Lecture X

Alternate Designs for Special Magnets

(alternate to conventional cosine theta)

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The purpose of this lecture is to give you a feeling of how alternate designs are developed through a series of examples.

Note: The selected examples are those where I was involved. This is by no means the only new designs (there are many others there) and by no means the only way of developing alternate designs (there are, by definitions, other alternate ways of doing).

New Magnet Designs for Future Accelerators

- Sometime the challenging technical requirements of a particular application can be better met if we think outside the box rather than just using the conventional designs

- Some time the general requirements of a common application can be met more economically if we think outside the box rather than just using the conventional designs and magnet technology

  ♣For example, cosine theta superconducting magnet designs with Niobium Titanium conductor technology has been in use for decades. This is a fairly well optimized design and technology and the cost is now unlikely to change significantly.

  ♣To change the construction and operating cost significantly, one must think differently (that is, think about new magnet designs and technologies).

It is not necessary that new designs will always give a better solution (in fact in most applications, it is unlikely that it will), but one has to try !

Conventional Magnet Designs and Technology

Tevatron Dipole

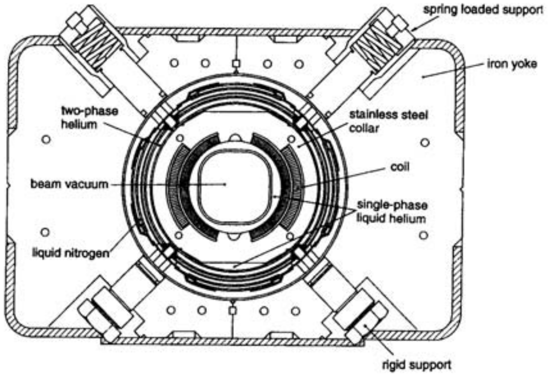
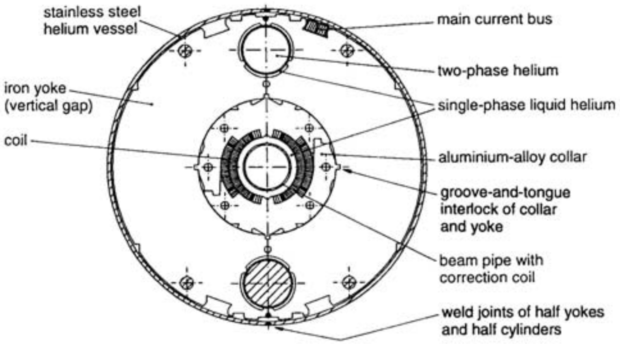
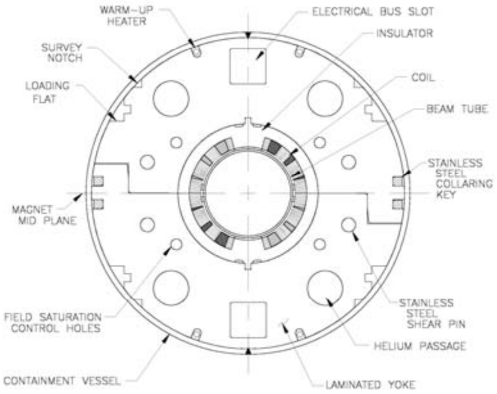


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

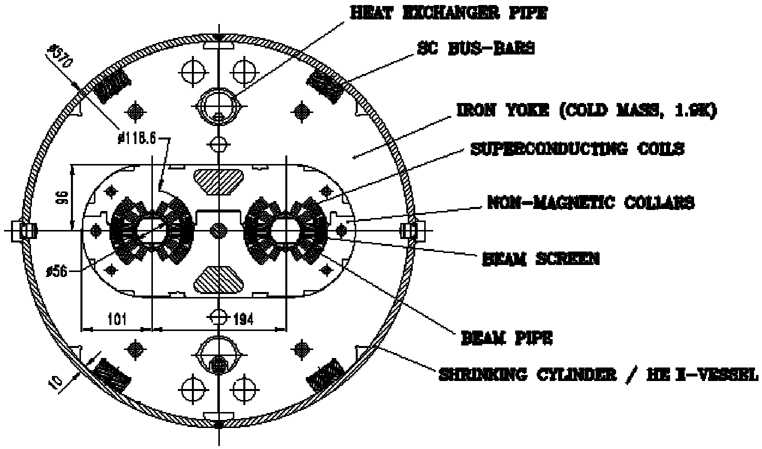
HERA Dipole



RHIC Dipole

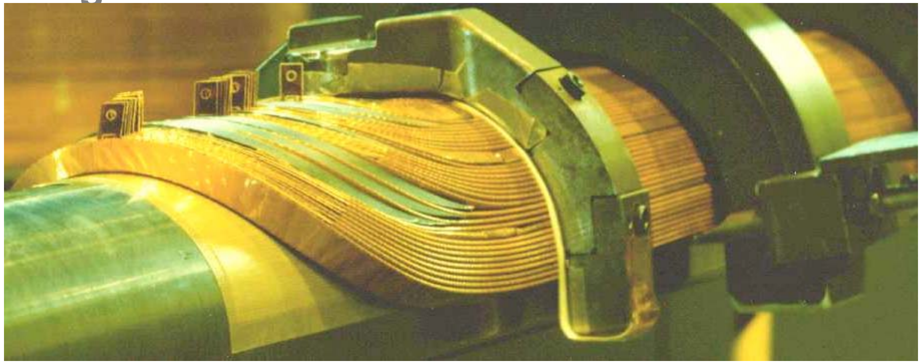


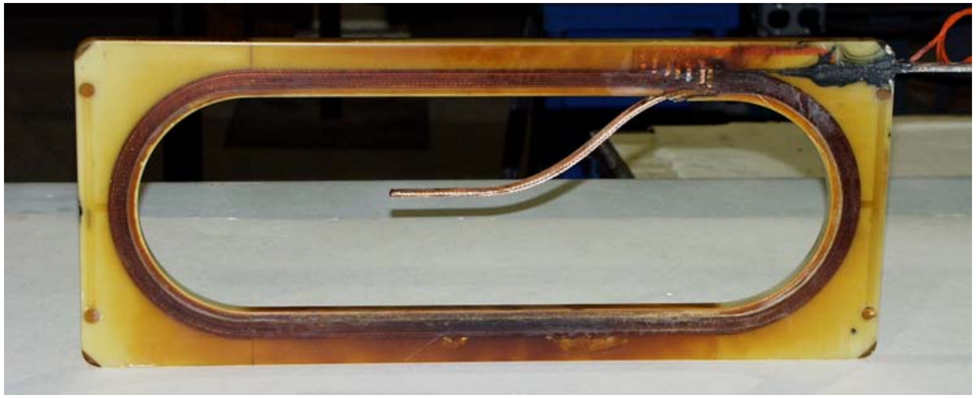
LHC Dipole



- All designs use cosine theta coil geometry
- All magnets use Nb-Ti Superconductor
- The technology has been in use for decades.
- The cost is unlikely to be reduce significantly.

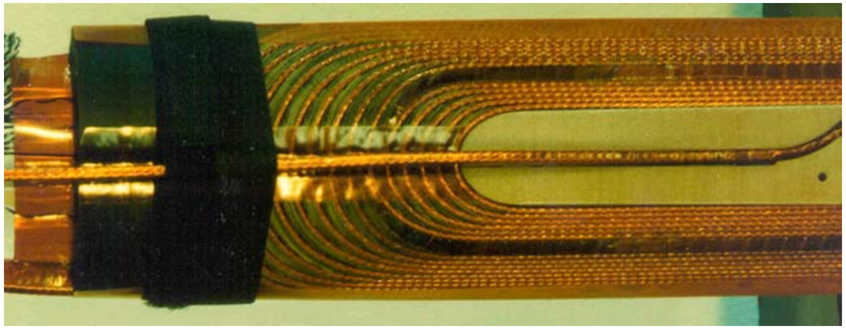
Cylindrical Cosine Theta Coil Geometry and Flat Racetrack Coil Geometry

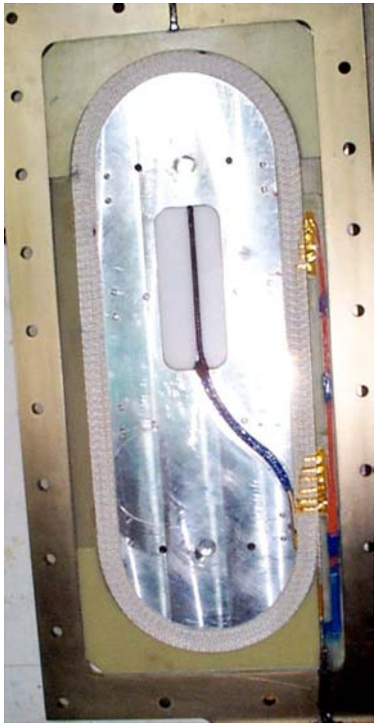




Cosine theta (cylindrical or shell type coil geometry).

Standard geometry for getting a good field quality with a lot of experience. Complex ends, may not be the best for high field magnets.



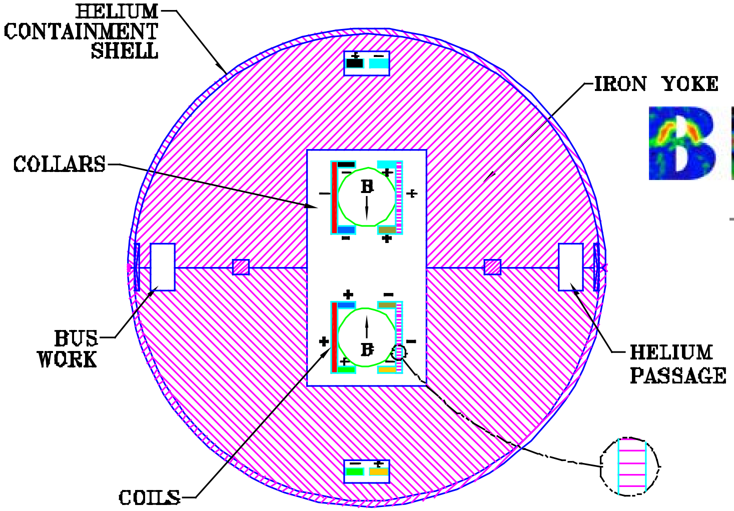


Racetrack geometry (flat coils), 2-d coils with simpler ends.

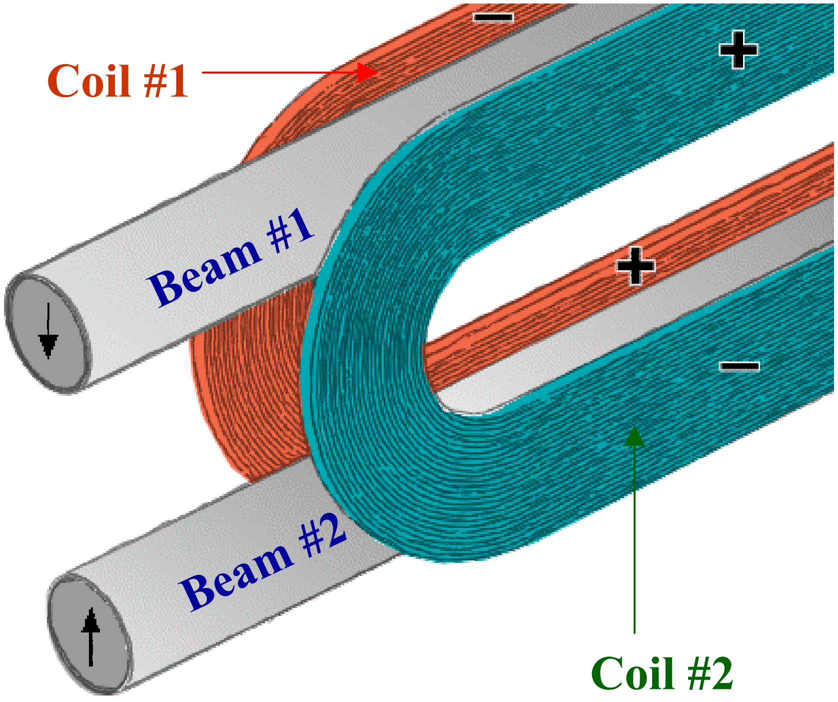
Good for high field magnets, particularly with brittle materials. Good for lower cost R&D magnets and may allow lower cost production magnets.

But limited magnet experience. Perception is that the racetrack coil magnets need much more conductor or may not produce good field quality. New design optimizations in last few years show that not to be the case.

Common Coil Design

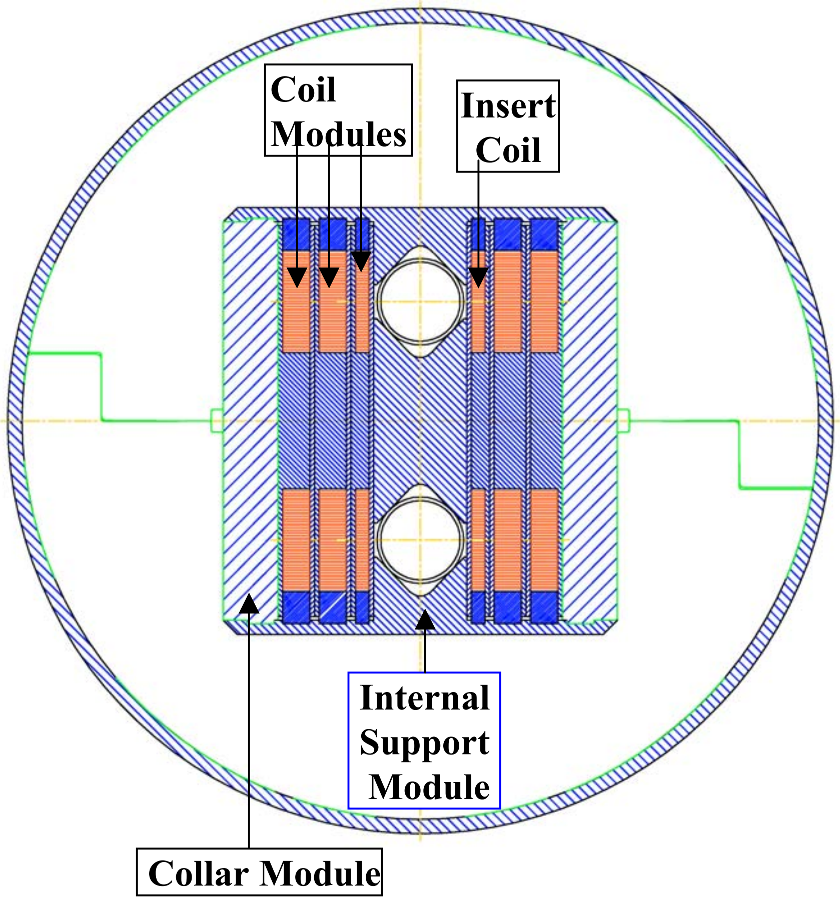


- **Simple 2-d geometry with large bend radius** (determined by spacing between two apertures, rather than aperture itself)
- **Conductor friendly (no complex 3-d ends, suitable for brittle materials - most for H.F. are - Nb_3Sn and HTS)**
- **Compact (quadrupole type cross-section, field falls more rapidly)**
- **Block design (for handling large Lorentz forces at high fields)**
- **Combined function magnets possible**
- **Minimum requirements on big expensive tooling and labor**
- **Lower cost magnets expected**
- **Efficient and methodical R&D due to simple & modular design**



Main Coils of the *Common Coil Design*

Modular Design for A New Cost-effective R&D Approach



- **Replaceable coil modules**
- **Change cable width or type**
- **Vary magnet aperture**
- **Study support structure**
- **Combined function magnets**

