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SUPERCONDUCTING MAGNET DIVISION

D2 Conceptual Design and Field Quality Optimization

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Design Specifications

- Aperture: 105 mm

  Also examined:

  - 95 mm (produces a more conventional design)
  - 100 mm (RHIC insertion dipole - detailed proven coil design exists)

- Inter-beam distance: 186 mm
  - note this is smaller than 192 mm spacing in nominal LHC dipole
- Target operating point on load-line: 70%
- Integrated field: 35 T.m
- Magnetic length: below 10 m (means field 3.5 T or more)

Background

BNL has designed, built and delivered 80 mm D2 magnets. However, there are major differences in this design:

- Significantly larger aperture (105 mm instead of 80 mm)
  - ❖ over 31% more flux for similar overall yoke and cryostat
- Smaller spacing (186 mm instead of 188 mm)
  - ❖ less iron (21 mm instead of 48) between two apertures for more flux makes cross-talk at higher field a particular challenge

This makes a major impact on field errors due to iron saturation and also on the fringe field outside the cryostat

Summary of Results (Preview)

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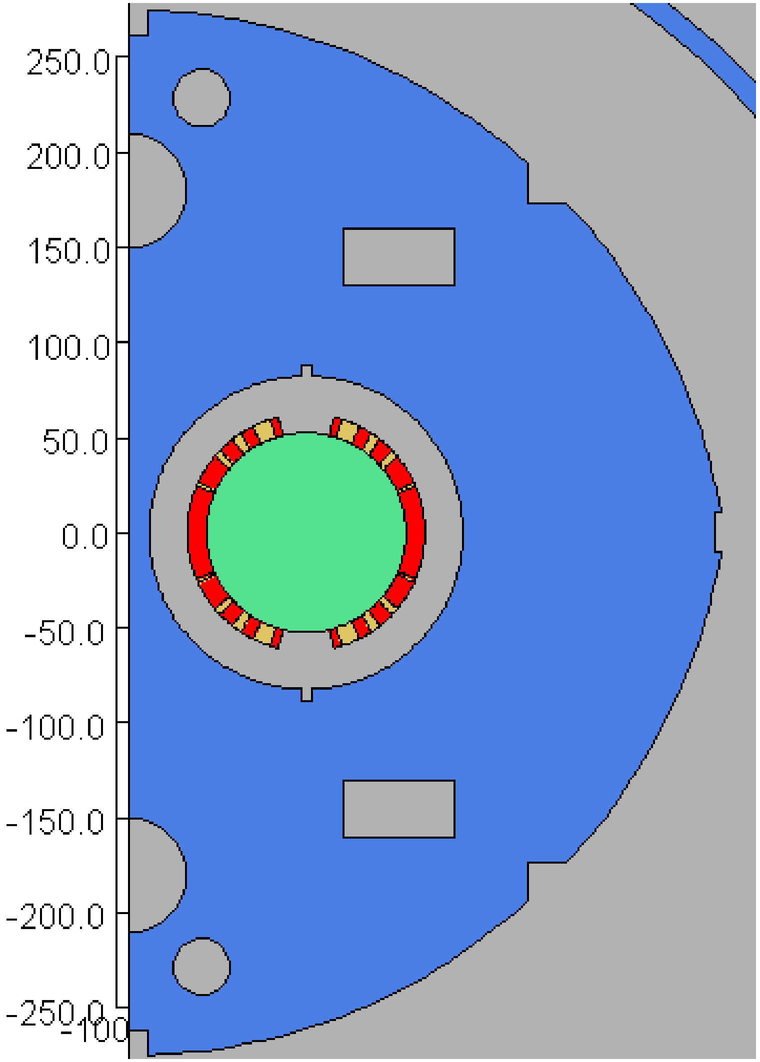
	Recombination dipole D2 field quality version 1.4 - October 1 2013 - R_{ref}=35 mm								
	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
2	0.000	25.000	0.000	0.000	25.000	0.200	2.500	0.200	2.500
3	18.000	-15.000	-14.200	3.800	3.000	0.727	-1.500	0.727	-1.500
4	-8.000	10.000	0.000	-8.000	2.000	0.126	0.200	0.126	0.200
5	4.000	-5.000	-1.000	3.000	-1.000	0.365	-0.500	0.365	-0.500
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Saturation induced harmonics

Harmonic	Previous Recommendations	Optimized Design
b_2	25	<4
b_3	15	<2
b_4	10	<1
b_5	5	<3

Major Difference Between
LHC Main Dipole and D2 Dipole

Right-half of the x-section



- Like LHC main dipole, LHC insertion D2 is also a 2-in-1 dipole.
- In main ring dipoles, however, the field in two apertures is in opposite direction allowing one side to provide return flux path to the other.
- This is not the case in D2 since the field is in the same direction. This means that the flux on one aperture must return on the same side.
- Reducing cross-talk due to proximity of two apertures (quadrupole harmonic, etc.) and other harmonics arising from the insufficient iron at midplane is the major challenge.
- In 80 mm D2 we were able to overcome this by the unique oblate yoke design developed at BNL which provided extra iron at the midplane.
- 105 mm D2 has more flux and less spacing.

Impact of Relative Polarity (1)

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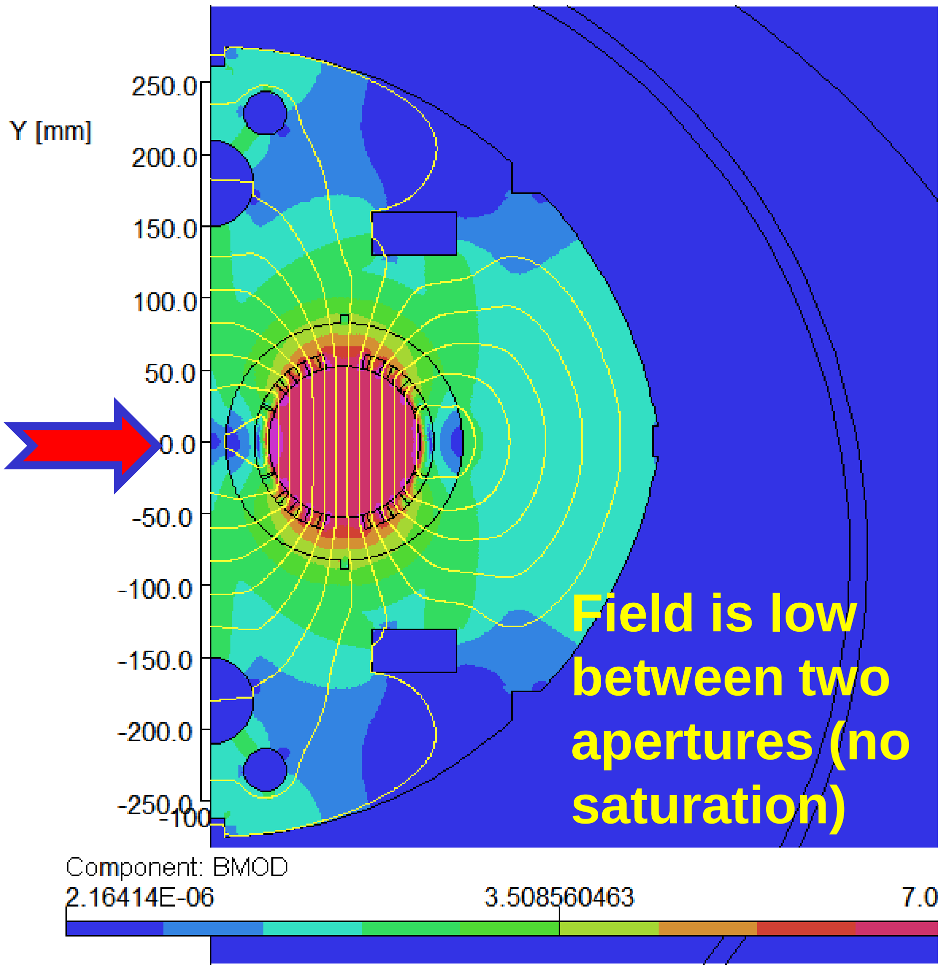
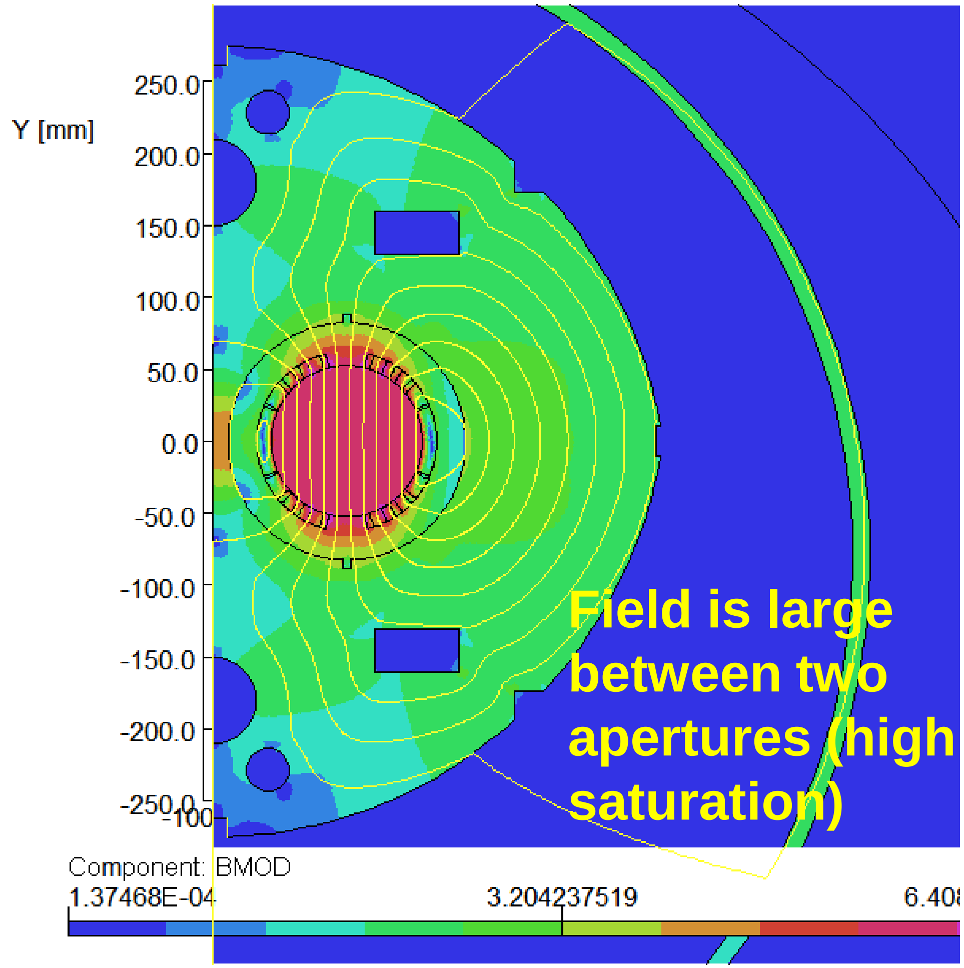
Field in the opposite direction (LHC main dipoles)	Field in the same direction (D2 dipoles)





20 mm SS collar (as in previous BNL D2)

Impact of Relative Polarity (2)

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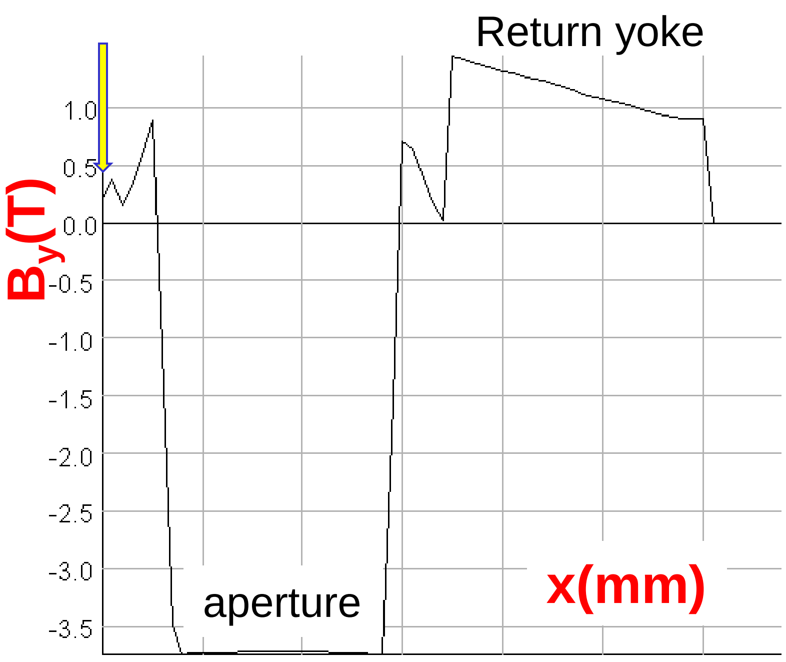
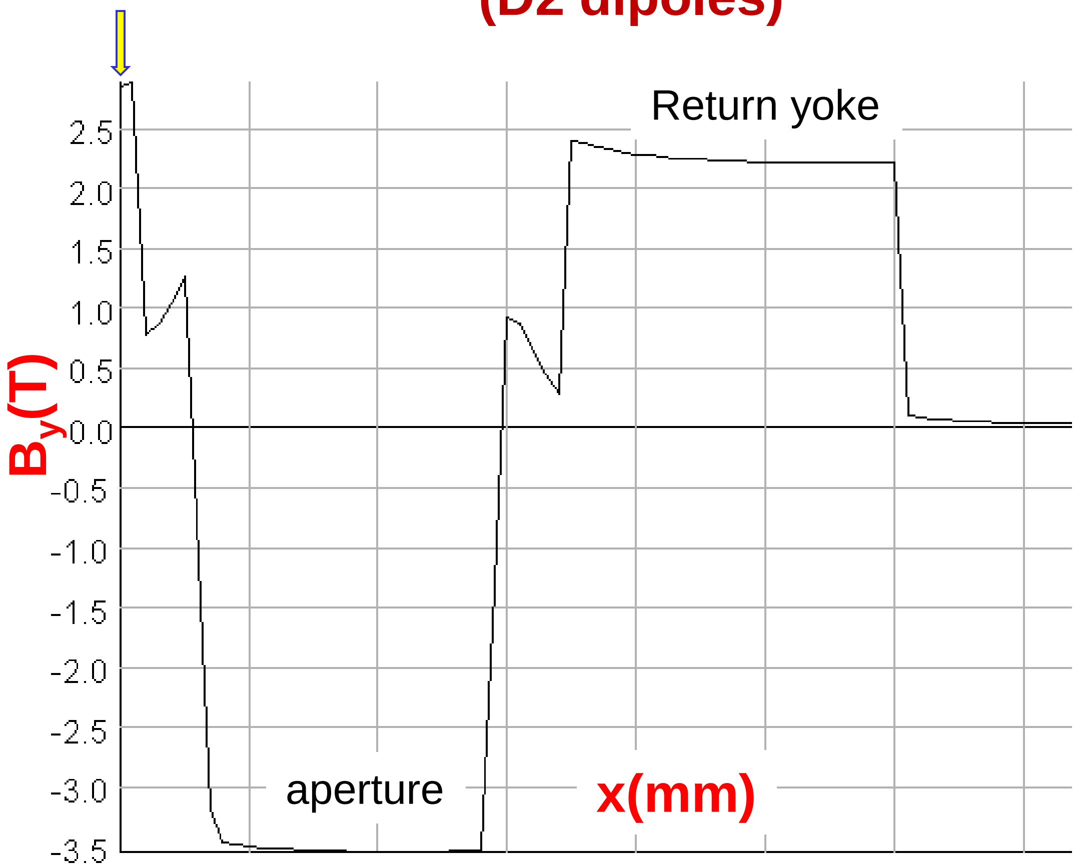
Field in the opposite direction (LHC main dipoles)



