Lecture XI

High Field Magnet Designs & Technology

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Scope of This Lecture

In this presentation, we shall cover only a few of the topics whose knowledge is essential in designing modern high field magnets.

However, high field magnet technology is a vast and involved field.

Here are some of the topics that are not covered during this course but, whose understanding is essential for a high field R&D program :

- Conductor R&D
- Mechanical design and analysis: Support structure and internal stress analysis is very important in the design of high field magnets
- Tooling & construction: An important aspect of the high field magnet engineering
- Quench protection

Main Issues in High Field Magnets

Superconductor:

- The superconductor used in the magnet must have good current density at high fields

Mechanical Support Structure:

- The support structure must be able to withstand large Lorentz forces

  Forces $\propto B^2$

  In a cosine theta dipole with current at radius "a", $F_x = \frac{2B_o^2}{3\mu_o} a$
- Minimize conductor motion that causes quench
- Minimize internal stress on conductor in very high field magnets

  Stress management (Texas A&M)

Magnetic Design:

- Optimize a design to deal with the above two challenges and if possible find one where the above two problems are inherently reduced
- Maintain an acceptable field quality throughout the operating range

Challenges with High Field Magnet Technology

• Present high field technology is in R&D phase. High field superconductors and high field magnets present several new challenges, in addition to those that are present in any superconducting magnet.

• All high field superconductors known today are brittle and stress/strain sensitive. Strain may bring a significant degradation in conductor performance.

• In high field magnets, Lorentz forces are very large. The support structure must be able to contain these forces. In addition, the deflections on conductors should be kept below a certain value.

• The above guidelines play a major role in high field magnet design and high field magnet construction technology.

• The coils are vacuum impregnated to fill gaps in order to avoid even small deflections in coils during excitation that may cause local strain on the conductor.

• Superconducting cables, coils and magnets are designed and constructed in such that the conductor at any place or at any stage is not subjected to excessive stress/strain - during high temperature reaction of conductor, during coil manufacturing, during magnet assembly, during cool down or under large Lorentz forces.

Challenges with High Field Superconductors

- Of all high field superconductors available now, only Nb_3Sn has the requisite conductor performance that one can consider making high field (10-20 T) magnets for accelerator applications.
- It is produced in quantities that one can make R&D and specialty magnets. We hope that the Nb_3Sn production can be scaled-up in the future (may be starting with ITER) and the cost reduced to a level that it can be used in large projects.
- HTS is a developing technology that has a potential of making a substantial difference in some special high field magnets. The conductor production continues to show progress and is now available in sufficient quantities to make R&D coils.
- Other conductors, such as Nb_3Al (a conductor that is more tolerant to strain) MgB_2 (the new low temperature superconductor with high critical temperature), are available only in limited quantities.

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.

Why Wind & React Technology is so Popular?

- Almost all successful high field short R&D accelerator magnets have been built using “Wind & React” approach.

- The “Wind & React” approach, for the most part, bypasses the problems associated in dealing with the brittle materials, as the coil is wound before the reaction when the material was not brittle.

- One must still be careful in handling the reacted coils, leads, etc., but this handling is significantly less than that required in the “React & Wind” approach.

- Once the coil is reacted, it is quickly impregnated. The impregnated structure becomes a robust module which can, with care, be handled.

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.

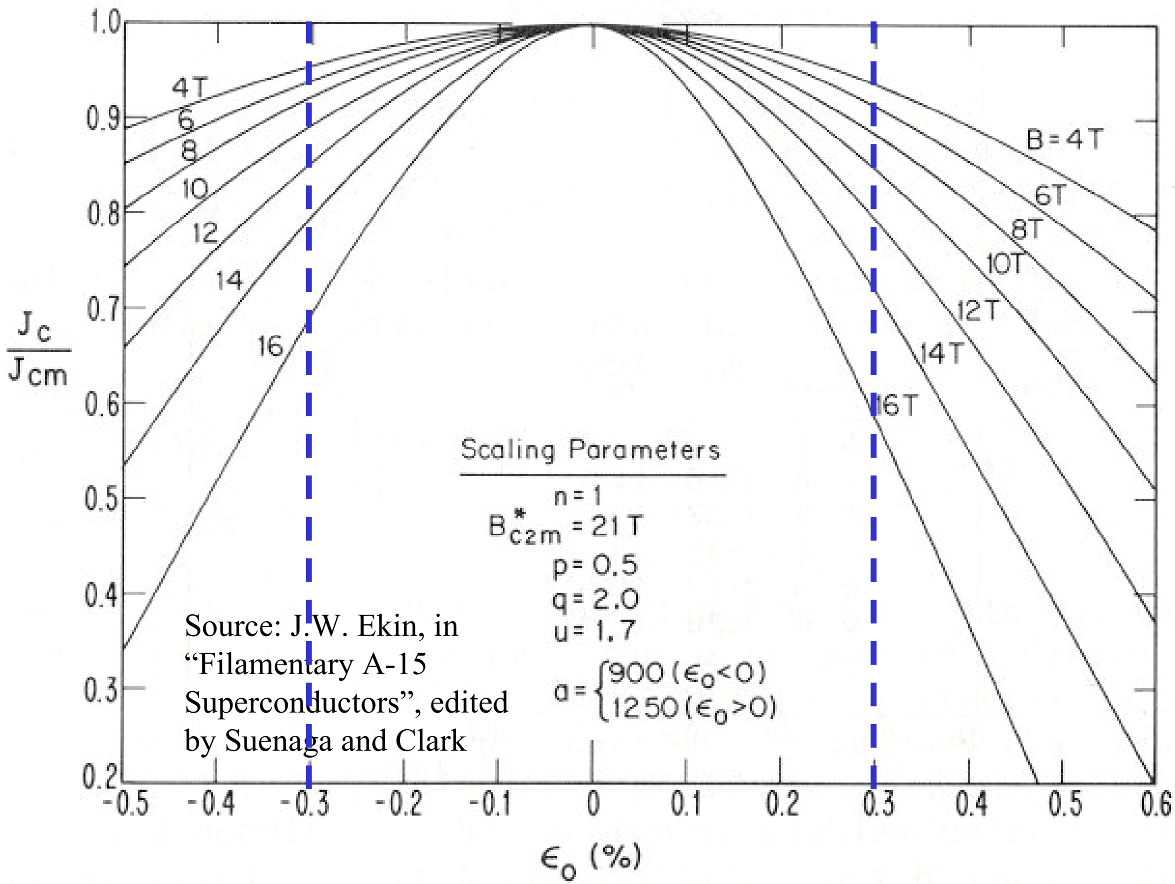
Challenges with React & Wind Approach

- 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, and in magnet designs and 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.

Strain and Field



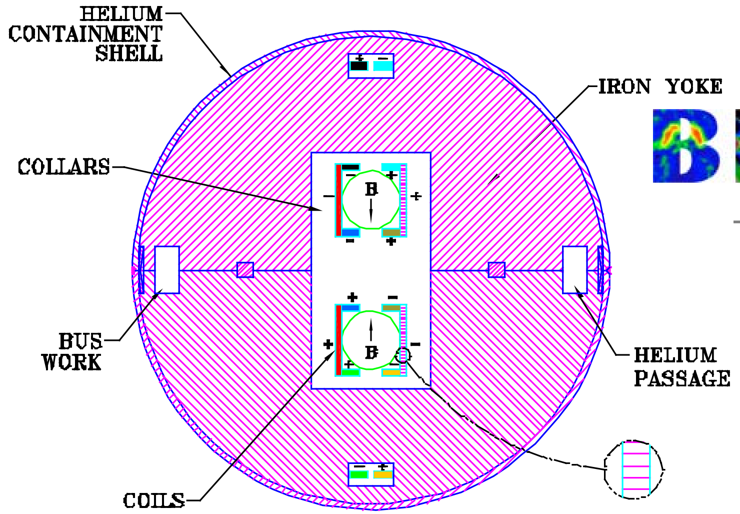
Relative critical-current density J_c/J_{cm} as a function of intrinsic strain $\varepsilon_0(\equiv\varepsilon-\varepsilon_m)$ for different magnetic fields, evaluated using Eq. (3) and the typical set of scaling parameters indicated in the figure.

When conductor is bent it stretches on its outer side and compress on its inner side.

It is generally thought that the axial strain produces similar internal deformation as the bending strain. However, there is some debate on it.

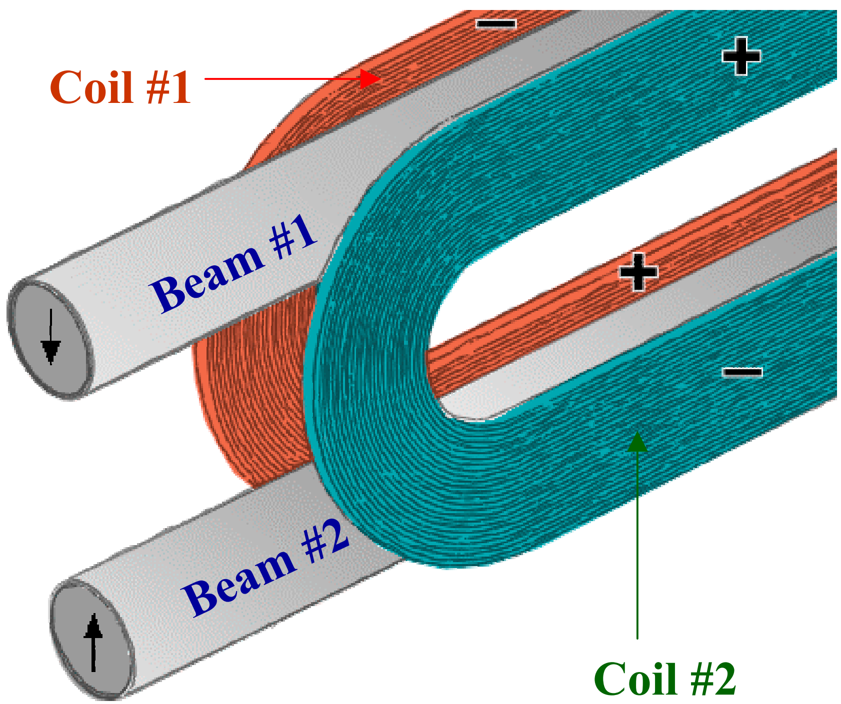
~0.3 % axial strain seems to be acceptable.

Perhaps ~0.5% may be tolerable, if "high strain" and "high field" are not at the same location (as is the case in the most designs of accelerator magnets).



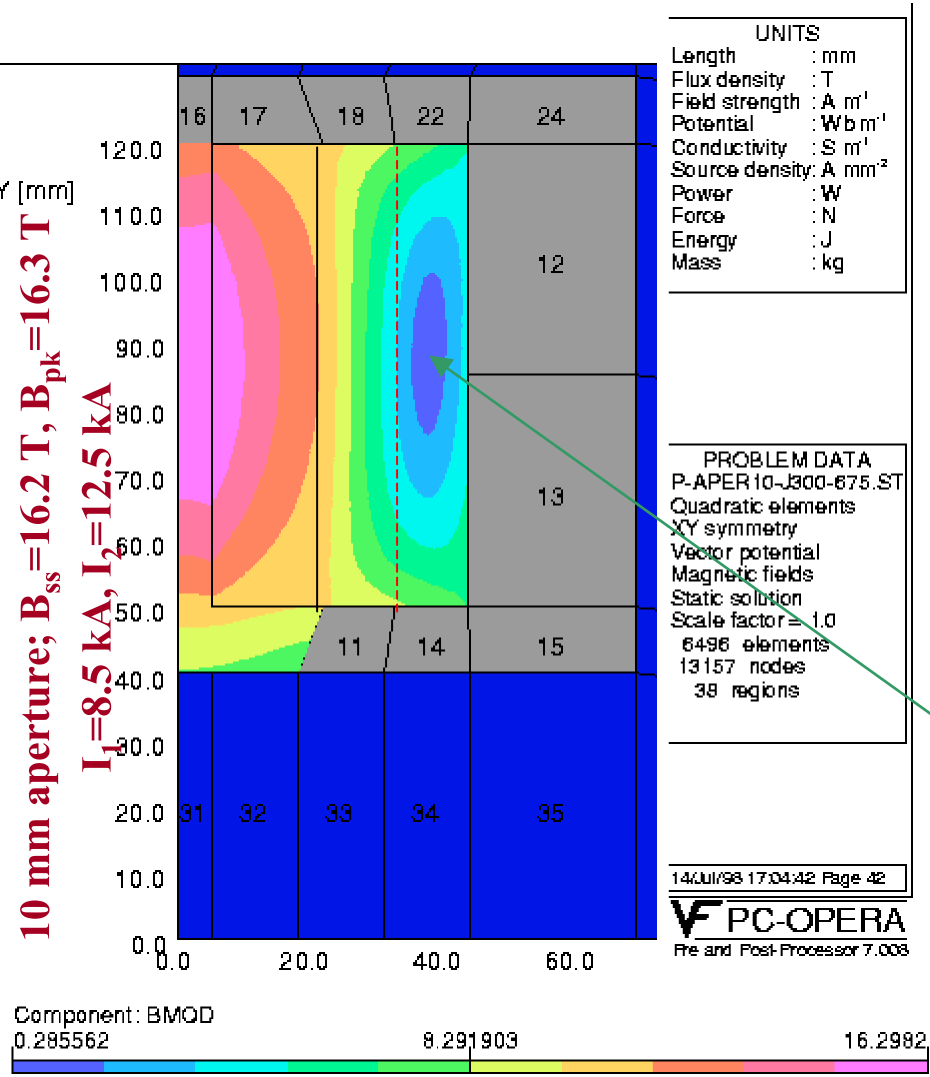
Common Coil Design

- **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 - most for H.F. are - Nb_3Sn 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*

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



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

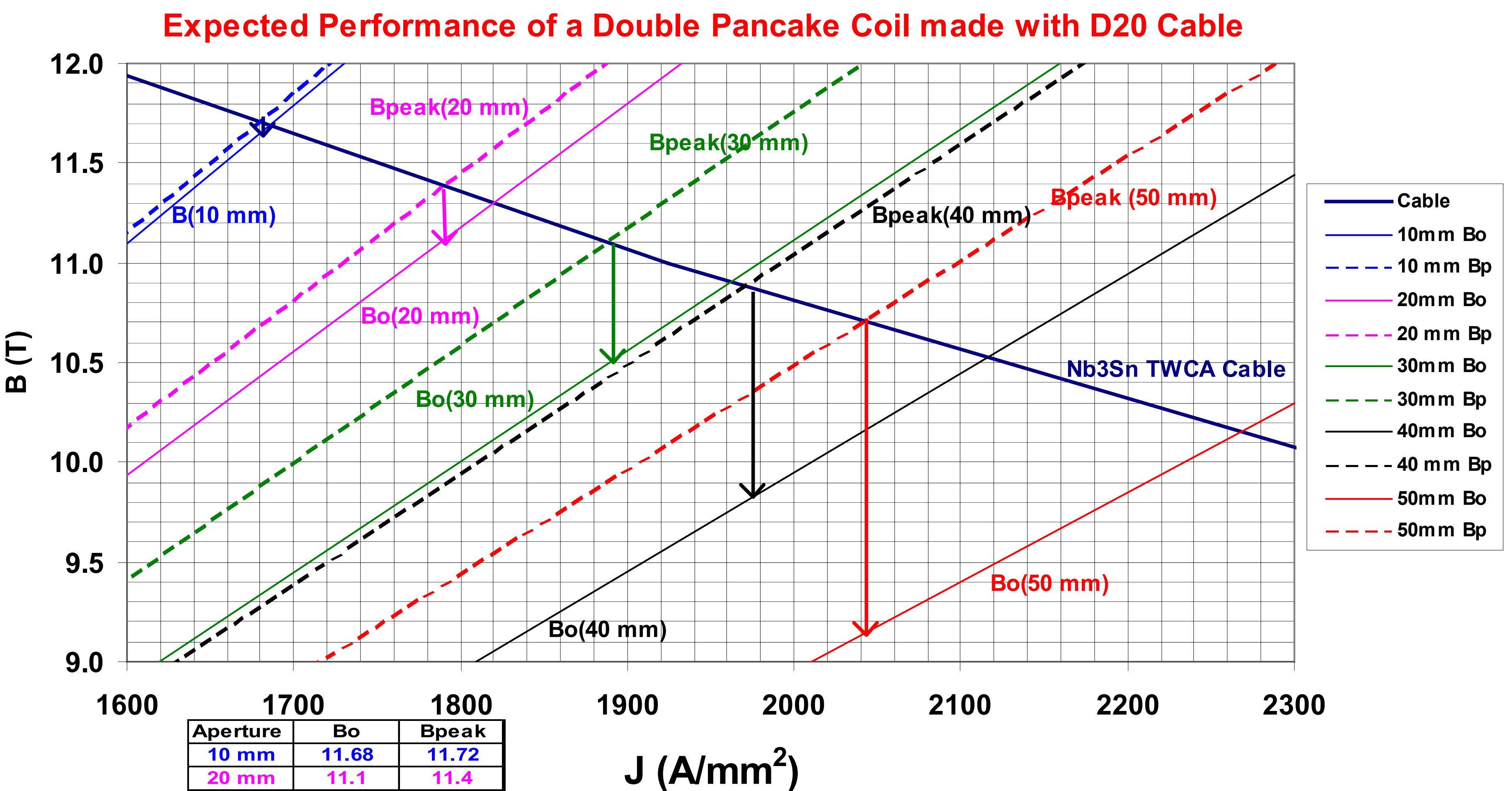
Determine stress degradation in an actual conductor/coil configuration

- 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?

