Racetrack Magnet Designs and Technologies

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Introduction

This presentation is NOT on the main LARP R&D program :

- **Build and demonstrate long Nb_3Sn cosine theta quad magnet**

But this could/should be LARP wider intellectual program :

- **Development of racetrack coil magnet designs and technologies**

Racetrack coil magnet designs for various LHC upgrades :

- **Common coil magnet system (main ring + injector)**
- **High Gradient racetrack coil quadrupole (modular design)**
- **Open midplane dipole**

Additional magnet technology opportunities offered by racetrack coils :

- **HTS**
- **React & Wind**

It may be possible to leverage BNL racetrack coil program for a limited technology development or examination of above.

Two Technologies for Brittle High Field Superconductors

Nb_3Sn becomes brittle (bad) only after it is heat treated or reacted.

This presents two options:

Wind & React

Wind the coil while the conductor it is still ductile (good). And then react the entire coil package which makes conductor brittle (bad).

React & Wind

React the conductor before winding the coils. This makes conductor brittle (bad). And then wind the coil with this brittle conductor making sure it is not damaged.

Obviously, "Wind & React" technology is a relatively safer approach. This is why it has been used in most "R&D" programs. After all, any demonstration that one can build magnets with brittle Nb_3Sn conductor is a big leap in magnet technology.

Then why even consider a more risky "React & Wind" Technology?

See next few slides for some important benefits of "React & Wind".

Advantages and Challenges with "Wind & React" and "React & Wind"

Wind & React Technology

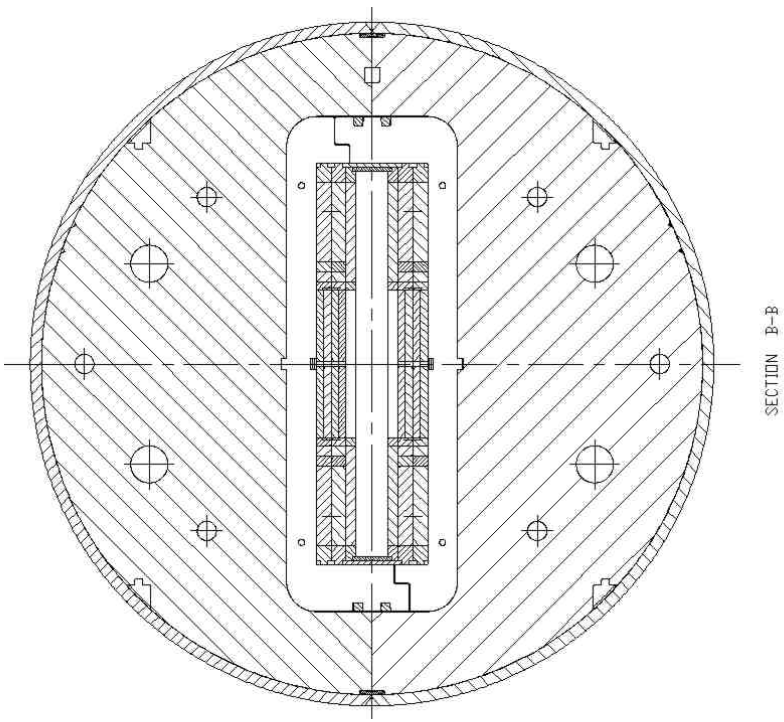
- The advantage of "Wind & React" is that the coil is wound when the conductor is still ductile. Then the entire coil package (consisting of insulation, wedges, end spacers) is heat treated.
- The challenge is to minimize the integrated strain build-up in long magnets due to differential thermal expansion of different materials in the coil package.

React & Wind Technology

- The advantages of "React & Wind" are that with no high temperature reaction involved (and hence no differential thermal expansions), the technology (a) is expected to be more scalable for long magnets (major challenges are similar in short and long magnets), (b) may utilize a significant part of NbTi industrial technology to build Nb_3Sn/HTS long magnets and (c) allows the use of more varieties of materials in coil package (insulation, wedges, end spacers, etc.).
- The challenge in "React & Wind" is to wind the coil with the pre-reacted brittle conductor while minimizing the degradation and/or damage to an acceptable level. One should develop "conductor friendly magnet designs" that minimize strain on brittle superconductors and demonstrate the technology in a real magnet.

Some Major Features of BNL Nb_3Sn 10^+ T React & Wind Common Coil Dipole

- Modular "common coil design" with racetrack coils having large bend radii
- React and Wind Nb_3Sn Technology
- 10.4 T (designed initially for ~12 T, field reduced due to certain choices)
- Two 30 mm x 80 mm apertures
- Large tall clear space (~240 mm) for easy testing of coils in high background field (magnet does not have to be disassembled)
- Almost no cold pre-stress on coils
- Many other interesting features like, splice for current grading, etc.



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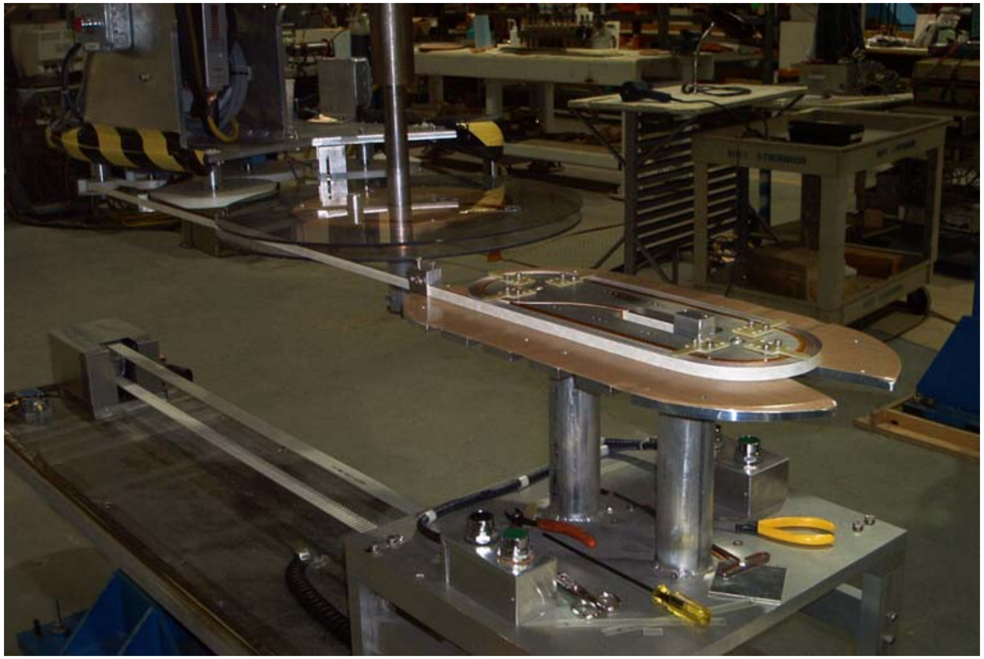
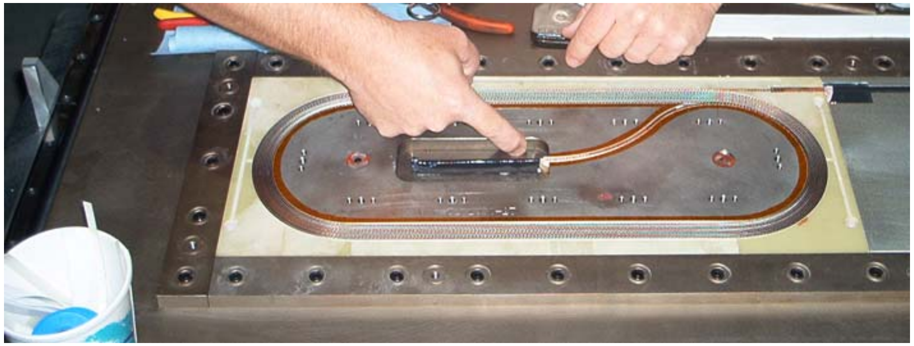
A Key Component in Developing "React & Wind" Technology : Automatic Coil Winder

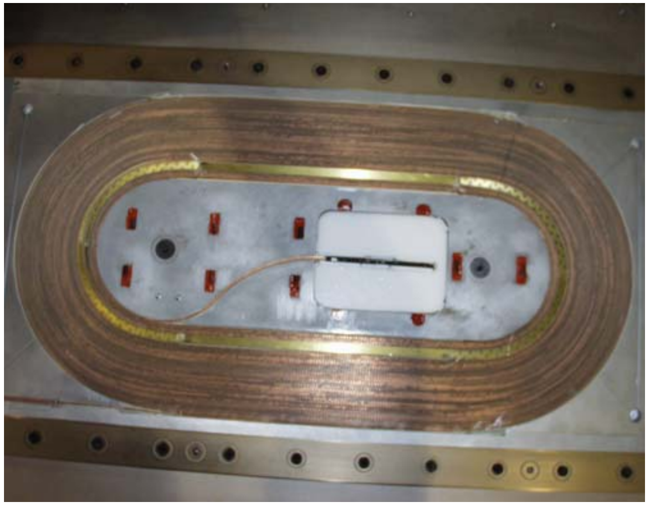


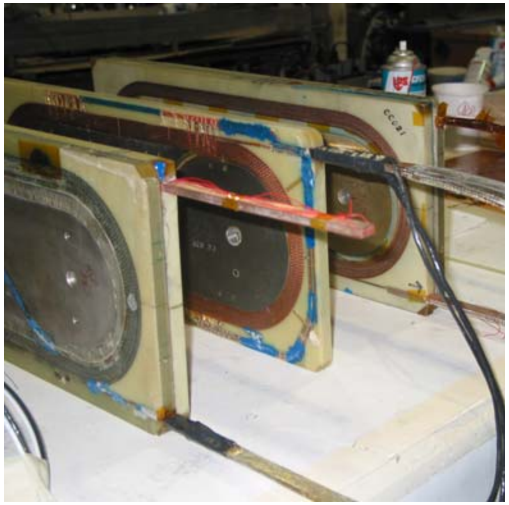
Each part and step in this new automatic coil winder is carefully designed to minimize the potential of bending degradation to brittle superconductors during the winding process. The machine is fully automated and computer controlled to minimize uncontrolled errors (human handling). All steps are recorded to carefully debug the process, as and if required.

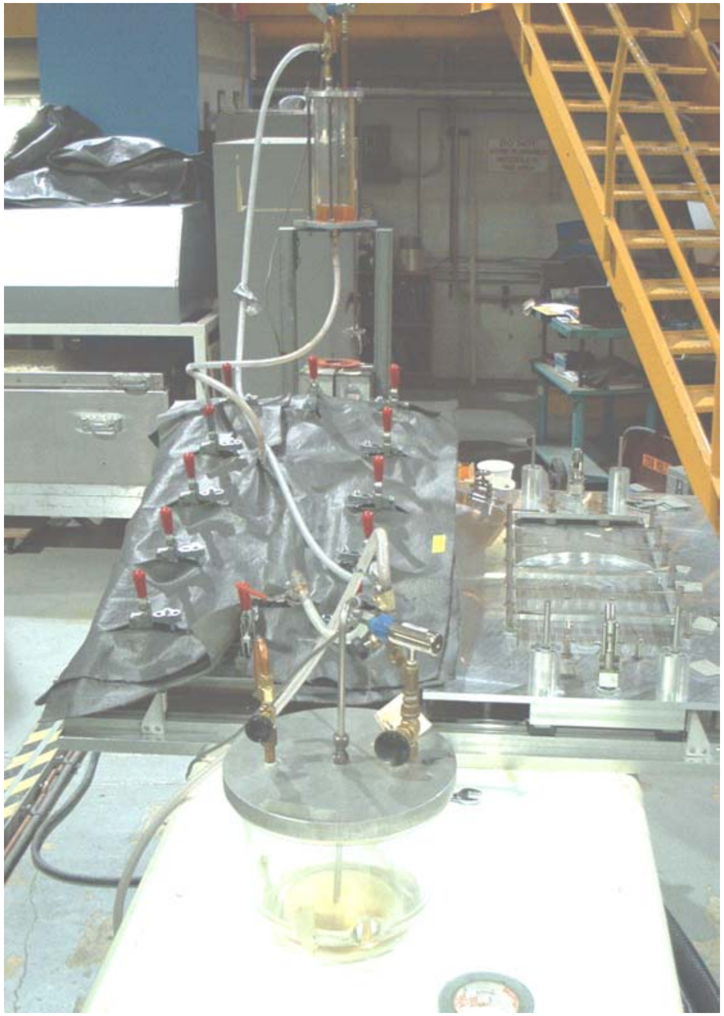
Racetrack Coil Modules and Vacuum Impregnation



Fully flexible coil module with perpendicular splice through the central low field region. Any coil module can be put any where in the magnet.







