Lecture IV

Magnetic Design
Coil Optimization

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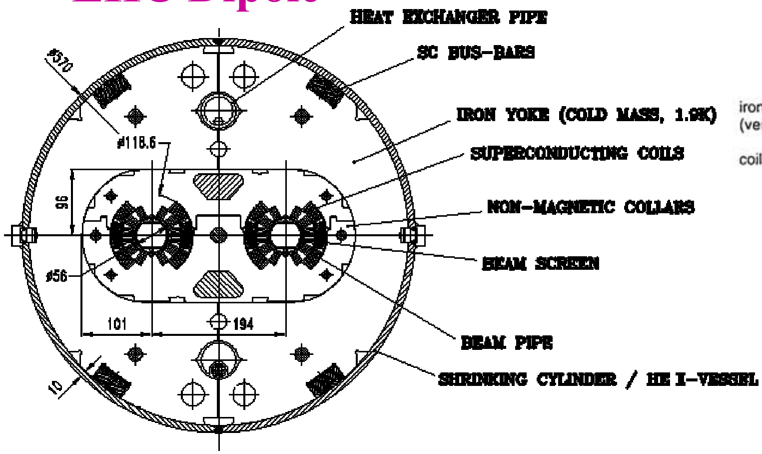
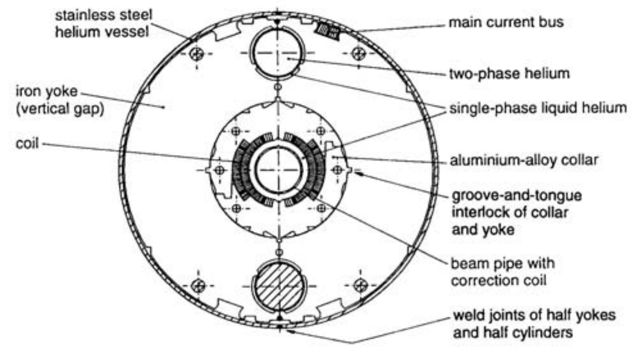
Coil Designs for Real Magnets

LHC Dipole

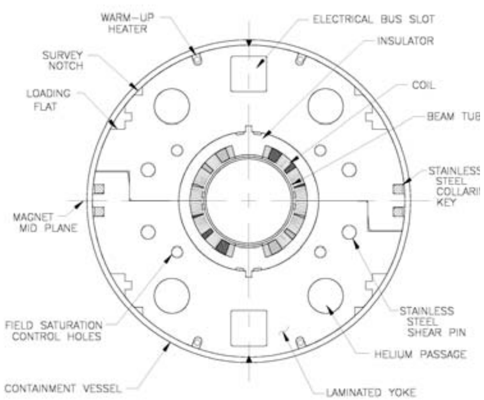


HERA Dipole



- **All magnets use NbTi Superconductor**
- **All designs use cosine theta coil geometry**

RHIC Dipole



Tevatron Dipole

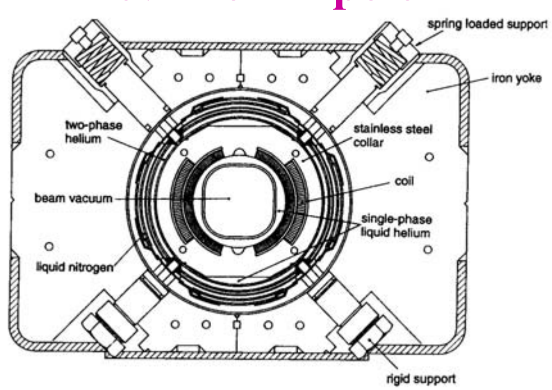


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

Do they really look like an ideal cosine theta current distribution?

Or that matter, even an elliptical geometry for conductor having a constant current density?

Coil Cross-section Optimization (1)

The optimization of a coil cross-section for a good magnetic design involves:

- Minimizing field harmonics
- Maximizing field and maximizing efficiency (field/turn)
- Minimizing Peak Field (Max. field on the conductor for given central field)

At first, it appears to be fairly straight forward process, thanks, in part, to the modern automated codes like ROXIE and PAR2DOPT, etc.,

In fact, one can build a magnet based on the optimized coil structure obtained by a relatively new user.

Coil Cross-section Optimization (2)

But the advanced cross-section optimization is a bit more involved:

- One must avoid designs that create mechanical difficulties
- One should look for flexibility to allow future adjustments
- Also look for special requirements in each application.

"One approach fits all", may not always be a good strategy.

My Experience:

• The initial design, quite often sets the eventual performance of the magnet, difficulties in manufacturing the magnet, etc.

• As compared to building magnets, the design process takes relatively few resources. Spend a reasonable time in looking for as many cases or options as possible despite the pressure of delivering a final design "yesterday".

• It is useful to automate the process so that one can examine many variations.

Field Harmonic Definitions

The field quality in magnets is expressed in terms of the normal and skew harmonic coefficients, b_n and a_n by the following expansion:

$$B_y + iB_x = 10^{-4} \times B_R \sum_{n=1}^{\infty} (b_n + ia_n)[(x+iy)/R]^{n-1}$$

where x and y are the horizontal and vertical coordinates, B_R is the field strength of the primary harmonics at the "reference radius" R. The values of the field harmonic are given in the units of 10^{-4}.

The definition used above (European convention) differs from that used in many U.S. publications (US convention), where $n-1$ is replaced by n and the summation starts from $n = 0$.

Note: US definition will be used while discussing earlier designs.

Field and Harmonics From A Radial Current Block (No Iron Present)

Consider a "*Radial Block*" between radii ρ_1 & ρ_2 and angle ϕ_1 & ϕ_2 having a current density of *J*. The total current (*I*) and harmonics (A_n, B_n) are given by:

$$I = \frac{1}{2} J (\rho_2^2 - \rho_1^2)(\phi_2 - \phi_1)$$

n = 1 refers to dipole.

R_o is the reference radius.

$$A_1 = -\frac{\mu_o J}{2\pi}(\rho_2 - \rho_1)\left[cos\,(\phi_2) - cos\,(\phi_1)\right],$$

$$A_2 = -\frac{\mu_o J R_o}{2\pi} ln\left(\frac{\rho_2}{\rho_1}\right)\left[cos\,(2\phi_2) - cos\,(2\phi_1)\right],$$

for $n \geq 3$

$$A_n = \frac{\mu_o J}{2\pi}\frac{R_o^{n-1}}{n\,(n-2)}\left(\frac{1}{\rho_2^{n-2}} - \frac{1}{\rho_1^{n-2}}\right)\left[cos\,(n\phi_2) - cos\,(n\phi_1)\right]$$

$$B_1 = -\frac{\mu_o J}{2\pi}(\rho_2 - \rho_1)\left[sin\,(\phi_2) - sin\,(\phi_1)\right],$$

$$B_2 = -\frac{\mu_o J R_o}{2\pi} ln\left(\frac{\rho_2}{\rho_1}\right)\left[sin\,(2\phi_2) - sin\,(2\phi_1)\right],$$

for $n \geq 3$

$$B_n = \frac{\mu_o J}{2\pi}\sum_{n=3}^{\infty}\frac{R_o^{n-1}}{n\,(n-2)}\left(\frac{1}{\rho_2^{n-2}} - \frac{1}{\rho_1^{n-2}}\right)\left[sin\,(n\phi_2) - sin\,(n\phi_1)\right]$$

See supplementary notes for these and other derivations.

Homework Assignment (one block)

Assume that a current block is between radii 10 cm and 12 cm and it starts at an angle $\Phi = 0$.

Find the subtended angle (or the angle at which the block must end) for

- The normal sextupole harmonic to be zero. Is it a unique solution?
- Assume that you have dipole symmetry. How many other blocks must be present to generate this symmetry (give number and angles).
- Compute the values of the first three non-zero allowed harmonics in Tesla (A_n and/or B_n) at a reference radius of 6 cm.
- Do the above for the decapole harmonic to be zero. Is it a unique solution?
- Can you find a solution for which both sextupole and decapole harmonics are zero? The block does not have to start from an angle $\Phi = 0$.

What happens if it is in a cylindrical iron cavity having a permeability of (a) 10, (b) 100 and (c) 1000.

Hint: You can use the method of images.

Additional assignment: Make OPERA2d or POISSON model to study above.

Homework Assignment (two blocks)

Assume that there are two current blocks. First between radii 10 cm and 11 cm and second between 11 cm and 12 cm. Both start at an angle $\Phi = 0$.

Find the subtended angle (the angle at which block must end) for the normal sextupole harmonic and decapole harmonics to be zero.

Is it a unique solution?

What happens if it is in a cylindrical iron cavity having a permeability of

(a) 10

(b) 100 and

(b) 1,000.

Hint: You can use the method of images.

<u>Additional assignment</u>: Make OPERA2d or POISSON model to study above.

How to Look for Optimal X-sections (1)

1. Look for designs that look similar to cosine theta distribution (experience)

2. Use special techniques/software to find good designs (artificial intelligence)

3. Cover a large range of combinations and find the best

My recommendation, go for the 3rd option (several thousand cases):

> It does not take long to look a large number of possibilities - less than a few seconds per case if the peak field is not computed.

- **To save time compute peak field only in promising solutions.**

How to Look for Optimal X-sections (2)

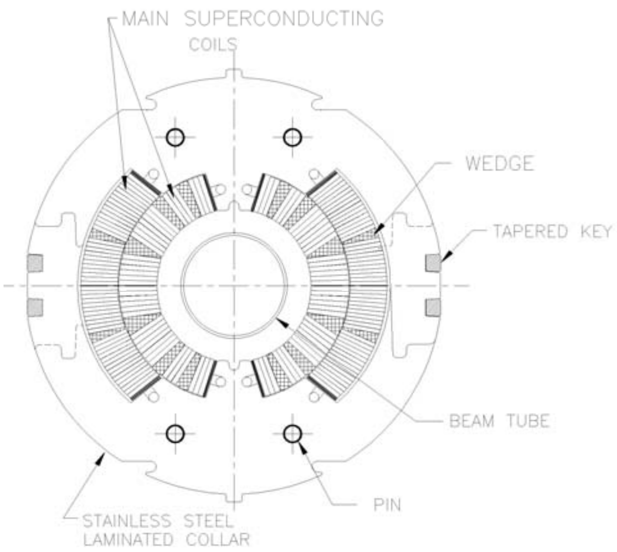
Develop a front-end program to automatically create several cases for a series optimization run.

In this optimization:

- **Vary number of blocks and number of turn in those blocks.**
- **Vary starting condition of wedges, etc.**

Post-process results to select a limited number of cases with filters for harmonics, etc.

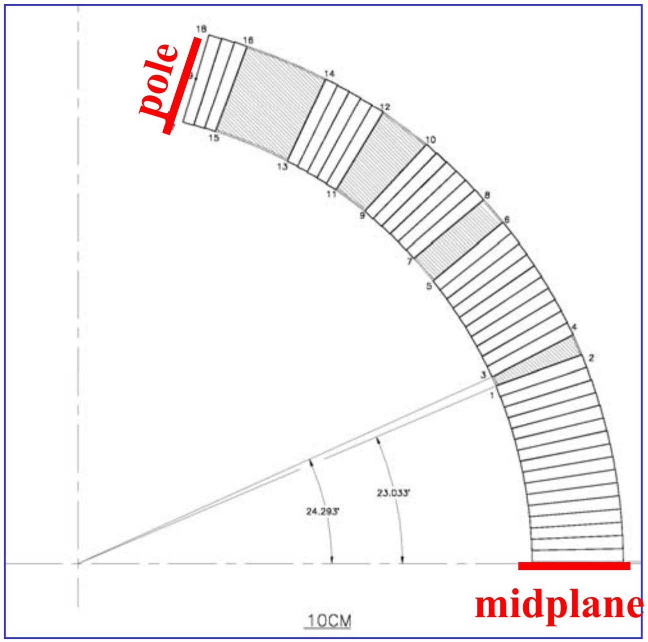
- **Compute peak field for these selected cases.**

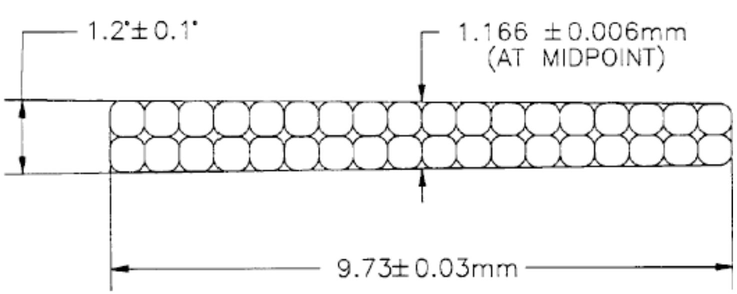


Go back and carefully evaluate and further optimize these few cases for performance, mechanical layout, flexibility, sensitivity, and/or any other requirement.

An Example of Pre-processor for Generating Cases for a Series Run

A D07GEN Run






```
       1 N1          19.00000    0.         1.         30.
 enter min,max number of turns for blk [and increament in FOR017]
13  21  2
       3 N2          16.00000    0.         1.         30.
 enter min,max number of turns for blk [and increament in FOR017]
12 18 3
       5 N3          13.00000    0.         1.          4.
 enter min,max number of turns for blk [and increament in FOR017]
10 14 1
       7 N4            10.0        0.0        0.          4.
 enter min,max number of turns for blk [and increament in FOR017]
8 12 1
       9 N5           6.00000    0.         1.          4.
 enter min,max number of turns for blk [and increament in FOR017]
3  8 1
      11 N5            4.0        0.0        0.          4.
 enter min,max number of turns for blk [and increament in FOR017]
2  6 1
 -------------------------------------------------------
 YOU HAVE SPECIFED # cases=       47250
  Enter start cycle, end cycle [<cr> for all]
10001  20000
 Base design has total turns =          68
 ENTER min,max number of total turns
67 69
 Do you wish a constraint on a subtotal?
 eg total number of turns for inner layer-- (yes/[NO])
y
 Enter First, Last blocks to be included in sum
1  3
 ENTER lower,upper limits of sum
20  40
```

An Example of Post-processor for Selecting Cases

A PARSLCT Run

```
BNLADA>ty LANL-73TX1D.PARSLCT;
 LANL quad ***SELECT CASES***                 10-DEC-01 11:18:39    BNLADA$DKA200:[GUPTA.LANL]LANL-73TX1D.D04;1
# WMP    BLOCKS      RIN      ROUT   Current  Thickness  KEYSTONE  AzInsul     <-----   Cable Information
1 4.0     11.        18.2165   19.3845    1.         53.0       3.2     3.45
Turns  Chisq   T.F.  Pole    b2    b4   b6    b8    b10   b12    W1     W2     W3     W4     W5  CASE  ENHin  BssInf
JKDA56 0.720  0.337 43.00  -0.05  0.03 -0.85  0.00  0.00  0.00  0.469  2.185  0.764  9.297  0.303 301  26.598 24.93
JKDC45 0.951  0.341 43.00  -0.06 -0.13 -0.96  0.00  0.00  0.00  0.399  1.368  2.439  8.276  0.533 305  25.430 25.78
JKDC54 0.451  0.342 42.99  -0.13 -0.12 -0.65  0.00  0.00  0.00  0.309  1.542  2.103  8.304  0.755 306  24.999 26.10
JKDC63 0.579  0.342 42.97  -0.07 -0.17 -0.74  0.00  0.00  0.00  0.300  1.514  2.084  8.372  0.721 307  24.740 26.28
JOAA46 0.447  0.339 43.00   0.08 -0.03 -0.66  0.00  0.00  0.00  0.493  2.666  0.324  8.964  0.572 346  25.952 25.40
JOAA55 0.570  0.339 42.99   0.00  0.09 -0.75  0.00  0.00  0.00  0.499  2.622  0.413  9.046  0.429 347  25.924 25.42
JOAA73 0.641  0.339 43.00   0.05  0.04 -0.80  0.00  0.00  0.00  0.476  2.623  0.325  9.126  0.468 349  25.554 25.67
JOAC44 0.698  0.343 42.92   0.01  0.02 -0.83  0.00  0.00  0.00  0.387  1.691  2.273  8.287  0.303 350  24.896 26.20
 100 cases examined.  8 cases selected for: CHISQ< 5.0000 TF> 0.300 POLE<85.00; |bn|< 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
A=10 B=11 C=12 D=13 E=14 F=15 G=16 H=17 I=18 J=19 K=20 L=21 M=22 N=23 O=24 P=25 Q=26 R=27 S=28 T=29 U=30 V=31 W=32 X=33 Y=34 Z=35
FILEname =          BNLADA$DKA200:[GUPTA.LANL]LANL-73TX1D.D04;1
```

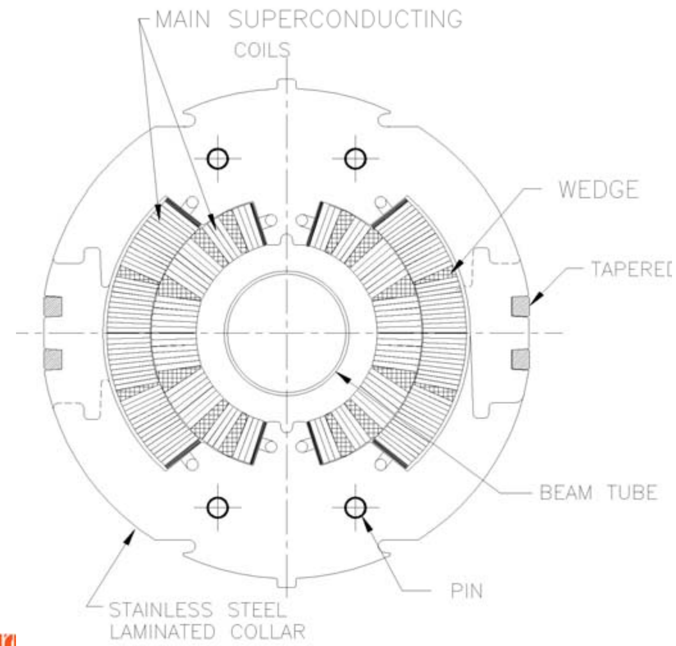
Influence of Coil Parameters in the SSC 50 mm Aperture Dipole

Note the order of magnitude of change in harmonics due to a 25 micron change in dimension.

