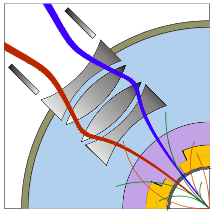

# D1 Field Quality


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BNL


APUL CD1 Review

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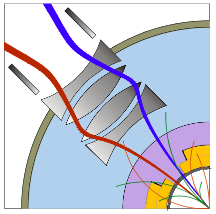
Brookhaven Nation Laboratory

# Outline

- Field quality overview
- Field quality examples from RHIC
- Field quality with D1 oblate yoke
- Methods of improving field quality relative to RHIC
- Redesign of coil ends to improve mechanical performance
- Magnetic forces between the two individual cold masses
- Summary

# Overview

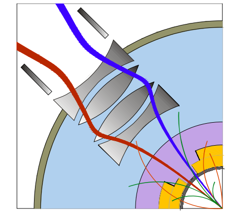


- Issues, challenges and strategies for obtaining the required field quality
- Coil cross-section
  - Flexible but no change in basic cross-section over existing DX
- Yoke design to minimize harmonics while meeting other requirements
  - Yoke design is well advanced, except for minor iterations for cooling holes/channels. Minor iterations can still be accommodated
- Alternate coil end design
  - New end design with ROXIE is complete (except for minor adjustments)
- Lorentz Forces between the two LDX coldmasses
  - It's a small effect
- Response to the field quality specifications from CERN
  - Specifications are more demanding than achieved in DX
- Summary

# Issues

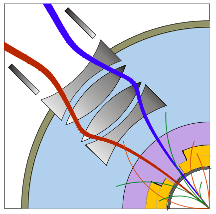
- In terms of field quality expectations in APUL D1 dipoles, we should benefit from the fact that similar 180 mm dipoles have been built and tested before for RHIC insertion region. The field quality in those 13 RHIC DX dipoles has been measured and except for a few lower order harmonics, it is generally acceptable for LHC upgrade.
- However, when looked at in detail, the situation is not so straight forward.
- For good field quality and correct pre-stress, we generally want coil size to be within 50 microns or less of the design. However, for a 71 turn coil it is already exceeded by about an order of magnitude by the cumulative cable tolerances of +/- 6 microns. *(In RHIC DX, we had to increase number of turns to 71 from original design of 70.)*
- Since the iron yoke (both geometry and material) is different; saturation-induced allowed harmonics will be different.  Moreover, Lorentz force-induced harmonics could be different. In addition, there are skew harmonics because of the non-symmetric placement of the coldmass in the cryostat.

# Challenges and Strategy

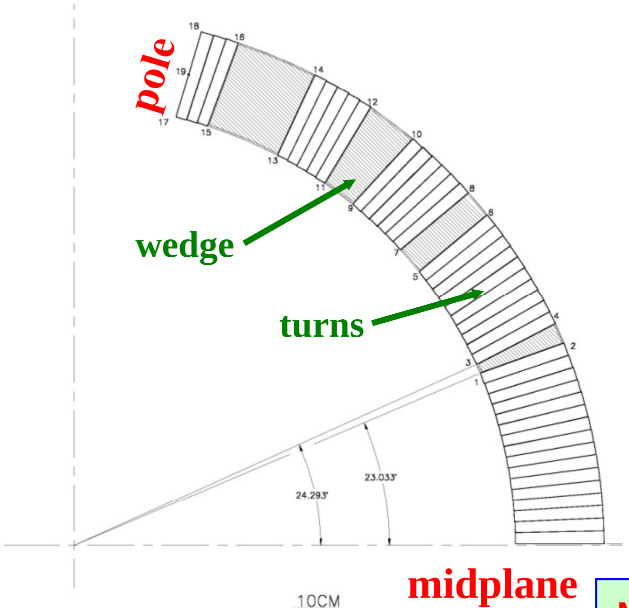


- Field quality in the first magnet (even that based on an earlier design) could be off for a variety of reasons. For achieving $10^{-4}$ field errors, the devil is in the details.
- Cross-section iterations are the traditional method for assuring good field quality.
- However, these iterations consume significant time and money.
- Eliminating them, as proposed for the D1 magnets for APUL, is a good example of "Value Engineering". Absence of them obviously creates some risk.
- Thus the main field quality challenge of the program is the absence of building a "*pre-production magnet*" before the prototype is built.
  - The first magnet should be usable in the machine (or at most be spare).
  - No planned change in iron or coil design from beginning to end.
  - Only minor adjustments are allowed/planned to control the field quality through the production (from the first magnet to the last magnet).
- The key to "risk mitigation" is a "flexible design" plus careful and thoughtful planning.
- This presentation will outline our strategy based on the past successful experiences in various RHIC magnets. We are reasonably confident that it can be done (again).

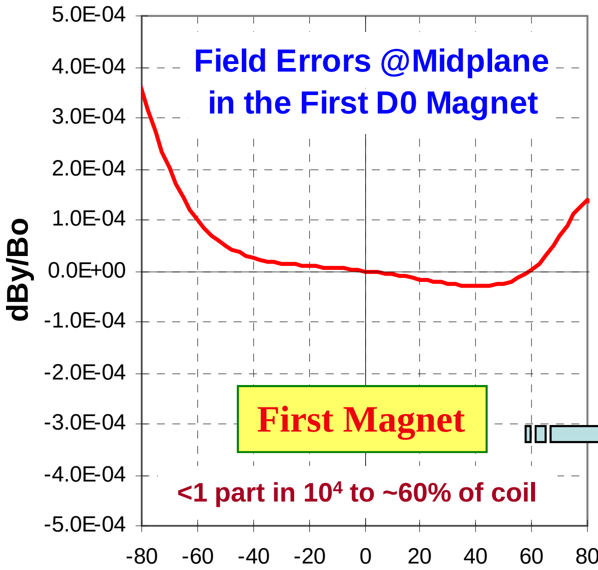
# Plan for Flexible Coil Cross-section in APUL D1
## (Do the same as done in 100 mm RHIC IR Dipole)

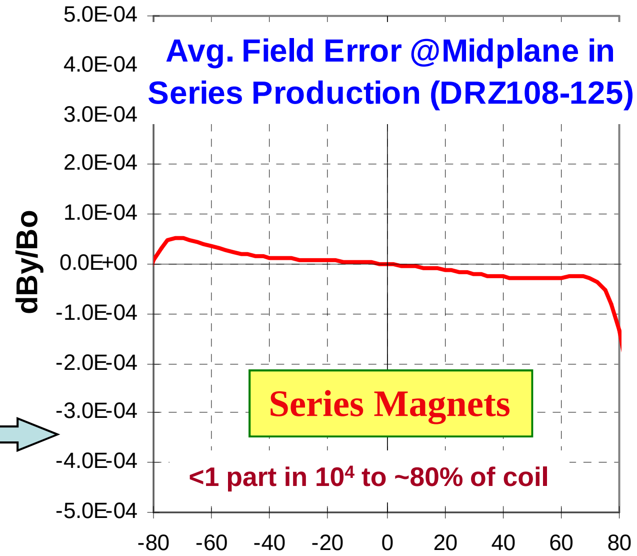


- In 100 mm RHIC IR dipoles, we developed techniques that were simple to implement but yet powerful enough to produce the very first magnet with accelerator grade field quality in (field errors ~1 part in $10^4$ up to 60% coil radius).
- The flexibility was obtained by starting with more than minimum midplane and pole shims. Then adjustment in the size of them allowed an easy way of tuning field harmonics during the production without changing the actual coil cross-section.
- It resulted in very good field quality magnets – we achieved average error <1 part in $10^4$ up to ~80% of coil radius (almost entire vacuum pipe).




