Conceptual Magnetic Design of 105 mm Aperture Dipole D2

Ramesh Gupta
Brookhaven National Laboratory

April 10, 2013

Main Goals of D2 Magnetic Design

<u>Baseline specifications and performance targets (CERN):</u>

- Aperture: 105 mm
- Inter-beam distance: 186 mm

  (note this is different from 192 mm nominal LHC)
- Target operating point on load-line: 70%
- Integrated field: 35 T.m
- Magnetic length: below 10 m

  (there is interest in a shorter magnet, say around 8 m, if possible)

Background

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

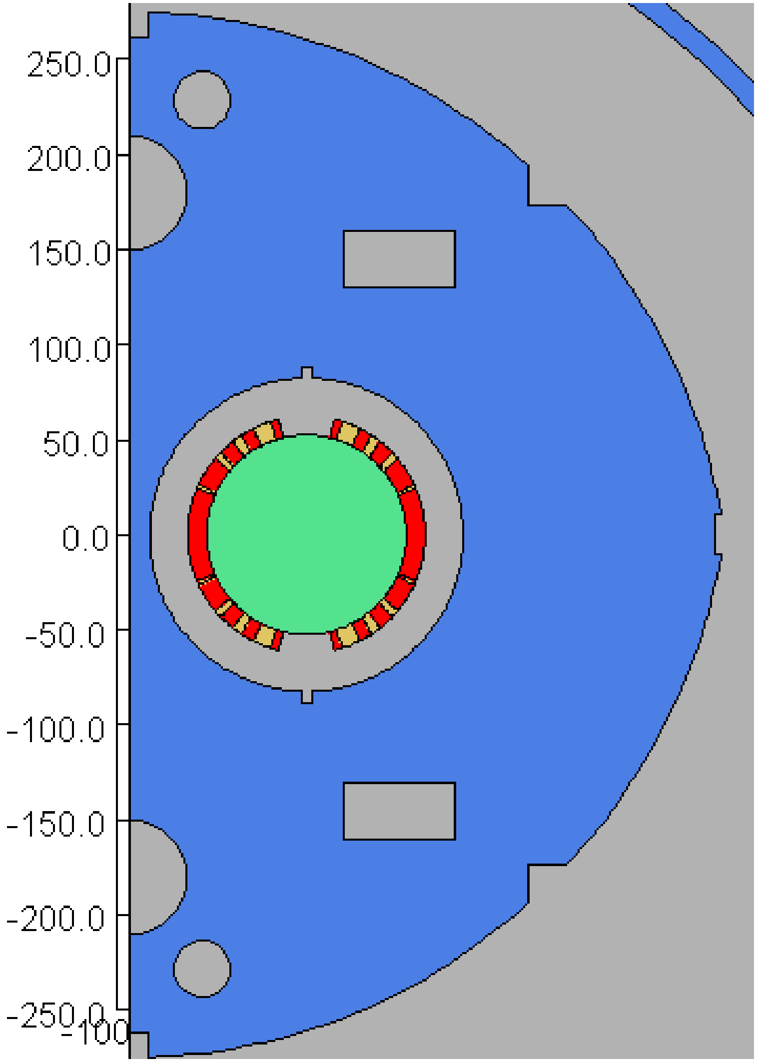
- Significantly larger aperture (105 mm instead of 80 mm)
  - ❖ over 31% more flux for similar overall yoke and cryostat
- Smaller spacing (186 mm instead of 188 mm)
  - ❖ less iron (21 mm instead of 48) between two apertures for more flux makes cross-talk at higher field a particular challenge

Iron Yoke for 2-in-1 Dipole
(with field in the same vs. opposite direction)

LARP

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

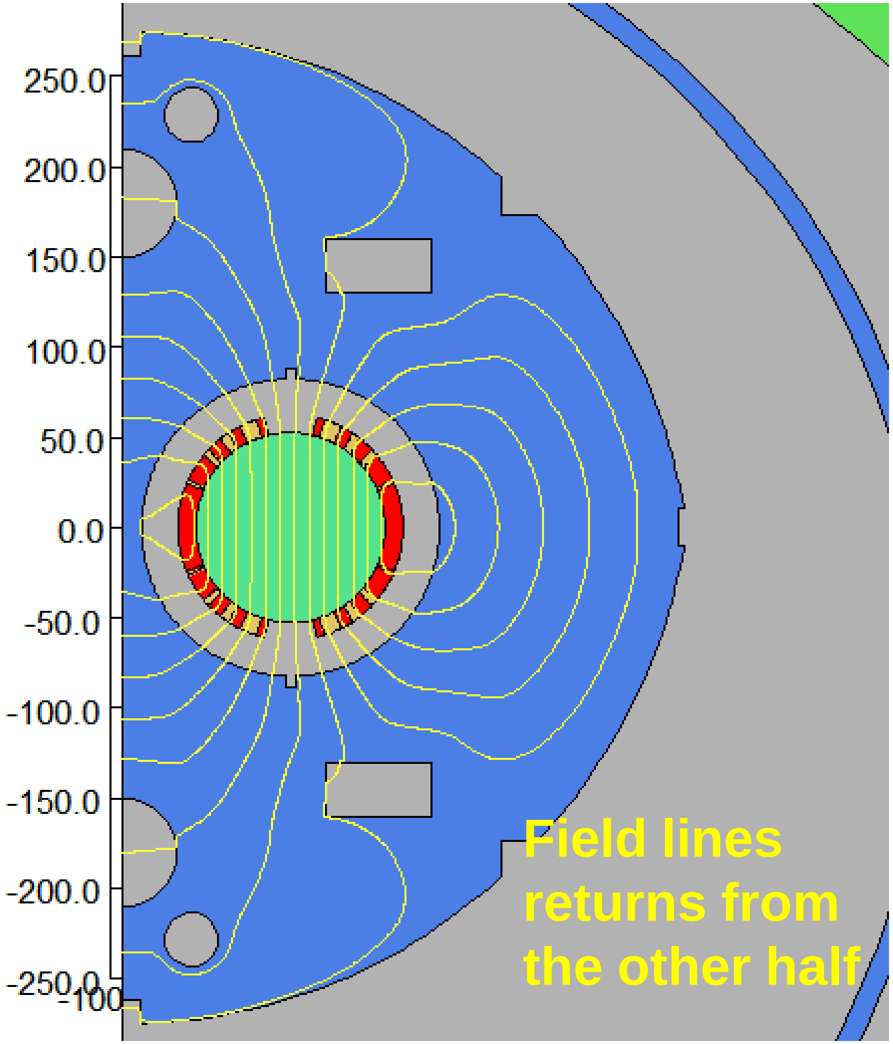
Right-half of the x-section



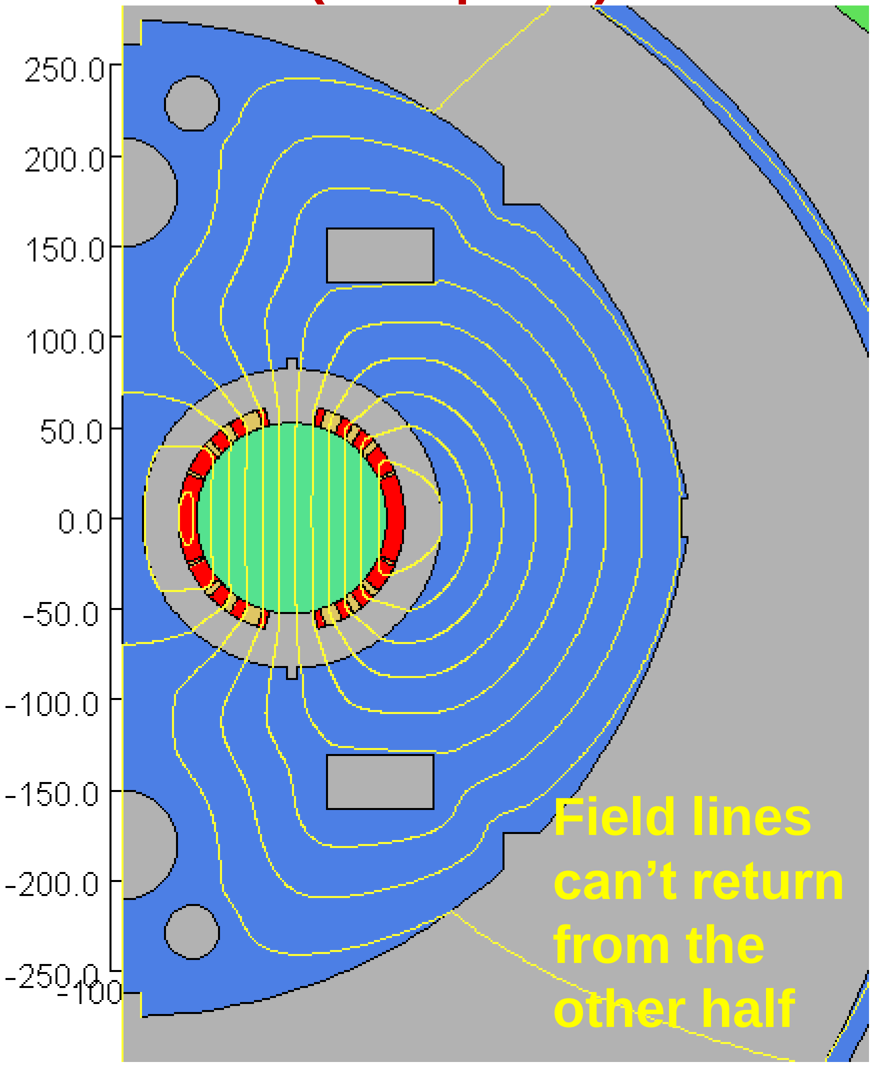
- Like LHC main dipole, LHC insertion D2 is also a 2-in-1 dipole.
- In main ring dipoles, however, the field in two apertures is in opposite direction allowing one side to provide return flux path to the other.
- This is not the case in D2 since the field is in the same direction. This means that the 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. Let's examine this in 105 mm which has more flux and less spacing.

Impact of Relative Polarity (1)

Field in the opposite direction (LHC main dipoles)



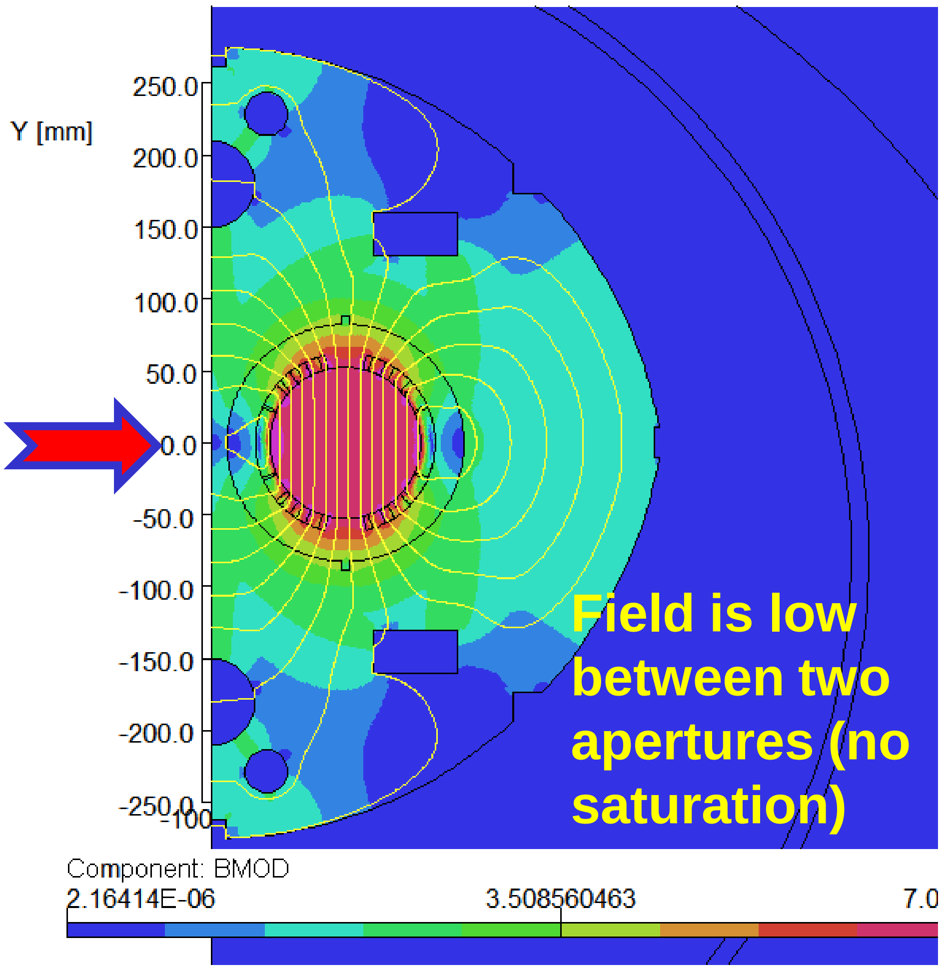
Field in the same direction (D2 dipoles)

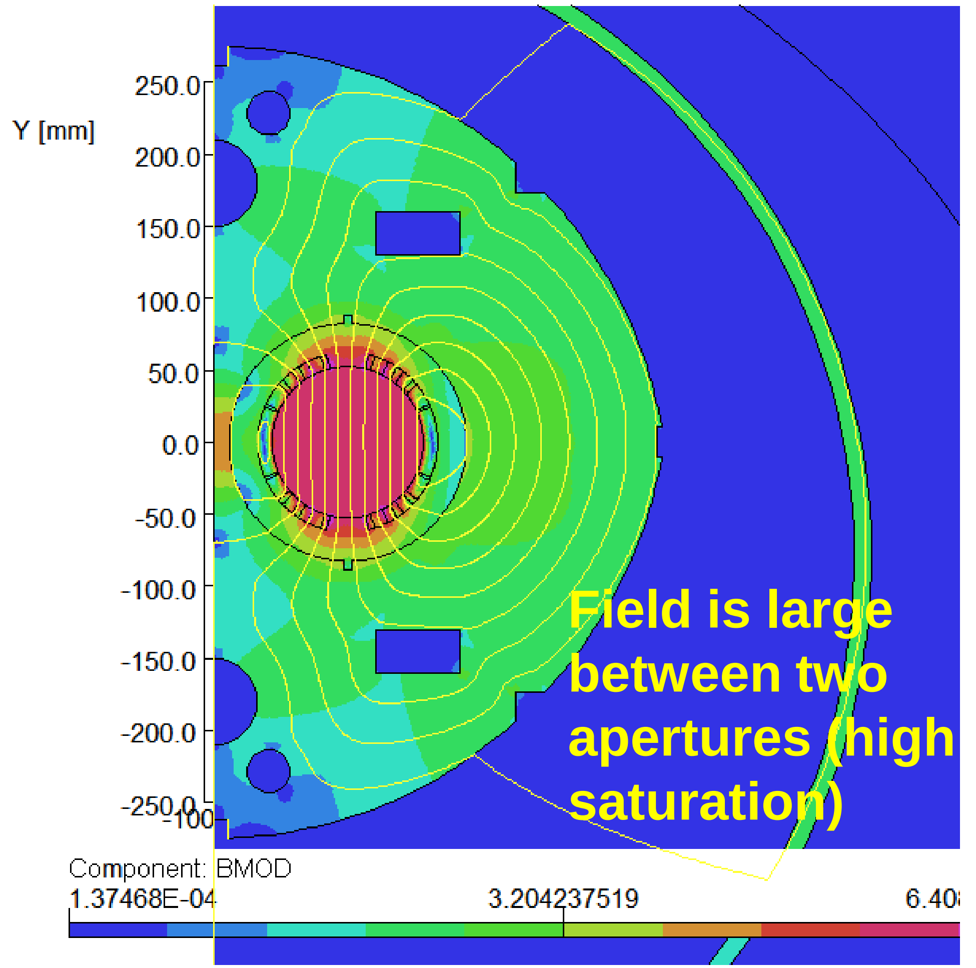


Impact of Relative Polarity (2)

Field in the opposite direction (LHC main dipoles)

Field in the same direction (D2 dipoles)