Table 4.3.1: The effect of a +25μm change in a wedge thickness or pole width on the transfer function and the field harmonics in the SSC 50 mm aperture dipole magnet. The field harmonics are calculated with a 10 mm reference radius. The numbering of the wedges is counter-clockwise from the midplane. The pole width is measured from the vertical axis.

(coil radius = 25 mm, reference radius = 10 mm)

Parameter changed	δTF $10^{-4}\frac{T}{kA}$	δb_2 10^{-4}	δb_4 10^{-4}	δb_6 10^{-4}
Wedge No. 1	-0.78	-0.24	0.01	0.005
Wedge No. 2	0.42	0.30	0.03	-0.005
Wedge No. 3	1.16	0.36	-0.02	0.00
Wedge No. 4	-0.29	-0.06	0.00	0.00
Pole Width (inner)	2.0	0.23	-0.03	0.005
Pole Width (outer)	1.13	0.21	0.00	0.000



Wedge No. 4 is in outer layer.

Influence of Coil Parameters in the RHIC 80 mm Aperture Dipole

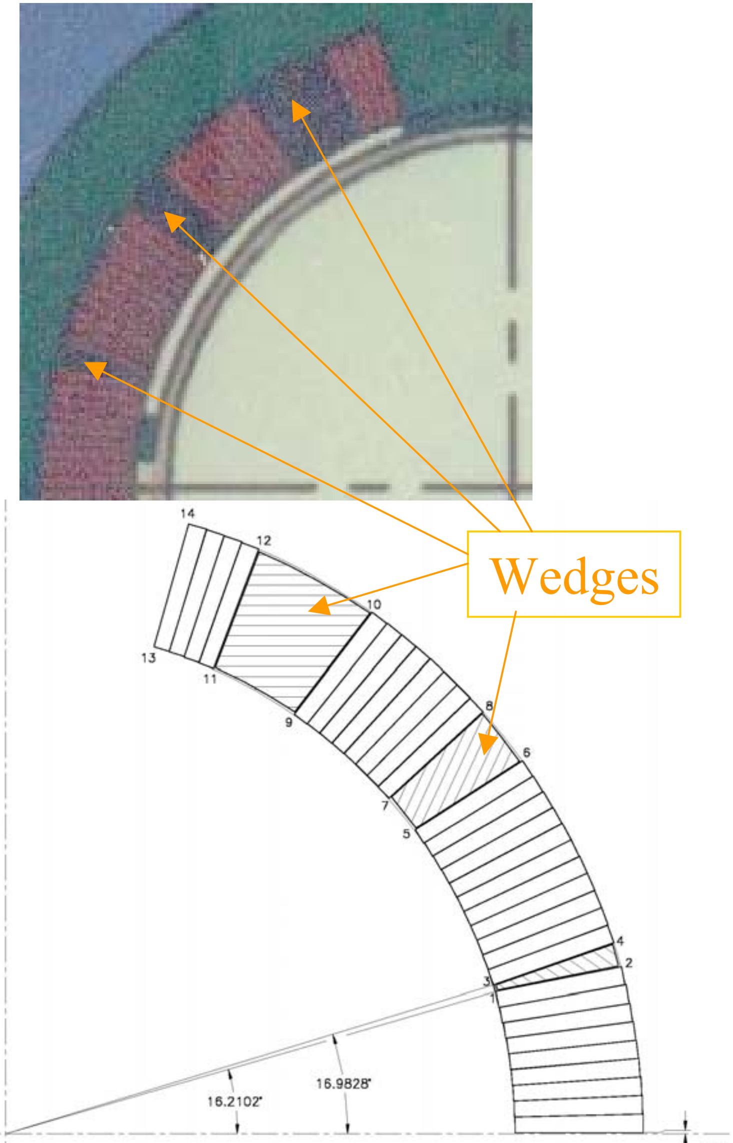


Table 4.3.2: The computed change in the transfer function and field harmonics produced by a $+25\mu m$ (0.001″) change in the wedge thickness, pole width or midplane gap in the RHIC 80 mm aperture arc dipoles. The field harmonics are calculated with a 25 mm reference radius. The numbering of the wedges starts at the midplane. The pole width and midplane gap are measured from the vertical and horizontal axis, respectively.

(coil radius = 40 mm, reference radius = 25 mm)

Parameter changed	δTF $10^{-4}\frac{T}{kA}$	δb_2 10^{-4}	δb_4 10^{-4}	δb_6 10^{-4}	δb_8 10^{-4}
Wedge 1	-0.6	-0.98	-0.122	0.061	0.043
Wedge 2	0.1	0.69	0.423	0.022	-0.050
Wedge 3	1.1	1.42	-0.090	-0.068	0.041
Pole Width	1.7	1.11	-0.154	0.039	-0.014
Midplane Gap	-0.9	-1.68	-0.557	-0.156	-0.050

Notice that the magnitude of change in harmonics due to a 25 μ*m* change, is much larger in RHIC dipole than in SSC dipoles.

WHY?

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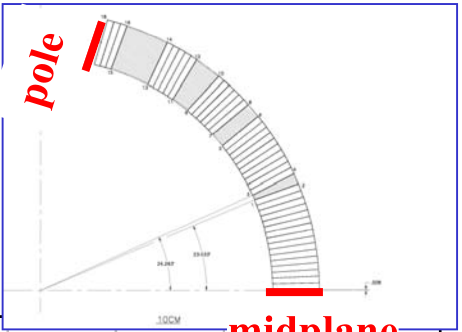
Change in Harmonics for 0.1 mm Change in Dimension in D0 Dipole



RHIC Insertion Dipole D0 with single layer coil

Coil inner radius = 100 mm,

Harmonic reference radius = 65 mm

"D0 MAGNET" : Rough Cross section Optimization Spread sheet

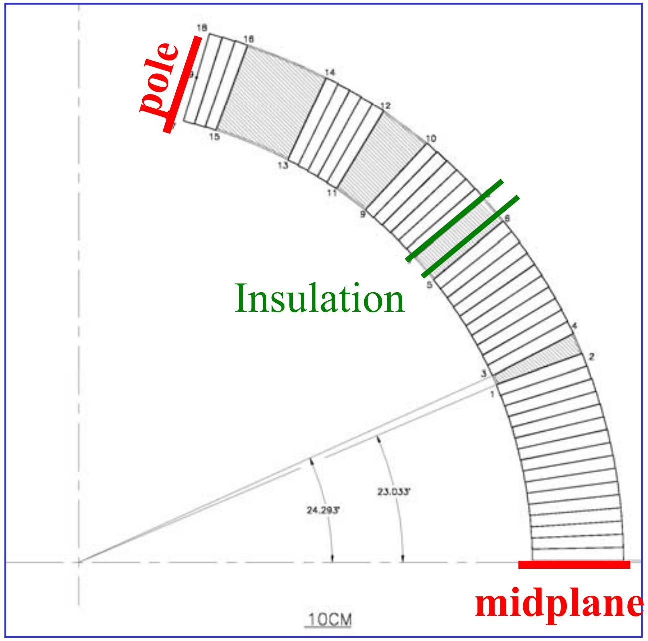
To iterate cross section for b2 & b4 with midplane and pole shims and fixed wedge changes, go to line b65:b72

Expected Parameters of the Iterated Design						b2	b4	b6	b8	b10	b12	b14	b16
Coil Prestress	1	mil from the target.		Expected Harmonic		6.23	2.24	0.54	0.240	-0.012	0.132	-0.047	-0.099
Coil Size						db2	db4	db6	db8	db10	db12	db14	db16
Target Increase	5	in Coil size	Mutliply	Change(mil)	Target b2n	-8.00	-2.30	-0.16	-0.15	0.016	-0.15	0.039	0.096
Total Increase	6	mil in compression				-1.77	-0.06	0.38	0.09	0.00	-0.02	-0.01	0.00
Midplane(mil)	1	Fixed Pole	0.25	4	-0.00333	-5.79	-1.85	-0.48	-0.16	-0.06	-0.02	-0.01	0.00
PoleShim(mil)	1	Decrease Pole	0.25	4	0.006	3.98	-0.53	0.09	-0.05	0.01	0.00	0.01	0.00
Wedge1(mil)	4	Fixed Pole	1	4	-0.0012	-1.32	0.53	0.48	0.14	0.02	-0.01	-0.01	0.00
Wedge2(mil)	0	Fixed Pole	0	4	0.00119	3.05	1.28	-0.06	-0.16	-0.01	0.02	0.01	0.00
Wedge3(mil)	0	Fixed Pole	0	4	0.00314	4.80	0.30	-0.37	0.02	0.03	-0.01	0.00	0.00
Wedge4(mil)	0	Fixed Pole	0	4	0.00508	4.89	-0.65	-0.01	0.04	-0.04	0.01	0.00	0.00
Midplane+4mil	0	Increase Pole	0	4	-0.0097	-9.76	-1.31	-0.57	-0.11	-0.07	-0.02	-0.02	0.00
Wedge1+4mil	0	Increase Pole	0	4	-0.00758	-5.28	1.06	0.389	0.187	0.006	-0.006	-0.013	0
Wedge2+4mil	0	Increase Pole	0	4	-0.0052	-0.91	1.81	-0.155	-0.117	-0.018	0.025	-0.002	0
Wedge3+4mil	0	Increase Pole	0	4	-0.00323	0.83	0.82	-0.462	0.067	0.023	-0.004	-0.006	0.004
Wedge4+4mil	0	Increase Pole	0	4	-0.0013	4.07	-1.37	0.439	-0.127	0.174	-0.184	-0.057	0

A Flexible Design from the Beginning

Design Philosophy:

- Start out with a design 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 the first two allowed harmonics and pre-stress or cable insulation. This approach was used extensively in various RHIC magnets.

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

Change in Midplane Gap to Adjust Harmonics

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

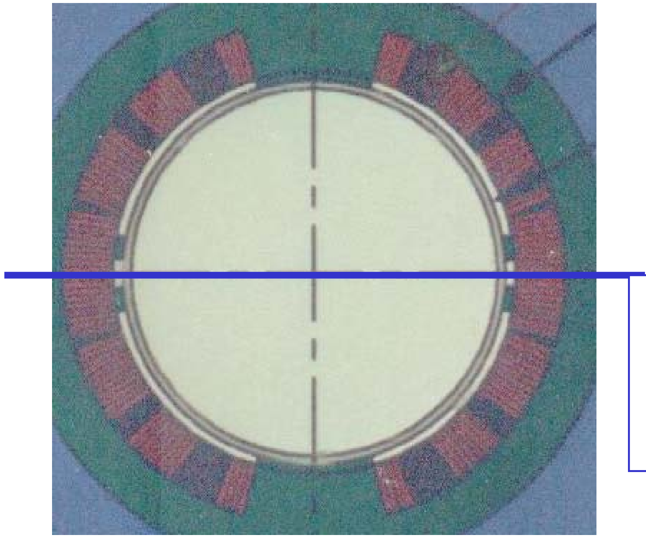


Table 4.4.1: The computed and measured change in field harmonics at 25 mm reference radius due to a change in the coil midplane gap. The midplane gap was increased from 0.114 mm to 0.16 mm in the rebuilt 80 mm aperture RHIC model dipole magnet DRS009. In the production magnets, the midplane gap was changed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

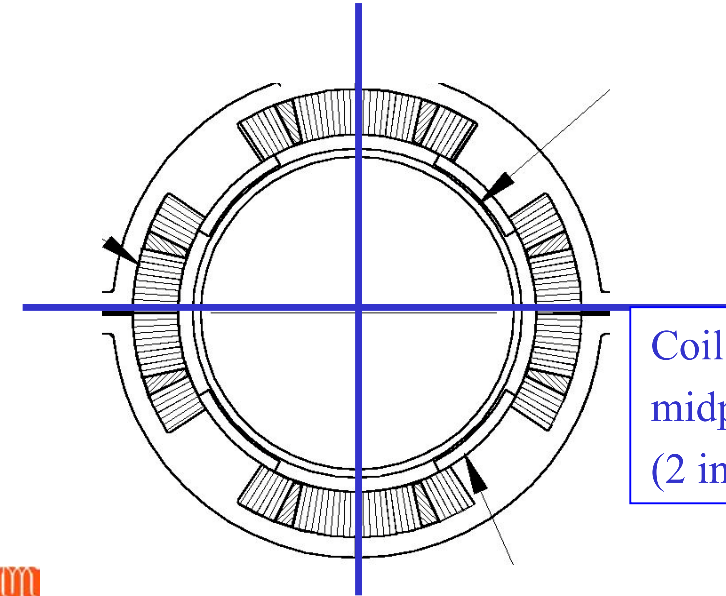


Table 4.5.1: The measured and computed change in field harmonics caused by an asymmetric increase in the coil-to-midplane gap in the prototype 130 mm aperture RHIC interaction quadrupole QRI002. The gap was increased by 0.1 mm in the horizontal plane only. The harmonics are given at a reference radius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

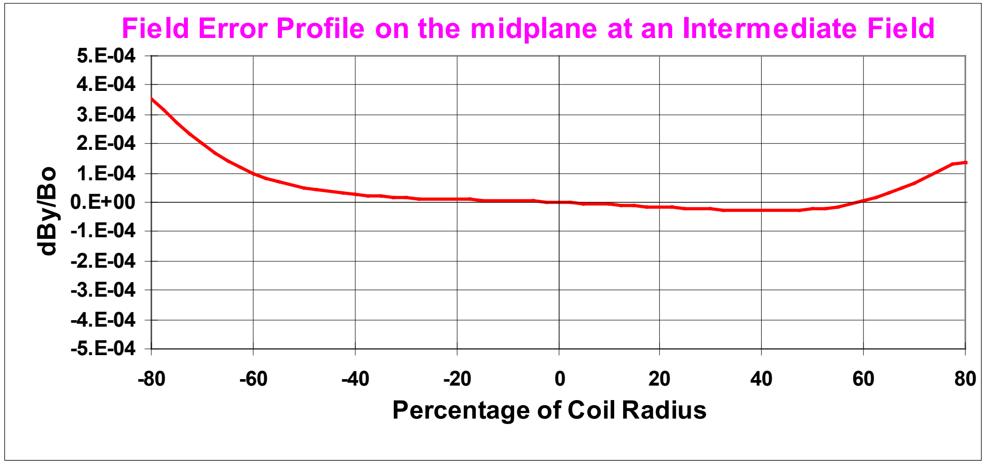
	Δb_3	Δb_5	Δb_7	Δb_9
Computed	-6.8	-1.3	-0.45	-0.16
Measured	-6.5	-1.2	-0.30	-0.17

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



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

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

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

Later magnets had adjustments for integral field and saturation control.

The coil cross-section never changed.