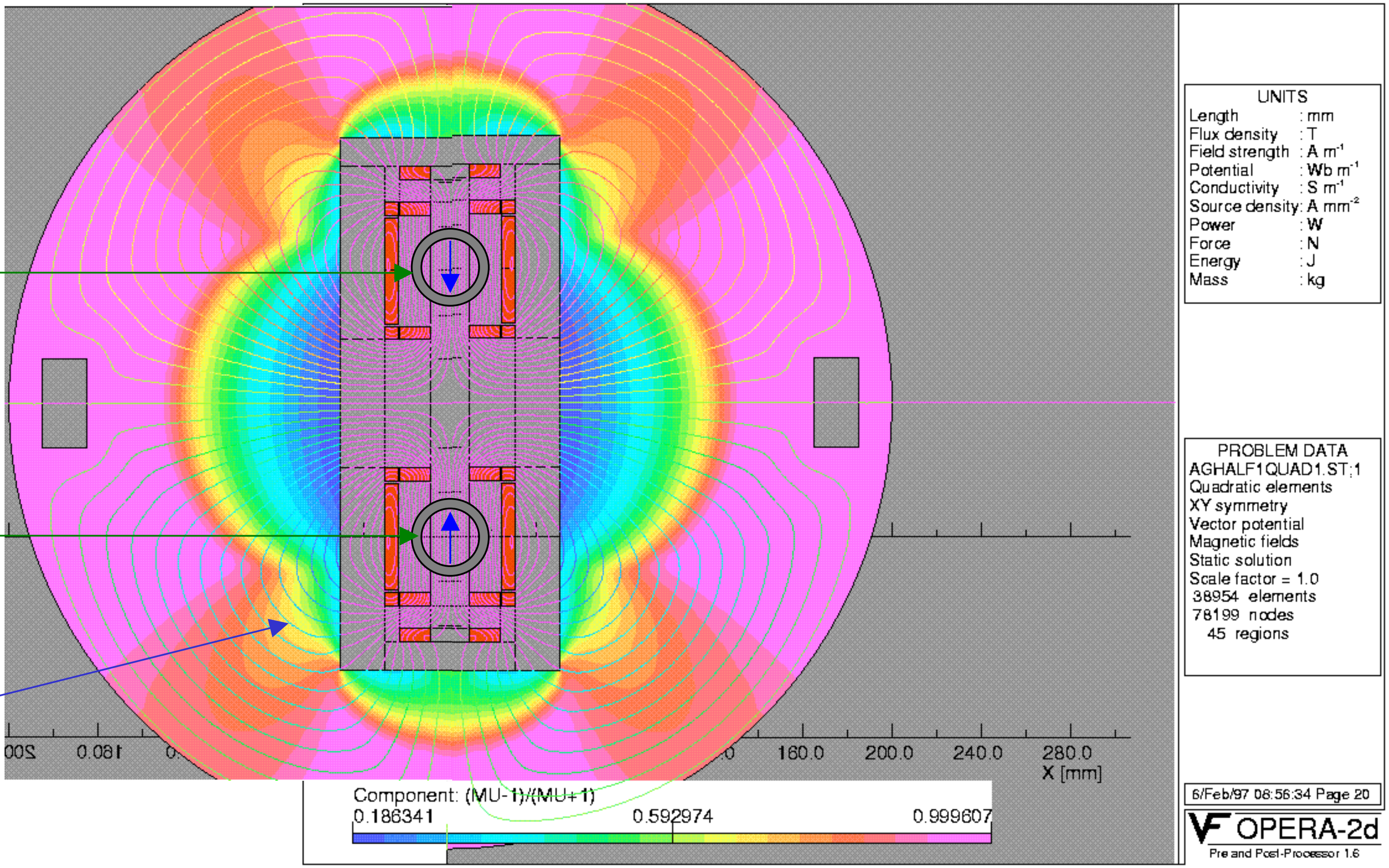
☐ **Traditionally such changes required building a new magnet !**

In fact, during last several years, the common coil design has served as a good modular design for carrying out a cost effective and systematic R&D at various US labs.

Field Lines at 15 T in a Common Coil Magnet Design

Aperture #1

Aperture #2



UNITS

Length	: mm
Flux density	: T
Field strength	: A m^{-1}
Potential	: Wb m^{-1}
Conductivity	: S m^{-1}
Source density	: A mm^{-2}
Power	: W
Force	: N
Energy	: J
Mass	: kg

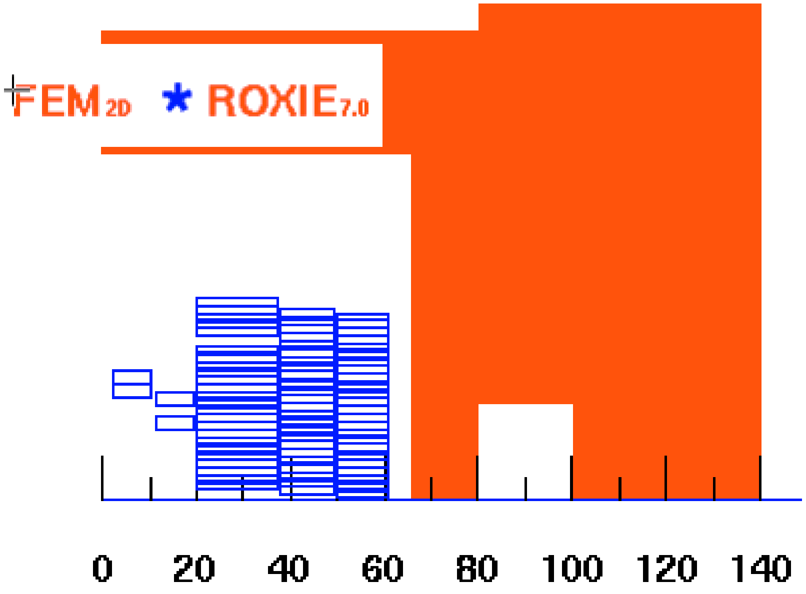
PROBLEM DATA
AGHALF1QUAD1.ST;1
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 1.0
38954 elements
78199 nodes
45 regions

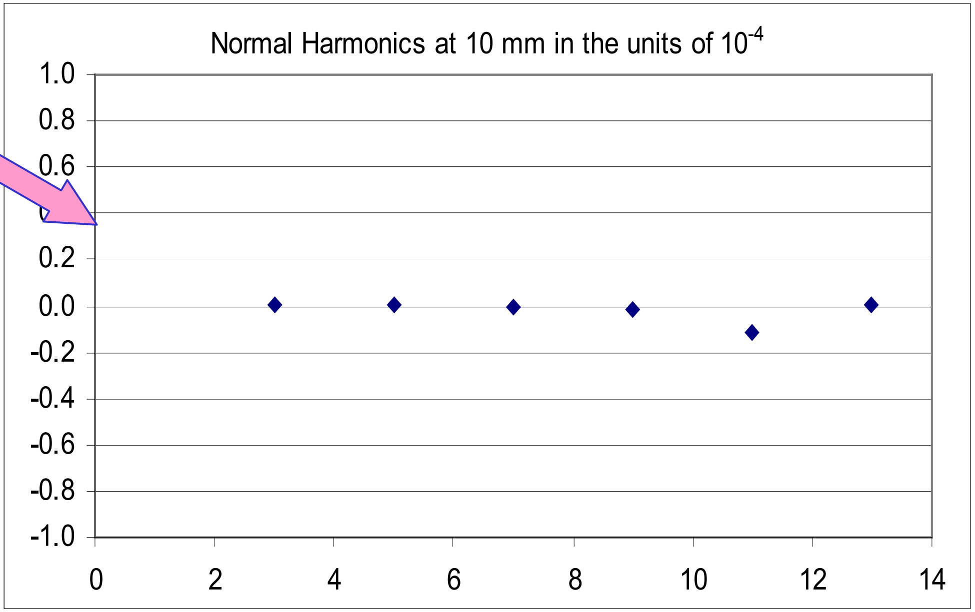
Place of the maximum iron saturation
(would not be the case if we used rectangular yoke)

Progress in Field Quality (Geometric Harmonics)

Question: Can a racetrack coil configuration with a geometry that does not necessarily look like *"cosine theta"*, produce designs with low field harmonics?

Typical Requirements:
~ part in 10^4, we have part in 10^5





The above model uses all flat coils.

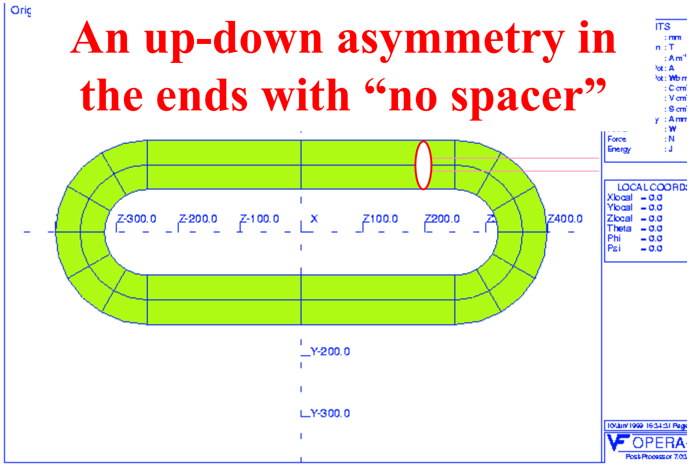
(from 1/4 model)

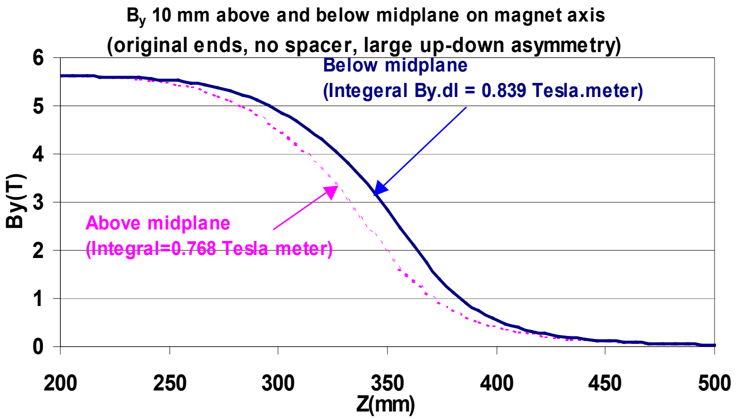
MAIN FIELD: -1.86463 (IRON AND AIR):

b 1:	10000.000	b 2:	0.00000	b 3:	0.00308
b 4:	0.00000	b 5:	0.00075	b 6:	0.00000
b 7:	-0.00099	b 8:	0.00000	b 9:	-0.01684
b10:	0.00000	b11:	-0.11428	b12:	0.00000
b13:	0.00932	b14:	0.00000	b15:	0.00140
b16:	0.00000	b17:	-0.00049	b18:	0.00000

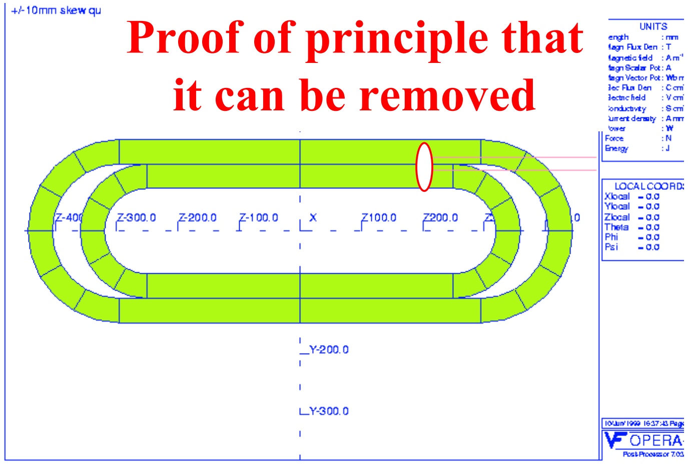
Field Quality Optimization in the Common Coil Design (Magnet Ends)

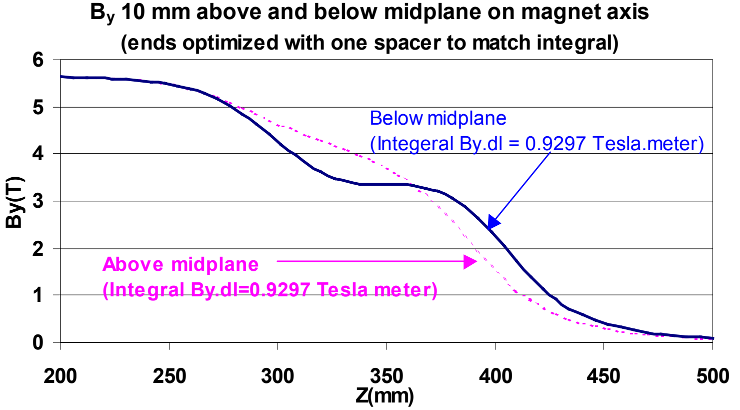
Up-down asymmetry gives large skew harmonics, if done nothing. Integrate By.dl 10 mm above and 10 mm below midplane.

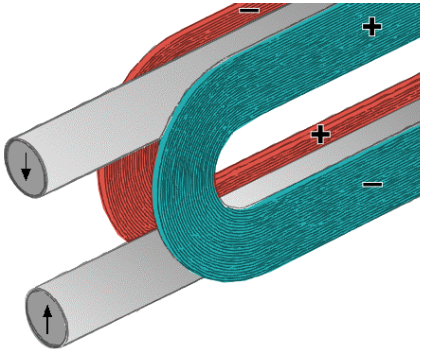

An up-down asymmetry in the ends with "no spacer"


B_y 10 mm above and below midplane on magnet axis (original ends, no spacer, large up-down asymmetry)

Up-down asymmetry can be compensated with end spacers. One spacer is used below to match integral By.dl 10 mm above & below midplane.


Proof of principle that it can be removed


B_y 10 mm above and below midplane on magnet axis (ends optimized with one spacer to match integral)

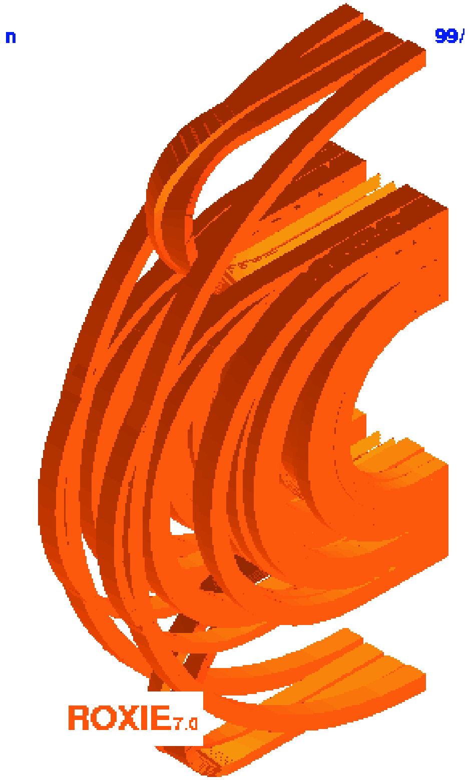


A large Bz.dl in two ends (~1 T.m in 15 T magnet).

- Is it a problem?
- Examine AP issues.
- Zero integral.
- Lead end of one magnet + Return of the next magnet will make it cancel in about ~1meter (cell length ~200 meters).

An Example of End Optimization with ROXIE (iron not included)

End harmonics can be made small in a common coil design.

