

# Magnet R&D Issues for the Future

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- **Develop new designs and theoretical formalism**
  - Apart from advancing the present design and technology, examine alternate design concepts
  - Develop new model/formalism where the present one does not work so well; e.g. computation of random errors in magnets
- **Systematically understand existing technology**
  - Experimental program to objectively understand the rules
    - art of building magnets => science of building magnets
  - This would reduce conservatism and hence reduce the cost
- **Develop new technology**
  - First do at small scale: cost effective & rapid turn around
  - Then demonstrate them in an accelerator type magnet

# Lowering the Cost of Magnets

- Develop designs that have smaller coldmass  
If there are technical questions, examine them experimentally
- Minimize the conductor amount  
While comparing two completely different designs (at a few percent level compare other factors for cost minimum)
- Investigate the lower cost manufacturing techniques

## Magnet Cost: Coldmass and/or Yoke Size

Smaller coldmass is expected to reduce the cost of magnets

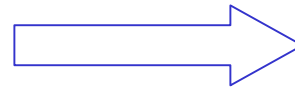
Recent cosine theta warm iron designs from Fermilab are interesting examples

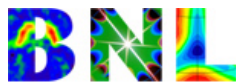
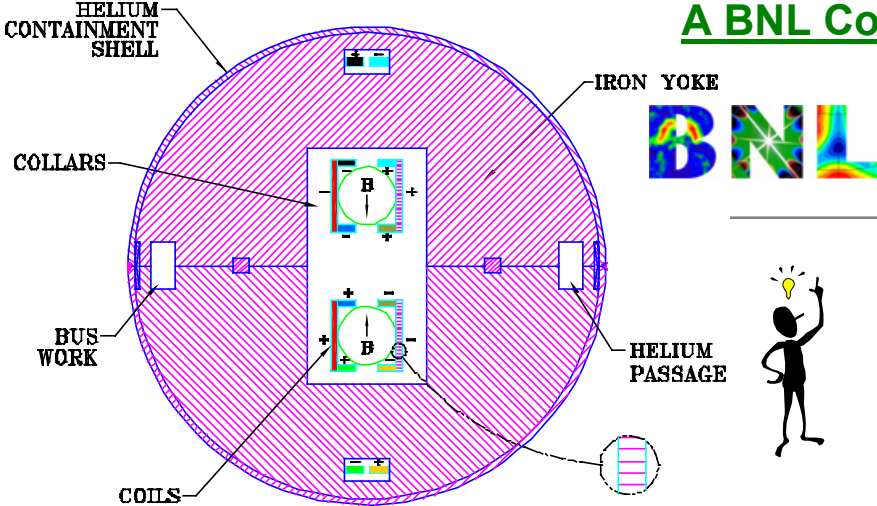
We should examine warm iron designs for common coil as well

However, yoke also contributes to the support structure, depending on the design

We should look for the overall cost minimization

Yoke size in common coil designs

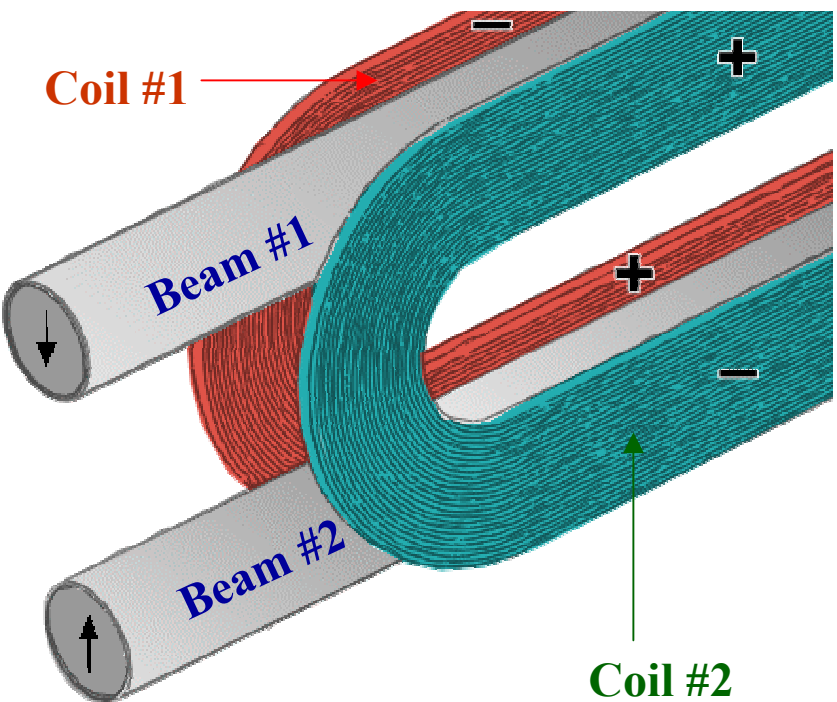




# Common Coil Design



- **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 - most for H.F. are - Nb<sub>3</sub>Sn and HTS)
- **Compact** (compared to single aperture LBL's D20 magnet, half the yoke size for two apertures)
- **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**

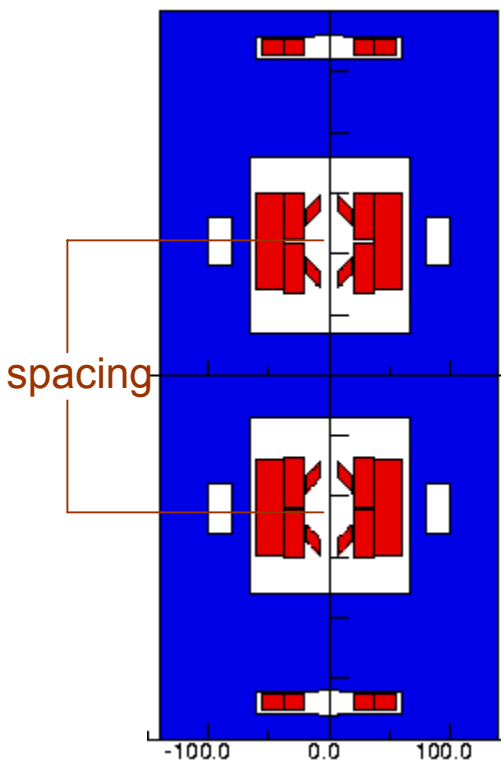
# Common Coil Design Optimization (Aperture Spacing/Magnet Size)

The common coil commercial claimed that it makes compact magnet. However, increased aperture spacing in any 2-in-1 magnet would increase the size of the yoke. Increase may be due to (a) field quality considerations or (b) due to cable degradation consideration. This may not be necessary.