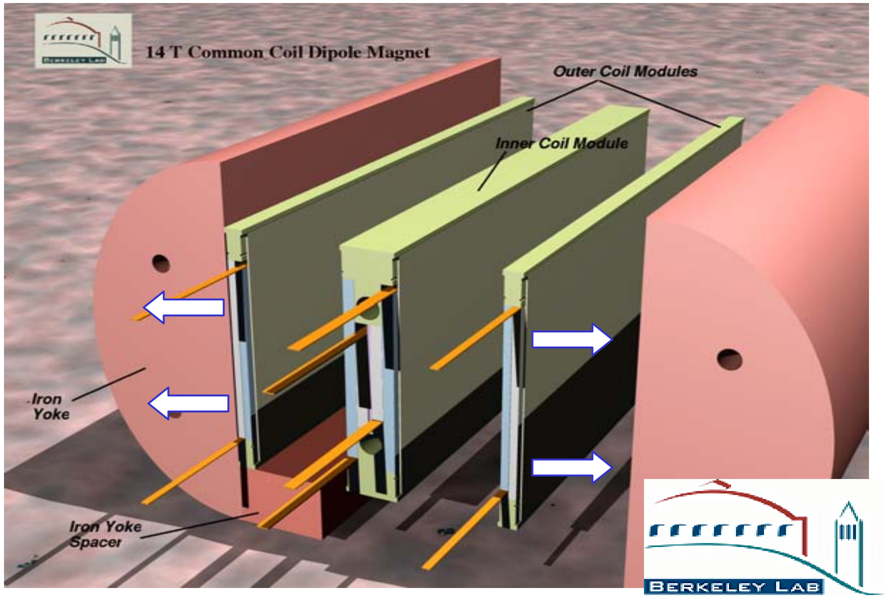
Simulate future (better J_c) conductor

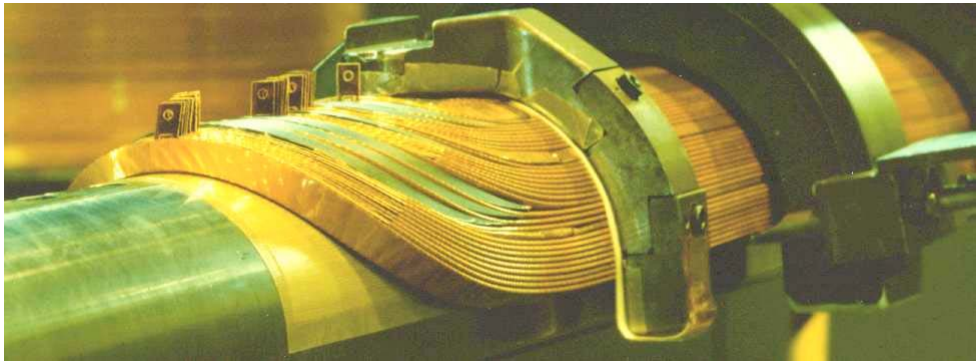
Change in Aperture for Various Field/Stress Configurations



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

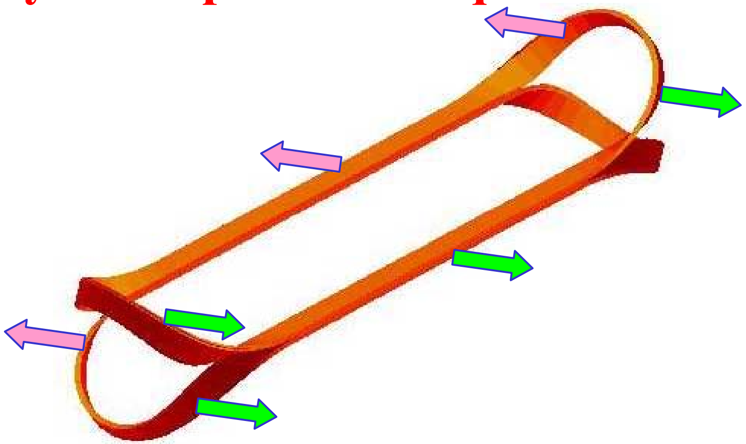
Lorentz Forces in High Field Magnets (Cosine Theta and Common Coil)





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.



Persistent Current-induced Harmonics
(may be a problem in Nb_3Sn magnets, if nothing done)

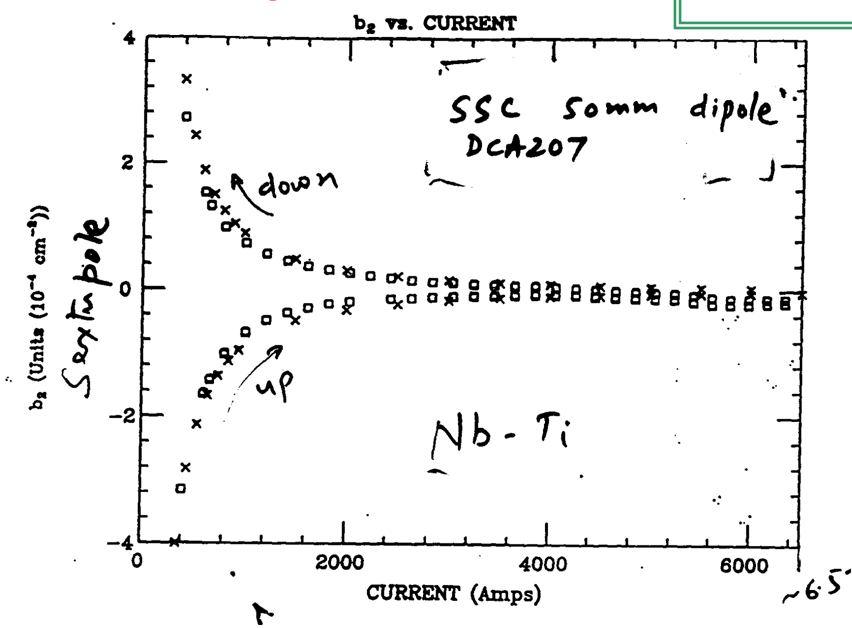
• **Nb_3Sn** superconductor, with the technology now in use, is expected to generate persistent current-induced harmonics which are **a factor of 10-100 worse** than those measured in Nb-Ti magnets (because of higher Jc and higher filament size).

• In addition, a snap-back problem is observed when the acceleration starts (ramp-up) after injection at steady state (constant field).

Magnetization :

$$M = \frac{4}{3\pi} J_c a$$

Measured sextupole harmonic in a Nb-Ti magnet



Measured sextupole harmonic in a Nb_3Sn magnet

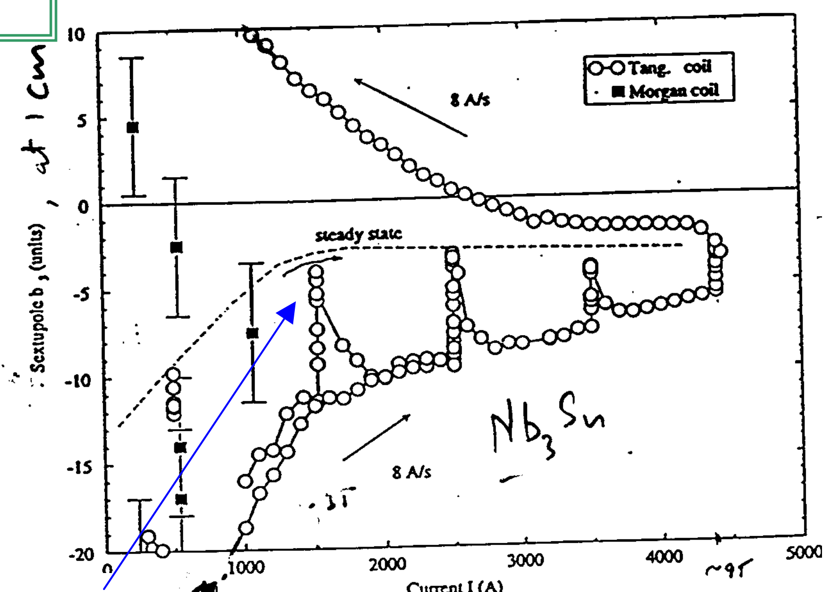


Fig. 6.. Measured sextupole at low field (direction of arrow indicates up or down current).

Either reduce the effective filament diameter or come up with a magnetic design that minimizes the effect of magnetization in the magnets (LBL, FNAL, TAMU).

High Field Magnet R&D in US

High field accelerator magnet R&D in US is taking place at BNL, FNAL and LBL. In addition Texas A&M is also involved. The following have been the major elements of the national high field magnet R&D program till recently.

LBL:

- "Wind & React" Nb_3Sn magnets (cosine theta, common coil and racetrack)
- Holder of the record of highest field magnet (~16 T)

FNAL:

- "Wind & React" cosine theta and "React & Wind" Common coil with Nb_3Sn
- A number of parallel programs

BNL:

- HTS & Nb_3Sn "React & Wind" Common Coil
- Recently "Wind & React" racetrack coil program has also been started

Texas A&M University

- Stress Management Designs

Most current effort is focused on the development of long quads for LHC IR upgrade (LARP).

High Field Magnet R&D Program at Texas A&M

Stress Management for Very High Field Magnets

Stress Management (1)

At very high fields, stress accumulation due to Lorentz forces becomes very large.

Large stress can cause conductor degradation.

Proposed stress management manages stress accumulation, by intercepting and reducing it.

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

ON THE FEASIBILITY OF A TRIPLER UPGRADE FOR LHC*

P. McIntyre[#] and A. Sattarov, Texas A&M University, College Station, TX 77883 U.S.A.

STRESS MANAGEMENT

To be successful such a strategy must also cope with the strain sensitivity of both materials. As field increases, Lorentz stress increases $\propto B^2$. But Nb_3Sn undergoes reversible degradation for stress $\sigma > 150$ MPa, and Bi-2212 undergoes irreversible degradation for strain $\varepsilon > 0.6\%$.

Lorentz stress accumulates through the thickness of a superconducting coil. The field acts upon each cable element in turn and the forces add up as they are passed to the outside structure. This accumulation is unavoidable in coils of cos θ geometry because the entire coil is one mechanical assembly.

A new generation of Nb_3Sn dipoles has been under de-

*Work supported by US Dept. of Energy, grant # DE-FG03-95ER40924, and by EC Research Infrastructure Activity FP6: 'Structuring the European Research Area' program, CARE-RII3-CT-3003-506395.
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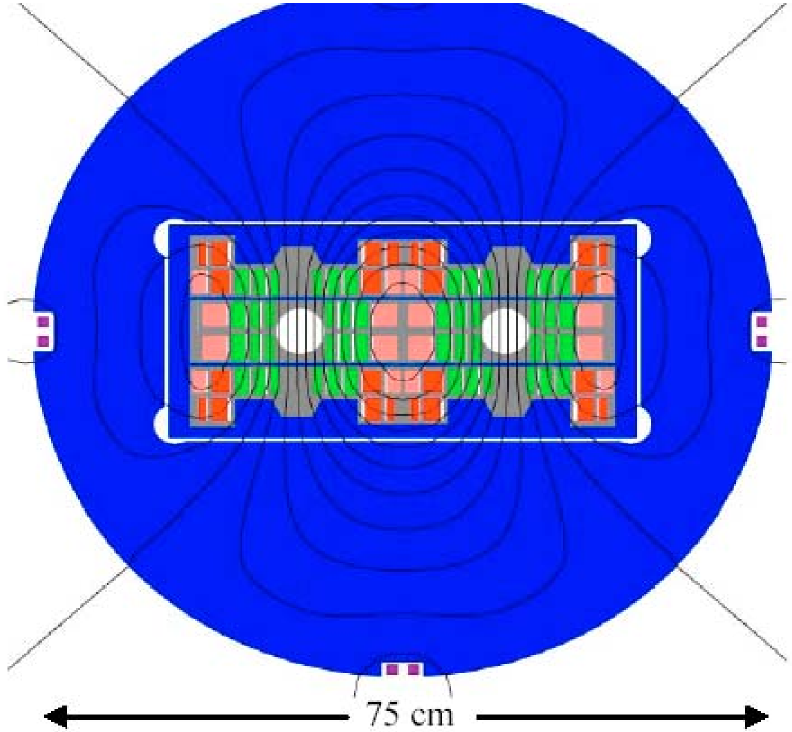


Figure 1. 24 Tesla hybrid dipole for LHC tripler.

Stress Management (2)

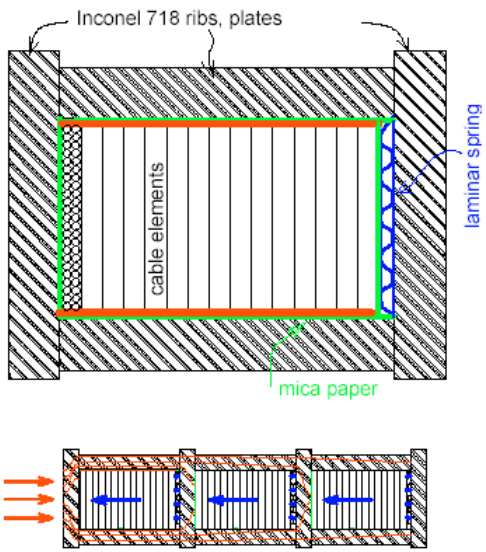
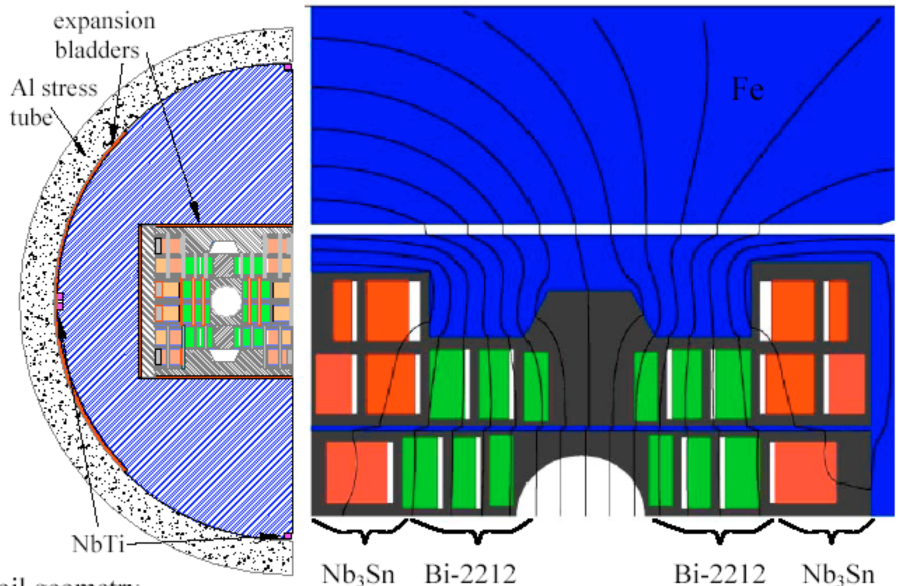


Figure 2. Stress management in a block coil geometry.



Courtesy:
McIntyre, Texas A&M

Figure 4. Elements of the hybrid coil dipole: a) half-section showing bladders; detail showing flux plate.

Figure 3. Applying laminar springs, ribs and plates to inner winding of Nb_3Sn.

- **Stress is not allowed to accumulate**
- **Accumulated Stress intercepted**
  peak value reduced
- **Pre-stress is applied to minimizes conductor motion**

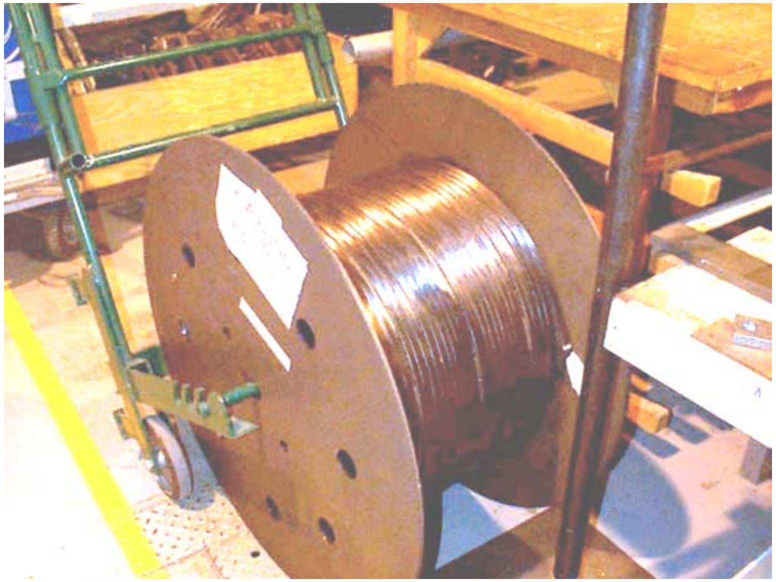
Highlight and Selected Pictures and Processes from BNL High Field Magnet R&D Program

- "React & Wind" Common coil with Nb_3Sn and HTS
- A number of HTS conductor, coil and magnet programs
- Currently playing a major role in long length "Wind & React" coils for LHC IR upgrade through racetrack coils

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.



