Alternate Designs for High Field and Specialty Magnets

(alternate to cosine theta)

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Design Considerations

There are two classes of magnets:

- Main ring magnets

  Large number

  Design should be driven by cost

    cost is determined by material and labor

- Insertion region magnets

  Small number

  Design should be driven by performance (we can allow bigger cost per magnet)

    Material and labor cost does not matter

    Magnet R&D would determine the cost

♠ Perhaps different design principles should apply to two.

Major Accelerator Projects with Superconducting Magnets

Machine	Location	Energy	Circumference	Status
Tevatron	Fermilab, USA	900 GeV (p) X 900 GeV (p-)	6.3 km	Commisioned: 1983
HERA	DESY, Germany	820 GeV (p) X 30 GeV (e)	6.4 km	Commisioned: 1990
SSC	SSCL, USA	20 TeV (p) X 20 TeV (p)	87 km	Cancelled: 1993
UNK	IHEP, Russia	3 TeV	21 km	Suspended
RHIC	BNL, USA	100 GeV/amu X 100 GeV/amu (proton: 250GeV X 250 GeV)	3.8 km	Commisioned: 2000
LHC	CERN, Europe	7 TeV (p) X 7 TeV (p)	27 km	Expected: 2005

	Dipoles				**Quadrupoles**			
Machine	B(T)	Aper(mm)	Length(m)	Number	Grad(T/m)	Aper(mm)	Length(m)	Number
Tevatron	4	76.2	6.1	774	76	88.9	1.7	216
HERA	4.68	75	8.8	416	91.2	75	1.9	256
SSC	6.7	50	15	7944	194	40	5.7	1696
UNK	5	70	5.8	2168	70	70	3	322
RHIC	3.5	80	9.7	264	71	80	1.1	276
LHC*	8.3	56	14.3	1232	223	56	3.1	386

LHC magnets operate at 1.8 K, whereas all other magnets at ~4.2 K.

Present Magnet Design and Technology

Tevatron Dipole

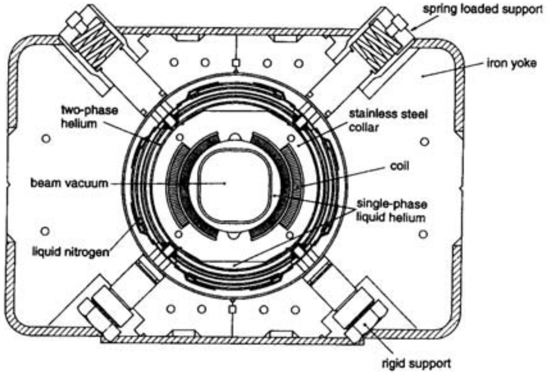
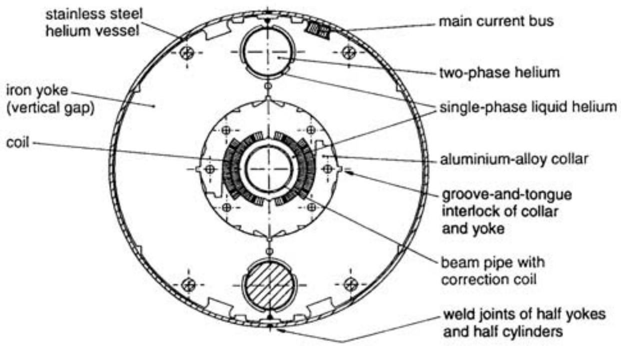
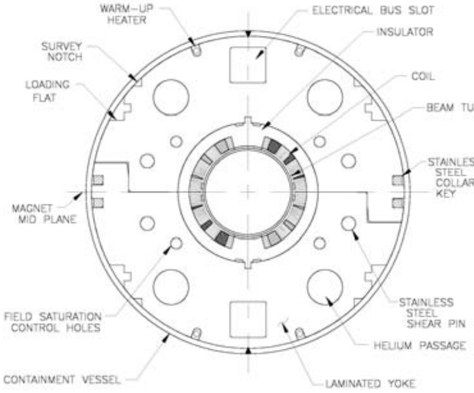


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

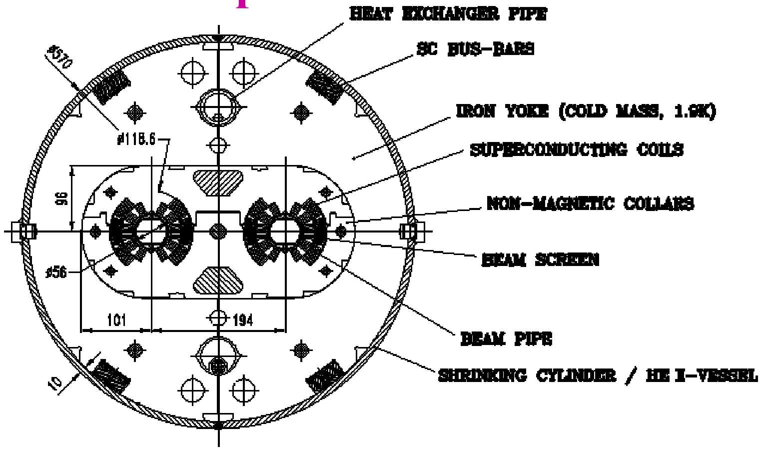
HERA Dipole



RHIC Dipole



LHC Dipole



1.8 K operation

- All magnets use Nb-Ti Superconductor
- All designs use cosine theta coil geometry
- The technology has been in use for decades.
- The technology has reached the limit and can’t produce 10^{+} T field magnet.

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

Minimize internal stress on conductor in very high field magnets

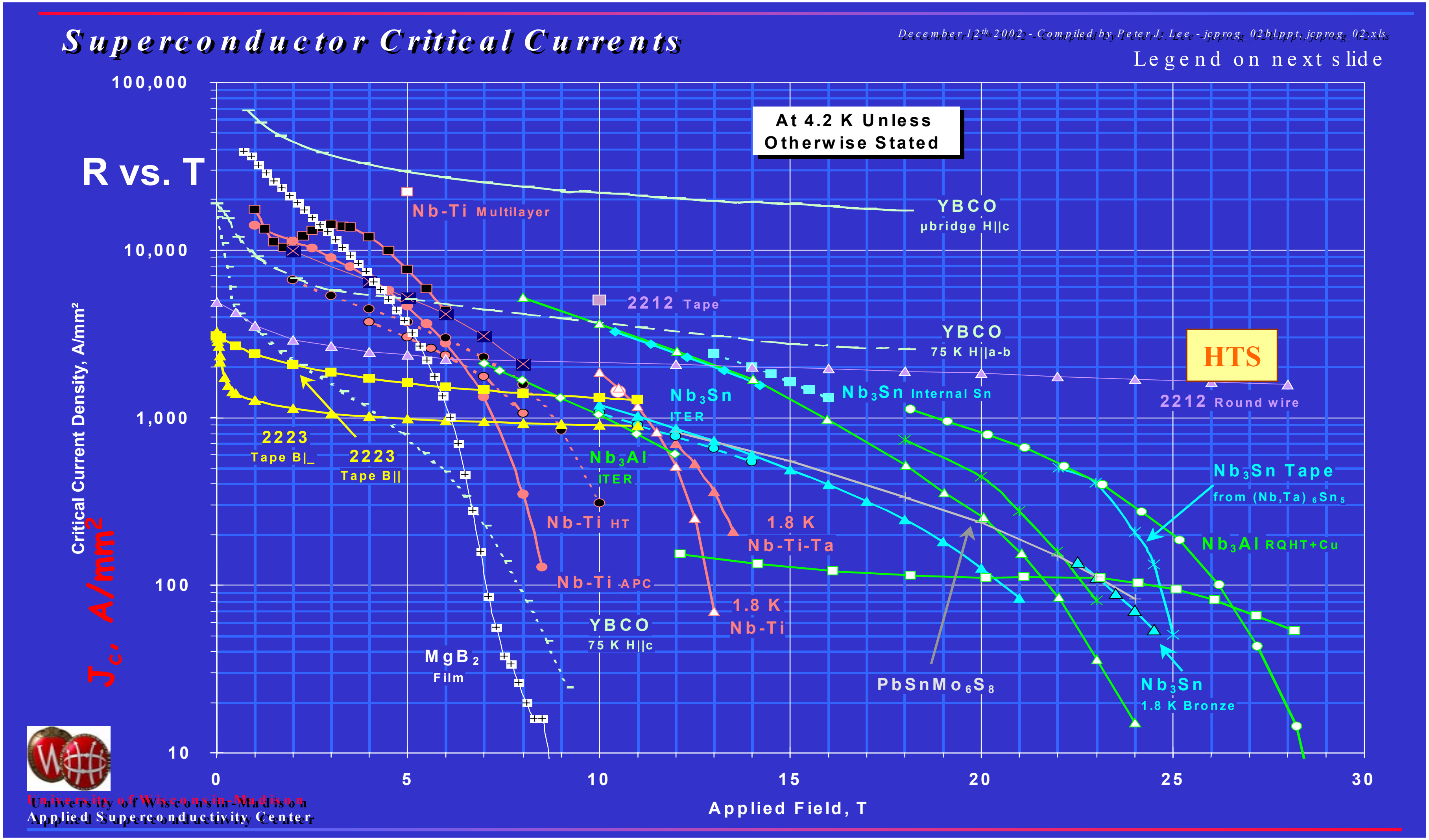
Stress management (Texas A&M)

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

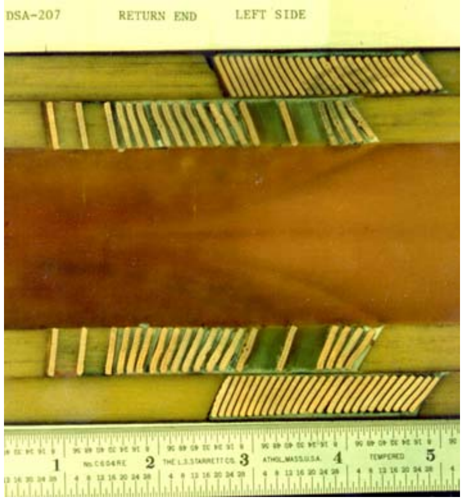
Performance of Some Superconductors



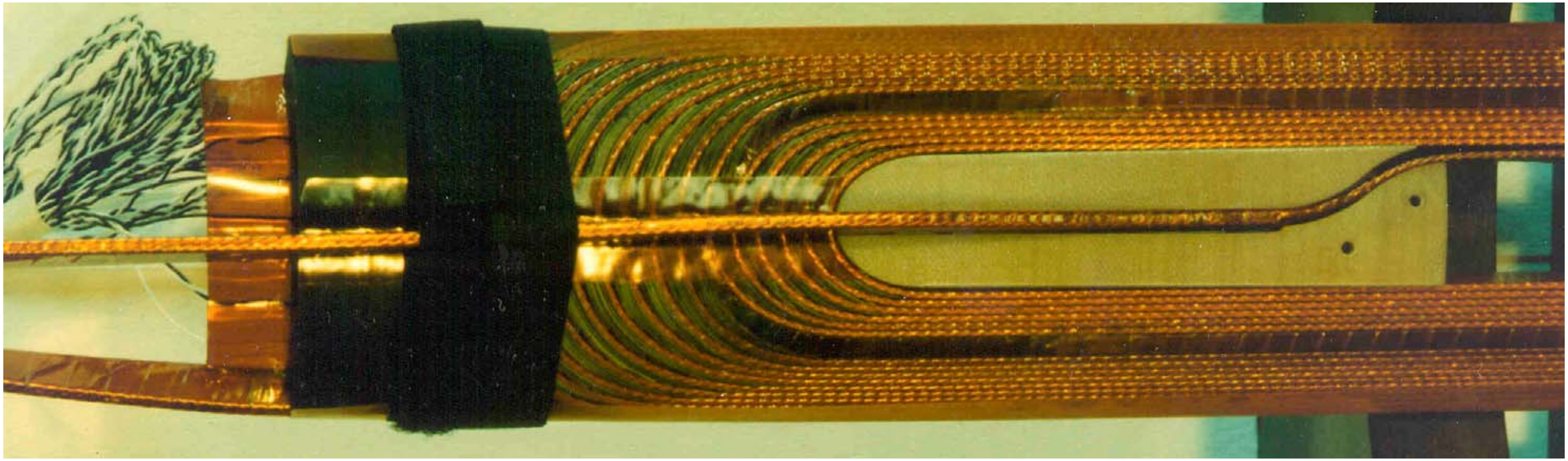
Applied Field, T

Ends in Accelerator Magnets

- All high field conductors of today must be reacted (heat treated) at high temperature 600-900 degree Celsius to turn them in to superconductor.
- At that stage they become brittle in nature and will be degraded severely if bend on a tight radius
- The ends of the conventional cosine theta designs are not suitable for winding coils with brittle conductors



End of a conventional cosine theta magnet design



Two Technologies for Brittle High Field Superconductors

The material become brittle only after it is heat treated (reacted) to turn the mixture into a superconducting material.

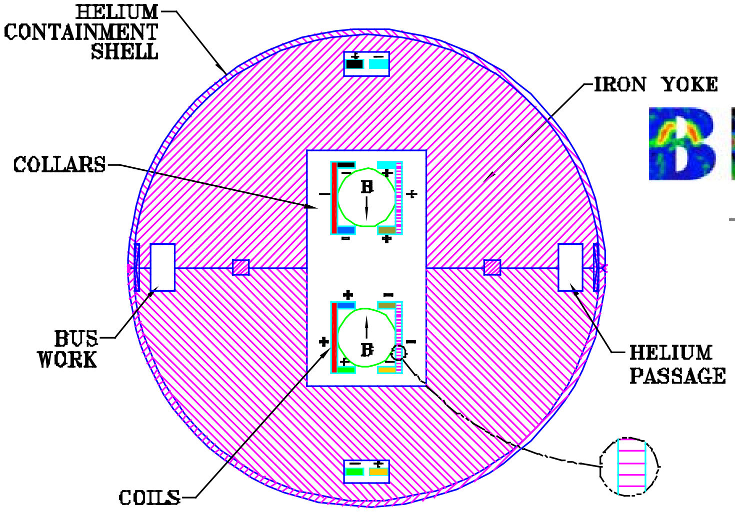
This presents two options:

Wind & React

Wind the coil before the reaction when the conductor is still ductile and react the entire coil package as a whole at a high reaction temperature.

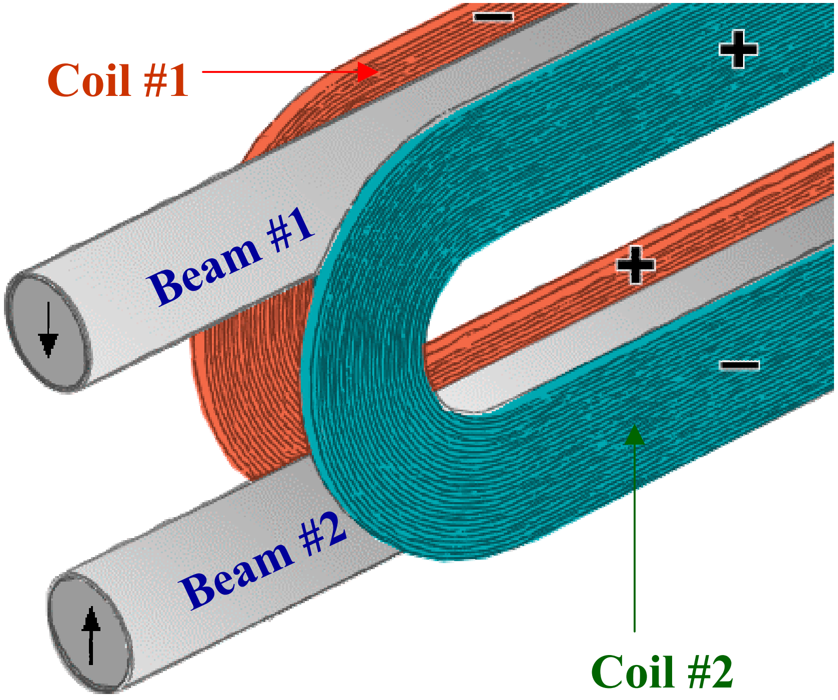
React & Wind

React the conductor alone at high reaction temperature and wind the coil with the brittle conductor. The coil package does not go through the high temperature reaction cycle.



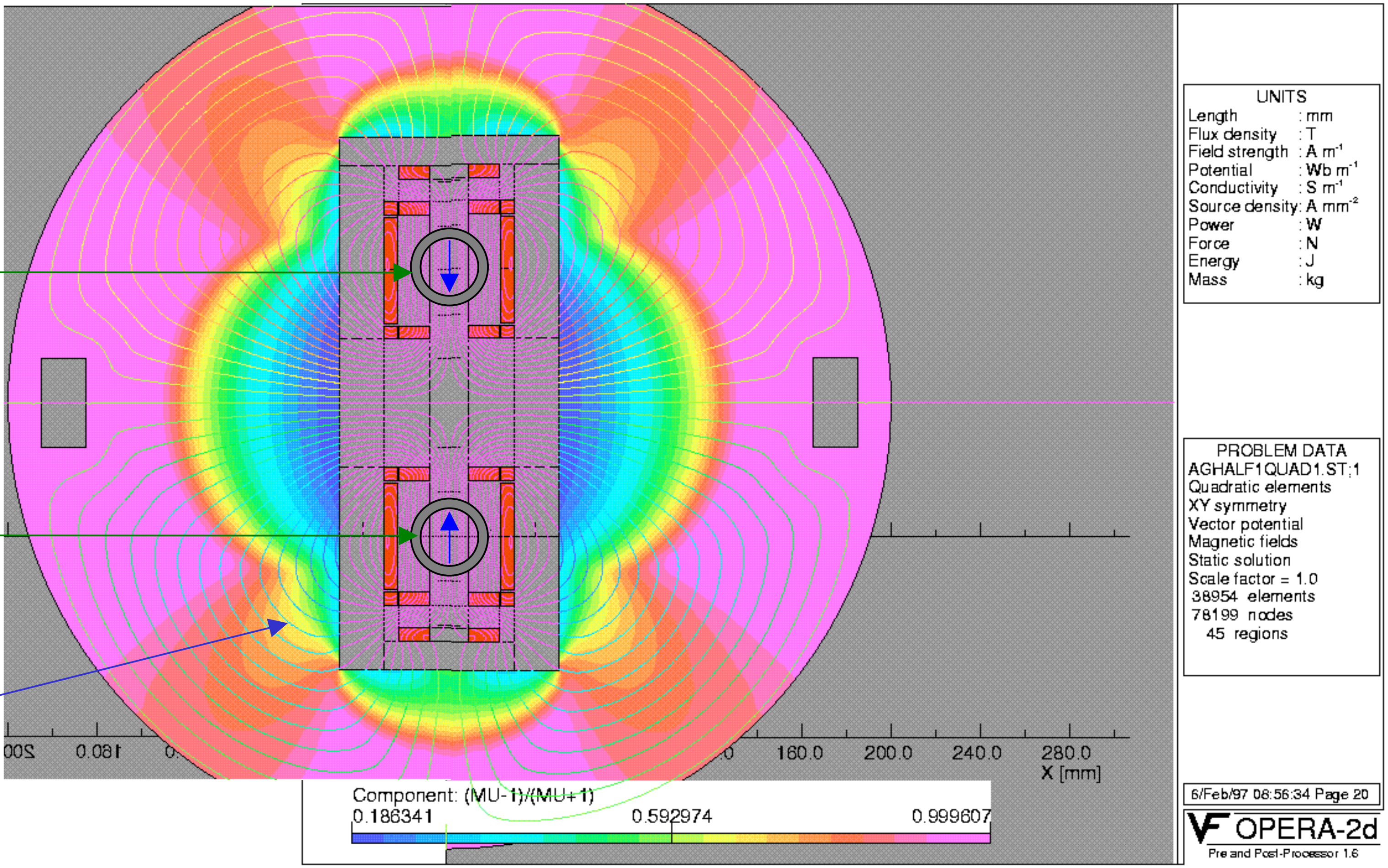
Common Coil Design

- 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$_3$Sn 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
- 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

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

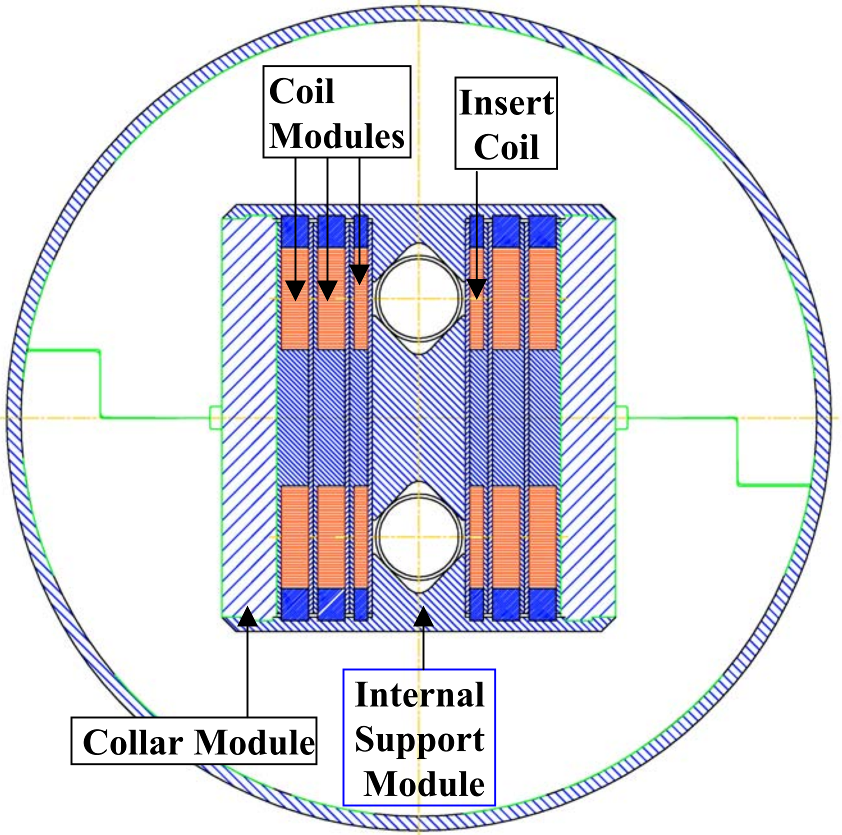
Aperture #1

Aperture #2

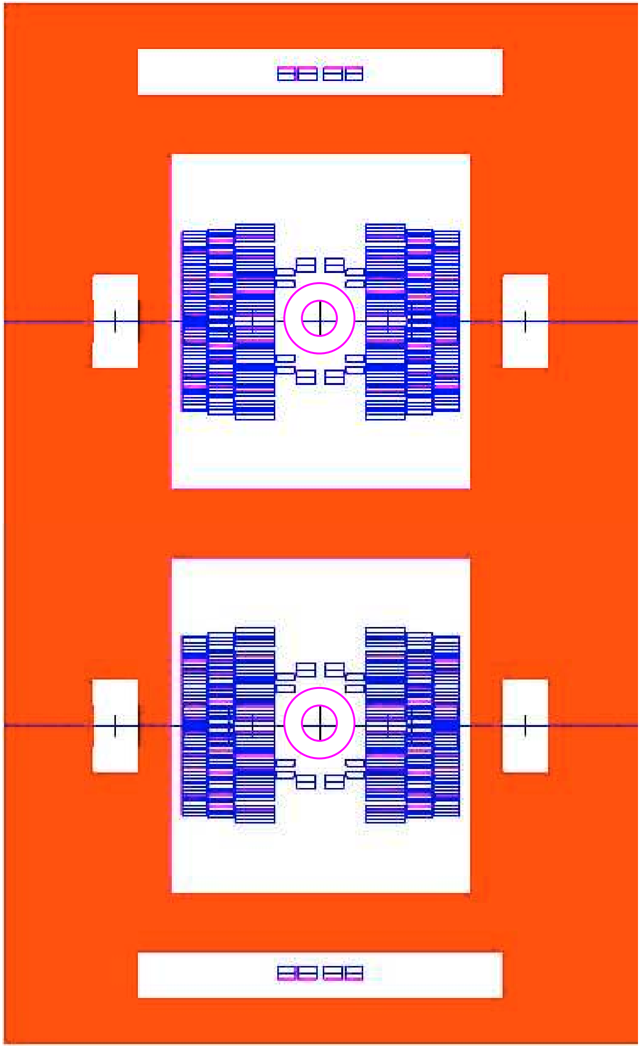
Place of maximum iron saturation

How Does a Common Coil Magnet Look?

R&D Magnet Design



A ~15 T Field Quality Magnetic Design



RHIC: 3.5 T

SSC: 6.6 T

LHC 8.4 T

(forces go as B^2)

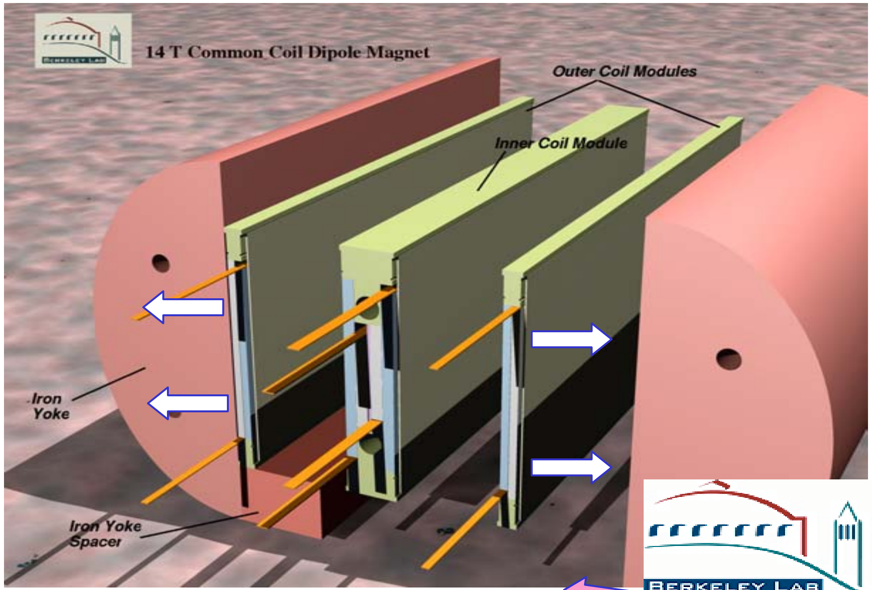
15 T is based on the best available Nb_3Sn conductor available today:

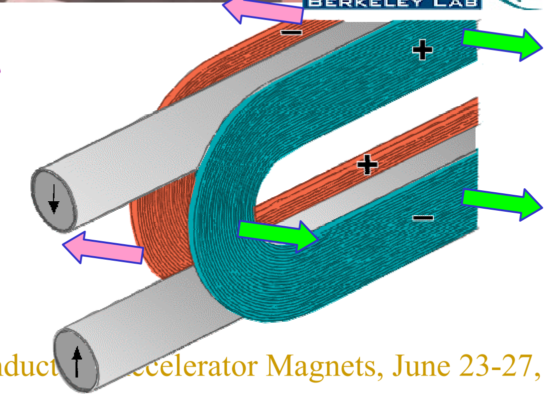
$J_c = 2200\ A/mm^2$ (12T,4.3K).

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

Lorentz Forces in High Field Magnets (Common Coil)

In common coil design, geometry and forces are such that the impregnated solid volume can move as a block without causing quench or damage. The geometry minimizes the large internal motion.



