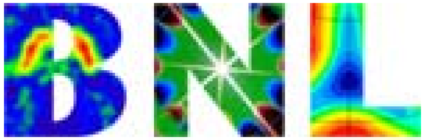
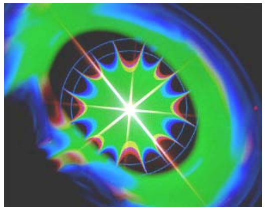
High Field Magnet Designs

(with an emphasis on alternate magnet designs --- alternate to cosine theta)

Ramesh Gupta
Superconducting Magnet Division
Brookhaven National Laboratory
Upton, NY 11973 USA





Main Issues in High Field Magnets

Superconductor:

The superconductor used in the magnet must have good current density at high fields

Mechanical Support Structure:

The support structure must be able to withstand large Lorentz forces

Forces $\propto$ B^2

In a cosine theta dipole with current at radius "a", $F_x = \frac{2B_o^2}{3\mu_o} a$

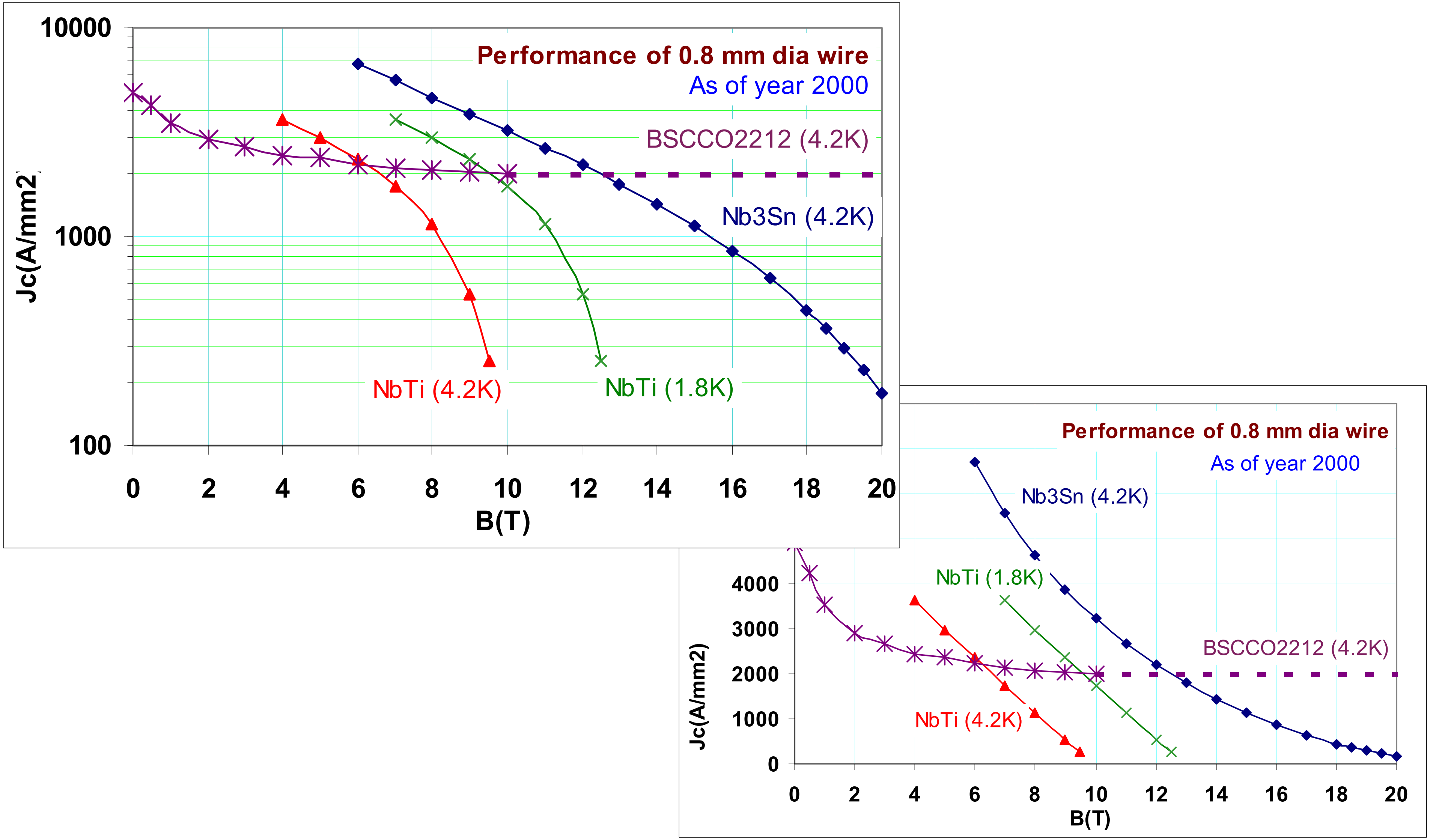
Minimize conductor motion that causes quench

Magnetic Design:

Maintain an acceptable field quality through out the operating range

Optimize a design to deal with the above two challenges and if possible find one where the above two problems are inherently reduced

Performance of Selected Superconductors



Present Magnet Design and Technology

Tevatron Dipole

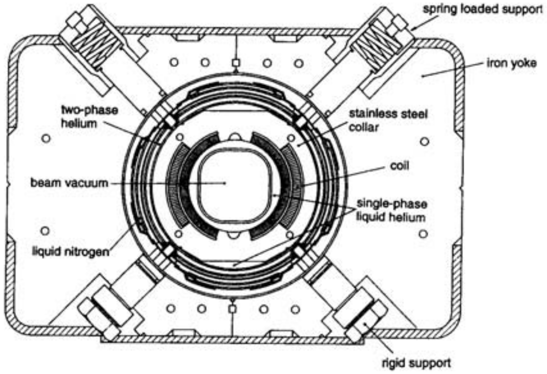
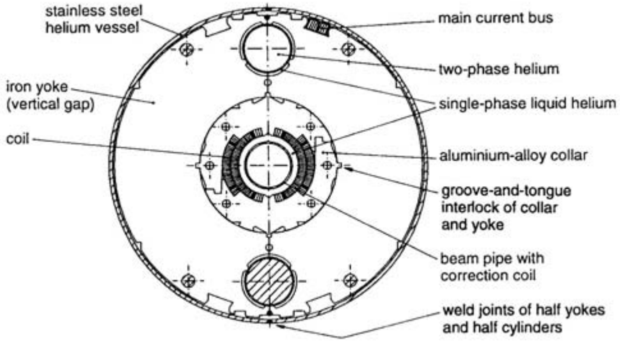
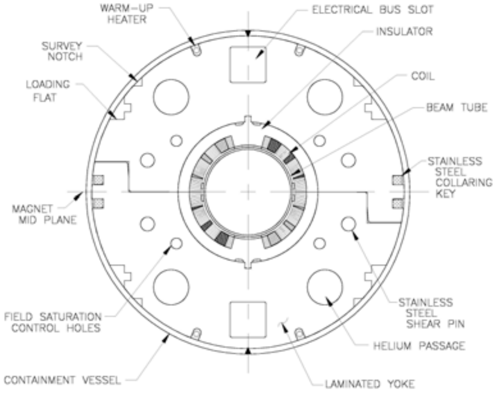


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

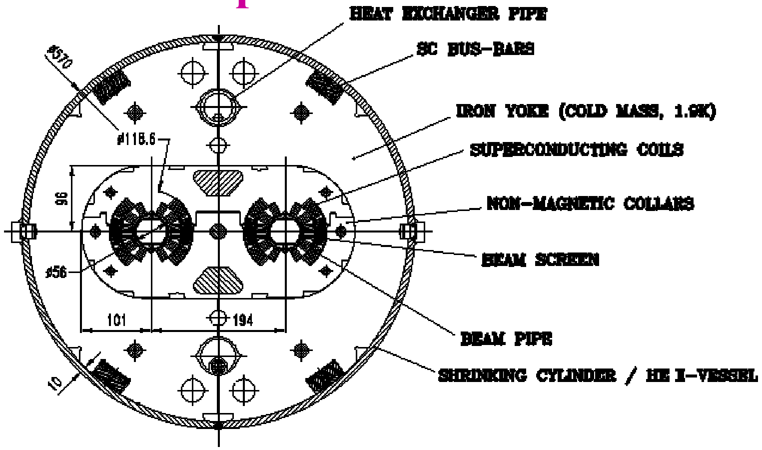
HERA Dipole



RHIC Dipole



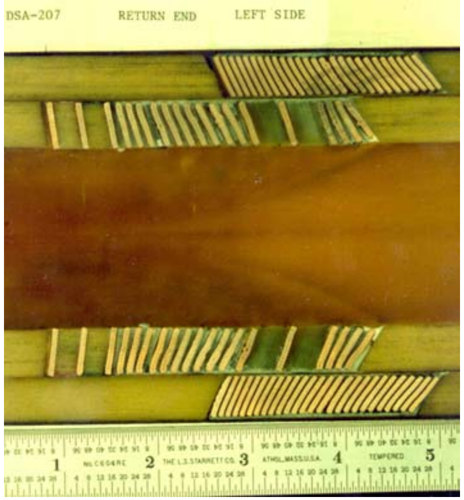
LHC Dipole



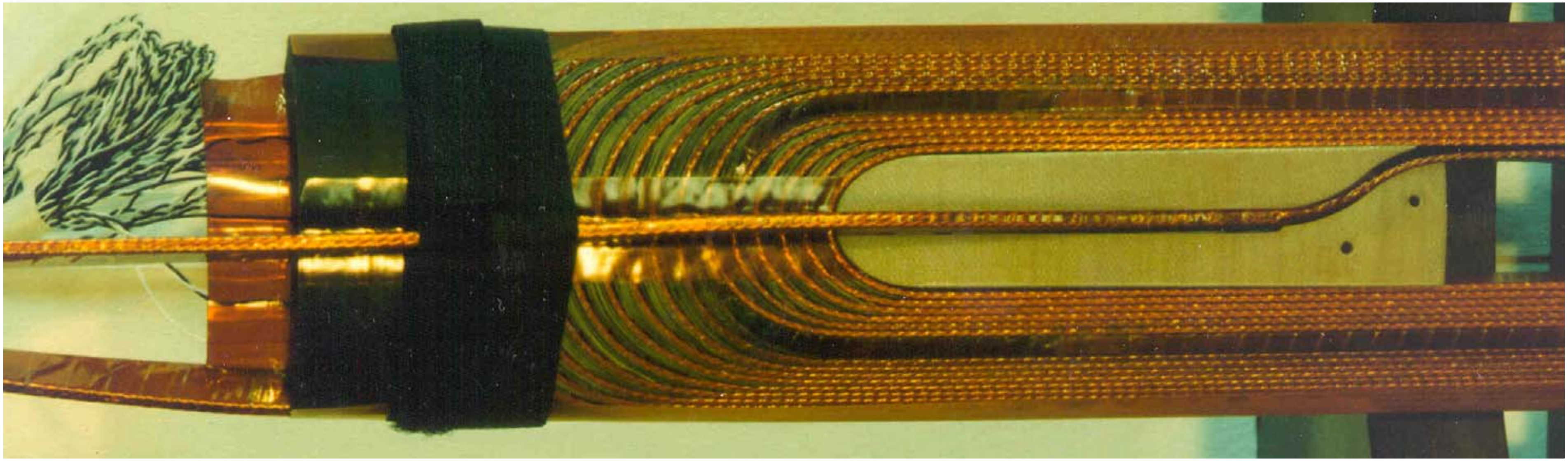
- All magnets use Nb-Ti Superconductor
- All designs use cosine theta coil geometry
- The technology has been in use for decades.
- The cost is unlikely to reduce significantly.

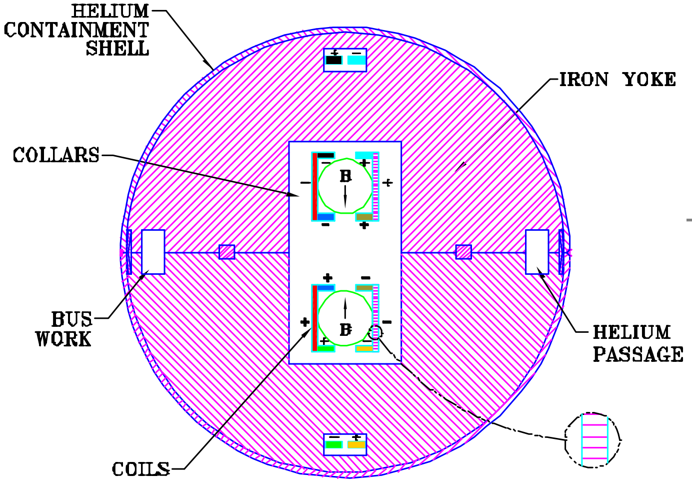
Ends in Accelerator Magnets

- All conductors that can be used today in high field magnets are brittle in nature
- The ends of the conventional cosine theta designs are not well suited for them



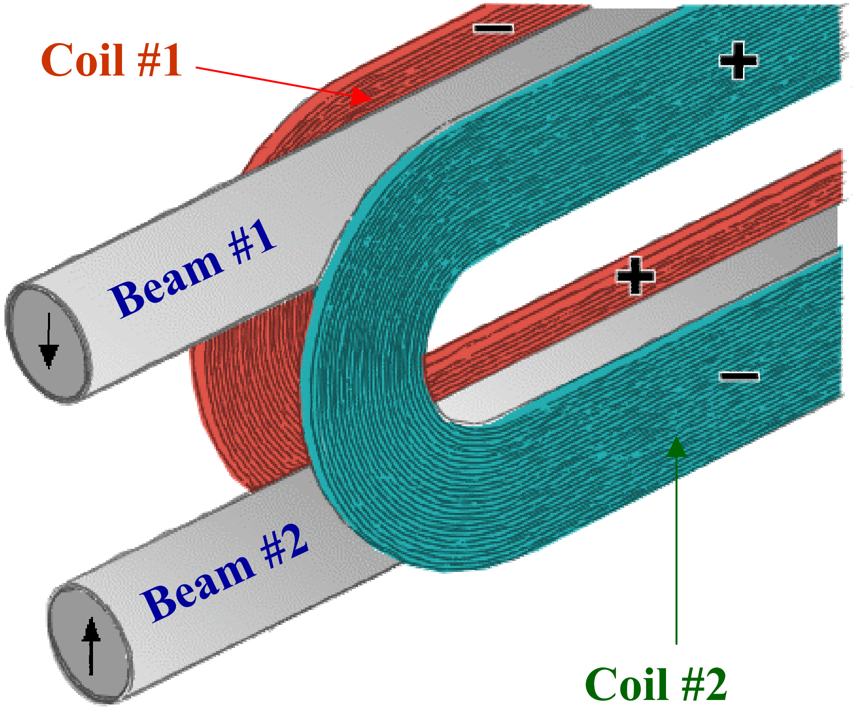
End of a conventional cosine theta magnet design