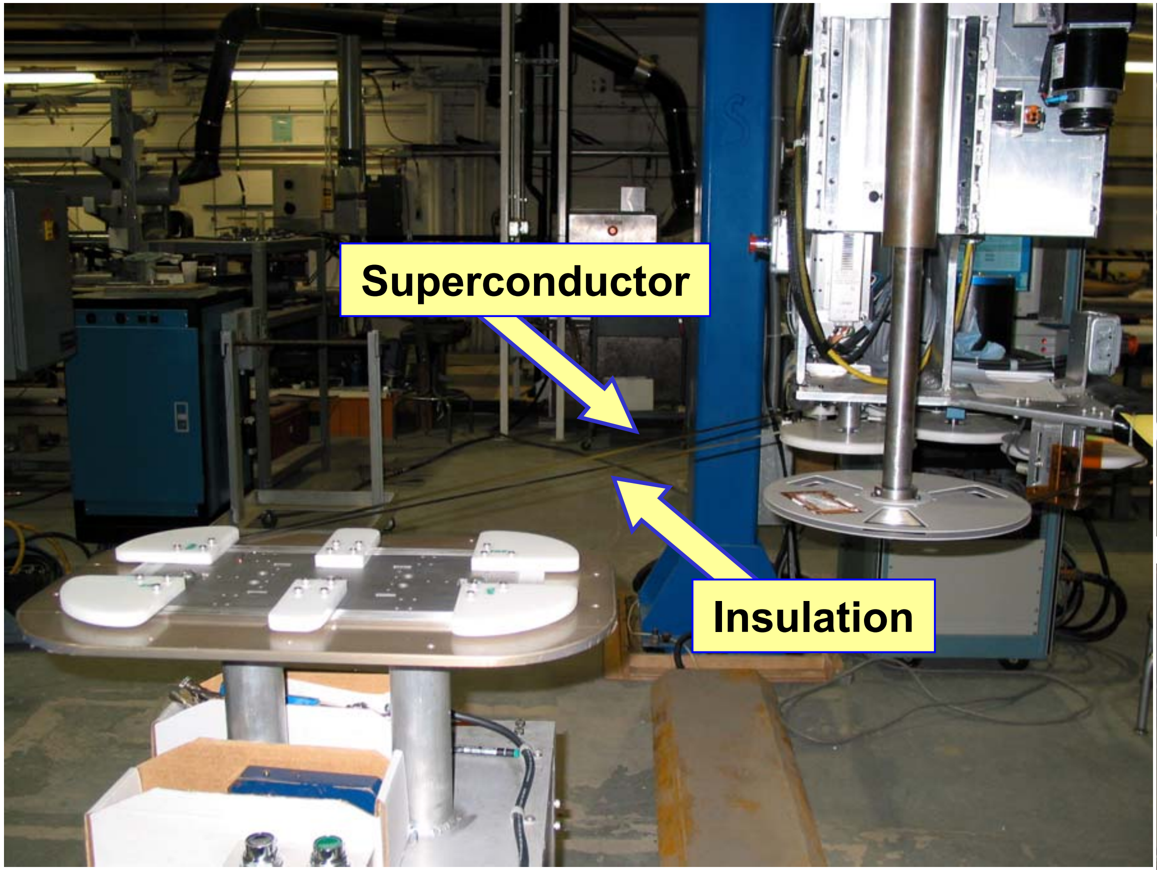
Nb_3Sn cable after reaction.

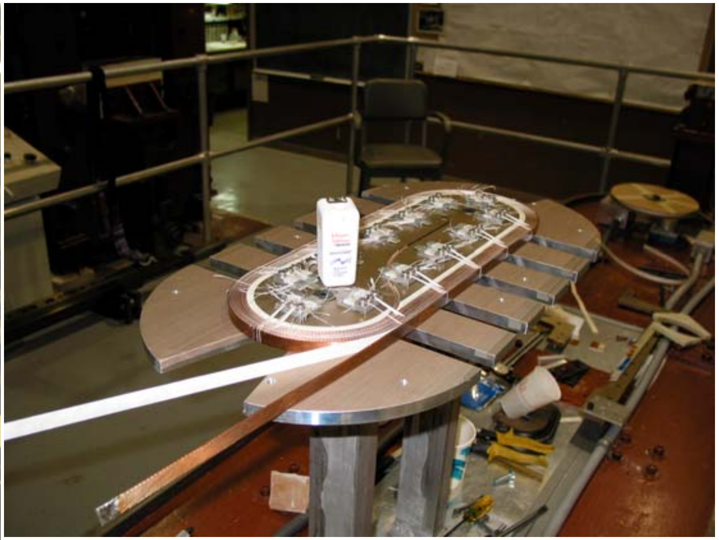
Reaction Process at BNL

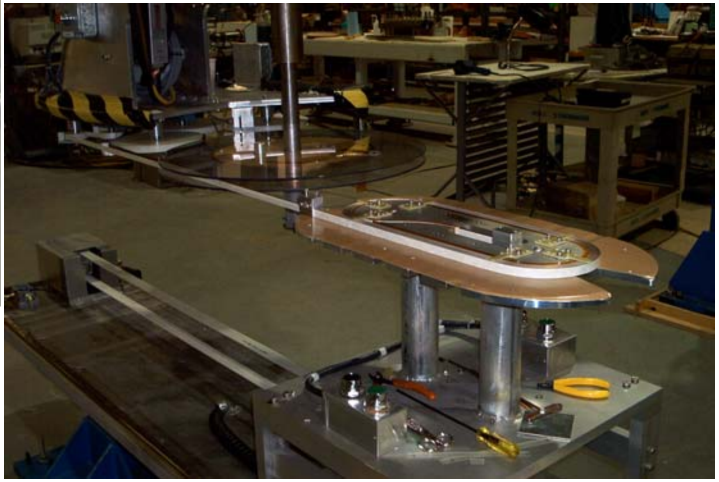
• Spools for reacting (heat treatment) Nb_3Sn cable (see two pictures on right).

• 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

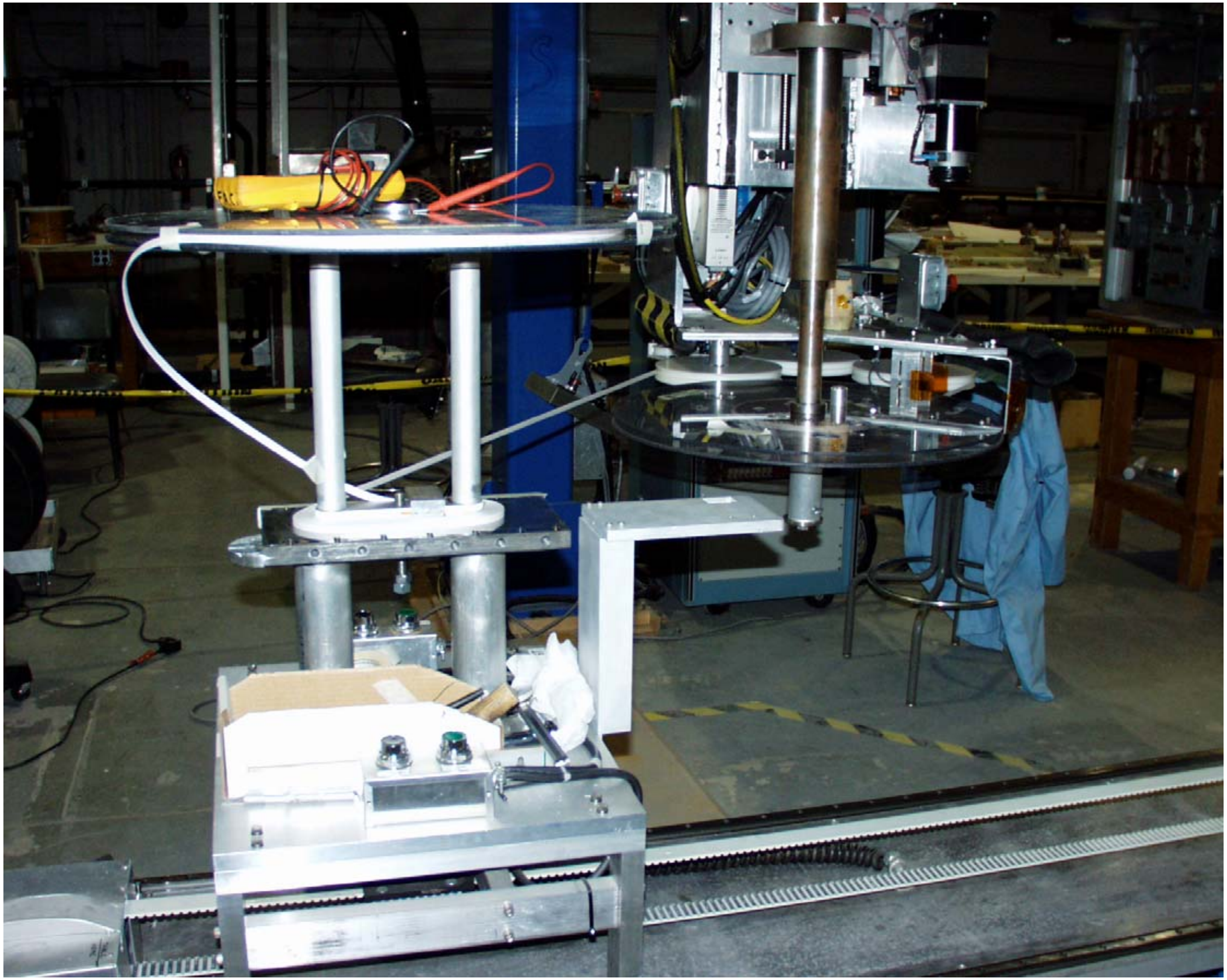




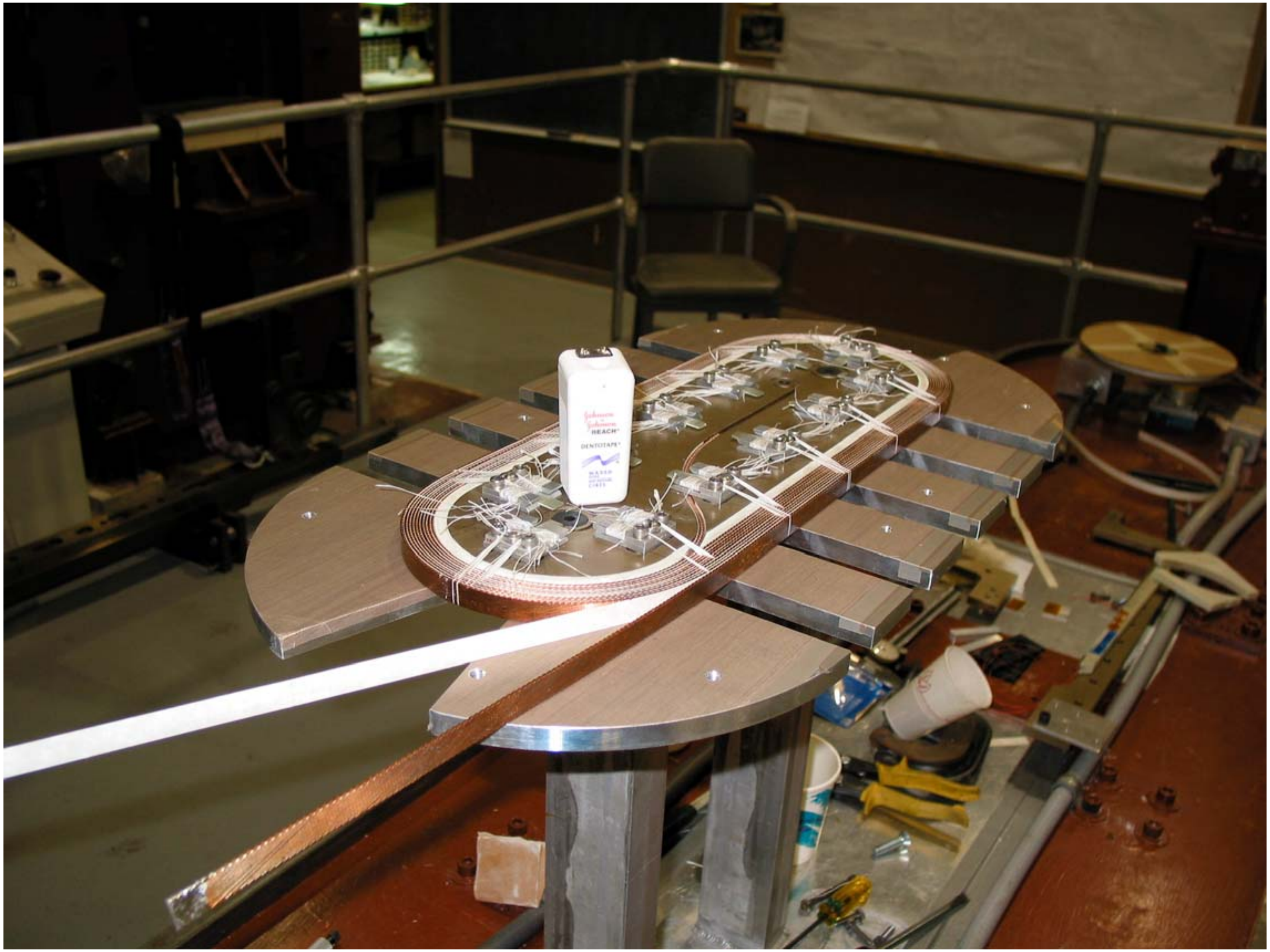


A coil being wound in a computer controlled winding machine.

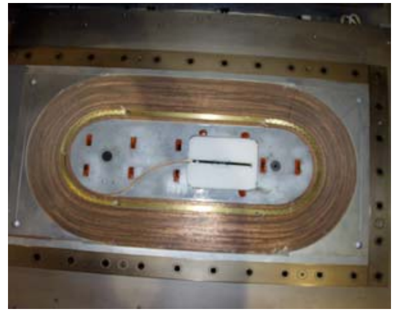
Double-Pancake Winding with Sleeve Insulation

