Racetrack Coil Magnets with High Field Superconductors

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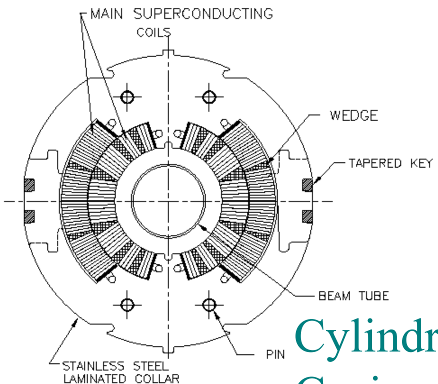
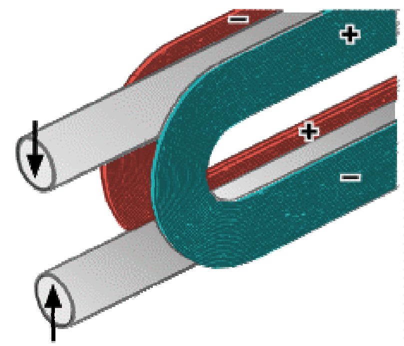
Technology and design issues in magnets made with "High Field Superconductors" :

- Technology options for magnets with high field superconductors
- Test results on Nb_3Sn "React & Wind" magnets at BNL
- Racetrack coil designs for high field superconductors
- A rapid turn around and cost-effective magnet R&D approach
- Recent calculations at KEK for future magnets with Nb_3Al

High Field Magnet Designs and Technology

Conventional		Alternate
Ductile: NbTi Easy to make coil with	**Conductors**	Brittle: Nb_3Sn, Nb_3Al and HTS
Cylindrical Cosine Theta	**Magnet Designs**	Example: Racetrack Common Coil
Large resources committed to developing each magnet	**R&D Approach**	Experimental program: Rapid turn around, less expensive





Two Technologies for Brittle High Field Superconductors

The material becomes 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.

Wind & React Vs React & Wind Approach (1)

In the “Wind & React” approach, the integrated build-up of differential thermal expansion and the associated build-up of stress/strain on brittle Nb_3Sn during reaction process is proportional to the length of magnet. This could have a significant impact on magnet manufacturing and on magnet performance.

The “React & Wind” approach eliminates the need to deal with the differential thermal expansions between the various materials of coil modules during the high temperature reaction process. These length dependent issues become more critical as magnets get longer.

Wind & React Vs React & Wind Approach (2)

- The “React & Wind” approach allows one to use a variety of insulation and other materials in coil modules as the coil and associated structure are not subjected to the high reaction temperature.

- The “React & Wind” approach appears to be more adaptable for building long magnets by extending present NbTi manufacturing techniques and tooling. One must look into general differences between long and short magnets. However, unlike the “Wind & React” technology, no new complications/issues are expected.

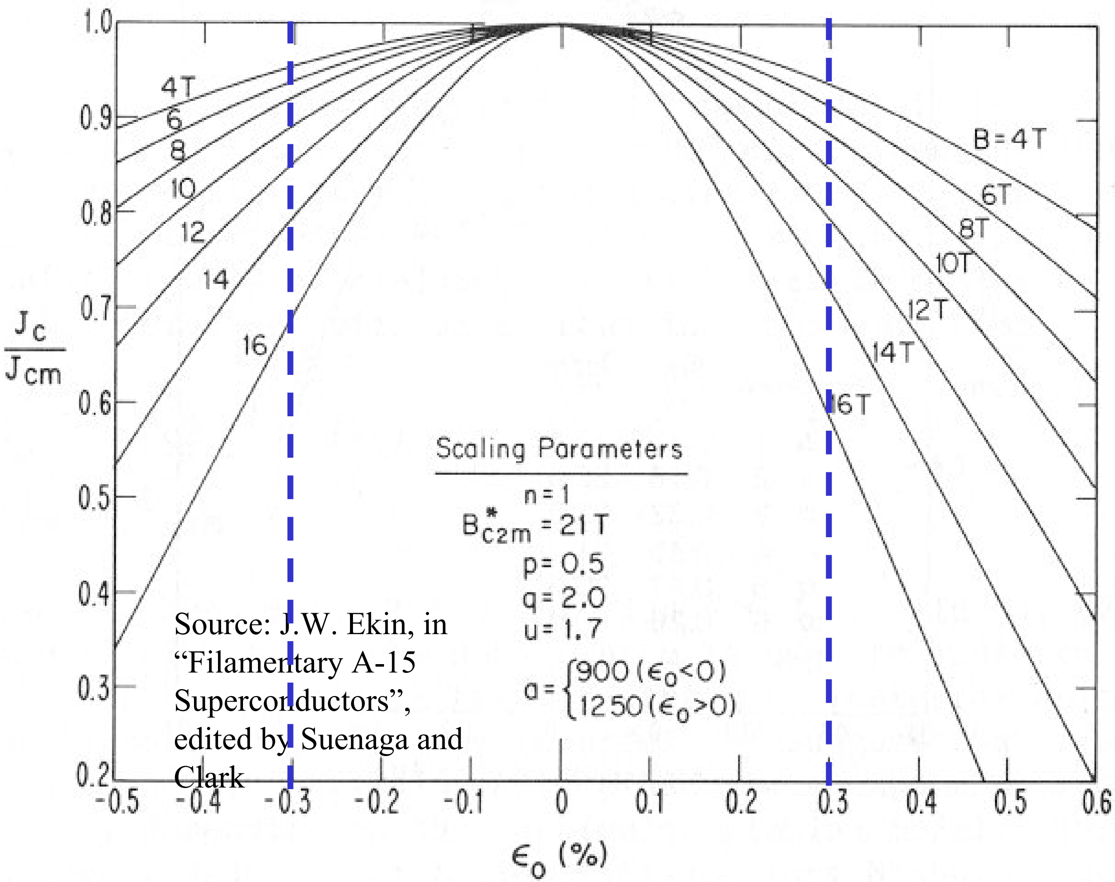
Challenges with React & Wind Approach

• The conventional pre-reacted Nb_3Sn Rutherford cable is brittle and is prone to significant degradation or even damage during winding and other operations.

• Bend radius degradation is an important issue and plays a major role. This issue must be addressed in conductor designs, in magnet designs and in magnet tooling.

• The magnet design and manufacturing process must be developed and proven by a successful test to demonstrate that the “React and Wind” technology can be used in building high field Nb_3Sn accelerator magnets.

J_c, Strain and Field in Nb_3Sn



Relative critical-current density J_c/J_{cm} as a function of intrinsic strain $\varepsilon_0(\equiv\varepsilon-\varepsilon_m)$ for different magnetic fields, evaluated using Eq. (3) and the typical set of scaling parameters indicated in the figure.

A 15% drop in Jc means about 4% drop in Bss. 0.3 % axial strain may be acceptable at 12 T, in particular since "high strain" and "high field" are not usually at the same location.

One should place limit to 0.2% for a 14 T design.

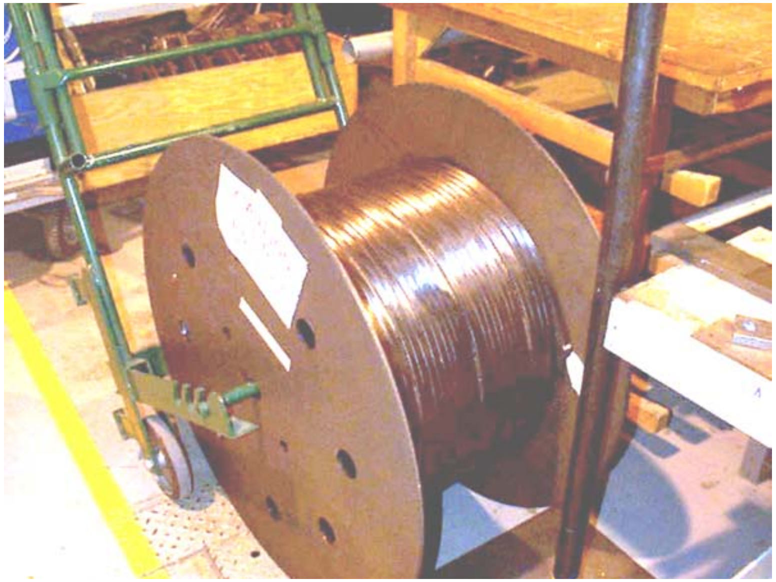
Conductor R&D may reduce bending strain in Nb_3Sn.

Use smaller diameter strand for a lower bending strain.

Nb_3Sn Reaction Facility at BNL

Large (1.5 m^3) reaction furnace at BNL.

It is used for reacting large spools of cable for "React & Wind" coils and medium length "Wind & React" coils for Nb_3Sn magnets.



Nb_3Sn cable after reaction.

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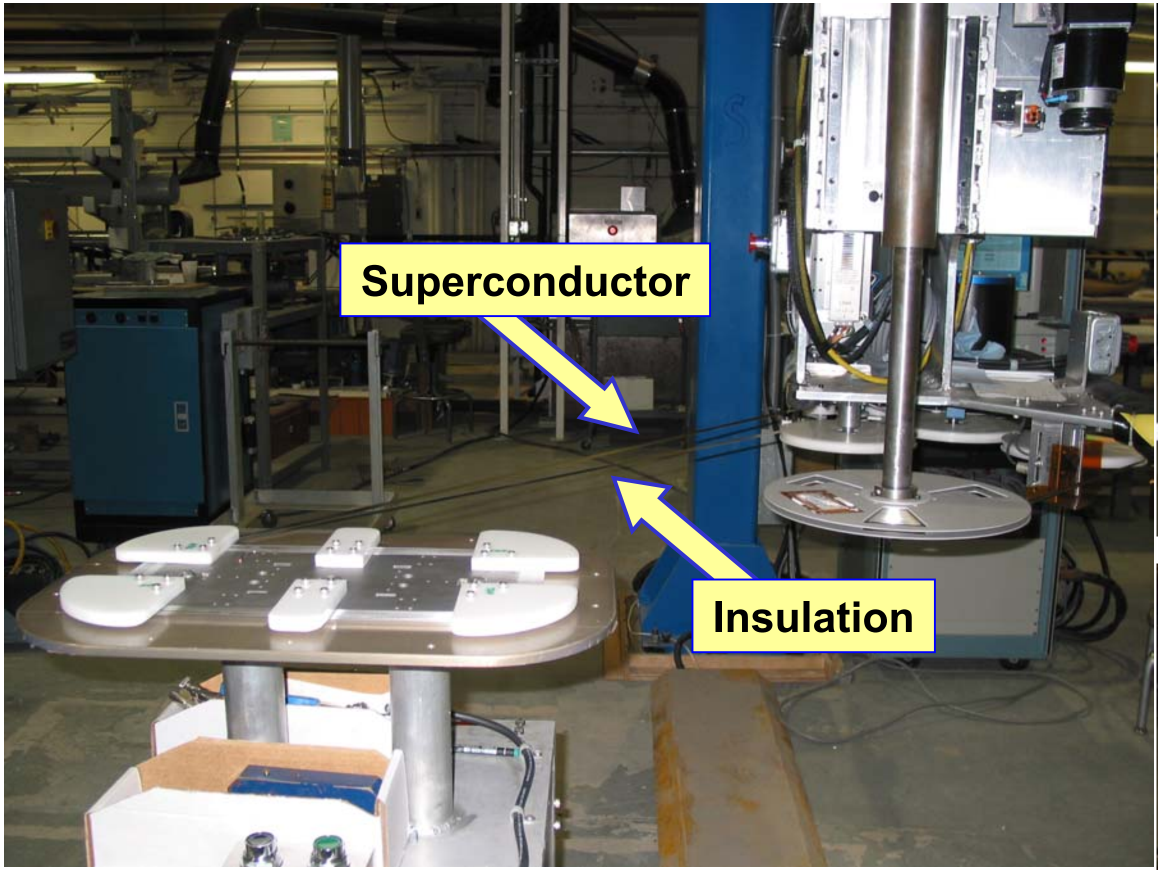
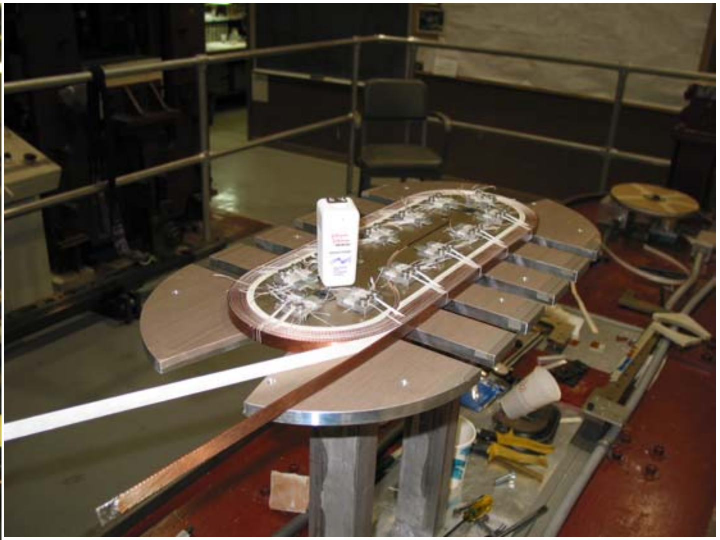
Reaction Process at BNL

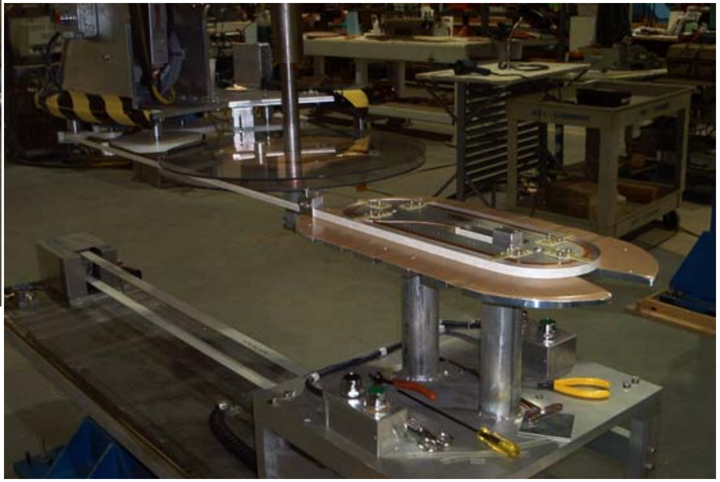
• Spools for reacting (heat treatment) Nb_3Sn cable (see two pictures on right).

• Wires in the cables should not be allowed to sinter during the reaction. To achieve this, wires in the cable are coated with a thin layer of oil before the reaction using an oil impregnation setup (see picture).

Coil Winding







A coil being wound in a computer controlled winding machine.

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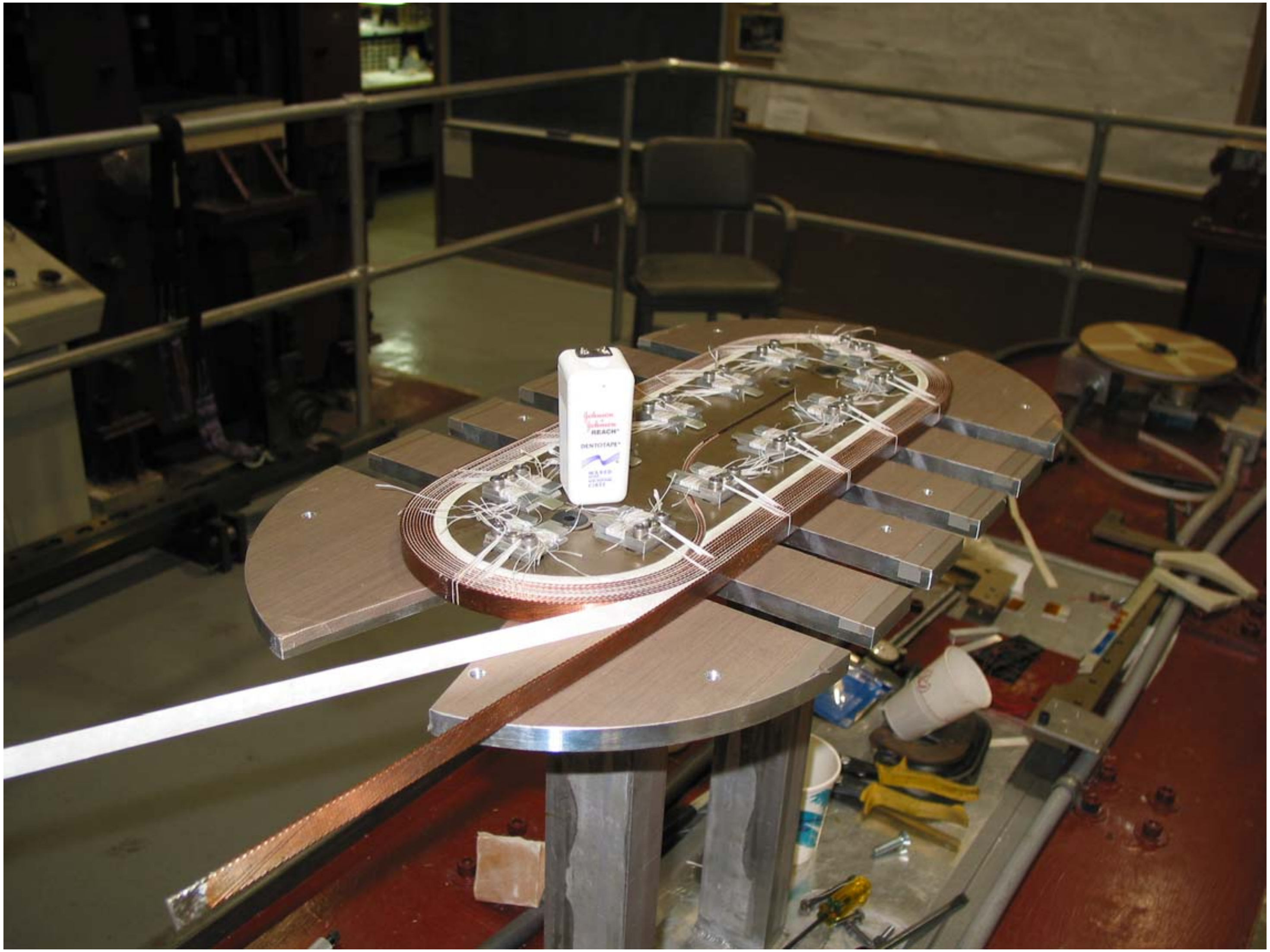
Cable Coil with Nomex Tape Insulation



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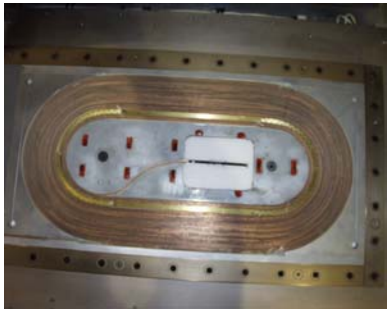
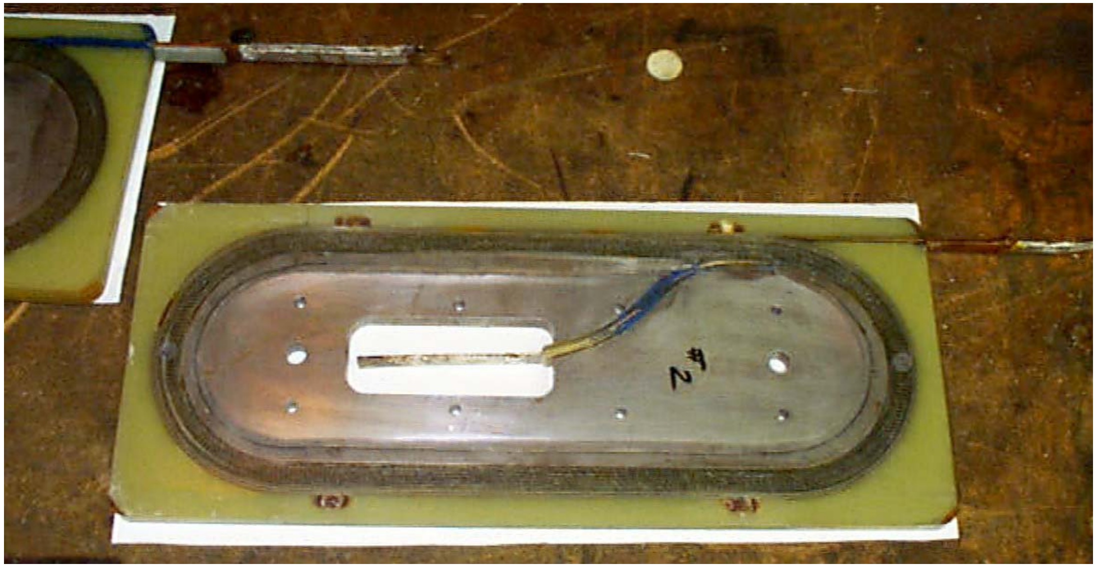
Vacuum Impregnation

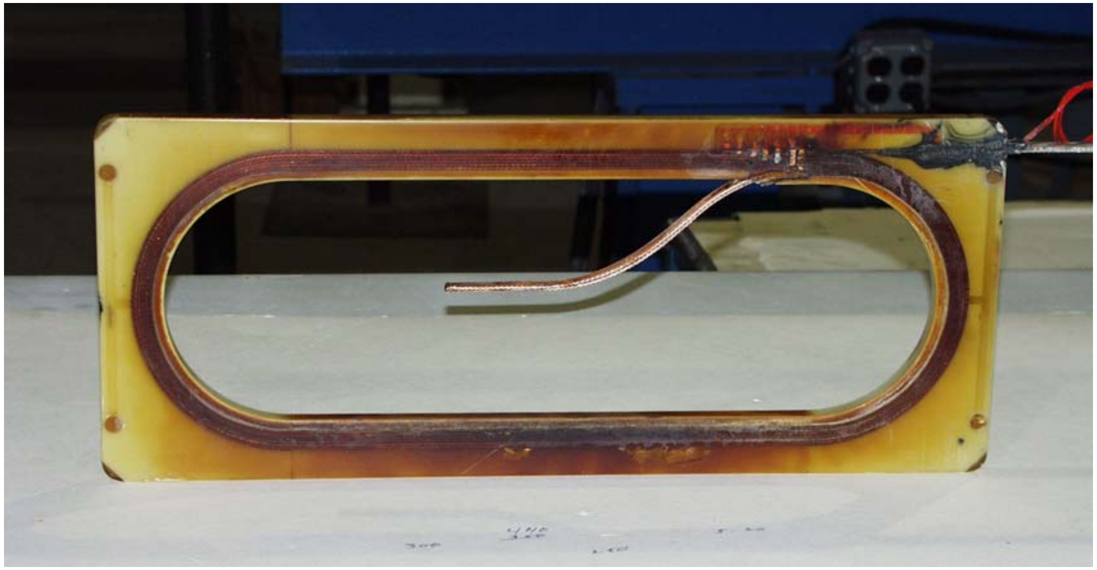


Epoxy Impregnated Coils



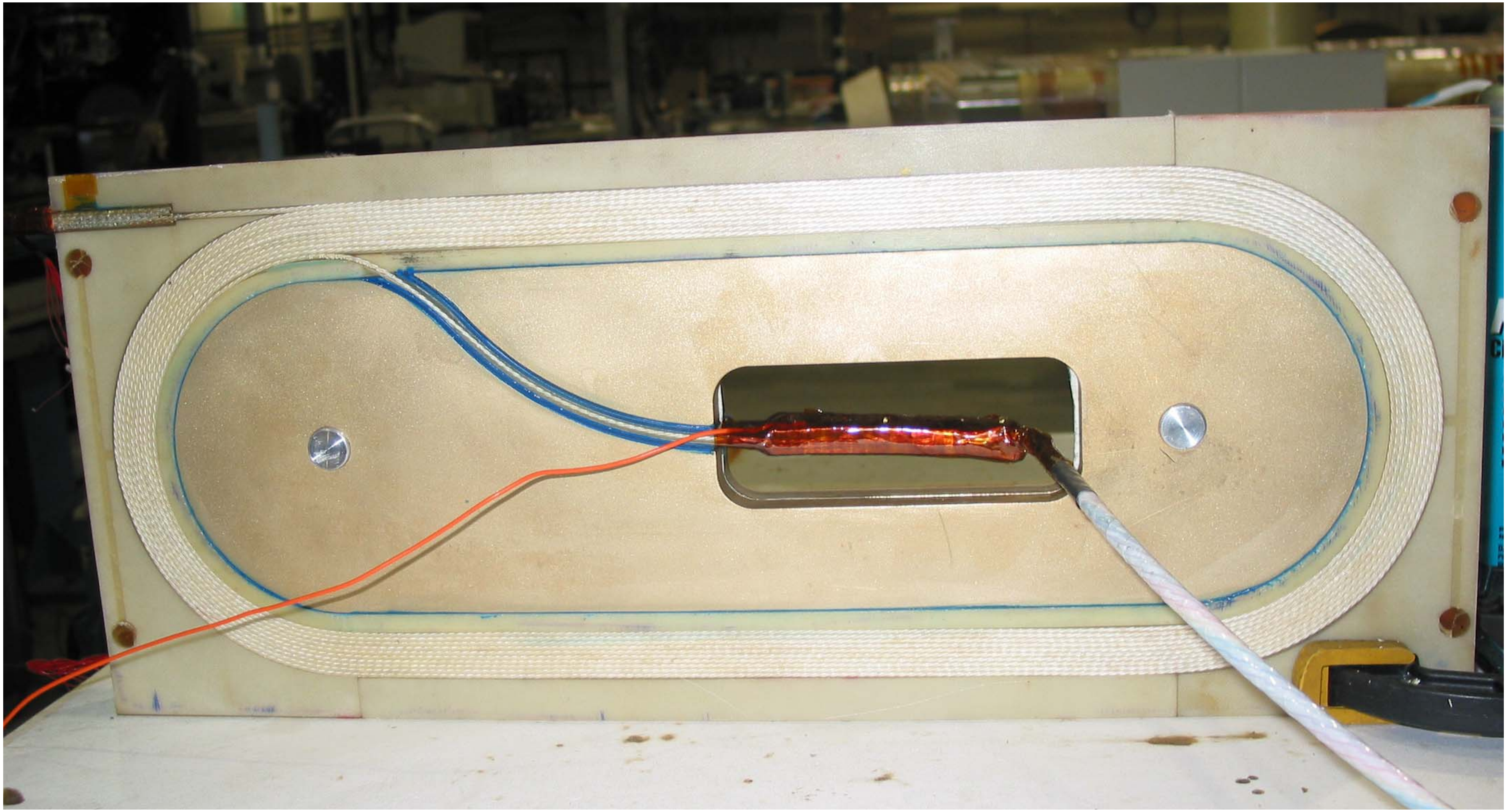
Vacuum impregnated coils made with the "React & Wind" technique.