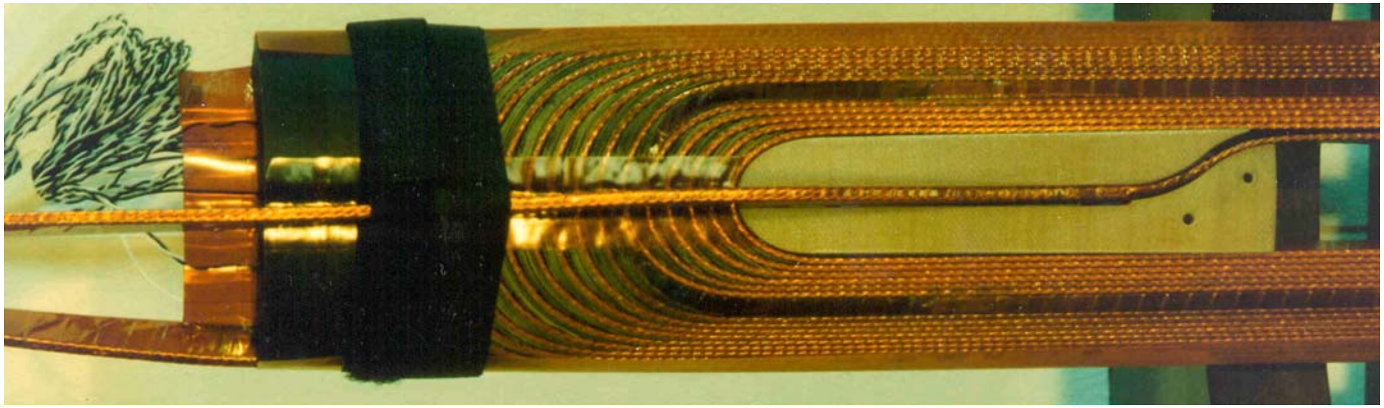


Horizontal forces are larger

LBL got 14.7 T in this design

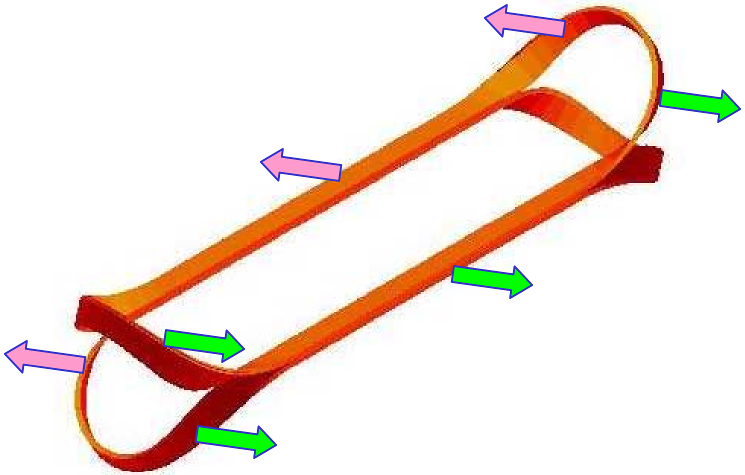
One LBL test magnet survived about 1 mm of such motion. This is about a factor of 10 more than what is generally acceptable. We must check how far we can go in allowing such motions in the body and ends of the magnet. This may significantly reduce the cost of expensive support structure that must be put to contain large Lorentz forces. Field quality optimization should include the harmonics due to such movement as a function of field (as was done in SSC and RHIC magnet designs).

Lorentz Forces in High Field Magnets (Cosine Theta)

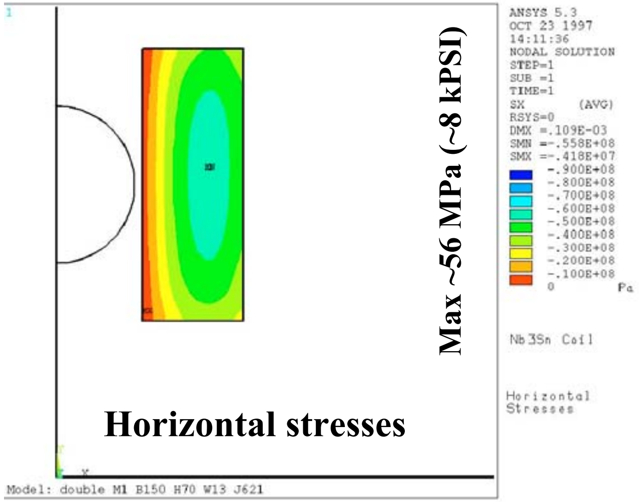


In high field magnets, the Lorentz forces are very large

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.



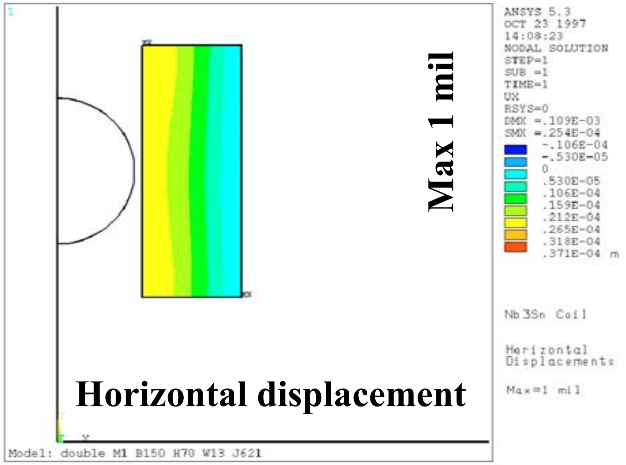
ANSYS Calculations



Max ~56 MPa (~8 kPSI)

Horizontal stresses

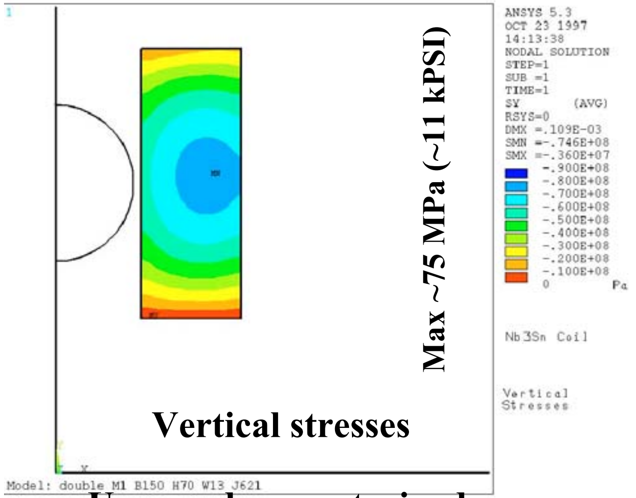
(Right edge constrained)



Max 1 mil

Horizontal displacement

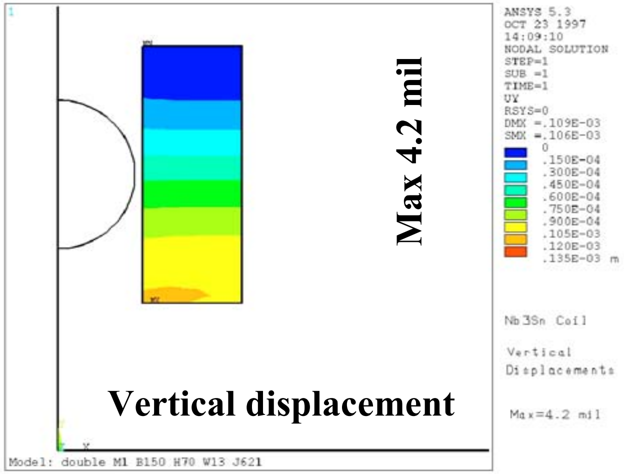
Computed at ~9.6 T (design field 7T)



Max ~75 MPa (~11 kPSI)

Vertical stresses

Upper edge constrained



Max 4.2 mil

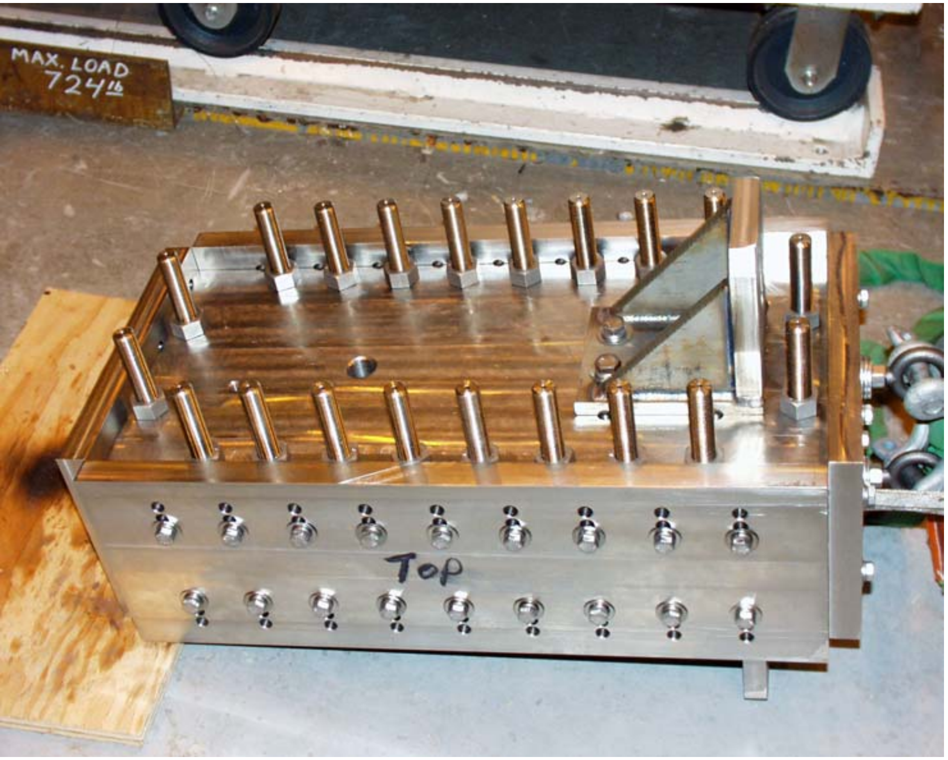
Vertical displacement

**Ken Chow's
Analysis at LBL**

4 T Support Structure

Two coils in a support structure

New 9 T Support Structure



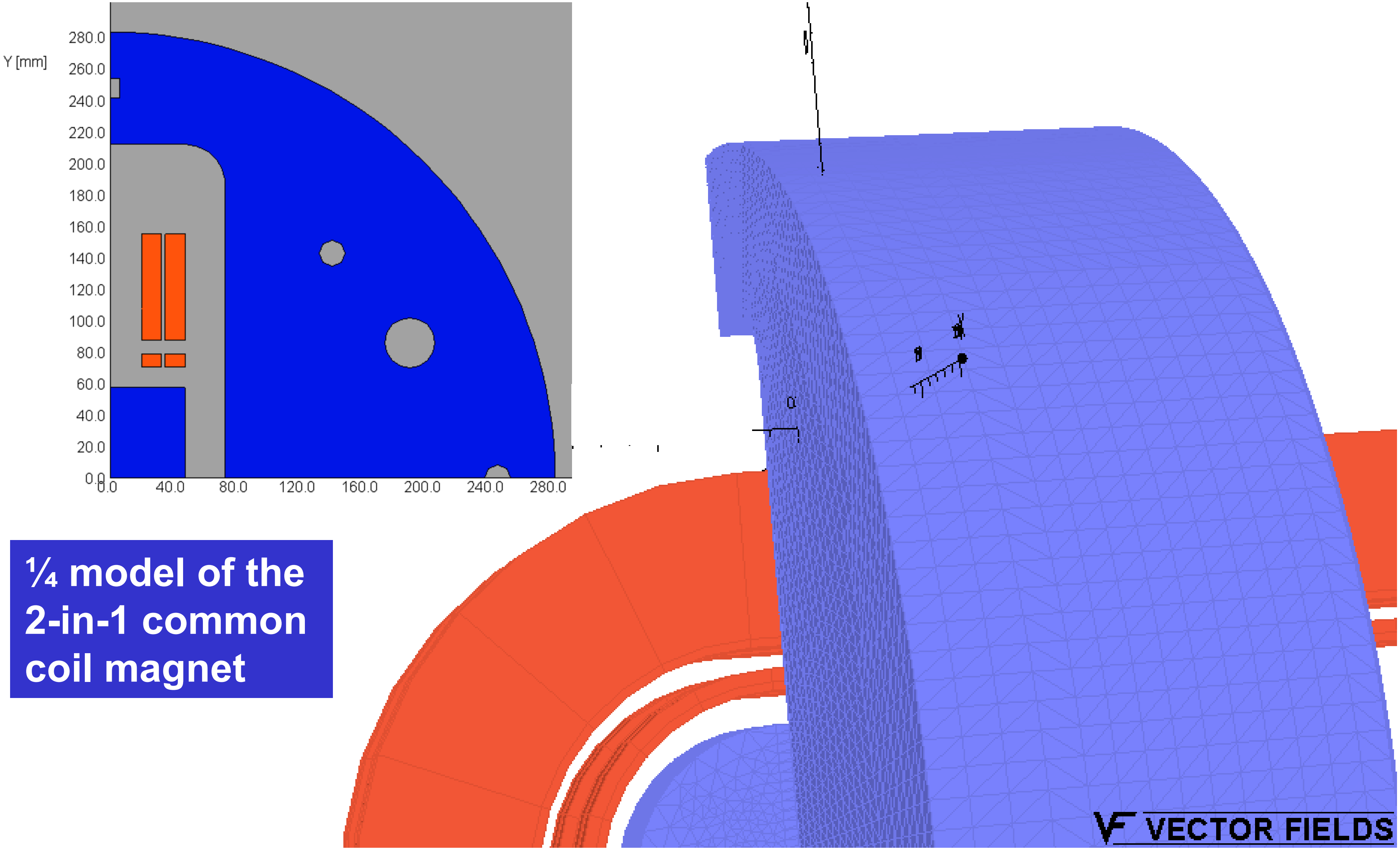
Versatile: Can test from one to six coils with three different currents.

Good for testing HTS coils in background field.

Basic Parameters of 12 T Design

Coil aperture	40 mm
Number of layers	2
Computed quench field at 4.2 K	12 T (12.6 T option)
Peak Fields, inner & outer layers	13.0 T & 8.0 T
Quench current	13.0 kA (11.2 kA, 16.8 kA)
Wire Non-Cu J_{sc} (4.2 K , 12 T)	~2000 A/mm^2
Strand diameter	0.8 mm
No. of strands, inner & outer layers	30, 30
Cable width, inner & outer layer (insulated)	12.5 mm, 12.5 mm
Cu/Non-Cu ratio, inner & outer	0.86, 1.53
No. of turns per quadrant of single aperture	90/2 = 45
Max. height of each layer from midplane	85/2 = 42.5 mm
Bore spacing	220 mm
Minimum coil bend radius (in ends)	70 mm
Outer yoke radius	283 mm

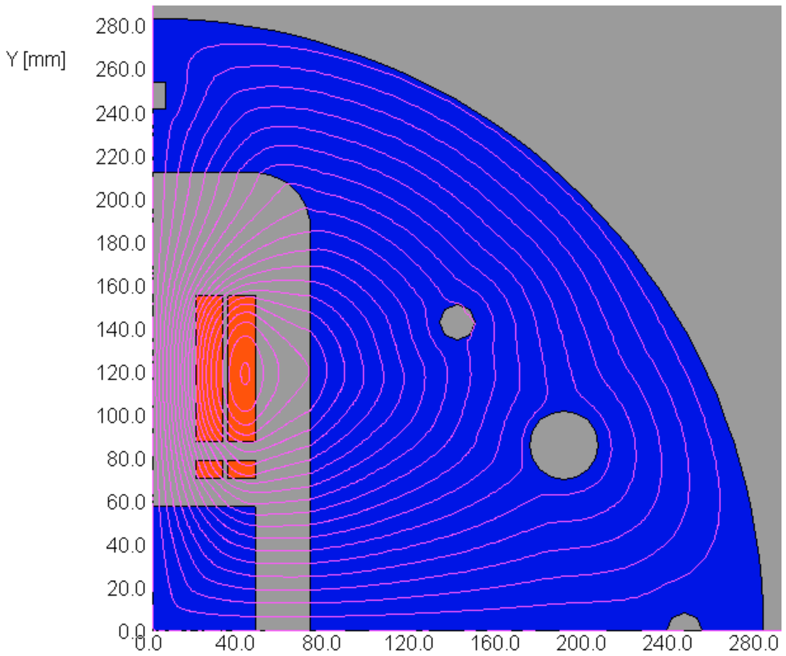
Magnetic Models of the Design



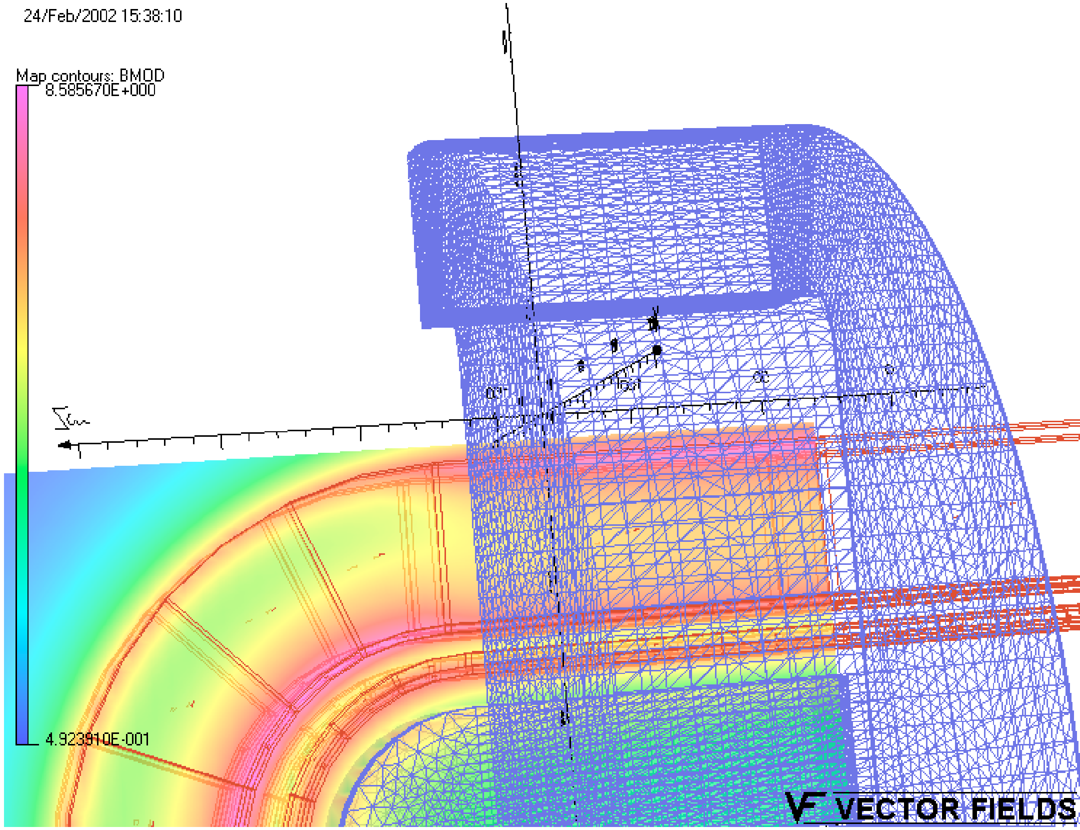
¼ model of the 2-in-1 common coil magnet

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.

Expected Performance When Coils in Both Layers Carry Equal Current

Bss = 12 T

Expected Performance of BNL 12 T Design 45 turn (equal current)

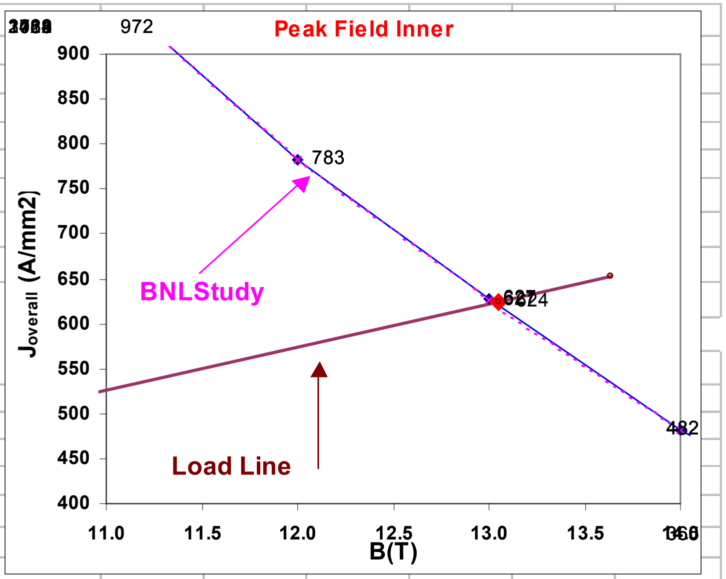
1.04		600.0		600.0	
	Jsc-in	**Joverall-in**	**Jsc-out**	**Joverall-out**	
	1598	**624**	**2167**	**624**	
1162		1255			767
Bss(T)	**Iss-in(kA)**	**Bpeak(in)**		**Iss-out(kA)**	**Bpeak(out)**
12.08	**12.94**	**13.05**		**12.94**	**7.98**
Bss		**Enhcment**			**Enhcment**
		1.080			**0.660**
		Inner		**Outer**	
J_{cu}(A/mm^2) @Quench		**1854**		**1421**	
	Cu/Non-Cu	0.86	Cu/Non-Cu	1.53	

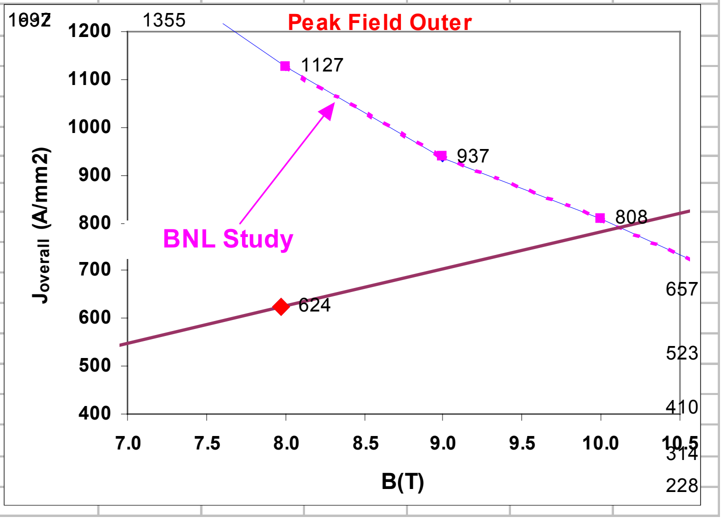
Inner wire & cable expected performance — **30 strand (0.8 mm) cable**

Non-Cu(%)	**53.7**	(LBL Spec=59%)	Iwire(15T)	**252**	(LBL Spec=305)
B(T)	**Jc(A/mm2)**	Jwire(A/mm2)	***Iwire(A)***	Icable(A)	***Joverall***
10	**3026**	***1625***	***817***	***24503***	***1182***
11	**2488**	***1336***	***672***	***20149***	***972***
12	**2005**	***1077***	***541***	***16239***	***783***
13	**1605**	***862***	***433***	***12997***	***627***
14	**1234**	***662***	***333***	***9989***	***482***
15	**934**	***501***	***252***	***7560***	***365***
					Insulated

Outer wire & cable expected performance — **30 strand (0.8 mm) cable**

Non-Cu(%)	**39.6**	(LBL Spec=37%)	Iwire(10T)	**559**	(LBL Spec=537)
B(T)	**Jc(A/mm2)**	Jwire	***Ic (wire)***	Ic Cable	***Joverall***
8	**3915**	***1550***	***779***	***23377***	***1127***
9	**3255**	***1289***	***648***	***19438***	***937***
10	**2808**	***1112***	***559***	***16770***	***809***
11	**2282**	***904***	***454***	***13628***	***657***
12	**1817**	***720***	***362***	***10852***	***523***
13	**1425**	***564***	***284***	***8508***	***410***
14	**1092**	***432***	***217***	***6518***	***314***
15	**791**	***313***	***157***	***4724***	***228***
					Insulated

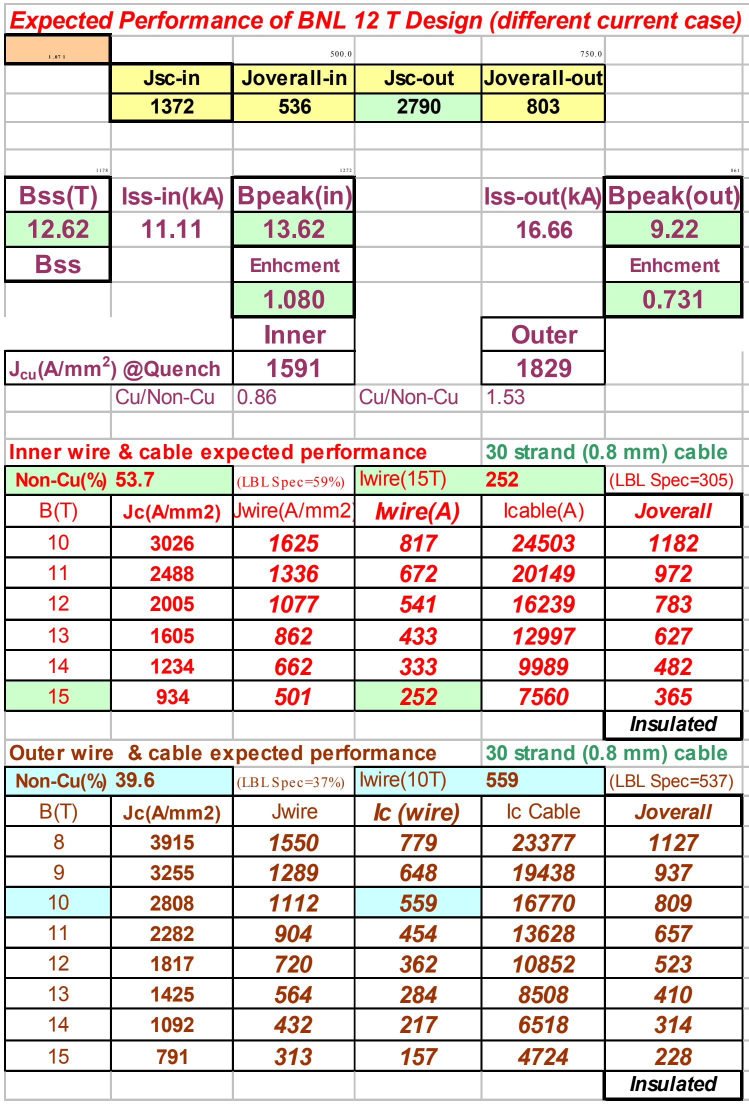




Expected Performance When Coils in Both Layers Carry Different Currents

Bss = 12.6 T

Apart from producing higher field, the different current option would scientifically examine the influence of Cu/Sc ratio and Jcu on coil performance.