Coil impregnation fixture

Quench Plot of BNL React & Wind Common Coil Dipole DCC017

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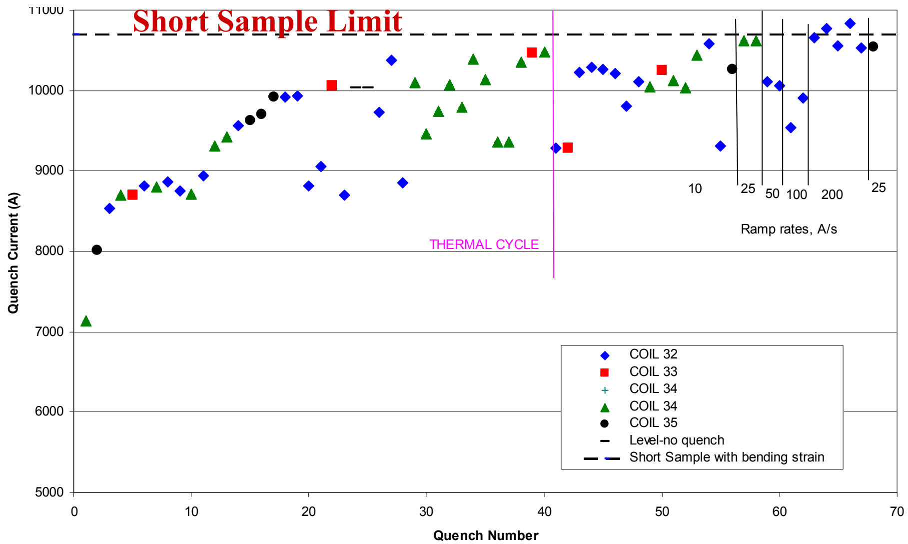
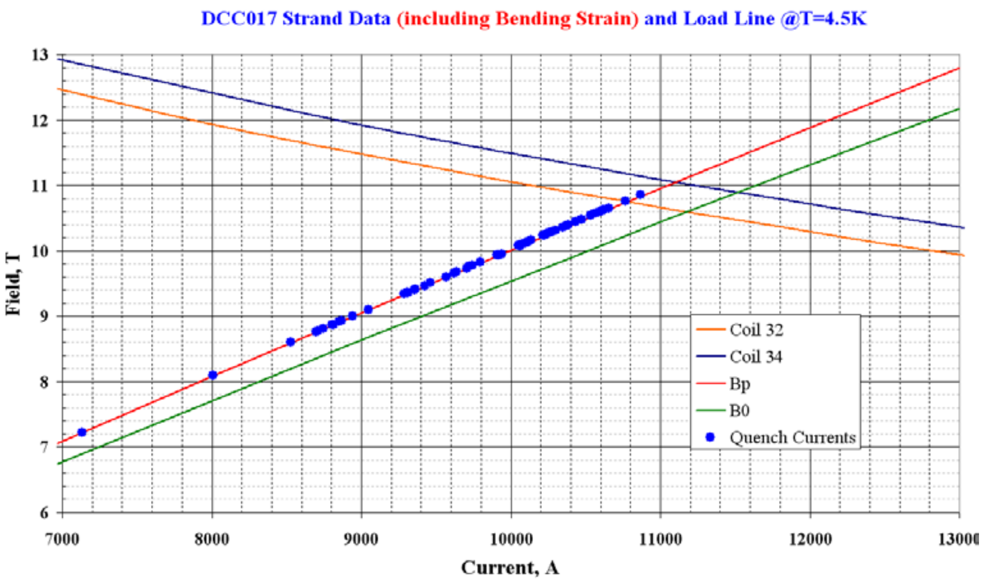
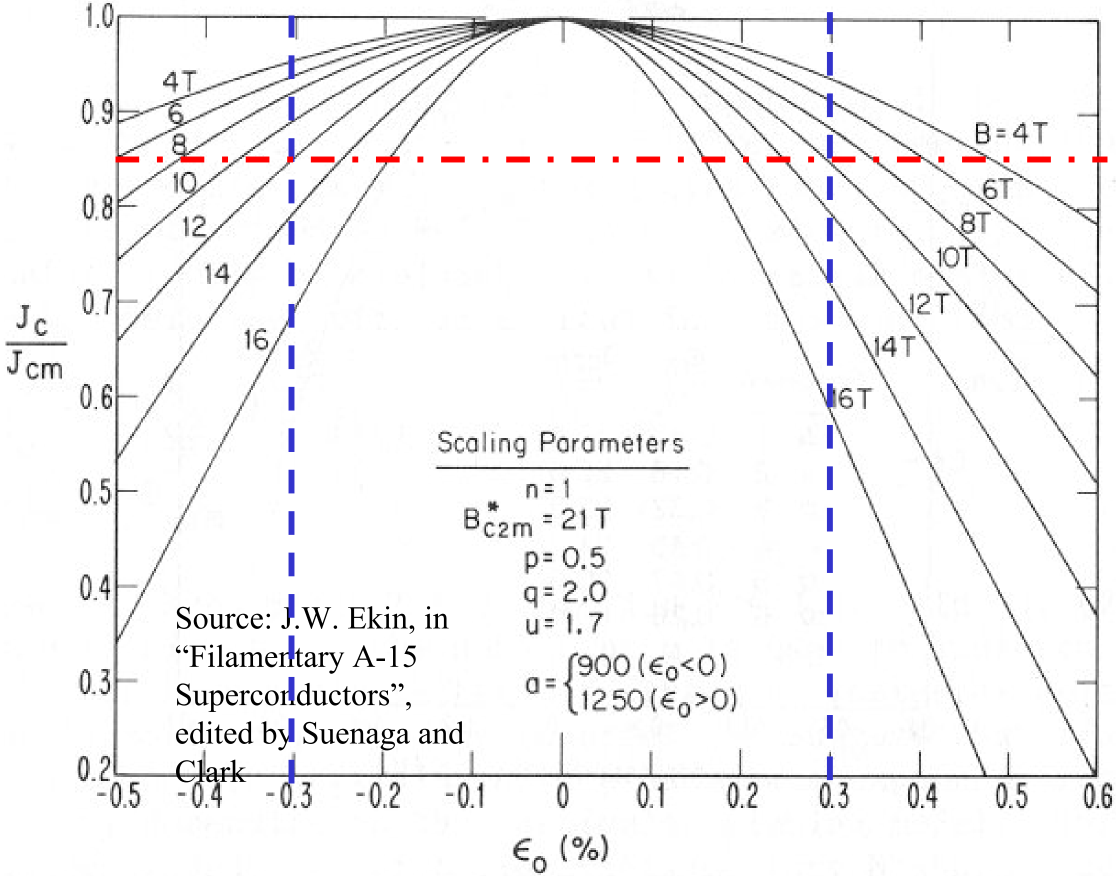




- Main purpose of this R&D program was to determine: **"Can *React & Wind* technology produce magnets without damage or significant degradation"?**
- **The construction and test of this magnet proves that "yes it can" !**
- **Magnet reached the computed short sample (based on two extracted strand measurements of cables used in coils).**
- Quench performance was reasonable for the first technology magnet.
- Several other non-tradition design and construction principles were also probed (e.g. tall open gap for insert coil testing).
- Given this successful test and benefits of "React & Wind", some one should continue with this attractive technology.

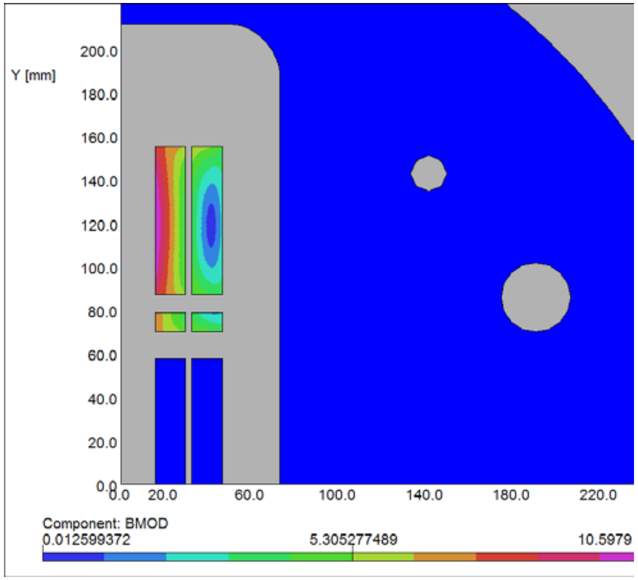
J_c, Strain and Field in Nb_3Sn



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 J_c corresponds to ~4% drop in B_{ss}. 0.3 % strain may be acceptable for a 12 T magnet. One should place limit at 0.2% for a 14 T design.

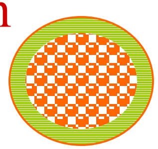
Also note that "high strain" and "high field" are not usually at the same location.



Bending Strain in Magnets Made with React & Wind Technology

BNL common coil design has bend radius of 70 mm and uses 0.8 mm wire, as compared to FNAL common coil design with 90 mm radius and 0.7 mm wire.

Corresponding bending strain in wire is 0.6% in BNL and 0.4% in FNAL designs (in both cases it was effectively reduced by half - 0.3% in BNL design and 0.2% in FNAL design - by reacting cable to 2x radius drum).



Arup Ghosh used the radius of the "area of superconductor in the wire" rather than the radius of "wire" itself in the bending degradation calculations. This corresponds to even a smaller value of bending strain and the test results are consistent with that.

FNAL has done a lot of systematic studies on the influence of bending strain in various wires and cables. Different wires have different bending degradation.

Reducing bending degradation in Nb_3Sn wire and cable will be one important area of productive research for developing high field "React & Wind" magnet technology.

A ~15 T magnet should be possible with Nb_3Sn "React & Wind" Technology.

Wind & React Vs. React & Wind

Issues	Wind & React	React &Wind
Use of "Brittle Superconductors"	Safest bet on working with brittle superconductor is "Wind & React" and that's why it is most popular for the demonstration of successful R&D magnets. (+)	Biggest challenge for "React & Wind". Brittle superconductor must go through all steps of coil manufacturing. That's why it is the least popular for R&D magnets. Design and automate all aspects of tooling to minimize potential for such damage or degradation. (-)
Insulation and use of other material in coil	Limited choices (insulation generally thicker) as they must withstand high reaction temperatures. (-)	Can use a variety of insulation and other material in coil as none go through high reaction temperature. (+)
Length scale-up issues	Biggest challenge for "Wind & React". Integrated build-up of material in the ends and in transition region as coil gets longer due to differential thermal contraction. (-)	A successful demonstration of technology in short magnet directly applies to long magnets, as the coil does not go through high reaction temperature. This is the biggest strength and argument of "React & Wind" (+)
Industrialization	More new technologies (-)	Less new technologies (+)
Biggest challenge for future technology	Length scale-up issues, particularly in magnet designs with complex ends (-).	Magnet and conductor designs to minimize the bending strain (+).

Test Results of HTS Coil and Magnets and It's Relevance to LHC Upgrade

React & Wind appears to be must for High Temperature Superconductors (HTS) as the coil must go through very high reaction temperature (~880 K) and the reaction temperature must be kept uniform within 1/2 degree in the entire coil package.

Possible Application of HTS in Accelerator Magnets

Low Field, High Temperature Application

Example: Rare Isotope Accelerator (RIA) or Future Synchrotron Radiation Source

- The system design benefits enormously from HTS because HTS offers the possibility of magnets to operate at a temperature higher than 4K (20-65 K).
- Recent design developments are increasing the chances of making HTS magnets competitive to water-cooled copper magnets in many applications.

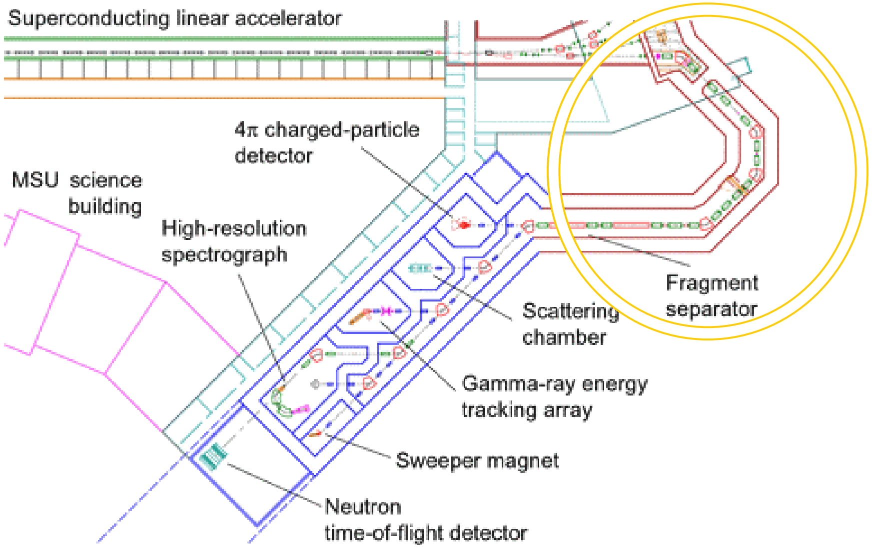
High Field, Low Temperature Application

Example: IR Magnets for LHC Luminosity Upgrade or Common Coil Magnets (may be in hybrid designs with Nb_3Sn or Nb_3Al) for LHC Energy Upgrade

- At very high fields no superconductor carries as much J_c or J_e as HTS does.

- In both cases, HTS magnets can tolerate a large energy deposition.
- The coil temperature need not be controlled precisely. It can be allowed to increase by an order of magnitude more than that in LTS (either due to energy deposition or due to simpler cryo-system). HTS allow a few degrees, LTS a few tenth of a degrees.

Medium Field Superferric HTS Quad for Rare Isotope Accelerator (RIA)



- Quads in RIA's Fragment Seperator region are subjected to huge radiations (~15 kW).
- A proper magnet design reduced this huge 15 kW to merely 130 W in cold structure.
- 130 W is still a large amount of heat load to be removed at 4 K.
- We are developing HTS magnets operating at ~30 K to remove this energy more economically.
- An R&D magnet has been built and tested with "*commercially available HTS*" from American Superconductor Corporation (ASC).
- Next few slides will indicate that how far along we have come with HTS technology.
- HTS seems to be ready for use in accelerator and beam line magnet applications. One should now consider it seriously for potential savings in "cost of ownership" .

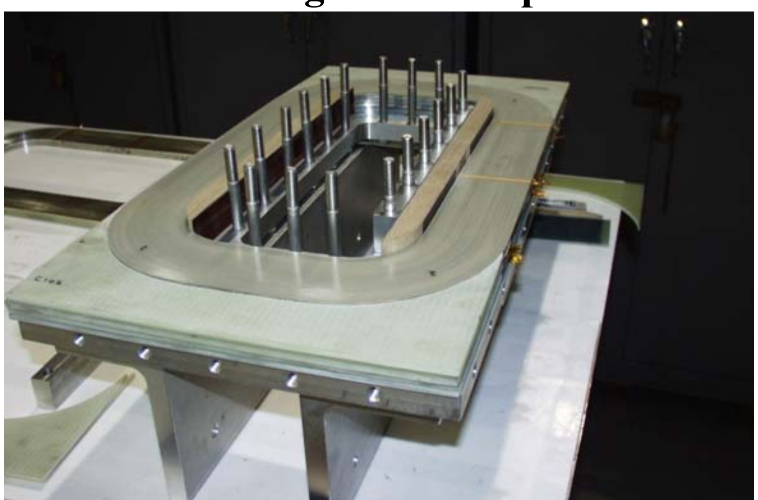
RIA HTS Quadrupole At Various Stages of Construction and Testing


HTS coil winding with SS tape insulator

The RIA HTS model magnet has been successfully built and tested at BNL.

Experiments of magnet operating with large energy depositions (tens of watts in 0.3 meter long magnet) have also been carried out.