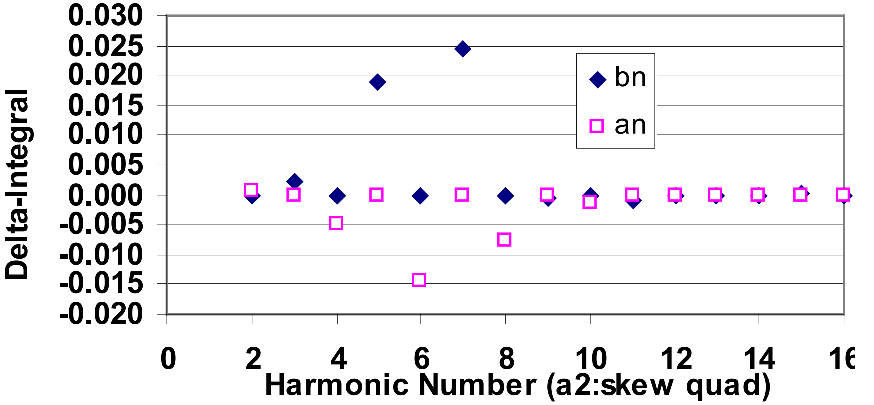


End harmonics in Unit-m

n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00

Contribution to integral (a_n,b_n) in a 14 m long dipole ($<10^{-6}$)

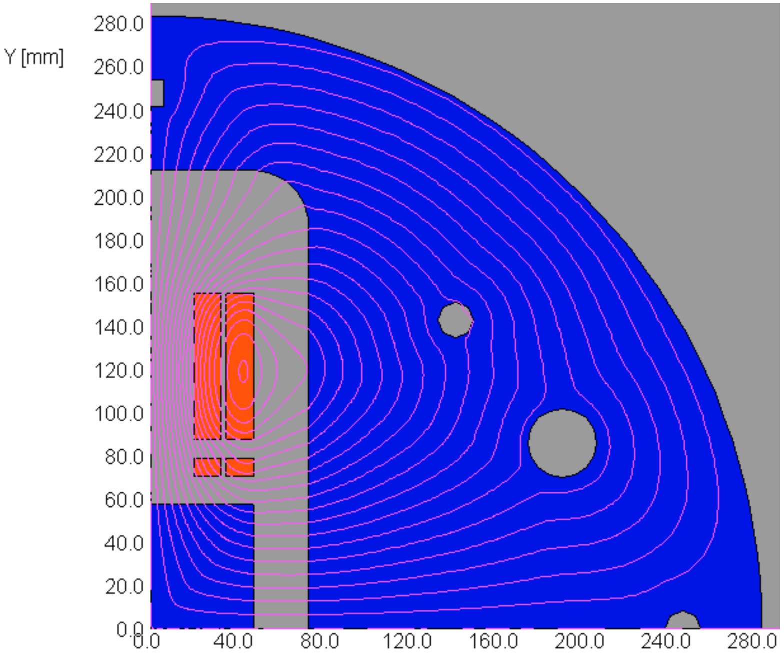
n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000



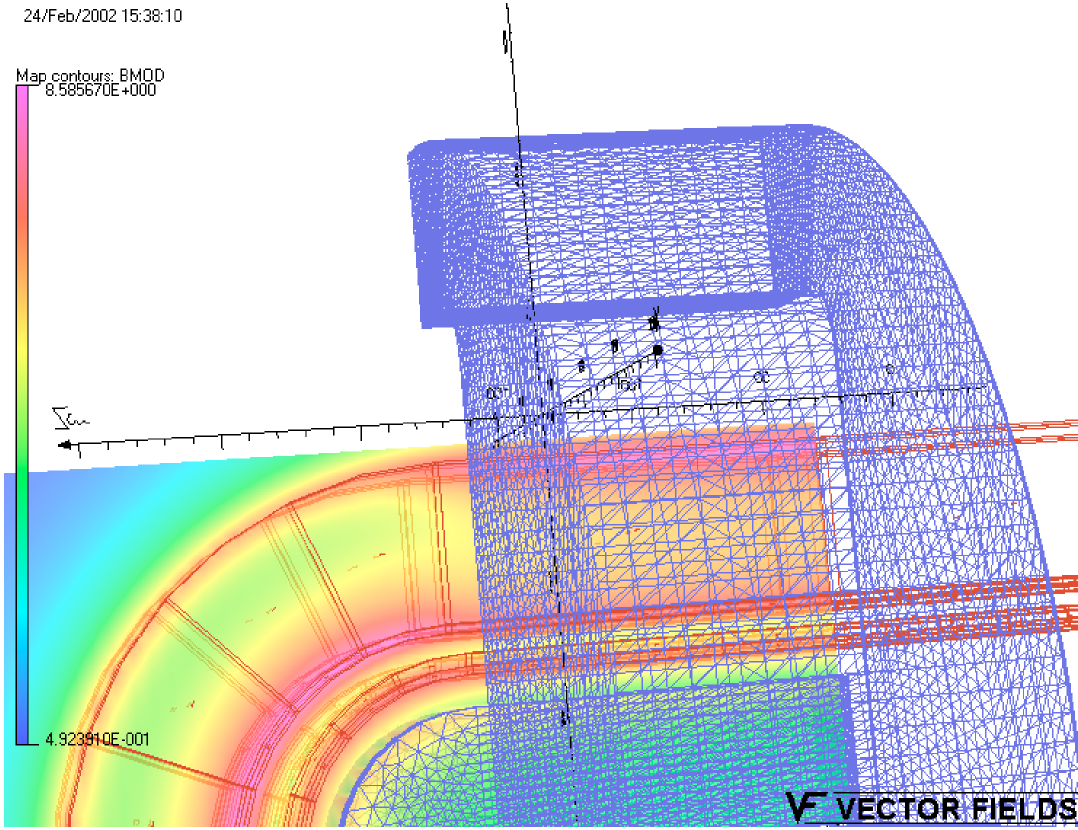
Generally speaking, integral end harmonics less than 0.1 unit-meter are considered to be "good".

Spacers in the Body and Ends to Minimize Peak Fields

¼ model of the 2-in-1 common coil magnet



Field lines in 2-d model.



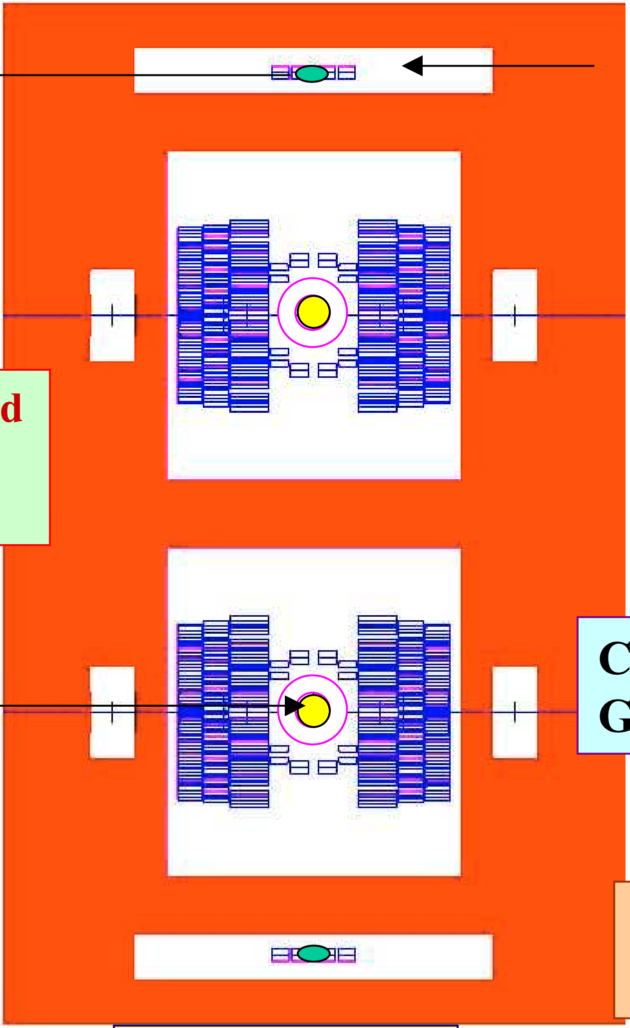
Field Contours in 3-d model.

Non-magnetic material over coil and end spacers are used to minimize peak field in the end region.

A Common Coil Magnet System

A Solution to the Persistent Current Problem

A 4-in-1 magnet for a 2-in-1 machine



Inject in the iron dominated aperture at low field and accelerate to medium field

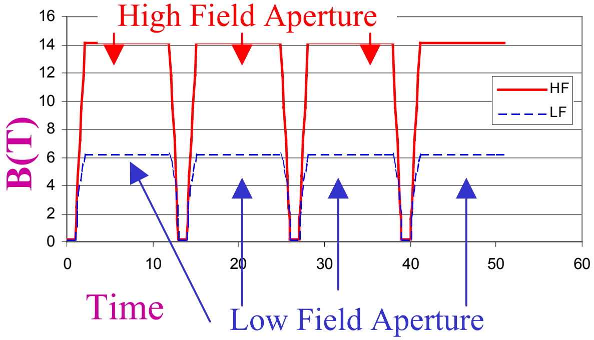
Injection at low field in iron dominated aperture should solve the large persistent current problem associated with Nb3Sn

Transfer to conductor dominated aperture at medium field and then accelerate to high field

Conductor dominated aperture
Good at high field (1.5-15T)

Iron dominated aperture
Good at low field (0.1-1.5T)

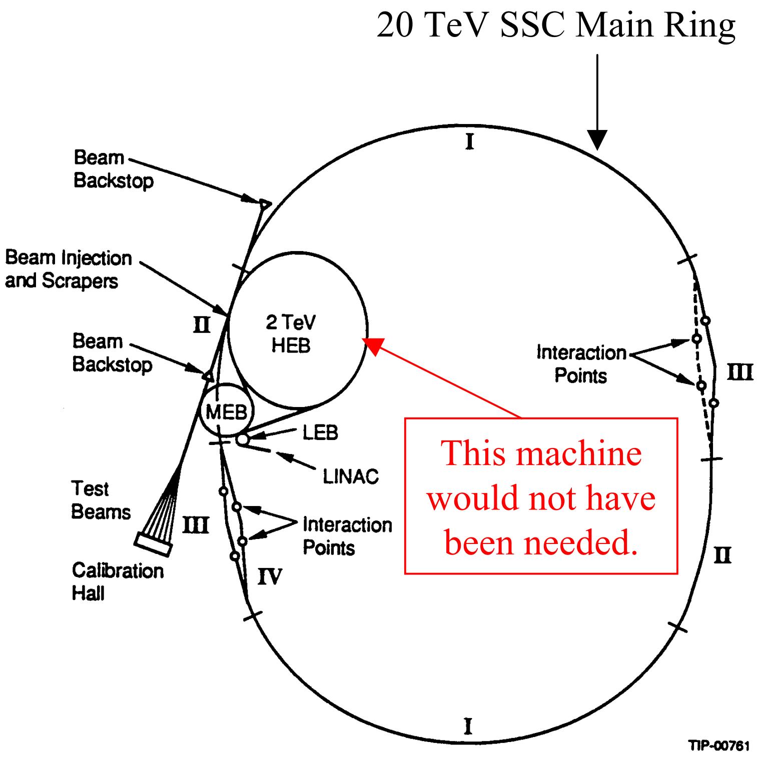
Field profile with time



Compact size

AP issues? Compare with the Low Field Design.

Possibility of Removing the Second Largest Machine (HEB) from the vlhc complex



20 TeV SSC Main Ring

This machine would not have been needed.

Figure 4.1.1.1-4. Schematic layout of SSC.

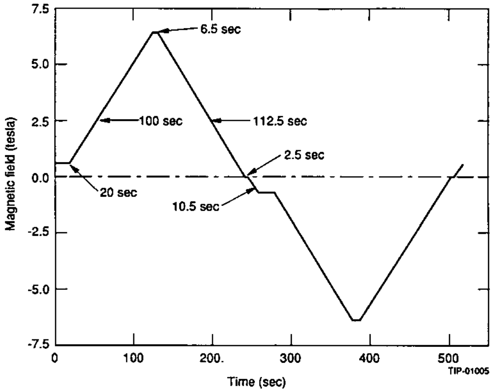


Figure 4.1.2.4-1. The suggested slow, alternating ramp scenario of the HEB.

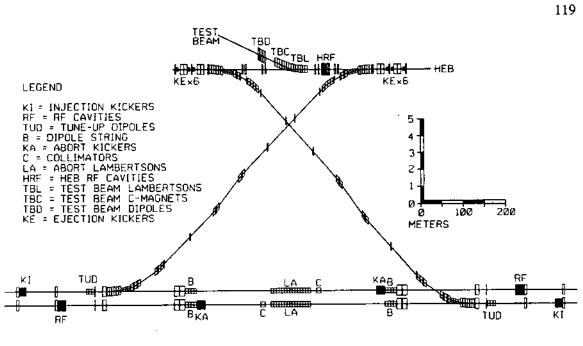


Figure 4.1.1.3-4. Elevation view of collider utility region.

- In the proposed system, the High Energy Booster **(HEB)** - the entire machine complex - will not be needed. Significant saving in the cost of construction and operation.
- Many consider that HEB, in some ways was quite challenging machine: superconductor (2.5 μ instead of 6 μ filaments), bipolar magnets, etc.

Common Coil Magnet System
(Estimated cost savings by eliminating HEB)

SSC: 20+20 TeV;

VLHC: 50+50 TeV

Based on 1990 cost in US$

2 TeV HEB Cost in SSC (derived):
$700-800 million

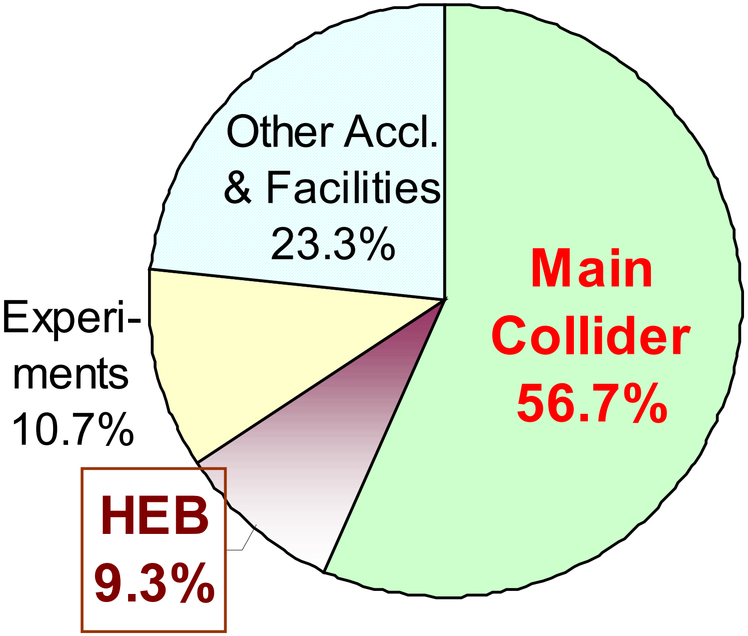
Estimated for 5 TeV (5-50 TeV vlhc):
~$1,500 million (in 1990 US$)

A part of this saving (say ~20-30%) may be used towards two extra apertures, etc. in main tunnel. Estimated savings ~ $1 billion.

Cost savings in equivalent 20xx $?

Cost Distribution of Major Systems

(Reference SSC Cost: 1990 US $7,837 million)

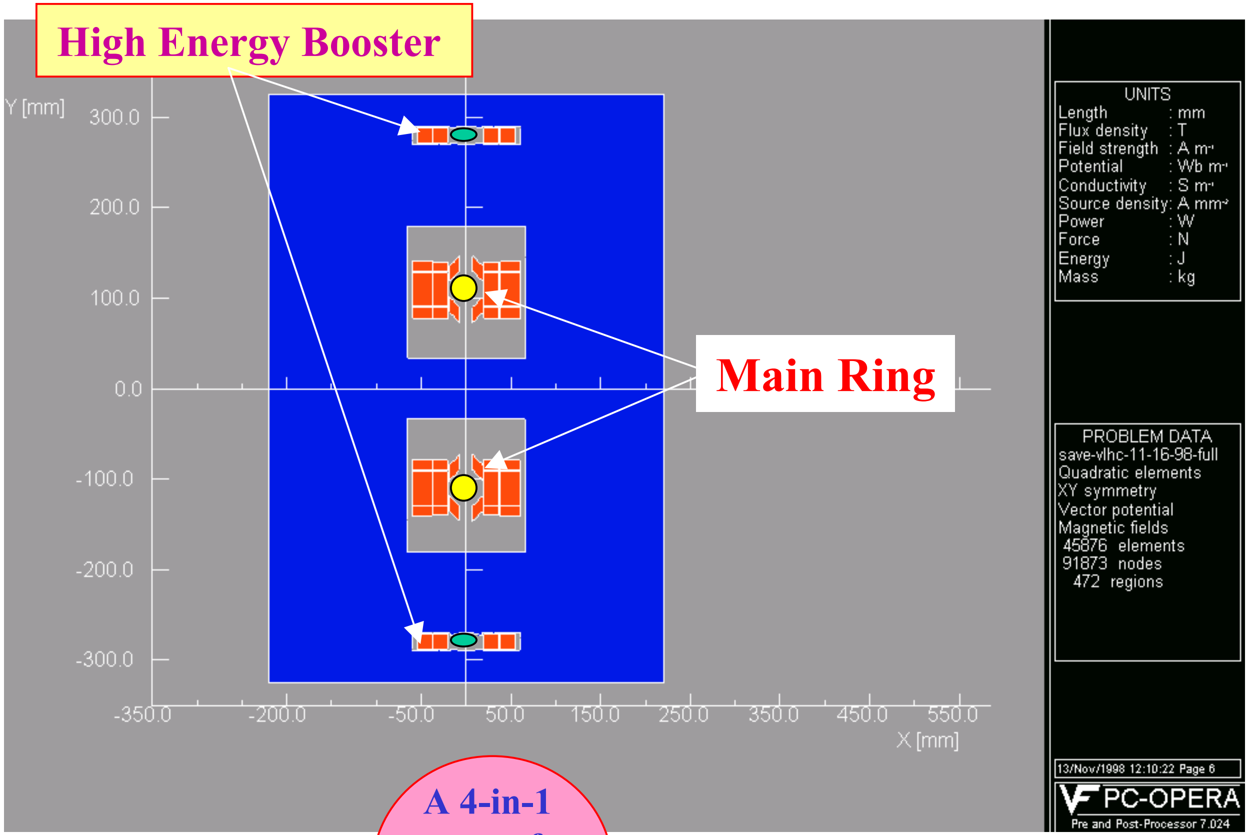


(Derived based on certain assumptions)

A Combined Function Common Coil Magnet System for Lower Cost VLHC

In a conventional superconducting magnet design, the right side of the coil returns on the left side. In a common coil magnet, coil from one aperture returns to the other aperture instead.