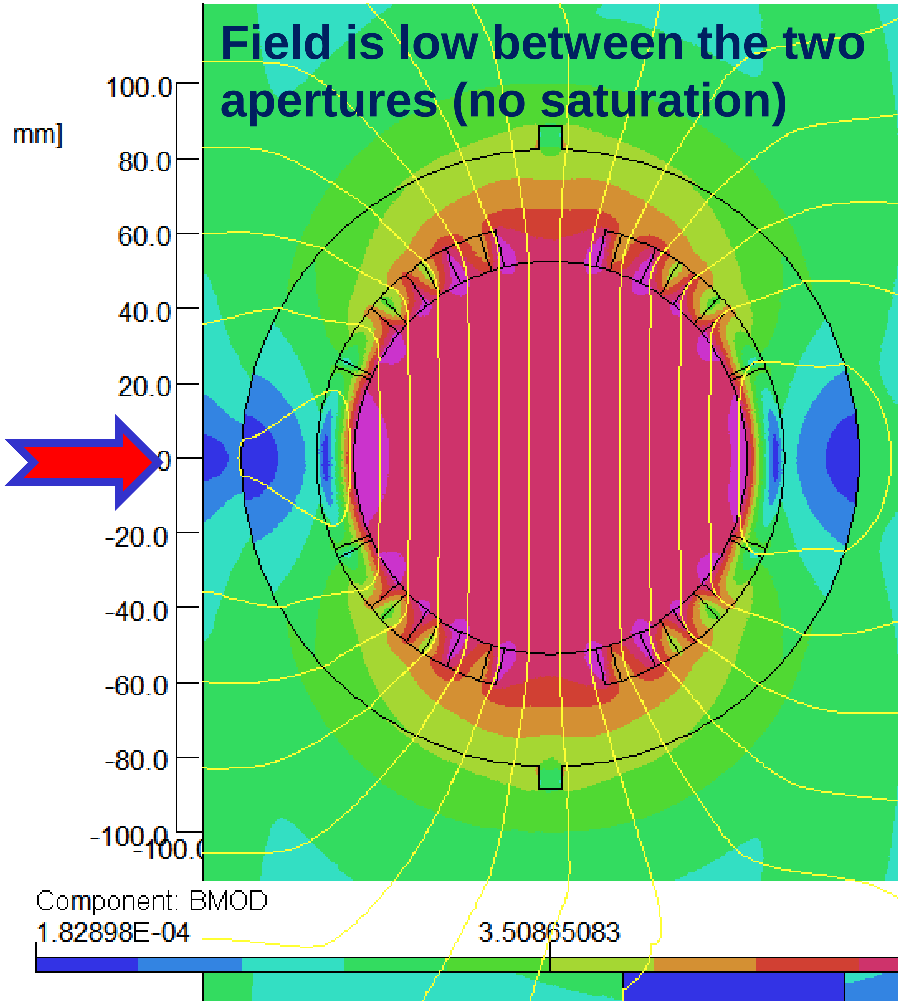


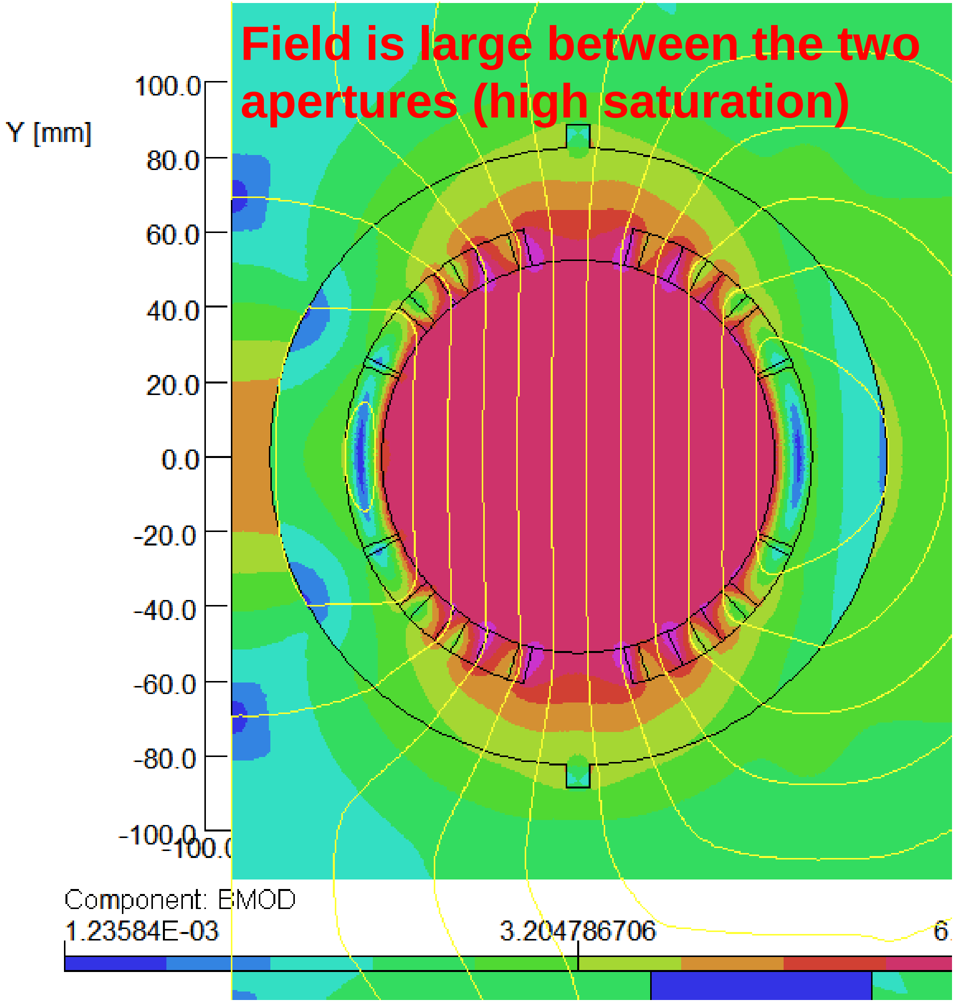
20 mm SS collar (as in previous BNL D2)

Impact of Relative Polarity (3)

Field in the opposite direction (LHC main dipoles)

Field in the same direction (D2 dipoles)

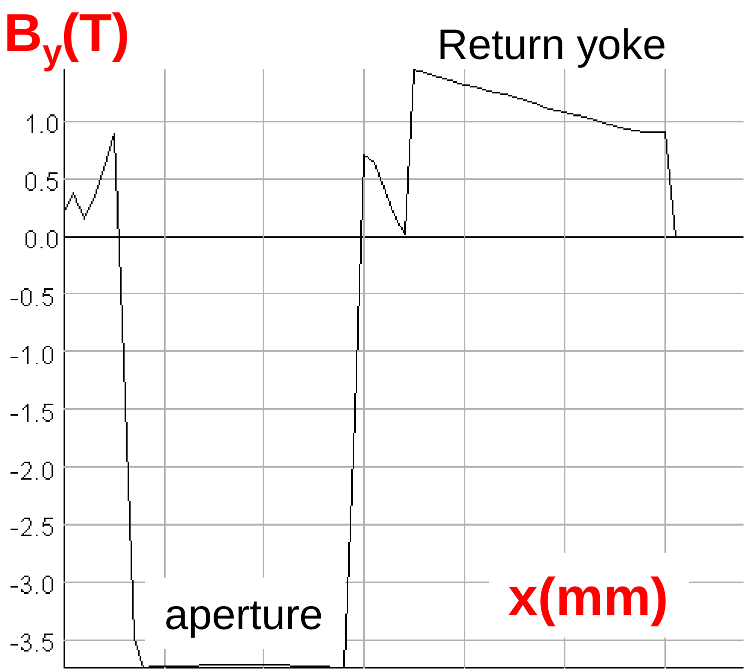




Impact of Relative Polarity (3)

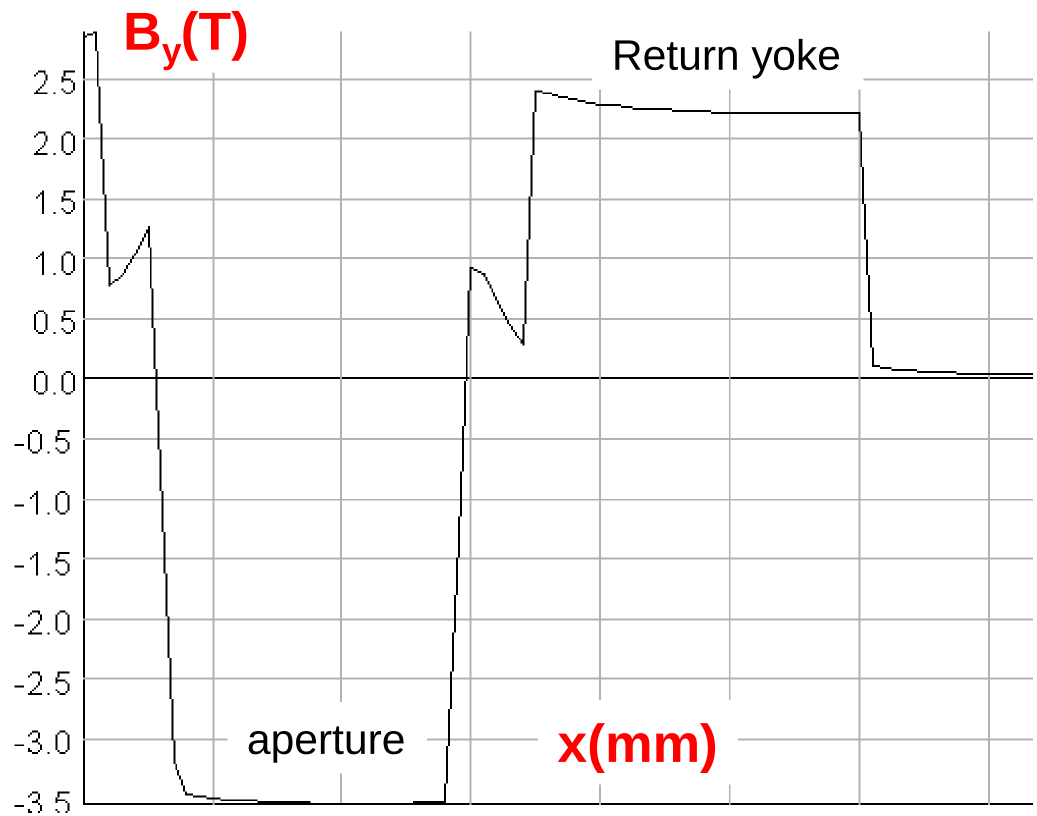
BROOKHAVEN NATIONAL LABORATORY
SUPERCONDUCTING MAGNET DIVISION

Field in the opposite direction (LHC main dipoles)



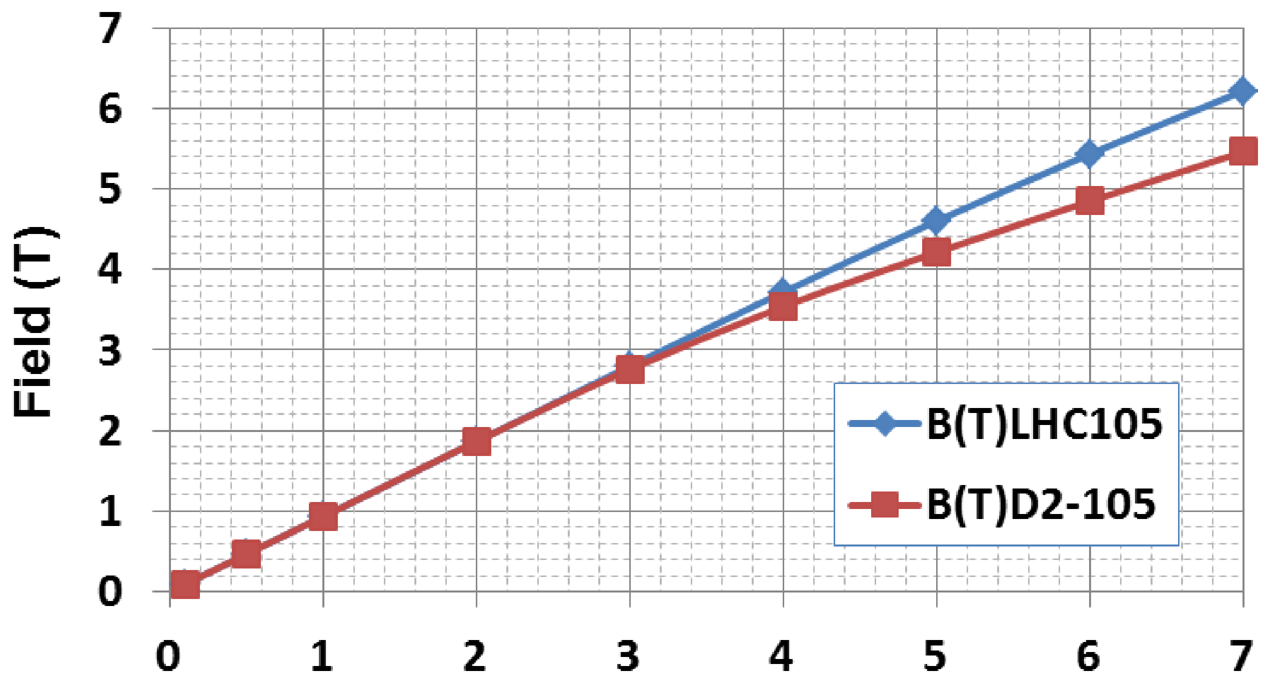
Field is lower at the center of the magnet and in the return yoke

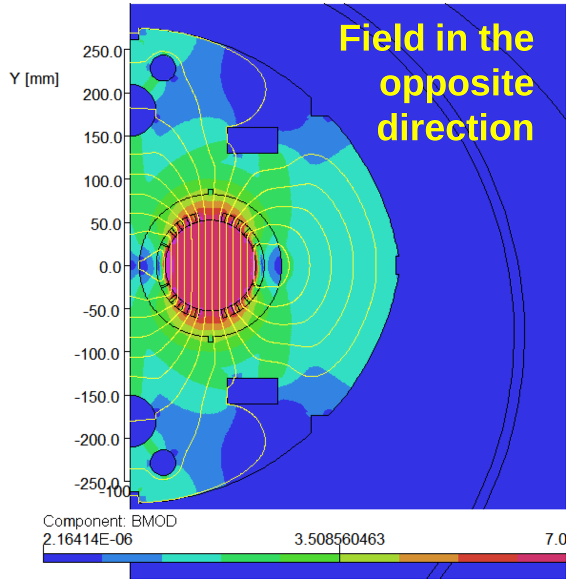
Field in the same direction (D2 dipoles)

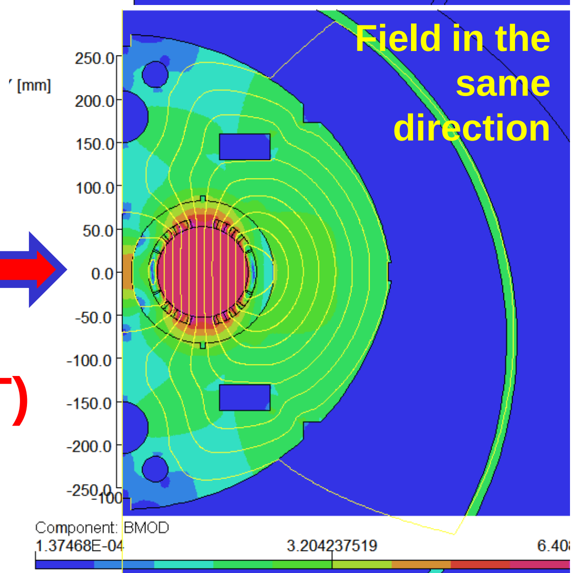


Field is higher at the center of the magnet and also in the return yoke

Impact of Relative Polarity on Transfer Function







Insufficient yoke iron in 105 mm aperture D2.

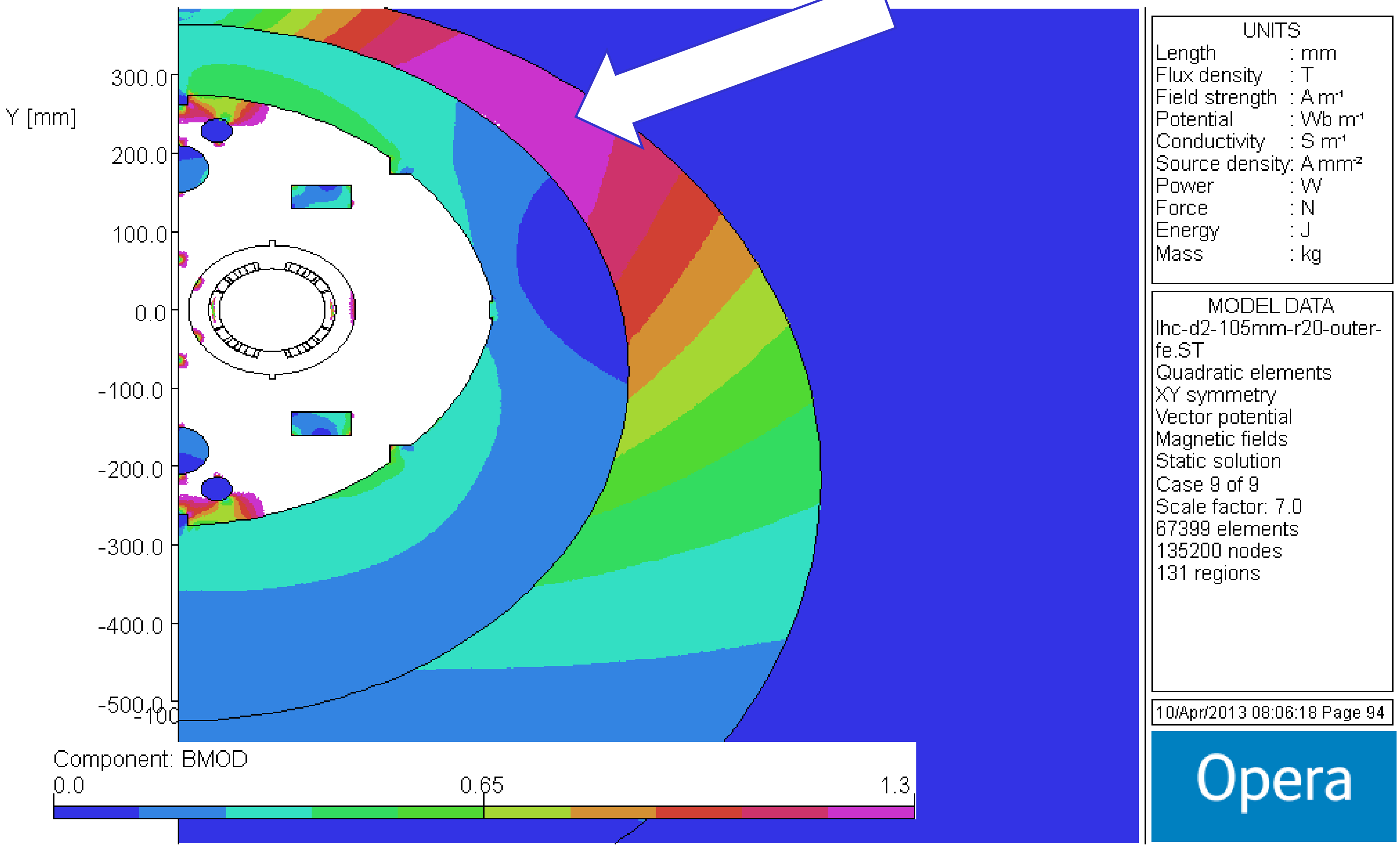
<u>See @quench:</u>

(a) Field at midplane between two apertures (~3 T)