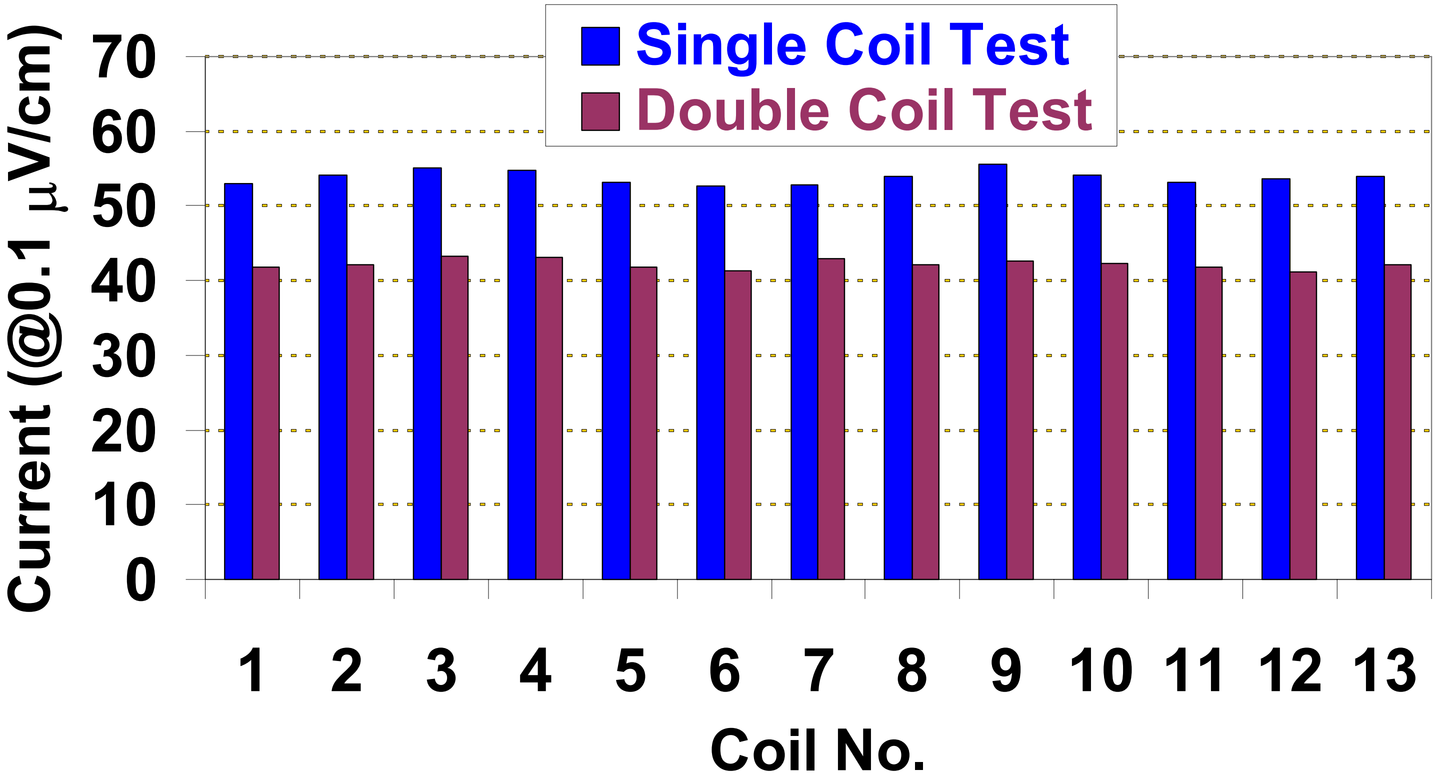

Cold iron magnetic mirror test with six coils


HTS coils during magnet assembly


Warm iron magnetic mirror test with twelve coils

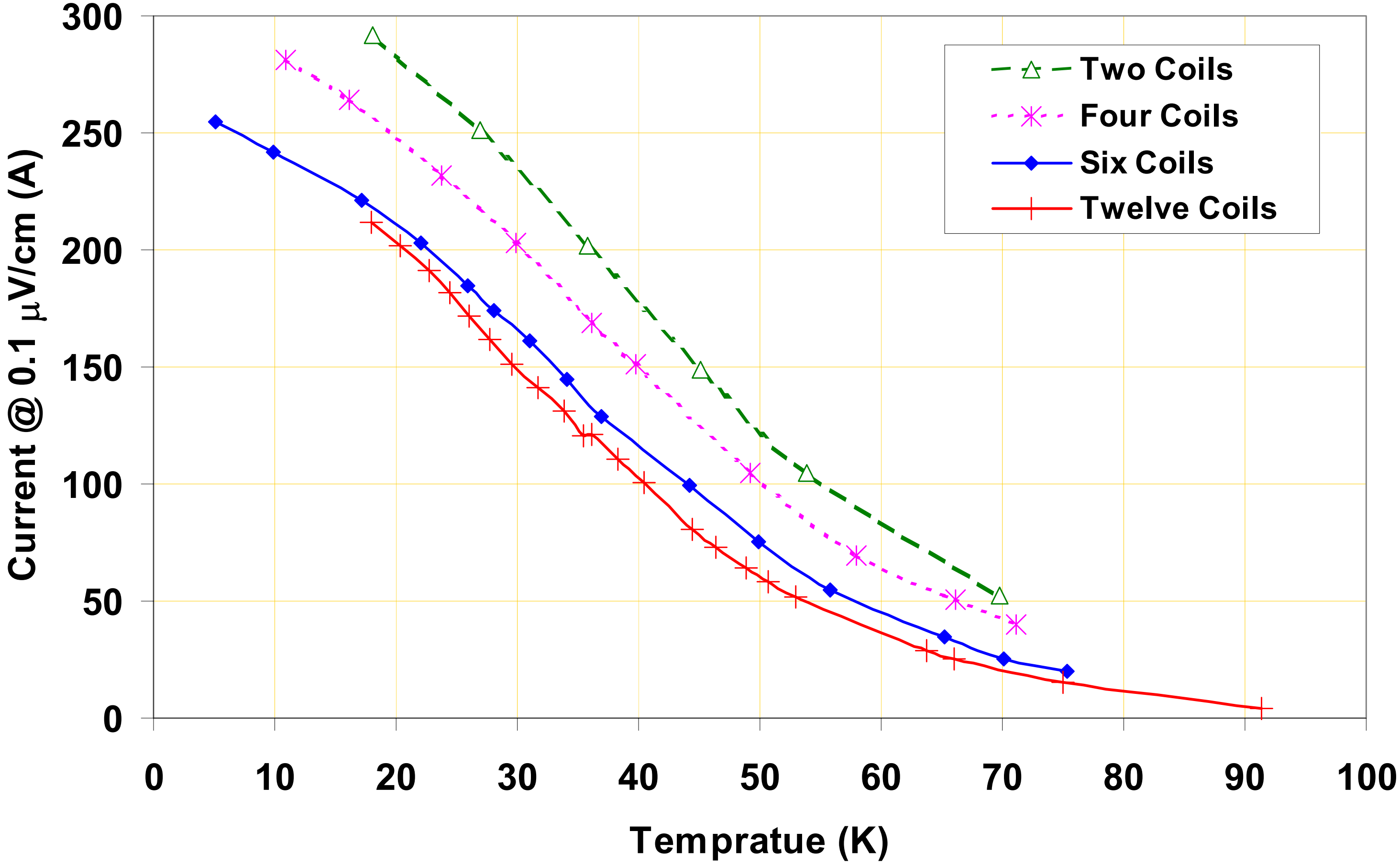
Performance of 13 HTS Coils (Each made with ~220 meter of tape)

Coils can be made without damaging or degrading conductor. Also note the uniformity in performance of coils made with commercially available HTS.



The current at a voltage gradient of 0.1 μ V/cm (10 μ V/meter) over the total length of the coils at 77 K.

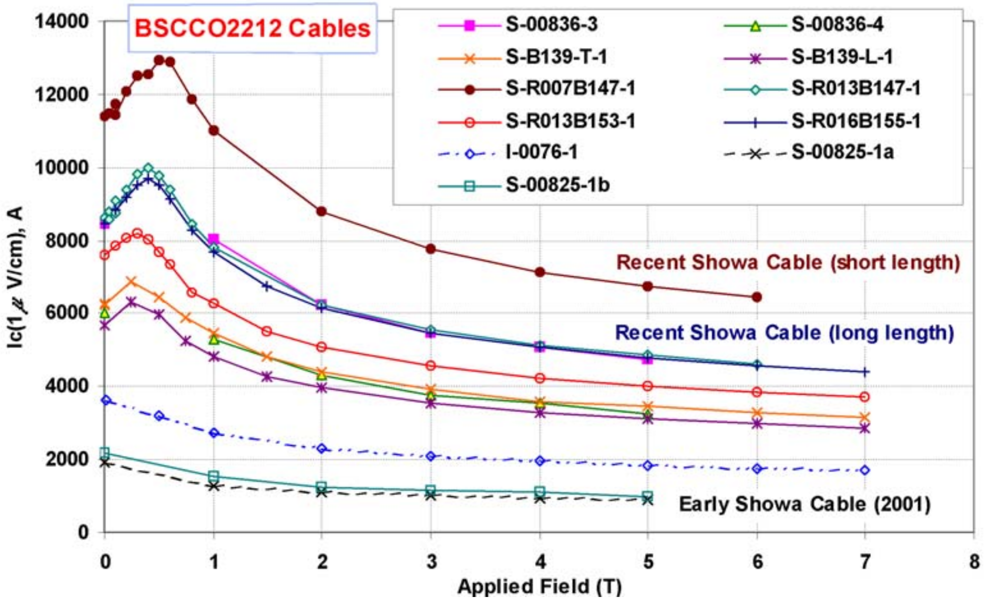
RIA HTS Model Magnet Test Results for Various Configurations



More coils create more field and hence would have lower current carrying capacity

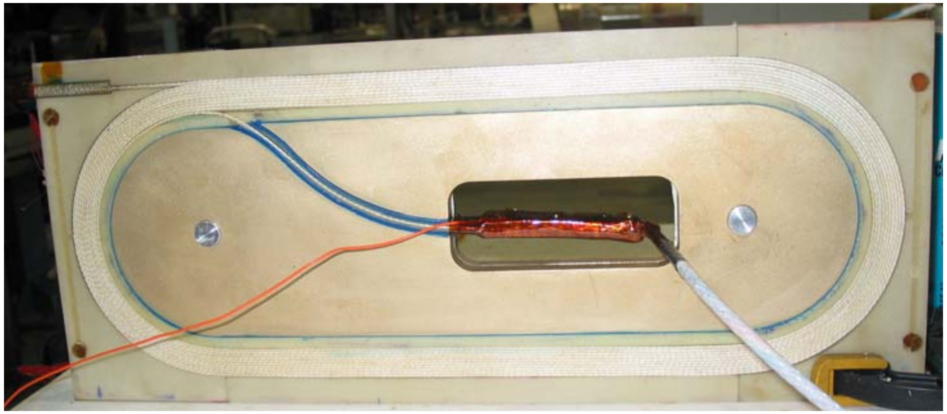
A summary of the temperature dependence of the current in two, four, six and twelve coils in the magnetic mirror model. In each case voltage appears on the coil is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for four coils.

HTS Coils and Magnet at BNL with Rutherford Cable

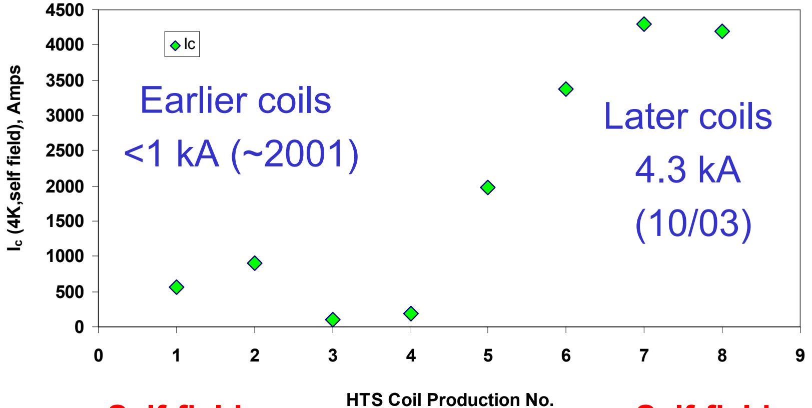


Cable made at LBL, reacted at Showa, tested at BNL

Modern HTS cables, coils & magnets can carry a significant current.



HTS coil wound and tested in a common coil magnet at BNL

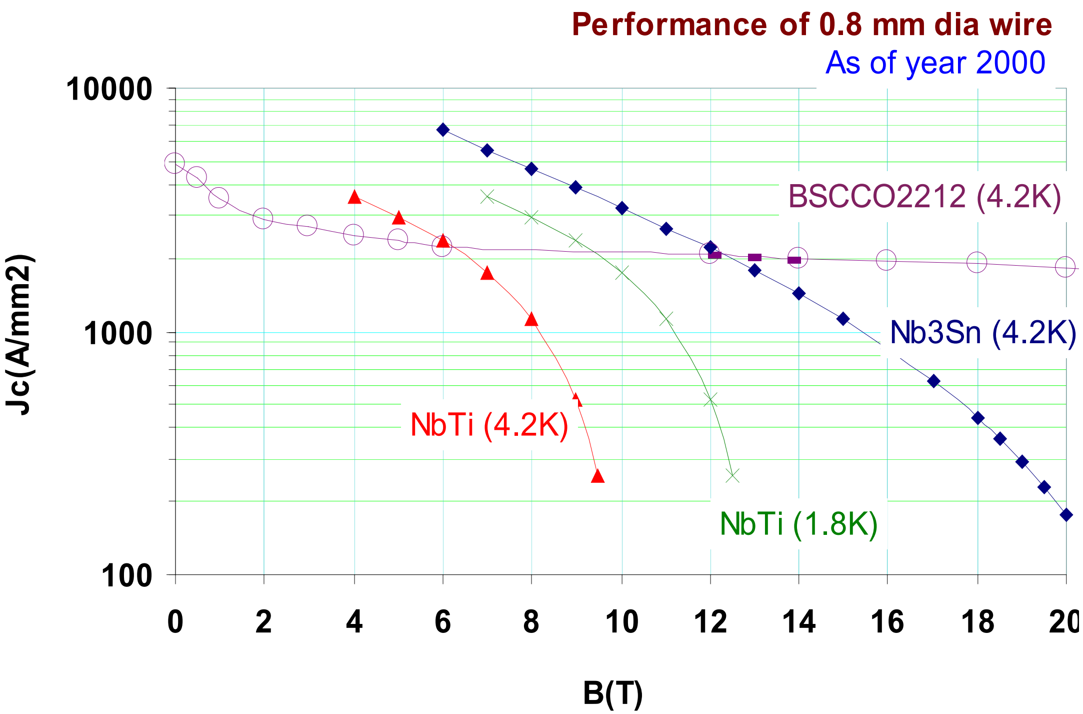


Self-field <0.05 T

Self-field ~ 1.85 T

Superconductors for High Field Magnets

Graph below compares the critical current density (J_c) for various superconductors as a function of field.



However, for magnet design calculations purpose, one must compare the overall current density in coil which includes, copper, insulator, etc.

Also for machine design purpose, one must consider the operating field and not the field on the conductor. This means that one should also include peak enhancement and some operating margin. The two usually add to about 20% more to the design field.

Thus for a 15 T magnet, compare conductor performance at 18 T.

Overall Current Density in Commercially Available High Field Superconductors

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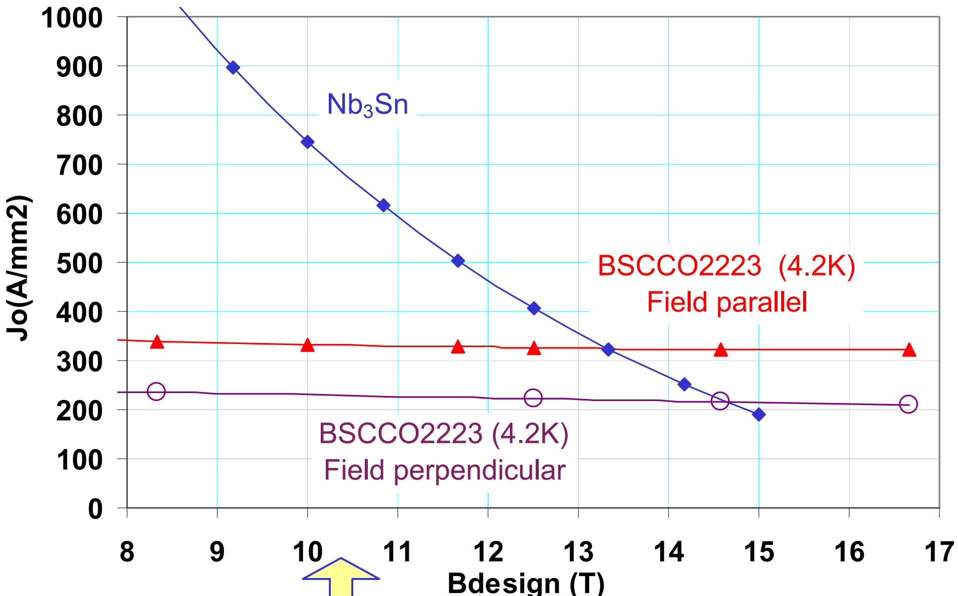
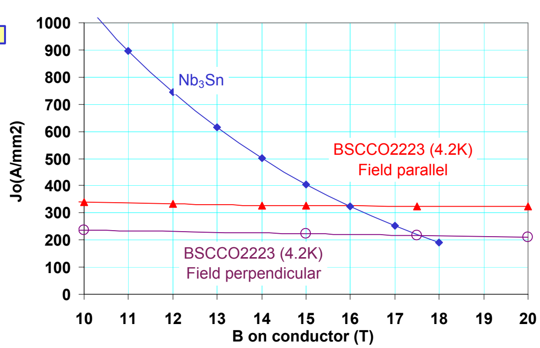
Overall current density as a function of design field in commercial high field superconductors



Design operating field is generally 20% over the conductor field due to peak field and margin.



Commercially available HTS now offer more current density than Nb_3Sn to design magnets at an operating field over 13.5 T to 14.5 T.