Coil with bobbin attached

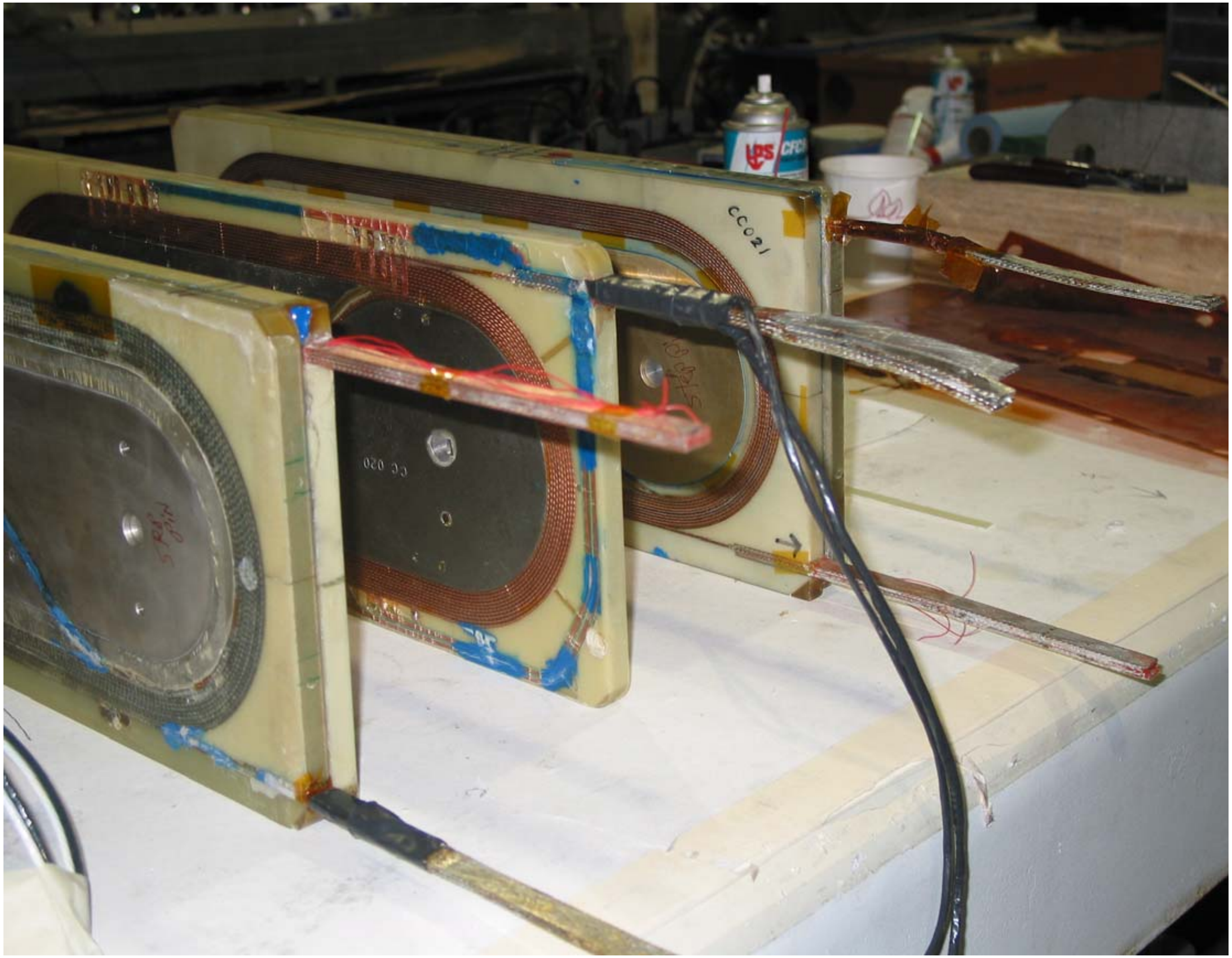


Coil without bobbin attached (free space in the middle)

HTS Cable Coil

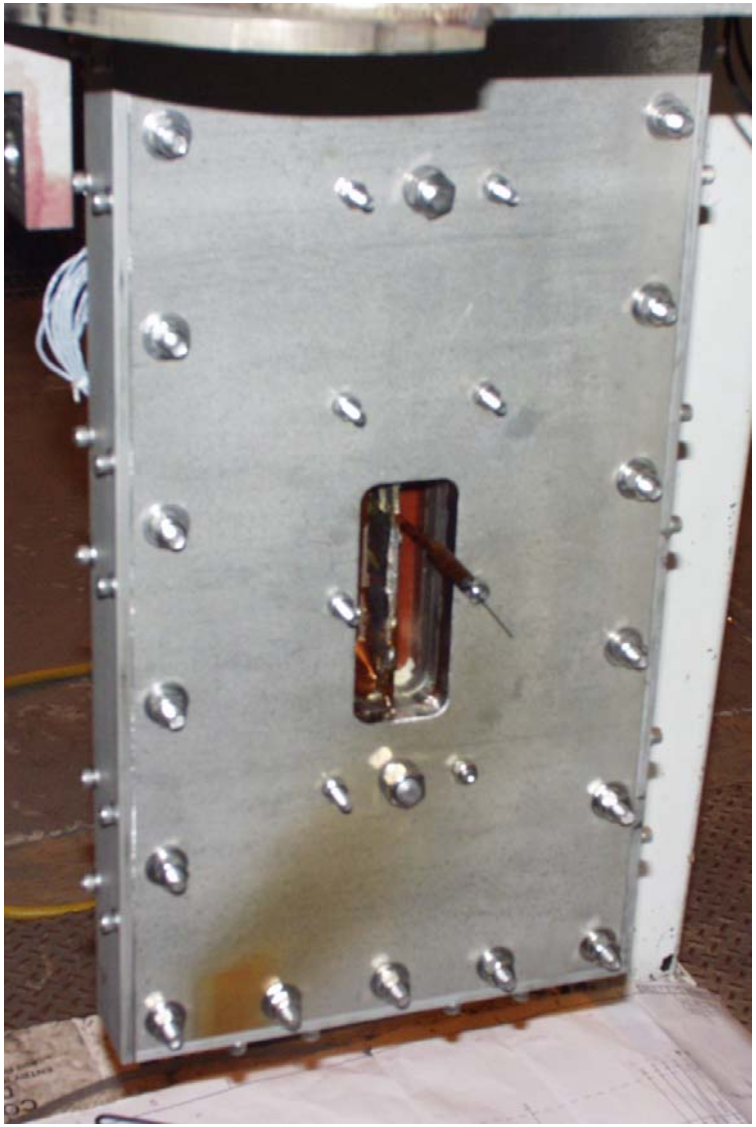


A Series of Racetrack Coils



BNL makes racetrack coils in a modular fashion. These modules (cassettes) are placed in a flexible structure to do a variety of experiments with a rapid turn around.

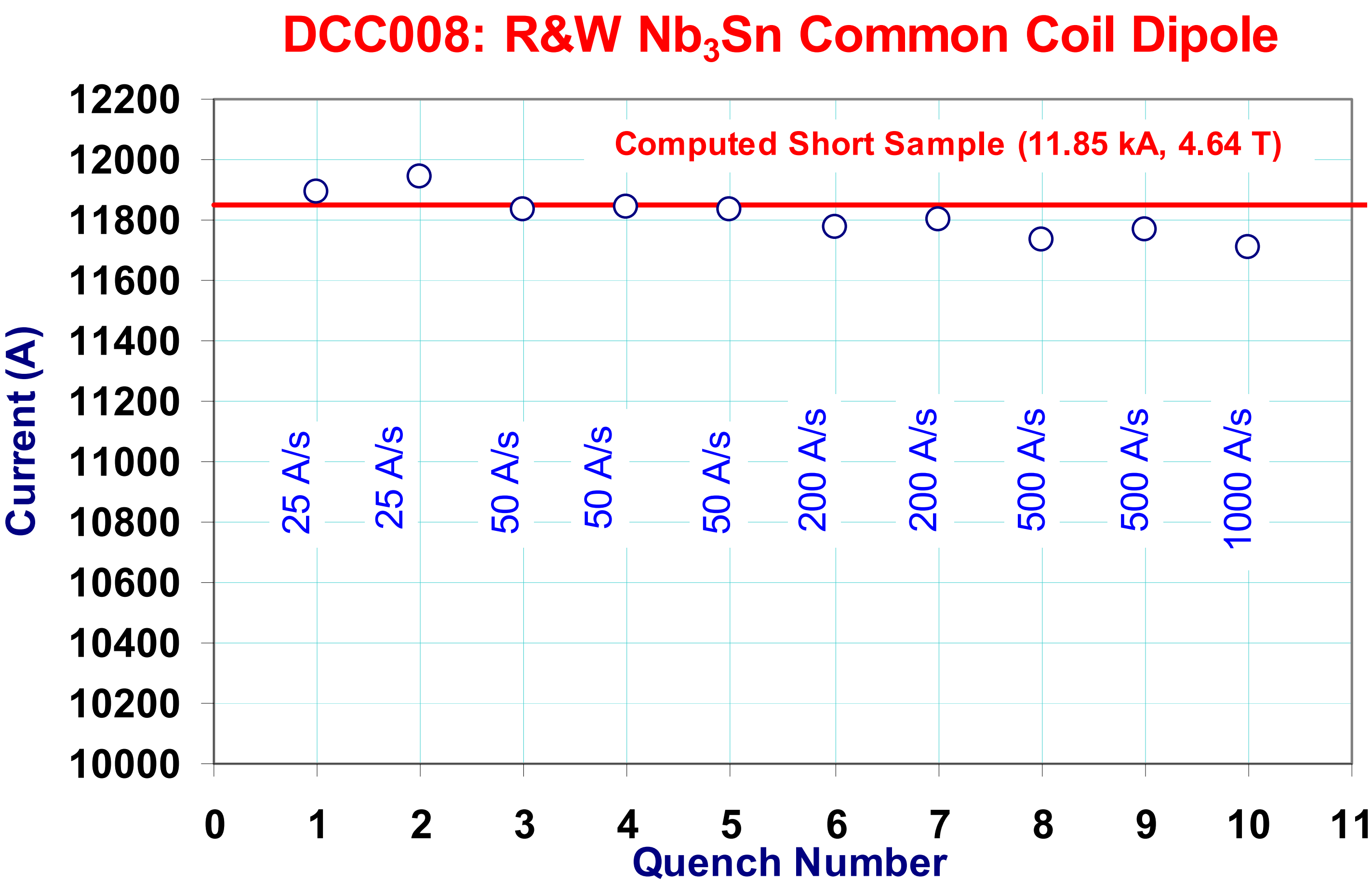
Two Support Structures for Medium Field Common Coil Design at BNL



Test Results on Nb_3Sn

"React & Wind" Magnets at BNL

Initial Experience with React & Wind Nb_3Sn Technology Magnet at BNL

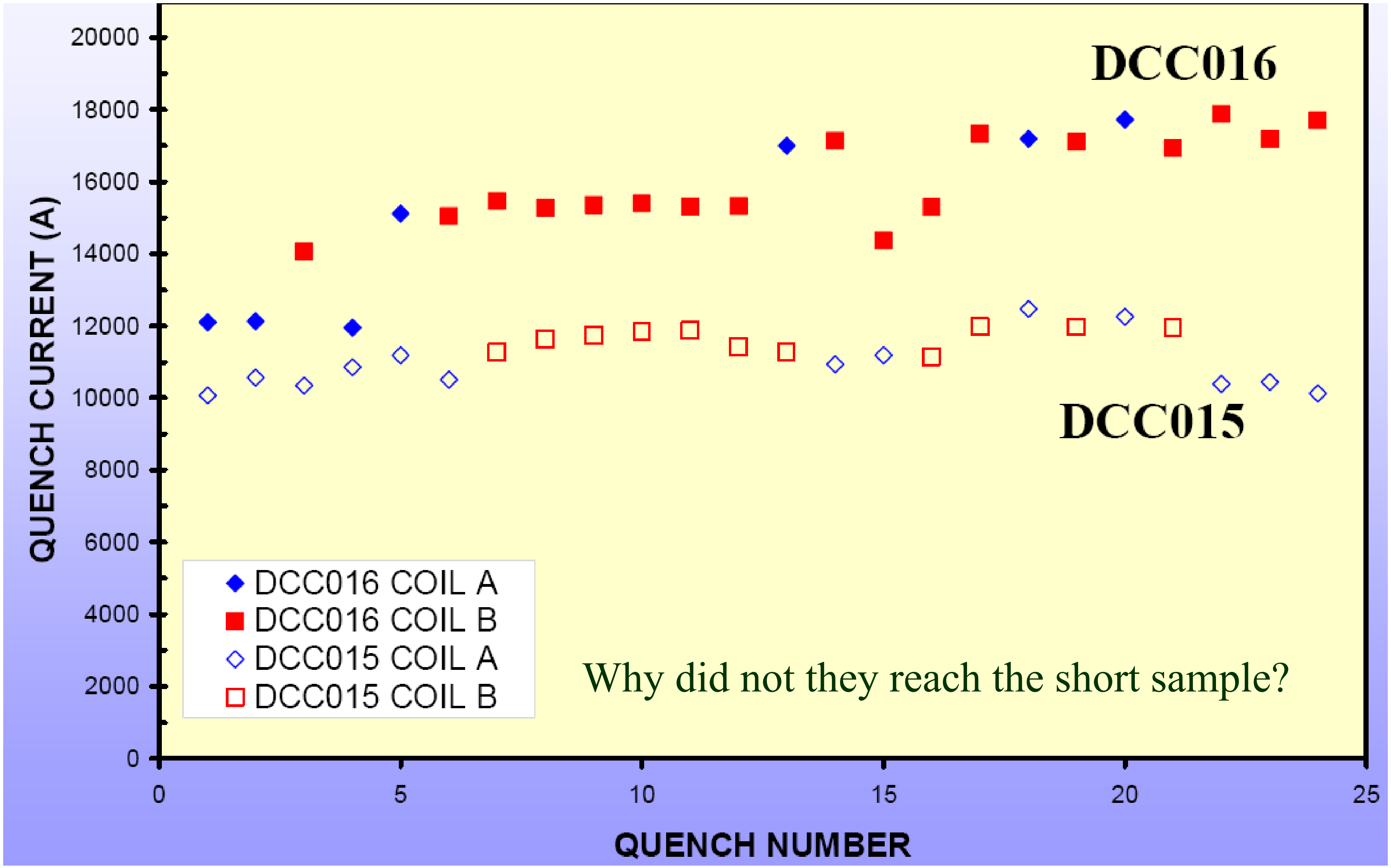


- Magnet reached the short sample in the first quench itself.
- The magnet was made with chrome-plated ITER cable.

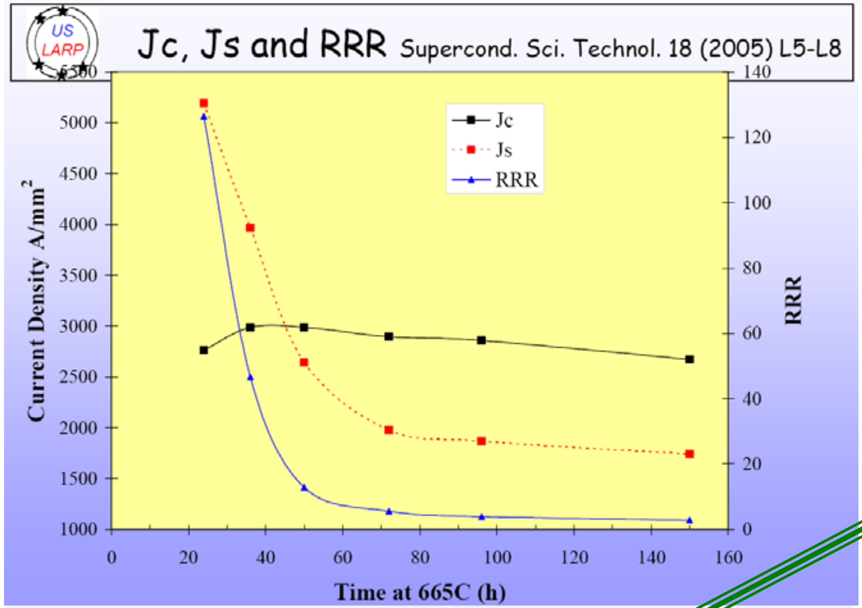
This shows that at least at low fields (up to 4.6 T), degradation, if any, is small.

Good test result from the first "React & Wind" common coil dipole magnet

Performance of Later Magnets

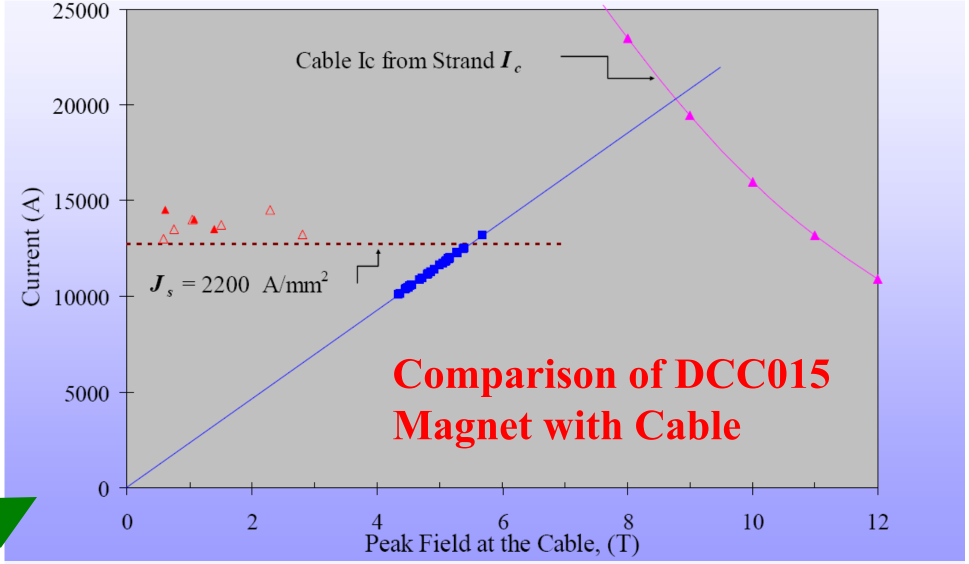


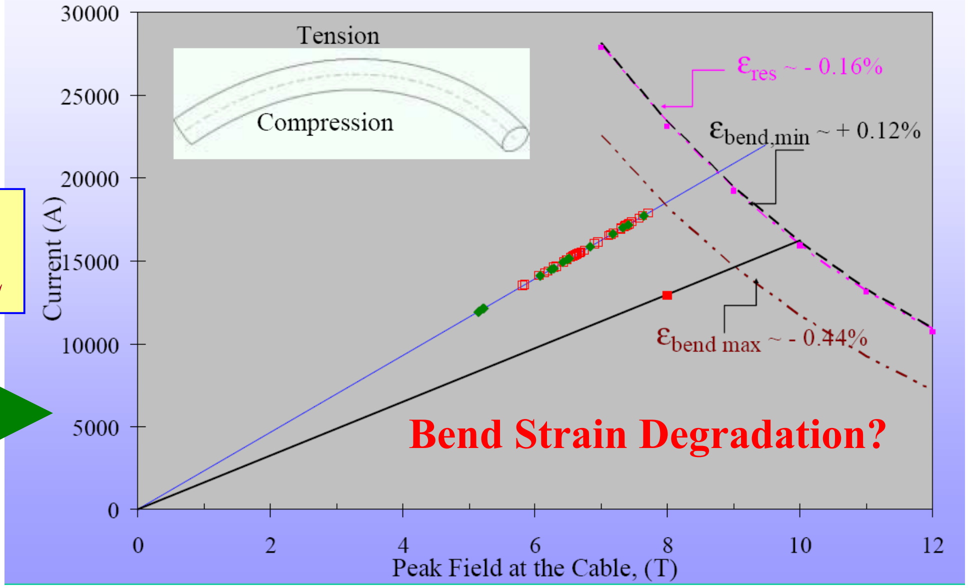
Conductor Instability and Bending Degradation



- DCC015
  - Manufacturer reaction HT 675C/150 hrs
  - RRR ~ 5
- DCC016
  - Modified HT 665C/72 hrs
  - Coil A ➢ RRR ~ 50
  - Coil B ➢ RRR ~ 90
  - No change in Jc(12T)

Courtesy: Ghosh, BNL

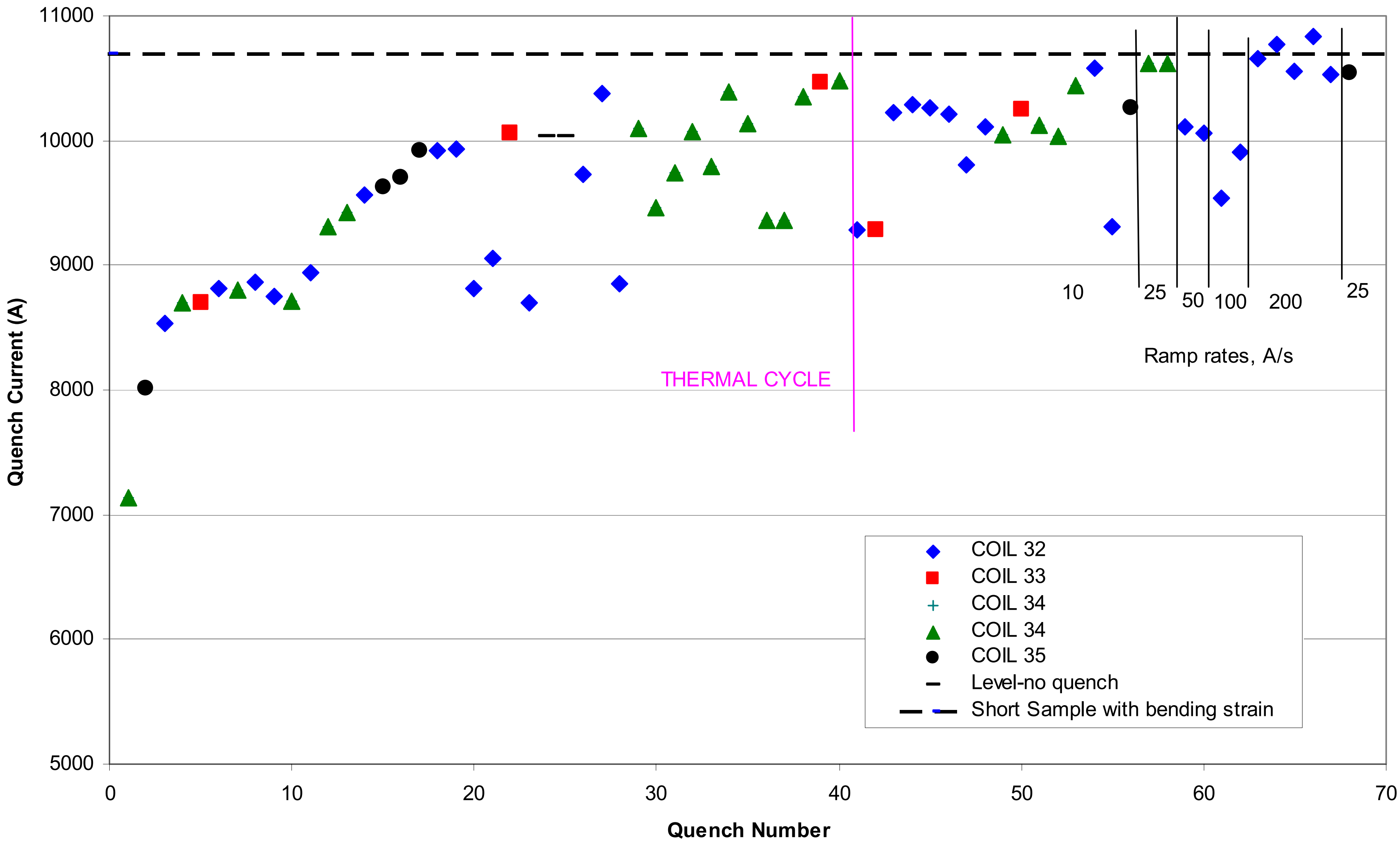




BNL 12 T Nb_3Sn Common Coil React & Wind Dipole Magnet During Final Assembly

Magnet tested in February 2006.
Reached computed short sample.

