Lecture V

Magnetic Design
Yoke Optimization

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Use of Iron Yoke in the Conductor Dominated Magnets (1)

Why should we use yoke in the conductor dominated magnets?

Specially in high field magnets, where most of the field is provided by coil. Disadvantage of yoke is that it increases the coldmass. That means it increases the size, weight and the volume to be cooled down.

Reason No. 1:

- For a variety of reasons, the magnetic field, at a certain distance away from magnet aperture, should become sufficiently small.
- In almost all cases, and in virtually all accelerator magnets built so far, the iron yoke over the coil has been found to be the most cost effective method of providing the required magnetic shielding.

Shielding

The shielding against the fringe field can be either provided by the iron yoke or by the additional outer coils having an opposite polarity of the main coils.

Home Assignment on the Shielding by Coils:

- A thin cosine theta dipole coil is placed at a radius of 10 cm. This coil generates a central field of 0.5 T. Compute the relative strength of an additional thin coil at a radius of 20 cm that is placed to cancel the fringe field far away from coil regions. Also compute the change in central field caused by this additional coil? Compute the change in central field, if instead of additional coil, a thick iron yoke is placed at a radius of 20 cm to provide the required shielding. What happens, if the yoke shielding is brought right at 10 cm. In these calculations, ignore saturation of the iron yoke and assume that it has infinite permeability.
- Do the similar computations for quadrupole coils generating a field gradient of 5 T/mm.
- Generally speaking what would you use in your design for providing shielding and why? In which case you would prefer the additional coil and in which the yoke?

Yet another possibility: Superconducting shield -- again, extra conductor.

Use of Iron Yoke in the Conductor Dominated Magnets (2)

Why should we use yoke in the conductor dominated magnets?

Reason No. 2:

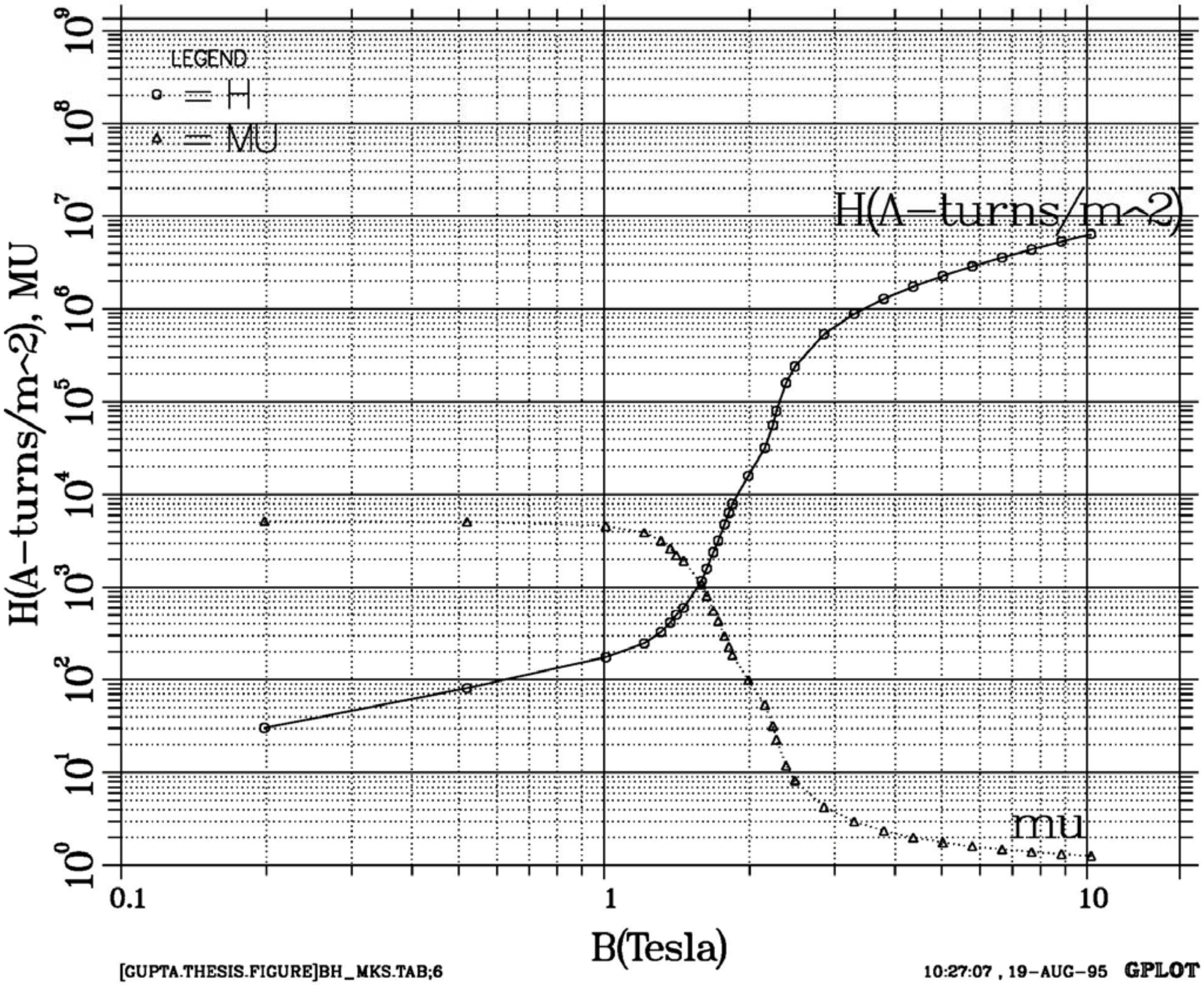
• The magnetized iron gives an additional contribution to the field generated by coils.

• However, the gain does not come without any pain, particularly as we get more and more ambitious (higher contribution, higher field). The iron starts saturating at high field. That makes field contribution non-linear and field errors in the magnet (harmonics) depend on the central field.

• The trick is to develop techniques to benefit from the gain while minimizing the pain.

•The purpose of this course is to make you familiar with those techniques by presenting the state-of-art.

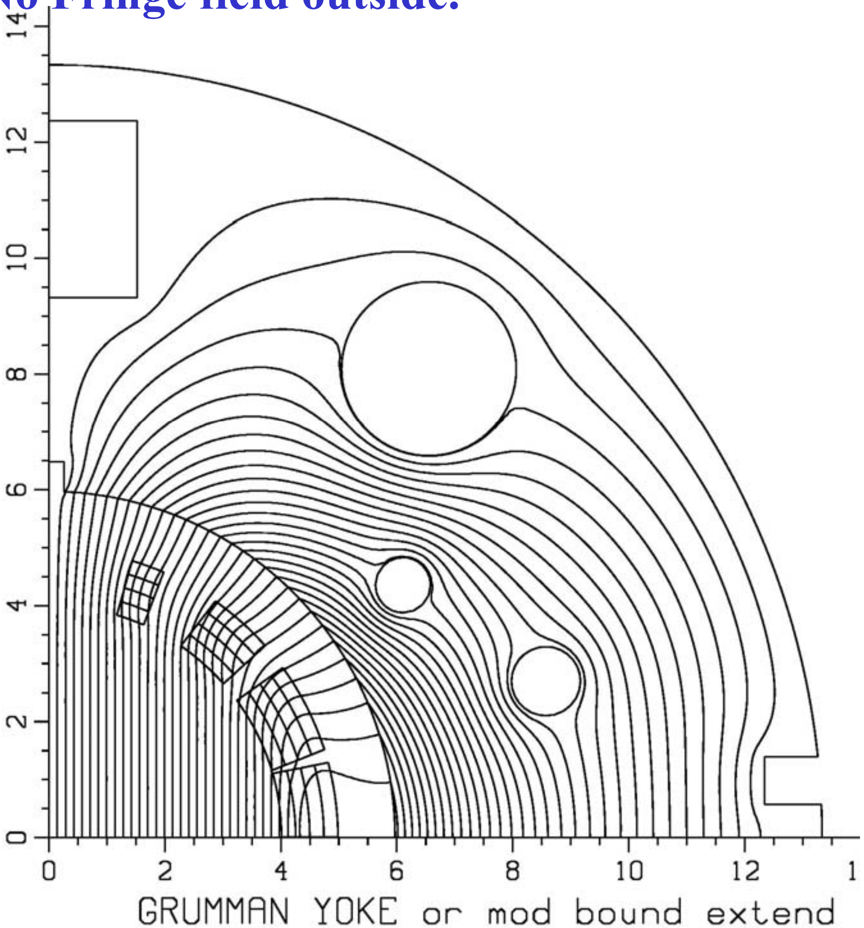
BH Table Used in Calculations

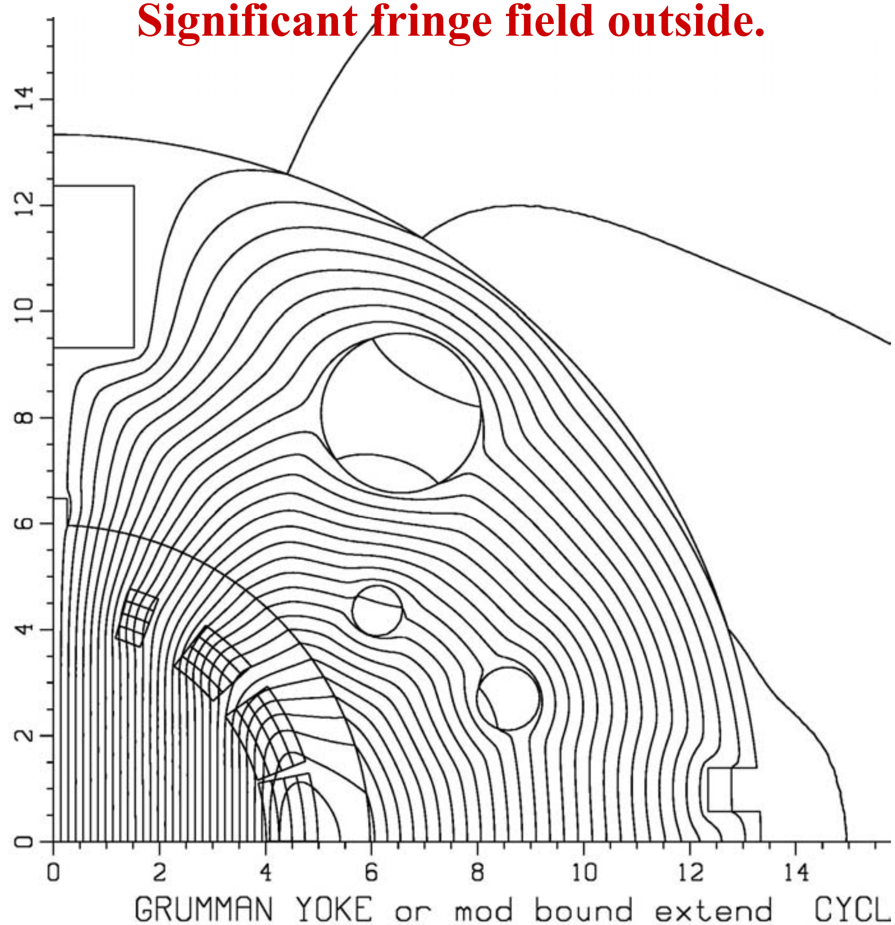


Iron Yoke in RHIC Dipole

Yoke can contain field lines at low fields (~0.7 T, ~1 kA). No Fringe field outside.

Yoke can not contain field lines at high fields (~4.5 T, ~7 kA). Significant fringe field outside.



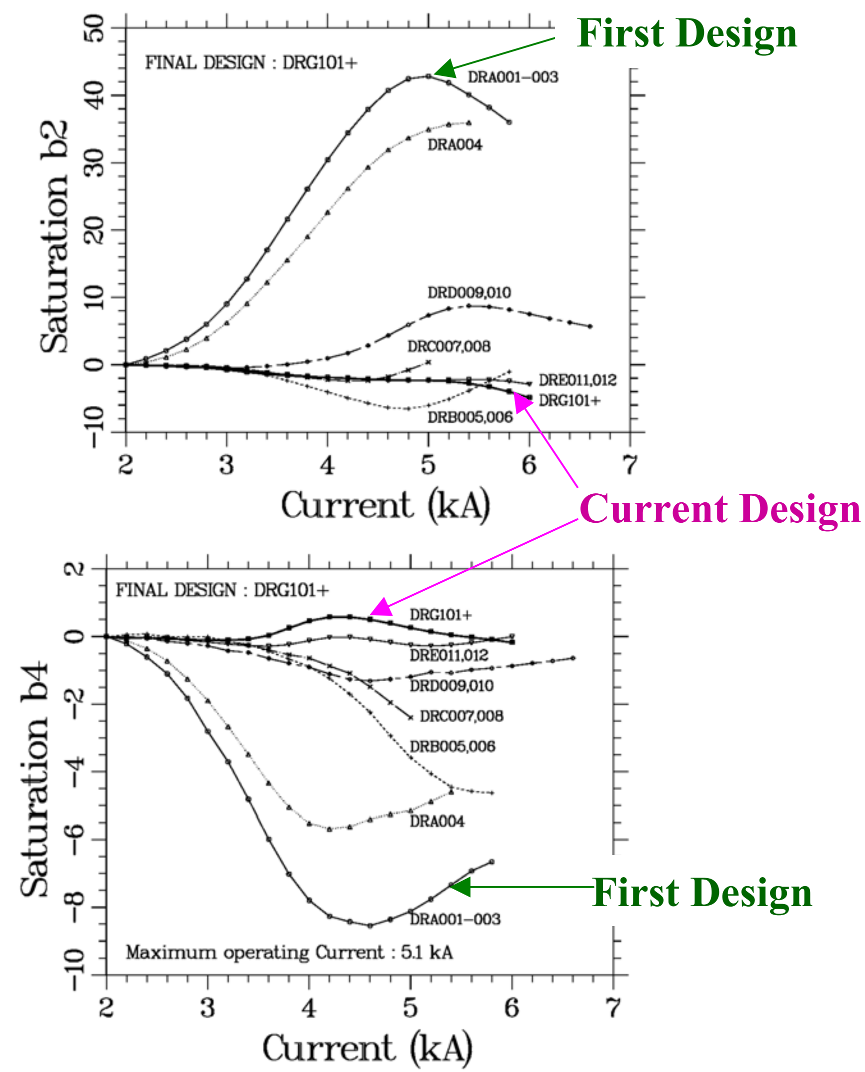


Saturation in RHIC Arc Dipole

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 conventionally expected from the large saturation of the iron yoke. This course will teach you techniques on how to reduce the current-dependence of field harmonics.



Consequences of the Saturation of the Iron Yoke

Iron yoke provides a good shielding against the fringe field. Moreover, the iron gets magnetized such that it adds to the central field generated by the coil.

In cosine theta magnets (a=coil radius, R_f=yoke inner radius and R_a=outer radius):

$$B_y(r,\theta) = -\frac{\mu_o I_o}{2a} \cos((m-1)\theta)\left(\frac{r}{a}\right)^{m-1} \times$$

$$\left[1 + \frac{\mu-1}{\mu+1}\left(\frac{a}{R_f}\right)^{2m} \frac{\left[1-\left(\frac{R_f}{R_a}\right)^{2m}\right]}{\left[1-\left(\frac{\mu-1}{\mu+1}\right)^2\left(\frac{R_f}{R_a}\right)^{2m}\right]}\right]$$

At low fields, μ is large and $(\mu-1)/(\mu+1)$ is nearly one. In principle, the yoke can double the field. However, at high fields the iron magnetization becomes non-linear and μ approaches one. This makes the relative contribution of the field from the iron become smaller as compared to that of the coil. Moreover, the field distribution inside the aperture changes, which in turn makes the field harmonics depend on the field.

COS($m\theta$) Coil in Iron Shell

***R_f*: Iron inner radius**
***R_a*: Iron outer radius**
***a* : Coil Radius**

$$S_\mu = \frac{\mu - 1}{\mu + 1} \frac{\left[1 - \left(\frac{R_f}{R_a}\right)^{2m}\right]}{\left[1 - \left(\frac{\mu-1}{\mu+1}\right)^2 \left(\frac{R_f}{R_a}\right)^{2m}\right]}$$

$$A_z(r,\theta) = \frac{\mu_o I_o}{2m} \cos(m\theta) \left(\frac{r}{a}\right)^m \left[1 + S_\mu \left(\frac{a}{R_f}\right)^{2m}\right],$$

$$B_\theta(r,\theta) = -\frac{\mu_o I_o}{2a} \cos(m\theta) \left(\frac{r}{a}\right)^{m-1} \left[1 + S_\mu \left(\frac{a}{R_f}\right)^{2m}\right],$$

$$B_r(r,\theta) = -\frac{\mu_o I_o}{2a} \sin(m\theta) \left(\frac{r}{a}\right)^{m-1} \left[1 + S_\mu \left(\frac{a}{R_f}\right)^{2m}\right].$$

For the m^{th} order multipole (m=1 for dipole), the ratio of the field provided by the iron yoke to the field provided by the current sheet is given by :

$$\frac{B_{fe}}{B_c} = S_\mu \left(\frac{a}{R_f}\right)^{2m}. \tag{3.1.3}$$

The theoretical maximum value of the above is 1.0 at low field (large μ) when $R_f = a$. In RHIC arc dipole magnets this ratio is ~0.55 (55%) at low field and ~0.50 (50%) at high field.

Note: μ is assumed to be constant in the entire iron yoke.