HTS should now be considered in those high field magnet applications where the performance and not the cost is the driver.

Data used in making plots (details)

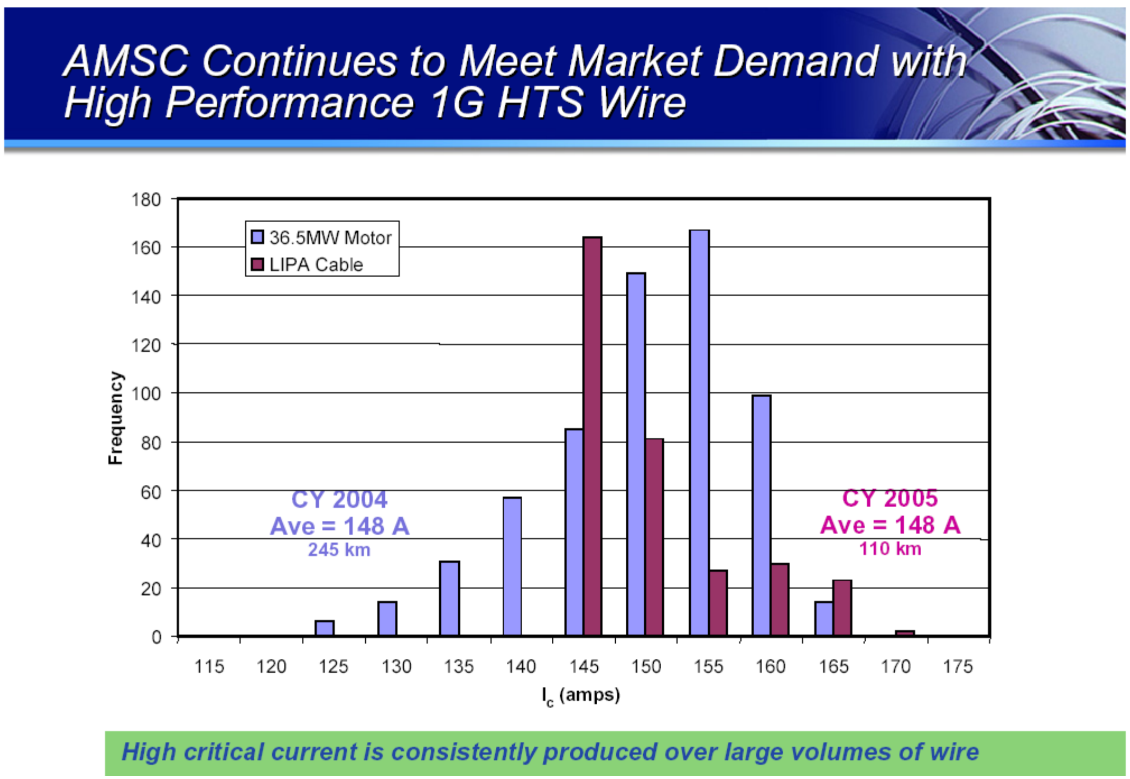
Nb_3Sn: Wire/cable specified for present LARP Quad (Jc@12T=2400A/mm2, Cu/Sc=1.0, insulation 250 micron per turn)

HTS: 155A at 77K – can be ordered today from ASC Website. Scaling used for 77 K to 4K. Kapton/SS tape for insulation.

Usable Conductors Performance in Near Future High Field Superconductors

So what's in future (speculating improvements in a few years)?

Stable Nb_3Sn with J_c(12T) may be available at 2800 A/mm^2 instead of 2400 A/mm^2 used in previous slide.



Courtesy: Garry Ferguson, American Superconductor

BSCCO 2223 (1G) performance of sorted wires may improve to 180 A (which is ~10% over 165 A already achieved at ASC with sufficient frequency), instead of 155 A used in comparison.

The two gives about the same relative improvement in J_o (J-overall). The field at which HTS J_o becomes more than Nb_3Sn does not change much.

Superior Mechanical Properties of HTS in High Field Magnet Applications

HTS High Strength Plus Wire

- Designed for applications where the wire must be mechanically strong and have high current density, such as many coil and magnet applications
- Tolerant to small winding diameters or bend radii
- High tensile strength
- High engineering current density

American Superconductor

Bismuth based, multi-filamentary, high temperature superconductor wire encased in a silver alloy matrix with a thin stainless steel lamination.

Average thickness:	0.255 - 0.285 mm
Minimum width:	4.2 mm
Maximum width:	4.4 mm
Min. double bend diameter (RT):	38 mm[i]
Max. Rated tensile stress (RT):	200 MPa[i]
Max. Rated wire tension (RT):	21 kg
Max Rated tensile stress (77K)	250 MPa[i, ii]
Max. Rated tensile strain:	0.4%[i, ii]

Customer Options:

Minimum amperage (Ic)	Average engineering Current density (Je)[iii]
125 A[ii]	10,700 A/cm²[ii]
135 A[ii]	11,600 A/cm²[ii]
145 A[ii]	12,500 A/cm²[ii]
155 A[ii]	13,300 A/cm²[ii]

Continuous piece length: 100 to 400m[iv]
Insulation options: PTFE or Kapton wrap
Splice options: spliced wire available in longer lengths

[i] Greater than 95% Ic retention
[ii] 77K, self-field, 1μV/cm
[iii] Je is a calculated value based upon average thickness and width
[iv] Longer continuous lengths available upon request

- **HTS can tolerate large stress (250 MPa rather than 150 MPa or so for Nb_3Sn). This value can be further increased with more SS enforcement.**
- **HTS bend radius in R&W magnets can be much smaller (19 mm rather than 70 mm to 100 mm in Nb_3Sn).**

Availability of Second Generation (2G) HTS (YBCO) in Sufficient Quantities

- Second generation (2G) HTS (YBCO) is now starting to become available in larger quantities. For example, even now it can be purchased in 100 m length from American Superconductor. Based on the length scale-up approach used, much larger lengths are expected to become available in future.

- The cost of second generation wire (tape) is projected to be much smaller than the cost of first generation HTS (BSCCO).

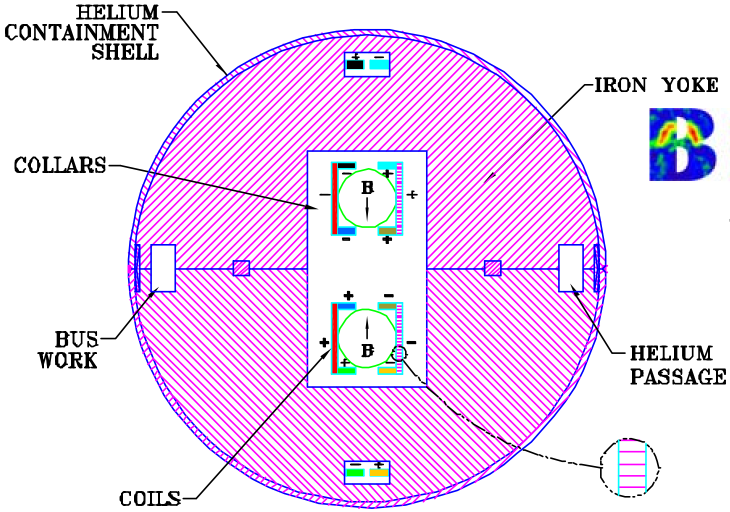
- Second generation wire also has some superior technical properties. In particular incorporation of nano-dots dramatically improves its “in-field” characteristics/performance.

Racetrack Coil Magnet Designs

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

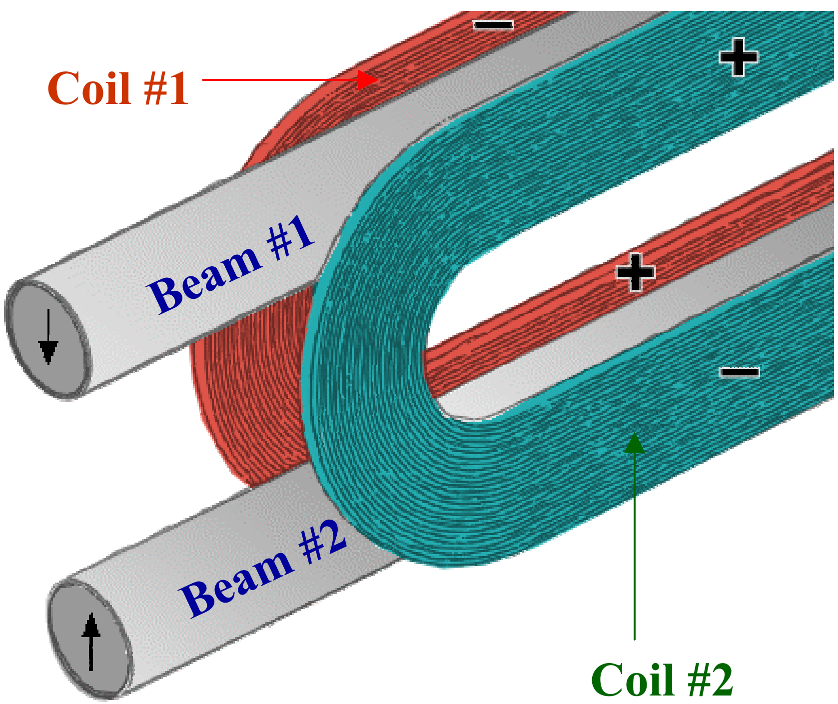
Note:

These designs are technology independent. That means one can either use “Wind & React” or “React & Wind” technology with these designs.



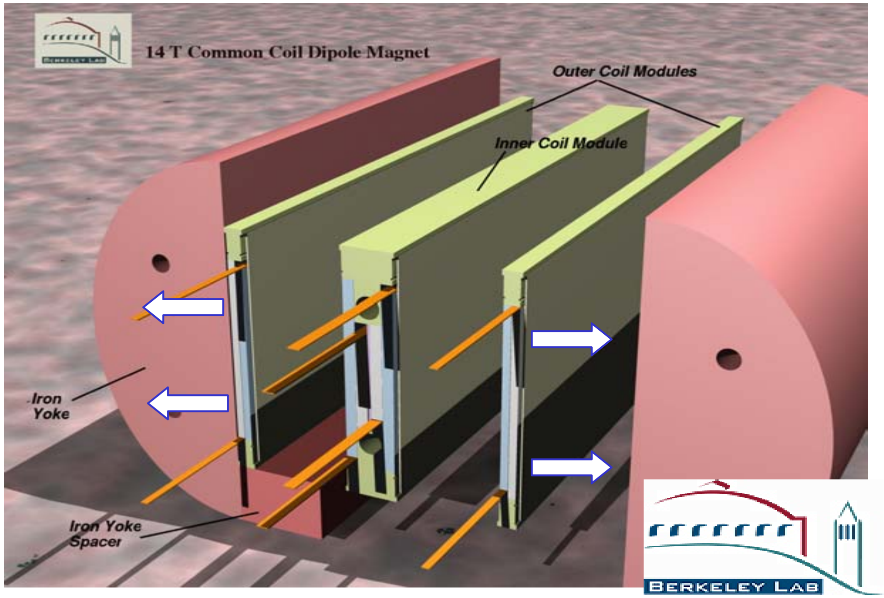
Common Coil Design

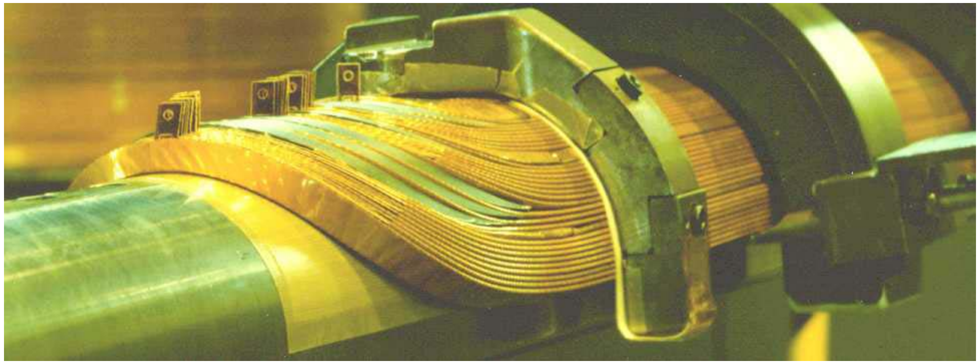
- **Simple 2-d geometry with large bend radius** (determined by spacing between two apertures, rather than aperture itself)
- **Conductor friendly (no complex 3-d ends, suitable for brittle materials such as Nb_3Sn, Nb_3Al and HTS)**
- **Compact (quadrupole type cross-section, field falls more rapidly)**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

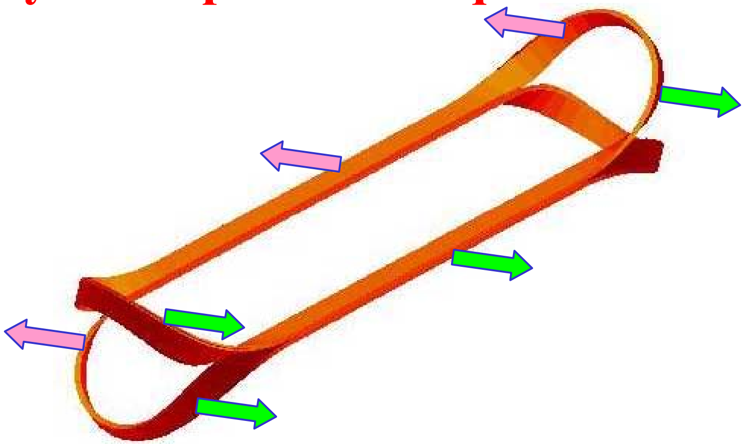
Lorentz Forces in High Field Magnets (Cosine Theta and Common Coil)





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.

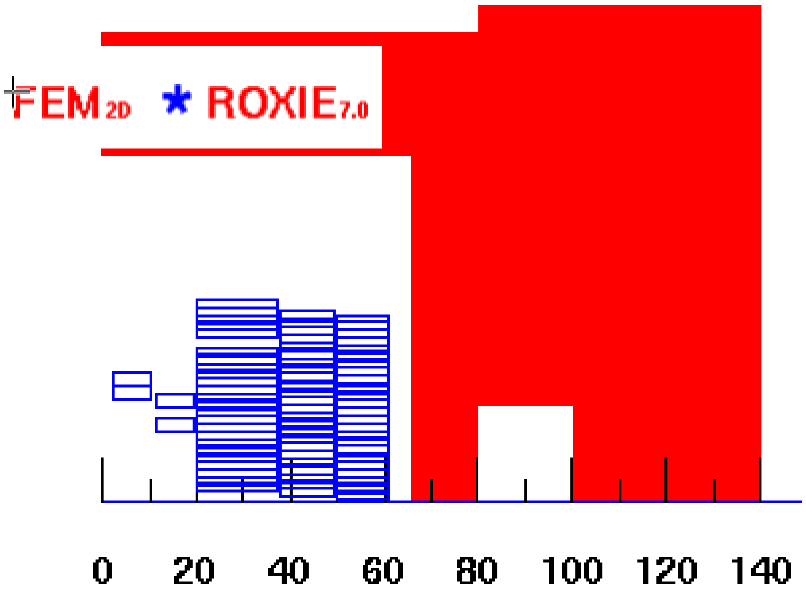
In the common coil design, geometry and Lorentz forces (mostly horizontal) are such that the impregnated modules move as a block. Therefore, the common coil geometry minimizes the internal motion and that should reduce the chance of quench or damage.