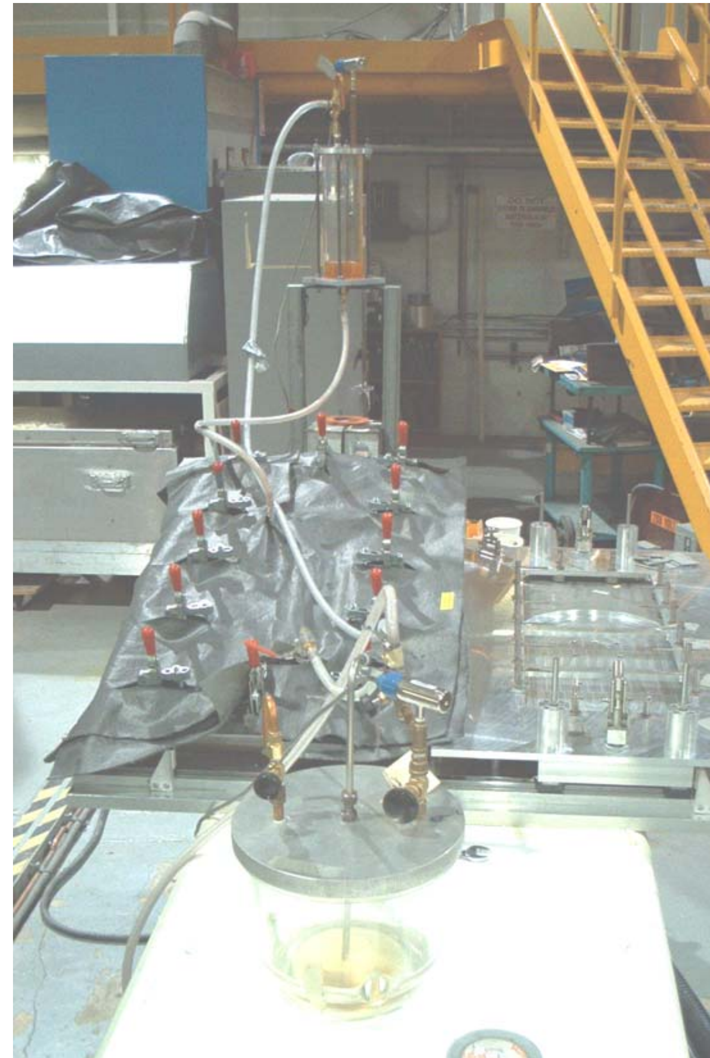


Cable Coil with Nomex Tape Insulation

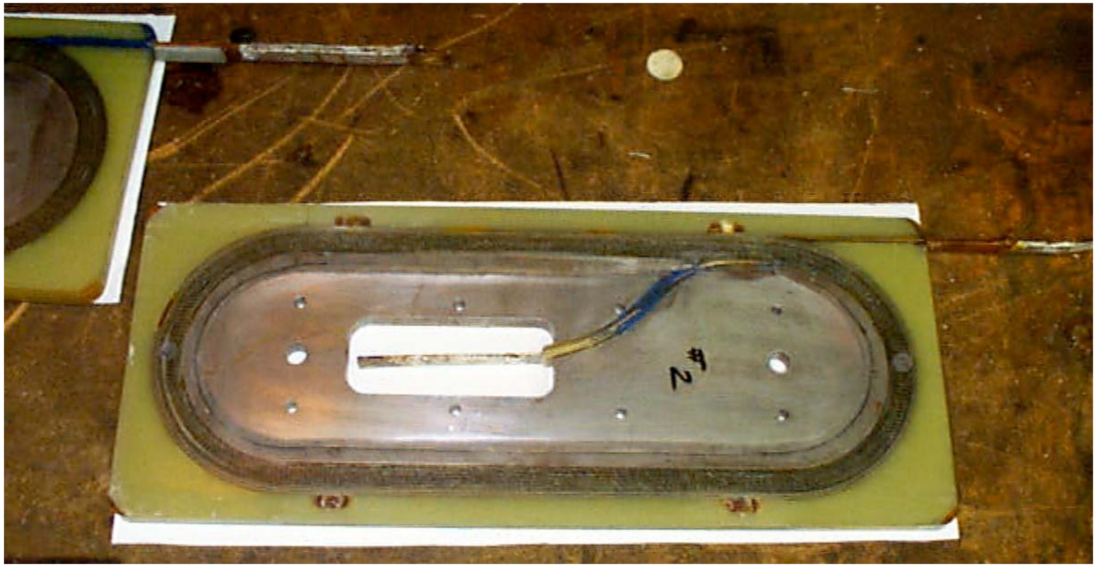


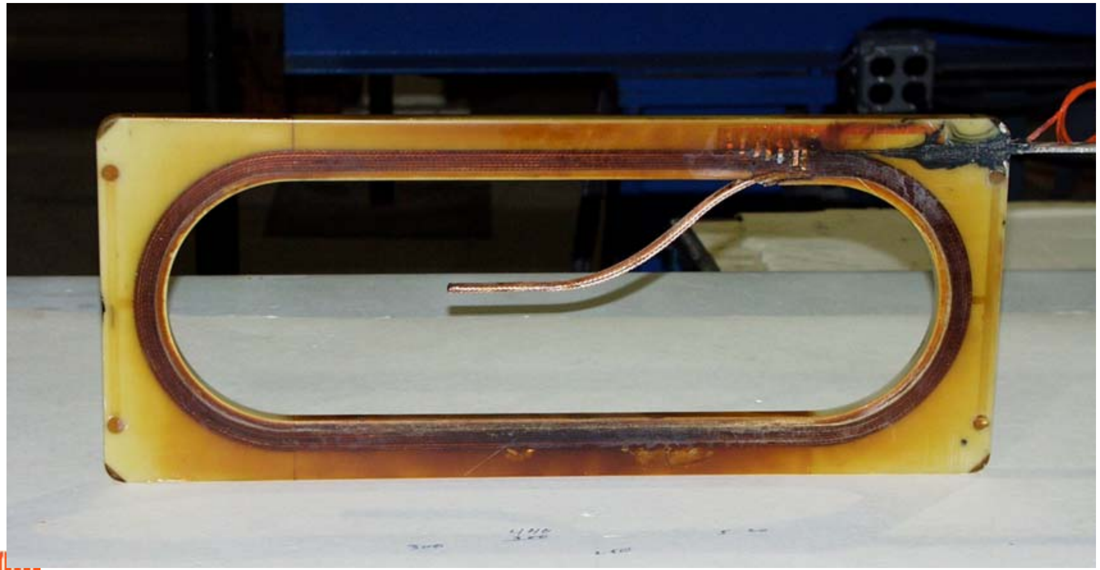
Vacuum Impregnation





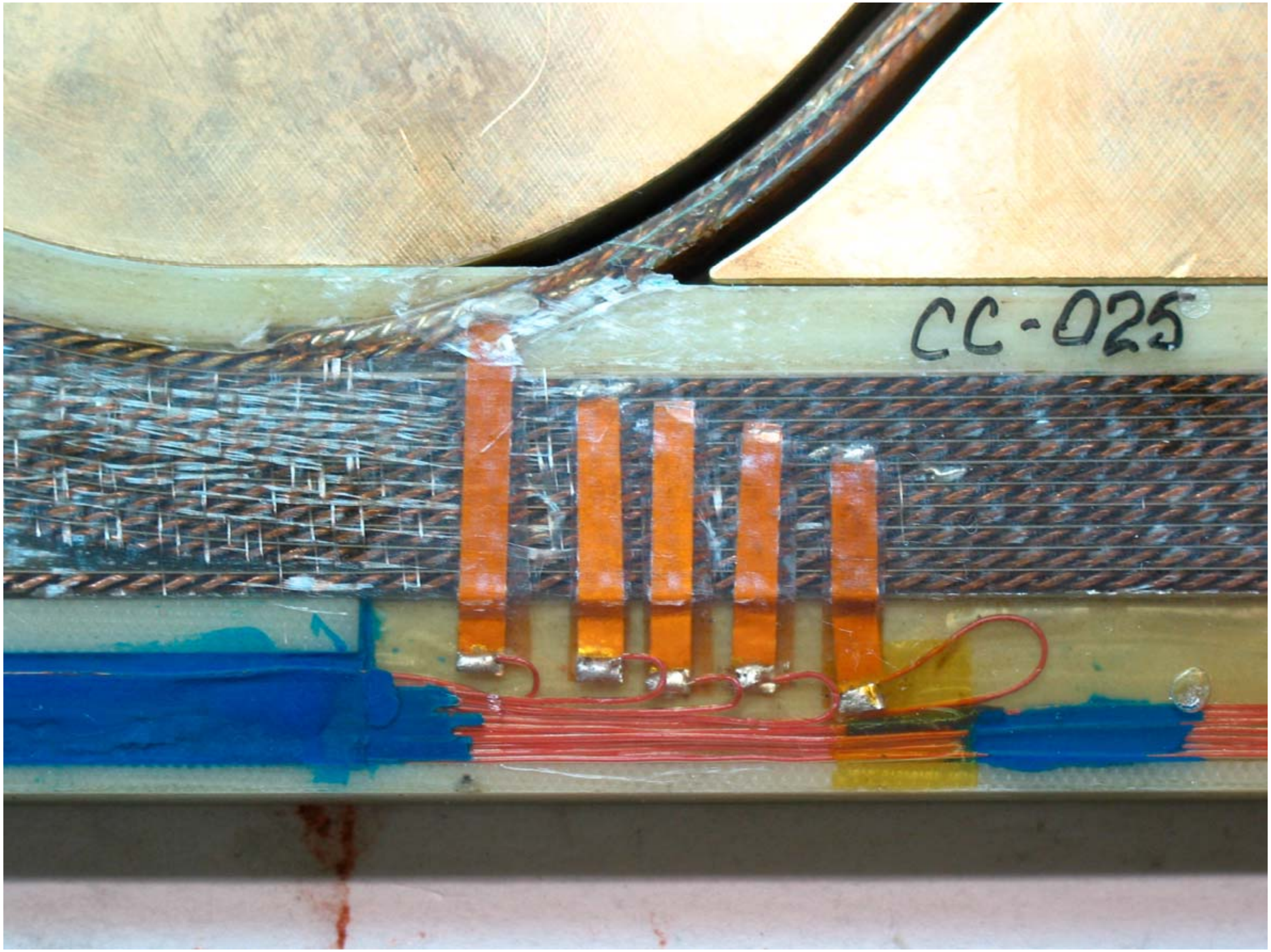
Epoxy Impregnated Coils



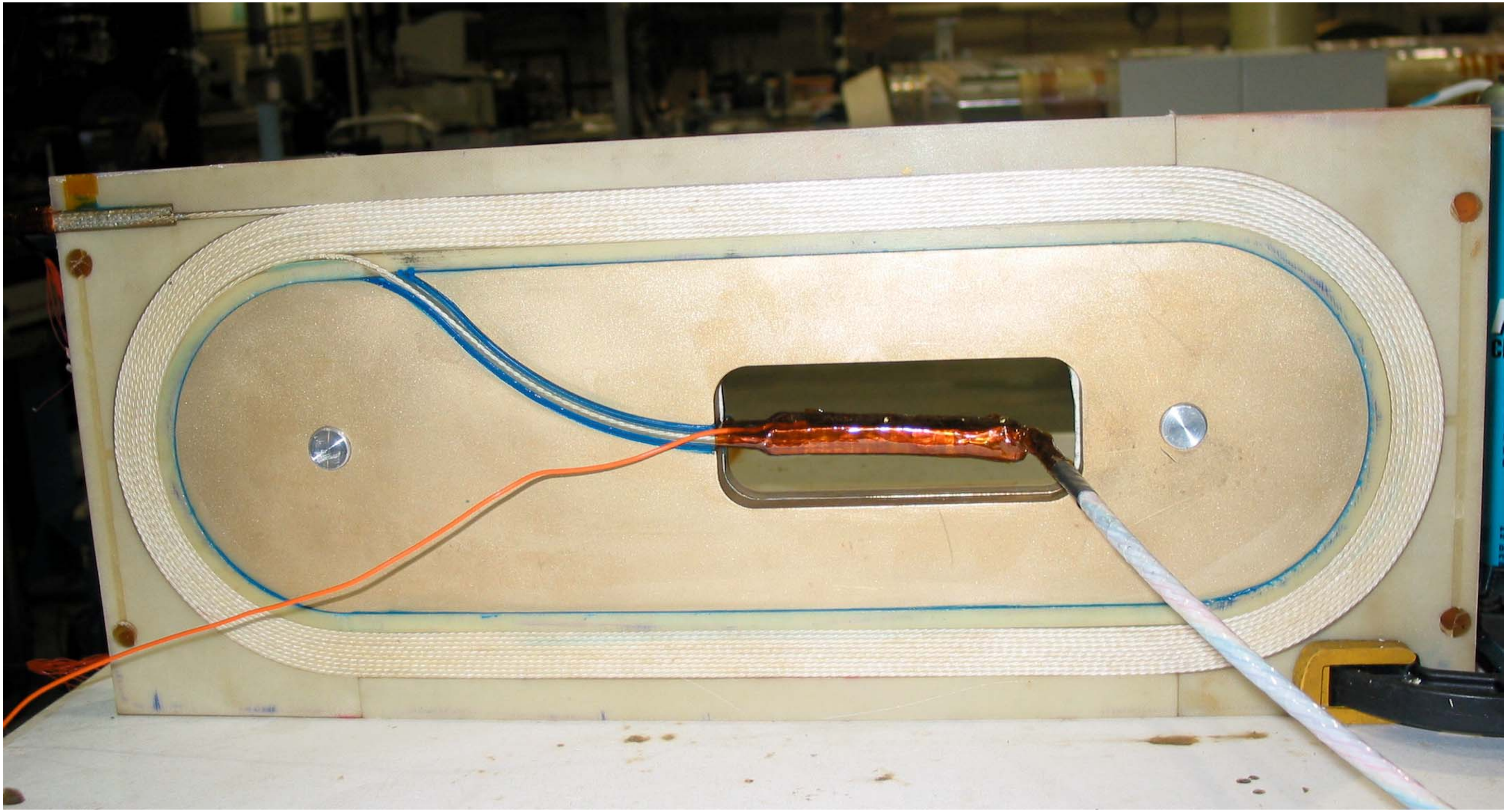


Vacuum impregnated coils made with the "React & Wind" technique.

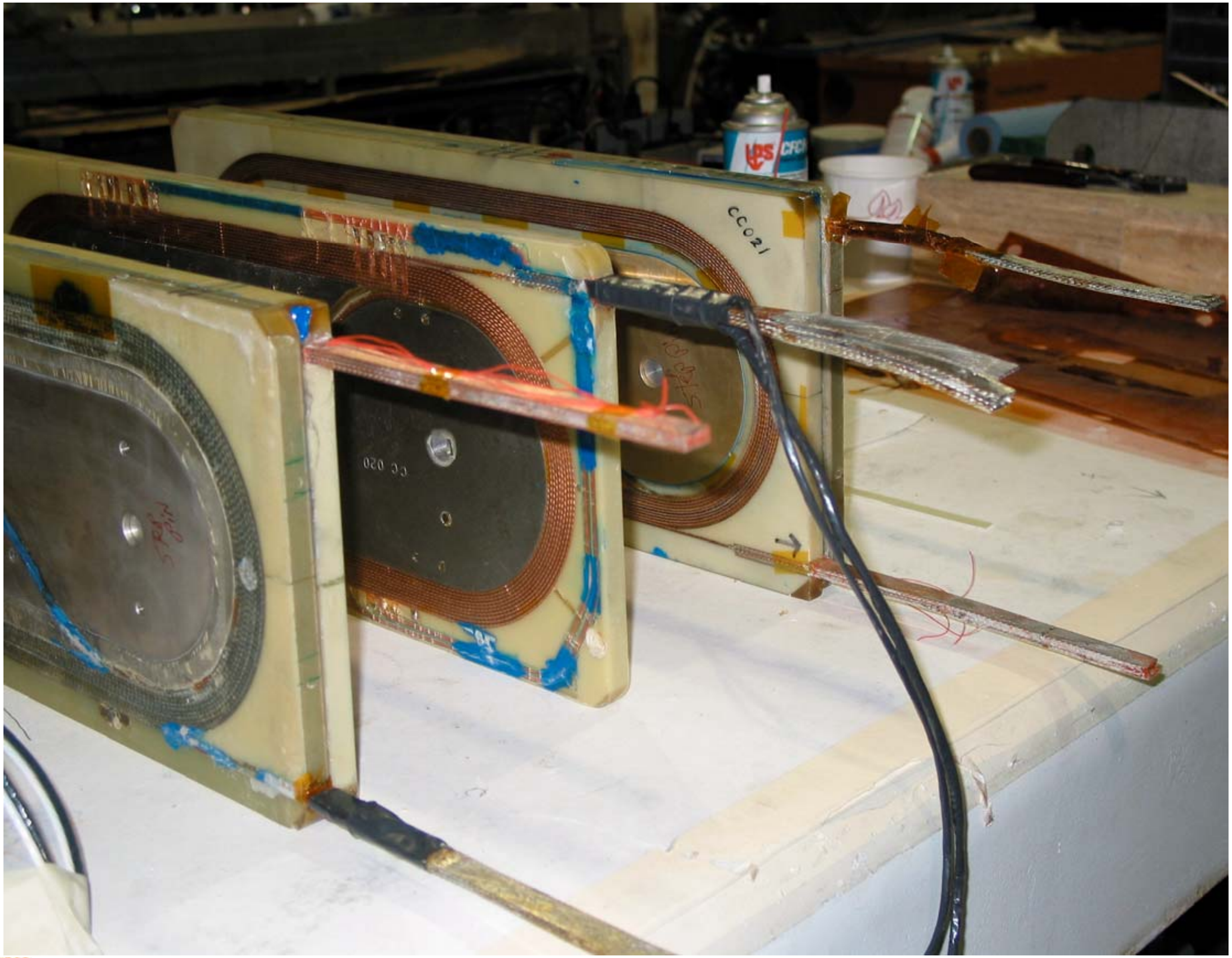
Voltage Taps to Help Determine Quench Location