RHIC 100 mm D0

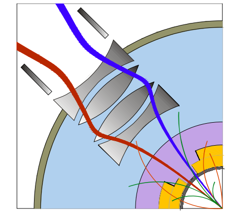


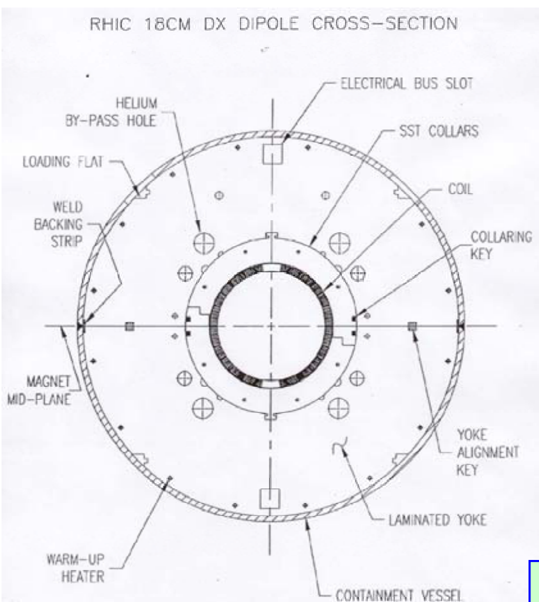

Much faster and much cheaper than conventional iterations

# Plan for Flexible Yoke Cross-section in APUL D1

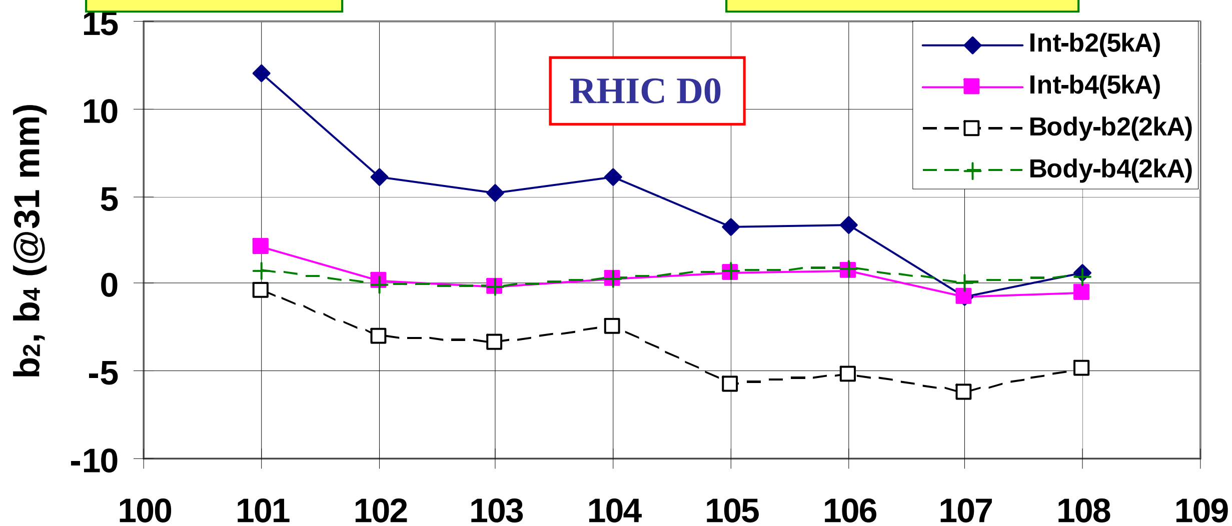
## (Do similar to was done in 100 mm RHIC IR Dipole)



- Have extra strategically located saturation control holes in the yoke lamination and fill them up with iron rods as needed.
- This takes care of both saturation-induced harmonics (culprit iron) and Lorentz force induced harmonics (culprit coil, particularly if there is a small radial gap of ~50 micron or so between coil & collar, built-up due to normal tolerances in parts).
- Final result of this adjustment is a smaller change in harmonic as a function of current, independent of who the culprit is.

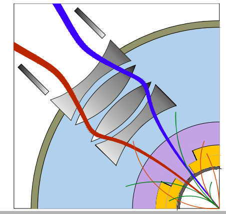



**First Magnet** → **Series Magnets**

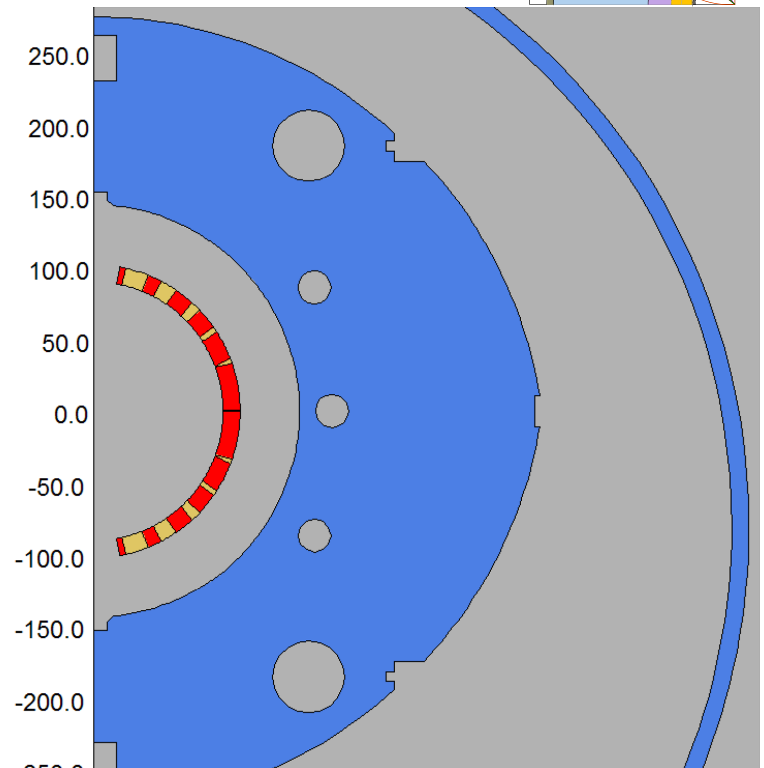



Much faster and much cheaper than conventional iterations

# New D1 Yoke Design (oblate)



- Iron saturation (plus Lorentz force) induced harmonics (normal and skew due to cryostat) are controlled with the help of saturation control holes
- These holes are in addition to the helium holes.
- As such the three holes shown near the yoke inner radius are adequate to obtain low computed change in harmonics as a function of current.
- However, we have additional tuning flexibility by allowing the three holes to be partially filled with the low carbon steel (magnetic) rods.
- The length of each rod will be determined after the initial magnetic measurements.
- These holes and rods effectively facilitate the iteration of yoke without changing the geometry.
- It also provides the capability fine turning.
- Big holes may be revised to accommodate cooling.