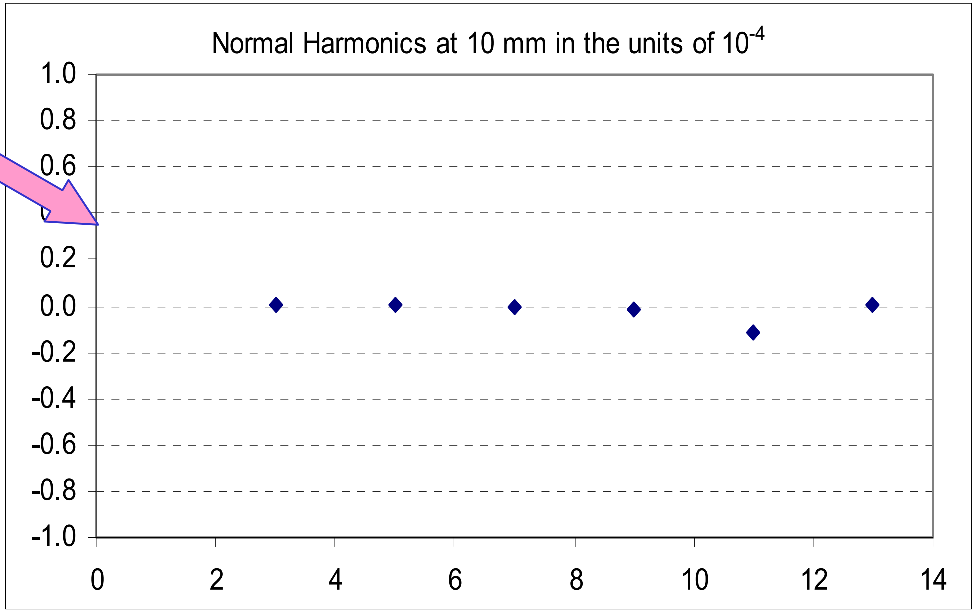
Progress in Field Quality (Geometric Harmonics)

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.



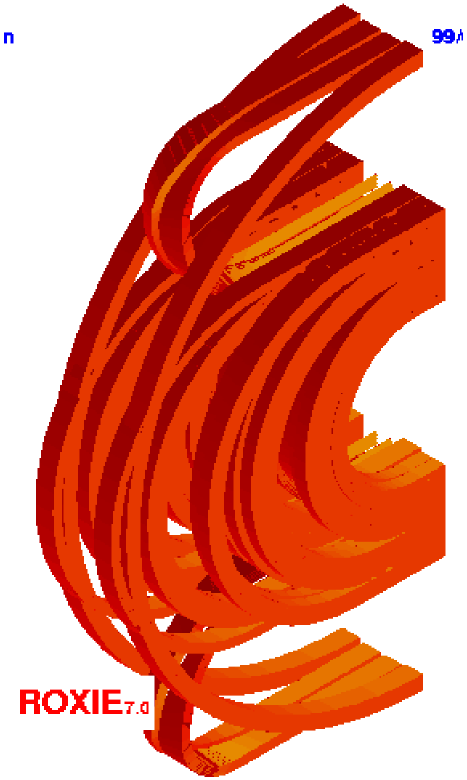
(from 1/4 model)

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.

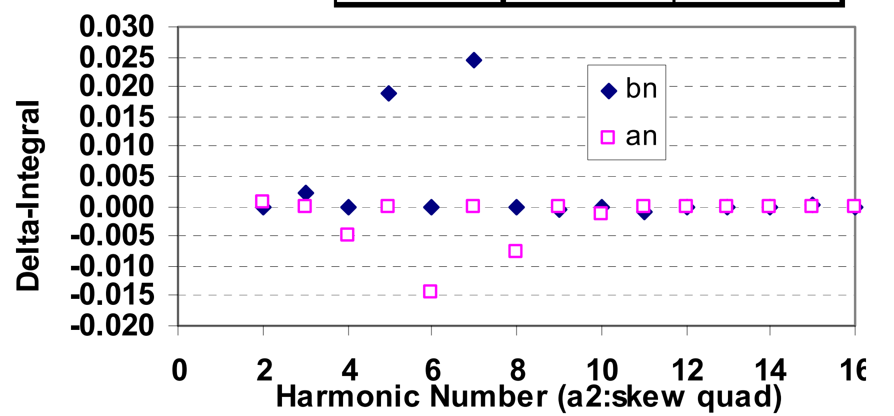


End harmonics in Unit-m

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 ($<10^{-6}$)

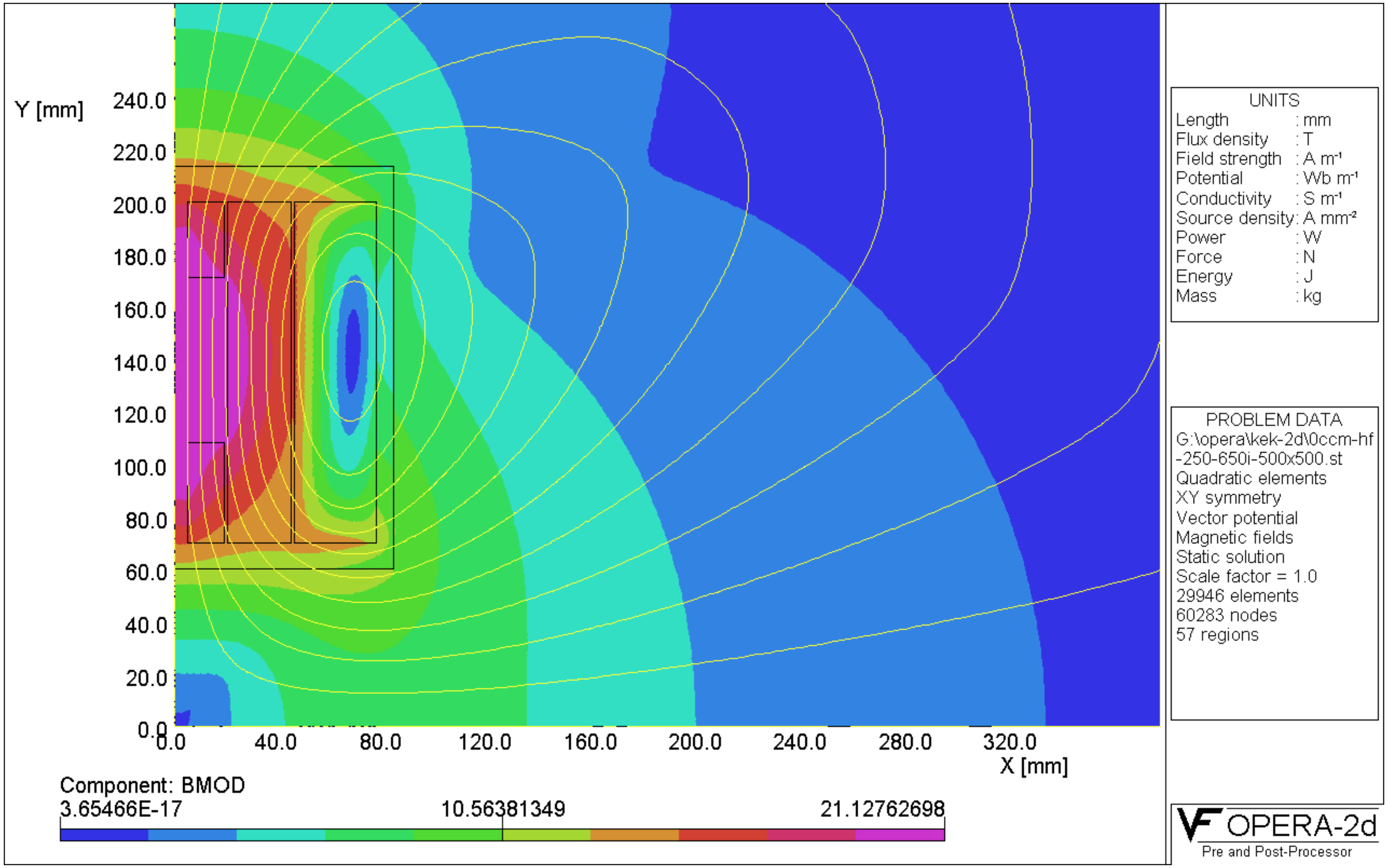
n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000



Poor field quality, excessive conductor requirements, etc. are myth about block designs. A properly designed block dipole uses similar conductor and gives similar field quality as cosine theta does.

20+ T Hybrid Common Coil Dipole Design for LHC Energy Upgrade

Central Field = 20^{+} T



Inner coils:

HTS (>20 T)

Outer coils:

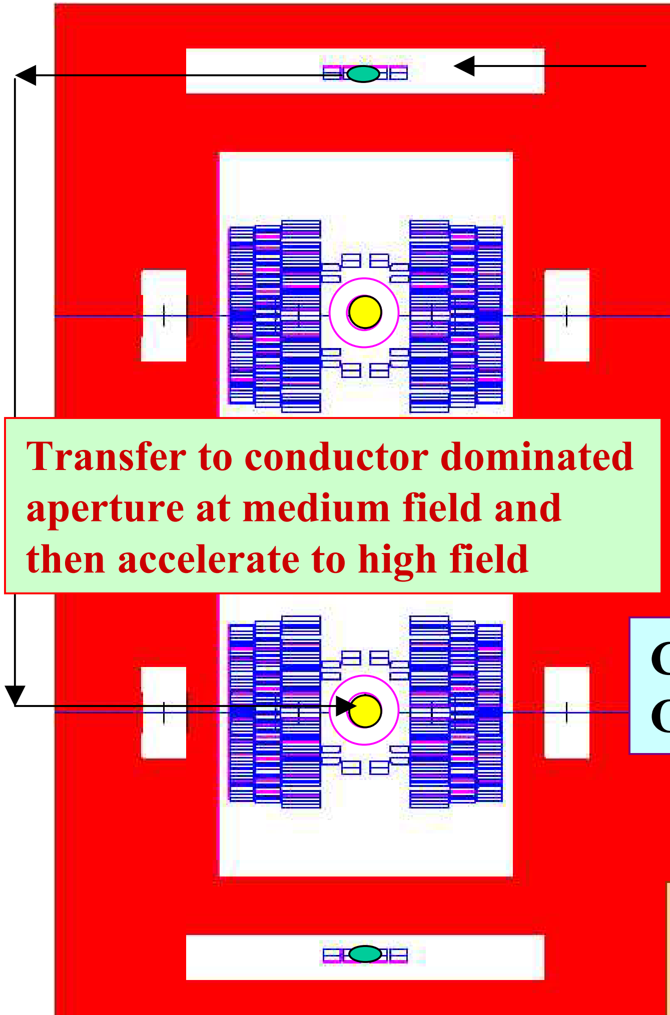
Nb_3Sn (<15 T)

One quadrant of model (1/2 of one of two apertures)

Common Coil Magnet System (Injector + Main Ring) for the LHC Energy Upgrade

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

Due to lack of space for an additional ring in the LHC tunnel, LHC ring can not be used as an injector and must be removed for LHC energy upgrade. The proposed 4-in-1 magnet concept allows the same magnet to be used for both injector and main ring. It also provides significant savings in cost over the separate injector case.



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 problems associated with Nb_3Sn

Conductor dominated aperture Good at high field (1.5-20 T)

Iron dominated aperture Good at low field (0.56-1.5T)

Compact size

*Concept developed while I was at LBL

Common Coil Magnet System (Economical and Technical Advantages)

• **Large Dynamic Range**

~ 40 instead of usual 8-20.

May eliminate the need of the second largest ring. Significant saving in the cost of LHC 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.

• **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!
Reduce high field aperture, say to 25 mm?

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

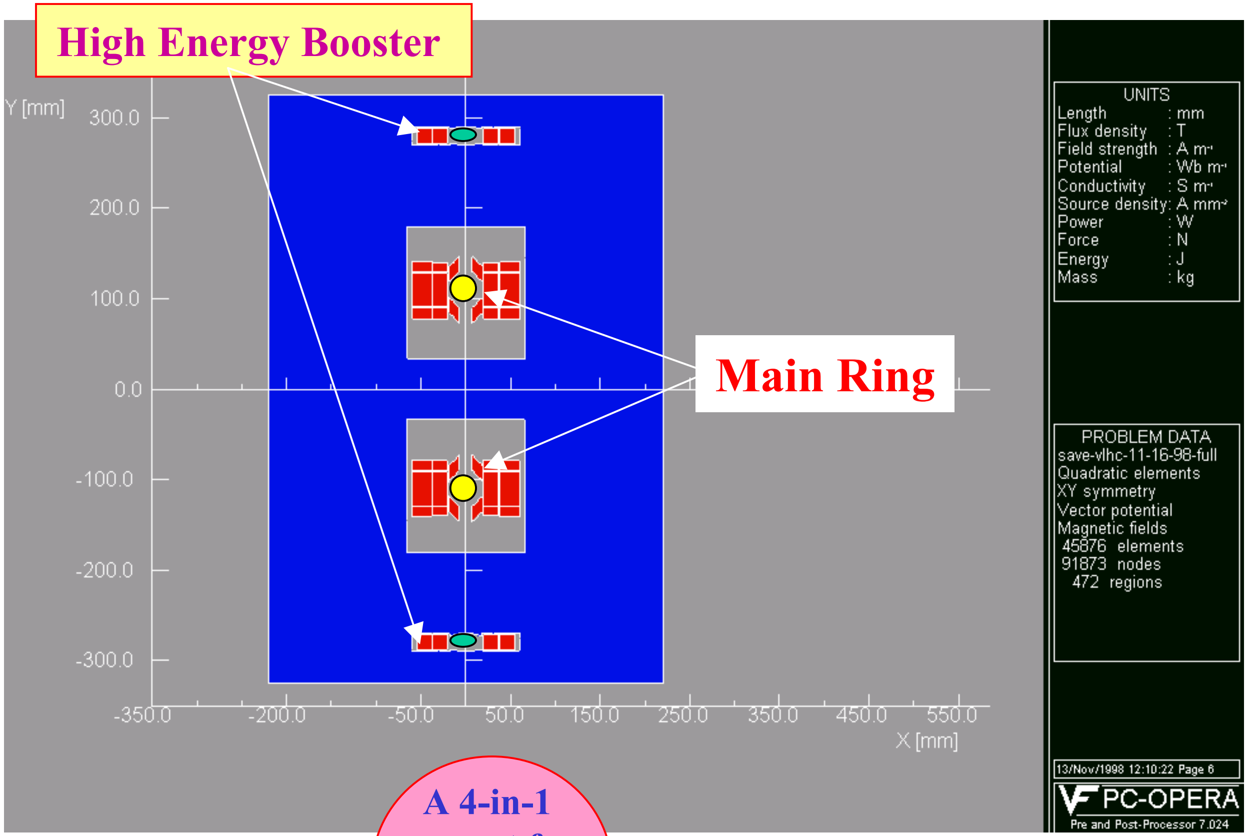
• **Compact Magnet System**

As compared to two machines with several apertures.

