BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Report from the LHC IR Upgrade Meeting

High Field Magnet R&D

Ramesh Gupta

Superconducting Magnet Division

Webpage of upgrade meeting talks

http://magnets.smd.bnl.gov/staff/gupta/talks/lhc-ir-upgrade/index.htm

Magnet Requirements

General magnet requirements for LHC luminosity upgrade:

- Larger aperture (needed in most lattices)
- Larger pole tip field (required in all lattices)
- Larger temperature margin (useful in all cases)

The present NbTi Technology is not suitable for the required pole tip field of >10 T.

RHIC: 3.5 T (4.2 K)
SSC: 6.6 T (4.2 K)
LHC: 8.4 T (1.8 K)

LHC dipoles are almost at the limit of NbTi technology.

The presentation will include a brief explanation of new magnet technologies and issues.

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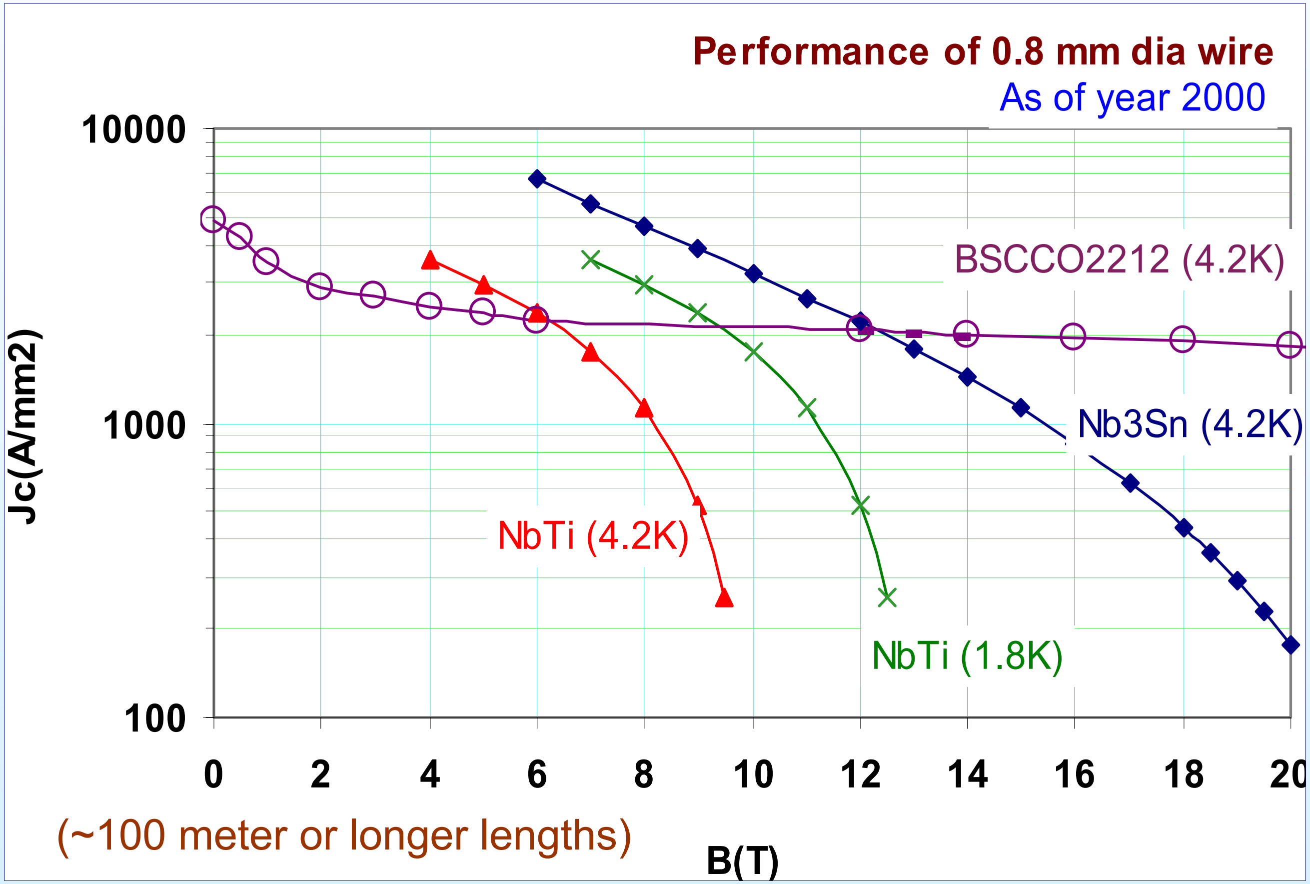
High Field Superconductors

Critical Current Density (J_c) as a function of field



- High Field Superconductors, Nb_3Sn and BSCCO (HTS), are brittle in nature.
- Reaction at high temperature (~650 C for Nb_3Sn and ~890 C for HTS) is required.
- NbTi designs and manufacturing techniques can not be used as such.

Two R&D Philosophies

We have 12-15 years (present estimates) for LHC IR Upgrade

- Not enough time to do major new R&D
- Adapt present R&D results for building machine magnets

We have time to explore alternate designs and technologies

- Choose after ~5 years of R&D which technology to use

Personal opinion:

12-15 year is about the right time frame to explore "new designs and technologies". More than that may be too early to create people's interest.

Also, for a longer period, these "new designs and technologies" might be "out of date" before used, because of more inventions and advancements in the field.

IR Magnet Design Considerations

Differences between the IR magnets and main magnets:

- Only a few IR magnets as compared to a large number of main magnets.
- A few magnets may make a large difference in luminosity performance.
- The cost of material is a fraction of the overall cost of R&D and production.

These contrasts suggest that we should be open to using different design strategies for IR magnets, as compared to what we do in main magnets.

- They can use much more expensive materials.
- They can be more complicated in construction, as we need only a few.

⇒ This makes a good case for HTS in IR magnets.

