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# OPTIMIZATION OF OPEN MIDPLANE DIPOLE DESIGN FOR LHC IR UPGRADE*

PAC 05 Particle Accelerator Conference, Knoxville, Tennessee, USA • May 16-20, 2005

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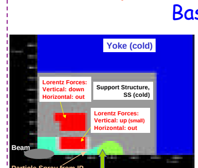
**High luminosity Interaction Regions (IR) present a hostile environment for superconducting magnets due to large amount of particle spray from p-p collisions:**

- **"Dipole First Optics" reduces long-range beam-beam effects and makes correction of field errors in quadrupole more robust.**
- **Heat removal poses a significant challenge, both in terms of technical performance and in terms of economical operation of IR magnets.**

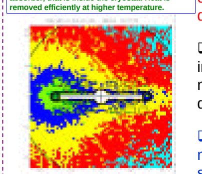
**This paper summarizes the basic design strategy, challenges and a number of iterations carried out over a period of a few years.**

## 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.

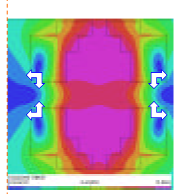
❑ Calculations for the dipole first optics show that the proposed design can tolerate ~ 9kW/side energy deposited for $10^{35}$ upgrade in LHC luminosity, whereas in conventional designs it would cause a large reduction in quench field.

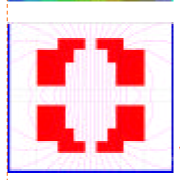
❑ The requirements for increase in CERN cryogenic infrastructure and in annual operating cost would be minimum for the proposed design, whereas in conventional designs it will be enormous.

❑ 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.

*Work supported by the U.S. Department of Energy.

## LARP Dipole Design Development

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

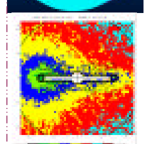
- **energy removal**
- **magnetic**
- **mechanical**
- **and beam physics**

**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.**

## A True Open Midplane Design

By open midplane, we mean <u>truly</u> 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.

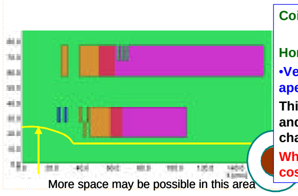
In earlier "open midplane designs", although there was "<u>no conductor</u>" at the midplane, but there was some "<u>other structure</u>" between the upper and lower halves of the coil. Secondary showers from that <u>other structure</u> deposited a large amount of energy on the coils.

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.**

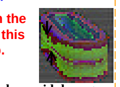
**The desired goal is that the gap is large enough so that most showers pass through without hitting anything before hitting the warm target.**



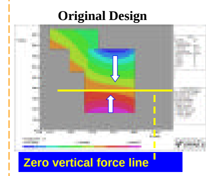

**Coil-to-coil gap in latest design = 34 mm (17 mm half gap)**
**Horizontal aperture = 80 mm**
**•Vertical gap is > 42% of horizontal aperture (midplane angle: 23°)**
**This makes obtaining a high field and a high field quality a kind challenging task !**
**What part of cosine (q) is left in that cosine (q) current distribution now?**

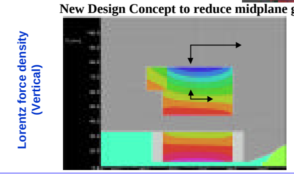
## Navigation of Lorentz Forces

### 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.**

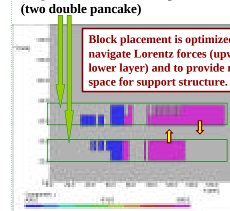



**Since there is no downward force on the lower block (there is slight upward force), we do not need much support below it, if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.**

## Basic Layout of The Current D1 Design

**Magnet is consisted of simple racetrack coils (two double pancake)**



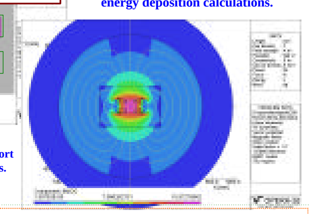

**Lorentz force is upward in lower blocks. This eliminates the need of midplane support structure to contain vertical Lorentz forces.**

Current grading rather than cable grading.