Average Field errors ~10^{-4} up to 80% of the coil radius

Note:

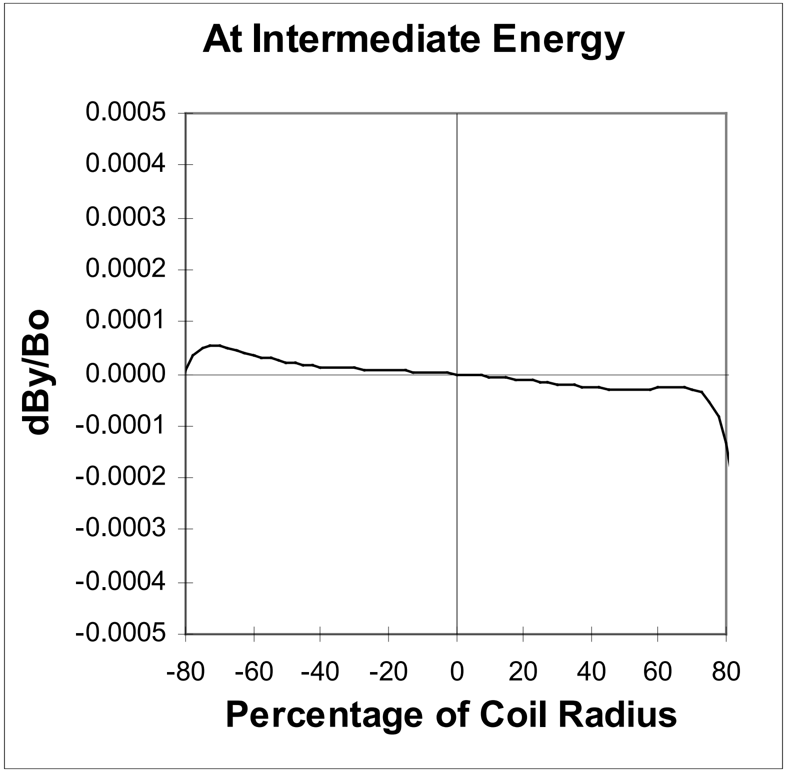
80% of coil radius, not just 2/3.

At 80%, you are close to inner radius of beam tube. This means that almost entire physical aperture has become a good field aperture.

Geometric Field Errors on the X-axis of RHIC DRZ magnets (108-125)

Coil X-section was not changed between 1st prototype and final production magnet

A Flexible & Experimental Design Approach Allowed Right Pre-stress & Right Harmonics



Estimated Integral Mean in Final Set

(Warm-cold correlation used in estimating)

Harmonics at 3kA (mostly geometric)

Reference radius is 31 mm (Coil 50 mm)

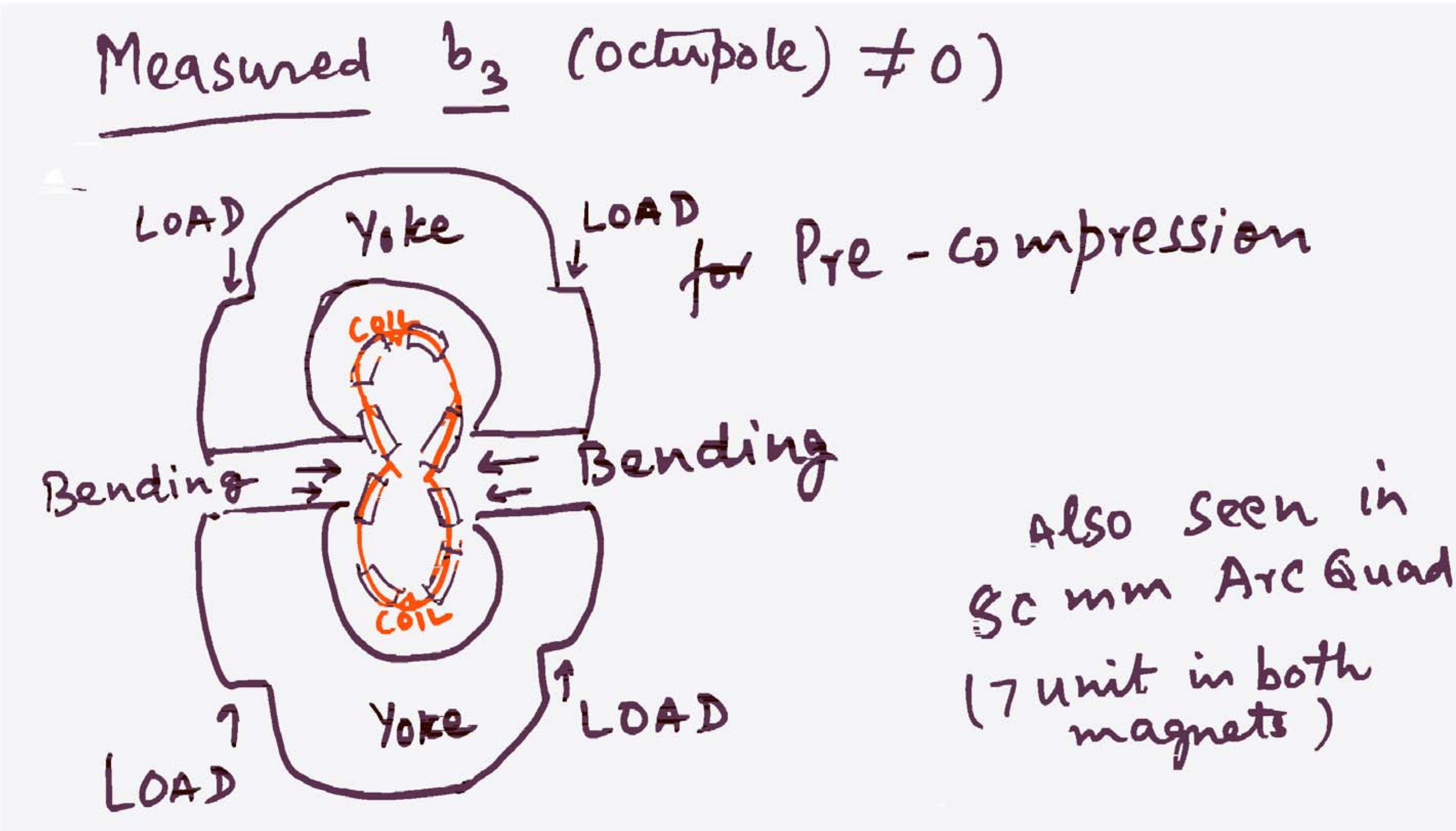
b1	-0.28	a1	-0.03
b2	-0.26	a2	-3.36
b3	-0.07	a3	0.03
b4	0.15	a4	0.48
b5	0.00	a5	0.04
b6	0.32	a6	-0.24
b7	0.00	a7	0.01
b8	-0.08	a8	0.05
b9	0.00	a9	0.00
b10	-0.12	a10	-0.02
b11	0.03	a11	-0.01
b12	0.16	a12	0.06
b13	-0.03	a13	0.03
b14	-0.10	a14	0.02

**Raw Data Provided by Animesh Jain at BNL*

Field errors are 10^{-4} to 80% of the aperture at midplane.

(Extrapolation used in going from 34 mm to 40 mm; reliability decreases)

Octupole in Quadrupoles When Quad Assembled Like Dipoles



A Simple Method For Removing Octupole From Quad

BASIC Problem

(a) Trying to assemble quad like dipole

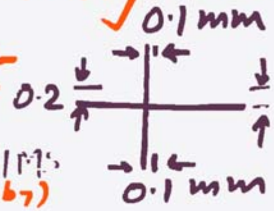
or

(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 for a change)

2. Create delibrate asymmtry in coil to compensate for that



→ Easy, Tested and Worked

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

Type this slide.

Give actual values of midplane gaps (shims) with pictures indicating what was used where.

Minimization of Non-allowed Harmonics

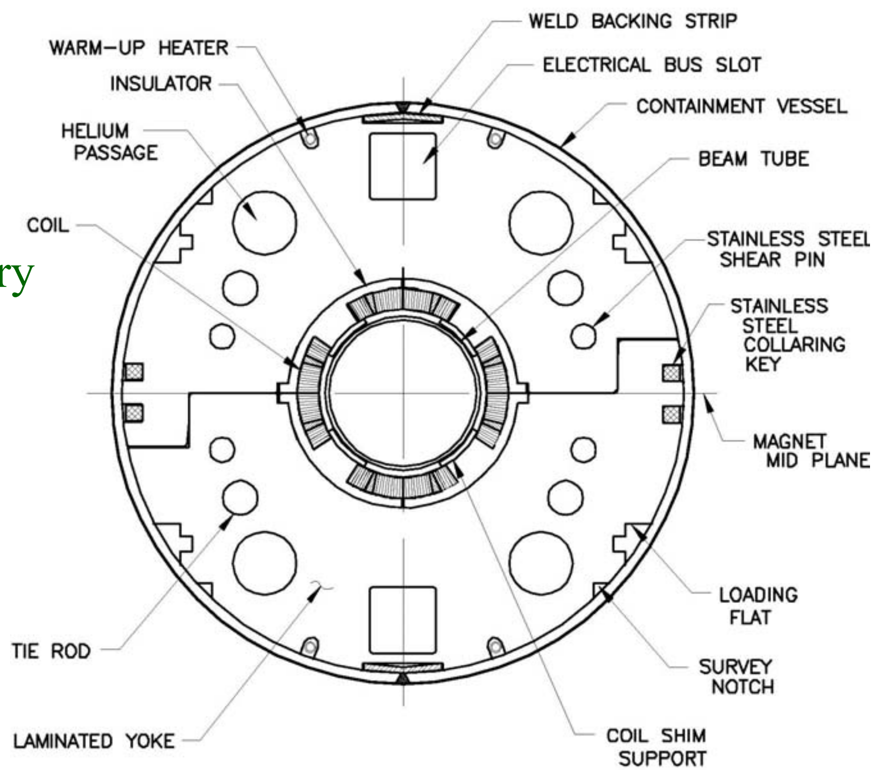
Non-allowed harmonics are those that are not allowed by basic symmetry.

In quadrupoles, the allowed harmonics are b1, b5, b9, b13, etc.

- For cost reasons, RHIC quadrupoles are assembled like dipole (i.e. with 2-fold symmetry rather than 4-fold).
- Also note that pole notch is only at two places instead of four, as required by quad symmetry.

Both of above generate octupole (b3) and other higher order harmonics (b7, b13, …) that are not allowed in an ideal quad. The magnitude of octupole generated by the first source is several units, whereas the magnitude generated by the second source is a few tenth.

RHIC ARC QUADRUPOLE



A deliberately designed asymmetry in the coil midplane gaps (gap between coils at the vertical plane vs. gap at the horizontal plane) cancels the octupole from the above sources.

Optimization/Calculations of Other Quantities

- Minimization of field harmonics is the primary and the most time consuming task of optimizing a coil geometry.
- However, the overall coil design requires calculations and optimization of several other quantities.

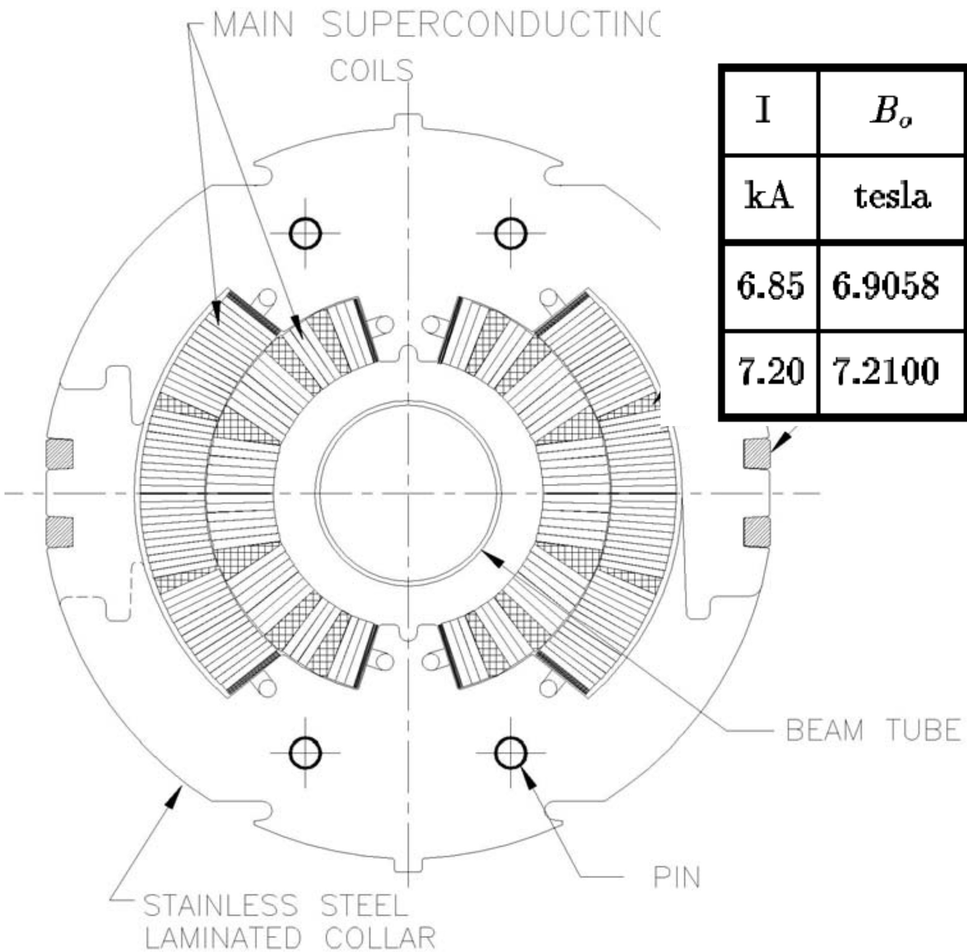
They will be explained in the next few slides.

- The peak field is the maximum field on the superconducting coil, whereas the field enhancement ratio is the peak field on the coil as compared to the field at the magnet center at the same current.
- One major concern is the minimization of this enhancement ratio.
- Magnet performance is limited by the maximum field on the superconductor and the useful field is determined by the field at the magnet center for that peak field on the coil at a given current.

Computed Peak Fields in SSC Dipoles

Table 6.2.6: Peak fields in the SSC 50 mm dipole as computed using code MDP.

I	B_o	Inner			Outer		
kA	tesla	B_{pk},T	$\frac{B_{pk}}{B_o}$	Location	B_{pk},T	$\frac{B_{pk}}{B_o}$	Location
6.85	6.9058	7.2374	1.048	5%	6.0016	0.869	11%
7.20	7.2100	7.5595	1.048	5%	6.2660	0.869	11%



Computed Performance of SSC Dipole

Table 6.2.7: Expected quench performance of the SSC 50 mm dipole with 5% cable degradation ($J_c = 2612.5 A/mm^2$) and at 4.35 K temperature. S_{quench} is the computed current density in the copper at quench and $S_{6.7T}$ at the design field of 6.7 Tesla.

Layer ↓	Cu/Sc Ratio	B_{ss} tesla	I_c A	B_{margin} %over 6.7T	T_{margin} kelvin	S_{quench} A/cm^2	$S_{6.7T}$ A/cm^2
Inner	1.7	7.149	7126	6.7	0.519	736	681
	1.5	7.273	7273	8.6	0.625	788	715
	1.3	7.399	7411	10.4	0.730	853	759
Outer	2.0	7.268	7267	8.7	0.580	919	834
	1.8	7.445	7470	11.1	0.709	980	865

the magnet will quench at the design central field (B_{design}=6.7 tesla). The field margin is defined as follows

$$B_{margin}\,(\%) = \frac{B_{ss} - B_{design}}{B_{design}} \times 100$$

Error in Parts and Influence in Field Harmonics on SSC Dipole

Table 6.2.8: The effect of a 0.05 mm increase in the given parameter on the transfer function and the field harmonics.

Parameter changed	TF T/kA	b_2 10^{-4}	b_4 10^{-4}	b_6 10^{-4}
Radius of Block No. 1	0.31	-0.25	-0.10	-0.01
Radius of Block No. 2	-0.32	0.31	0.12	0.01
Radius of Block No. 3	-0.12	0.36	-0.02	-0.01
Radius of Block No. 4	-0.20	0.33	-0.08	0.01
Radius of Block No. 5	-0.11	-0.04	-0.01	0.00
Radius of Block No. 6	-0.78	0.22	0.03	0.00
RMS Blocks	0.38	0.27	0.07	0.01
Thickness of Wedge No. 1	-1.56	-0.48	0.02	0.01
Thickness of Wedge No. 2	0.83	0.59	0.05	-0.01
Thickness of Wedge No. 3	2.32	0.71	-0.04	0.00
Thickness of Wedge No. 4	-0.57	-0.11	0.00	0.00
RMS Wedges	1.48	0.52	0.03	0.01
Cable thickness inner	2.63	1.08	0.05	-0.01
Cable thickness outer	1.99	0.48	0.02	0.00
RMS Cable thickness	2.33	0.83	0.04	0.01
Pole angle inner	-4.01	-0.45	0.06	-0.01
Pole angle outer	-2.26	-0.42	0.00	0.00
RMS Pole angles	3.25	0.43	0.04	0.01

Stored Energy and Inductance Calculations

The stored energy and the inductance are related through the following formula :

$$Stored\ Energy = \tfrac{1}{2} Inductance \times (Current)^2.$$

The inductance decreases at high field as the iron yoke saturates.

The results of POISSON computations for the SSC 50 mm aperture dipole are given at 6.5 kA in Table 6.2.9 for the stored energy per unit length and the inductance per unit length. The total stored energy and the inductance for a 15 m long dipole are also given.