SESSION 2: IR Layout and Magnet Parameters

Baseline LHC interaction regions	R. Ostojic	14:00-14:30	CERN
Simplest upgrade - same optics, larger aperture quads		14:30-15:30	Fermilab
Optics and layout	T. Sen		
Energy deposition	N. Mokhov		
Magnet parameters	A. Zlobin		
Layouts and magnet parameters using HTS quadrupoles	S. Peggs/R. Gupta	15:30-16:00	BNL
Layout with D1 first		16:30-17:00	CERN (similar to VLHC/BNL)
Optics and layout	O. Bruning		
Magnet parameters	TBD		
DISCUSSION		17:00-18:00	

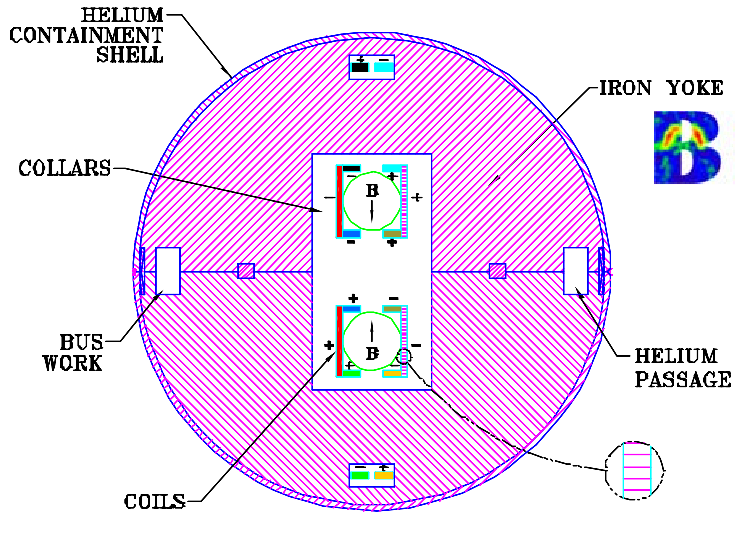
SESSION 3:
Magnet Technology and Conductor Developments

Cos(theta) quadrupole design	A. Zlobin	09:00-09:25	Fermilab
IR Quad R&D Programme	S. Gourley	09:25-09:40	LBL
Flat coil quadrupole design	S. Russenschuck	09:40-09:55	CERN
HTS magnets and alternative design for Nb_3Sn quads	R. Gupta	09:55-10:20	BNL

BNL is proposing “React & Wind” quadrupoles, most others “Wind & React”.

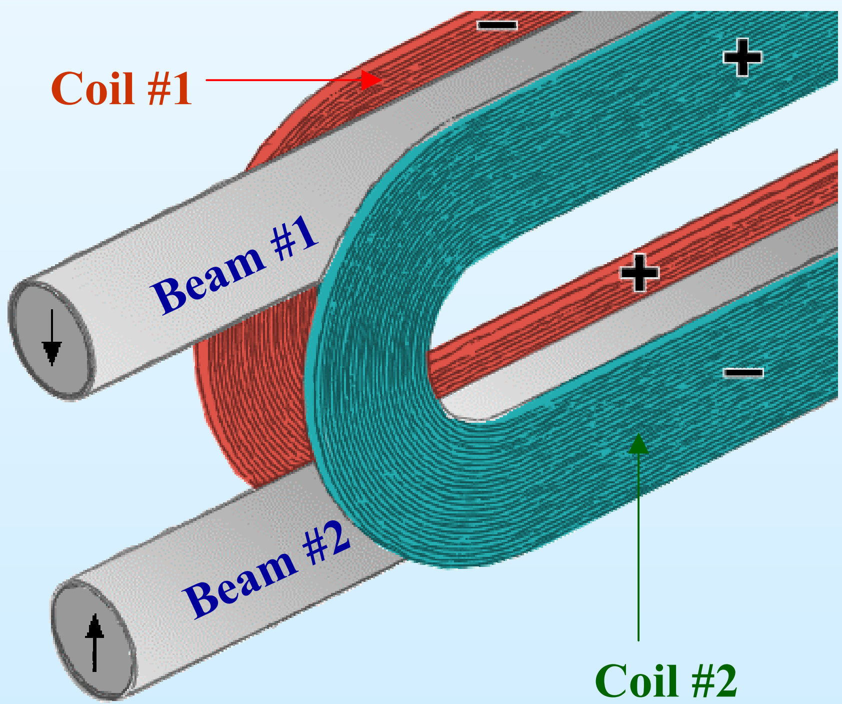
In “Wind & React” approach one does not have to wind coils with brittle materials. But every thing must go through high reaction temperature.

We have come up with quadrupole design concepts suitable with “React & Wind” approach, just as in common coil dipole magnets.



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 HTS and Nb_3Sn)**
- **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*

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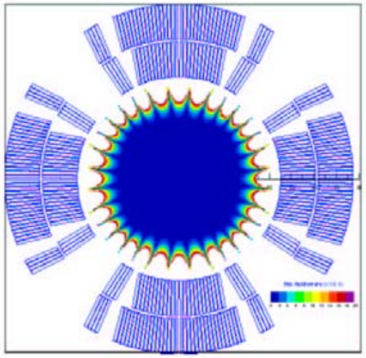
SESSION 4: PANEL DISCUSSION
Technology and R&D of High Field Magnets

-CERN	L. Rossi	10:35-10:45	Built ~10 T Nb_3Sn dipole
- FNAL	A. Zlobin	10:45-11:00	Started Nb_3Sn R&D ~4 years ago. A few magnets have been built
- LBNL	S. Gourlay	11:00-11:15	14.7 T (**highest field to date**) Common coil Nb_3Sn dipole
- BNL	R. Gupta	11:15-11:30	• First lab to build Nb_3Sn accelerator dipole and quad (both W&R, R&W) • First lab to build (recently) **HTS** accelerator type magnet - short coils • Lab to propose common coil design
-Twente University	A. den Ouden	11:30-11:45	Built ~11.5 T Nb_3Sn dipole
- CEA	A. Devred	11:45-12:00	Program to build Nb_3Sn quad
- KEK	K. Tsuchiya	12:00-12:15	Program to build Nb_3Al quad
- INFN	F. Broggi	12:15-12:30	Program to build Nb_3Sn quad

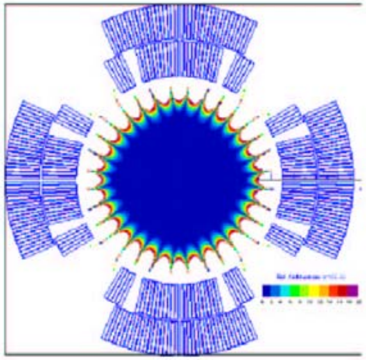
Fermilab Approach: Nb_3Sn in a Design Similar to the Presently Used

Magnetic design: Coil and Cable



? Design I, 12 mm collar (spacer), mechanical support by iron yoke and skin

Design II, 30 mm stand-alone collar mechanical structure ?