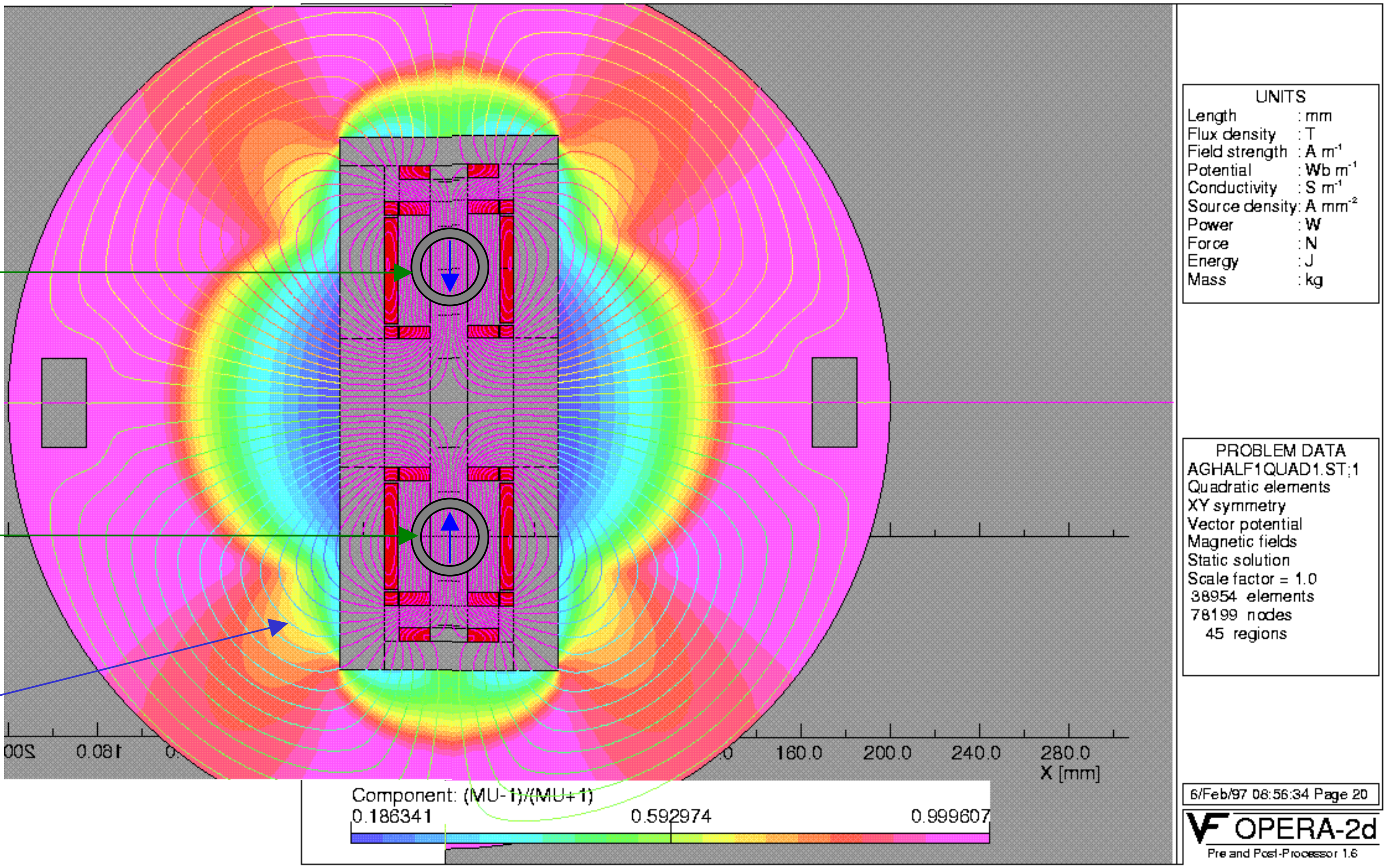
Common Coil Design
(The Basic Concept)

- **Simple 2-d** **geometry with large bend radius (no complex 3-d ends)**
- **Conductor friendly** **(suitable for brittle materials - most are - Nb_3Sn, HTS tapes and HTS cables)**
- **Compact** **(compared to single aperture LBL's D20 magnet, half the yoke size for two apertures)**
- **Block design** **(for large Lorentz forces at high fields)**
- **Efficient** **and methodical** **R&D** **due to simple &** **modular design**
- **Minimum** **requirements on big expensive** **tooling and labor**
- **Lower cost magnets** **expected**



Main Coils of the *Common Coil Design*

Field Lines at 15 T in a Common Coil Magnet Design



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

Component: (MU-1)/(MU+1)
0.186341 0.592974 0.999607

6/Feb/97 08:56:34 Page 20

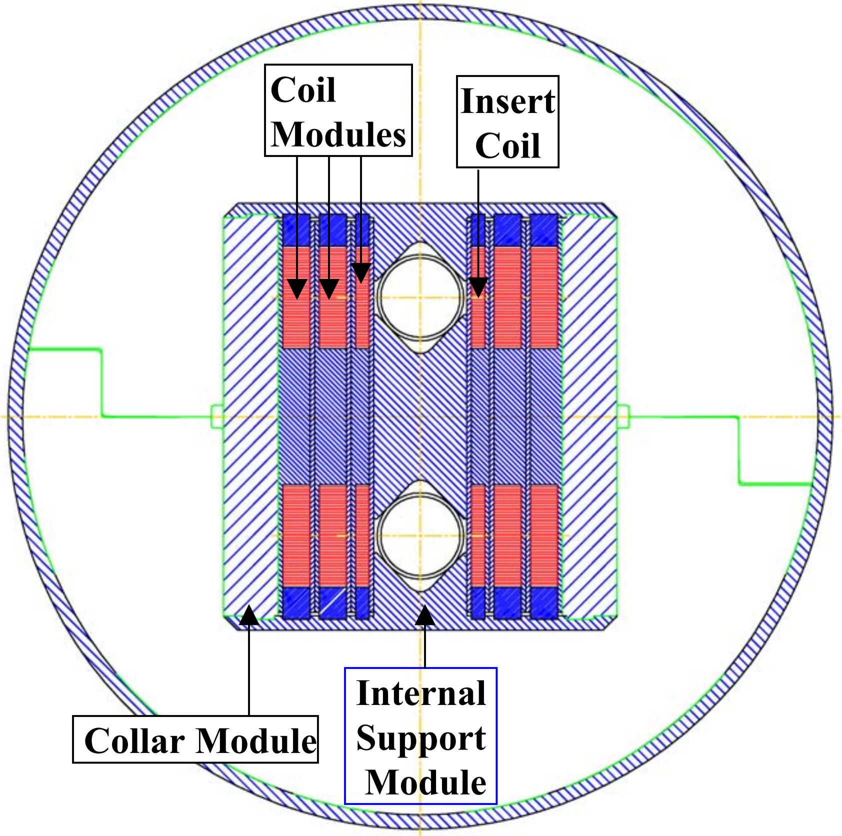
Aperture #1

Aperture #2

Place of maximum iron saturation

How Does a Common Coil Magnet Look?

R&D Magnet Design



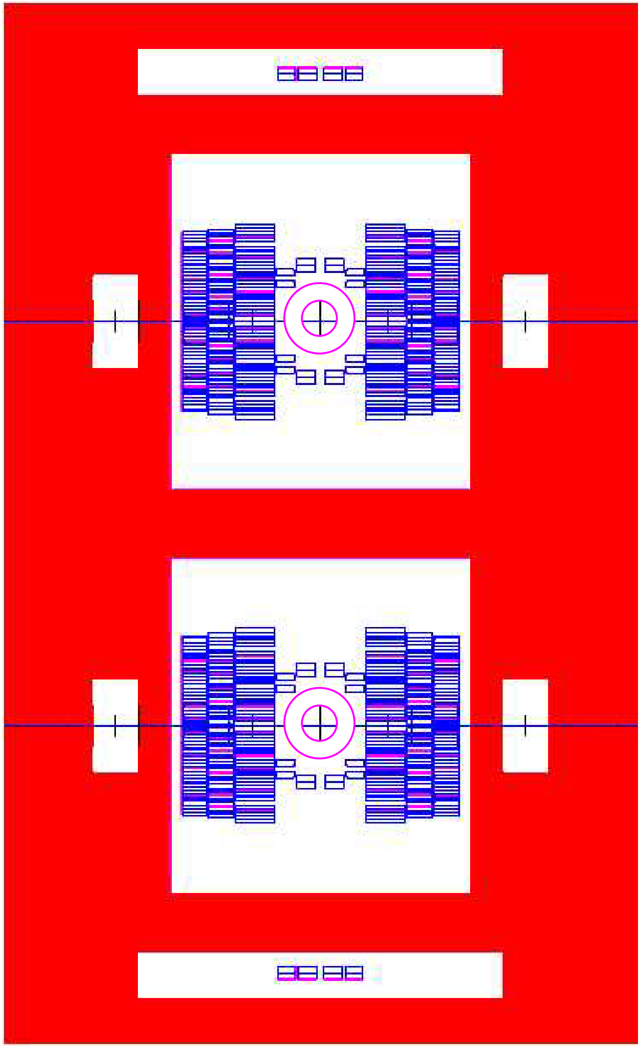
Coil Modules

Insert Coil

Collar Module

Internal Support Module

A ~15 T Field Quality Magnetic Design



RHIC: 3.5 T

SSC: 6.6 T

LHC 8.4 T

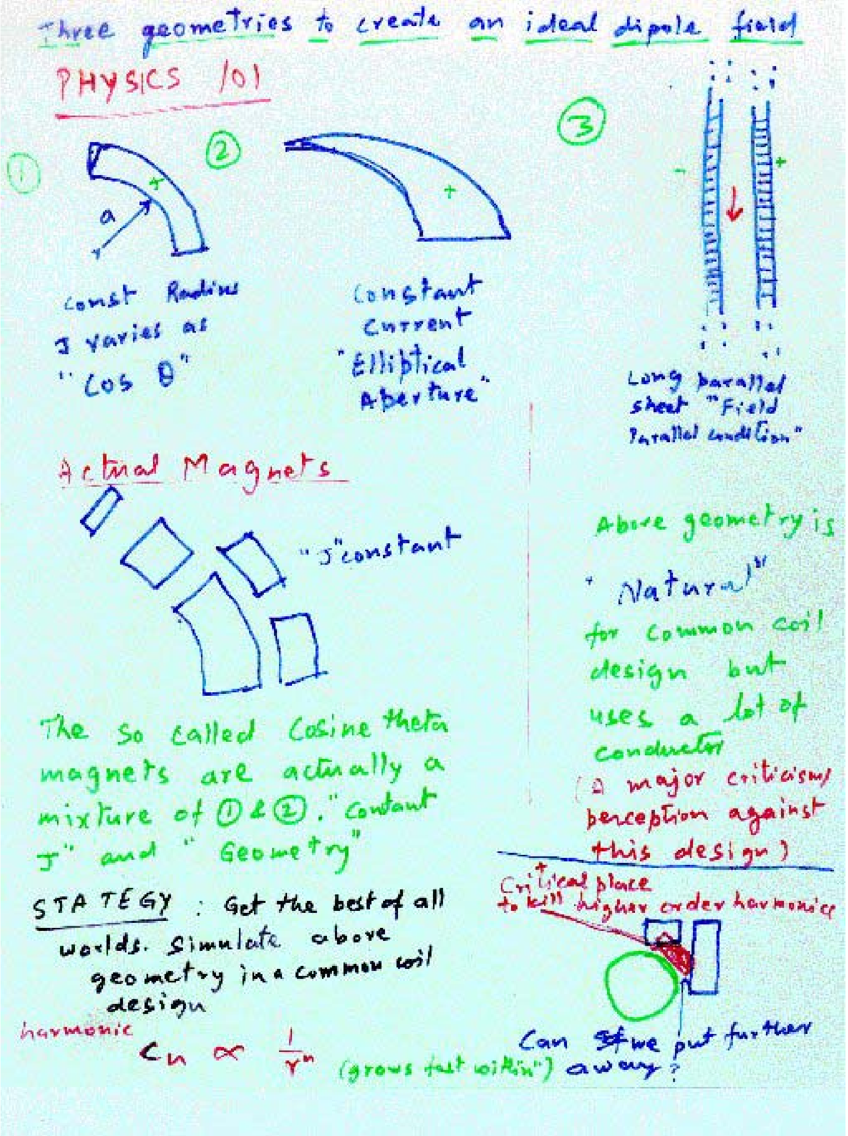
(forces go as B^2)

15 T is based on the best available Nb_3Sn conductor available today:

$J_c = 2200\ A/mm^2$ (12T,4.3K).

Goal: $J_c = 3000\ A/mm^2$.

Field Quality optimization from 1st Principle



Three geometries to create an ideal dipole field

PHYSICS 101

① Const Radius
J varies as
"Cos θ"

② Constant
Current
"Elliptical
Aperture"

③ Long parallel
sheet "Field
Parallel condition"

Actual Magnets

"J" constant

The so called Cosine theta magnets are actually a mixture of ① & ②. "Constant J" and "Geometry"

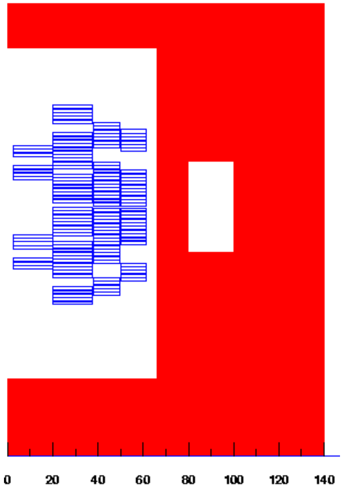
Above geometry is "Natural" for common coil design but uses a lot of conductor
(a major criticism/perception against this design)

Critical place to kill higher order harmonics

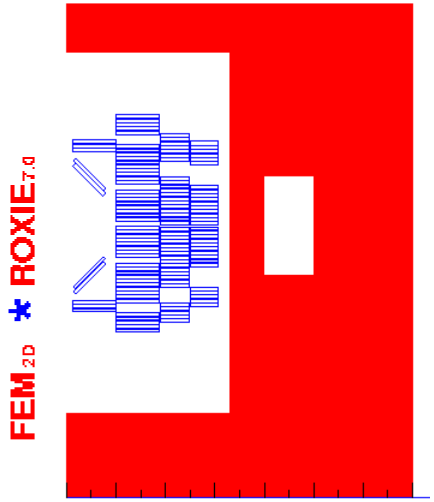
STATEGY : Get the best of all worlds. Simulate above geometry in a common coil design

harmonic $C_n \propto \frac{1}{r^n}$ (grows fast within) Can we put further away?