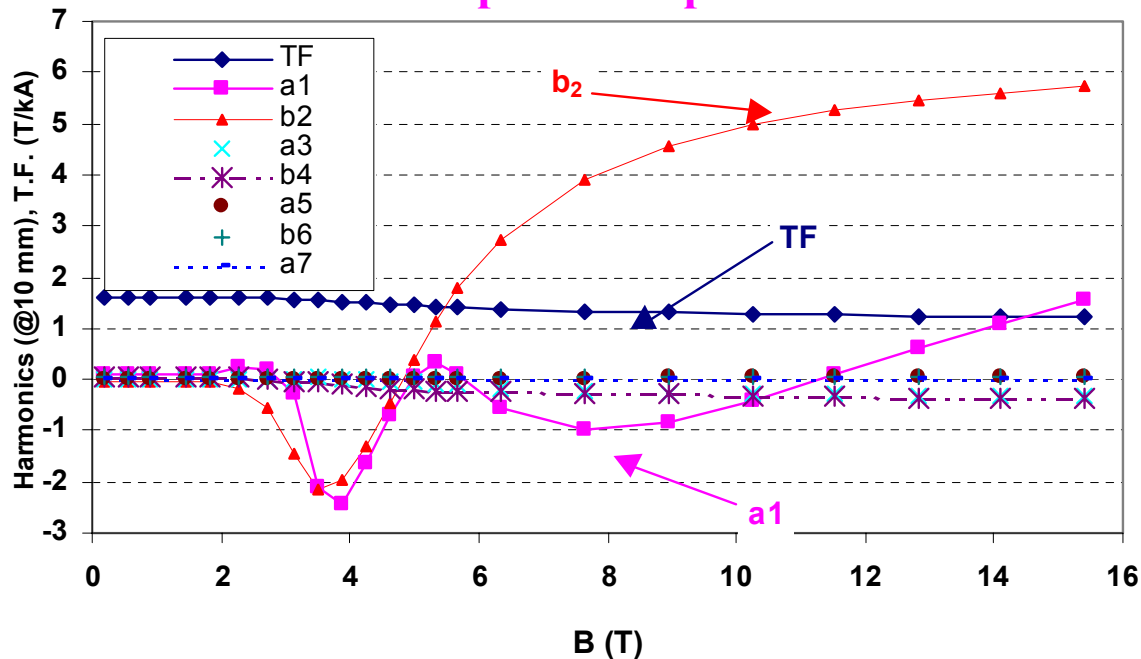
Field Quality: See example below => low a1 saturation for an aperture separation of 220 mm

**Ignore coils,  
examine yoke**

A Compact Design (lower cost) 15 T, 4-in-1 dipole.  
2.4 times smaller than single aperture 13.5 T D20;  
1.4 times smaller than dual aperture 9-10 T LHC



**a1 saturation for aperture separation of 220 mm**

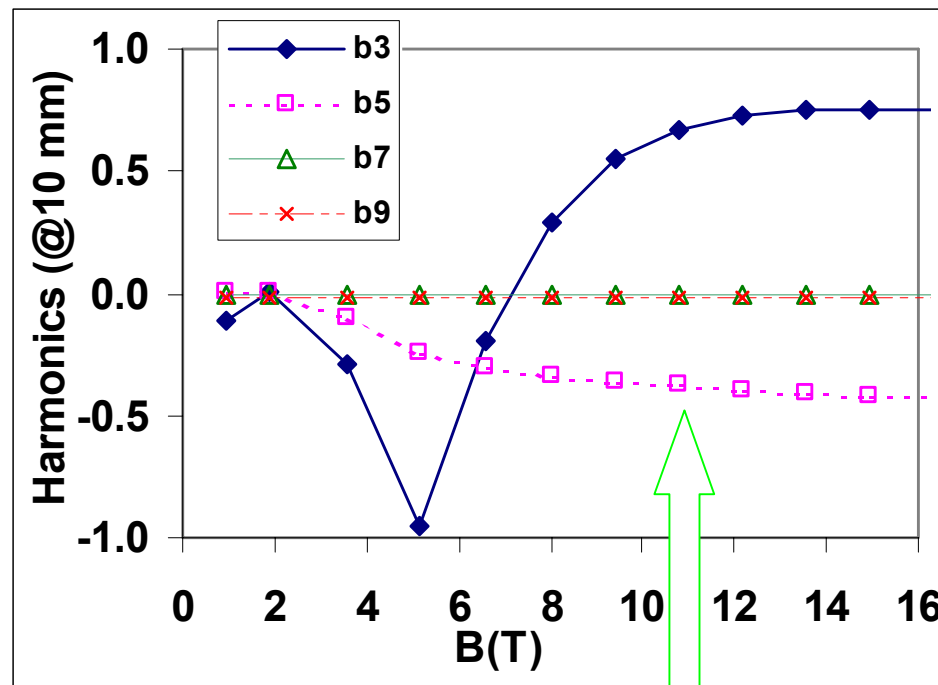


# Reduction in Allowed Saturation-induced Harmonics

**New designs: ~ part in  $10^4$**   
**Satisfies general accelerator requirement**

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

b3 is sextupole here



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

# Small Yoke: Cable Degradation Issue

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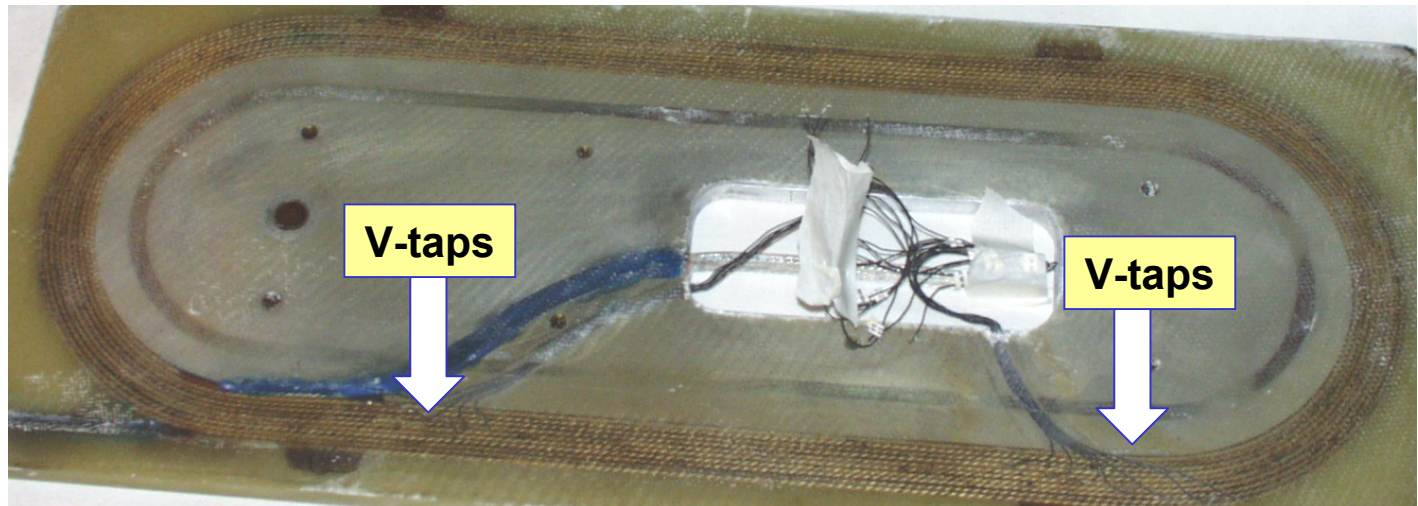
We use bend diameter of 140 mm (LBL also uses the same numbers in the common coil magnets built so far).

There are no experimental evidence of any cable degradation at this bend diameter (and many conductor expert say no theoretical reasons, as well).

Cable degradation in  $Nb_3Sn$  was perhaps over-stated (LBL 14.7 T magnet)

Then why have increased aperture spacing (in a properly optimized design, as demonstrated), it is not needed for field quality reasons.

Have many voltage taps to find degradation or other problems, experimentally.



Compromise first and find later may be prudent philosophy when developing a magnet for specific application in a time bound project. But it may not be the best way to develop technology as we get stuck with those compromises.



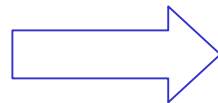
## Magnet Cost: Amount of Conductor Required

Don't worry at a few percent level at this stage.

But pay serious attention at 10% or more level. After all, in conductor dominated magnet, the cost of conductor plays a dominating role in the determining the cost of the magnet.

Properly optimized designs of both common coil and cosine theta magnets should use about the similar amount of conductor for the similar field quality.