Cable parameters.

Parameter	Design I	Design II
Number of strands	42	42
Strand diameter, mm	0.700	0.700
Cable width, mm	15.500	15.138
Cable inner edge thickness, mm	1.118	1.080
Cable outer edge thickness, mm	1.350	1.391
Cabling angle, degree	14.5	14.5
Keystone angle, degree	0.860	1.180
Average packing factor, %	87.0	89.0
Inner edge compression, %	20.1	23.0
Outer edge compression, %	3.60	0.64
Width compression, %	-2.4	0.00
Insulation thickness, mm	0.200	0.180

Two-layer shell-type design

Design-type considerations:
- Fabrication
- Mechanics
- Cooling
- Protection

12 March 2002, CERN
LHC IR Upgrade Collaboration Meeting

A. Zlobin, Fermilab
Two-layer Shell-type Low-beta Nb3Sn Quadrupoles for the LHC IR Upgrade

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Fermilab Quadrupole Design: Larger Aperture but Similar Gradient

Target parameters and conditions

Target parameters are (same or better than that for MQXB):

- Magnet (coil) bore – 90 mm
- Nominal field gradient – 205 T/m or higher
- Nominal temperature – 1.95 K or 4.3 K
- Margin along the load line – 15-20%
- Field quality – as MQXB (error tables v.3) or better
- Robust mechanics
- Sufficient temperature margin
- Quench protection
- Life time

Proposed Fermilab Program: Very Extensive

Program Stages

Short model R&D:

Phase I – 70-mm Nb3Sn quadrupoles in MQXB collar.

- short mechanical model (magnet mechanics and assembly)
- 3 1-m long models (G>210 T/m with present Nb3Sn strands, mechanics and quench performance)

Phase II – 90-mm Nb3Sn quadrupoles.

- 6 2-m long models (mechanical, thermal, magnetic and quench studies)
- justification of magnet critical current and critical temperature margin
- specifications for superconductor, cable, insulation and magnet components

Phase III – Reproducibility and long-term performance studies.

- 5 identical 2-m long models of final design,
- reproducibility of main parameters (quench performance and field quality)
- long-term performance during current and thermal cycling, repeated quenching
- magnet stability to radiation and beam losses
- magnet string tests

12 March 2002, CERN
LHC IR Upgrade Collaboration Meeting

A. Zlobin, Fermilab
Nb3Sn Low-beta Quadrupole R&D at Fermilab

4

Fermilab R&D Tasks

R&D tasks

- Proposed program includes positive results obtained at UT, LBNL and Fermilab
- The program address the following issues:
  - Magnet design
  - Technology
  - Performance
  - Components

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A. Zlobin, Fermilab
Nb_3Sn Low-beta Quadrupole R&D at Fermilab

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Someone overlooked the pioneering role of BNL in this technology.

LBL Quadrupole Proposal

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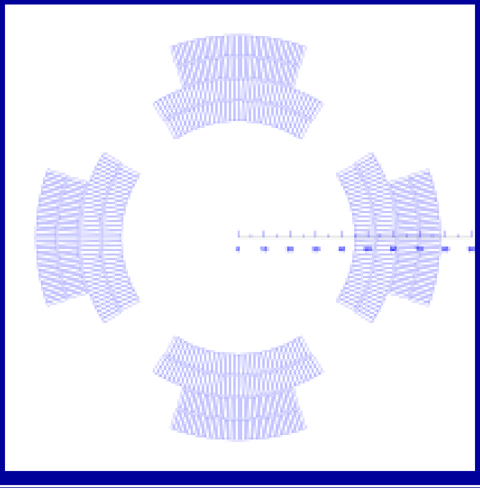
Four -layer Cos(2θ)

(Jc:2.0/4.2 - No degradation)



Parameter	Unit	Inner	Outer
G_{ss}	T/m	260	
B_{pk}	T	12.7	10.8
I_{ss}	kA	7.7	7.9
L	mH/m	24.4	
$A^{(oct)}$	mm^2	624	
R^{iron}	mm	90	

Param.	Unit	Inner	Outer
Str. Diam.	mm	0.8	0.65
$N_{strands}$		18	23
Cab. Width	mm	7.71	7.71
Mid-thick	mm	1.43	1.15
Keystone	deg	1.63	0.89
Insulation	mm	0.1	0.1
$N_t^{(oct)}$		37	36
Cu/Sc		1.0	1.5
J_{cu}^{ss}	kA/mm^2	1.7	1.7

Geom. harm.
(r_0 = 22 mm)
(10^{-4} units)