HTS Cable Coil

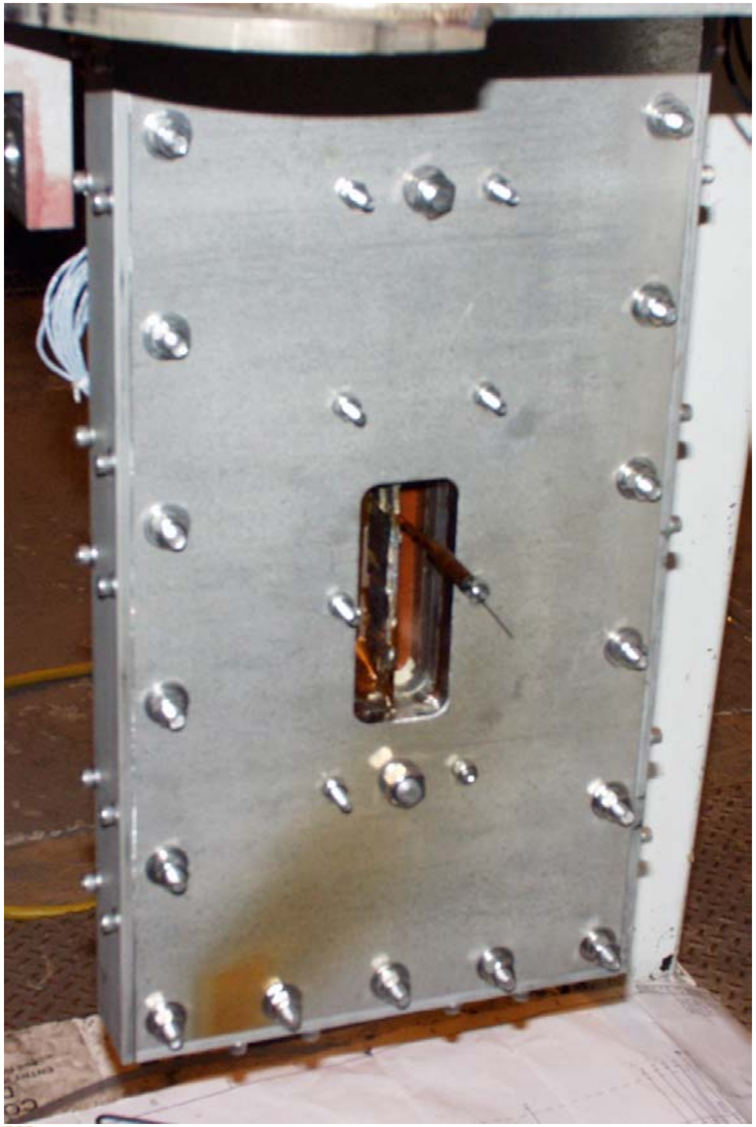


A Series of Racetrack Coils

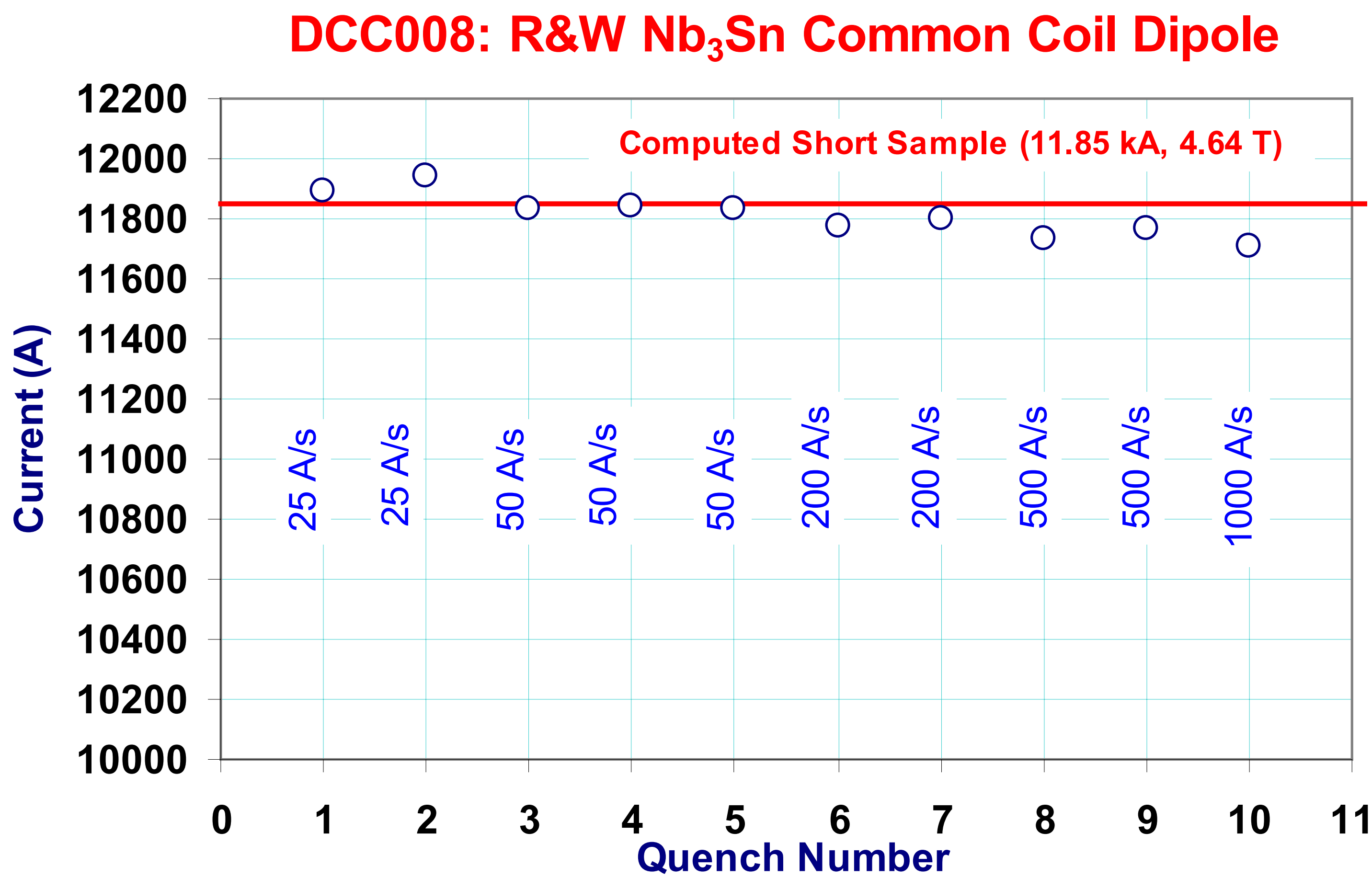


BNL makes racetrack coils in a modular fashion. These modules (cassettes) are placed in a flexible structure to do a variety of experiments with a rapid turn around.

Two Support Structures for Medium Field Common Coil Design at BNL



Initial Experience with React & Wind Nb_3Sn Technology Magnet at BNL

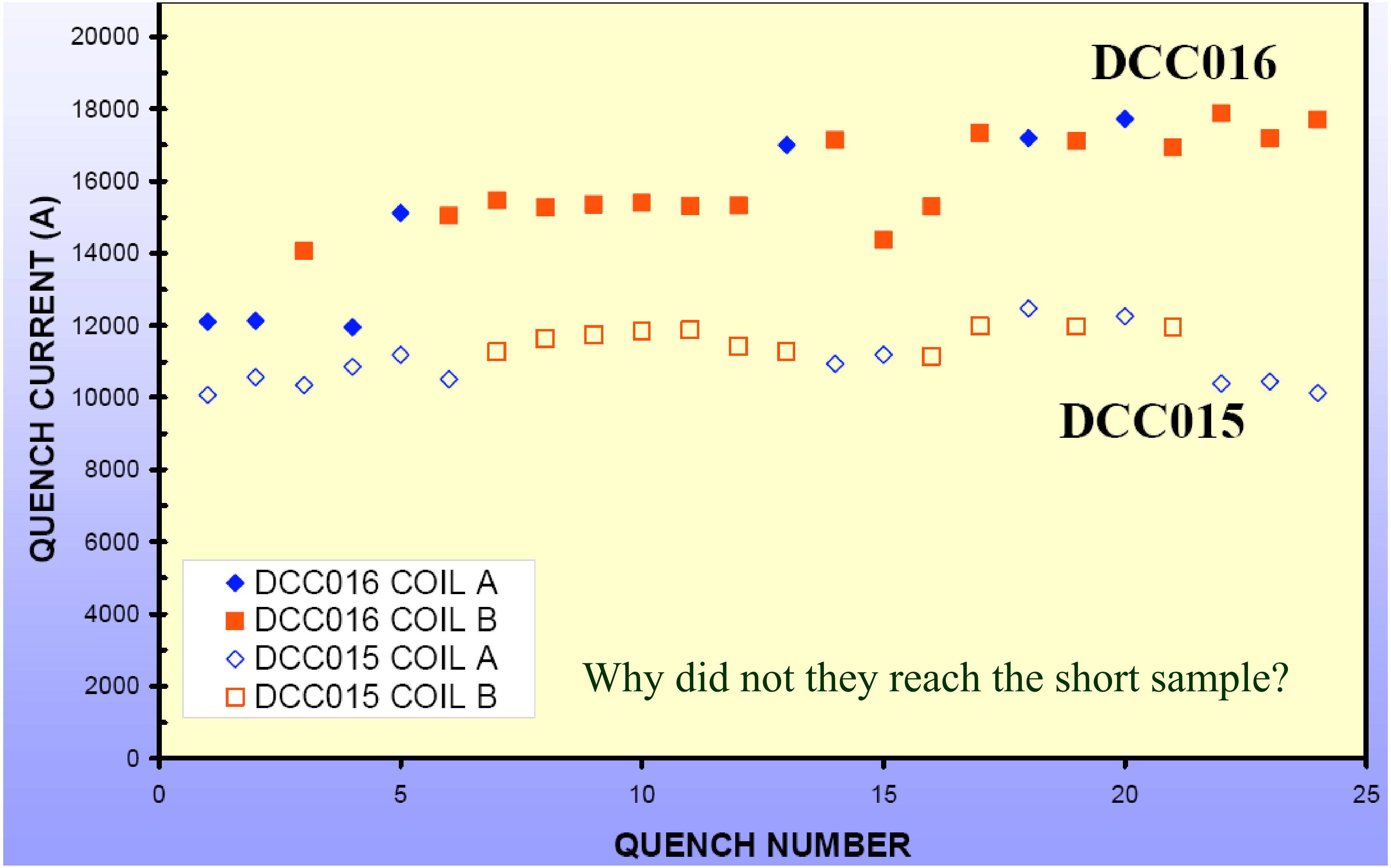


- Magnet reached the short sample in the first quench itself.
- The magnet was made with chrome-plated ITER cable.

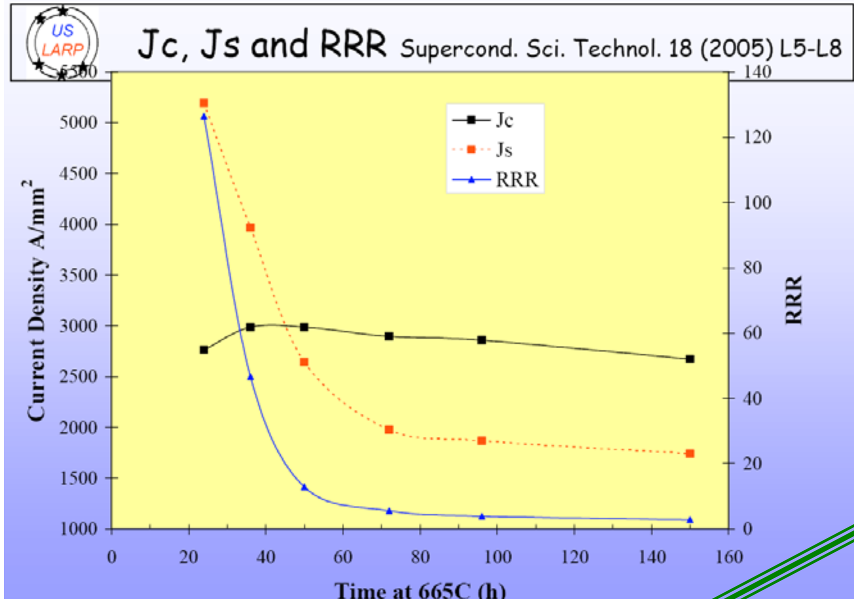
This shows that at least at low fields (up to 4.6 T), degradation, if any, is small.

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

Performance of Later Magnets

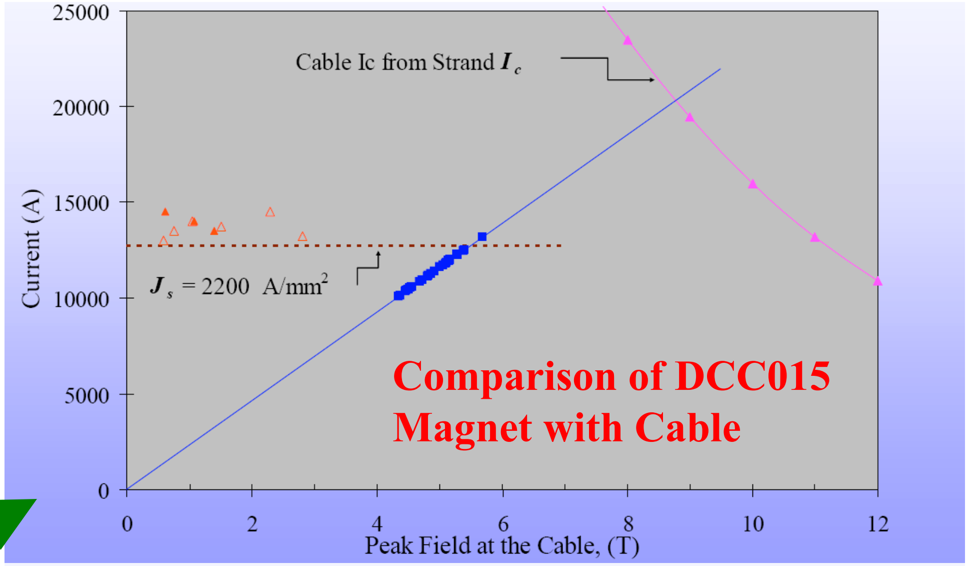


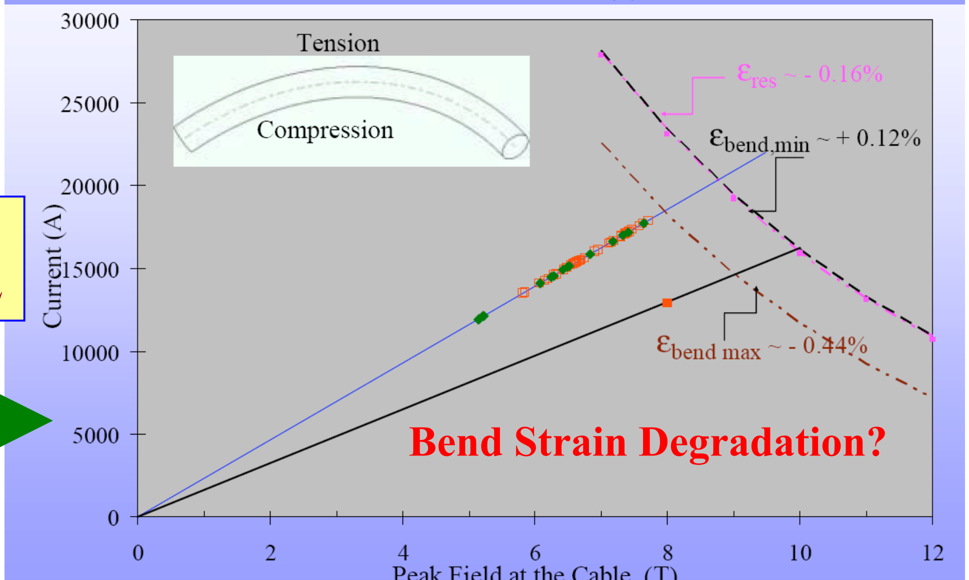
Conductor Instability and Bending Degradation



- 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





Magnet Analysis

- Magnetic Instability can limit magnet performance
  - However the threshold J_s can be increased by HT optimization such that it does not limit magnet performance
- Quench performance of DCC016?
  - Reached 80% of 30x virgin strand Ic
  - Cabling degradation is small ➢ From extracted strand test < 5 %
  - Flux-Jump magnetic instability ➢not likely as the quenches are in both coils
  - Bend strain degradation not known ➢ max. bend strain ~ 0.28%
  - Erratic quench behaviour ⇨ conductor motion
  - Ramp rate dependence