Field Enhancement for $COS(m\theta)$ Coil in Iron Shell

The field enhancement factor B_{enhc} due to the iron is defined as the field provided by the iron to the total field and is given by :

$$B_{enhc} = \frac{S_\mu \left(\frac{a}{R_f}\right)^{2m}}{\left[1 + S_\mu \left(\frac{a}{R_f}\right)^{2m}\right]}. \tag{3.1.4}$$

The enhancement in the field due to the iron yoke is in the range of 20% to 40% in the magnets examined in this thesis.

The vector potential and the field components at the inside surface of the iron in air at $r = R_f$ are obtained from Eqs. (1.5.115) as :

$$A_z\left(R_f,\theta\right) = \frac{\mu_o I_o}{2m}\ cos\left(m\theta\right)\left(\frac{a}{R_f}\right)^m\left[1 + S_\mu\right], \tag{3.1.5a}$$

$$B_\theta\left(R_f,\theta\right) = \frac{\mu_o I_o}{2a}\ cos\left(m\theta\right)\left(\frac{a}{R_f}\right)^{m+1}\left[1 - S_\mu\right], \tag{3.1.5b}$$

$$B_r\left(R_f,\theta\right) = -\frac{\mu_o I_o}{2a}\ sin\left(m\theta\right)\left(\frac{a}{R_f}\right)^{m+1}\left[1 + S_\mu\right]. \tag{3.1.5c}$$

Understanding The Iron Saturation (1)

For large μ (low field), S_μ is $\simeq 1$; therefore the magnetic field at $r = R_f$ would have only a radial component (field perpendicular condition) with its magnitude doubled over its value in the absence of the yoke. The magnitude of field for any μ is obtained as $|B| = \sqrt{(B_r^2 + B_\theta^2)}$. Therefore,

$$|B(R_f,\theta)| = \frac{\mu_o I_o}{2a}\left(\frac{a}{R_f}\right)^{m+1}\sqrt{1 + S_\mu^2 - 2S_\mu\ cos\,(2m\theta)}. \qquad (3.1.6)$$

In a magnet, the normal poles are at $\theta = (2n-1)\frac{\pi}{2m}$, with n=1,2,...,2m (m is 1 for dipoles and 2 for quadrupoles, etc.) and the coil midplanes are at $\theta = (n-1)\frac{\pi}{m}$. At the poles Eq. (3.1.6) reduces to

$$|B(R_f, \text{poles})| = \frac{\mu_o I_o}{2a}\left(\frac{a}{R_f}\right)^{m+1}(1 + S_\mu), \qquad (3.1.7)$$

and at the midplanes to

$$|B(R_f, \text{midplanes})| = \frac{\mu_o I_o}{2a}\left(\frac{a}{R_f}\right)^{m+1}(1 - S_\mu). \qquad (3.1.8)$$

Since S_μ is nearly one at low fields and nearly 0 at high fields, the ratio B/I_o at the yoke inner surface decreases at the poles and increases at the midplanes as the field increases from low to high.

Field and Saturation Parameters in RHIC Dipole with Circular Iron Yoke

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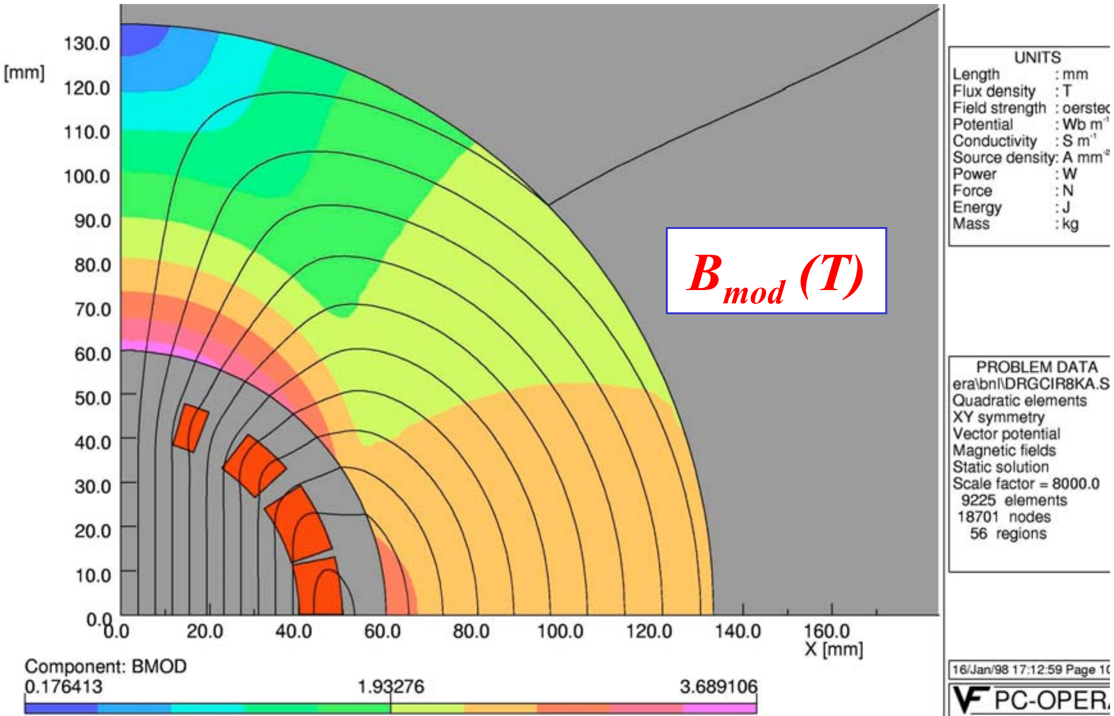

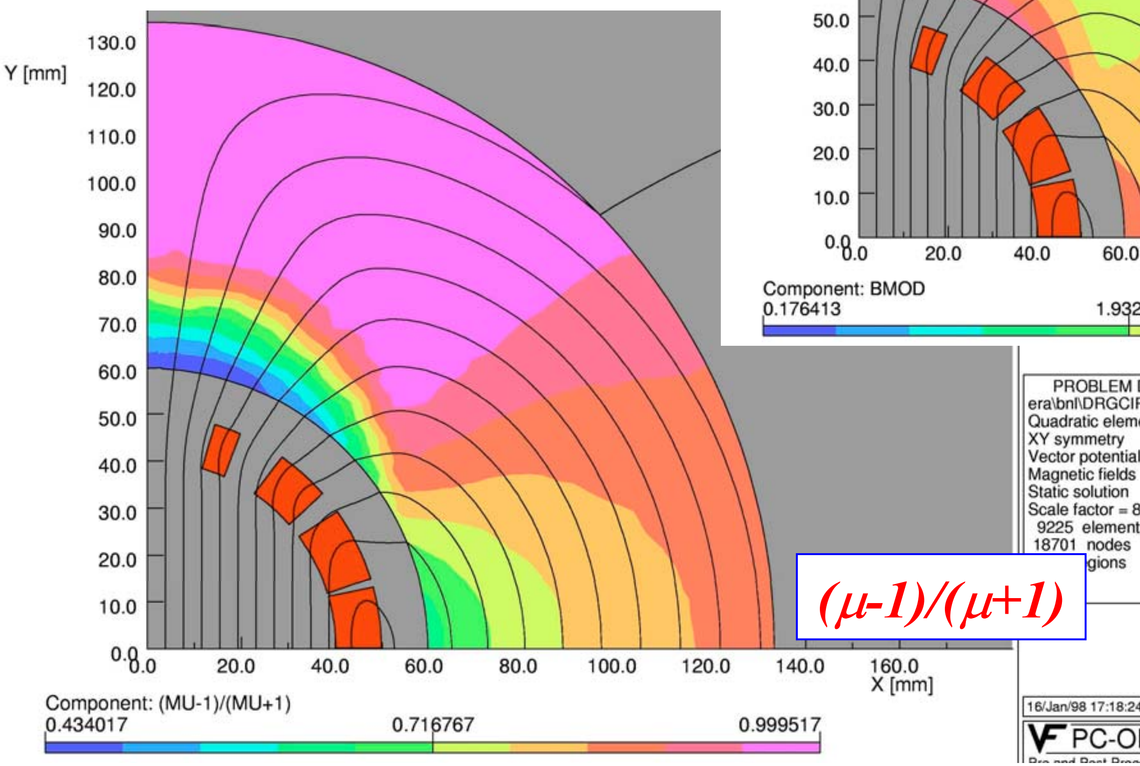

Note the differences between the pole and yoke.

Understanding The Iron Saturation (2)

To study a relative change in the azimuthal field distribution, two limiting cases are examined. First for the case when the iron saturation is negligible (low field and hence large μ in iron) and the saturation parameter (S_μ) is one. In this case the expression given in Eq. (3.1.6) reduces to :

$$|B(R_f,\theta)| = \frac{\mu_o I_o}{a} \; |sin(m\theta)| \; \left(\frac{a}{R_f}\right)^{m+1}, \qquad (3.1.9)$$

and then the case when the saturation parameter (S_μ) is zero (the maximum saturation case with $\mu \simeq 1$), the expression given in Eq. (3.1.6) reduces to

$$|B(R_f,\theta)| = \frac{\mu_o I_o}{a}\left(\frac{a}{R_f}\right)^{m+1}. \qquad (3.1.10)$$

A comparison of Eq. (3.1.9) and Eq. (3.1.10) shows that there is a change in the azimuthal distribution of the field at the yoke inner surface in the two cases. Whereas, at low fields, the magnitude of the field at the yoke inner radius changes as sin(mθ), it is completely independent of the angle at high fields. Therefore, yoke saturation causes a change in the azimuthal field distribution which in turn would cause a change in field harmonics.

Understanding The Iron Saturation (3)

The actual situation is much more complex than the expressions derived here under the assumption of constant μ in the iron everywhere. In a realistic case μ is not constant in the iron and varies as the field varies as a function of radius and angle. A local change in field, therefore, also causes a local change in μ which is not accounted in the above expressions. That situation is too complex to be solved analytically. However, most qualitative conclusions reached under the constant μ assumptions remain valid and are useful to develop strategies to minimize the dependence of field harmonics on iron saturation.

At low and medium field, the magnetization in the iron is such that it is maximum at the poles (90° and 270° in dipoles and 45°, etc. in quadrupoles) and minimum at the midplane (0° and 180° in dipoles and 0°, 90°, etc. in quadrupoles). However, most of the flux from the aperture returns through the iron yoke at the midplane and at high field this changes the distribution of flux lines such that the iron may be more magnetized at the midplane depending on the yoke thickness. This is the basis of the statement given earlier that the azimuthal distribution of the magnetization in the iron is a function of the central field. The harmonics in the aperture of the magnet change with central field if the iron magnetization approaches the saturation magnetization and if there is a significant variation in the azimuthal distribution of this iron magnetization, particularly near the

First order optimization: Force a similar yoke saturation between midplane and pole

Method of Image Current to Understand and Minimize the Saturation-induced Harmonics

The contribution of a circular iron yoke with constant permeability (μ) can be described with the help of image currents. Note that in this case there will be only a radial component of the field at yoke inner surface. The field of a line current (I) at a radius *"a"* inside a circular iron cavity of radius R_f is given by:

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

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

The image current will be at the same angular location, however, the magnitude and the radial location are given by:

$$I' = \left(\frac{\mu-1}{\mu+1}\right) I,$$

$$a' = \frac{R_f^2}{a}.$$

Development of the proposed approach for minimizing saturation induced harmonics with the help of image current method

The image current *"I"* of a line current at a radius *"a"* will be at the same angular location, however, the magnitude and the radial location are given by:

$$I' = \left(\frac{\mu - 1}{\mu + 1}\right) I,$$

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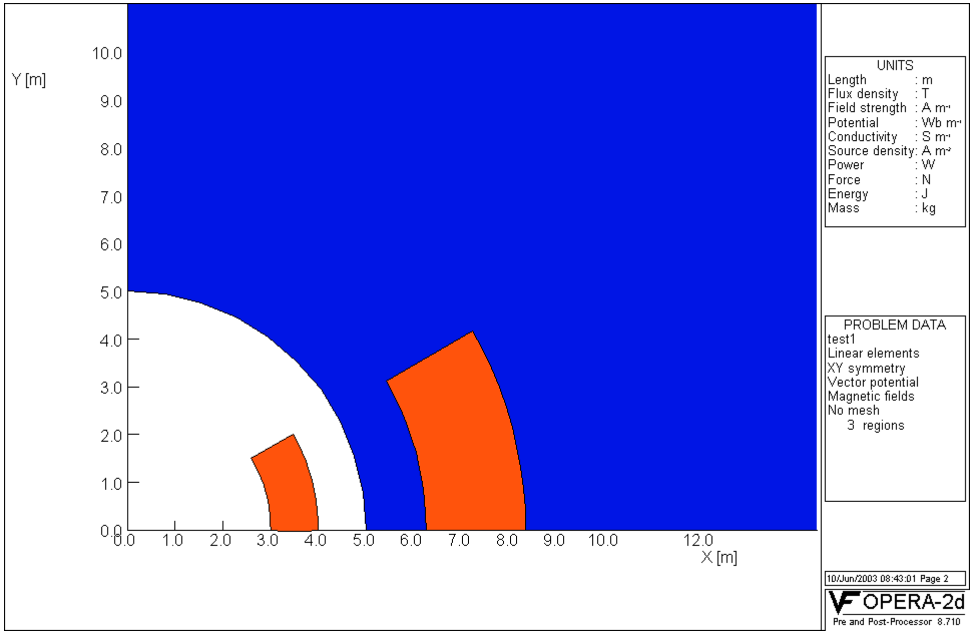


> The block may be described by a series of line currents and the image block by a series of image currents. The image block will produce a field (and harmonics) that is similar in shape as the main field, if the μ of the iron is constant.

> In a real magnet with saturating, non-linear iron, it seems intuitively likely that the change in field shape (and harmonics) can be minimized by minimizing the variation in μ and the quantitative deviation can be measured by (μ-1)/(μ+1).

A Conceptual Model for Understanding and Minimizing the Saturation-induced Harmonics

The contribution of a circular iron yoke with infinite permeability can be described with the help of image currents. A series of image currents (second term in the following expression) will retain the original angular distribution and the magnitude of them will be proportional to original current, if the mu is constant in the iron (uniform magnetization across the iron).

In that case only the primary component depends on the magnetization and no other harmonics will change. Moreover, the change in primary component is related to $(\mu-1)/(\mu+1)$.

$$B_y(r,\theta) = -\frac{\mu_o I_o}{2a} \cos((m-1)\theta) \left(\frac{r}{a}\right)^{m-1} \times \left[1 + \frac{\mu-1}{\mu+1}\left(\frac{a}{R_f}\right)^{2m} \frac{\left[1-\left(\frac{R_f}{R_a}\right)^{2m}\right]}{\left[1-\left(\frac{\mu-1}{\mu+1}\right)^2\left(\frac{R_f}{R_a}\right)^{2m}\right]}\right]$$

The above theory does not work if the magnetization is not uniform. However, even in that case one can still develop a conceptual understanding and minimize the saturation-induced harmonics by using the following hypothesis. Describe coil with a series of line current and assume that the image current is still at the same angular location but the magnitude is related to the average mu in the vicinity of the angular location where the line currents are.

The variation in saturation induced harmonics can be minimized, if the variation in iron magnetization, as measured by $(\mu-1)/(\mu+1)$, is minimized.

Significant Difference With The Conventional Method

In order to achieve a more uniform magnetization (iron saturation), one can force the field lines in the region where the iron was magnetized less. This will increase the overall magnetization in the iron, but the attempt should be to force a more uniform magnetization, particularly in the iron region that is closer to aperture.

The conventional method called for not allowing the iron to saturate (too much magnetized). Minimizing non-linear iron means minimizing the saturation induced harmonics. This meant keeping the iron away from the coil as that is a high field region. However, that also meant reducing the contribution of the iron to the total field as the iron near the aperture (coil) contributes more. In brief, the old method relied on reducing the region of iron that saturates.

The major difference between the method used in RHIC magnets, as compared to the earlier designs, with which major accelerator magnets have been built, that here the attempt was to increase (forced) the saturation (to make it uniform) and before the attempt was to decrease it.

The close-in iron for obtaining higher field need not compromise the field quality as long as the iron saturation can be kept uniform, particularly in the iron region that is closer to aperture.

