Magnetic Field Control

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Similarities Between RHIC and KEK Magnets

- The iron is very close to the coil in both *RHIC dipole and quadrupole magnets* and in *KEK combined function magnets*.

- Earlier one would have expected a large value of saturation-induced harmonics in such cases. However, we have employed a number of techniques to make saturation-induced harmonics very small.

- We would share our experience with you.

Saturation in RHIC Arc Dipole

In RHIC dipole, iron is closer to coil and contributes ~ 50% of the coil field:

3.45 T (Total) ~ 2.3 T (Coil) + 1.15 (Iron)

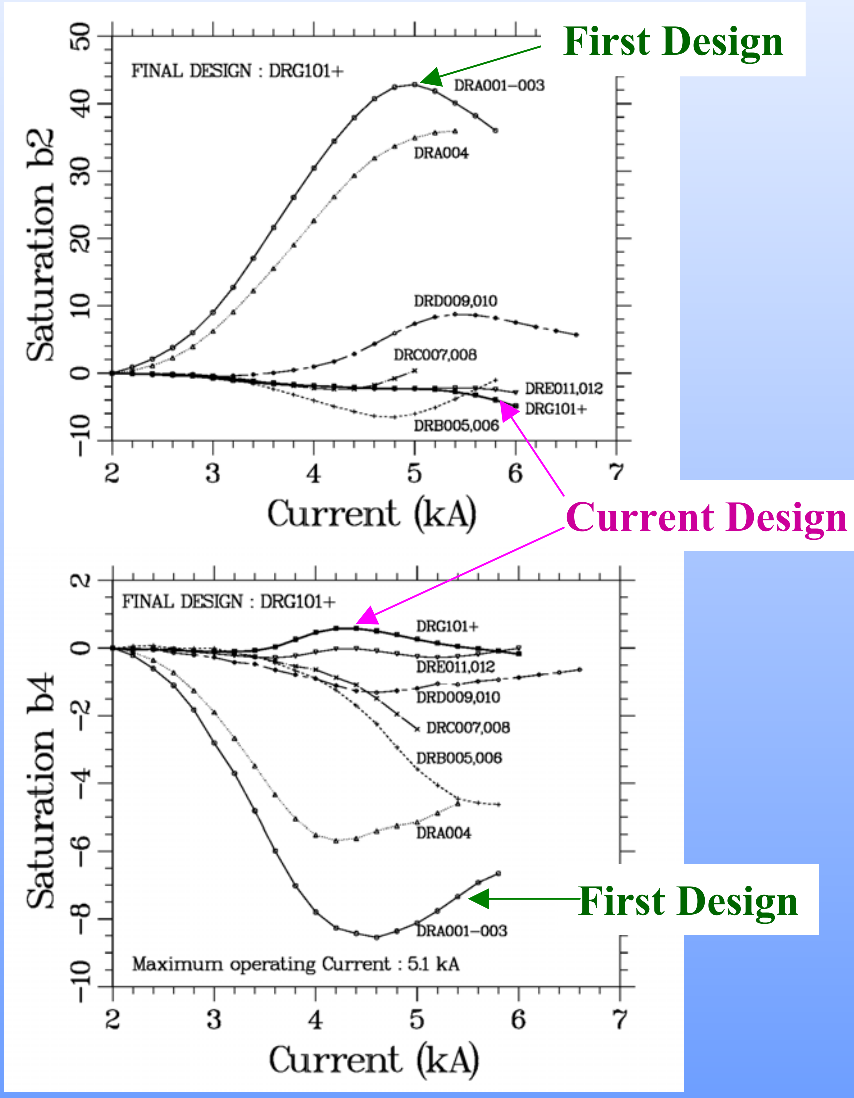
Initial design had bad saturation,

(as expected from conventional wisdom), but a number of developments made the saturation induced harmonics nearly zero!

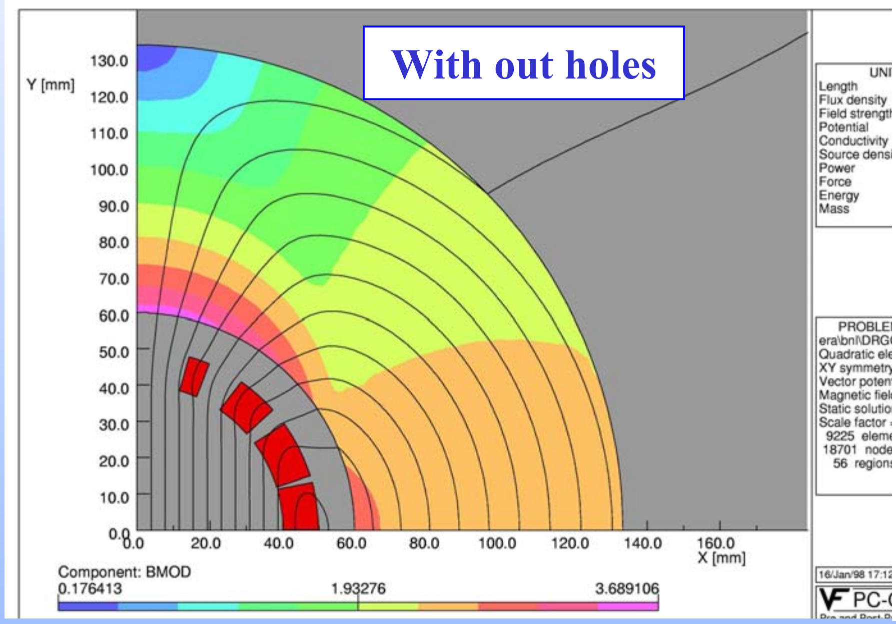
Only full length magnets are shown.

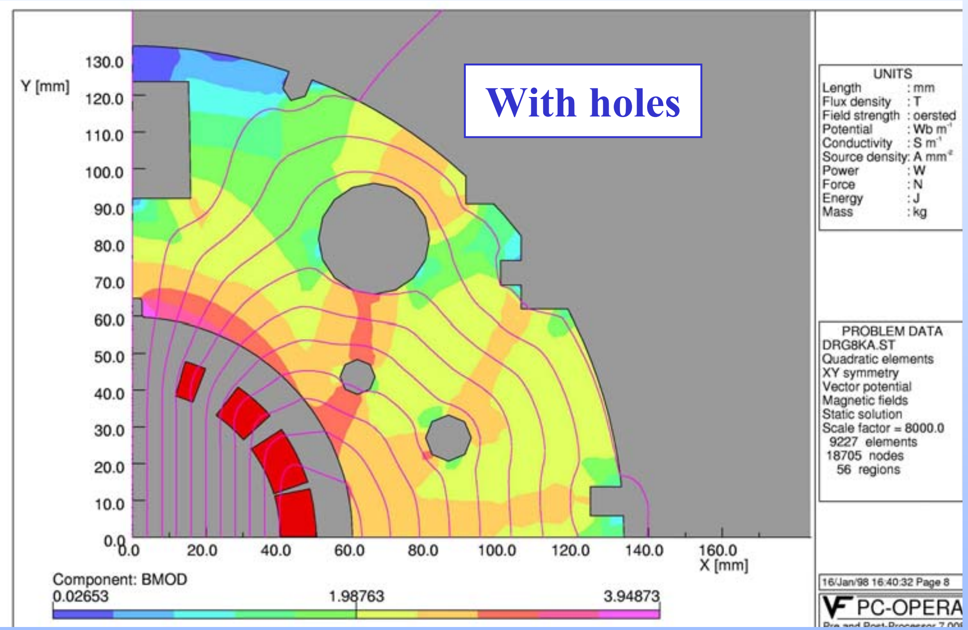
Design current is ~ 5 kA (~3.5 T).