Table 6.2.9: Stored Energy and Inductance at 6.5 kA as computed with the code POISSON for the SSC 50 mm aperture dipole.

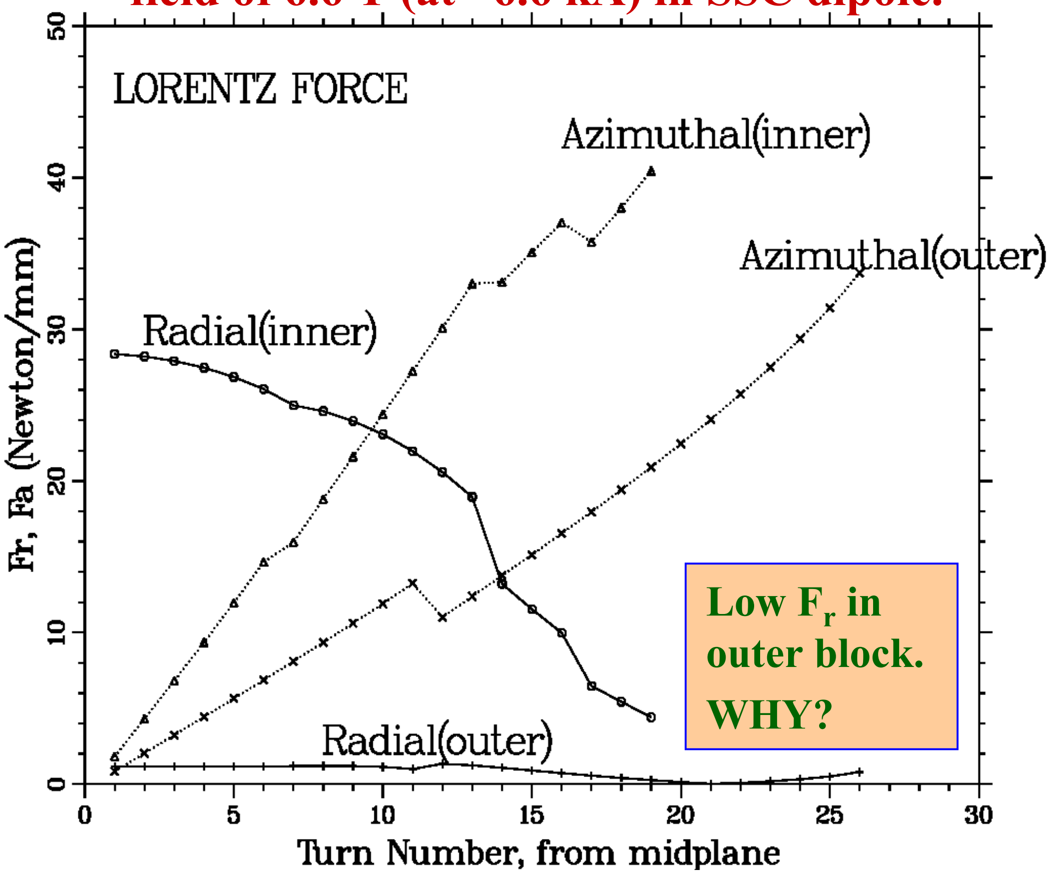
2-d Modeling programs compute stored energy. Don't forget to multiply by the program symmetry.

Stored Energy per unit length, kJ/m	105.0
Stored Energy for 15 m long Dipole, kJ	1575.6
Inductance per unit length, mH/m	4.972
Inductance for 15 m long Dipole, mH	74.585

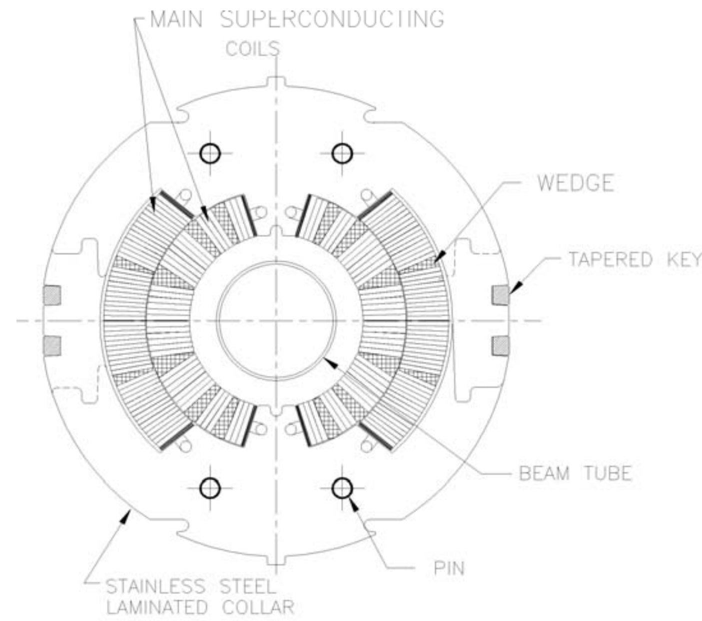
Lorentz Forces on the Individual Turns of the SSC Dipole

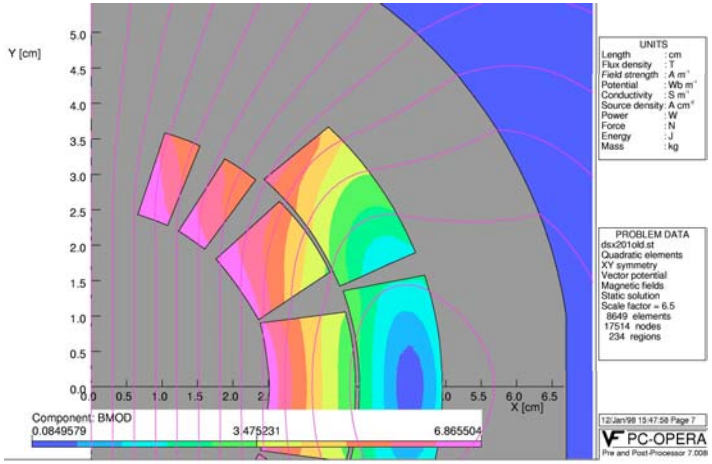
Figure 6.2.5: The magnitude of the components of the Lorentz force on the individual turns in a SSC 50 mm prototype magnet. The radial component of the force (F_r) pushes the coil outward and the azimuthal component (F_a) compresses the coil towards the midplane (horizontal plane). There are 19 turns in the inner layer and 26 turns in the outer layer of each quadrant.

Computed Lorentz forces at the design field of 6.6 T (at ~6.6 kA) in SSC dipole.



Low F_r in outer block. WHY?

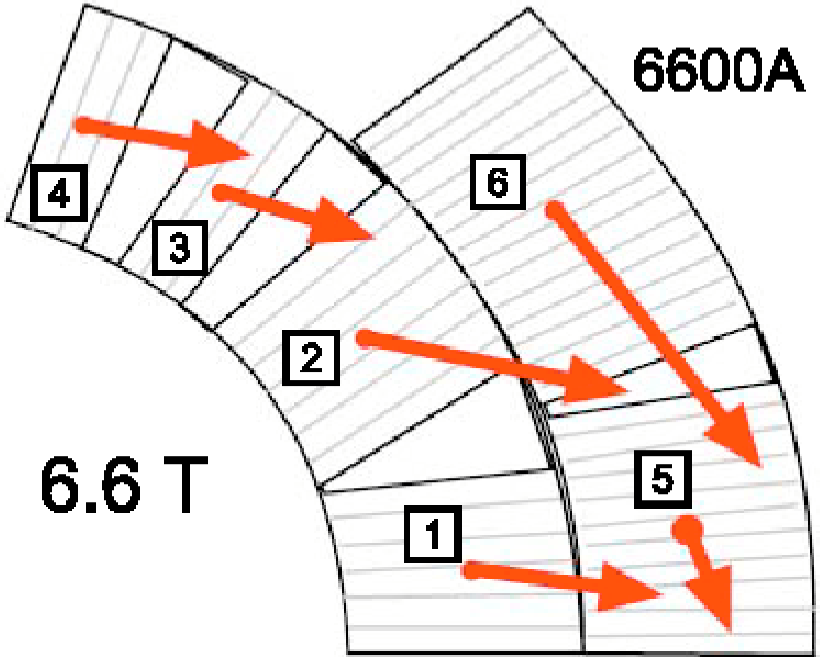




Forces in the Current Blocks of the SSC Dipole

The table summarizes the forces on the blocks in the example SSC dipole.

BLOCK	F_X, lb./in	F_Y, lb/in	F_X,N/m	F_Y,N/m
1	1005.46	-108.98	1.76E+05	-1.91E+04
2	1312.68	-237.56	2.30E+05	-4.16E+04
3	612.52	-151.97	1.07E+05	-2.66E+04
4	650.99	-116.62	1.14E+05	-2.04E+04
5	231.73	-384.60	4.06E+04	-6.74E+04
6	1208.86	-1371.22	2.12E+05	-2.40E+05
Total	5022.24	-2370.96	8.80E+05	-4.15E+05



Goals of End Design

Magnetic Design

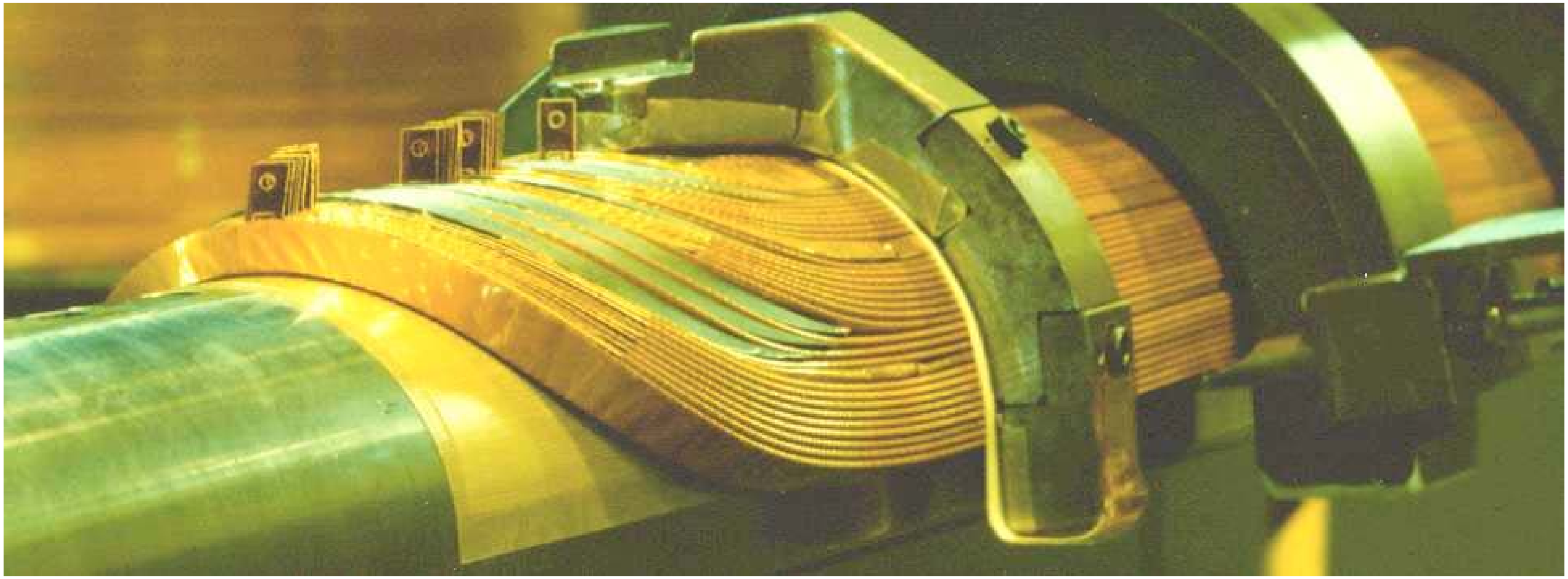
- Optimize for low integrated harmonics
- Guide design towards lower peak field without large increase in length
- Compute cross talk and fringe fields

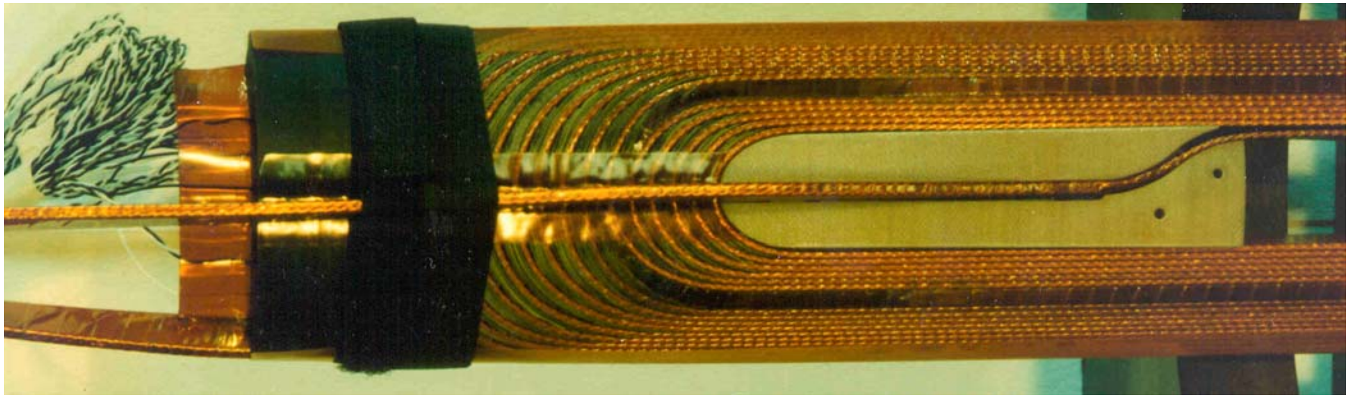
Mechanical Layout

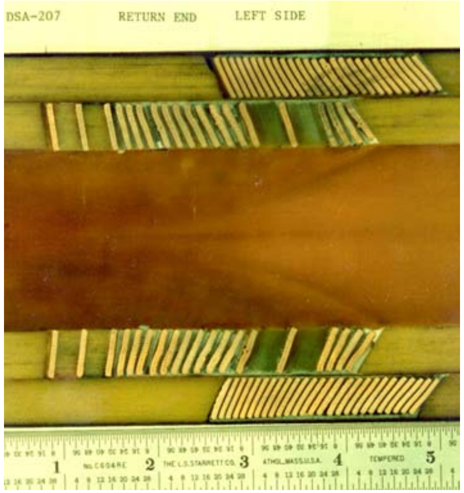
- Minimize strain and tilt of the cable in the end. Minimize large changes
- Cable and entire ends should be well supported (constrained)

In low field magnets, magnetic design drives the end design, whereas, in high field (high force) magnets, the mechanical design must!

Ends of Cosine Theta Cable Magnets



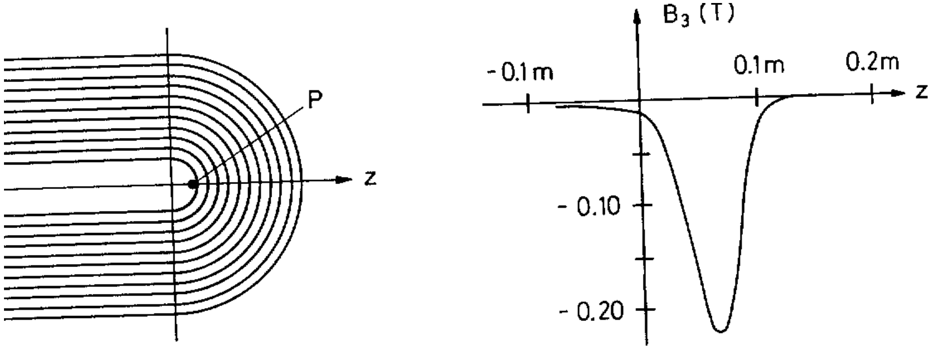




End Harmonic Optimization (conceptual)

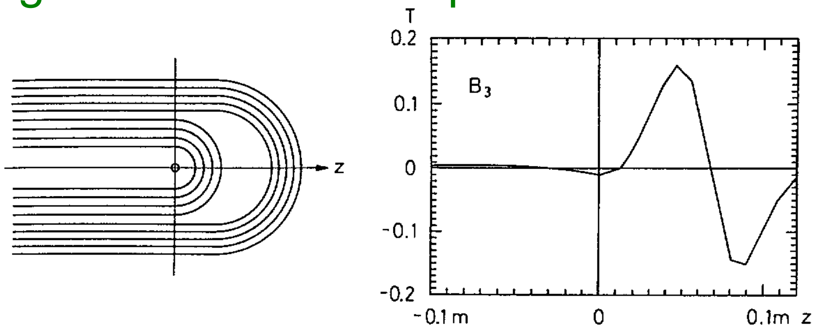
Ends without spacer

(large harmonics and peak field)



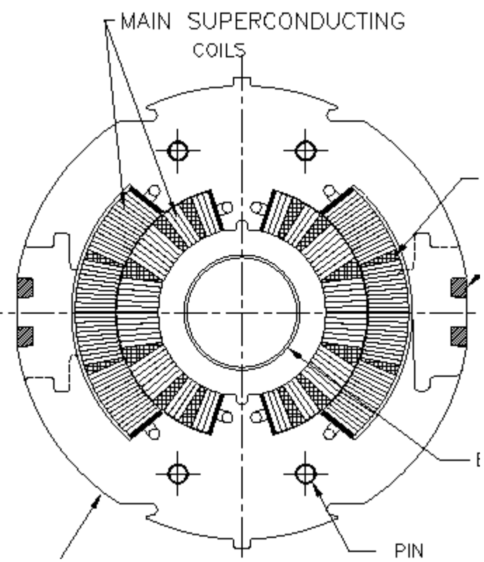
Ends with spacer

(integrated harmonics & peak field reduced)



a) Schematic view of HERA coil head with spacers

b) Computed sextupole field of HERA dipole



- End spacers increase the straight section length of some turns (turns at midplane go further out)
- Now consider the integral field generated by each turn. The harmonic component generated by a turn will depend on the angular location of it. The integral strength will depend on the length.
- A proper choice of end spacers can make integral end-harmonics small. However, note that the local values are large.
- Spacer also reduce the maximum value of field on the conductor (peak field) in the end.