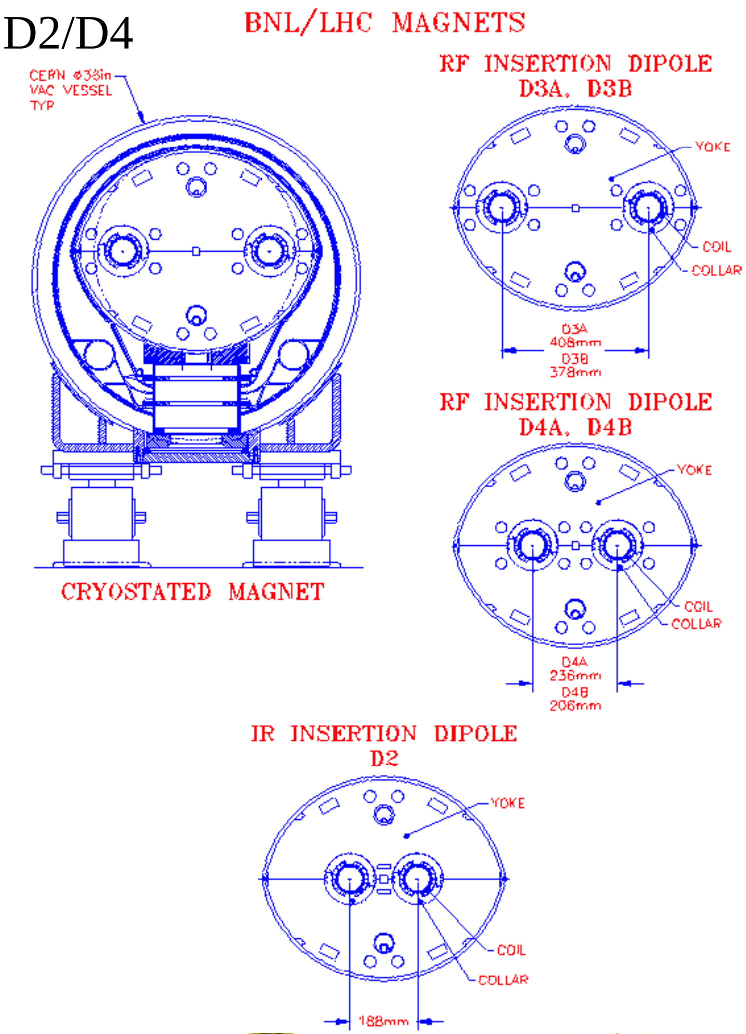

**At present we are leaving ~120 $cm^2$ empty space in yoke for helium (similar to what is in insertion quads).**

# Background on Oblate Yoke Option

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

- This saved significant effort and money by allowing 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.

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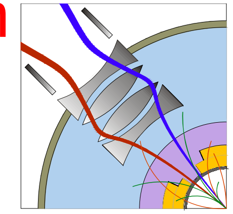
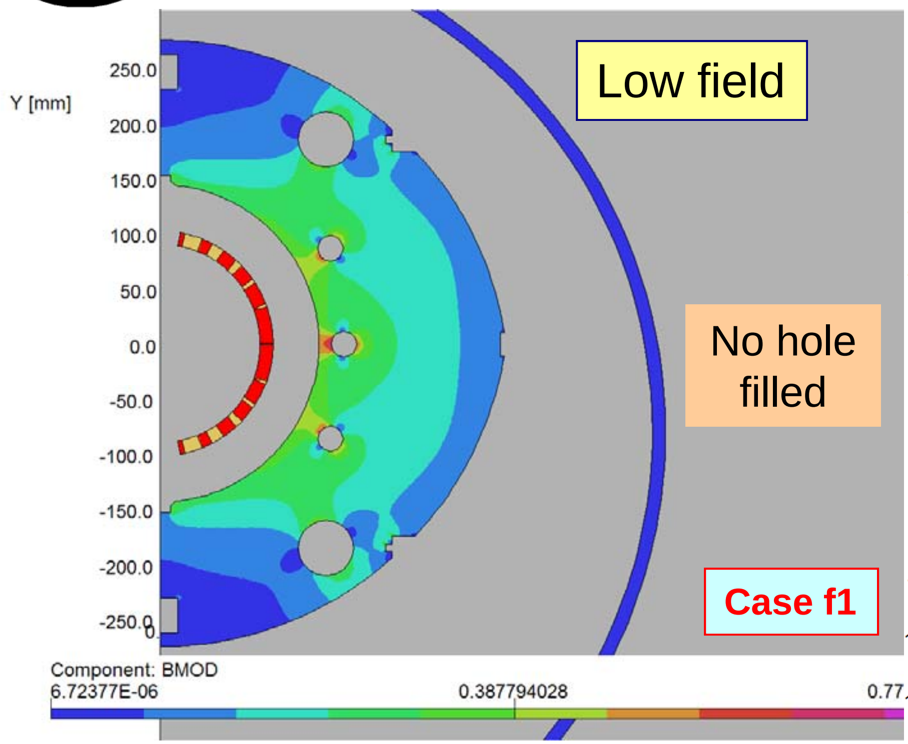
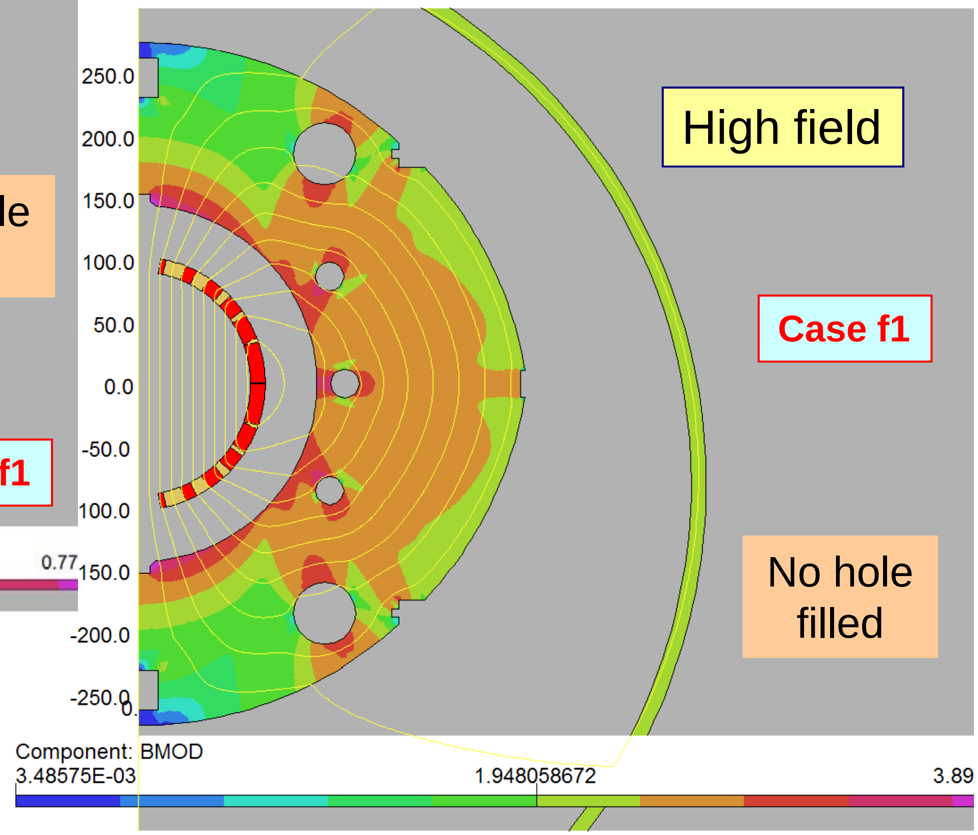
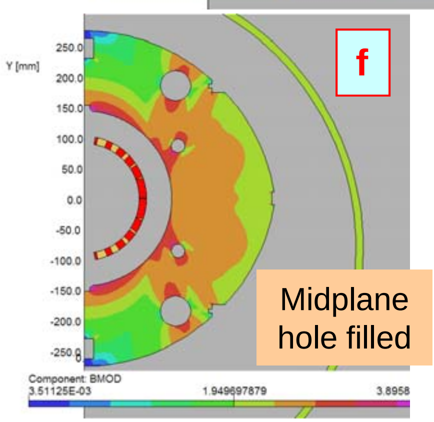
# Saturation Control Holes are Used to Force Uniform Magnetization of Iron Near the Yoke Inner Surface

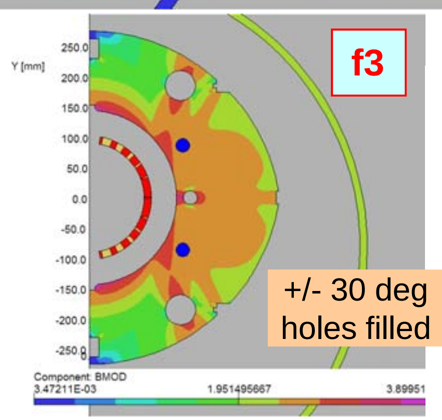





Note difference between low field and high field.