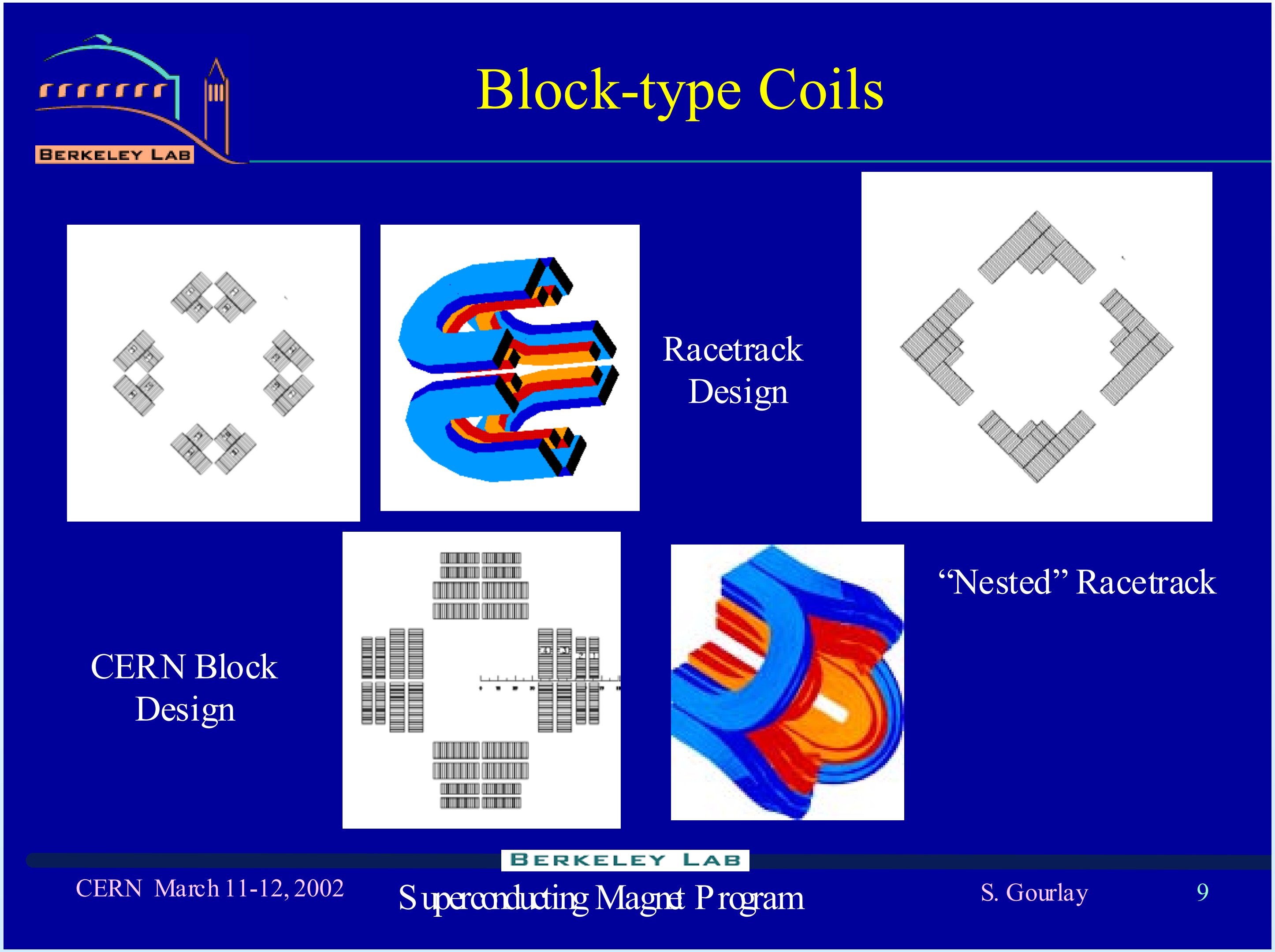
b_6	b_{10}	b_{14}
0.2	-0.8	0.04

BERKELEY LAB

CERN March 11-12, 2002 Superconducting Magnet Program S. Gourlay 5

LBL has made the high field Nb3Sn magnet: A 14.7 T common coil dipole

LBL Block Coil Investigations



During the meeting LBL proposed that it would like to carry out "Wind & React" Block Coil Quad R&D

BNL Vision: Time to Explore Alternate Designs & Technologies

BNL has been long history of sticking its neck out in proposing and developing new magnet designs and R&D approaches.

It was first to start serious Nb_3Sn accelerator magnet R&D. It also proposed new magnet designs (e.g., common coil) and new R&D approaches (e.g., rapid turn around). Like any other new proposals they first met initial skepticism but now they are being used as the mainstream activities at many places.

Recently we have been talking about HTS technology.

We have built and tested a few short HTS coils and despite earlier warnings from others, we have not seen any major degradation so far.

Now HTS is being (will be) taken more seriously for small scale applications - LHC IR upgrade being an ideal example.

10 Turn Coil Program

To keep material cost low, we use small amount of superconductor

Straight section is only a foot long

Number of turns are only 10

We work with sketches, not drawings and detail procedures.

We try to work with low tolerances, in house production of parts

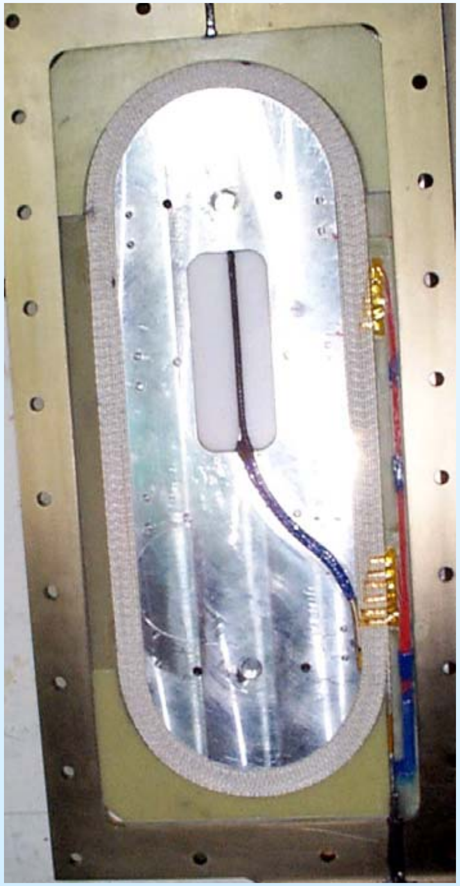
We use technicians in various groups, whenever and wherever they become available (usually for short times).

This creates a real challenge in carrying out R&D but this is how we have been able to manage limited resources to make meaningful progress.

This philosophy also offers a low cost rapid turn around R&D approach where one could systematically study various ideas.

HTS Test Coils and Magnets at BNL

BNL has built many test coils (14) and magnets with HTS cable and tape.