Block Structure

Straight section (6 blocks, 70 turns):

30 20 10 4 3 3 (counting from midplane)

3 3 4 10 20 30 (counting from pole)

End section (8 blocks, 70 turns):

10 5 8 4 13 4 6 20

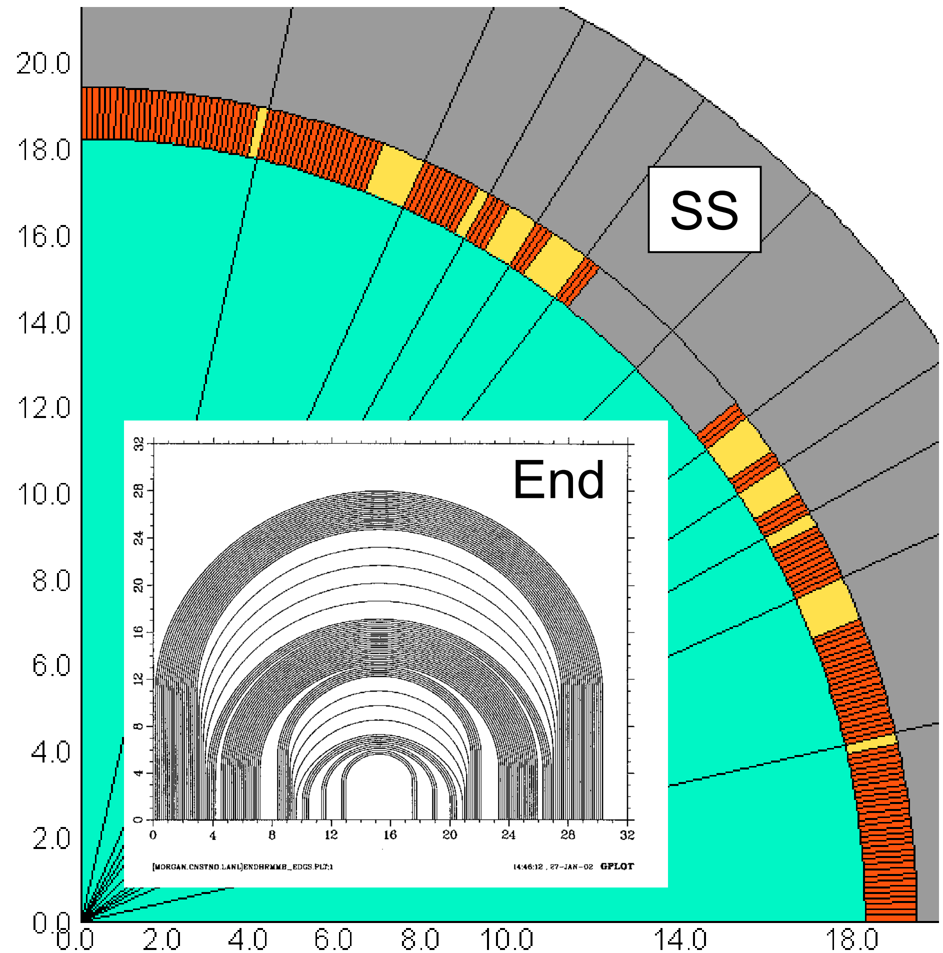
(counting from pole)

Straight section => pole

3,3,4 => 10

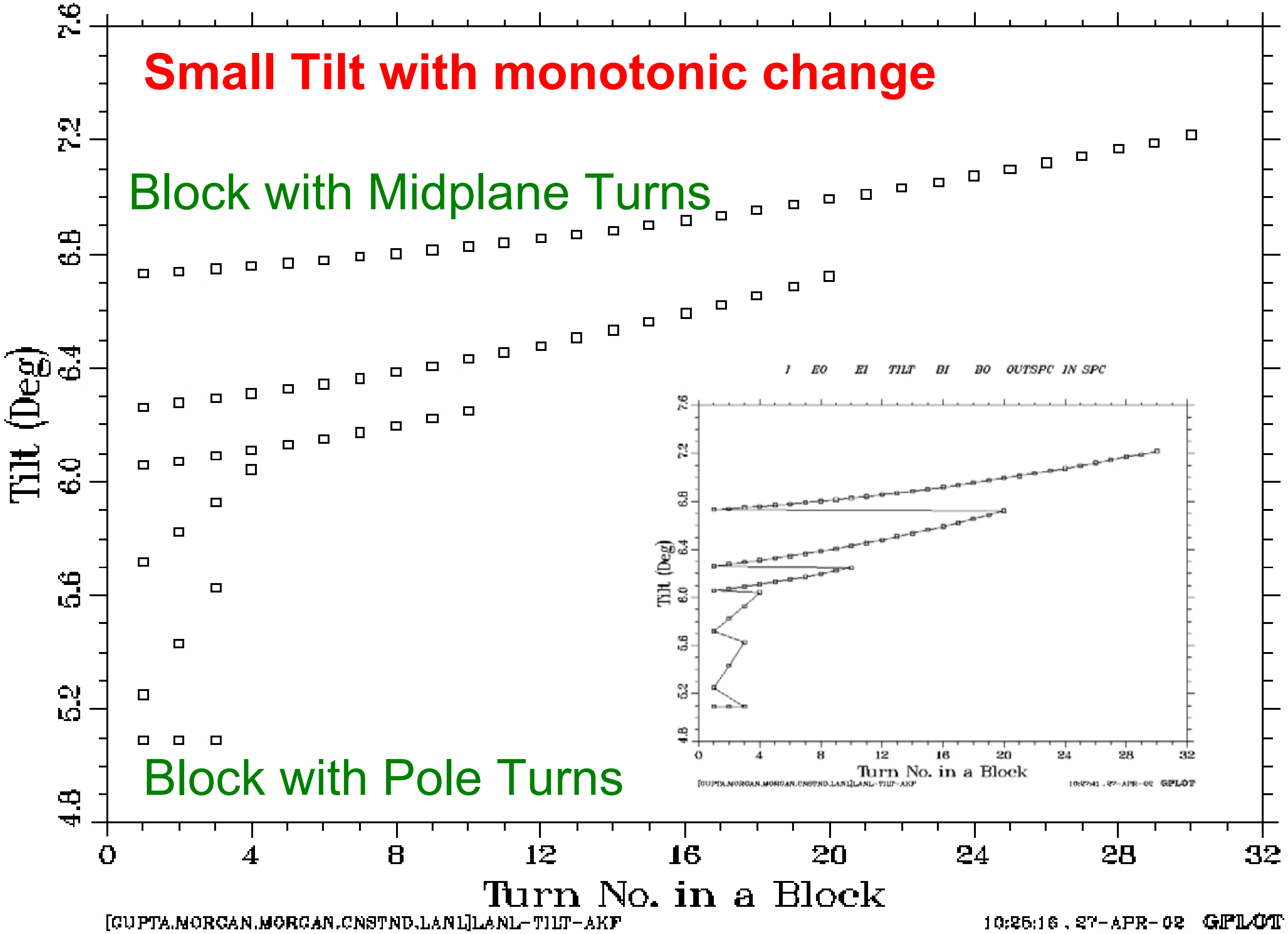
4,10, 20 => 5, 8, 4, 13

30 => 4, 6, 20



Equal spacing in "Red Color" blocks is used as harmonic optimization parameters

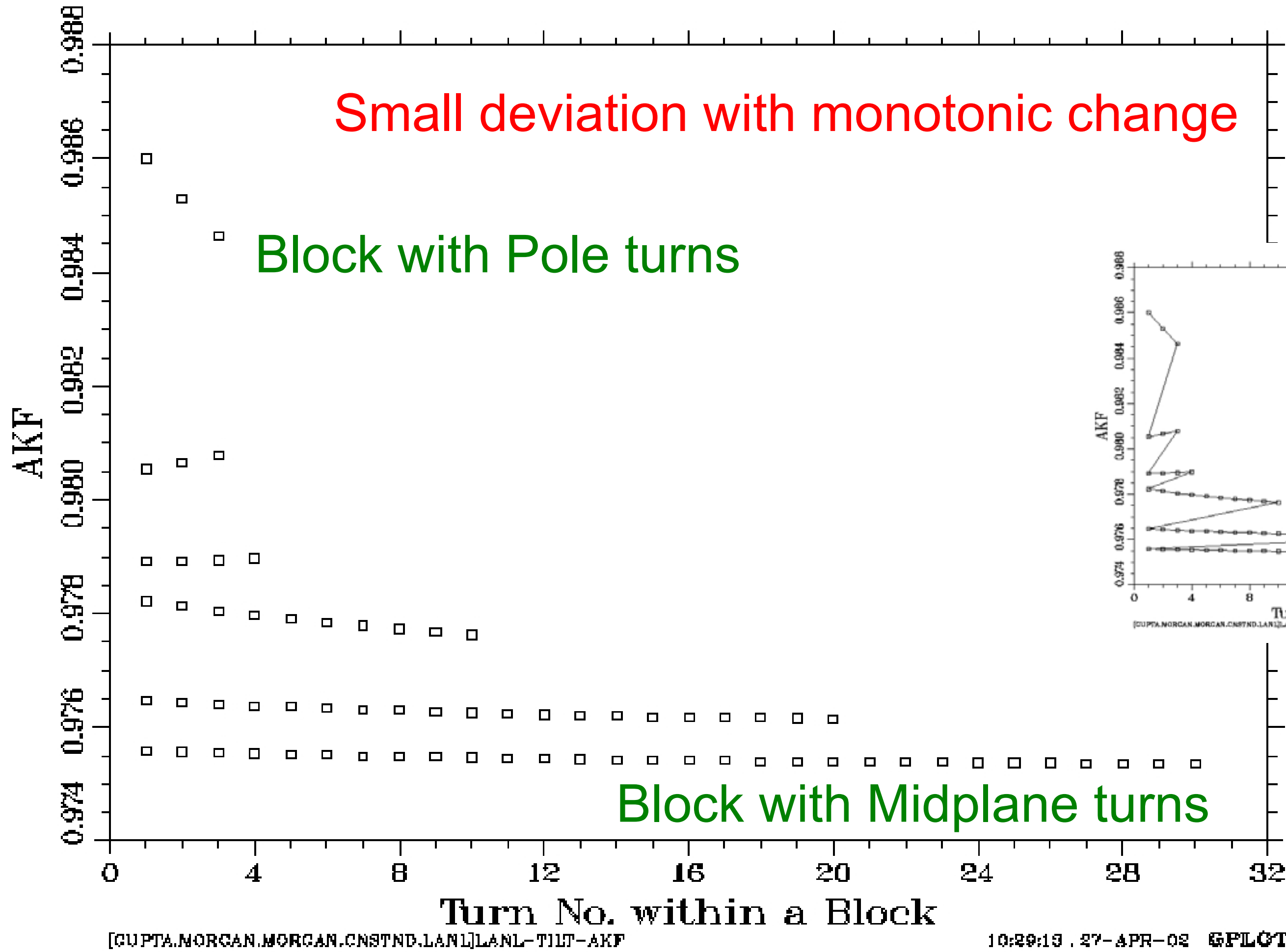
Tilt of Turns in Various End Blocks

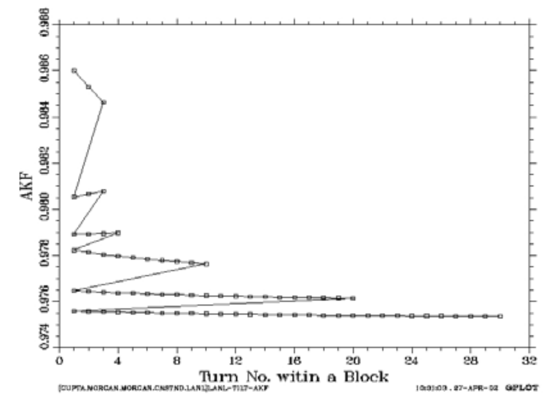


The AKF Parameter of Turns in Various End Blocks

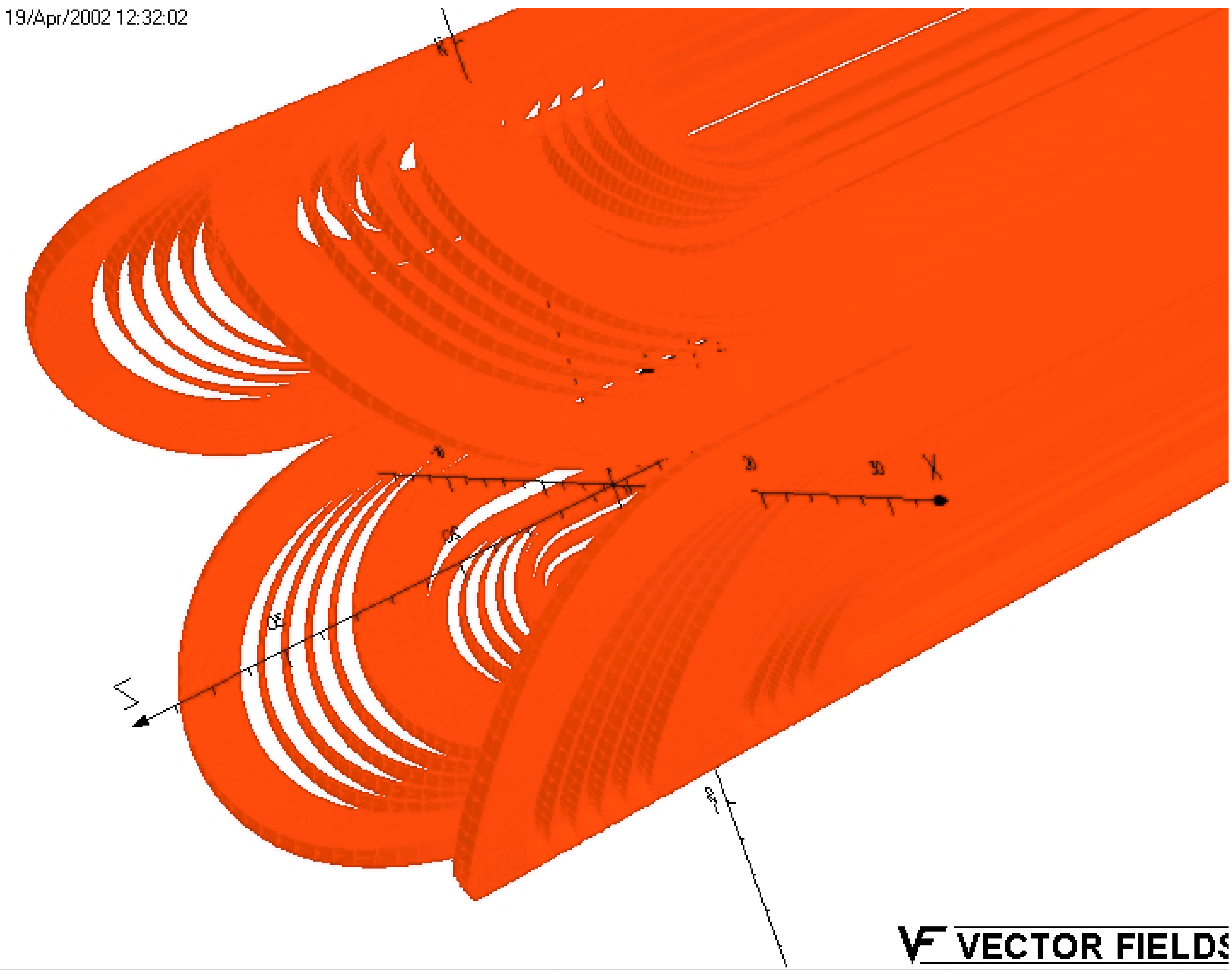
AKF indicates the deviation from constant perimeter (hence strain on the cable)