Also note the influence of some holes filled.

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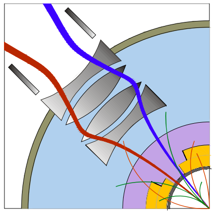
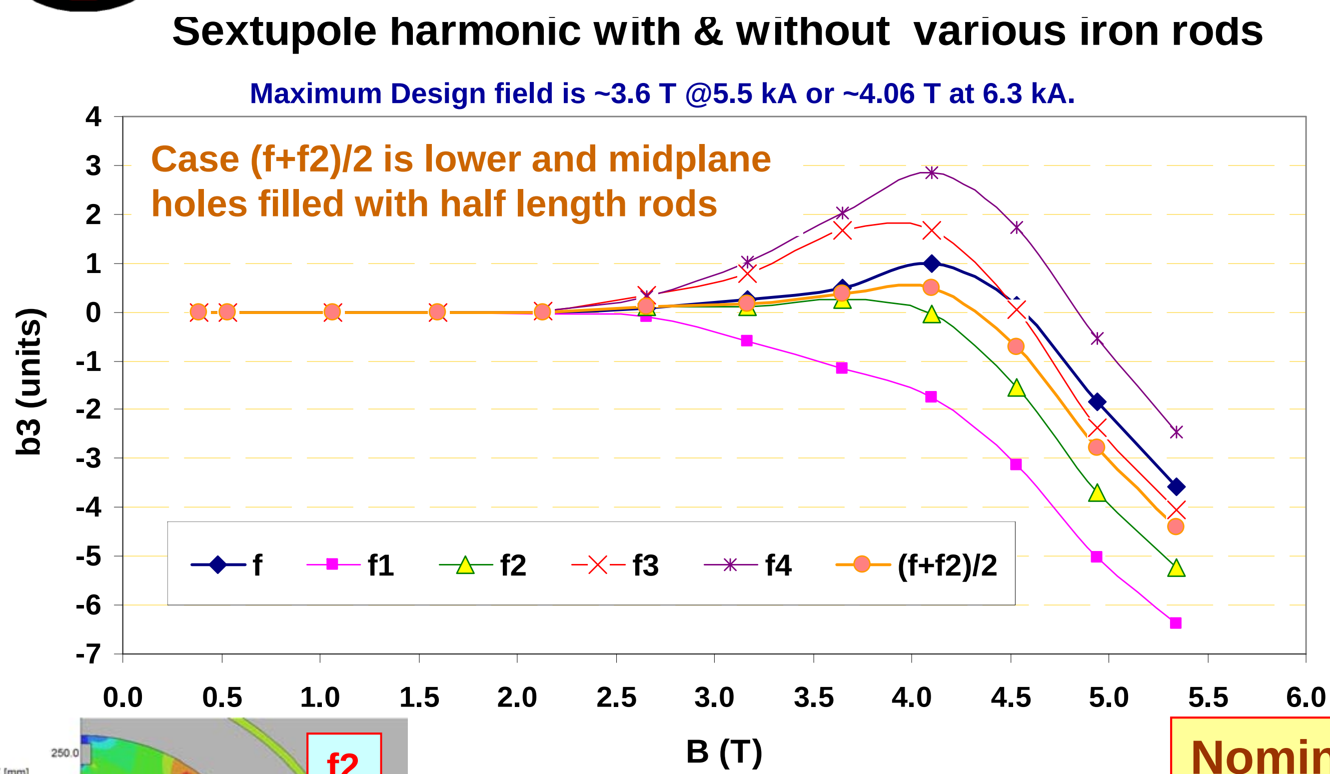
# Computed Field Dependence of $b_3$

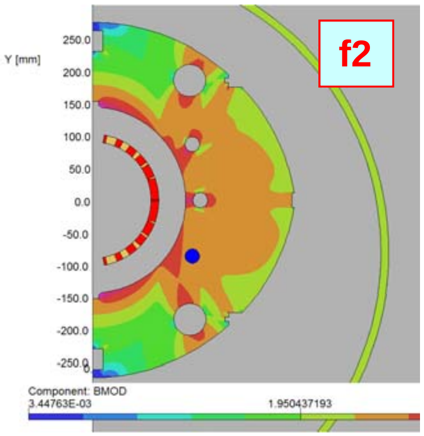
## (with and without holes filled with iron rods)






- There is a clear ability to change the variation in saturation induced harmonic in either direction.
- Holes cover a reasonable range of expected variations.

Saturation induced $b_3$ in the original design was ~3 units.



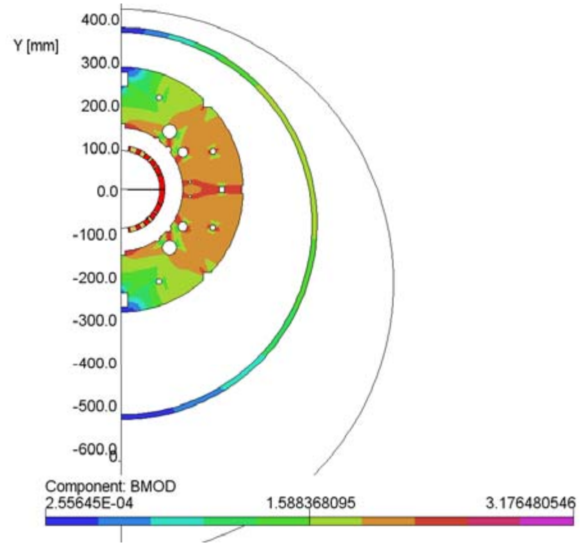

- f : Only midplane hole filled
- f1 : No hole filled
- f2 : Only lower hole filled
- f3 : Lower and upper holes filled
- f4 : Midplane and lower holes filled

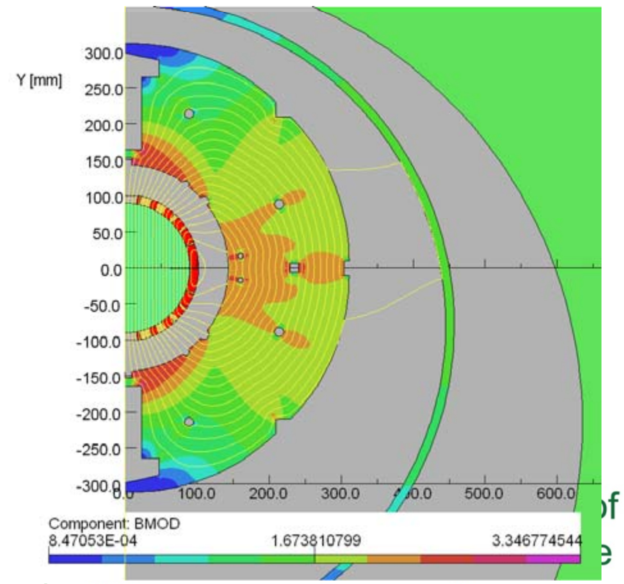
**Nominal case for low $b_3$:**

- **Fill lower and midplane holes with half length rods.**
- **Adjust only midplane rod for $b_3$ tuning - no $a_2$ change.**