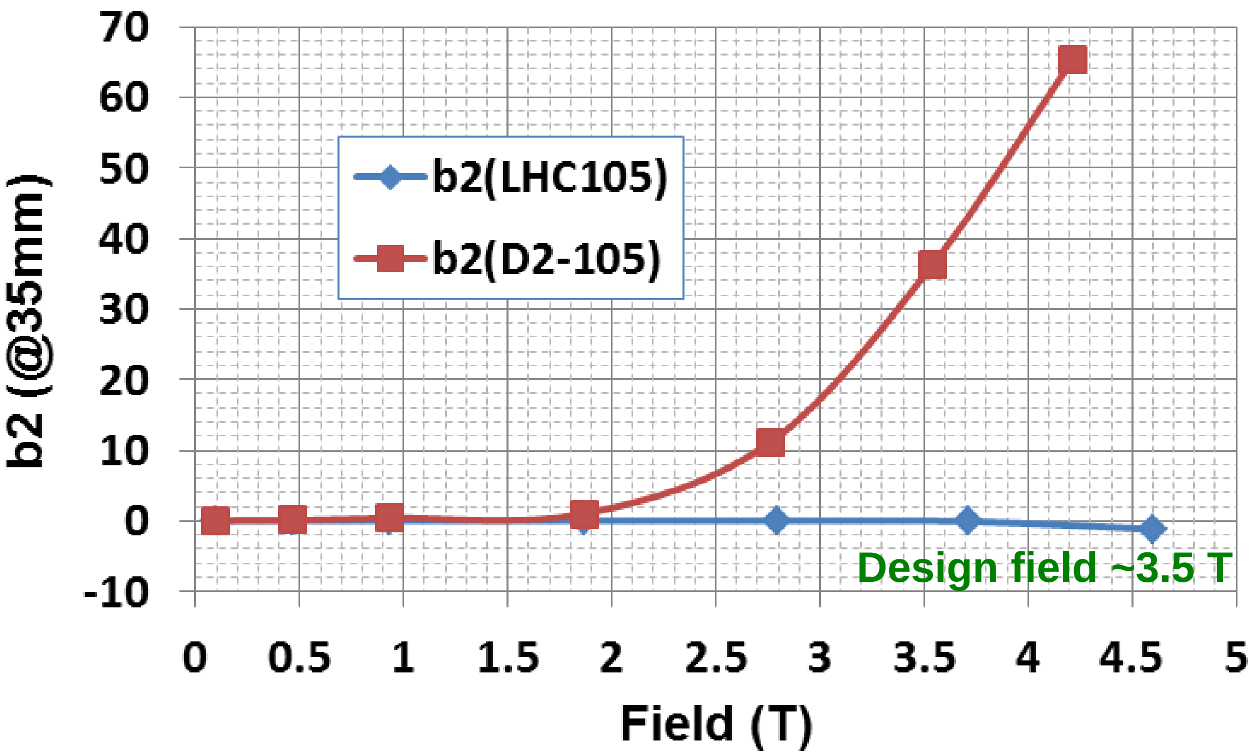
Field is lower **(~0.5 T)** at the center of the magnet and in the return yoke **(~1 T)**

Field in the same direction (D2 dipoles)

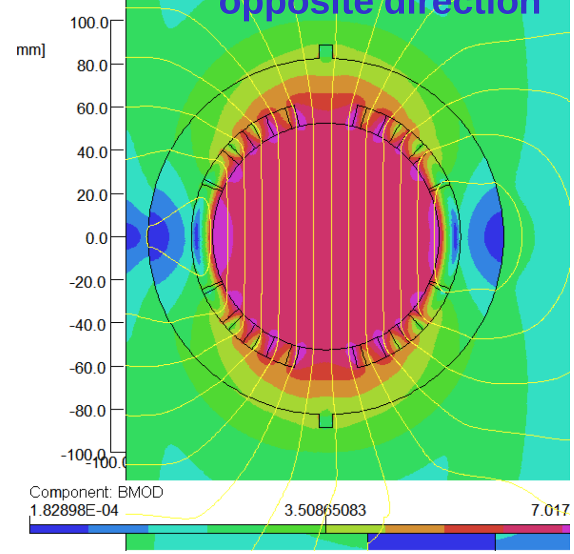


Field is higher **(>2.5 T)** at the center of the magnet and also in the return yoke **(>2 T)**

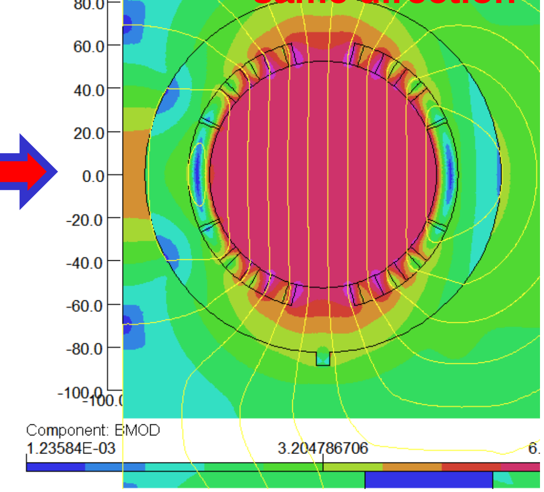
Impact of Relative Polarity (3)
Semi-allowed b_2 (cross-talk)



Field in the opposite direction



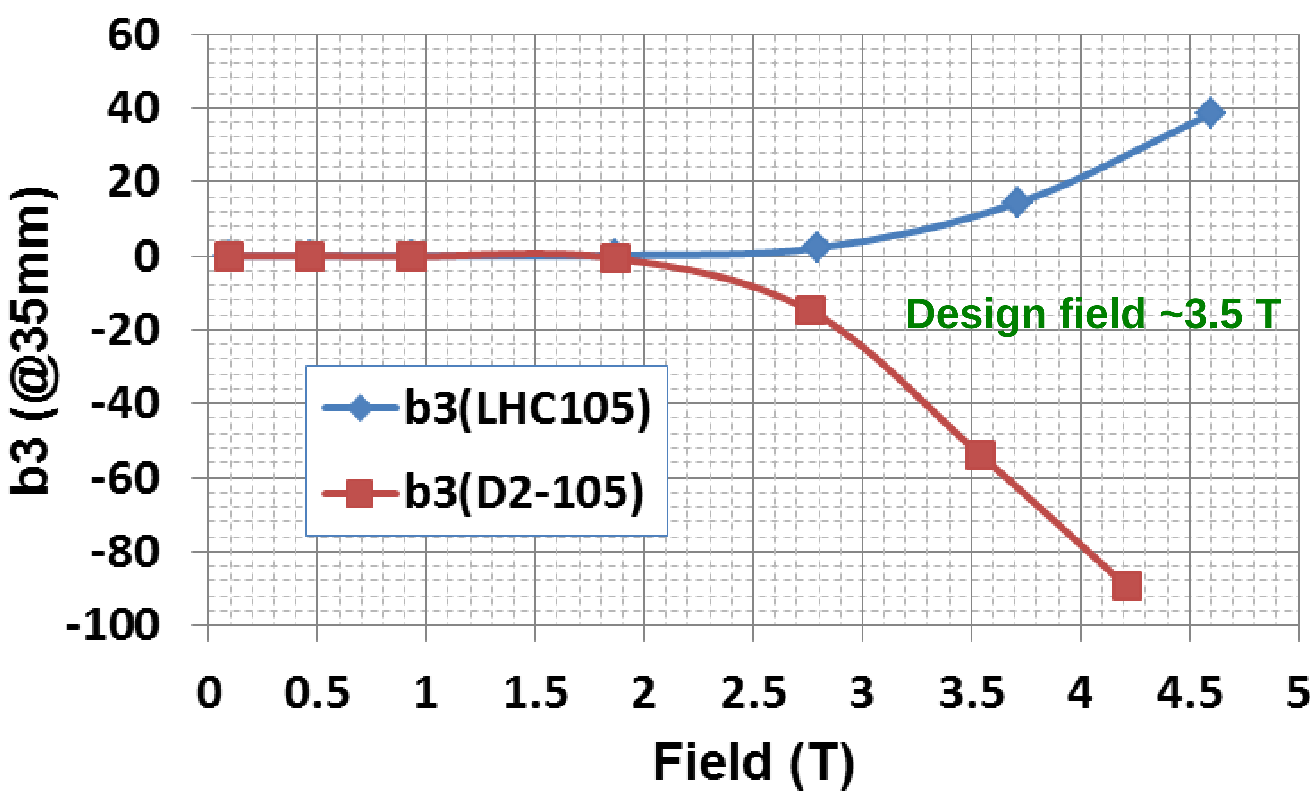
Field in the same direction

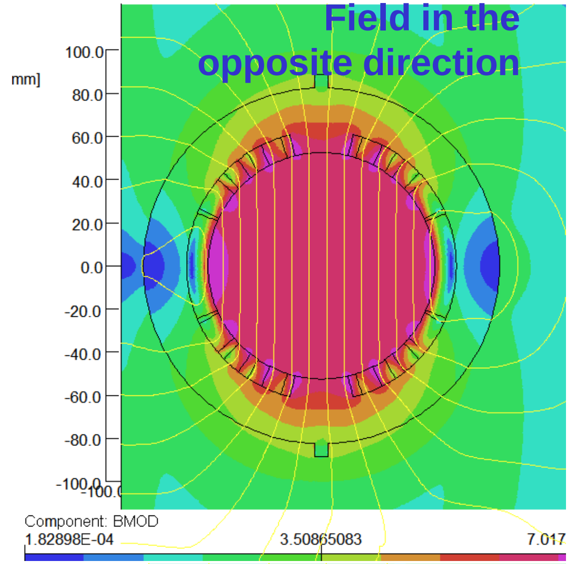


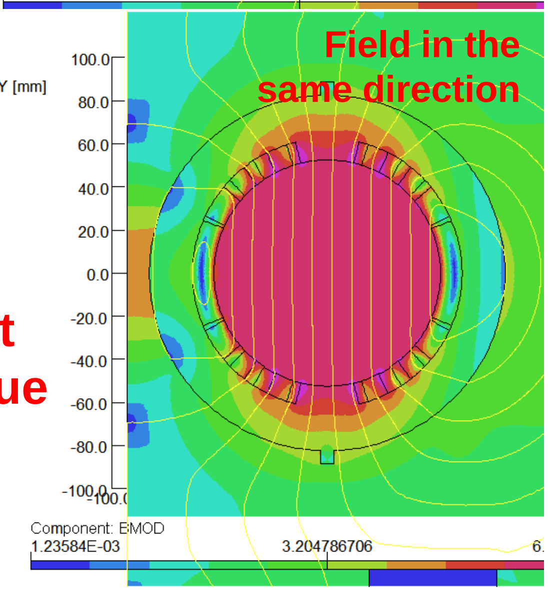
Large cross-talk due to insufficient iron in D2 at midplane between the two apertures.

(also applies to higher order terms such as b_4, b_6, …)

Impact of Relative Polarity (4)
Allowed b_3 (normal saturation)







Saturation induced sextupole (b_3) in D2. Positive in the first case due to pole saturation, negative in the second case due to large midplane saturation because of insufficient iron.