US Convention: b_2 is sextupole



Saturation Control in RHIC Dipoles
Variation in |B| in Iron Yoke

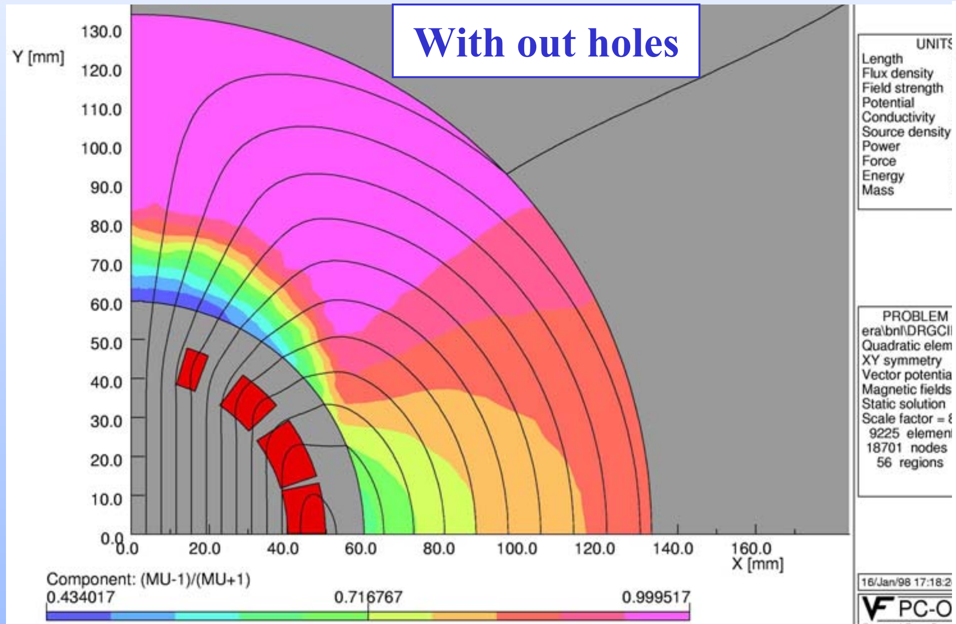


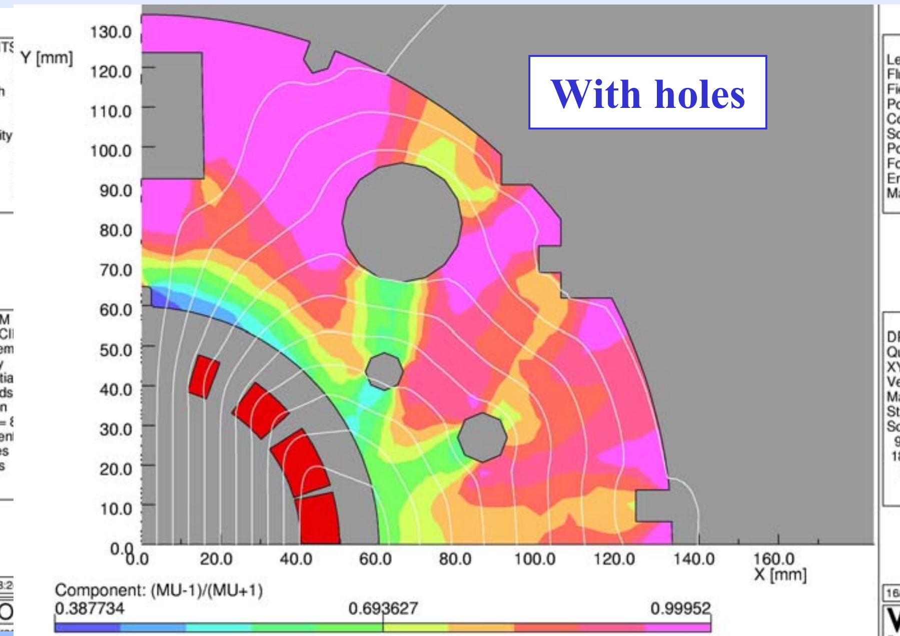


- Compare azimuthal variation in |B| with and without saturation control holes. Holes, etc. increase saturation in relatively lower field regions; a more uniform iron magnetization reduces the saturation induced harmonics.
- Old approach: reduce saturating iron with elliptical aperture, etc.
- New approach: increase saturating iron with holes, etc. at appropriate places.

Saturation Control in RHIC Dipoles

Variation in (μ-1)/(μ+1) in Iron Yoke





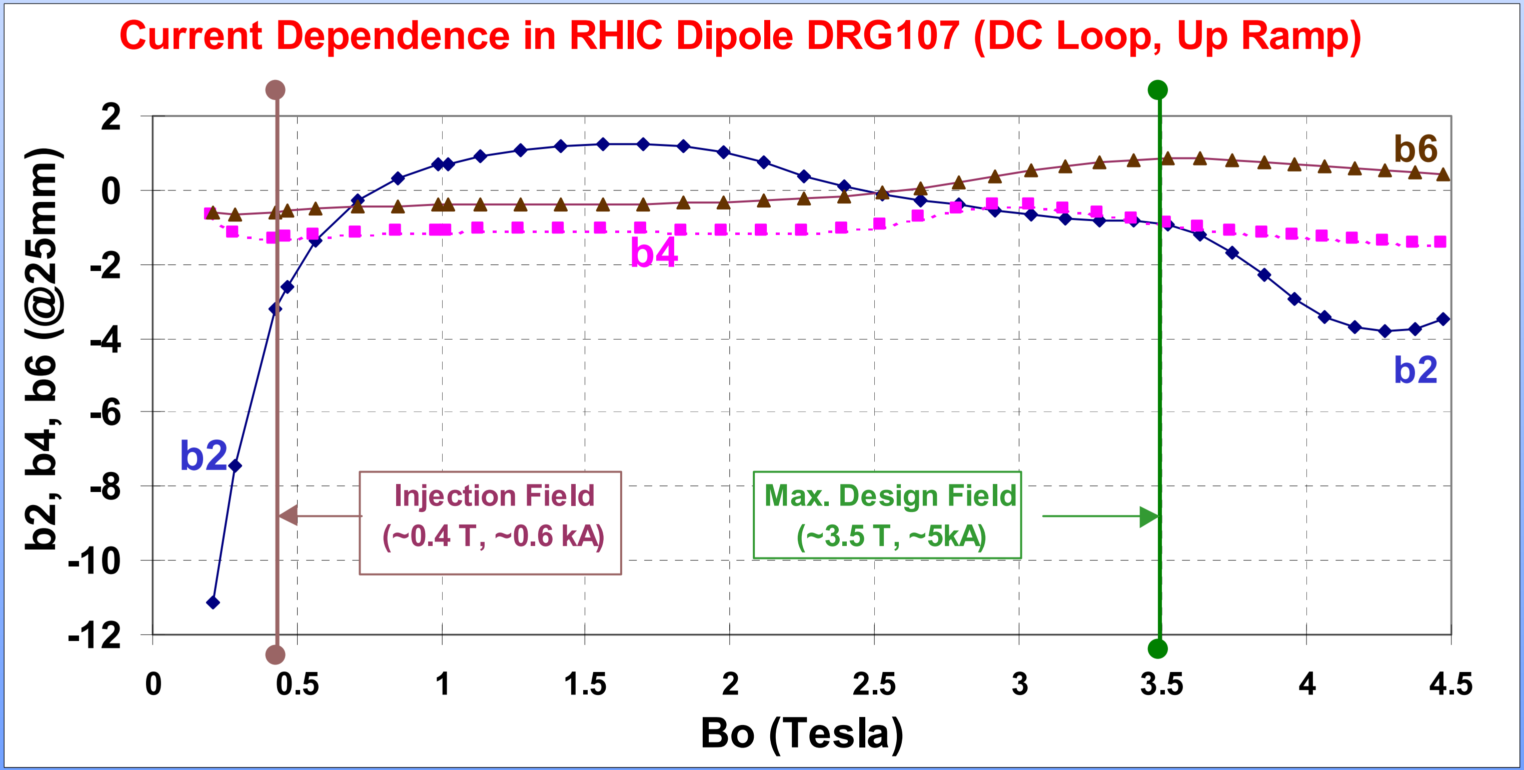
- It is better to examine (μ-1)/(μ+1) instead of |B|. As it appears in various formula, e.g.

$$B_\theta = \frac{\mu_o I}{2\pi r} + \frac{\mu_o I}{2\pi a}\sum_{n=1}^{\infty}\left(\frac{a}{r}\right)^{n+1} \cos\left(n\left(\phi-\theta\right)\right)\left[1-\frac{\mu-1}{\mu+1}\left(\frac{r}{R_f}\right)^{2n}\right]$$

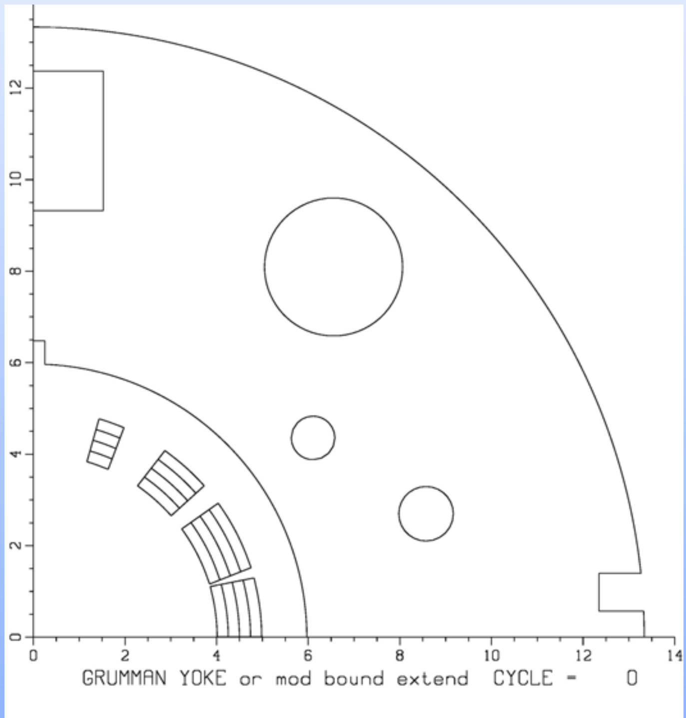
  It also provides a better scale to compare the magnetization (see pictures).
- Compare the azimuthal variation in (μ-1)/(μ+1) with and without saturation control holes, particularly near the yoke inner surface. A more uniform iron magnetization reduces the saturation induced harmonics.