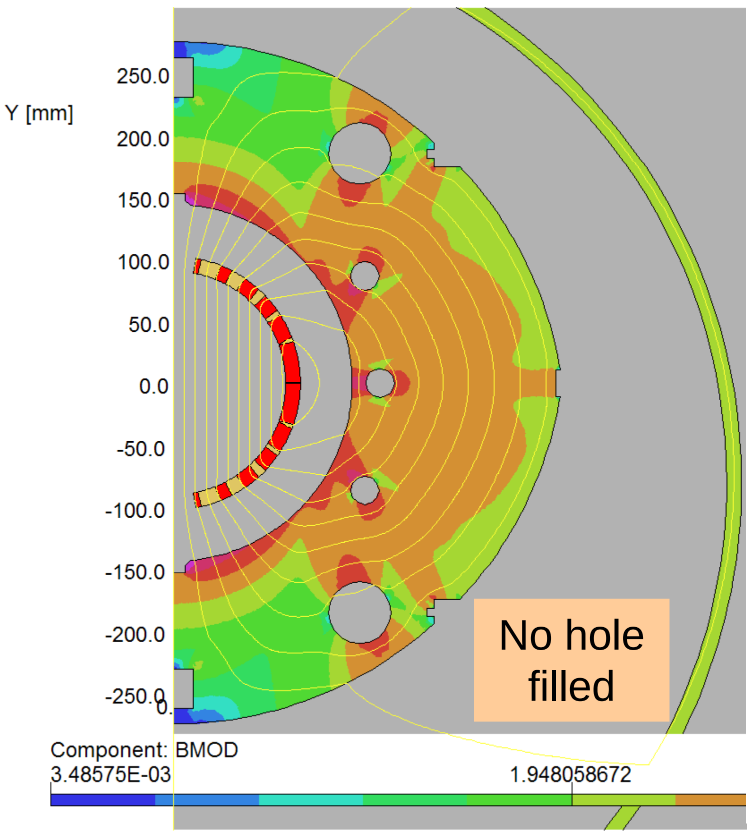
# Skew Quad ($a_2$) Harmonic at High Fields

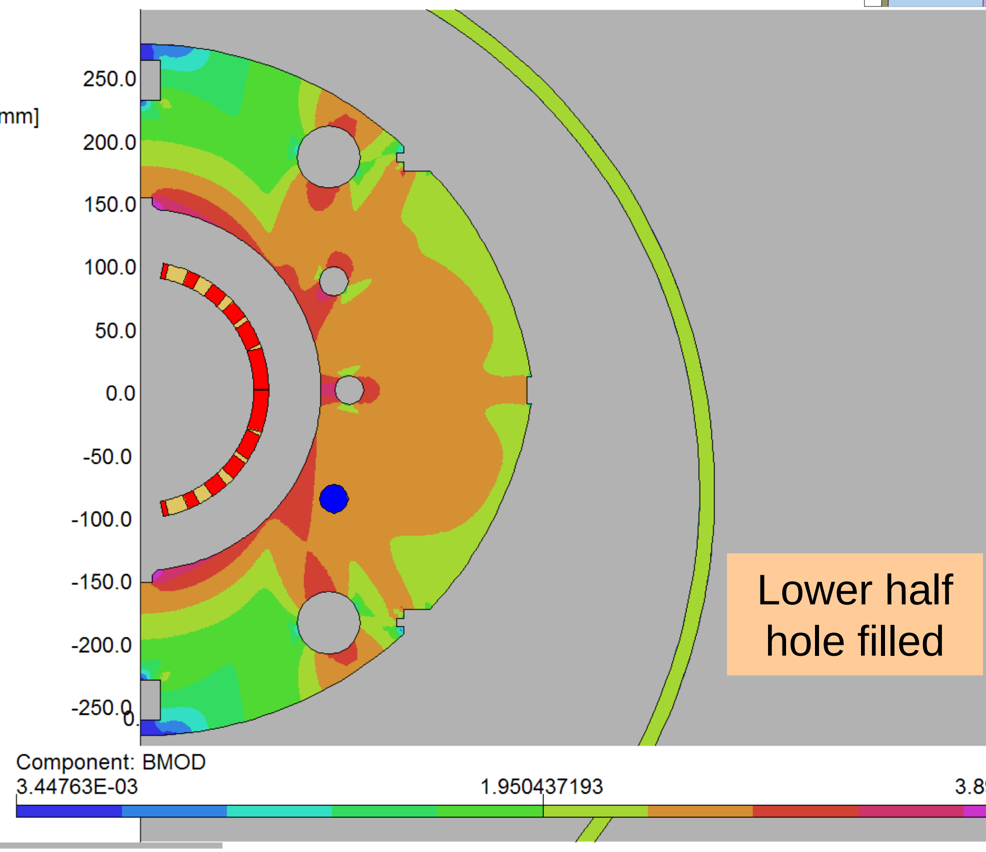
- Non symmetric vertical placement of the coldmass inside the steel cryostat creates skew quadrupole harmonic ($a_2$) at high fields when the flux leaks out of the yoke.
- In RHIC dipoles, this was partly compensated by placing heavier yoke packs in the lower side.
- We could use a similar technique here.
- Additional asymmetry can also be created with some strategically located holes in a symmetric yoke and then partially filling one or more of them in the lower yoke half only.
- This asymmetry compensates for the proximity of the cryostat to the upper half. It is a simple, powerful and flexible technique.  It is the baseline plan.
- [Alternative: use stainless steel cryostat]