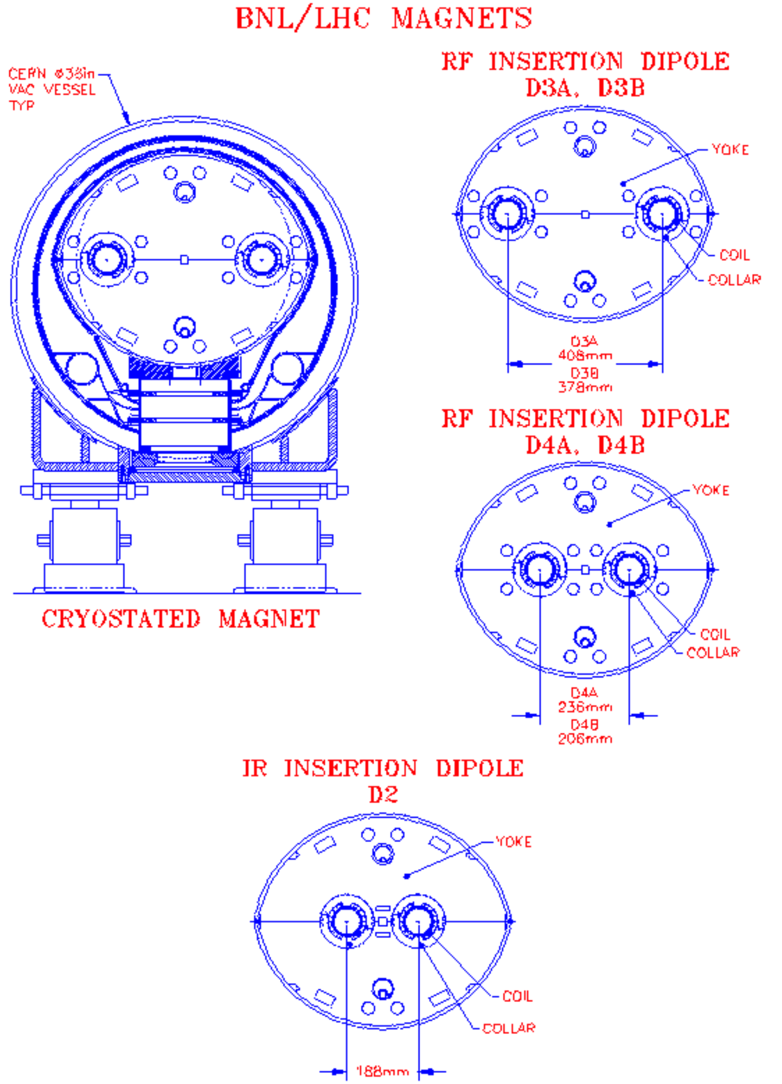
(also applies to higher order terms such as b_5, b_7, …)

Design Approach

- **Optimized yoke to reduce saturation induced harmonics (particularly non-allowed harmonics)**
- **Design coil to cancel the harmonics due to non-circular yoke aperture**
- **Main challenge is the yoke optimization because of larger aperture and the field in the same direction:**
  - **Not enough iron (oblate yoke helps)**
  - **Iron between the two aperture gets saturated**
  - **Over hundred cases examined using a variety of techniques**

Background on Oblate Yoke Option

- **Oblate yoke has now been successfully used in LHC D2/D4**



- This saved significant effort and money by allowi us to use standard LHC cryostat and posts.

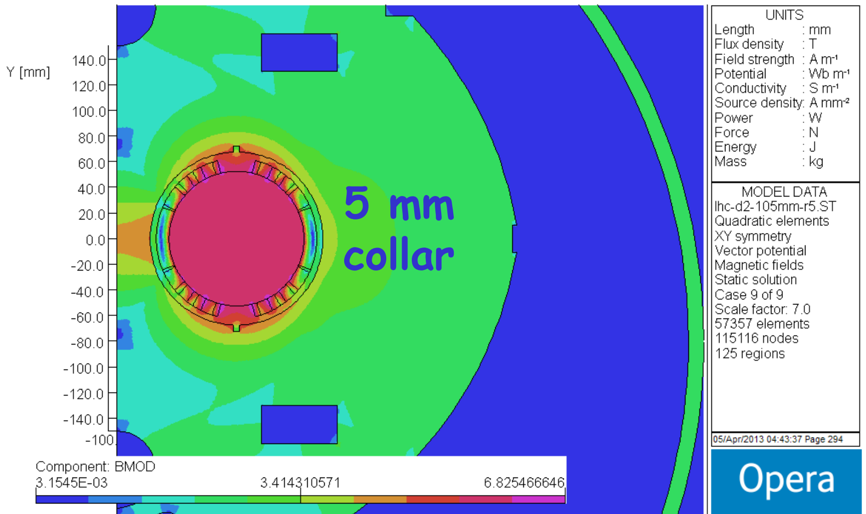
From MT15 Paper

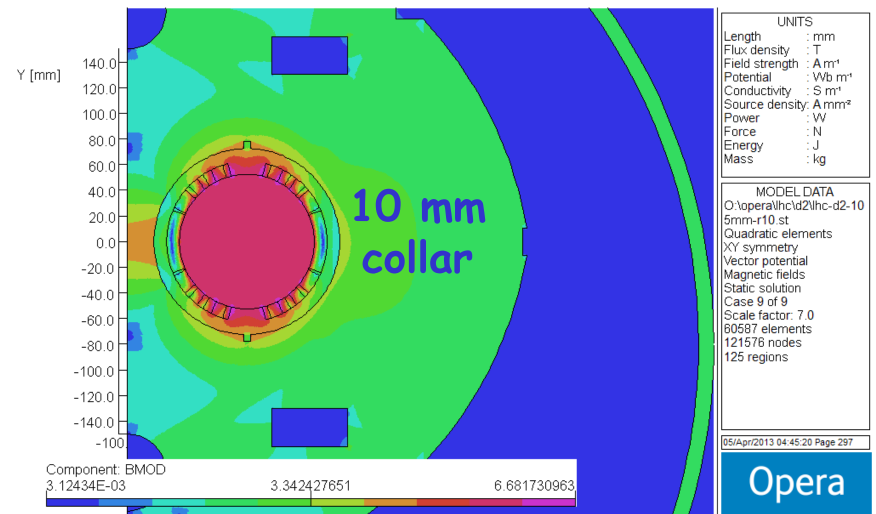
The proposed oblate-shaped yoke also offers a way to reduce the overall cryostat size in future magnets. In most magnets, the horizontal size is determined by the magnetic and mechanical designs and the vertical size is determined by the heat leak budget and post design. The two are then added to determine the overall size. In modifying the circular yoke shape to an oblate shape, yoke iron is removed from the vertical plane, as this material does not contribute to the magnetic and mechanical design. The vertical space, thus saved, can be utilized by the post and thermal shielding, reducing the overall size. The validity of this design will be tested in the first model magnet to be built at BNL prior to the production run of the LHC insertion magnets.

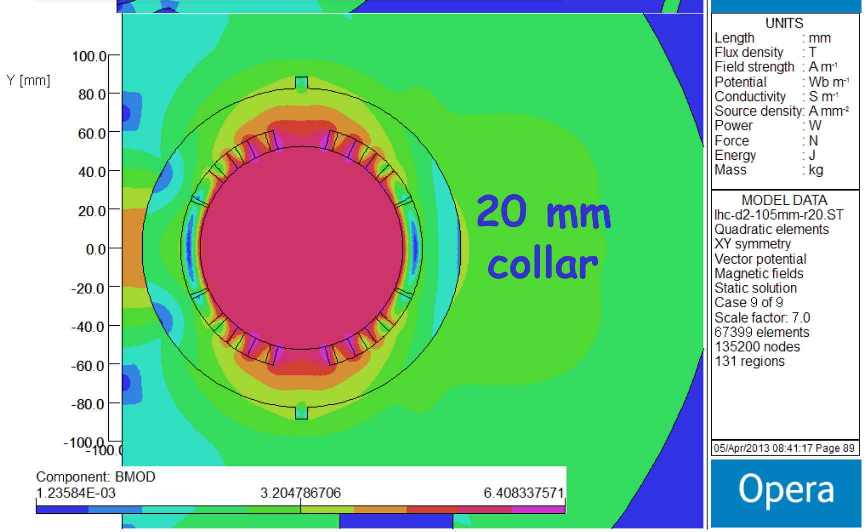
Variation in Collar Width

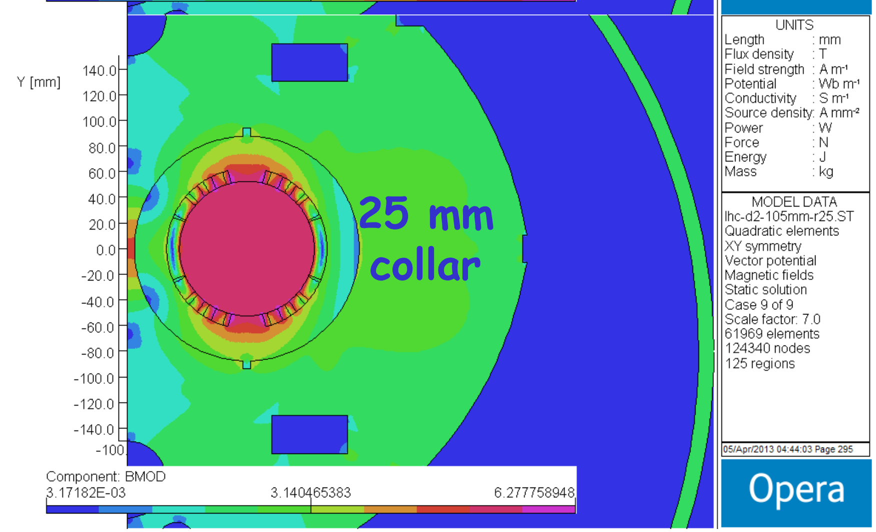
(presented at CM20 – April 2013)

- **Smaller collar allows more iron within the same envelop (caution: has impact on mechanical design).**



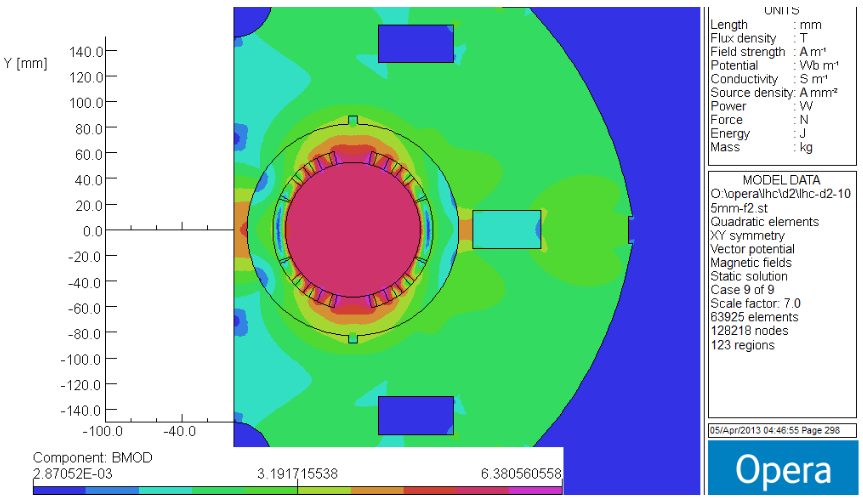


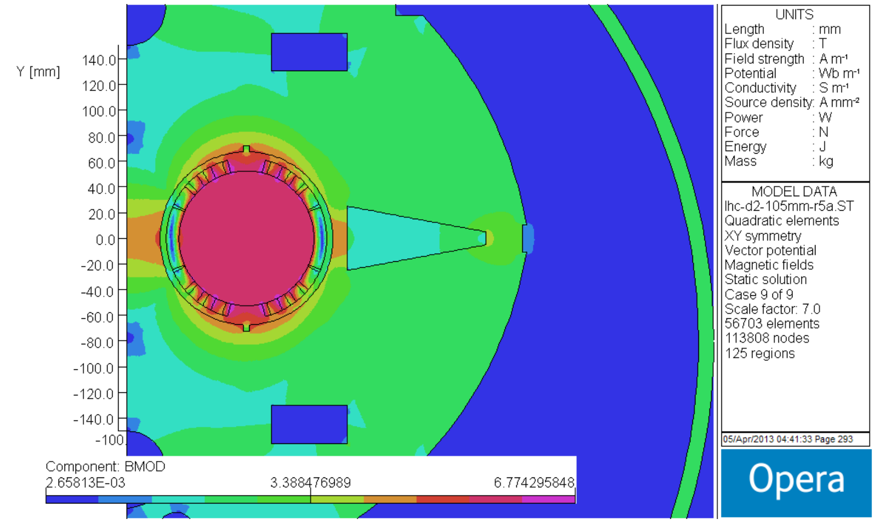


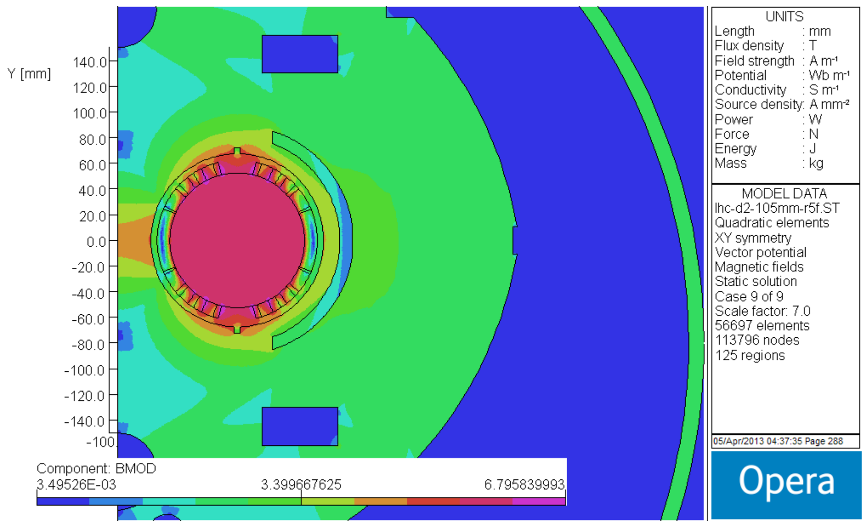


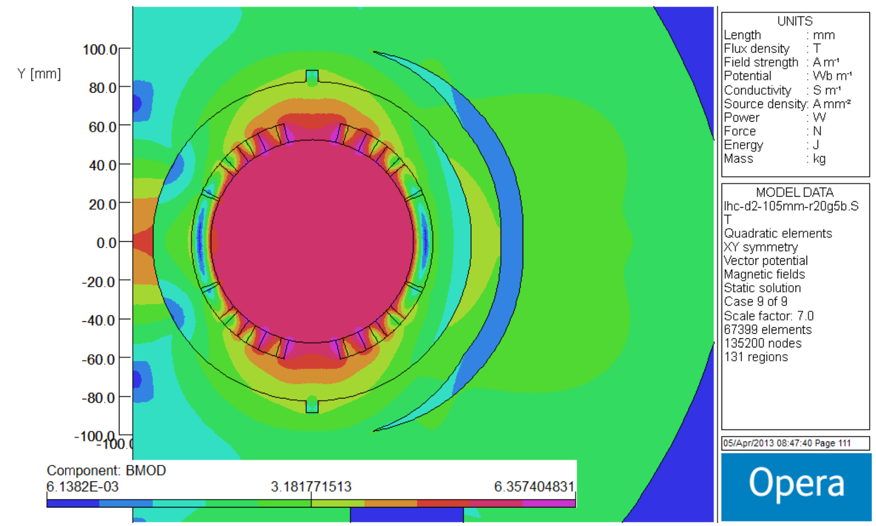
Approaches Previously Examined

A few presented at CM20 – April 2013 (#1)