Quench Plot of BNL React & Wind Common Coil Dipole DCC017



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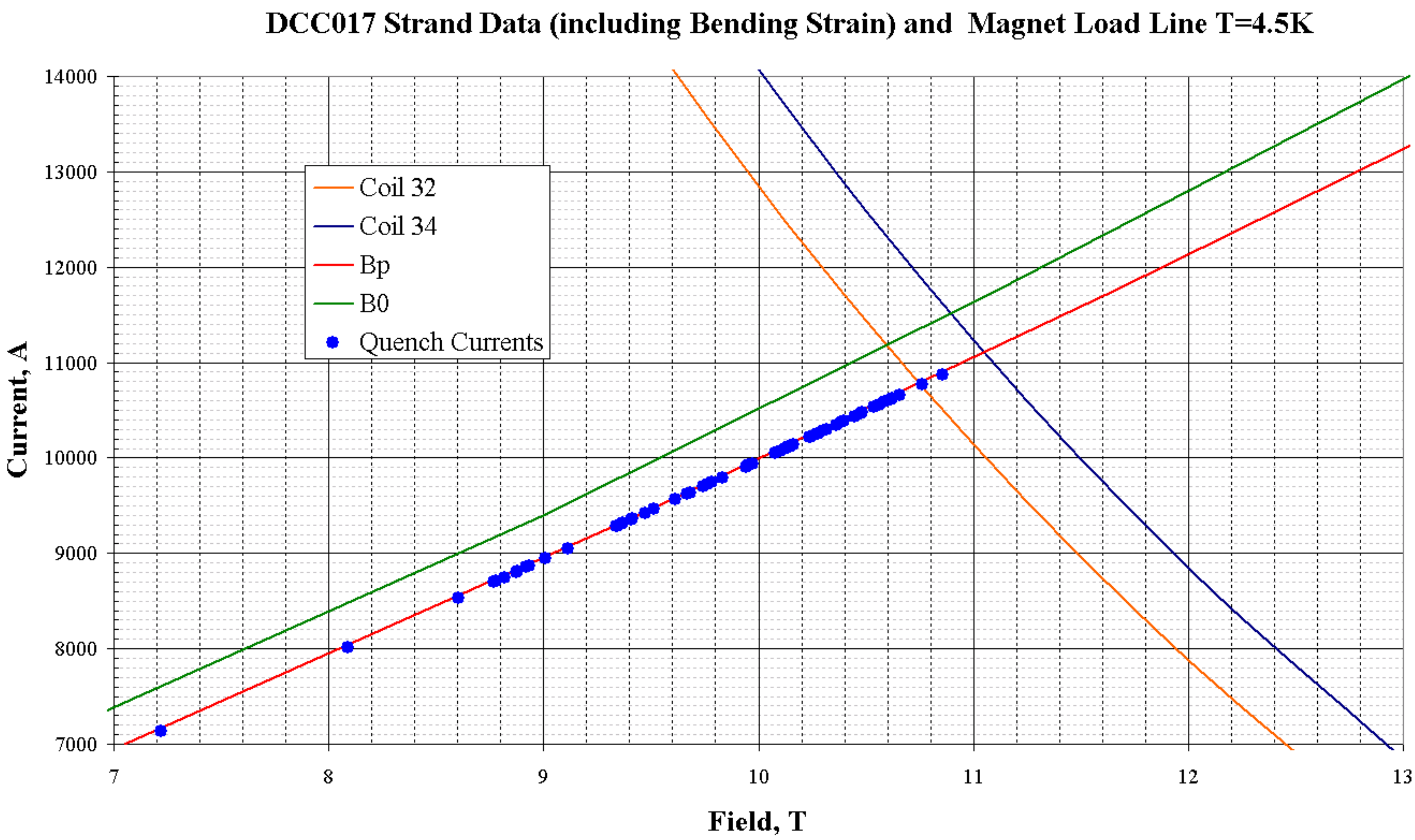
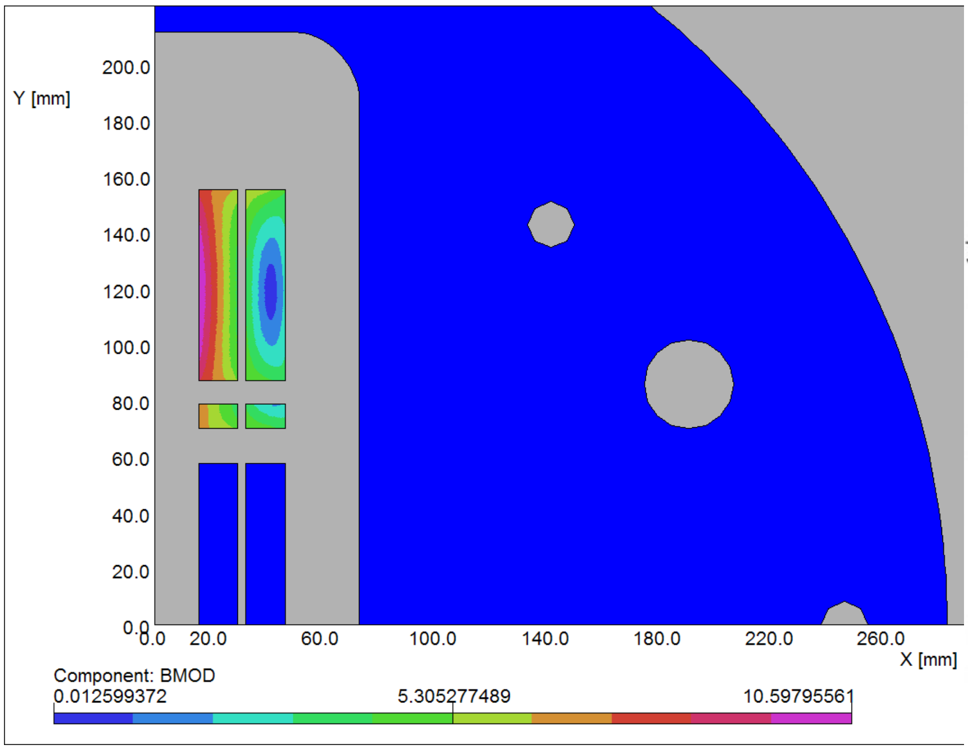
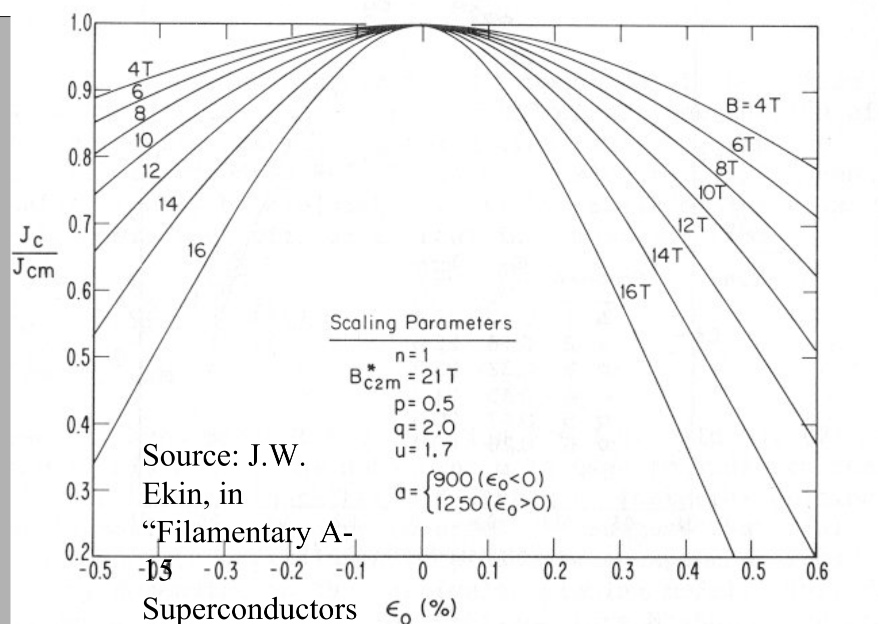
Load-line and Peak Field Line with Extracted Strand Measurements



Bending Strain Degradation in Nb_3Sn

Note: Peak Field and Bending Strain do not occur at the same location





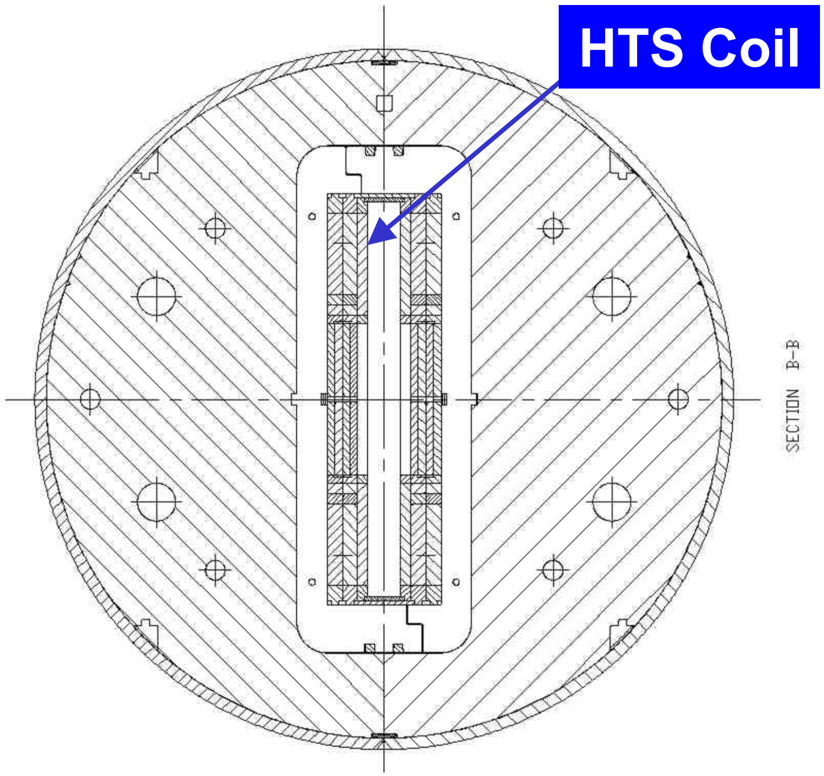
Source: J.W. Ekin, in "Filamentary A-15 Superconductors", edited by Suenaga and Clark

Relative critical-current density J_c/J_{cm} as a function of intrinsic strain $\varepsilon_0(\equiv\varepsilon-\varepsilon_m)$ for different magnetic fields, evaluated using Eq. (3) and the typical set of scaling parameters indicated in the figure.

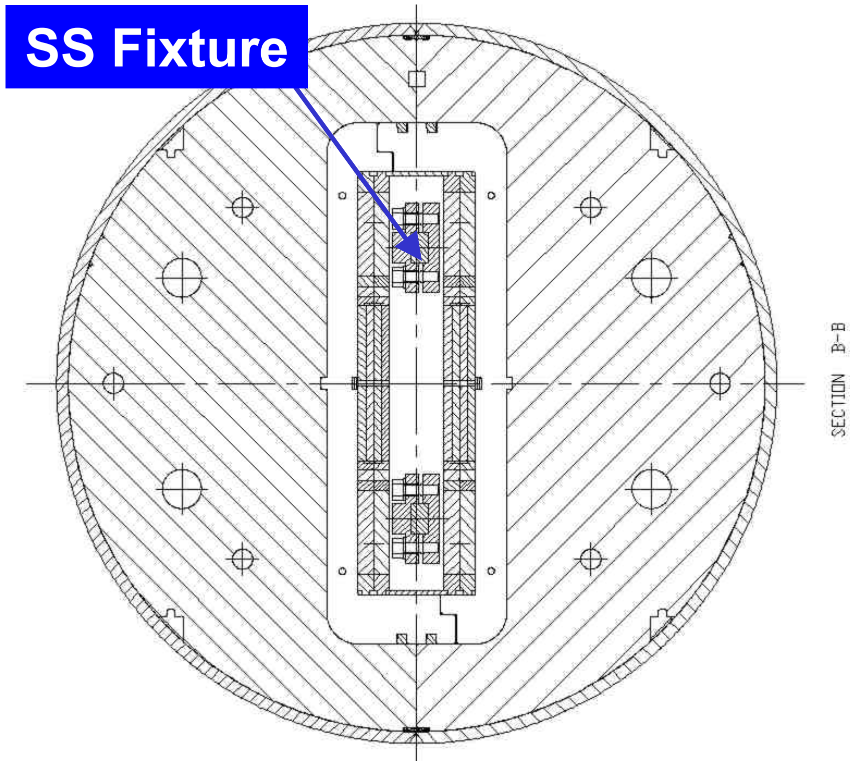
Bending strain is computed on superconductor diameter (area), not copper (diameter) clad over it. Please note that superconductor diameter is smaller than copper wire diameter.

Insert Coil and Sample Test Scenarios

An interesting feature of the design, which will make it a truly facility magnet, is the ability to test short sample and HTS insert coils without disassembling it.



HTS insert coil test configuration



Short sample test configuration

Racetrack Coil Magnet Designs

- Common Coil Magnet Design
- Open Midplane Dipole Design
- Modular Quadrupole Design

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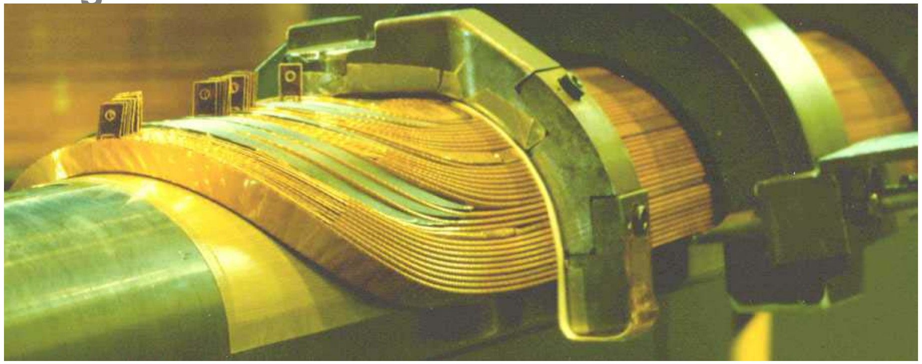
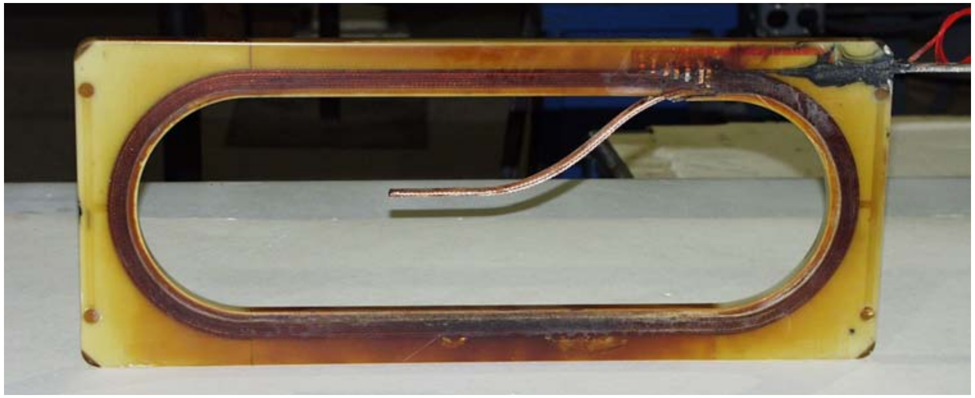
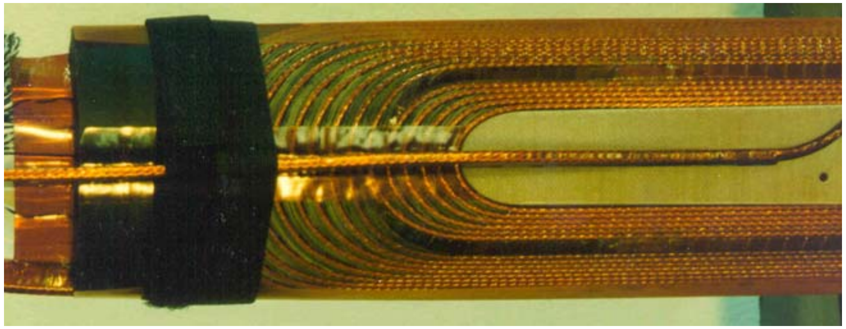
Cylindrical Cosine Theta Coil Geometry and Flat Racetrack Coil Geometry

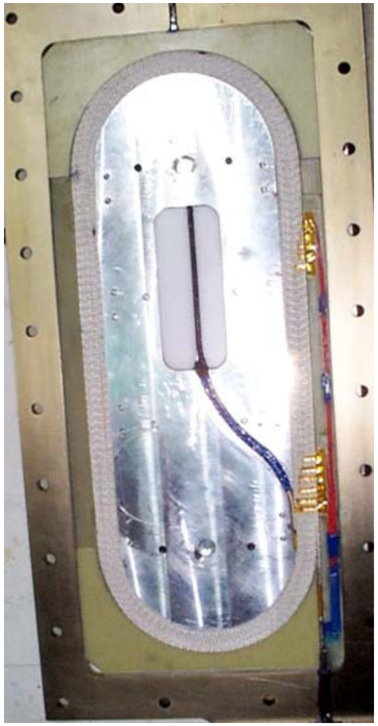




Cosine theta (cylindrical or shell type coil geometry).

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



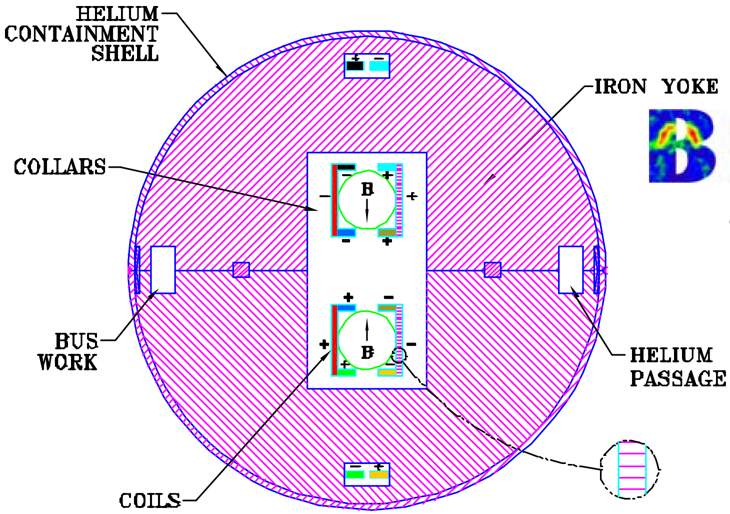


Racetrack geometry (flat coils), 2-d coils with simpler ends.

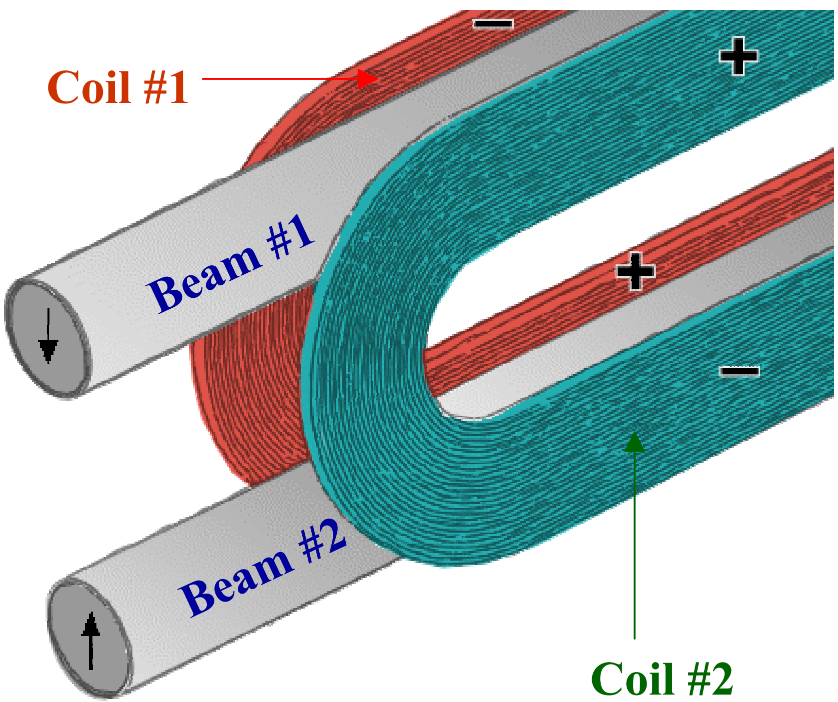
Good for high field magnets, particularly with brittle materials. Good for lower cost R&D magnets and may allow lower cost production magnets.

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

Common Coil Design

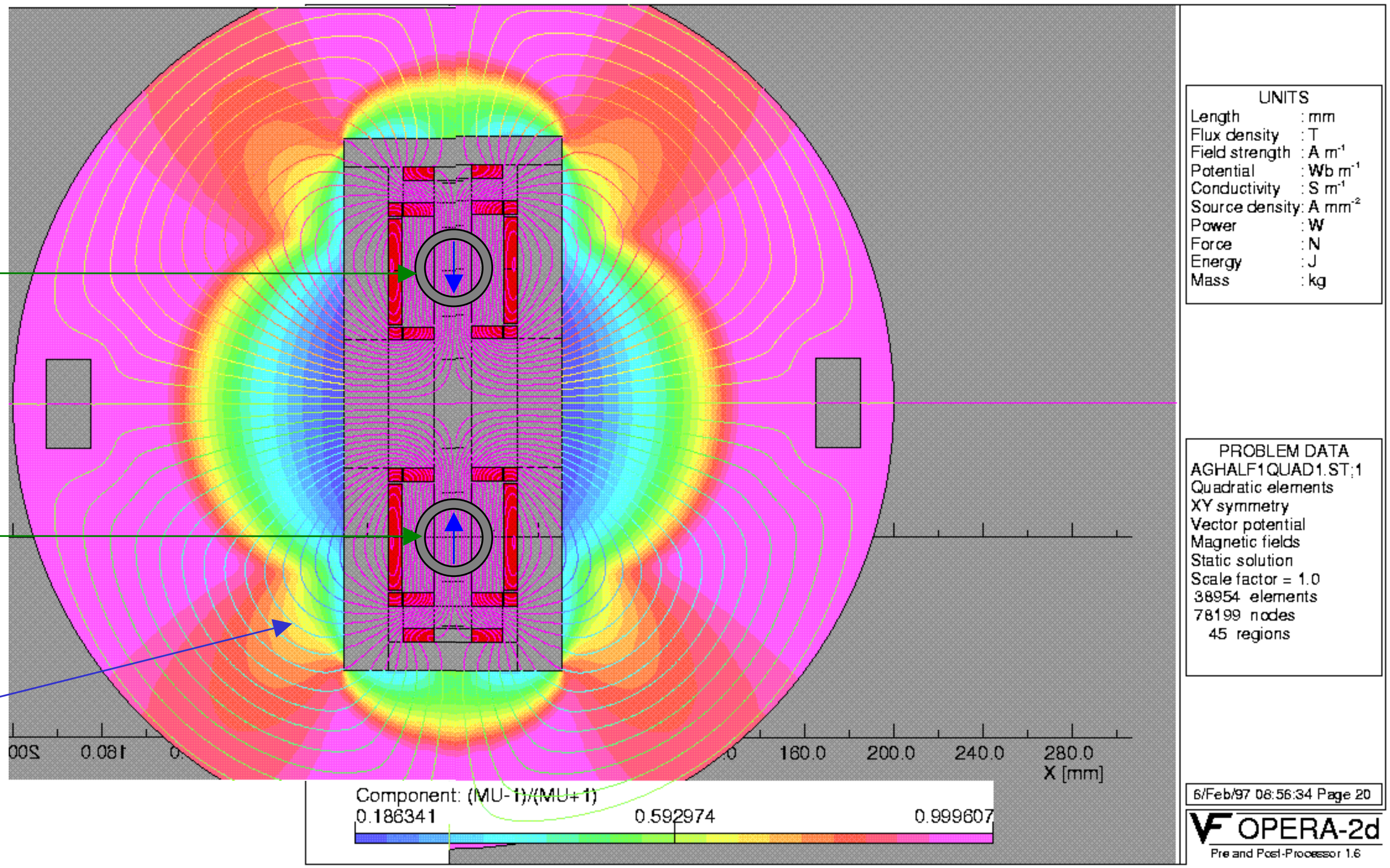


- **Simple 2-d geometry with large bend radius** (determined by spacing between two apertures, rather than aperture itself)
- **Conductor friendly (no complex 3-d ends, suitable for brittle materials such as Nb_3Sn, Nb_3Al and HTS)**
- **Compact (quadrupole type cross-section, field falls more rapidly)**
- **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

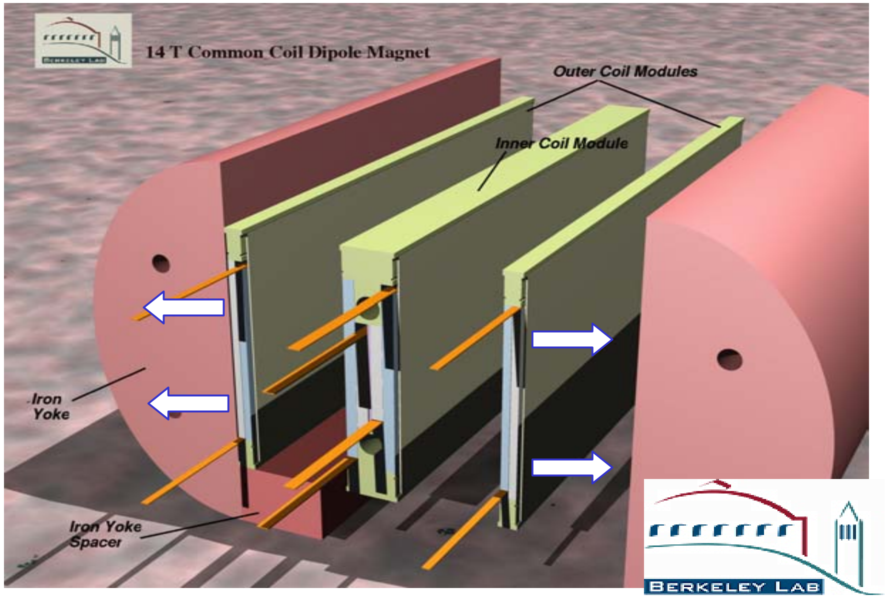


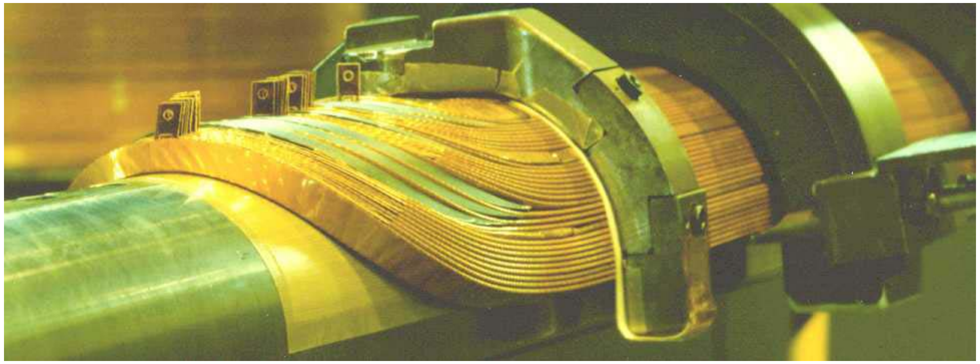
Aperture #1

Aperture #2

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

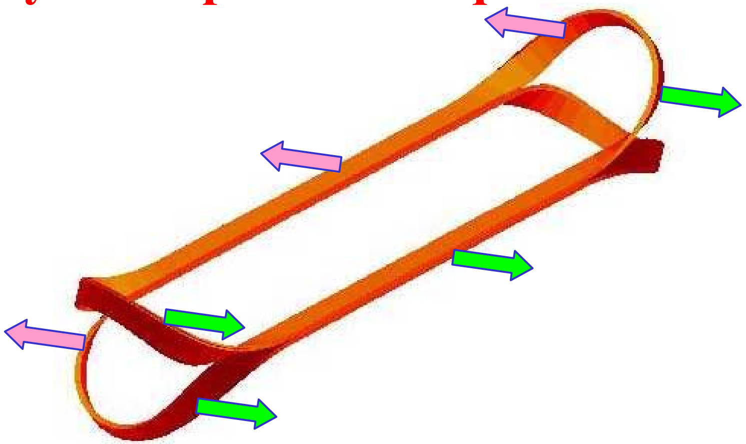
Lorentz Forces in High Field Magnets (Cosine Theta and Common Coil)





In cosine theta geometry the two side of the coil cannot move as a block. Therefore, the Lorentz forces put strain on the conductor at the ends and that may cause premature quenches.