Saturation in RHIC Arc Dipole

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

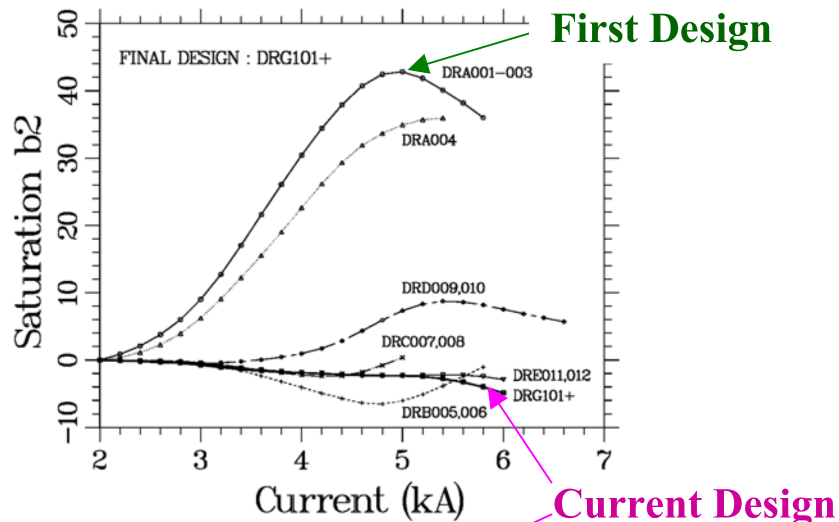
3.45 T (Total) ~ 2.3 T (Coil) + 1.15 (Iron)

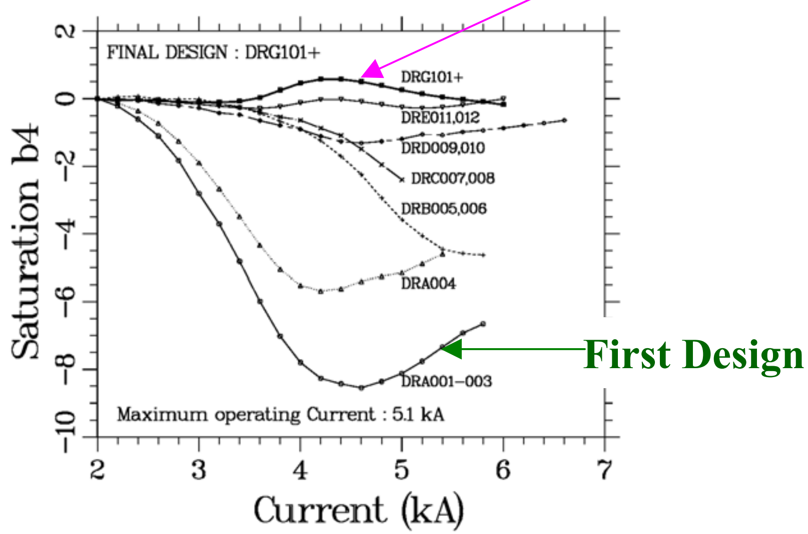
Initial design had bad saturation,

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

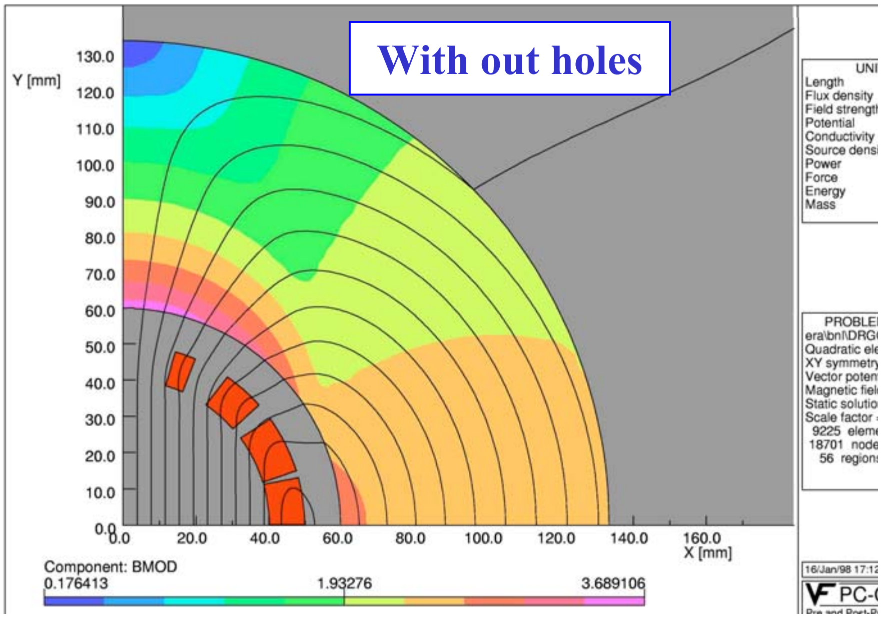
Only full length magnets are shown.

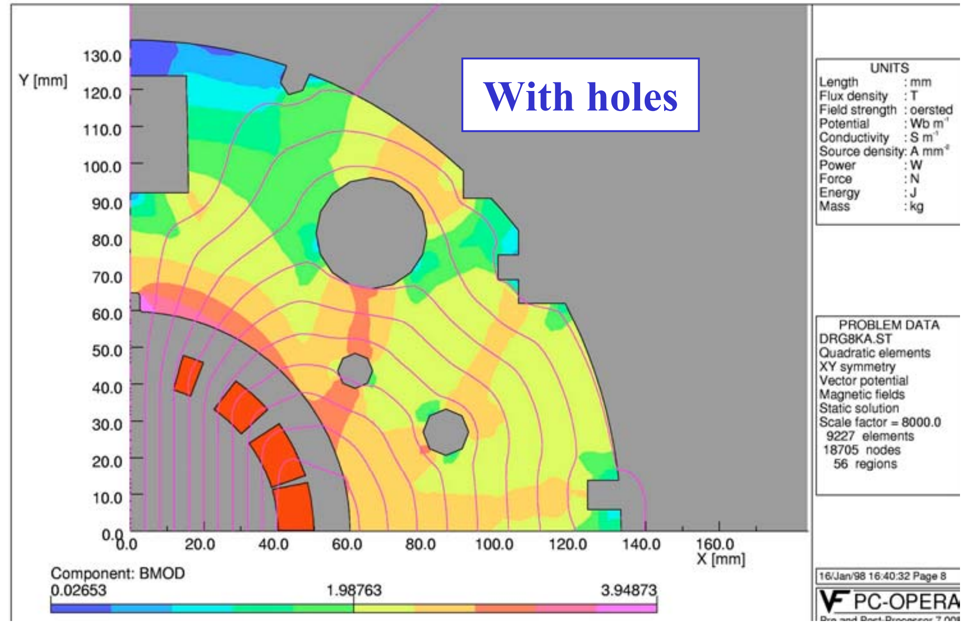
Design current is ~ 5 kA (~3.5 T).





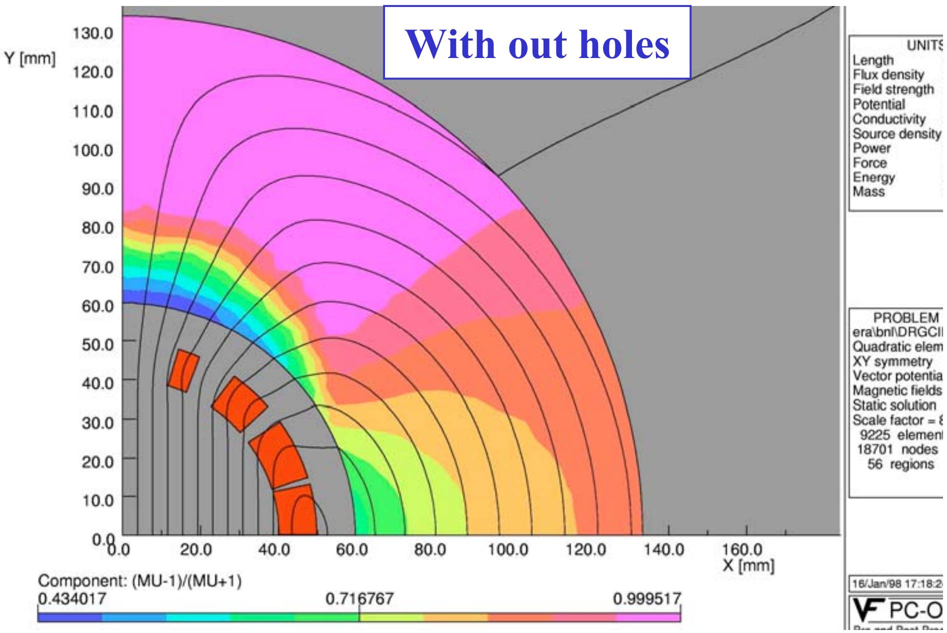
Saturation Control in RHIC Dipoles
Variation in |B| in Iron Yoke

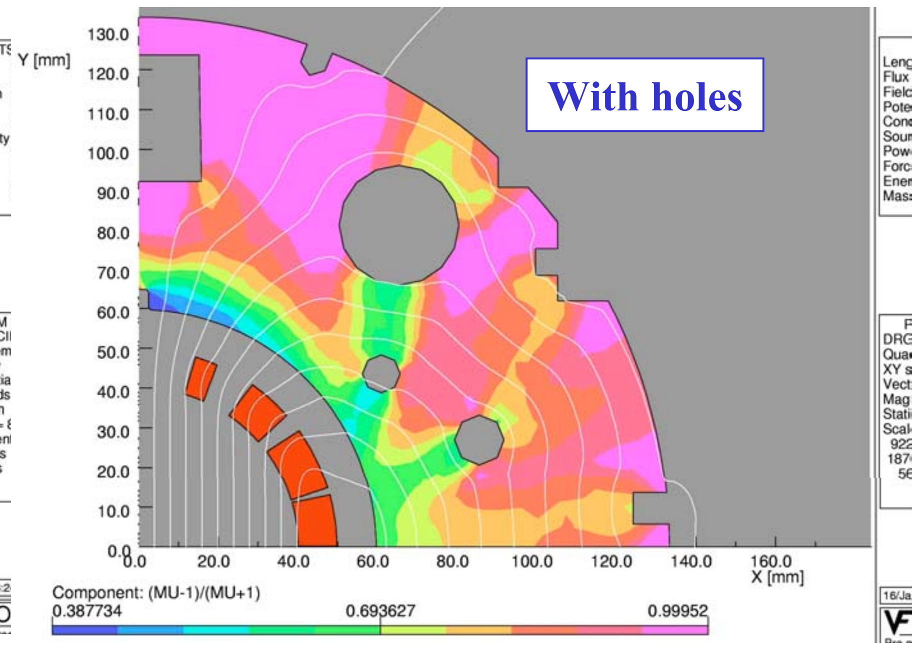




- Compare azimuthal variation in |B| with and without saturation control holes. Holes, etc. increase saturation in relatively lower field regions; a more uniform iron magnetization reduces the saturation induced harmonics.
- Old approach: reduce saturating iron with elliptical aperture, etc.
- New approach: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

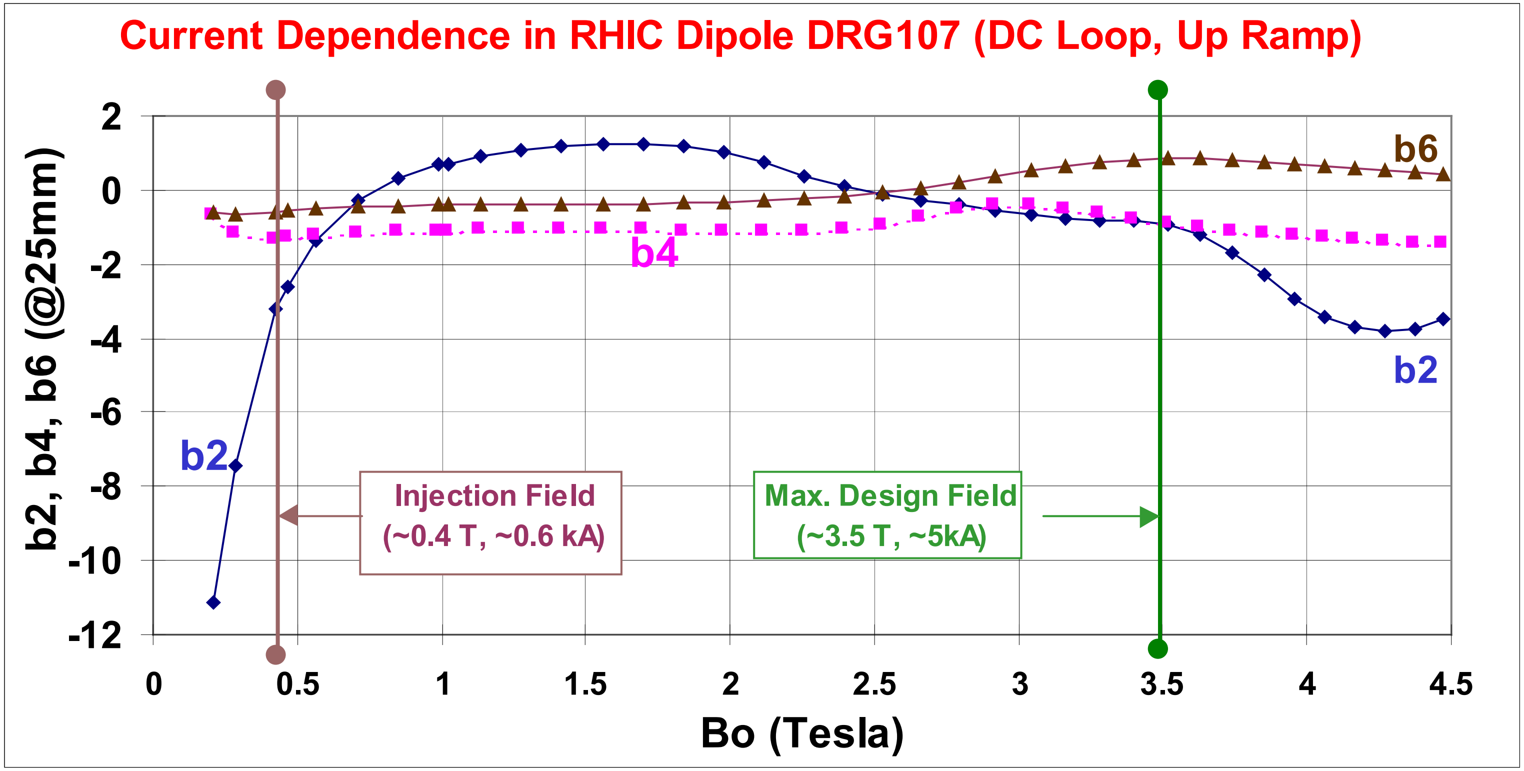
$$B_\theta = \frac{\mu_o I}{2\pi r} + \frac{\mu_o I}{2\pi a}\sum_{n=1}^{\infty}\left(\frac{a}{r}\right)^{n+1} \cos(n(\phi-\theta))\left[1-\frac{\mu-1}{\mu+1}\left(\frac{r}{R_f}\right)^{2n}\right]$$

  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.

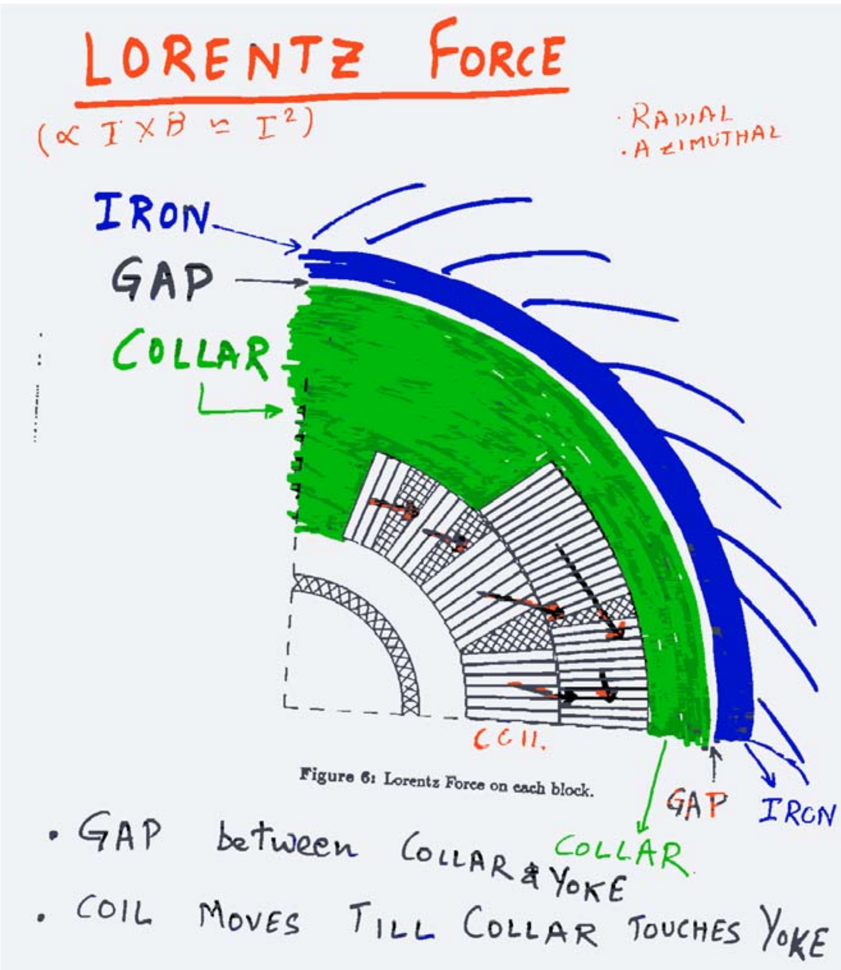
Current Dependence Beyond Design Field

- In all known major accelerator magnets (superconducting and iron dominated), the harmonics fall rapidly beyond the maximum design field. They are relatively flat in this design approach . Please note the difference in scale (50 units in previous slides in b_2 plots). It (a) shows a major impact of this design approach on field quality and (b) may have relevance to RHIC upgrade as most magnets in RHIC have ~30% quench margin over the maximum design field.