HTS Cable Coil

HTS Cable Coils in support structure

Two HTS tape coils in common coil configuration

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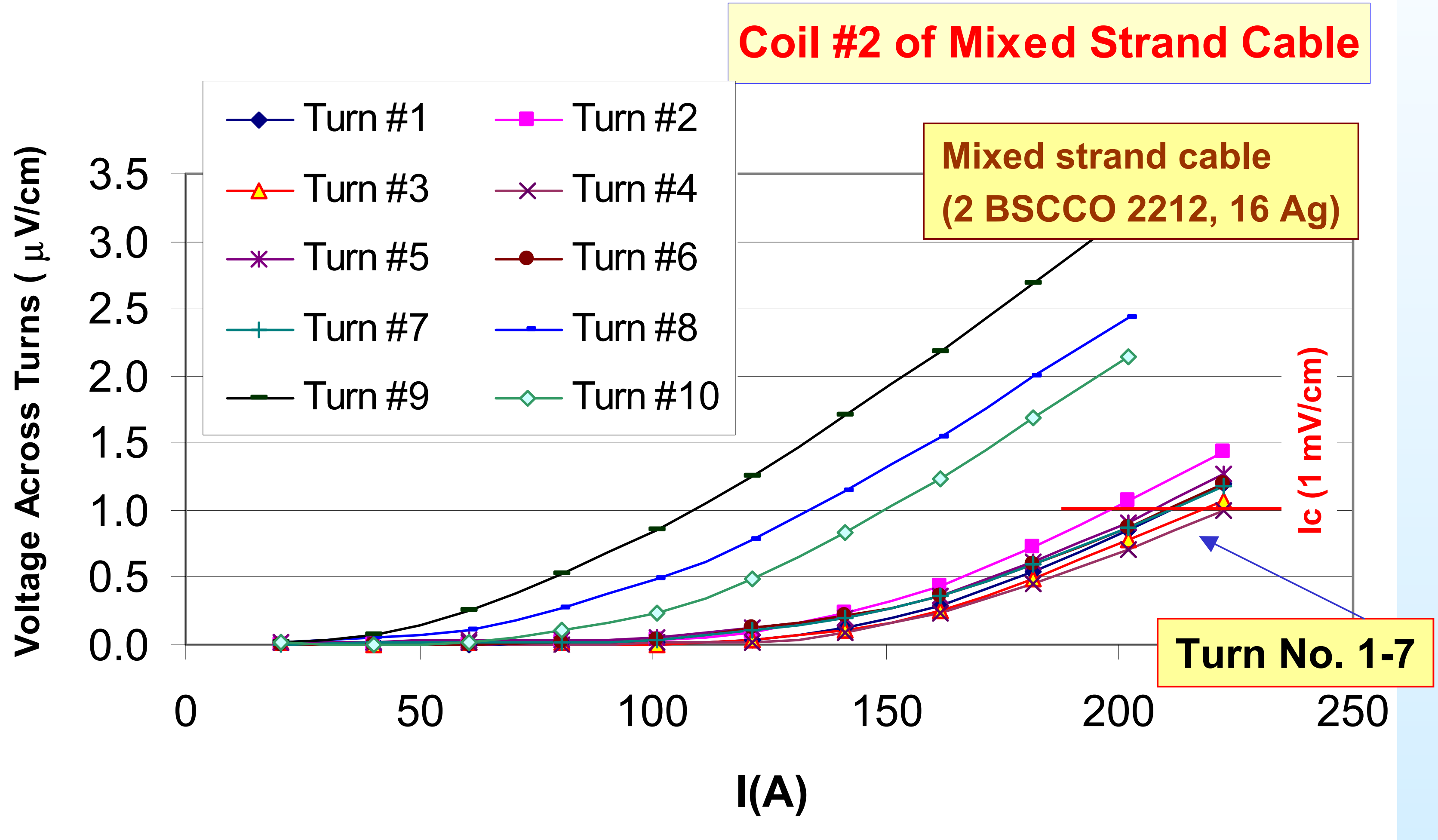
Measured I_c of Various Turns of Common Coil Magnet DCC006



Turns No. 1-7 show an I_c close to the best (~200 A) measured in cable prior to winding.

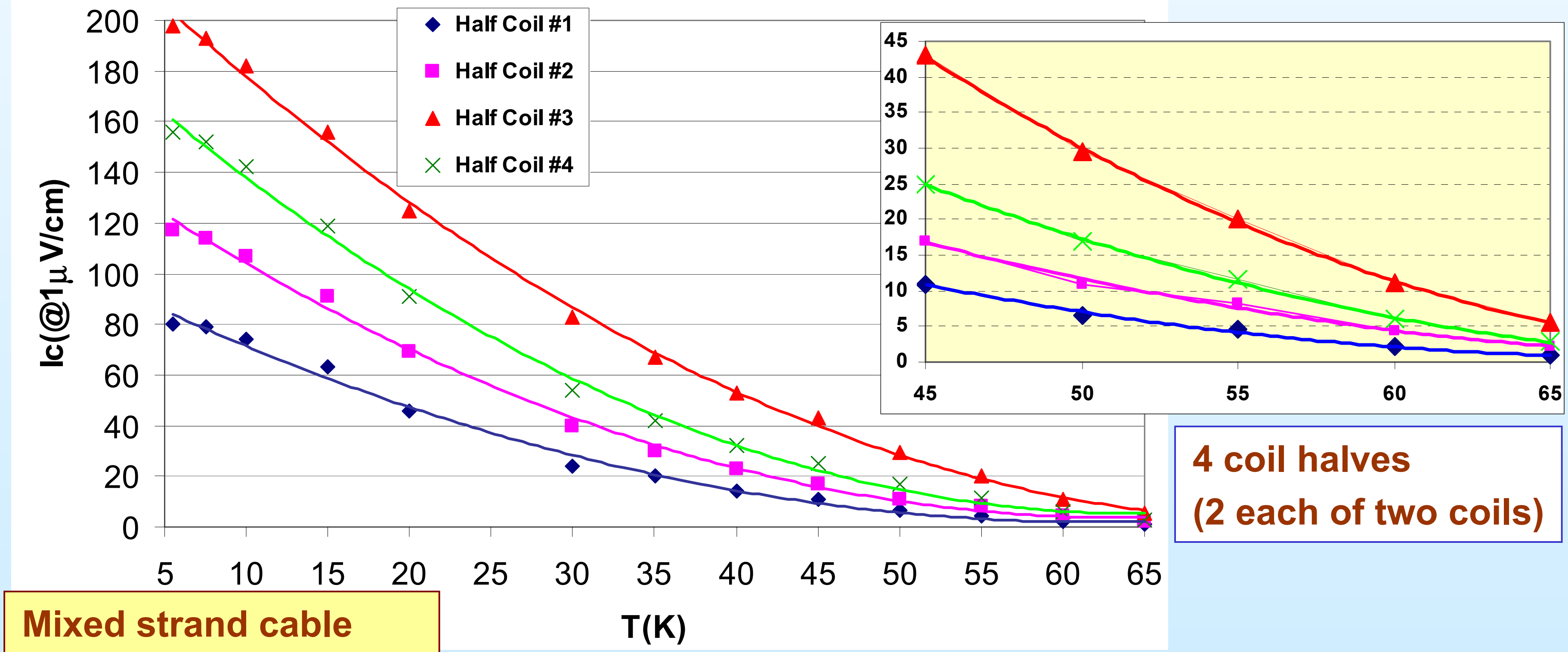
<u>This suggest a low level of degradation!</u>

High Temperature Performance of HTS Coils Built at BNL

Remember: HTS is also a High Temperature Superconductor!