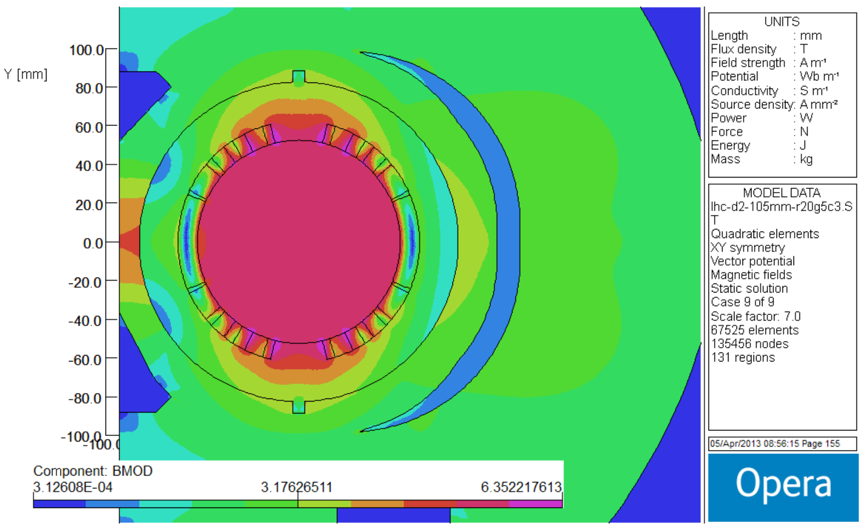


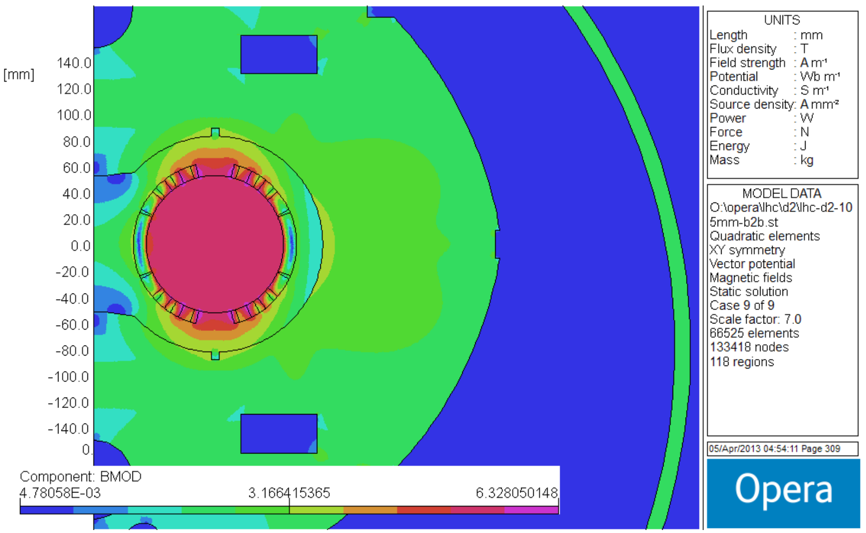


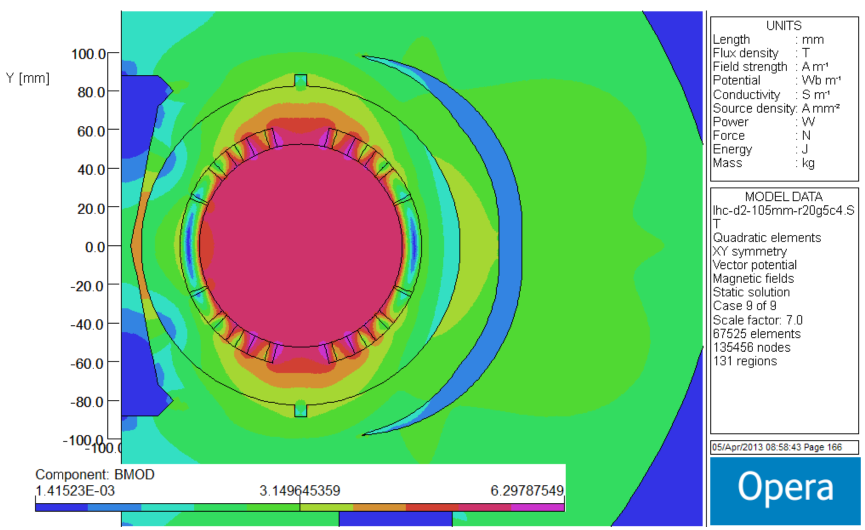
X=4

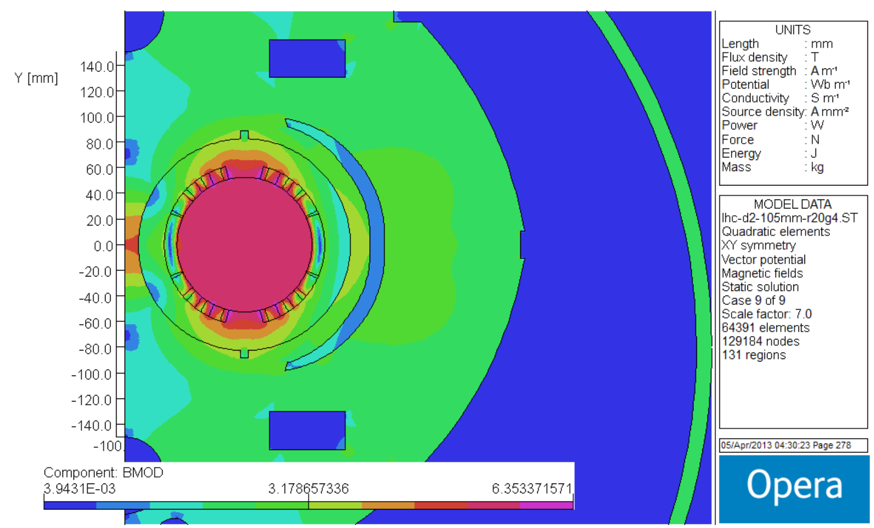
Approaches Previously Examined

A few presented at CM20 – April 2013 (#2)



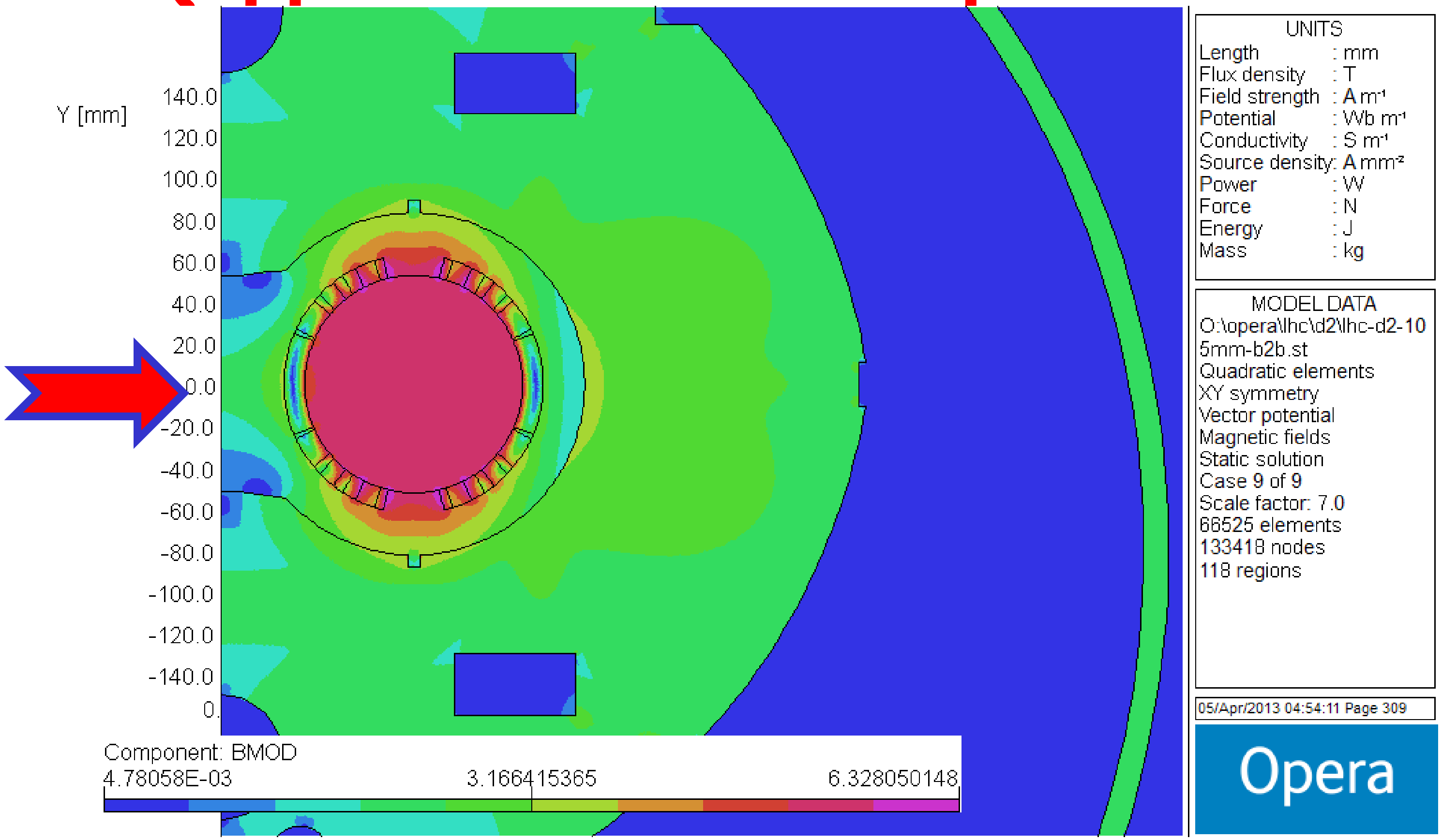






X=4

Iron removed between the two apertures
(approach further optimized now)



δb_2 : +17

δb_3 : -43

δb_4 : +1

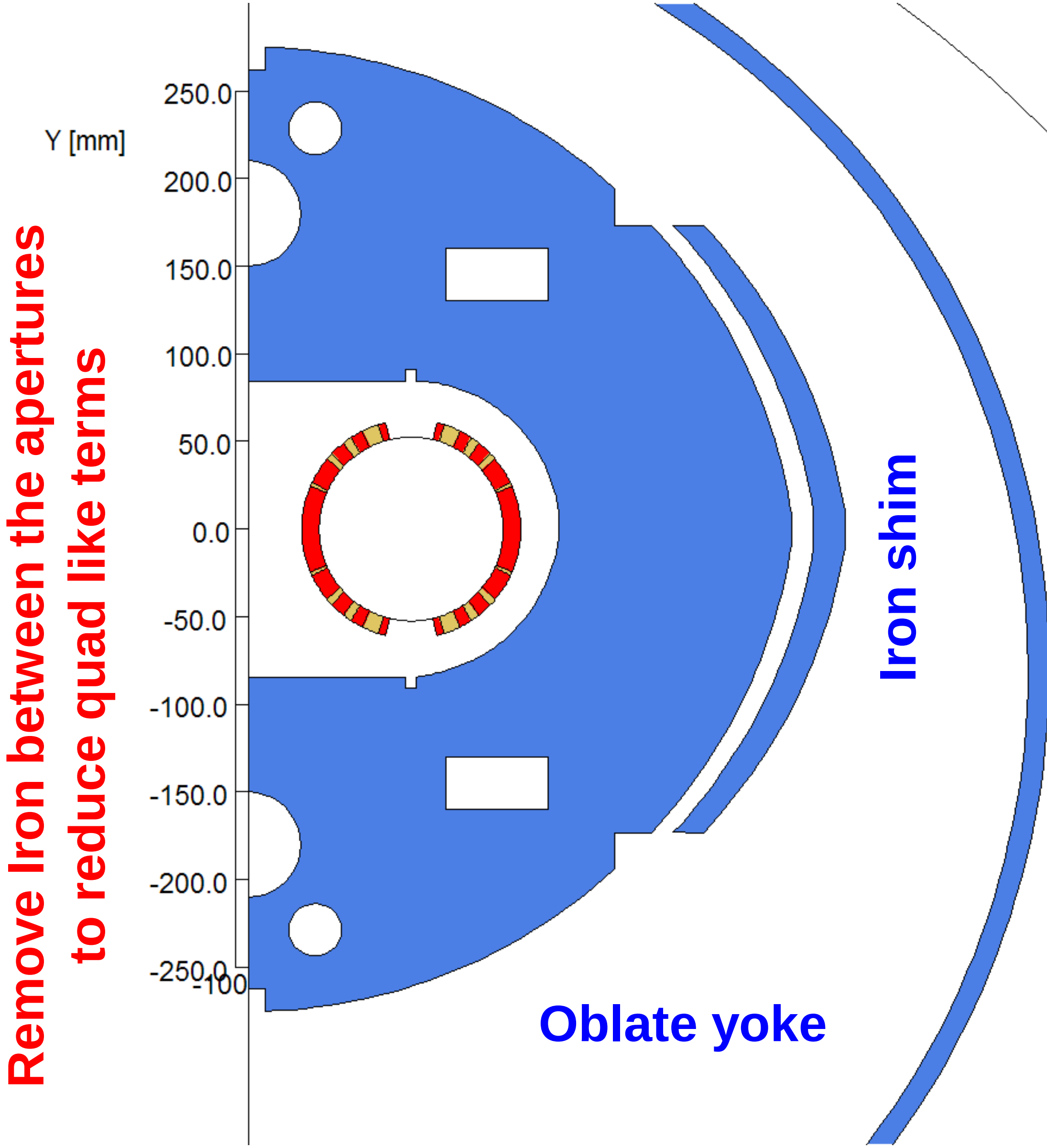
δb_5 : -3

δb_6 : -1

Change in quad term (saturation) becomes half but the absolute value (optimized for circular aperture) for b_2 becomes about 100 unit and for b_4 becomes about 30 unit.