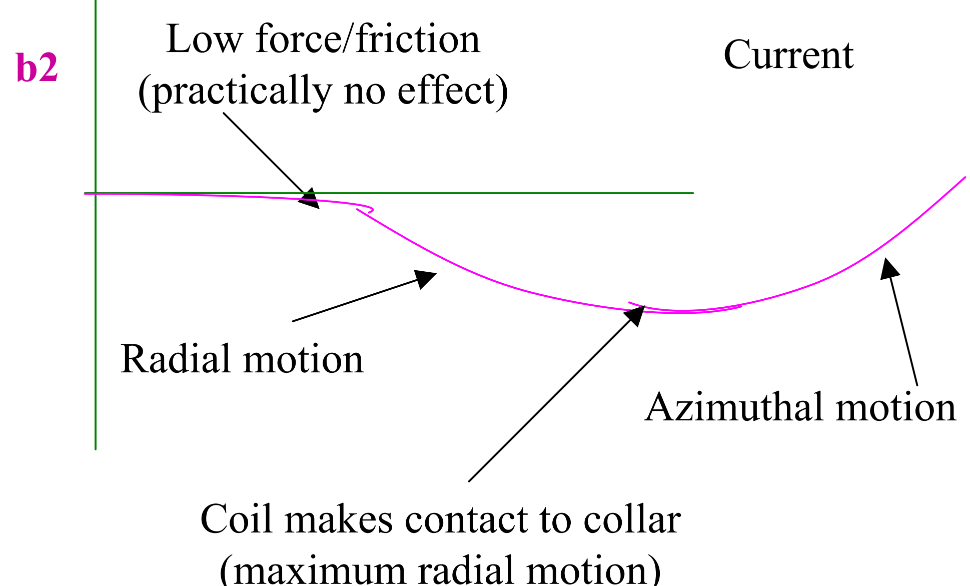


Influence of Lorentz Forces on Field Harmonics

The measured current dependence in field harmonics is a combination of saturation-induced harmonics, and the Lorentz force-induced harmonics.



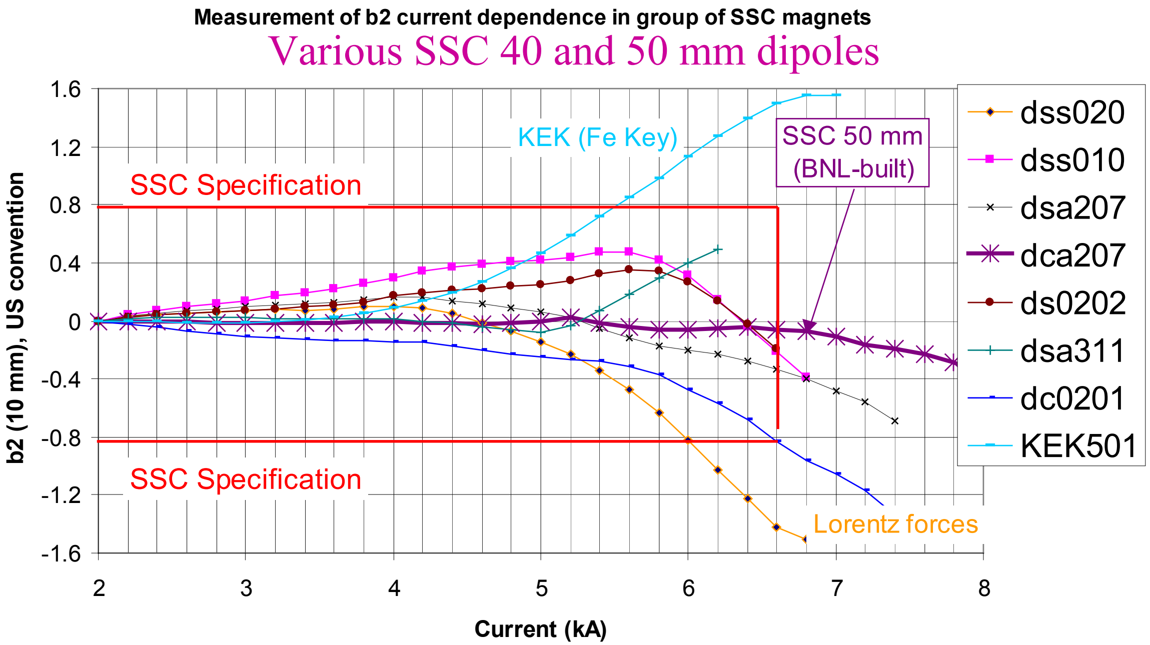
A typical Sextupole current dependence due to Lorentz forces (schematic)



Assignment: Make a similar sketch for b4 (decapole).

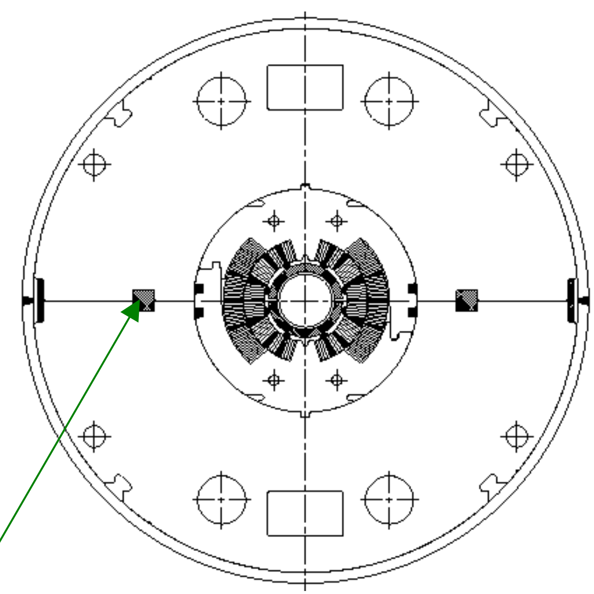
A small radial gap in magnets (50-100 micron), could be present due to tolerances in collar o.d. and yoke i.d. In SSC that means ~-1 unit of sextupole. Such errors can be accommodated in a flexible design - key material,etc.

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.

Yoke Cross-section Optimization

To do detailed magnetic design, you must use one of several available computer codes.

Some popular codes that are currently being used for designing accelerator magnets:

- POISSON, etc. (Developed in labs, public domain)
- OPERA, ANSYS, etc. (Commercial)
- ROXIE (Developed in labs, commercial & requires licensing)

In addition, various labs have written in-house computer codes to fulfill their special requirements. For example, all RHIC coils, for a variety of magnets, are designed with PAR2dOPT at BNL. And new codes are being developed for racetrack coils.

Setting-up A Magnetic Model With A Minimum Geometry

To make an efficient use of the computer resources and to get more accurate results in minimum time, setup the basic model with proper boundary conditions.

For example, for a dipole magnet, usually you need to model only a quadrant of the geometry, with the following boundary conditions:

- a field perpendicular boundary on the x-axis
- a field parallel boundary on the y-axis
- and infinite boundary condition on the other side(s), or else extent the other boundary far away so that the field near the end of boundary becomes very small.

Question: What will you do in the case of a quadrupole magnet?

Magnet Yoke Optimization

Generally speaking, first determine the yoke envelop

- **Yoke inner radius**

  Mechanical (Lorentz forces) & magnetic issues (iron saturation)

- **Yoke outer radius**

  Mechanical (size and space consideration) & magnetic issues (iron saturation, fringe fields)

… and then optimize the internal geometry

- **Accommodate holes, etc for cooling, assembling and other mechanical purpose**
- **Try to place above holes at strategic places and put extra holes, etc., if necessary.**

Yoke Inner Radius

To first order, the yoke inner radius depends on the mechanical design chosen to contain the Lorentz forces

- It is typically over 15 mm plus the coil outer radius, if stainless steel or aluminum collars are used

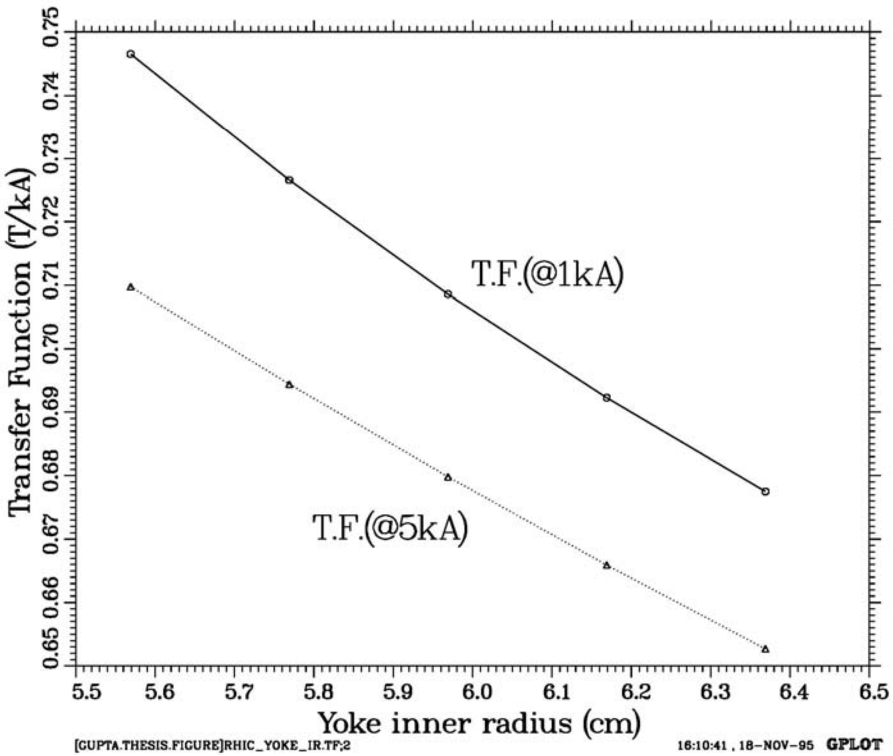
  Example: SSC or LHC dipoles

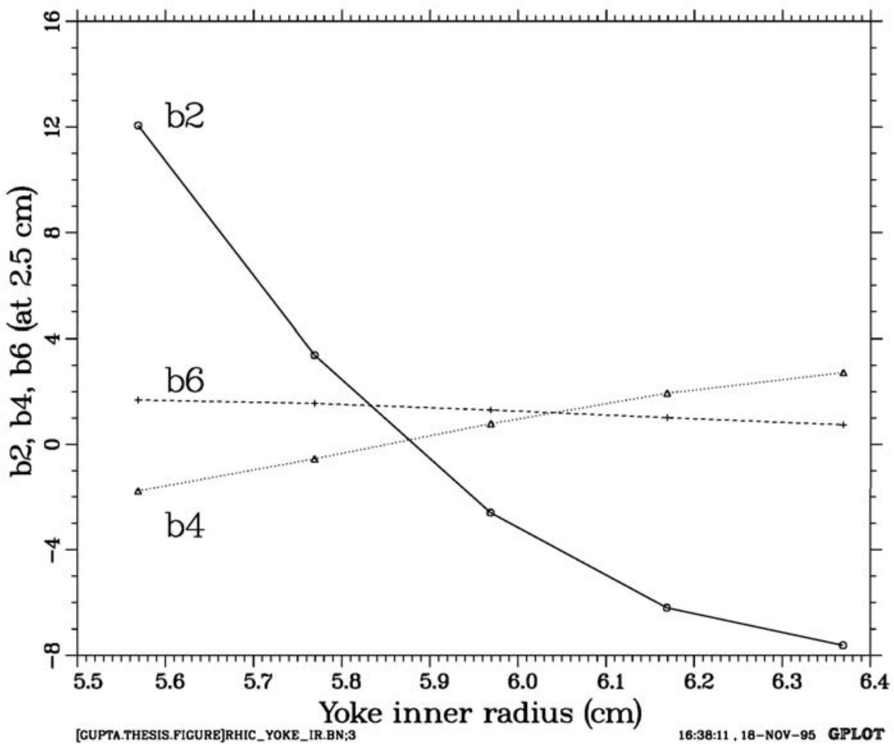
- It is typically 5-15 mm plus the coil outer radius, if the yoke is also used as collar (material between the coil and yoke acts as an spacer)

  Example: RHIC Dipole and Quadrupole Magnets

Smaller inner radius brings iron closer to the coil and adds to the field produced by the coil alone. However, it also increases the saturation-induced harmonic due to non-linear magnetization of iron at high fields.

Variation in Yoke Inner Radius in RHIC 80 mm Aperture Dipole





Yoke Outer Radius

The yoke outer radius should not be unnecessarily large, as that:

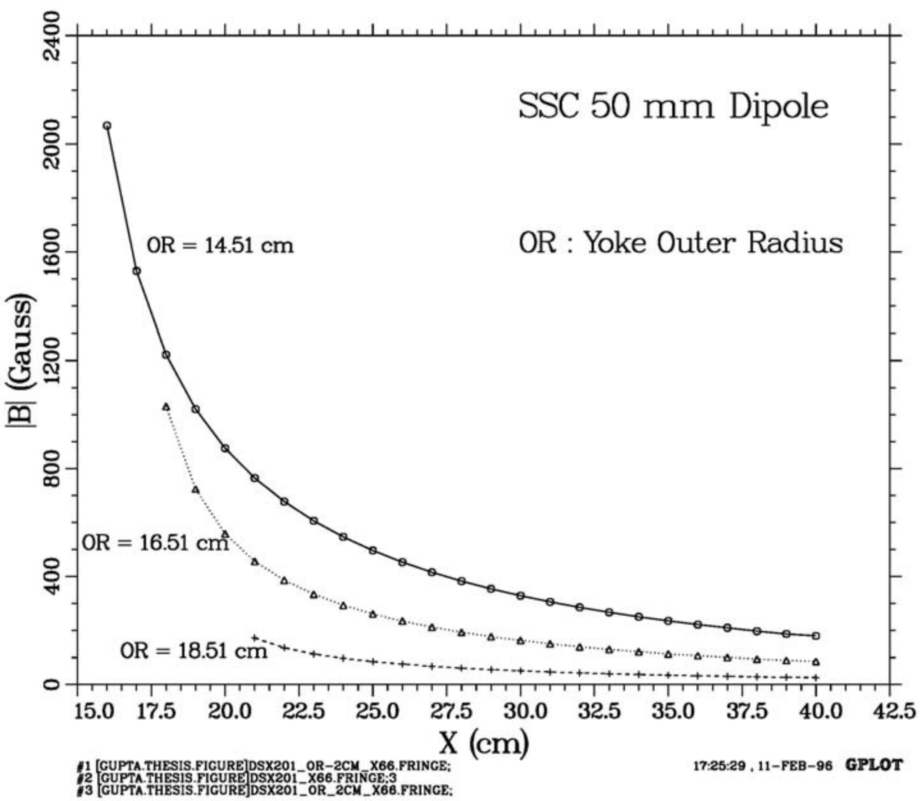
- May increases the over all dimensions
- May increases the magnet weight
- May increases the over all cost

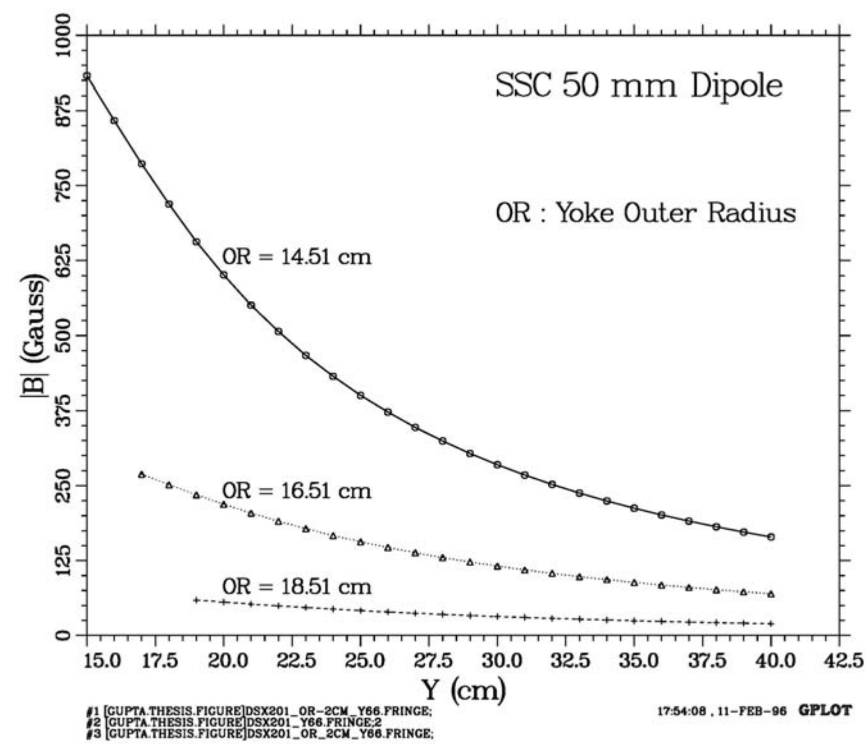
However, the yoke outer radius should not be too small either, as that:

- May increases the fringe field
- May reduce the central field significantly
- May increase the saturation induced harmonics

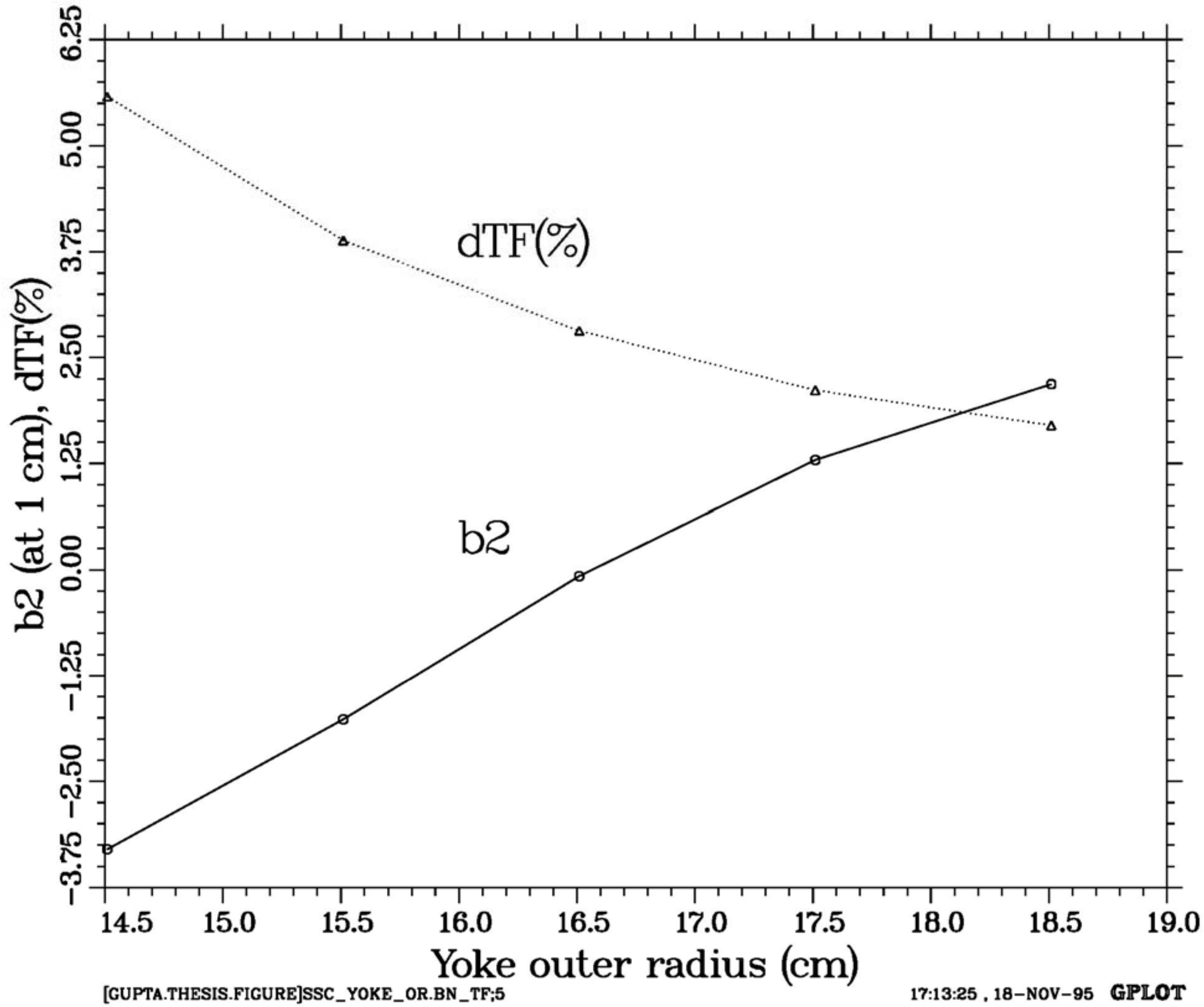
Fringe Field for Various Outer Yoke Radii

Fringe field in the SSC dipole at the design field of 6.6 T outside the yoke for various values of yoke outer radius. These models assume that there is no cryostat outside the coldmass.