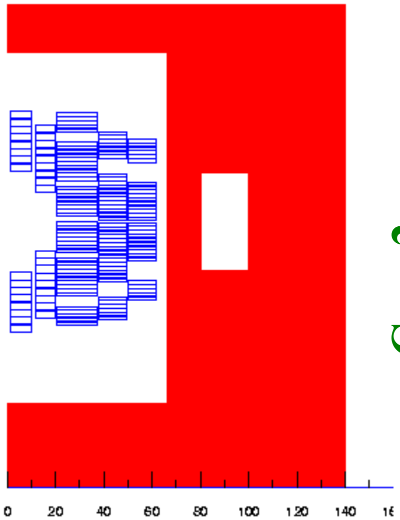
A Few Possible Configurations for Auxiliary Coils



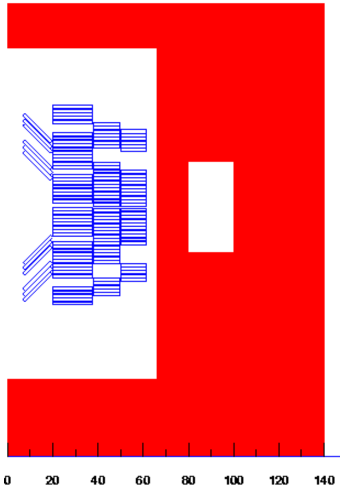
Case 1a



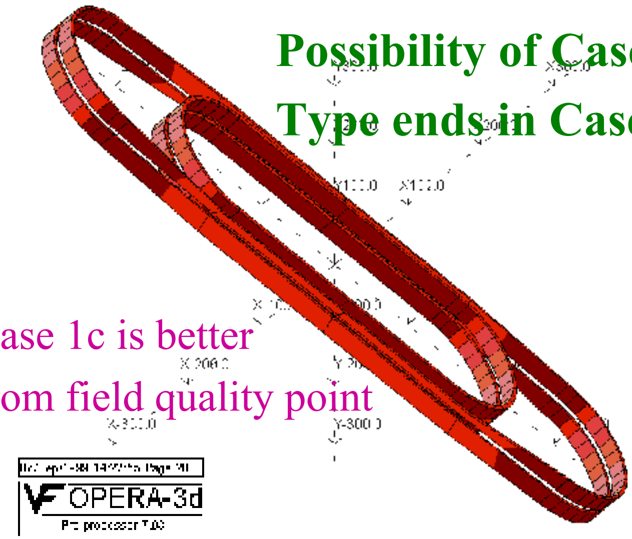
Case 1c



Case 2

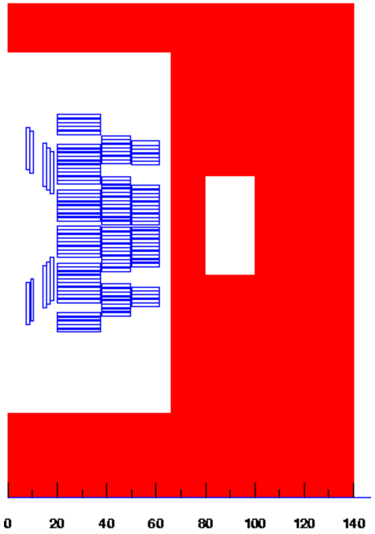


Case 1b



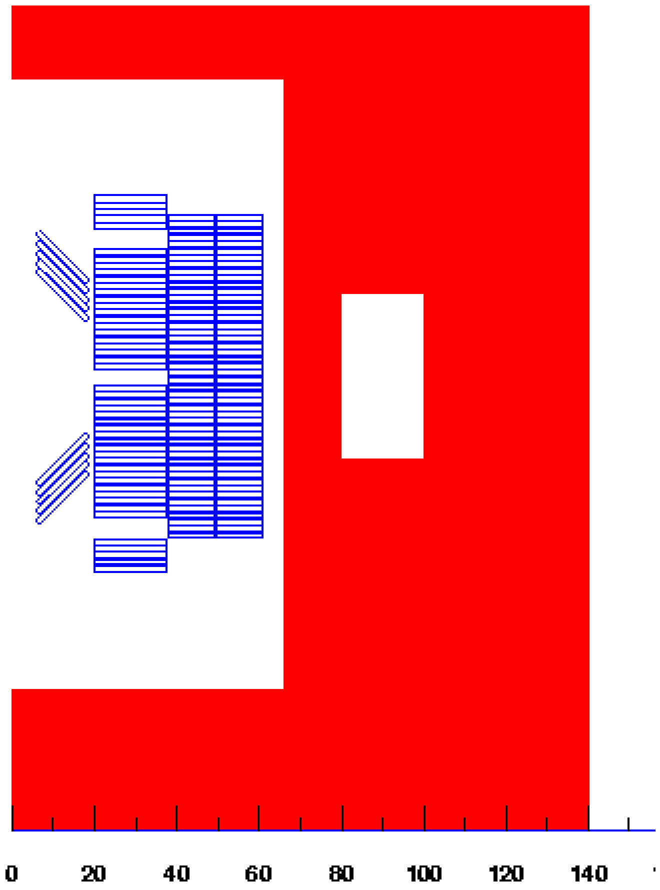
Possibility of Case 1a Type ends in Case 1c

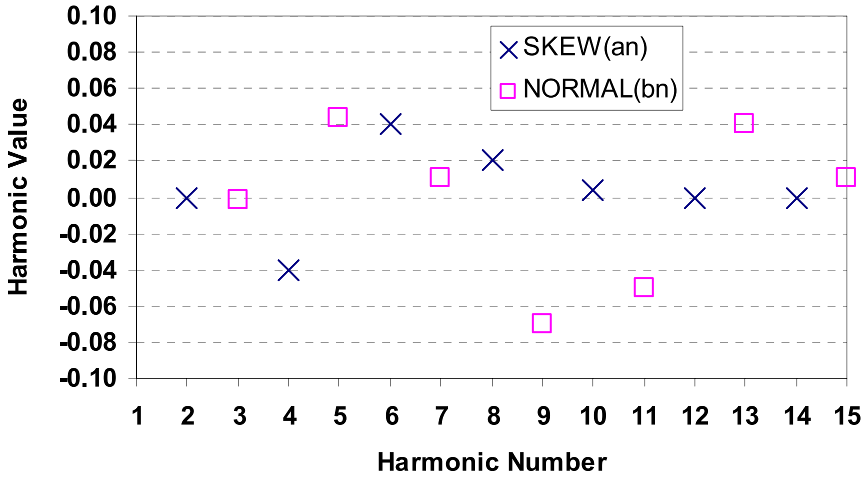
Case 1c is better from field quality point



Case 3

Geometric Harmonics



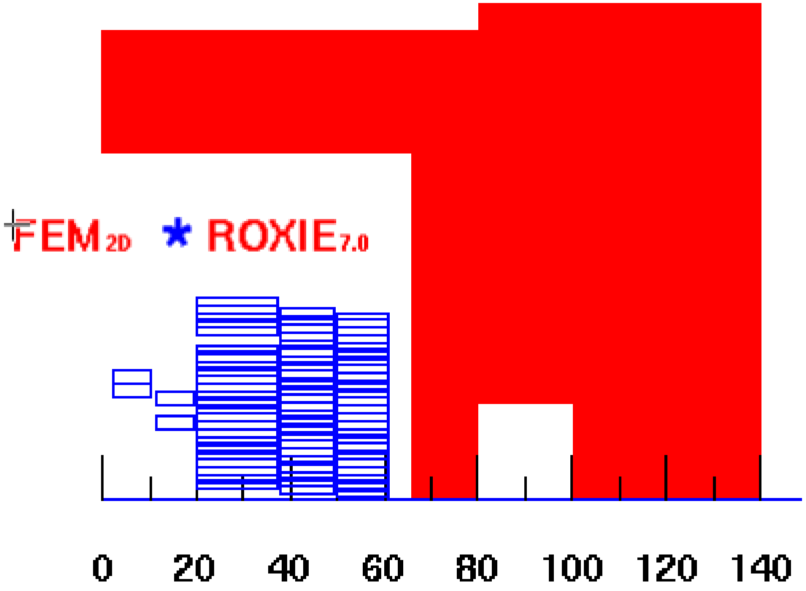


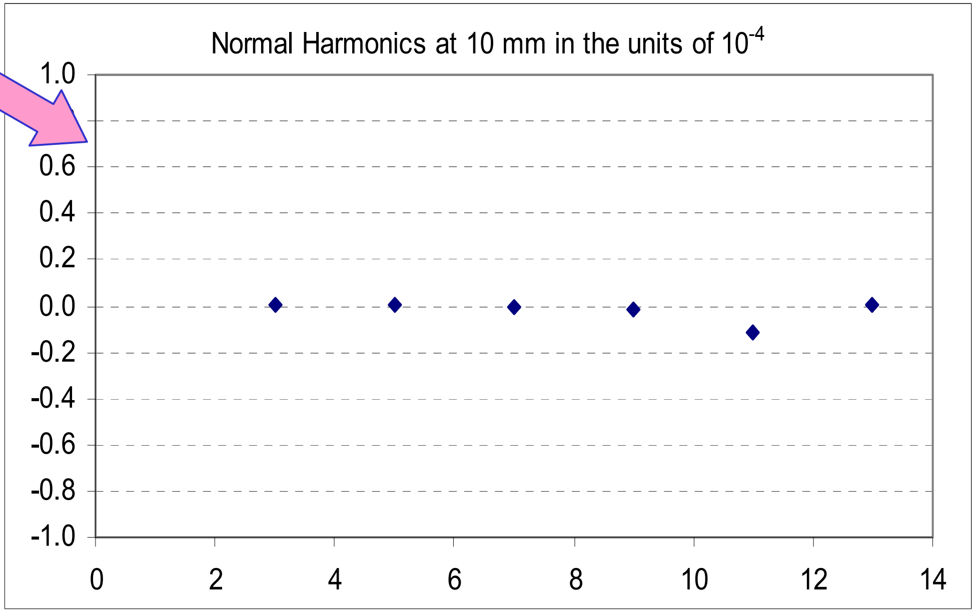
All harmonics are $<10^{-5}$ (<0.1 unit)

n	SKEW(a_n)	NORMAL(b_n)
2	0.00	
3		0.00
4	-0.04	
5		0.04
6	0.04	
7		0.01
8	0.02	
9		-0.07
10	0.00	
11		-0.05
12	0.00	
13		0.04
14	0.00	
15		0.01

Progress in Field Quality
Geometric Harmonics

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





(from 1/4 model)

MAIN FIELD: -1.86463 (IRON AND AIR):

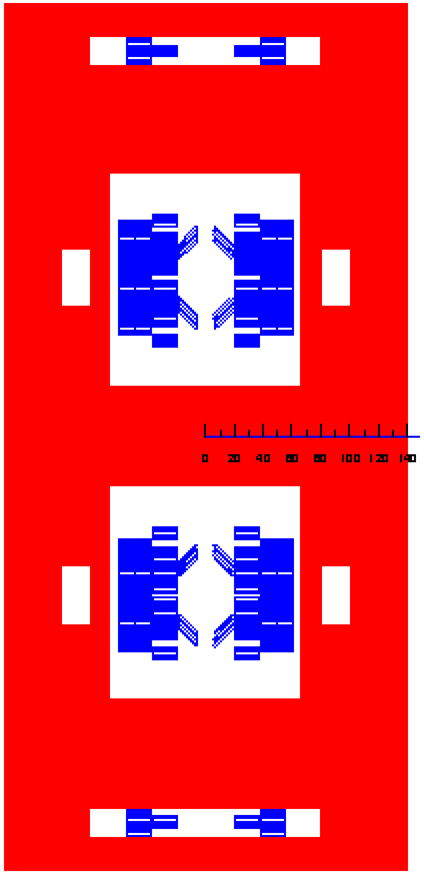
b 1:	10000.000	b 2:	0.00000	b 3:	0.00308
b 4:	0.00000	b 5:	0.00075	b 6:	0.00000
b 7:	-0.00099	b 8:	0.00000	b 9:	-0.01684
b10:	0.00000	b11:	-0.11428	b12:	0.00000
b13:	0.00932	b14:	0.00000	b15:	0.00140
b16:	0.00000	b17:	-0.00049	b18:	0.00000

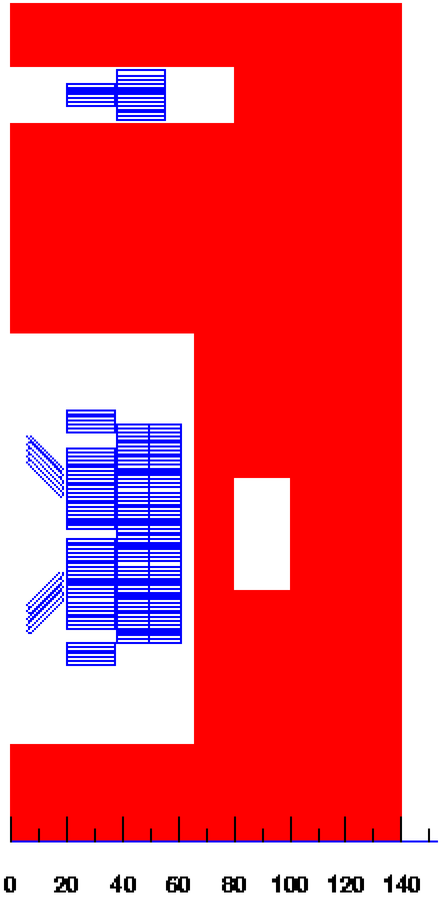
Earlier models used slanted auxiliary coils.

The above model uses all flat coils.

BNL design uses very small spacing between modules. Above design is consistent with that.