Large Deviation from 1.0 is bad





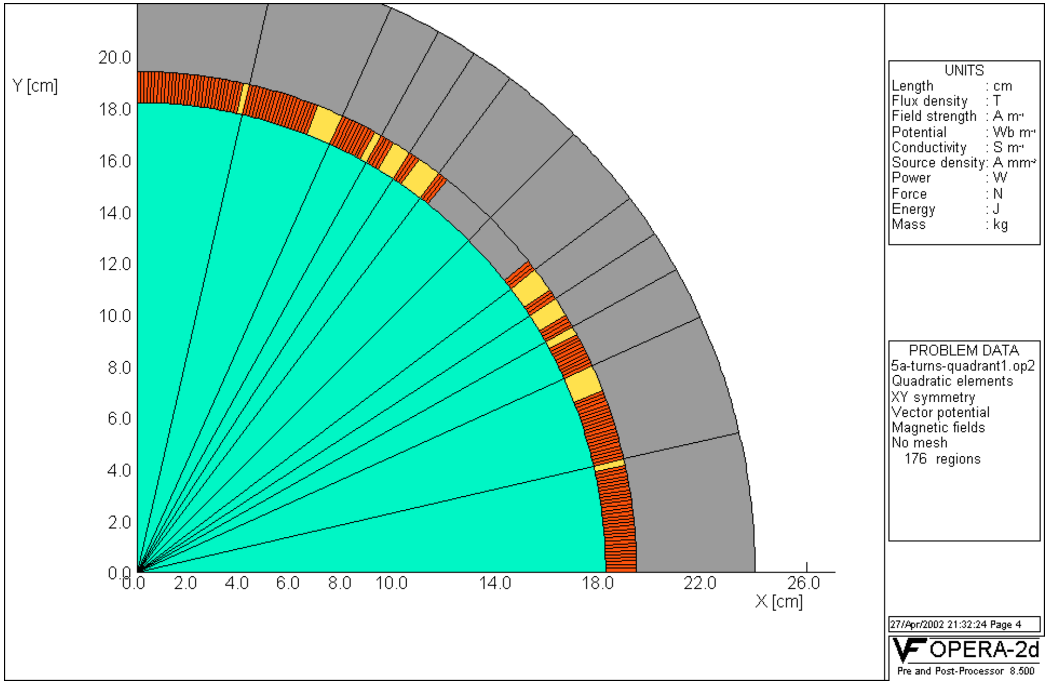
Coil End: Design A



Peak Field Minimization

A high peak field reduces the magnet quench performance.

➢ **A large effort must be undertaken in 2-d optimization.**



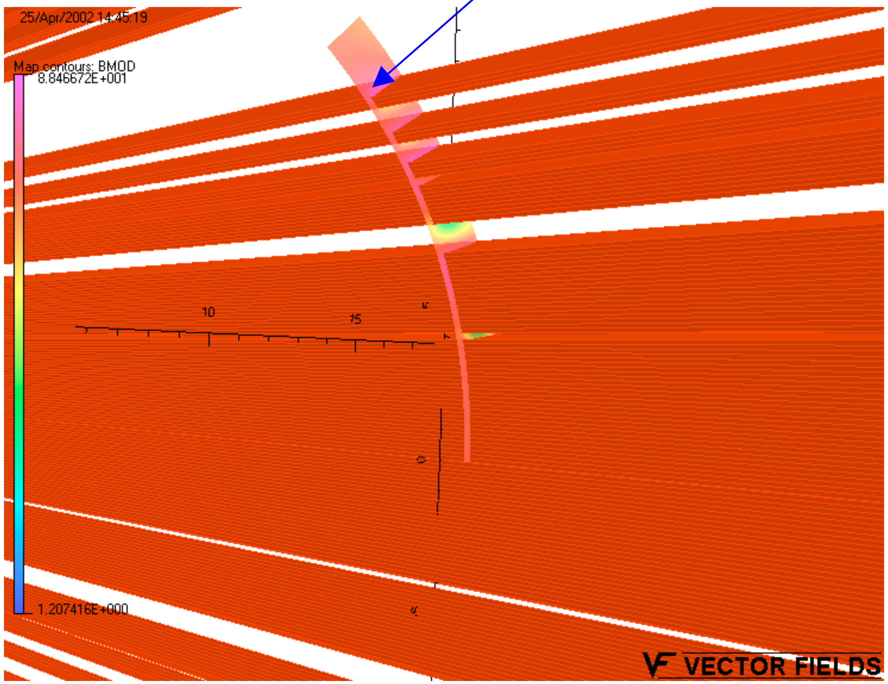
Usually about a thousand cases are examined to :

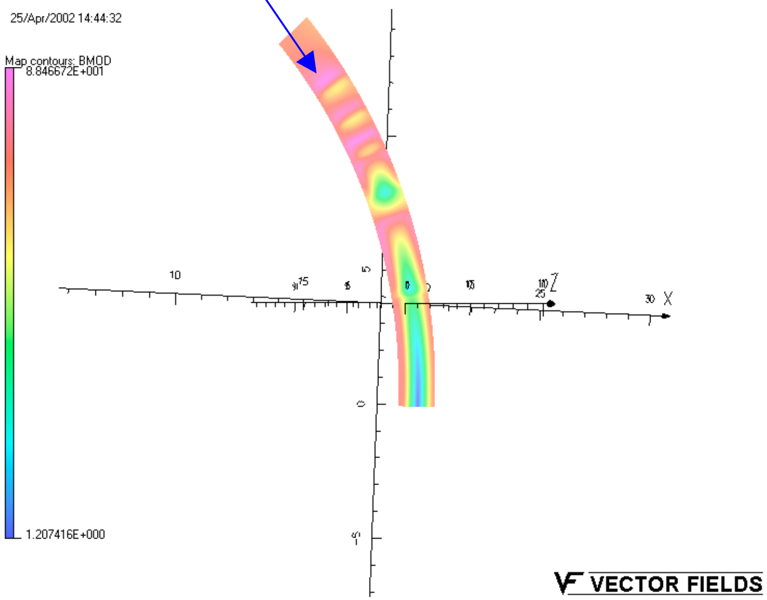
- Minimize harmonics
- Find a solution with lower peak field
- Good mechanical turn configuration (wedges, tilt angle, etc).

A series of computer programs have been written to carry out the above optimization in an exhaustive and systematic manner.

Peak Field in the Body of the Magnet

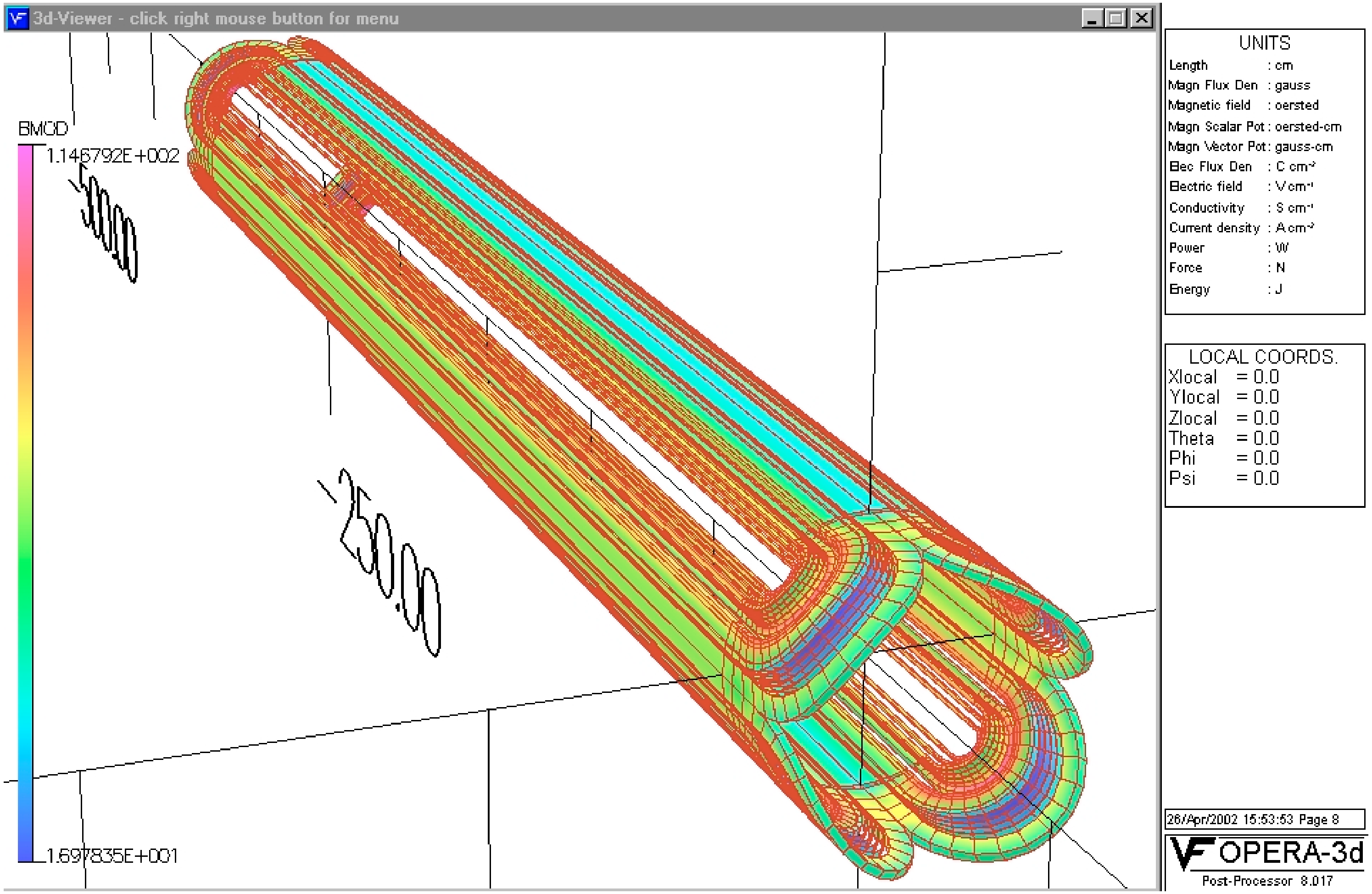
Peak Field Location (pole turn)



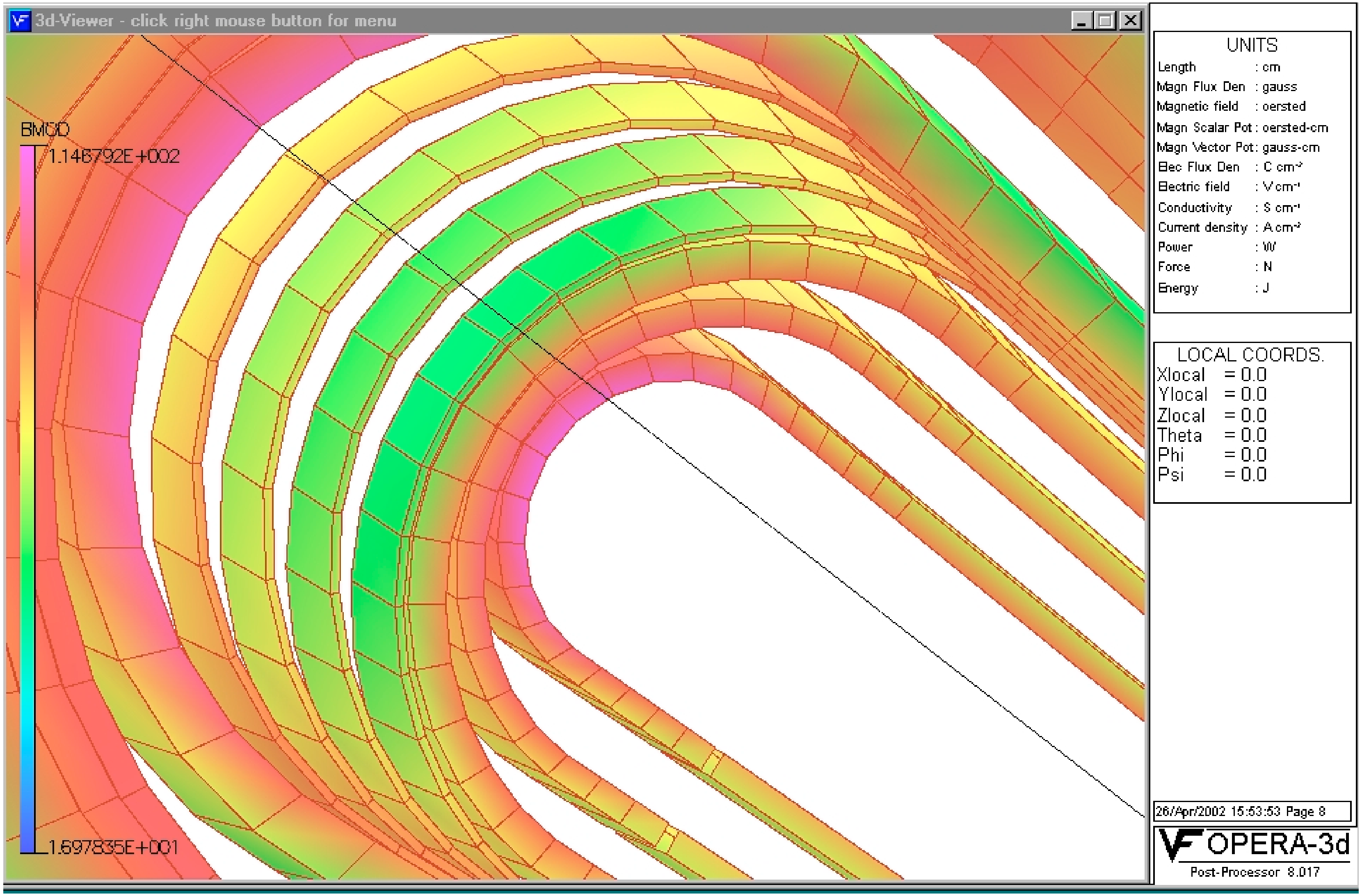


Peak Field in the End

An example of an End Design

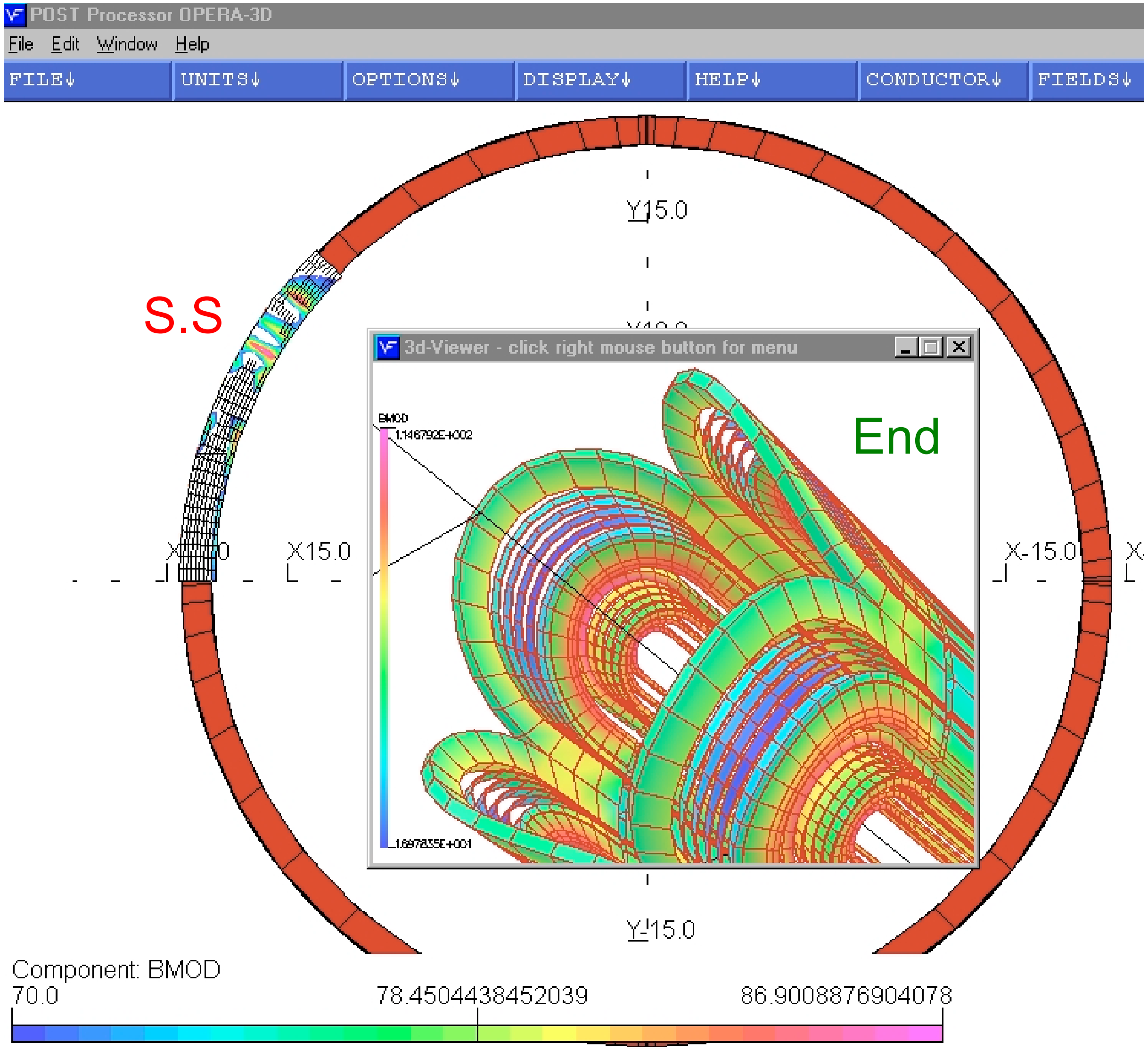


Peak Field in the End



Peak Field in the End

How does it compare to Body?