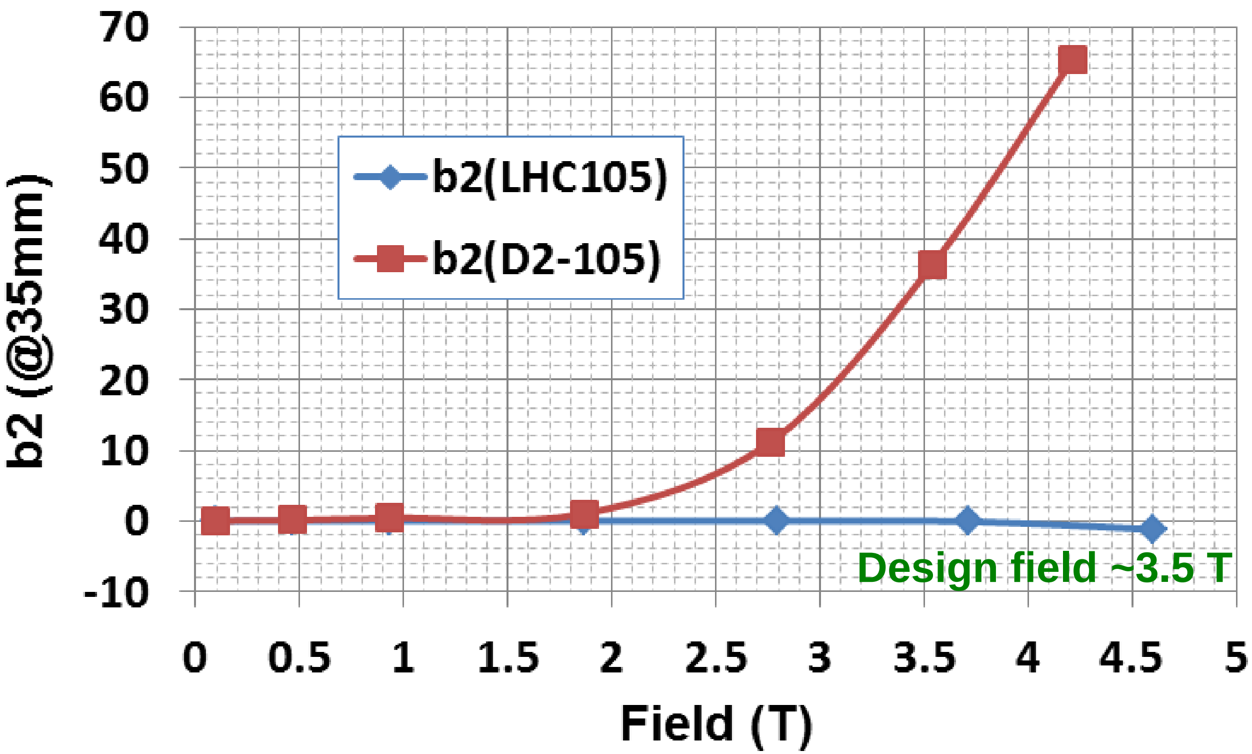
(b) Field on cryostat wall - unusually high (~2 T)

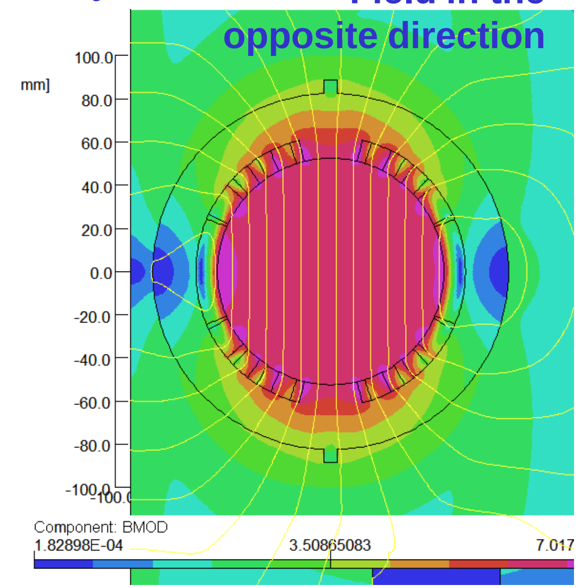
Leakage/Fringe Field

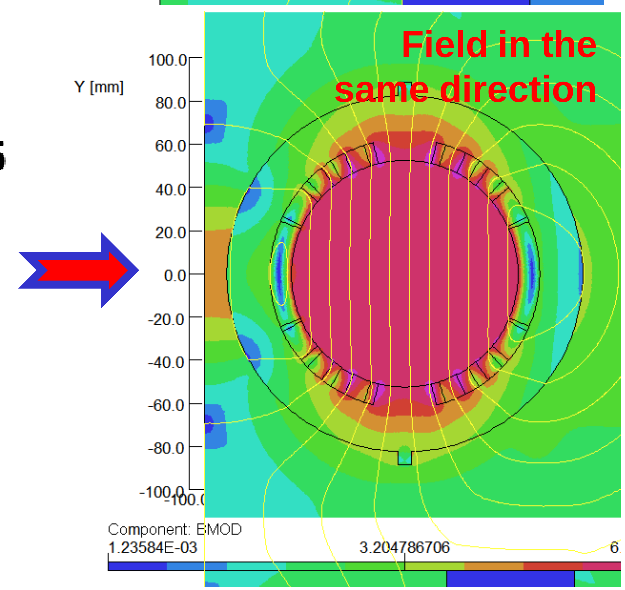
Leakage field is so high that if you wrap a good amount of extra iron on cryostat wall, you get 1.3 T over there



Impact of Relative Polarity on Quad Harmonic (cross-talk)

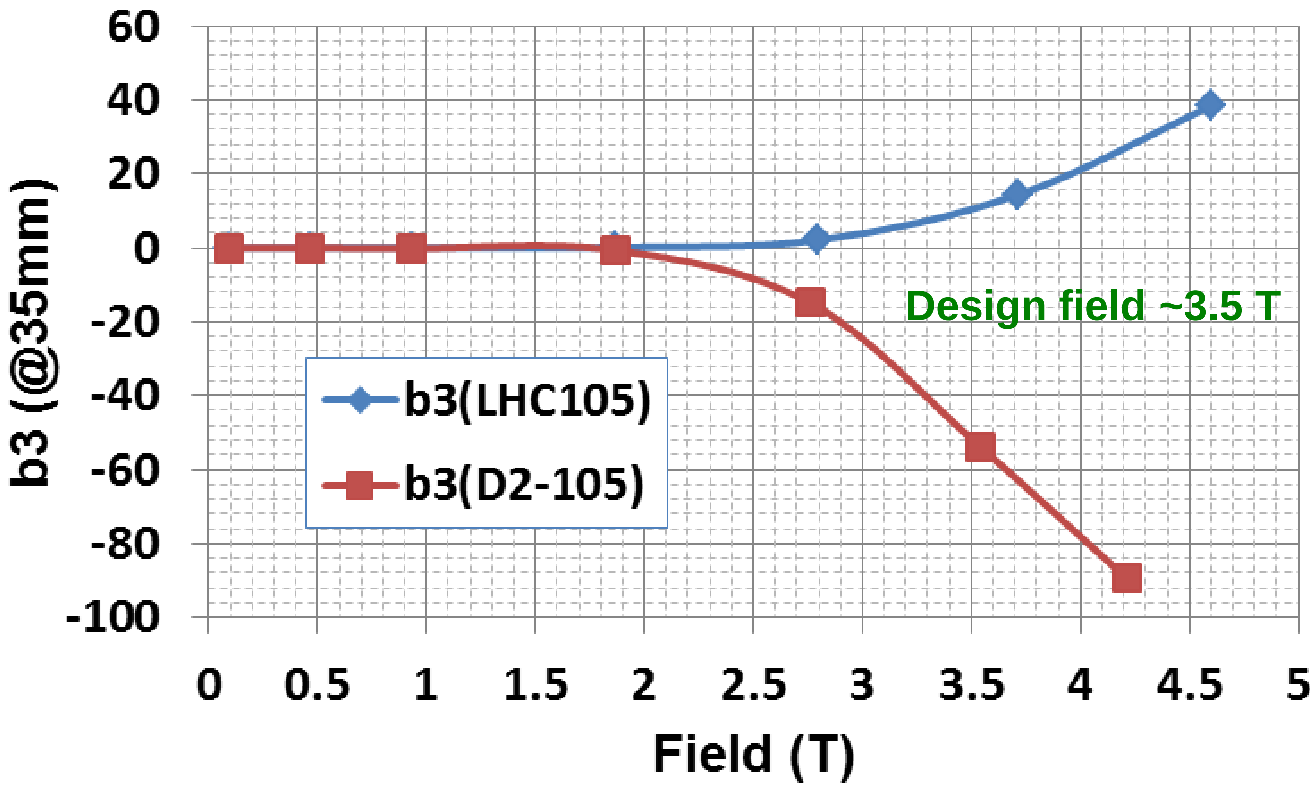


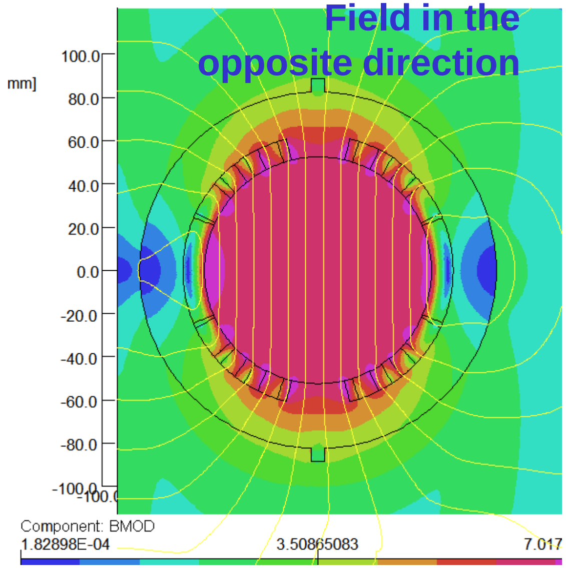


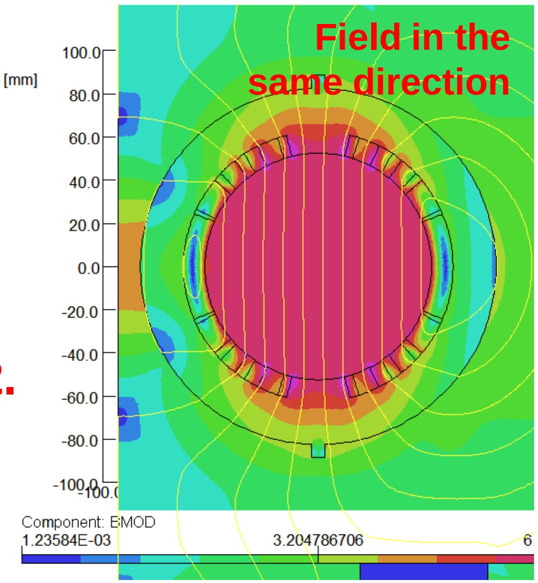


Large cross-talk due to insufficient iron in D2 at midplane between the two apertures.

Impact of Relative Polarity on Sextupole Harmonic



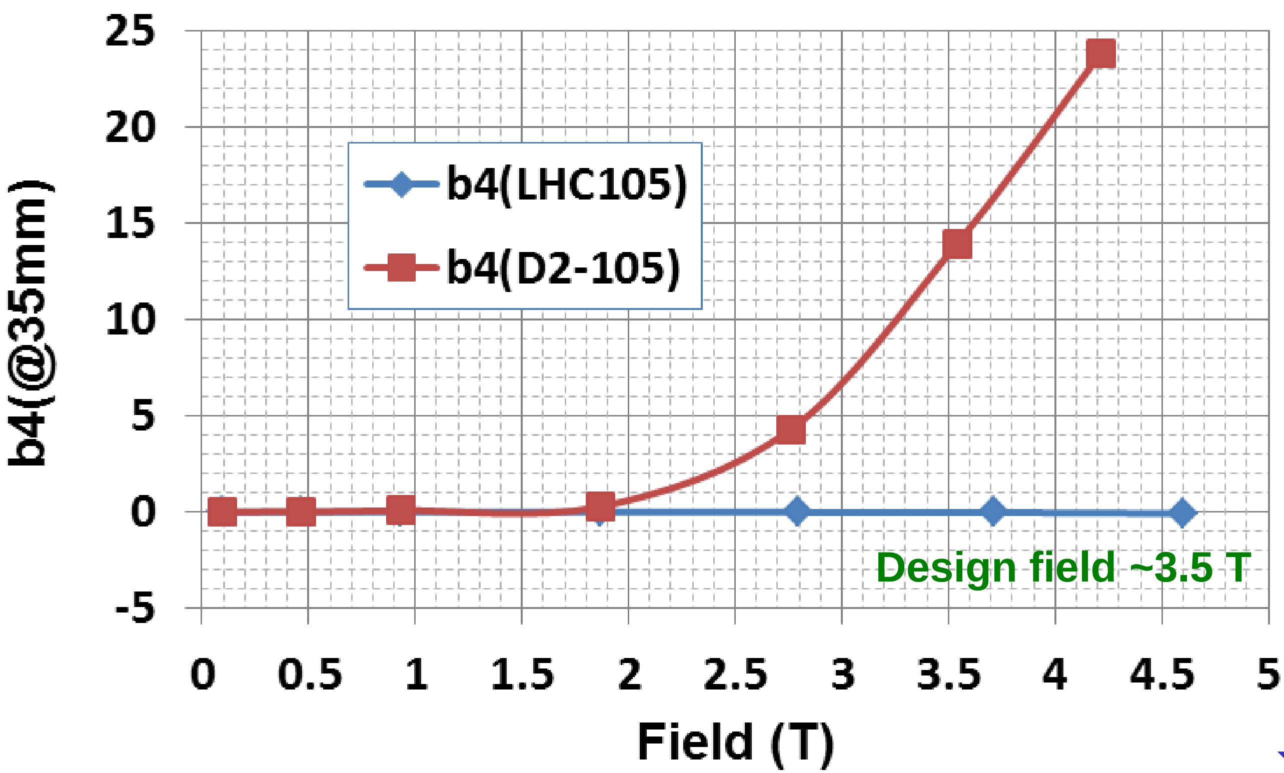


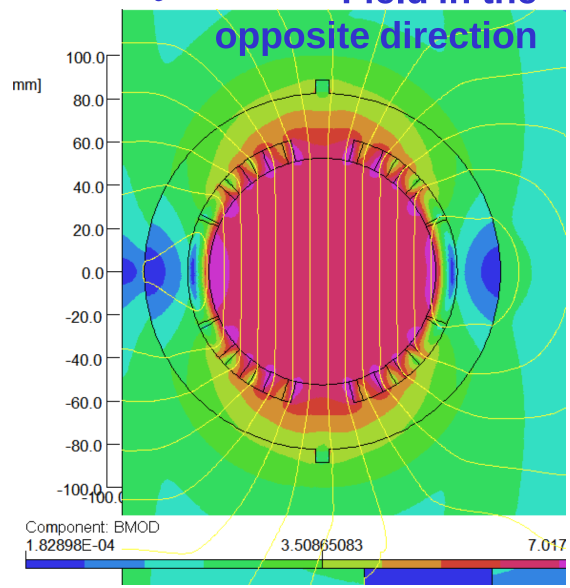


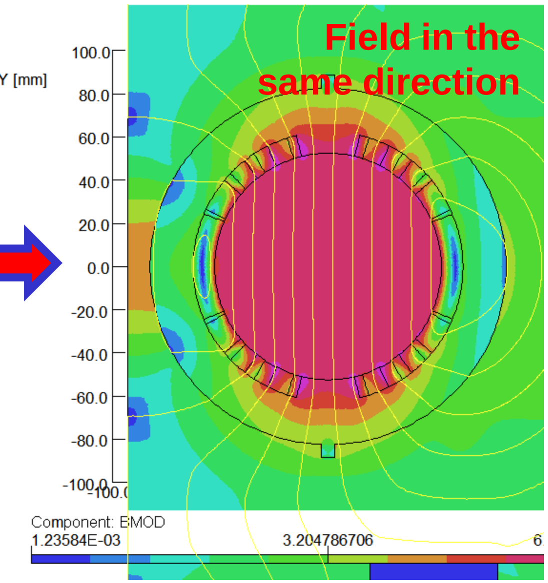
Significantly larger saturation induced sextupole (b3) in D2.

Positive in the first case due to a larger pole saturation, negative in second case due to larger midplane saturation.

Impact of Relative Polarity on Octupole Harmonic (cross-talk)





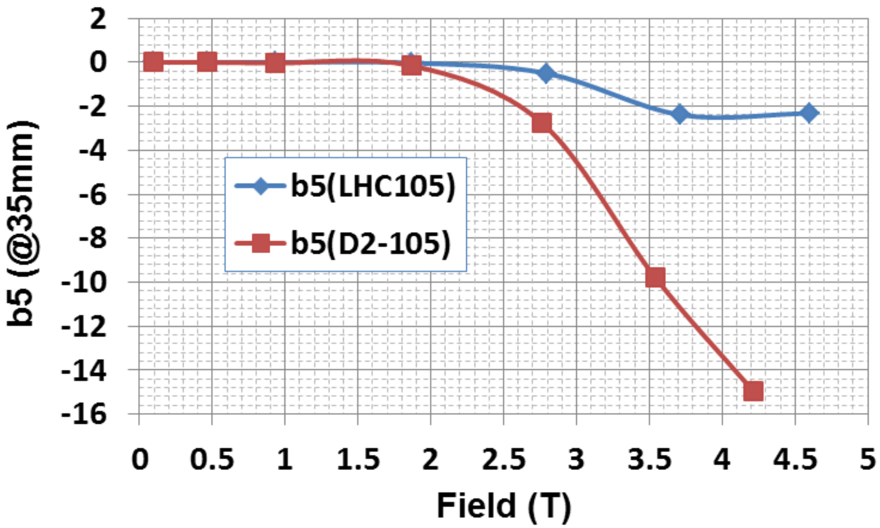


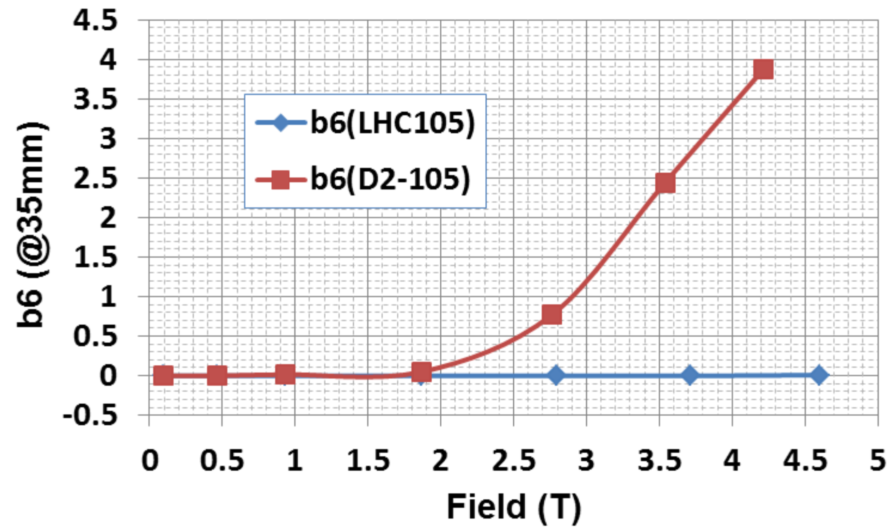
Large cross-talk due to insufficient iron in D2 at midplane between the two apertures.