Optimized Yoke

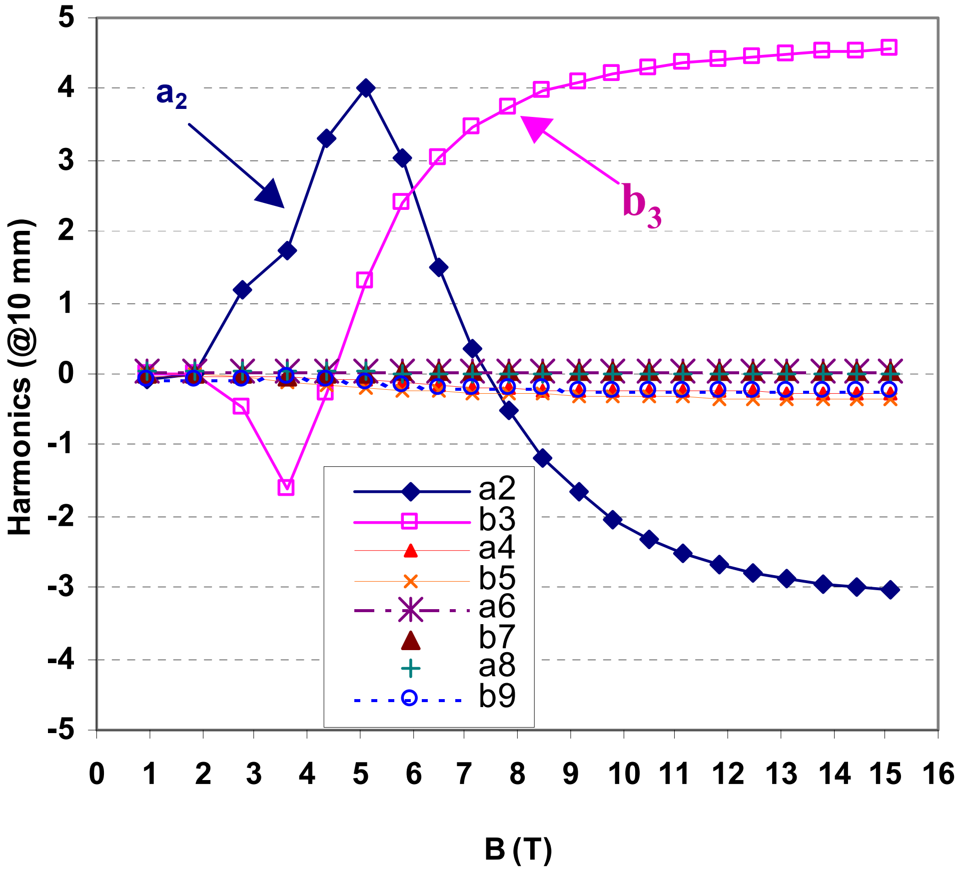




Saturation Induced Harmonics

Yoke optimization for small saturation induced harmonics
(a single power supply solution)

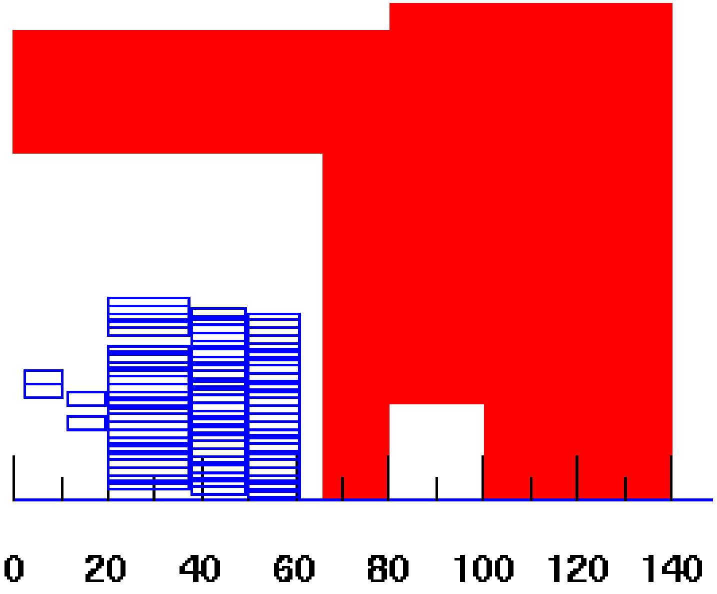
B(T)	a2	b3	a4	b5	a6	b7	a8	b9
0.94	-0.09	0.01	-0.04	0.00	0.04	0.01	0.02	-0.07
1.88	0.00	0.00	-0.04	0.00	0.04	0.01	0.02	-0.07
2.80	1.19	-0.48	-0.04	-0.03	0.04	0.00	0.02	-0.06
3.61	1.73	-1.63	-0.04	-0.12	0.04	-0.03	0.02	-0.05
4.37	3.30	-0.28	-0.06	-0.17	0.04	-0.01	0.02	-0.09
5.10	4.00	1.31	-0.09	-0.21	0.04	0.02	0.02	-0.14
5.80	3.02	2.39	-0.13	-0.23	0.03	0.03	0.02	-0.17
6.48	1.50	3.03	-0.16	-0.24	0.03	0.04	0.01	-0.19
7.16	0.37	3.46	-0.19	-0.26	0.03	0.05	0.01	-0.20
7.83	-0.52	3.75	-0.21	-0.27	0.03	0.05	0.01	-0.21
8.50	-1.17	3.96	-0.22	-0.28	0.02	0.05	0.01	-0.22
9.16	-1.67	4.11	-0.23	-0.30	0.02	0.06	0.01	-0.22
9.83	-2.04	4.22	-0.24	-0.31	0.02	0.06	0.00	-0.23
10.49	-2.30	4.31	-0.24	-0.32	0.02	0.06	0.00	-0.23
11.15	-2.51	4.37	-0.25	-0.33	0.02	0.06	0.00	-0.23
11.81	-2.67	4.42	-0.25	-0.34	0.02	0.06	0.00	-0.24
12.48	-2.79	4.46	-0.26	-0.34	0.02	0.06	0.00	-0.24
13.14	-2.87	4.50	-0.26	-0.35	0.02	0.06	0.00	-0.24
13.80	-2.94	4.52	-0.26	-0.36	0.02	0.06	0.00	-0.24
14.46	-3.00	4.54	-0.26	-0.36	0.02	0.06	0.00	-0.24
15.12	-3.05	4.56	-0.26	-0.37	0.02	0.06	0.00	-0.25

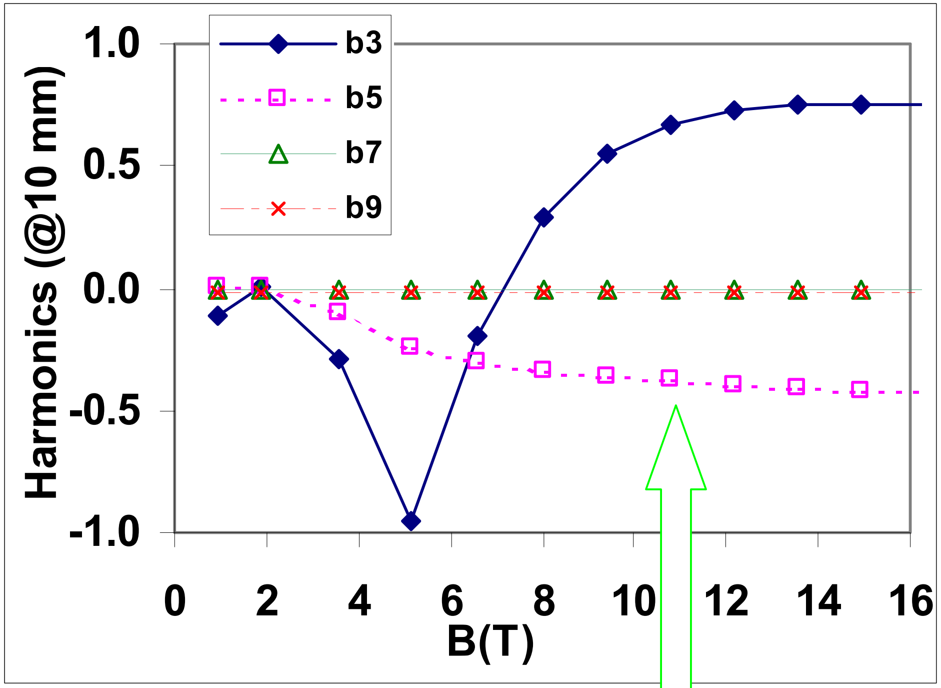


Saturation-induced Harmonics

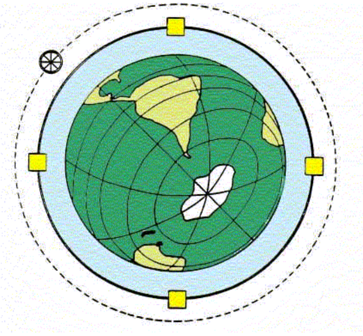
Use cutouts at strategic places in yoke iron to control the saturation.

Saturation induced harmonics part in 10^4
Satisfies general accelerator requirement



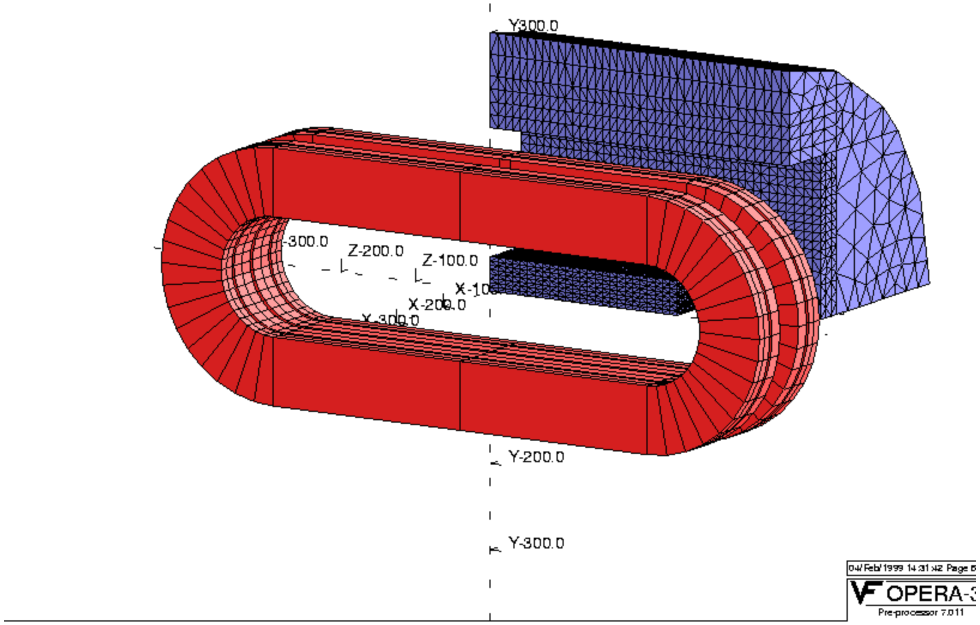


Low saturation induced harmonics till 15 T with a single power supply



A magnetic design for VLHC (Very Large Hadron Collider)

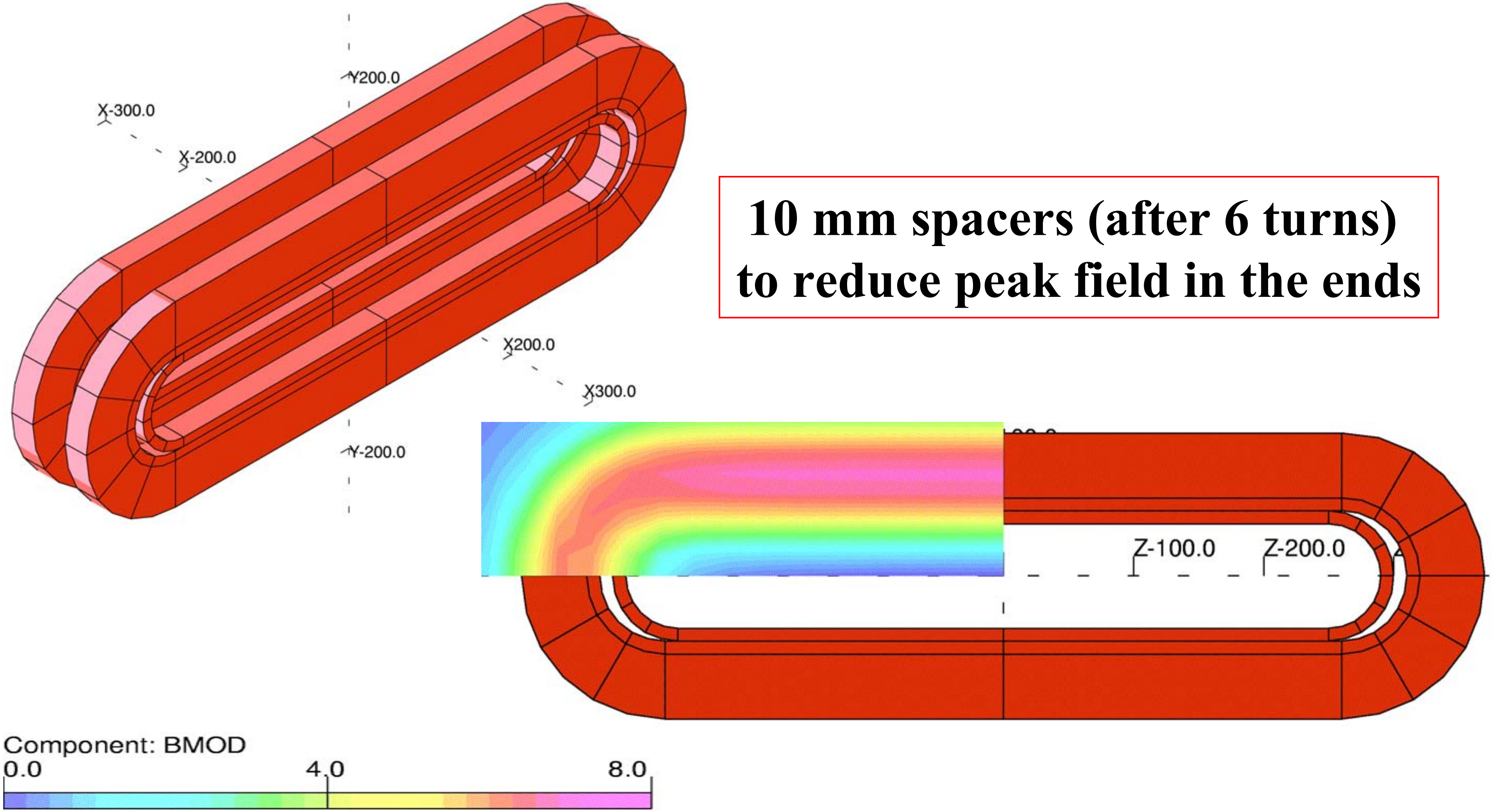
Iron Yoke in the Design



Computed Quench Performance:
~14 T at 4.2 K
(assuming no cable degradation)

- Iron yoke is placed around the coil and also in between the two apertures.
- Design appears a bit closer to the eventual machine magnet (last magnet had no iron).
- Iron and coils (in the body and ends) in this design are optimized for high quench field.
- Future designs will also be optimized for producing field quality magnets.