Expected Performance of BNL 12 T Design (different current case)

1 .07 1		500.0		750.0	
	Jsc-in	Joverall-in	Jsc-out	Joverall-out	
	1372	536	2790	803	
1178		1272			861
Bss(T)	Iss-in(kA)	Bpeak(in)		Iss-out(kA)	Bpeak(out)
12.62	11.11	13.62		16.66	9.22
Bss		Enhcment			Enhcment
		1.080			0.731
		Inner		Outer	
J_{cu}(A/mm^2) @Quench		1591		1829	
	Cu/Non-Cu	0.86	Cu/Non-Cu	1.53	

Inner wire & cable expected performance				30 strand (0.8 mm) cable	
Non-Cu(%)	53.7	(LBL Spec=59%)	Iwire(15T)	252	(LBL Spec=305)
B(T)	Jc(A/mm2)	Jwire(A/mm2)	Iwire(A)	Icable(A)	Joverall
10	3026	1625	817	24503	1182
11	2488	1336	672	20149	972
12	2005	1077	541	16239	783
13	1605	862	433	12997	627
14	1234	662	333	9989	482
15	934	501	252	7560	365
					Insulated

Outer wire & cable expected performance				30 strand (0.8 mm) cable	
Non-Cu(%)	39.6	(LBL Spec=37%)	Iwire(10T)	559	(LBL Spec=537)
B(T)	Jc(A/mm2)	Jwire	Ic (wire)	Ic Cable	Joverall
8	3915	1550	779	23377	1127
9	3255	1289	648	19438	937
10	2808	1112	559	16770	809
11	2282	904	454	13628	657
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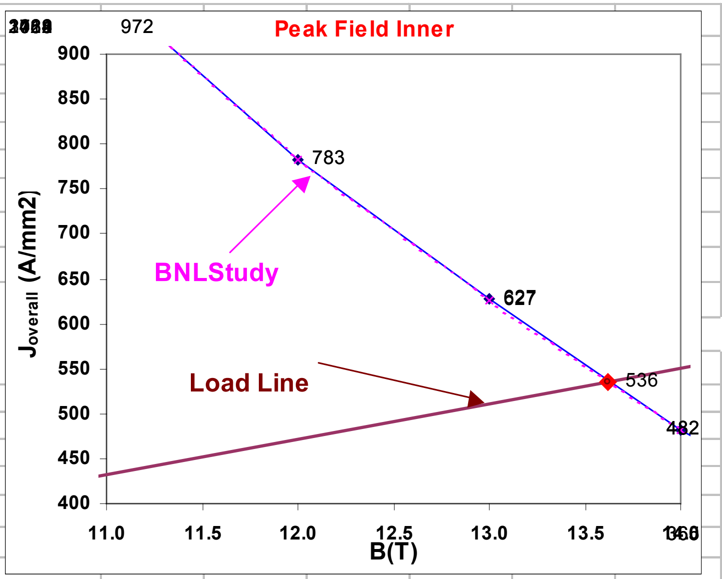
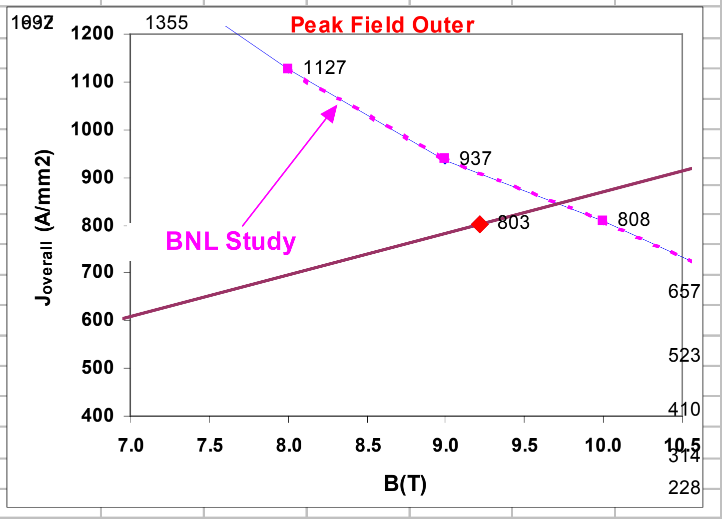
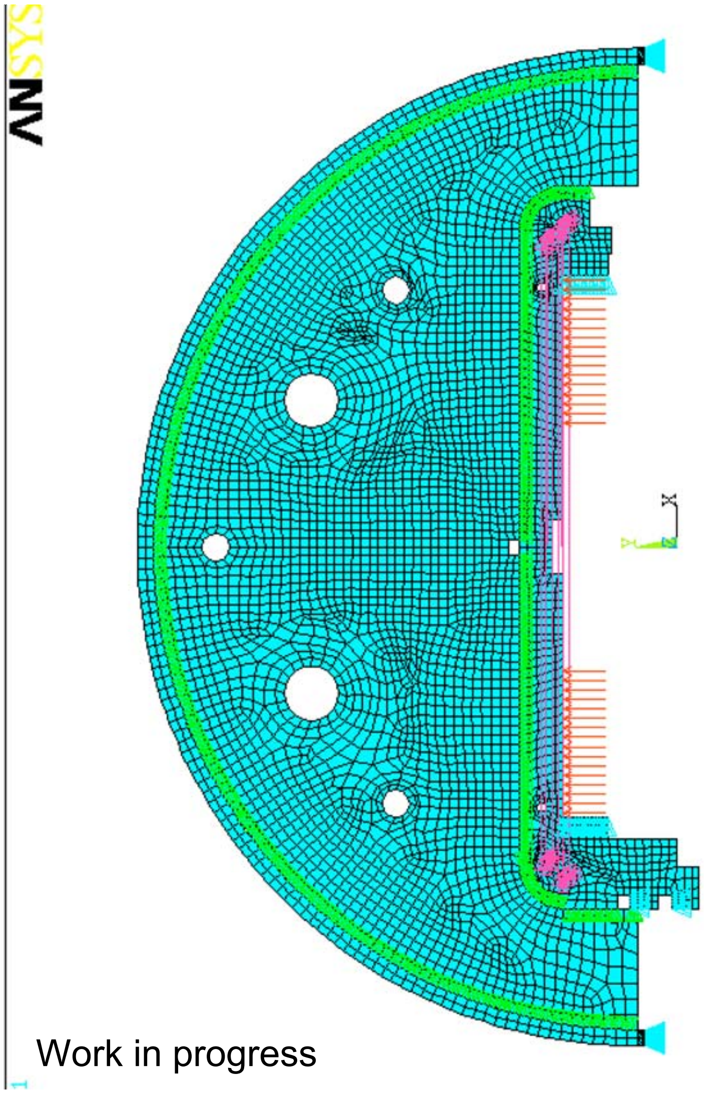
15	791	313	157	4724	228
					Insulated





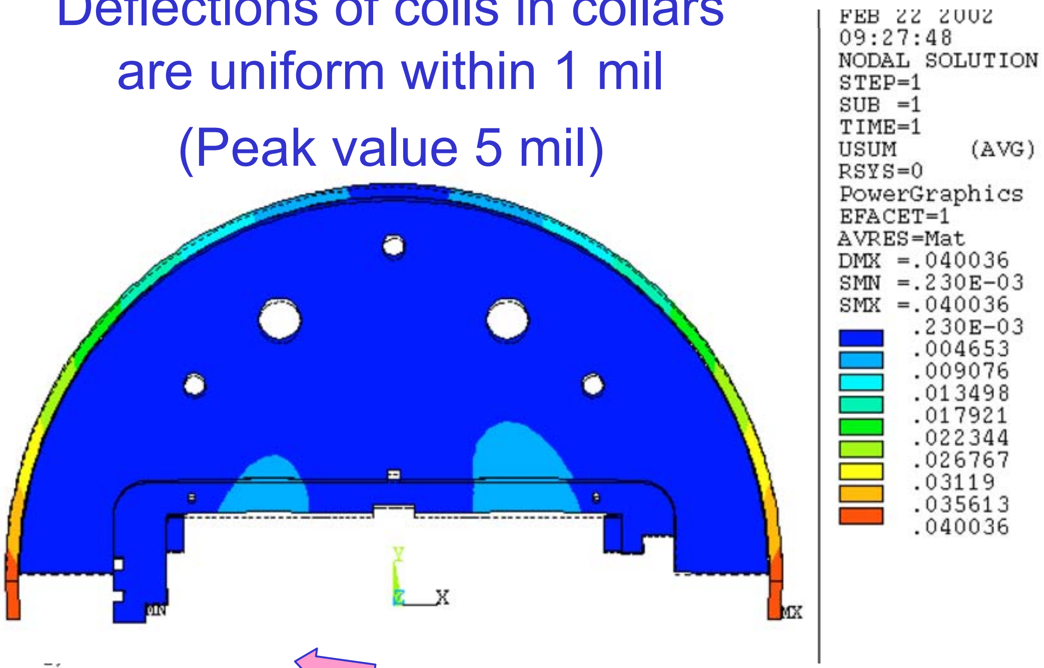
ANSYS Analysis of 12 T Magnet

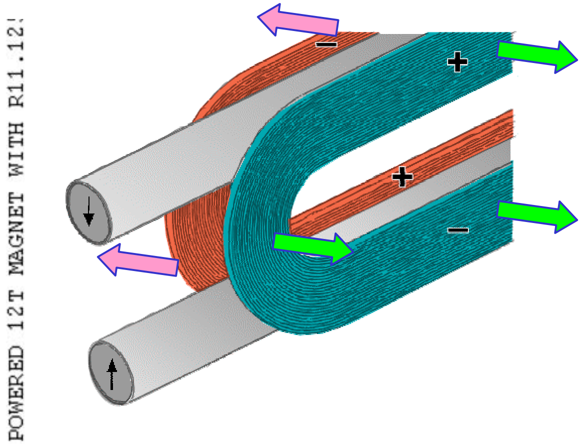


Work in progress

Deflections of coils in collars are uniform within 1 mil

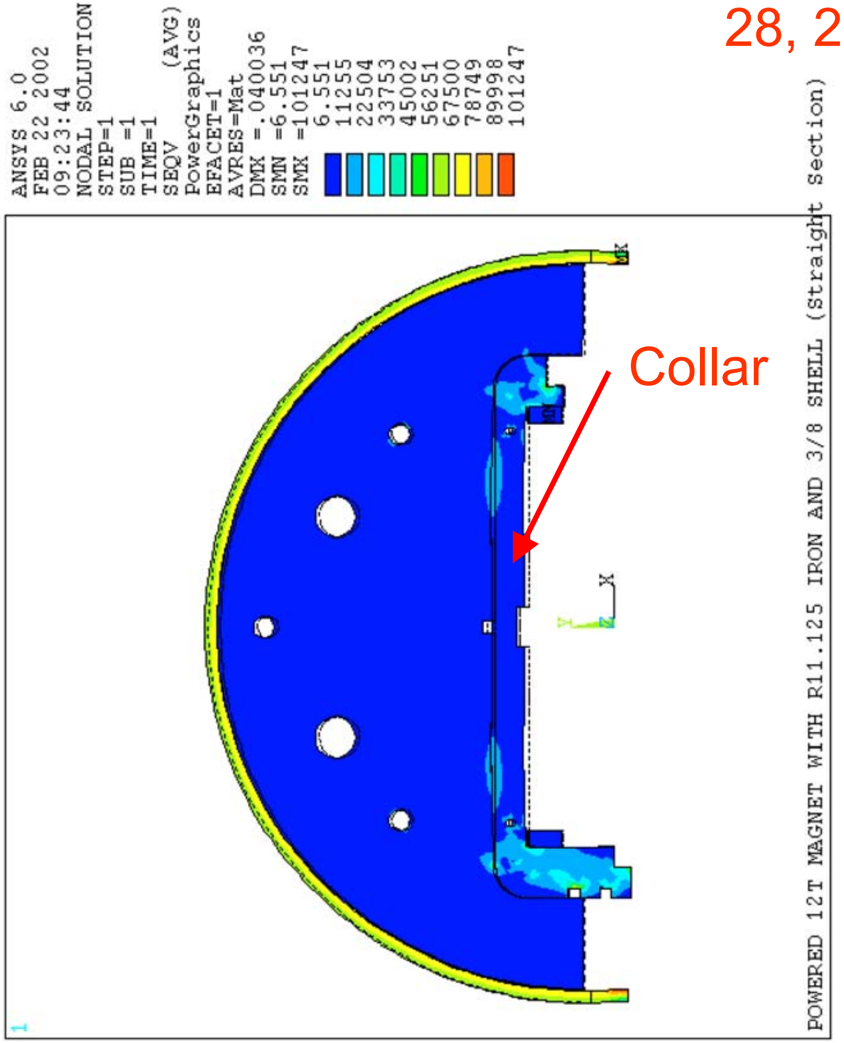
(Peak value 5 mil)





Common coil design can tolerate much larger overall coil motion as long as the relative variation is small

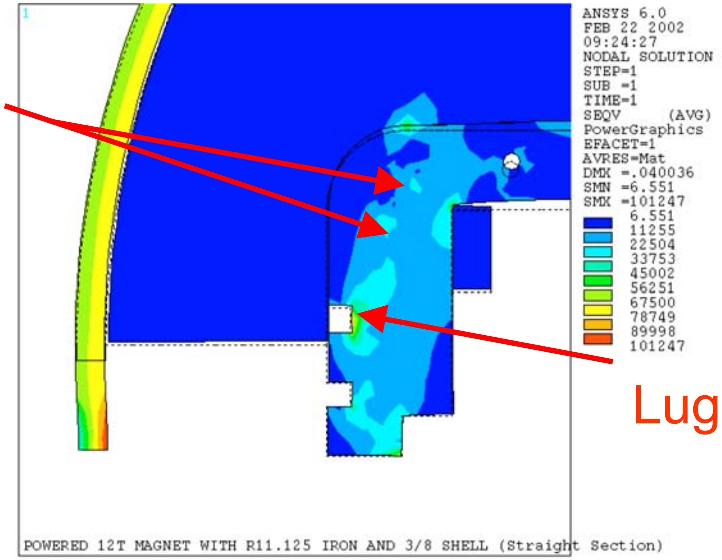
Stresses in Collar Region



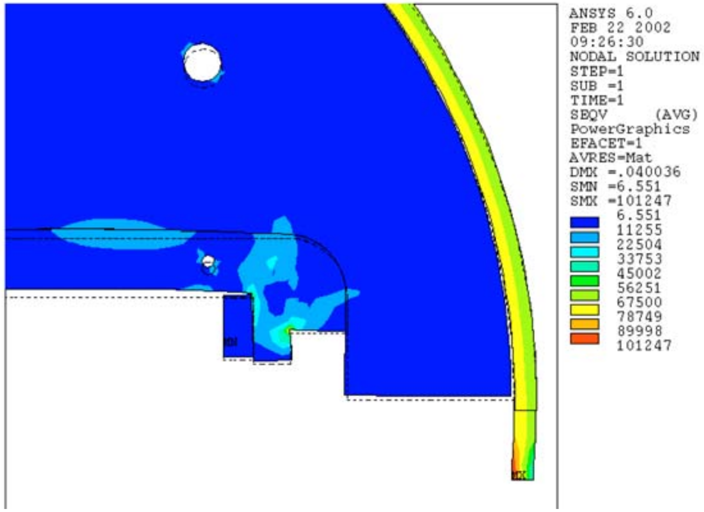
Collar

Spot weld

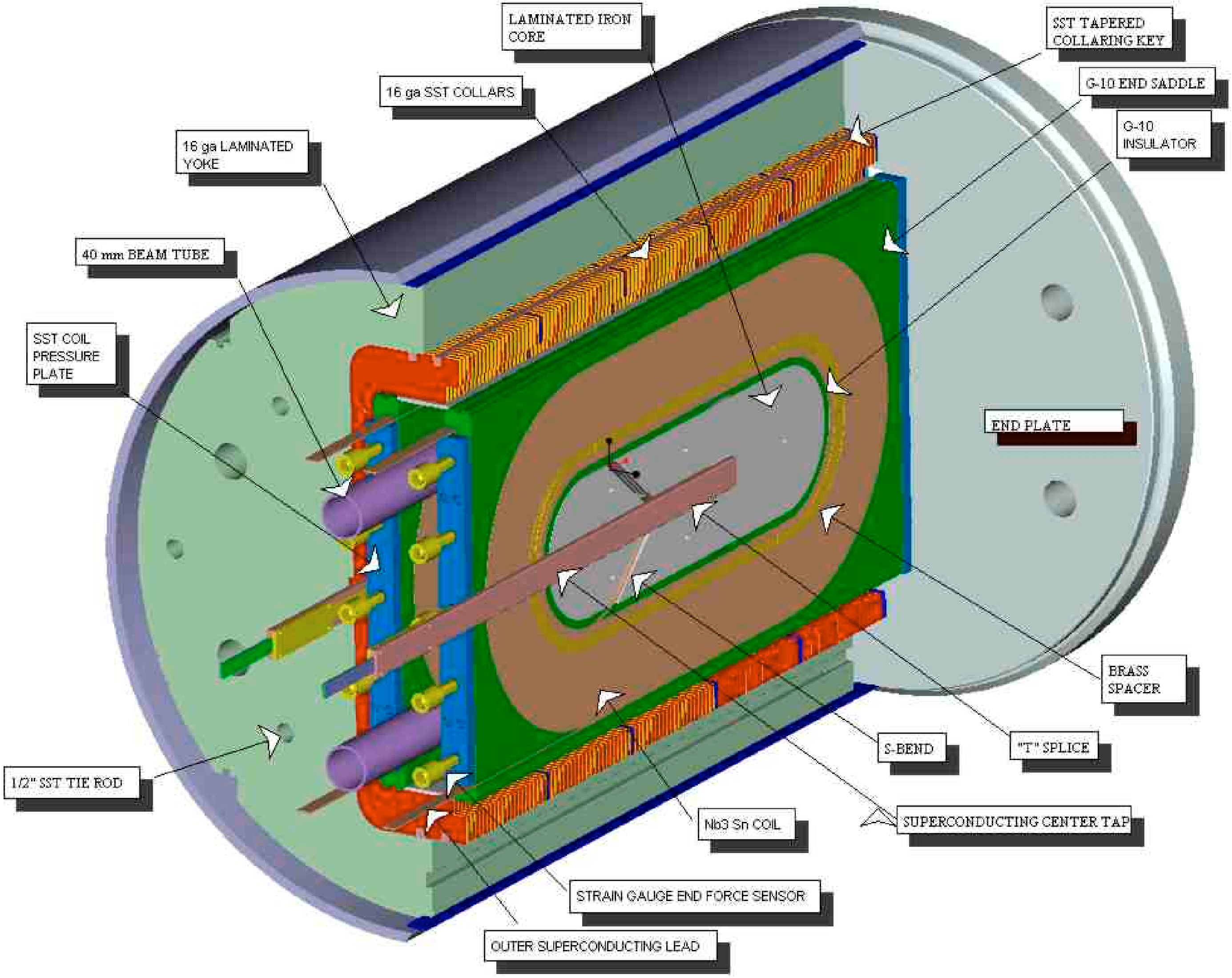
28, 22 ksi



Lug 78 ksi



BNL 12 T Nb_3Sn Common Coil Background Field Dipole



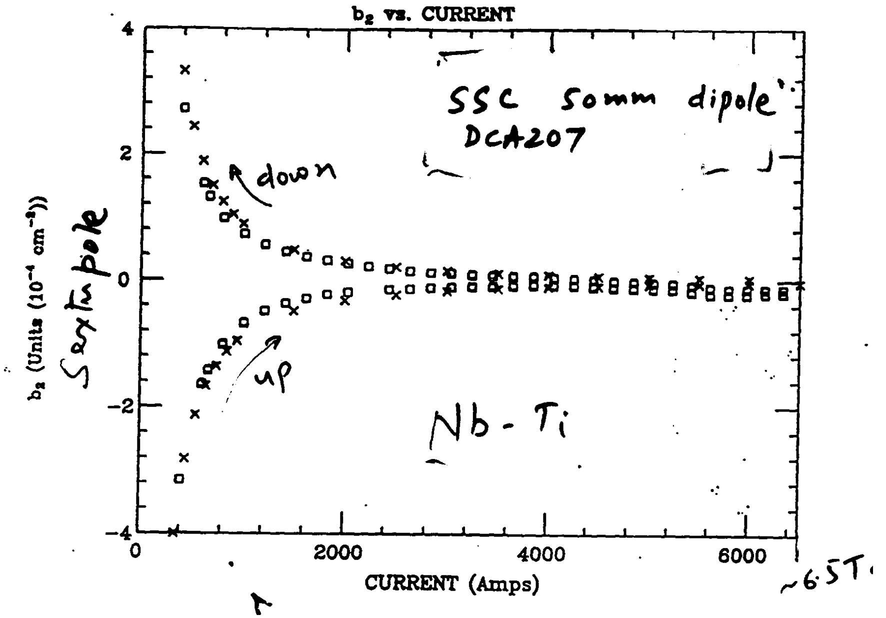
Nb_3Sn conductor for both inner and outer layers is provided by OST

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

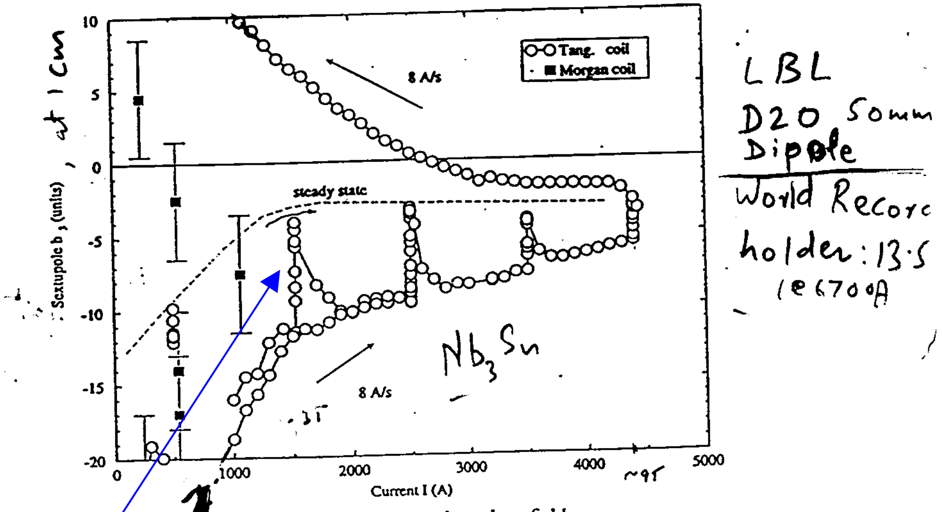


Fig. 6.. Measured sextupole at low field (direction of arrow indicates up or down current).

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 :

$$2\mu_0 M = 2\mu_0 \frac{2}{3\pi} \nu J_c d \qquad ①$$

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

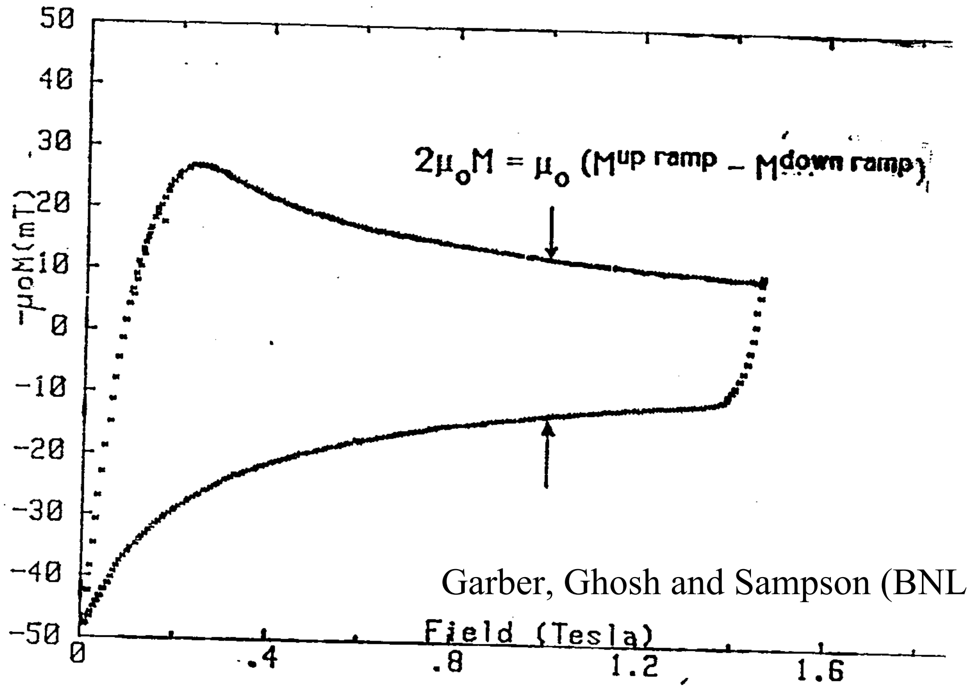
(b) Effective filament diameter is larger by about an order of magnitude

Conductor solution:

Reduce effective filament diameter.

A challenge; in some cases it also reduces J_c.

Measured magnetization



Garber, Ghosh and Sampson (BNL)

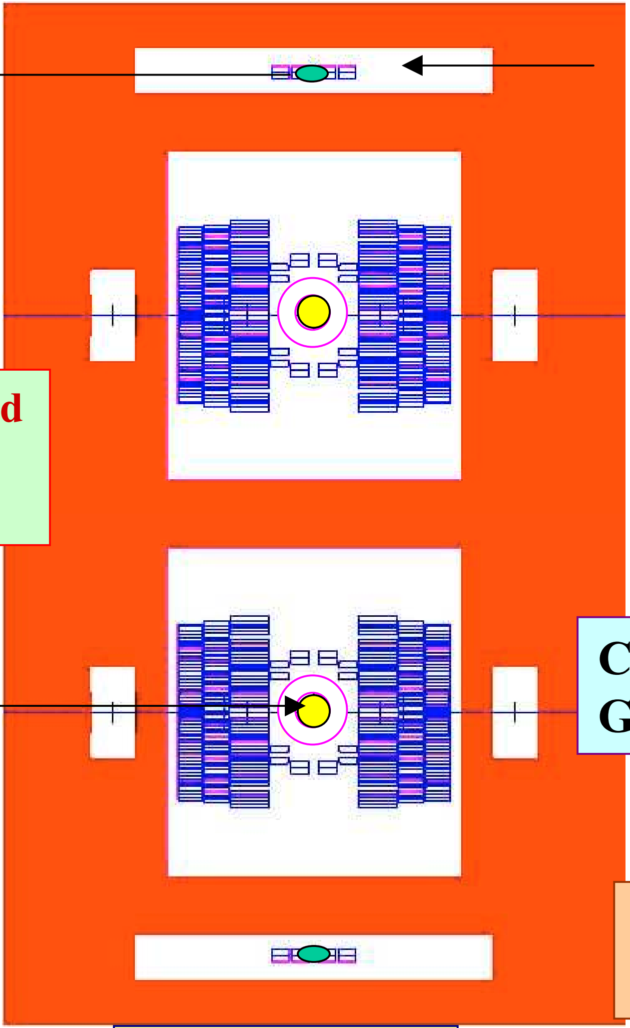
Fig. of a typical magnetization loop.

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

A Common Coil Magnet System

A Solution to 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

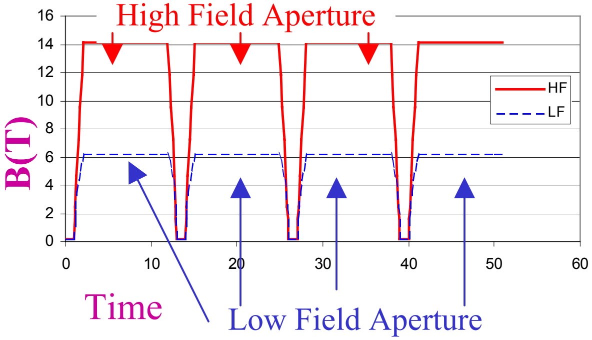
Injection at low field in iron dominated aperture should solve the large persistent current problem associated with Nb3Sn

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)

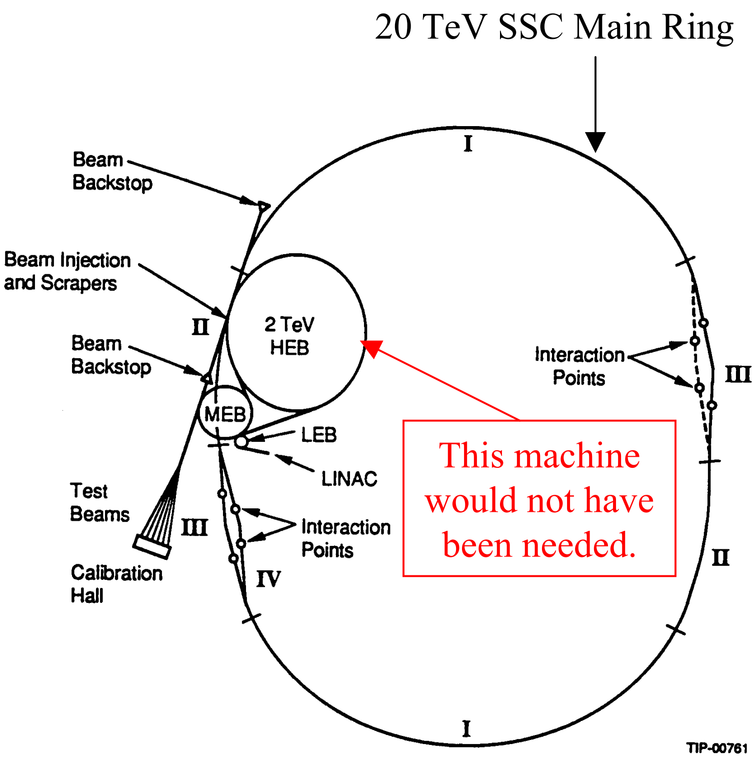
Field profile with time



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.

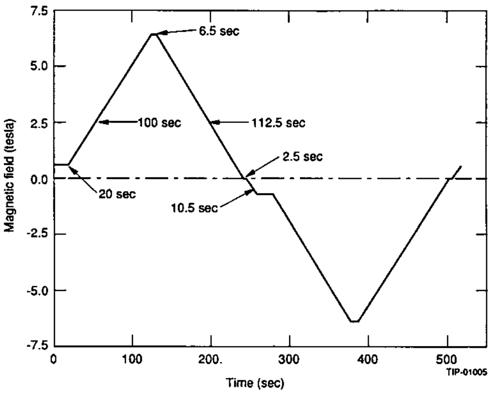


Figure 4.1.2.4-1. The suggested slow, alternating ramp scenario of the HEB.

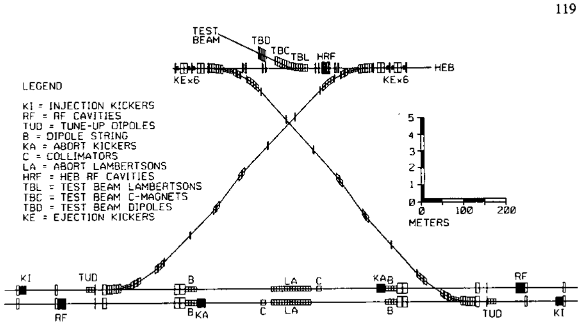


Figure 4.1.1.3-4. Elevation view of collider utility region.

- 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

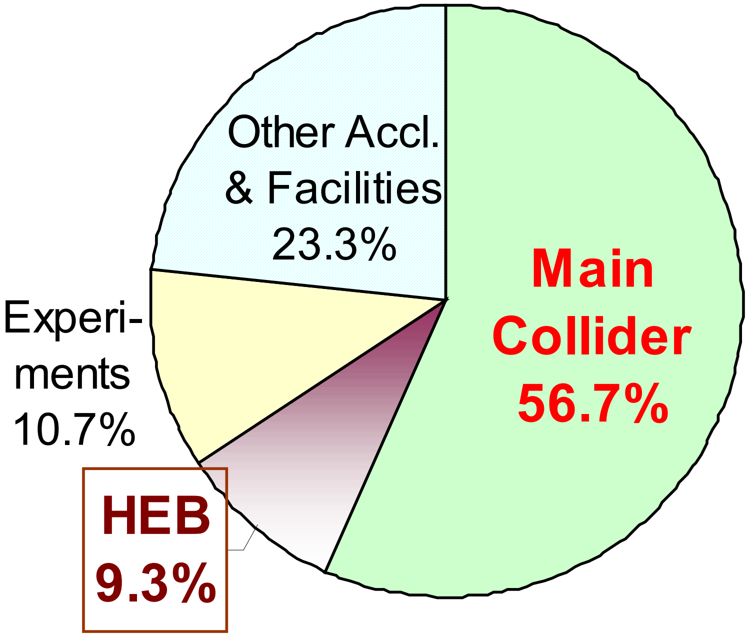
Estimated for 5 TeV (5-50 TeV vlhc):
~$1,500 million (in 1990 US$)

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)

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.