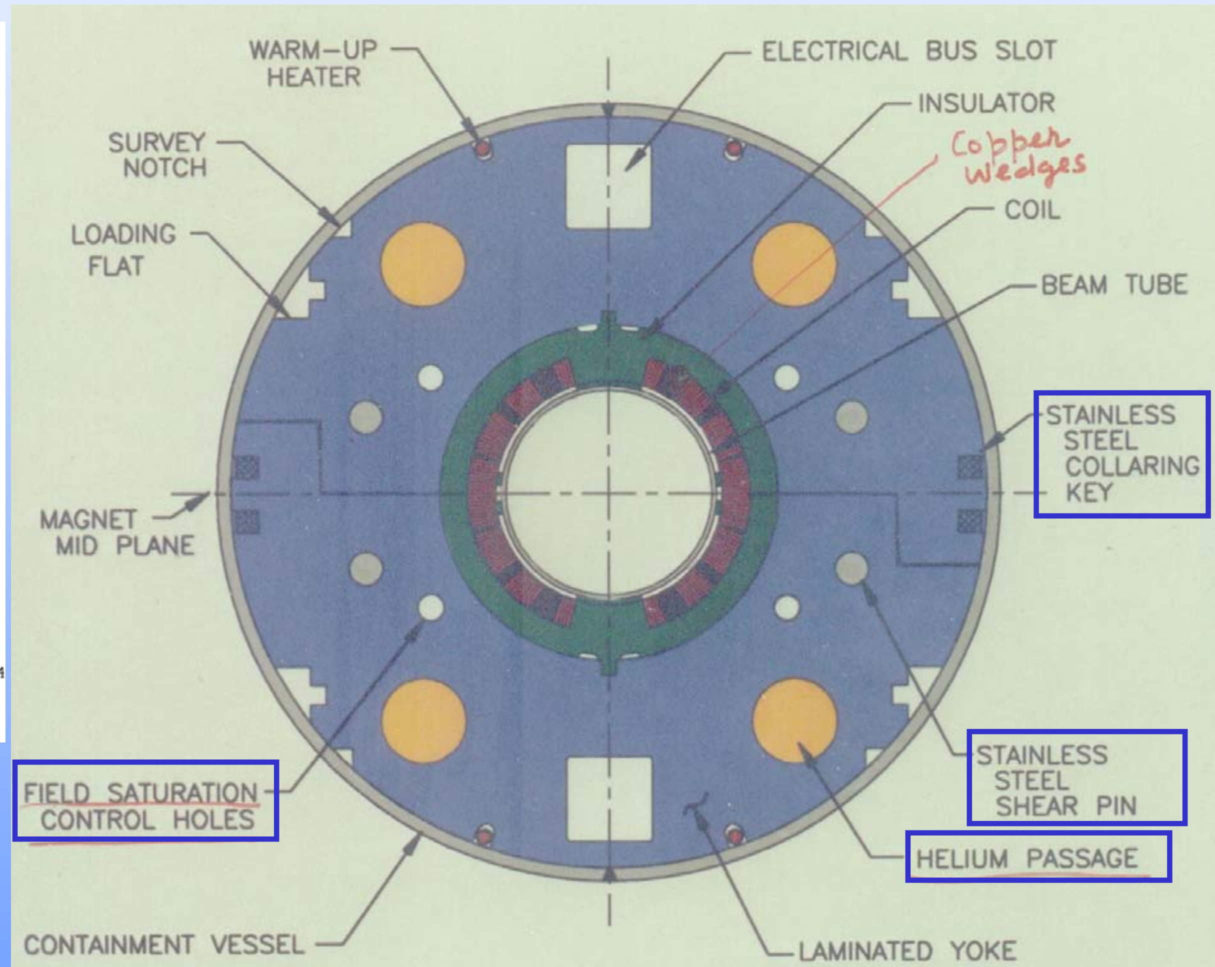
Current Dependence Beyond Design Field

In all known major accelerator magnets (superconducting and iron dominated), the harmonics fall rapidly beyond the maximum design field. However, in this design approach they become relatively flat. Please note the difference in scale .



RHIC Arc Dipole
(with saturation control features indicated)





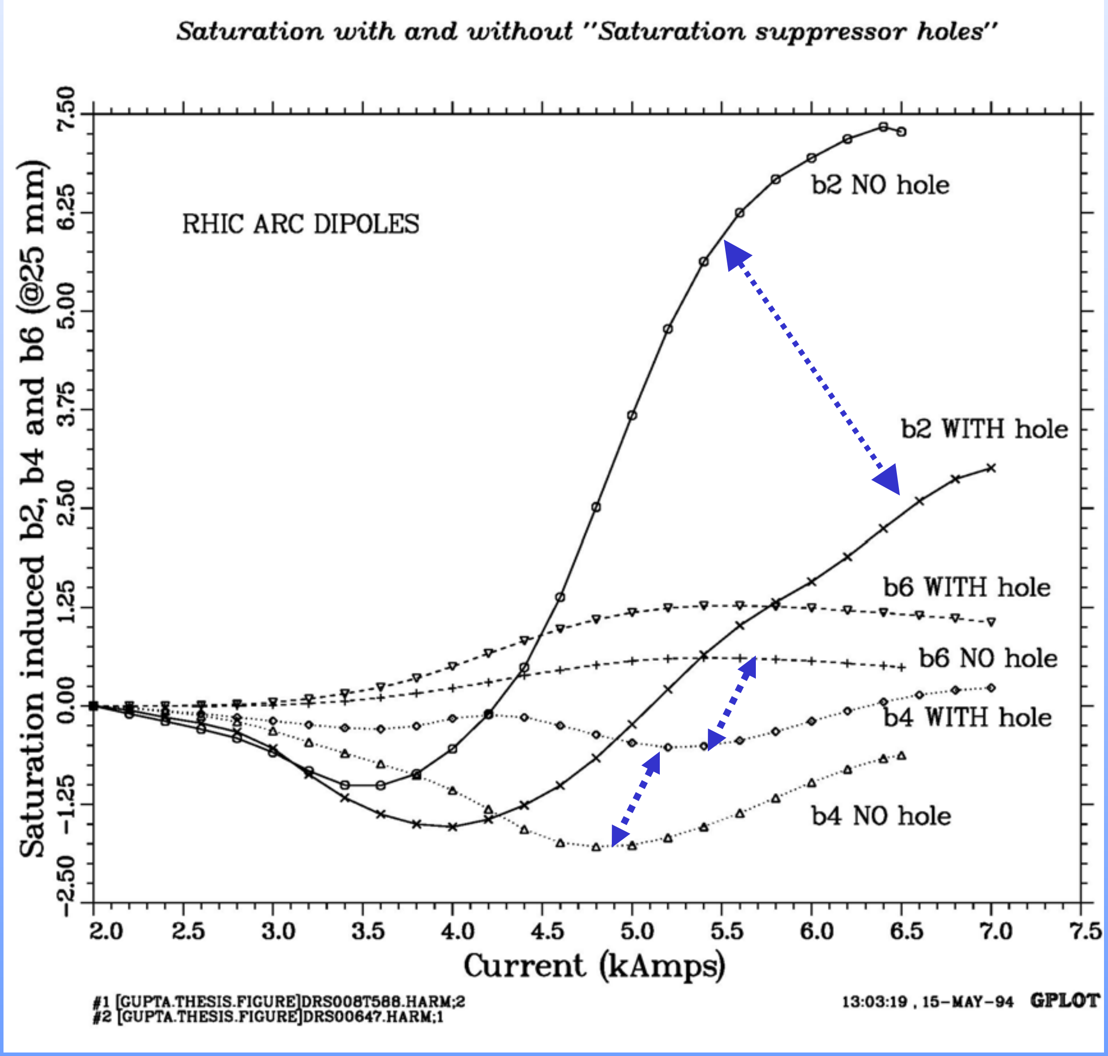
Magnetic Model of the RHIC arc dipole with saturation control holes, etc.

Influence of Saturation Control Hole

A RHIC 80 mm dipole was rebuilt after punching saturation control holes in the lamination.

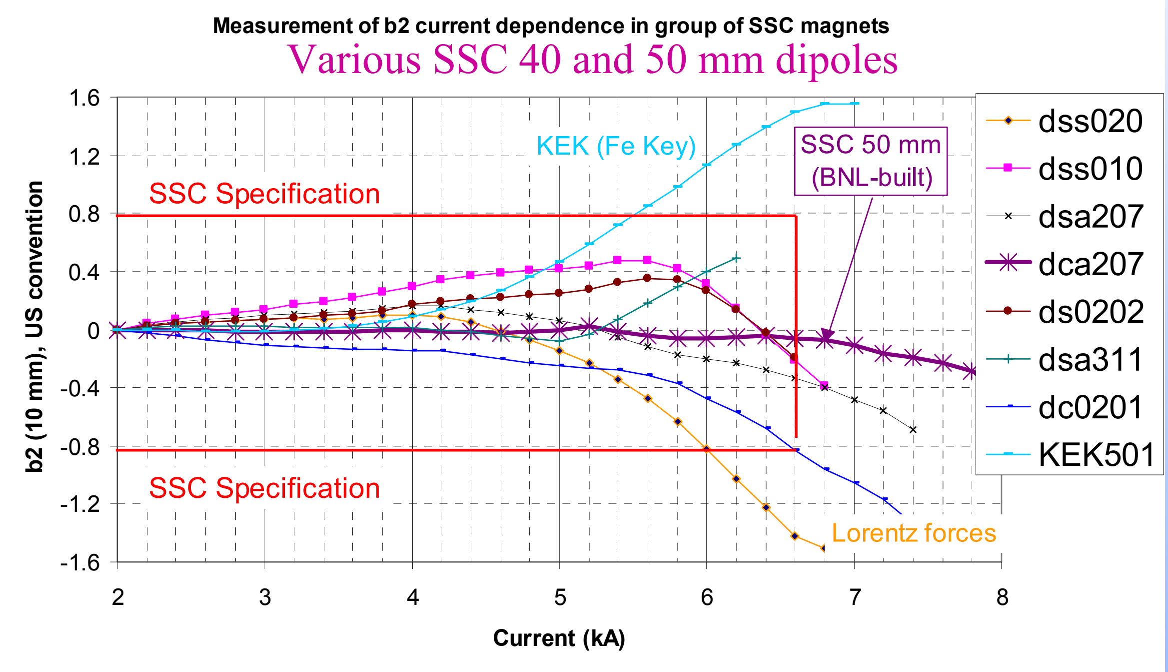
A significant reduction in the saturation-induced (current dependence of) field harmonics can be seen.