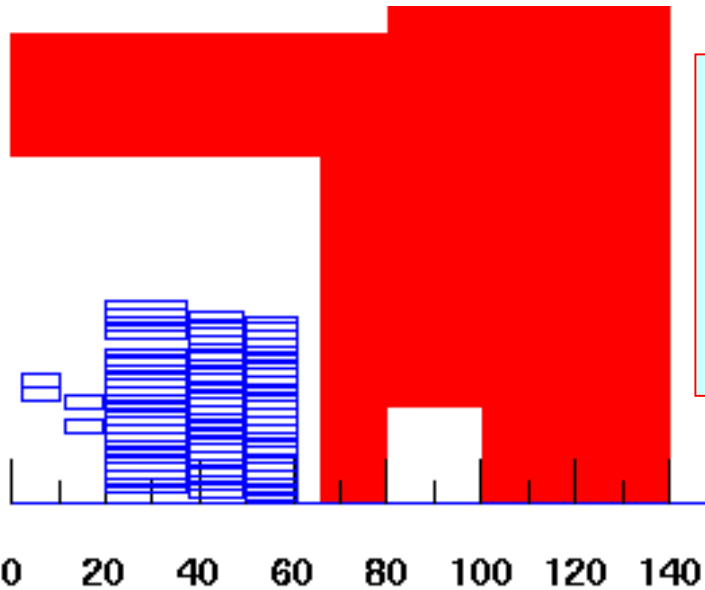
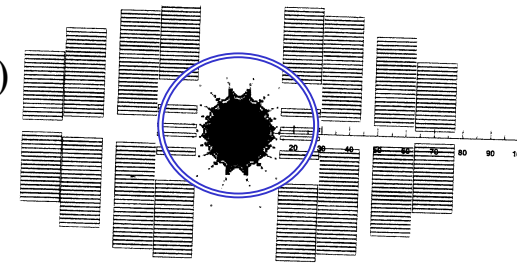
Proof follows



# Different Designs for Field Quality Design Optimization and conductor requirements

Conductor is cost driver (10% difference should be an important design consideration)

(Sabbi, et.al)



Recent common coil design from Fermilab uses the similar amount of conductor as cosine theta design

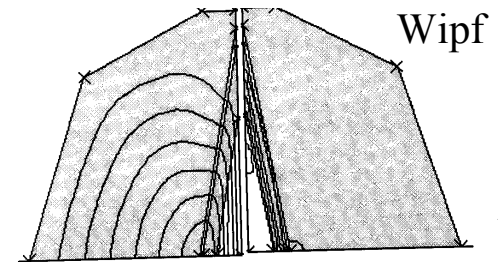
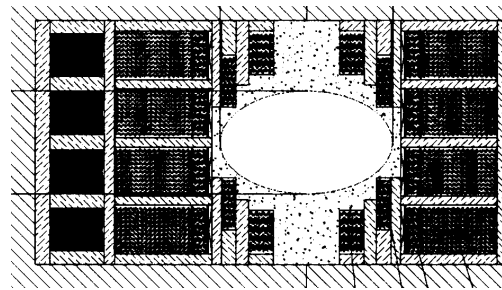


Fig 21: Idea for possible high field dipole based on Leeb and Umstatter design [22]: picture shows flux lines on left hand side and constant field contours on right left hand side

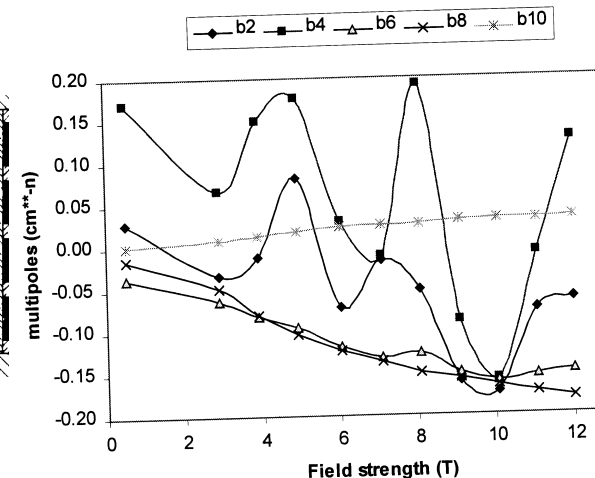
MAIN FIELD: -1.86463 (IRON AND AIR):

Harmonics:  $10^{-5}$

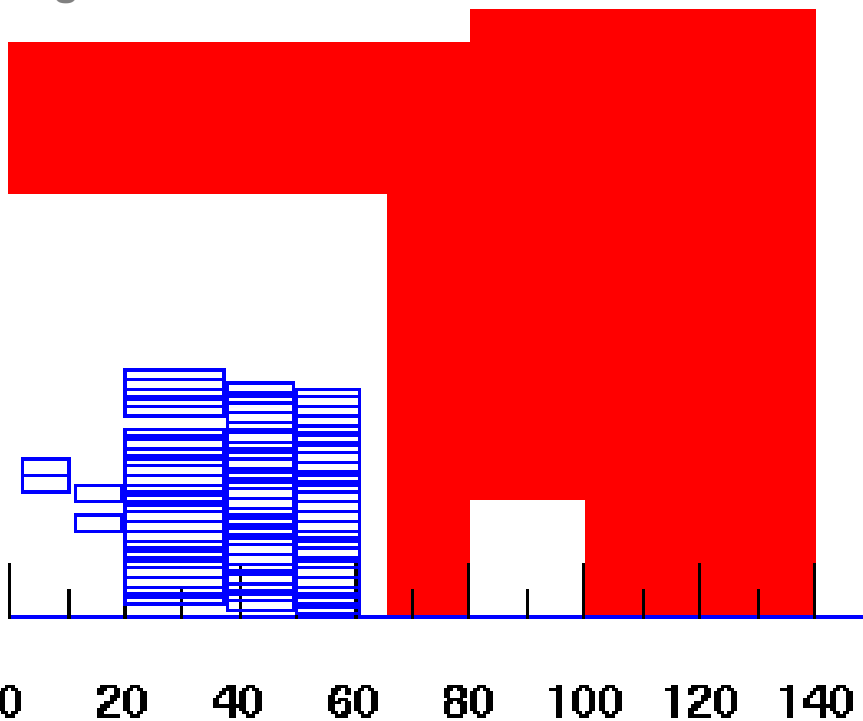
b 1: 10000.000	b 2: 0.00000	b 3: 0.00308
b 4: 0.00000	b 5: 0.00075	b 6: 0.00000
b 7: -0.00099	b 8: 0.00000	b 9: -0.01684
b10: 0.00000	b11: -0.11428	b12: 0.00000
b13: 0.00932	b14: 0.00000	b15: 0.00140
b16: 0.00000	b17: -0.00049	b18: 0.00000



Texas A&M  
(McIntyre, et.al)

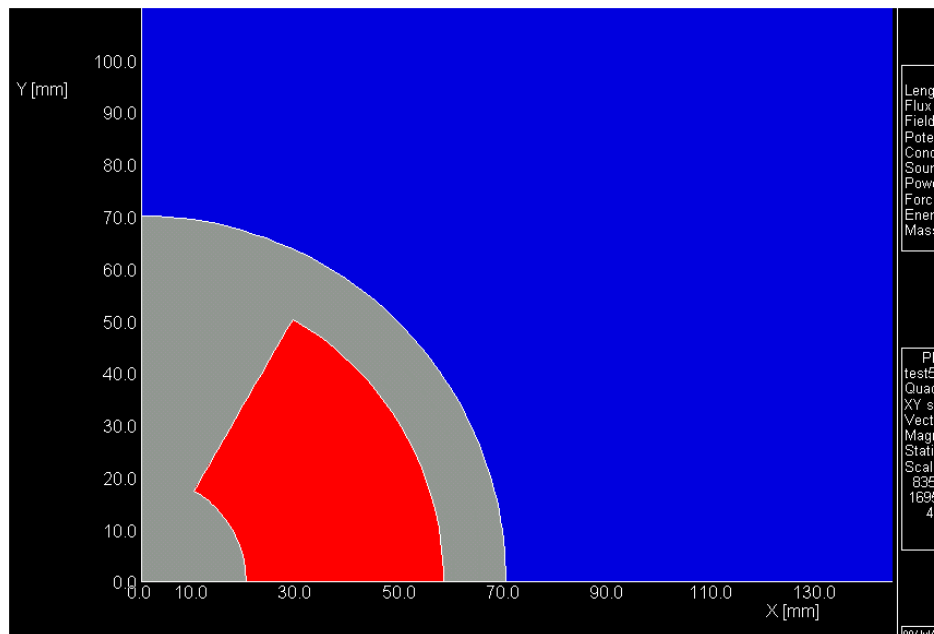


# Comparison of Conductor Uses in Common Coil and Cosine Theta Designs



Common coil design with good field quality  
(all harmonics  $\sim 10^{-5}$  or less at 10 mm)

**B<sub>ss</sub> ~ 14.7** with  $J_c = 2200 \text{ A/mm}^2$  at 12 T



A cosine theta design with 60 degree block.