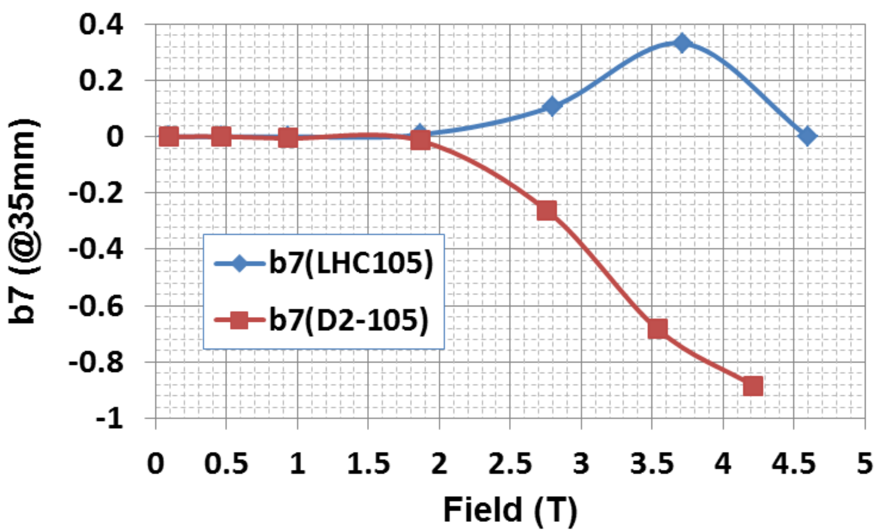
Impact of Relative Polarity on Other Harmonics

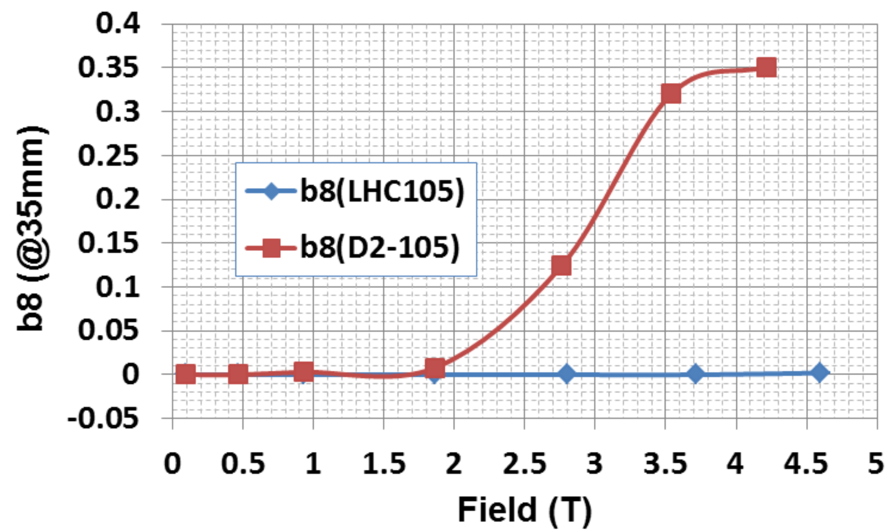
BROOKHAVEN NATIONAL LABORATORY
SUPERCONDUCTING MAGNET DIVISION

LARP









Design field ~3.5 T

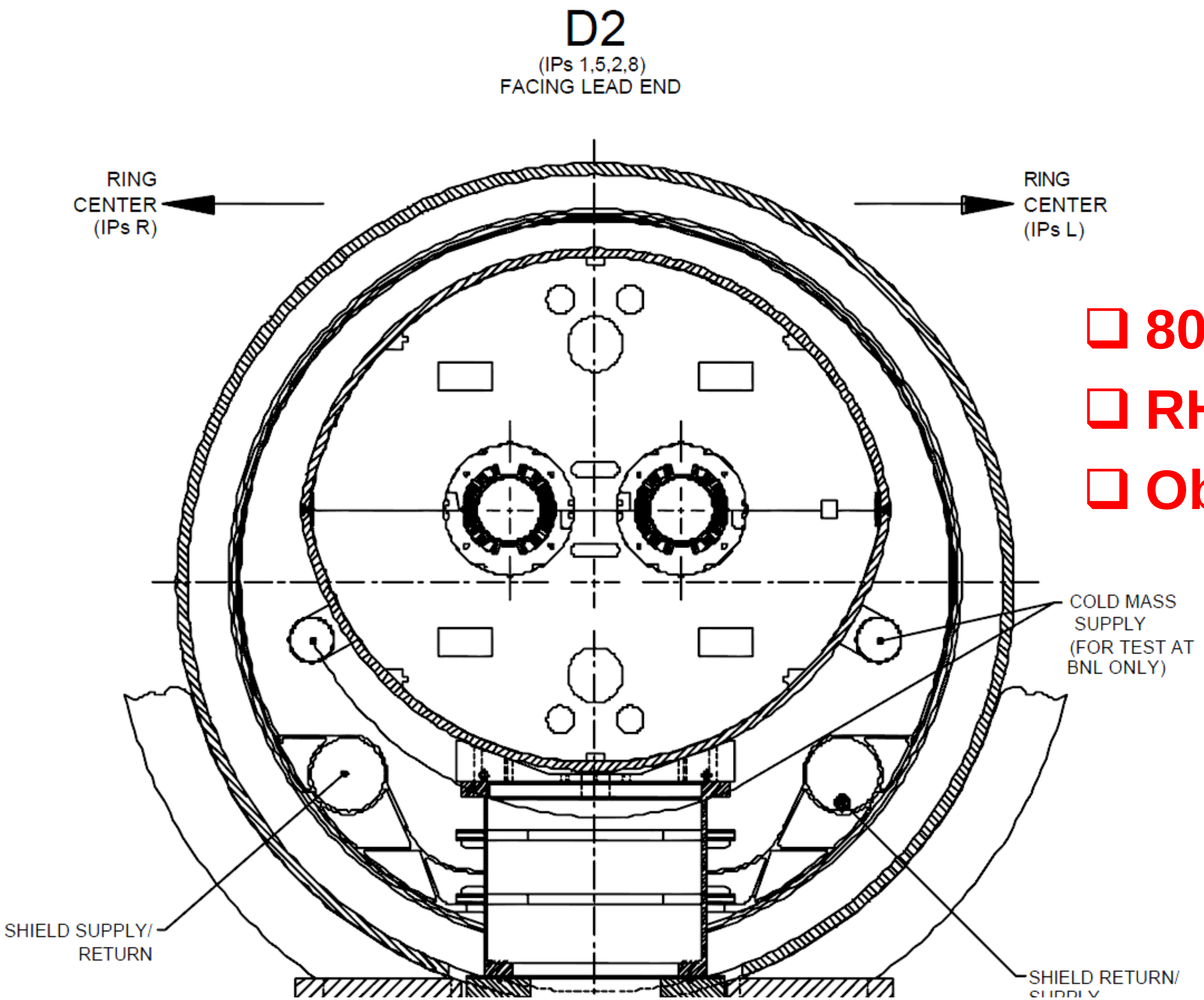
A quick review (3 slides only) of what we did and what we got in 80 mm LHC D2

(we did manage a good field quality in those magnets)

References

1. J. Muratore, et al., Test Results for Initial Productions of LHC Insertion Region Dipole Magnets, 8th European Particle Accelerator Conference at Paris, France (2002).
2. E. Willen, et al., Superconducting Dipole Magnets for the LHC Insertion Regions, 7th European Particle Accelerator Conference at Vienna, Austria (2000).
3. A. Jain, et al., Field Quality in the Twin Aperture D2 Dipole for LHC Under Asymmetric Excitation, Particle Accelerator Conference at New York, USA (1999).
4. A. Jain, et al., Magnetic Design of Dipole for LHC Insertion Region, 6th European Particle Accelerator Conference at Stockholm, Sweden (1998).
5. R.C. Gupta, et al., Coldmass for LHC Dipole Insertion Magnets, Presented at the Fifteenth International Conference on Magnet Technology (MT-15) at Beijing, China (1997).

LHC 80 mm D2 in Cryostat



- ❑ **80 mm aperture**
- ❑ **RHIC dipole coil**
- ❑ **Oblate Yoke**

The low field transfer function is 0.6345 T/kA for all the three cases. Fig. 3 shows the change in transfer function (from the low field value) in the right aperture as a function of the dipole field in this aperture. For a given

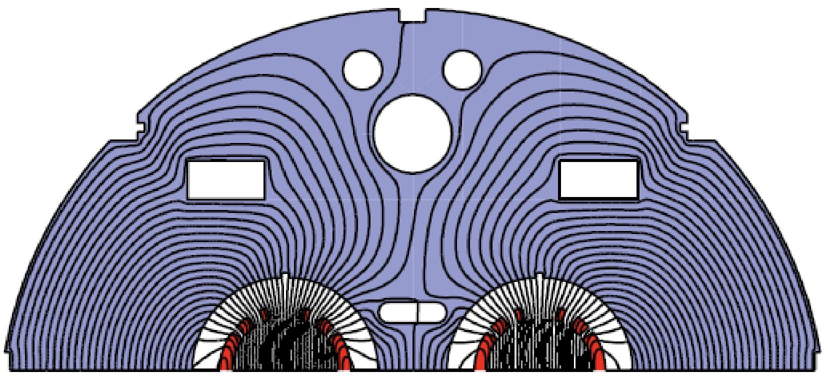


Fig. 2: Field lines calculated using OPERA-2D at 3.77 T (6kA) in the right aperture, with 15% more current in the left aperture

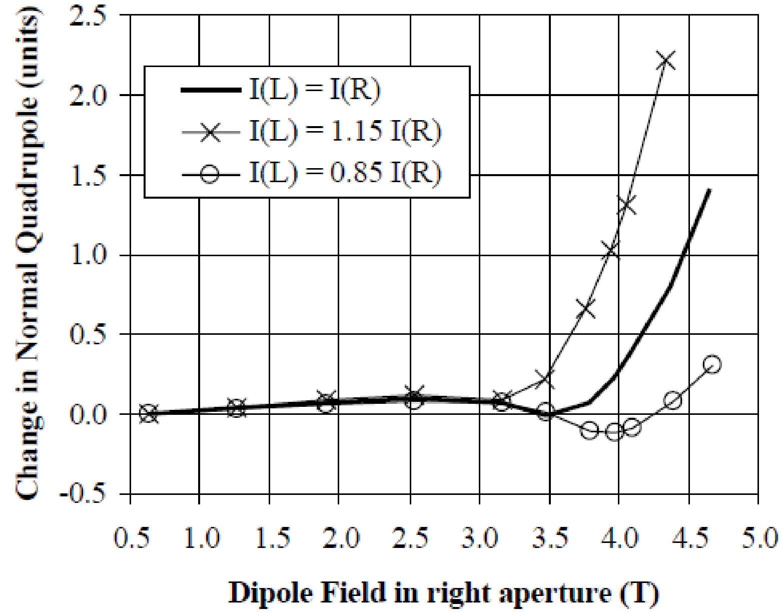
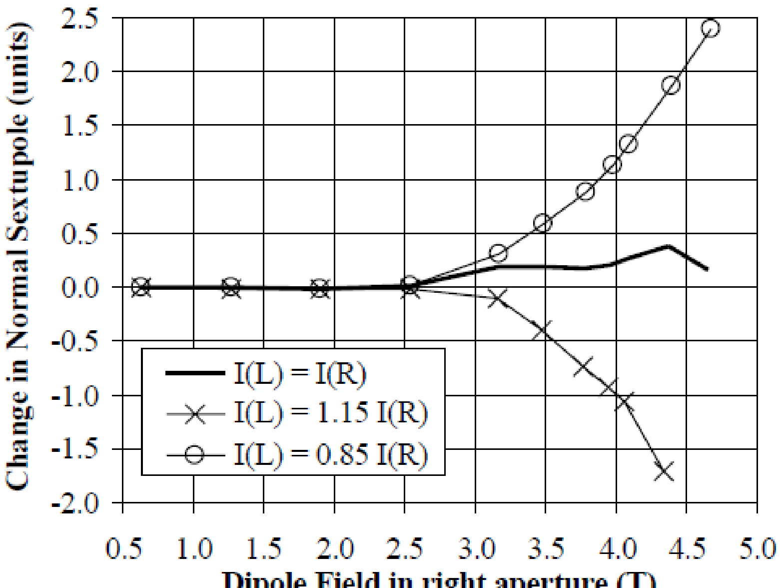
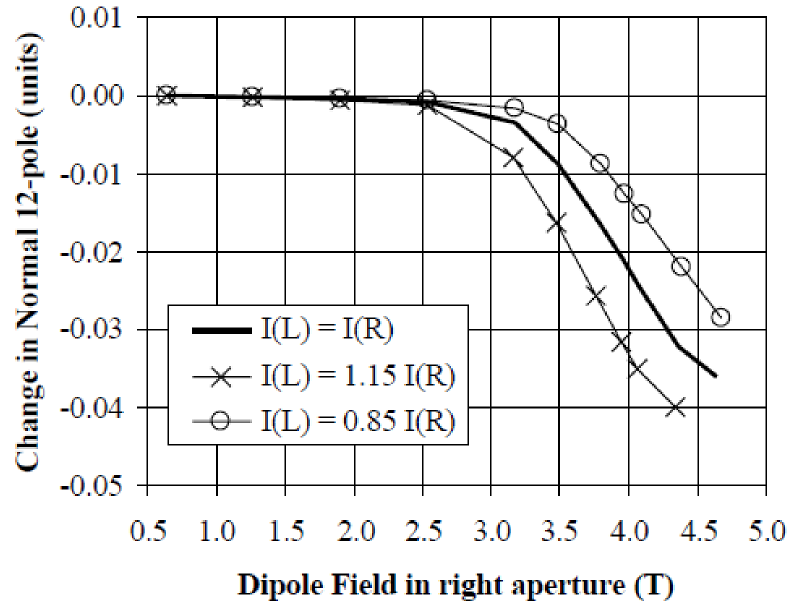


Fig. 4: Saturation behavior of the quadrupole term

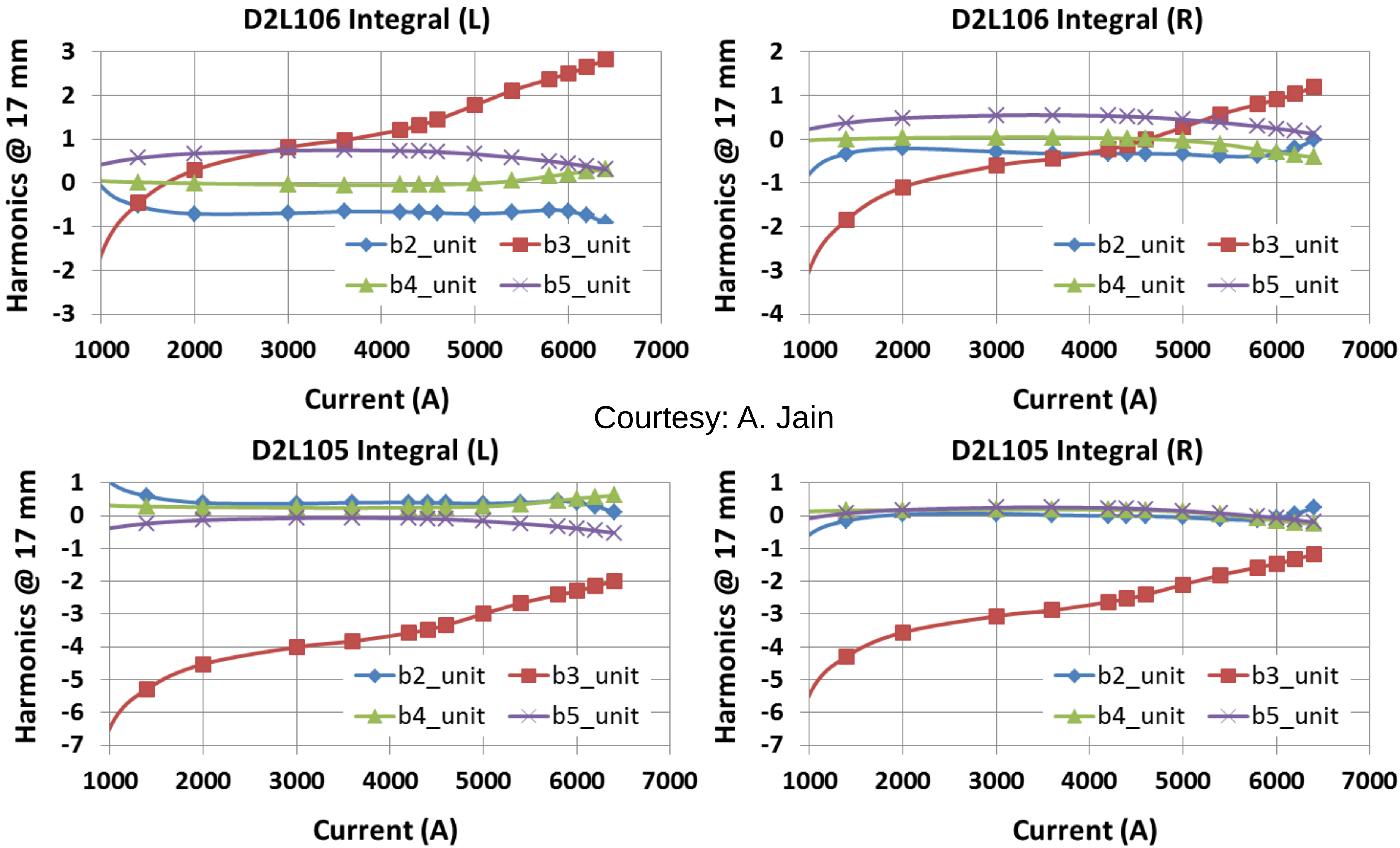




A. Jain, et al. (PAC99)

Measured Harmonics in 80 mm D2

(6 measured, 2 shown)