- A combined magnet design is possible as the coils on the right and left sides are different.
- Therefore, combined function magnets are possible for both low and high field apertures.
- Note: Only the layouts of the higher energy and lower energy machines are same. The "Lattice" of the two rings could be different.



UNITS
Length : mm
Flux density : T
Field strength : A m^{-1}
Potential : Wb m^{-1}
Conductivity : S m^{-1}
Source density: A mm^{-2}
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
save-vlhc-11-16-98-full
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
45876 elements
91873 nodes
472 regions

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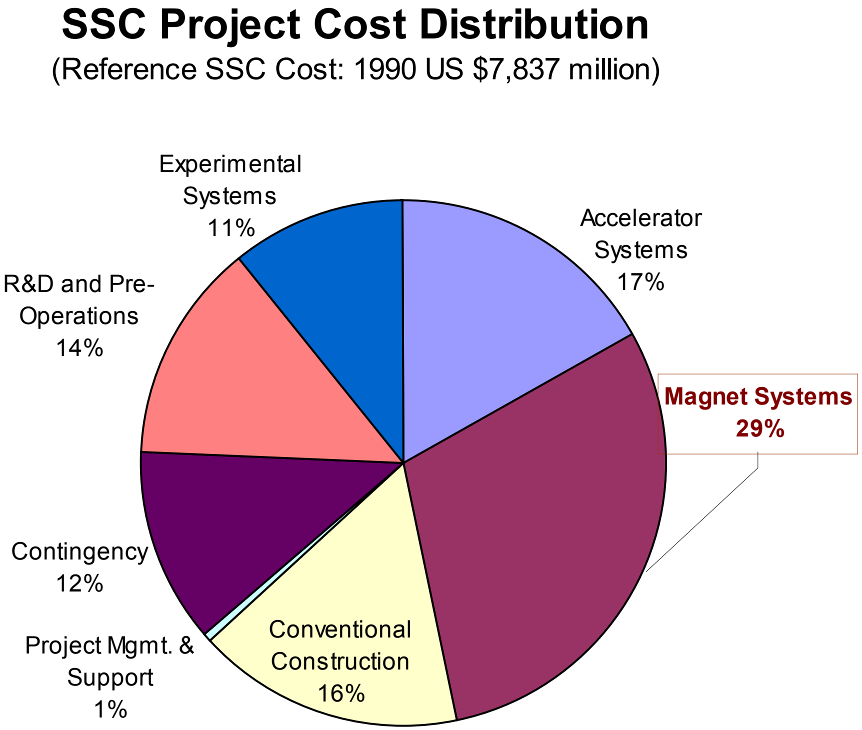
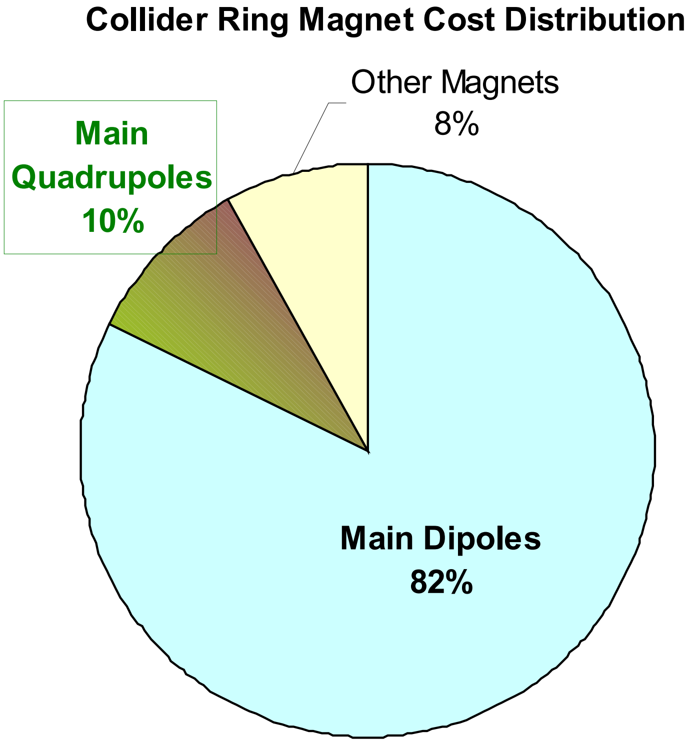
A 4-in-1 magnet for a 2-in-1 machine

A Combined Function Magnet Option (Estimated cost savings for VLHC)





Total:
$2,037 million

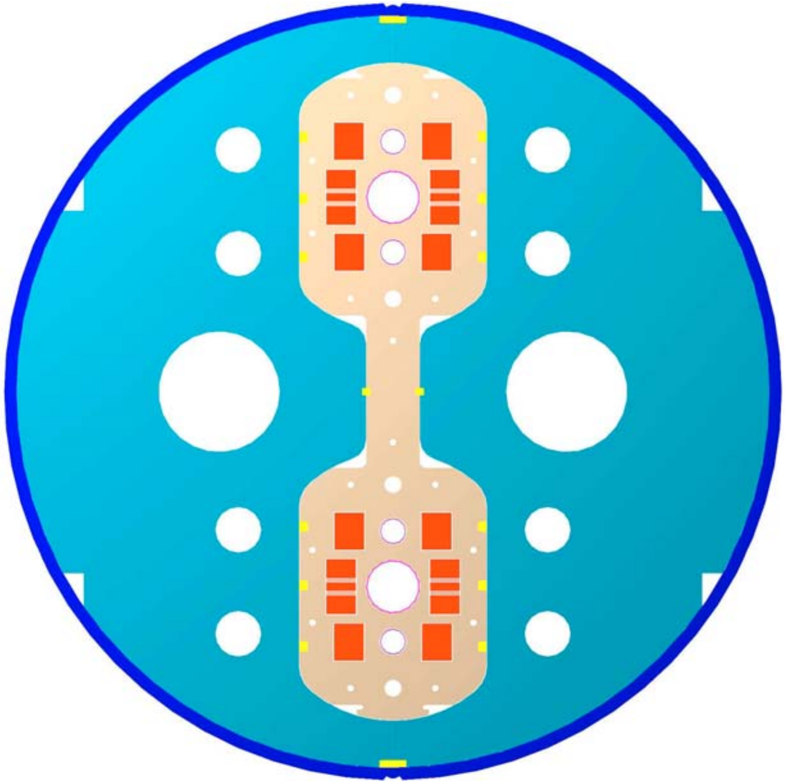
AP Challenge:

Retaining the benefits of the *Synchrotron Damping* in the *High Field Magnet* vlhc option.

SSC (20 TeV) Main Quads: ~$200 million; VLHC (50 TeV) Main Quads: ~$400 million (x2 not 2.5).

Additional savings from tunnel, interconnect, etc.

Status of R&D on Common Coil Magnets



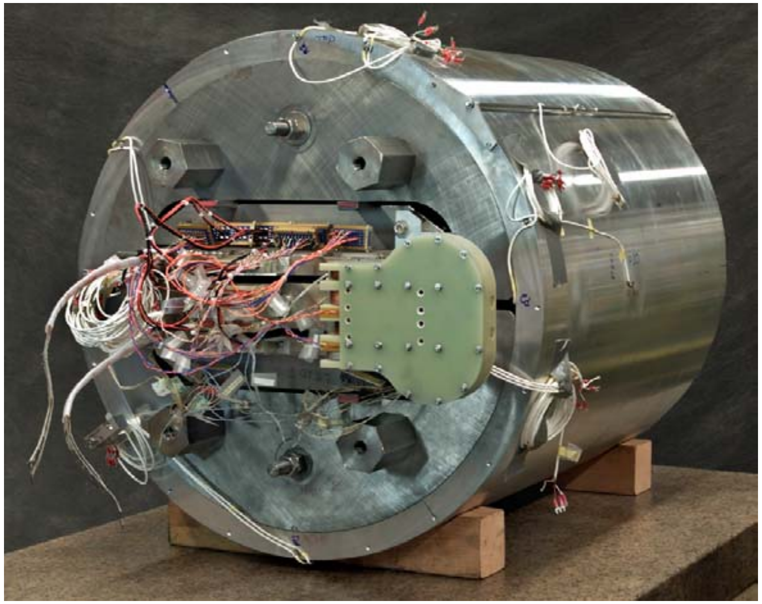
Fermilab Design of Common Coil Magnet for VLHC-2

- A large number of papers (~50) written (a number of designs with good field quality magnets have been presented)
- A significant number (30+) of R&D test magnets built in last few years
- Magnets with both “React & Wind” and “Wind & React” approaches are built
- New superconductors (HTS) are introduced in accelerator magnets
- All three major US labs have built magnets based on this design

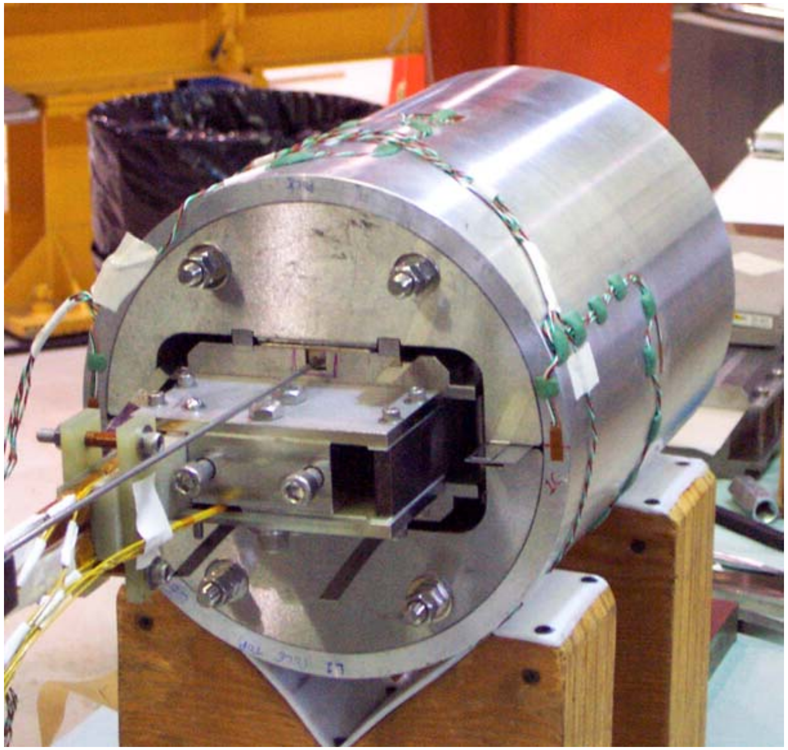
Common Coil Magnets Built at BNL, FNAL, LBNL

BNL

LBNL

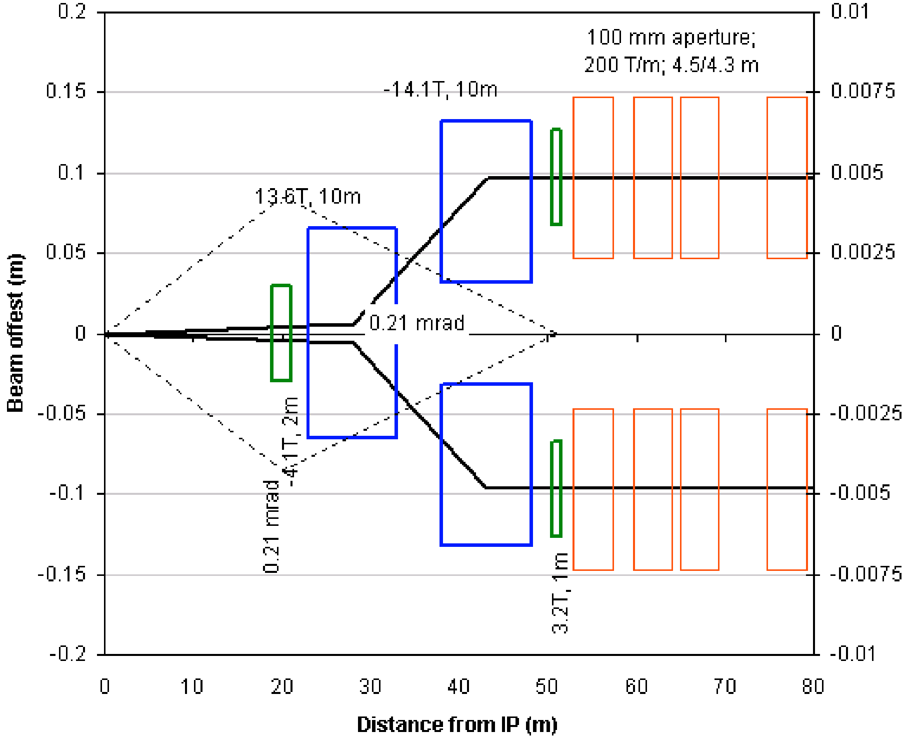


FNAL

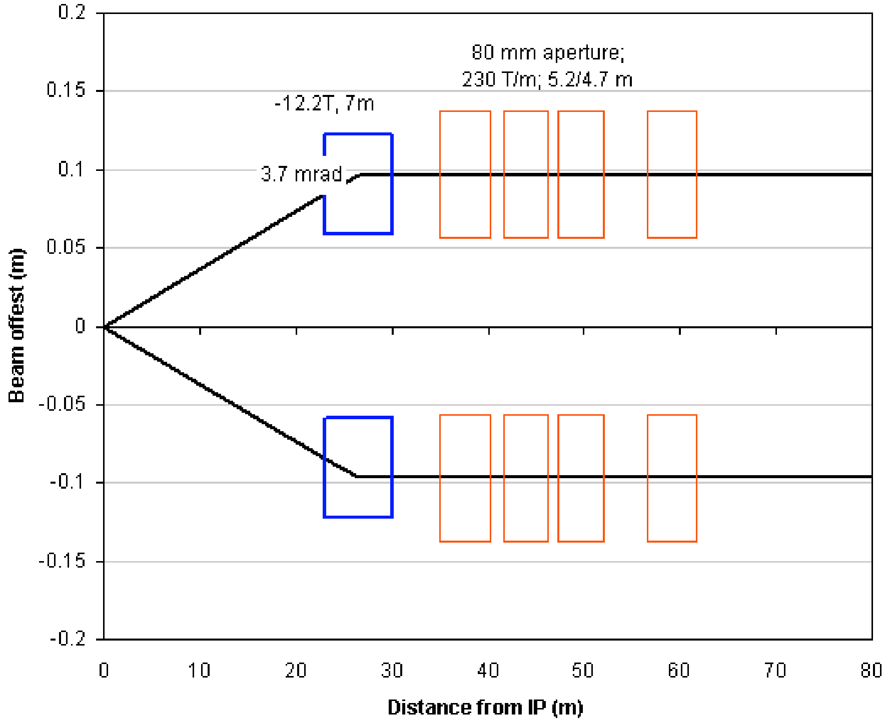


Open Midplane Dipole for A Possible LHC IR Upgrade

Possible Layouts of LHC IR Upgrade Optics for "Dipole First" Option



Small crossing angle



Large crossing angle

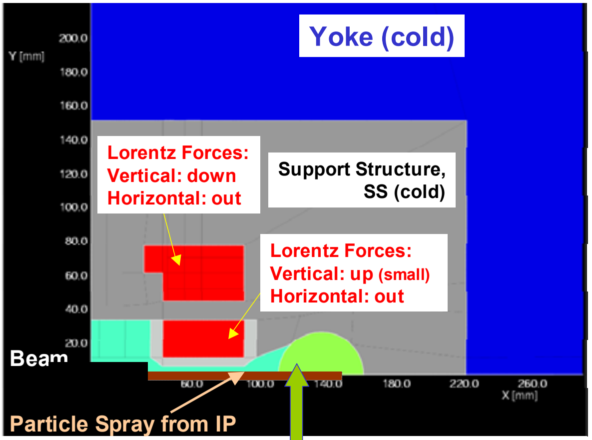
Courtesy: Jim Strait

Special Considerations for LHC Upgrade Dipole Design in "Dipole First Optics"