A few degree increase in temperature, either from energy deposition of decay particles, or from mechanical motion, has a small effect on critical current.

HTS magnets will not quench easily, they can tolerate much more beating!



4 coil halves
(2 each of two coils)

Mixed strand cable
(2 BSCCO 2212, 16 Ag)

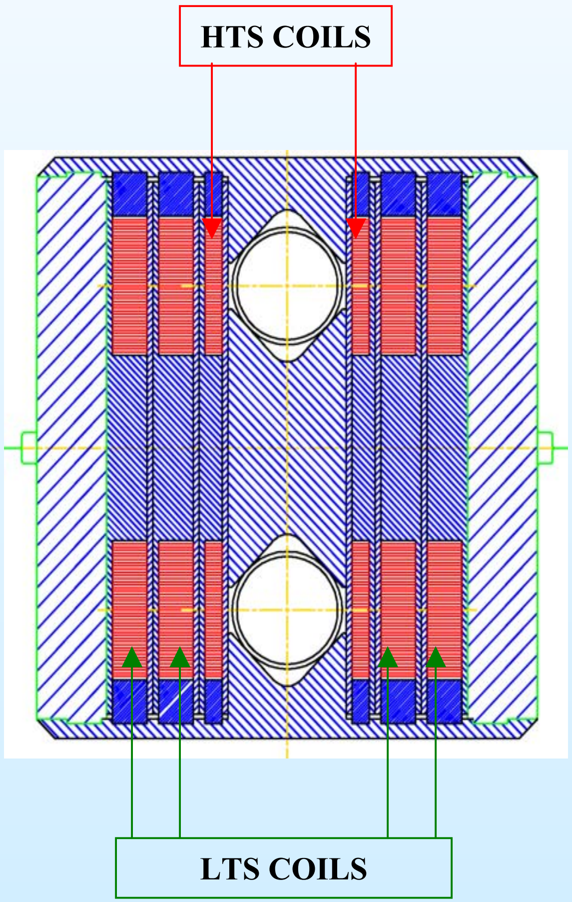
HTS R&D at BNL

- We have demonstrated that small HTS coils can be made without large degradation.

- This is a significant progress (real and psychological) as it reduces "the intimidation factor" of brittle HTS materials.

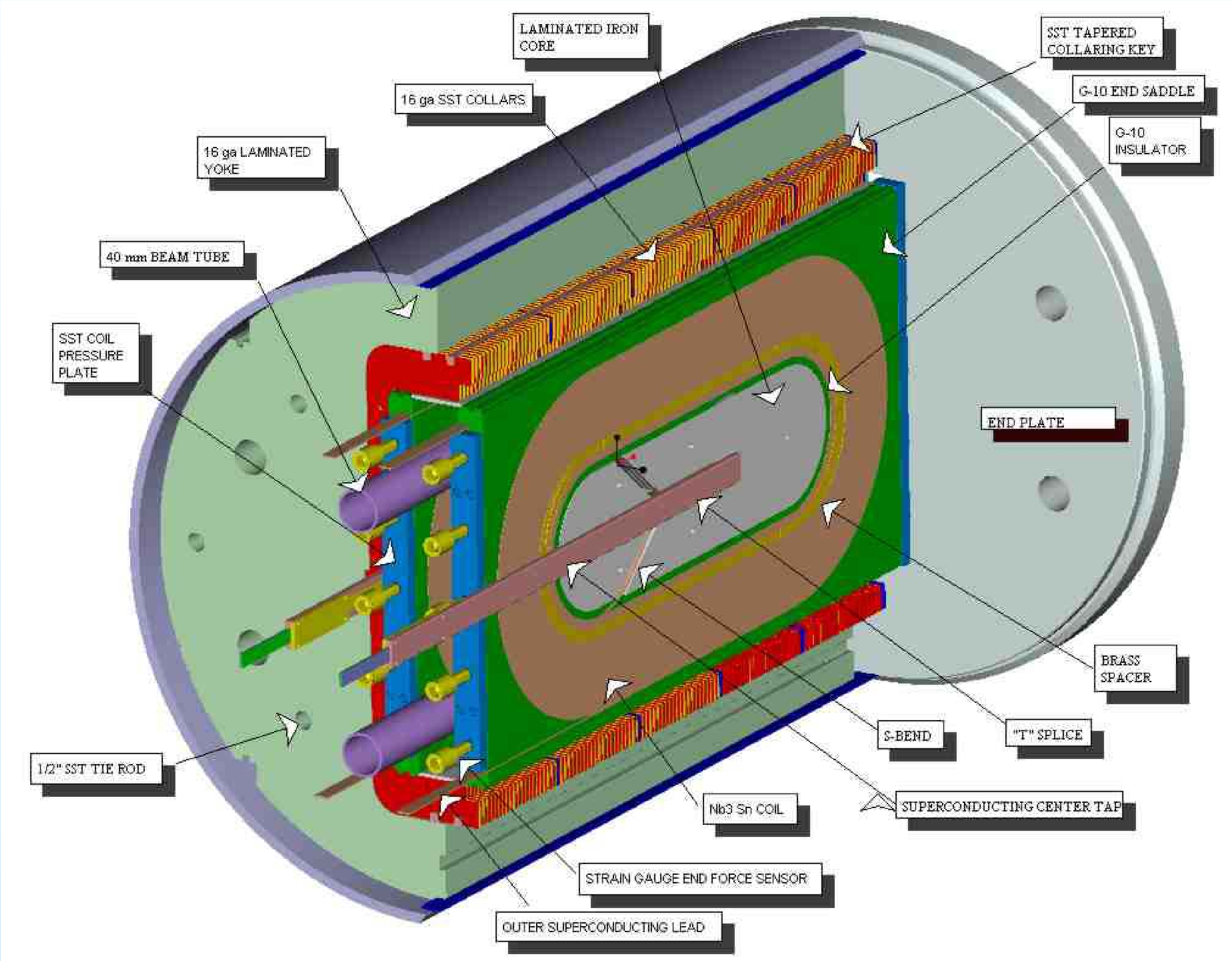
- But there is a long way to go to demonstrate that long coils and magnets can be made. We also need to show that HTS coils will behave well in high stress, high field environment.