# Change in Yoke Saturation by Filling Saturation Control Hole in Lower Half Only

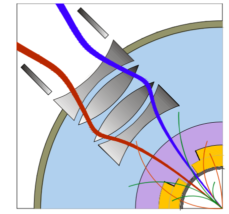


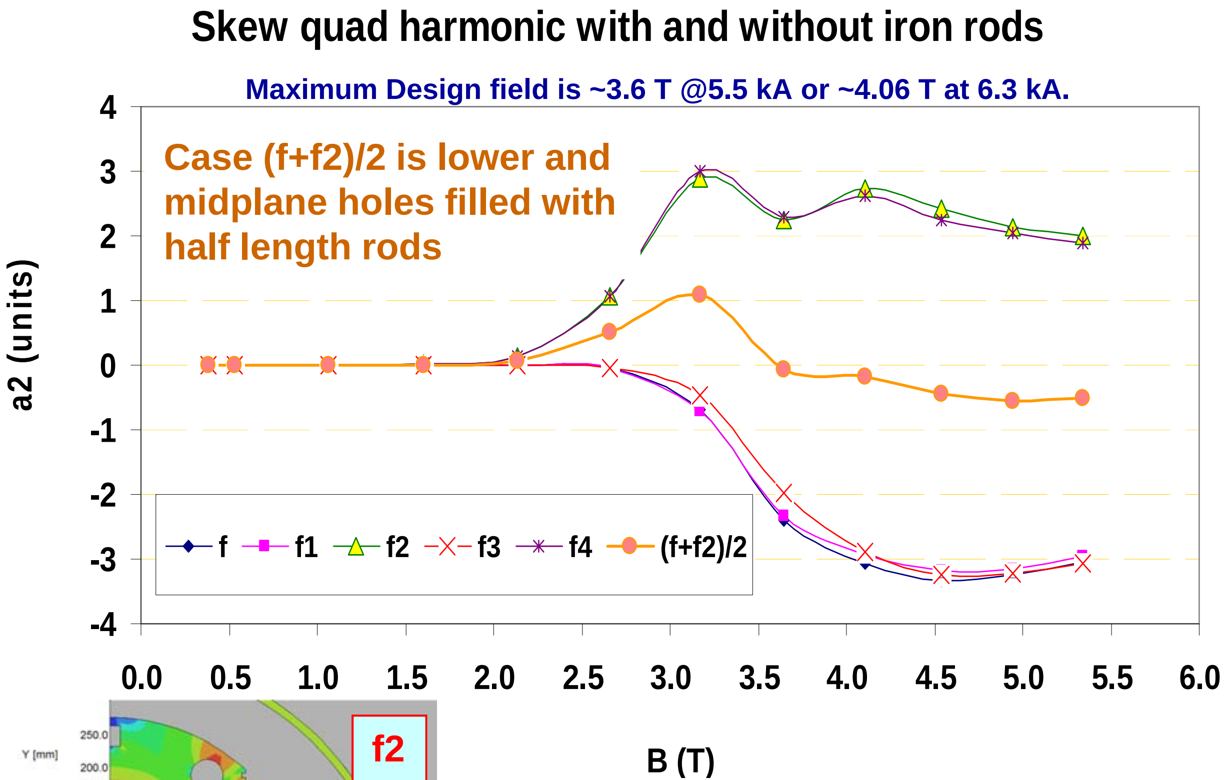




Filling of hole in lower half by low carbon steel magnetic yoke can compensate for the proximity of the cryostat to the upper half.

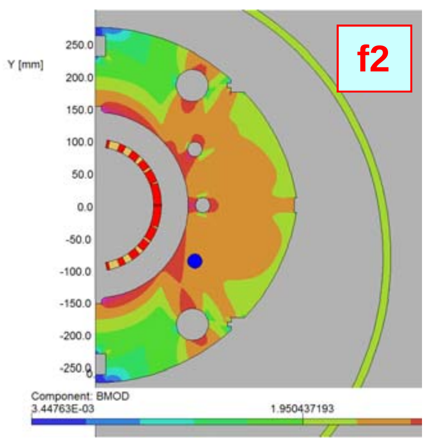
# Computed Field Dependence of $a_2$

## (with and without holes filled with iron rods)






- There is a clear ability to change the variation in saturation induced harmonic in either direction.
- Holes cover a reasonable range of expected variations.
- Location and size of the hole may be optimized to reduce intermediate peak.




- f : Only midplane hole filled
- f1 : No hole filled
- f2 : Only lower hole filled
- f3 : Lower and upper holes filled
- f4 : Midplane and lower holes filled

**Nominal case for low $a_2$ (and also $b_3$):**

- **Fill lower and midplane holes with half length rods.**
- **Adjust length of these rods for tuning.**

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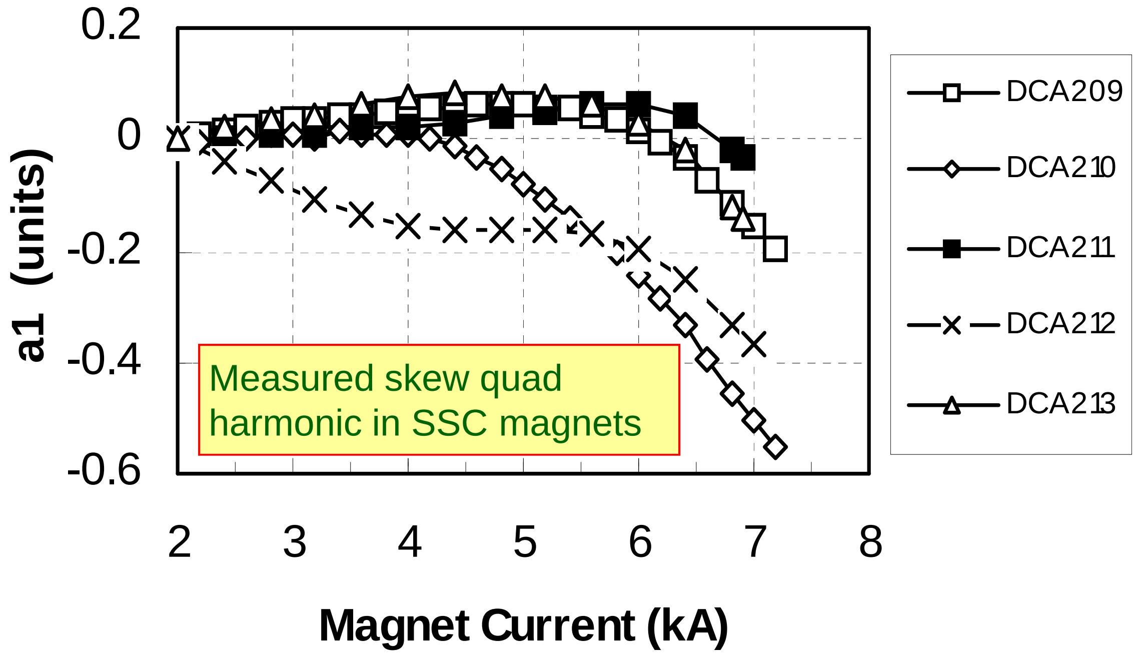
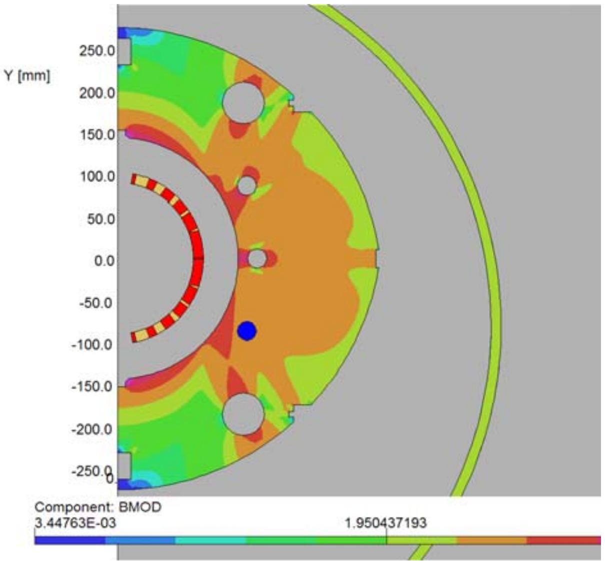
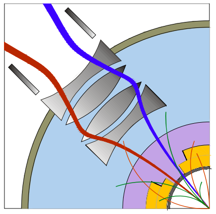
# Ability of Saturation Control Hole to Reduce Magnet to Magnet Variation in Saturation




- Significant magnet to magnet variation in saturation induced skew quad in SSC magnets.
- Length of the magnetic rod can be adjusted after the measurements to reduce this magnet to magnet variation.
- Cold measurements of saturation harmonics with steel cryostat only at CERN – baseline: calculate effect of steel – option: stainless steel cryostats

# Magnetic Forces Between the Two Coldmasses

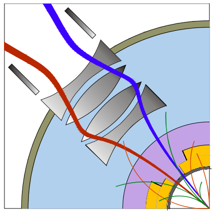


- At one stage there was a concern about the magnetic interaction between the two coldmasses placed in close proximity.
- If the two coldmasses are very close, then the leakage field from the one on other would create additional magnetic force on each magnet.
- We considered the case when the space between the two end plates was only a few centimeters (remember, there is a much larger space between the actual coil ends because of the end saddles and endplates inside).
- The computed value of force (based on rough calculations) was small : ~ 4 kN per end. This is not surprising as the leakage field is relatively small.
- Moreover, since then the spacing between the two coldmasses has now been significantly increased (~0.5 meter).
- Conclusion: not a problem