- **Small saturation-induced quad, some sextupole**

6 KA gives ~3.6 T

Initial Optimization of the Magnetic Design of 105 mm D2 Dipole

1. **Coil cross-section**
2. **Yoke cross-section**

Coil Cross-section Design

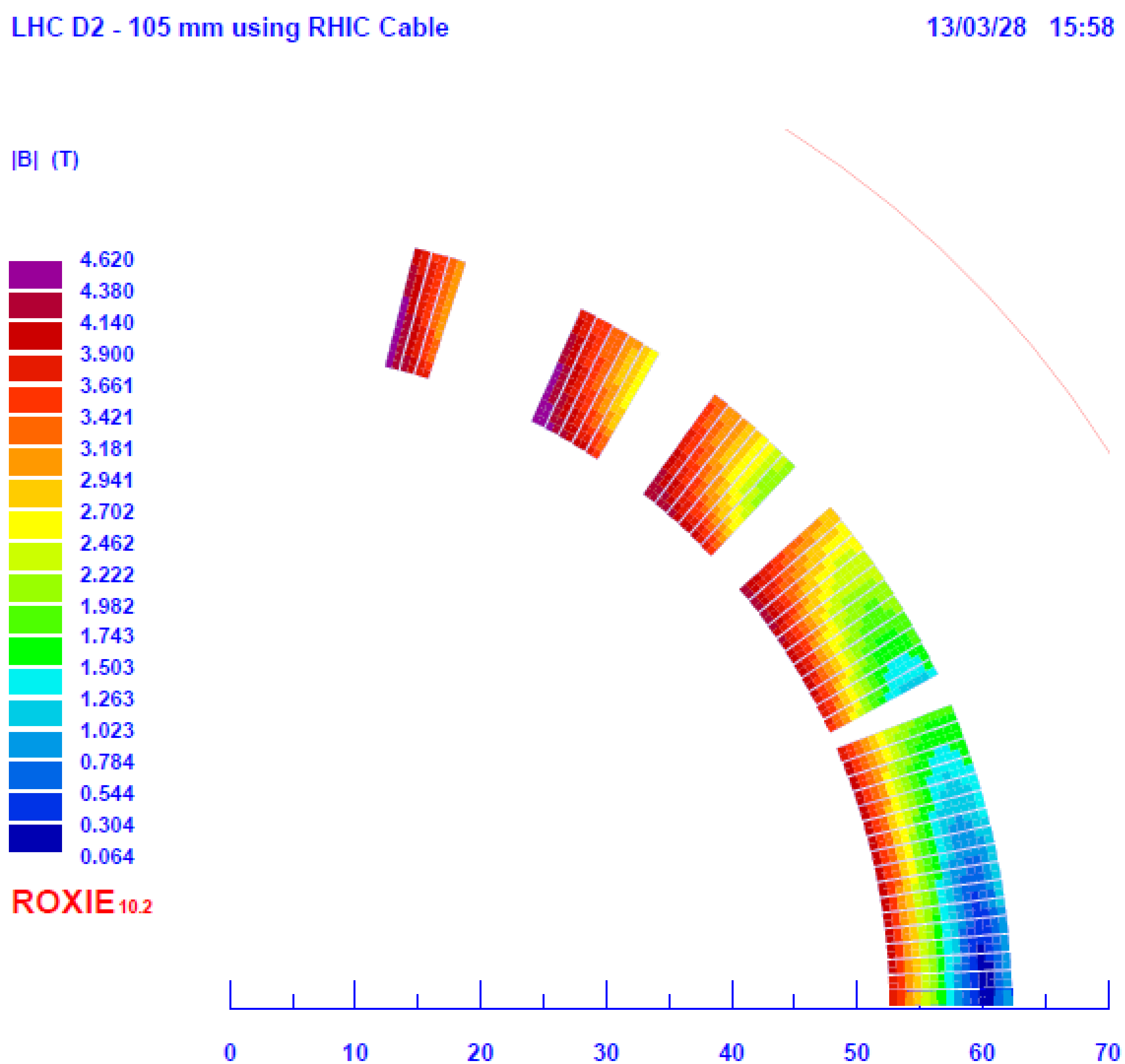
- The aperture of RHIC insertion dipole D0 is100 mm. This is very close to 105 mm.
- RHIC D0 is a fully optimized and proven design. Several (all – no prototype) good field quality magnets have been built and all except one spare are being used in the interaction region which requires good field quality.
- 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.

Parameters of RHIC 100 mm D0 Dipole

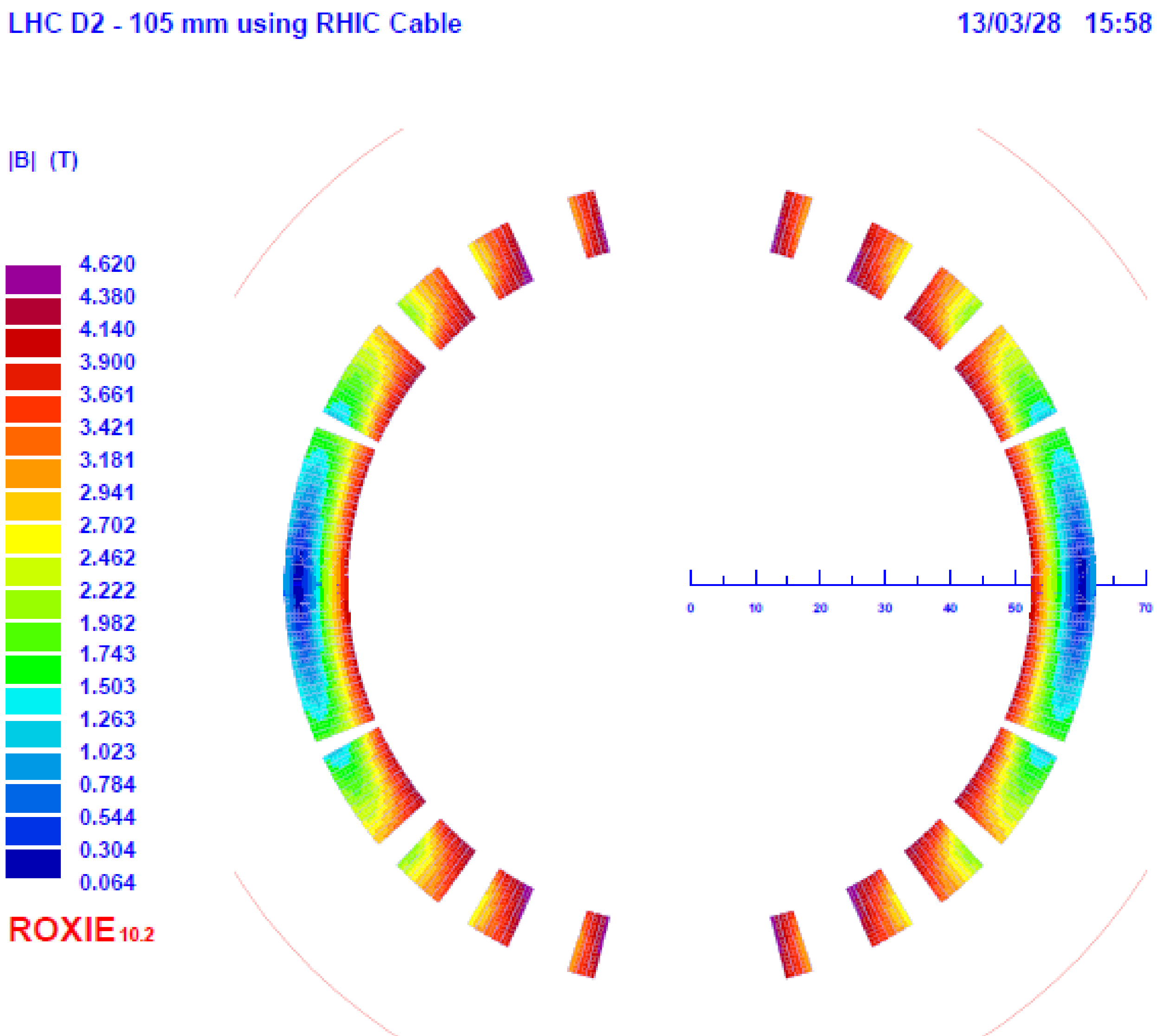
Coil ID	100 mm
Coil OD	120 mm
Number of turns per pole	40
Magnetic length	3.6 m
Iron inner diameter	139.4 mm
Iron outer diameter	310 mm
Shell thickness	6.35 mm
Operating temperature	4.6 K
Design current	5.0 kA
Design field	3.5 T
Quench current	7.4 kA

My Screenshot: 11-15-11 14:41:56

LHC 105 mm D2 Coil Cross-section (optimized with ROXIE)



LHC 105 mm D2 Coil Cross-section



105 mm D2 Coil Harmonics @35 mm (2/3 coil radius, not 17 mm)

Optimization with ROXIE

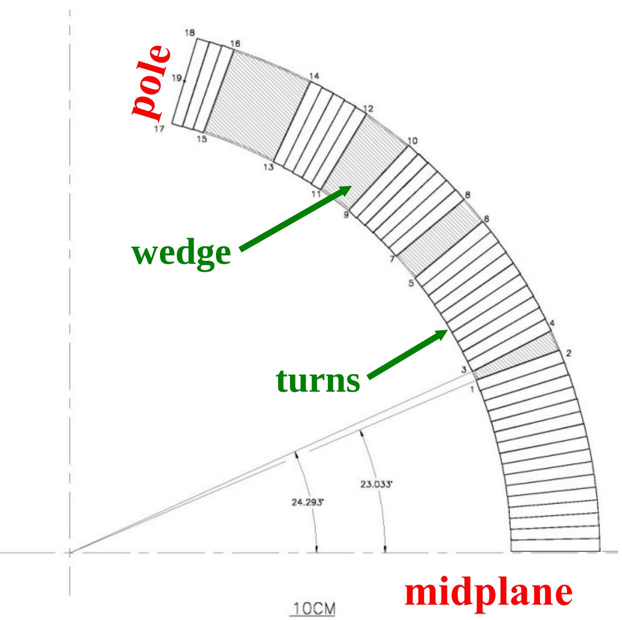
```
REFERENCE RADIUS (mm) .............................     35.0000
X-POSITION OF THE HARMONIC COIL (mm) ..............      0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ..............      0.0000
MEASUREMENT TYPE ....................... ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................   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
```

- **Harmonics (specially higher order terms) are much smaller @17 mm**

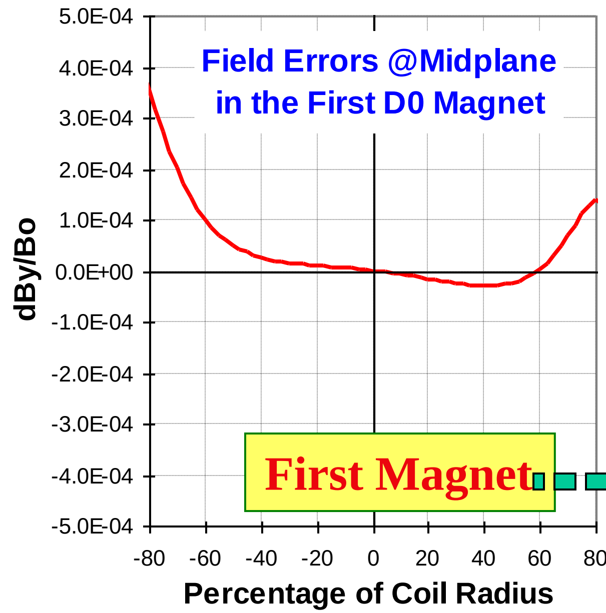
Flexible Coil Cross-section in LHC D2
(Could do the same as done in 100 mm RHIC Dipole)

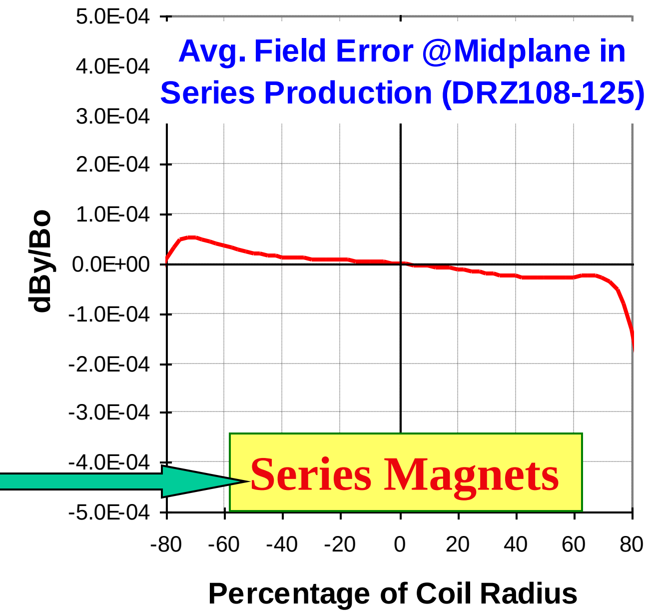
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

- Simple techniques (midplane + pole shims) produced accelerator grade field quality in the very first magnet (field errors ~1 part in 10^4 up to 60% coil radius).
- This flexibility in the design allowed easy harmonic tuning during the production without changing coil or yoke.
- It resulted in good field quality magnets - average error <1 part in 10^4 up to ~80% of coil radius (almost entire vacuum pipe).



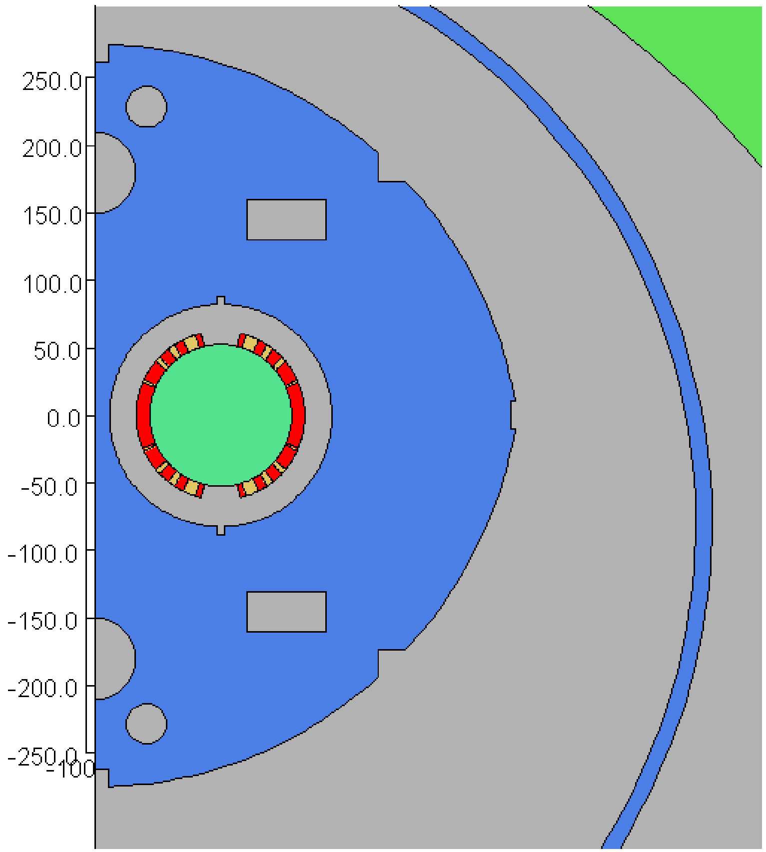
RHIC 100 mm D0





Much faster and much cheaper than conventional iterations

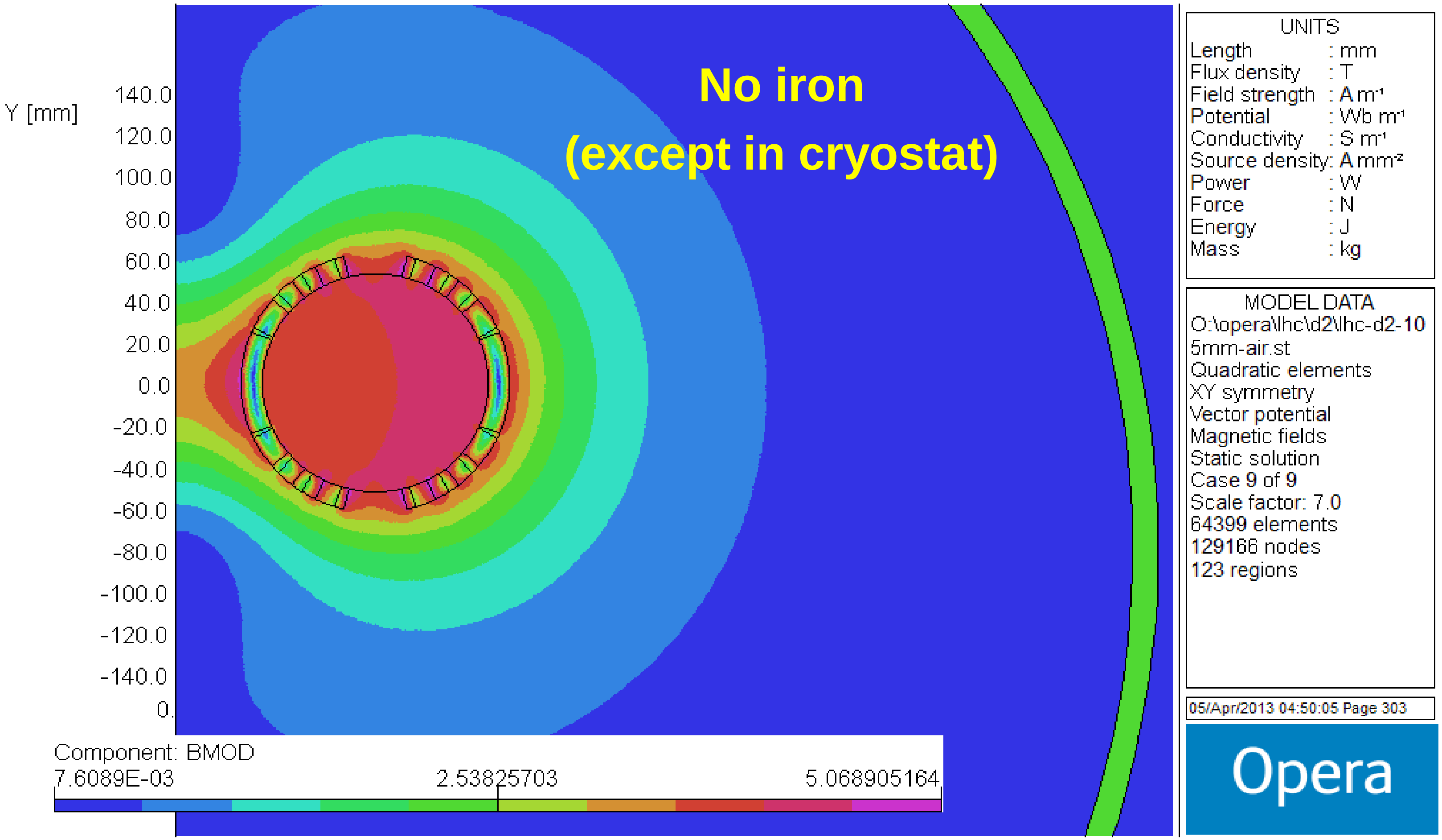
Yoke Cross-section Investigations



Major Challenge

Maximum Estimate of Cross-talk

- **OK, so iron is bad. It saturates. Get rid of it. This also gives the max cross-talk.**
- **Quadrupole term becomes ~400 units. Getting rid of this and other harmonics will make a funny and inefficient coil cross-section. This not practical.**