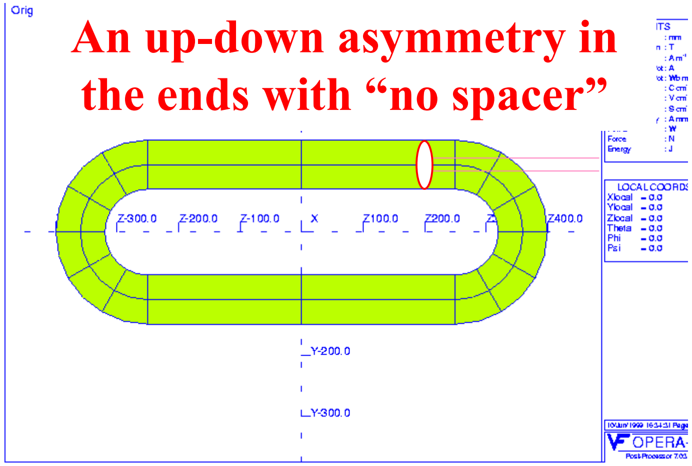
TOSCA Analysis for Ends



10 mm spacers (after 6 turns)
to reduce peak field in the ends

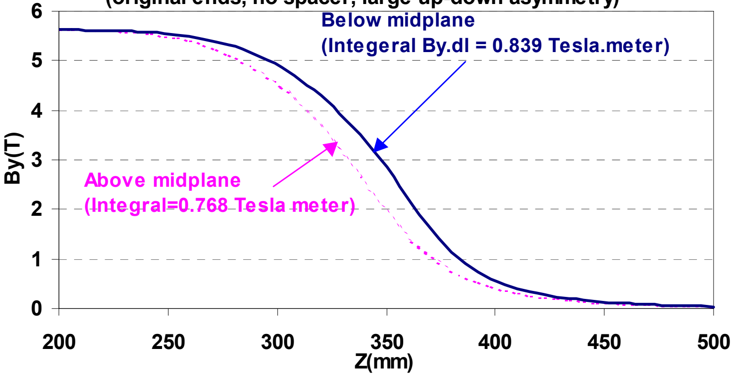
Field Quality Optimization in the Common Coil Design (Magnet Ends)

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”

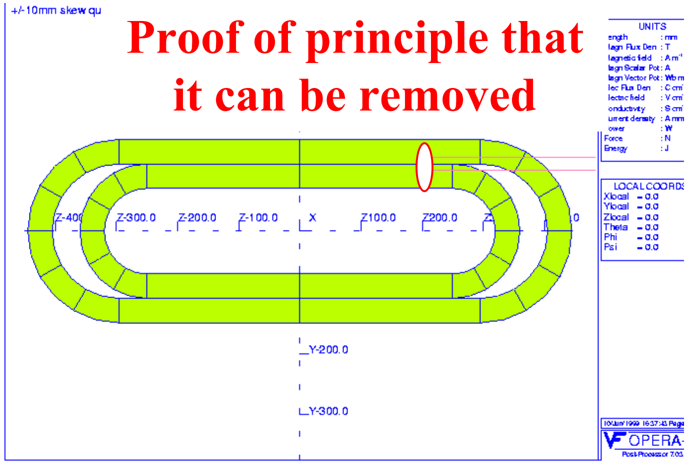
B_y 10 mm above and below midplane on magnet axis (original ends, no spacer, large up-down asymmetry)



Below midplane (Integeral By.dl = 0.839 Tesla.meter)

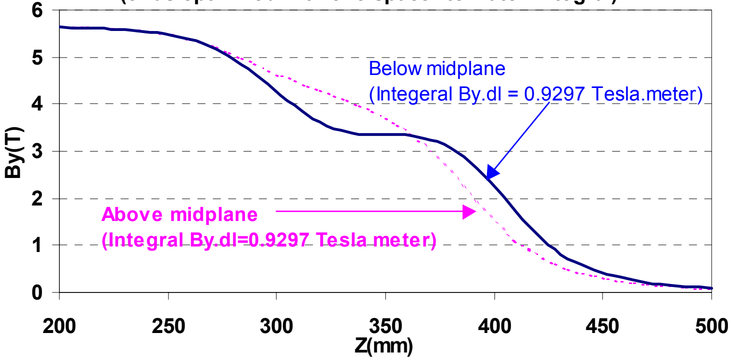
Above midplane (Integral=0.768 Tesla meter)

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)



Below midplane (Integeral By.dl = 0.9297 Tesla.meter)

Above midplane (Integral By.dl=0.9297 Tesla meter)

Computer code ROXIE (developed at CERN) will be used to efficiently optimize accelerator quality magnet design.

Young Post-doc (Suitbert Ramberger).

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).
- Small v X B.

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

Proof:

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

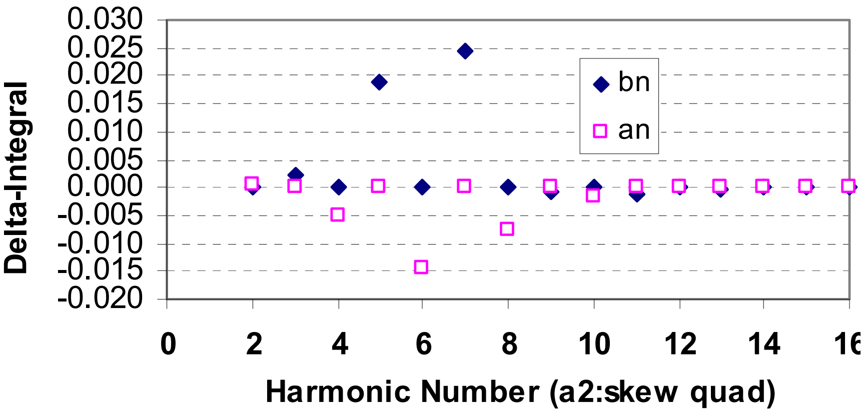
(Very small)

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

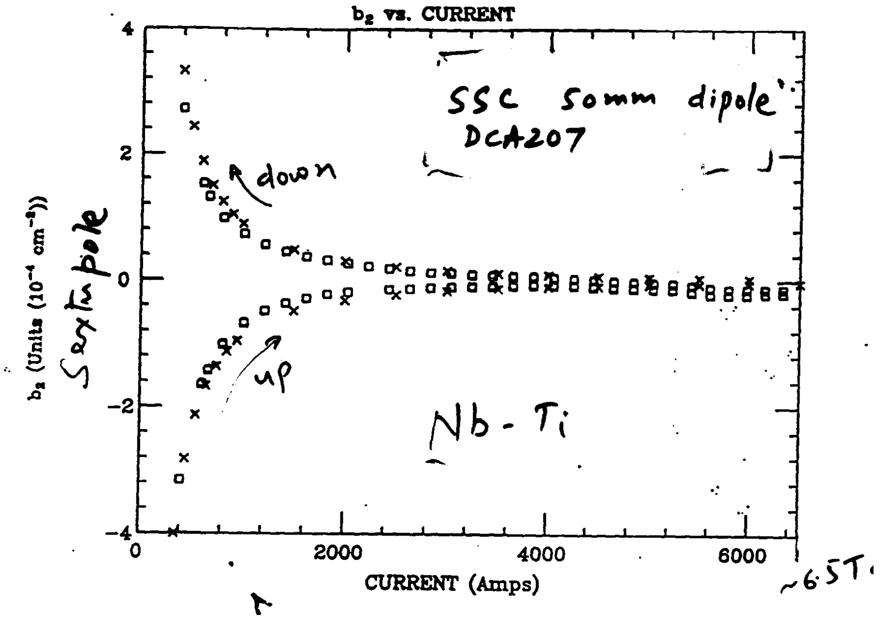


Persistent Current-induced Harmonics
(may be a problem in Nb_3Sn magnets, if done nothing)

Nb_3Sn superconductor, with the technology under use now, is expected to generate persistent current-induced harmonics which are **a factor of 10-100 worse** than those measured in Nb-Ti magnets.

In addition, a snap-back problem is observed when the acceleration starts (ramp-up) after injection at steady state (constant field).

Measured sextupole harmonic
in a Nb-Ti magnet



Measured sextupole harmonic
in a Nb_3Sn magnet

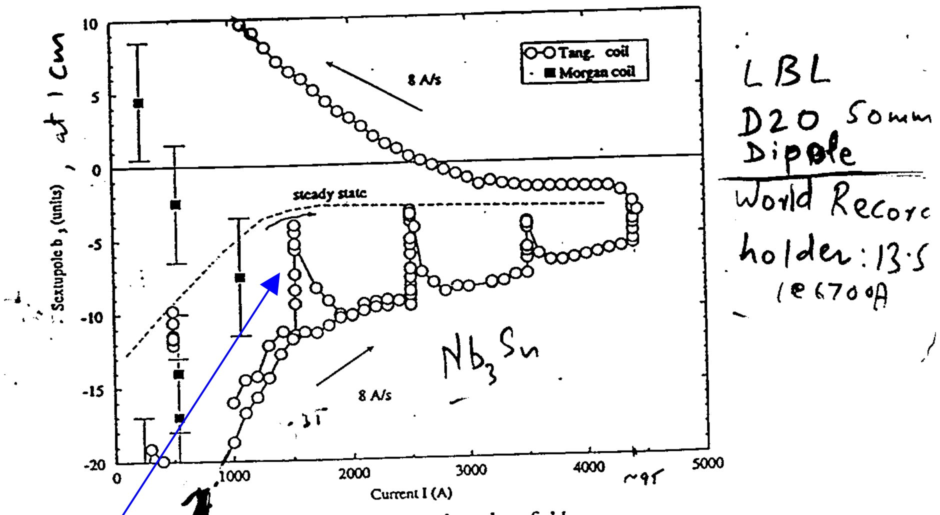


Fig. 6., Measured sextupole at low field (direction of arrow indicates up or down current).

Snap back

The iron dominated aperture in a common coil magnet system overcomes the major problem associated with magnets using Nb3Sn superconductor.

Persistent Current-induced Harmonics

Traditional solution: work on the superconductor

Persistent current induced magnetization :

$$2\mu_o M = 2\mu_o \frac{2}{3\pi} \nu J_c d \qquad ①$$

J_c , CRITICAL CURRENT DENSITY

d , FILAMENT DIAMETER

ν , VOL. FRACTION OF NbTi

$$M_s = M/\nu \qquad ②$$

Problem in Nb_3Sn Magnets because

(a) Jc is higher by several times

(b) Effective filament diameter is larger

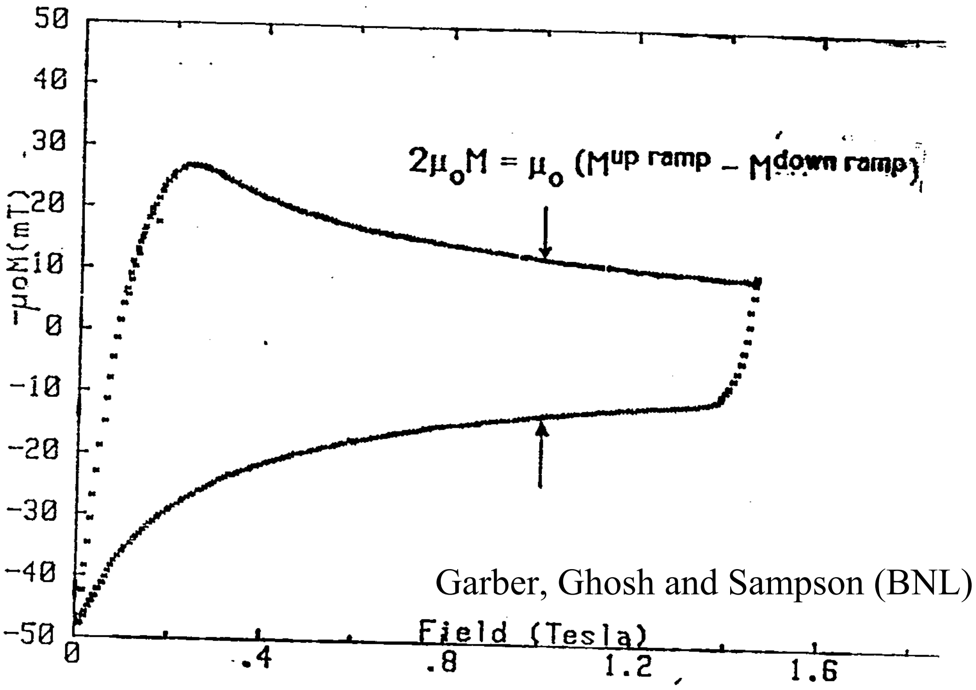
by about an order of magnitude

Conductor solution:

Reduce effective filament diameter.

A challenge; in some cases it also reduces J_c.

Measured magnetization



Garber, Ghosh and Sampson (BNL)

Fig. of a typical magnetization loop.

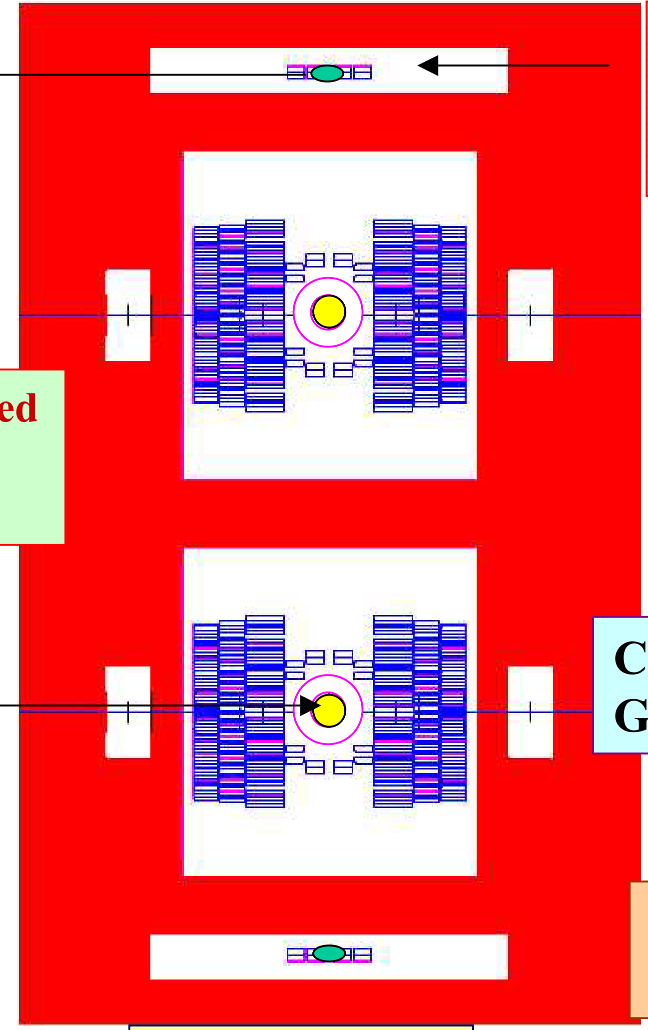
Note: Iron dominated magnets don’t have this problem.

A Common Coil Magnet System for VLHC

A Solution to Persistent Current Problem

May eliminate the High Energy Booster (HEB)

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

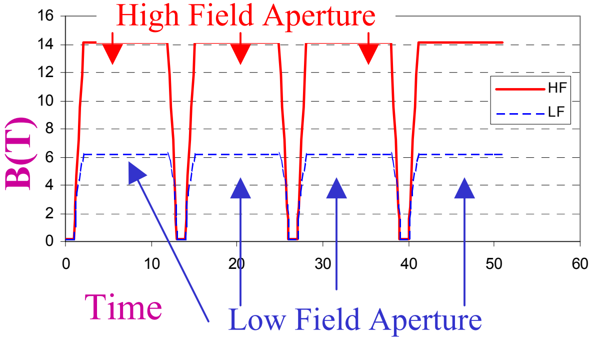
Transfer to conductor dominated aperture at medium field and then accelerate to high field

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

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

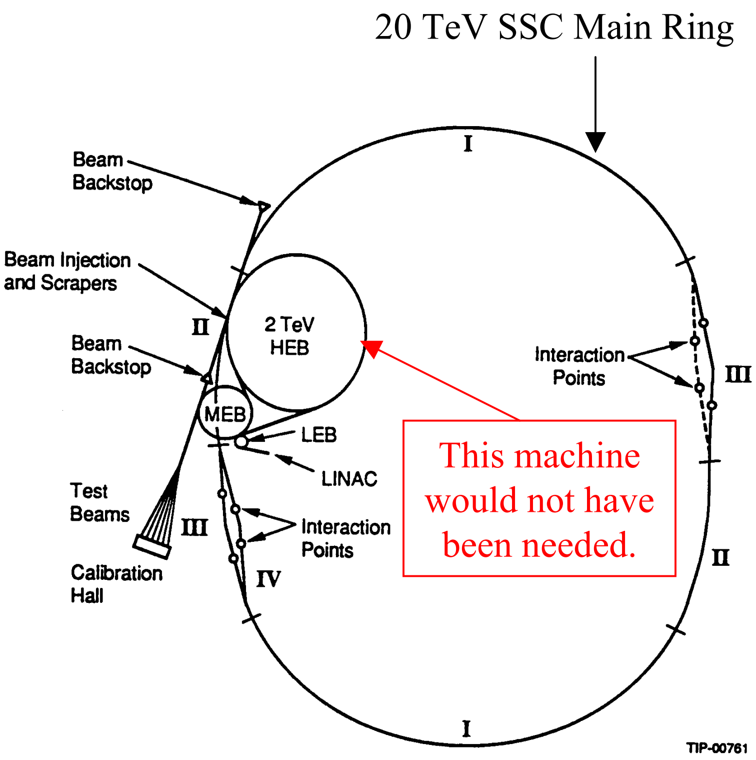
Compact size

Field profile with time



AP issues? Compare with the Low Field Design.