Variation in Yoke Outer Radius in SSC 50 mm Aperture Dipole

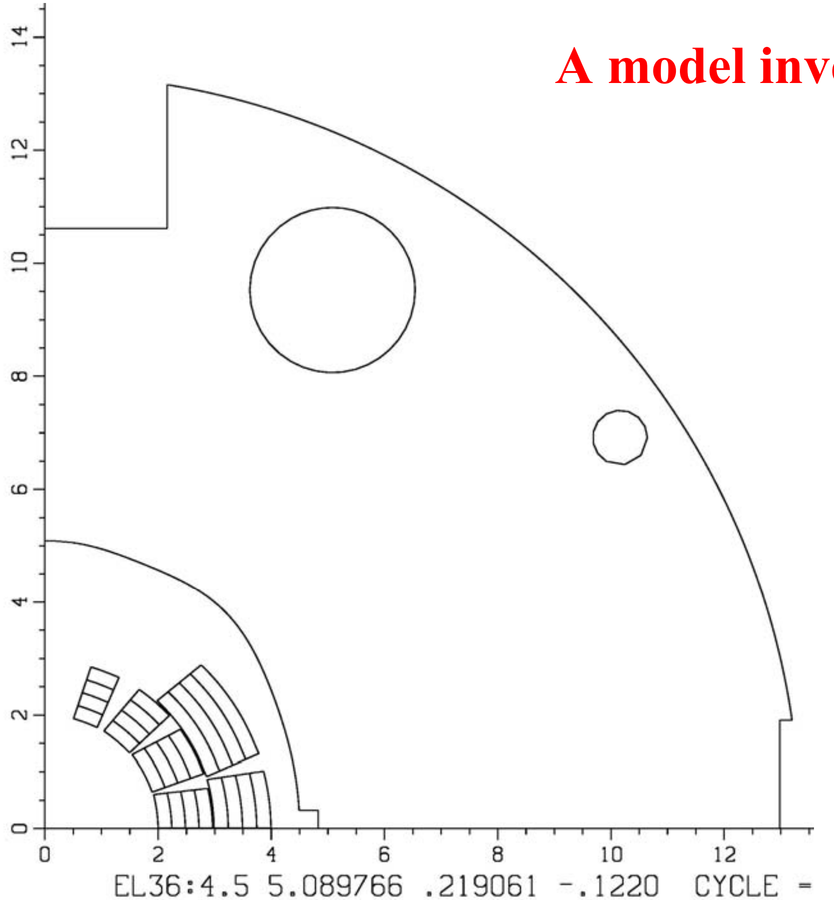


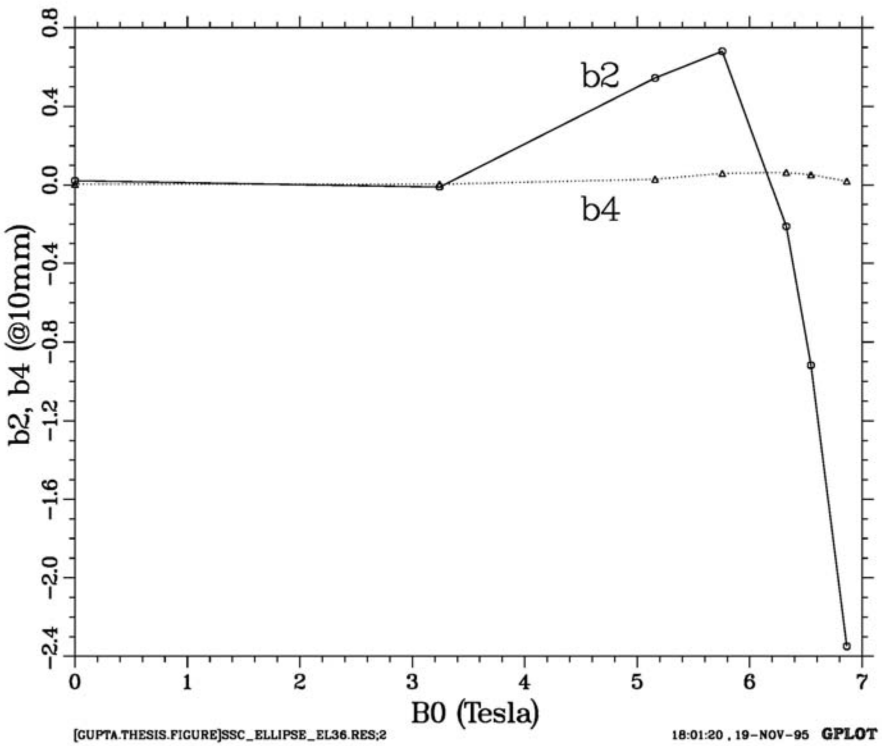
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Elliptical Aperture to Reduce Saturation-induced Harmonics

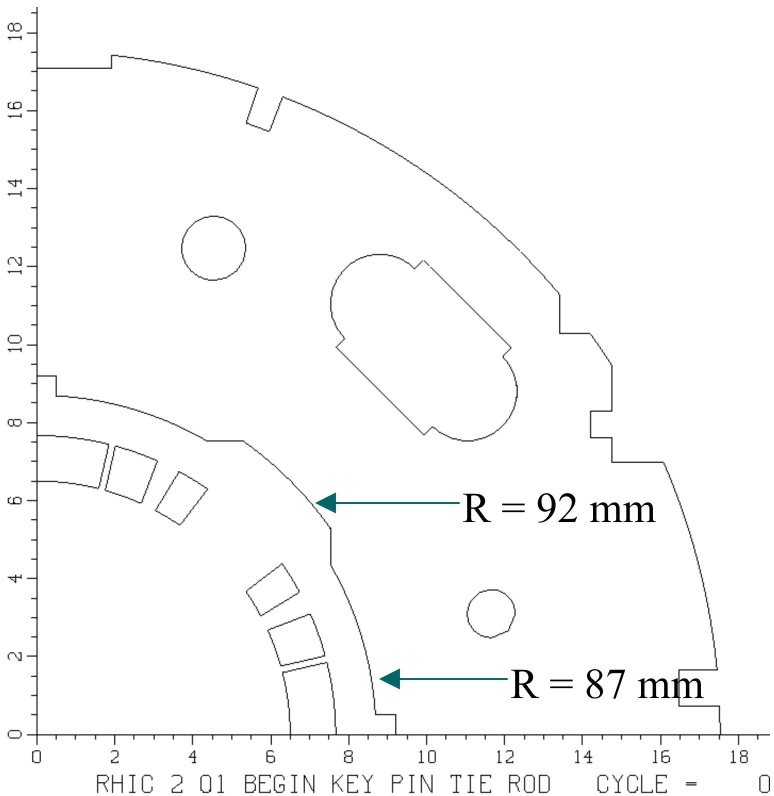
A model investigated for SSC 40 mm dipole magnet.



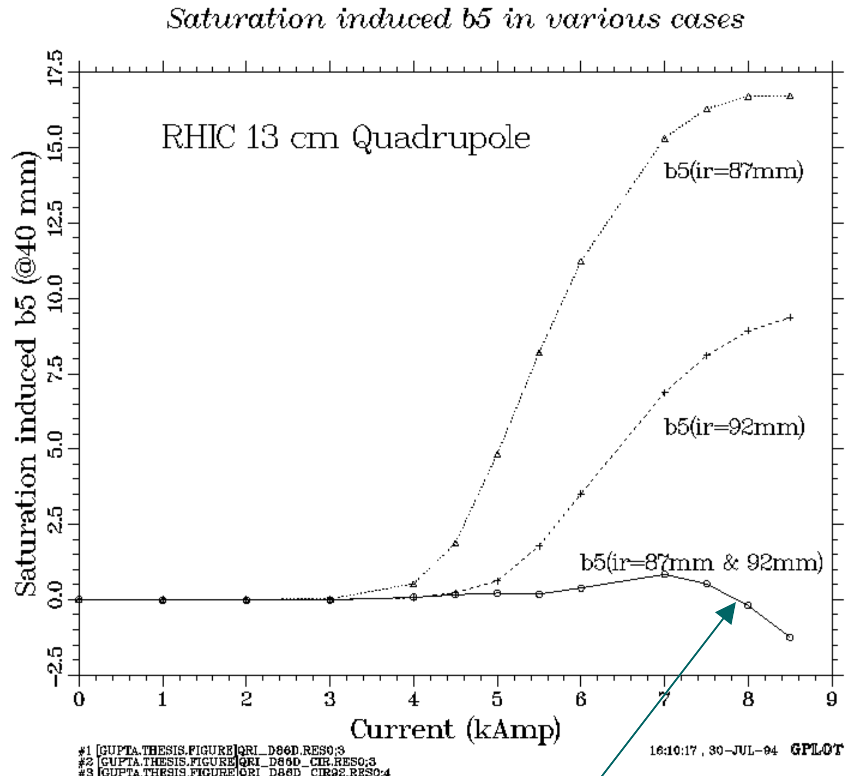


In order to reduce, the saturation-induced harmonics, the iron is selectively removed from the region (pole), where it was saturating more due to higher field.

Saturation Control in RHIC IR Quads



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

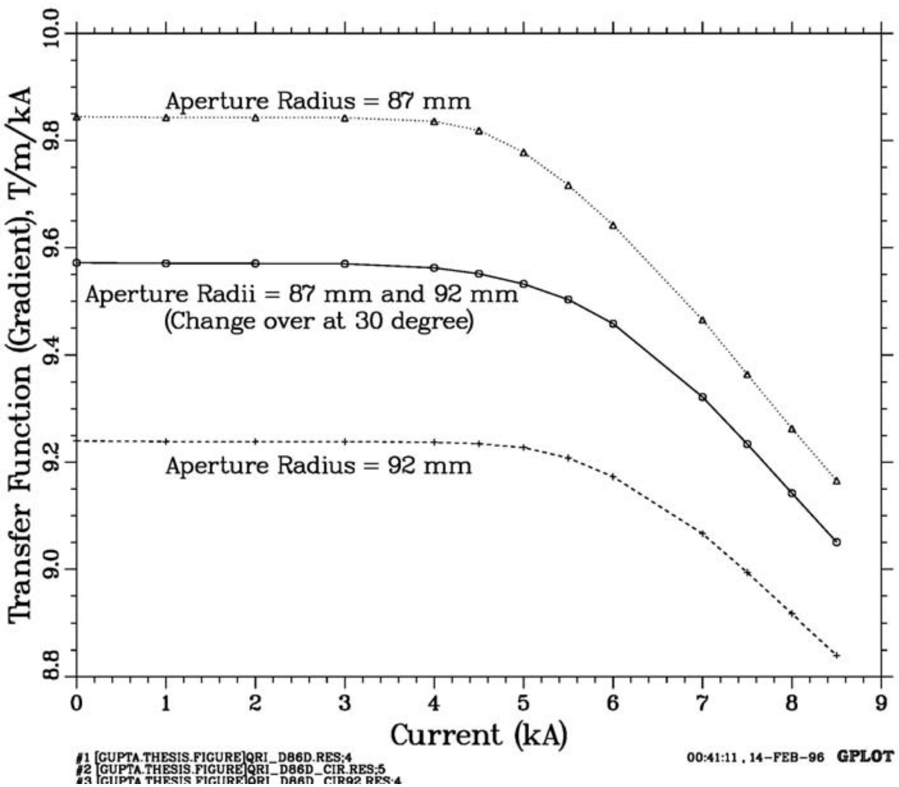


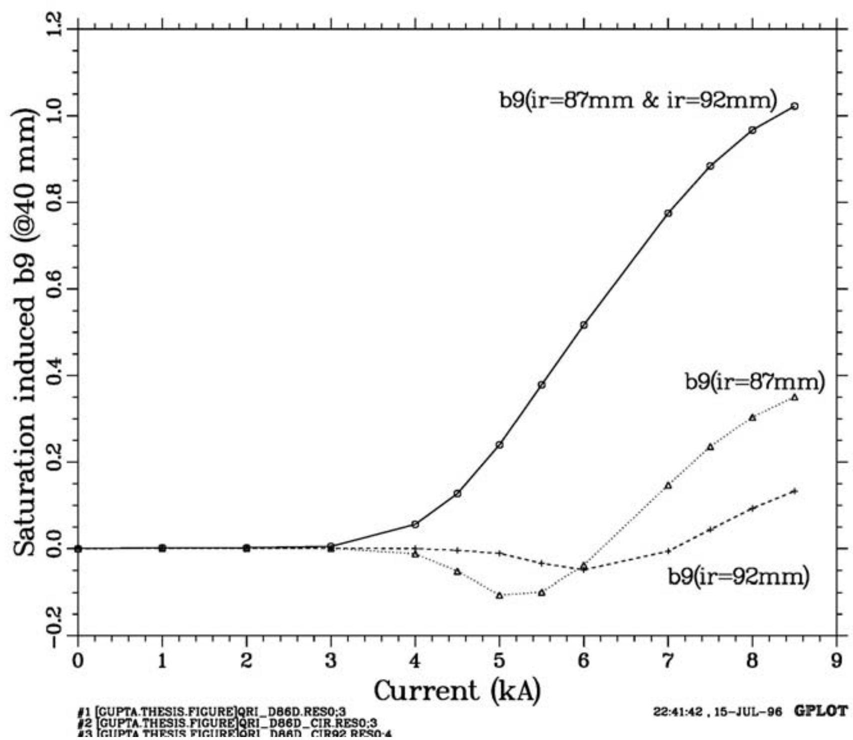
Optimized design

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

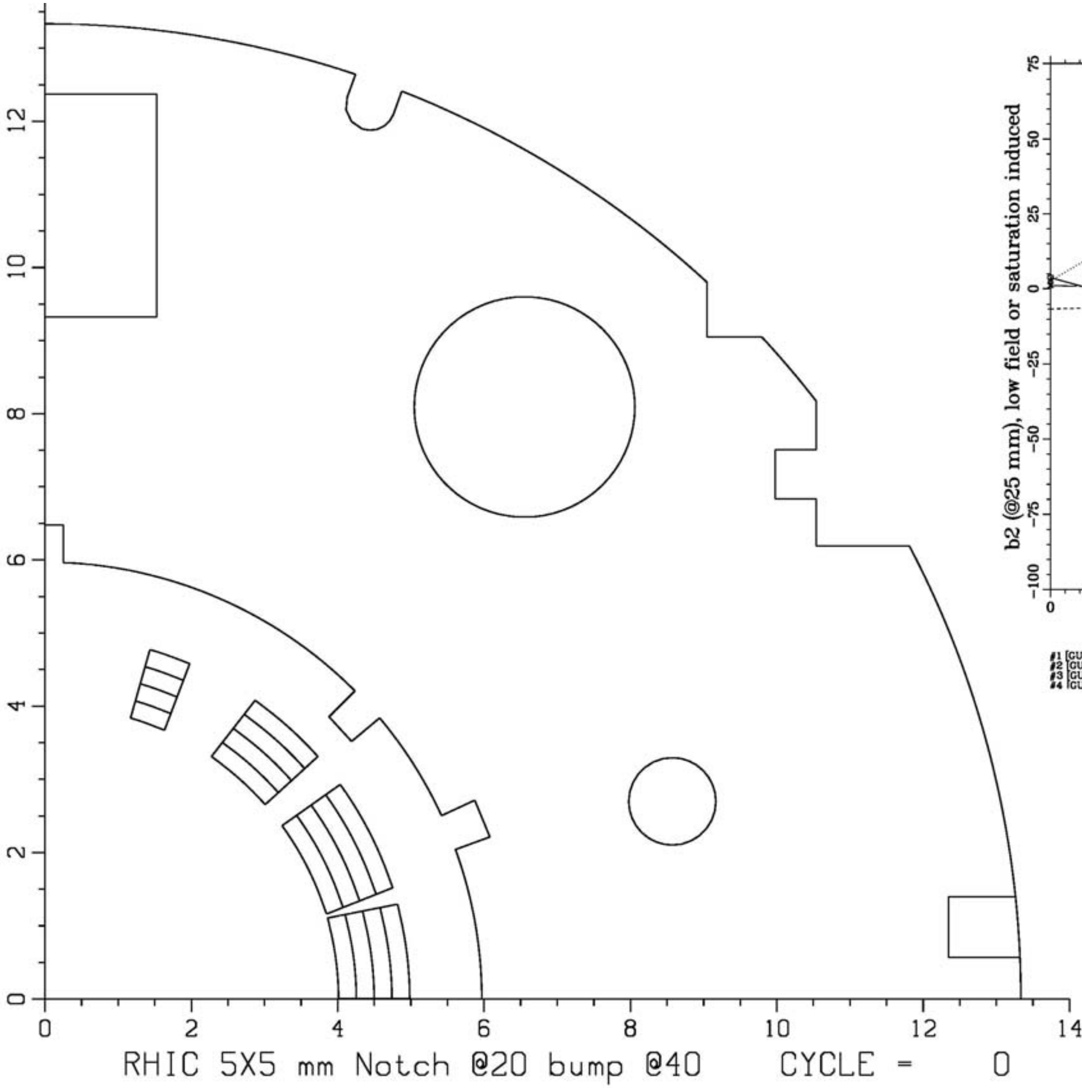
Influence on T.F. and b_9 of 2-radius Design