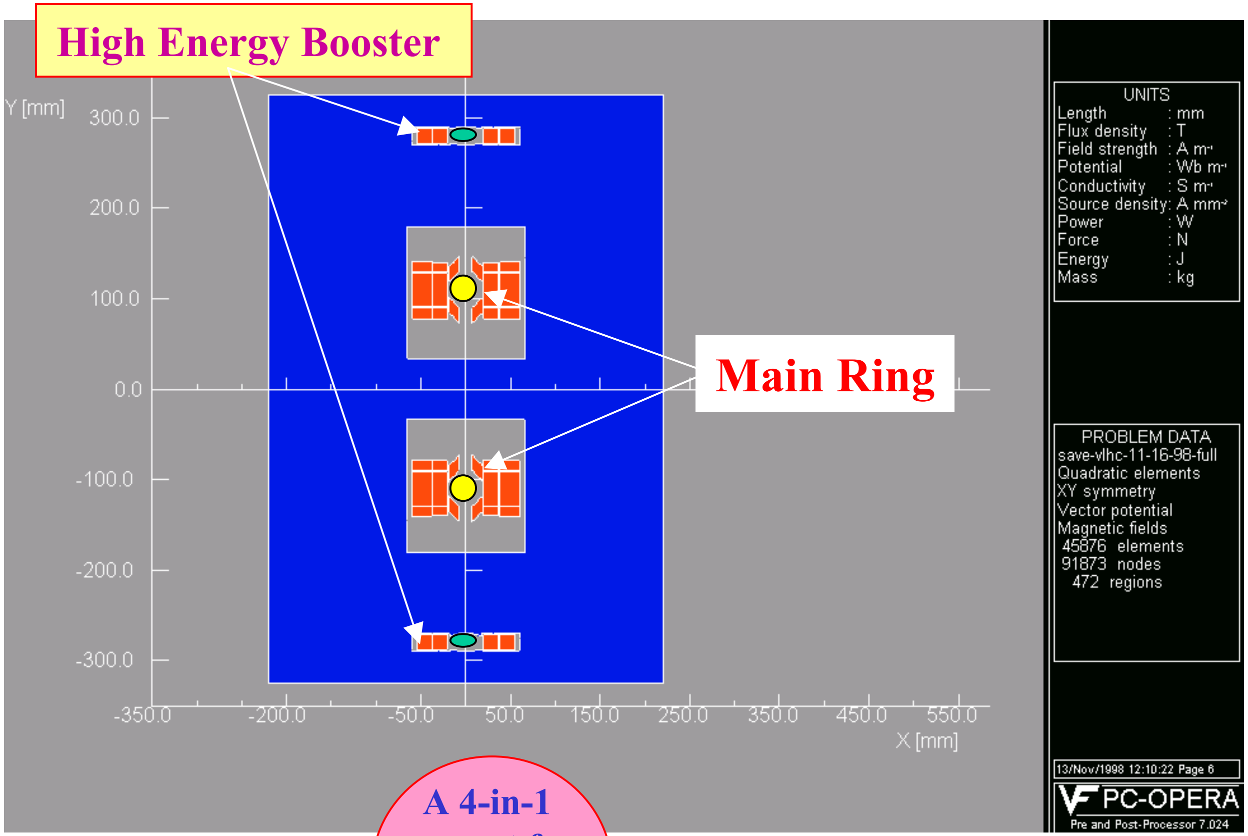
Accelerator Physics Issues

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.

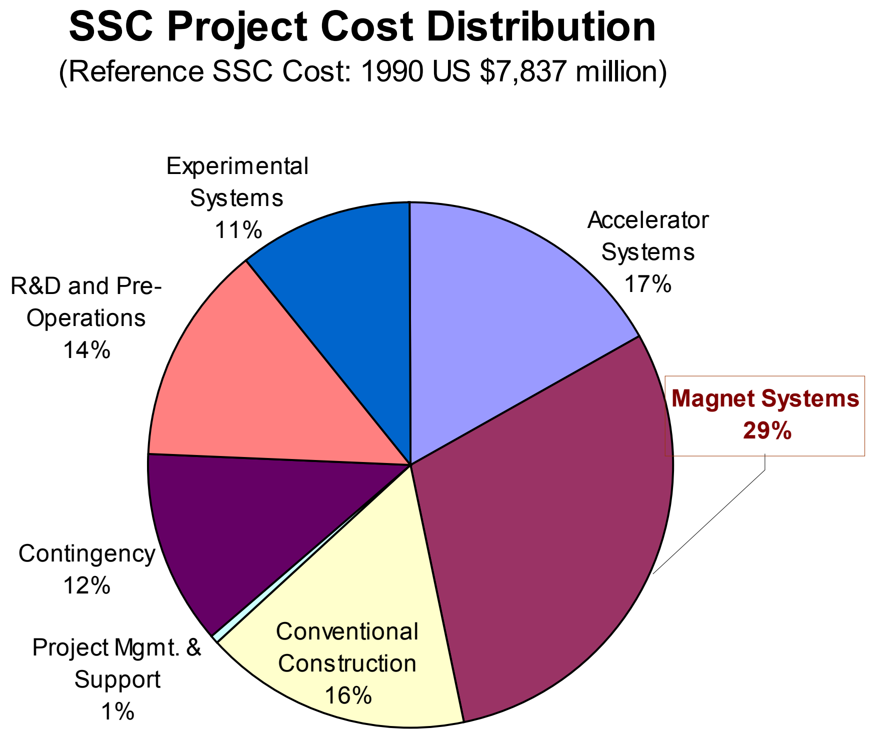


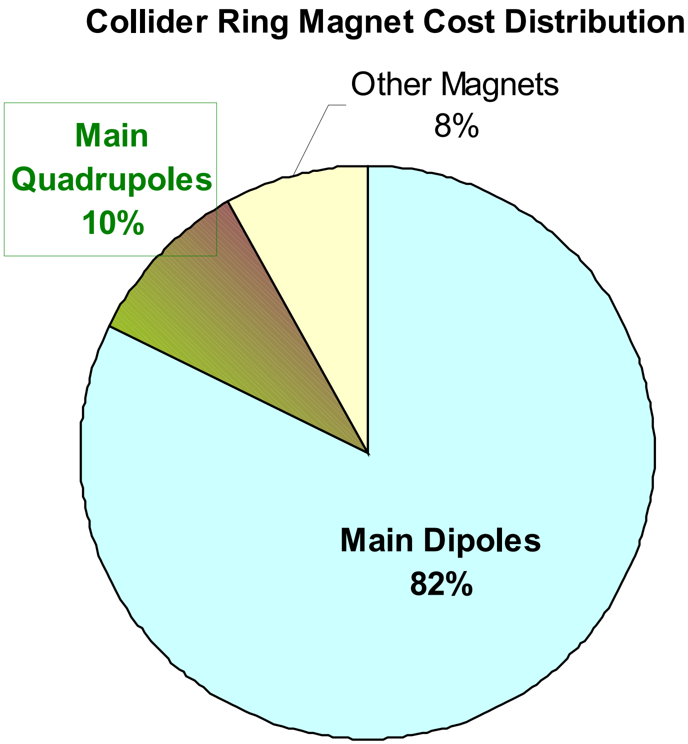
UNITS
Length : mm
Flux density : T
Field strength : A m^{-1}
Potential : Wb m^{-1}
Conductivity : S m^{-1}
Source density: A mm^{-2}
Power : W
Force : N
Energy : J
Mass : kg

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

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

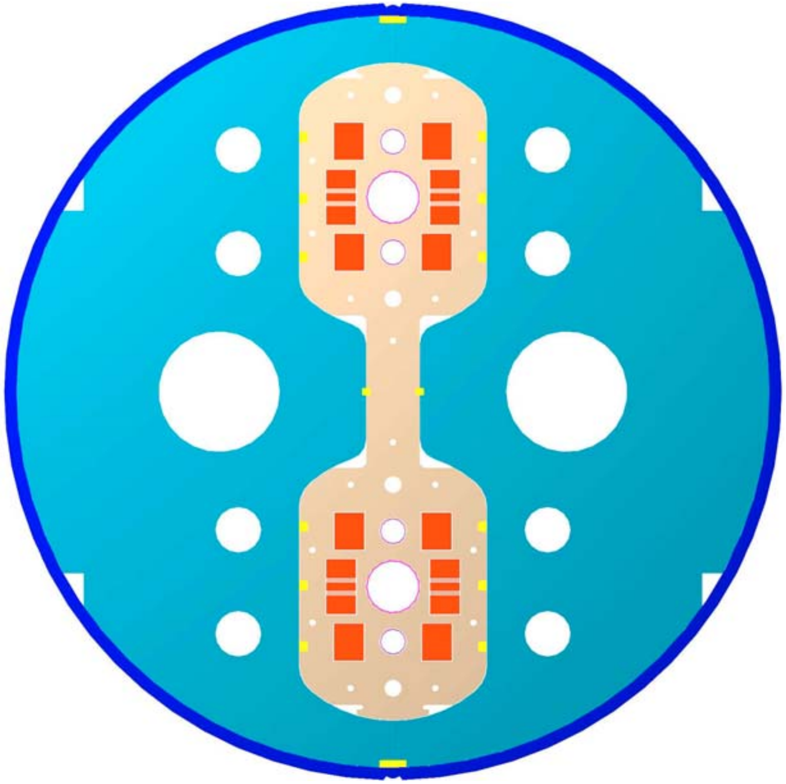
AP Challenge:

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 (~40) written (number of designs with good field quality shown)

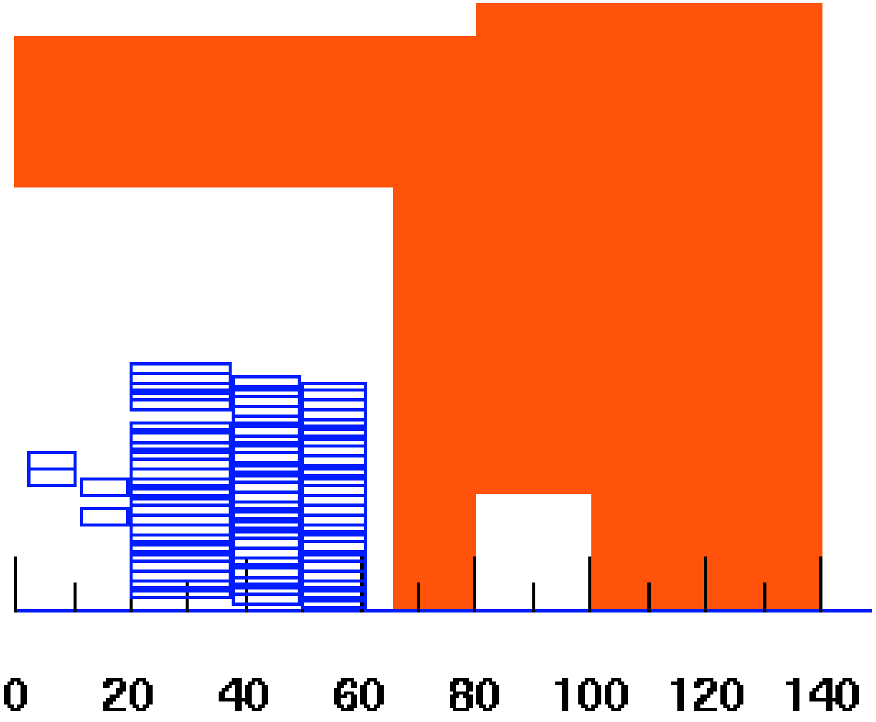
- All three major US labs are working on this design

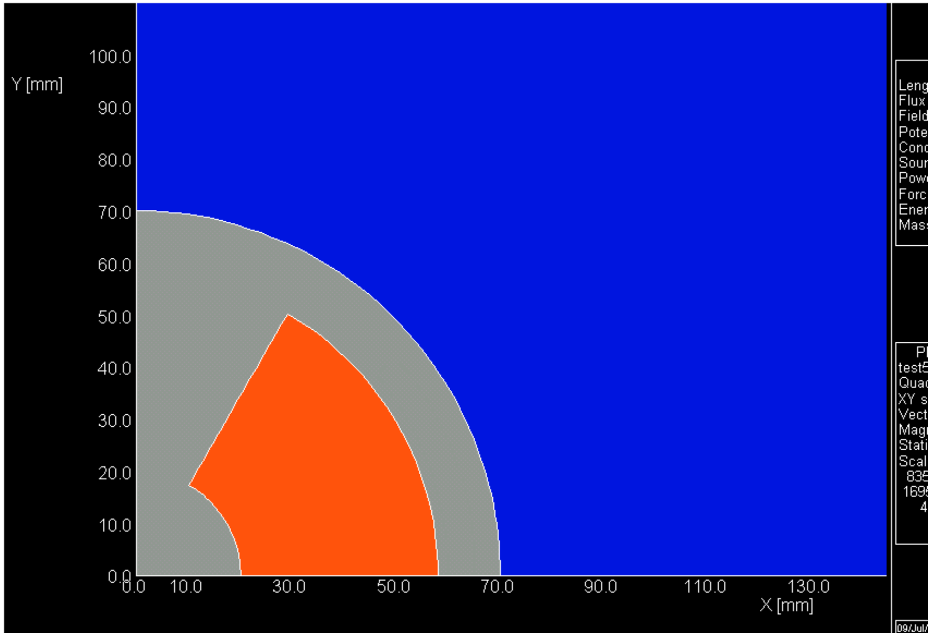
- A significant number (10+) of R&D test magnets built in last few years

- Record magnetic field is obtained (14.7 T @LBL)

- New material (HTS) introduced in accelerator magnets

Comparison of Conductor Uses in Common Coil and Cosine Theta Designs





Common coil design with good field quality (all harmonics ~10-5 or less at 10 mm)

Bss ~ 14.7 with Jc=2200 A/mm2 at 12 T

A cosine theta design with 60 degree block.

Radial width (no wedge) adjusted to get same conductor area as in common coil.

Jc=2200 A/mm2; Cu/Sc=0.9; Jcu ~1600 A/mm2

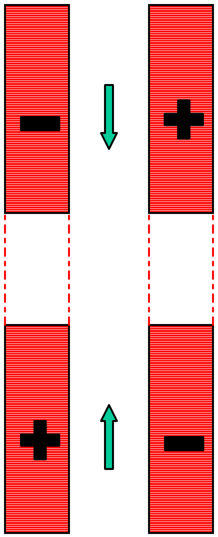
Bss ~14.3 T

Suggested Conclusion:

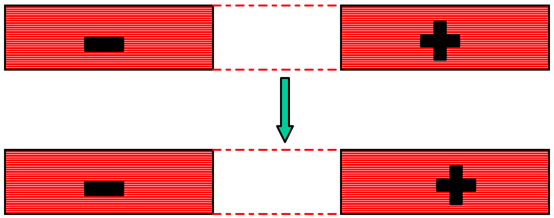
Optimized designs of Common Coil and Cosine theta use about the same conductor.

Muon Collider Dipole Design and Configuration

Hadron collider configuration

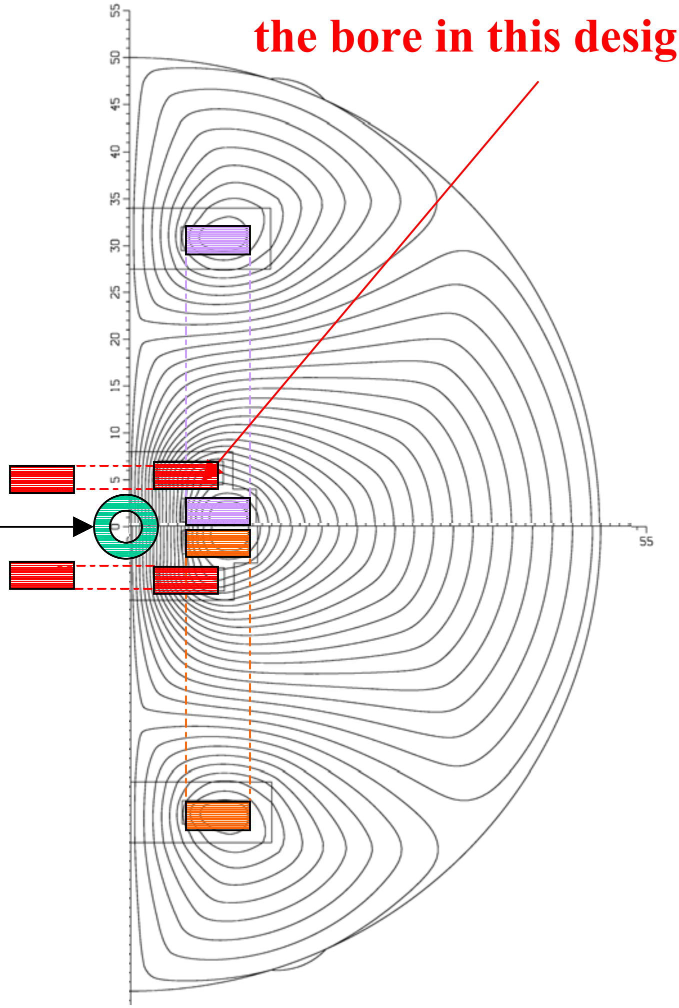


Powering differently changes common coil design test to muon collider design test



muon collider configuration

Note : A high stress test is created here



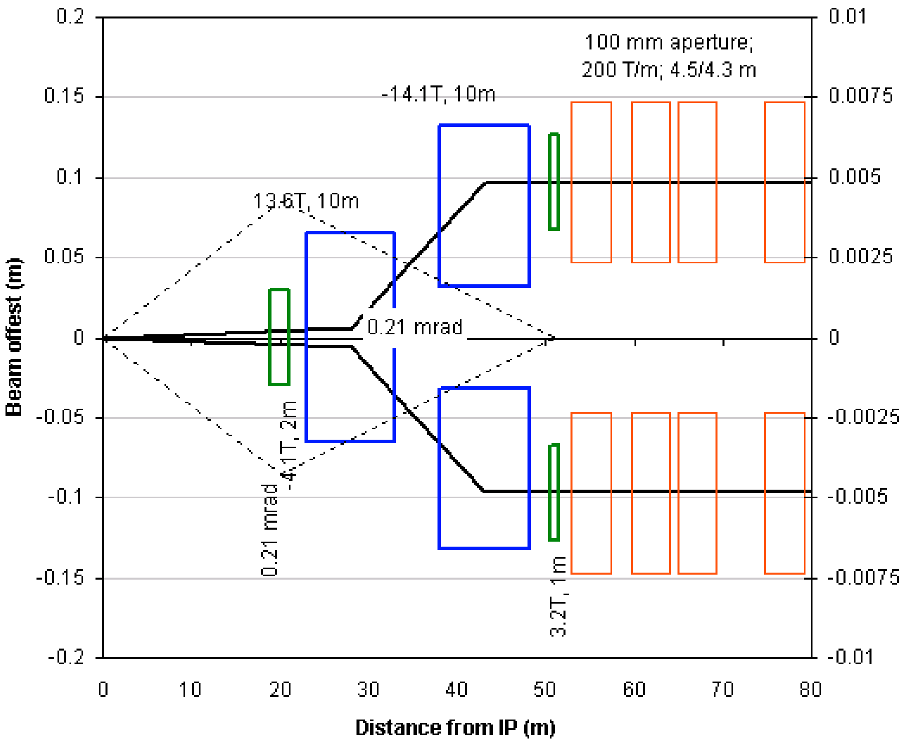
Racetrack coils clear the bore in this design

Tungsten & bore tube

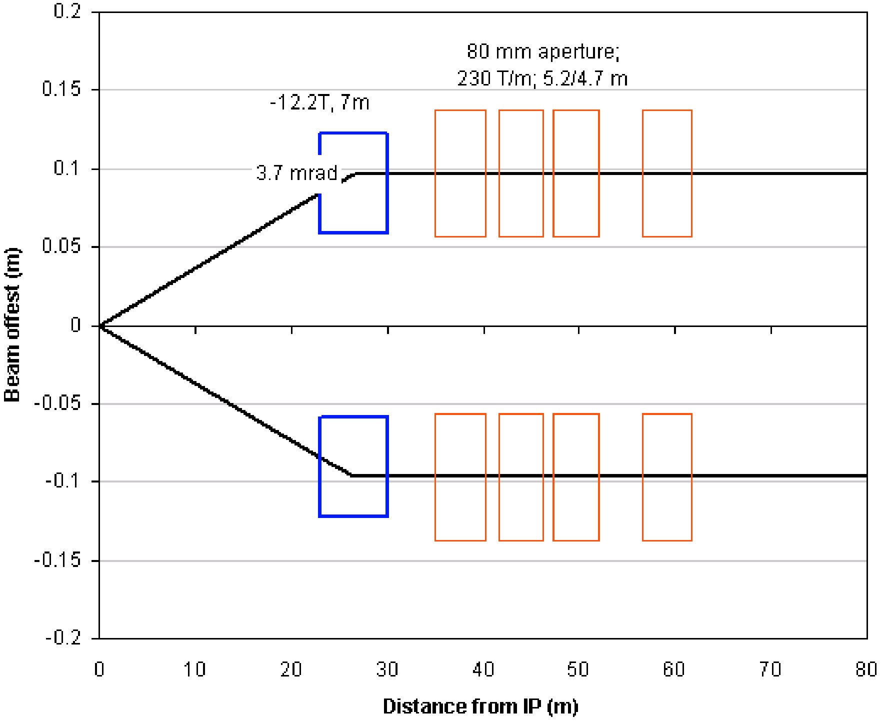
Some Special Considerations for LHC Upgrade Magnet Designs

- Need high field/gradient and/or large aperture magnets
  - Use superconductors that has not been used in accelerator magnets before: Nb_3Sn, Nb_3Al, HTS, etc.
- Hostile environment for superconducting magnets due to large amount of particle spray from Interaction Point (IP): ~9 kW of power from each beam for 10^{35} luminosity
  - Expected energy densities (several hundreds of W/m) in D1
  - Energy deposition is anisotropic, large peak at the midplane
  - Consider quench and radiation damage issues due to this large local energy deposition. Cryogenic and thermal performance of magnets may pose significant challenge
- BNL has been developing alternate magnet designs based on racetrack coils with open midplane to deal with such issues.

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



Small crossing angle

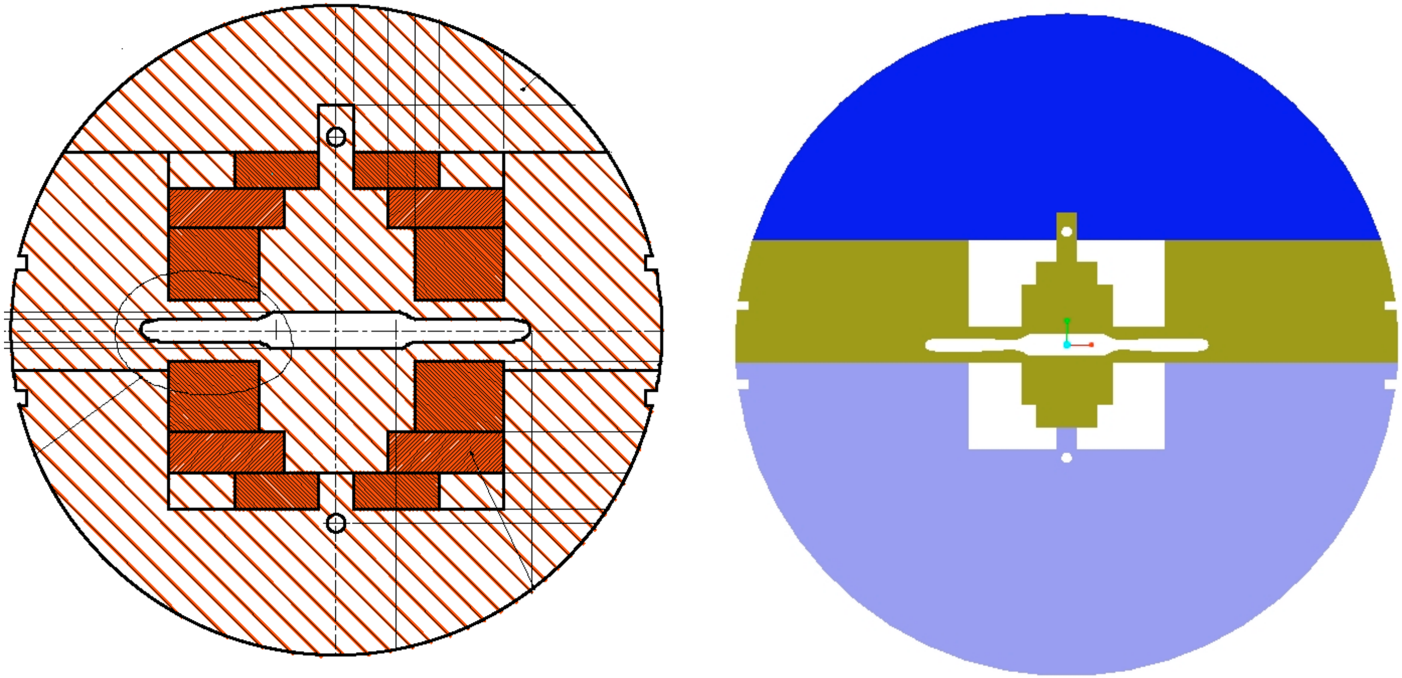


Large crossing angle

Courtesy: Jim Strait

LHC IR Dipole: Collared Coil Support Structure (Preliminary)

Open midplane for decay products to pass through without hitting the coils.



Open midplane means no coil or support structure; otherwise showers are created which hit the coil.

Bss: ~15T
Aperture:
H: ~90 mm
V: 20 mm

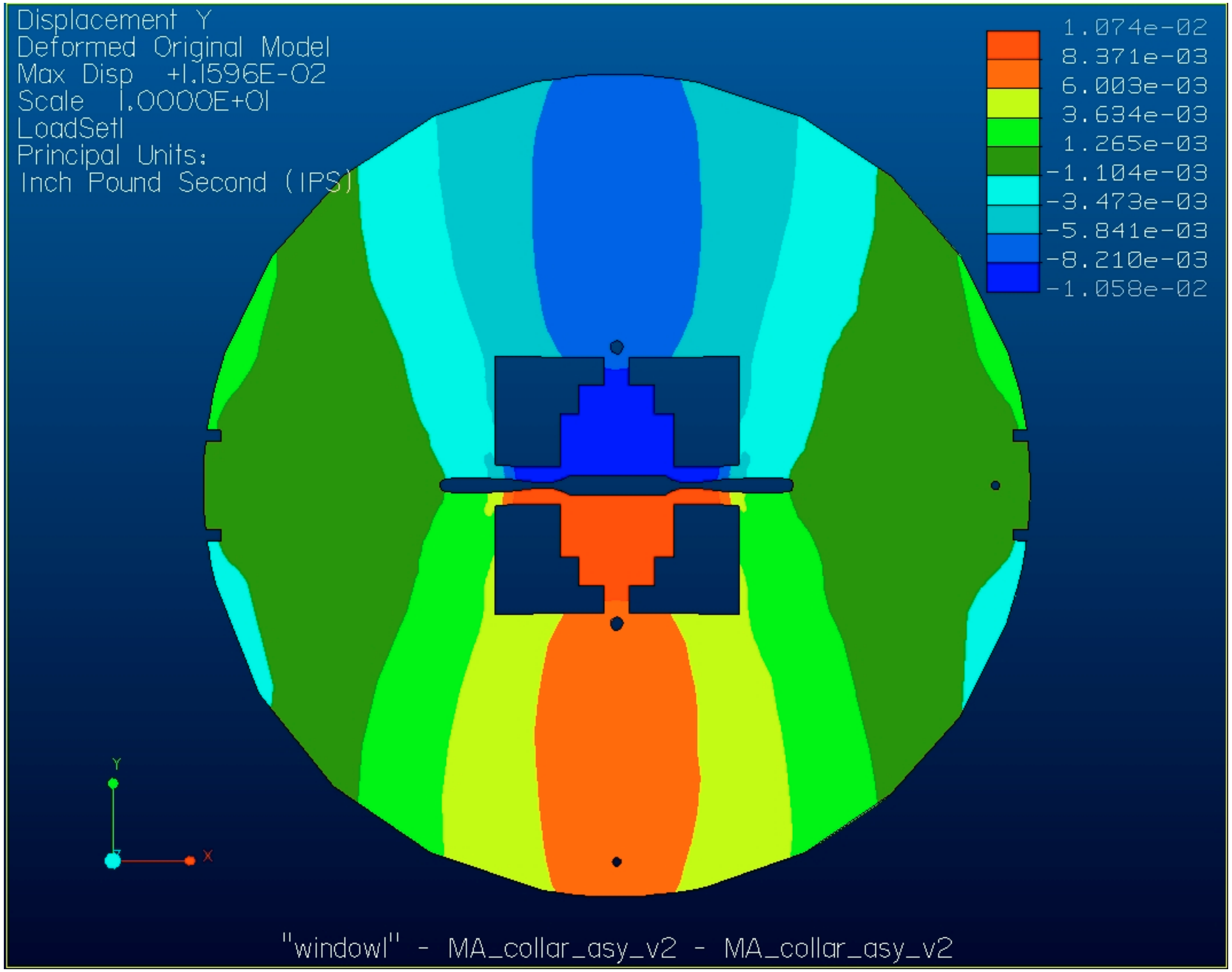
Decay products hit the external structure at 4K.