- **To have low base line harmonics, the coil cross-section needs to be re-optimized and to have right-left asymmetry.**

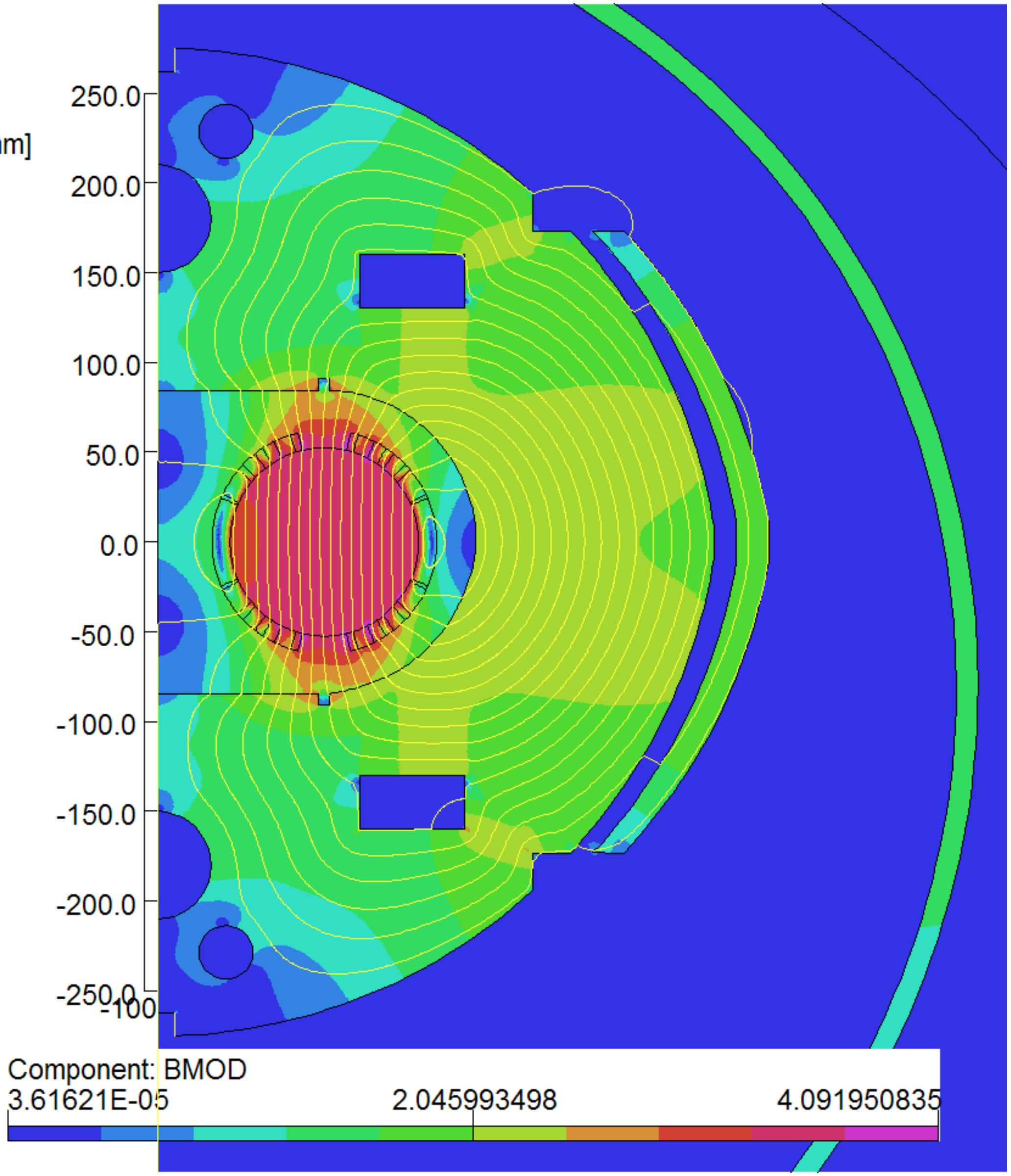
Model



However, add iron to increase transfer function, reduce leakage field and also reduce allowed terms

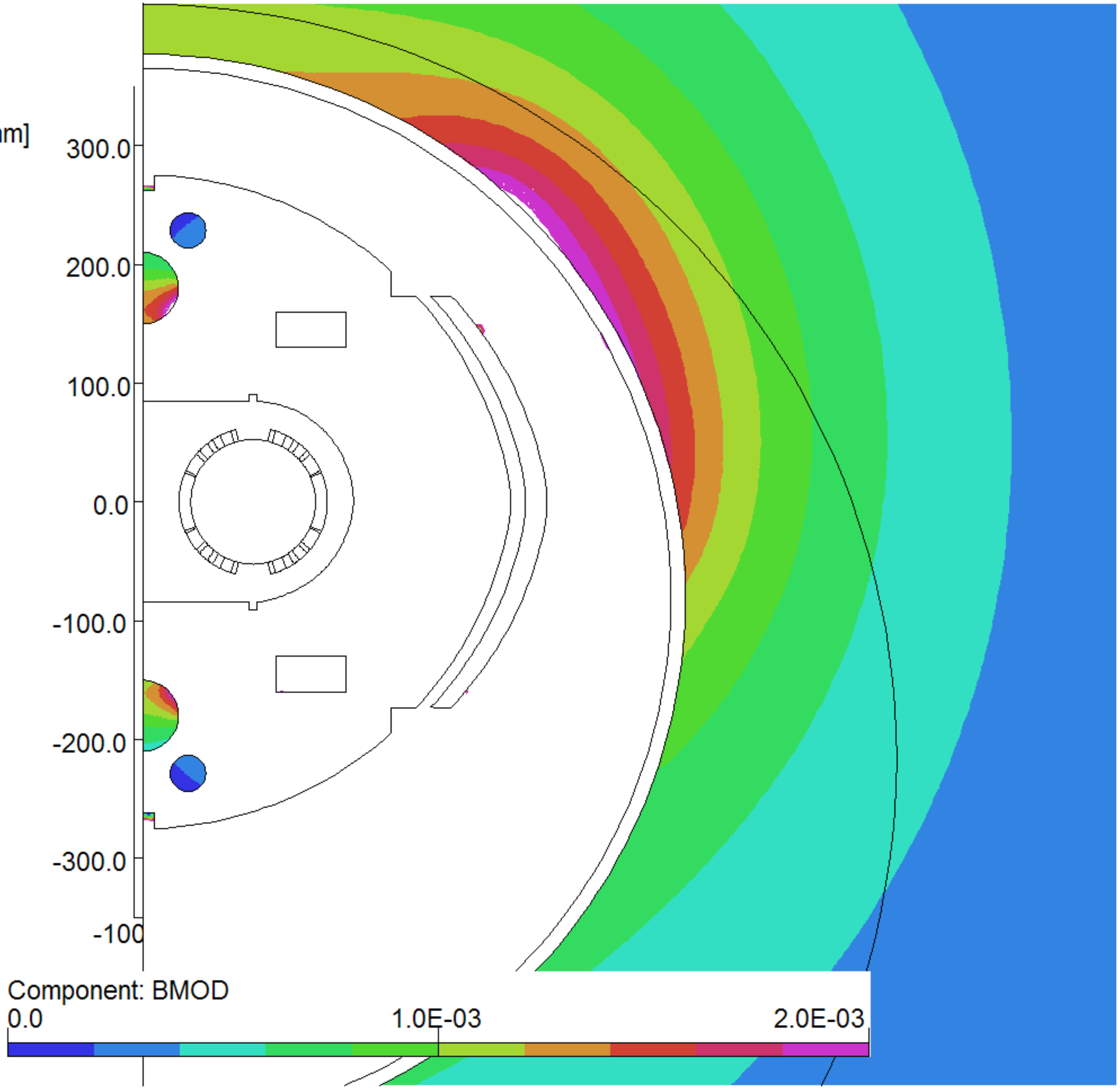
- **Oblate Yoke**
- **Add iron outside the Shell**
  - **as used in the recent D1**