Variation in Collar Width

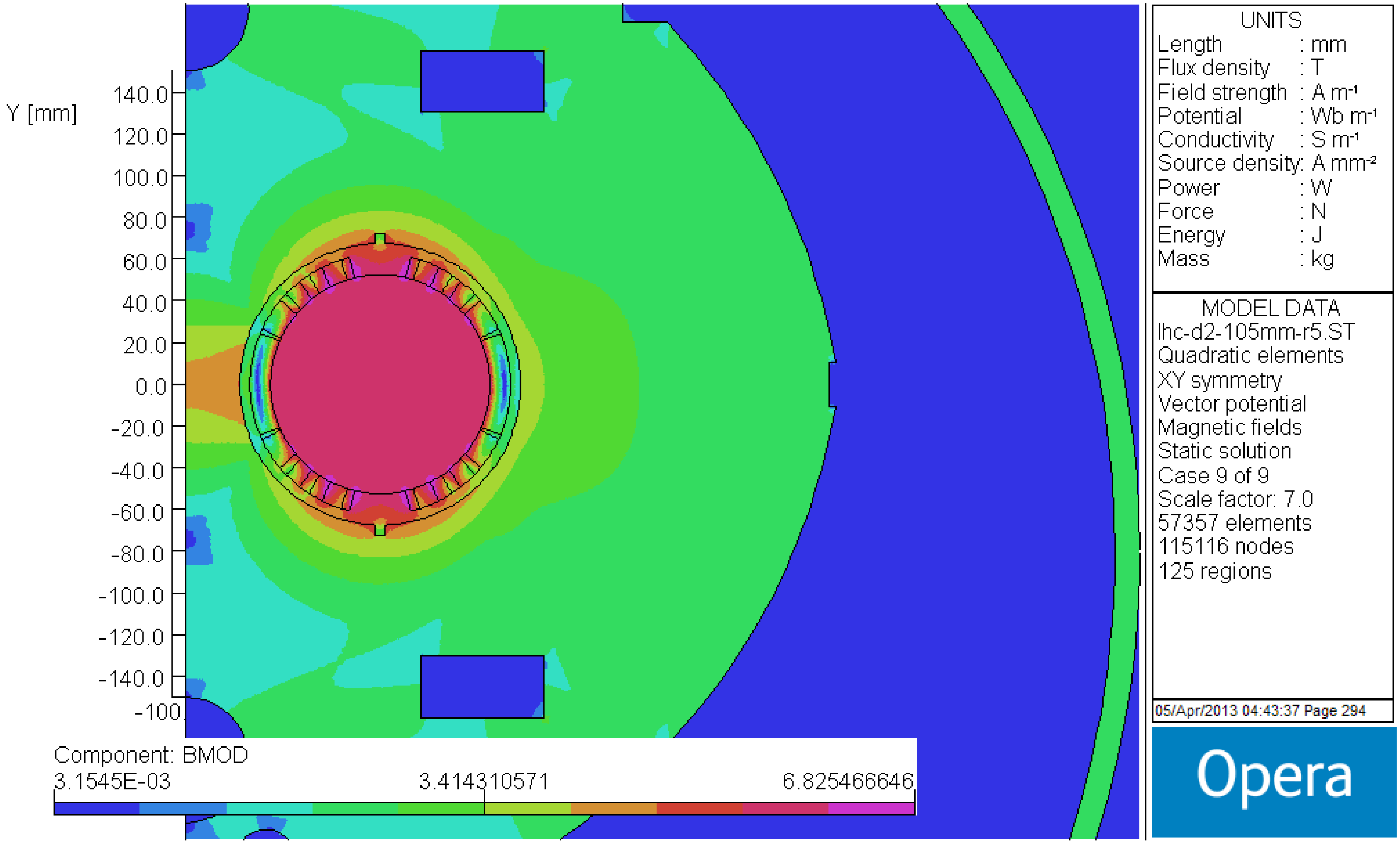
- So more iron is needed . Add it within the same envelop.
- What if SS collar thickness is reduced from 20 mm for extra iron (mechanical structure becomes complicated).

Collar (mm)	B@~5.5kA	db2@35mm	db3@35 mm
20 mm	3.54	37	-54
10 mm	3.82	36	-33
5 mm	3.98	38	+29, -4

➢ More iron gives a significantly higher field for the same current and it also reduces the saturation induced harmonics b2 , b3, etc. (compare b2 at the same field)

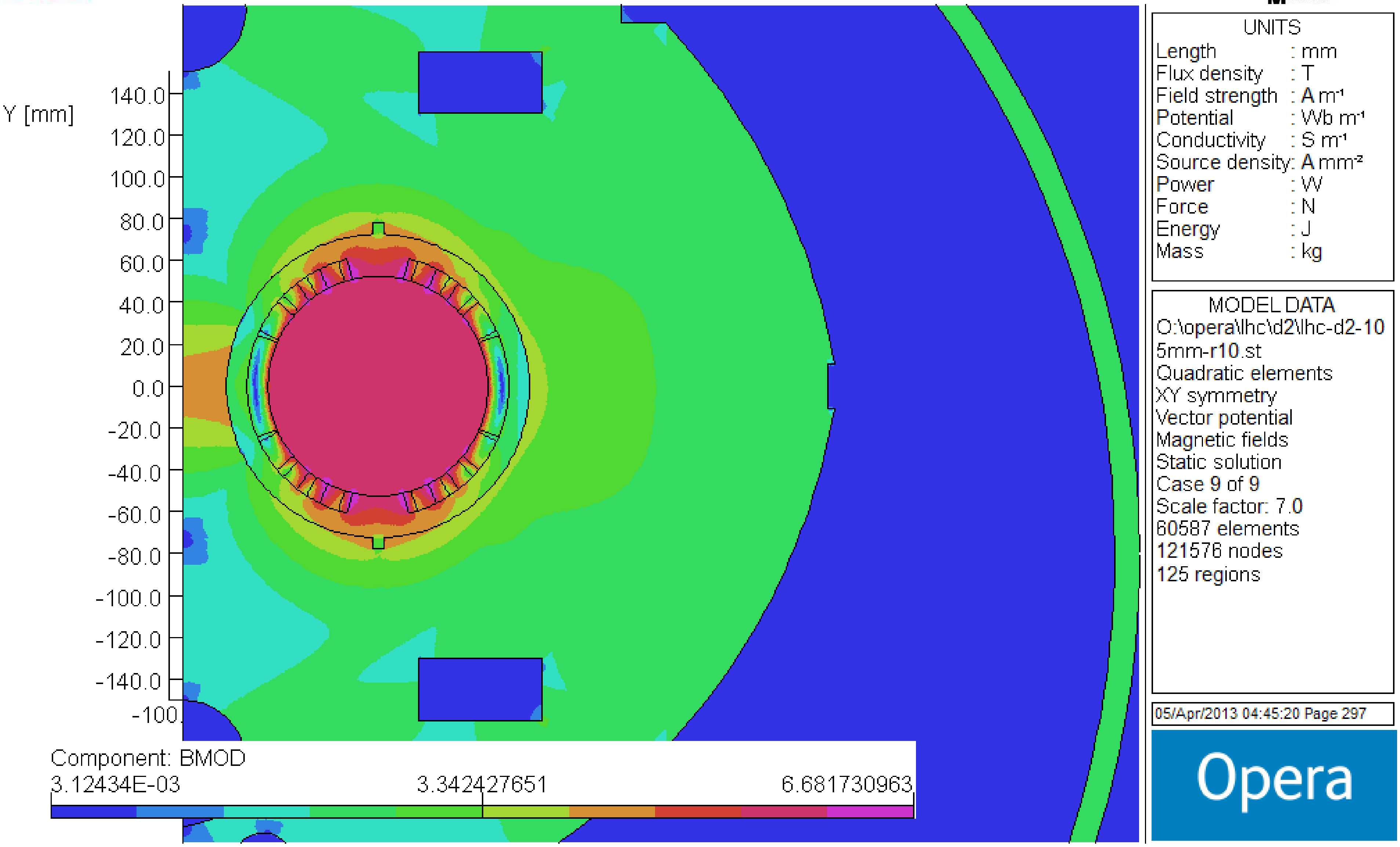
X=4

5 mm collar



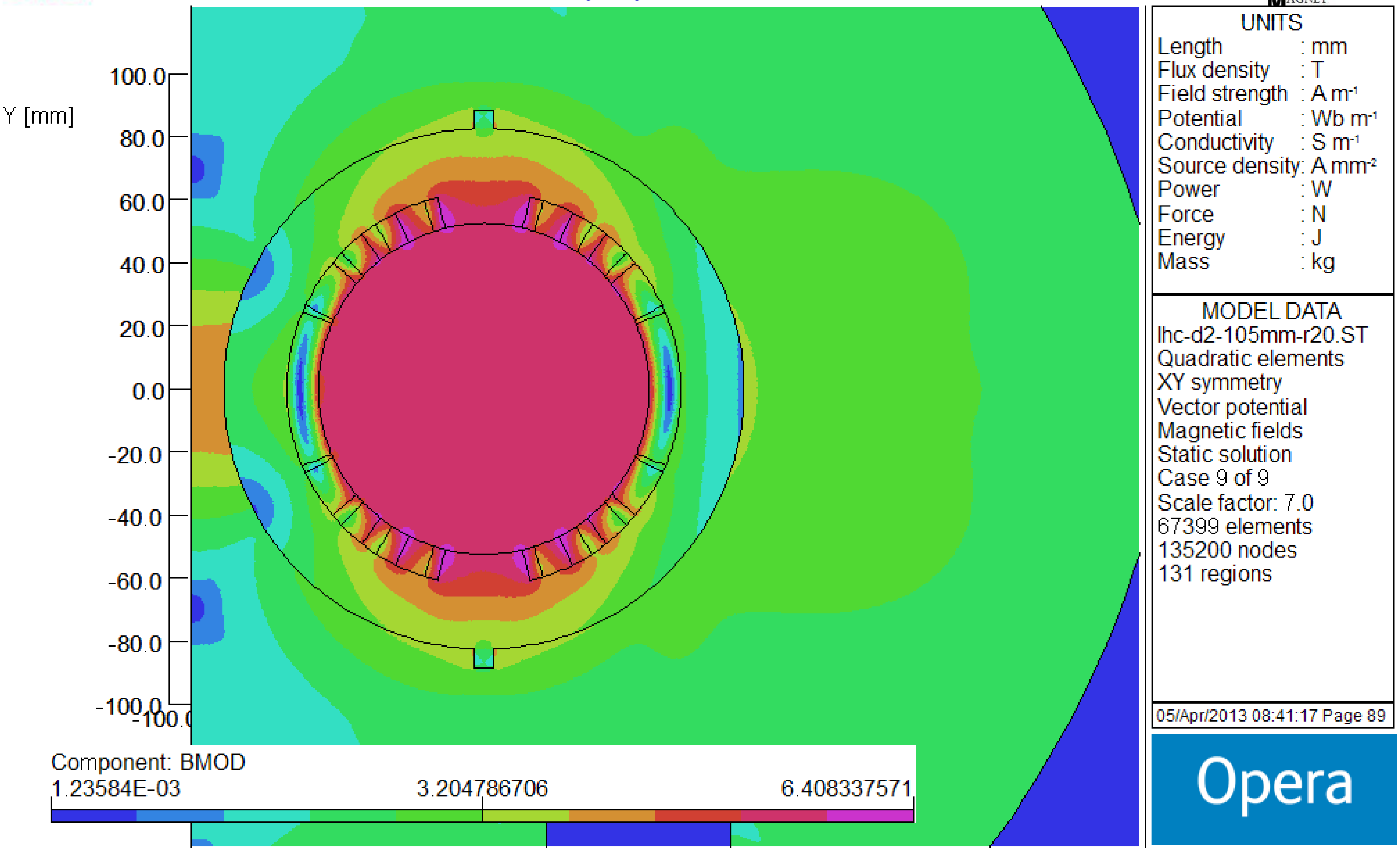
Y [mm]
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
-120.0
-140.0
-100
Component: BMOD
3.1545E-03
3.414310571
6.825466646
UNITS
Length : mm
Flux density : T
Field strength : A m-1
Potential : Wb m-1
Conductivity : S m-1
Source density: A mm-2
Power : W
Force : N
Energy : J
Mass : kg
MODEL DATA
lhc-d2-105mm-r5.ST
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 9 of 9
Scale factor: 7.0
57357 elements
115116 nodes
125 regions
05/Apr/2013 04:43:37 Page 294
Opera

10 mm collar



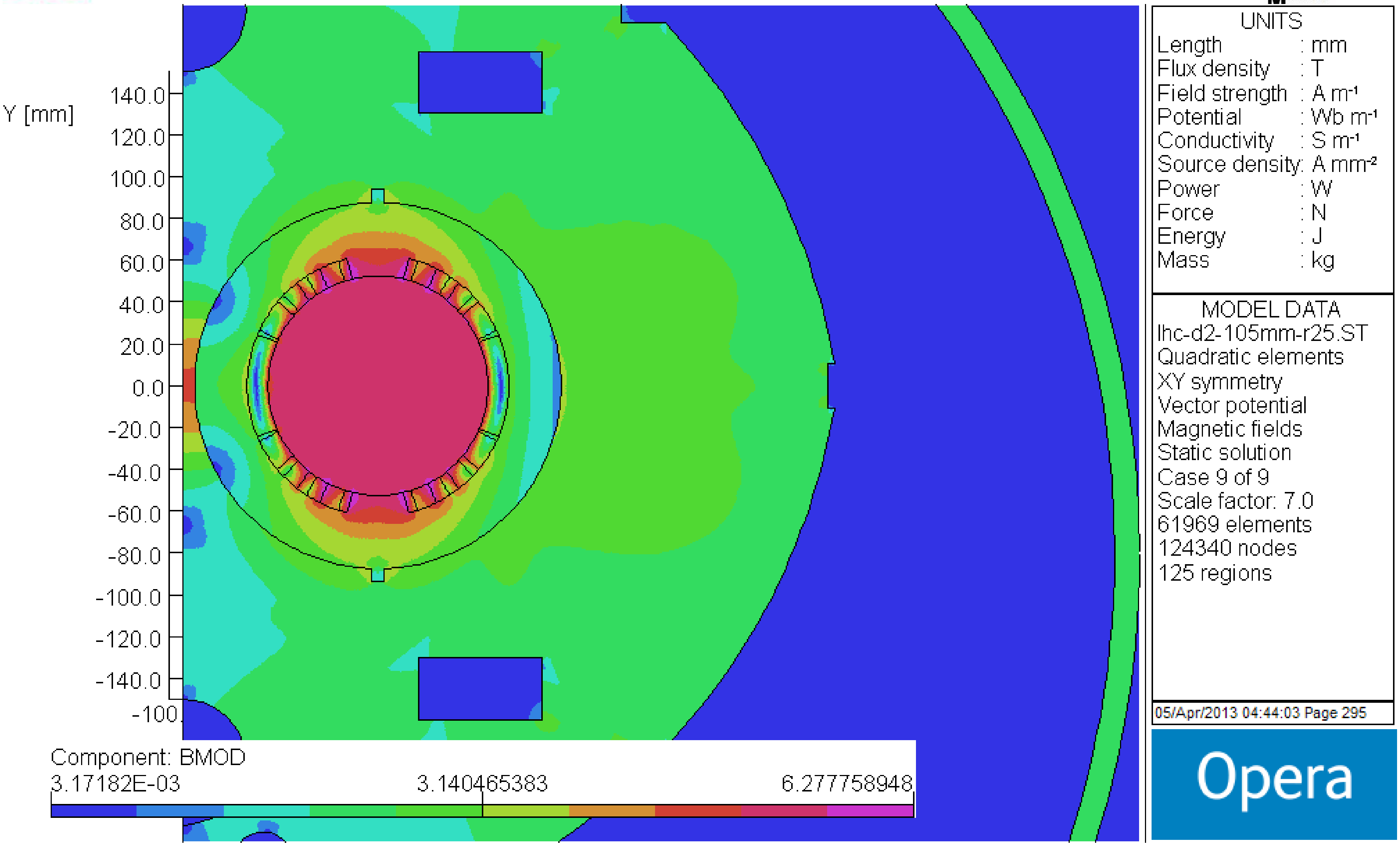
Y [mm]
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
-120.0
-140.0
-100.
Component: BMOD
3.12434E-03
3.342427651
6.681730963
UNITS
Length : mm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A mm⁻²
Power : W
Force : N
Energy : J
Mass : kg
MODEL DATA
O:\opera\lhc\d2\lhc-d2-10
5mm-r10.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 9 of 9
Scale factor: 7.0
60587 elements
121576 nodes
125 regions
05/Apr/2013 04:45:20 Page 297
Opera

20 mm collar



UNITS
Length : mm
Flux density : T
Field strength : A m-1
Potential : Wb m-1
Conductivity : S m-1
Source density: A mm-2
Power : W
Force : N
Energy : J
Mass : kg
MODEL DATA
lhc-d2-105mm-r20.ST
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 9 of 9
Scale factor: 7.0
67399 elements
135200 nodes
131 regions
05/Apr/2013 08:41:17 Page 89
Y [mm]
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
Component: BMOD
1.23584E-03
3.204786706
6.408337571
Opera