Courtesy:
Ghosh, BNL

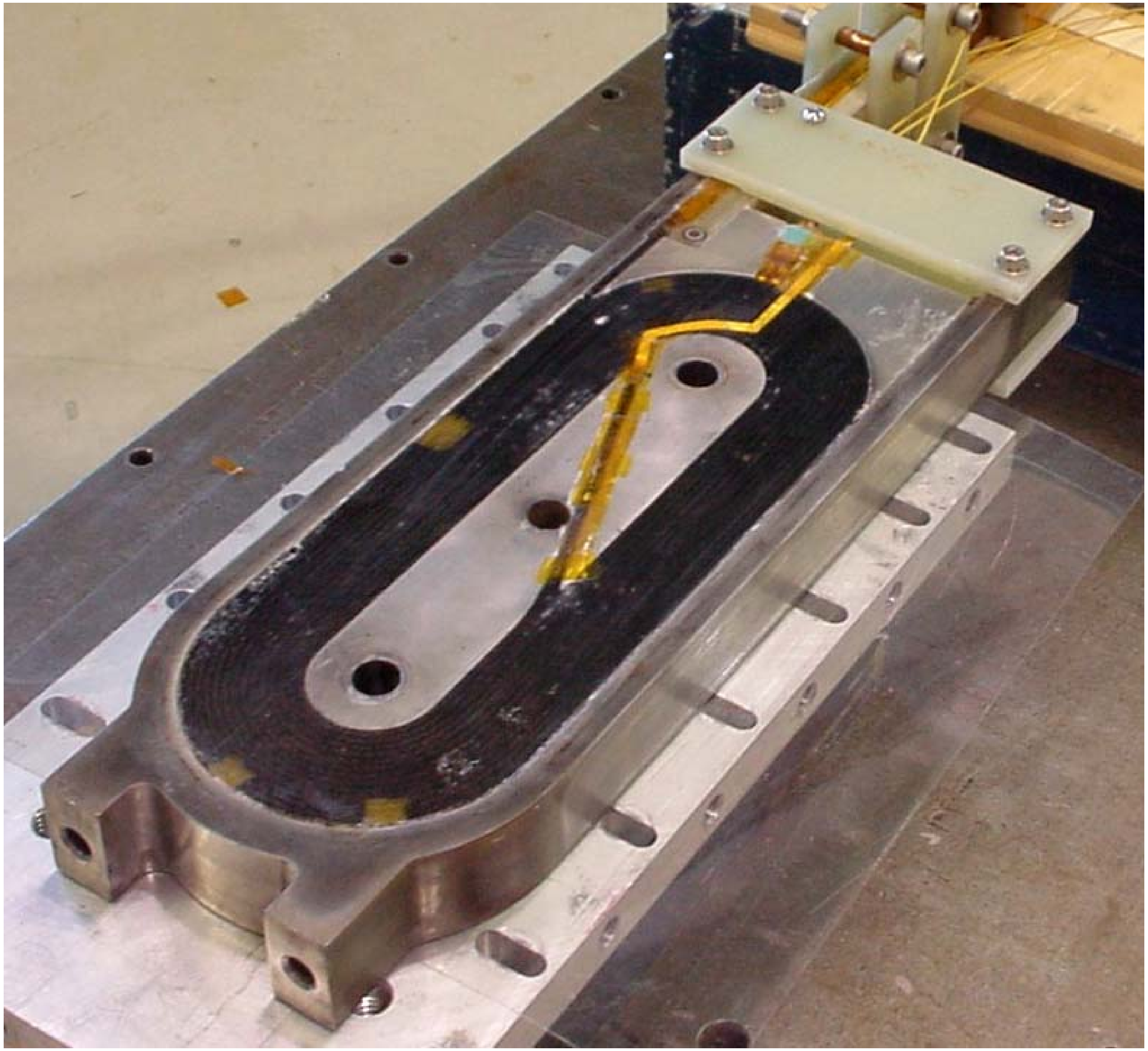
BNL 12 T Nb_3Sn Common Coil React & Wind Dipole Magnet During Final Assembly

Magnet test expected in Feb. 06.

Highlights and Selected Pictures from FNAL High Field Magnet R&D Program

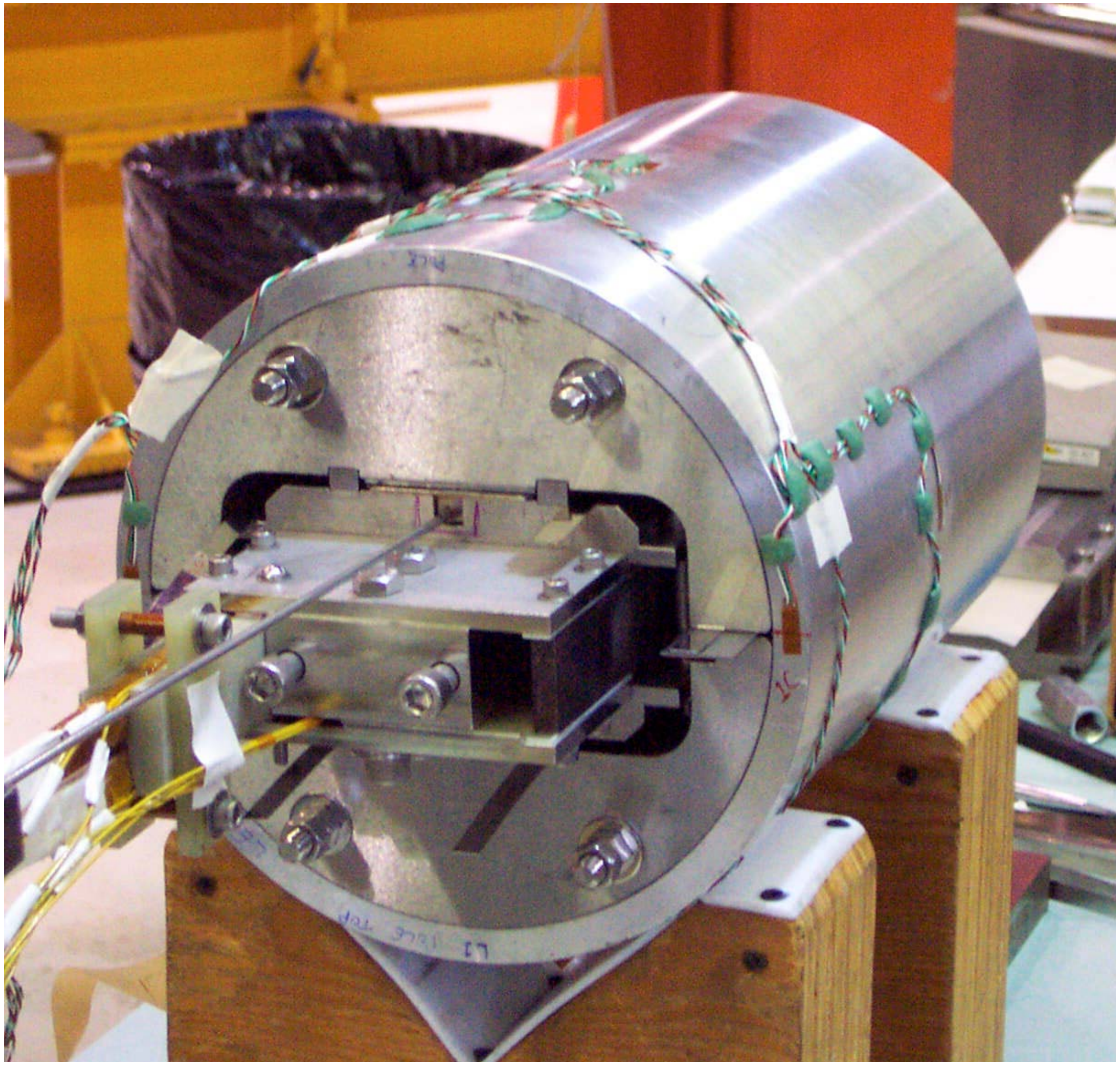
- “Wind & React” cosine theta and “React & Wind” Common coil with Nb_3Sn
- A number of parallel programs
- Currently playing a major role in LHC IR upgrade quadrupole program

Epoxy Impregnated Racetrack Coil for Common Coil Magnet at FNAL



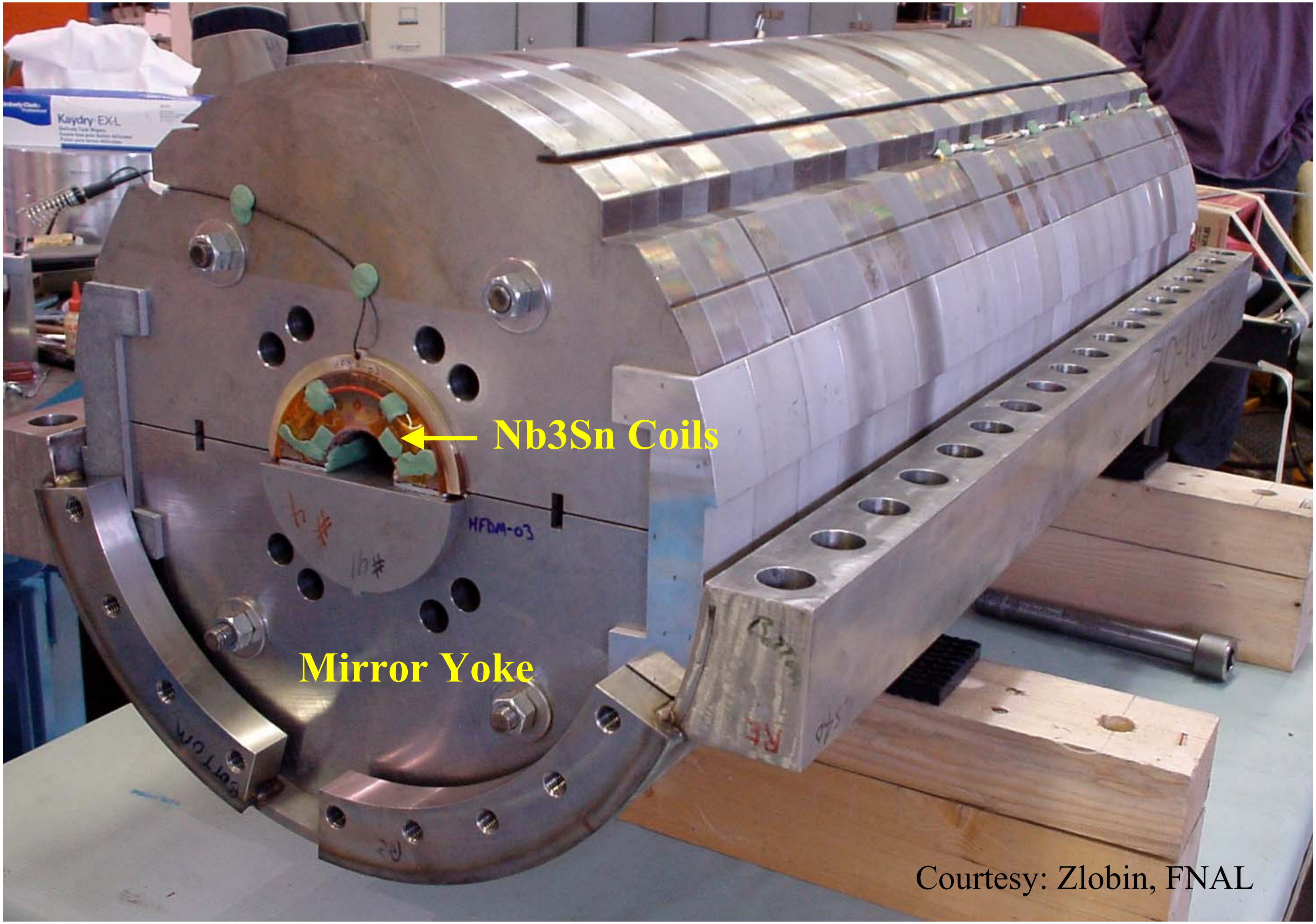
Courtesy: Zlobin, FNAL

Short Common Coil Nb_3Sn Test Magnet at Fermilab

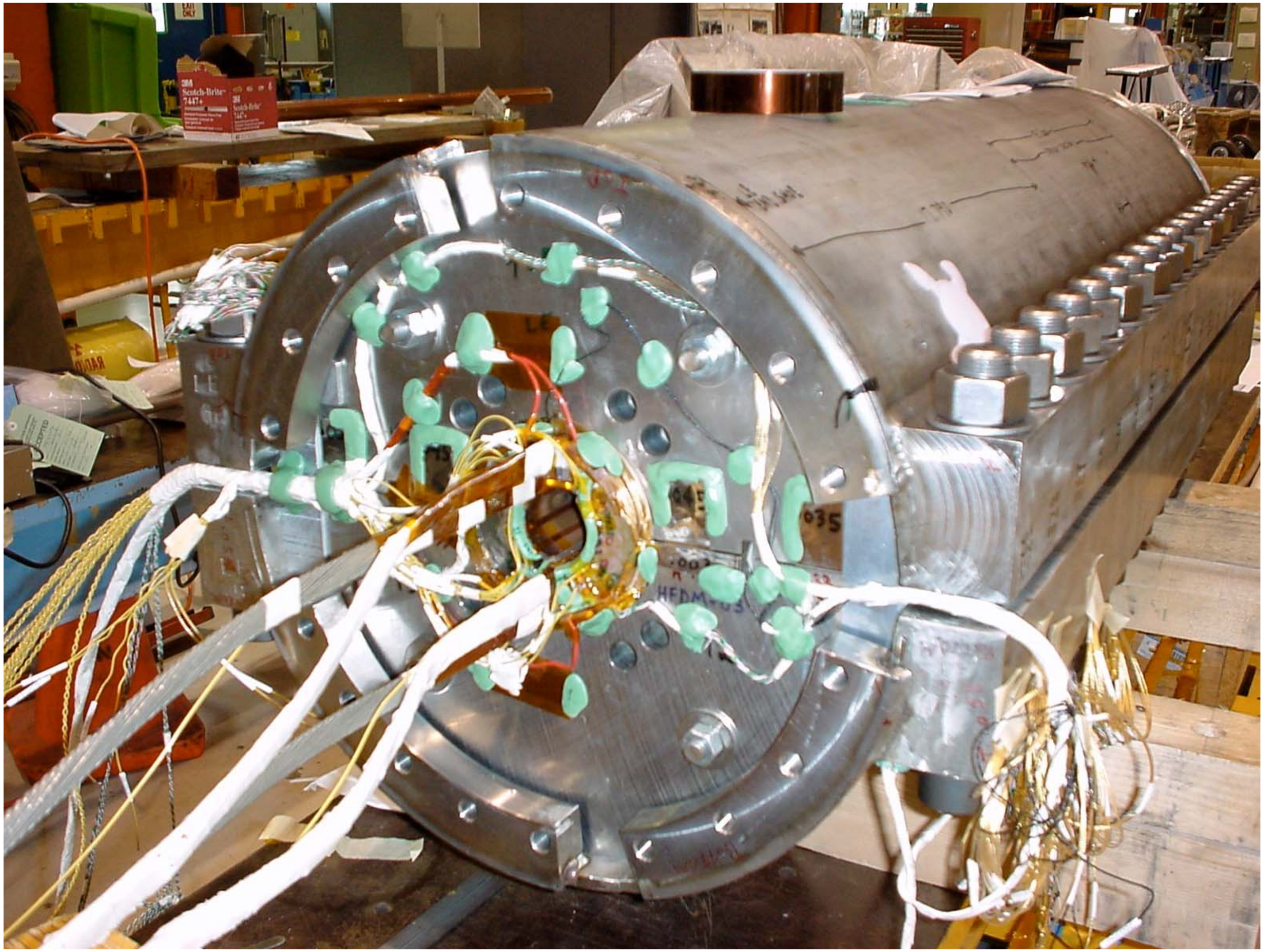


Courtesy: Zlobin, FNAL

Mirror Cosine Theta Nb_3Sn Dipole Magnet HFDM03 at FNAL

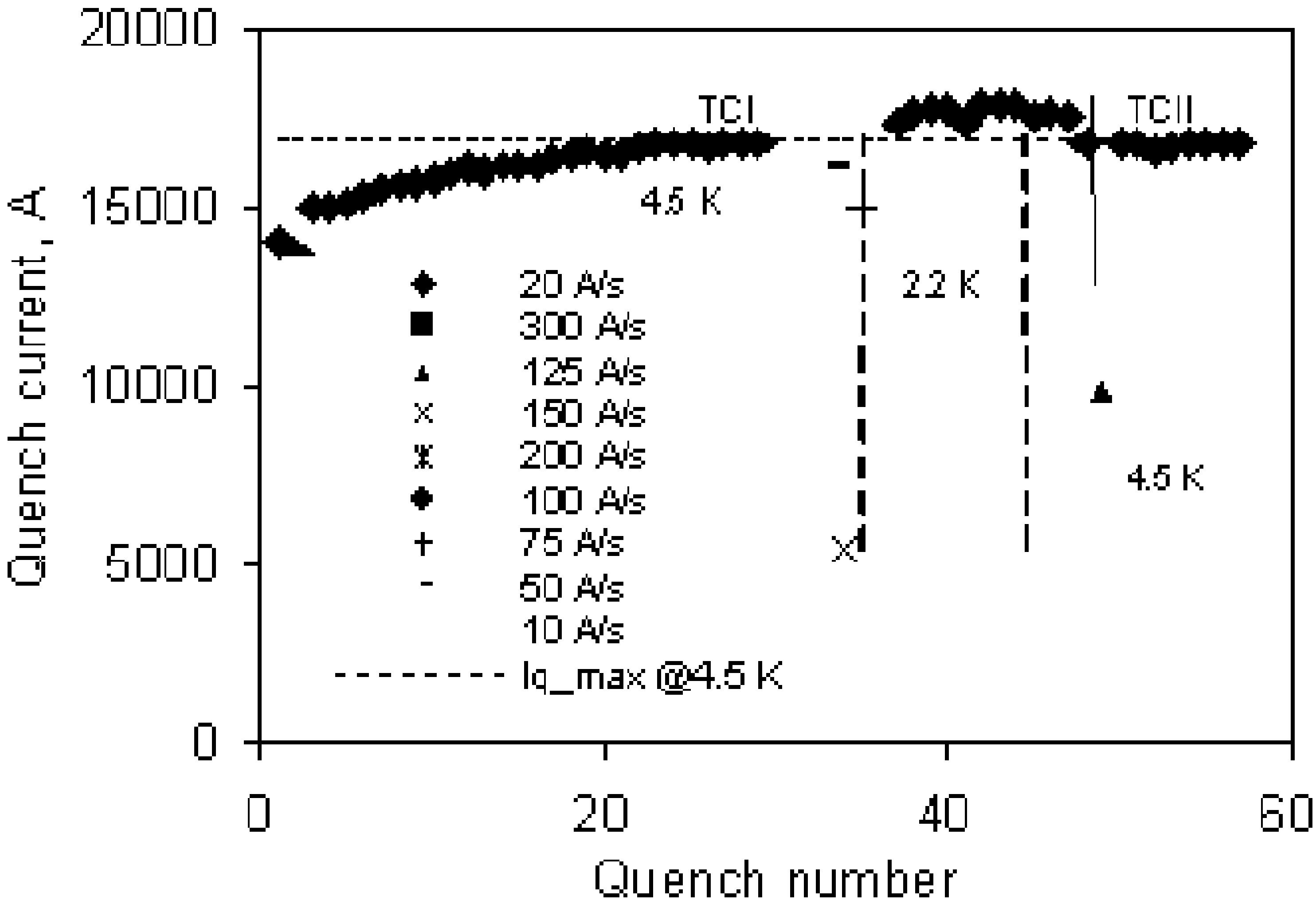


Cosine Theta Dipole HFDM05 at FNAL



Courtesy:
Zlobin, FNAL

Quench History of Nb_3Sn Model Dipole HFDM05 at FNAL



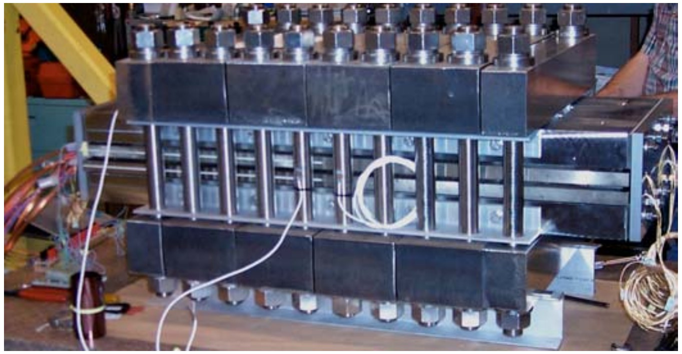
Model reached its short sample limit of 9.5 T at 4 K and 9.5 T at 2.2 K.