This feature was adopted in the RHIC production magnets.

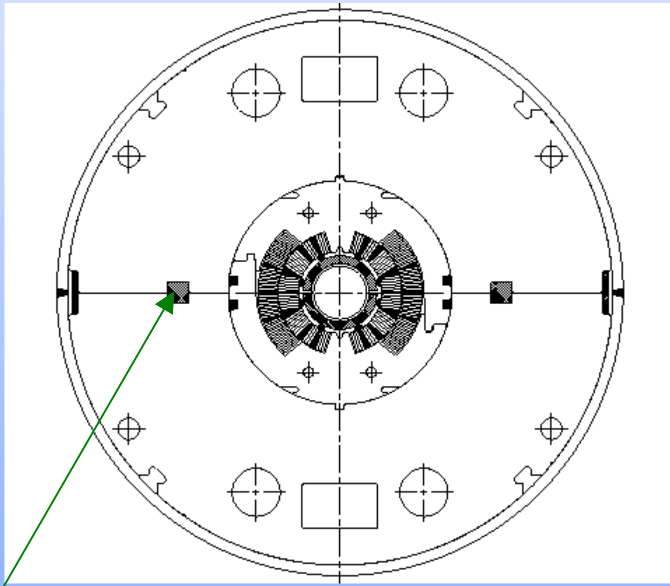


Brookhaven National Laboratory
Superconducting Magnet Division

Measured Current Dependence in Sextupole Harmonic in Various Full-length SSC Magnets



Cross section of SSC 50 mm Dipole
Yoke optimized for low saturation



Near zero current dependence in b_2 variation in first design itself in BNL built SSC 50 mm long magnets.

Specifications was 0.8 unit.

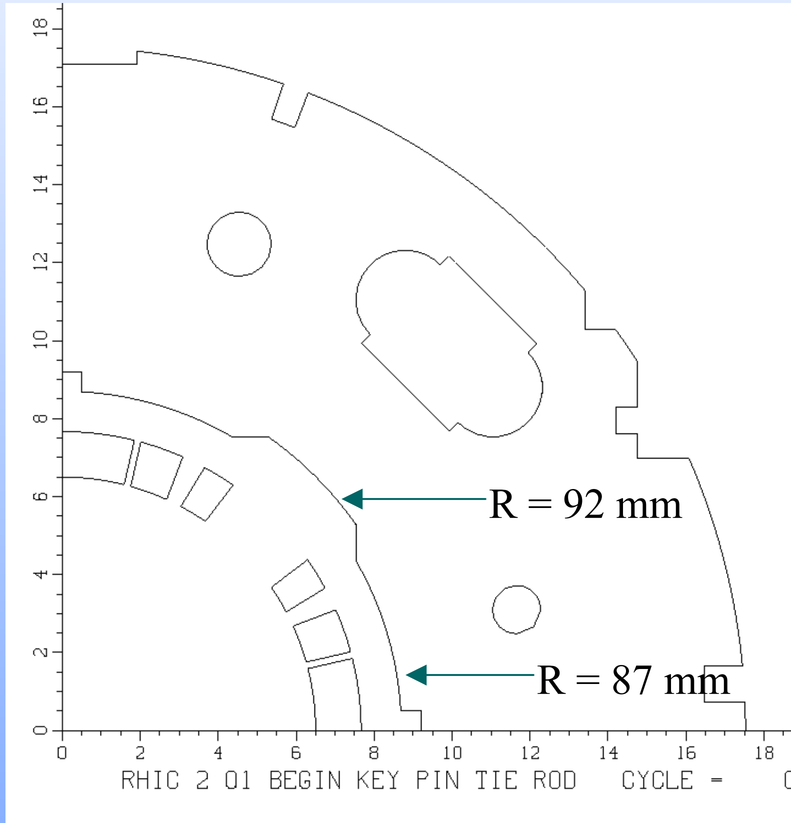
A much larger value in earlier SSC 40 mm design.

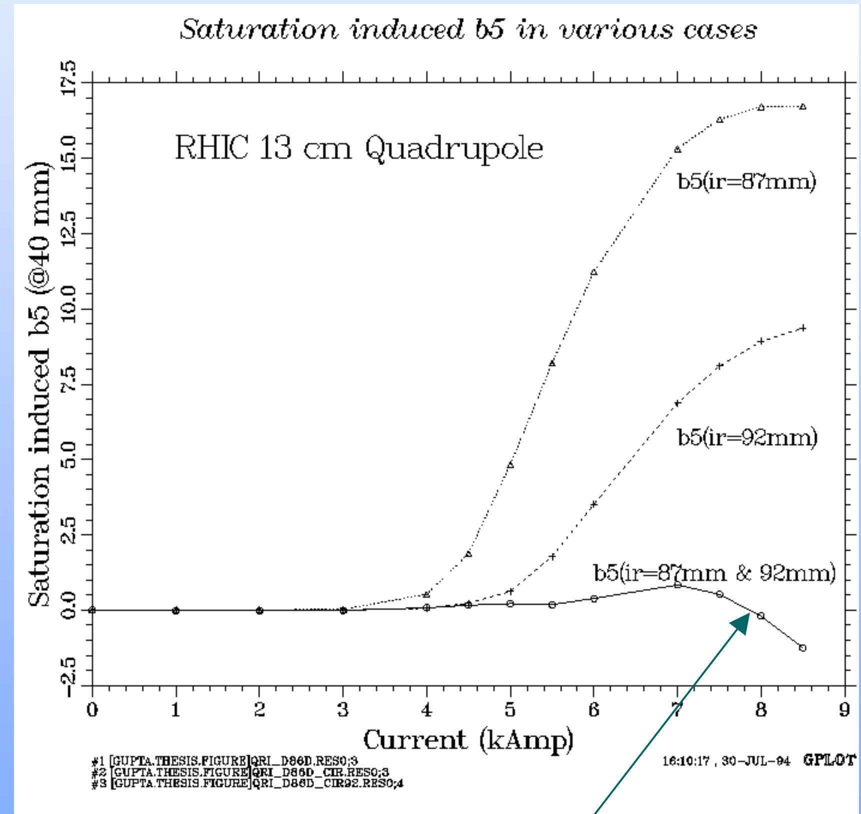
b_2 change from yoke magnetization & Lorentz forces.

Non-magnetic key to force uniform saturation
Could also have been used to adjust current dependence after design, as in RHIC magnets.

Major progress in reducing the saturation-induced harmonics.

Saturation Control in RHIC IR Quads





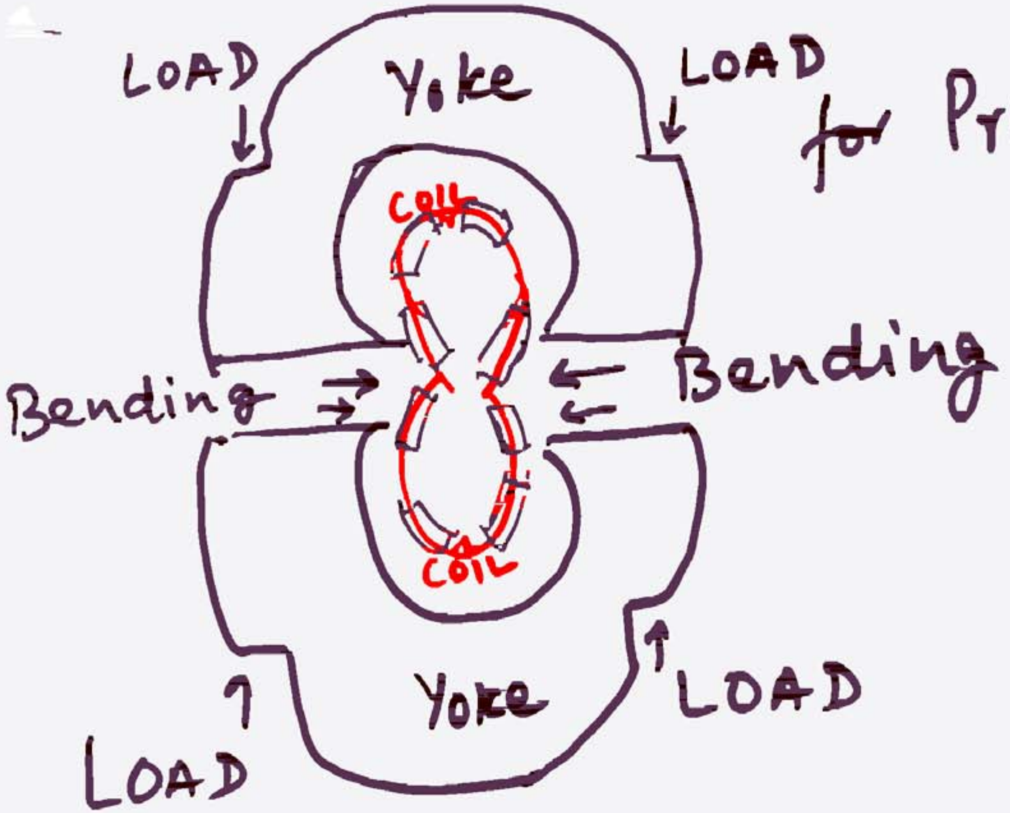
Optimized design

POISSON model of a quadrant of the 130 mm aperture RHIC Insertion quadrupole.

