</u> experience in building large Nb_3Sn magnets and given that "React & Wind" Technology is relatively easier to scale in going from short to long magnets and that it offers several other advantages in choices of material etc., "React & Wind" Technology should be a part of LARP base program.

There is no technical reason to eliminate "React & Wind" for future high field Nb_3Sn magnet R&D. It also makes the magnet development program a bit more broader.

A smaller aperture, lower cost open midplane dipole option is presented which is intended to satisfy all significant requirements (budget and technical) and becomes a part of D1 package. "Retaining Dipole First Option" keeps the overall LARP IR upgrade options a bit more broader - both from magnet R&D and from beam optics point of view.