12 T Background Field Magnet: Important Next Step in HTS R&D



- At present, HTS alone can not generate the fields we are interested in.
- Nb_3Sn coils provides high background fields. The HTS coils will be subjected to high field and high stresses that would be present in an all HTS magnet. Therefore, several technical issues will be addressed.
- Since 12 T Nb_3Sn magnet uses similar technology (building high field magnet with brittle material), it also provides a valuable learning experience in building an all HTS high field magnet.

Overall Design of BNL 12 T Common Coil Background Field Dipole



First Likely Application of HTS: Interaction Region (IR) Magnets

Interaction region magnets for the next generation colliders can benefit a lot from:

- the ability to produce very high fields
- the ability to deal with large energy deposition
- the ability to operate at elevated temperatures that need not be uniform

For these IR magnets, the performance, not the material cost is the issue.

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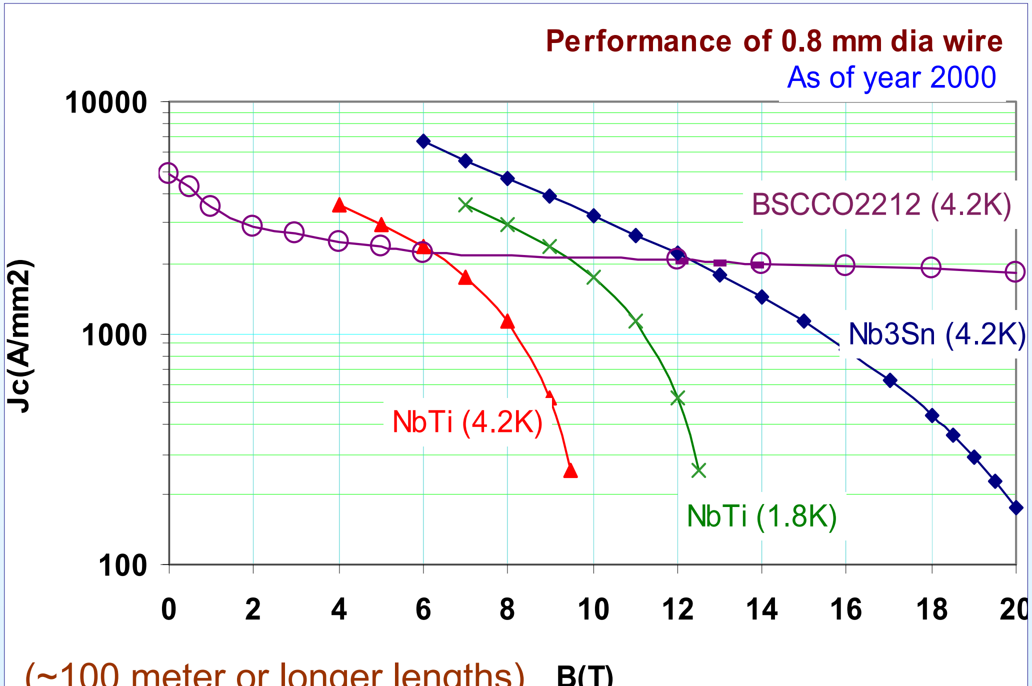
HTS: A High Field Superconductor



Year 2000 data for J_c at 12 T, 4.2 K

Nb_3Sn: 2200 A/mm^2

BSCCO-2212: 2000 A/mm^2

Cu(Ag)/SC Ratio

BSCCO: 3:1 (all cases)

Nb_3Sn: 1:1

or J_{cu}=1500 A/mm^2

Near future assumptions for J_c at 12 T, 4.2 K

Nb_3Sn: 3000 A/mm^2 (DOE Goal)

BSCCO-2212: 4000 A/mm^2 (2X today)

Expected performance of all Nb_3Sn or all HTS magnets at 4.2 K for the same amount of superconductor:

Year 2000 Data	
All Nb_3Sn	All HTS
12 T	5 T
15 T	13 T
18 T	19 T*

*20 T for Hybrid

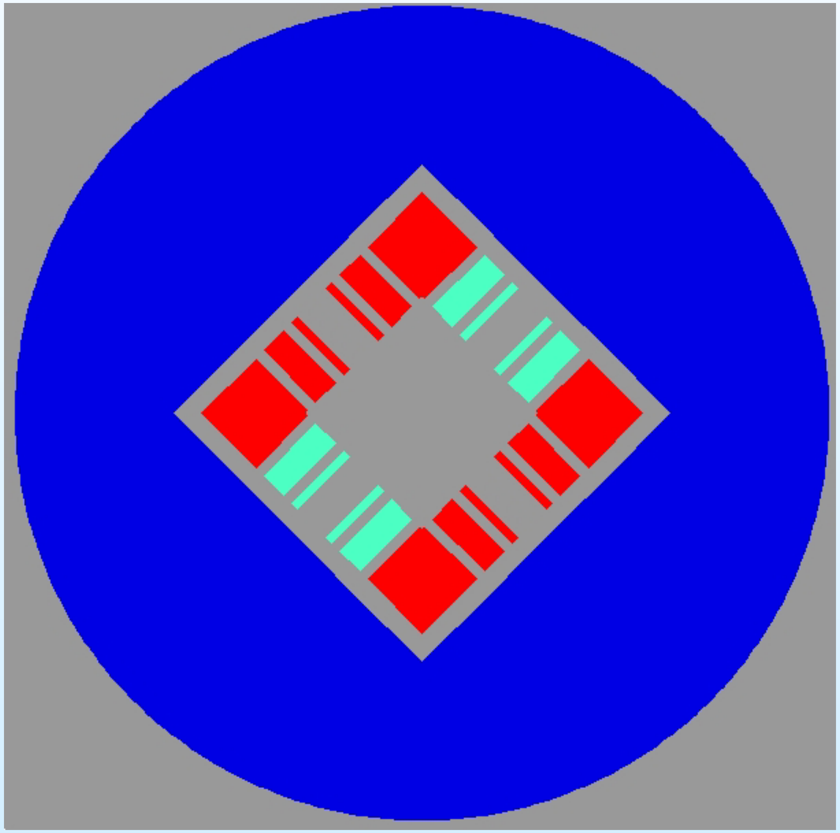
Near Future	
All Nb_3Sn	All HTS
12 T	11 T
15 T	16 T
18 T	22 T

⇨ In high luminosity operation, HTS is preferable due to its higher temperature margin.