The magnetic and mechanical designs will be optimized more after the initial energy deposition calculations (NEWS FLASH: just completed).

Field quality is poor and the coils should be brought closer to midplane.

Mechanical Analysis: Collar deflections at the design field

Preliminary design and analysis



See relative change in deflection at the bottom of support structure.

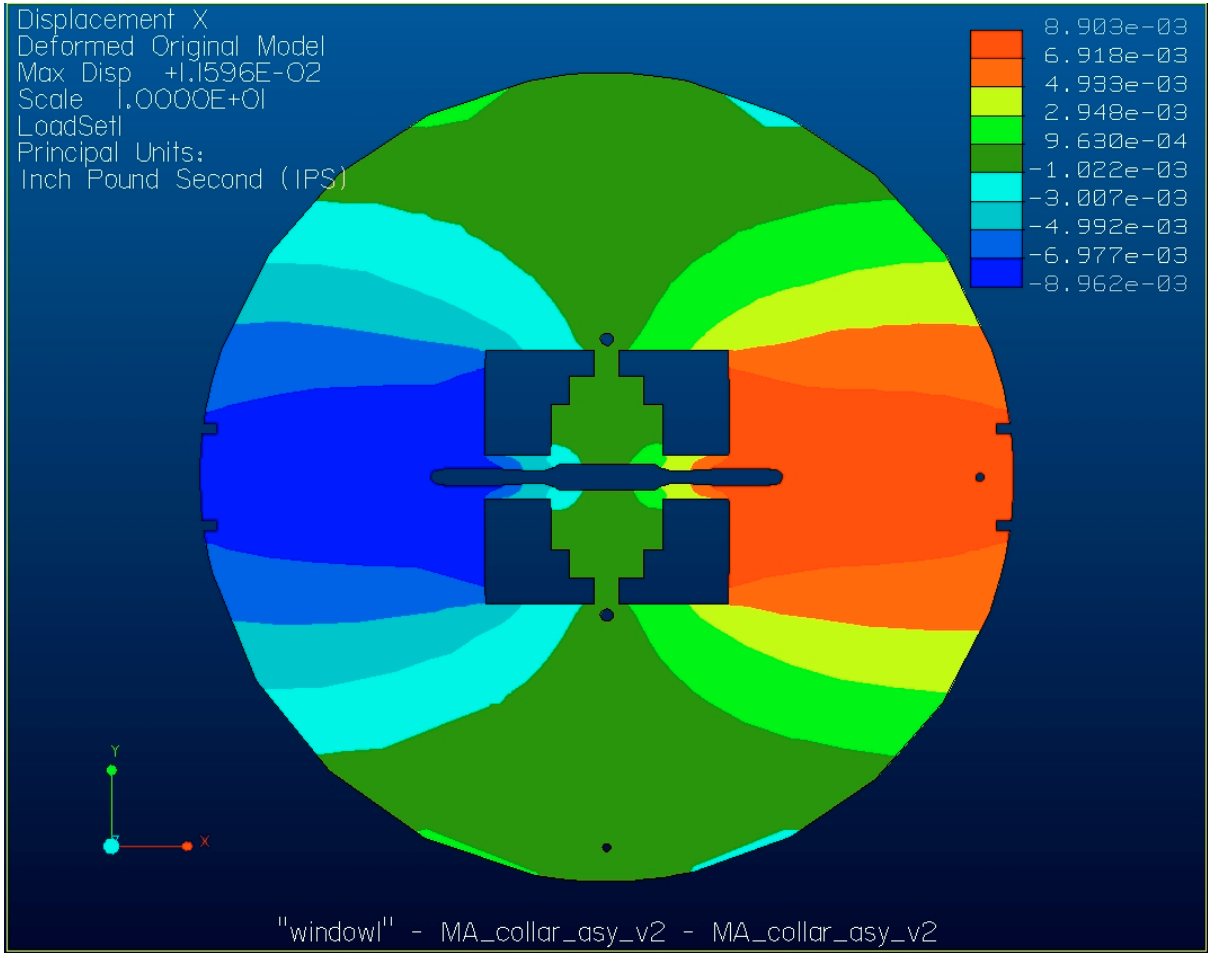
For quench performance, a variation in displacement may be more relevant than the absolute value.

Further reduction in deflections possible through distributed support tiers.

Maximum vertical deflection: ~ 11 mil (0.28 mm)

Mechanical Analysis:
Collar deflections at the design field

Preliminary design and analysis

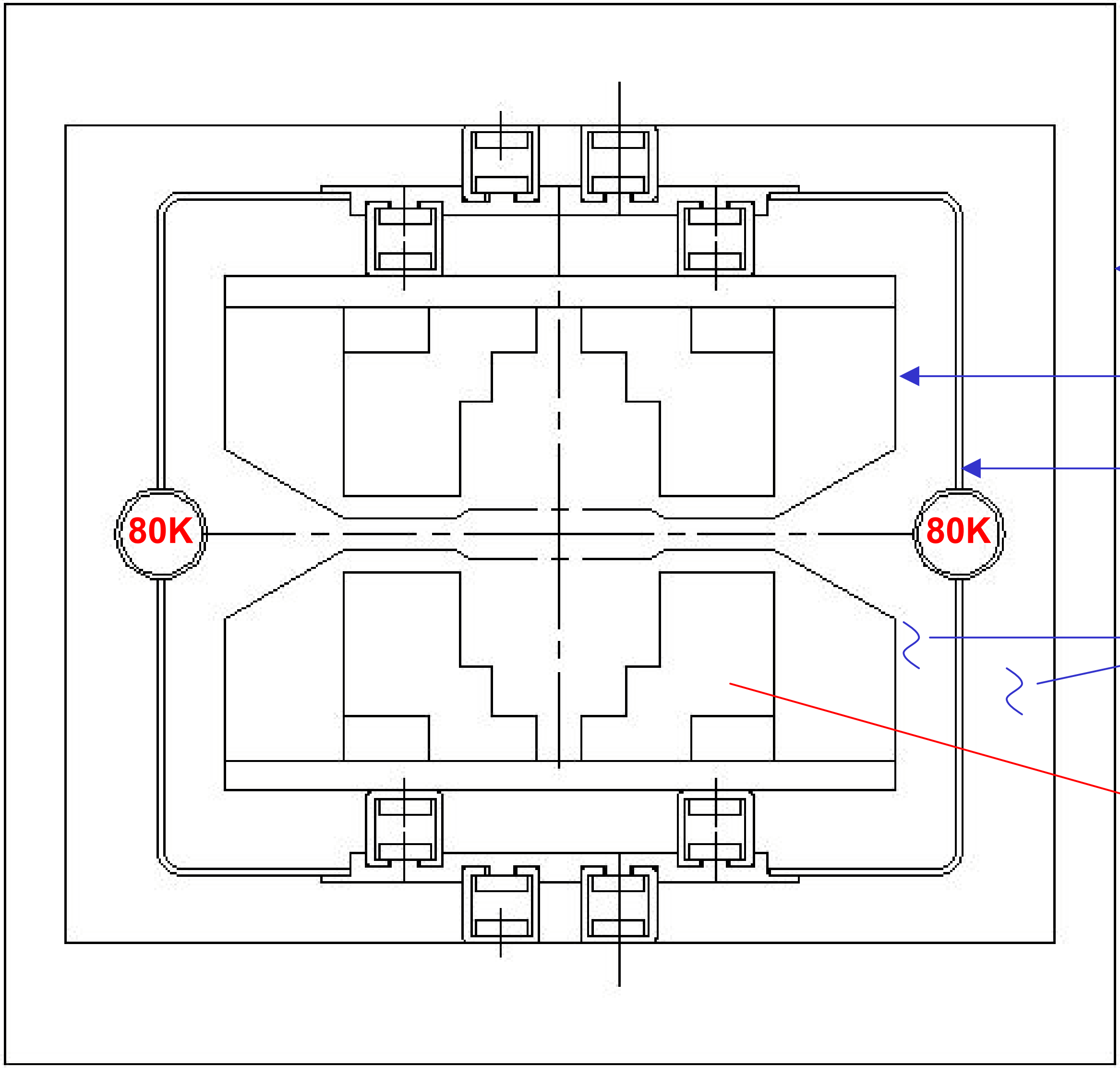


Collar thickness can be increased, as necessary, to reduce horizontal deflections.

Next: Examine the displacement within the coil structure.

Maximum horizontal deflection: ~ 9 mil (0.23 mm)

LHC IR Dipole: Another Concept for Support Structure



Dump IP shower in a relatively warmer structure

(more efficient heat removal)

Cryostat (300K)

Coldmass (4K)

Heat Shield (80K)

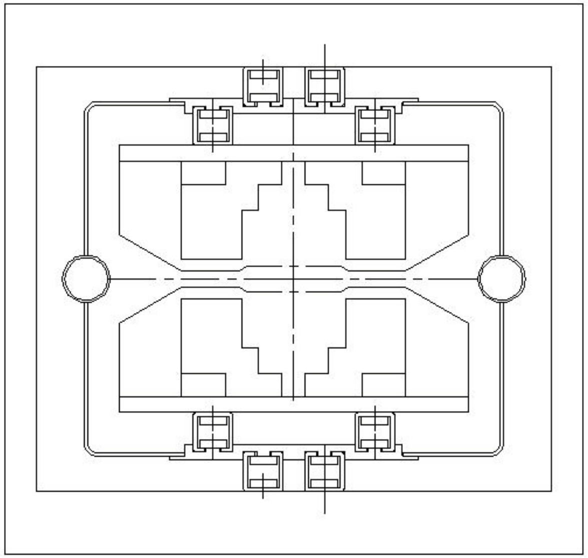
Vacuum Space

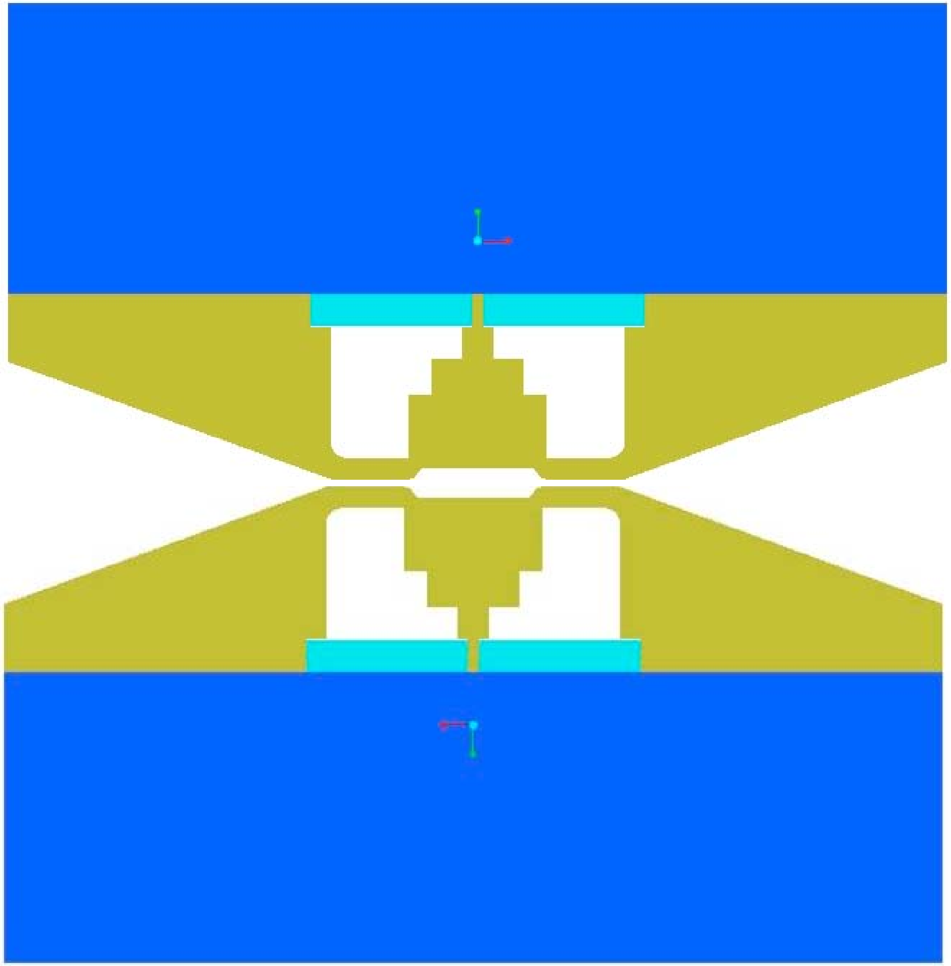
Superconducting coils

Warm Iron Design

LHC IR Dipole: Another Concept for Support Structure

Mechanical design and analysis of the concept, where heat is deposited in a relatively warmer region, has just started.



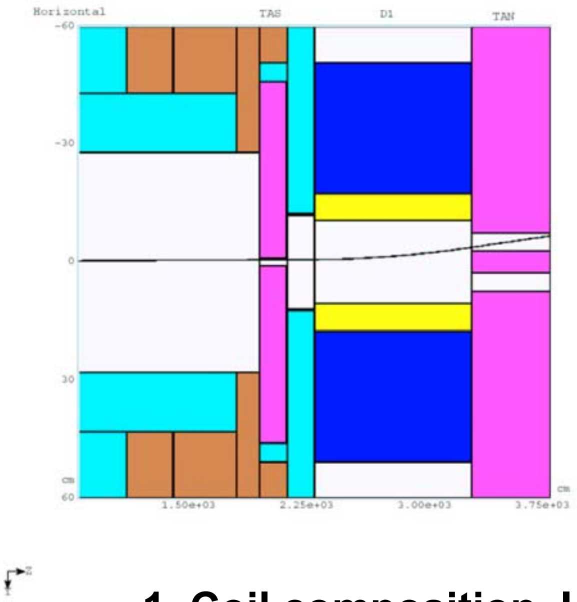


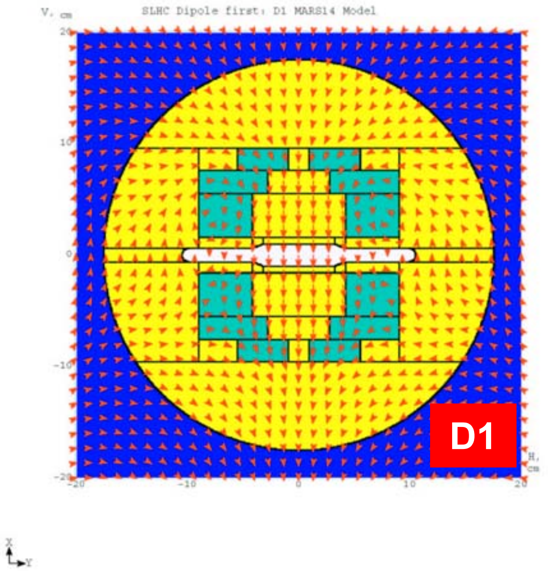
Energy Deposition Calculations

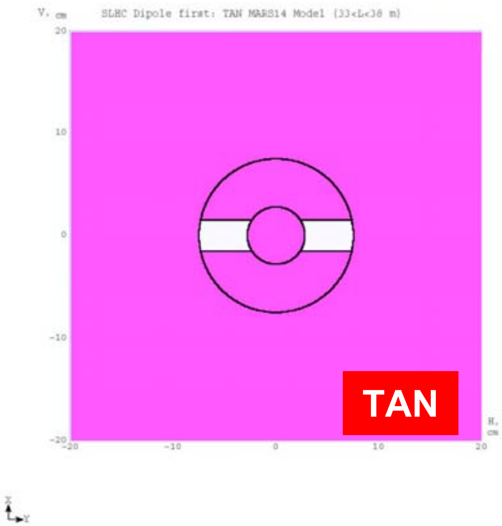
Basic Geometry

Calculations by Nikolai Mokhov, Fermilab

TAS **D1** **TAN**





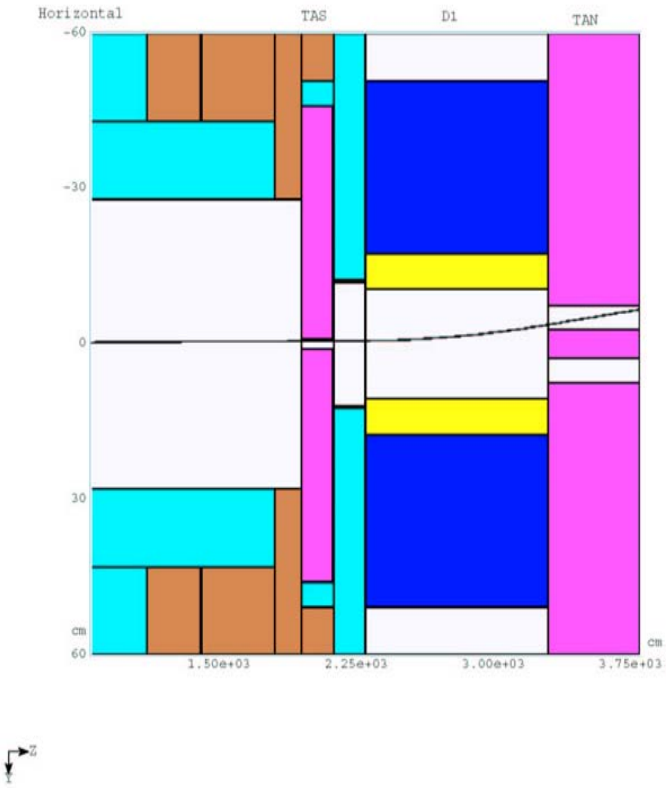


1. Coil composition. I use the first one out of two models I have:
   NbSn SC coil, 0.02 He + 0.38 Cu + 0.2 Al + 0.4 (Nb3Sn)
   0.24 Nb3Sn + 0.70 CuSn + 0.06 Ta
2. D1 is L=10 m, B=13.6 T, with 50.8-cm radius yoke, no cryostat yet, but I can add it if you give me its parameters.
3. Horizontal separation, horizontal crossing with a half-angle of 0.21 mrad, 1.8-m long TAS in front of D1, no corrector, no field

More Details on Model

The current model with Ramesh's 13.6 T, 10-m long dipole, horizontal crossing, 10^35 luminosity, includes:

1. CMS detector with 4-T solenoidal field.
2. Copper TAS at 19.45 < z < 21.25 m with a 9-mm radius round aperture, 900-mm OD; note Ramesh's minimal half-aperture at the axis is 10 mm; it will be smaller if we include a beampipe in D1; we should always avoid a direct vision of the IP by D1 inner parts.
3. SS beam pipe at 21.25 < z < 23 m, 240-mm ID, 246-mm OD (no rather complicated warm-to-cold transition (between TAS and D1) with pumps, liners, instrumentation etc as we have in the baseline LHC model) -> please advise.
4. Detailed geometry, materials and magnetic field in D1 up to 508-mm radius, but currently there is no
   - end plates -> please advise;
   - cryostat and any yoke supports at r > 508 mm -> please advise;
   - beam pipe inside D1; based on preliminary tracking I am not sure about its parameters -> please advise and then we will converge taking into account 3-D energy deposition distributions of the no-pipe runs;
   - corrector or any other magnet combined with the TAS absorber.
5. A copper "TAN" at 33 < z < 38 m with two apertures I determined on the basis of beam tracking plus LHC standard margins.



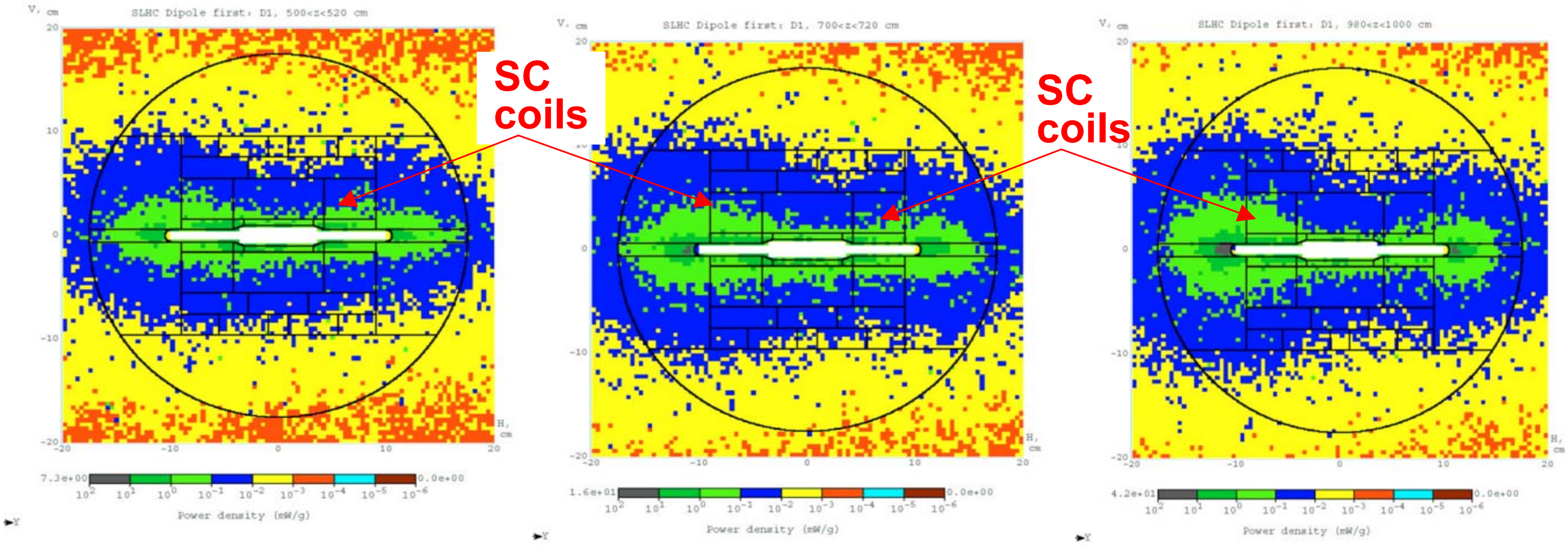
Cheers,

Nikolai

Energy Deposition Calculations

Energy deposition at various axial position along the axis

Computed by Nikolai for a Luminosity of 10^{35} (10X over present design)



SC coils

SC coils

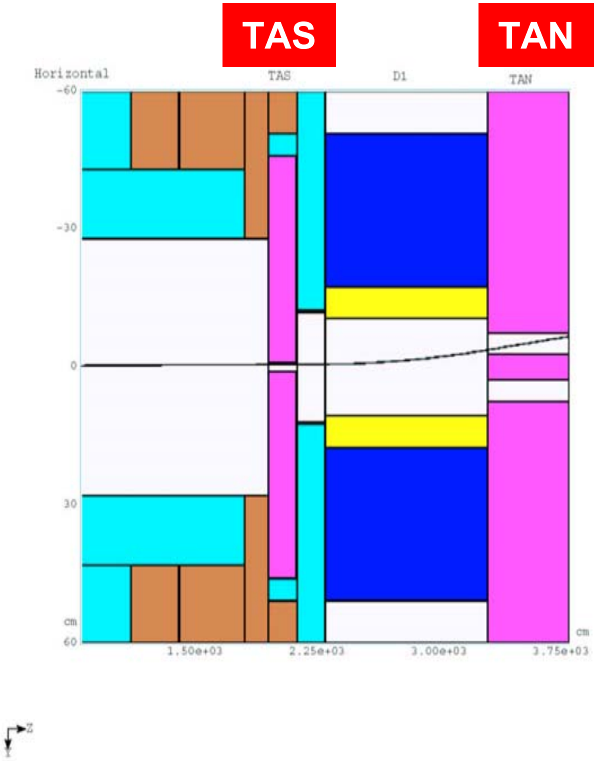
@Middle (z=>5m-5.2m)

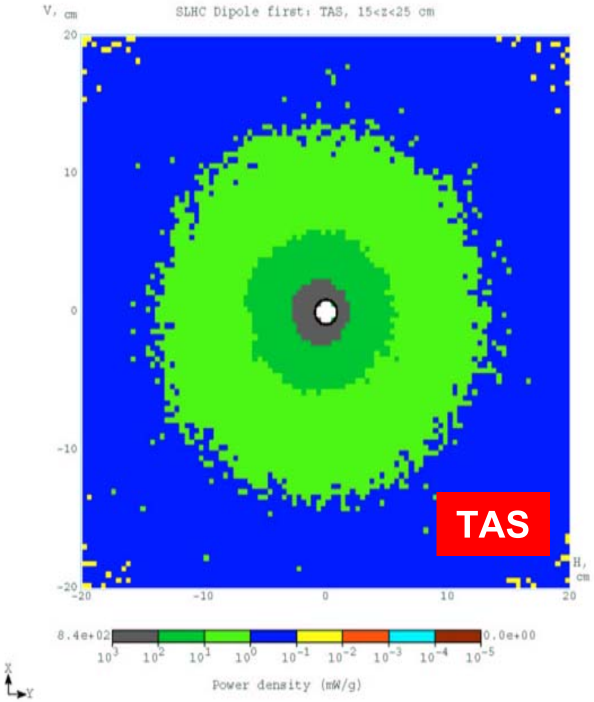
@70% (z=>7m-7.2m)

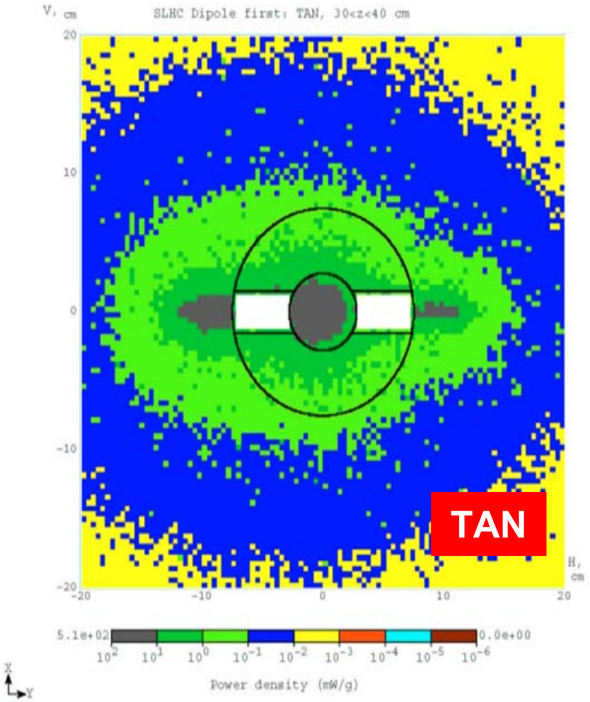
@End (z=>9.8m-10m)

Peak power density in the superconducting coils is only 1-1.3 mW/g, i.e., below our current quench limit of 1.6 mW/g even at 10^35 luminosity!!!

Energy Deposition in TAS & TAN







Total power dissipation:

TAS: 3.17 kW, D1: 0.90 kW, TAN: 2.45 kW.