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

$J_c = 2200 \text{ A/mm}^2$ ;  $\text{Cu/Sc} = 0.9$ ;  $J_{cu} \sim 1600 \text{ A/mm}^2$

**B<sub>ss</sub> ~ 14.3 T**

## Suggested Conclusion:

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

# Auxiliary Coils or Similar Scheme

Conductor requirement would be high if significant amount of conductor is removed from midplane and no conductor is placed beyond 60-70 degree (or near pole)

Does the auxiliary coil or similar configuration compromise the magnet performance?

Find out experimentally. Accumulated forces are small there. Design structure to reduce cost.

Recent designs from LBL for RD5 (5?)

Recent design from FNAL.

# Magnet Cost: Conductor Usage Grading

Grading increases number of coils and hence the labor.

But grading reduces the amount of conductor.

In conductor dominated magnet, specially in Nb<sub>3</sub>Sn magnets, the grading may bring large saving.

SSC used , 15% grading.

I increased that to ~50% (ref RD3, PAC 99 and MT16 paper, etc.)

My preference would be two layers of main coils.

Splice may be in the middle in low field area (works well, as shown in BNL magnets). Splice is an issue, once developed it gets solved. But increases in conductor usage stays as a permanent magnet cost.

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

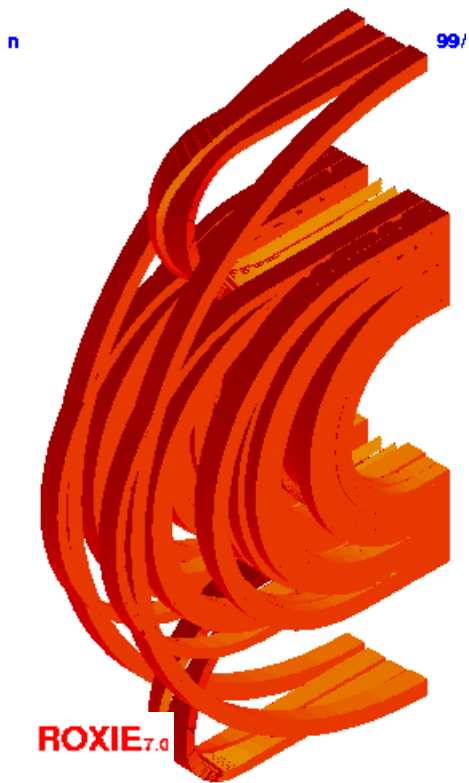
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**Proof:**

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

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

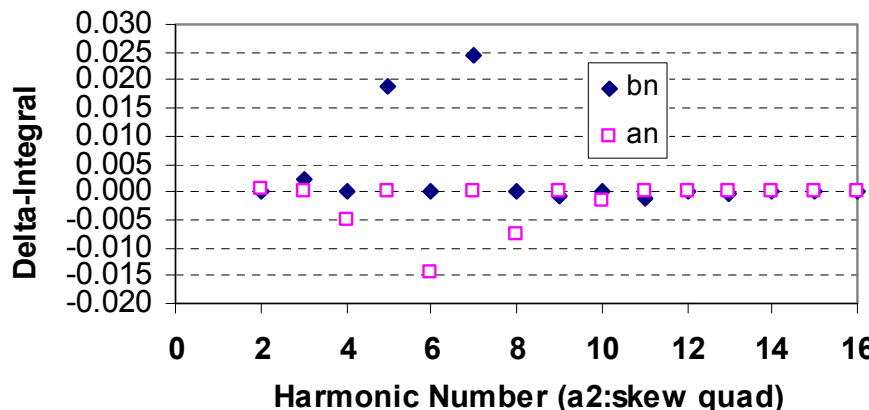
(Very small)



End harmonics in Unit-m

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

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



## Other places to minimize conductor

Physical size of the hole (aperture)

Why should it be more than that in stage 1?

Beam liner

Size? Can we be clever?

Support structure (new, coming from magnet design considerations)

Large fraction, ~3 mm on each side (19 mm physical aperture => to 25 mm coil aperture means 30% more conductor.

**Very expensive in terms of increased conductor cost.**

Do we really need it?

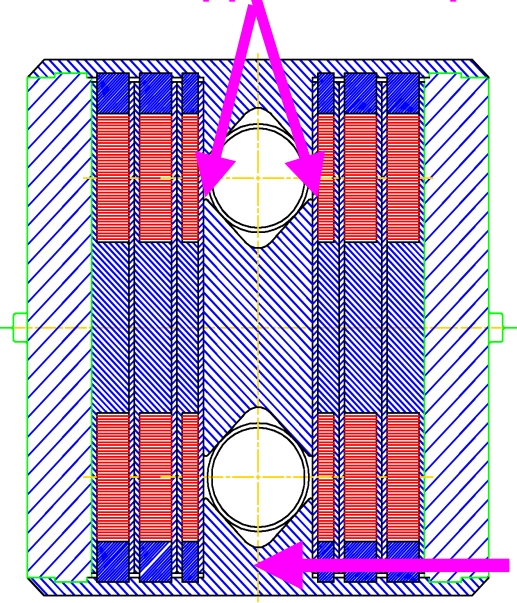
Field Quality: NO

Mechanical considerations: examine alternate structures experimentally

# Support Structure Consuming Expensive Space

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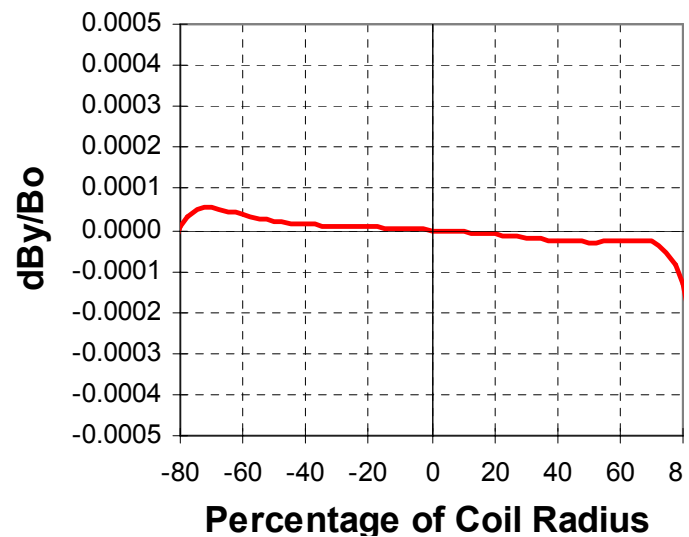
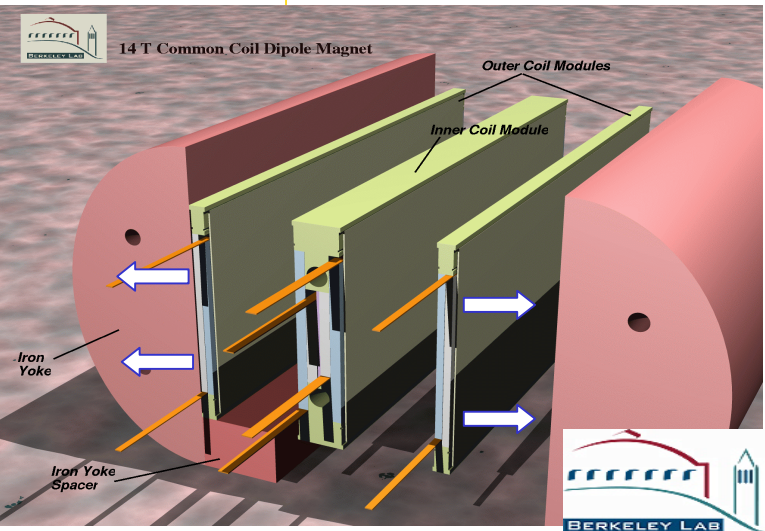
Internal support at midplane