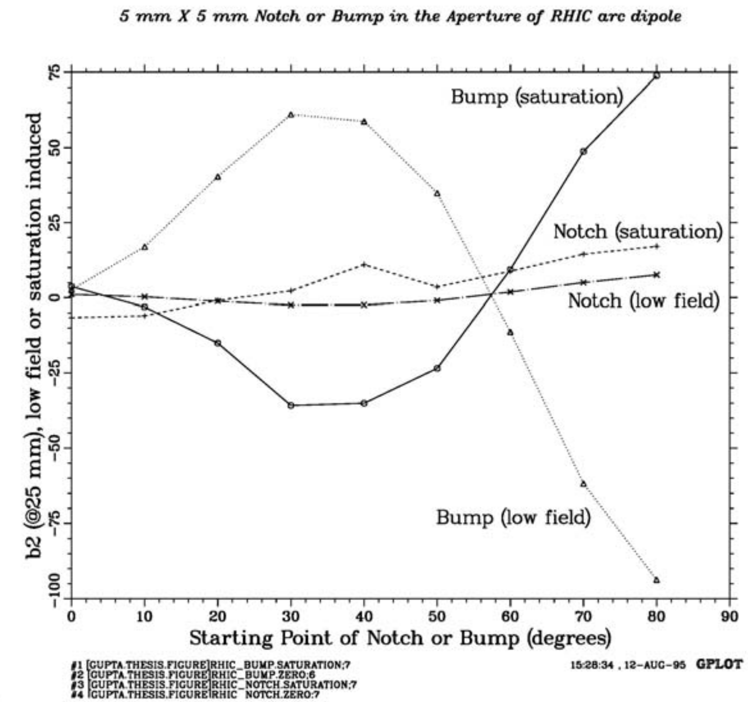
RHIC 13 cm aperture interaction region quadrupole





Influence of Notch/Tooth





Influence of 5mmX 5 mm notch or tooth as a function of angle.

Saturation Control Holes

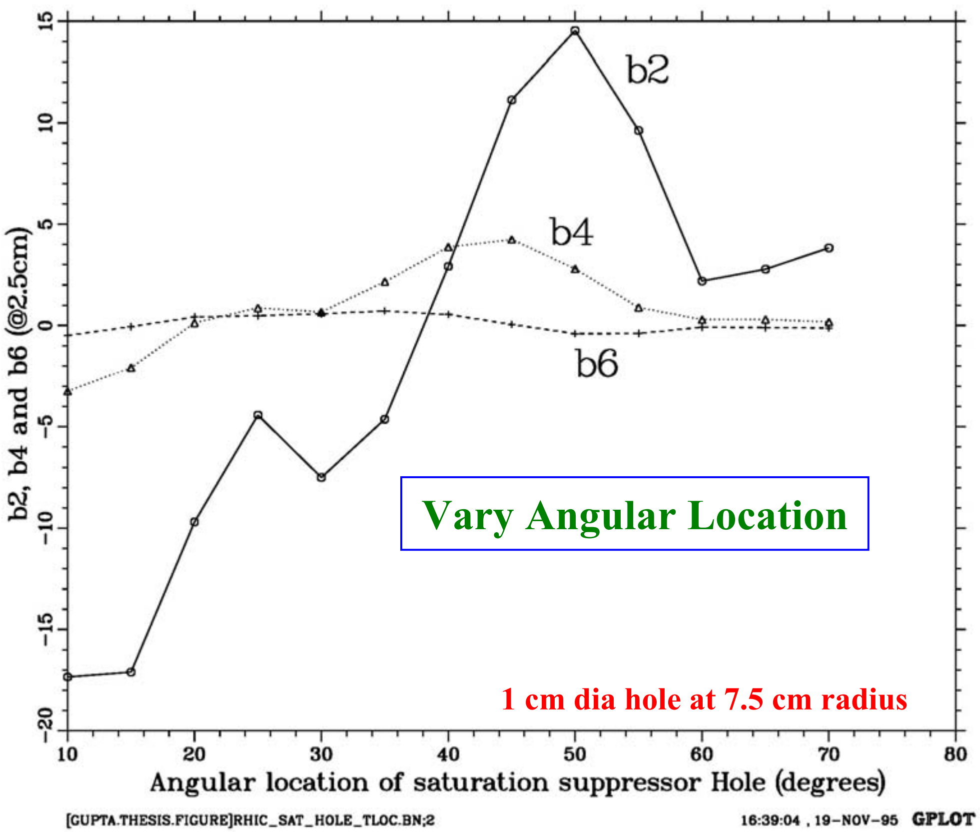
- **The most powerful tool to control the saturation, or rather force a uniform saturation, is to use saturation control holes.**

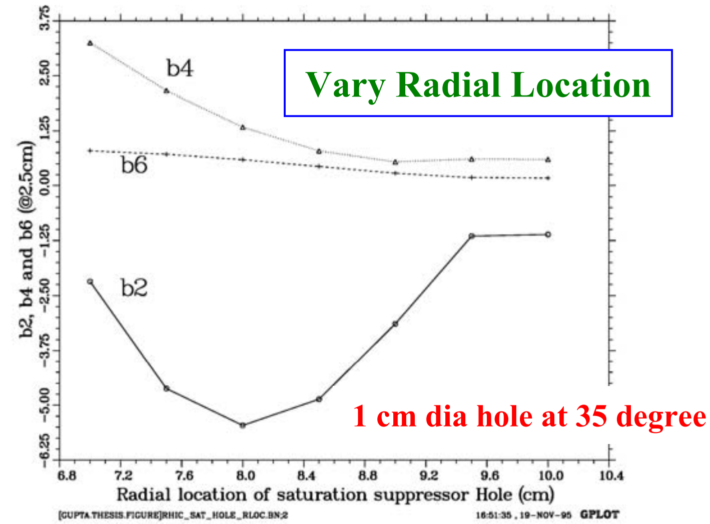
- One can either use the holes, that must be there for other purpose, or put some new one that are dedicated for the sole purpose of controlling saturation.

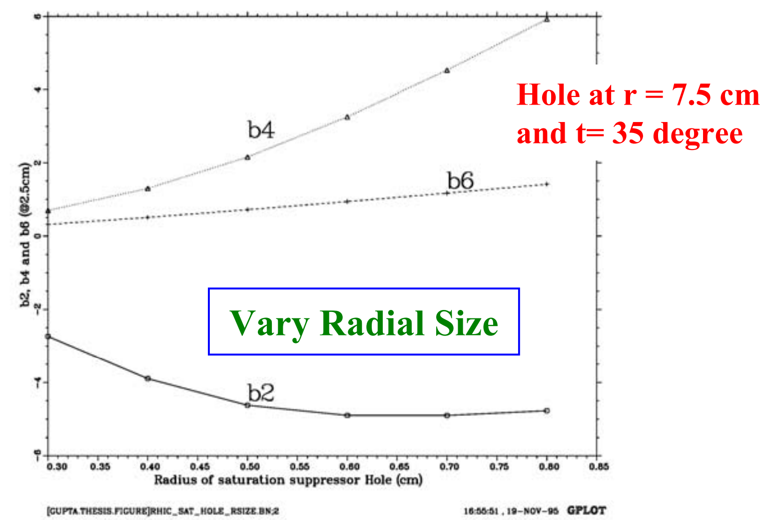
- Example of existing holes:
  - Big helium holes for cooling (generally good flexibility in choosing the location and some in choosing the size also).
  - Pins for putting yoke laminations together (flexibility in choosing material, magnetic steel or non-magnetic steel), and small flexibility in size and location.
  - Yoke-yoke alignment keys (flexibility in choosing material, magnetic steel or non-magnetic steel), and small flexibility in size and location.
  - And some other in special cases, like tie rods, etc.

Influence of An Additional Saturation Control Yoke in RHIC Dipole

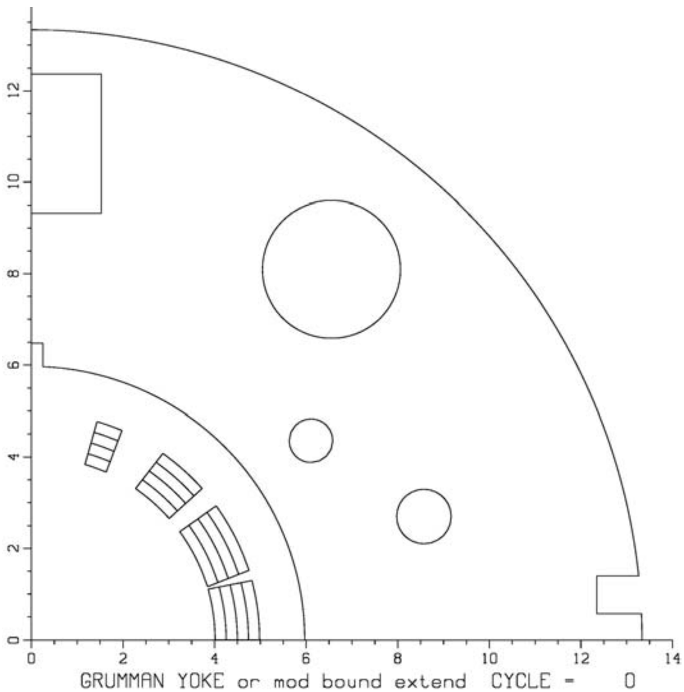
Saturation-induced harmonics in RHIC dipoles at the design current (5kA).



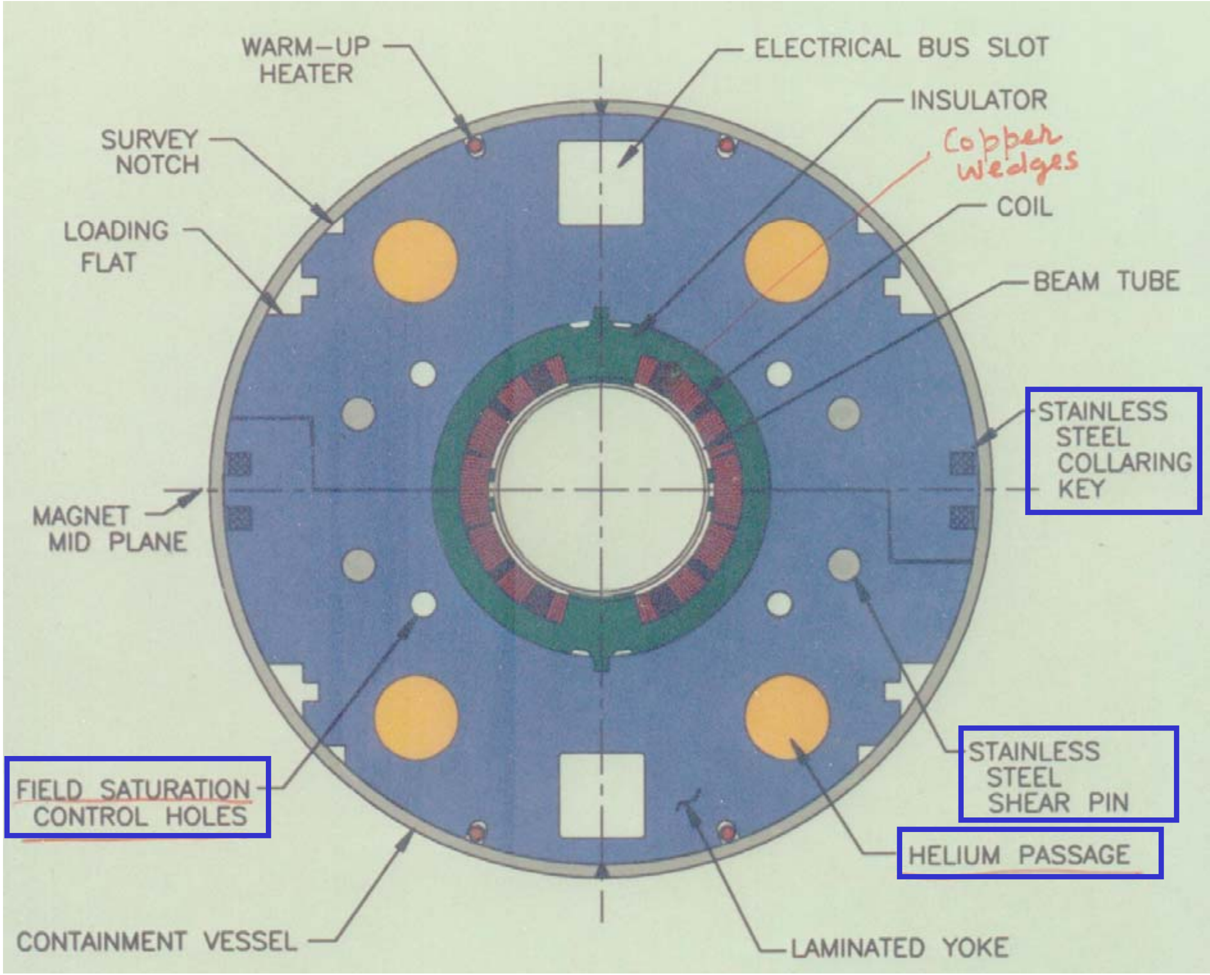




RHIC Arc Dipole
(with saturation control features indicated)



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

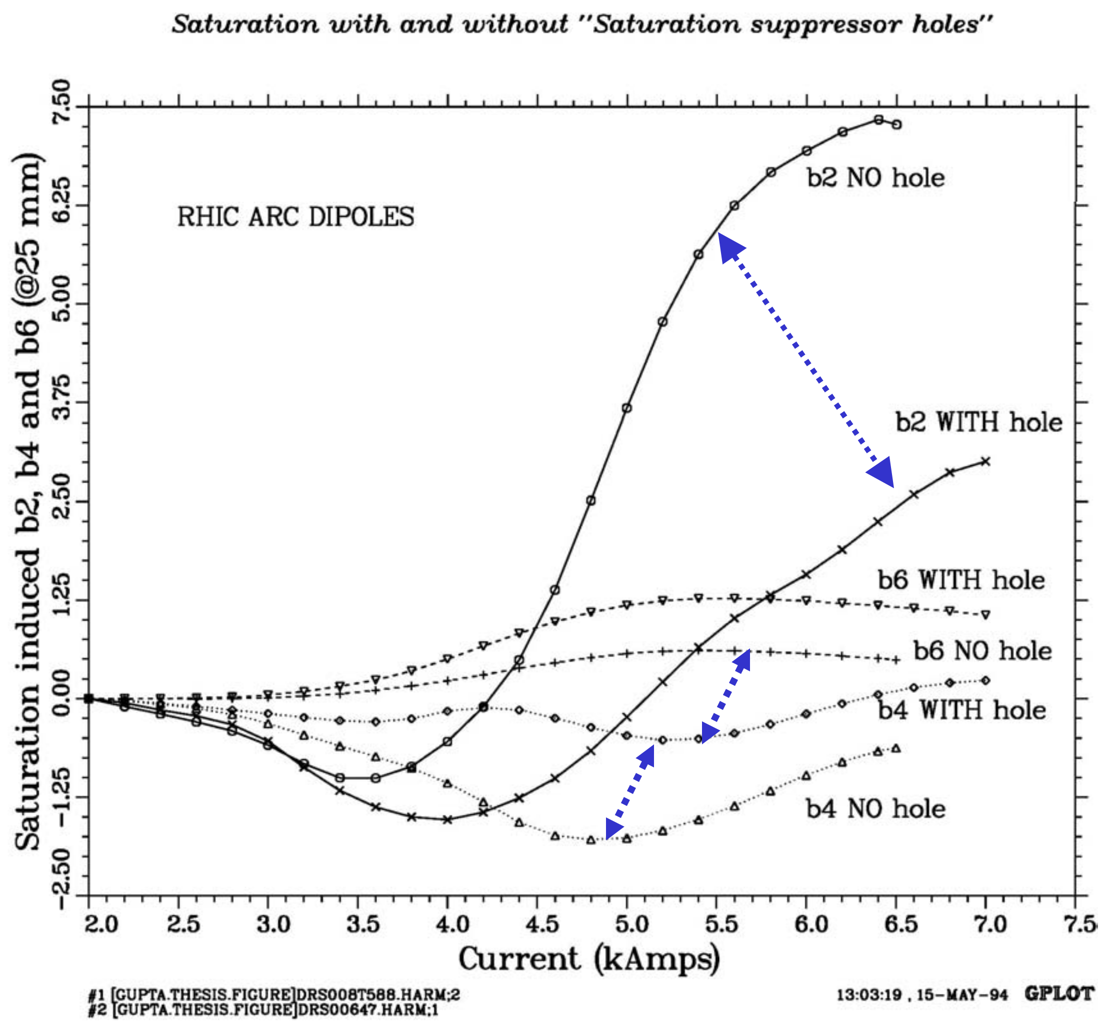


Influence of Saturation Control Hole

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.