Field and Field Lines at Design



Oblate Yoke and Iron Shims are helping in containing flux lines

Small Leakage Field

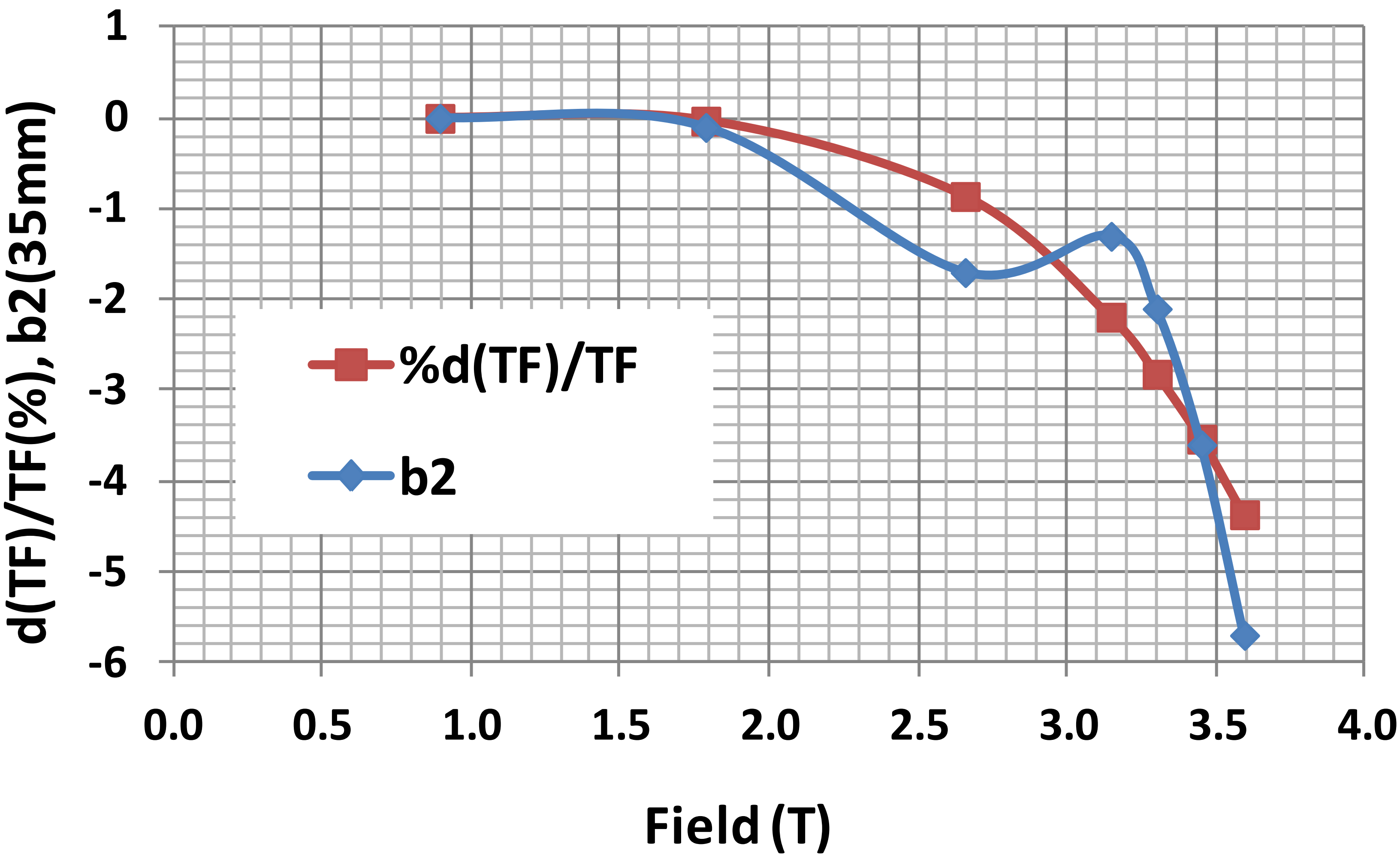


See field outside the cryostat

Maximum scale: 2 mT

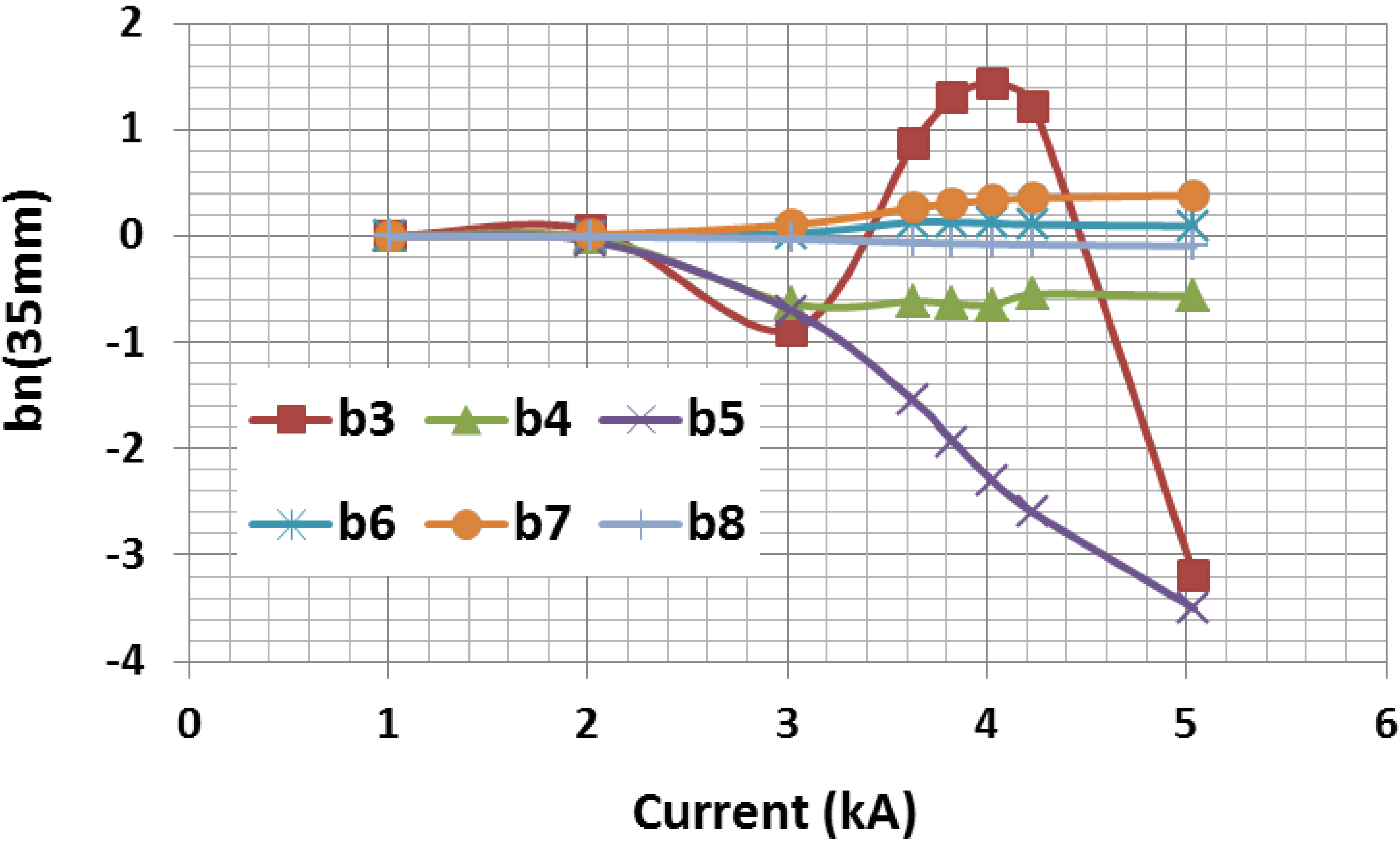
Oblate Yoke and Iron Shims are helping in containing flux

Saturation Harmonics (b_2) at 35 mm and Change in Transfer Function

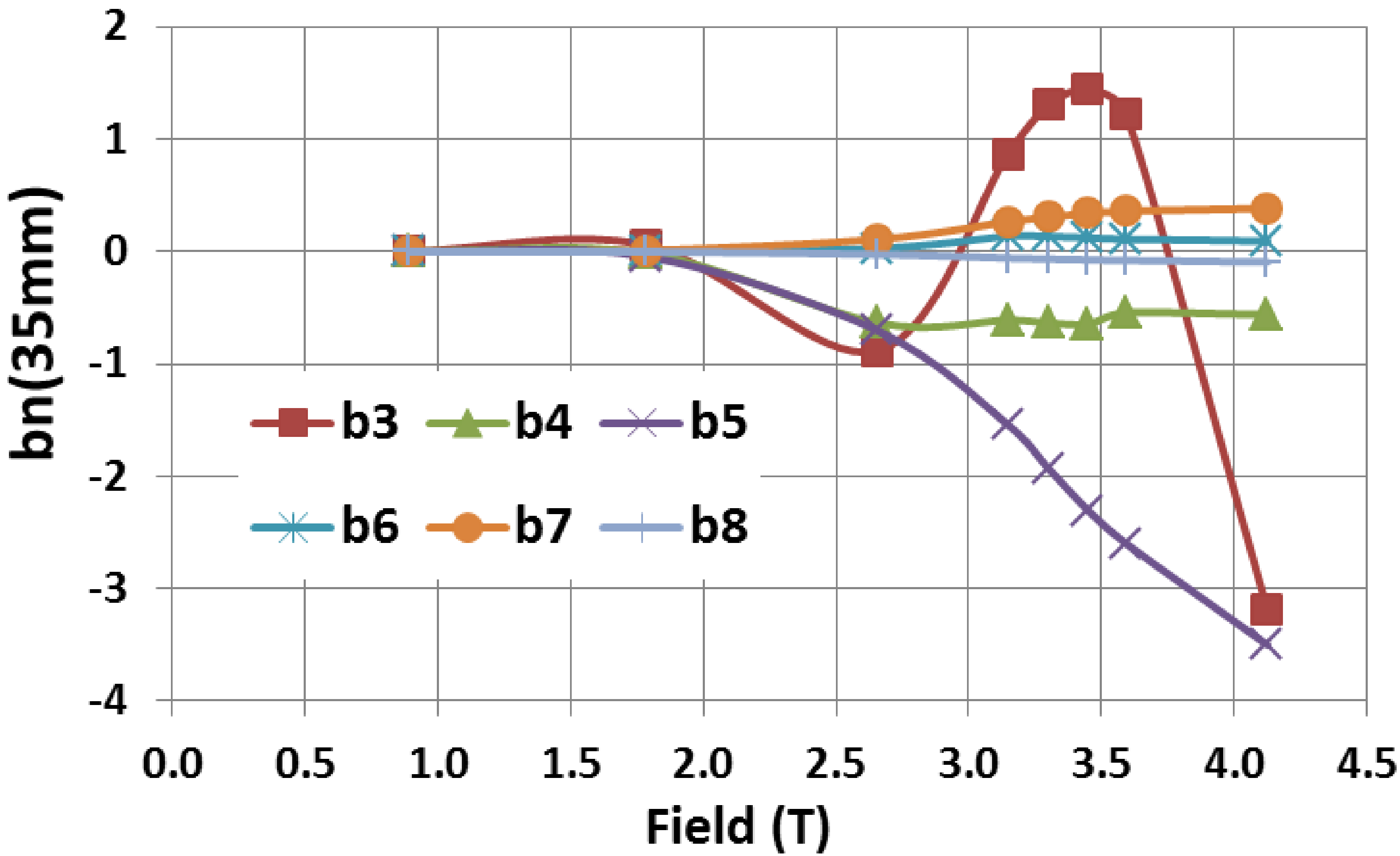


Quad saturation is <5 unit up to 3.5 T. Loss in Transfer Function is <5% even with significant contribution from iron.

Saturation Harmonics at 35 mm as a Function of Current



Saturation Induced Harmonics (b_3-b_8) at 35 mm as a Function of Field



~ 3 units up to 4 T (design field is 3.5 T)

Summary of Results (Preview)

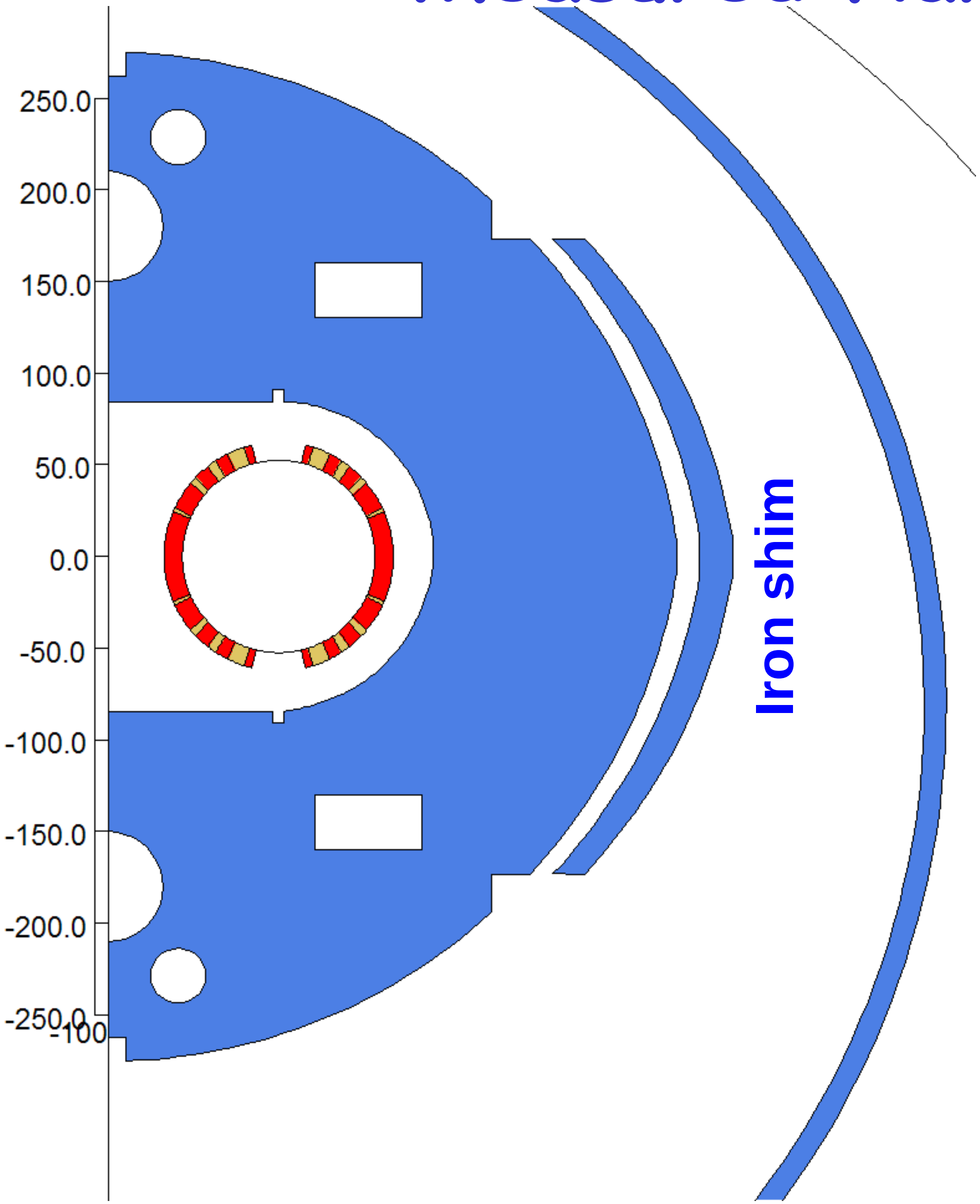
	Recombination dipole D2 field quality version 1.4 - October 1 2013 - R_{ref}=35 mm								
	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
2	0.000	25.000	0.000	0.000	25.000	0.200	2.500	0.200	2.500
3	18.000	-15.000	-14.200	3.800	3.000	0.727	-1.500	0.727	-1.500
4	-8.000	10.000	0.000	-8.000	2.000	0.126	0.200	0.126	0.200
5	4.000	-5.000	-1.000	3.000	-1.000	0.365	-0.500	0.365	-0.500
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Saturation induced harmonics

Harmonic	Previous Recommendations	Optimized Design
b_2	25	<4
b_3	15	<2
b_4	10	<1
b_5	5	<3

- **Higher orders are < 1 units**

Use of Iron Shims to Minimize Measured Harmonics



- Iron Shim outside the Helium vessel is placed to provide critical extra iron over the oblate shape.
- This shim can also be used to obtain low harmonics at high fields despite the differences between the calculations and measurements for b_3.
- This approach has been successfully used in recent LHC D1 dipole built at BNL.

Method Used in Adjusting b_3 at High Field In Recent LHC D1 Dipole Built at BNL

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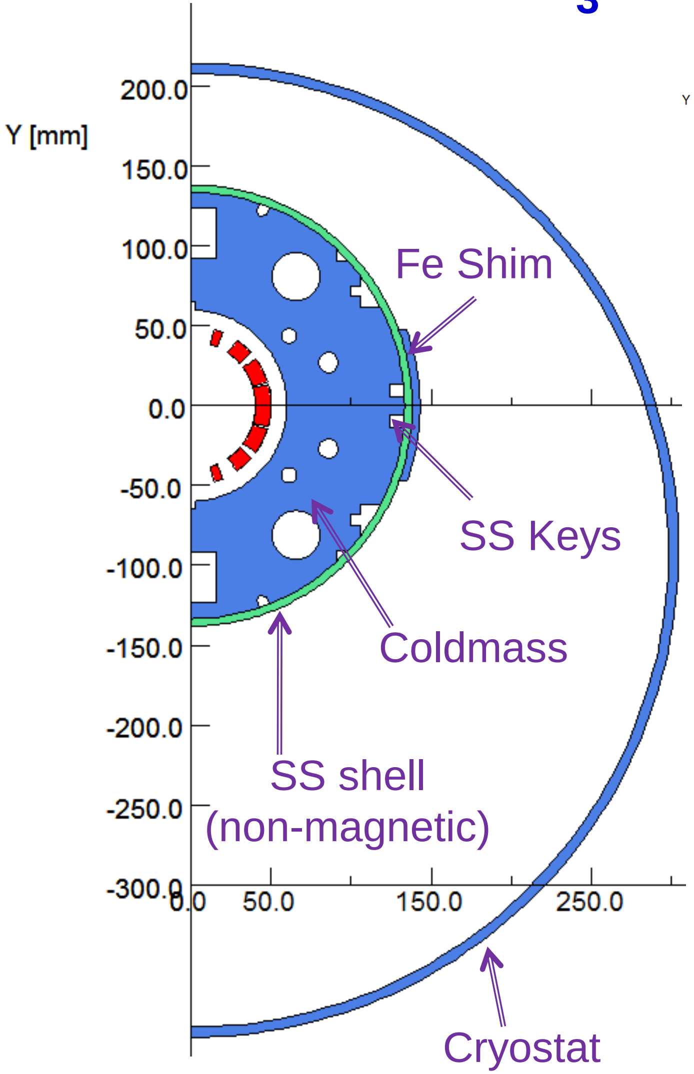
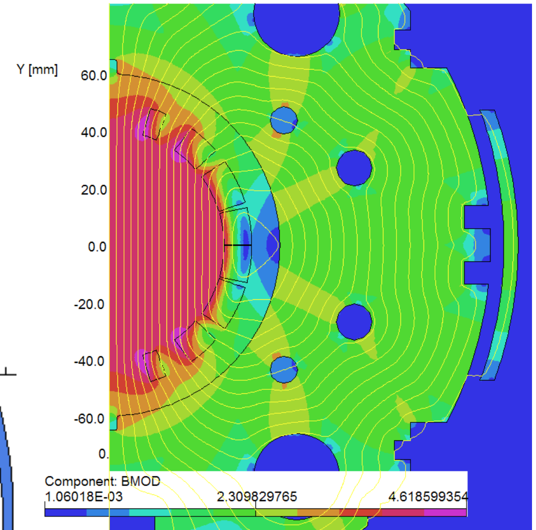
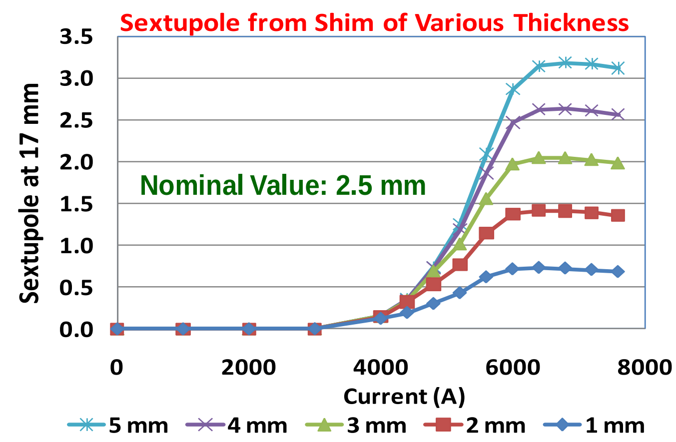
Saturation b_3 is adjusted by adjusting shim thickness