In this example, the peak value is larger in the end than in the body of the magnet.

In a typical end design, one removes iron (or increases yoke i.d.) to reduce field in the end.

Peak Field in the Ends

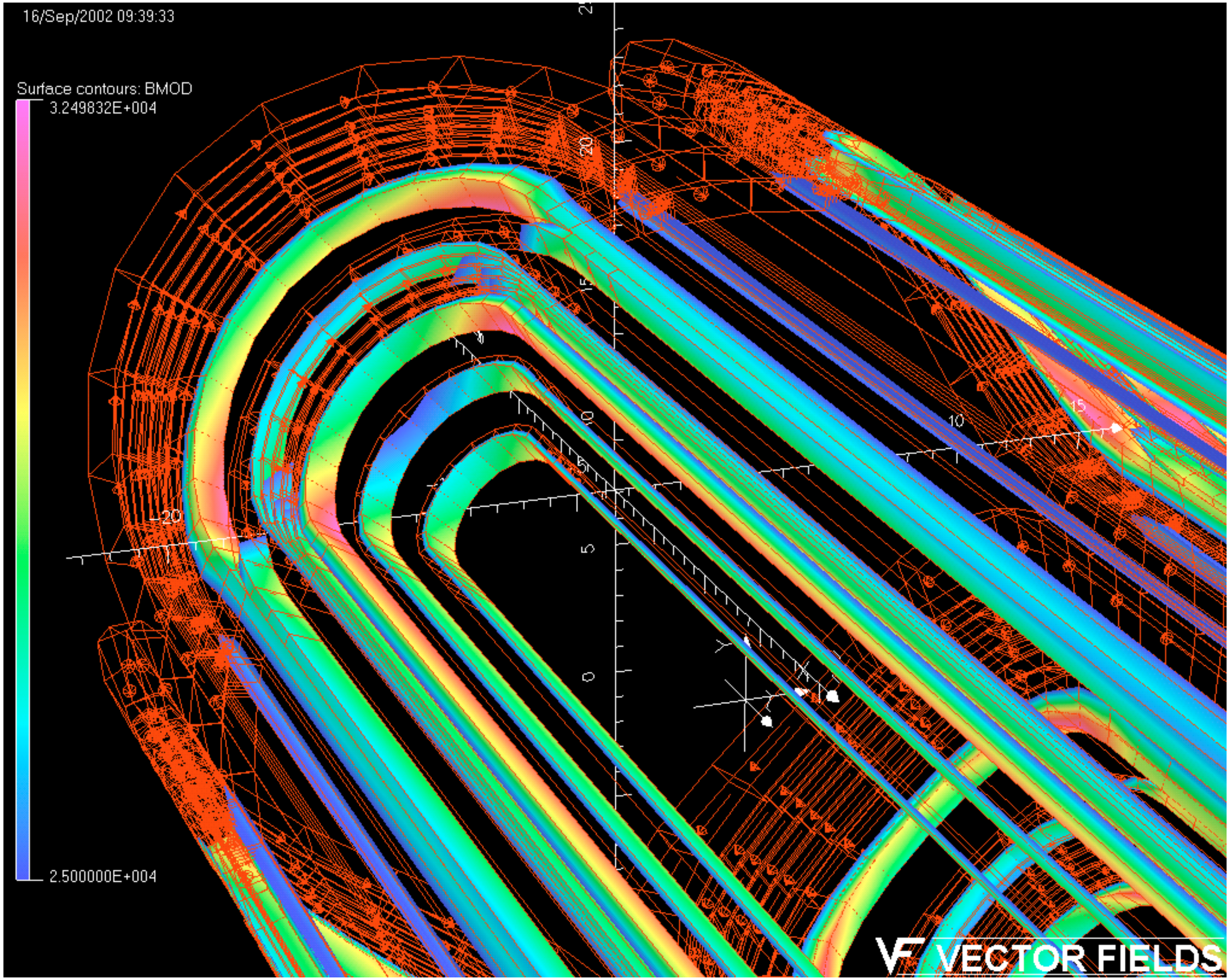
In cosine theta magnets, the conductors in the Ends are more strained and the mechanical design is generally less robust.

Therefore, one would like the peak field in the Ends to be less than that in the body of the magnet, to give conductor a larger margin.

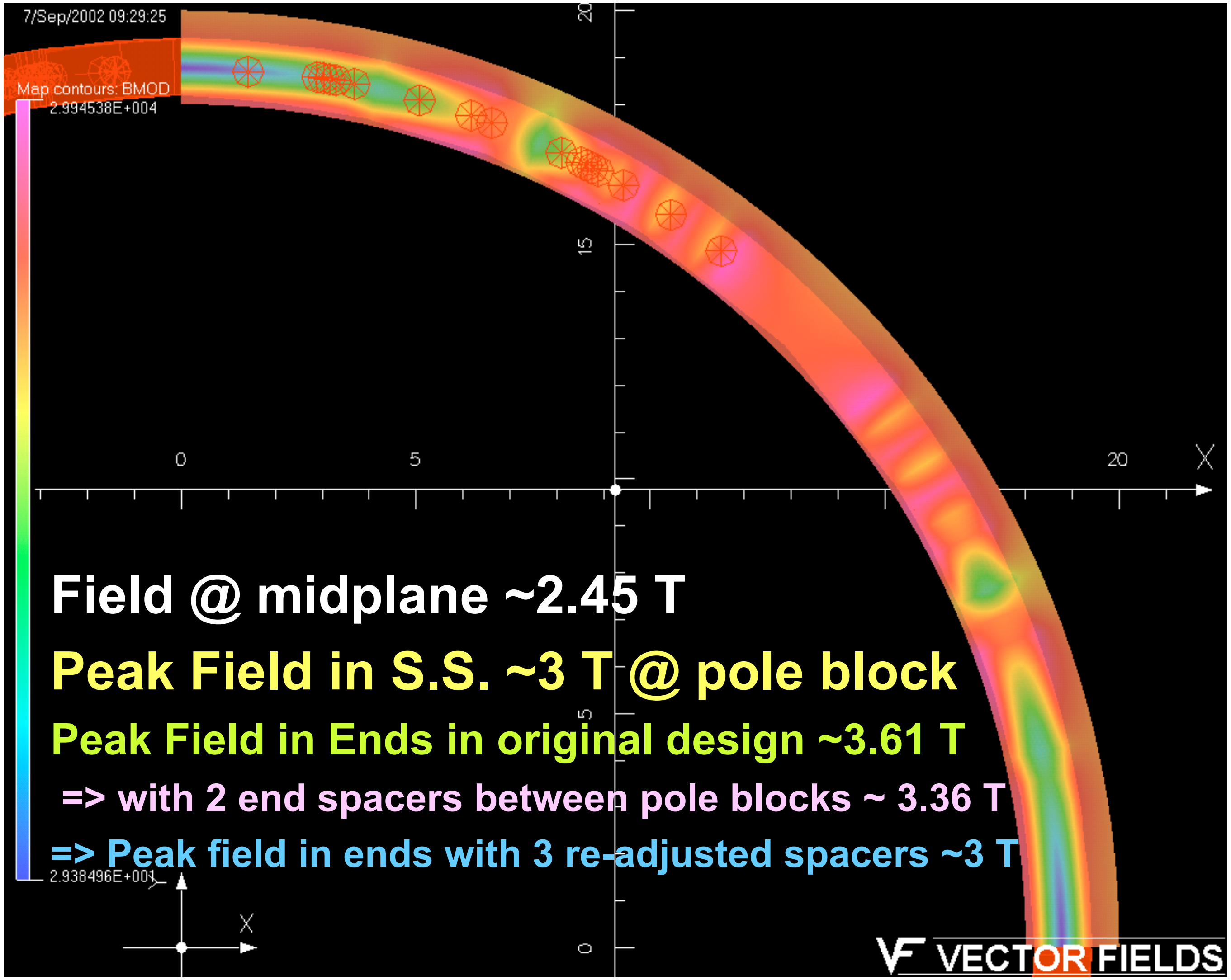
Ends with 3 Re-adjusted Spacers

Example (optimized):

Re-adjusted end spacer brings field in the ends down to S.S. level.



Peak Field
Straight Section vs. Ends



Field @ midplane ~2.45 T

Peak Field in S.S. ~3 T @ pole block

Peak Field in Ends in original design ~3.61 T

=> with 2 end spacers between pole blocks ~ 3.36 T

=> Peak field in ends with 3 re-adjusted spacers ~3 T

Block Structure

Straight section (6 blocks, 70 turns):

30 20 10 4 3 3 (counting from midplane)

3 3 4 10 20 30 (counting from pole)

End section (8 blocks, 70 turns):

10 5 8 4 13 4 6 20

(counting from pole)

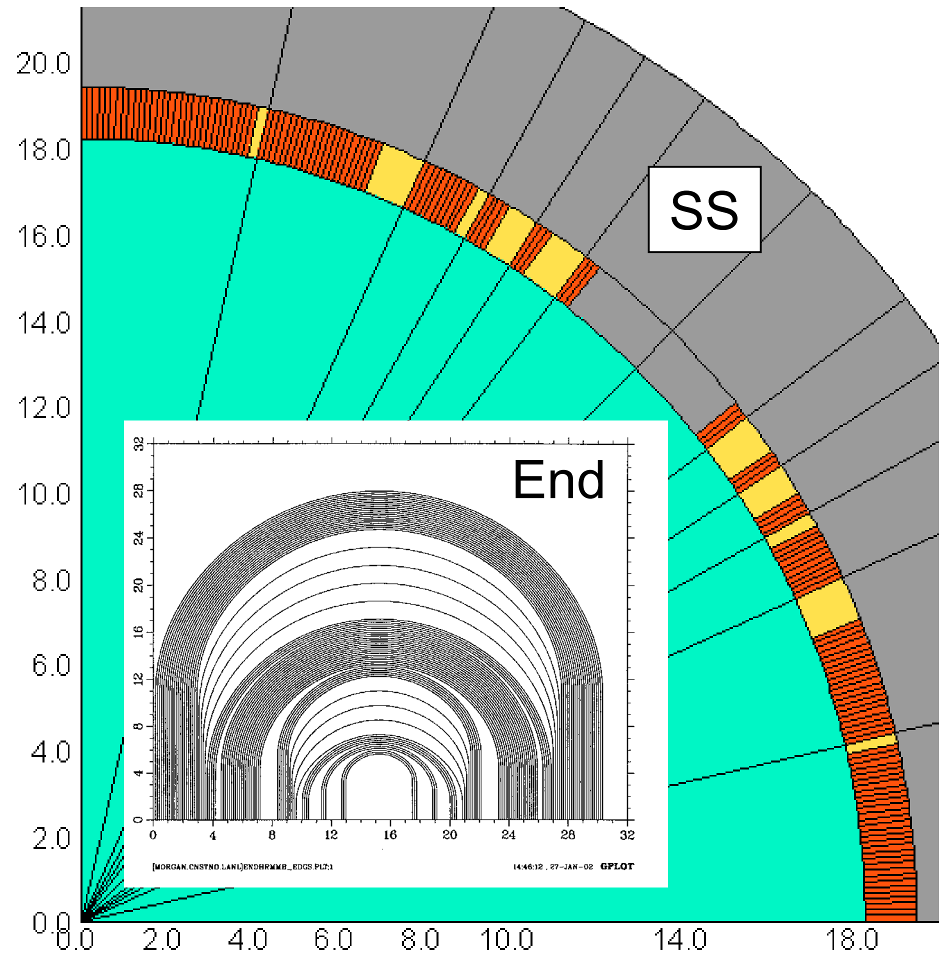
Straight section => pole

3,3,4 => 10

4,10, 20 => 5, 8, 4, 13

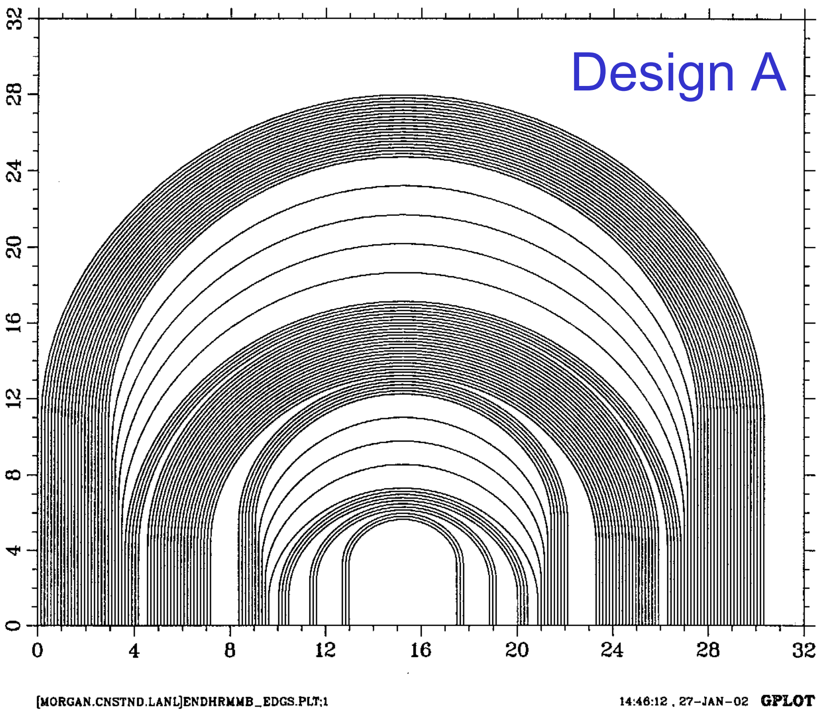
30 => 4, 6, 20

Must avoid large Ultum spacers (subdivide, if necessary)



Equal spacing in "Red Color" blocks is used as harmonic optimization parameters

End Harmonic Optimization: SMINSQ



Block configuration:

(8 blocks, 70 turns):

10, 5, 8, 4, 13, 4, 6, 20

(counting from pole)

Parameters optimized:

- End spacers in block #2 (with 5 turns) and end spacer in block #7 (with 4 turns).
- All spacers with in a block have the same size.

Changing the size of two group of end spacers was adequate to get all harmonics small.