**Design/Quench/Peak Field: 13.5 T/15 T/16 T**
**Nominal horizontal coil spacing : 120 mm**
**Nominal vertical coil spacing : 40 mm**

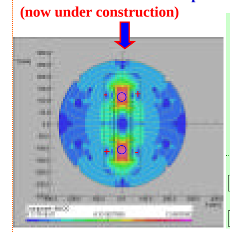
Number of layers : 4
**Number of turns: 230**

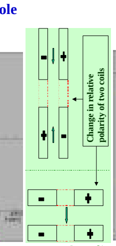
**Midplane gap is determined by energy deposition calculations.**



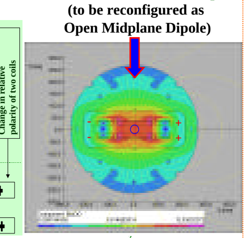
## Twin Aperture Common Coil Dipole Reconfigured As A Single Aperture Open Midplane Dipole

**BNL 12 T Common Coil Dipole (now under construction)**






**BNL 12 T Common Coil Dipole (to be reconfigured as Open Midplane Dipole)**



**<u>Common Coil as POP</u> ($J_c$=1800 A/mm$^2$, 3000 A/mm$^2$)**

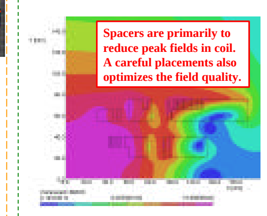
**Nominal horizontal coil spacing: 140 mm**
**Nominal vertical coil spacing: 34 mm**
**Number of turns (layers): 90 (2)**

**Central/Peak Field (for 1800 A/mm$^2$): 9.3 T/11.4 T**
**Total Lorentz Force, Vertical (Horizontal): -2.71 (2.73) MN/m**

**Central/Peak Field (for 3000 A/mm$^2$): 11.2 T/13.8 T**
Total Lorentz Force, Vertical (Horizontal): -4.0 (4.1) MN/m

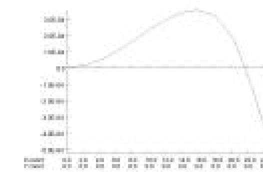
## Peak Field Enhancement and Field Quality

**<u>Field Contour at 15 T Central Field</u>**




**Peak Field Enhancement : 16T/15T = ~6.6%**
**(a typical value is obtained despite a large midplane gap)**

**<u>Field Errors at the Midplane</u>**



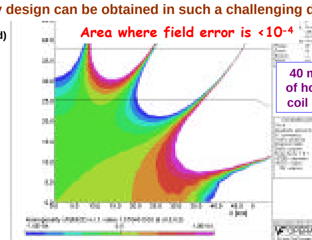
**Appears to meet the present design guidance. Detailed field harmonics are yet to be optimized. However, $10^{-4}$ relative errors at midplane suggest that we should be able to meet the typical goals.**

## Field Harmonics and Relative Field Errors In An Optimized Design

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

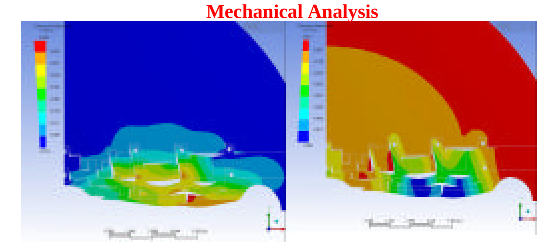
**(Beam @ x=+/- 36 mm at far end)**
**(Max. radial beam size: 23 mm)**
**<u>Geometric Field Harmonics:</u>**

| | 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 |
| 16 | 0.00 | 0.00 |
| 17 | 0.01 | 0.00 |
| 18 | 0.00 | 0.00 |
| 19 | 0.00 | 0.00 |
| 20 | 0.00 | 0.00 |