Simple, economical and yet powerful method to adjust saturation-induced harmonics in as built dipoles – no need to cut the weld of helium vessel, etc.

LHC 80 mm APUL D1 Dipoles #106 & #107 built at BNL

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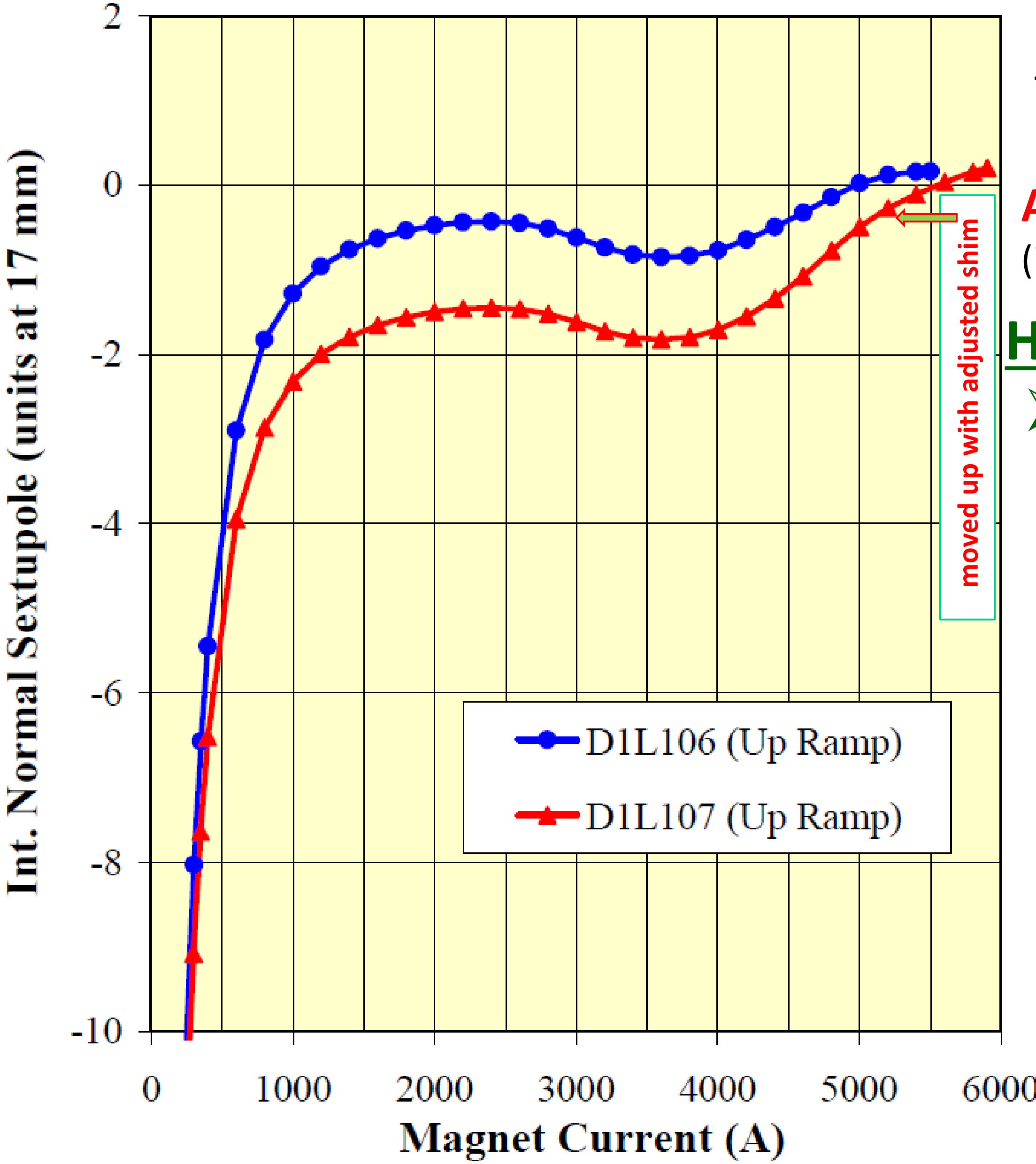


Program Goal:

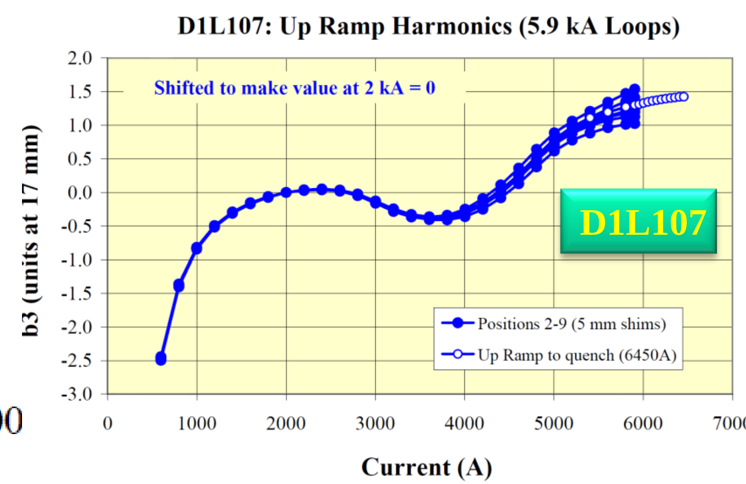
Sextupole < 2 unit @5600

Achieved: ~ 0.2 unit @5600 in both

(initial adjustment was made with pole shims)

Highlights of the Technique:

- **Adjustable iron shims outside Helium vessel moved sextupole (b_3) to near zero at high fields**



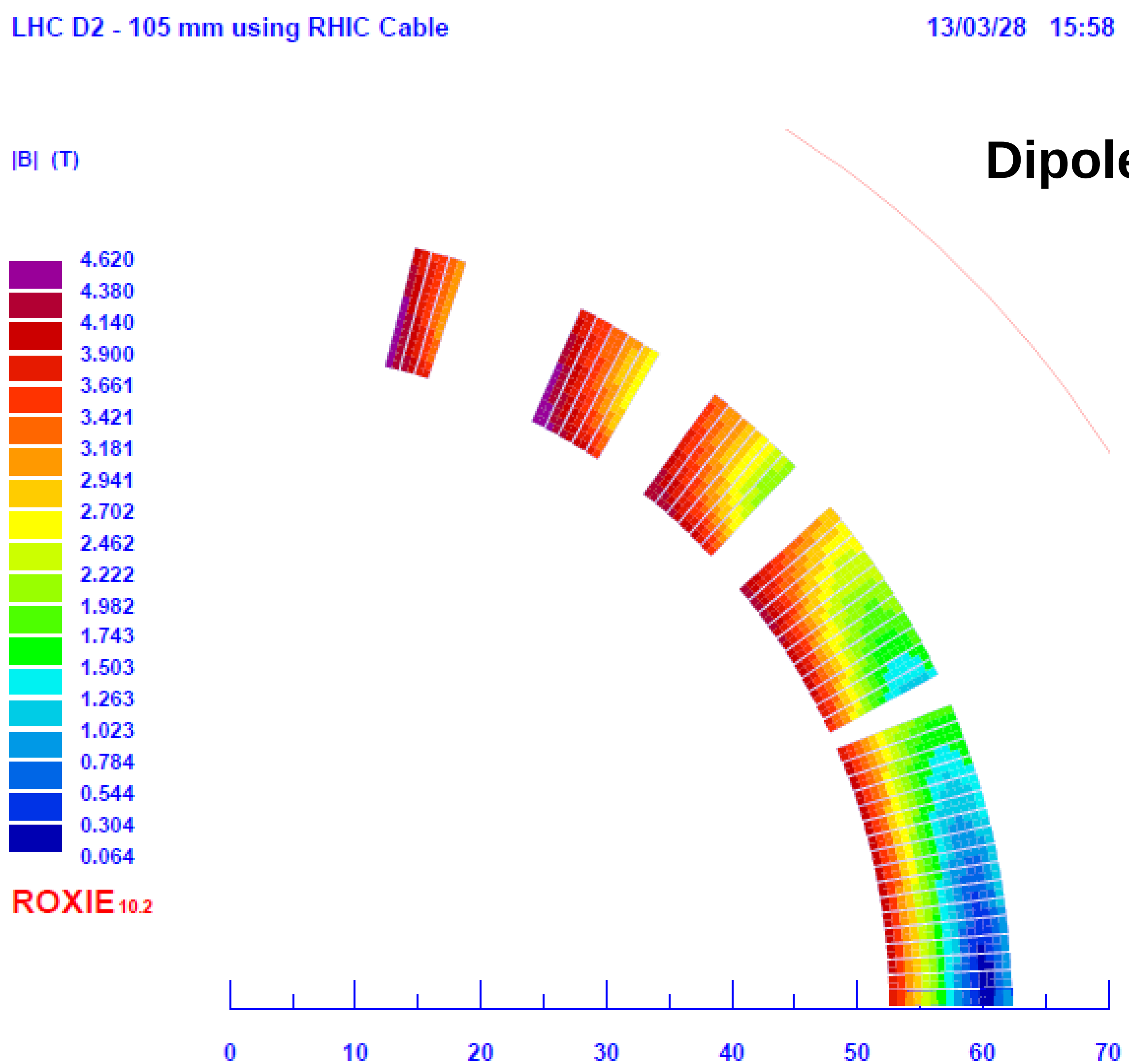
Measured data courtesy Animesh Jain

Coil Cross-section Design

- The aperture of RHIC insertion dipole D0 is100 mm. This is very close to 105 mm.
- RHIC D0 is a fully optimized and proven design. Several good field quality magnets have been built.
- Therefore, a reasonable starting point could be to scale and tweak the coil design of RHIC D0.
- RHIC 100 mm D0 had 40 turns in five blocks. Allow 42 turns in five blocks of the 105 mm LHC D2 coil.
- Use ROXIE to fine tune the coil cross-section.
- First start with the cross-section having dipole symmetry.
- Then adjust it to compensate for the non-zero harmonics.