Alternate Magnet Design for a Compact ν Factory Storage Ring

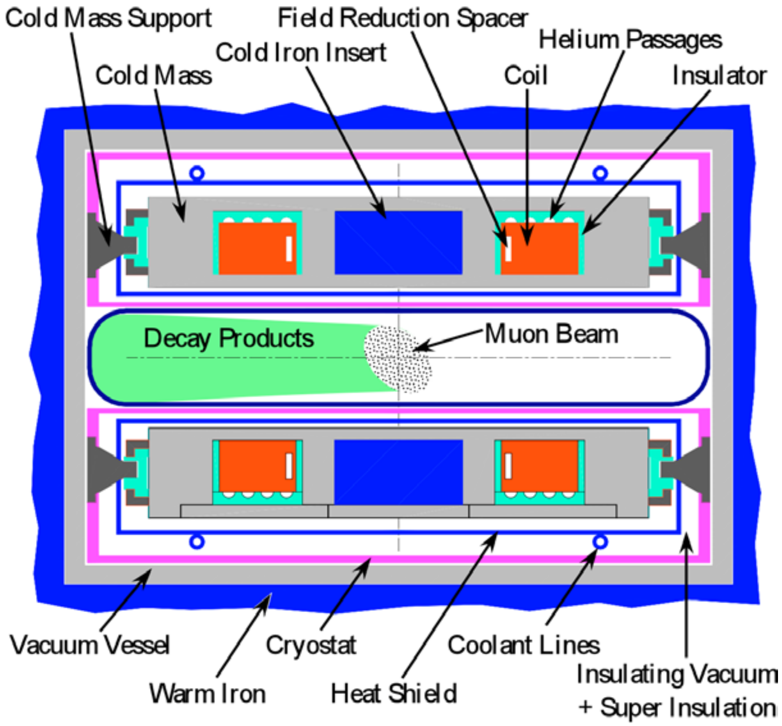
Guiding Principles:

Decay products clear s.c. coils

- Flat coils with open midplane gap

Minimize environmental impact

- High field magnets, efficient design



Technical Issues:

Brittle High field superconductors

- Nb_3Sn "React & Wind" Technology

Large Lorentz forces

- Support structure for various configurations

An integral design for dipole & quadrupole

Large heat leak

Compact cryostat

Tooling design for magnet

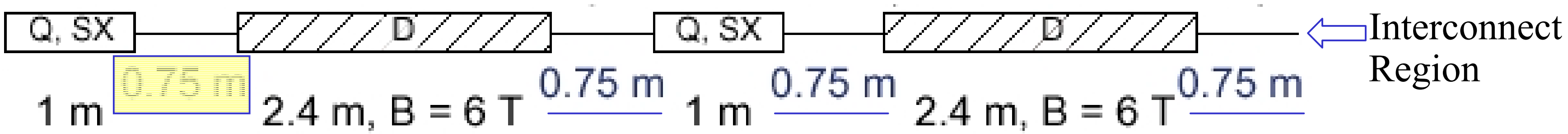
Magnet test configuration setup

Lattice & Magnet Designs for a Compact Ring

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

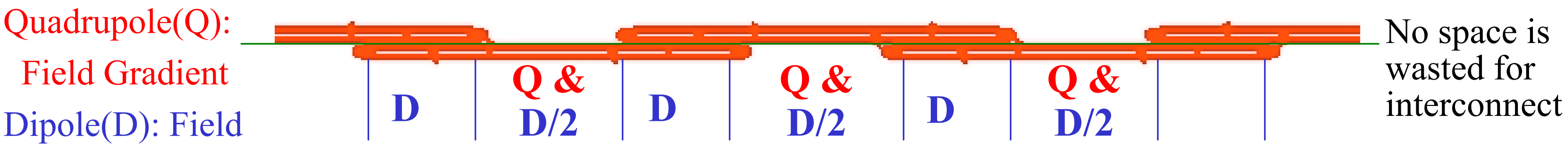
Skew quadrupoles do NOT need conductor at midplane (B. Parker)

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



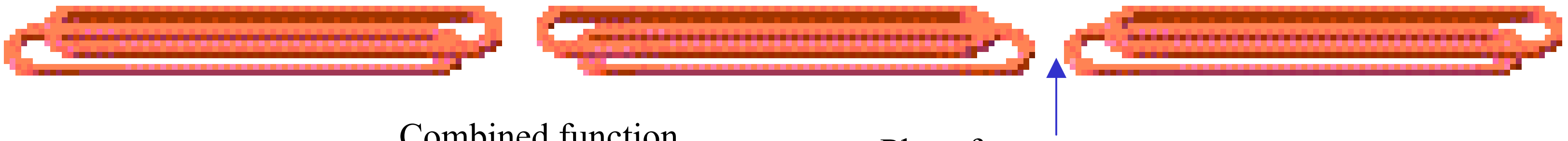
Gets worse at lower energy (50 => 20 GeV in study 2)

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



Shorter cells ⇨ smaller aperture, improved beam dynamics

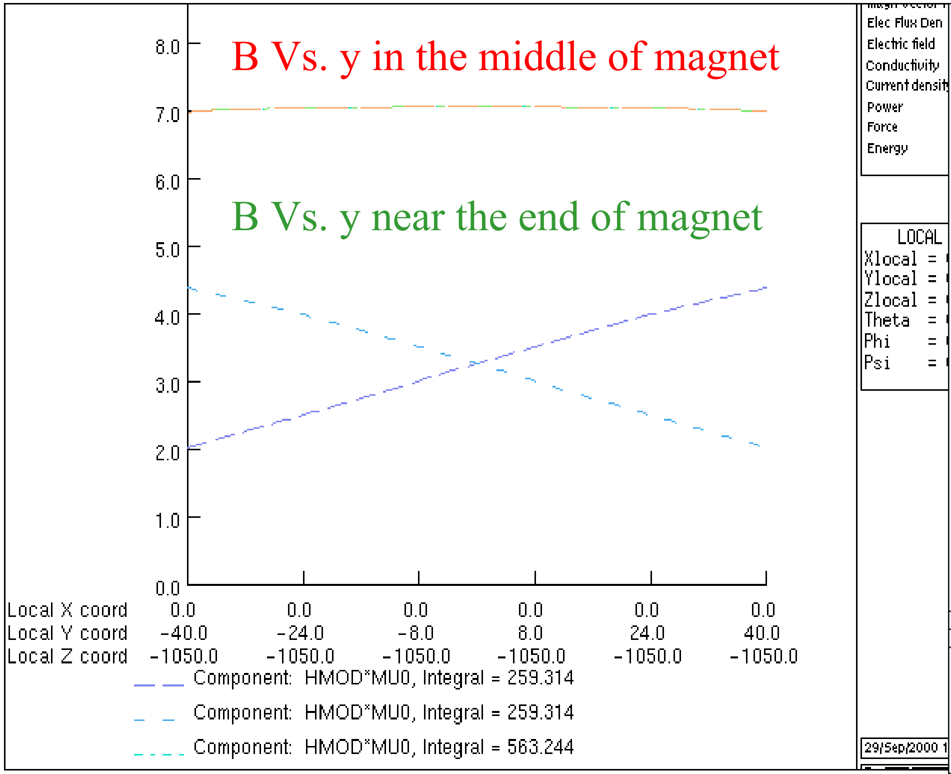
Skew Quad Lattice by Axially Shifting Coils



Dipole section

Combined function
magnet section

Place for corrector, etc.



B Vs. y in the middle of magnet

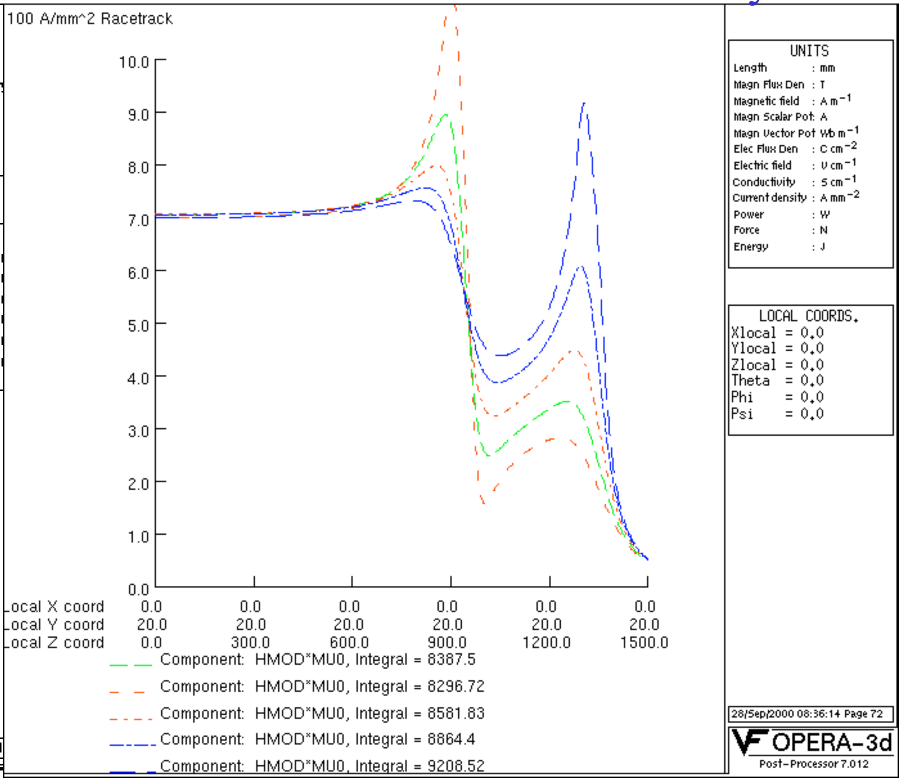
B Vs. y near the end of magnet

Component: HMOD*MU0, Integral = 259.314

Component: HMOD*MU0, Integral = 259.314

Component: HMOD*MU0, Integral = 563.244

Axial scan of B for various y



Component: HMOD*MU0, Integral = 8387.5

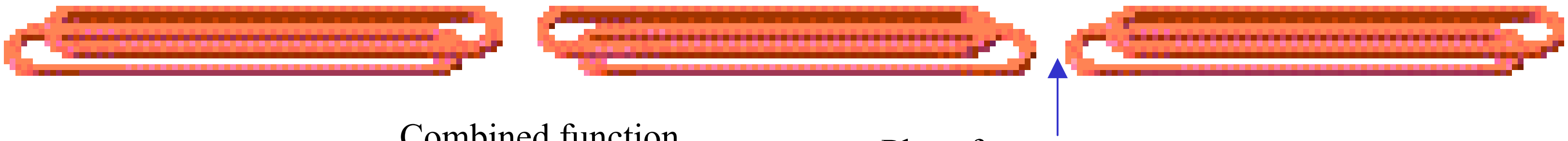
Component: HMOD*MU0, Integral = 8296.72

Component: HMOD*MU0, Integral = 8581.83

Component: HMOD*MU0, Integral = 8864.4

Component: HMOD*MU0, Integral = 9208.52

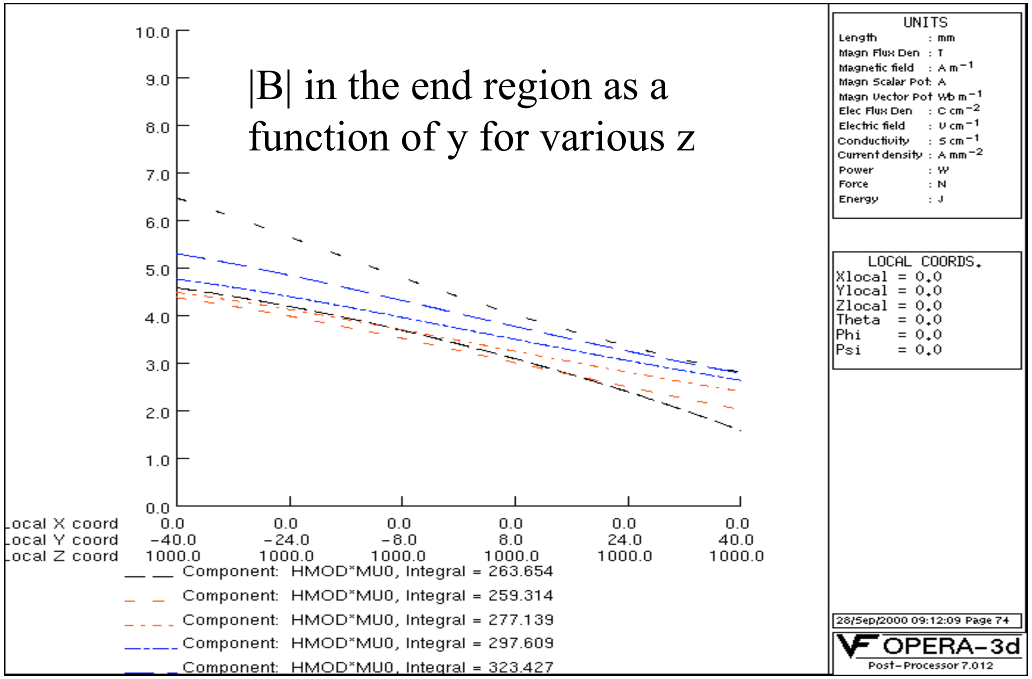
Skew Quad Lattice by Axially Shifting Coils



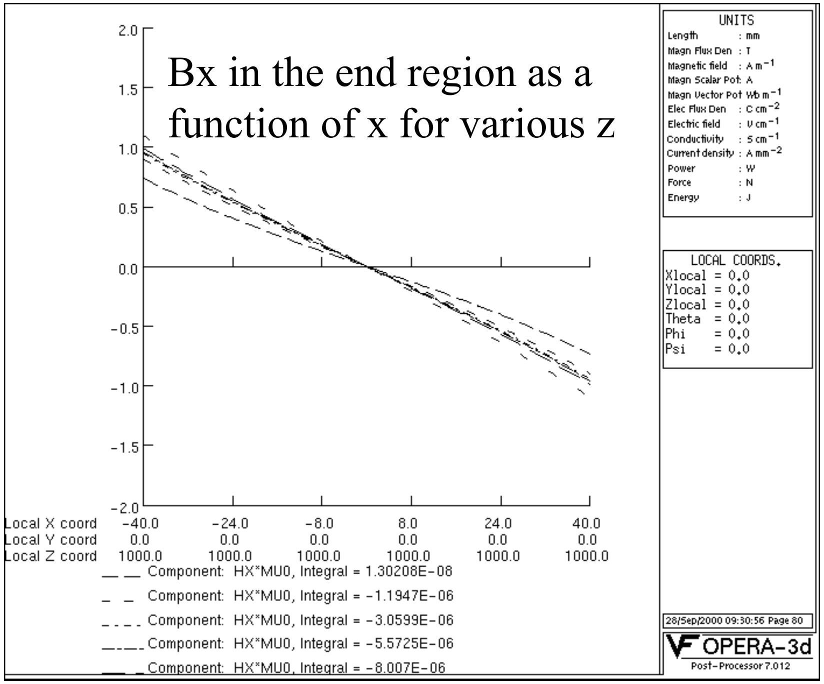
Dipole section

Combined function
magnet section

Place for corrector, etc.



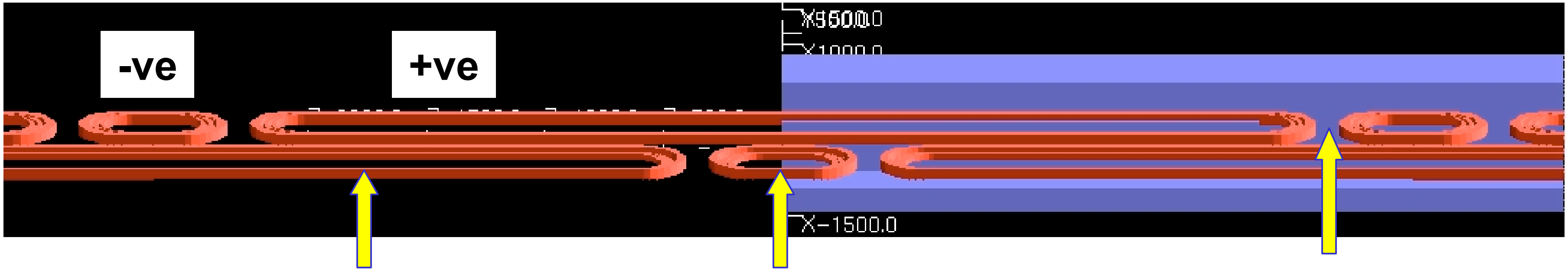
|B| in the end region as a function of y for various z



Bx in the end region as a function of x for various z

Alternate End Design Concept

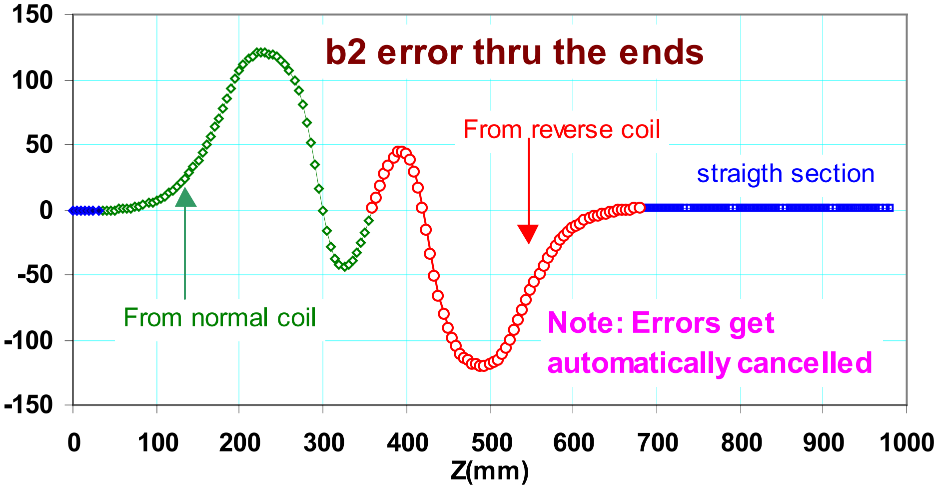
- Reverse coils to cancel field harmonics in ends (also generate skew quad)



Normal Coils
Dipole

Reverse Coils
Skew Quad

One Coil
1/2 & 1/2



New Magnet System Design

> Good field quality

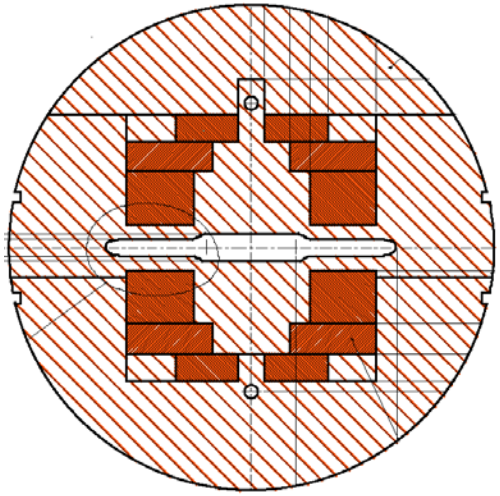
> Makes ring small

Important for BNL site

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

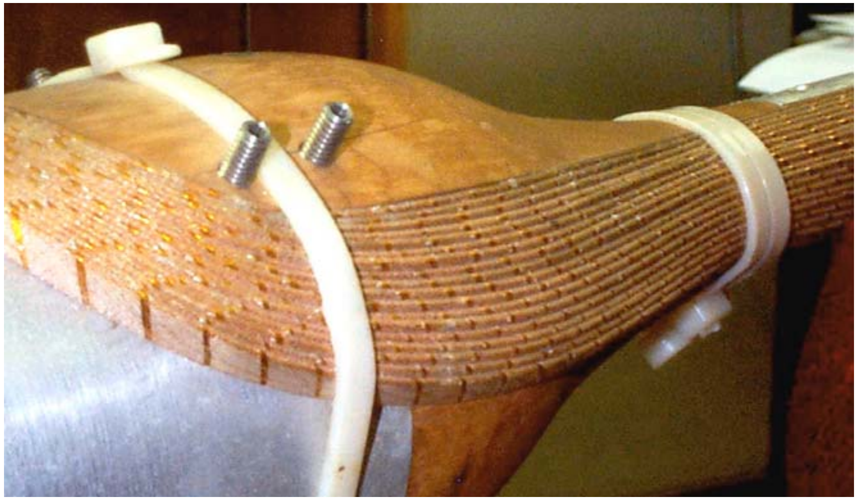
End Concept for "React & Wind" Dipole

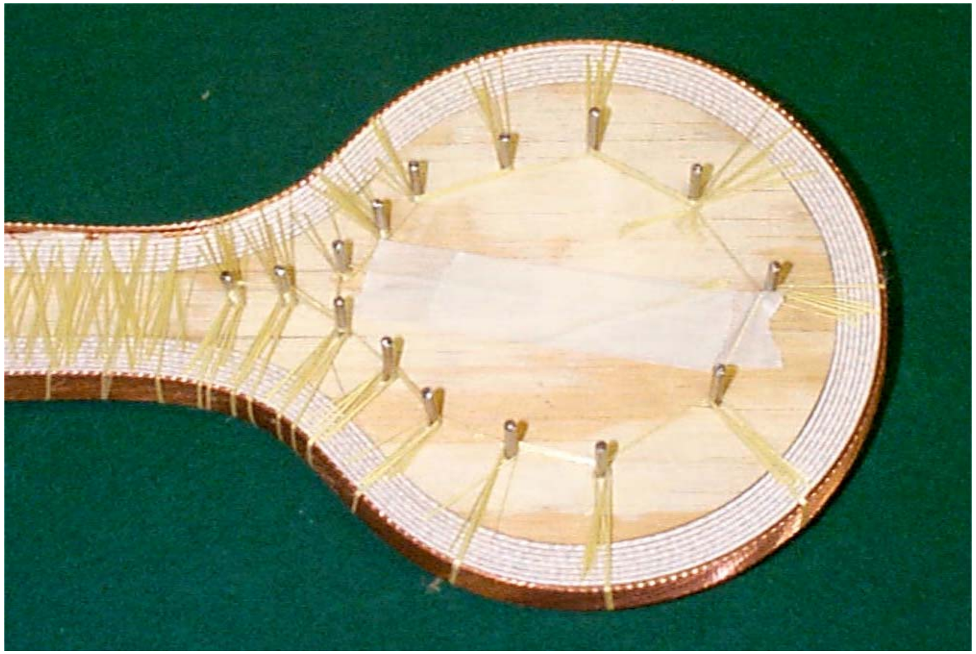
The following type of ends will retain a flat racetrack coil geometry



Earlier Design:

Dogbone Ends (~20 years ago)





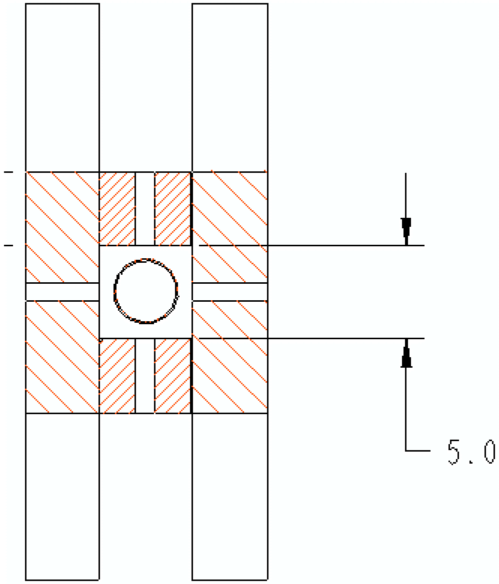
New Techniques:

Kevlar Strings for Reverse Bend

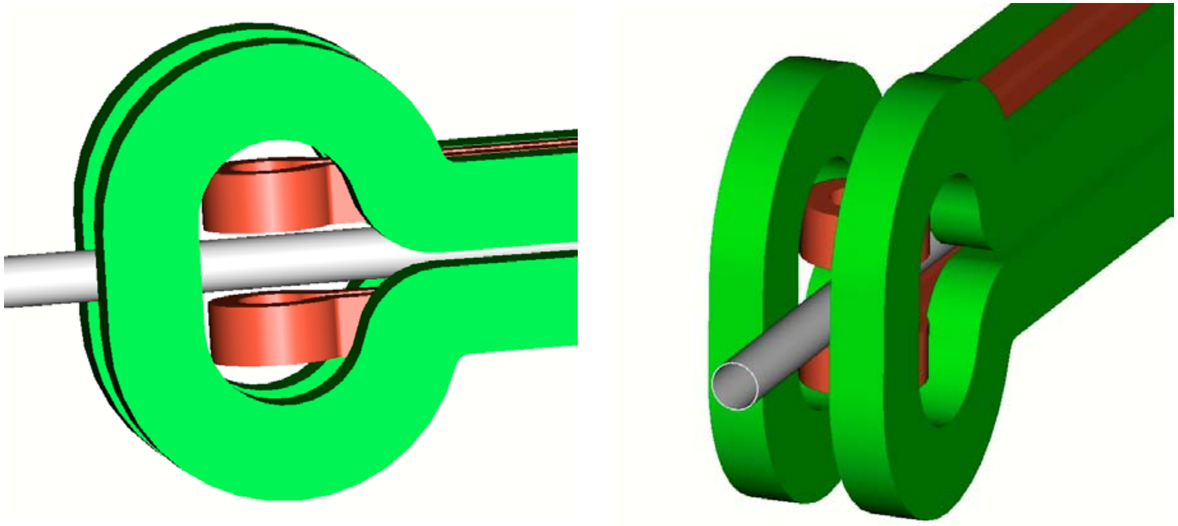
New End Design Concepts

Following few slides will present a number of thought techniques for "React & Wind Ends". These conceptual geometries may be used in evolving some new end designs that have good mechanical and magnetic characteristics.

Main Goal: Large bend radius and properly supported cable through out the ends.

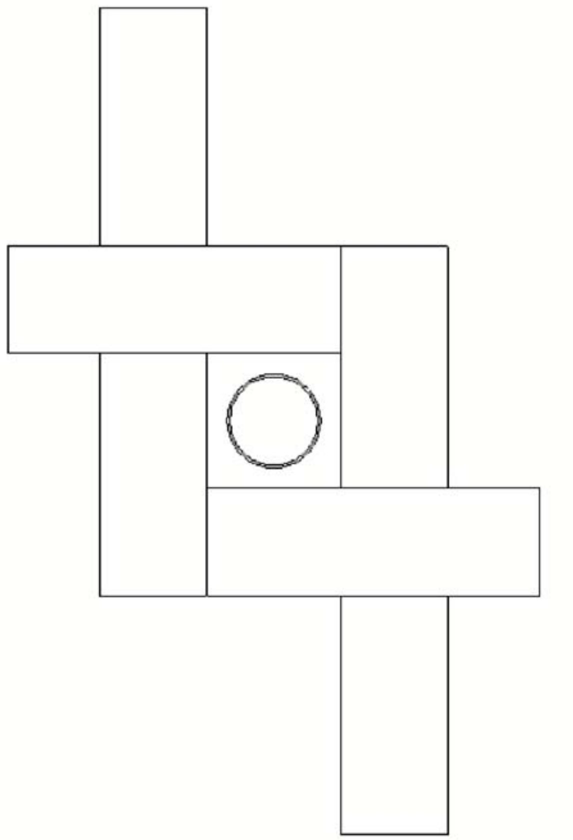


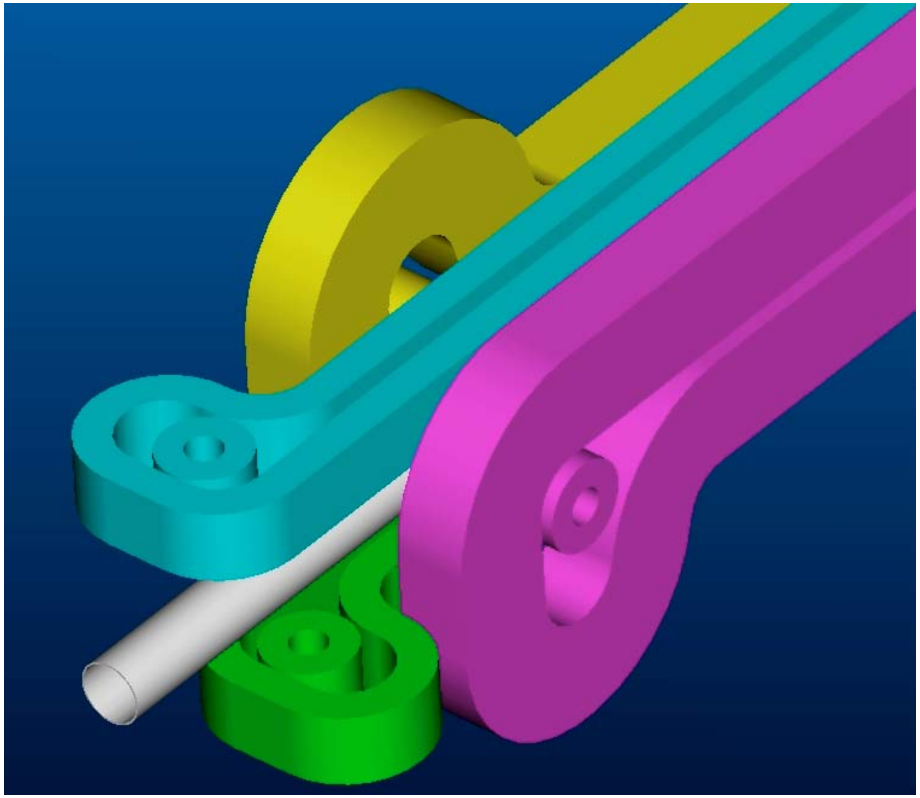
Flat Coil Ends: Nested Coils



New End Design Concepts (contd.)