# APUL D1 Error Table, V1

(based on RHIC experience, sent to CERN for review)

**LE + Body + NLE + space + NLE + Body + LE**



**LHC/BNL/D1 Version (1c)**

Expected values of integral harmonics at 2000 A in
180 mm aperture D1 dipoles (consisted of two LDX):

(assumes one LDX coldmass with 2 warm and 2 cold measurements to be used for tuning of INTEGRAL geometric and saturation harmonics)

***** Reference Radius is 40 mm *****

Harmonics in units (European notation; n=3 is sextpole)

[ <bn> = mean, d(bn) = uncertainty in mean ]

[ sig(bn) = sigma for bn, sig(an) = sigma for an ]

| n | <bn> | d(bn) | sig(bn) | <an> | d(an) | sig(an) |
|---|---|---|---|---|---|---|
| 2 | 0.0 | 0.5 | 0.6 | 0 | 2 | 2 |
| 3 | 0 | 2 | 1 | -1 | 2 | 0.3 |
| 4 | 0.0 | 0.2 | 0.1 | 0.0 | 0.3 | 0.4 |
| 5 | 0.0 | 1.0 | 0.1 | 0.0 | 0.1 | 0.05 |
| 6 | 0.0 | 0.05 | 0.02 | 0.0 | 0.10 | 0.05 |
| 7 | -0.2 | 0.3 | 0.02 | 0.0 | 0.02 | 0.02 |
| 8 | 0.000 | 0.002 | 0.003 | 0.0 | 0.02 | 0.01 |
| 9 | -0.05 | 0.100 | 0.003 | 0.0 | 0.01 | 0.001 |
| 10 | 0.00 | 0.001 | 0.001 | 0.0 | 0.005 | 0.001 |
| 11 | -0.02 | 0.020 | 0.0003 | 0.0 | 0.0003 | 0.0002 |
| 12 | 0.00 | 0.0001 | 0.0001 | 0.0 | 0.0002 | 0.0002 |
| 13 | 0.01 | 0.010 | 0.0001 | 0.0 | 0.0001 | 0.0001 |
| 14 | 0.00 | 0.0001 | 0.0001 | 0.0 | 0.0001 | 0.0001 |
| n | <bn> | d(bn) | sig(bn) | <an> | d(an) | sig(an) |

The CERN specification requires these low-order harmonics to be similar to the RHIC D0 magnet ( factor of two lower than for DX)

**These are associated low field harmonics**

Following harmonics may show significant variation as a function of current
(as compared to the uncertainty in mean)
Persistant current changes are incorporated in <b3> and saturation in d(b3) and d(a2)

| I (A) | <b3> | d(b3) | sig(b3) | <a2> | d(a2) | sig(a2) |
|---|---|---|---|---|---|---|
| 360 | -5 | 2.5 | 1.1 | 0 | 2 | 2 |
| 1000 | -1 | 2 | 1 | 0 | 2 | 2 |
| 2000 | 0 | 2 | 1 | 0 | 2 | 2 |
| 4000 | 0 | 2 | 1 | 0 | 2.5 | 2.2 |
| 5600 | 0 | 2 | 1 | 0 | 2.5 | 2.5 |
| 6500 | 0 | 2.5 | 1.0 | 0 | 3.0 | 3.0 |
| 7500 | 0 | 3.0 | 1.1 | 0 | 3.0 | 3.5 |

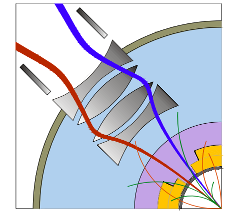
**LHC/BNL/D1 Version (1c)**

Ramesh Gupta, July 6, 2009

**Maximum Design field is ~3.6 T @5.5 kA or ~4.06 T at 6.3 kA.**

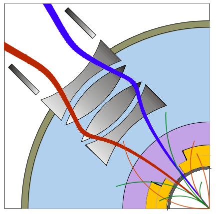
**Reference radius is only 40 mm for a coil radius of 90 mm.**
- **Expect smaller higher order harmonics**

# Discussion of Improvements to the Field Error Table



- Background on Error Table
  - Earlier version of BNL error table was primarily based on RHIC DX and other magnets (along with taking credit for certain harmonic tuning)
  - Generally, doing better means some additional steps will be required
- Systematic Errors
  - We have worked on the design to reduce systematic errors ( see earlier slides in this presentation related to harmonic tuning)
- Random Errors
  - These are associated with the magnet construction
  - Since we are not planning to change construction methods, no significant change should be expected in the random harmonics of LHC cold masses.
  - However, we have looked at the number of ways to reduce random errors. The next few slides will outline current thinking and work in progress
- Additional Limit on Individual Magnet and Coldmass
  - CERN has asked us to put limits on individual magnets, as the series is small and every magnet will be individually accepted. In general, the low order harmonics should be similar (or better) than those for the BNL built D1 magnets already operating in LHC.”

# Approach : Use Unique Configuration of the D1 Magnet



- Each D1 consists of two LDX coldmasses. CERN requires minimization of the integral field errors (beam is forgiving on the local variations).
- Let us consider separately the reduction of (a) random skew quadrupole and (b) random sextupole harmonics, both by a factor of two.
- Skew quad error harmonic changes sign if a dipole is rotated by 180 degree.
- We are planning to build magnets in such a way that the relative orientation between the two neighboring coldmasses is determined only after the magnetic measurements and before two LDX are joined to make a D1. This can also be done to a good extent based on the magnetic measurements of collared coils, if we choose to perform them.
- This will reduce skew quad by at least a factor of two (least reduction if one has a large magnitude and other is zero). This would reduce systematic too.
- Random sextupole error can be reduced by sorting of coldmasses or collared coil.
- However, sorting may impact the schedule since the two LDX coldmasses cannot be joined to make one D1 as soon as they are ready. One would perhaps need a pair of LDX coldmasses in hand to sort.
- This sorting should further reduce skew quad harmonic as well.

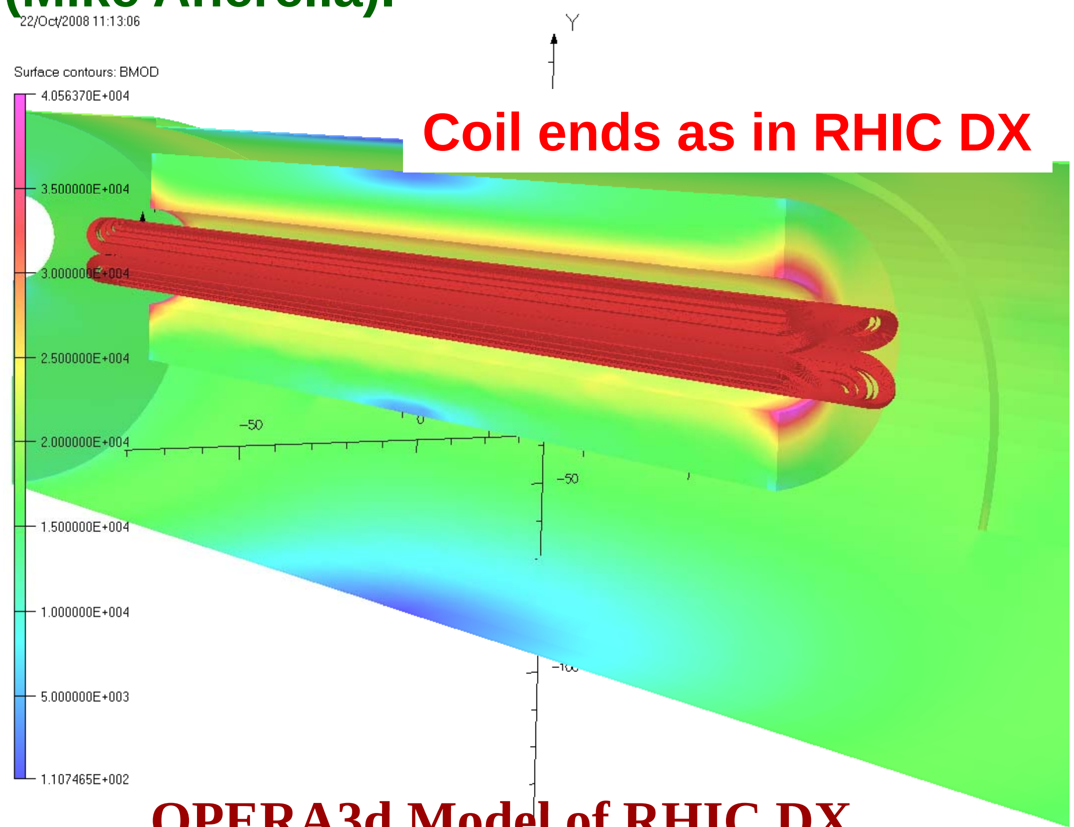
# Status of Our Ability to Meet the Field Error Table (as specified by CERN)