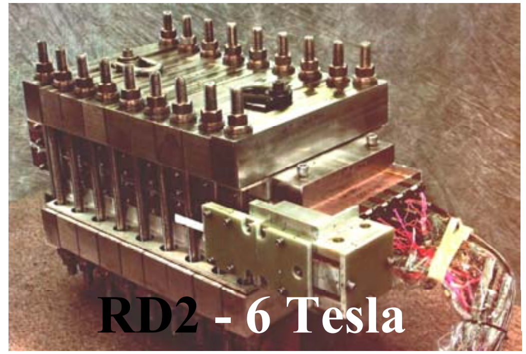
Courtesy: Zlobin, FNAL

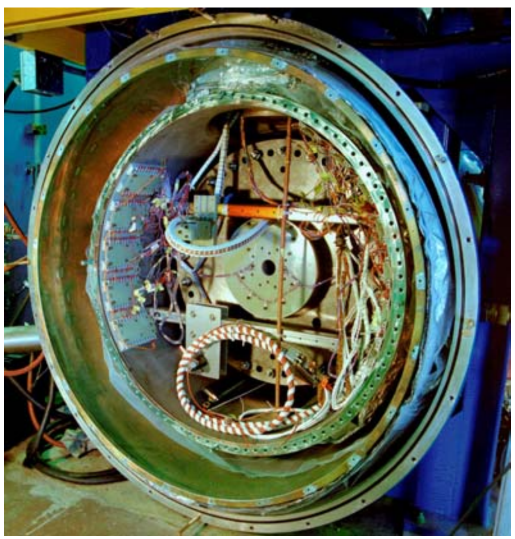
Highlights and Selected Pictures from LBNL High Field Magnet R&D Program

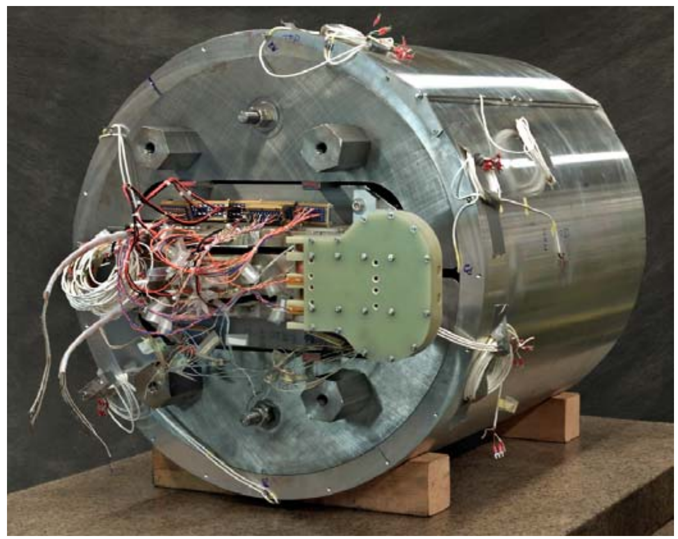
- "Wind & React" Nb3Sn magnets (cosine theta, common coil and racetrack)
- Holder of the record of highest field magnet (~16 T)
- Currently playing a major role in LHC IR upgrade quadrupole program

LBNL Prototype Highlights









Courtesy: Sabbi, LBNL

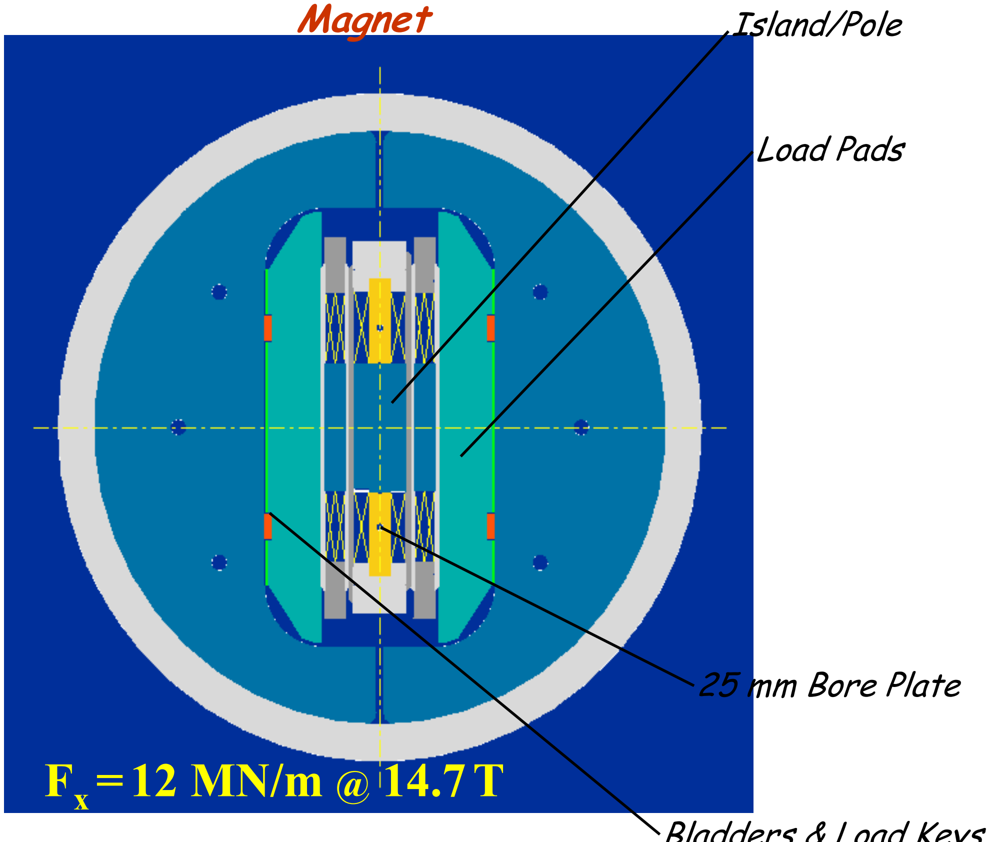
Prototype Objectives and Features of LBNL Magnets

Magnet	Year	Field	Type	Design Features
D19H	1996	10.2 T	Cos θ	Coil Fabrication Process
D20	1997	13.5 T	Cos θ	Clear bore 50 mm, body/end optim.
RD2	1998	5.9 T	Comm. Coil	New "RD" configuration
RT-1	1999	12.2 T	Comm. Coil	High Field in RD configuration
RD3b	2001	14.7 T	Comm. Coil	New support structure, high stress
RD3c	2002	10.0 T	Comm. Coil	Clear bore 35 mm, auxiliary coils
HD-1	2003	(16.2 T)	Block	New "HD" configuration
RD3d	(2004)	(11.0 T)	Comm. Coil	Bore 40 mm, saturation, end field

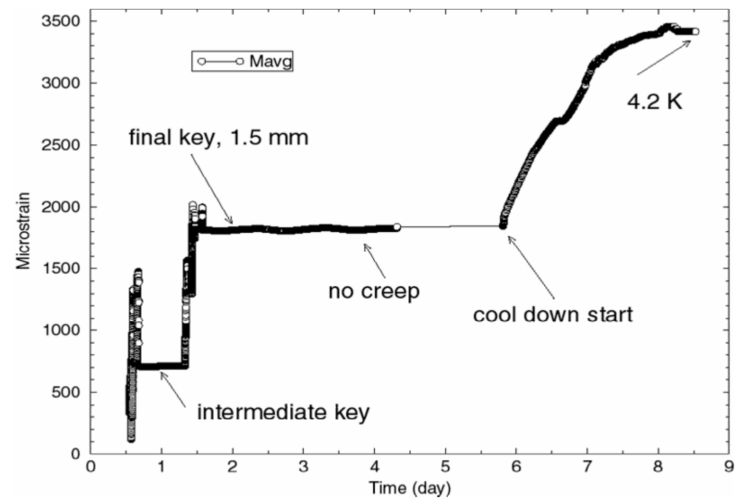
Courtesy: Sabbi, LBNL

RD Series: Support Structure at LBNL

RD3b Common Coil Magnet



RD3b Magnet Assembly and Cooldown



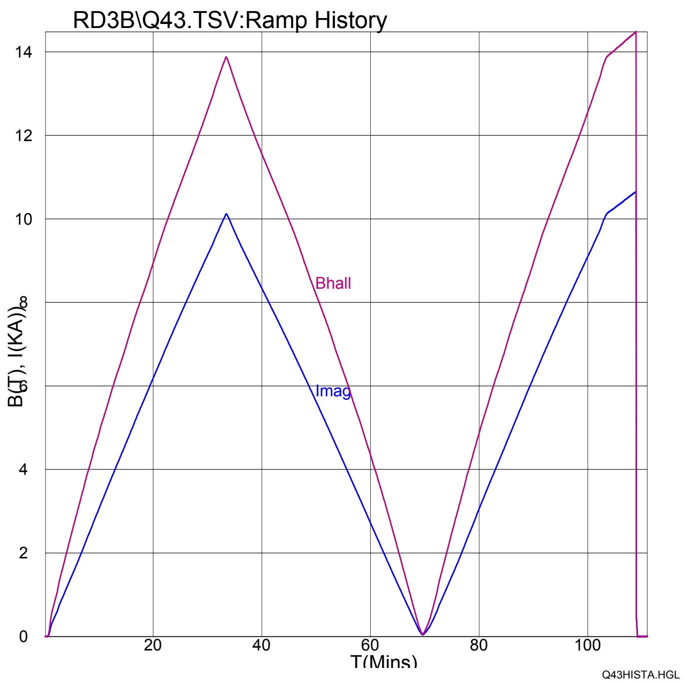
Pressurized Bladders

Courtesy: Sabbi, LBNL

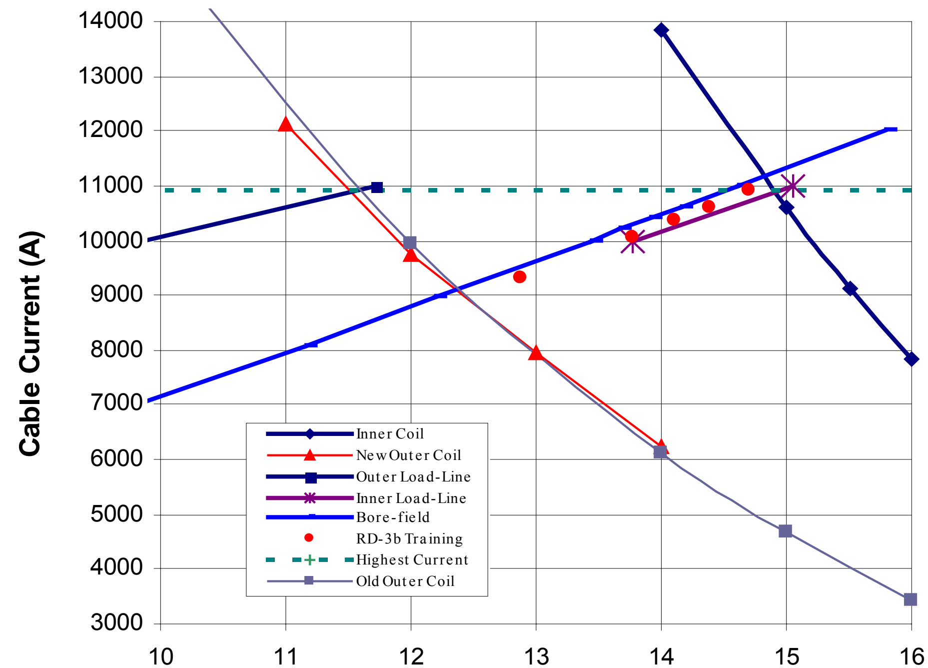
RD Series (LBNL): Conductor Limits

RT-1, RD3B – No performance degradation up to 14.7 T, 120 MPa

Common coil 2-in-1 dipole



RD3B ramp cycle to quench (#43)



RD3B load lines and conductor limit B [T]

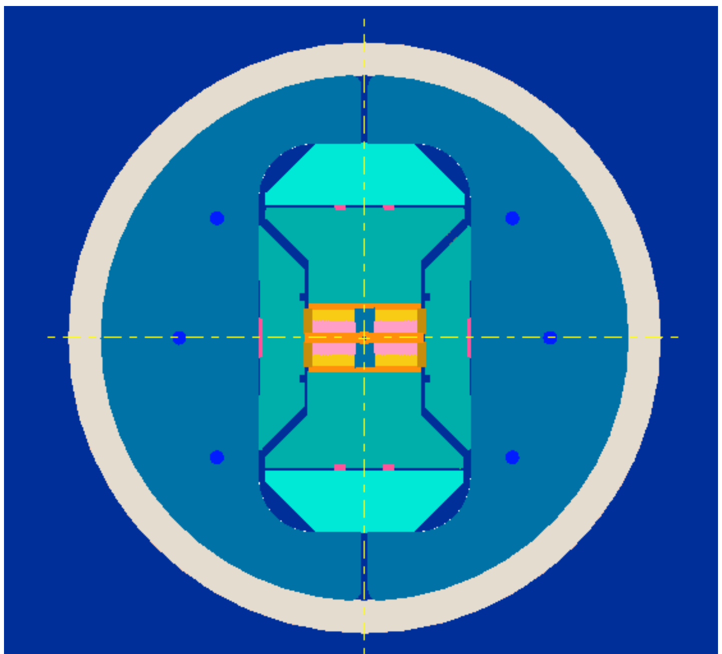
Courtesy: Sabbi, LBNL

LBNL HD Series Dipoles

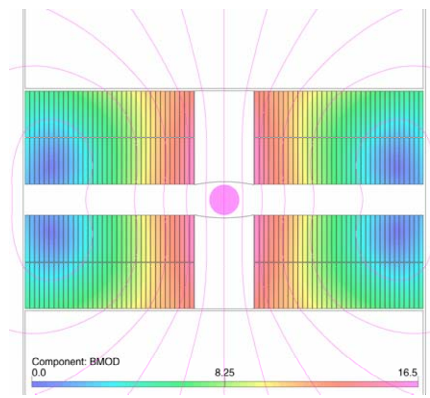
New High Field Dipole Test Configuration

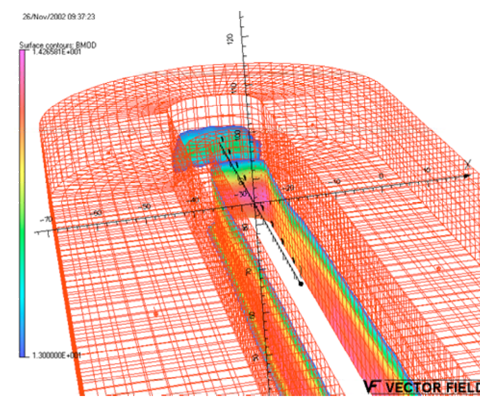
<u>Design Features:</u>

- Single bore
- Two flat double pancakes
- Horizontal configuration
- Dipole field 15-18 T