Since the holes are less effective for controlling saturation in quadrupoles, a 2-radius method was used.

Octupole in Quadrupoles When Quad Assembled Like Dipoles

Measured b_3 (octupole) $\neq 0$)



for Pre-compression

Also seen in 80 mm Arc Quad (7 unit in both magnets)

A Simple Method For Removing Octupole From Quad

BASIC Problem

(a) Trying to assemble quad like dipole

or

(b) Starting Yoke i.d. is circular (which becomes non-circular after assembly)

FIX

1. Start out-of-round yoke; so that when assembled, it is round
→ Too late for that (and too expensive to change)

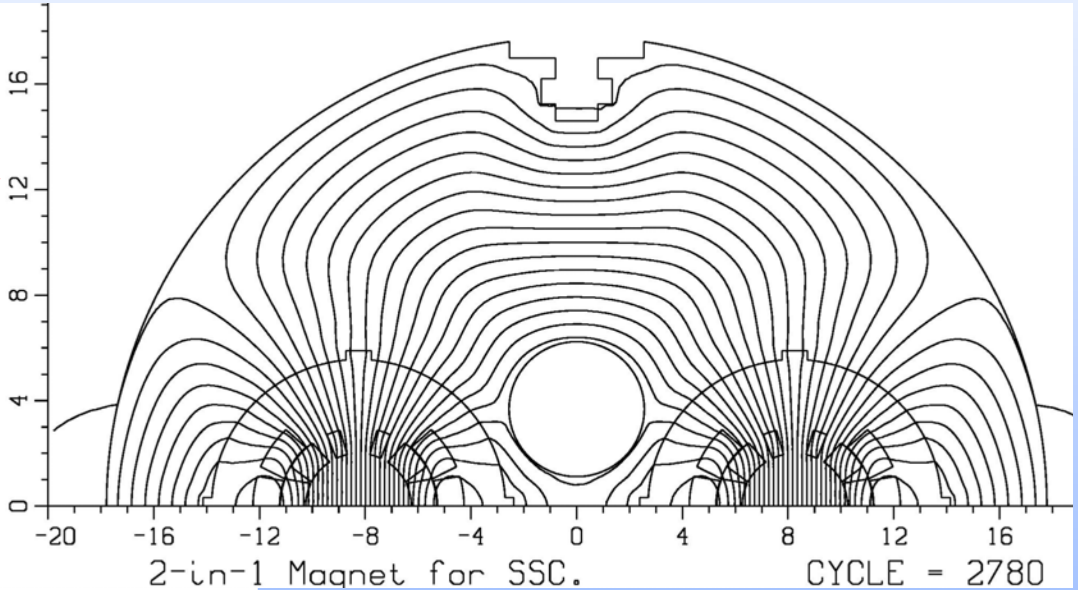
2. Create deliberate asymmetry in coil to compensate for that

→ Easy, Tested and Worked

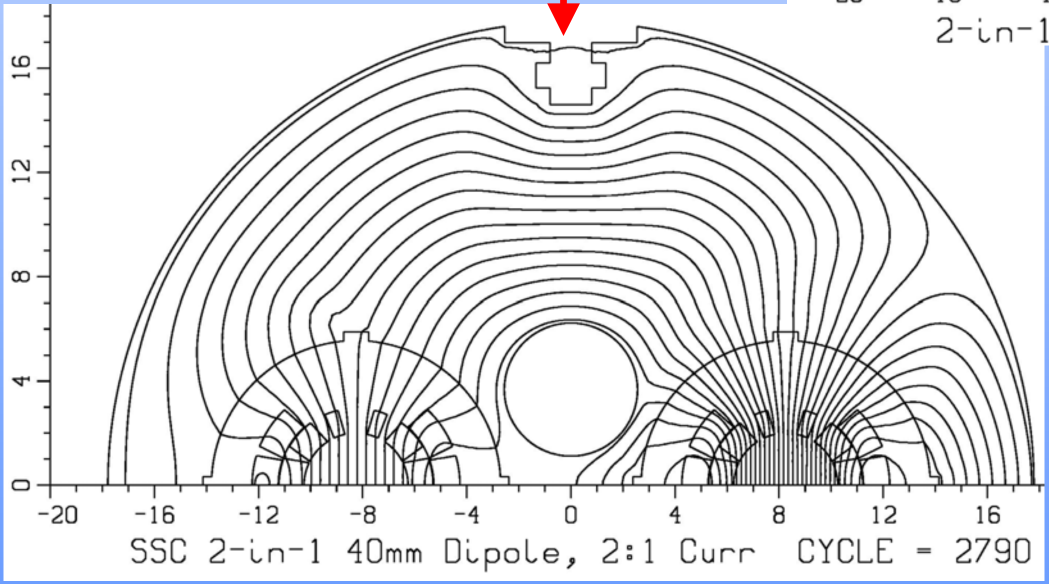
AND/OR → USE MAGNETIC TUNING SHIMS (b_3 & b_7)

Saturation Control in SSC 2-in-1 Dipole

The case when the current in the same in the two apertures



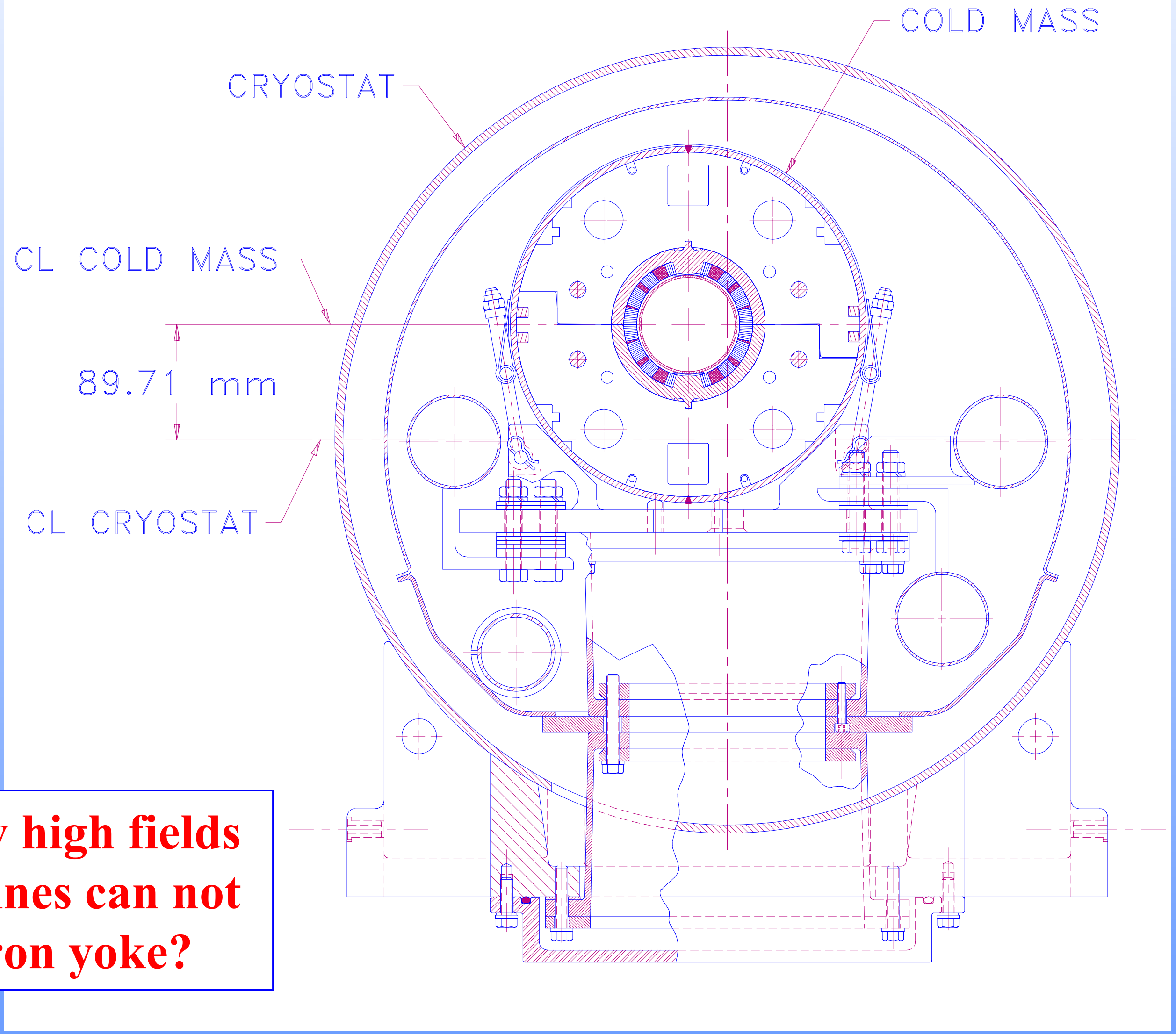
The case when the ratio of the current in the two aperture is 2:1



The hole in between the two apertures minimizes the normal quadrupole harmonics at high fields.