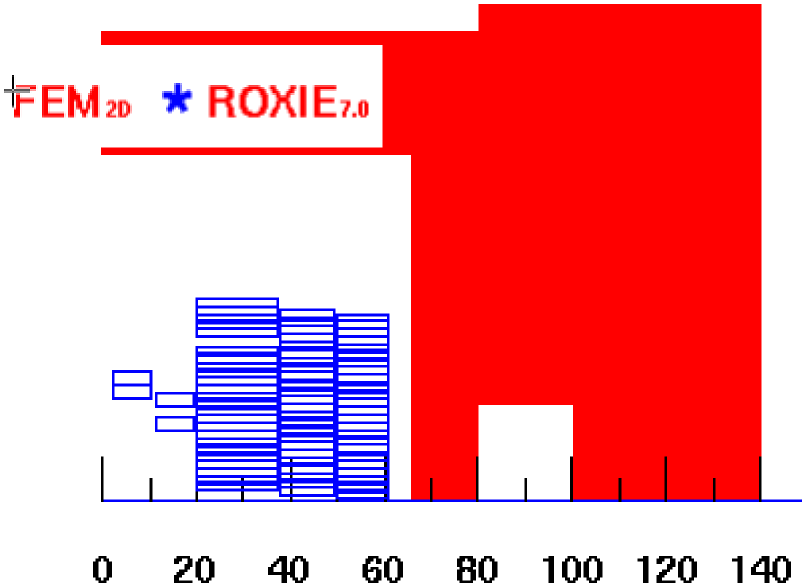
In the common coil design, geometry and Lorentz forces (mostly horizontal) are such that the impregnated modules move as a block. Therefore, the common coil geometry minimizes the internal motion and that should reduce the chance of quench or damage.



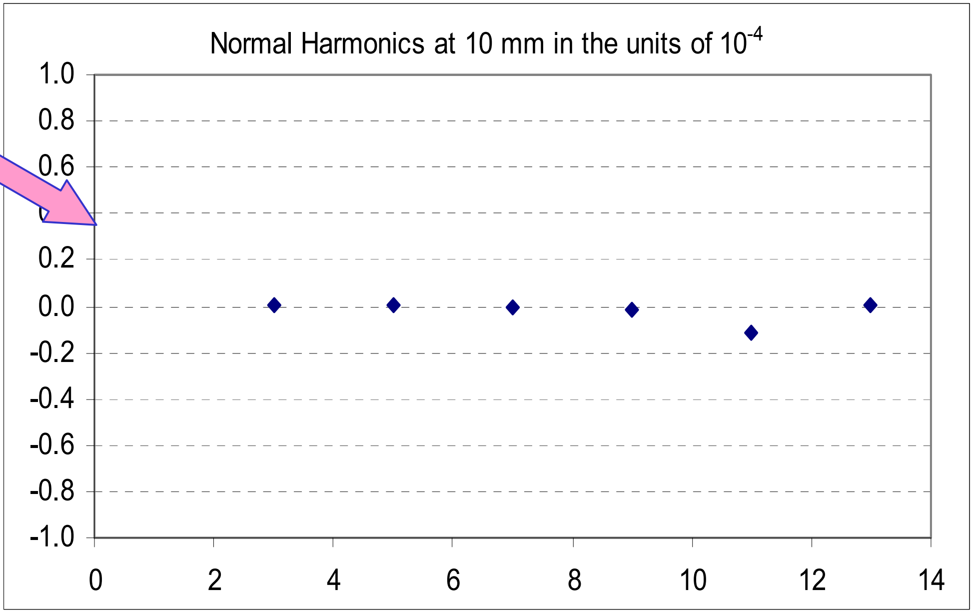
Progress in Field Quality (Geometric Harmonics)

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

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



The above model uses all flat coils.



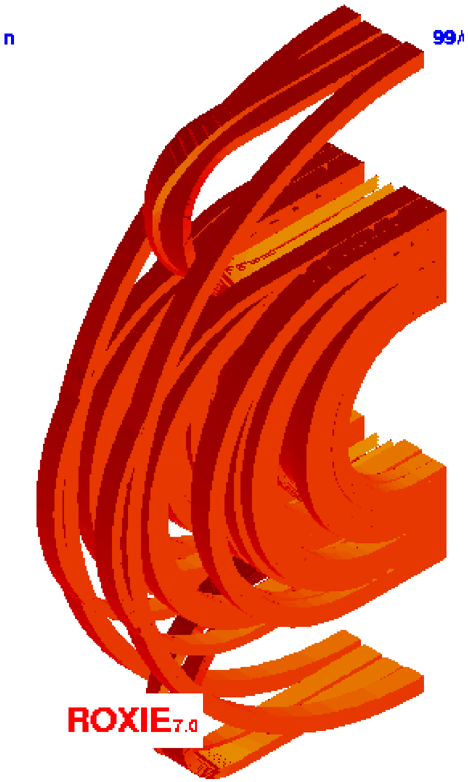
(from 1/4 model)

MAIN FIELD: -1.86463 (IRON AND AIR):

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

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

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

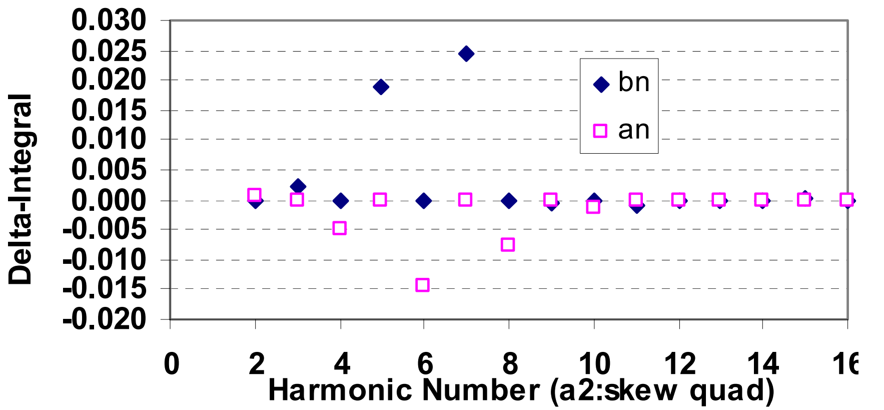


End harmonics in Unit-m

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

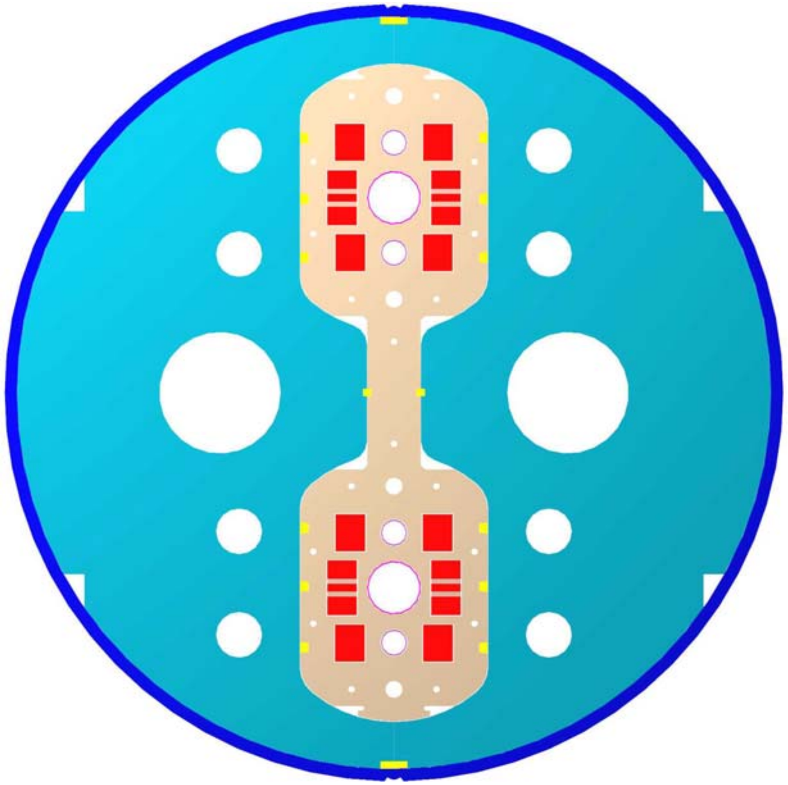
Contribution to integral (a_n,b_n) in a 14 m long dipole ($<10^{-6}$)

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



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

Status of R&D on Common Coil Magnets



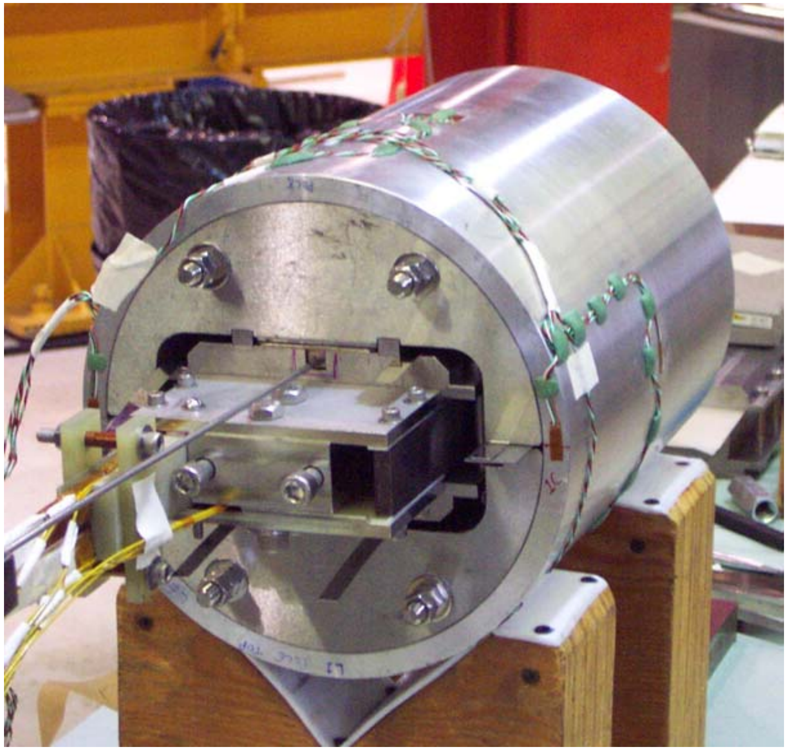
Fermilab Design of Common Coil Magnet for VLHC-2

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

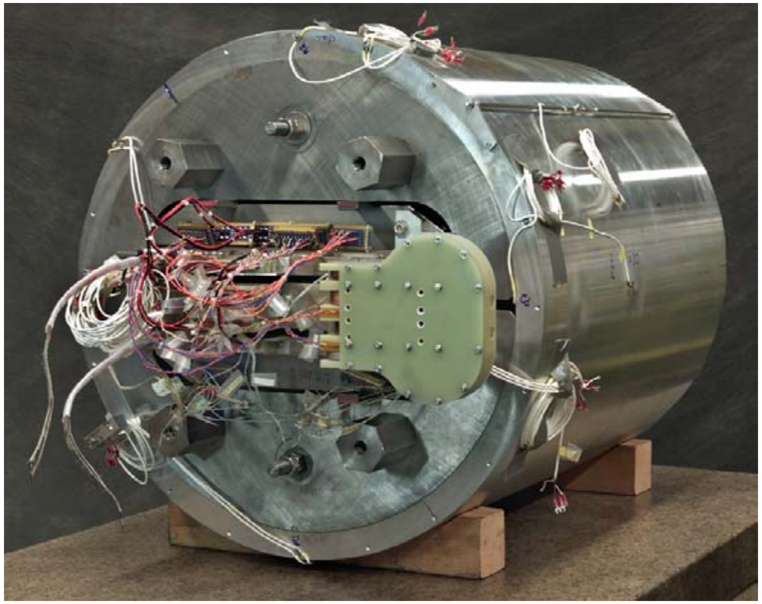
Common Coil Magnets Built at BNL, FNAL, LBNL

BNL

FNAL

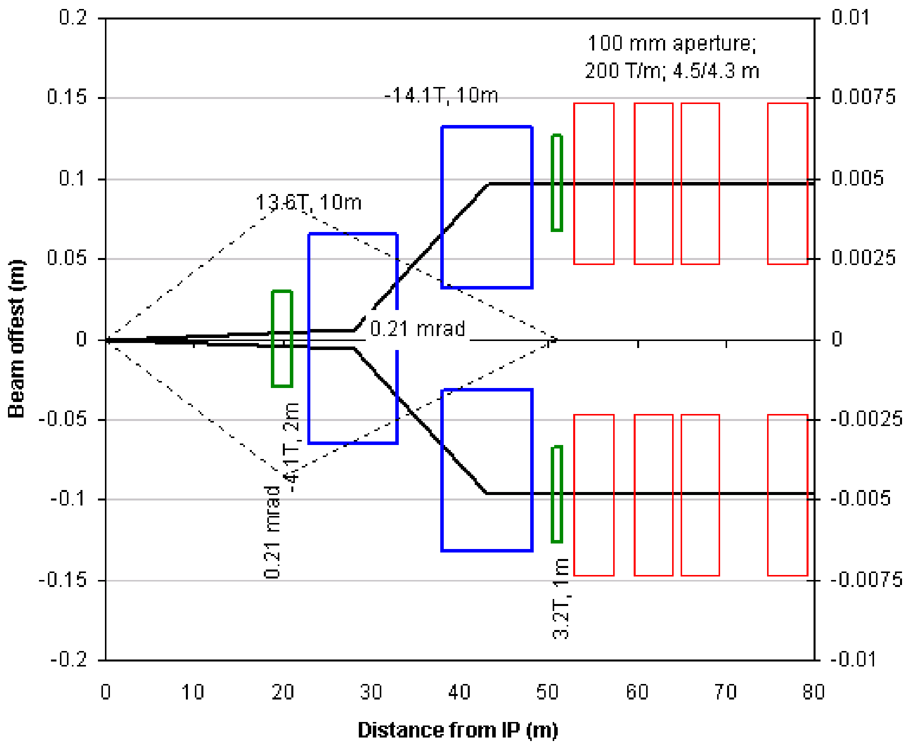


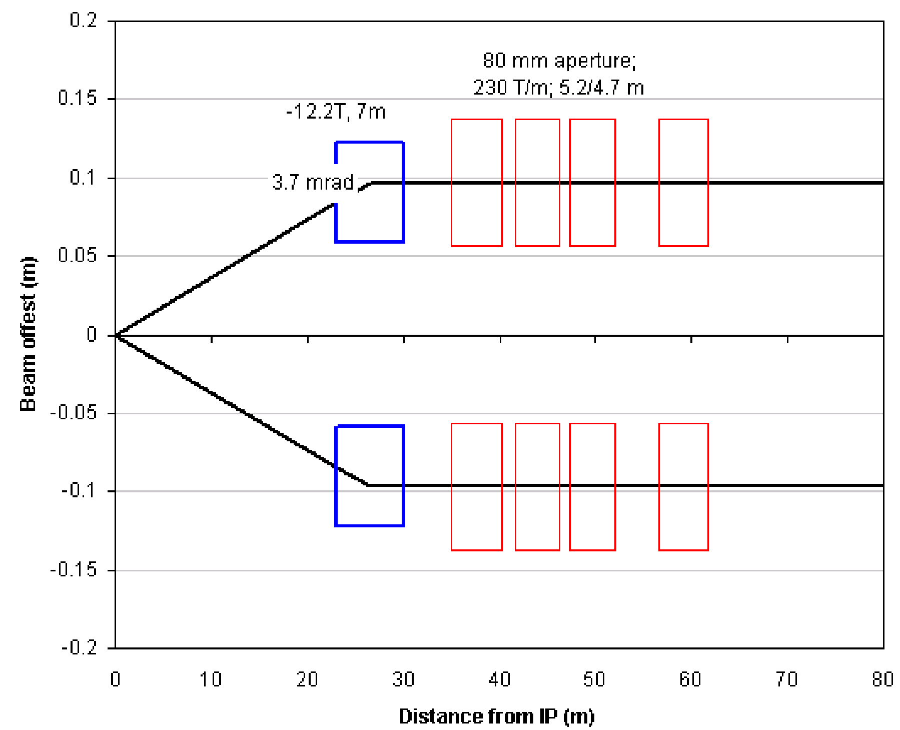
LBNL



Open Midplane Dipole for A Possible LHC IR Upgrade

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





Small crossing angle

Large crossing angle

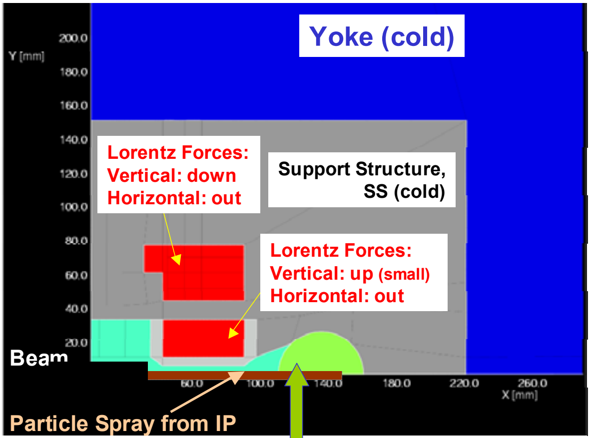
Courtesy: Jim Strait

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

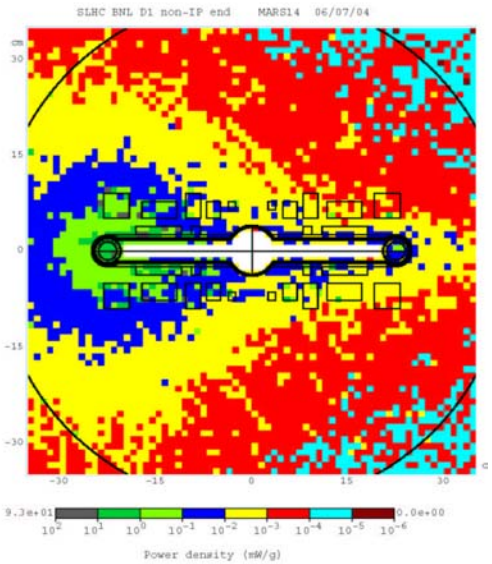
High luminosity (10^{35}) Interaction Regions (IR) present a hostile environment for superconducting magnets by throwing ~9 kW of power from each beam

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

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

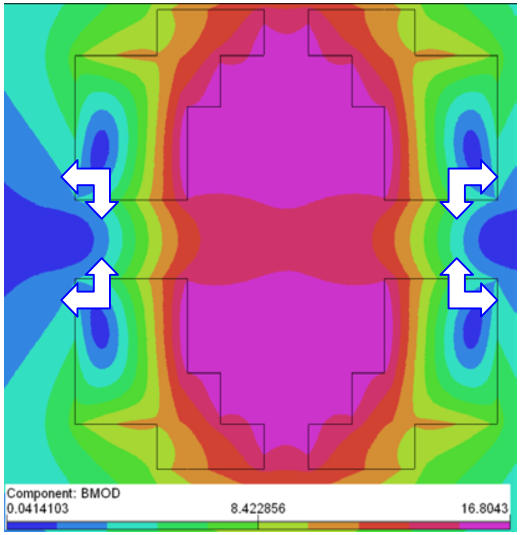


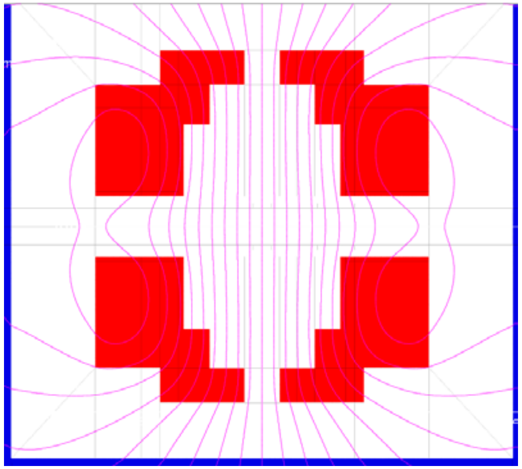
A large amount of particles coming from high luminosity IP deposit energy in a warm (or 80 K) absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.



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

Open Midplane Dipole Design
Challenges

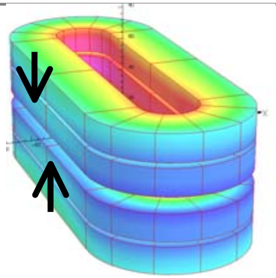




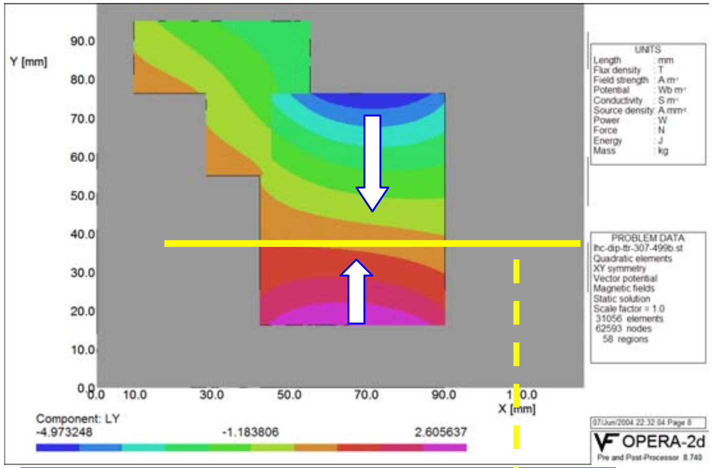
- Attractive vertical forces between upper and lower coils are large than in any high field magnet. Moreover, in conventional designs they react against each other. Containing these forces in a magnet with no structure between the upper and lower coils appears to be a big challenge.
- The large gap at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

Navigation of Lorentz Forces
A new and major consideration in design optimization

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



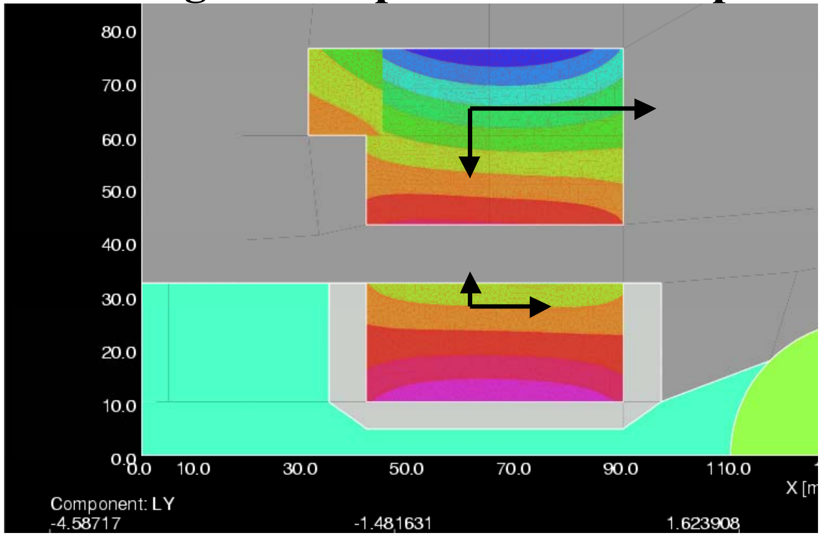
Original Design



Zero vertical force line

Lorentz force density (Vertical)

New Design Concept to reduce midplane gap



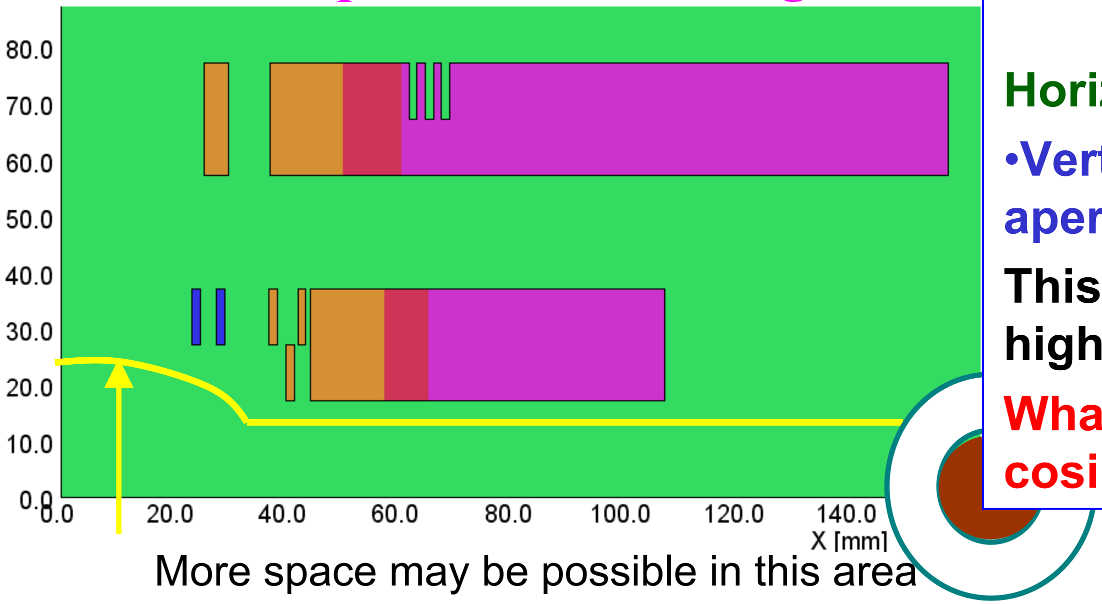
Since there is no downward force on the lower block (there is slight upward force), we do not need much support below it, if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

Magnetic Design and Field Quality

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

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

One quadrant of the design



More space may be possible in this area

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

Horizontal aperture = 80 mm

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

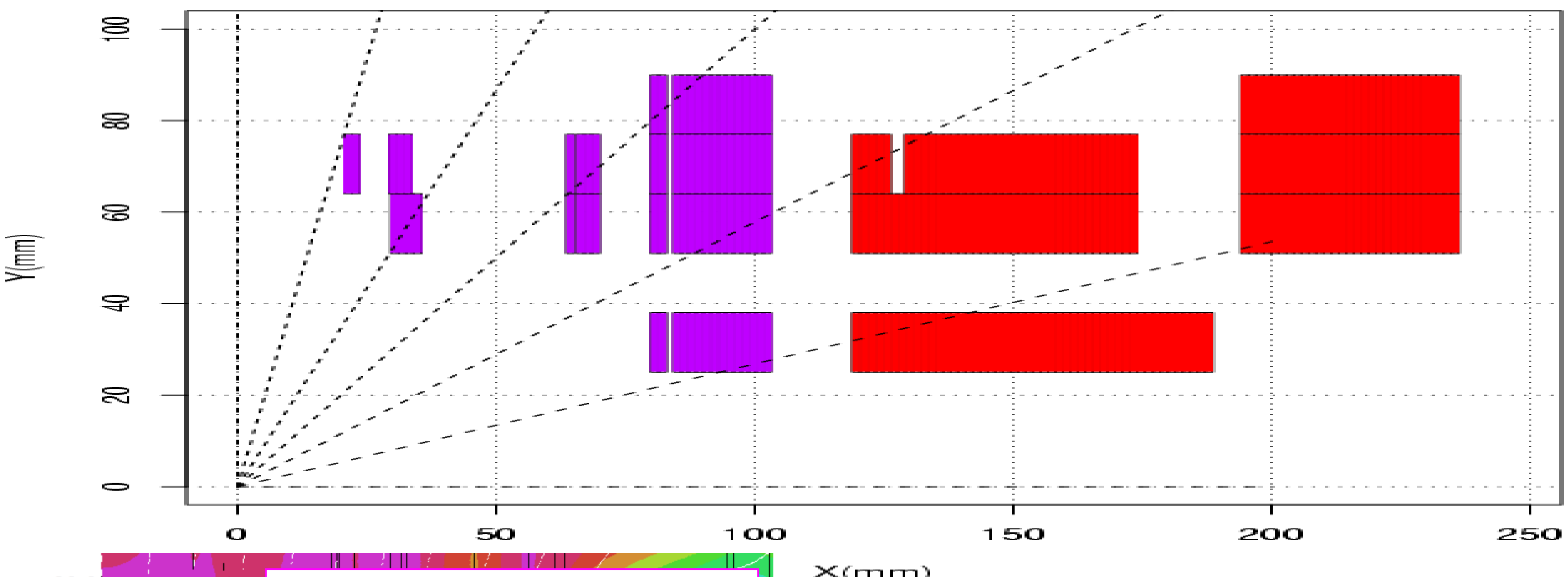
This makes obtaining high field and high field quality a challenging task !