Is this adequate

Used in early BNL common coil concept design. Mechanical designs of other common coil magnets are different; but this ugly feature did not disappear.

Investigate alternate mechanical designs.  
**Do we need it for field quality purpose?**  
See 80% good field aperture in RHIC D0.



Average Field errors  $\sim 10^{-4}$   
up to 80% of the coil radius



# Pre-stress and Support Structure Studies/Experiments

## Strategy:

### Vertical pre-stress:

If large vertical pre-stress is not needed, one does not have to use those 3 mm support on either side of the coil. LHC and many other magnet test results suggest that it may not be needed. Try experimentally in this geometry.

LBL RD2 experience: Did not matter till 6 T

**Remember the implications: it increases coil aperture and hence conductor uses. This is a pretty expensive structure.**

### Horizontal pre-stress:

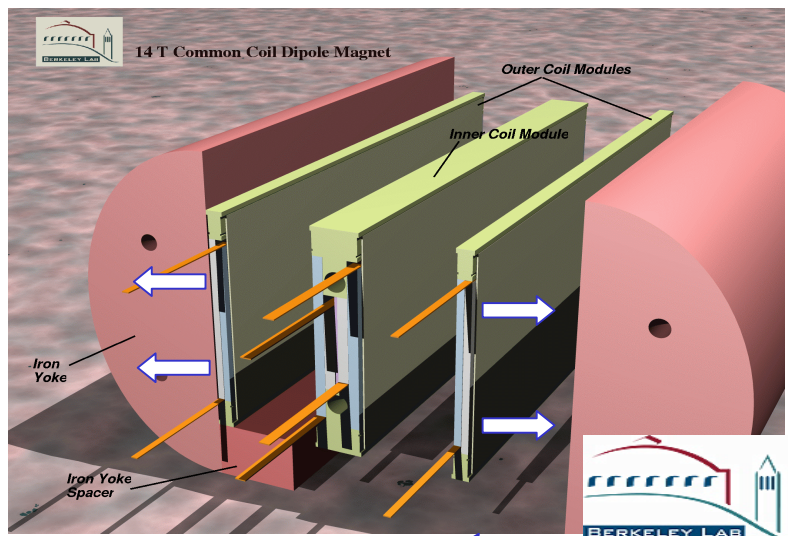
Assure contact between coil and external support structure at low field.

Contain outward Lorentz forces.

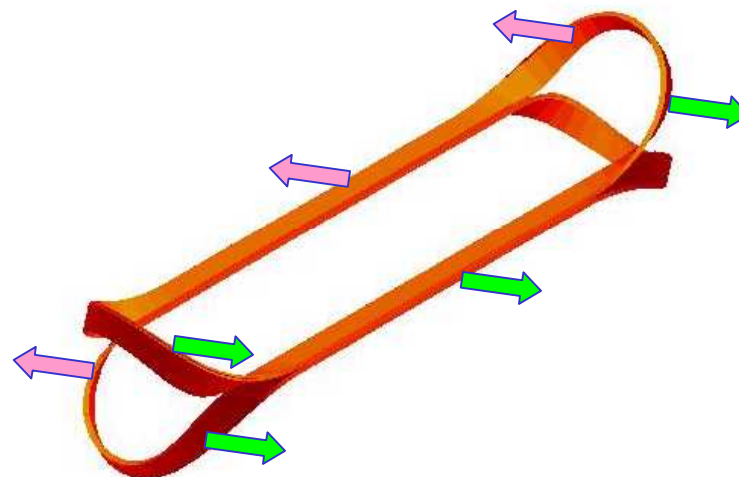
# Common Coil Design in Handling Large Lorentz Forces in High Field Magnets

**Superconducting Magnet Division**

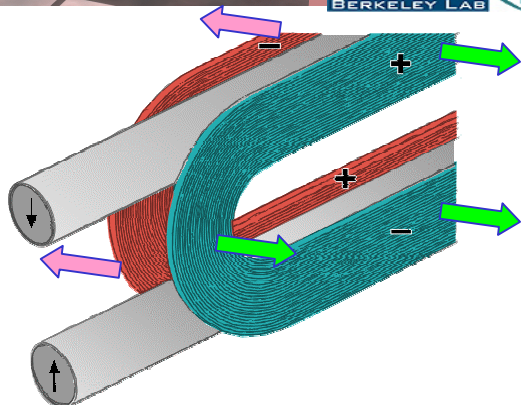
In common coil design, geometry and forces are such that the impregnated solid volume can move as a block without causing quench or damage. Ref.: over 1 mm motion in LBL common coil test configuration).



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



Horizontal forces are larger



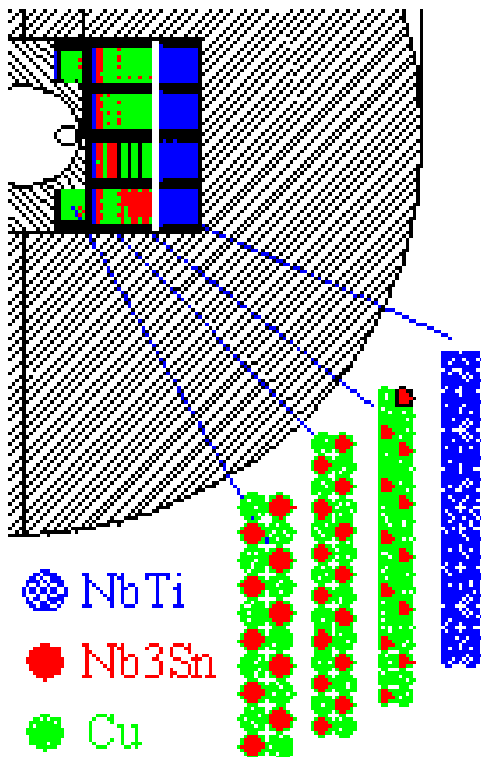
We must check how far we can go in allowing such motions in the body and ends of the magnet. This may significantly reduce the cost of expensive support structure. Field quality optimization should include it (as was done in SSC and RHIC magnet designs).