A Combined Function Common Coil Magnet System for Lower Cost VLHC

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

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



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

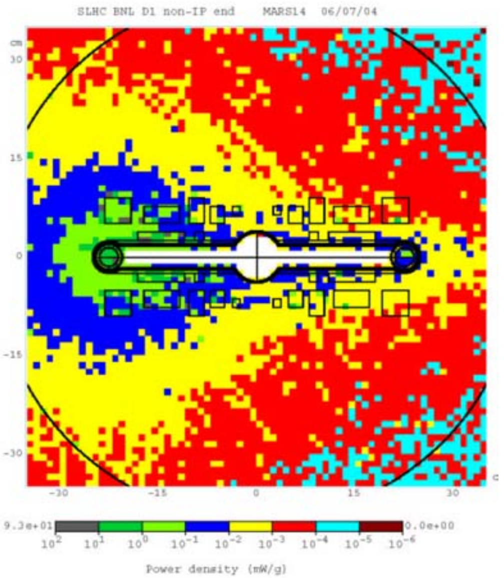
Open Midplane Dipole for

LHC IR Upgrade in Dipole First Optics

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:

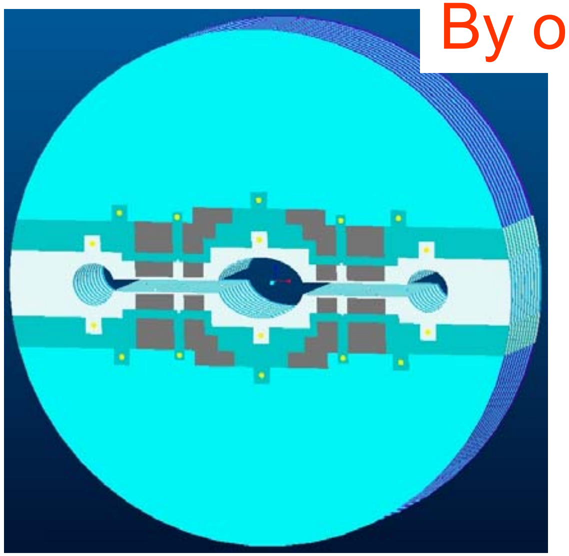


- How to design magnets that can survive these large heat and radiation loads against pre-mature quench and life time of magnet components?

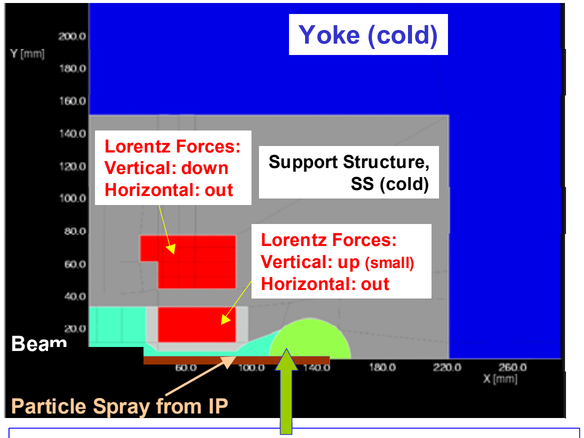
- What is the cost of removing these large heat loads both in terms of "new infrastructure" and "operating cost" ?

In the proposed "Open Midplane Design" the particle spray from IP deposits most of its energy in a warm absorber instead in superconducting coils or other cold structures.

A True Open Midplane Design



By open midplane, we mean truly open midplane:



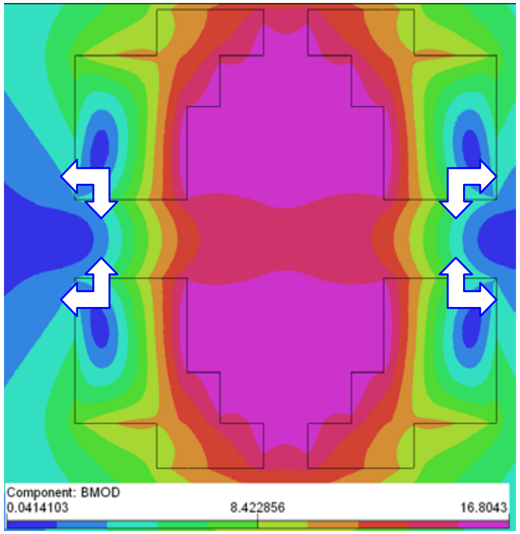
A large amount of particles coming from high luminosity IP deposit energy in a warm (or 80 K) absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.

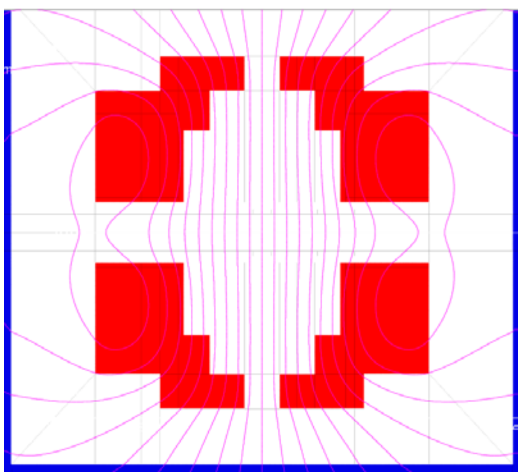
Particle spray from IP (mostly at midplane), passes through an open region to a warm (~80 K) absorber sufficiently away from the coil without hitting superconducting coils or any structure near it.

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.

Therefore, earlier designs did not work so well in protecting superconducting coils from energy deposition.

Open Midplane Dipole Design
Challenges





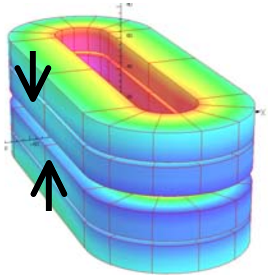
- In usual cosine theta or block coil designs, there are large attractive forces between upper and lower coils. How can these coils hang in air with no structure in between?
- The ratio of peak field in the coil to the design field in the aperture appears to become large for large midplane gaps.
- The large gap at midplane appears to make obtaining good field quality a challenging task. Gap requirements are such that a significant portion of the cosine theta, which normally plays a major role in generating field and field quality, must be taken out from the coil structure.

Could there be a solution that can satisfies all of above requirements?

With such basic challenges in place, don't expect the design to look like what we are used to seeing in conventional magnets.

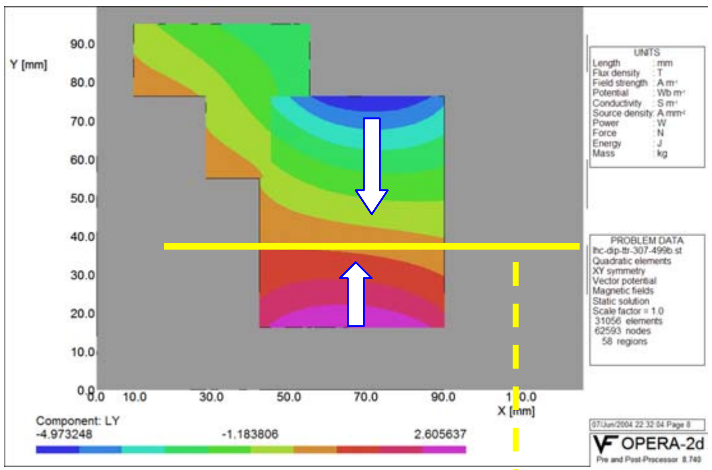
Challenge #1: Lorentz Forces between coils

A new and major consideration in design optimization



In conventional designs the upper and lower coils rest (react) against each other. In a truly open midplane design, the target is to have no structure between upper and lower coils. Structure generates large heat loads and the goal is to minimize them.

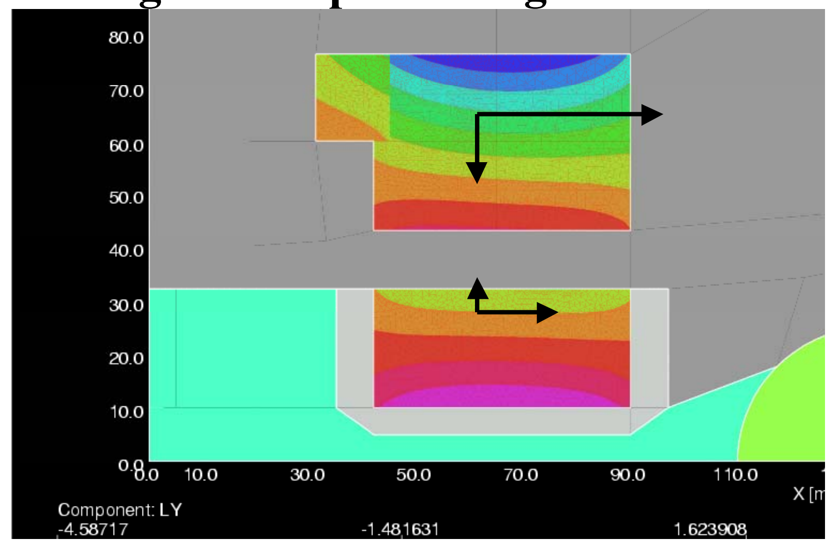
Original Design



Zero vertical force line

New Design Concept to navigate Lorentz forces

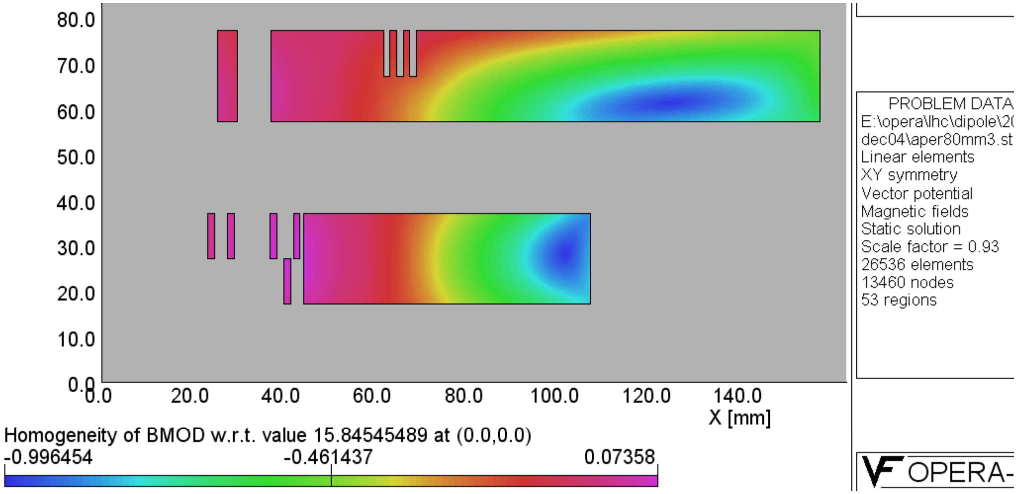
Lorentz force density (Vertical)

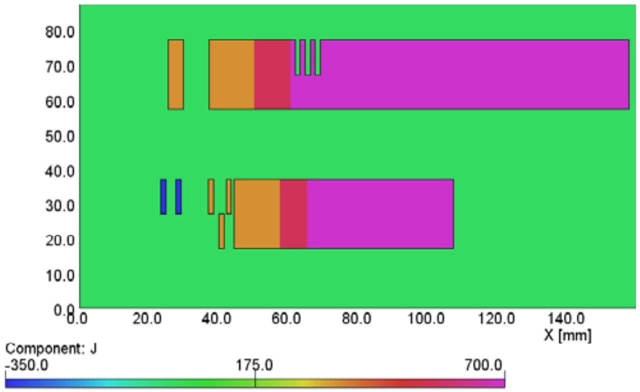


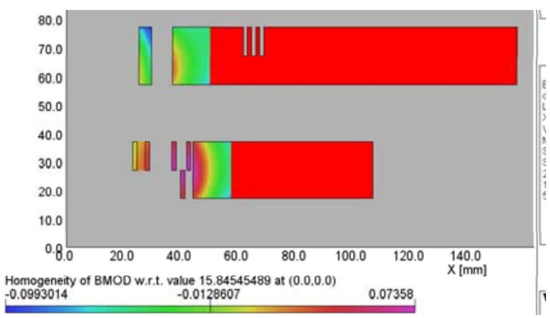
Since there is no downward force on the lower block (there is slight upward force), we do not need much support below if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

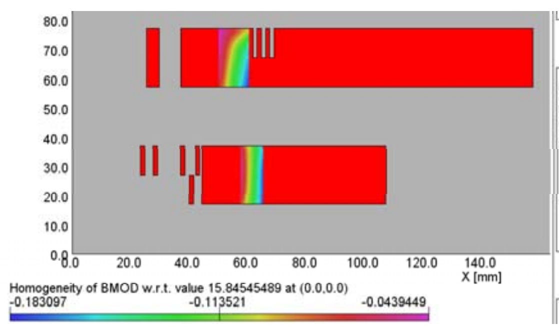
Challenge #2: Peak Field

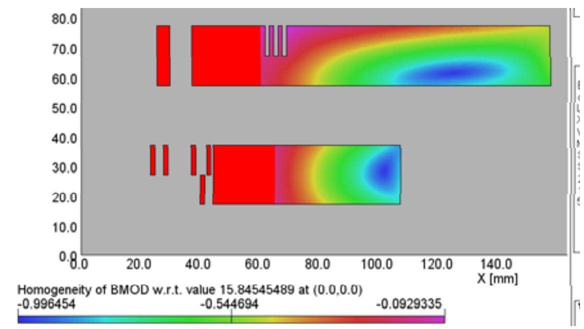
Several designs have been optimized with a small peak enhancement: ~7% over B_o











Quench Field: ~16 T with J_c = 3000 A/mm², Cu/Non-cu = 0.85

Quench Field: ~15.8 T with J_c = 3000 A/mm², Cu/Non-cu = 1.0

Challenge #3: Field Quality

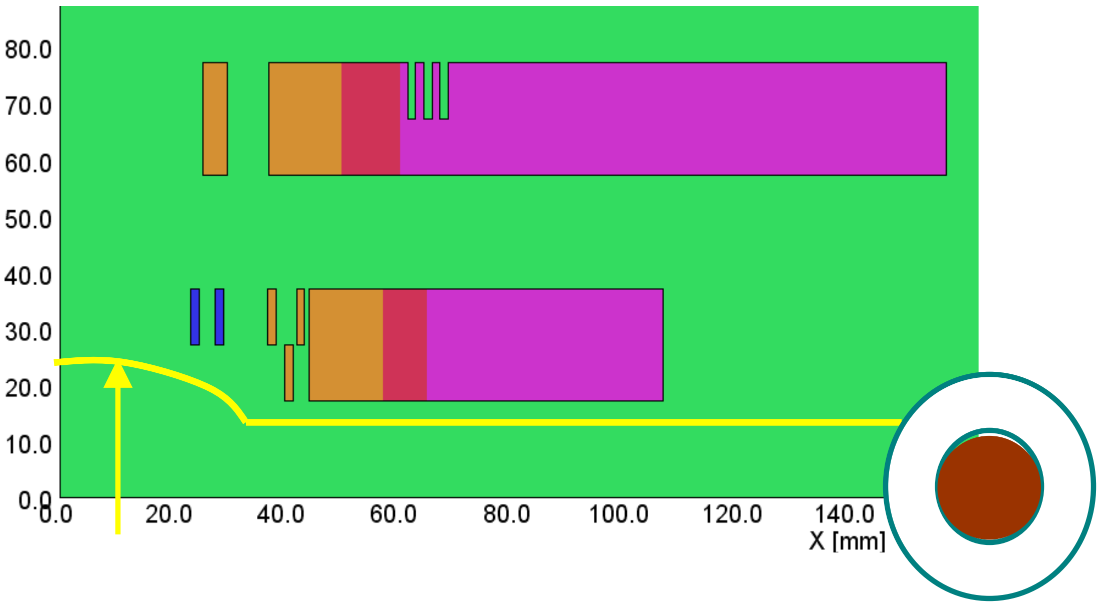
Coil-to-coil gap in this design = 34 mm (17 mm half gap)