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

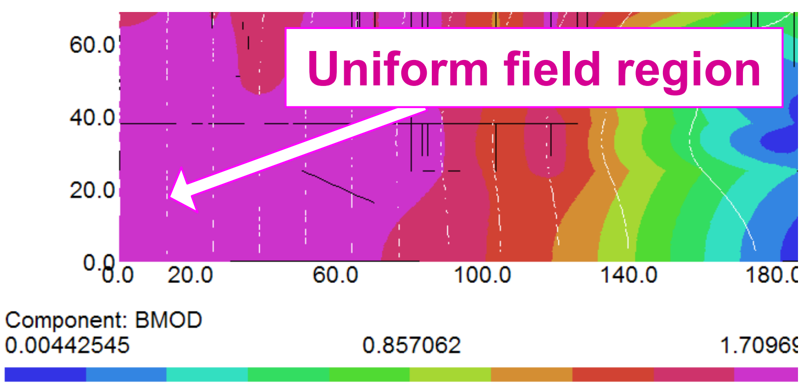
Hand Optimized Design =>
Fine-tuned by RACE2DOPT for Harmonic Minimization

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

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



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



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

➤ Does it look like simulating cosine theta any more?

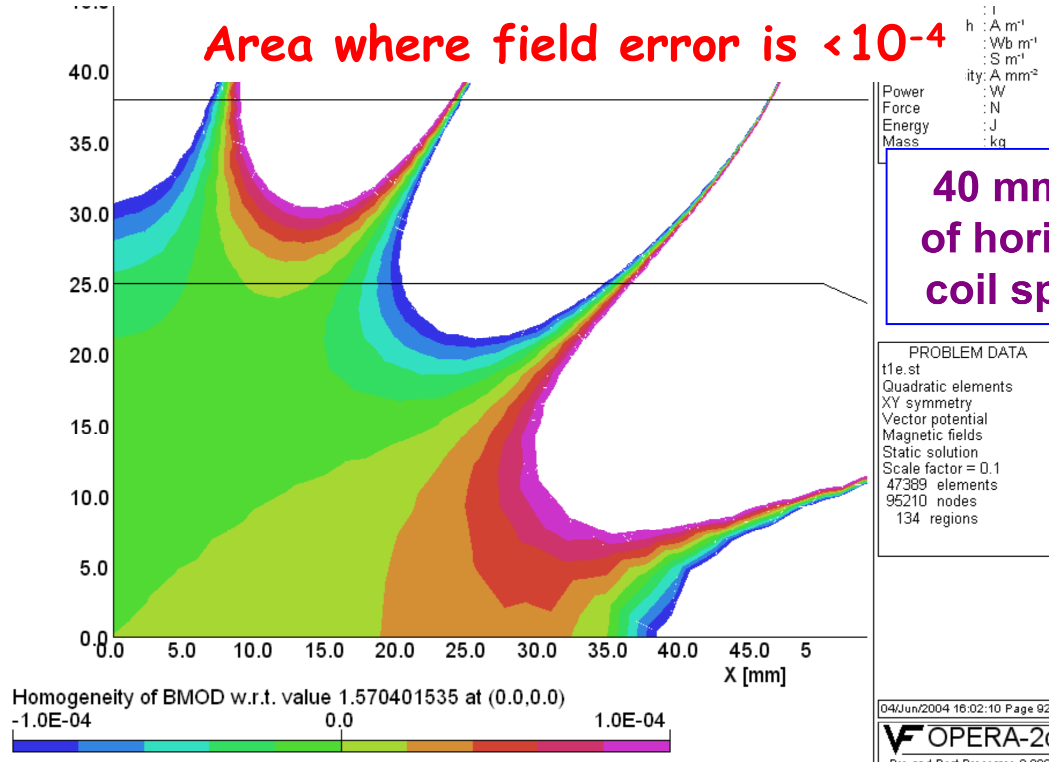
Field Harmonics and Relative Field Errors In An Optimized Design

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

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

Geometric Field Harmonics:

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

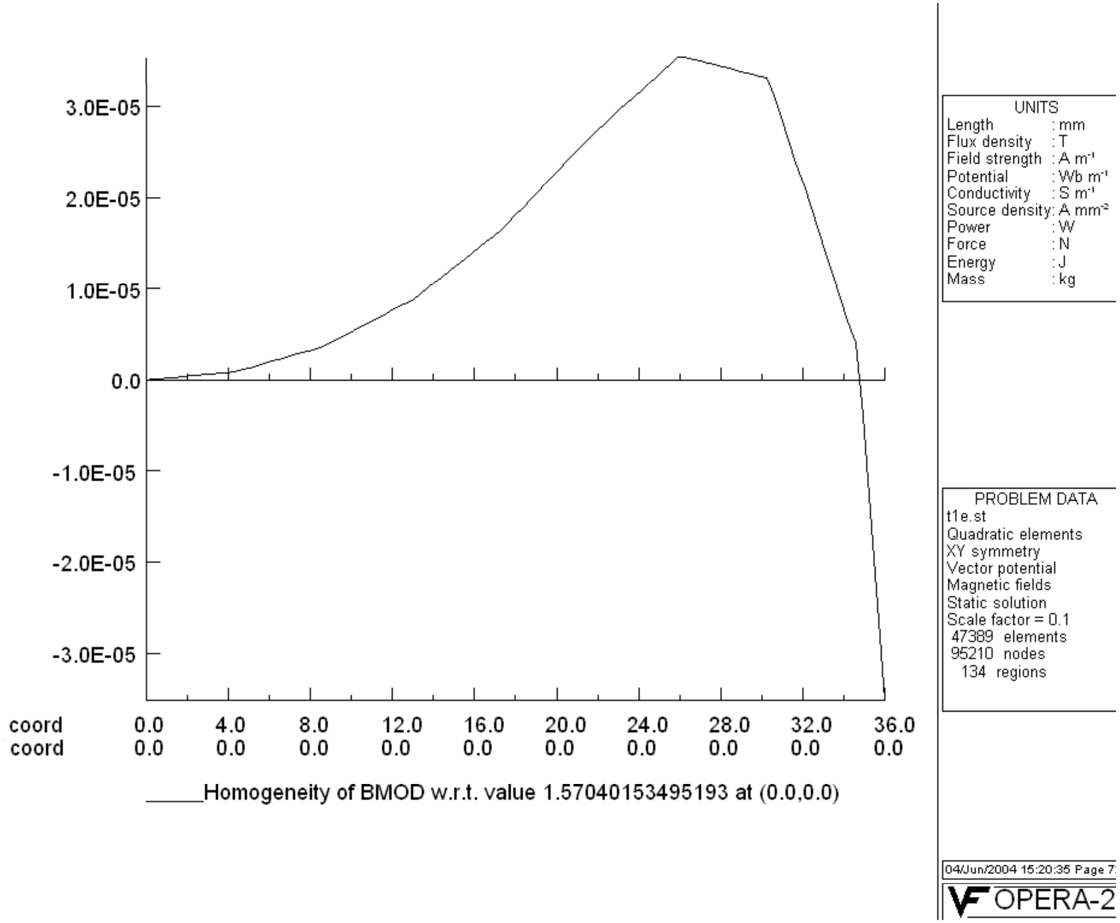


40 mm is ½ of horizontal coil spacing

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

Field Uniformity in An Optimized 15 T Open Midplane Dipole Design

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

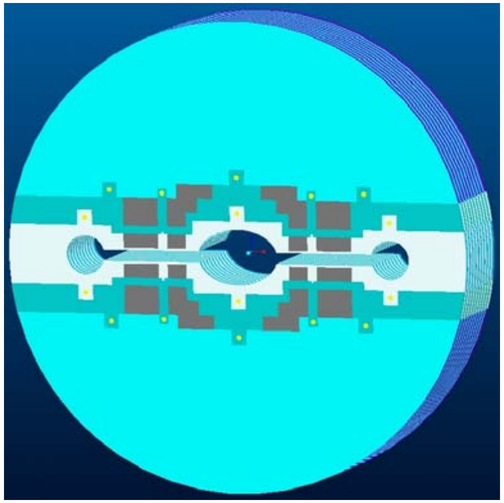


The maximum horizontal displacement of the beam at the far end of IP is +/- 36 mm.

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

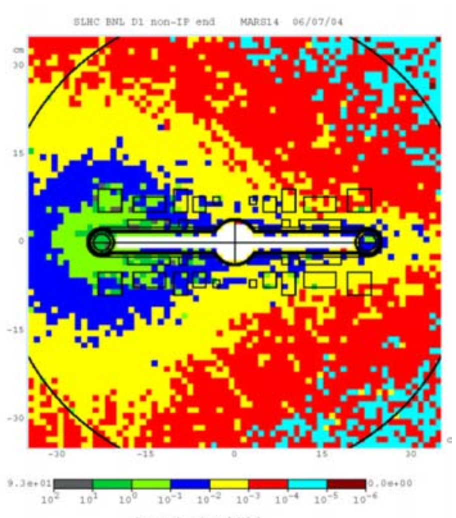
A True Open Midplane Design

By open midplane, we mean truly open midplane:



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

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



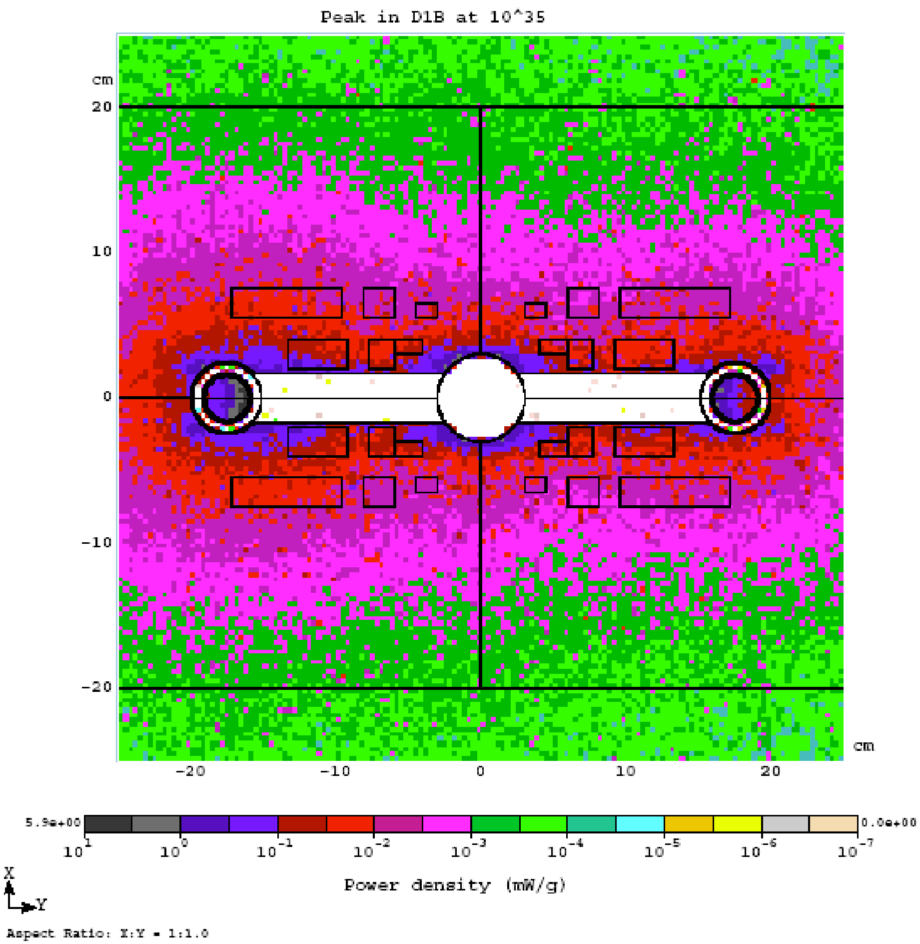
The energy deposited on the superconducting coils by this secondary shower became a serious problem. Therefore, earlier open midplane designs were not that attractive.

BROOKHAVEN NATIONAL LABORATORY

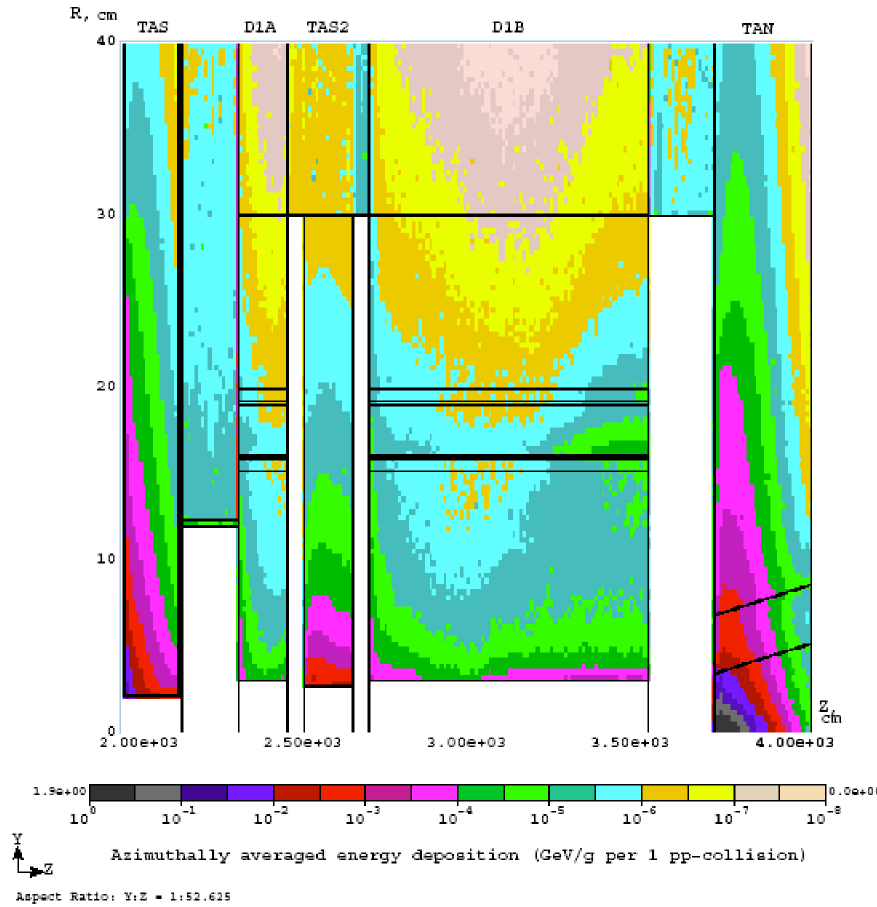
Superconducting Magnet Division

Energy Deposition in Open Midplane Dipole in Dipole First Optics

Courtesy: Nikolai Mokhov, FNAL



Power density isocontours at the non-IP end of the D1B.



Azimuthally averaged energy deposition iso-contours in the dipole-first IR.

Energy Deposition Summary (Nikolai Mokhov 04/05)

SUMMARY

- The open midplane dipole is very attractive option for the LARP dipole-first IR at $\mathcal{L} = 10^{35}$. The design accommodates large vertical forces, has desired field quality of 10^{-4} along the beam path and is technology independent.
- After several iterations with the BNL group over last two years, we have arrived at the design that – being more compact than original designs – satisfies magnetic field, mechanical and energy deposition constraints.
- We propose to split the dipole in two pieces, 1.5-m D1A and 8.5-m D1B, with a 1.5-m long TAS2 absorber in between.
- With such a design, peak power density in SC coils is below the quench limit with a safety margin, heat load to D1 is drastically reduced, and other radiation issues are mitigated. This is a natural two-stage way for the dipole design and manufacturing.

Fermilab

N. Mokhov

Summary of Design Iterations (A to F)

	A	B	C	D	E	F
H(mm)	84	135	160	120	80	120
V(mm)	33	20	50	30	34	40
V/H	0.39	0.15	0.31	0.25	0.43	0.33
B_o(T)	13.6	13.6	13.6	13.6	15	13.6
B_{ss}(T)	15	15	15	14.5	16	15
J_c(A/mm^2)	2500	3000	3000	3000	3000	3000
Cu/Sc	1	1,1.8	0.85	0.85	0.85	1
A(cm^2)	161	198	215	148	151	125
R_i(mm)	135	400	400	320	300	300
R_o(mm)	470	800	1000	700	700	700
E(MJ/m)	2.2	4.8	9.2	5.2	4.1	4.8
F_x(MN/m)	9.6	10.1	12.3	9.5	10.4	9.6
F_y(MN/m)	-3.0	-6.8	-8.7	-7.0	-5.1	-5.4

Modular Quadrupole Design for A Possible LHC IR Upgrade

Basic Considerations

Primary goal (or motivation):

Develop a racetrack quadrupole design that can generate a field gradient comparable to that created by cosine theta designs

Constraints:

For a few key IR magnets, the design should be efficient in creating field gradient; it need not be efficient in minimizing the conductor usages.

Advantages:

During the reaction process in long magnets, simple flat racetrack coils are less prone to damage or degradation in critical ends and transition regions.

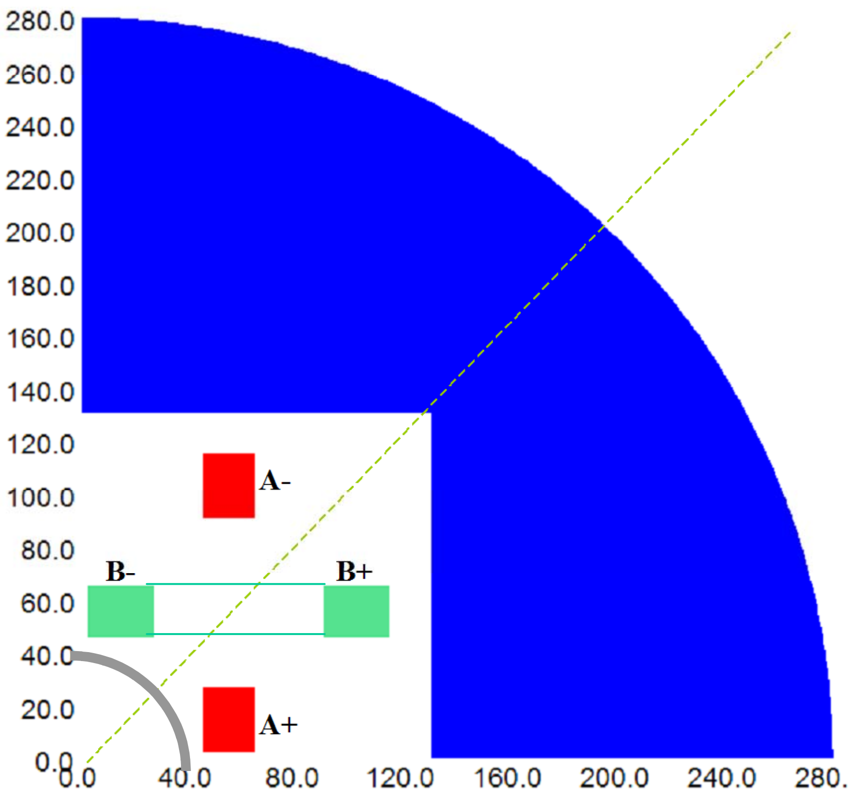
Racetrack coils (and associated tooling) are faster and more economical to build. It allows a modular design and modular R&D program.

Can make program flexible and versatile. One can use the same coils for varying quad aperture or even magnet type (quad or dipole) during the R&D phase.

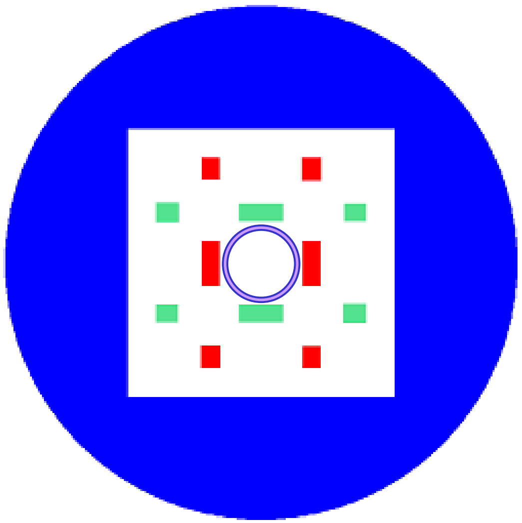
Modular Design for LARP Quadrupole

Cross-section of a Quadrant - made of 2 coils

(ideal eight fold quad symmetry - mirror symmetry at 45^o)

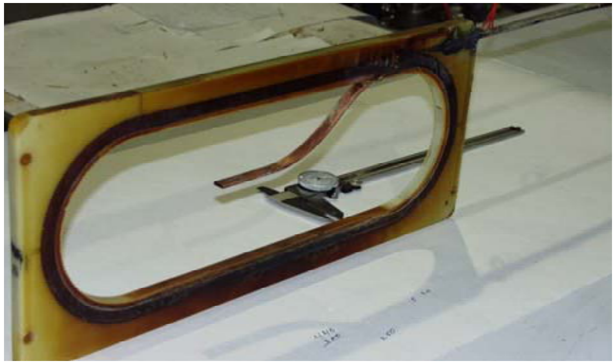


Full Model



Quadrupole with all 8 coils

In this design, horizontal (or vertical) coils must interleave in to other.



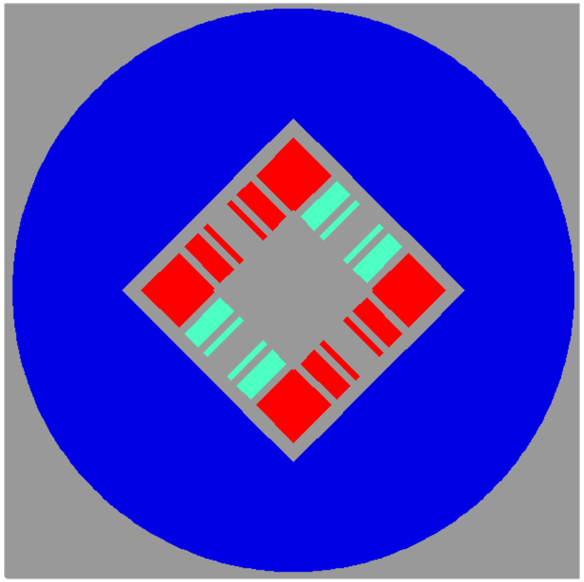
A bobbin-less coil

Most field comes from A+ (return A-) and B-(return B+).
B+ and A- make positive but only a small contribution.

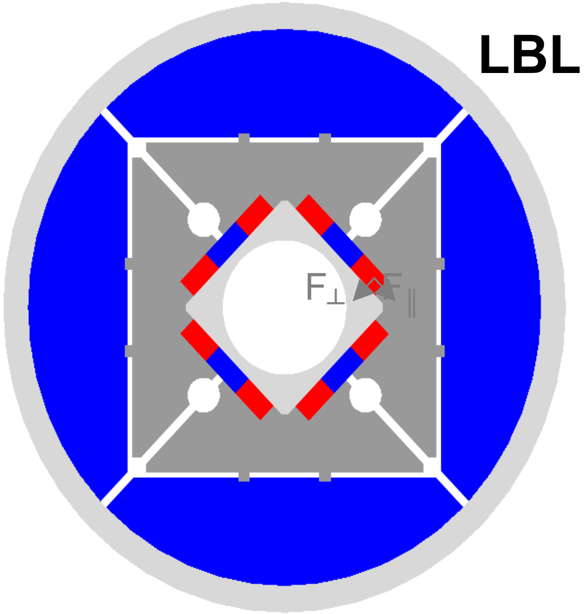
NOTE: The design needs about twice the conductor!