Non-symmetric Coldmass Placement in Cryostat

Design of the 80 mm aperture RHIC dipole coldmass in cryostat

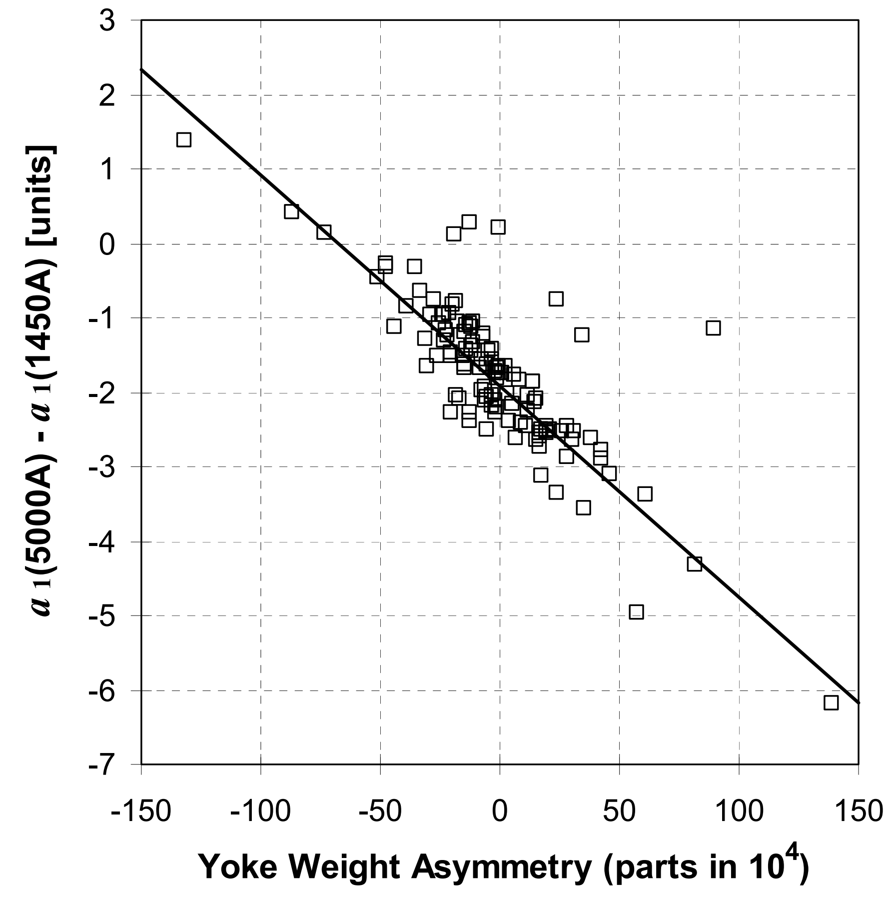


Coldmass (yoke) is made of magnetic steel and cryostat is made of magnetic steel.

What will happen at very high fields when the magnetic flux lines can not be contained inside the iron yoke?

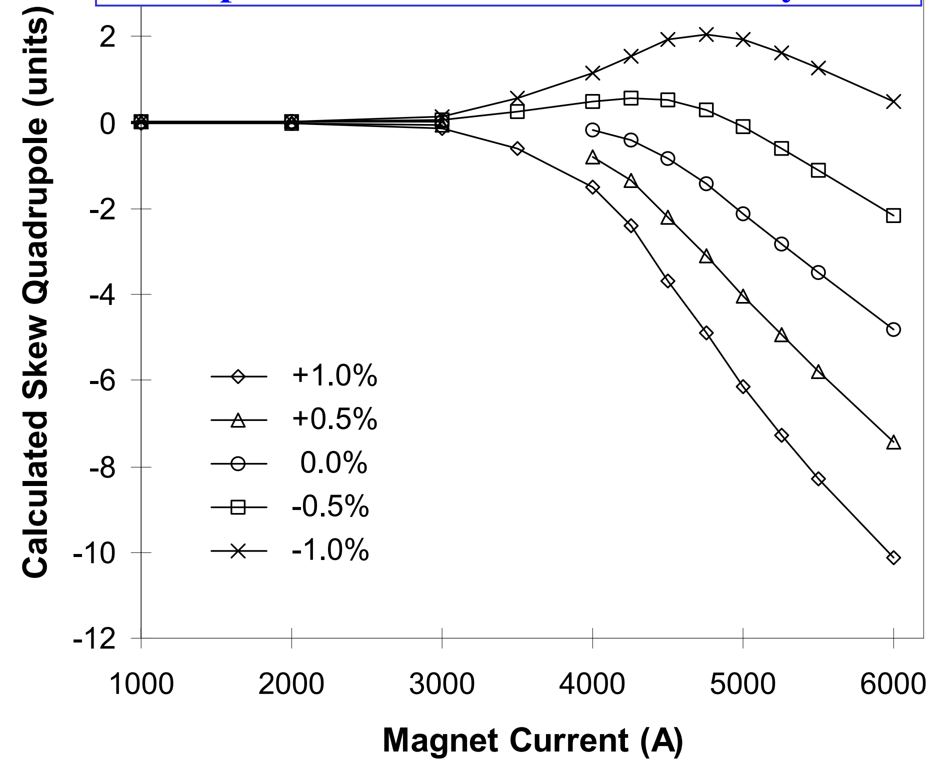
Reduction in Saturation-induced Skew Quad Harmonic (a_1) in RHIC Dipoles

$$\text{asymmetry} = \frac{\text{weight of Top part} - \text{weight of Bottom part}}{\text{Average weight of Top and Bottom parts}}$$



Correlation between the yoke weight asymmetry and the saturation-induced a_1.

The calculated current dependence of skew quadrupole term for various values of the asymmetry between the top and the bottom halves of the yoke.

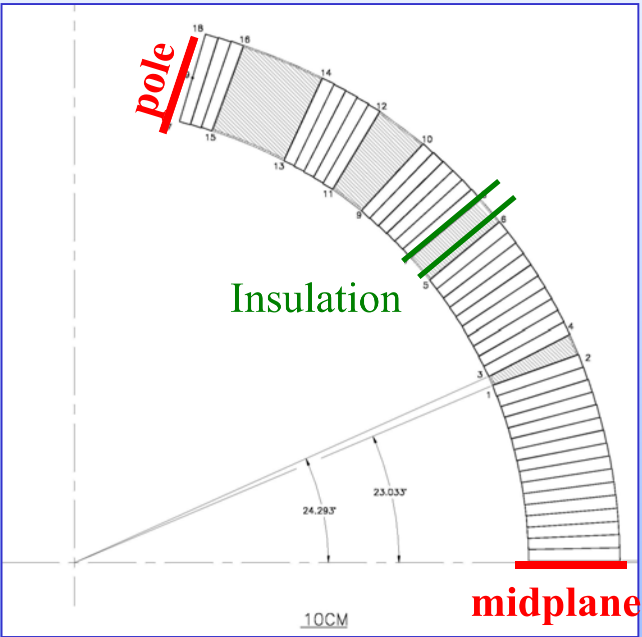


A Flexible Design from the Beginning

Design Philosophy:

• Start out a design from the beginning itself, that allows significant adjustability for field harmonics and mechanical parameters (cable thickness, wedges, etc.).

• A flexible design is generally economical, efficient and produces magnets with better performance. I think it's a prudent approach.



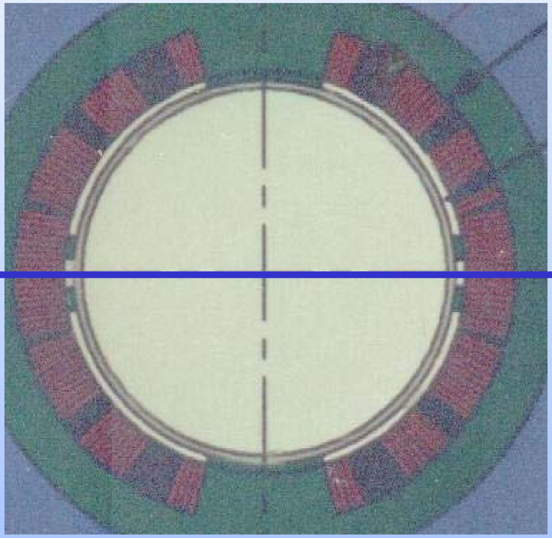
Geometric: Start with a larger than required shim and midplane cap. Then adjust it, as required without changing the cross-section of the cured coil. One can also adjust the layers of wedge/cable insulation, if needed. These three parameters can adjust, first two allowed harmonics and pre-stress or cable insulation. This approach was used extensively in various RHIC magnets.