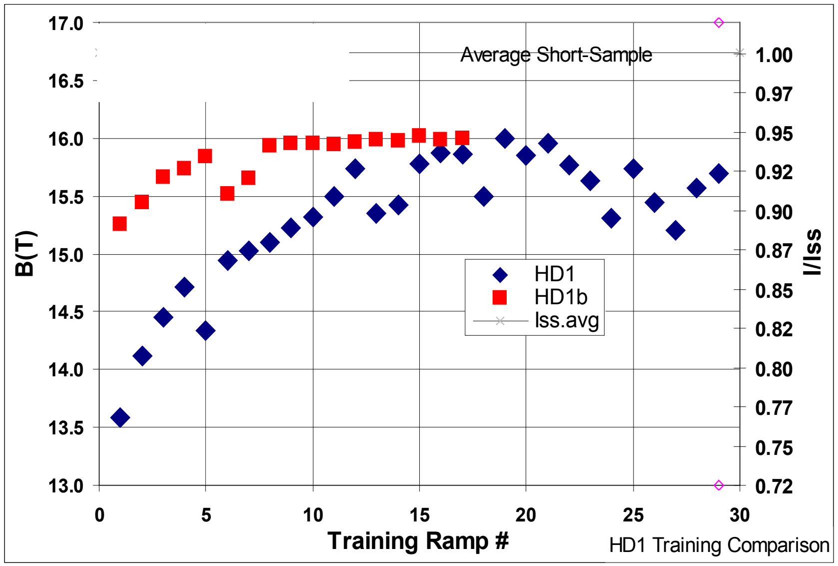


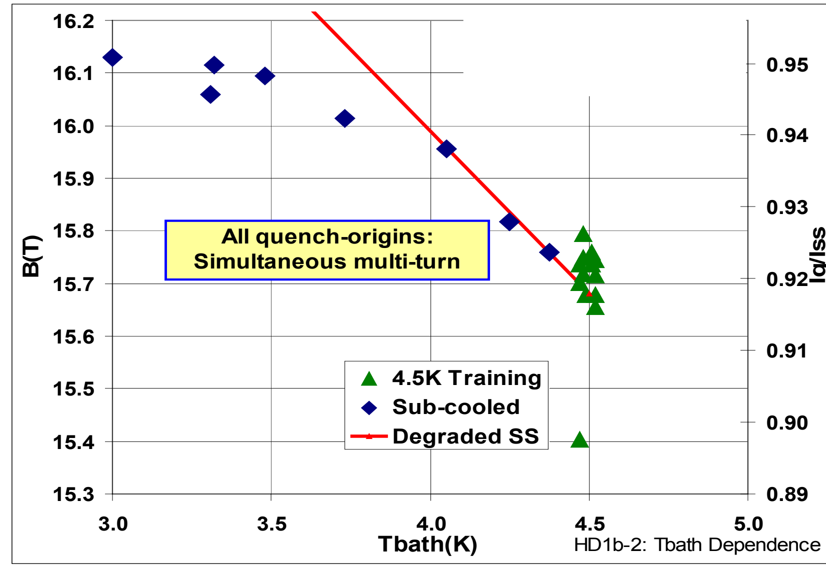
Magnet cross section

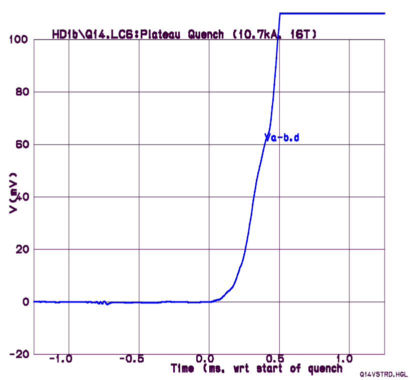


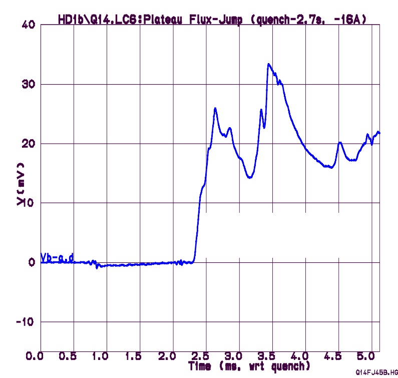


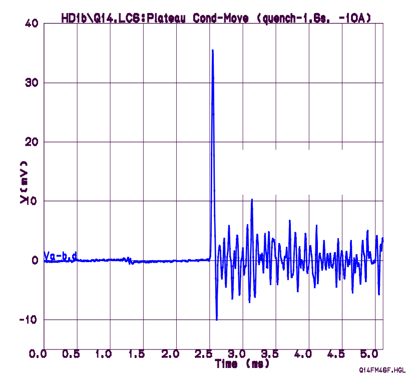
LBNL HD1b Results & Analysis









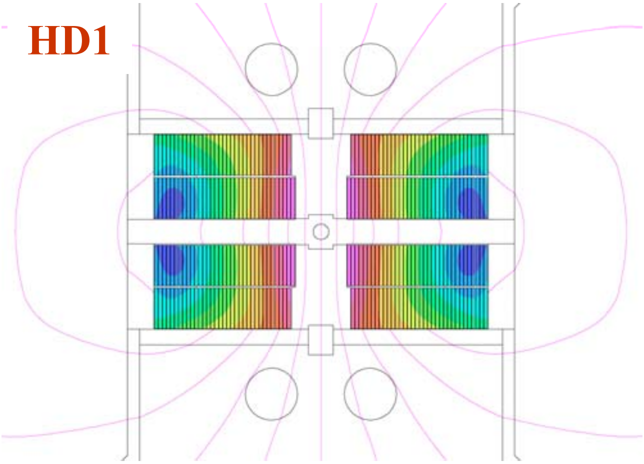


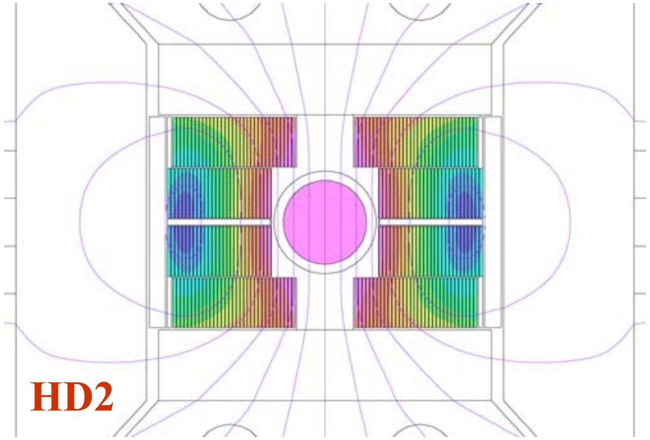
Record 16 T Single Aperture Dipole

Courtesy: Sabbi, LBNL

LBNL HD1 & HD2 Parameters

HD1





HD2

Parameter	Unit	HD1	HD2
Clear bore	mm	8	35
Coil field	Tesla	16.1	16.1
Bore field	Tesla	16.7	15.3
Max current	kA	11.4	15.2
Stored Energy	MJ/m	0.66	0.89
F_x (quadrant, 1ap)	MN/m	4.7	5.9
F_y (quadrant, 1ap)	MN/m	-1.5	-2.7
Ave. stress (h)	MPa	150	140

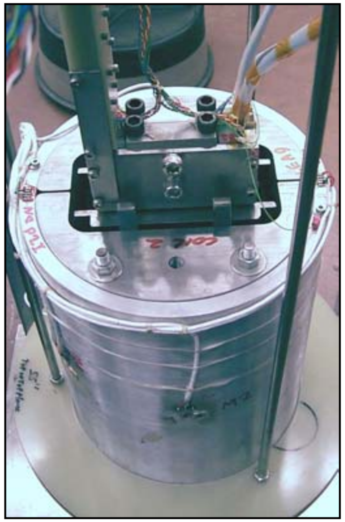
Parameter	Unit	HD1	HD2
Strand diameter	mm	0.8	0.8
Ic (16 T, 4.2 K)	A	322	322
No. strands		36	48
Cable width	mm	15.8	21.0
No. turns/pole		69	61

Single aperture dipoles

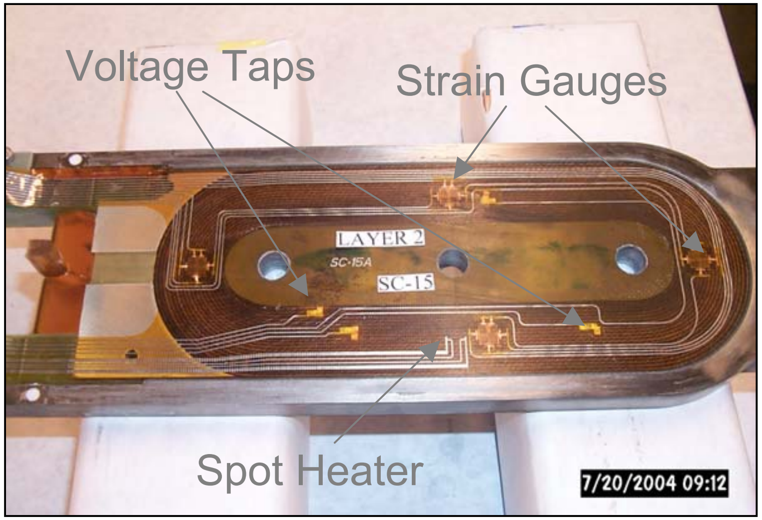
Courtesy: Sabbi, LBNL

Sub-scale magnet series at LBNL

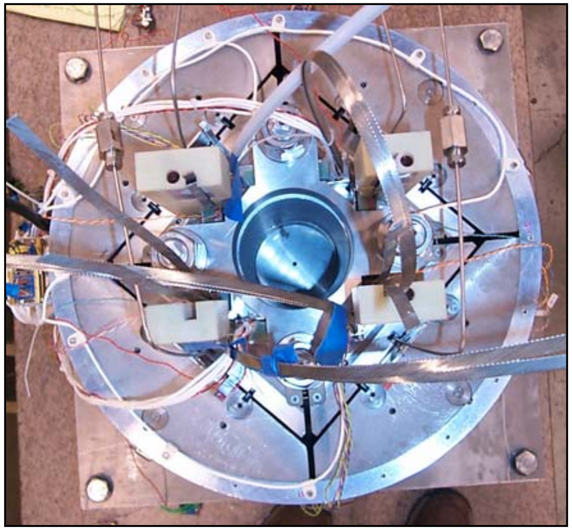
SM Dipole



SC Coil



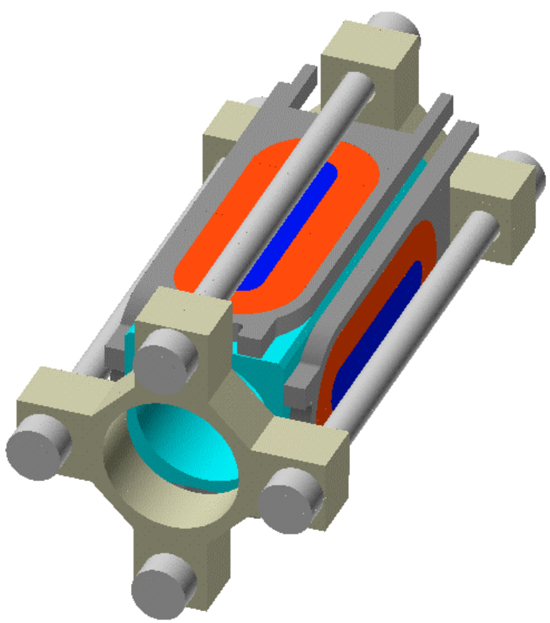
SQ Quadrupole

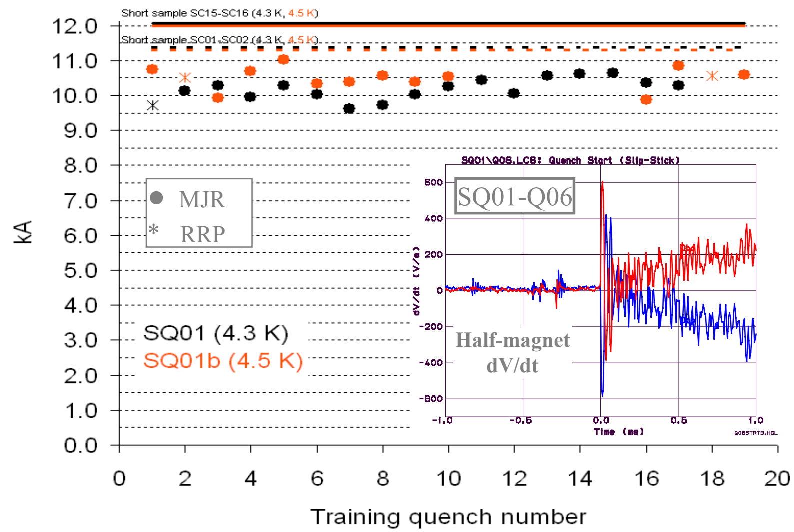


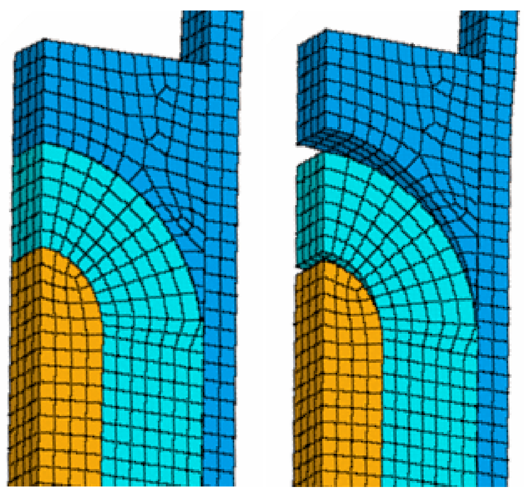
- Cost-effective, rapid turn-around tools for technology development
- R&D topics: conductor, cable, mechanics, materials, fabrication procedures
- Two-layer "SC" racetrack coils; field range of 9-12 Tesla; fully instrumented
- Testing in both dipole (SM) and quadrupole (SQ) configurations

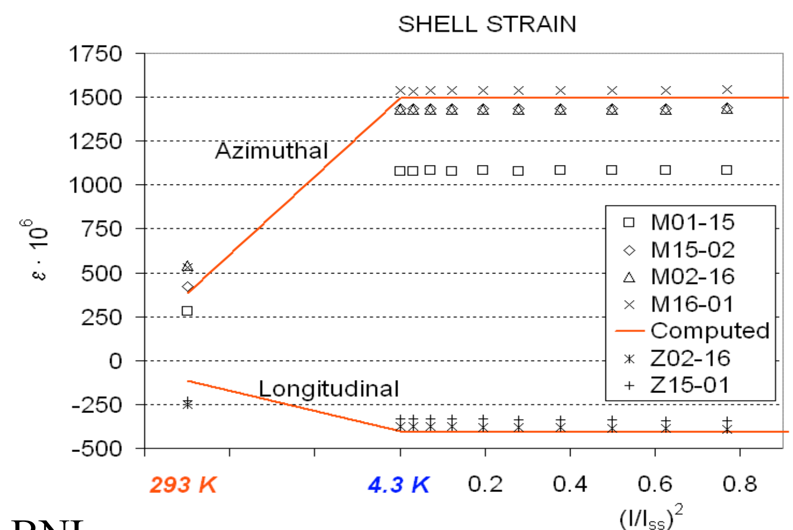
Courtesy: Sabbi, LBNL

LBNL Subscale Quad SQ01/SQ01b for LHC IR Technology Development









Courtesy: Sabbi, LBNL

Recap on Some Major Issues in High Field Accelerator Magnets

- All high field superconductors known today are brittle.
- Must learn how to use brittle superconductors.
- Conductor should not be damaged during magnet construction.
- Stress/strain should remain within acceptable limit during all phases of construction.
- One major design issue is the mechanical structure of the magnet. It must be able to withstand large Lorentz forces and should be able to keep deflections, stress/strain within conductor small during operation.
- Magnet should be well protected and large stored energy should be removed in a timely fashion.
- Conductor should be operated within stable regime.
- All field errors should remain within acceptable limits in an accelerator magnet. In particular, the persistent current induced harmonics should be kept small.

Summary

- This presentation gave you a feel of what is involved in developing a high magnet R&D program.
- It is important to learn (or have experts in your group) about the other critical topics on high field magnet technology that were not been included in this presentation.
- High field magnet technology has still not yet reached a stage that one can use these magnets in a large scale application. But we are at a stage that they can be considered for special applications.
- R&D programs and recent results from various laboratories (also see earlier work at CERN and Twente University in Europe) point to an exciting future.