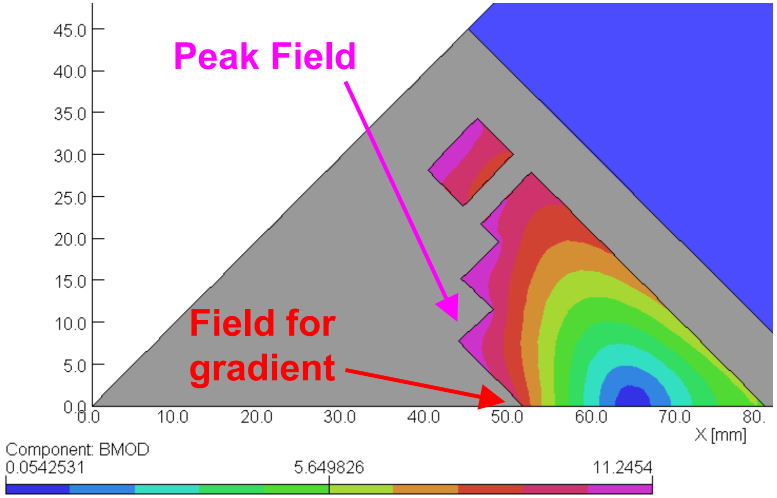
Previous Racetrack Designs
(Considered for LHC upgrade or VLHC)

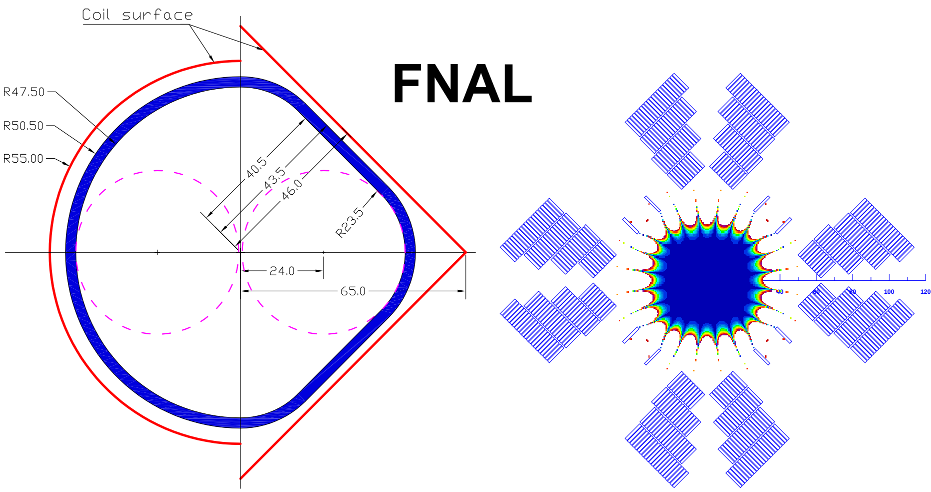
BNL designs for VLHC (ASC'02)



None of these designs were efficient in generating high gradient



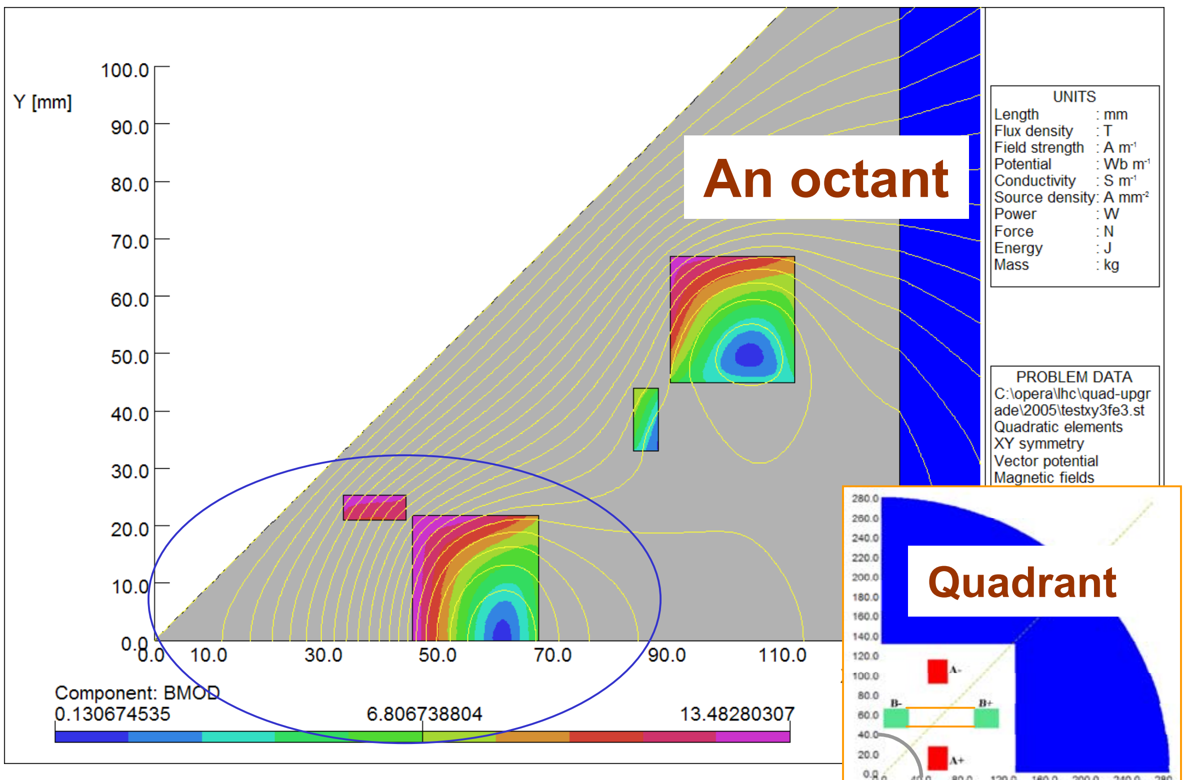




Efficient Design to Create Gradient
(not necessarily to minimize conductor usage)

- **The key is to have conductor at or near the midplane (@ quad radius).**

Quadrupole is different from dipole. Gradient implies increasing field on coil as one moves outward within the aperture. We loose substantially if conductor at midplane does not determine the field gradient.



OPERA2d model of the octant of a 2 layer, 90 mm aperture LARP "Modular Quadrupole Design".

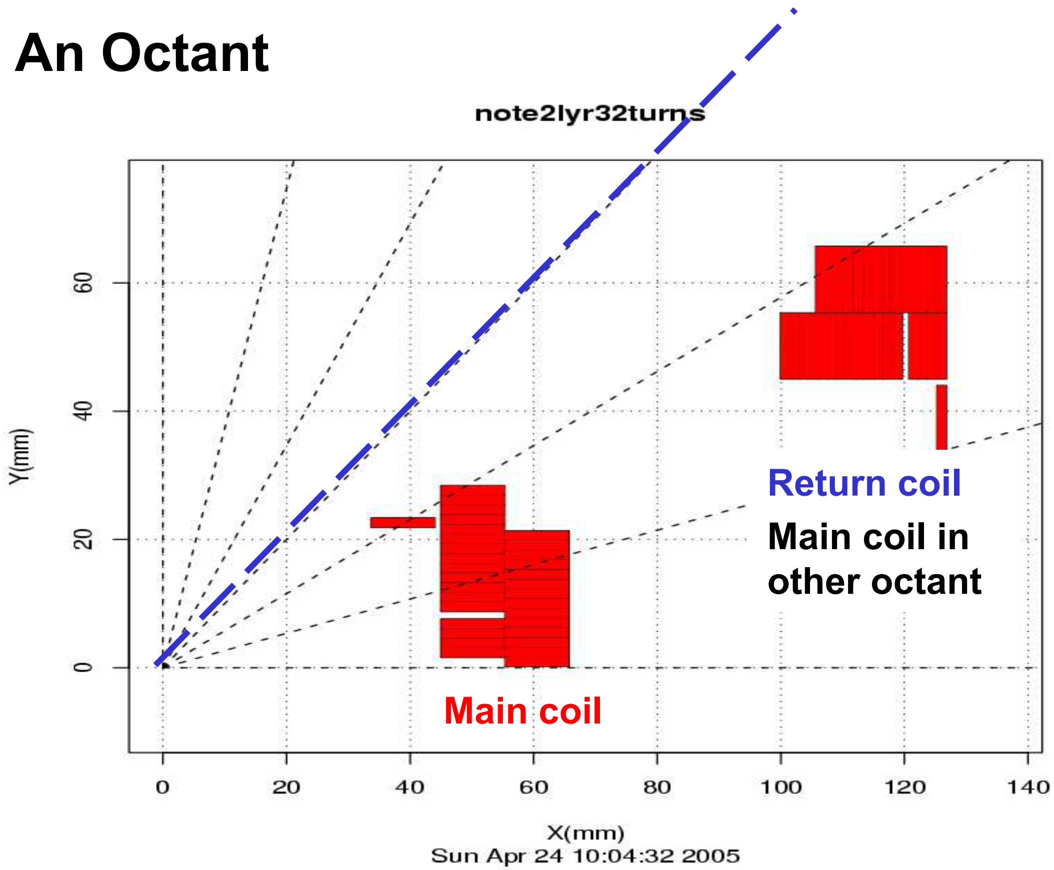
J_e = 1000 A/mm^2 generates a gradient of ~284 T/m.

Quench gradient ~258 T/m for J_c = 3000 A/mm^2 (4.2K, 12T).

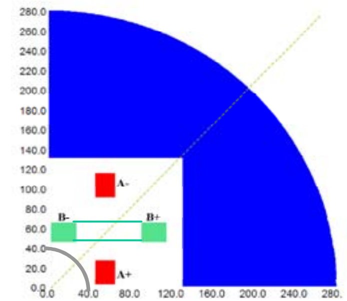
This is similar to what is obtained in competing cosine theta designs.

2-d Magnetic Design

An Octant



90 mm aperture LARP quadrupole design optimized for field quality with RACE2DOPT (Thank you Pat Thompson for this program).



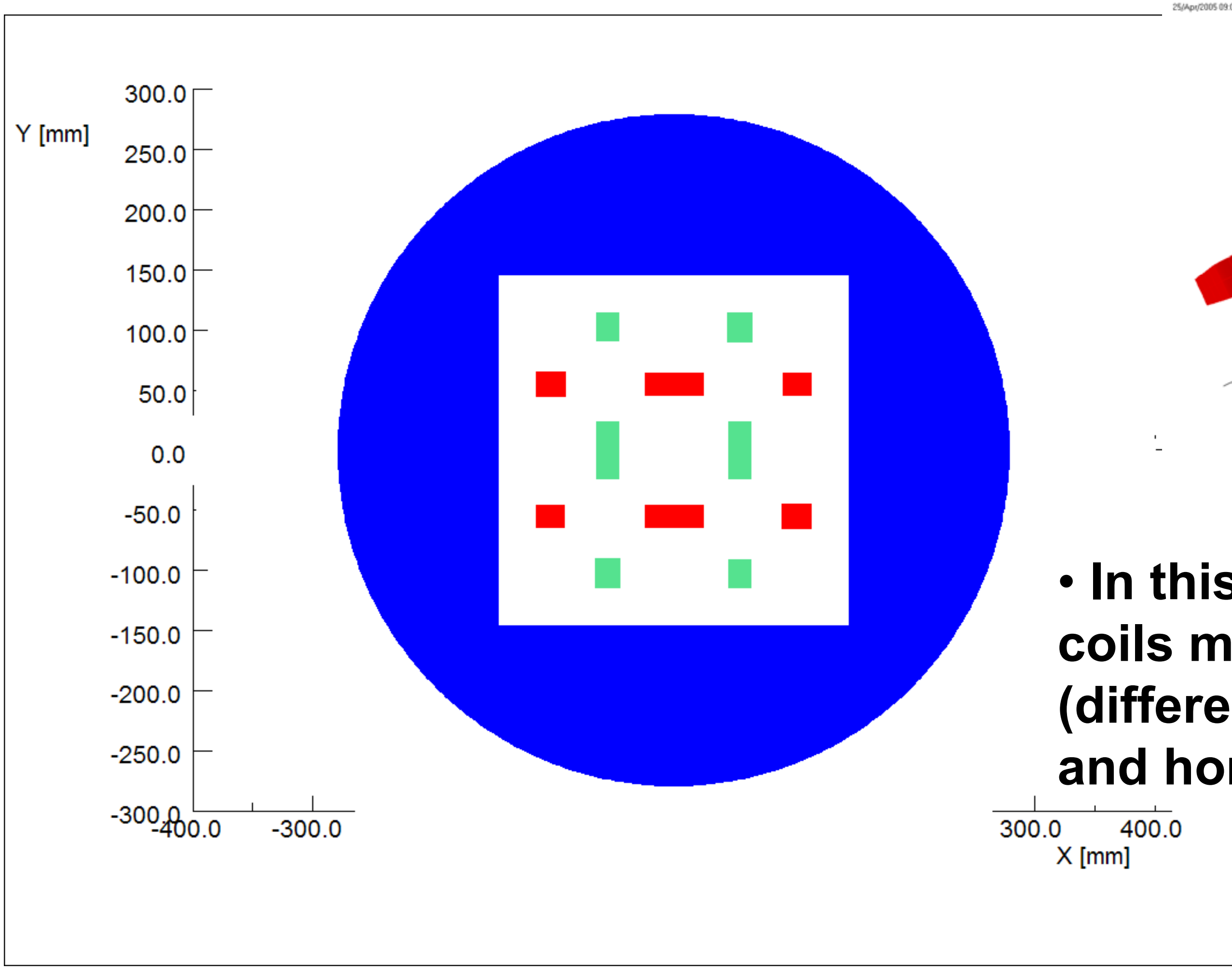
Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius).

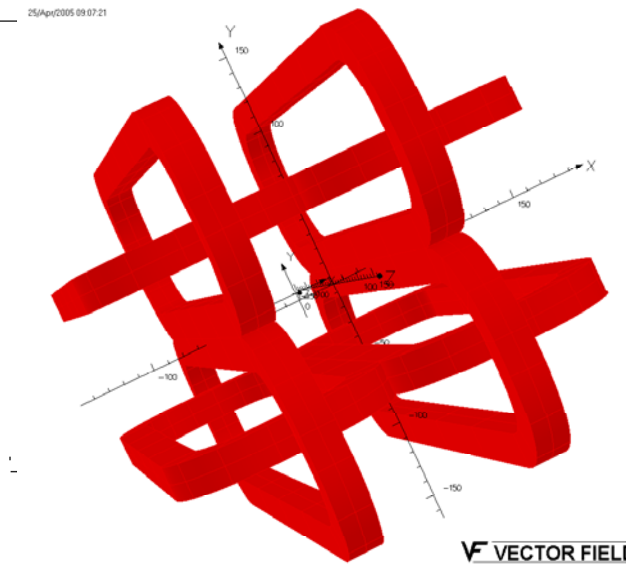
Harmonic	Value
b_6	0.005
b_{10}	-0.004
b_{14}	0.003
b_{18}	0.000

NOTE: The 2-d harmonics are essentially zero (within construction errors)

A Complication in the Design Just Presented

Symmetric Design

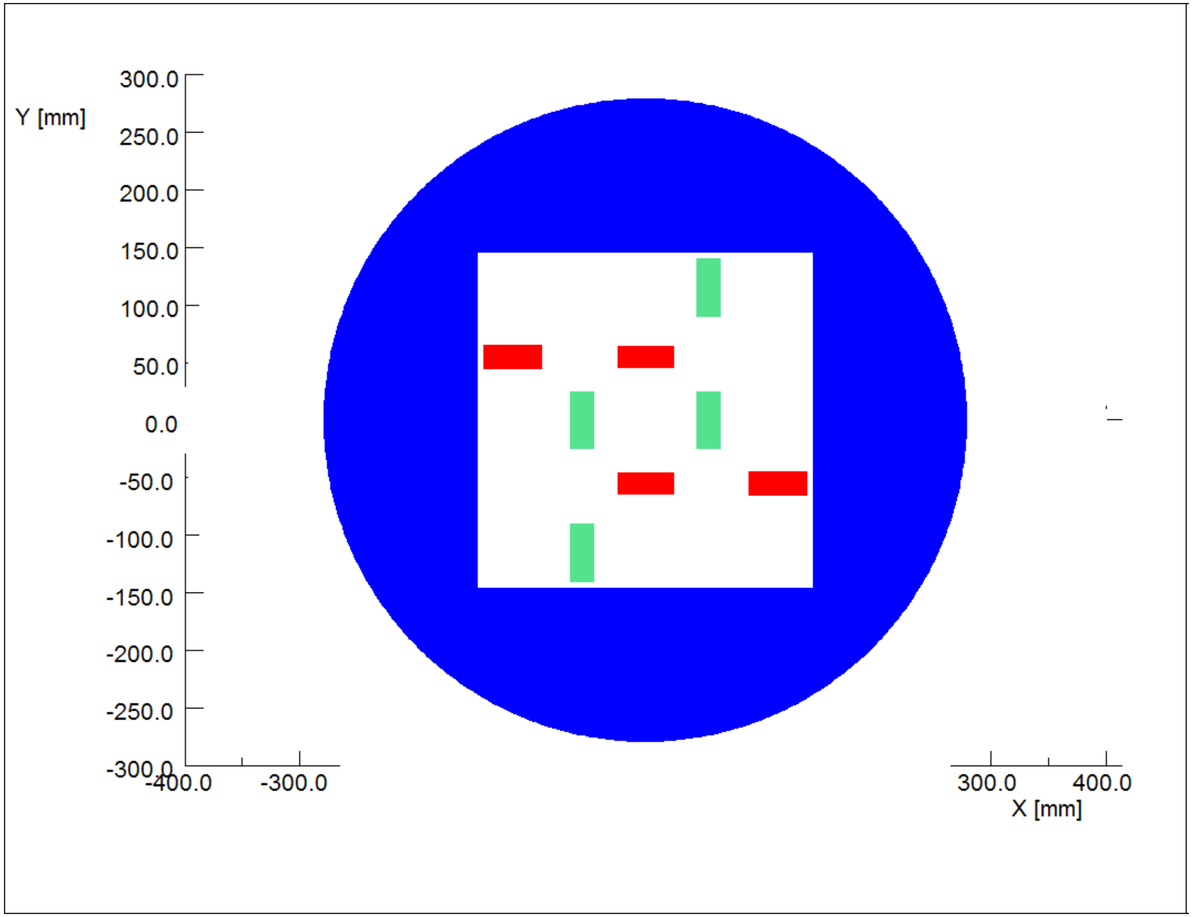




- In this particular version, coils must interleave (different lengths for vertical and horizontal coils)

A Simpler Modular Design

The design does not have mirror symmetry in each quadrant but 4-fold quadrupole symmetry is still present !



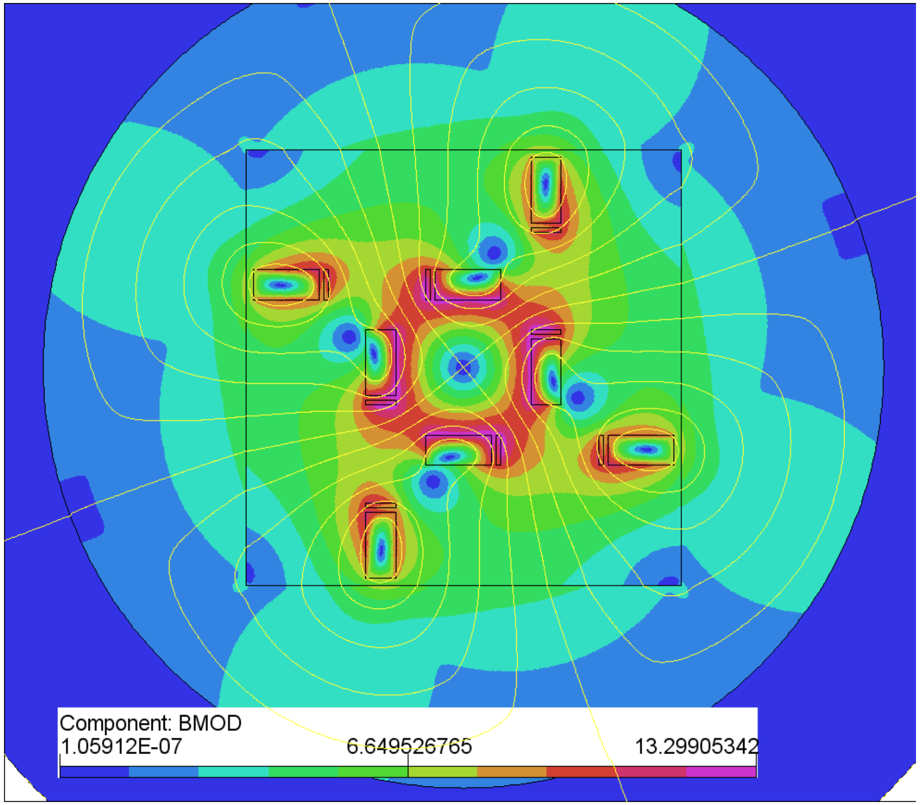
- **No interleaving of coils needed**
- **All coils have the same length**
- **Support structure may be simpler**

But magnetic design becomes more complicated.

In addition to b_6, b_{10}, b_{14} , ... one also gets a_6, a_{10}, a_{14} ,...

Magnetic Modelling

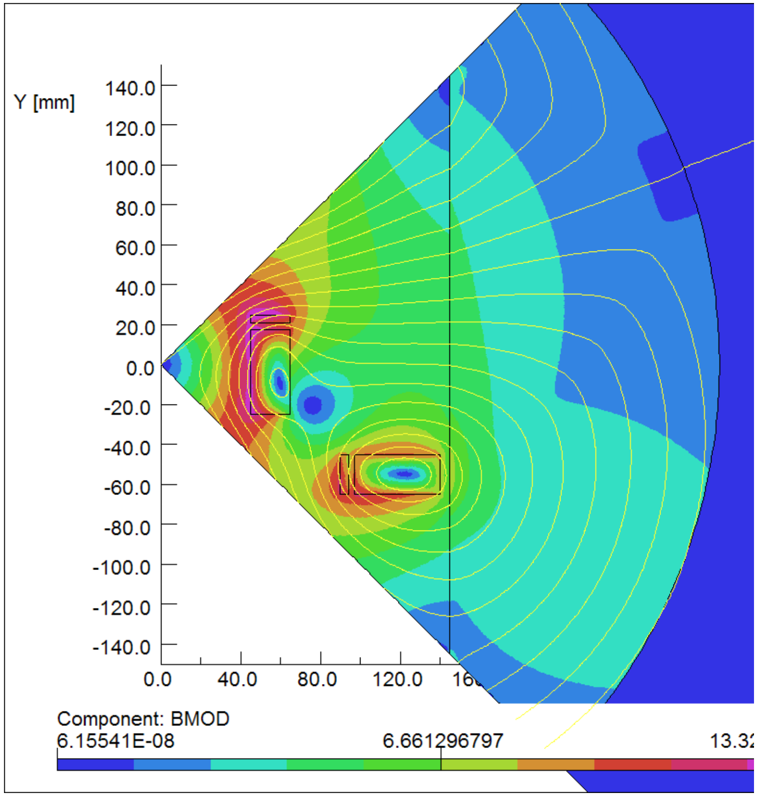
Complete Model



Magnetic Midplane need not be at the conventional location (may need a rotation)

Need only 1/4 model

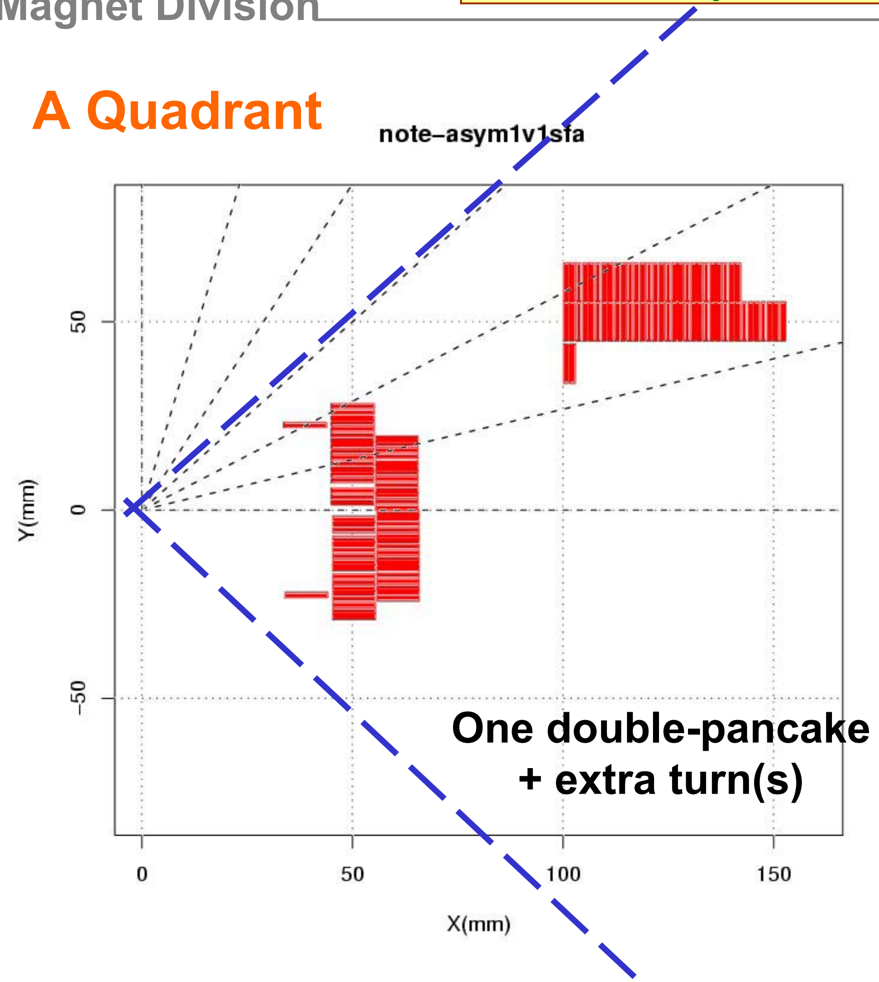
(with proper boundary conditions)



Question: Is it possible to develop a good magnetic design?

2-d Magnetic Design (simpler but asymmetric design)

A Quadrant



Field harmonics optimized with RACE2DOPT at 30 mm reference radius (in 10^{-4} units at 2/3 of coil radius).

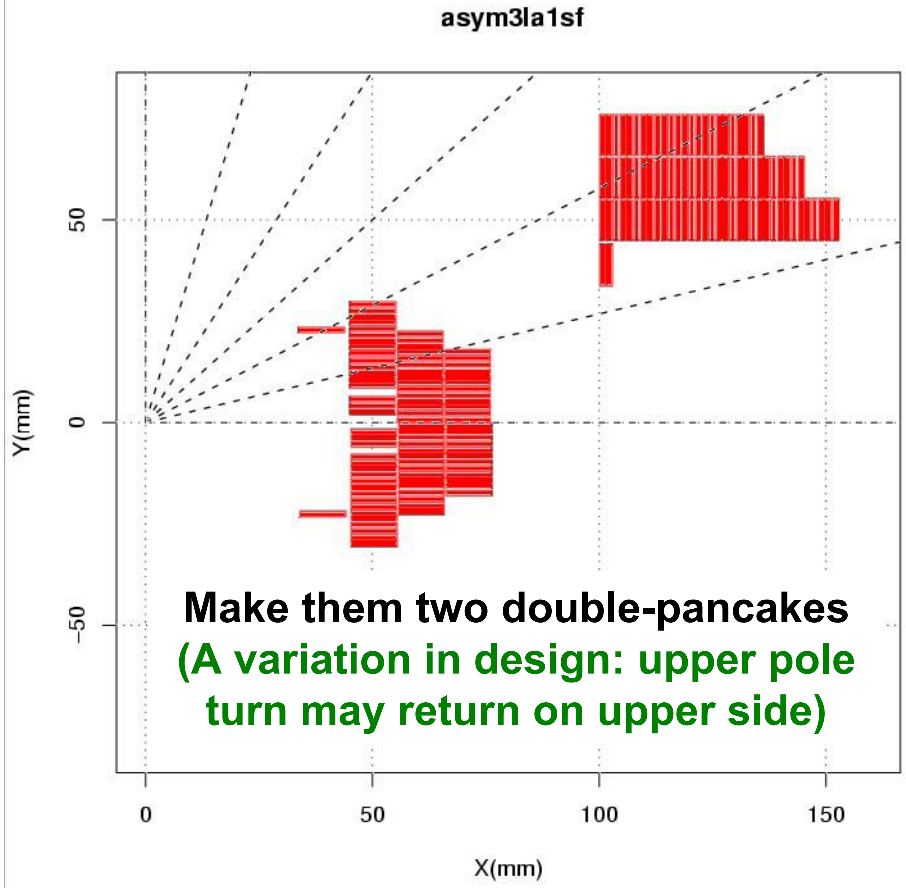
n	a_n	b_n
6	-0.0007	0.0000
10	0.0016	-0.0010
14	-0.0020	-0.0006
18	0.0000	0.0000

Asymmetric 2-layer design. Number of turns, transfer function, etc. are similar to symmetric design.
(Peak field found higher in this particular design)

NOTE: The 2-d harmonics are essentially zero (within construction errors).