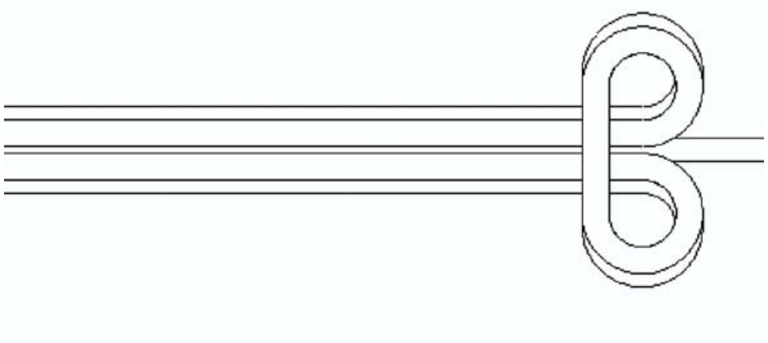
Flat Coil Ends: Sideway Overlap

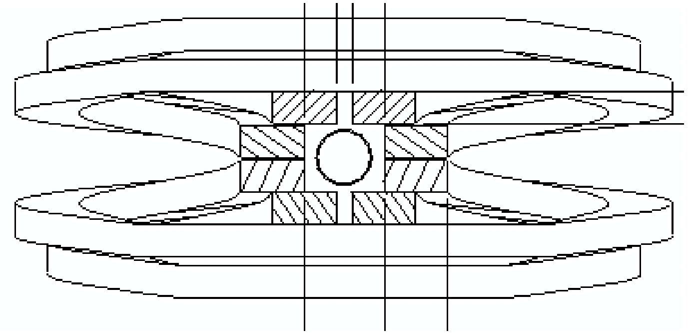


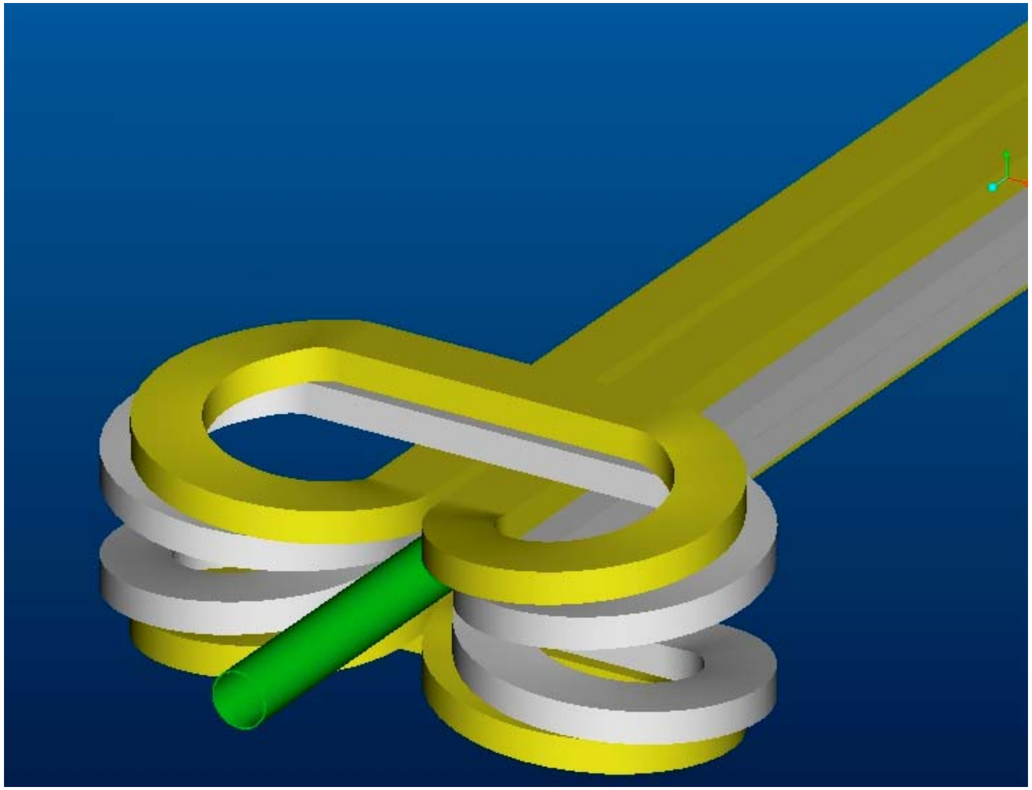


New End Design Concepts (contd.)

Overpass/Underpass (Clover Leaf) Ends: NO Reverse bend needed

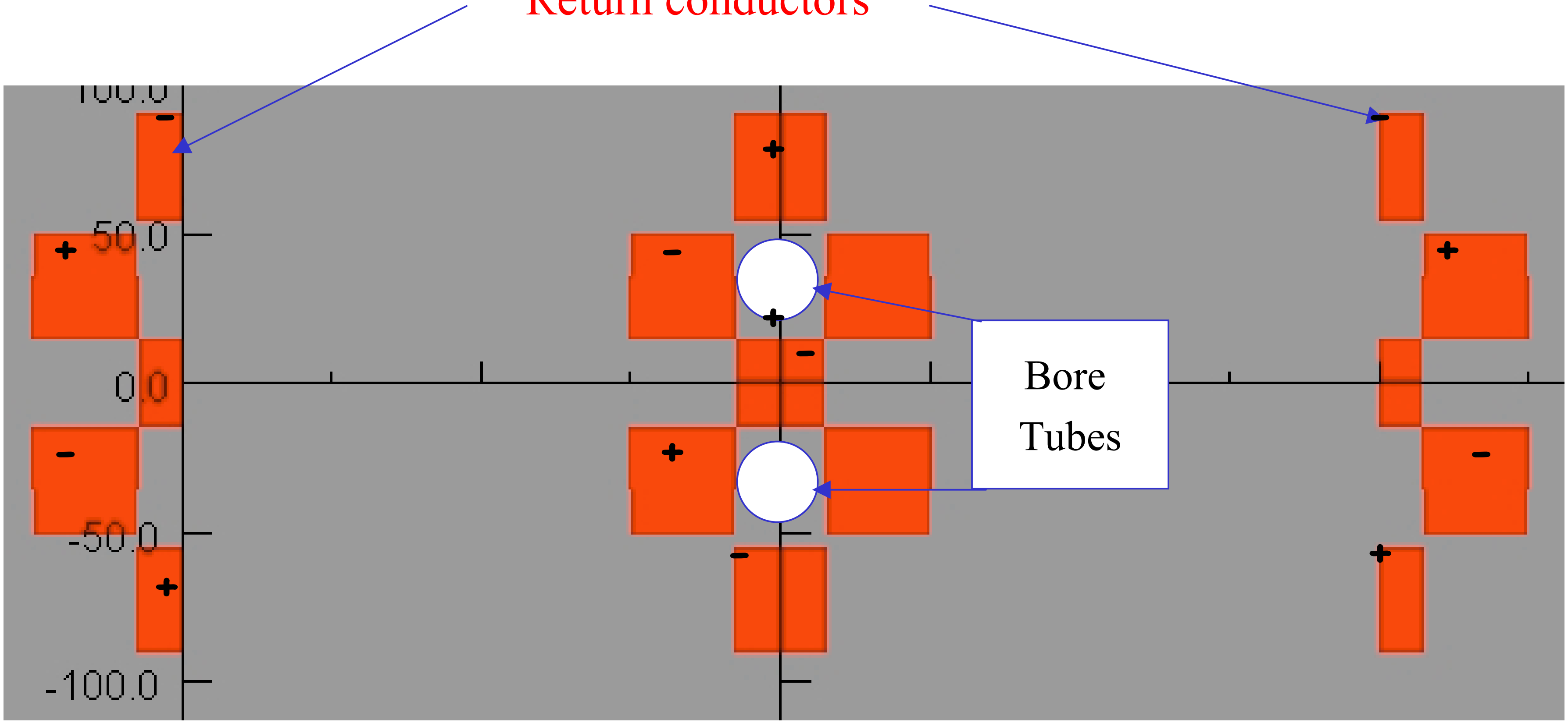






VLHC-2 Interaction Region Magnet Design (Preliminary)

Conductor friendly IR quad design



Return conductors

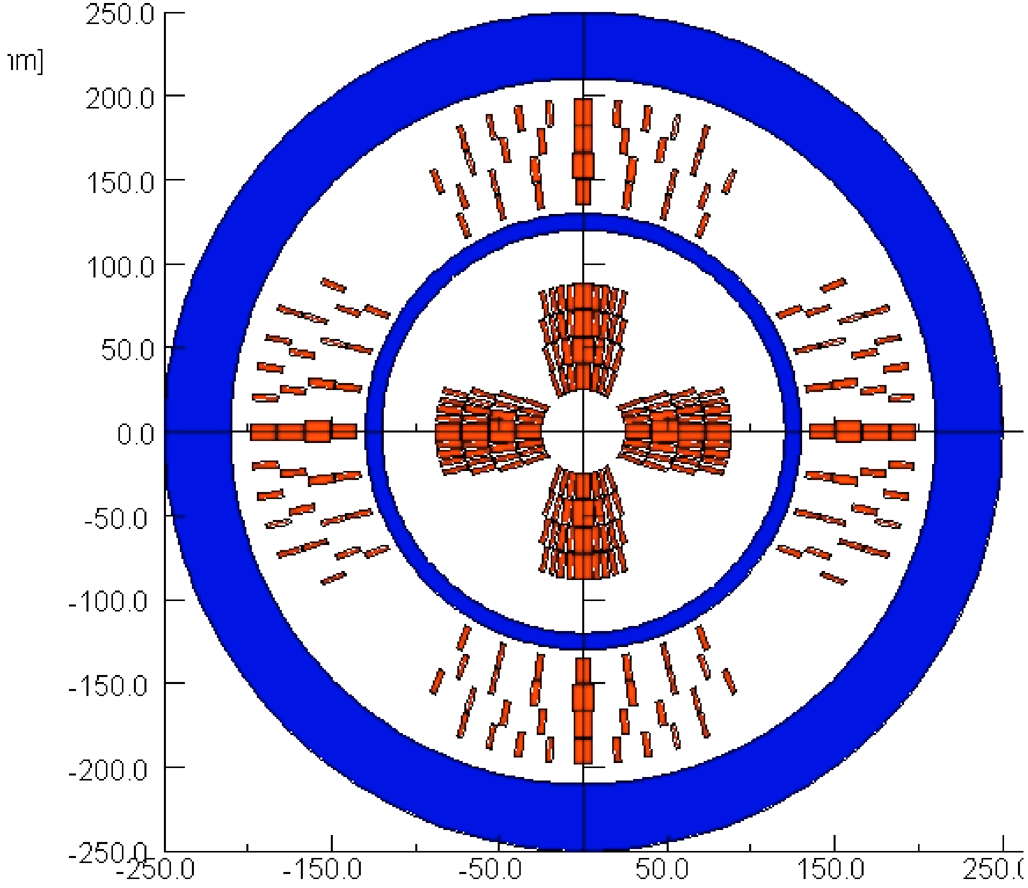
Bore Tubes

(simple racetrack coils with large bend radii allow the use of HTS)

A Concept for React & Wind Cosine 2Θ Quad Design for LHC IR Upgrade

The following design is made to allow large bend radii

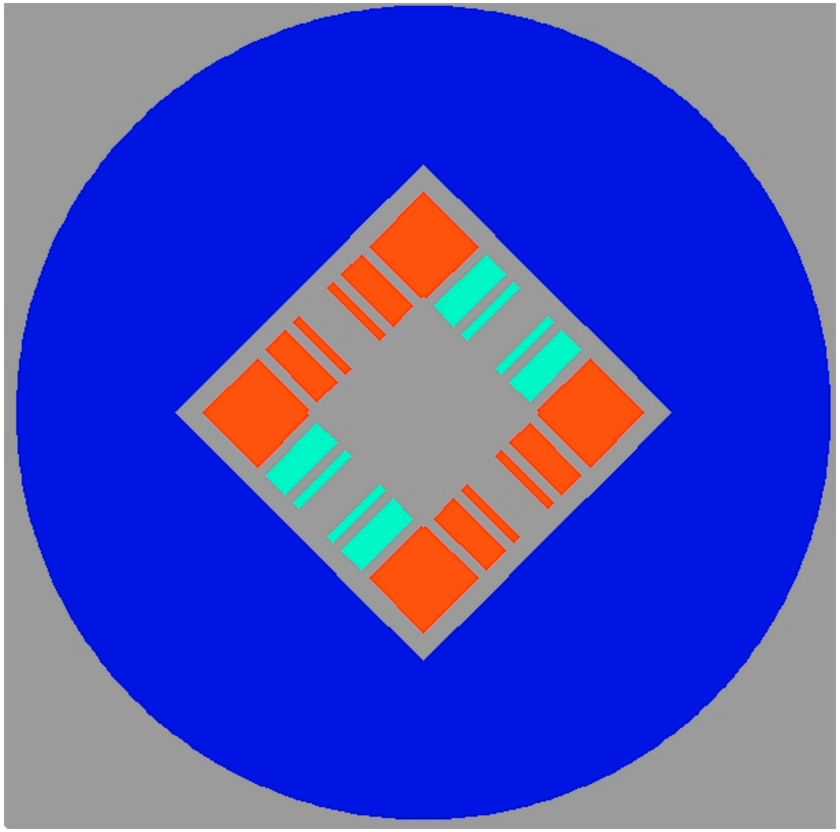
OPERA MODEL

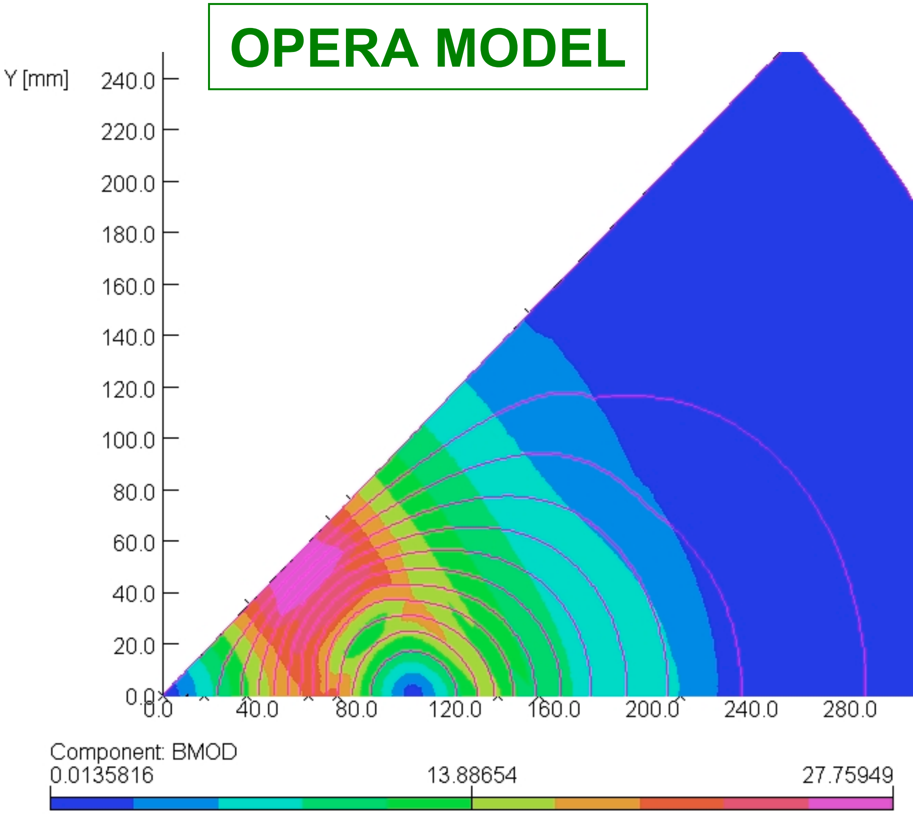


	Q0A	Q0B	
Aperture	50	70	mm
$G_{operating}$	540	320	T/m
B_{peak}	16	13	T
$P_{Luminosity}$>	1000		W

Block Type Quad Design for LHC IR
(Racetrack Coil Geometry)

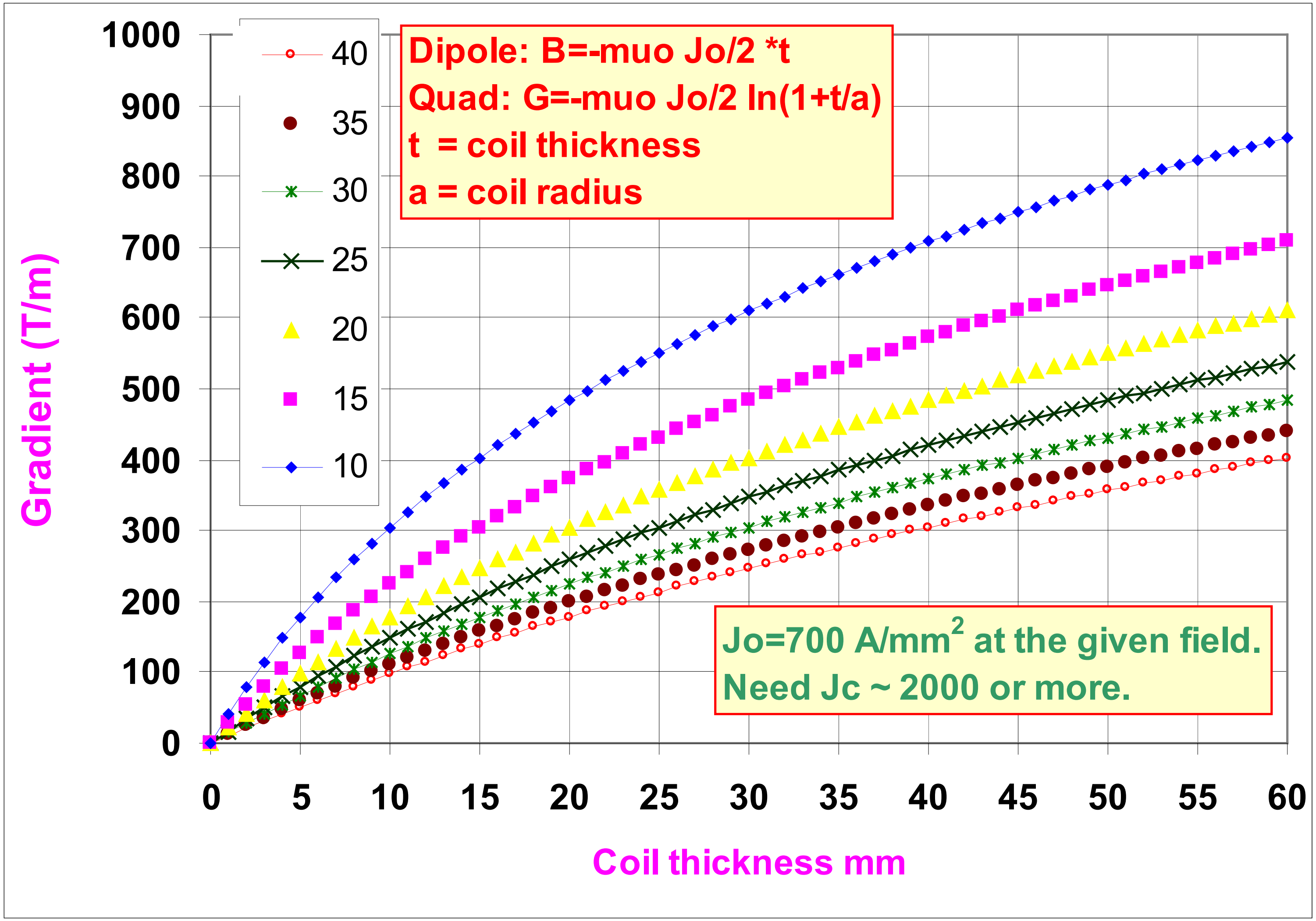
Gradient: 400 T/m; Jo = 1 KA/mm^2, Jc ~ 4-5 kA/mm^2




OPERA MODEL

<u>Note:</u> Peak field is not a major concern in HTS quadrupole designs.

Quadrupole Gradient for various coil radius



Dipole: B=-muo Jo/2 *t
Quad: G=-muo Jo/2 ln(1+t/a)
t = coil thickness
a = coil radius

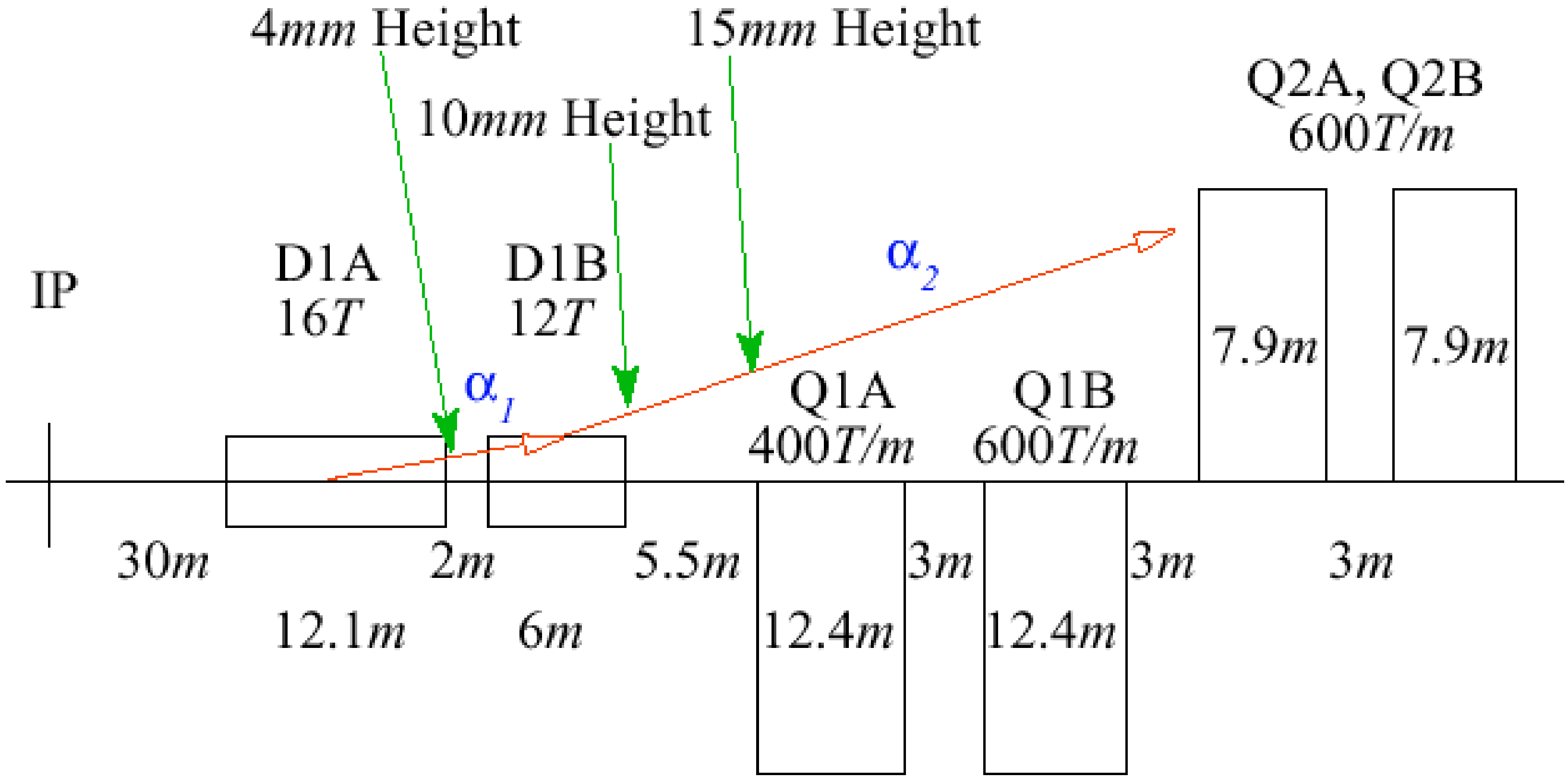
Jo=700 A/mm^2 at the given field.
Need Jc ~ 2000 or more.

Note: Legends are coil radius, not aperture

Important number is field: Gradient * coil radius = pole-tip field

VLHC-2 IR Layout for Flat Beam Optics

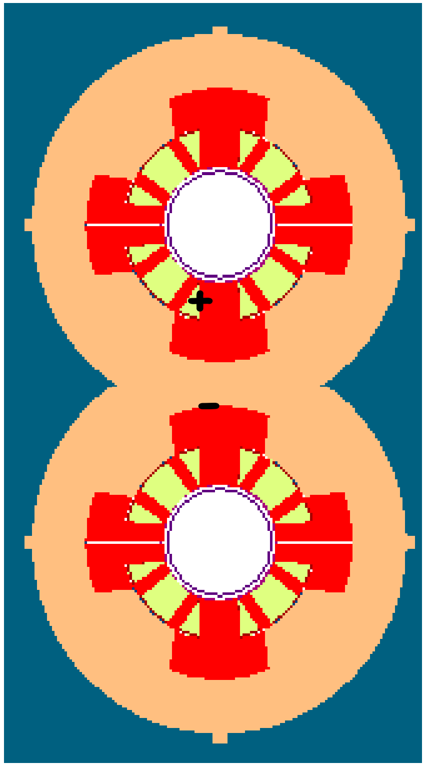
(relevance to magnet designs for “D1 first” optics?)



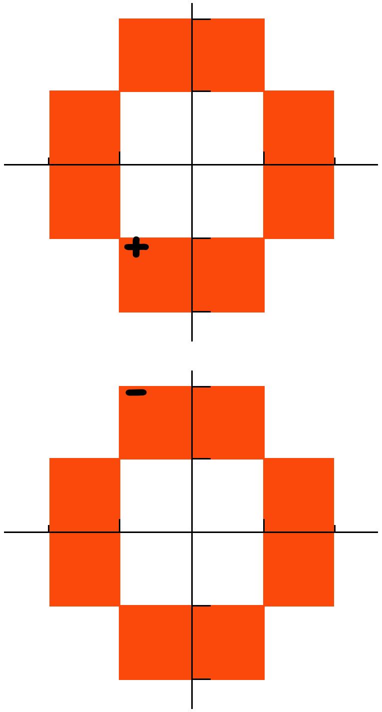
- Optics and magnet requirements (field & aperture) depends crucially on the minimum spacing in the first 2-in-1 IR Quadrupole **(doublet optics)**
- 23KW of beam power radiated from the IP makes this a natural for HTS.

VLHC-2 Interaction Region Magnet Design Concept

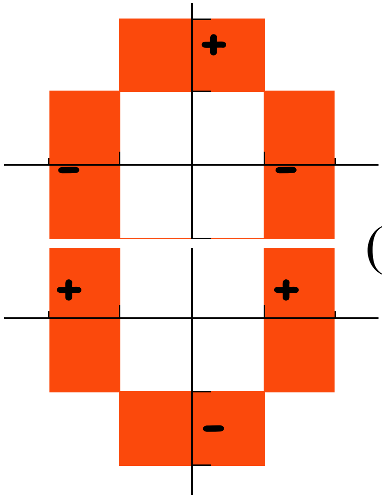
Conventional 2-in-1 cosine theta design



Panofsky 2-in-1 quad design



Modified Panofsky Quad with no spacing



(Bo not zero)

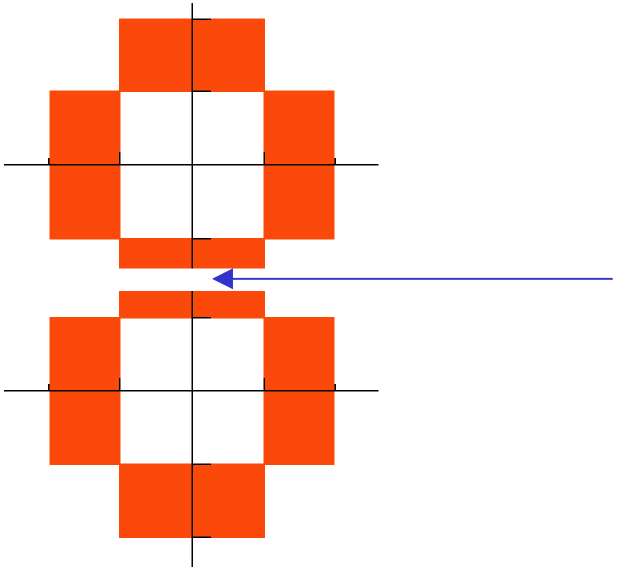
Spacing depends on the conductor and support structure requirements

Support structure and middle conductor is removed/reduced. This reduces spacing between two apertures significantly.

Variations of the Q1 Design

We have investigated several variations of the design shown in previous slide. Expect system optimization between field field strength, field quality and corrector designs.