Horizontal aperture = 80 mm

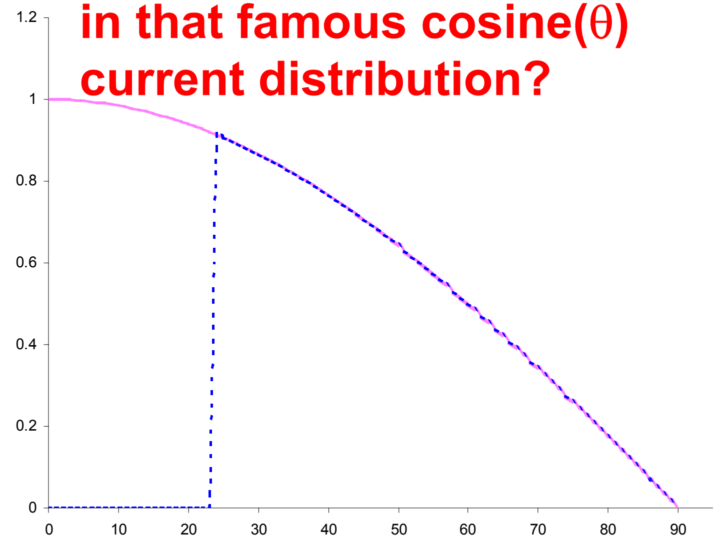
⇒ Vertical gap is > 42% of horizontal aperture (midplane angle: 23°)

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

One quadrant of the design



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

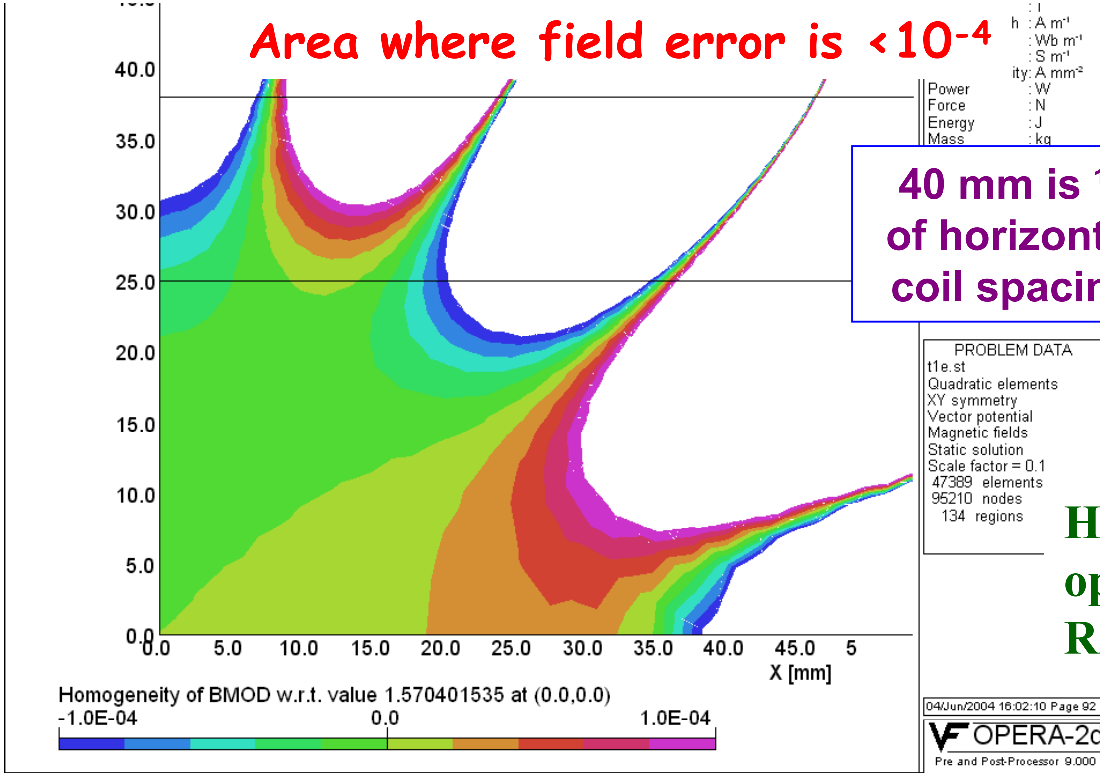


We did not let prejudices come in our way of optimizing coil - e.g. that the coil must create some thing like cosine theta current distribution !

Field Harmonics and Relative Field Errors in an Optimized Design

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

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



40 mm is ½ of horizontal coil spacing

Harmonics optimized by RACE2dOPT

(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

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.

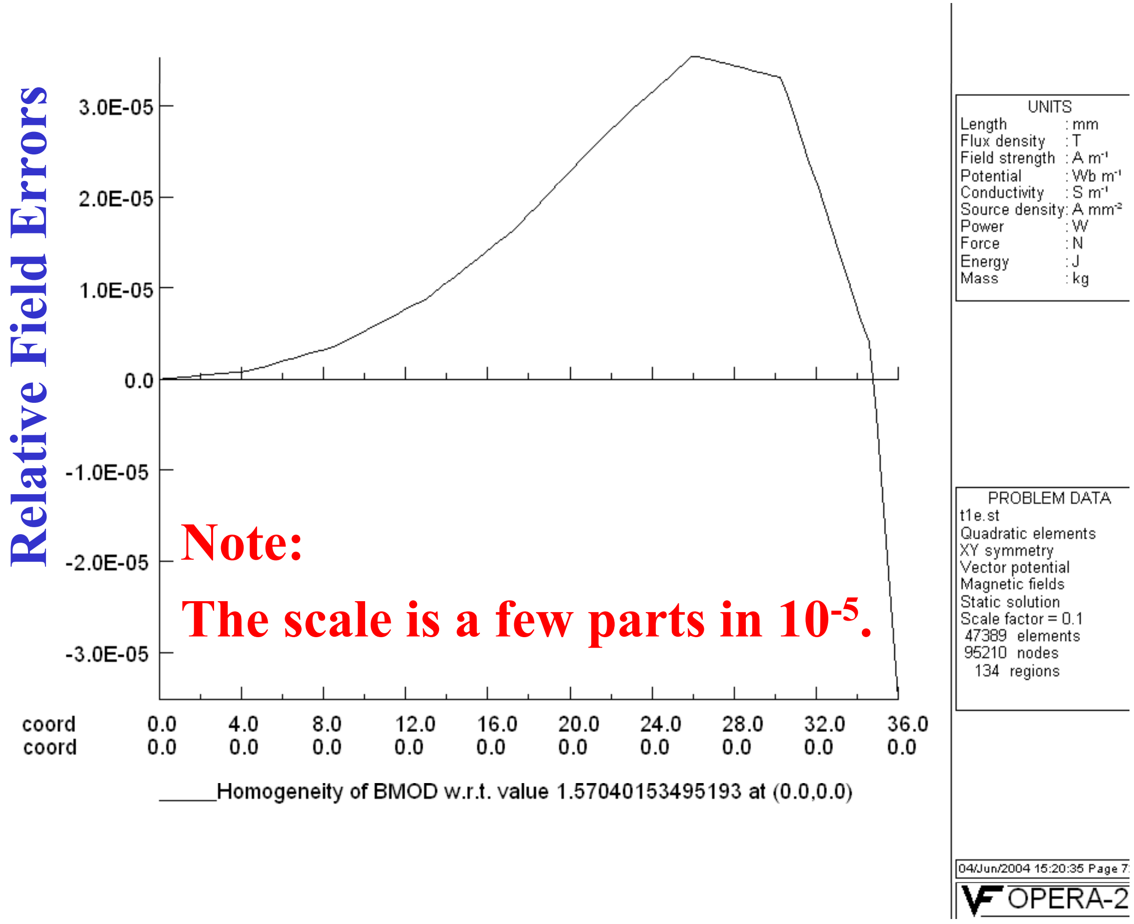
Optimization programs are being modified to include various scenarios.

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:



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.

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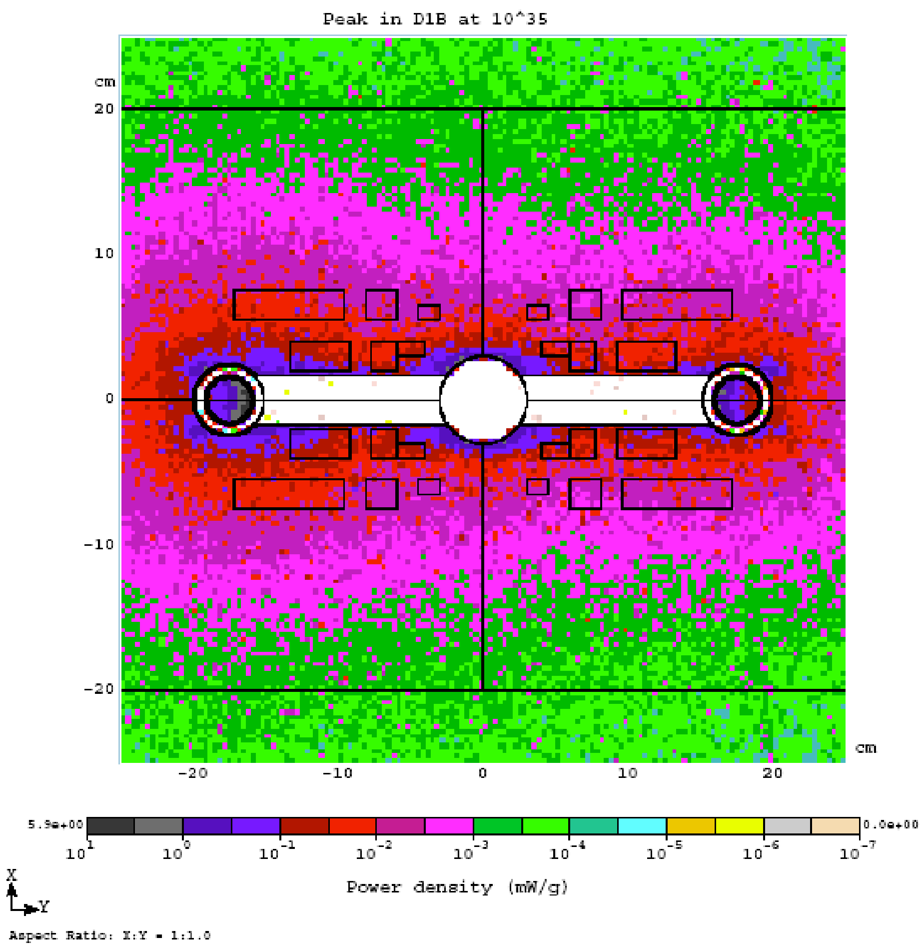
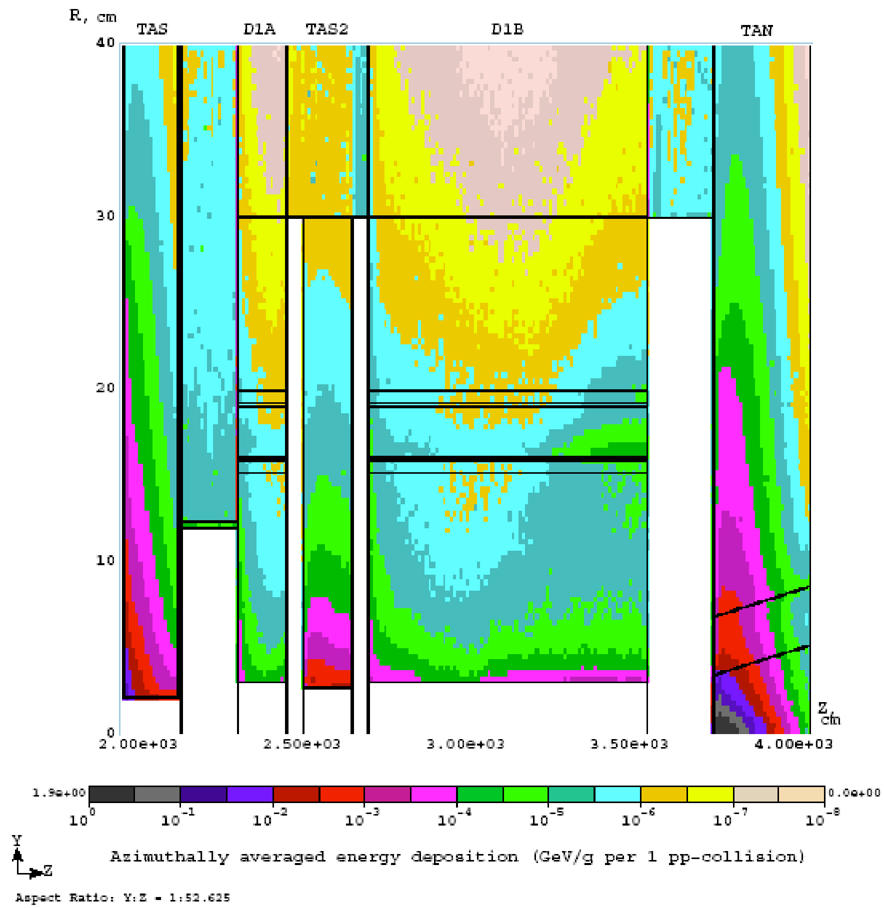
Bottom Line: The Energy Deposition in this Open Midplane Dipole Design

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

Design Iterations (A to F)

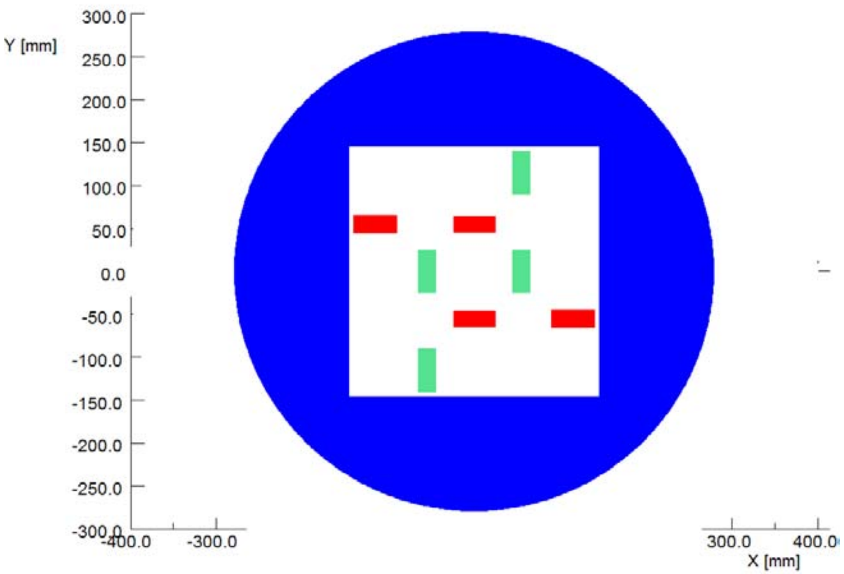
A number of designs were investigated. Here is a Summary:

	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

Modular Quadrupole Design Concepts

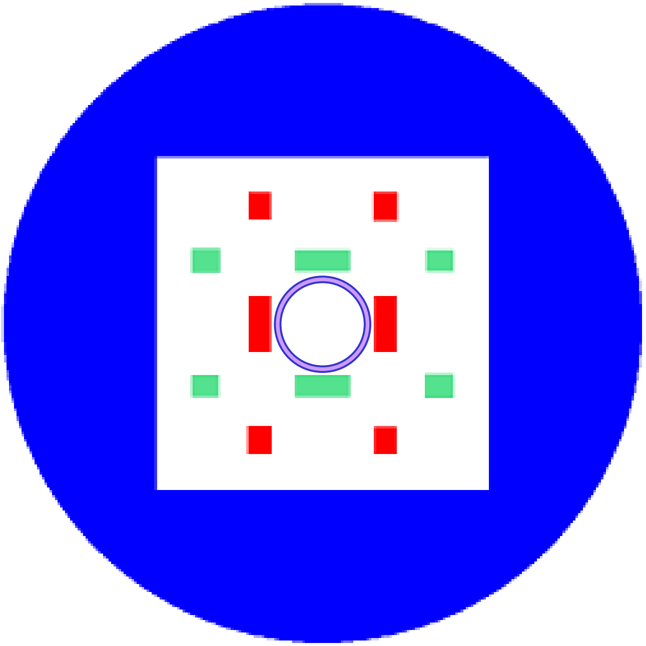
Type A: Simpler



This is not 8 fold symmetric.