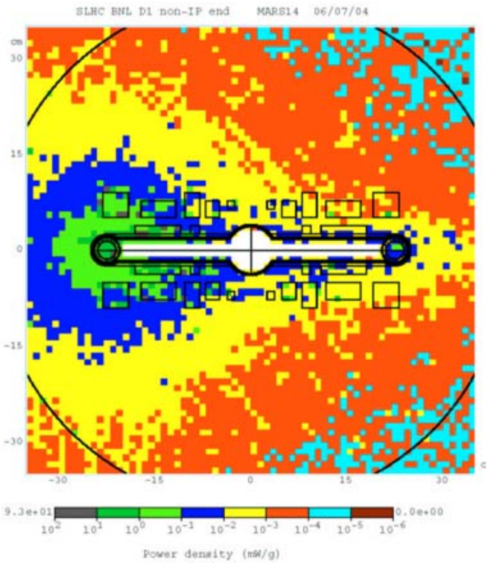
High luminosity (10^{35}) Interaction Regions (IR) present a hostile environment for superconducting magnets by throwing ~9 kW of power from each beam

- This raises two basic challenges :
  - How to design a magnet that can survive these large heat and radiation loads
  - What is the cost of removing these large heat loads both in terms of "new infrastructure" and "operating cost"

Open Midplane Dipole for LHC Luminosity Upgrade
Basic Design Features and Advantages

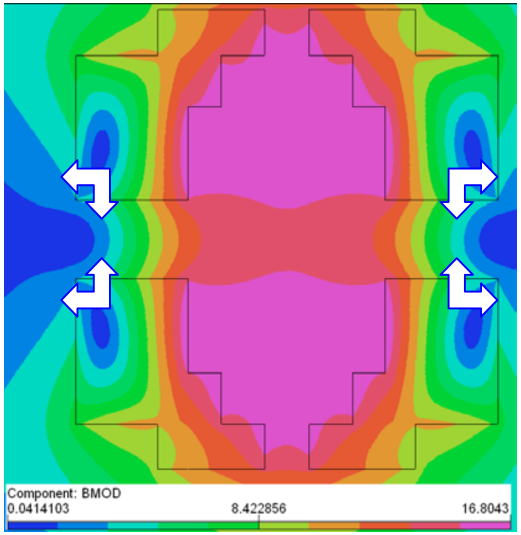


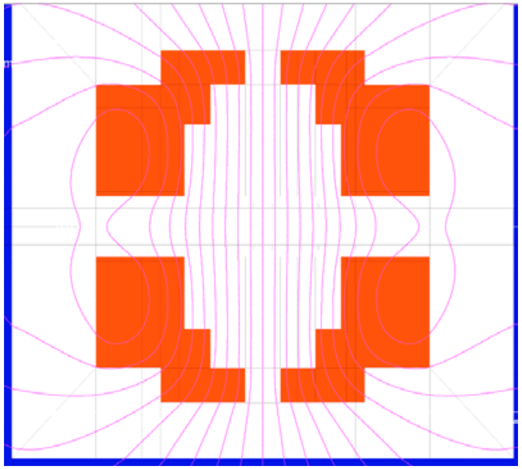
A large amount of particles coming from high luminosity IP deposit energy in a warm (or 80 K) absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.



- ❑ In the proposed design the particle spray from IP deposits most of its energy in a warm absorber, whereas in the conventional design most of the energy is deposited in coils and other cold structures.
- ❑ Calculations for the dipole first optics show that the proposed design can tolerate ~ 9kW/side energy deposited for 10^{35} upgrade in LHC luminosity, whereas in conventional designs it would cause a large reduction in quench field.
- ❑ The requirements for increase in the CERN cryogenic infrastructure and in the annual operating cost would be minimum for the proposed design, whereas in conventional designs it will be enormous.
- ❑ The cost & efforts to develop an open midplane dipole must be examined in the context of overall accelerator system rather than just that of various magnet designs.

Open Midplane Dipole Design
Challenges



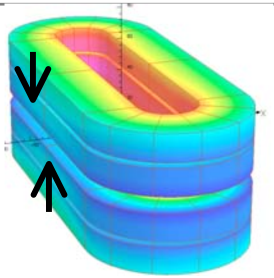


- Attractive vertical forces between upper and lower coils are large than in any high field magnet. Moreover, in conventional designs they react against each other. Containing these forces in a magnet with no structure between the upper and lower coils appears to be a big challenge.
- The large gap at midplane appears to make obtaining good field quality a challenging task.
- The ratio of peak field in the coil to the field at the center of dipole appears to become large as the midplane gap increases.
- Designs may require us to deal with magnets with large aperture, large stored energy, large forces and large inductance.
- With these challenges in place, don’t expect the optimum design to necessarily look like what we are used to seeing.

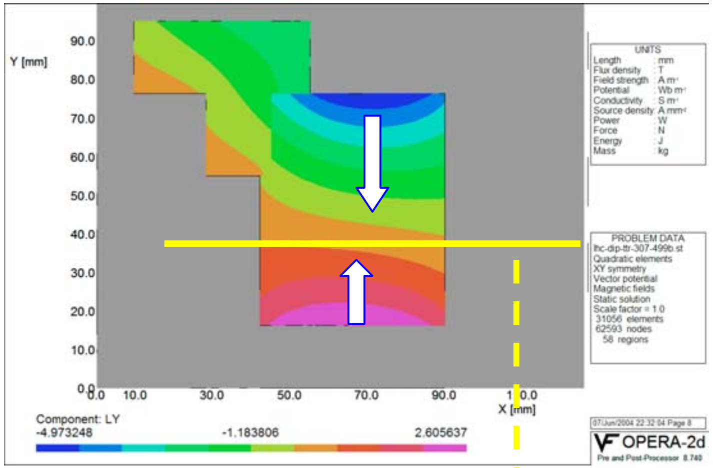
Navigation of Lorentz Forces

A new and major consideration in design optimization

Unlike in conventional designs, in a truly open midplane design the upper and lower coils do not react against each other. As such this would require a large structure and further increase the coil gap. That makes a good field quality solution even more difficult.



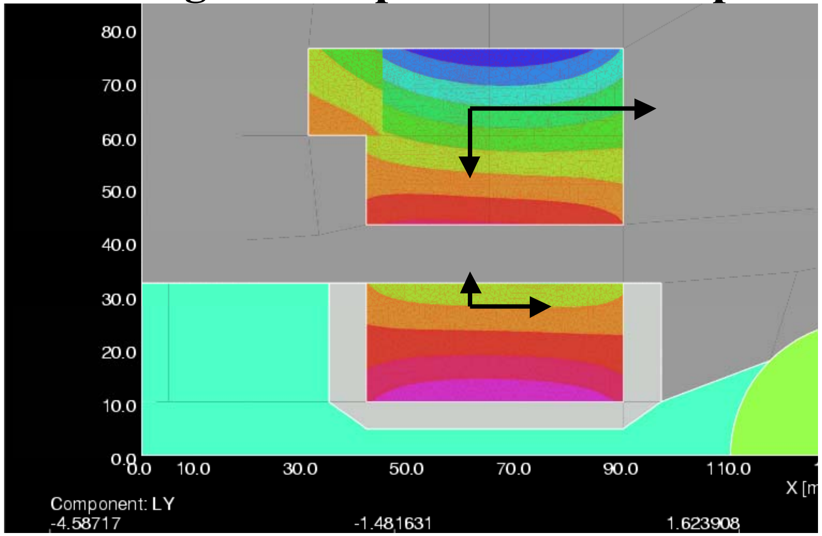
Original Design



Zero vertical force line

Lorentz force density (Vertical)

New Design Concept to reduce midplane gap



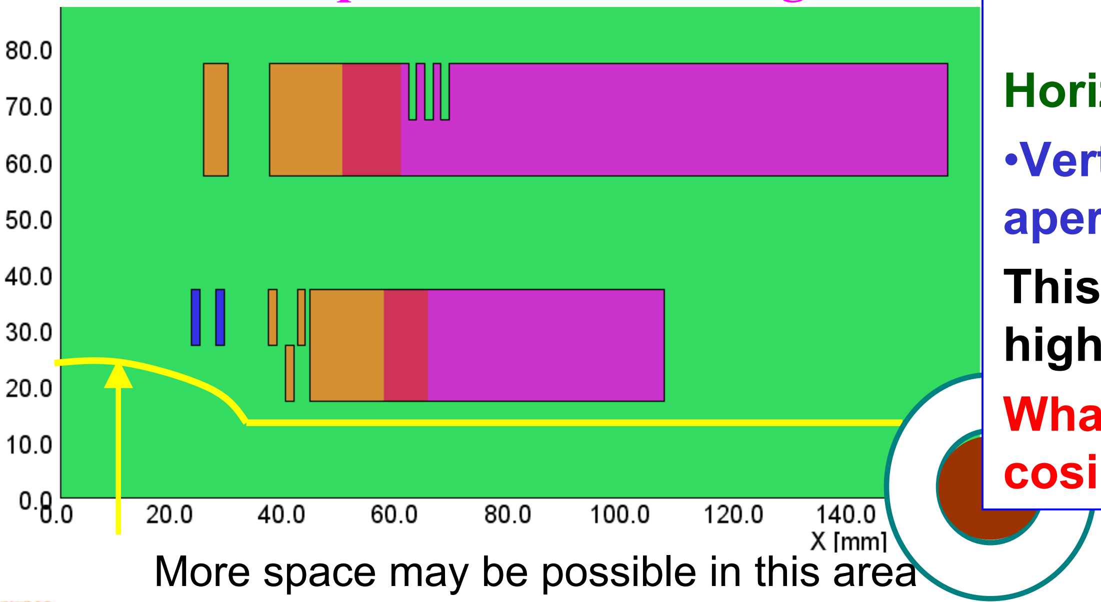
Since there is no downward force on the lower block (there is slight upward force), we do not need much support below it, if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

Magnetic Design and Field Quality

A **critical constraint** in developing the magnetic design of an open midplane dipole **with good field quality** has been the size of the **midplane gap for coil**.

The desired goal is that the gap is large enough so that most showers pass through without hitting anything before hitting the warm target.

One quadrant of the design



More space may be possible in this area

Coil-to-coil gap in latest design
= 34 mm (17 mm half gap)

Horizontal aperture = 80 mm

- Vertical gap is > 42% of horizontal aperture (midplane angle: 23°)

This makes obtaining high field and high field quality a challenging task !

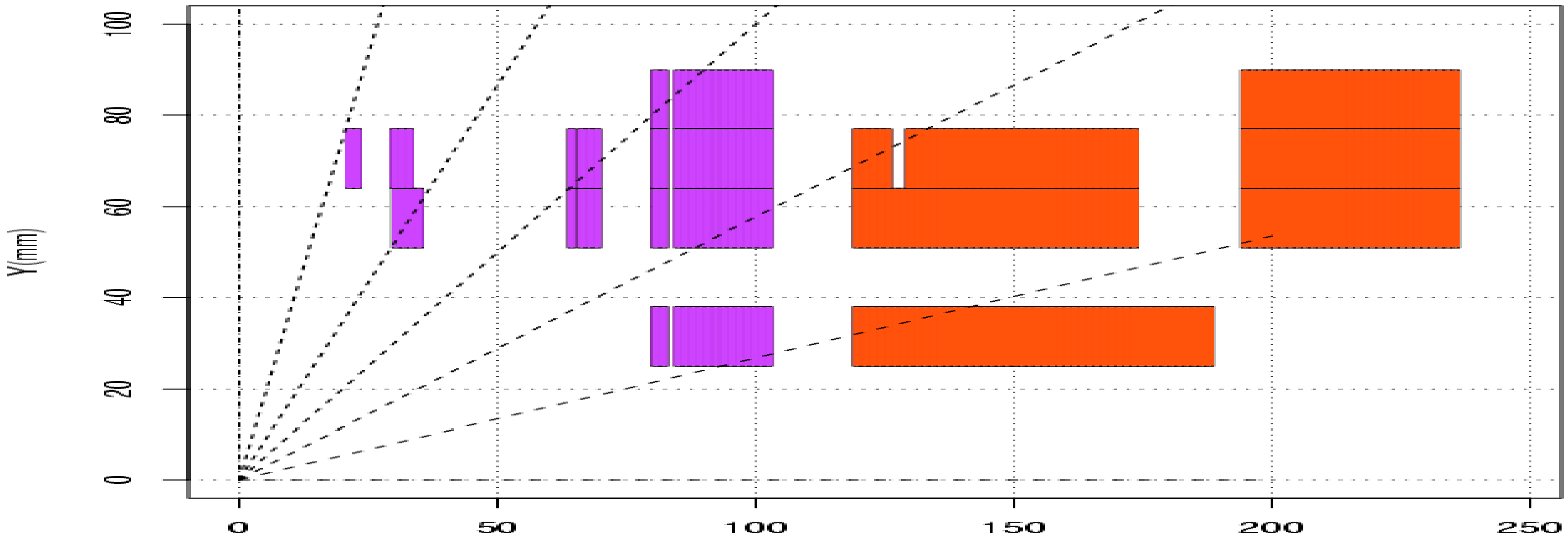
What part of cosine (θ) is left in that cosine (θ) current distribution now?

Hand Optimized Design =>

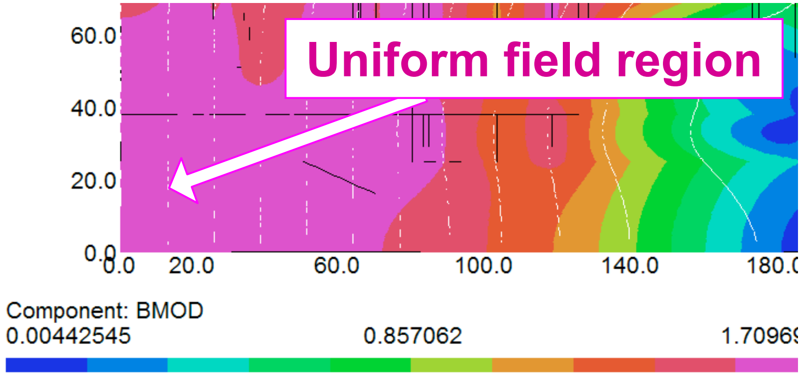
Fine-tuned by RACE2DOPT for Harmonic Minimization

The design is first navigated by hand for "Lorentz Forces", "Support Structure", "Energy Deposition", "Low Peak Field" and better than 10^{-3} "Field Quality".

Then a few select cases are optimized for field harmonics with RACE2DOPT (local code).



Red blocks have 50% higher J_e as compared to the blue blocks.



With several new criteria in optimization, and with no prejudice on how ultimate geometry should look like, we reached a vastly different looking solution.

- Does it look like simulating cosine theta any more?