# Schemes of Adding Cu to Nb<sub>3</sub>Sn to Reduce Overall Conductor Cost

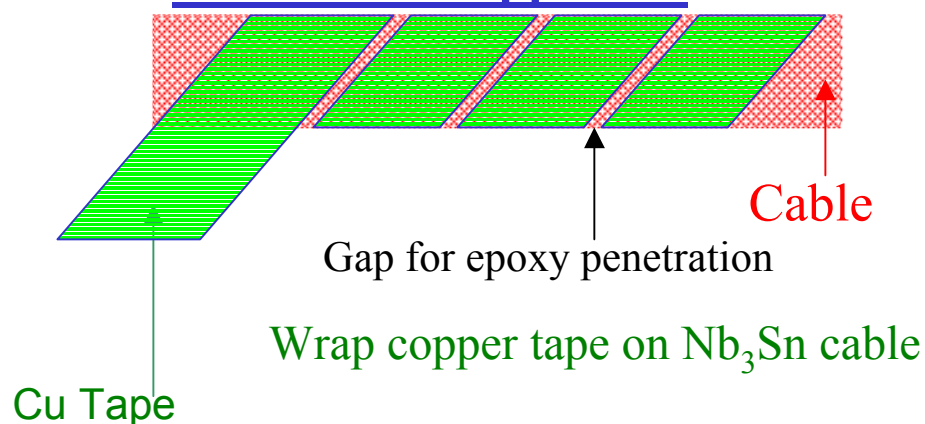
## Generally discussed

Mix copper strand with Nb<sub>3</sub>Sn strand

Peter McIntyre's Magnet Design



## An alternate approach



- Better packing factor
- Lower strand diameter
- Don't have to worry about matching strands of different materials
- Easy to make systematic studies: take same cable and vary copper tape
- How do two scheme compare in terms of role of Cu

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

# Highest Field Magnet

How high field we can reach?

When do we need stress management?

LBL results: 14.7 T

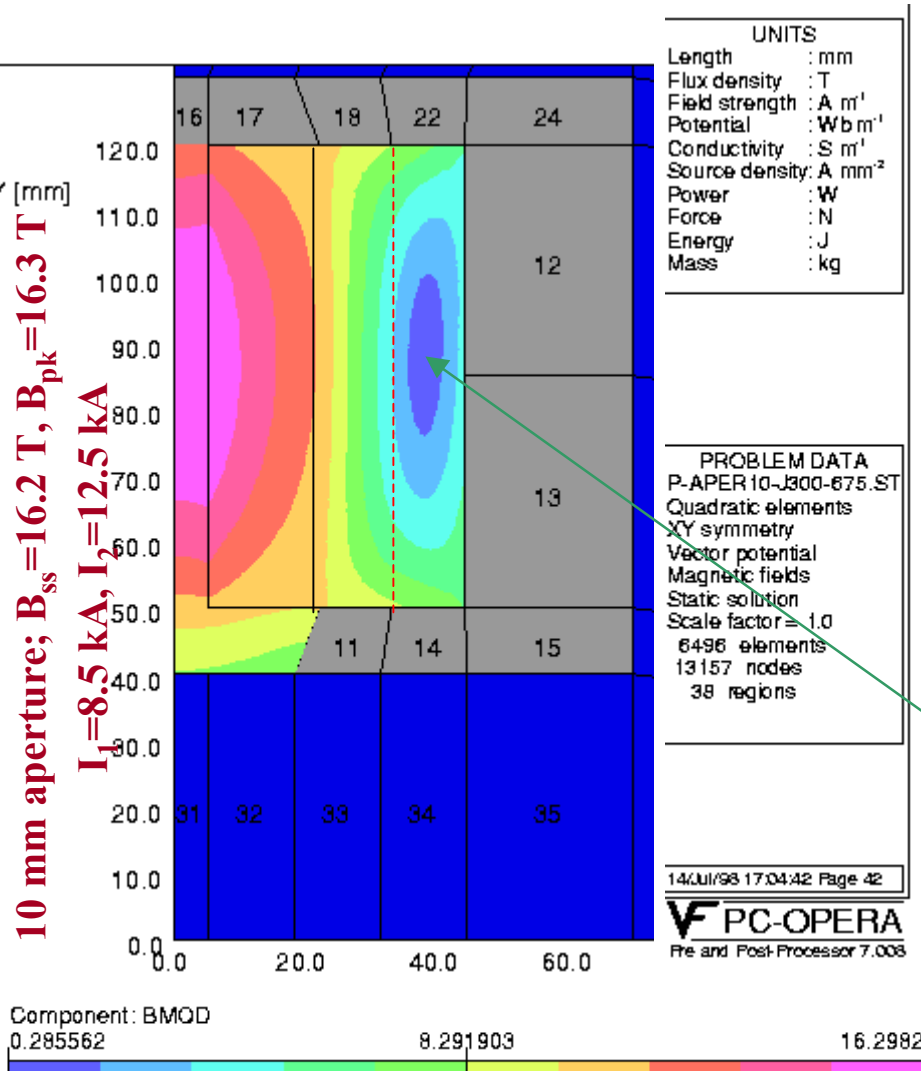
Did not see noticeable degradation till this field.

This is in contrast to what many feared ~5 years ago.

In magnet situation could be different from the sample test situation.

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

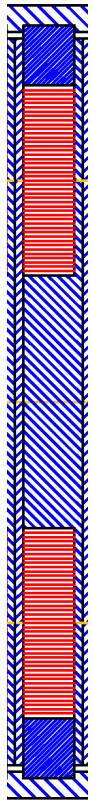
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- Vary aperture after the coils are made  
a unique feature of this design
- Lower separation (aperture)  
reduces peak field, increases T.F.  
=> Higher  $B_{ss}$
- May not be practical for machine magnet  
but an attractive way to address  
technology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

# Investigate Low-cost Magnet Manufacturing Process

One possible example:

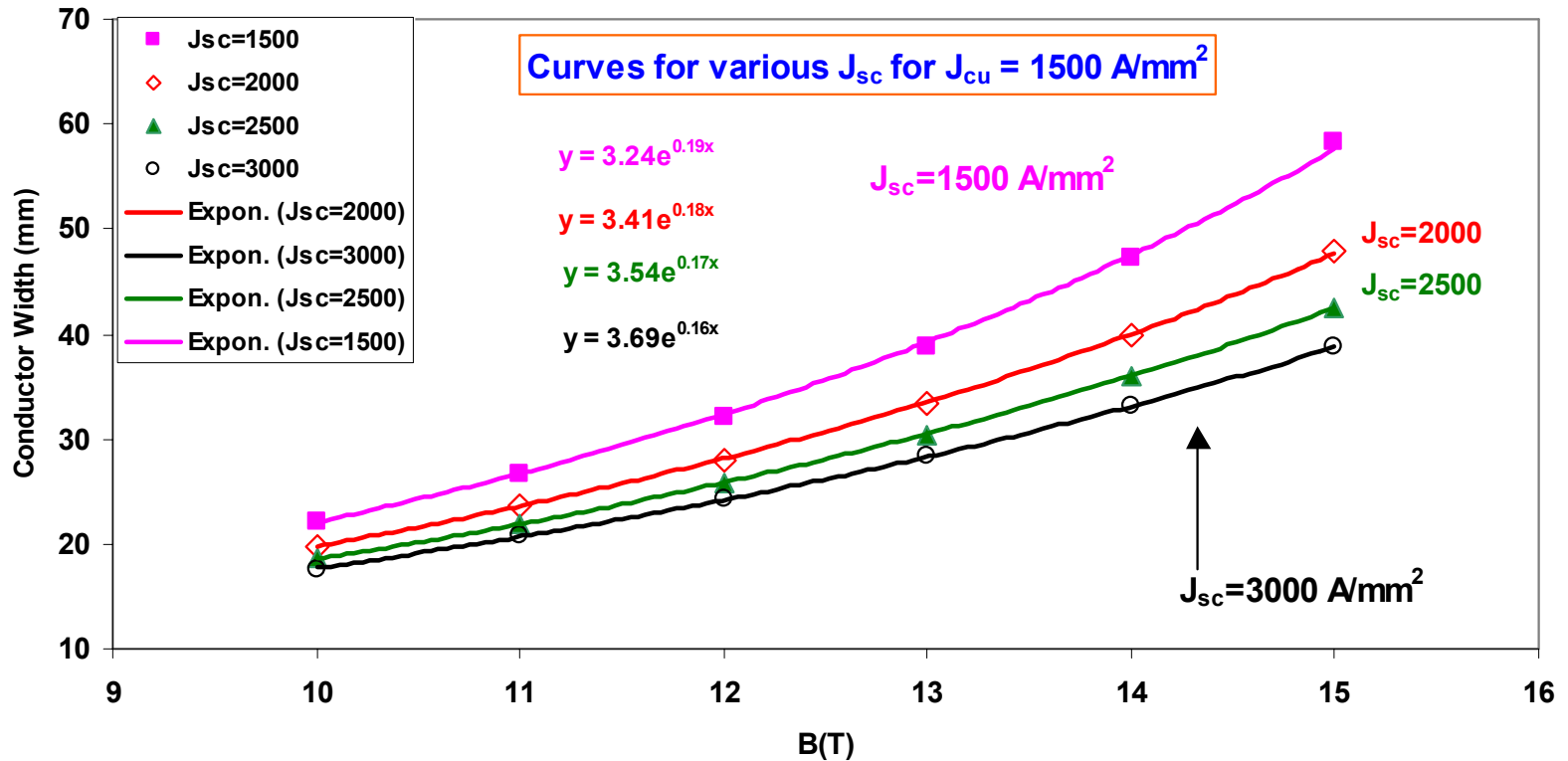


- Reduce steps and bring more automation in magnet manufacturing
- Current procedure : make cable from Nb-Ti wires => insulate cable => wind coils from cable => cure coils => make collared coil assembly
- Possible procedure : Cabling to coil module, all in one automated step - insulate the cable as it comes out of cabling machine and wind it directly on to a bobbin (module)

# Prioritizing Nb<sub>3</sub>Sn Conductor R&D

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There is only a small saving in conductor in going from 2500 A/mm<sup>2</sup> to 3000 A/mm<sup>2</sup> or beyond, particularly at ~12 T. Should we pay more attention to production cost or filament diameter instead?



Conductor area as a function of magnet aperture (a) is proportional to:

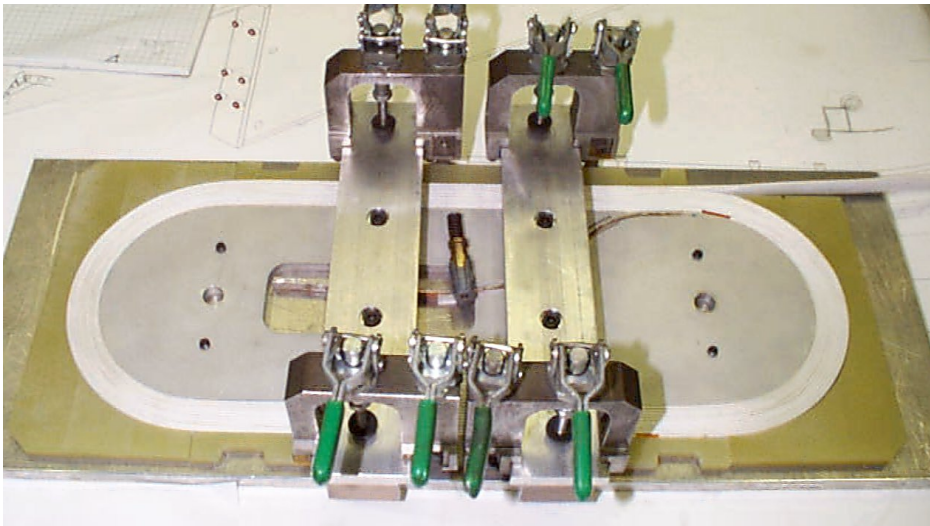
$$a * [1 + f(a)/4 * \text{thickness}]$$

a is magnet aperture, f(a) is a function of a (1 to first approximation)

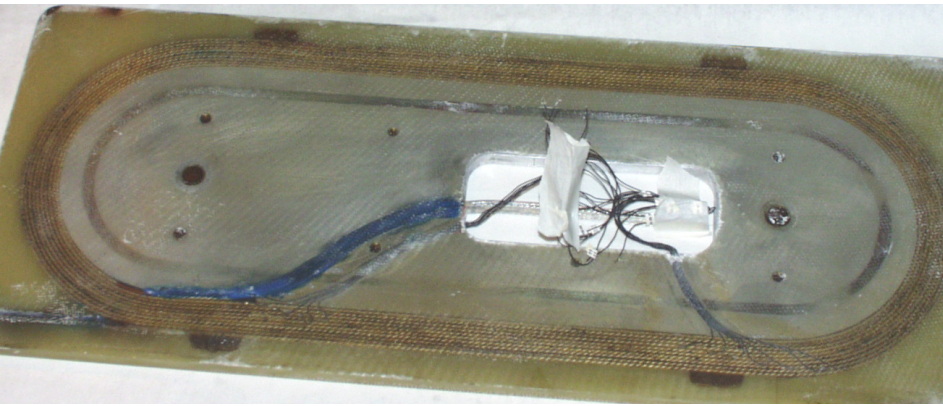
Conductor usage may not be linearly proportional to aperture in small aperture magnets.

# HTS Cable Magnet R&D

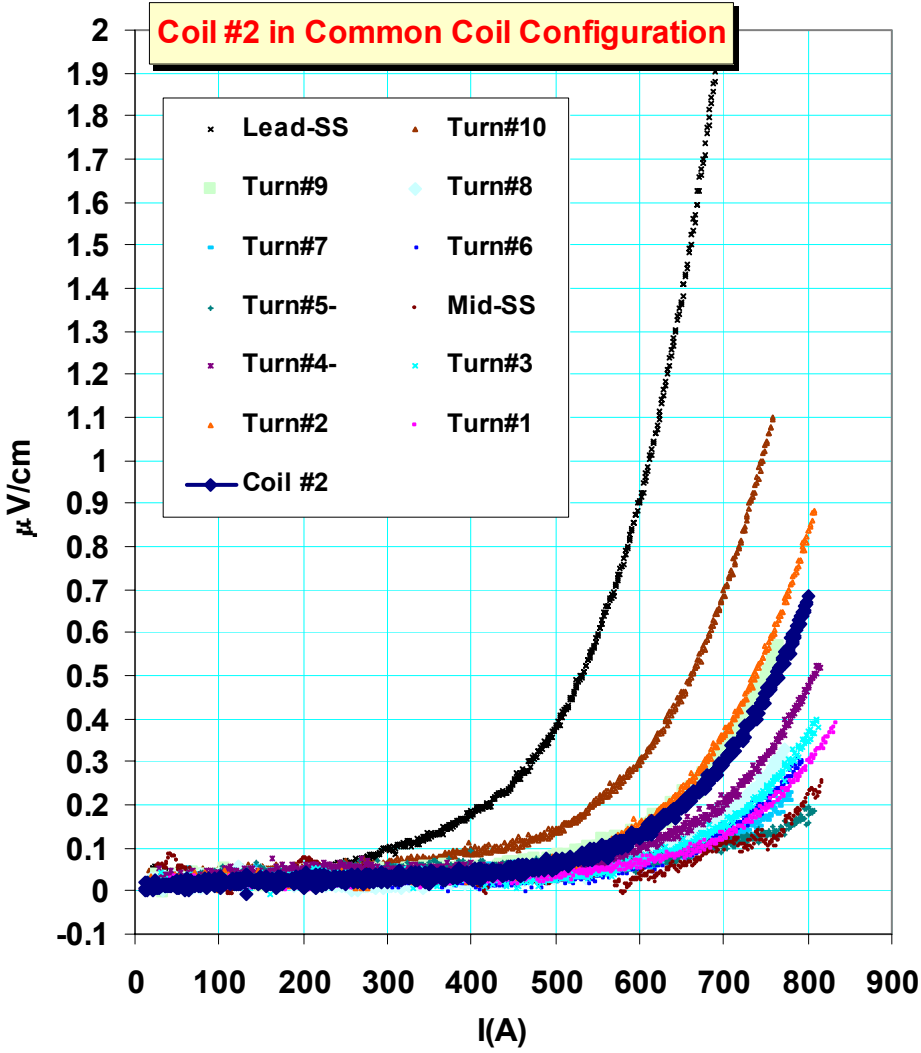
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HTS cable coil prior to vacuum impregnation