In addition to b_6, b_{10}, b_{14}, …, one also gets a_6, a_{10}, a_{14},… These harmonics need to be minimized.

Type B: Symmetric

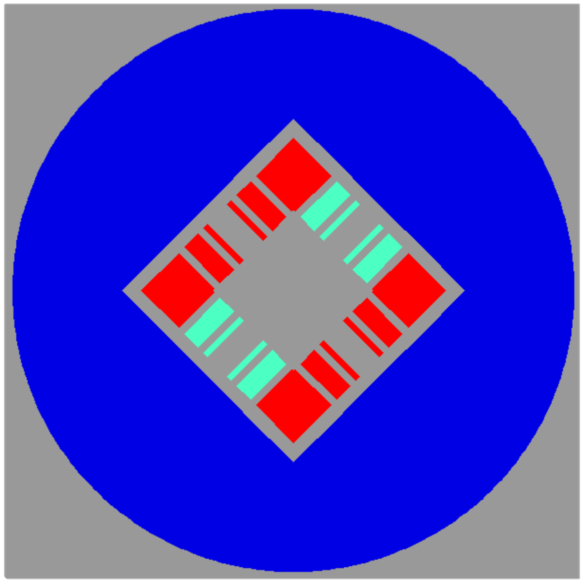


No skew harmonics due to symmetry.
Relatively more complex structure.
May have lower peak field. Note peak field is not a major concern for HTS.

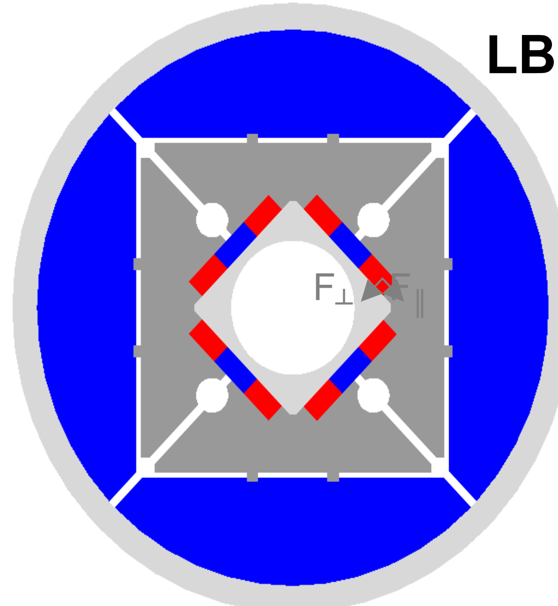
NOTE: The design needs about twice the conductor. But for a few high performance magnets, conductor cost is only a fraction of overall magnet development cost.

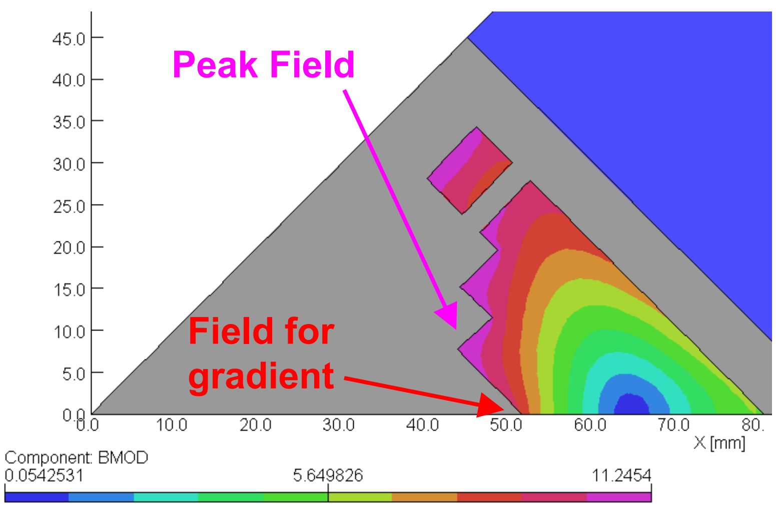
Previous Racetrack Designs
(Considered for LHC upgrade or VLHC)

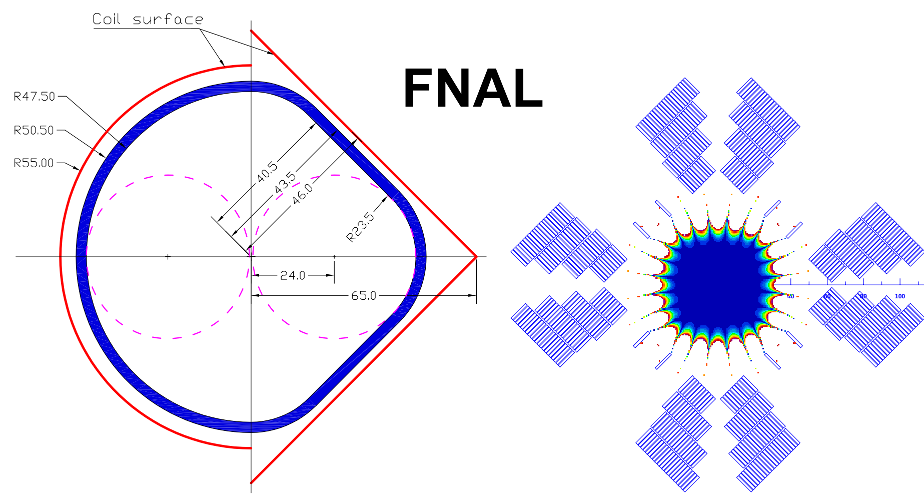
BNL designs for VLHC (ASC'02)



None of these designs were efficient in generating high gradient



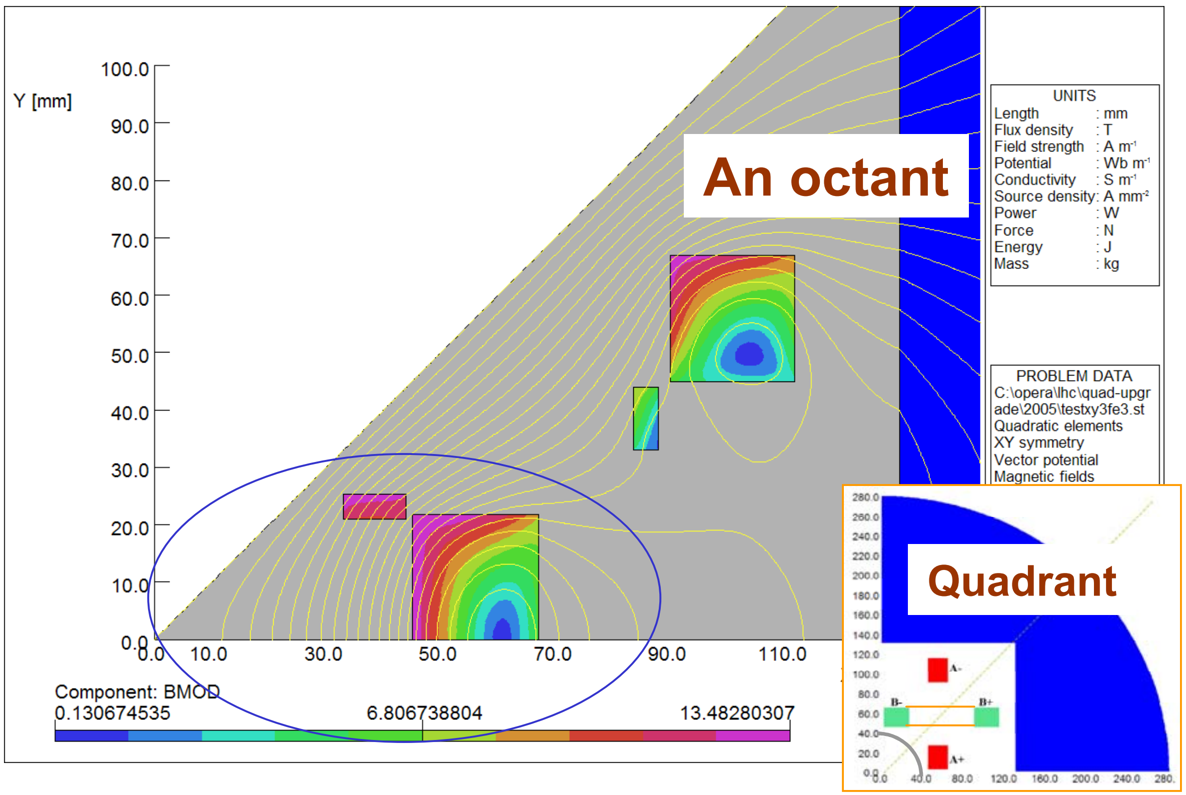




Efficient Design to Create Gradient
(not necessarily to minimize conductor usage)

• 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.

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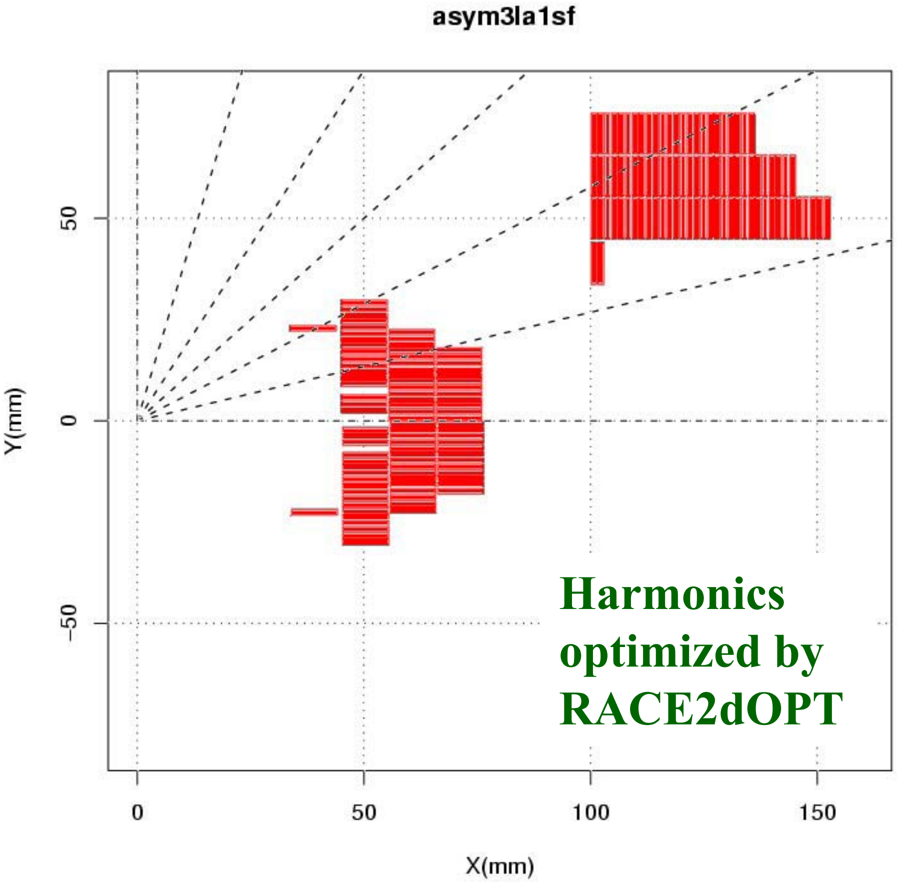
3-Layer Design for Higher Gradient

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



Field harmonics optimized with RACE2DOPT at 30 mm Ref. radius (in 10^{-4} units at 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

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

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.

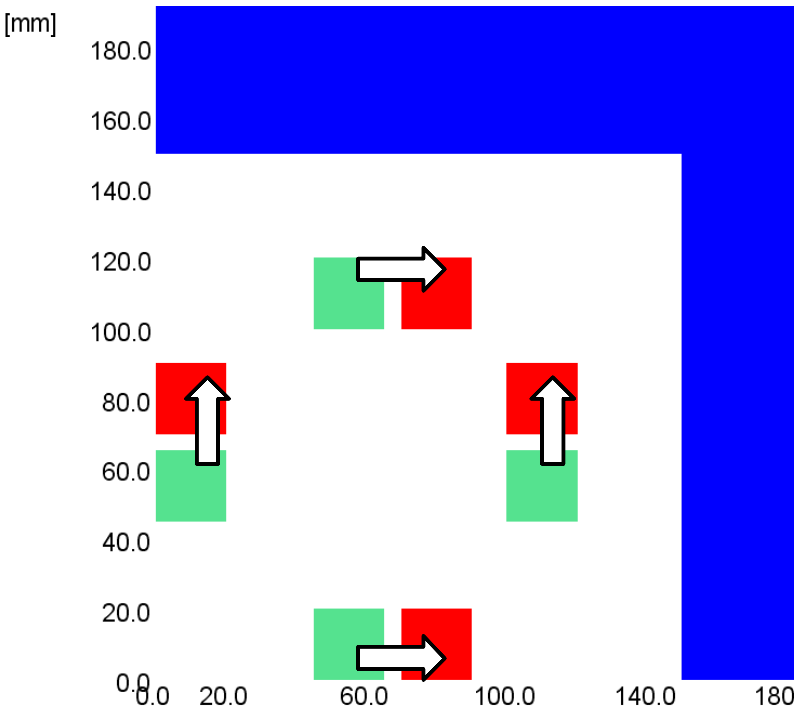
Coils are moved away from the center in going from

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.



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, coil and magnet parameters can be accommodated (such deviations are encountered during R&D phase)
- More unique R&D features for "proof-of-principle" magnets
  - To increase field gradient by simply adding more coil modules
  - To increase aperture move coils further out. This should help determine aperture and field gradient combination for beam optics by building and demonstrating a magnet at an early stage.
  - It allows a broad-based magnet R&D program, as high gradient modular quadrupole, common coil dipole, open midplane dipole, etc.- all can be built and tested using the same basic coil modules.

The support structures need to be designed to accommodate such provisions or it may be better to design separate structures for different applications.

Possible Evolution of BNL Racetrack Coil Program to Racetrack Design & Technology Study Program

- **BNL is building Nb_3Sn racetrack coils as a part of LARP magnet program.**
- **The coils with flat racetrack geometry are being built because they are simpler and offer a better likelihood of initial success.**
- **At present the BNL program is only a "coil program" with no path to any "LARP magnet design" directly attached to it.**
- **However, this "coil program" could evolve towards a limited examination of future designs and/or technology.**
- **In order to do above, the minimum coil bend radius must be increased. At present the bend radius is too small to be useful.**

Summary

- Racetrack coil geometry offers a good likelihood of success in making magnets with brittle conductors due to its simple, 2-d geometry.
- A number of racetrack coil magnet designs with good field quality have been developed. Few examples: common coil dipole, open midplane dipole, modular high gradient quadrupole, common coil magnet system.
- "React & Wind" approach with racetrack coil geometry offers a viable and attractive option for making "long" magnets with brittle conductors.
- Test results of BNL "React & Wind" common coil dipole shows that one can successfully build magnets using "React & Wind" Technology.
- Present day HTS provides higher engineering (overall) current density than Nb_3Sn in designing magnets that must operate above ~14 T.
- Racetrack coil magnet designs and technologies could/should be considered as a apart of LARP's broad magnet development program.
- BNL racetrack coil program can be evolved to study some of these racetrack coil designs and magnet technologies.