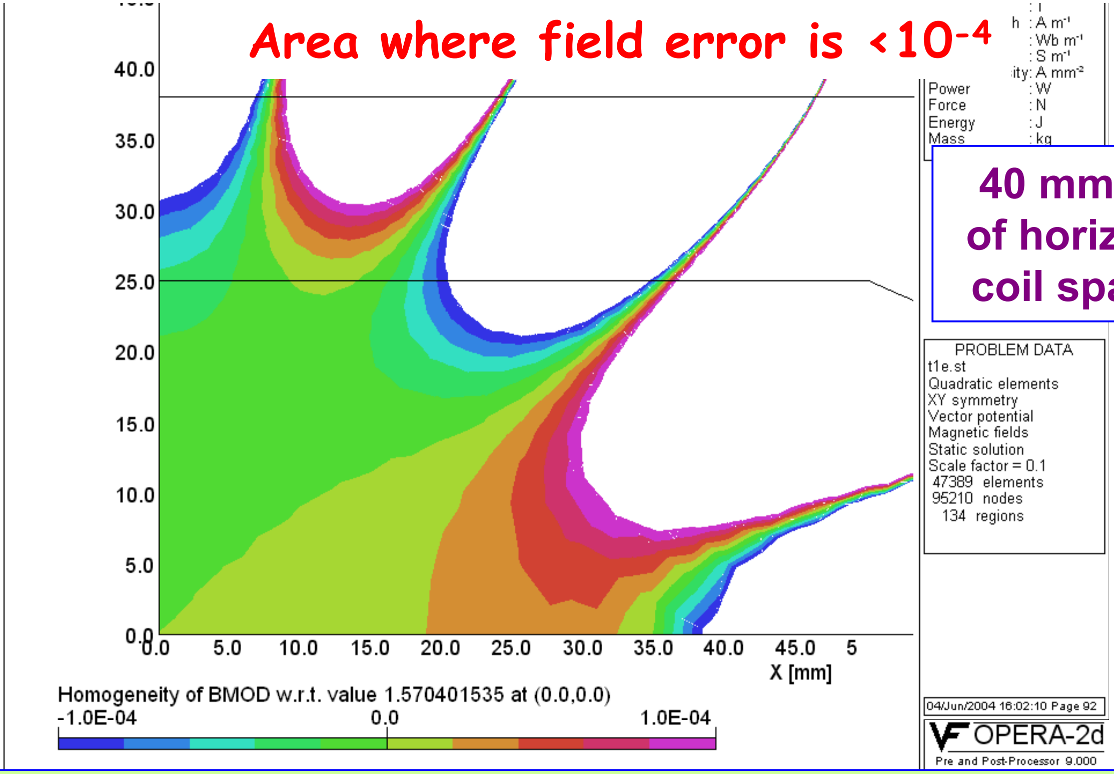
Field Harmonics and Relative Field Errors In An Optimized Design

Proof: Good field quality design can be obtained in such a challenging design:

(Beam @ x=+/- 36 mm at far end)
(Max. radial beam size: 23 mm)

Geometric Field Harmonics:

	Ref(mm)	Ref(mm)
n	36	23
1	10000	10000
2	0.00	0.00
3	0.62	0.25
4	0.00	0.00
5	0.47	0.08
6	0.00	0.00
7	0.31	0.02
8	0.00	0.00
9	-2.11	-0.06
10	0.00	0.00
11	0.39	0.00
12	0.00	0.00
13	0.06	0.00
14	0.00	0.00
15	-0.05	0.00
16	0.00	0.00
17	0.01	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00



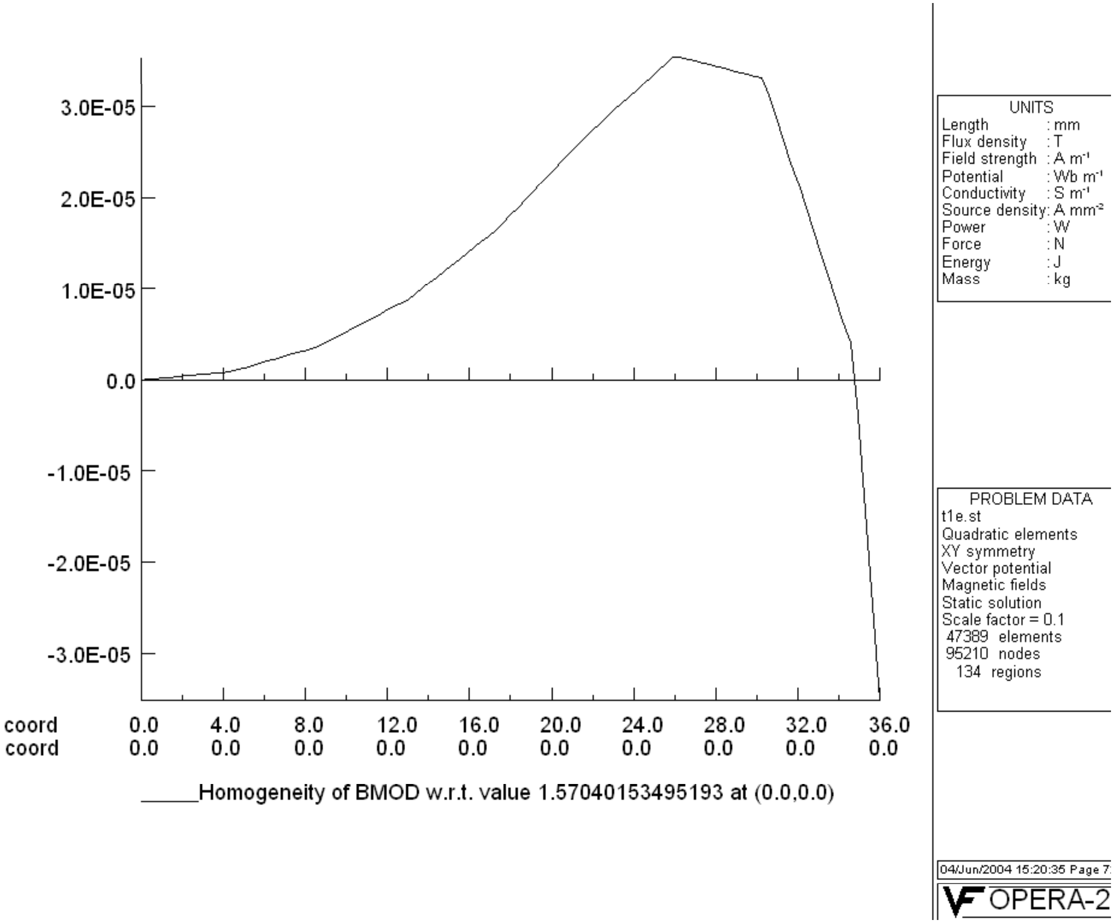
Area where field error is <10^{-4}

40 mm is ½ of horizontal coil spacing

Field errors should be minimized for actual beam trajectory & beam size.
It was sort of done when the design concept was being optimized by hand.
Optimization programs are being modified to include various scenarios.
Waiting for feed back from Beam Physicists on how best to optimize.
However, the design as such looks good and should be adequate.

Field Uniformity in An Optimized 15 T Open Midplane Dipole Design

Proof that good field quality can be obtained in such a wide open midplane dipole design (~1/2 of vertical and ~1/3 of horizontal aperture):



Homogeneity of BMOD w.r.t. value 1.57040153495193 at (0.0,0.0)

UNITS

Length	mm
Flux density	T
Field strength	A m^{-1}
Potential	Wb m^{-1}
Conductivity	S m^{-1}
Source density	A mm^{-2}
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA
t1e.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 0.1
47389 elements
95210 nodes
134 regions

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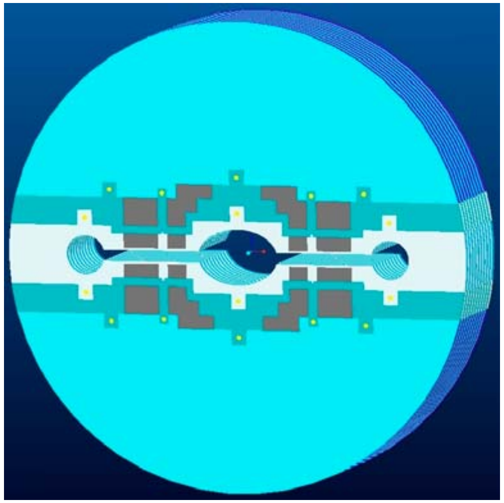
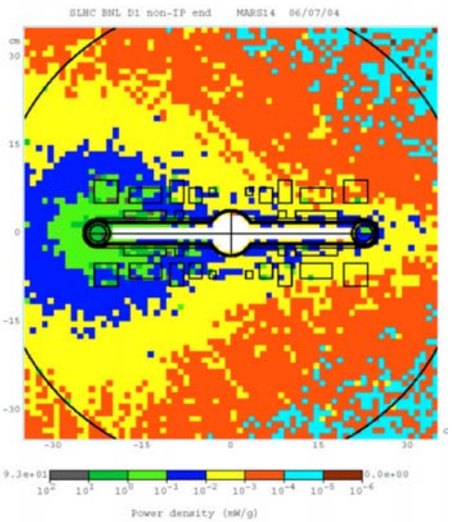
The maximum horizontal displacement of the beam at the far end of IP is +/- 36 mm.

The actual field errors in these magnets will now be determined by construction, persistent currents, etc.

A True Open Midplane Design

By open midplane, we mean truly open midplane:





Particle spray from IP (mostly at midplane), passes through an open region to an absorber sufficiently away from the coil without hitting anything at or near the superconducting coils.

In earlier "open midplane designs", although there was "no conductor" at the midplane, but there was some "other structure" between the upper and lower halves of the coil. Secondary showers from that other structure deposited a large amount of energy on the coils.

The energy deposited on the superconducting coils by this secondary shower became a serious problem. Therefore, earlier open midplane designs were not that attractive.

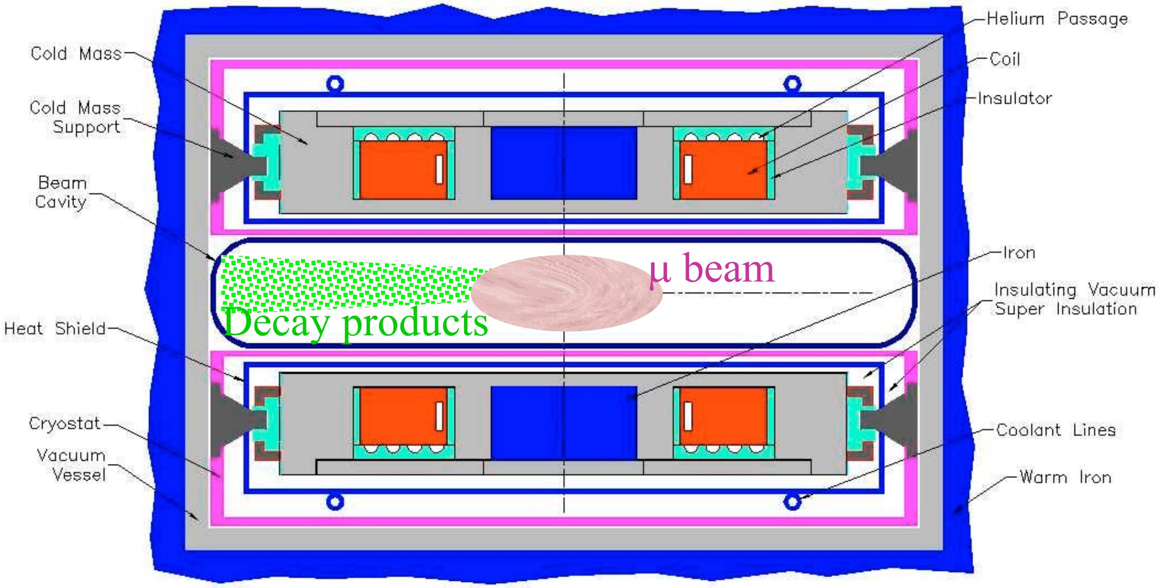
Alternate Magnet Design for a Compact ν Factory Storage Ring

Design Principles and Requirements:

Decay products clear superconducting coils

Compact ring to minimize the environmental impact (the machine is tilted)

⇨ Need high field magnets and efficient machine design



Storage ring magnet design

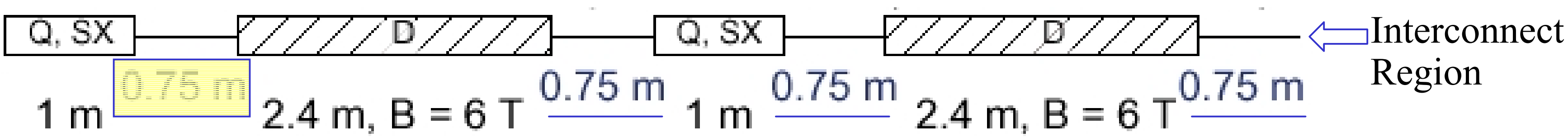
(simple racetrack coils with open midplane)

Lattice & Magnet Designs for a Compact Ring

- Dipoles are great but how about decay products hitting quads (more)

Skew quadrupoles do NOT need conductor at midplane (B. Parker)

- In study 1 (50 GeV), ~1/3 space was taken by inter-connect regions



Interconnect Region

Gets worse at lower energy (50 => 20 GeV in study 2)

- New magnet system design makes a productive use of all space

Quadrupole(Q): Field Gradient

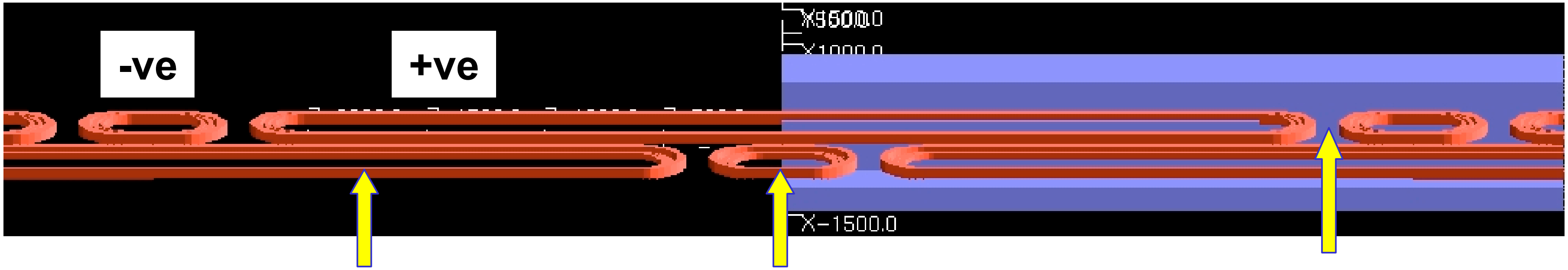
Dipole(D): Field

No space is wasted for interconnect

Shorter cells ⇨ smaller aperture, improved beam dynamics

Alternate End Design Concept

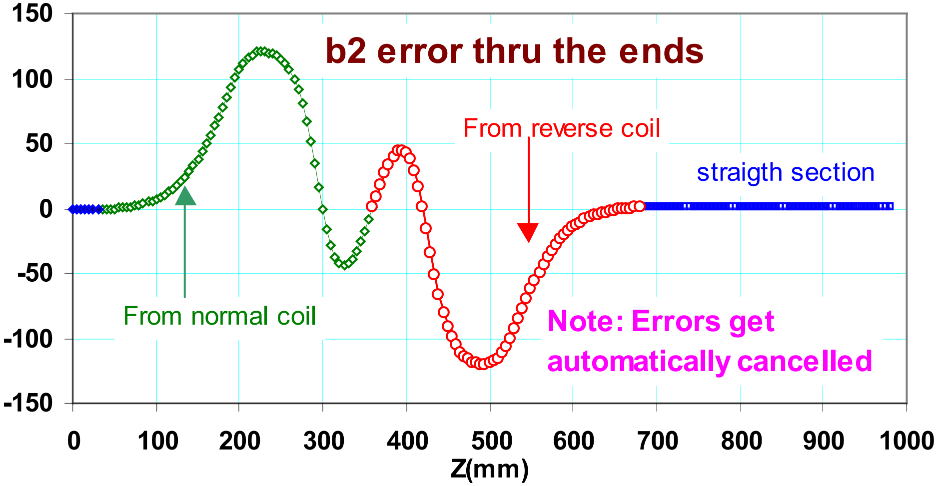
- Reverse coils to cancel field harmonics in ends (also generate skew quad)