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



This machine would not have been needed.

Figure 4.1.1.1-4. Schematic layout of SSC.

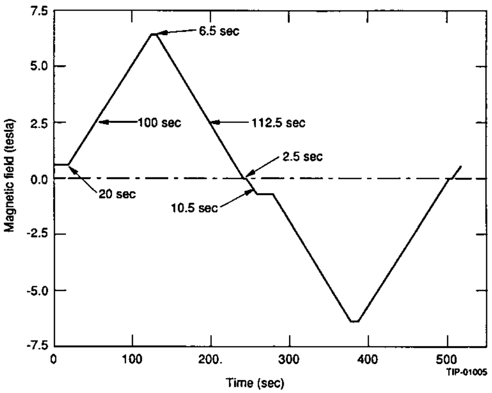


Figure 4.1.2.4-1. The suggested slow, alternating ramp scenario of the HEB.

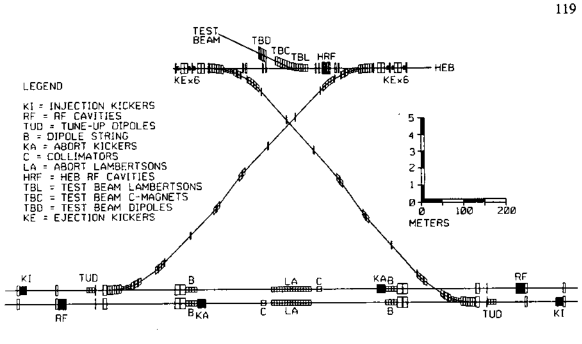


Figure 4.1.1.3-4. Elevation view of collider utility region.

- 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$

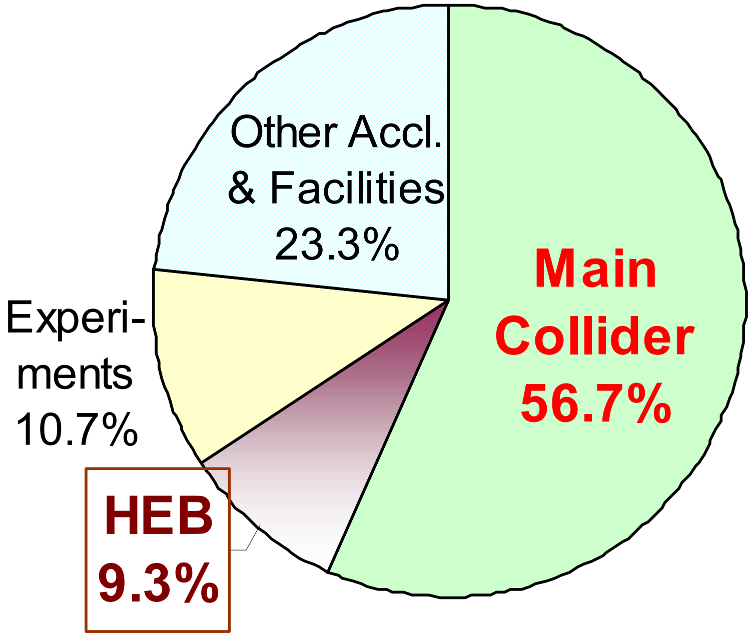
2 TeV HEB Cost in SSC (derived):
$700-800 million

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)

Advantages of Common Coil Magnet System with 4 Apertures (2-in-1 Accelerator)

- **Large Dynamic Range**

~150 instead of usual 8-20.

May eliminate the need of the second largest ring. Significant saving in the cost of VLHC accelerator complex.

- **Good Field Quality (throughout)**

Low Field: Iron Dominated

High Field: Conductor Dominated.

Good field quality from injection to highest field with a single power supply.

- **Compact Magnet System**

As compared to single aperture D20, 4 apertures in less than half the yoke.

- **Possible Reduction in High Field Aperture**

Beam is transferred, not injected
- no wait, no snap-back.

Minimum field seen by high field aperture is ~1.5 T and not ~0.5 T.

The basic machine criteria are changed!
Can high field aperture be reduced?

Reduction in high field aperture => reduction in conductor & magnet cost.

Magnet Aperture: MT and AP Issues

Main magnet aperture has an appreciable impact on the machine cost. The minimum requirements are governed by the following two issues:

Magnet Technology Issues

The conventional cosine theta magnets are hard to build below certain aperture as the bend radius and the end geometry would limit the magnet performance. In the common coil design, the magnet aperture and magnet ends are completely de-coupled. The situation is even better than that in the conventional block designs as not only that the ends are 2-d but the bend radius is much larger, as it is determined by the spacing between the two apertures rather than the aperture itself. This means that the magnet technology will not limit the dipole aperture.

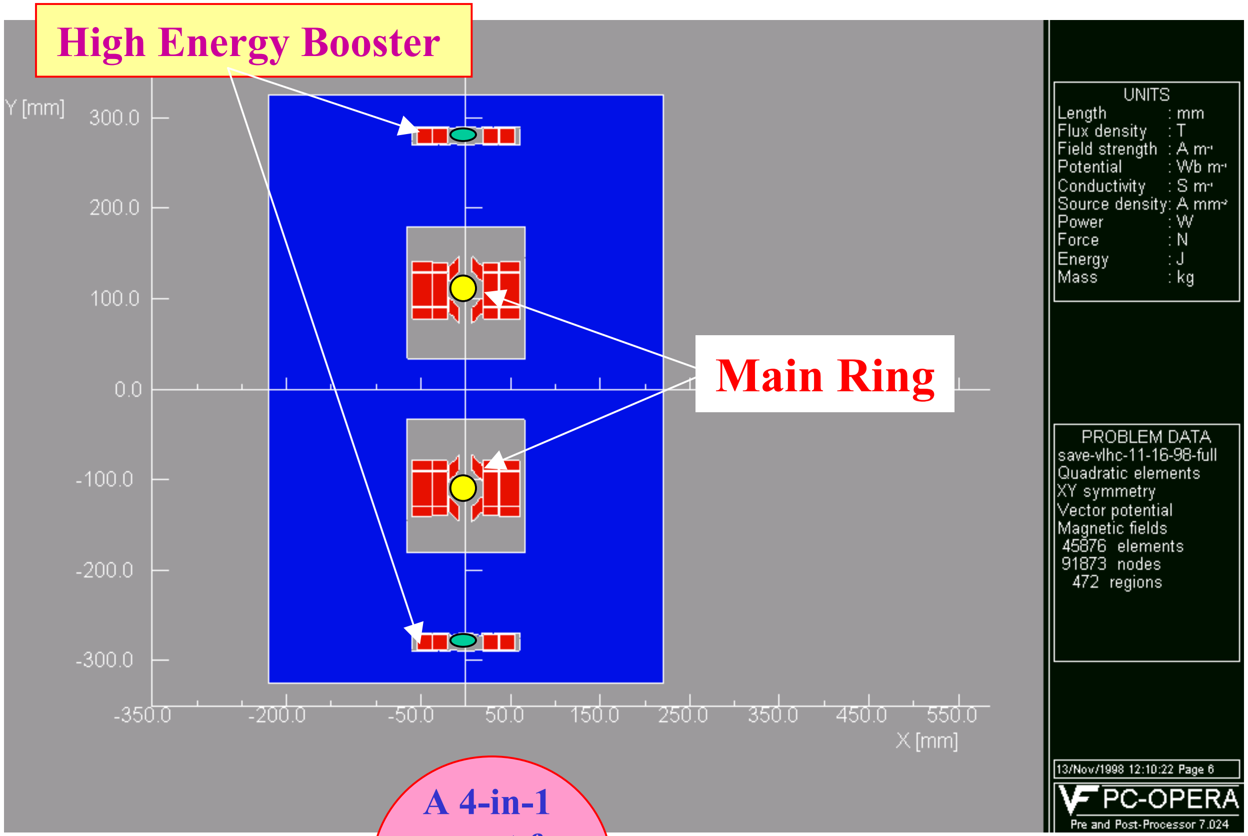
Accelerator Physics Issues

The proposed common coil system should have a favorable impact. The aperture is generally decided by the injection conditions. In the proposed system, the beam is transferred (not injected) in a single turn, on the fly, and the transfer takes place at a higher field. The magnets continue to ramp-up during beam transfer and thus the “snap-back” problem is bypassed. There is a significant difference at the injection from the conventional injection case. This and other progress in the field (feed-back system, etc.) should encourage us to re-visit the aperture issue.

A Combined Function Common Coil Magnet System for Lower Cost VLHC

In a conventional superconducting magnet design, the right side of the coil return on the left side. In a common coil magnet, coil from one aperture return 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.



High Energy Booster

Main Ring

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

13/Nov/1998 12:10:22 Page 6

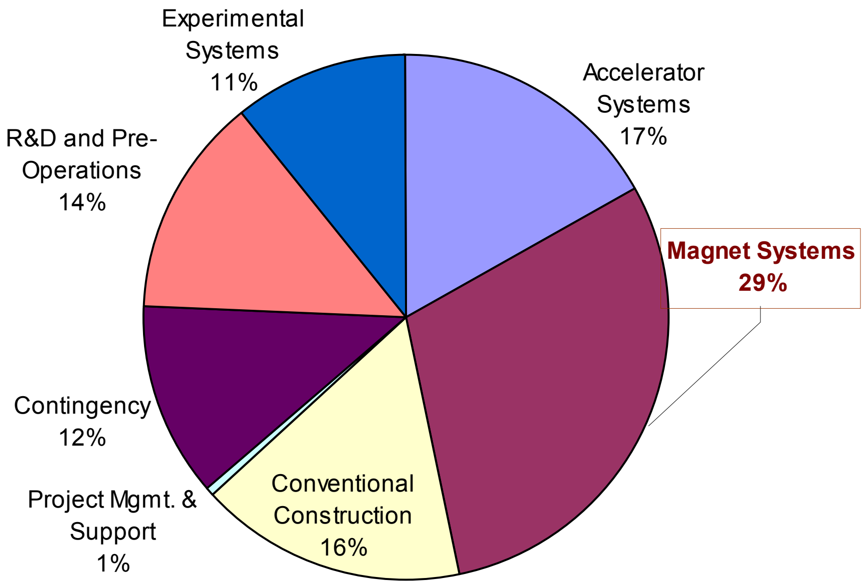
PC-OPERA
Pre and Post-Processor 7.024

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

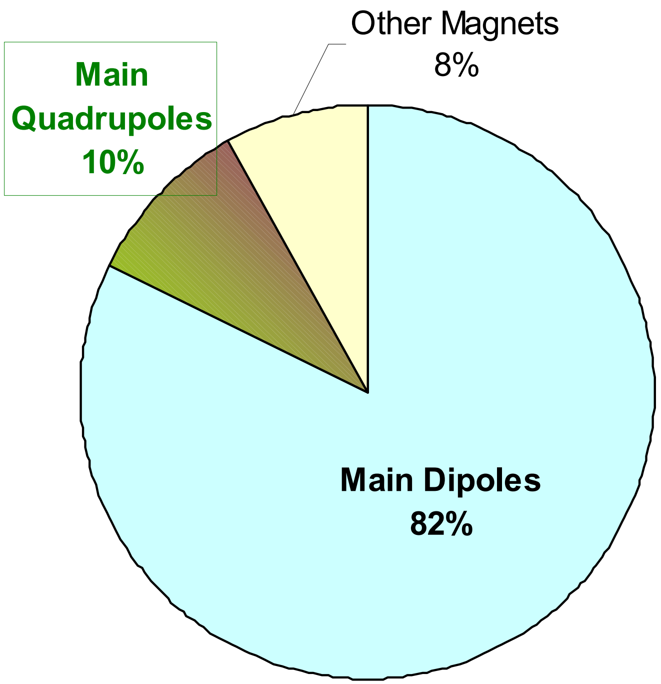
A Combined Function Magnet Option (Estimated cost savings for VLHC)

SSC Project Cost Distribution

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



Collider Ring Magnet Cost Distribution



Total:
$2,037 million

AP Challenge:

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

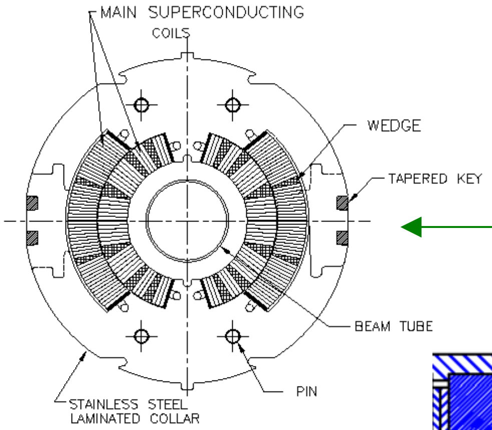
SSC (20 TeV) Main Quads: ~$200 million; VLHC (50 TeV) Main Quads: ~$400 million (x2 not 2.5).

Additional savings from tunnel, interconnect, etc.

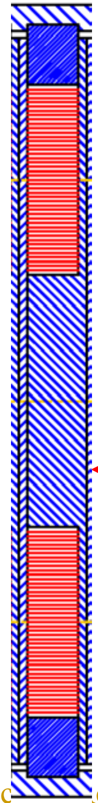
Estimated potential savings: ~$0.3-0.5 billion (1990 US$).

Cost savings in equivalent 20xx $?