3-Layer Design for Higher Gradient

Relative increase in transfer function (in 3 layer design, as compared to in 2 layer) : ~28%



Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius).

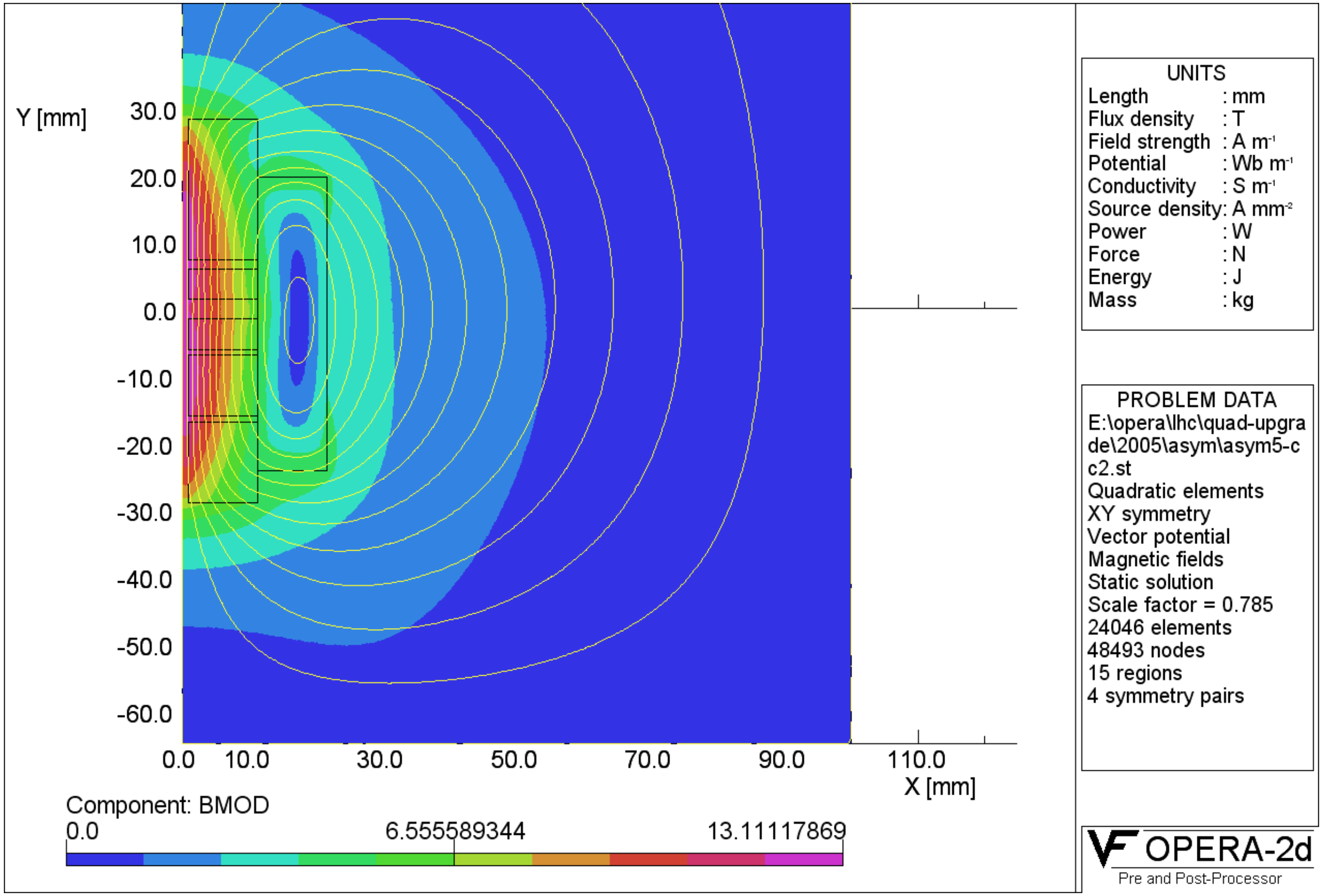
n	a_n	b_n
6	-0.0049	-0.0015
10	0.0006	0.0075
14	0.0018	0.0231
18	0.0000	0.0000

The 2-d harmonics are small

Case Study: Common Coil Dipole Test Scenario of Long Quad Coils

A pair of double pancake coil of LARP quad makes a 13.1 T long dipole.

Note: A long Nb_3Sn R&D dipole program is created out of quadrupole coils with only a modest additional resources.



Benefits of Modular Design

Simple, Fast, Flexible & Cost-effective

- Design is consisted of simple, flat, stackable, racetrack coil modules
  - Positive experience with common coil program
  - Fast and cost effective to start and to carry out systematic R&D
  - Large variations in cable and coil and magnet parameters can be accommodated
- Unique magnet R&D features
  - To increase field gradient add more coil modules
  - Depending on the coil geometry, coils modules can be switched in and out (one may do so based on performance - put better coils in)
  - Allows broad-based magnet R&D as proof-of-principle dipoles can as well be built and tested with these quad coils (small added cost)
- Of course, the support structure needs to be designed properly to accommodate such provisions. One may not be able to design a super structure to do all of above; some intermediate structure on coil(s) plus additional structure enclosing those coils may work better.

More Unique Features

Different Aperture With the Same Coils

One can study different aperture using the same coils in R&D magnets.

Final magnet design will be more optimized for a particular aperture, but this concept offers a cost-effective and fast turn around method to study most technical issues.

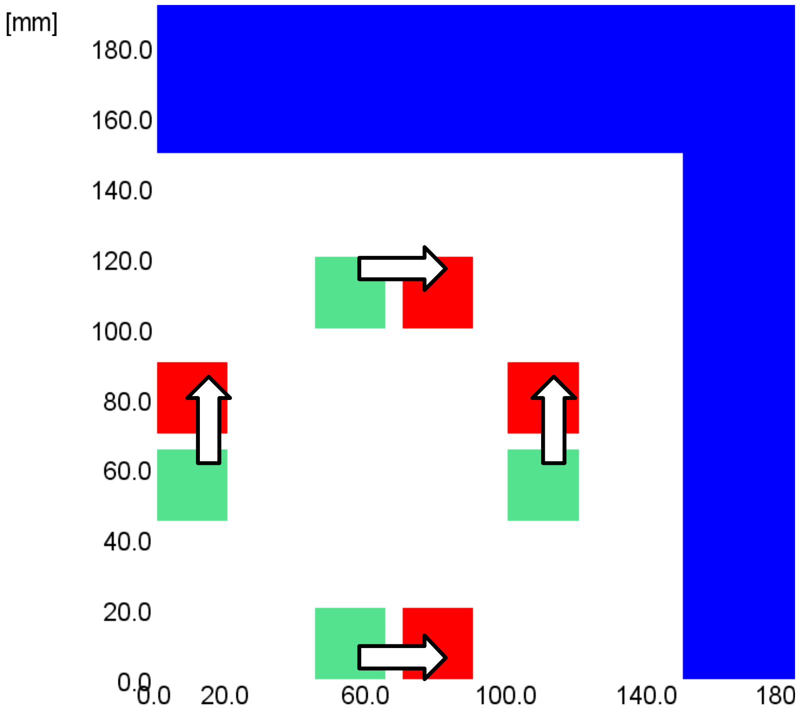
Coils are moved away from the center in going from

green aperture (90 mm)

to red aperture (140 mm).

A flexible and economical design/method to study various aperture and field gradient combinations is useful at this stage, as the magnet parameters can not be fixed yet.

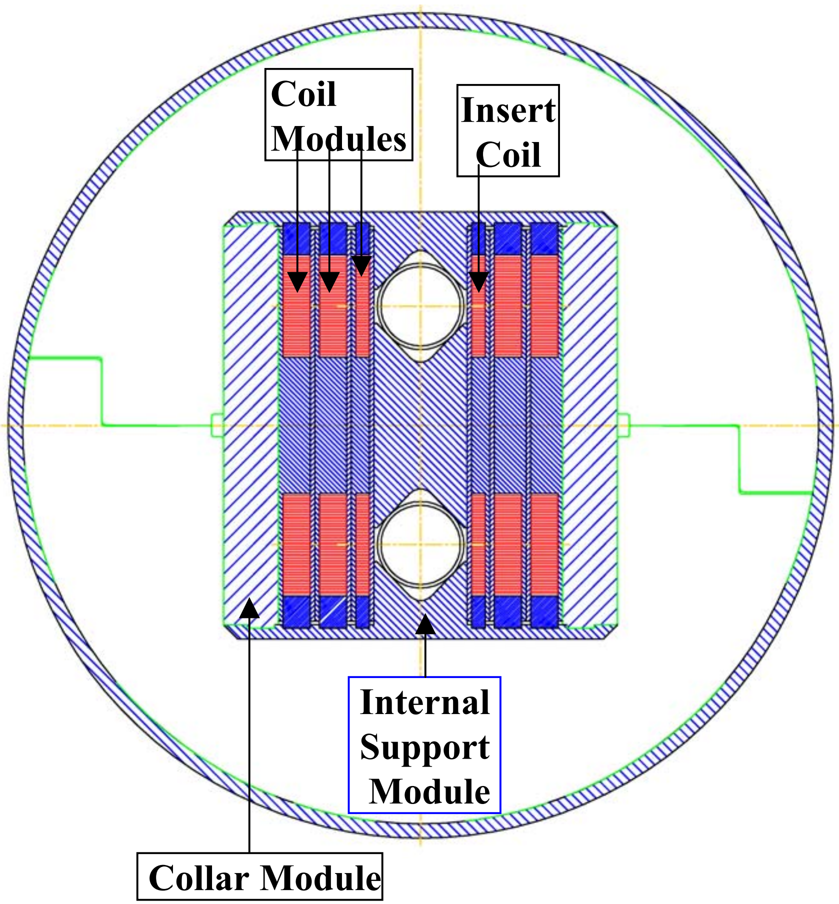
In fact, this feed back should help machine physicist to choose a set of parameters that represents an overall optimum from both magnet and beam optics point of view.



Common Coil Magnet Design for Conductor Test and Magnet R&D

- Simple
- Cost effective
- Rapid turn around
- Flexible

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

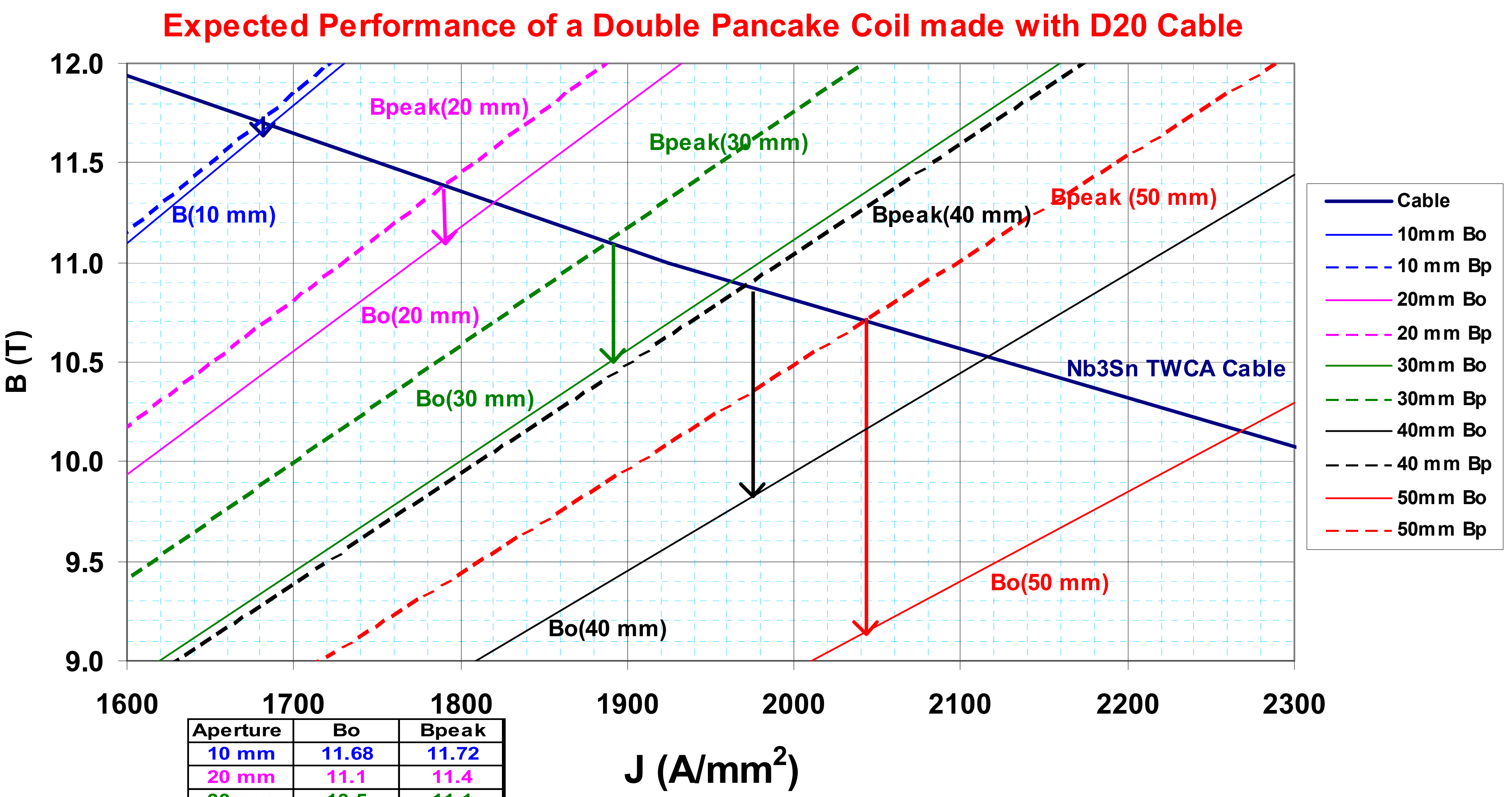


- Replaceable coil modules
- Change cable width or type
- Vary magnet aperture
- Study support structure
- Combined function magnets

- Traditionally such changes required building a new magnet !

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

Change in Aperture for Various Field/Stress Configurations

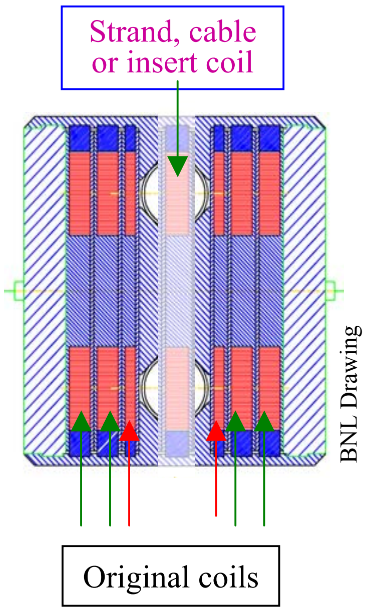


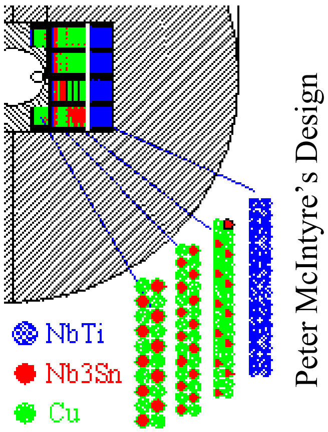
Aperture	Bo	Bpeak
10 mm	11.68	11.72
20 mm	11.1	11.4
30 mm	10.5	11.1
40 mm	9.8	10.9
50 mm	9.1	10.7

A Few Possible Topics for Cable and Magnet Designs

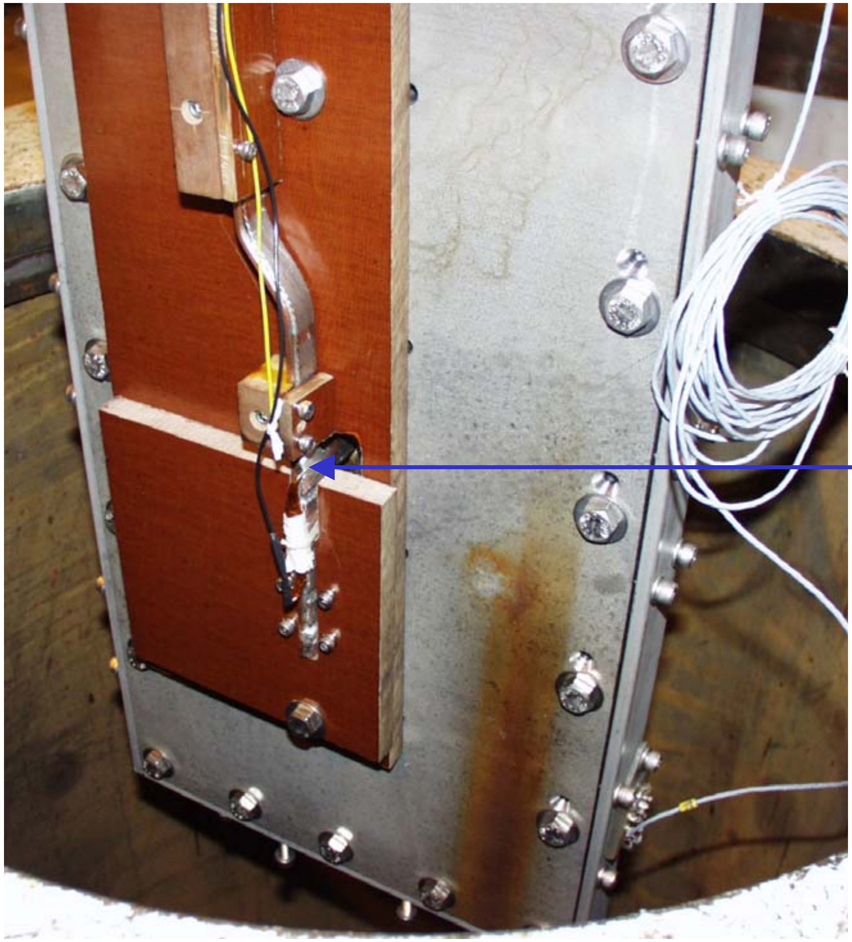
Examples of systematic and non-conventional design studies:

- Variation in cable/conductor configuration
  - Mixing Cu strand with Nb_3Sn superconductor
  - Heat treatment studies
- Different technologies
  - "*Wind & React*" Vs. "*React & Wind*"
- Different type of conductors than Nb_3Sn
  - Nb_3Al, HTS, etc.
- Different type of conductor geometry
  - Tape, cable
- Stress management module
- Different type of mechanical structures and variations in them
- Different cable insulation and insulating schemes

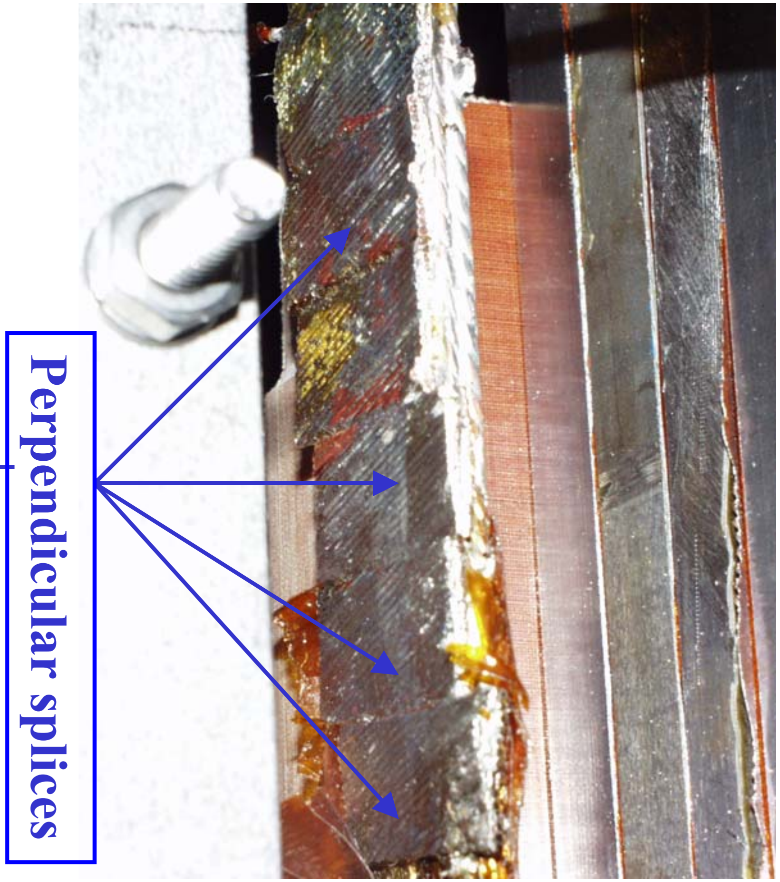




Internal Splice in Common Coil Design
(splices are perpendicular and are in low field region)



Splice for a single coil test (perpendicular splice take out the current to outside lead)



Internal splice between two coils in a common coil configuration (note several perpendicular splices)

A Personal Opinion

The "Common Coil Geometry" provides a unique and flexible *"Test Facility*"* for conductor and magnet development.

*a.k.a.:
Magnet R&D Factory

Recent Calculations at KEK for Future Magnets with Nb_3Al

- **Open Midplane Design with Nb3Sn conductor replaced with Nb3Al**
- **Rapid Turn Around Common Coil Design with minimum gap**
- **Quadrupole (cosine theta design and modular racetrack coil design)**

Potential Advantages of Nb_3Al over Nb_3Sn

(Figures from Yamamoto's write-up)

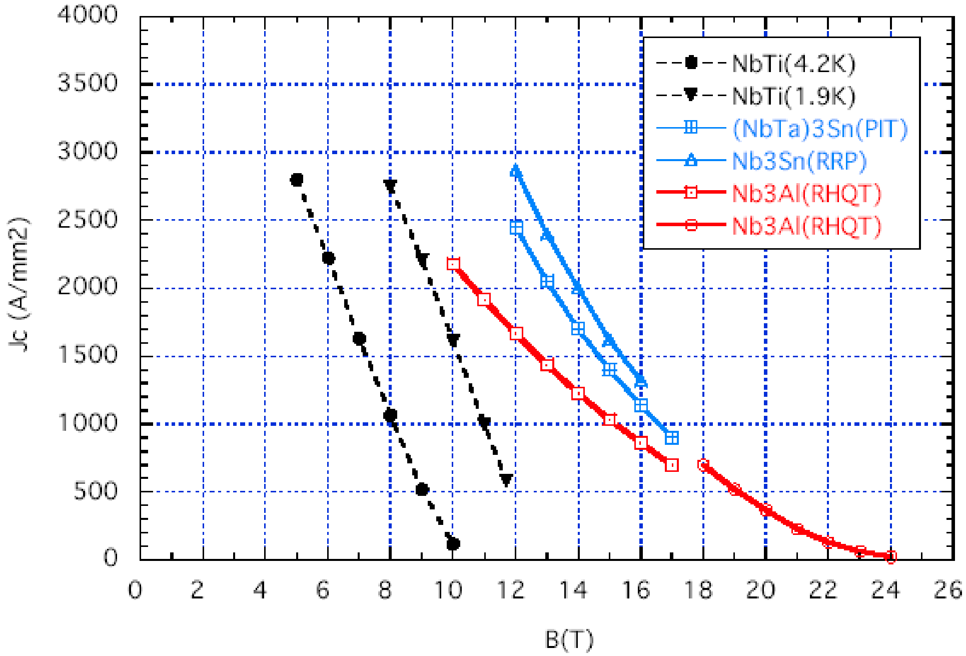


Fig 3. Magnetic field dependence of critical current densities for NbTi, Nb3Al, Nb3Sn. Around at 15 t, Jc of Nb3Al close to Nb3Sn.

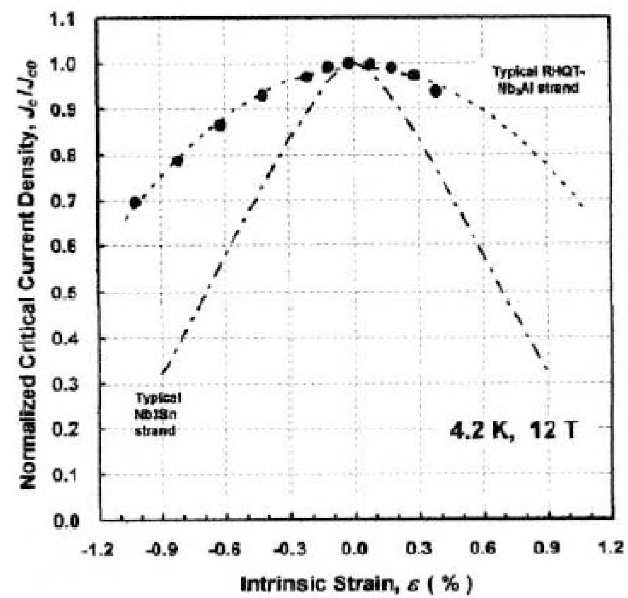


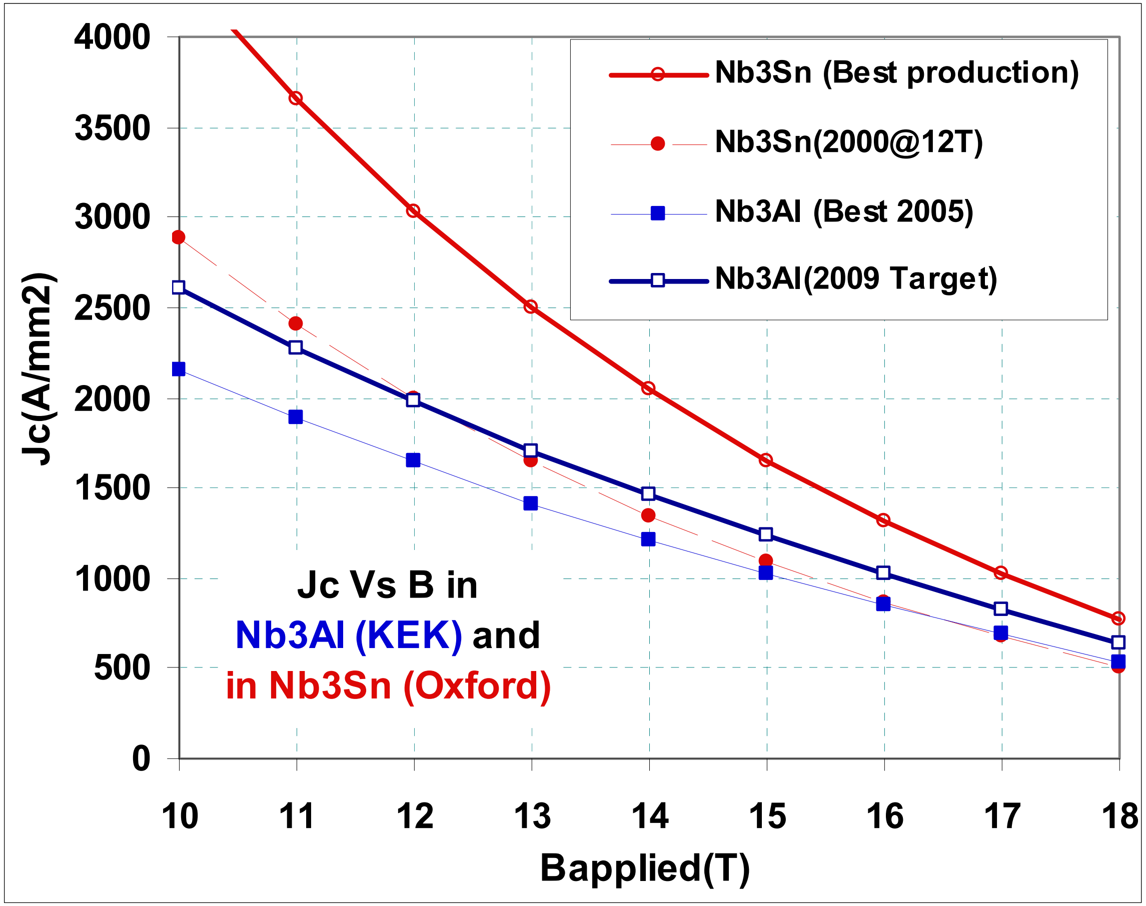
Fig. 4. Strain dependence of critical current density of Nb3Al and Nb3Sn.