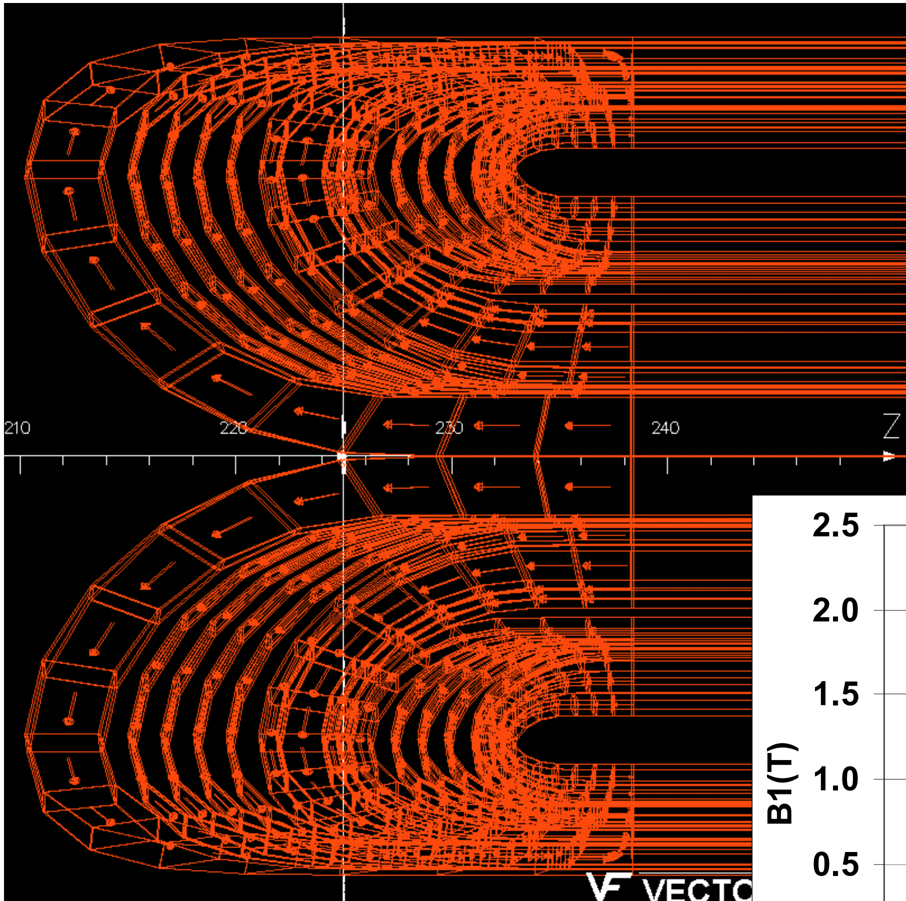
Computed values:

- B_5< 1 unit-meter;
- B_9 and B_{13} <0.1 unit-m

Effective Magnetic Length ~15.6 cm

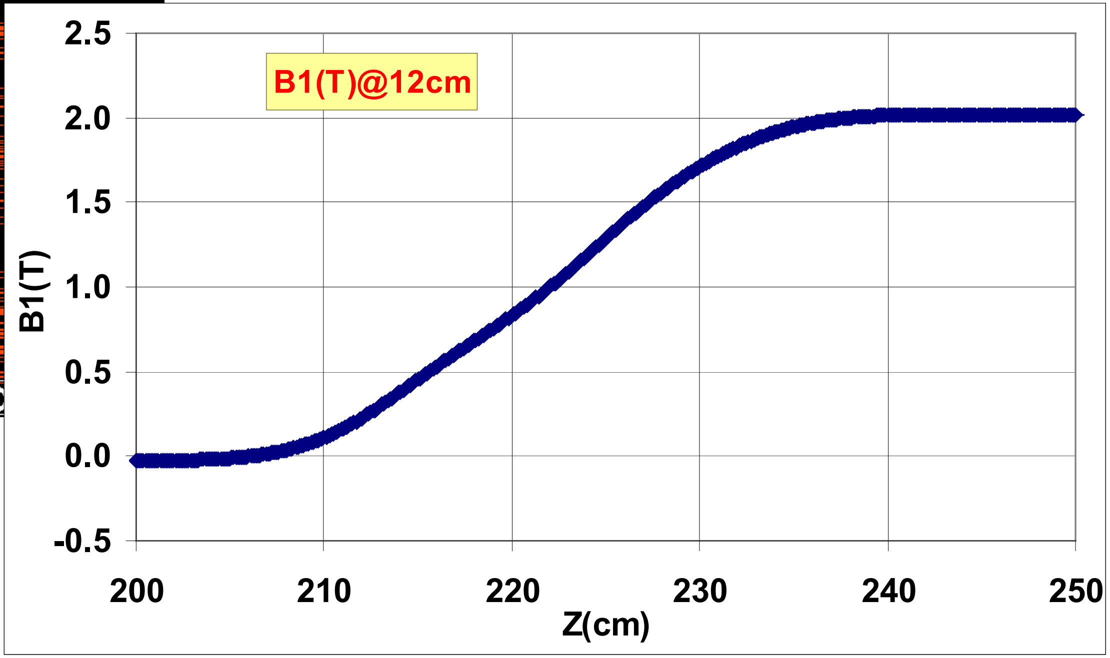
Mechanical Length ~28 cm + End Saddle

Field through the Coil Ends

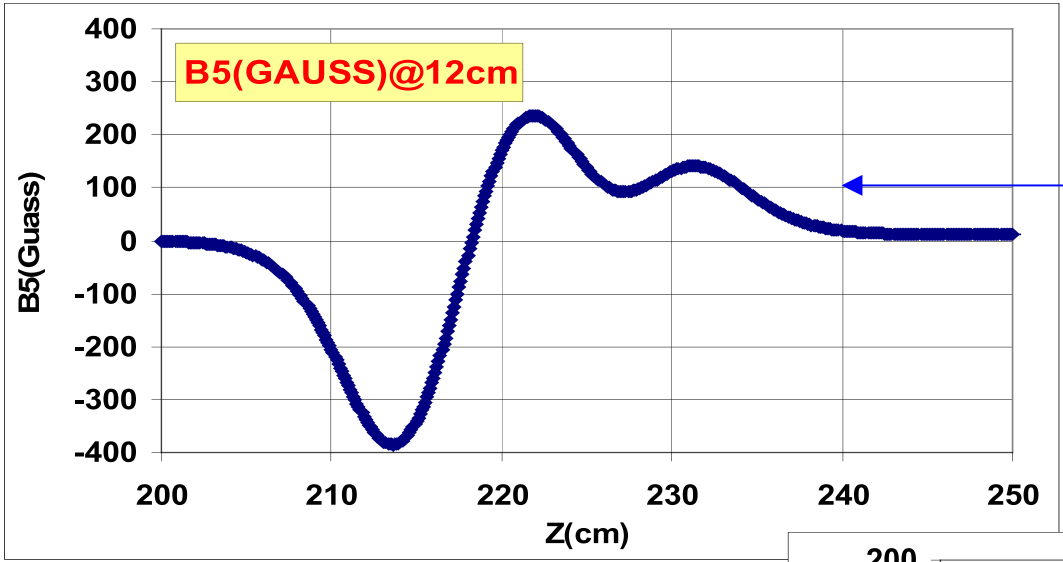


Mechanical length of this end (including end saddle) ~34 cm : ~ 2 coil diameters

Contribution to magnetic length ~16 cm

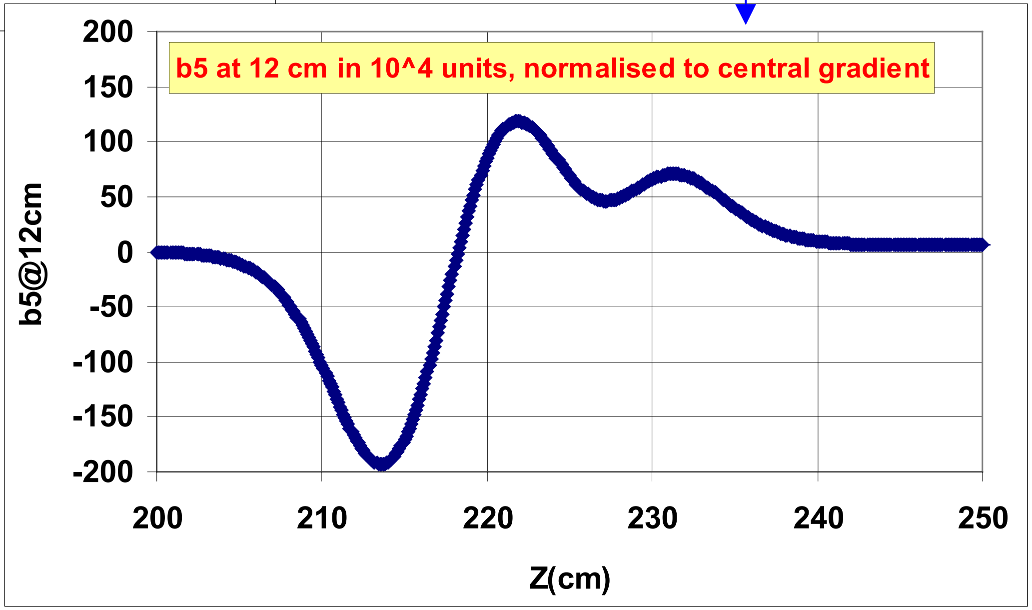


Field Harmonics through the End
b_5: dodecapole



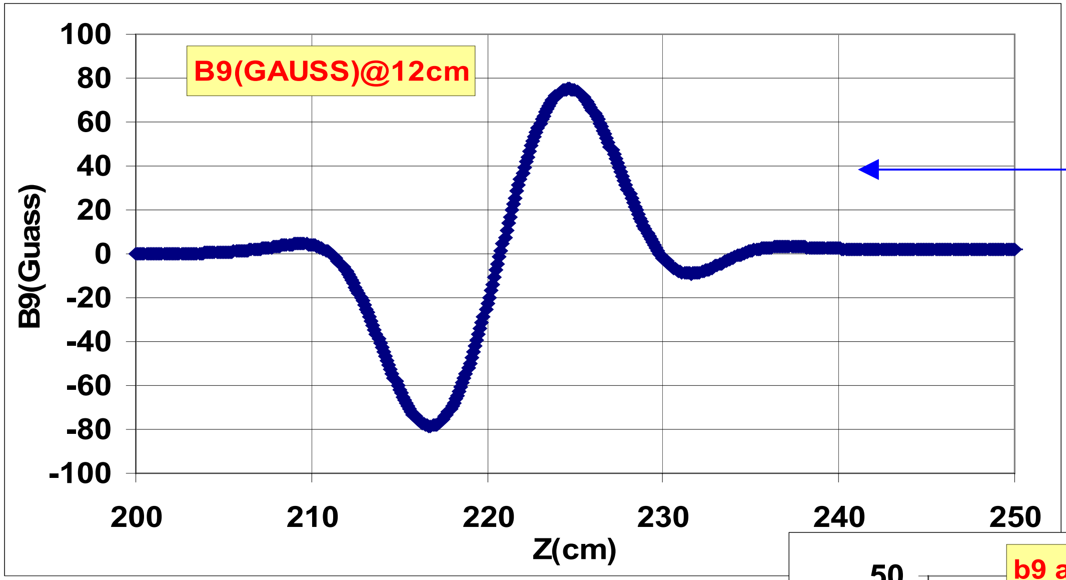
Harmonic in Gauss

Harmonic in Units



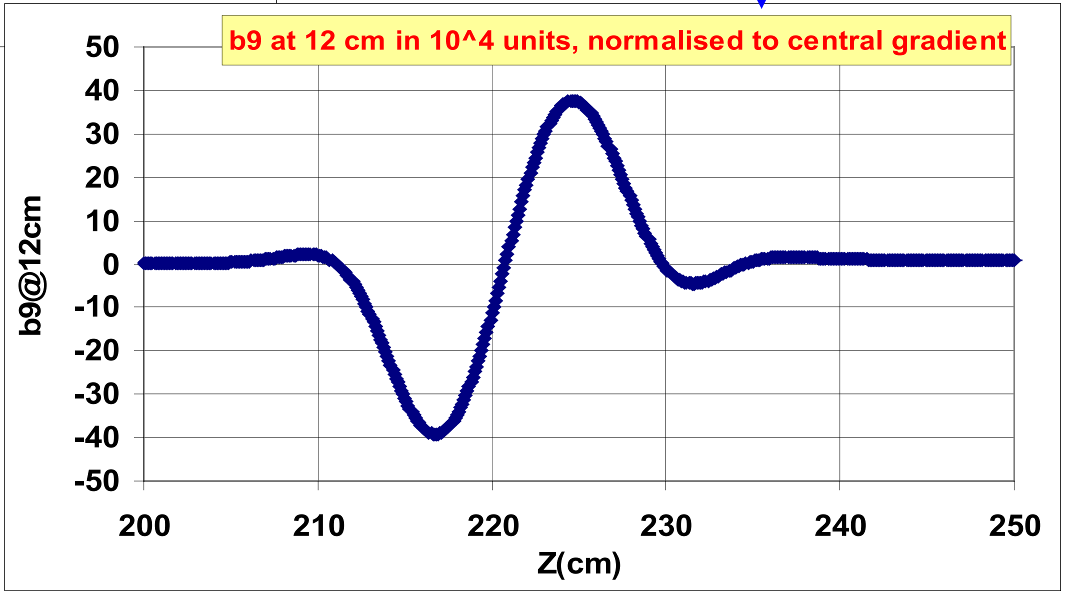
End spacers are optimized to produce low integral harmonics

Field Harmonics through the End : b_9



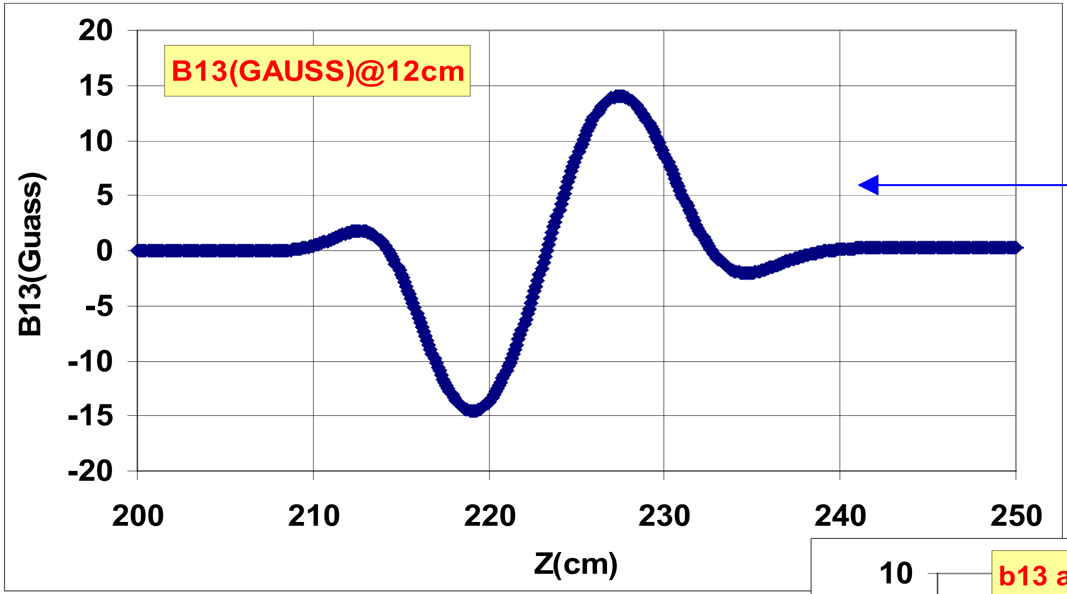
Harmonic in Gauss

Harmonic in Units



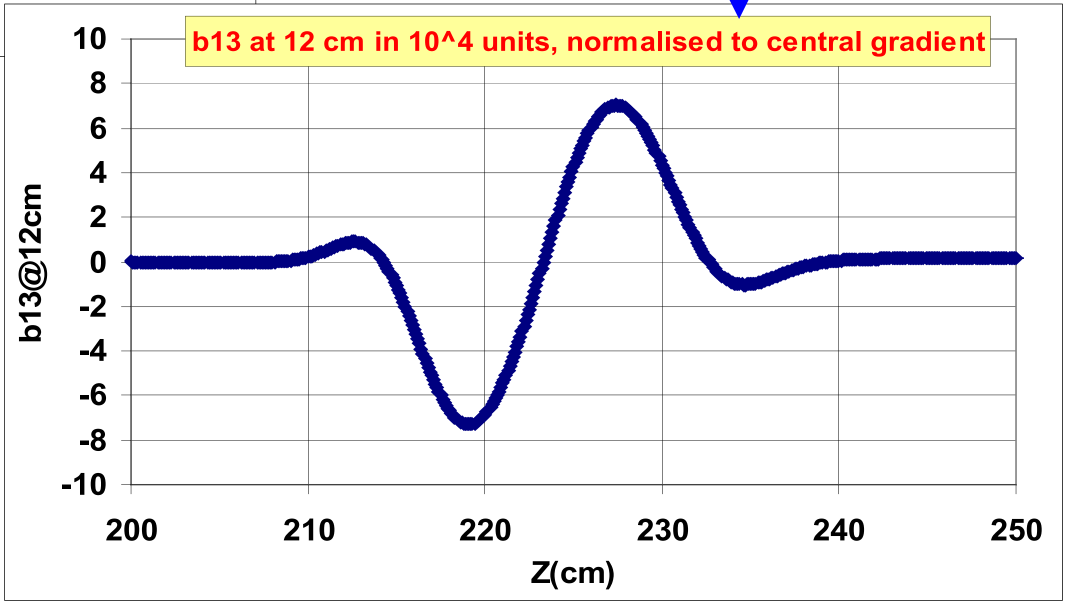
End spacers are optimized to produce low integral harmonics

Field Harmonics through the End : b_{13}



Harmonic in Gauss

Harmonic in Units



End spacers are optimized to produce low integral harmonics

SUMMARY

We are now expert (almost!) in:

2d coil design

Requires good mechanical, magnetic and flexible design.

3d coil design

Requires good mechanical and magnetic design.

We have studied 2-d and 3-d design optimization in *cosine "n" theta* (or cylindrical coil) geometry.

Optimization of alternate magnet designs with *racetrack coils* will be discussed in a separate lecture.