- With the flexible coil and flexible yoke design, we should be able to meet most systematic harmonic tolerances as requested by CERN. It might be tight in a couple of cases but not outside the realm of possibility.
- Want D1 random errors in some cases to be less than in RHIC DX. We should be able to achieve this with the sorting requested.
- Want the systematic value of integral skew sextupole be lower than in RHIC DX. That large value was related to the leads. We should be able to reduce it with a careful design of lead connections between the two coldmasses.
- Overall we are in a reasonable shape (but not in a too comfortable zone).

# Coil Ends

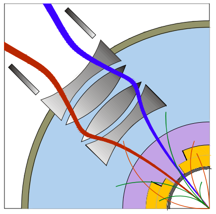
**The goal of this exercise is to develop an alternate end design to determine/compare by computer modeling the new improved ends with the original RHIC DX coil ends (Mike Anerella).**

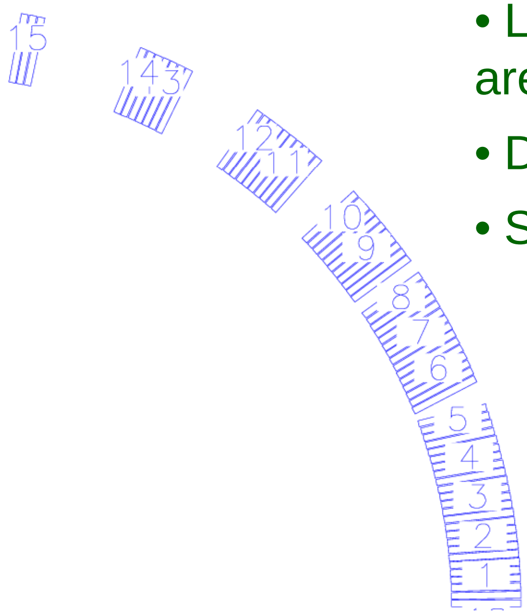
- The layout of the blocks and individual turns of coil ends is optimized using "differential geometry" method in ROXIE 10.1 (similar to the method used in program BEND) to improve the mechanical layout of the turns.
- The size and location of the end spacers is then optimized with ROXIE to obtain a good magnetic design with low end harmonics.




**OPERA3d Model of RHIC DX**

# New DX Ends Optimized with ROXIE



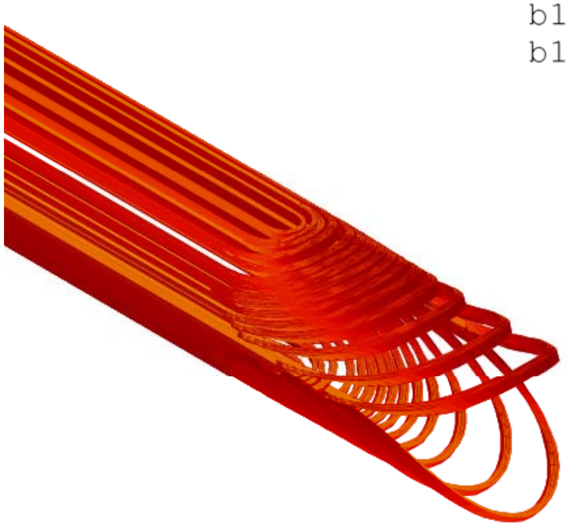



- Large blocks (blocks with large number of turns in cross-section) are divided such that most have five turns or less
- Differential geometry method is used for mechanical optimization
- Size of some spacers is optimized to obtain low end harmonics

| | |
|---|---|
| 3D AVERAGE MAIN FIELD (T) .......................... | -0.4130 |
| AVERAGE MAGNET STRENGTH (T/(m^(n-1)) ............... | -0.4130 |

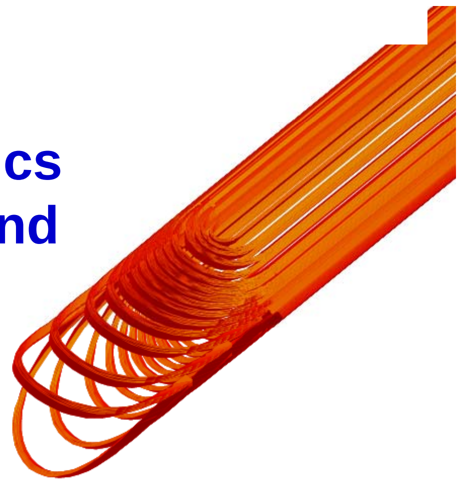
NORMAL 3D AVARAGE RELATIVE MULTIPOLES (1.D-4):

| | | | | | |
|---|---|---|---|---|---|
| b 1: | 10000.00000 | b 2: | 0.00000 | b 3: | 0.35792 |
| b 4: | 0.00000 | b 5: | -0.08180 | b 6: | 0.00000 |
| b 7: | -0.26283 | b 8: | 0.00000 | b 9: | 0.06756 |
| b10: | 0.00000 | b11: | 0.02140 | b12: | 0.00000 |
| b13: | -0.00090 | b14: | 0.00000 | b15: | -0.00112 |
| b16: | 0.00000 | b17: | -0.00016 | b18: | 0.00000 |
| b19: | -0.00007 | b20: | 0.00000 | b | |

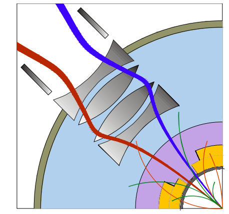


**Computed Integral Field Harmonics and Different Views of the New End**

**ROXIE 10.1**

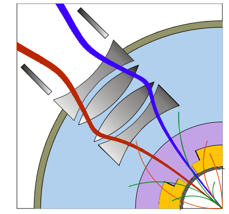


# Summary (1)



- The yoke and coil designs are nearly complete (some adjustments are still possible based on various needs).
- Strategies have been developed to meet tighter field quality specifications from CERN on certain harmonics.
- We are adopting a *value engineering* approach to save on cost and schedule by eliminating customary magnet iterations.
- The main field quality challenge of this program is to assure good field quality in production despite "NO *pre-production magnets*".
- With a *flexible design*, past experience and proper planning, we should be able to do it again as we did in RHIC.

# Summary (2)



- Forces between individual cold masses are negligible.
- A redesigned coil end with satisfactory harmonics and grouping of turns is now being analyzed for response to Lorentz forces.