(1) Critical current at High Fields

(2) Bending strain, in particular for "React & Wind" Technology

Nb_3Al and Nb_3Sn Used in the Comparisons in the Slides to Follow

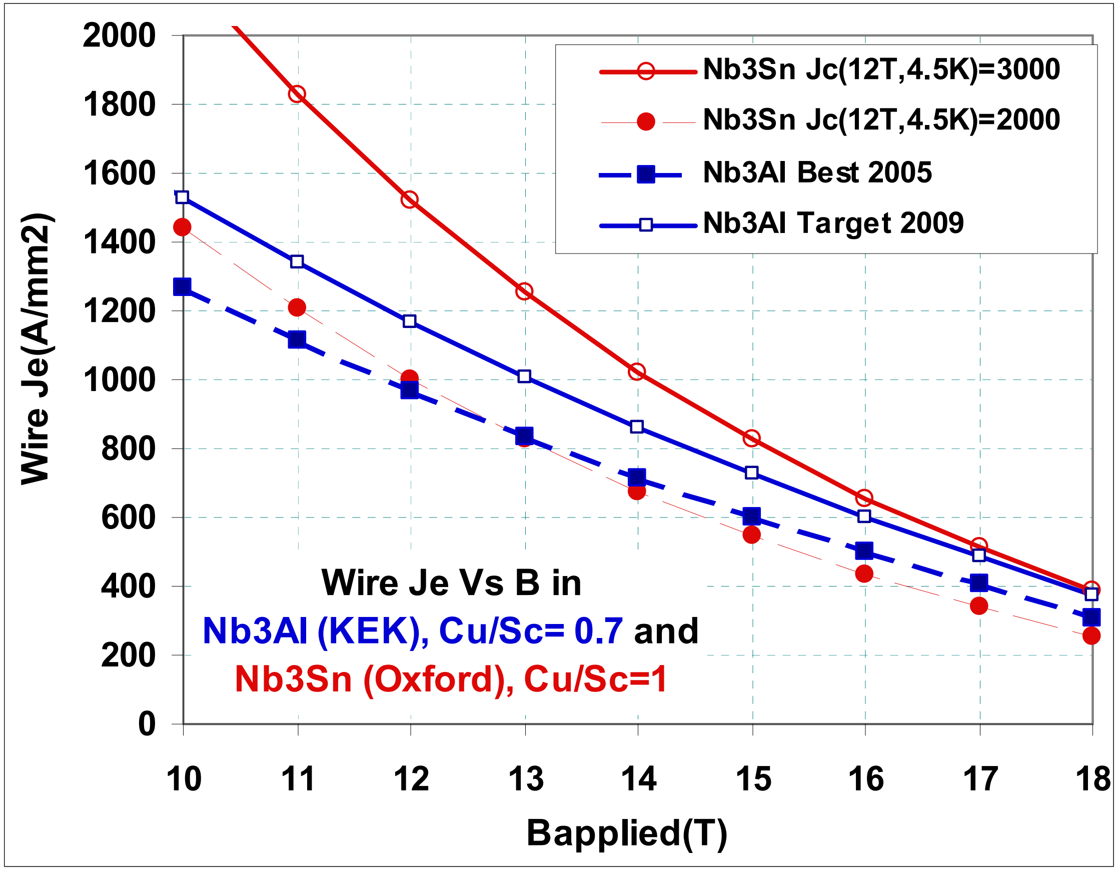
Critical current densities as a function of field:



J_c(12T,4K) of 3000 A/mm^2 was in the Nb_3Sn wire that was used in LBL 16 T magnet and 2000 A/mm^2 is the Nb_3Sn design value that is being used in the initial design calculations of LHC IR quad.

J_c(12T,4K) of 1645 A/mm^2 is in the Nb_3Al wire that was best measured in year 2005 and 2000 A/mm^2 is the Nb_3Al critical current density goal for year 2009.

Nb_3Al and Nb_3Sn Engineering Current Densities in Wires



Assumptions used:

Cu/Sc in Nb_3Al is 0.7 whereas in Nb_3Sn is 1:1.

The argument is that in very high field magnets one does not need much copper as the critical current becomes lower. In Nb_3Al having low copper is no problem (in fact, it comes out that way and more copper has to be platted later).

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Comparison of Various Nb_3Sn Designs with Different Jc(12T,4K) and Cu/Sc Ratios to same designs with Nb_3Al Jc=1645 A/mm² and 2000 A/mm², Cu/Sc Ratio is 0.7

Various Open Midplane Dipole Designs

Nb_3Sn

	A	B	C	D	E	F
H(mm)	84	135	160	120	80	120
V(mm)	33	20	50	30	34	40
V/H	0.39	0.15	0.31	0.25	0.43	0.33
B_o(T)	13.6	13.6	13.6	13.6	15	13.6
B_{ss}(T)	15	15	15	14.5	16	15
J_c(A/mm^2)	2500	3000	3000	3000	3000	3000
Cu/Sc	1	1,1.8	0.85	0.85	0.85	1
A(cm^2)	161	198	215	148	151	125
R_i(mm)	135	400	400	320	300	300
R_o(mm)	470	800	1000	700	700	700
E(MJ/m)	2.2	4.8	9.2	5.2	4.1	4.8
F_x(MN/m)	9.6	10.1	12.3	9.5	10.4	9.6
F_y(MN/m)	-3.0	-6.8	-8.7	-7.0	-5.1	-5.4

Nb_3Al

	A	B	C	D	E	F
B_{ss}(2005)	14.6	14.4	13.8	13.9	15.4	13.9
B_{ss}(2009)	15.2	15.0	14.5	14.6	16.1	14.7

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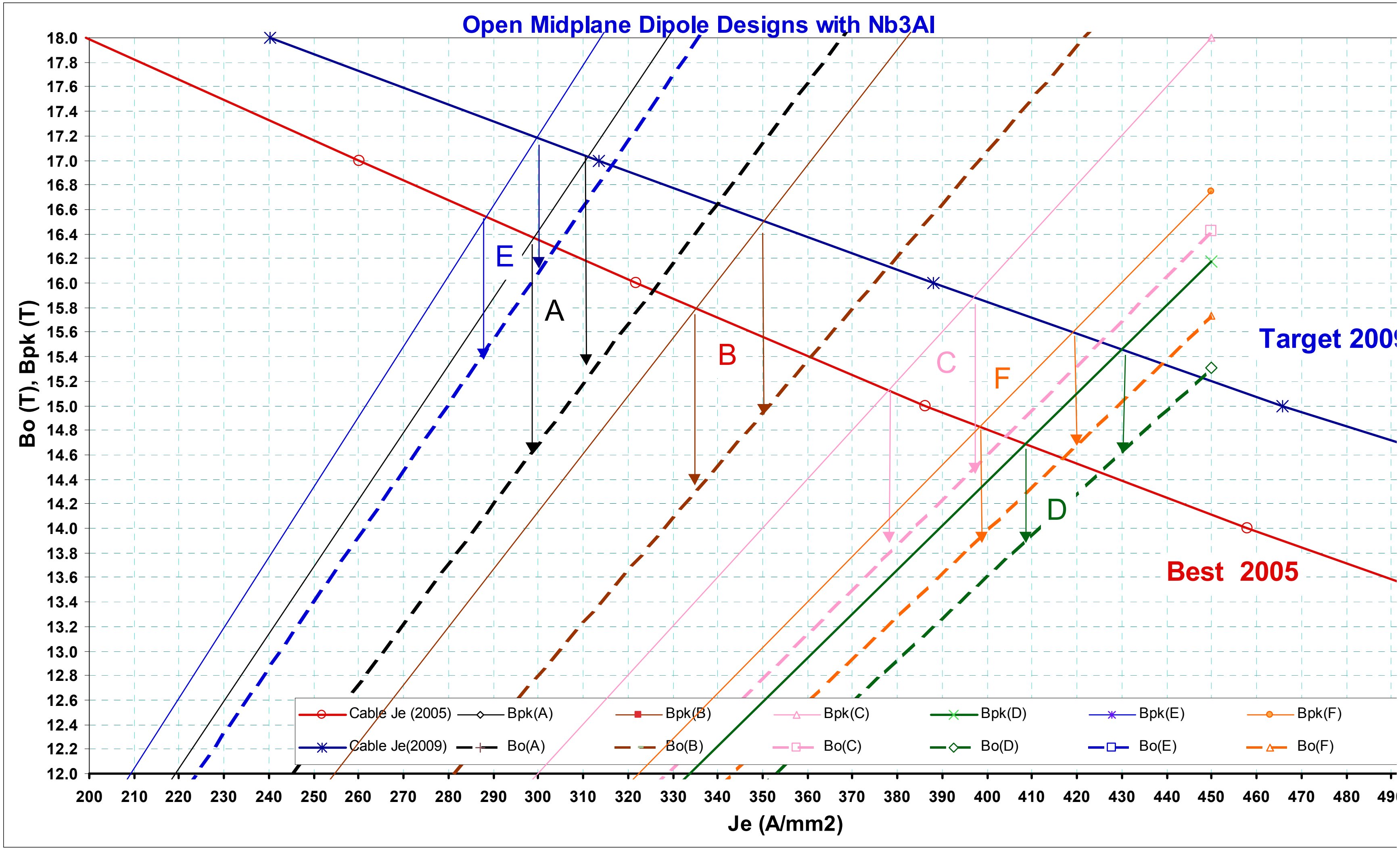
Details of Load line and Peak Field Line in Various Open Midplane Dipole Designs



KEK Coil Parameter Study

KEK Nb3Al common coil rapid turn around configuration

Field in Tesla at 8 kAmp for 10, 15 and 20 turn coils
(Note: Field may be limited by short sample current)

Number of coils refer to the number of coils on one side

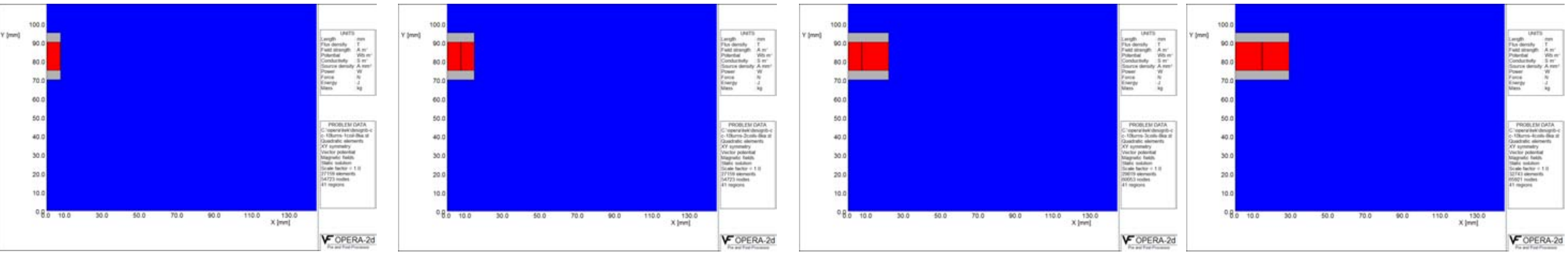
Cable has 18 strand of 0.7 mm dia
Bare cable thickness is 1.25 mm and width 6.7 mm
Insulated cable thickness is 1.5 mm and width 7.1 mm

Cable Parameters (estimated values for some)

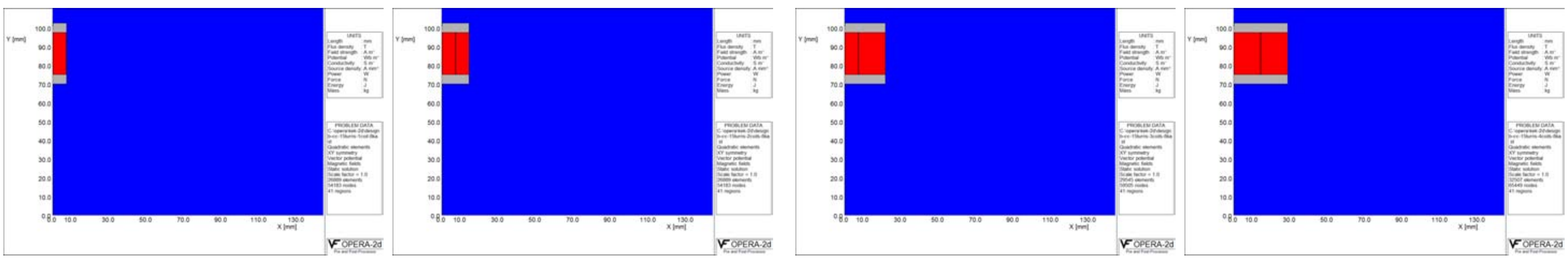
jsc (A/mm2)	**1000**	245.416	**2000**	1963.33
Cu/Sc	0.7	0.7	0.7	0.7
Jwire (A/mm2)	588.235	144.362	1176.4706	1154.9
strand dia	0.7	0.7	0.7	0.7
Iwire (A)	226.373	55.5556	452.74559	444.444
no. of strands	18	18	18	18
Icable (A)	4074.71	**1000**	8149.4206	**8000**
cable width bare (mm)	6.7	6.7	6.7	6.7
cable width insulated (mm)	7.1	7.1	7.1	7.1
cable thickness bare (mm)	1.25	1.25	1.25	1.25
cable thickness insulated (mm)	1.35	1.35	1.5	1.5
Je (A/mm2)	425.113	104.33	765.20381	751.174

Magnetic Model of Various Cases

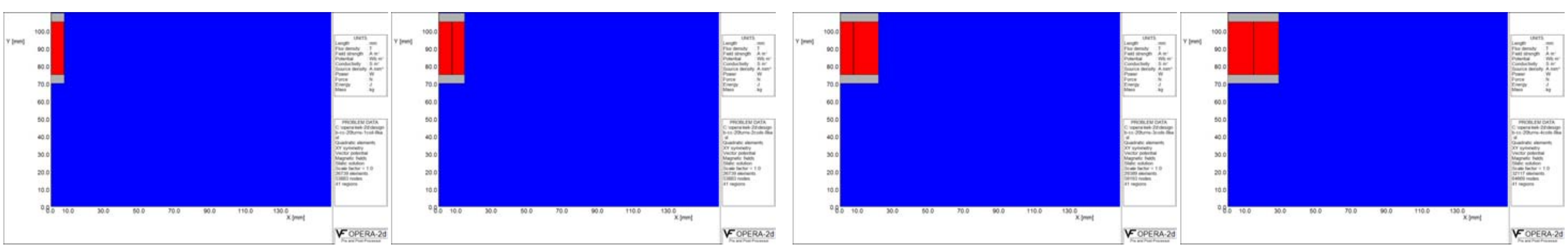
1 through 4 coils per quadrants with each coil having 10 turns:



1 through 4 coils per quadrants with each coil having 15 turns:



1 through 4 coils per quadrants with each coil having 20 turns:



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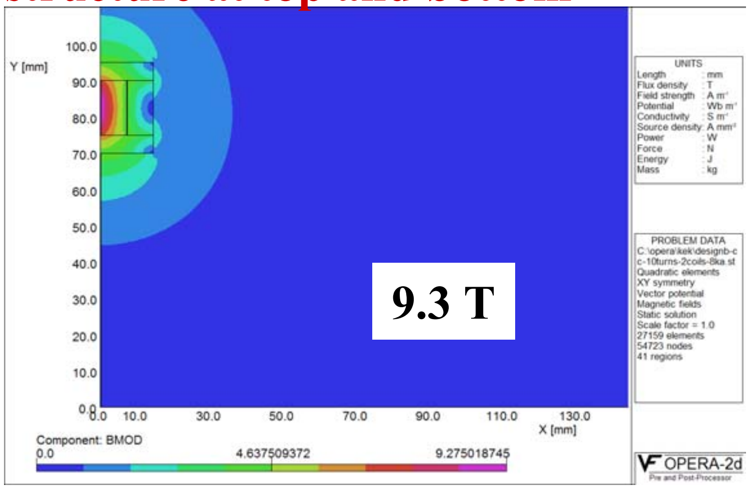
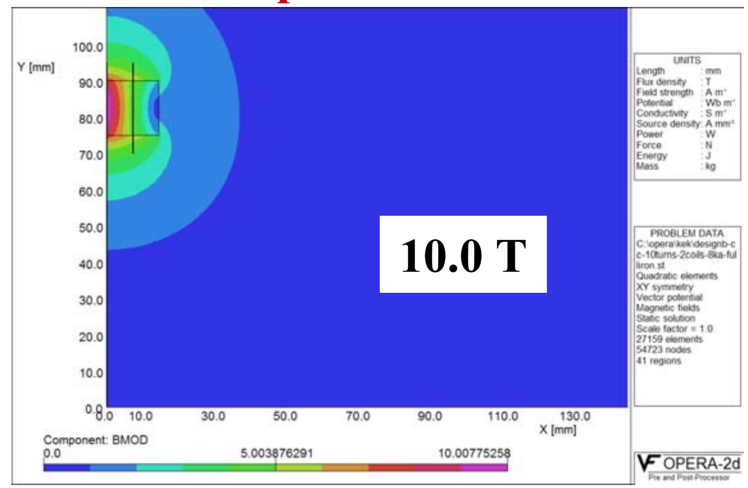
Maximum Field in Conductor at 8 kA for Various Cases of 2 Coils per Quadrant

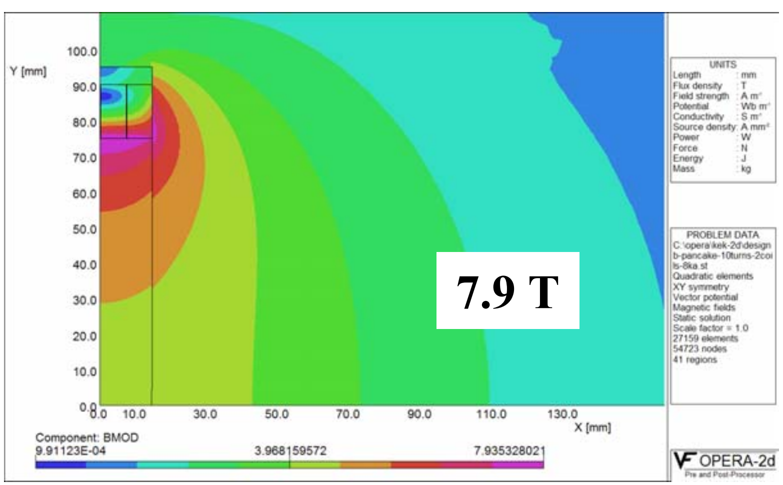
Common coil with small non-magnetic structure at top and bottom



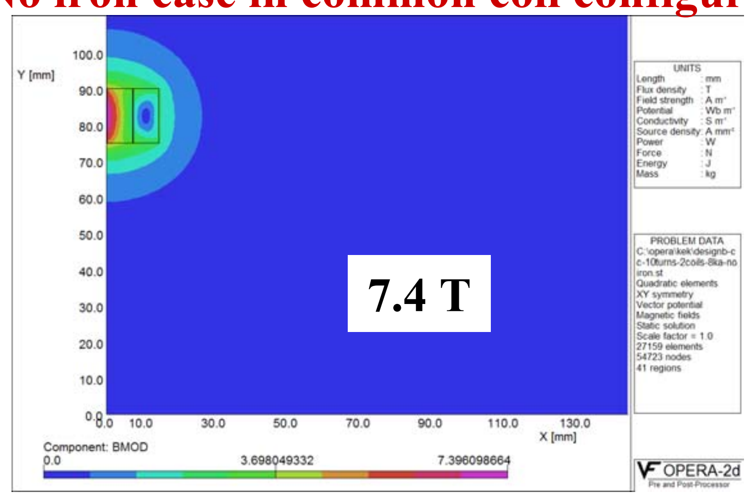
Common coil with no non-magnetic structure at top and bottom



Pancake configuration



No iron case in common coil configuration

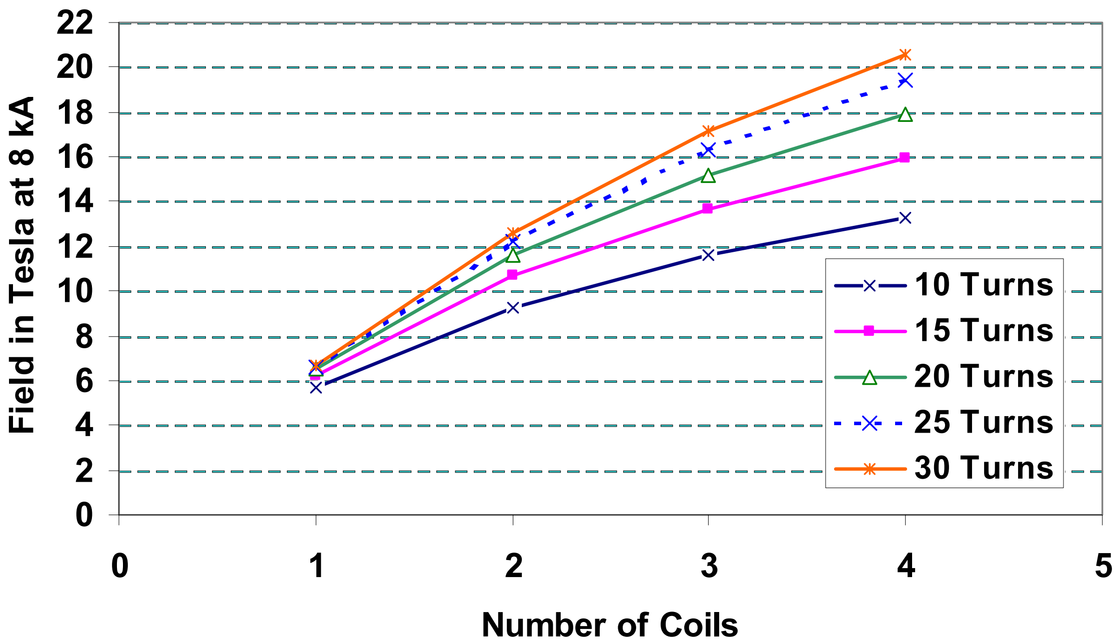


Maximum Computed Field in Conductor at 8 kA for Various Cases

Common coil rapid turn around structure with zero gap

Computed coil field at 8 kA (not quench field).

Coils	10 Turns	15 Turns	20 Turns	25 Turns	30 Turns
1	5.69	6.24	6.49	6.61	6.66
2	9.27	10.69	11.59	12.19	12.59
3	11.59	13.69	15.18	16.28	17.12
4	13.26	15.91	17.89	19.4	20.59



Estimated Cable Parameters and Computed Short Sample for KEK Nb_3Al Rapid Turn Around Program

Calculations assume 5% degradation and extra 0.3 mm insulation between layers.

Numbers could be ~2% higher without that.

Computed short sample currents with KEK 2005 Nb_3Al numbers

Coils	10 Turns	15 Turns	20 Turns	25 Turns	30 Turns
1					
2		7.9	7.5	7.3	7.1
3	7.5	6.8	6.3	6.1	5.9
4	6.9	6.1	5.7	5.3	5.2

Computed short sample currents with KEK 2009 Nb3Al numbers

Coils	10 Turns	15 Turns	20 Turns	25 Turns	30 Turns
1					
2		8.46	8.08	7.81	7.63
3	8.08	7.25	6.75	6.49	6.26
4	7.42	6.54	6.08	5.73	5.56

Computed short sample fields with KEK 2005 Nb_3Al numbers

Coils	10 Turns	15 Turns	20 Turns	25 Turns	30 Turns
1					
2		10.5	10.8	11.1	11.2
3	10.8	11.6	12.0	12.4	12.6
4	11.4	12.2	12.8	12.9	13.4

Computed short sample fields with KEK 2009 Nb3Al numbers

Coils	10 Turns	15 Turns	20 Turns	25 Turns	30 Turns
1					
2		11.3	11.7	11.9	12.0
3	11.7	12.4	12.8	13.2	13.4
4	12.3	13.0	13.6	13.9	14.3

A Dynamic Program with Modular Racetrack Coil R&D

One can use essentially the same coil to do a variety of R&D:

- **Zero aperture for conductor test and development**
- **Increase aperture for "Common Coil Magnet" development**
- **Investigate various technology and parameters**

Other useful configuration not discussed in details

- **Reconfigure for "Open Midplane Design Development"**
- **High Field Modular Quadrupole design with new support structure**

This is an ideal design/vehicle for a simple, systematic and cost-effective technology development program.

Designs for LHC IR Quadrupole

Calculations under progress and will not be covered today

- **Cosine two theta quadrupole design**
- **Modular racetrack coil quadrupole design**

Summary

We covered a lot !

It should be an exciting R&D program !!

Good luck !!!