A Possible Low-cost Magnet Manufacturing Process

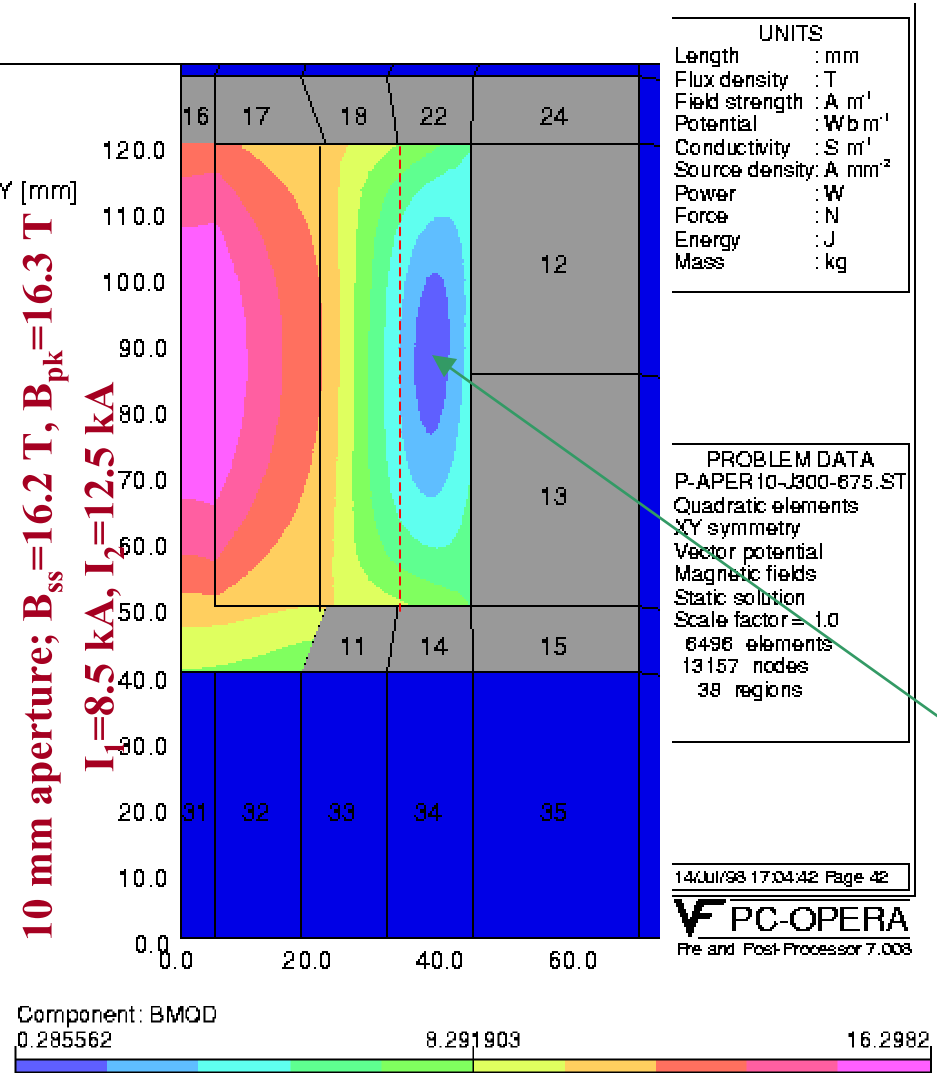


- Reduce steps and bring more automation in magnet manufacturing
- Current procedure : make cable from Nb-Ti wires => insulate cable => wind coils from cable => cure coils => make collared coil assembly



- Possible procedure : Cabling to coil module, all in one automated step - insulate the cable as it comes out of cabling machine and wind it directly on to a bobbin (module)

Investigations for Very High Fields (to probe the limit of technology)

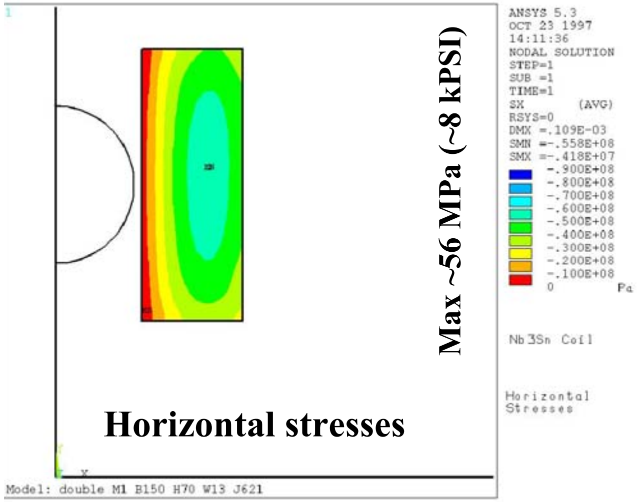


10 mm aperture; B_{ss}=16.2 T, B_{pk}=16.3 T

I_1=8.5 kA, I_2=12.5 kA

- Vary aperture after the coils are made
  - a unique feature of this design
- Lower separation (aperture)
  - reduces peak field, increases T.F.
  - => Higher B_{ss}
- May not be practical for machine magnet
  - but an attractive way to address technology questions
- Determine stress degradation in an actual conductor/coil configuration
  - Max. stress accumulation at high margin region
- When do we really need a stress management scheme (cost and conductor efficiency questions), and how much is the penalty?
- Simulate the future (better J_c) conductor

ANSYS Calculations



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RSYS=0
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SMX =-.418E+07
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   -.800E+08
   -.700E+08
   -.600E+08
   -.500E+08
   -.400E+08
   -.300E+08
   -.200E+08
   -.100E+08
   0           Pa

Nb3Sn Coil

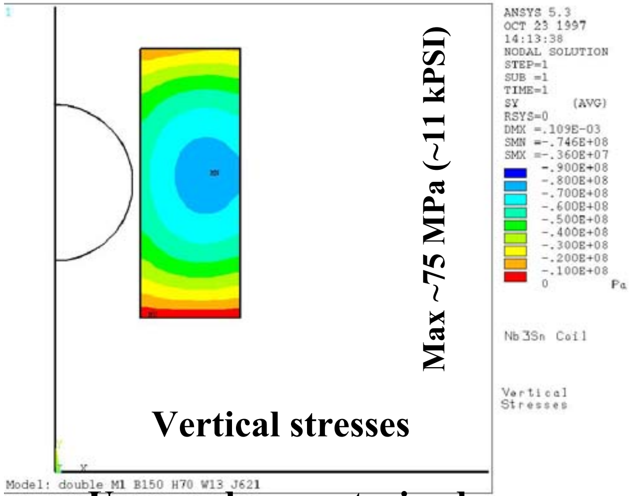
Horizontal
Stresses
```

Model: double M1 B150 H70 W13 J621

Max ~56 MPa (~8 kPSI)

Horizontal stresses

(Right edge constrained)



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   -.700E+08
   -.600E+08
   -.500E+08
   -.400E+08
   -.300E+08
   -.200E+08
   -.100E+08
   0           Pa

Nb3Sn Coil

Vertical
Stresses
```

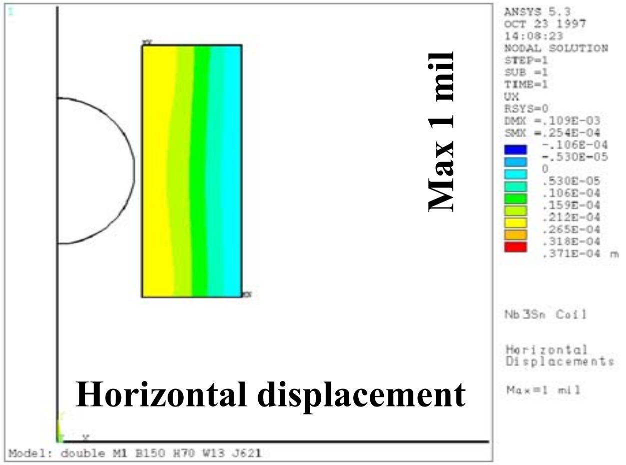
Model: double M1 B150 H70 W13 J621

Max ~75 MPa (~11 kPSI)

Vertical stresses

Upper edge constrained

Computed at ~9.6 T (design field 7T)



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   0
   .530E-05
   .106E-04
   .159E-04
   .212E-04
   .265E-04
   .318E-04
   .371E-04  m

Nb3Sn Coil

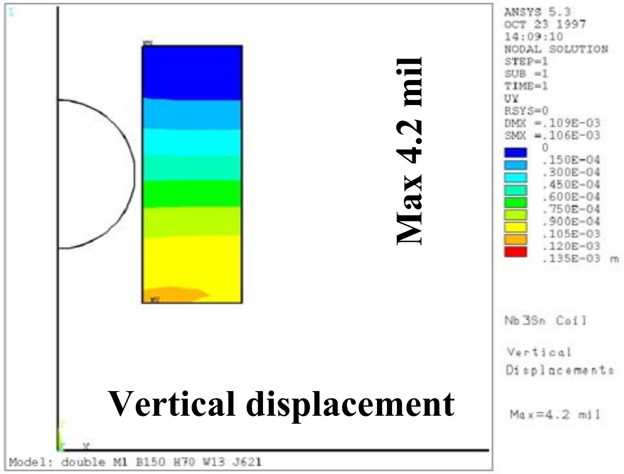
Horizontal
Displacements

Max=1 mil
```

Model: double M1 B150 H70 W13 J621

Max 1 mil

Horizontal displacement



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SUB =1
TIME=1
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RSYS=0
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   .150E-04
   .300E-04
   .450E-04
   .600E-04
   .750E-04
   .900E-04
   .105E-03
   .120E-03
   .135E-03  m

Nb3Sn Coil

Vertical
Displacements

Max=4.2 mil
```

Model: double M1 B150 H70 W13 J621

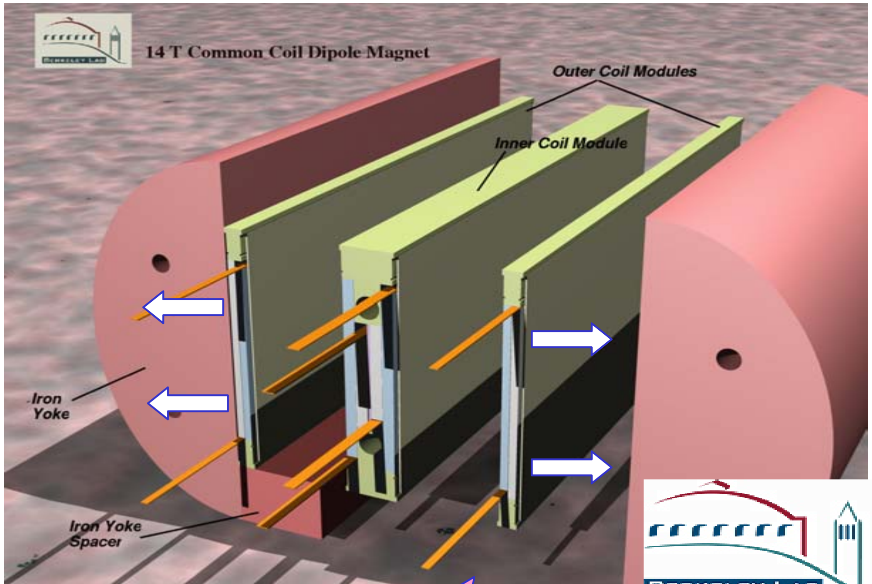
Max 4.2 mil

Vertical displacement

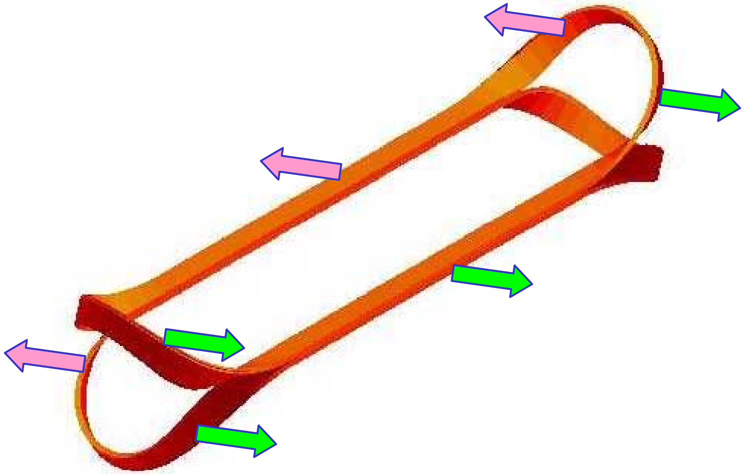
Ken Chow's Analysis

Common Coil Design in Handling Large Lorentz Forces in High Field Magnets

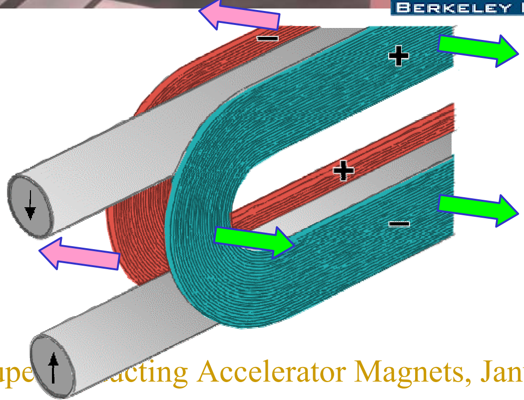
In common coil design, geometry and forces are such that the impregnated solid volume can move as a block without causing quench or damage. Ref.: over 1 mm motion in LBL common coil test configuration).



In cosine theta designs, the geometry is such that coil module cannot move as a block. These forces put strain on the conductor at the ends and may cause premature quench. The situation is somewhat better in single aperture block design, as the conductors don't go through complex bends.

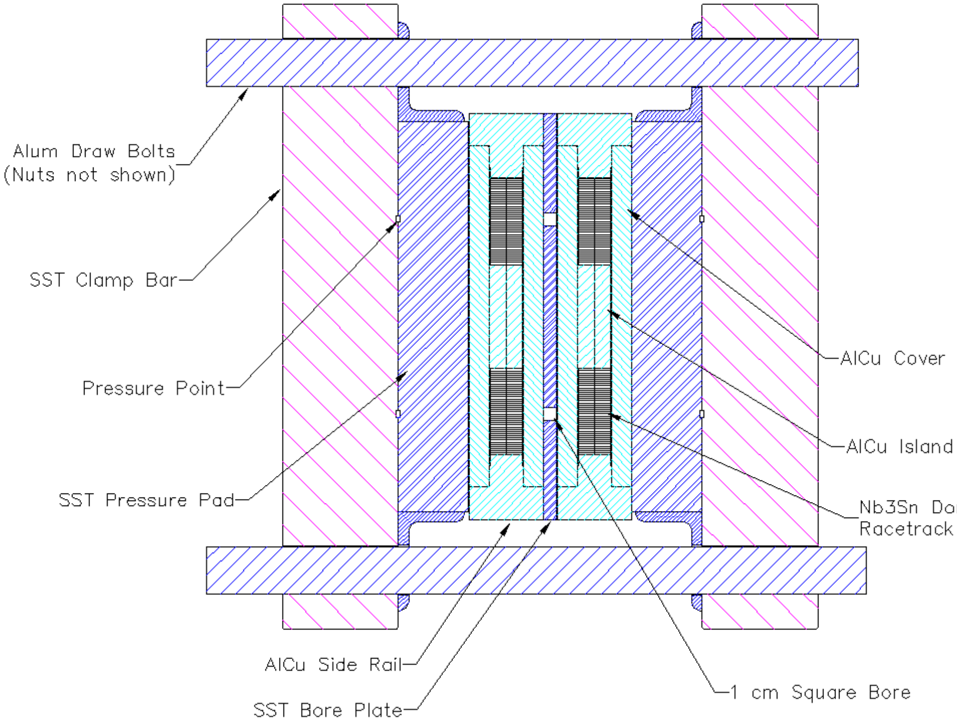


Horizontal forces are larger



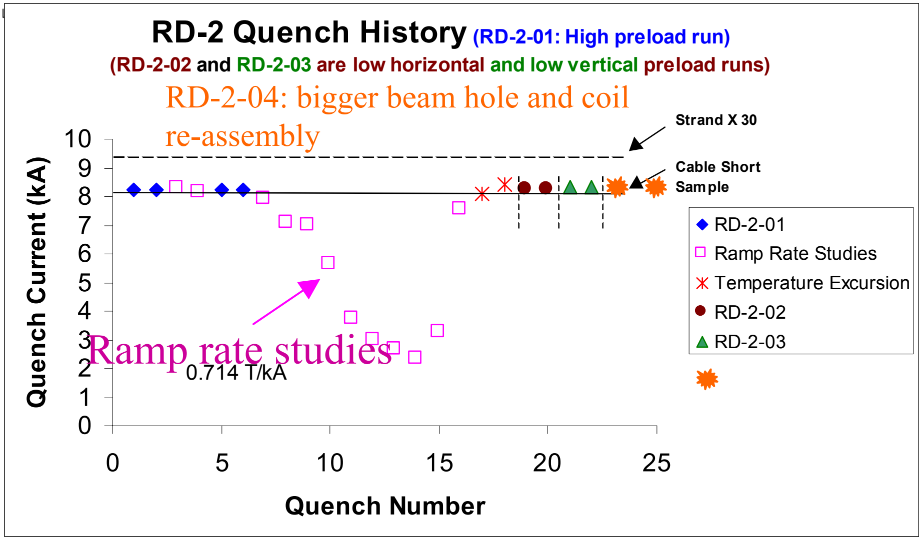
We must check how far we can go in allowing such motions in the body and ends of the magnet. This may significantly reduce the cost of expensive support structure. Field quality optimization should include it (as was done in SSC and RHIC magnet designs).