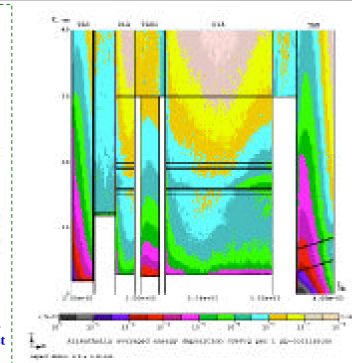

**Field errors should be minimized for actual beam trajectory & beam size. It was sort of done when the design concept was being optimized by hand. Optimization programs are being modified to include various scenarios. Waiting for feed back from Beam Physicists on how best to optimize. However, the design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

## Mechanical Analysis

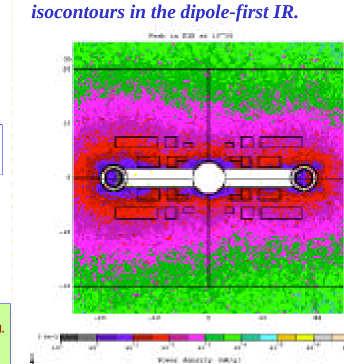


**In the June'04 design the relative values of the x and y deflections are 3-4 mil (100 micron) and the maximum value is 6-7 mil (170 micron).**

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



*Azimuthally averaged energy deposition isocontours in the dipole-first IR.*



*Power density isocontours at the non-IP end of the D1B.*

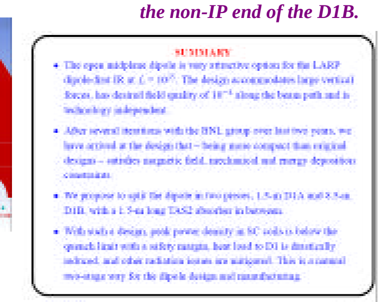
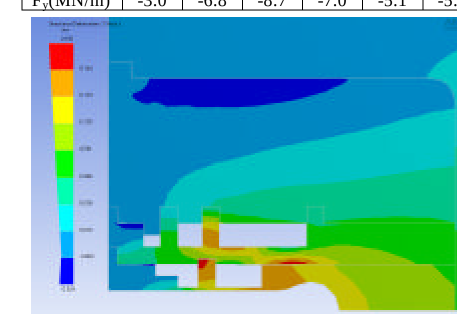



**Table : Summary of Design Iterations**

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| H(mm) | 84 | 135 | 160 | 120 | 80 | 120 |
| V(mm) | 33 | 20 | 50 | 30 | 34 | 40 |
| V/H | 0.39 | 0.15 | 0.31 | 0.25 | 0.43 | 0.33 |
| $B_o$(T) | 13.6 | 13.6 | 13.6 | 13.6 | 15 | 13.6 |
| $B_{ss}$(T) | 15 | 15 | 15 | 14.5 | 16 | 15 |
| $J_c$(A/mm$^2$) | 2500 | 3000 | 3000 | 3000 | 3000 | 3000 |
| Cu/Sc | 1 | 1,1.8 | 0.85 | 0.85 | 0.85 | 1 |
| A(cm$^2$) | 161 | 198 | 215 | 148 | 151 | 125 |
| $R_i$(mm) | 135 | 400 | 400 | 320 | 300 | 300 |
| $R_o$(mm) | 470 | 800 | 1000 | 700 | 700 | 700 |
| E(MJ/m) | 2.2 | 4.8 | 9.2 | 5.2 | 4.1 | 4.8 |
| $F_x$(MN/m) | 9.6 | 10.1 | 12.3 | 9.5 | 10.4 | 9.6 |
| $F_y$(MN/m) | -3.0 | -6.8 | -8.7 | -7.0 | -5.1 | -5.4 |



*Horizontal deflections in "Design F" in mm. Relative deflection are ~0.1 mm at design field.*

## SUMMARY

- The "Open Midplane Dipole Design" offers a good technical and an economical option for LHC luminosity upgrade in *"Dipole First Optics"*
- The challenging requirements of the design 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.
  - Energy deposition on the s.c. coils can be kept below quench limit and the component lifetime can be kept over 10 years.
  - Heat can be economically removed at a higher temperature with a warm absorber within coldmass.
- A proof of principle design has been developed and many iterations have been carried out to optimize the overall parameter space.
- The design brings a significant new addition to magnet technology.