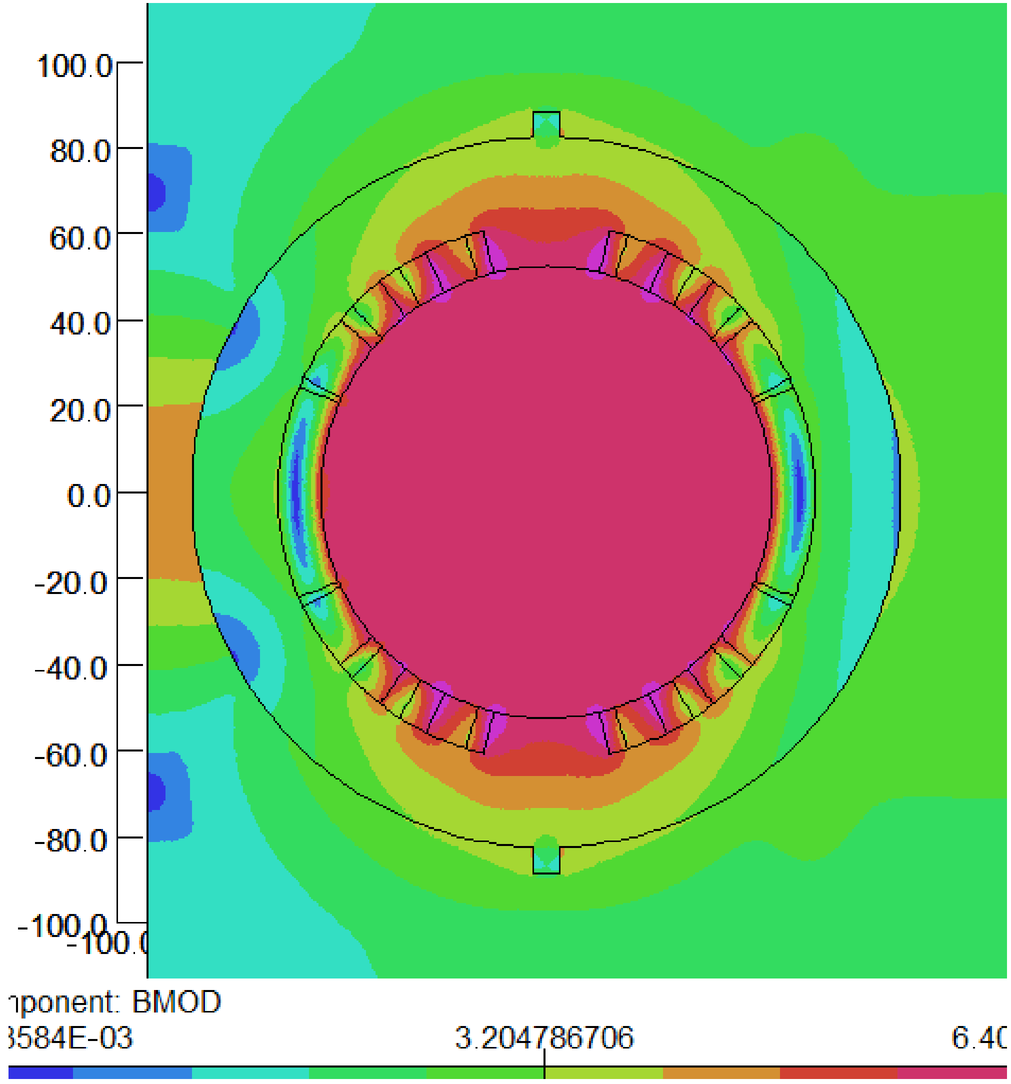
25 mm collar



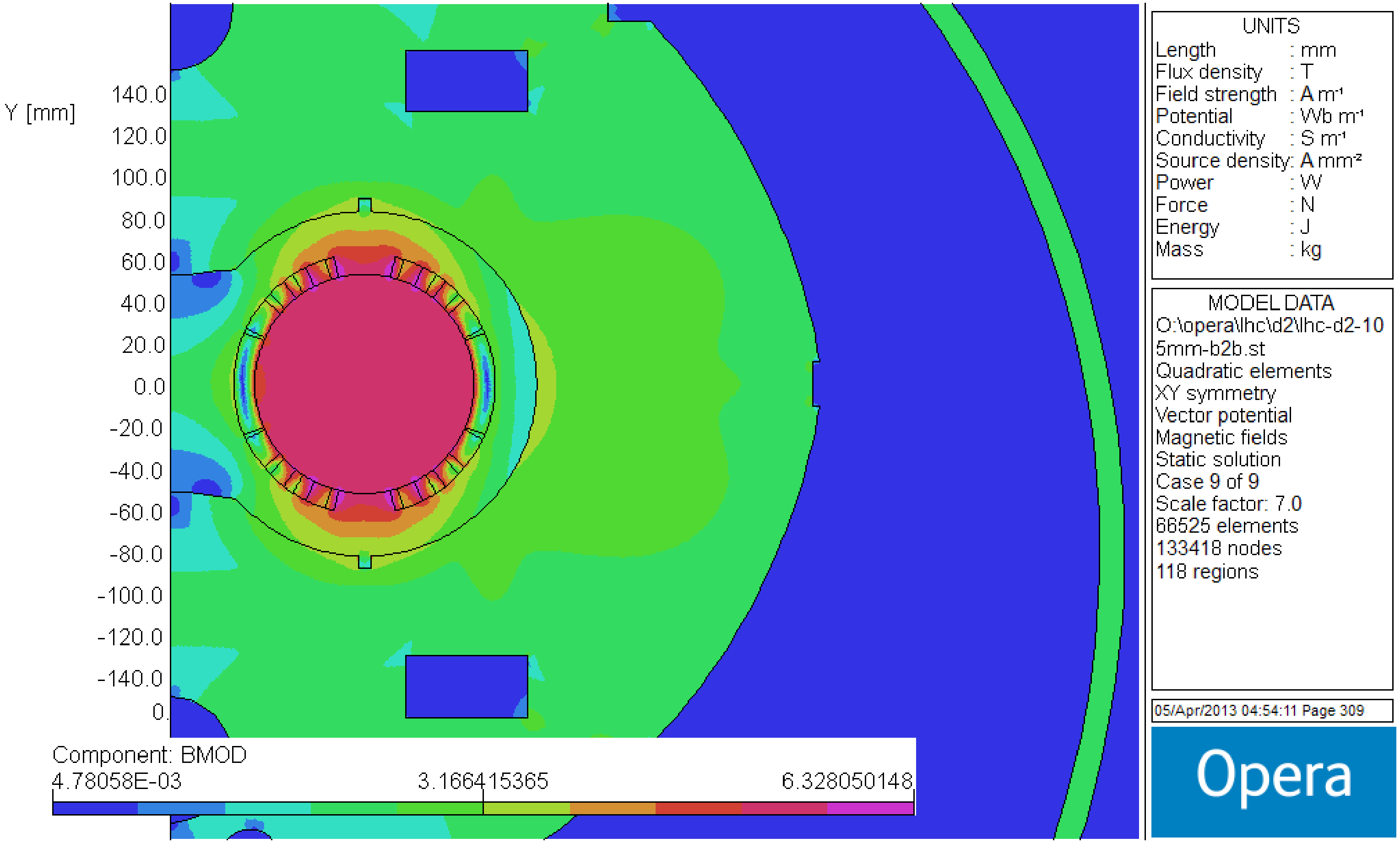
Y [mm]
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
-120.0
-140.0
-100.
Component: BMOD
3.17182E-03
3.140465383
6.277758948
UNITS
Length : mm
Flux density : T
Field strength : A m-1
Potential : Wb m-1
Conductivity : S m-1
Source density: A mm-2
Power : W
Force : N
Energy : J
Mass : kg
MODEL DATA
lhc-d2-105mm-r25.ST
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 9 of 9
Scale factor: 7.0
61969 elements
124340 nodes
125 regions
05/Apr/2013 04:44:03 Page 295
Opera

Managing Saturation to Minimize Saturation-induced Harmonics

- Saturation-induced harmonics are created when the field in iron near the aperture varies as a function of angle at high fields.
- See left-right difference and angular dependence of field
- Either removing saturating iron, or forcing a uniform saturation by holes, etc. should reduce the saturation-induced harmonics.



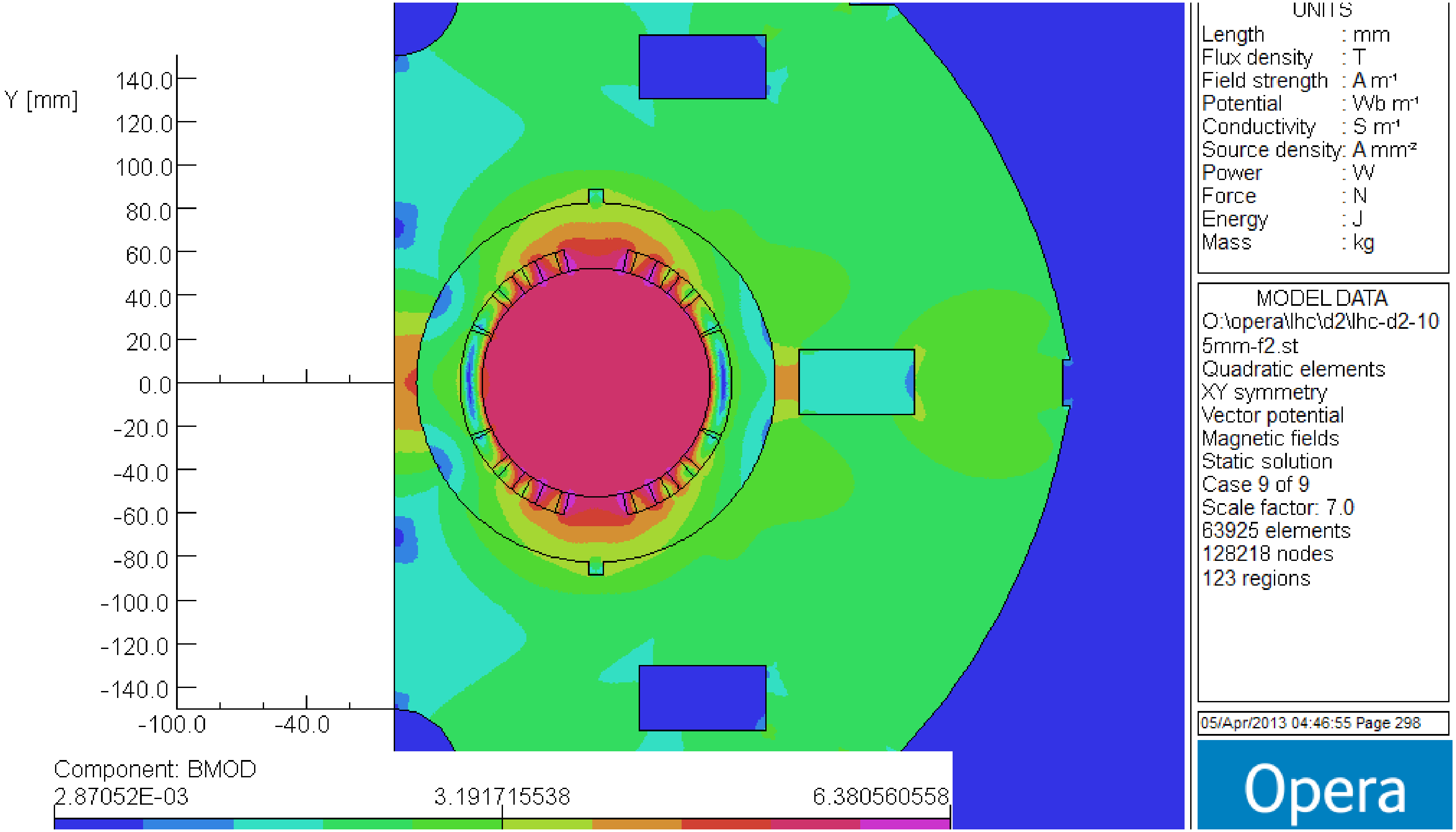
Iron removed between the two apertures



Change in quad term becomes half but the absolute value becomes about 100 unit and b4 becomes about 30 unit.

- Rest of the examples are for forcing saturation rather than removing.

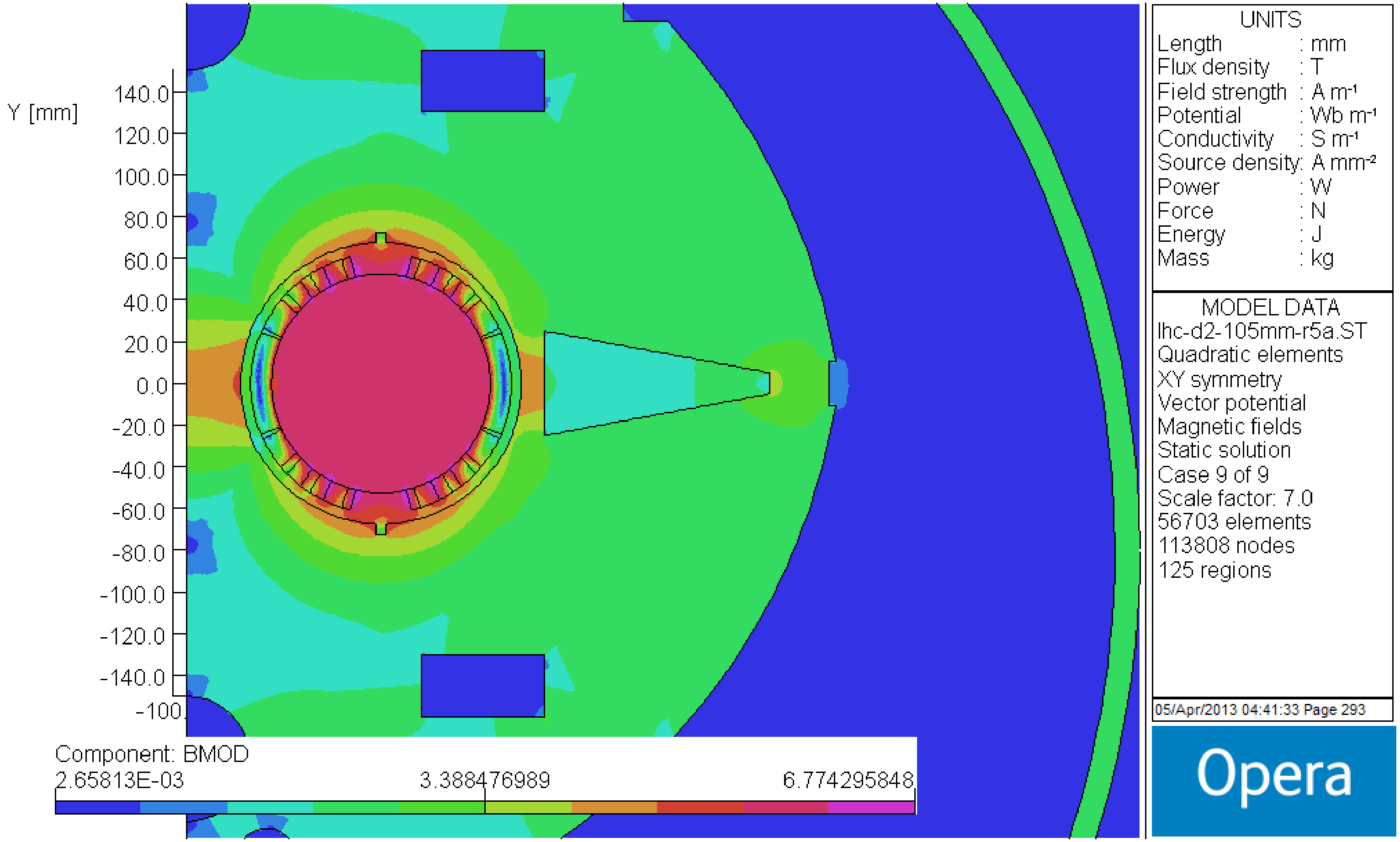
Midplane cutout to balance saturation between the left and the right side (20 mm collar)



Quad term becomes about half (~16 unit) and b4 <5 units @ 35 mm.

But b3 becomes large (about 100 units) due to larger midplane saturation.

5 mm collar with large cutout at midplane



Cross-talk becomes even smaller (b2 <7 unit and b4 <2 units @ 35 mm.

But b3 becomes large (over 100 units) due to larger midplane saturation.