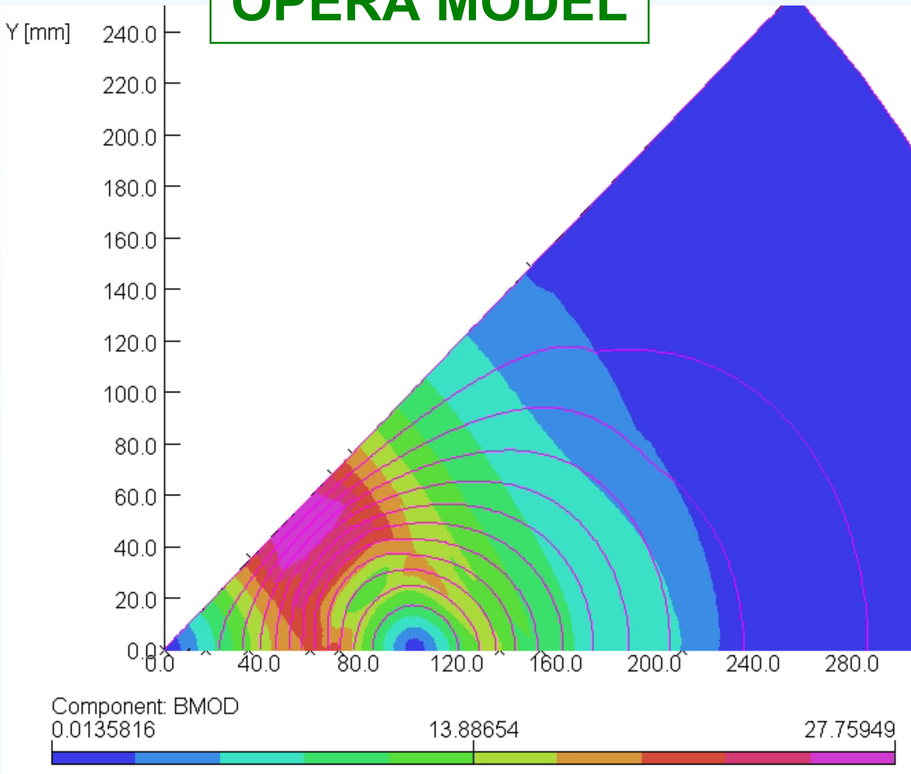
Investment in 2212 has been much less than in 2223, there may be room for relatively more improvement.

HTS Quad for LHC IR
(Racetrack Coil Geometry)

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



OPERA MODEL



Note: Peak field is not a major concern in HTS quadrupole designs.

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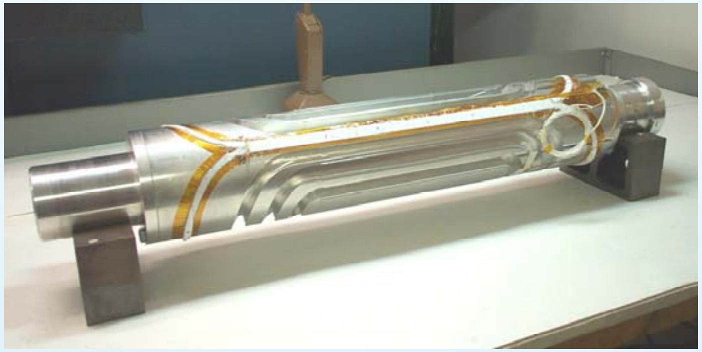
Nb_3Sn Magnet Program with Flexible Pre-reacted Cable

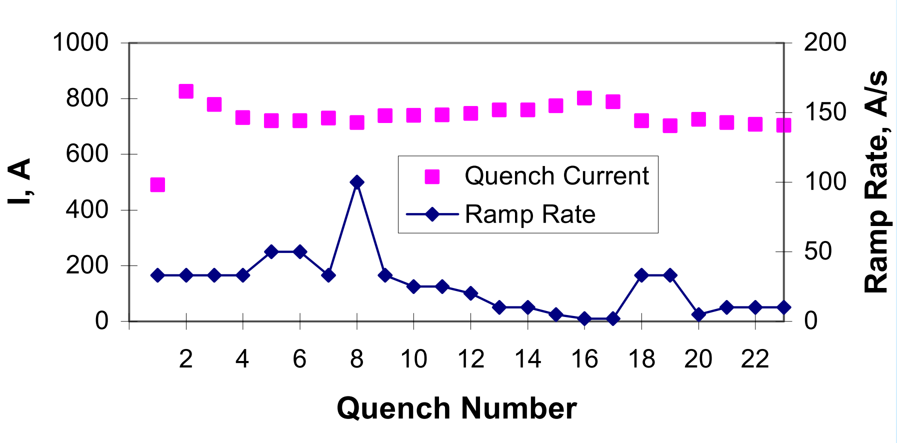
Erich Willen

A dipole coil using small-diameter, pre-reacted Nb_3Sn cable has been built and tested successfully. This proof-of-principal result opens the door to a promising, new approach to building high field magnets.



The quench results showed that the coil operated near the short-sample limit of the conductor, 820 A. The field at the winding is ~2.5T. The high current and low field, a difficult combination for stability in a superconductor, would be more favorable in a full scale magnet.

The construction technique subdivides the coil into many sectors, each independently supported, and can therefore control the Lorentz forces in high field magnets. This technique has been used to build many successful helical magnets for RHIC.



SUMMARY

- Given the time scale of LHC IR upgrade, the HTS option should also be examined.

- A conceptual direction of the program is outlined here that can be carried out with modest resources.

- This allows minimum development of HTS technology and evaluates its viability in time for making a technology choice for next generation IR's.

- We ought to do more than turning Nb_3Sn R&D magnets to machine magnets in next 10 years. If such R&D can not be justified in such situation, then when can it be?