Quench Performance of the First Common Coil Nb_3Sn Magnet



LBL Data

1. The magnet reached plateau performance right away (plateau seems to be on the cable short sample, not wire short sample).
2. Didn't degrade for a low horizontal pre-load (must for this design).
3. Didn't degrade for a low vertical pre-load (highly desirable).
4. Didn't degrade for a bigger hole (real magnets) and coil re-assembly.


RD-2 Quench History (RD-2-01: High preload run)

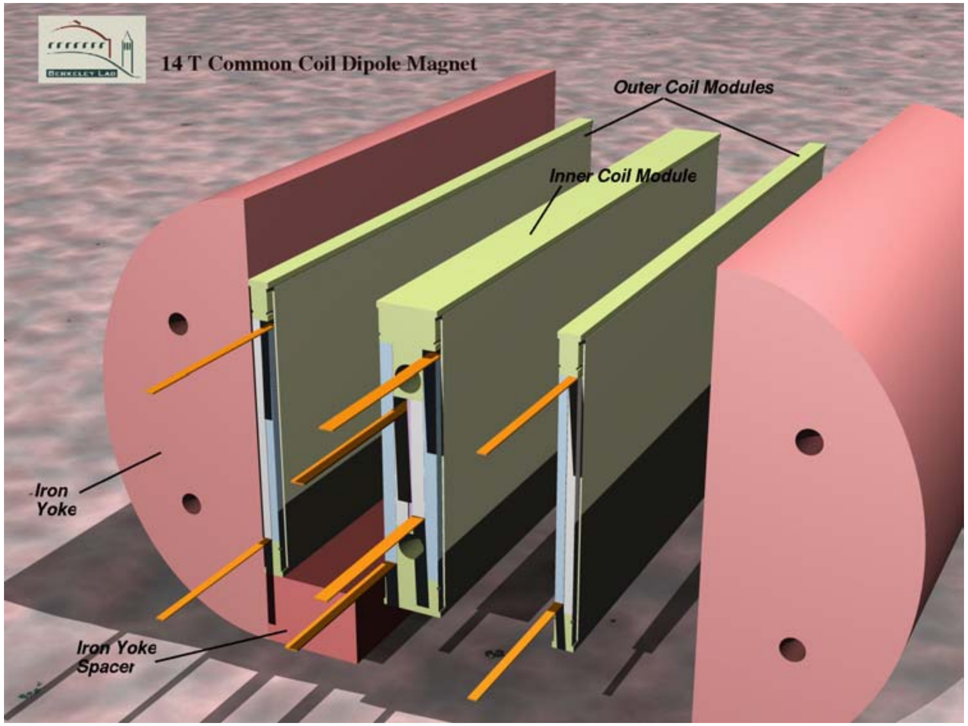
(RD-2-02 and RD-2-03 are low horizontal and low vertical preload runs)

RD-2-04: bigger beam hole and coil re-assembly

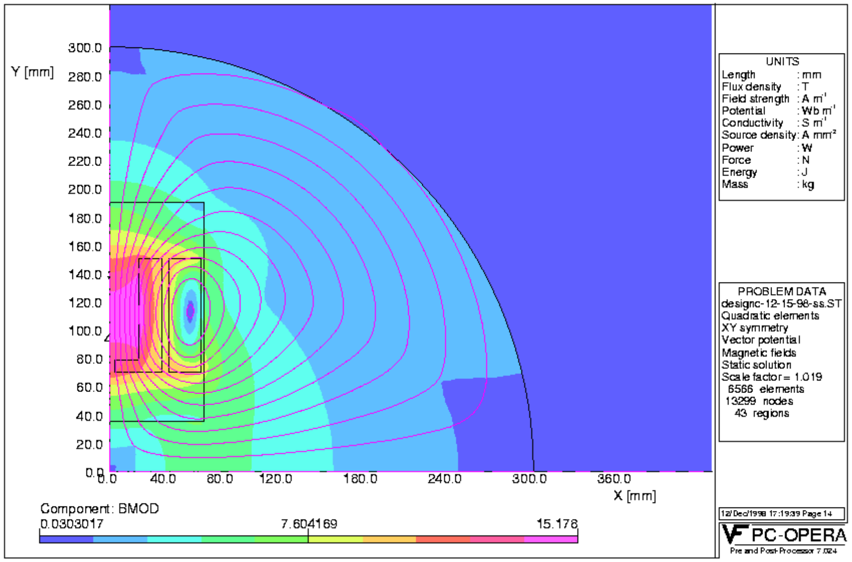
Ramp rate studies

Impressions of 14 T Common Coil Magnet (now under development)

From LBL



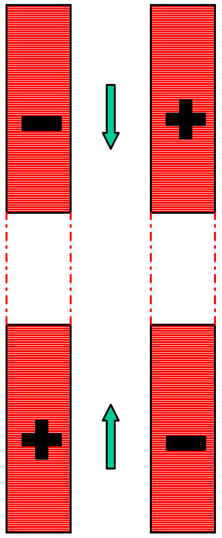
Magnetic Analysis of the cross-section
(1/4 of the coldmass; 1/2 of the upper aperture)



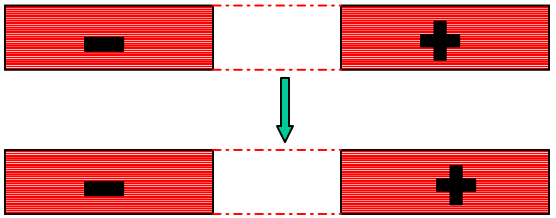
A designer (Larry Morrison) and an engineer (Ken Chow) turned into artists (good for explaining overall structure).

Muon Collider Dipole Design and Configuration

Hadron collider configuration



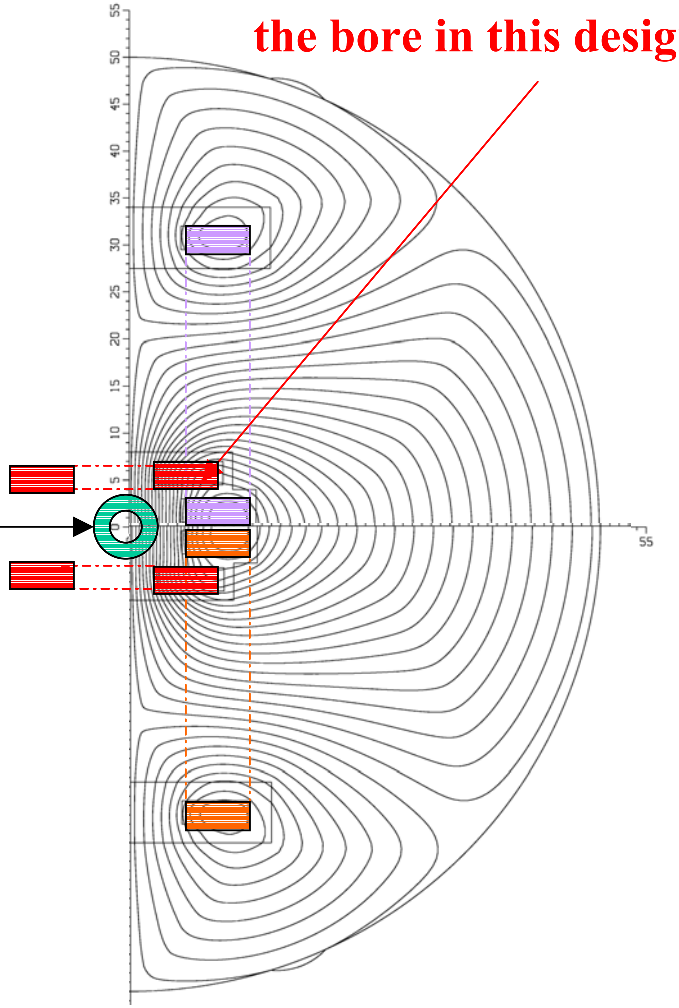
Powering differently changes common coil design test to muon collider design test



muon collider configuration

Note : A high stress test is created here

Racetrack coils clear the bore in this design

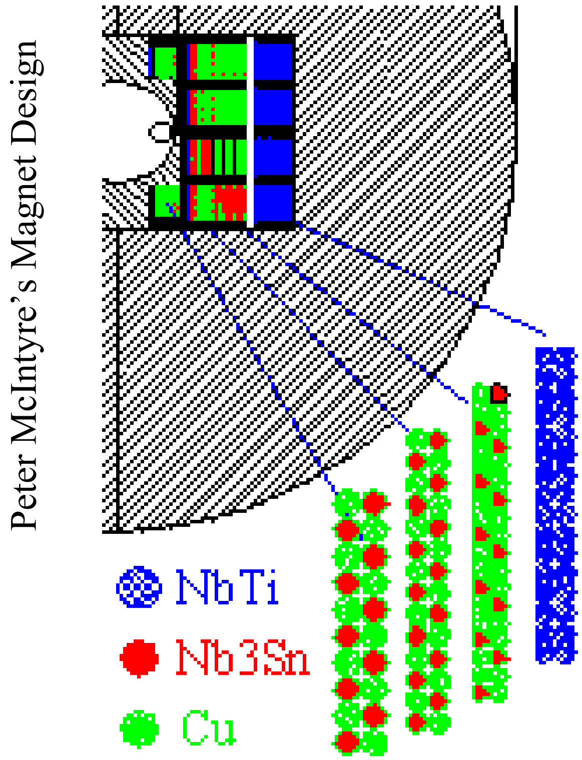


Tungsten & bore tube

Schemes of Adding Cu to Nb_3Sn to Reduce Overall Conductor Cost

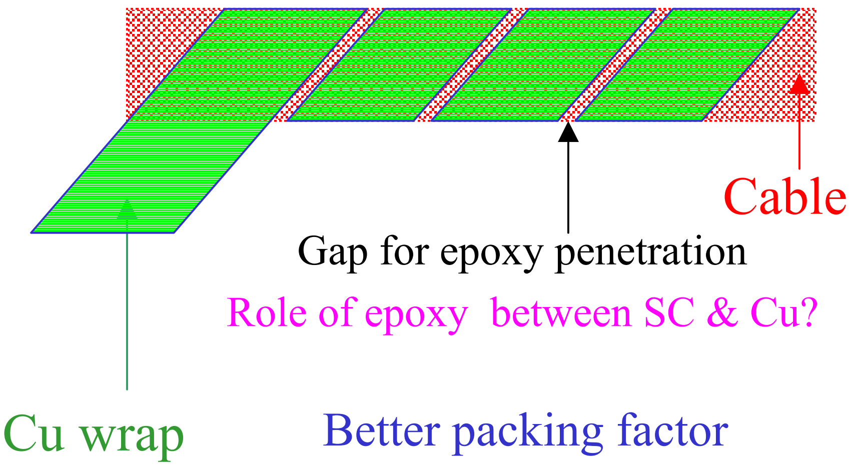
Generally discussed

Mix copper strand with Nb_3Sn strand



An alternate proposal

Wrap copper strip on Nb_3Sn cable



Role of epoxy between SC & Cu?

- Better packing factor
- Lower strand diameter
- May make better cable
- Better (no) matching of different strands

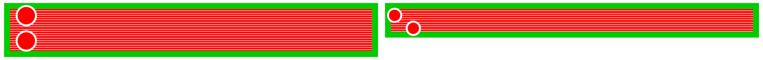
10-turn coil program is ideal for feasibility studies of such ideas.

An Alternate Approach for a More Efficient Cable Grading

Grading cable between layers allows a more efficient use of SC

Put more J where field is lower - creates higher B_{ss} - the goal of the program

- **Usual Grading : Change cable thickness between layers**



Works well but increases relative insulation (15% to 20%) - reduces efficiency

- **Alternate Grading : Change cable width between layers**

Keeps fraction of insulation ~same. Almost full gain of grading is realized

Used in the proposed 14 T design.

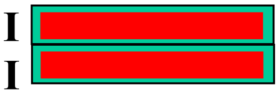
Flexible :

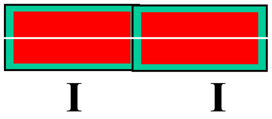
can change relative grading in cable after the strand is purchased

Cables for Higher Efficiency

(exploring ways to reduce insulation fraction)

- Currently insulation takes ~15% of the cable volume
  - If layers are graded, it goes to ~20% in outer layer
- This is large and we must attempt to reduce it
  - Examine alternate insulating materials
  - Examine alternate cabling+insulating schemes

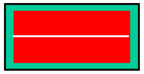




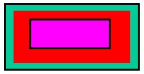
Same current, same inductance but less fraction of insulation (15% => **8%**)

Pair of cable during coil winding

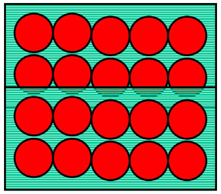
Cable on cable during cable winding



or



Current sharing issues



Possible Use of Proposed Cable in the High Field Magnet Design

Current High Field Design

inner layer 40 strand single pancake,

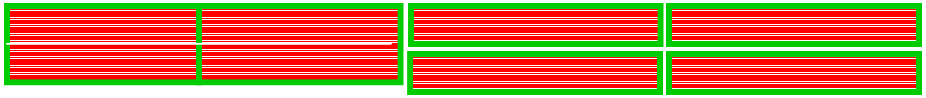
outer 2 layers 26 strand double pancake

uses width-grading for high efficiency (fill factor)

Possible Higher Field Design

inner 2 layers 20 strand double pancake,

outer 2 layers 26 strand double pancake



Will have more turns in critical inner layers and thus create even higher field