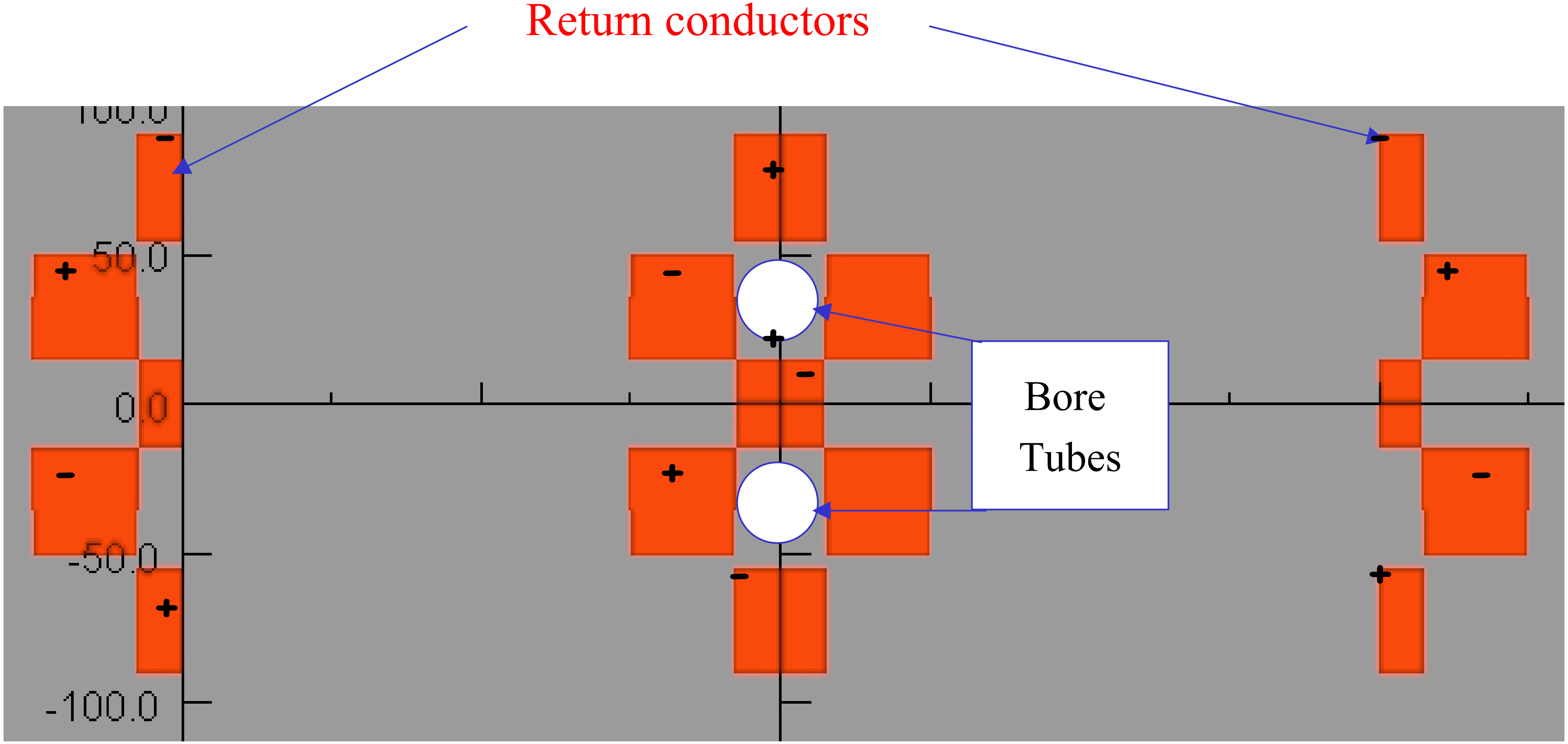
A design of particular interest (for neutrals) is the case when there is nothing present at the midpoint of two apertures.



Decay products from IR clear the superconducting coils

VLHC-2 Interaction Region Magnet Design (Preliminary)

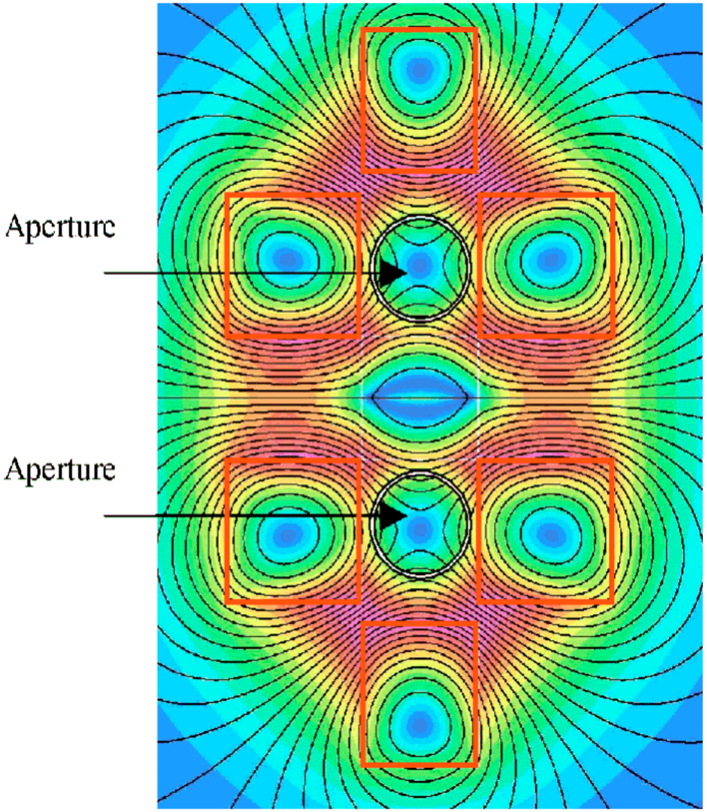
Conductor friendly and better field quality design

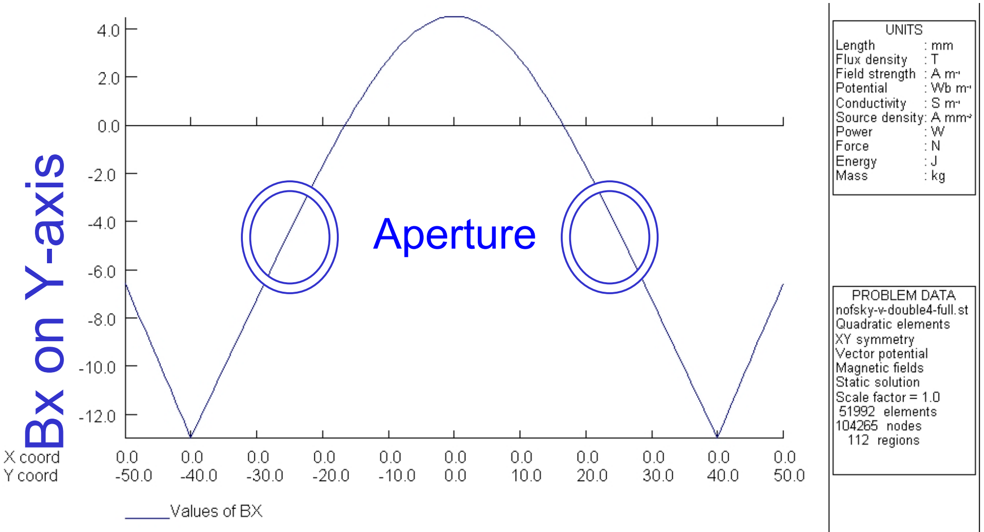


Support structure and middle conductor is removed/reduced. This reduces spacing between two apertures significantly.

Fields in the Proposed Double-Quad Design

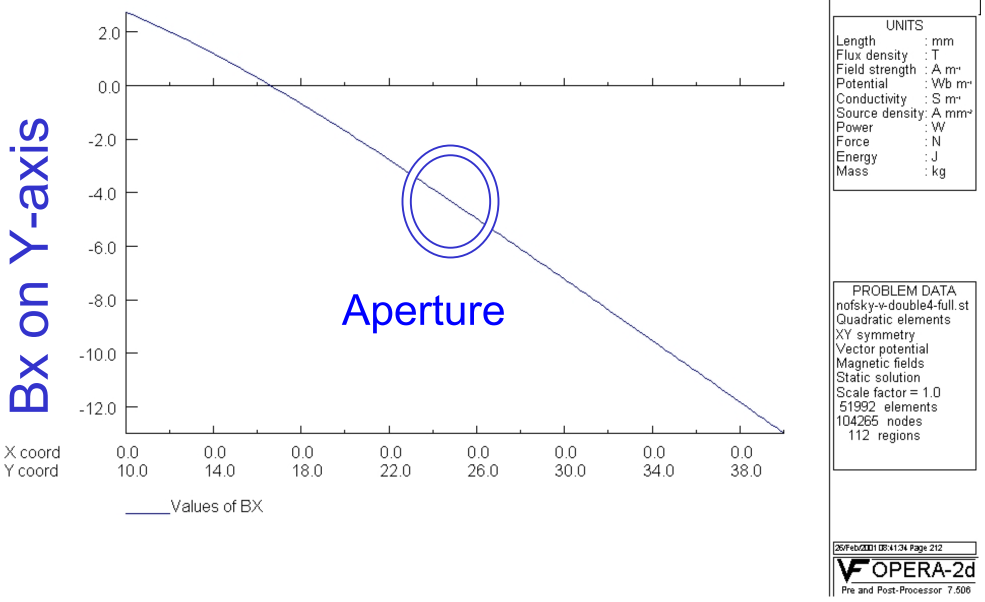
Field contours and field lines





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
nofsky-v-double4-full.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 1.0
51992 elements
104265 nodes
112 regions



UNITS
Length : mm
Flux density : T
Field strength : $A\ m^{-1}$
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Conductivity : $S\ m^{-1}$
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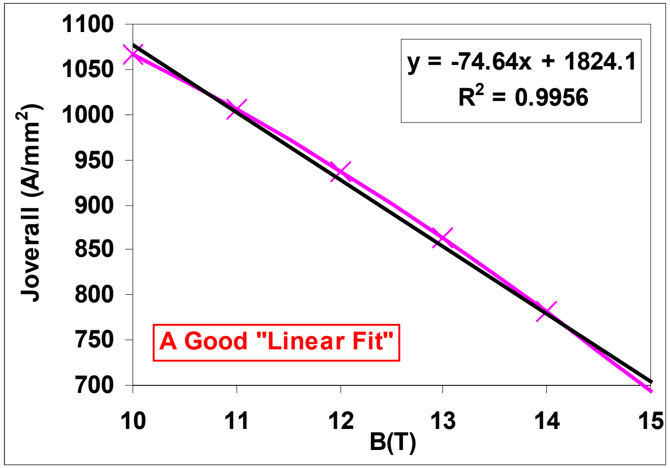
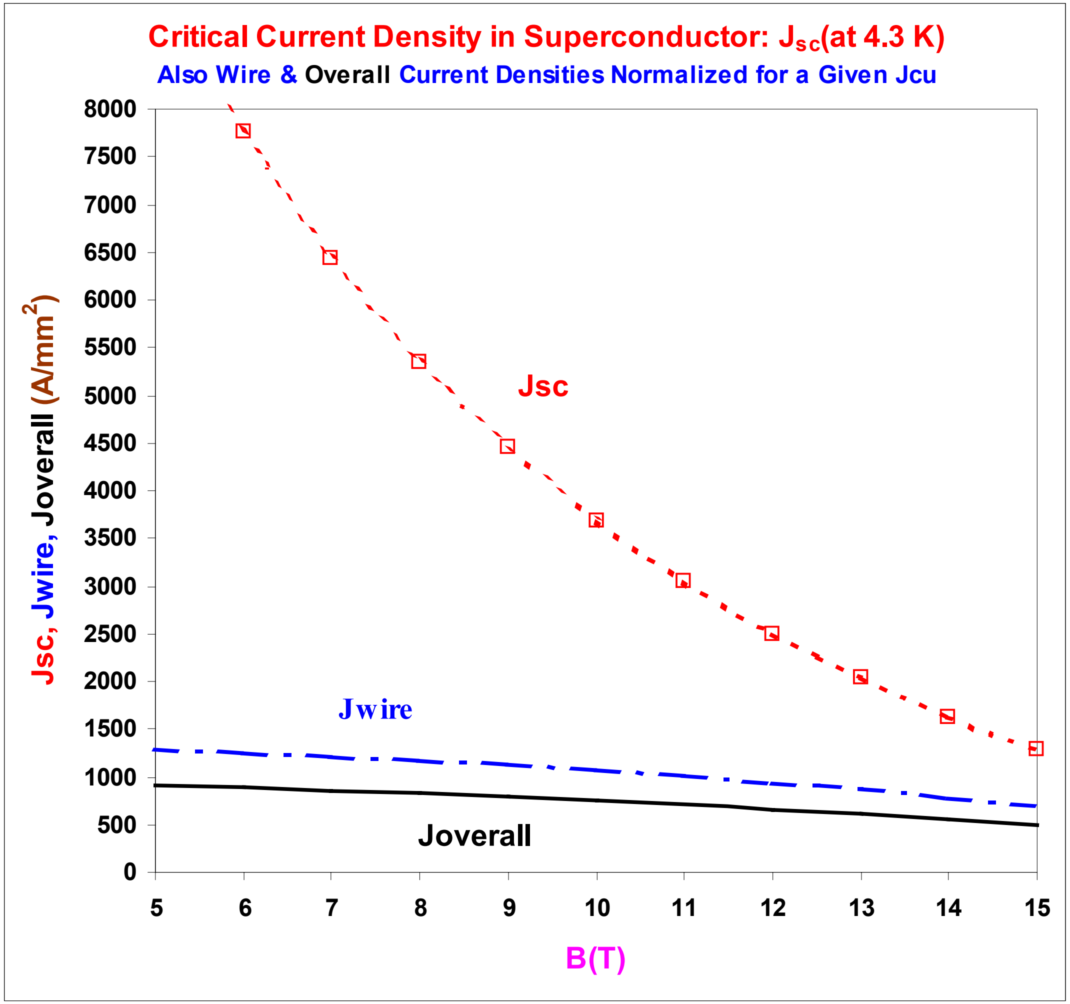
26/Feb/2001 08:41:34 Page 212

Usable current Density in Magnet Design

J_{sc}(12T,4.3K)	J_{cu}(A/mm^2)
2500	1500

Cu/Sc Ratio	B(T)	J_c(A/mm^2)	J_{wire} (A/mm^2)	Joverall
6.30	5	9454	1295	911
5.18	6	7766	1257	885
4.29	7	6431	1216	856
3.56	8	5347	1171	825
2.96	9	4446	1122	790
2.46	10	3689	1066	751
2.03	11	3048	1005	708
1.67	12	2500	938	660
1.35	13	2031	863	607
1.09	14	1631	781	550
0.86	15	1289	693	488
	Scaled from TWCA			Insulated




Critical Current Density in Superconductor: J_{sc}(at 4.3 K)

Also Wire & Overall Current Densities Normalized for a Given Jcu

Engineering (Operating) Current Density in Magnet Designs

J_{sc}(12T,4.3K)
2500

J_{cu}(A/mm^2)
1500

Cu/Sc Ratio	B(T)	J_c(A/mm^2)	J_{wire} (A/mm^2)	Joverall
6.30	5	9454	1295	911
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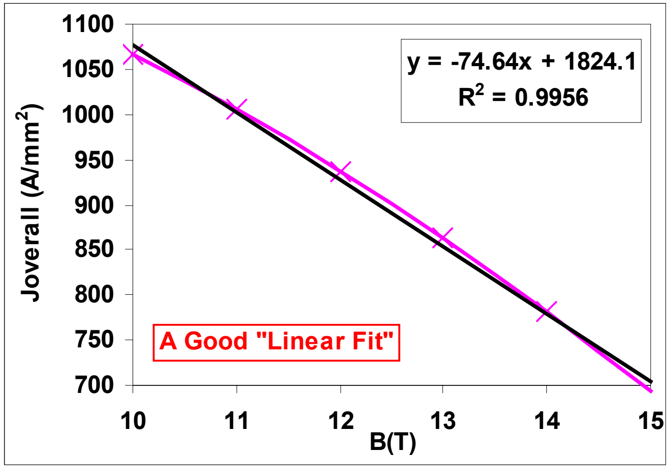
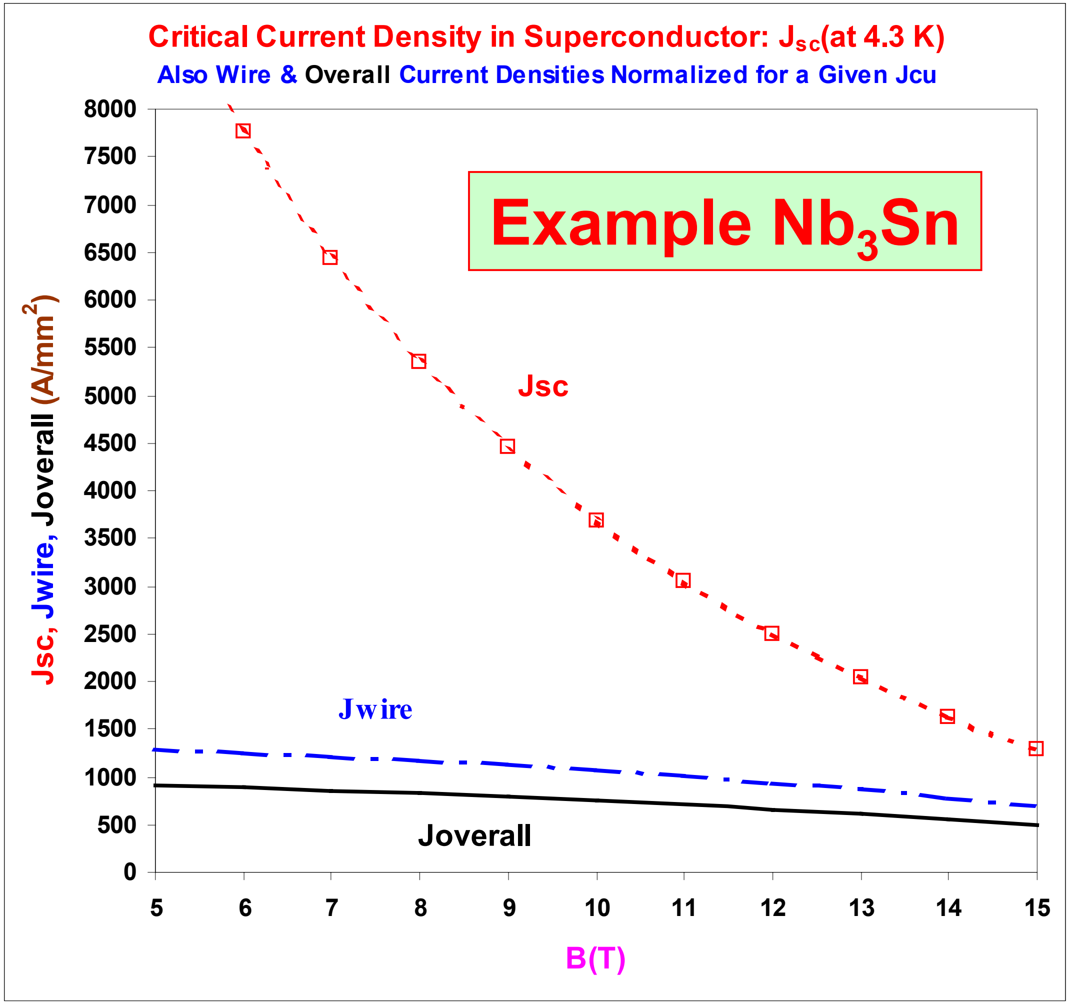


$y = -74.64x + 1824.1$

$R^2 = 0.9956$

A Good "Linear Fit"

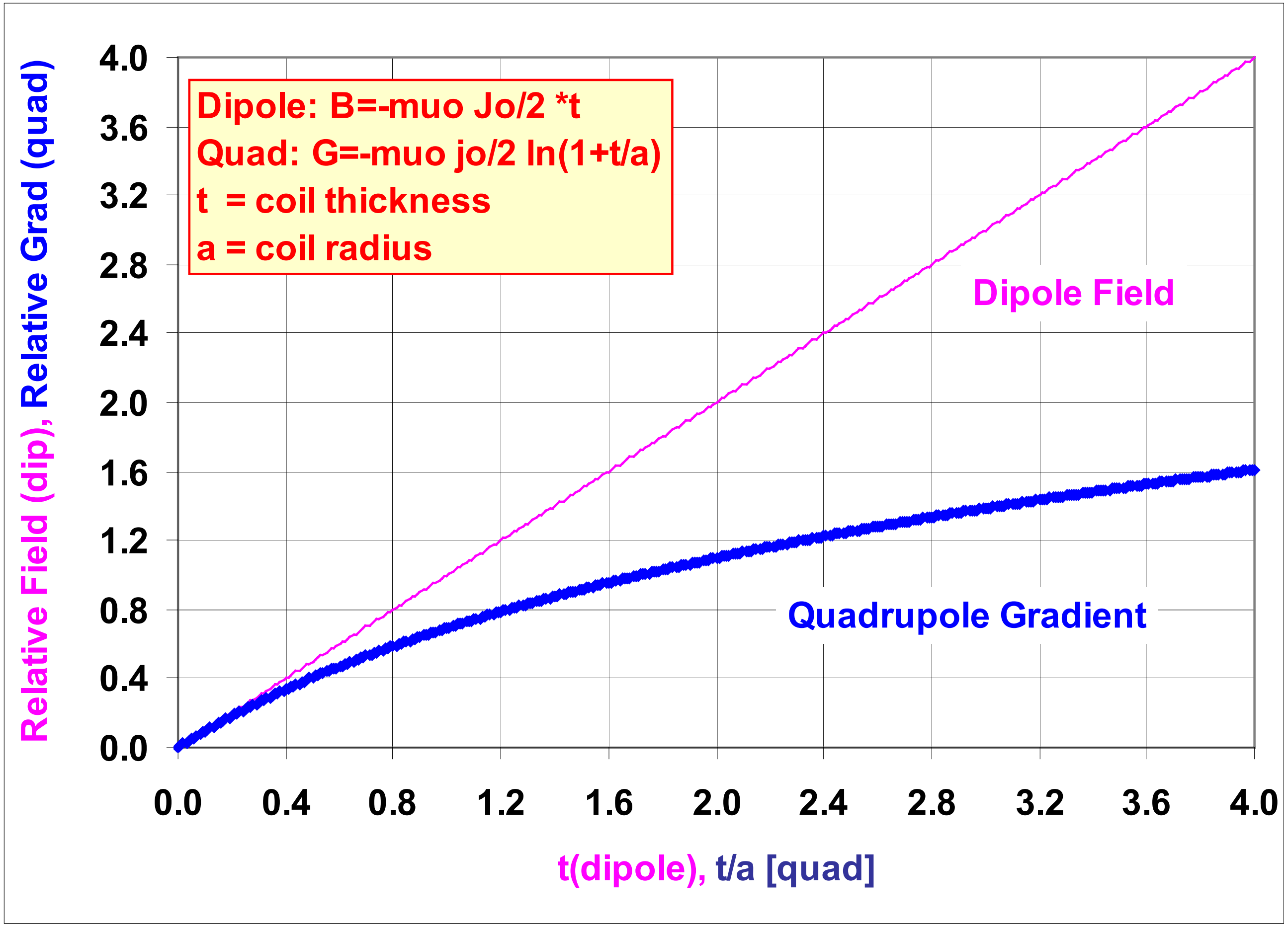

Critical Current Density in Superconductor: J_{sc}(at 4.3 K)

Also Wire & Overall Current Densities Normalized for a Given Jcu

Example Nb_3Sn

High Field Magnet Designs
A Basic Difference between Dipole and Quad

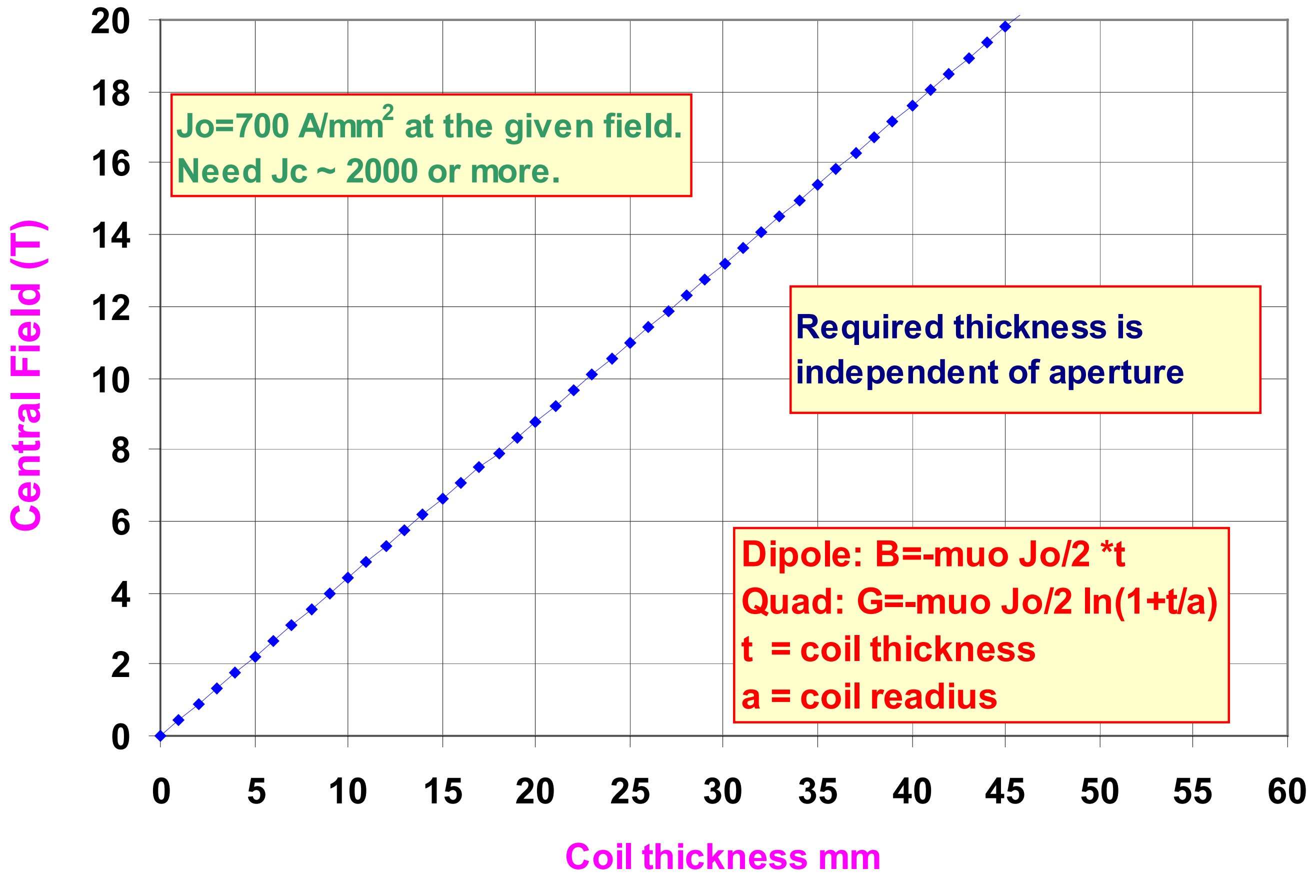
The increase in pole tip field is linear with coil thickness in dipole, but not so in quadrupole. The situation gets worse as we go to high gradients.



High current density at high fields is much more useful in high gradient quadrupoles than in high field dipoles.

Dipole Field Vs Coil Thickness (for any coil radius)

In dipoles, conductor amount is proportional to the aperture size (linear).



Jo=700 A/mm^2 at the given field.
Need Jc ~ 2000 or more.

Required thickness is independent of aperture

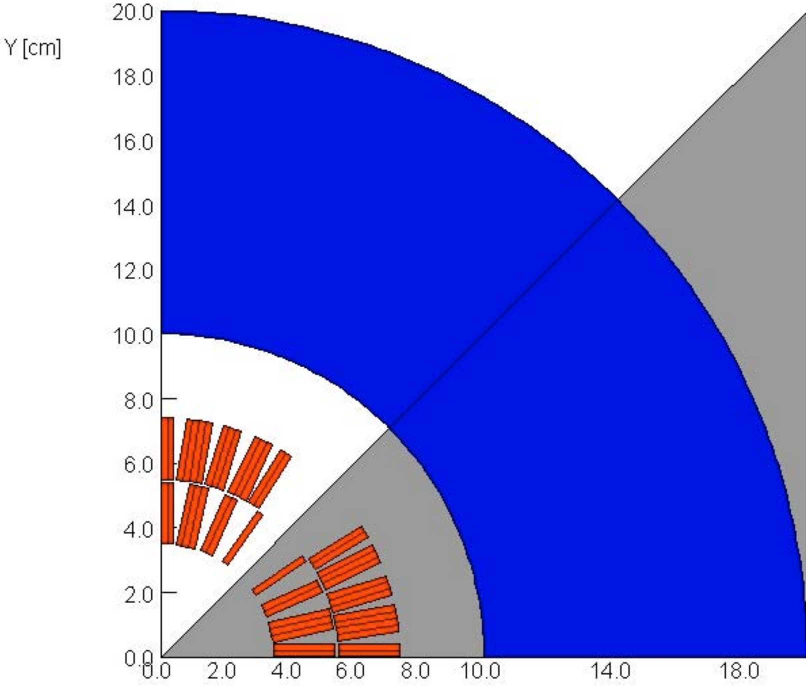
Dipole: B=-muo Jo/2 *t
Quad: G=-muo Jo/2 ln(1+t/a)
t = coil thickness
a = coil readius

The curve is computed for Jo=700 A/mm2. However, Jo is a function of the field. The curve scales as Jo.

Note: The coil thickness is proportional to the field, but the conductor amount is not proportional to the field. The conductor amount is computed/optimized differently.

Magnet/ Conductor Technology Options for High Field Quads

OPERA MODEL



- One option is to use "Wind and React" Approach. We are evaluating that.

- We are doing magnet R&D with "React & Wind" approach as it might be more suitable for long magnets. "React & Wind" approach also allows more options for insulation and structure materials as they don't need to go through the high temperature reaction cycle.

- One option under consideration under "React & Wind" approach is to evaluate possibilities of very small diameter flexible cable/wire, especially since the magnet need not ramp fast.

➢This requires a significant conductor R&D.

Primary goal of an R&D program should be to develop various magnet technology options so that one can later choose whatever works the best under the given situation.

SUMMARY

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

- High field magnets must deal with brittle superconductors.

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

- We invite you to join this challenging field, many possibilities for new magnet R&D.