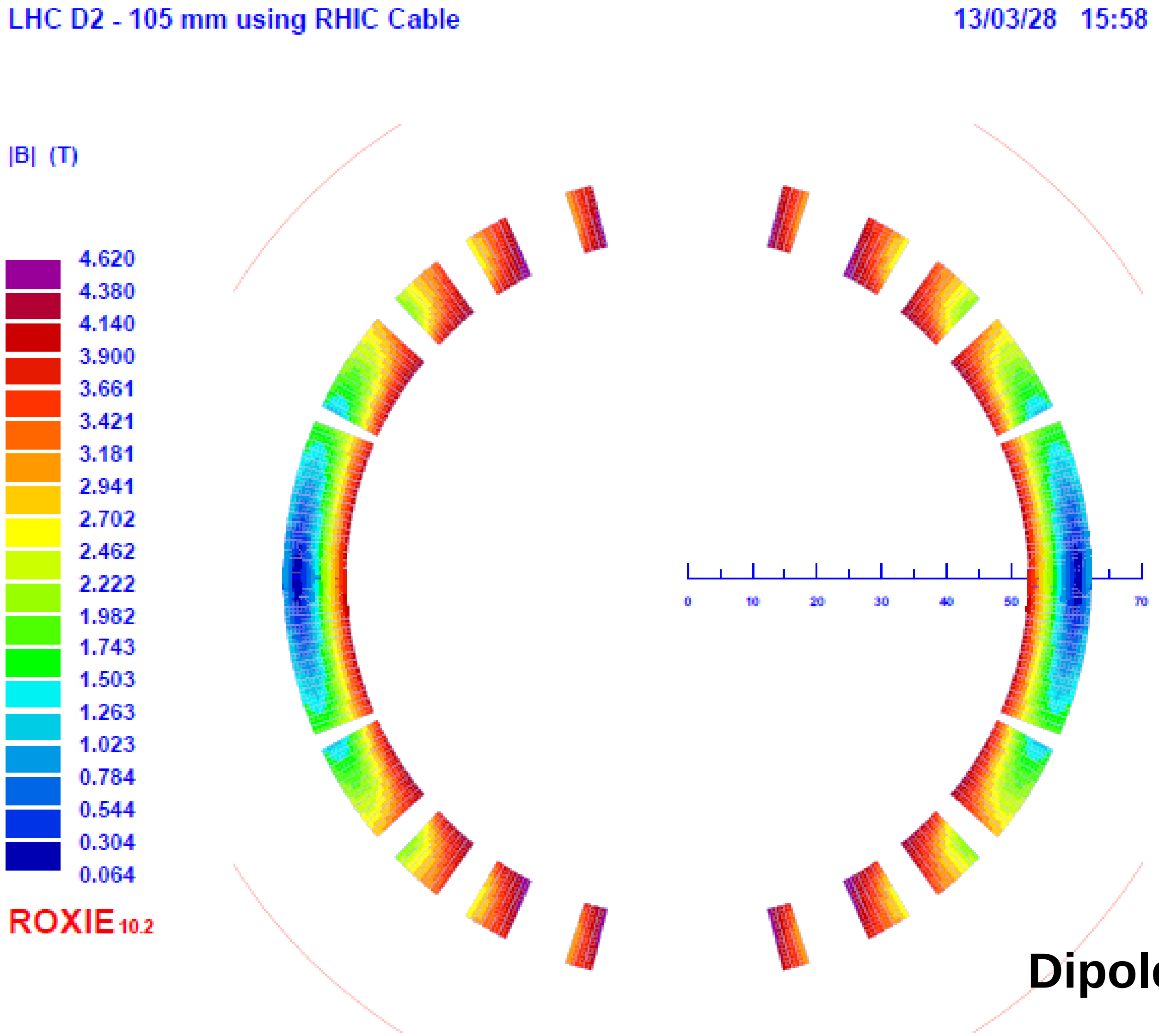
LHC 105 mm D2 Coil Cross-section

(optimized with ROXIE for circular yoke)



Dipole symmetry

LHC 105 mm D2 Coil Cross-section



Dipole symmetry

105 mm D2 Coil Harmonics @35 mm

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Optimization with ROXIE

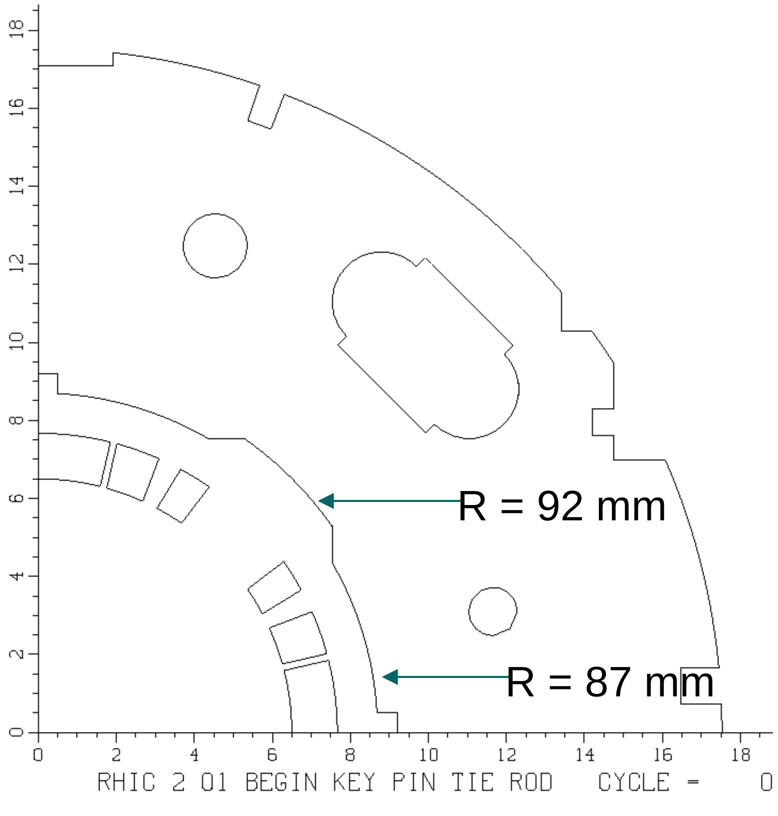
```
REFERENCE RADIUS (mm) ..............................    35.0000
X-POSITION OF THE HARMONIC COIL (mm) ...............     0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ...............     0.0000
MEASUREMENT TYPE ........................ ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ...................  0.2045E-02
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .....................................  -4.109409
MAGNET STRENGTH (T/(m^(n-1)) .......................    -4.1094

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:      0.00000  b 3:      0.03316
b 4:      0.00000  b 5:      0.03930  b 6:      0.00000
b 7:      0.14095  b 8:      0.00000  b 9:      0.14324
b10:      0.00000  b11:      0.48417  b12:      0.00000
b13:      0.39692  b14:      0.00000  b15:     -0.20657
b16:      0.00000  b17:     -0.35482  b18:      0.00000
b19:      0.07375  b20:      0.00000  b
```

Dipole symmetry

Optimization of Coil X-section with Non-Zero Geometric Harmonics



POISSON model of a quadrant of the 130 mm aperture RHIC IR quad

- Saturation in RHIC IR Quad was minimized with removing significant amount of saturating iron from the pole (similar challenge as here).
- The coil cross-section was re-optimized to compensate for the non-zero harmonics for a symmetric iron.
- We would use a similar approach in LHC 105 mm D2 dipole facing a similar challenge.

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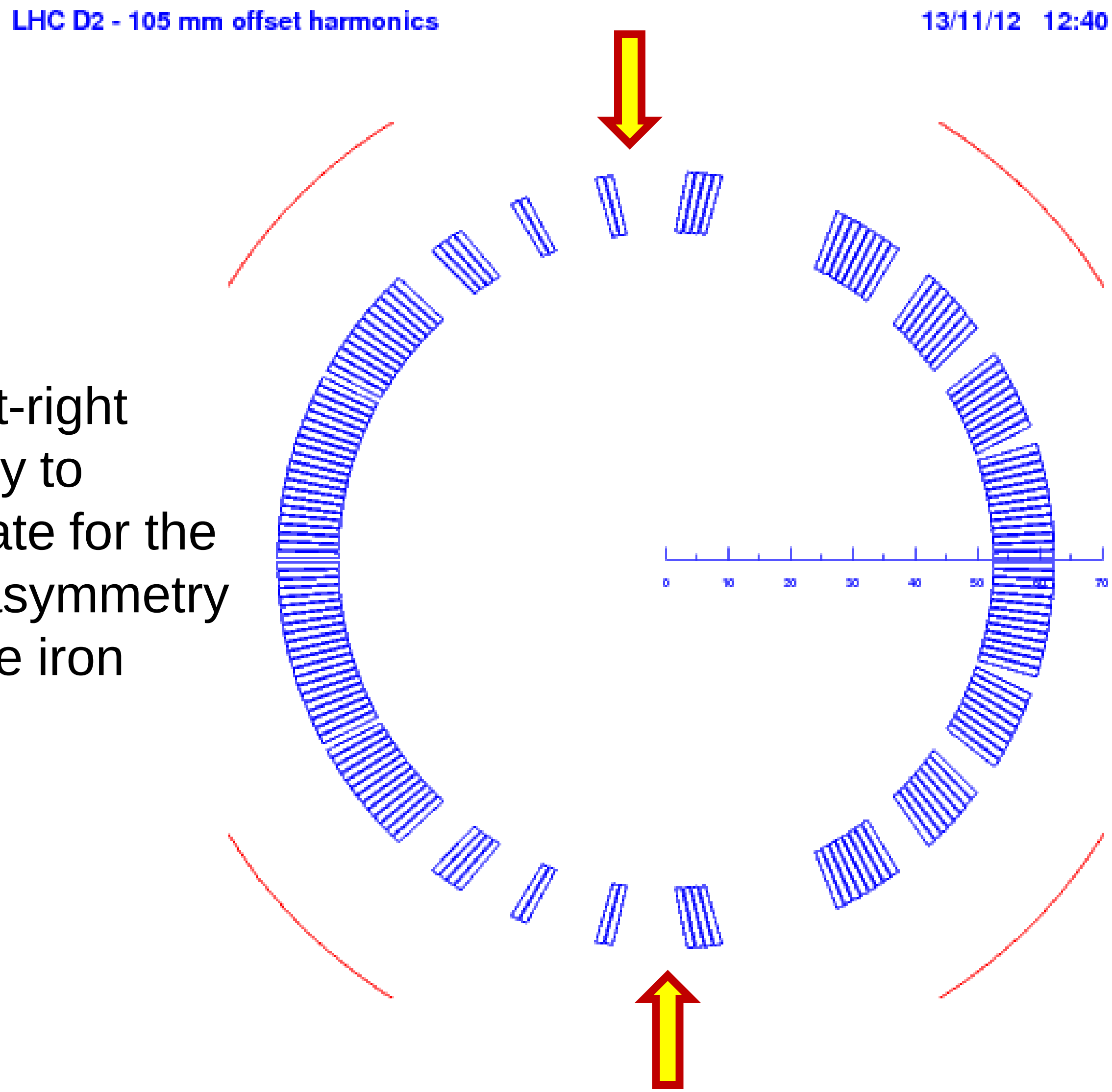
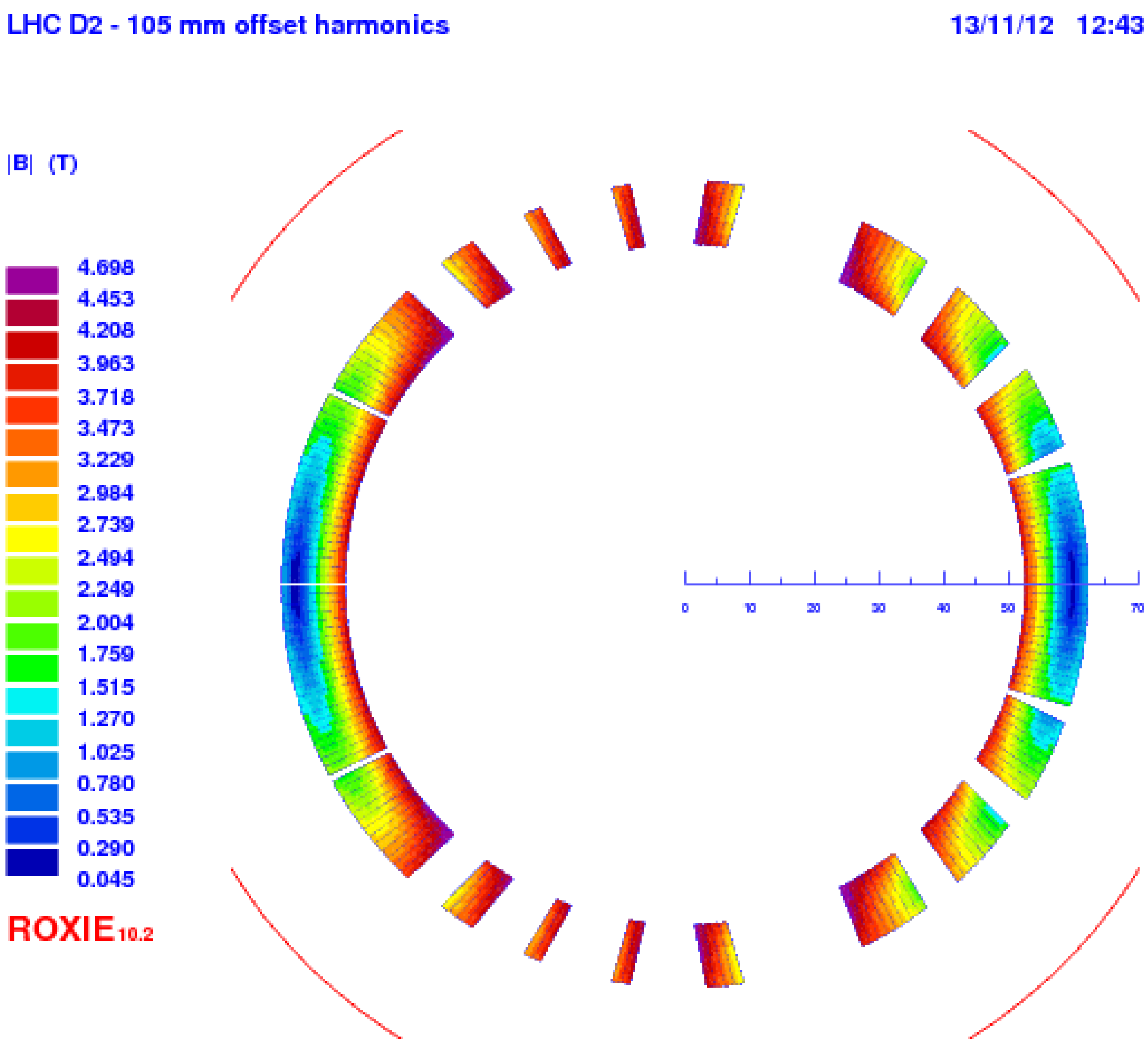
Coil to Off-set Non-zero Geometric Harmonics (1)



Note a left-right asymmetry to compensate for the left-right asymmetry in the yoke iron

The goal is to have small low field harmonics and ideally zero harmonics at the design field

Coil to Off-set Non-zero Geometric Harmonics (2)



Deliberate left-right asymmetry

SUMMARY

- Large increase in flux (over 31% due to increase in aperture - 80 mm to 105 mm) and field in the same direction makes the optimization of the yoke very challenging for the allowed and non-allowed harmonics.
- However, a technique has been developed (oblate yoke, missing iron between the aperture and extra iron outside the shell) that, in principle, can make the 105 mm dipole with low saturation induced harmonics (both allowed and non-allowed) and small fringe fields.
- Iron shim outside the Helium vessel can also be used to reduce measured b_3 – making the design even more dependable.
- With a properly optimized coil design, the expected harmonics can be reduced by a large amount over what was previously expected.