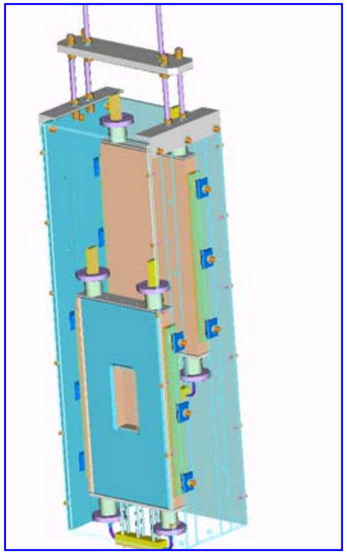


Normal Coils
Dipole

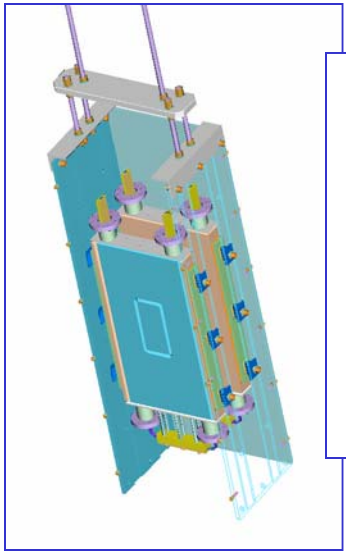
Reverse Coils
Skew Quad

One Coil
1/2 & 1/2





Staggered coil setup

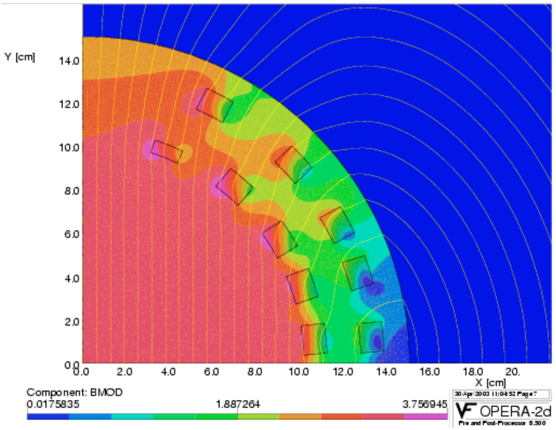


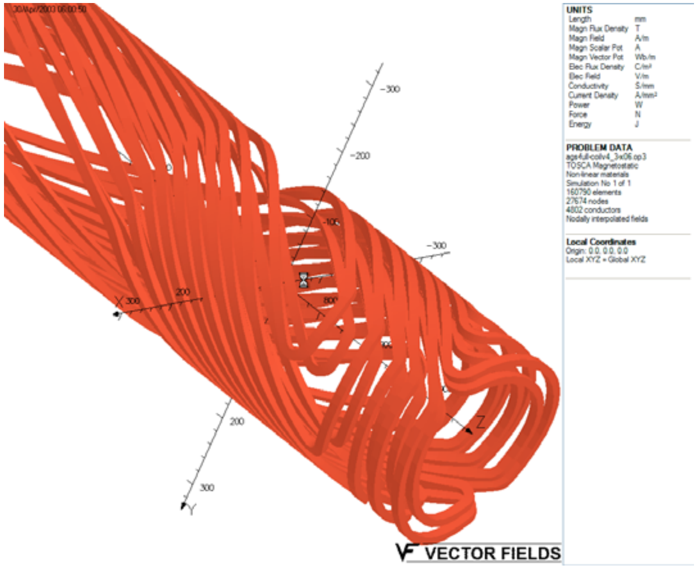
Dipole/ Quad test setup (switch relative current direction)

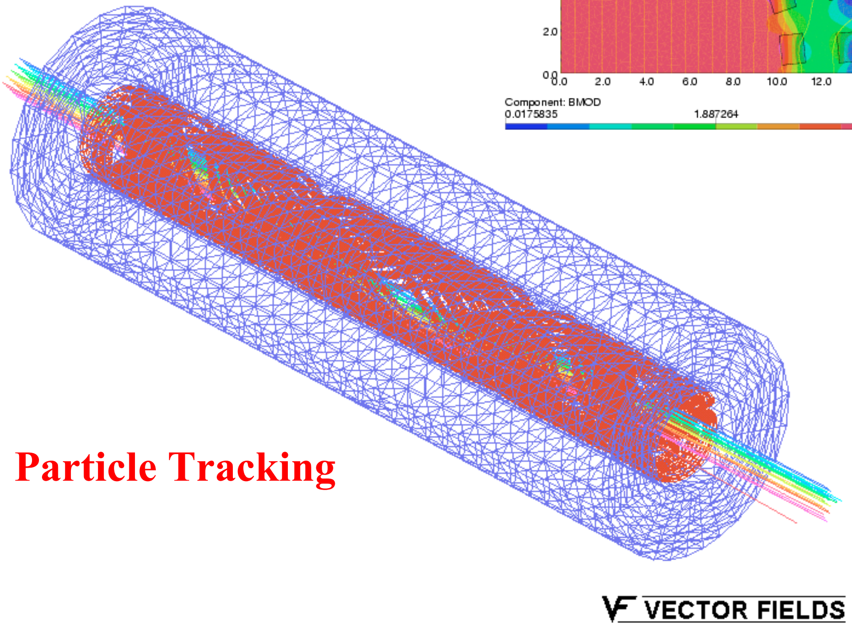
Note: Bx & By (normal and skew harmonics) are cancelled but Bz (axial field) is not.

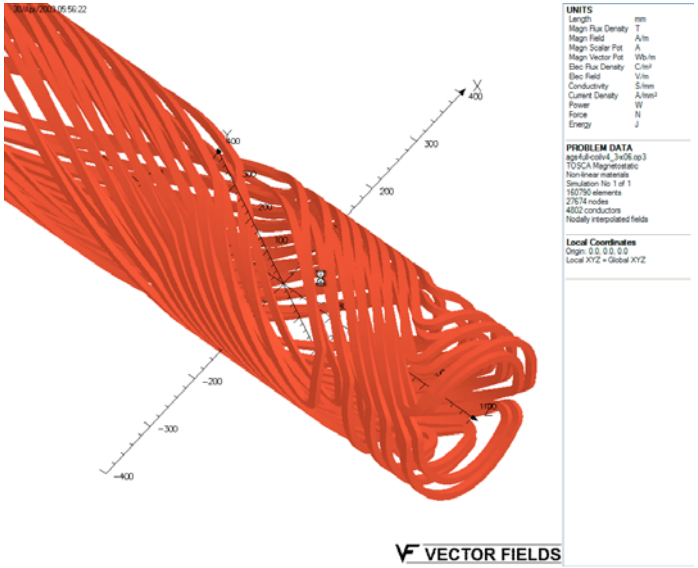
A Helical Magnet for the AGS at BNL (1)

This magnet uses helical coils to maintain the polarization of the beam as it passes spin resonances in AGS.



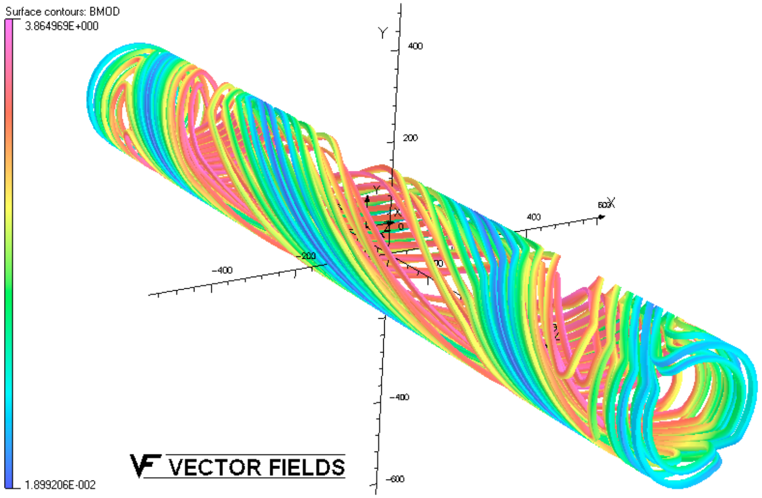


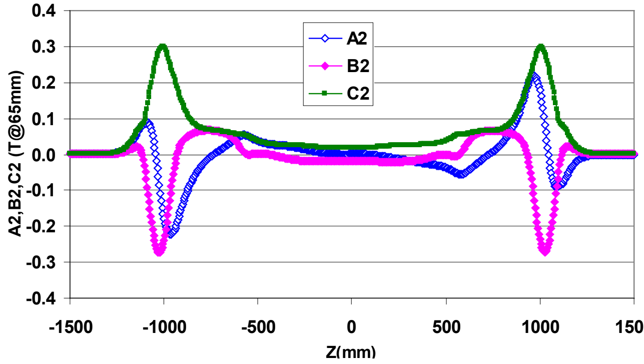


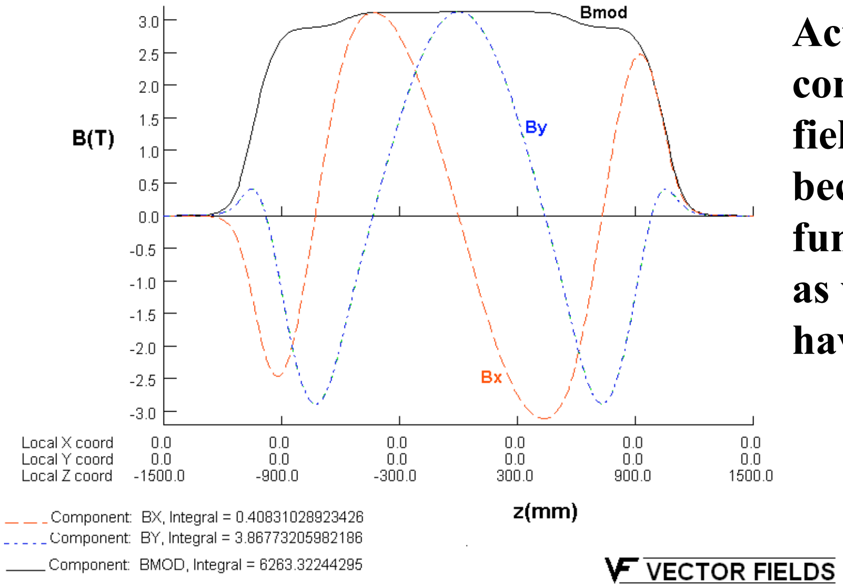


Note: Particle Tracking

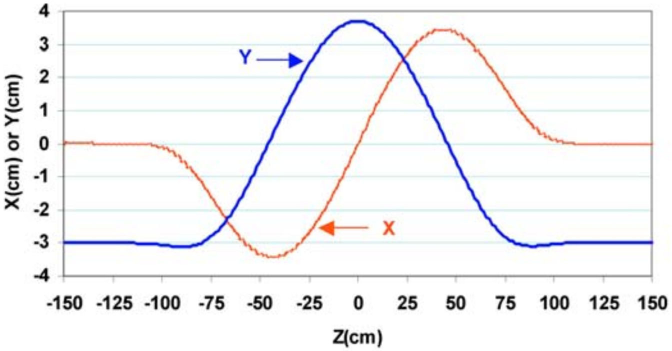
A Helical Magnet for the AGS at BNL (2)

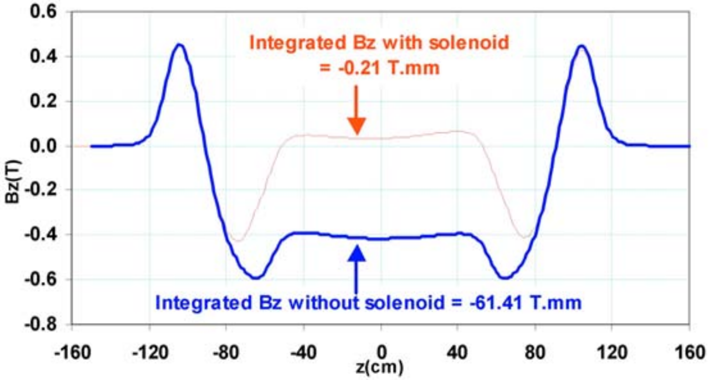






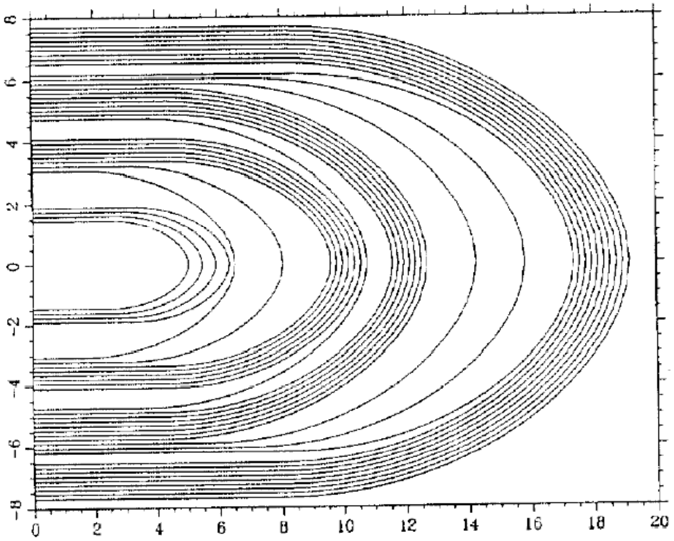
Actually, the conventional field harmonics become a function of "R" as we do not have 2-d fields.





Very Short Length Magnets

- Sometimes, you need to make magnets very short.
- Mostly because of limited availability of space.
- The question is how short magnets can one build?



Conventional Design. RHIC Dipole (Kahn, Morgan, et al.)

- In conventional approach, one first optimizes straight section and then the ends.
- The minimum physical space in ends is the space required by turns in straight section.
- In addition, often one puts the end spacer to minimize peak field and end harmonics.
- Similarly, there are spacers (wedges) in the straight section that reduces the maximum field that can be created within given slot.
- In conventional designs, these requirements limit the minimum length of the magnet still having a reasonable transfer function.

Effective magnetic length of ends is typically half the mechanical length of ends.

Optimum Integral Design for Making Very Short Magnets

In a typical conductor dominated design, first the coil cross section is initially optimized for the (2n) multipole to create a *cosine (nθ)* type azimuthal current distribution:

$$I(\theta) = I_o \,.\, \cos(n\theta)$$

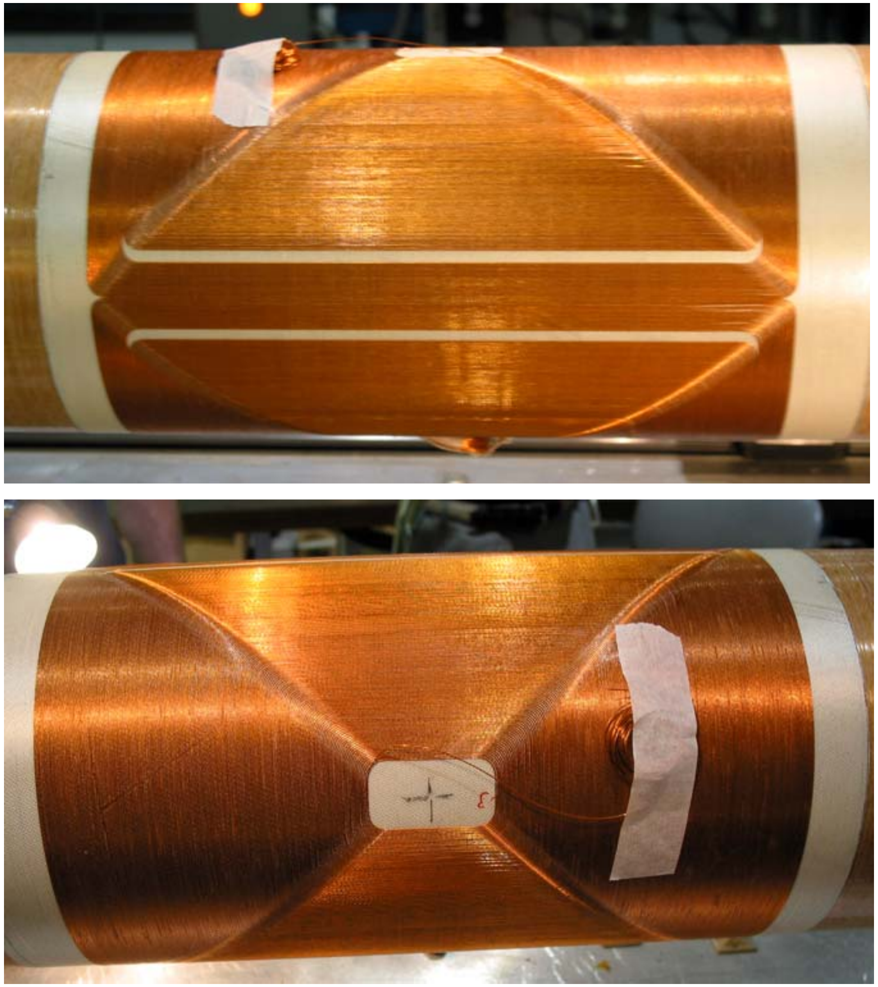
The ends are then optimized to minimize the integral end harmonics and to reduce the peak field on the conductor surface. This 2-step optimization creates a magnet with low integral harmonics but, unfortunately, also one that has a magnetic length that is smaller than the coil length, typically by a coil diameter/(*n*).