Saturation: Start out with holes and fill them with iron rods. Or, punch holes in laminations later.

In KEK, C.F. dipole, one may consider adjusting for quad and sextupole component.

Change in Midplane Gap to Adjust Harmonics

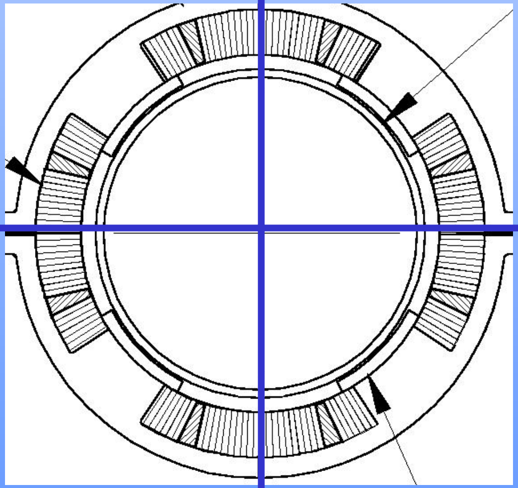
(can be easily done by changing the size of the ground-plane insulation cap)



Coil-to-coil midplane gap (1 in dipole)

Table 4.4.1: The computed and measured change in field harmonics at 25 mm reference radius due to a change in the coil midplane gap. The midplane gap was increased from 0.114 mm to 0.16 mm in the rebuilt 80 mm aperture RHIC model dipole magnet DRS009. In the production magnets, the midplane gap was changed back to 0.114 mm from 0.16 mm to adjust the b_4 harmonic.

	Δb_2	Δb_4	Δb_6	Δb_8
Computed	-3.0	-1.0	-0.28	-0.09
Measured	-3.0	-1.0	-0.29	-0.12



Coil-to-coil midplane gap (2 in quads)

Table 4.5.1: The measured and computed change in field harmonics caused by an asymmetric increase in the coil-to-midplane gap in the prototype 130 mm aperture RHIC interaction quadrupole QRI002. The gap was increased by 0.1 mm in the horizontal plane only. The harmonics are given at a reference radius of 40 mm.

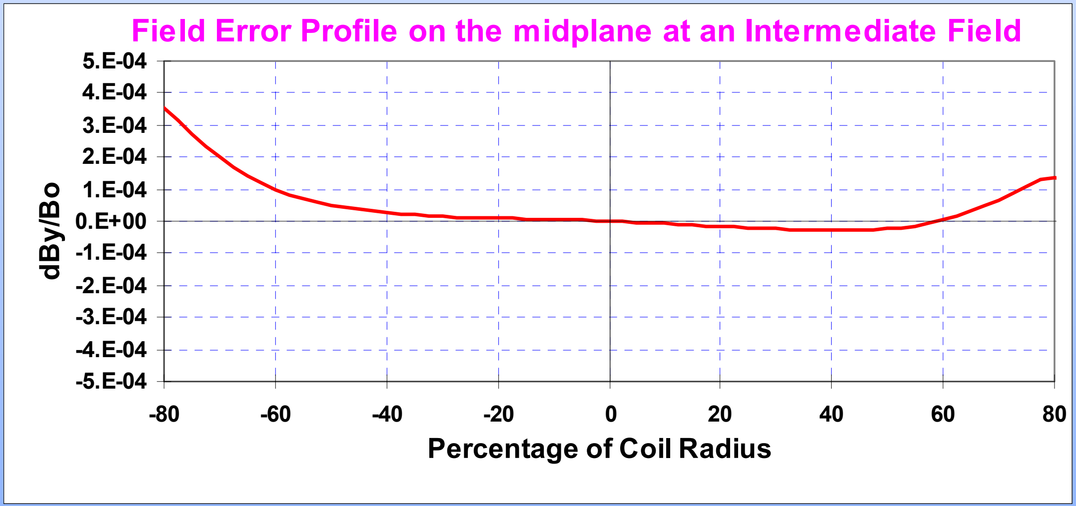
	Δb_3	Δb_5	Δb_7	Δb_9
Computed	-6.8	-1.3	-0.45	-0.16
Measured	-6.5	-1.2	-0.30	-0.17

RHIC 100 mm Aperture Insertion Dipole:
The first magnet gets the body harmonics right

Geometric Field Errors on the X-axis of DRZ101 Body

First magnet and first attempt in RHIC 100 mm aperture insertion dipole

A number of things were done in the test assembly to get pre-stress & harmonics right



Harmonics at 2 kA (mostly geometric).
Measured in 0.23 m long straigth section.

Reference radius = 31 mm

b1	-0.39	a2	-1.06
b2	-0.39	a3	-0.19
b3	-0.07	a4	0.21
b4	0.78	a5	0.05
b5	-0.05	a6	-0.20
b6	0.13	a7	0.02
b7	-0.03	a8	-0.16
b8	0.14	a9	-0.01
b9	0.02	a10	0.01
b10	-0.04	a11	-0.06
b11	0.03	a12	-0.01
b12	0.16	a13	0.06
b13	-0.03	a14	0.03
b14	-0.10	a15	0.02

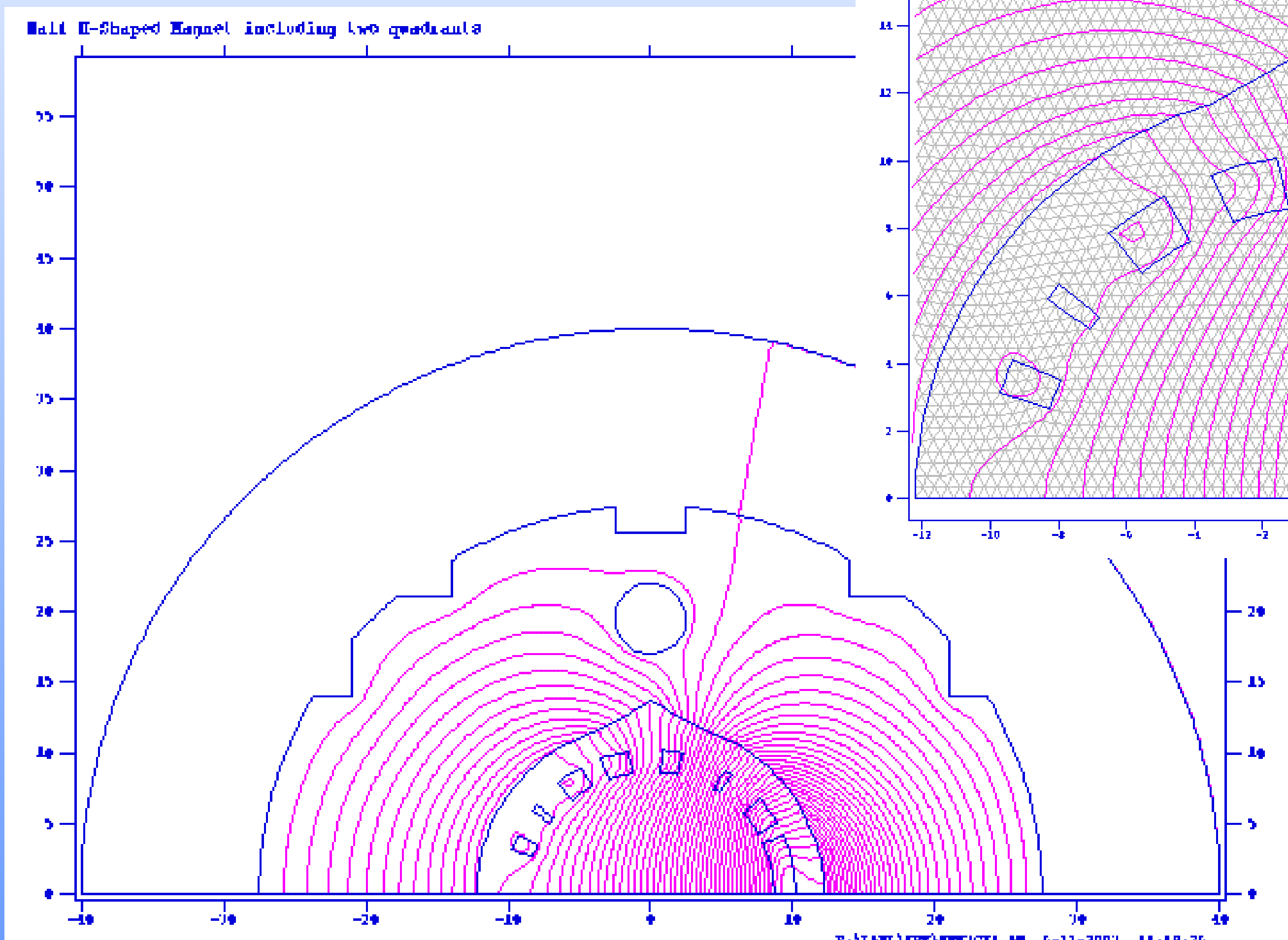
Note: Field errors are within 10^{-4} at 60% of coil radius and ~$4*10^{-4}$ at 80% radius.