Current Dependence in Non-allowed (Un-allowed) Harmonics

Non-allowed harmonics are those that are not allowed by magnet symmetry.

Current dependence means:

either the iron is not symmetric and/or the Lorentz forces are not

Allowed harmonics in dipoles:

Dipole, sextupole, decapole, … (Bo, b2, b4, b6, …, etc.) b_{2n}

Non-allowed harmonics in dipoles:

quadrupole, octupole, … (b_{2n+1}) : left-right asymmetry

All skew harmonics a_n : top-bottom differences

Allowed Harmonics in quadrupole

Quadrupole (B1), b5, b9, …

All others are not allowed

Current Dependence in Skew quad Harmonic (a_1) in Dipole

Skew quad harmonic (a_1) in dipole reflects a top-bottom asymmetry

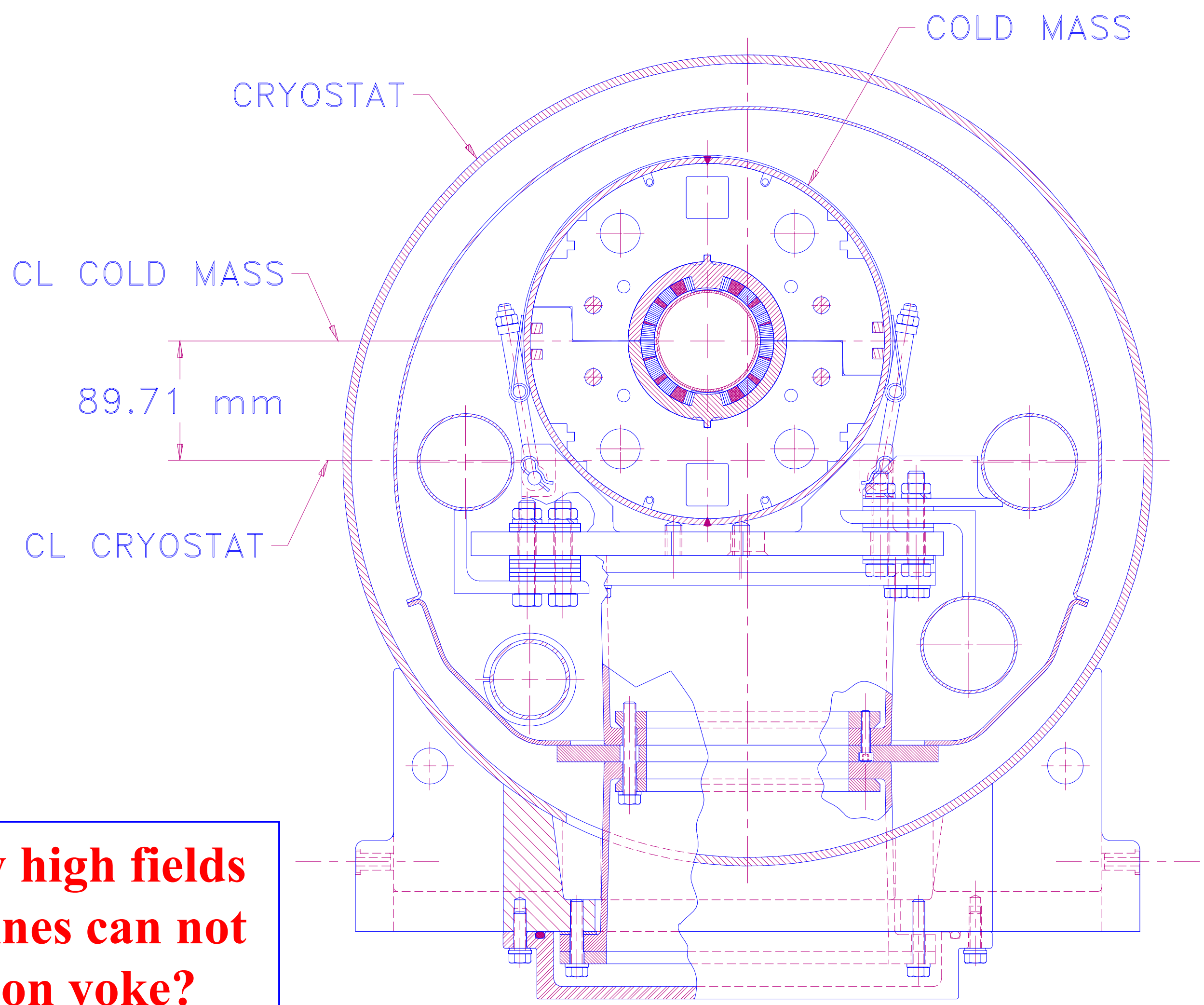
Suspect: Somehow the total amount of iron is not same on top and bottom
(at low field, not much iron is needed so it matters less
as long as the geometry is the same)
Another source: asymmetric Lorentz forces (unlikely)

Integral Difference: Overall asymmetry

Location-to-location Difference: Local asymmetry

Non-symmetric Coldmass Placement in Cryostat

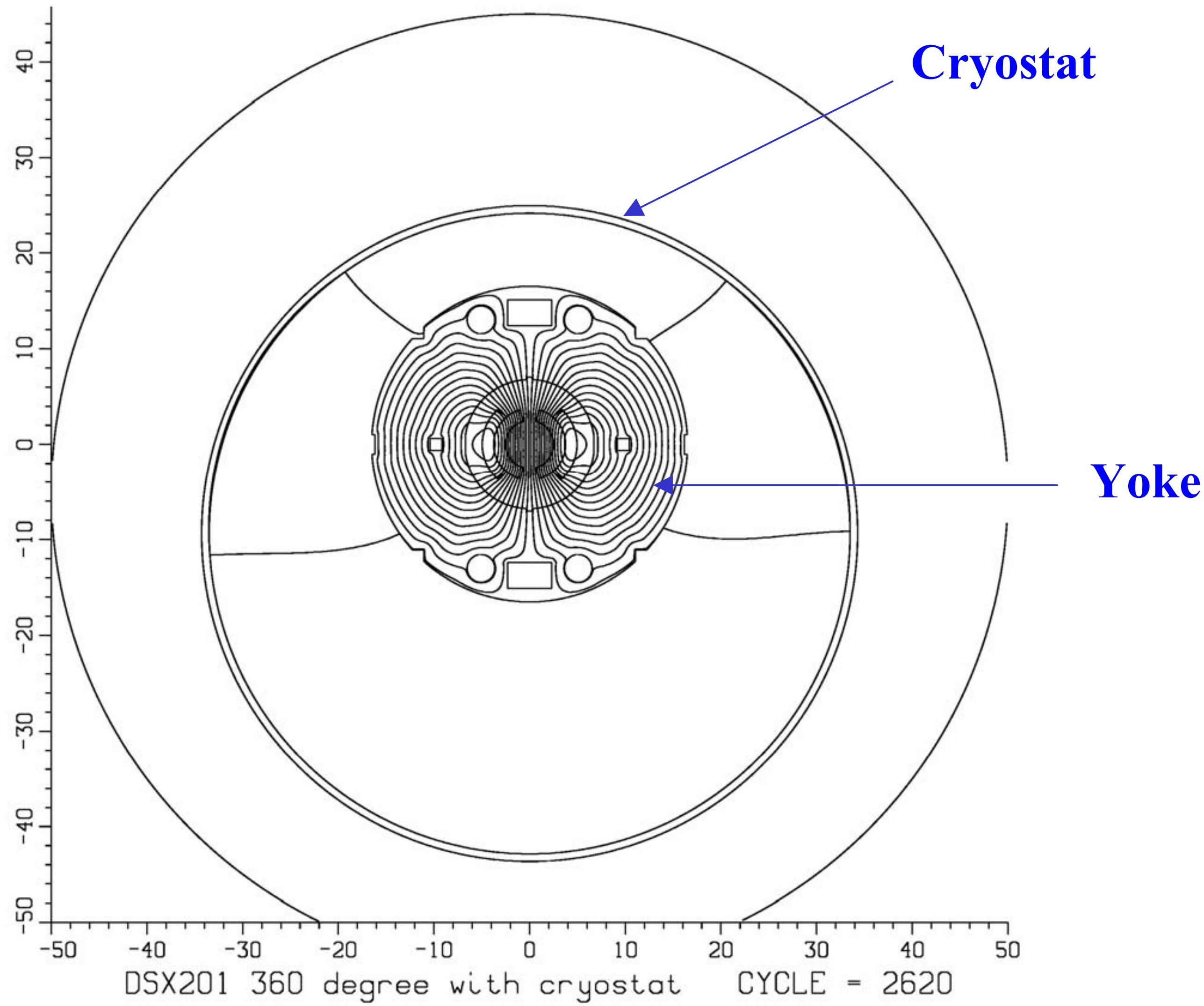
Design of the 80 mm aperture RHIC dipole coldmass in cryostat



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?

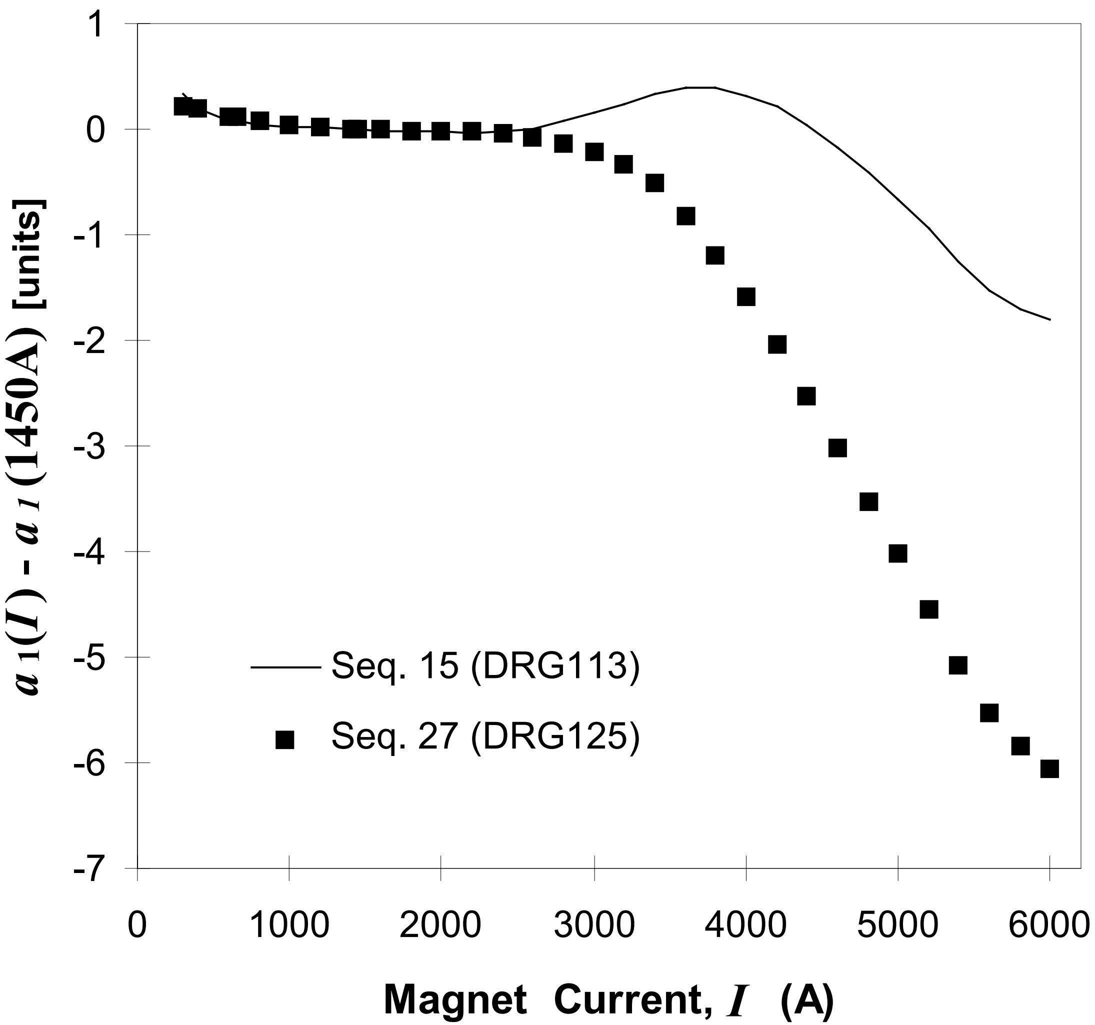
Leakage of Magnetic Flux Lines at High Fields in SSC Dipole



What harmonics will it create?

Note that the yoke iron is not placed symmetrically inside the cryostat.

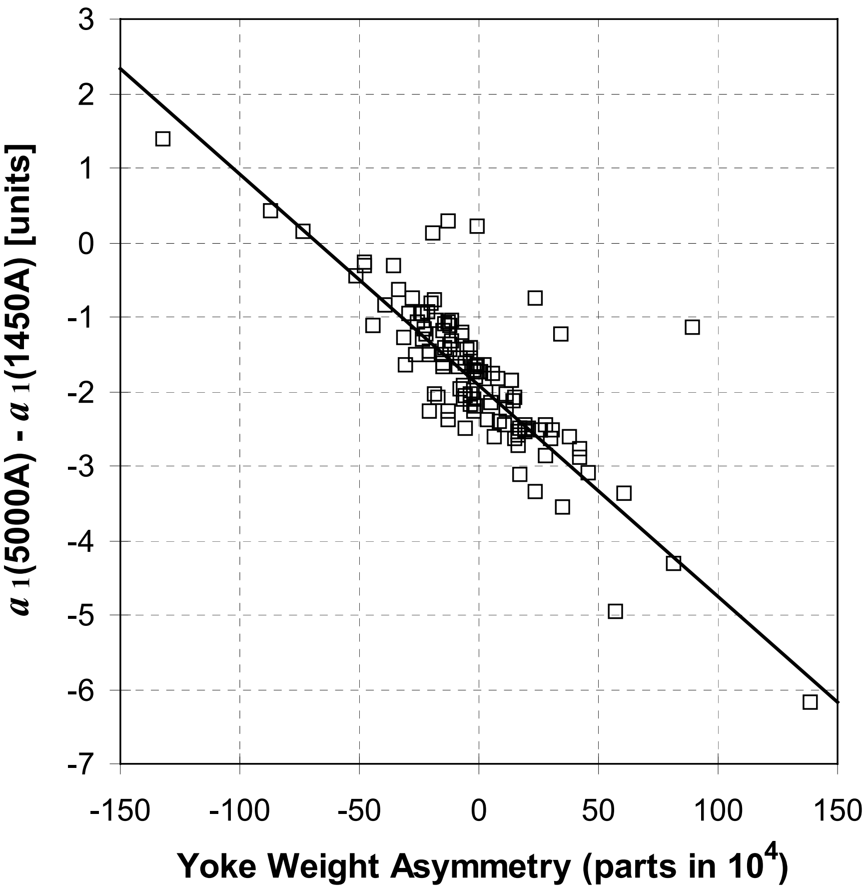
Measured Current Dependence in Two RHIC Dipoles



Current dependence of the skew quadrupole term in the dipoles DRG113 and DRG125. The magnitude of change between low currents and 5000A is the largest in DRG125 and is relatively small in DRG113.