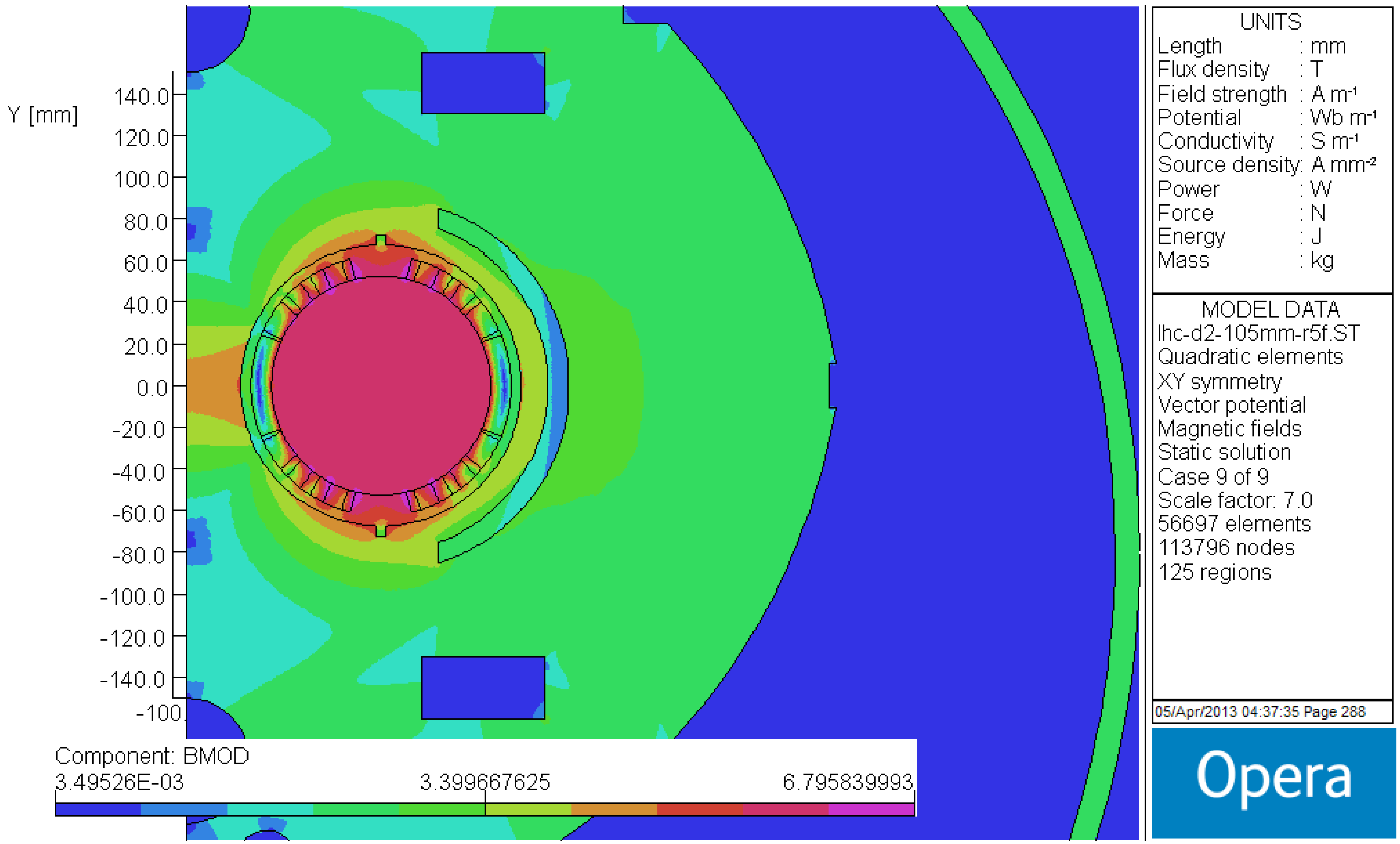
LARP

BROOKHAVEN NATIONAL LABORATORY

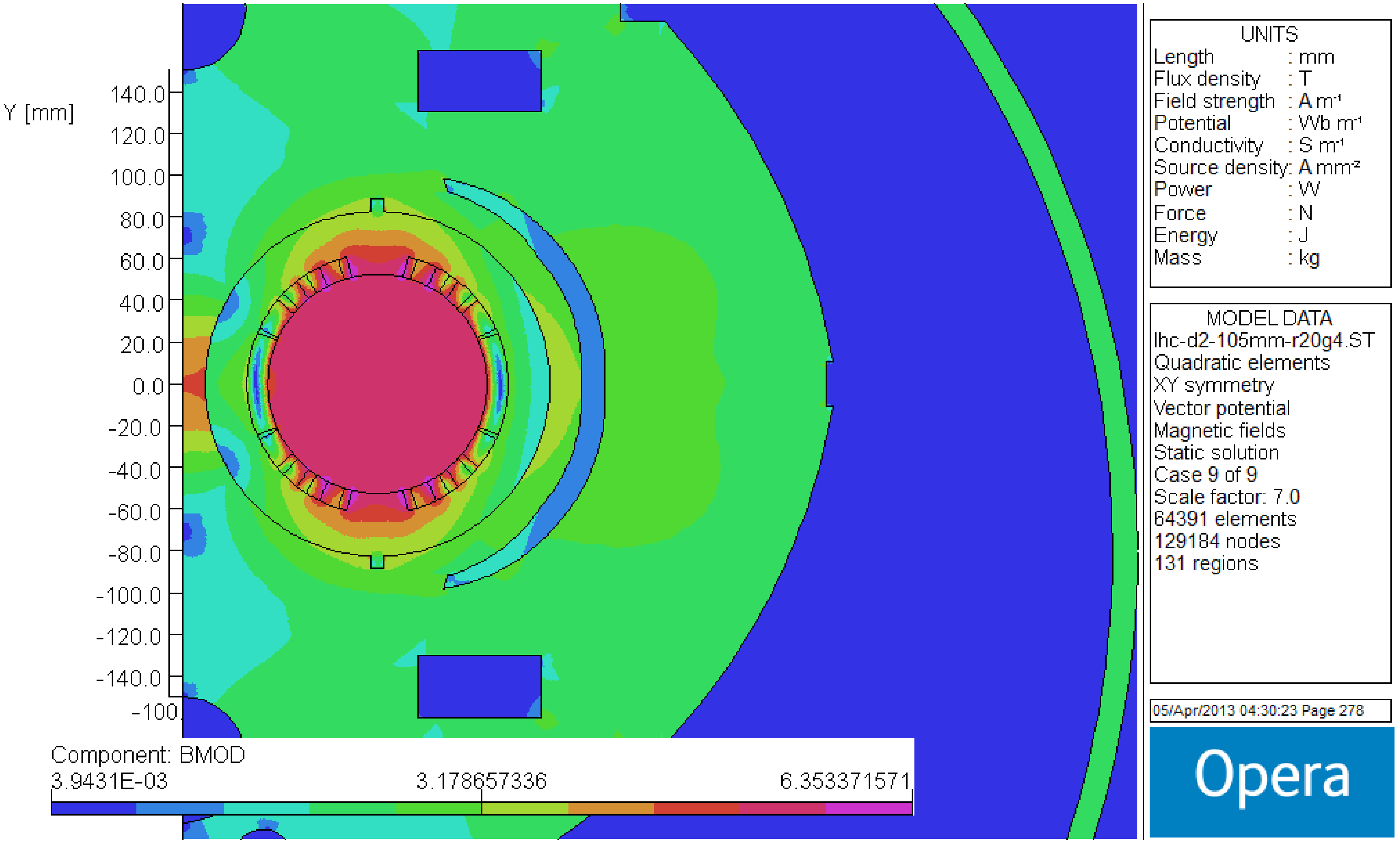
SUPERCONDUCTING MAGNET DIVISION

Several other cases are examined in the following slides but none has given yet a solution that has all small saturation induced harmonics

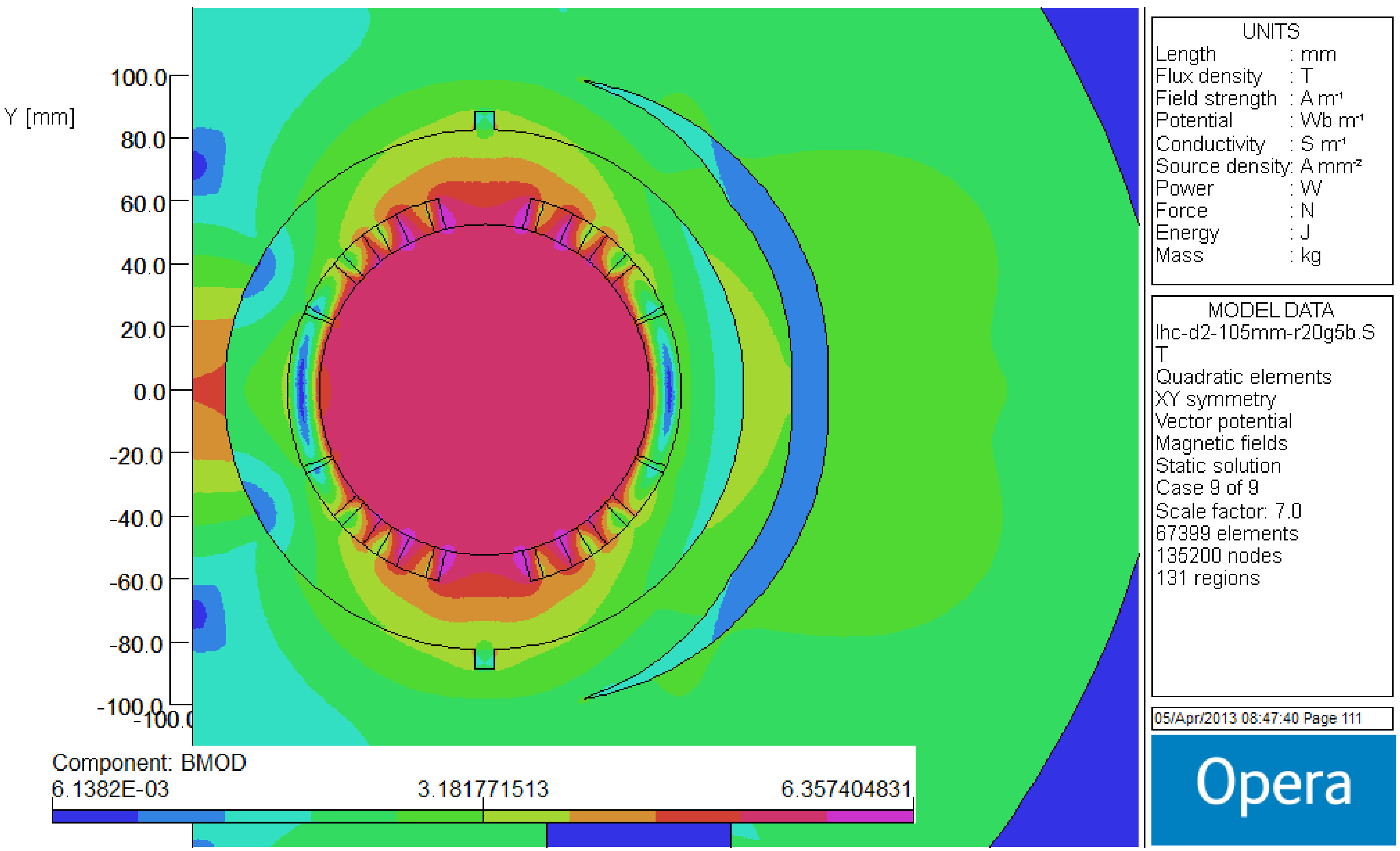
5 mm spacer with arc cutout



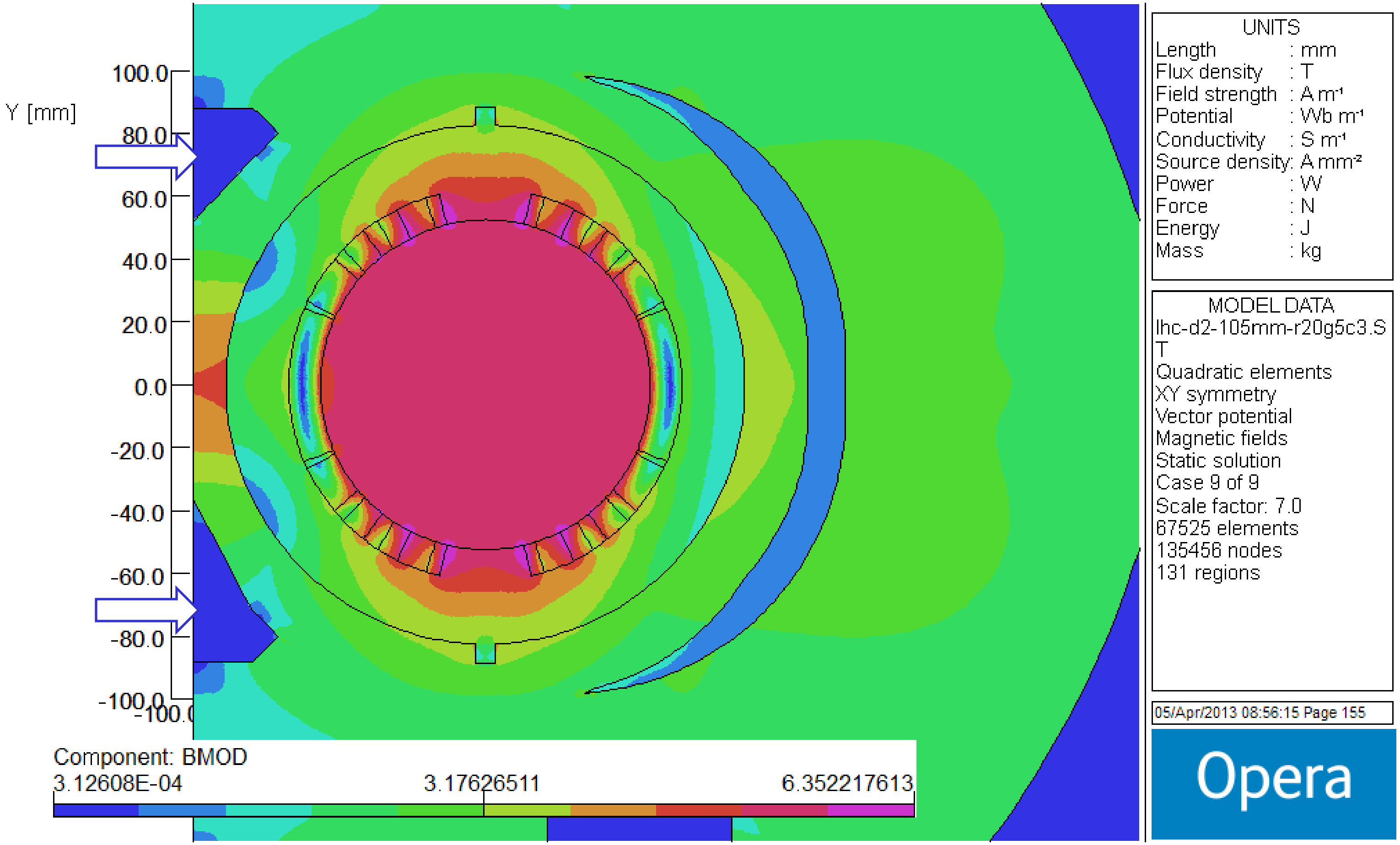
20 mm radially arc cutout



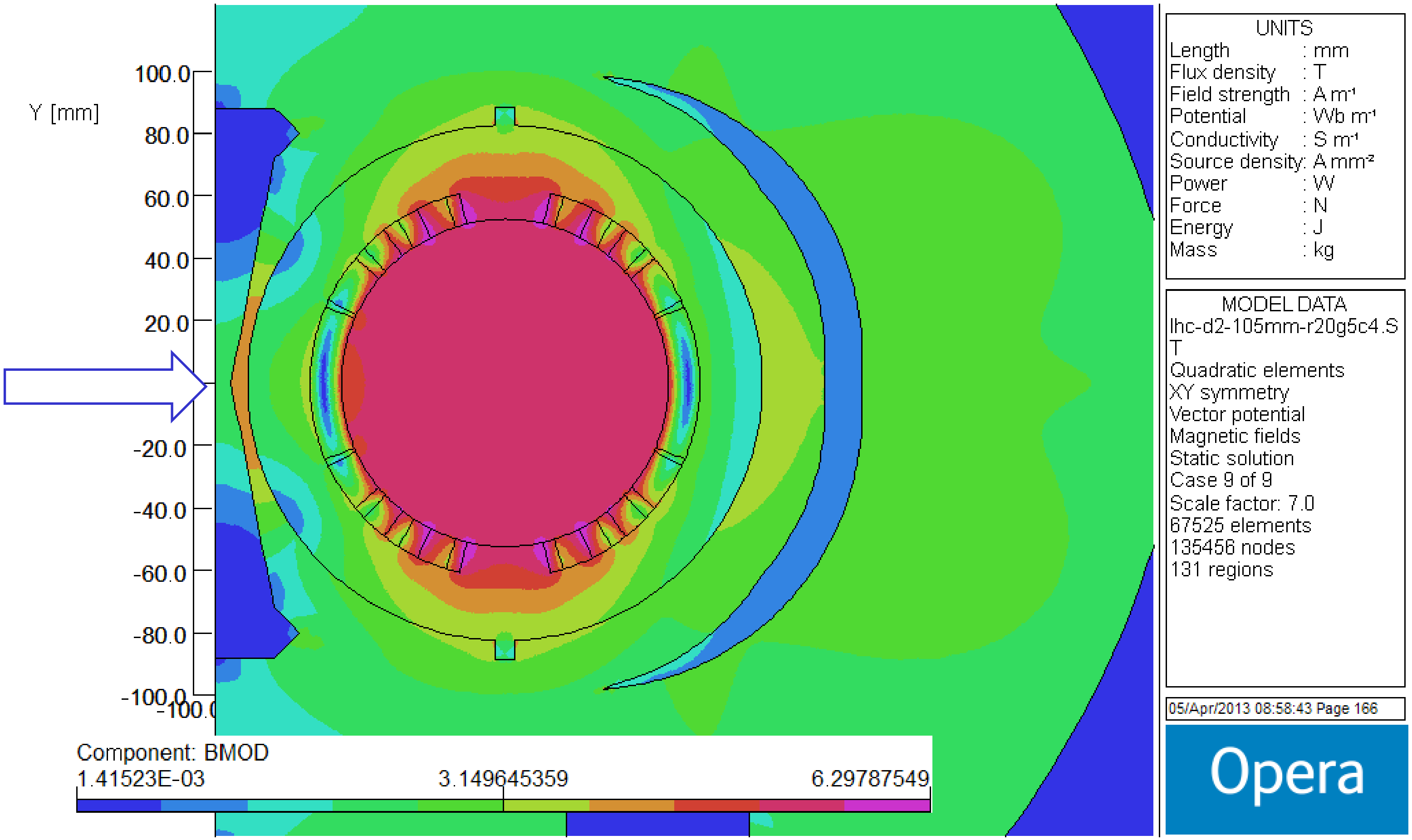
20 mm moon cutout



Cutout on both side #1



Cutout on both side #2



Discussion on Approach

- We are facing a challenging situation in going from 80 mm to 105 mm within the same yoke envelope when the since the flux is increased by over 31%. Moreover, the spacing between the two apertures is further reduced.
- There is a large difference in iron saturation between the left and the right and the pole and the midplane.
- With cutouts and holes, the right side of the aperture (at the midplane) can be forced to saturate evenly with the left side (reducing the cross-talk harmonics) but it increases the difference between pole and midplane saturation (increasing allowed harmonics).
- One can force pole saturation to increase to mitigate it.
- But we are facing a very highly saturating iron and significant fringe fields.

SUMMARY

- Large increase in flux (over 31% due to increase in coil aperture from 80 mm to 105 mm) makes yoke optimization very challenging.
- A number of techniques to reduce saturation induced harmonics have been attempted. However, so far none has produced a field quality that is typical for accelerator magnets.
- More work on optimization may continue but one should also consider alternatives:
  - Can one have a larger cryostat to allow more yoke iron?
  - Can one allow this magnet to have tens of units of harmonics?
  - Is a point optimization at high field advisable which may be influenced by iron properties (note that the saturation is high)?