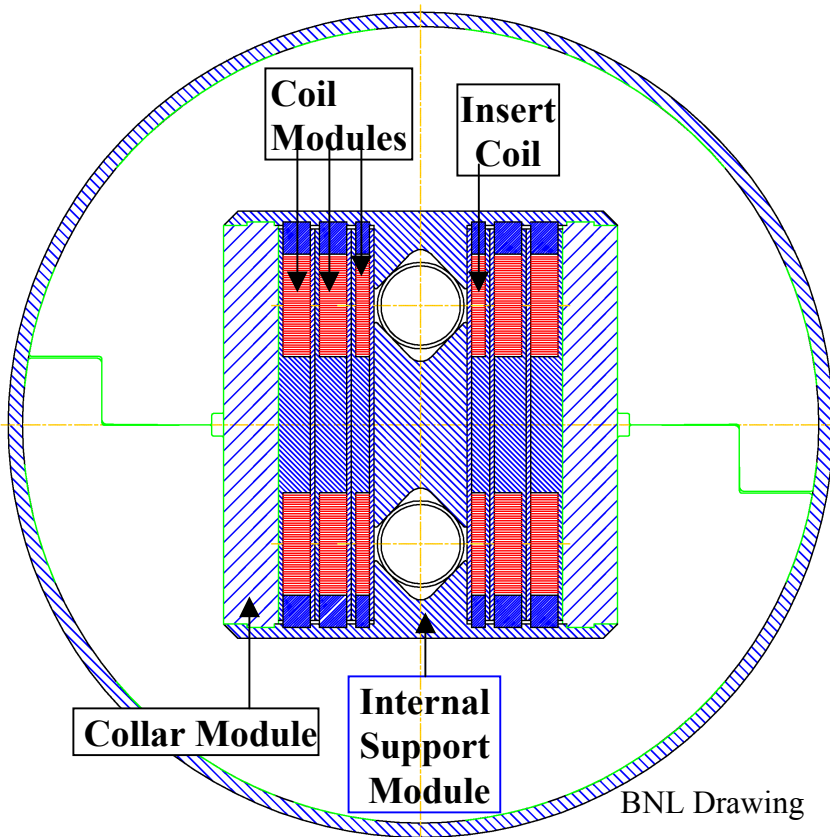
A coil cassette made with HTS cable after vacuum impregnation and instrumentation





# A Modular Design for a New and Low-cost Magnet R&D Approach

\*This could be a Magnet R&D Factory\*



- Replaceable coil module.
  - Change cable width or type.
  - Combined function magnets.
  - Vary magnet aperture for higher fields.
  - Study support structure.
- # Traditionally such changes required building a new magnet.
- # One can also can test modules off-line.

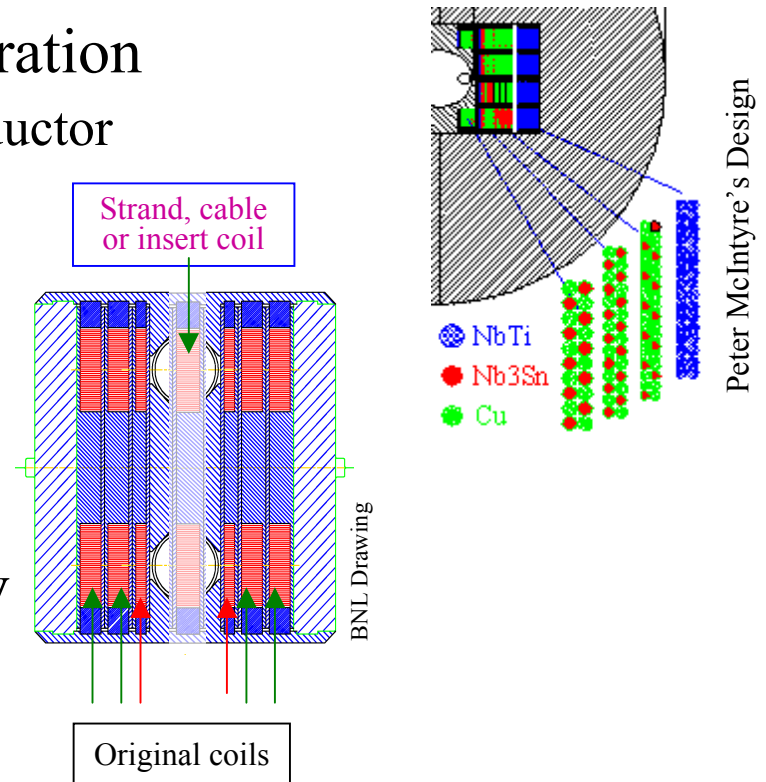
Not only that we must learn how to make magnets cheaper, we must also learn (due to limited funding), how to do magnet research cheaper which will lead to eventually making the magnets cheaper.

This is the time to explore and carry out an aggressive R&D program. Once the machine is funded, we are unlikely to take chances. The above facility allows that.

# 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<sub>3</sub>Sn superconductor
  - Heat treatment studies
- Different technologies
  - “Wind & React” Vs. “React & Wind”
- Different type of conductors
  - Nb<sub>3</sub>Al, 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



# Importance of Rapid Turn around Program

After making several react and wind Nb<sub>3</sub>Sn and HTS coils, we had one test where magnet could not go beyond 7% of short sample.

What happened here could perhaps have happened any where:

- in a short or a long magnet.

- in a magnet with a fewer or more turns.

This is a kind of learning/”dealing with accident” thing that must be allowed in a program that is intended to develop in new technology or push the existing beyond comfort zone.

We can make new coil(s) and do another test in a month  
no major setback only a learning experience.

It not only validates our magnet program philosophy but proves the importance of it in a true magnet R&D program.

# Experience with Rapid Turn Around Program at BNL

## Phase 2 status and progress in ~1+ year (a partial list)

- New engineering design and construction techniques developed
  - “React & Wind” HTS and Nb<sub>3</sub>Sn coil
- Rapid turn-around demonstrated
  - 9 racetrack 10-turn coils are built and 3 more are underway (5 HTS and 7 Nb<sub>3</sub>Sn coils)
- Five 4.2 K and a number of LN<sub>2</sub> tests of common coil design performed
- HTS and Nb<sub>3</sub>Sn cable tested as a function of field (a lot more testing on HTS)
- New top hat for ~25 kA testing complete
- Two support structures built; third 12 T is in conceptual state.
- New thinner fiberglass insulation in collaboration with industries
  - 3 varieties with 50% less thickness (equivalent gain in conductor J<sub>c</sub> is ~10%)
- Magnetic design of 12 T background field magnet completed; conductor ordered.

**Significant output with a limited resources !**

# Summary and Conclusions

Given the time scale of the next high field magnet project, taking the approach of making a magnet somehow work may not be sufficient.

We should experimentally examine and understand the limit of past technology and explore new.

We should examine alternate magnet design and technology and take advantage of different geometry, if we could.

Then only we can fully realized the cost saving potentials.