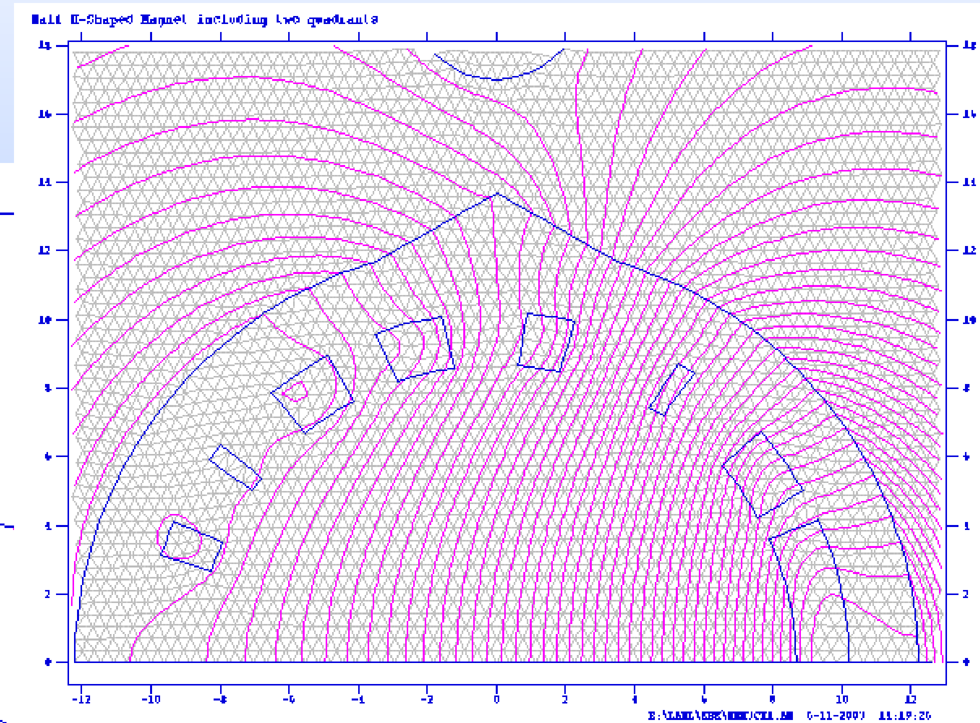
Later magnets had adjustments for integral field and saturation control.

The coil cross-section never changed.

All harmonics are within or close to one sigma of RHIC arc dipoles.

BASIC KEK Model on POISSON for Carrying Out Design Studies

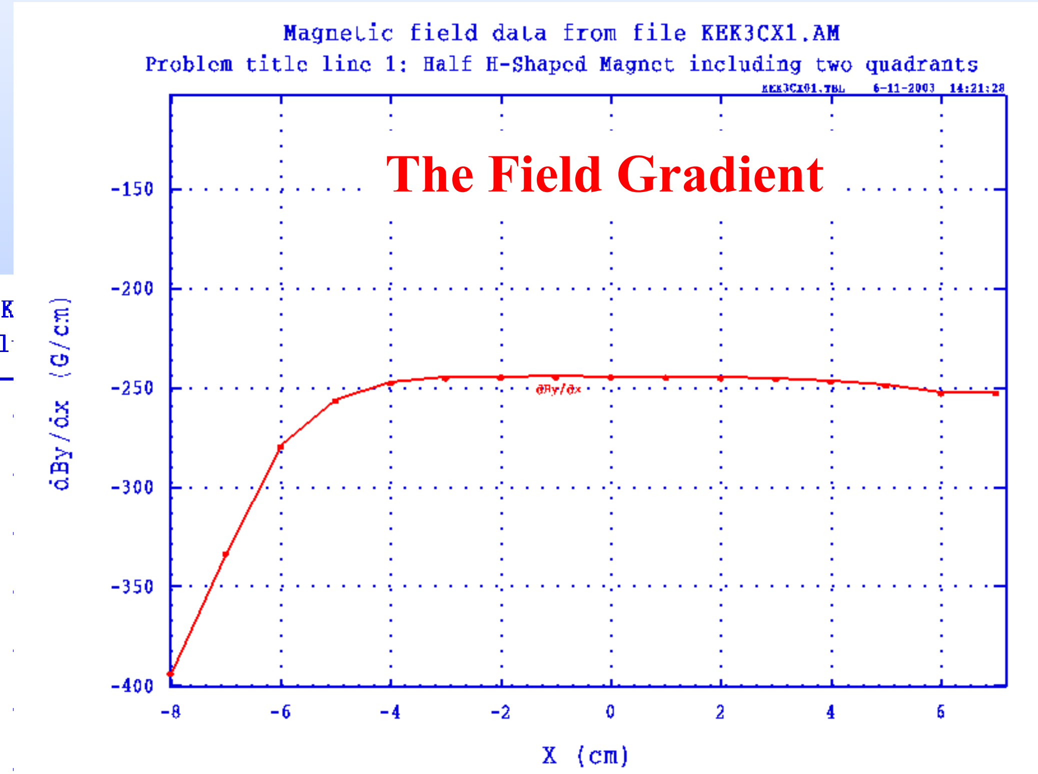


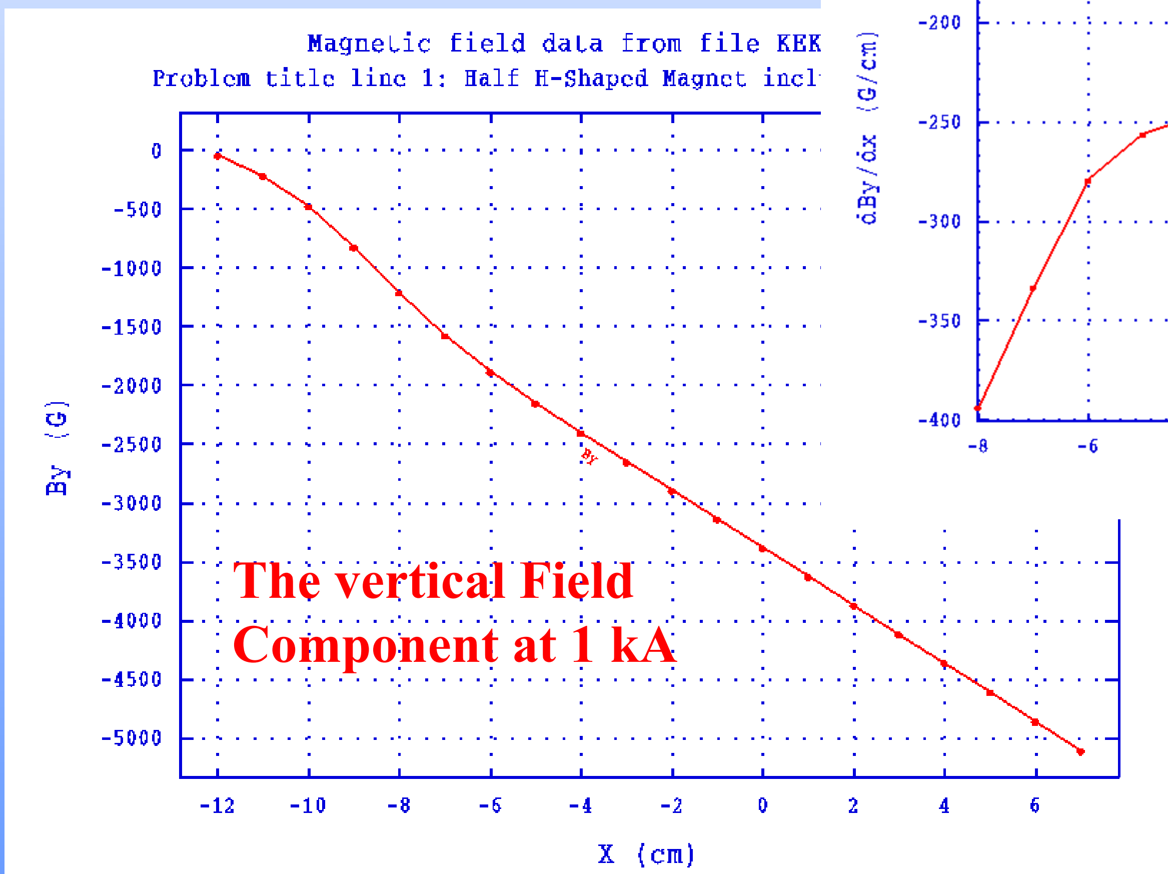


It's easier to put/vary the holes, etc. in POISSON, as mesh does not require topology to be fixed.

Computed Fields by POISSON

Results of preliminary work.





We are having a productive discussion for evaluating different ideas.

Some Possibilities in Fine-tuning of KEK Magnetic Design Optimization

Coil Geometry

• Flexible design: Increase midplane gap to allow adjustments on both side

Iron Geometry

• Need left-right asymmetry for difference in saturation

• Theoretical - off centered placement of coil

  • mechanical design and assembly implications

• Holes in the yoke

SUMMARY

- Presented our experience with RHIC and SSC magnet program and its possible relevance to KEK magnet program.
- Had good discussion for trying different ideas for simplifying and adjusting various parameters.
- I find it to be an interesting magnet program, perhaps the first superconducting combined function dipole.