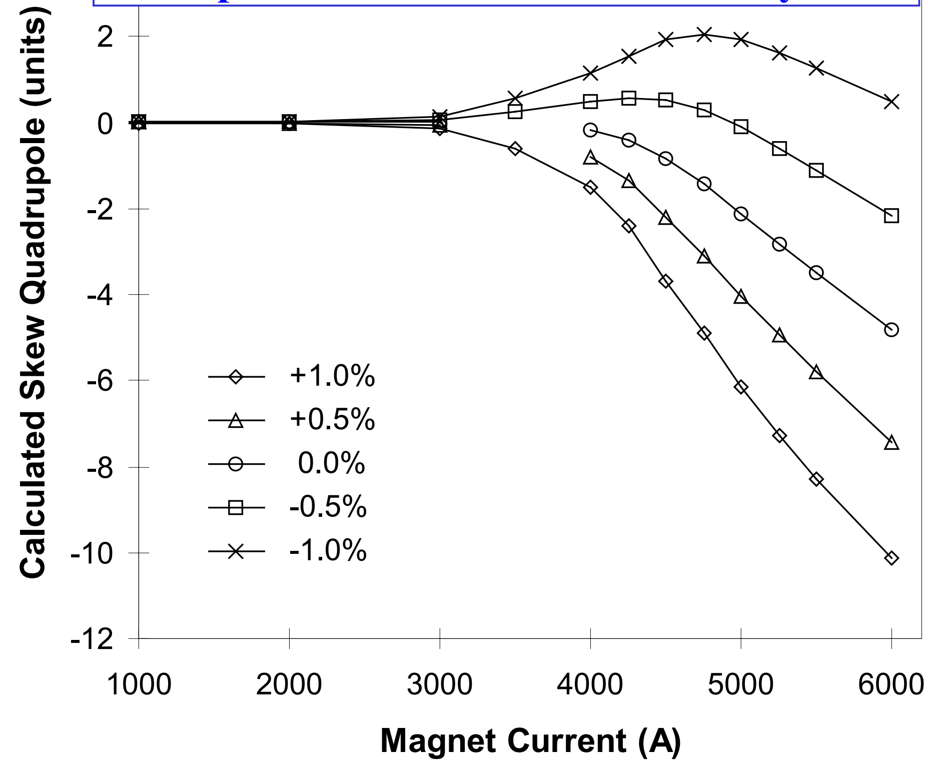
Reduction in Saturation-induced Skew Quad Harmonic (a_1) in RHIC Dipoles

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

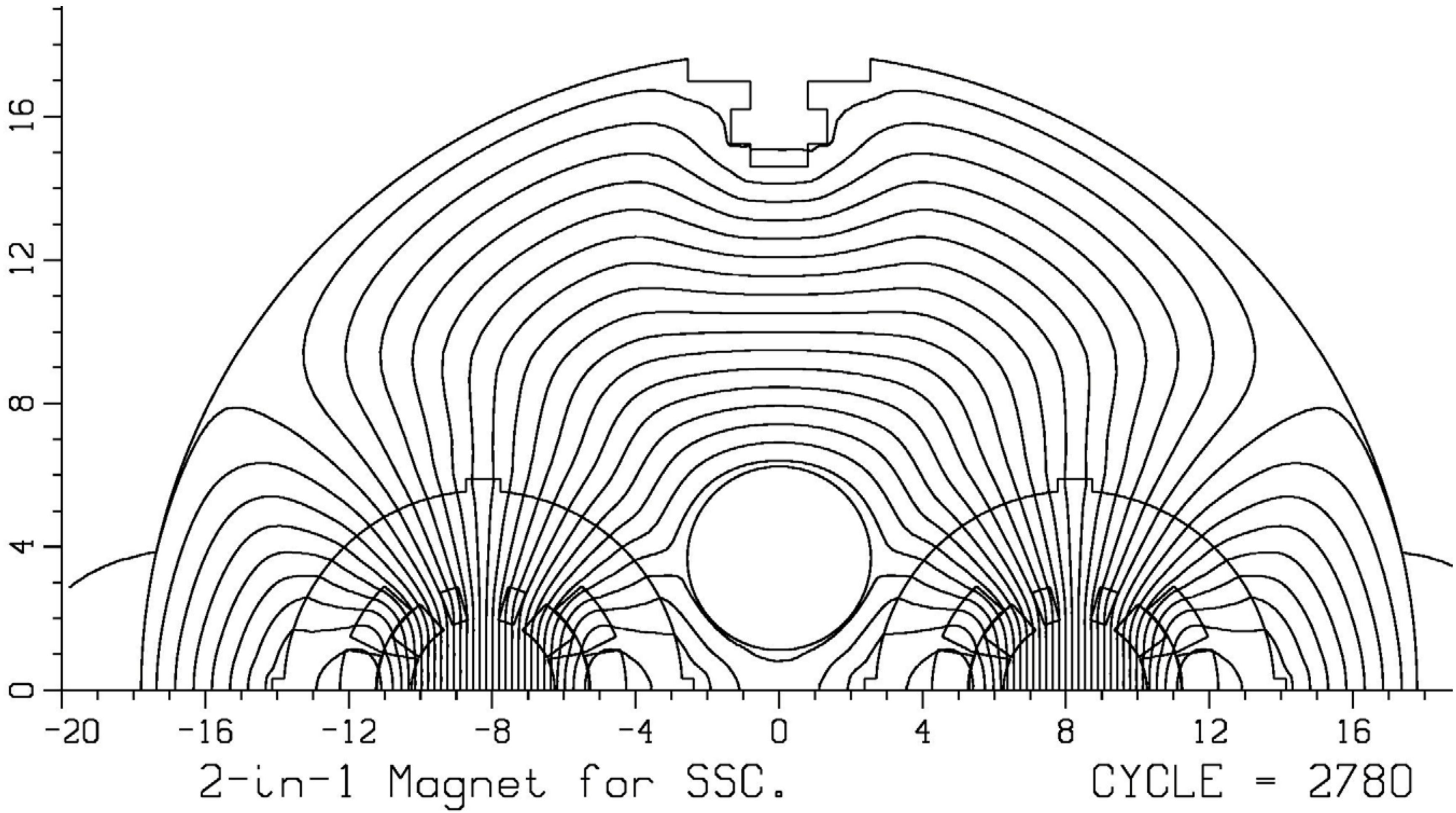


Correlation between the yoke weight asymmetry and the saturation-induced a1.

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

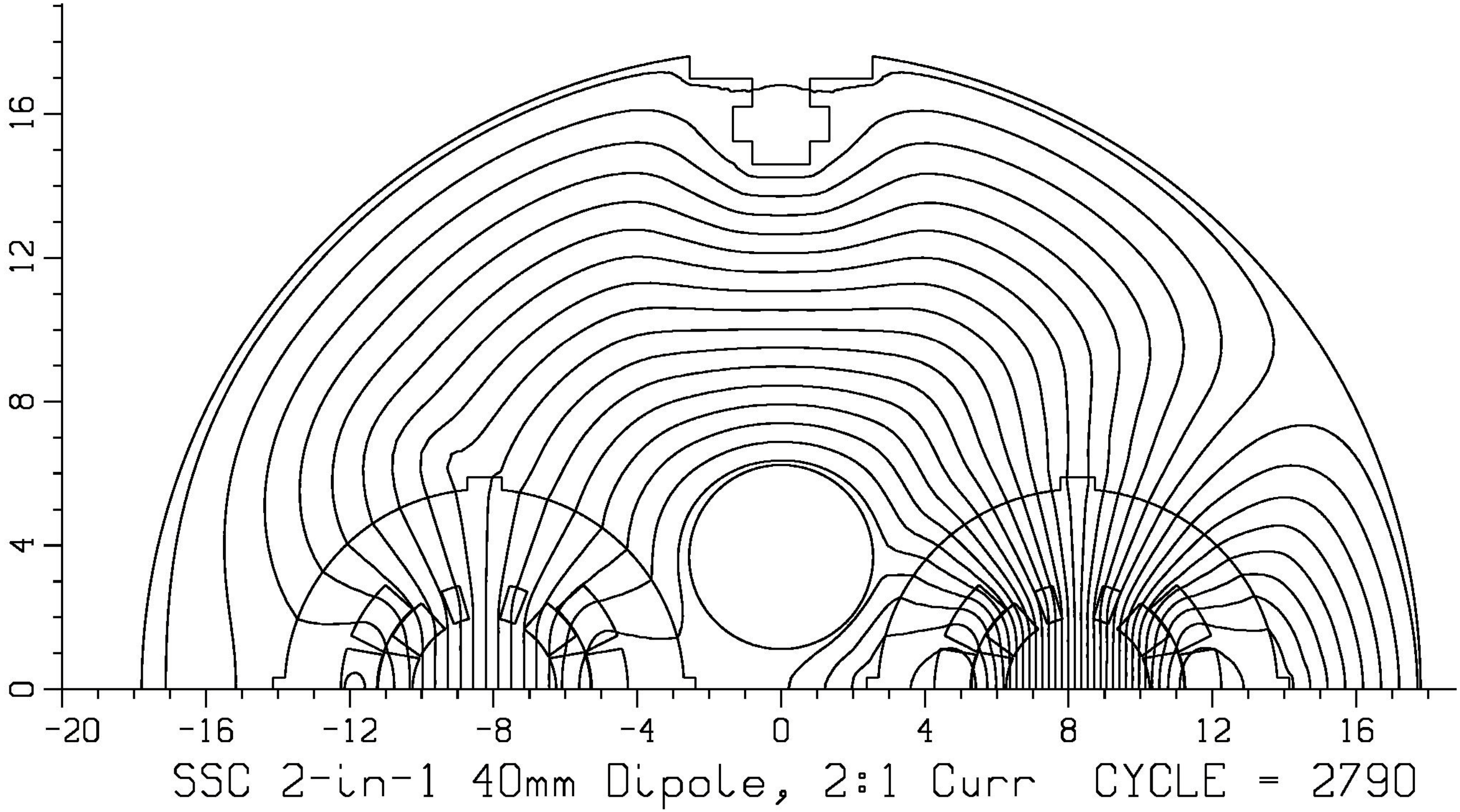


Field lines in SSC 2-in Dipole
(both aperture are excited at 6.6 T)



What field harmonics are allowed in this geometry?
At low fields and at high fields?

Field lines in SSC 2-in Dipole
(two aperture are excited in 2:1 ratio)



What field harmonics are allowed in this geometry?

At low fields and at high fields?

Three magnets with similar apertures Tevatron, HERA and RHIC

Tevatron Dipole (76.2 mm bore)

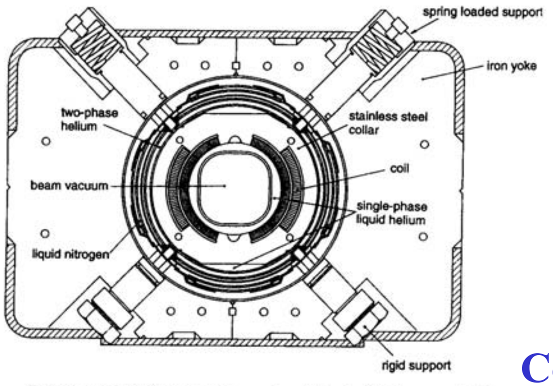
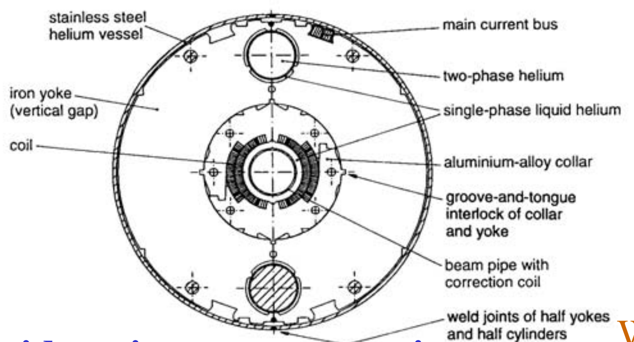
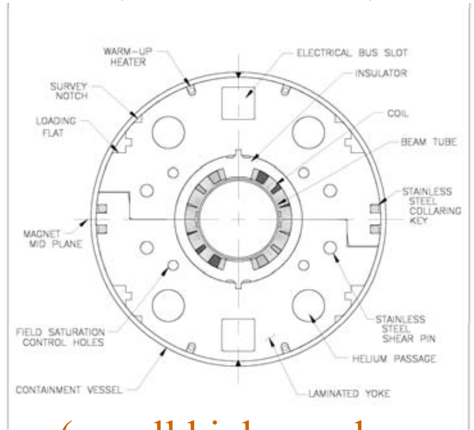


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

HERA Dipole (75 mm bore)



RHIC Dipole (80 mm bore)



Consideration on systematic errors

No Wedges (large higher order systematic harmonics expected). S.S. Collars - Iron away from coil (small saturation expected).

Wedges (small higher order harmonics expected). Al Collars - Iron away from coil (small saturation expected).

Wedges (small higher order harmonics expected). Thin RX630 spacers to reduce cost - Iron close to coil (large saturation from conventional thinking. **But reality opposite: made small with design improvements**).

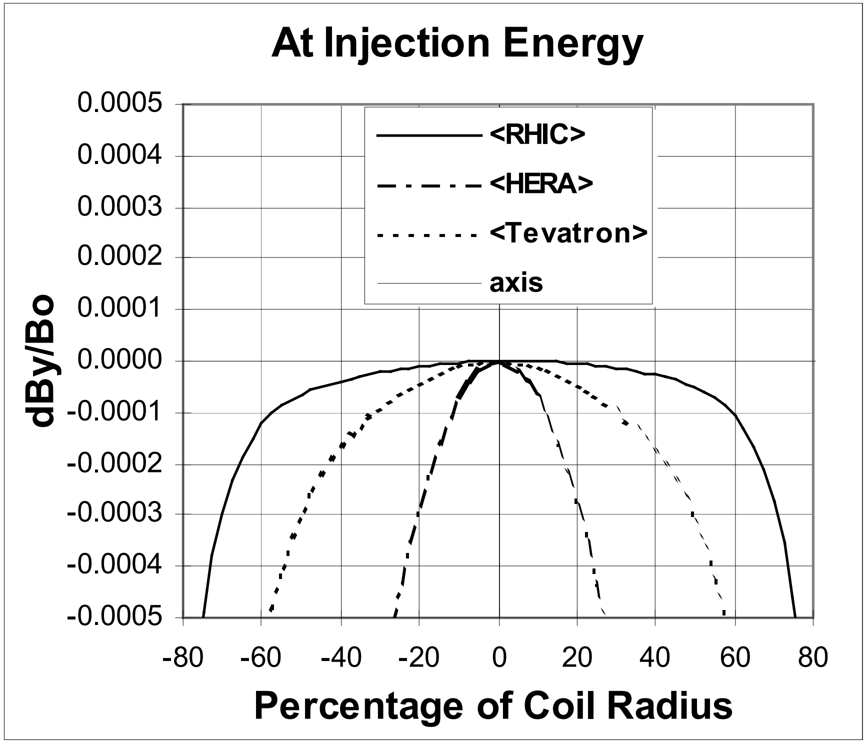
Collars used in Tevatron and HERA dipoles have smaller part-to-part dimensional variation (RMS variation ~10 μ) as compared to RX630 spacers (RMS variation ~50 μ) used in RHIC dipoles.

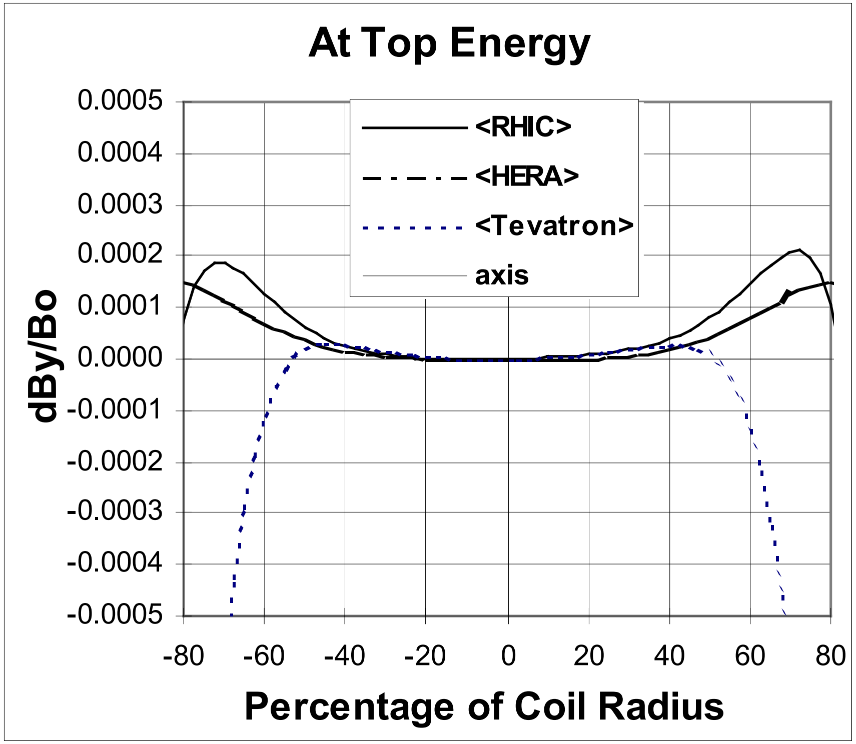
Conventional thinking : RHIC dipoles will have larger RMS errors. But in reality, it was opposite.

Why? The answer changes the way we look at the impact of mechanical errors on field quality !

Average Field Errors on X-axis

COIL ID : RHIC 80 mm, HERA 75 mm, Tevatron 76.2 mm





- Warm-Cold correlation have been used in estimating cold harmonics in RHIC dipoles (~20% measured cold and rest warm).
- Harmonics b_1-b_{10} have been used in computing above curves.
- In Tevatron higher order harmonics dominate, in HERA persistent currents at injection. RHIC dipoles have small errors over entire range.

SUMMARY: Yoke Optimization

- The yoke iron used in accelerating magnets to bring fringe field outside the magnet to an acceptable limit. In almost all cases, this is the most cost effective method.

- The iron yoke also gives an additional contribution to field. The contribution can be increased by bringing iron closer to the coil.

- A close-in iron would increase the iron saturation. However, a number of techniques have been demonstrated that the yoke can be forced to saturate uniformly and makes the saturation-induced harmonics small.

Therefore, one can now take the benefit of a good enhancement in field from the close-in iron, without sacrificing the field quality due to bad saturation induced harmonics due to non-linear yoke saturation.