In the proposed *Optimum Integral Design*, the length of the midplane turn is the same as the coil mechanical length (end-to-end) with bend radius of turns in the ends approaching zero. If there are no spacers in the ends or in the straight section, and if all turns are equally spaced, then the length of successive turns decreases linearly in going from midplane to pole. One way to obtain an ideal current distribution (in integral sense) is to modulate the length of each turn so that it is proportion to *cosine (nθ)*. In a more practical approach, the integral modulation will be obtained with the help of a computer program after distributing a total of "*N*" turns in a few end blocks and/or in a few cross-section blocks. The size of spacers between the blocks will be optimized to achieve an integral distribution varying azimuthally as:

$$I(\theta) \,.\, L(\theta) = I_o \,.\, L_i(\theta) \propto I_o \,.\, L_o \,.\, \cos(n\theta)$$

Since the cosine theta modulation is normalized to the current I_o and the length L_o (end-to-end coil length), this equation suggests that the integral field of the magnet may be closer to typical 2-d field times the mechanical length of the coil (L_o). This is a significant improvement from the designs where the loss in effective magnetic length from L_o is about a coil diameter/(*n*).

Short Dipole Built with Optimum Integral Design



AGS corrector dipole coil built on the Optimum Integral Design.

Note that the midplane turns span almost the full end-to-end coil length and the coil has a high fill factor.

Field harmonic are optimized in integral sense.

***I*(*θ*) distribution will be linear without spacer.**

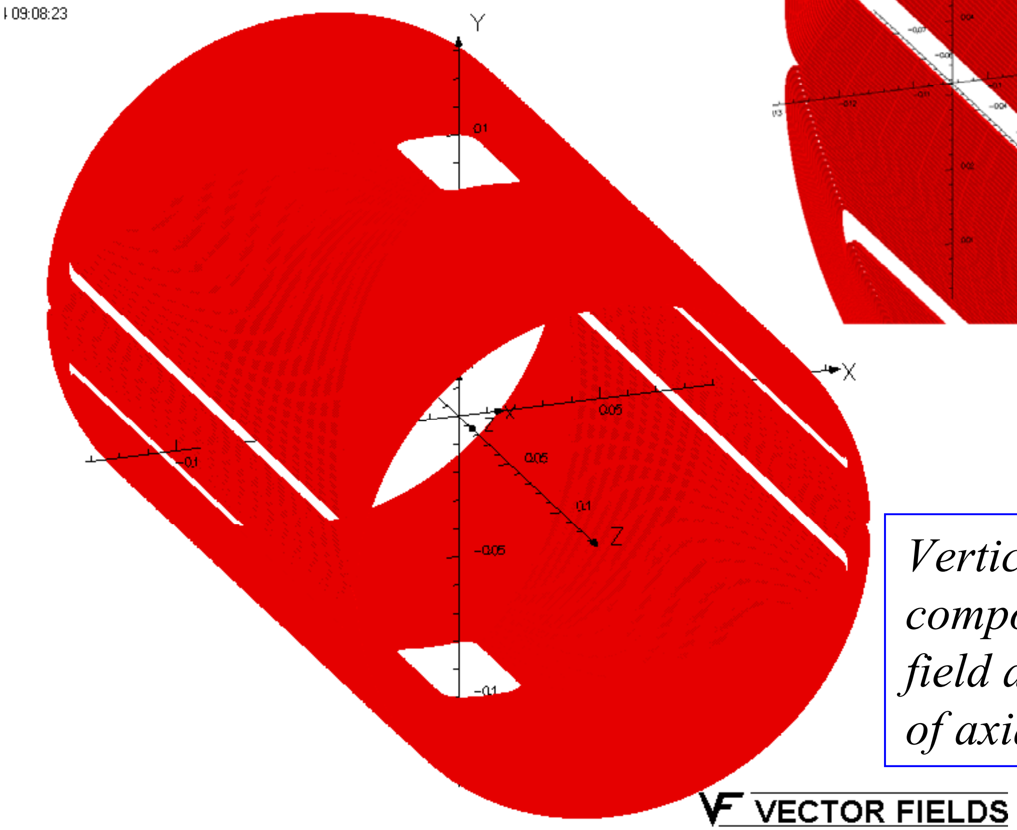
One spacer in between the turns and one at pole modulate it to cosine theta to a level acceptable for corrector magnets.

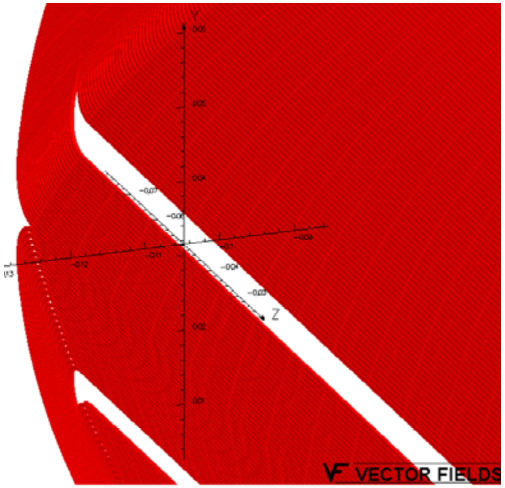
TABLE I
Computed Integral Field Harmonics in the AGS Corrector Dipole Design at a Reference Radius of 60 mm. The Coil Radius is 90.8 mm. Note b_2 is sextupole mutliplied by 10^4 (US conventions).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.0082 @ 25 A	0.4	0.8	-4.7	4.1	5.3	2.4

Reasonable agreement was found between calculations and measurements.

OPERA3-d Model of AGS Corrector Dipole Based on Optimum Integral Design



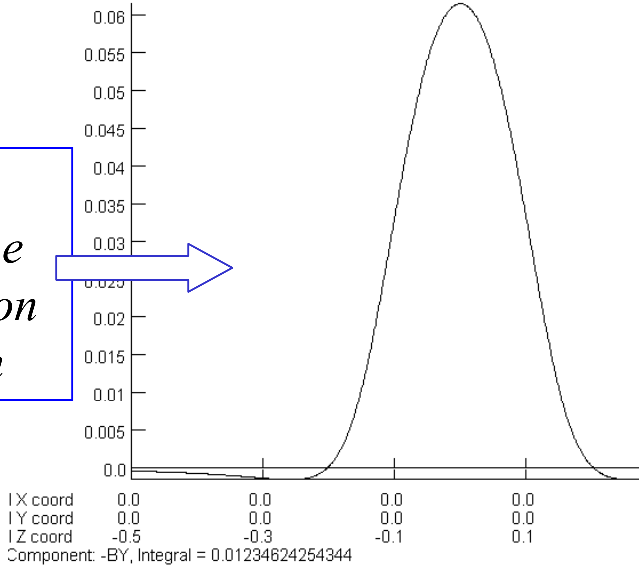


Conventional straight section is very small.

Or is it there any at all?

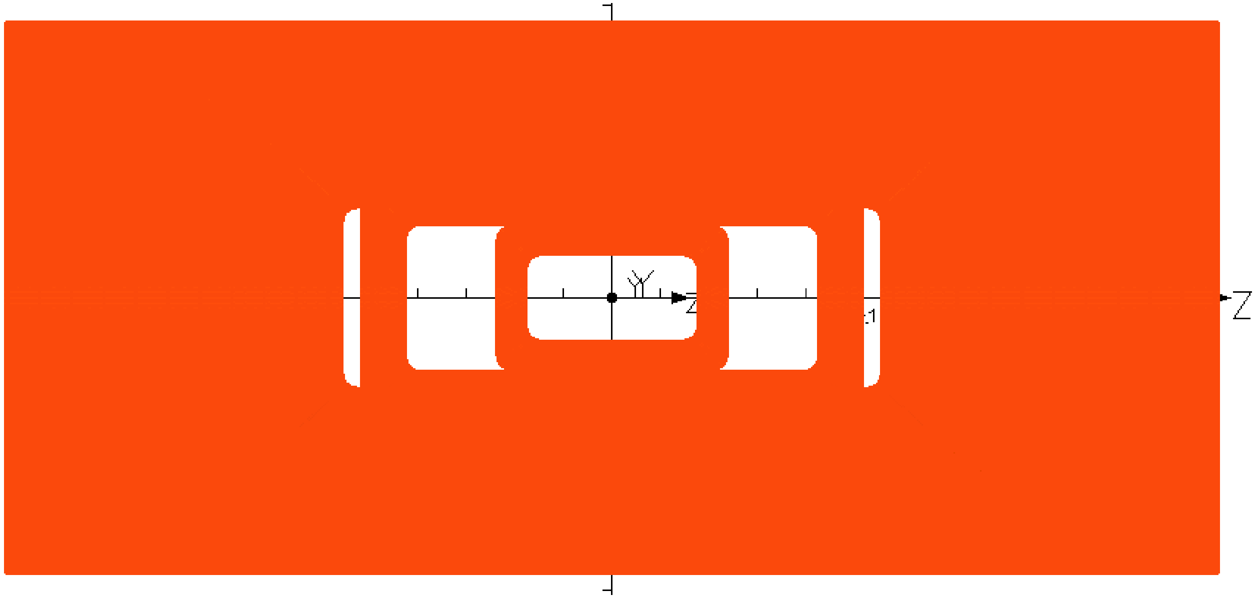
As such in this case, the straight section does not have any practical significance.

Vertical component of the field as a function of axial position



A Dipole Optimized with End Spacers Only (no wedges)

OPERA-3d model of a 2-layer coil (seen from the top/pole) based on the Optimum Integral Design. It has no spacers (wedges) in the cross-section and has only two each in the either end of the inner layer.

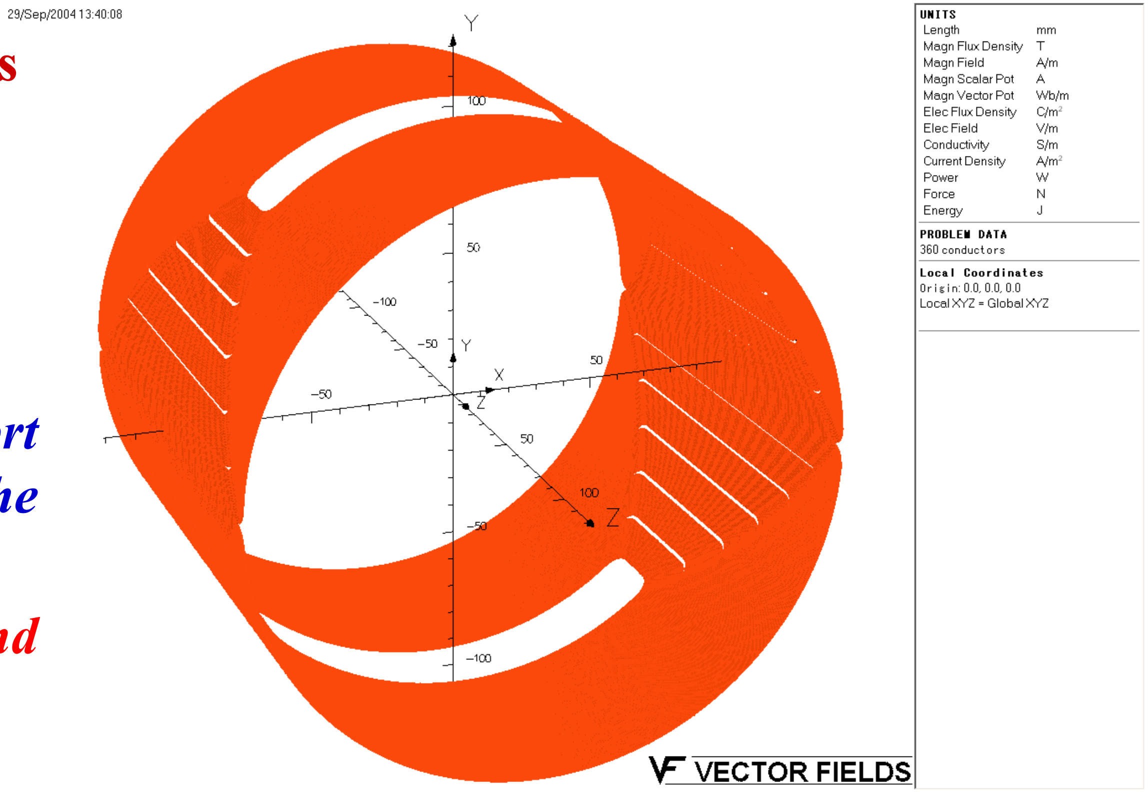


COMPUTED INTEGRAL HARMONICS IN A DIPOLE THAT IS OPTIMIZED WITH TWO END SPACERS ONLY AS NO STRAIGHT SECTION SPACER WAS USED. THE REFERENCE RADIUS IS 50 MM AND THE COIL RADIUS IS 111.9 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.247 @ 27 A	3.0	4.0	4.5	-0.6	0.1	0.0

Dipole with Coil Length Less Than Coil Diameter

In this example, no end spacers are used. The optimization is done with wedges (or cross-section spacers) only.



UNITS	
Length	mm
Magn Flux Density	T
Magn Field	A/m
Magn Scalar Pot	A
Magn Vector Pot	Wb/m
Elec Flux Density	C/m^2
Elec Field	V/m
Conductivity	S/m
Current Density	A/m^2
Power	W
Force	N
Energy	J

PROBLEM DATA
360 conductors

Local Coordinates
Origin: 0.0, 0.0, 0.0
Local XYZ = Global XYZ

OPERA3d model of a short length dipole based on the Optimum Integral Design.

Coil length is ~175 mm and coil diameter is 200 mm.

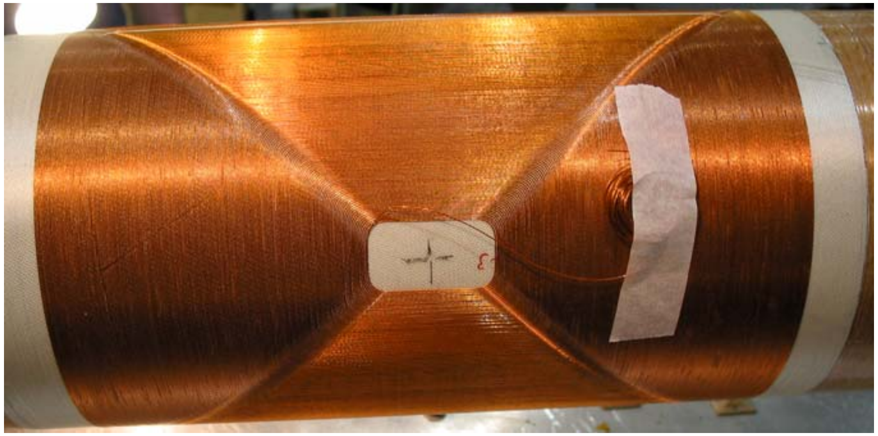
TABLE III
COMPUTED INTEGRAL FIELD HARMONICS FOR A SHORT DIPOLE (COIL LENGTH < DIAMETER) AT A RADIUS OF 66.6 MM. THE COIL RADIUS IS 100 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.00273 @ 25 A	0.0	0.0	0.0	0.0	0.0	0.0

Note: A very good field quality is obtained.

Other Multi-pole Magnets (How short can they be?)

- A Quadrupole with Coil Length Less Than Coil Radius
- A Sextuupole with Coil Length 1/3 of Coil Diameter



- **Remember you need some space to return the turns in the body of the magnet (of the order of diameter in dipole, of the order of radius in quadrupole, etc.).**
- **This design allows magnets to be practically as small as possible while allowing a good fill factor for turns and hence, in turn, a good transfer function.**
- **We have already proved that it is possible to obtain good integral field quality in such designs.**

SUMMARY

- New magnet designs are being investigated for next generation accelerator projects and upgrades.

- A variety of alternate magnet designs (alternate to conventional cosine theta geometry) based on racetrack coil magnets opens new and exciting possibilities for future high field magnets.

- We invite you to join this challenging field. There are still many opportunities to invent new designs and develop new and better and cheaper magnet technology. So please join us and ...

Have Fun !