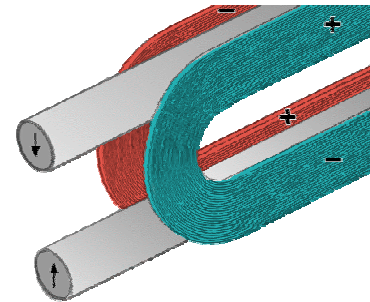




React & Wind Nb₃Sn Common Coil Dipole



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Presented by Ramesh Gupta

Overview

React & Wind Technology

- **Introduction**
- **Challenges**
- **Advantages**

Conductor Friendly Design To Mitigate Difficulties

React & Wind Nb₃Sn Common Coil Dipole DCC017

- **Purpose: Demonstrate Viability of React & Wind for High Field Magnets**
- **Tooling, Construction & Test Results**
 - **Emphasis on issues that are more critical to React & Wind**

Relevance to Future High Field Magnet Programs

- **Benefits and Limitations of “React & Wind”**

Summary

Special Consideration for Nb₃Sn Magnets

High temperature (~650° C) reaction is required to turn Nb-Sn mixture in to Nb₃Sn A15 phase which becomes superconducting at low temperatures.

Nb₃Sn is brittle after this high temperature reaction. Moreover, during the reaction, Nb-Sn expands and contracts while becoming sensitive to strain.

Two distinct approaches for making Nb₃Sn magnets:

1. Wind & React

First wind the coil and then react the entire coil package.

First “good news” then “bad news”!

2. React & Wind

First react the conductor and then wind the coil.

First “bad news” then “good news”!

“Wind & React” Approach (a popular choice for R&D magnets)

In “Wind & React” approach, coil is wound when the conductor is still ductile (good news).

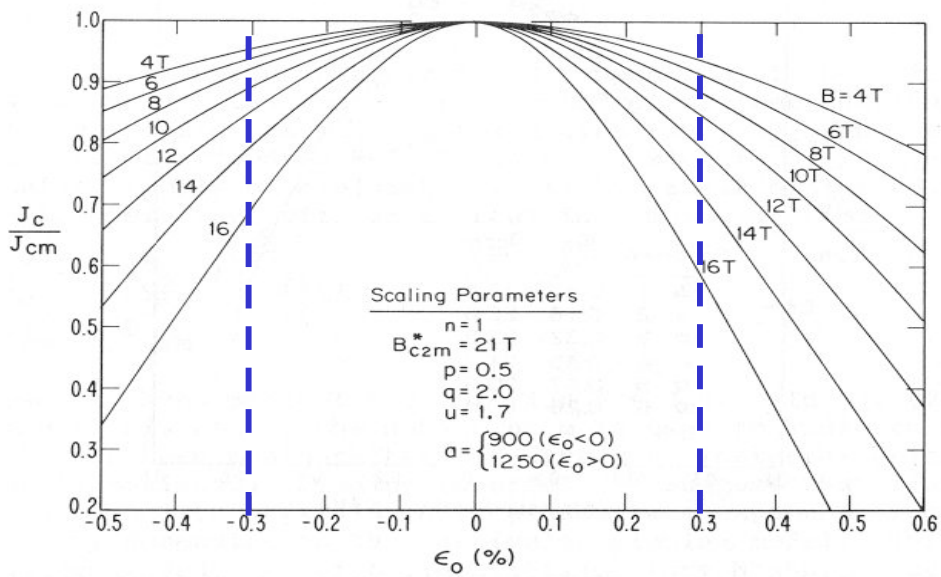
- **Handling of the brittle conductor is limited to things like making splices or putting coils in impregnation fixture, etc.**
- **Small bend radius is not a significant issue since the “reacted” Nb₃Sn conductor is not subjected to bending during coil winding.**
- **Complex geometries (such as those in cosine theta ends) can be handled provided the local strain during high temperature reaction is kept low.**

All of above makes “Wind & React” approach much safer than “React & Wind” for making high field “demonstration magnets”.

React & Wind Approach Challenges

- In the “React & Wind” approach one must wind the coil with the brittle pre-reacted Nb₃Sn conductor which is prone to significant degradation (bad news).
- Furthermore, bending strain consideration puts limitations:

1. Magnets cannot go to too high a field.
2. One cannot have too small bending radius.



Relative critical-current density J_c/J_{cm} as a function of intrinsic strain ϵ_0 ($\equiv \epsilon - \epsilon_m$) for different magnetic fields, evaluated using Eq. (3) and the typical set of scaling parameters indicated in the figure.

Note: There are other formulations available for computing influence of strain, field and temperature on Nb₃Sn J_c . They all show a similar pattern.

Why “React & Wind” Approach?

A Fair Question:

Why even consider an apparently more risky “React & Wind” technology when “Wind & React” has been successfully demonstrated in high field “Nb₃Sn R&D magnets”???

And the contention is:

“Wind & React” may be a safer choice for short R&D magnets. But for the ultimate goal of making “long productions magnets”, the “React & Wind” approach appears to be more promising!!!

➤ **More discussion in next two slides !**

Issues Related to Magnet Length

- ❑ A coil is made of several materials (superconductor, wedges, end spacers, insulation, etc). Bad news:
 - These materials have different thermal expansion.
- ❑ In the “Wind & React” approach, the integrated build-up of “differential thermal expansion” of various materials during the high temperature heat treatment may result in large accumulated strain in the ends of the magnets. Magnets with complex end geometries are more prone to degradation/damage due to this large local strain.
- ❑ Since the integral build-up is proportional to length, this issue becomes more critical in “Wind & React” as magnets get longer.
- ❑ LARP program is addressing this issue in “Wind & React” QUAD.

The “React & Wind” approach bypasses the issue of “differential thermal expansion” as the coil is wound after the reaction.

Other Advantages of React & Wind Approach

- In the “React & Wind” approach the coil and associated structure is not subjected to the high temperature reaction. This allows one to use a variety of insulation and other materials in coil modules.
 - » In “Wind & React”, one is limited in choosing insulating material, etc. since the entire coil package goes through reaction.
- The “React & Wind” approach appears to be more adaptable for building production magnets in industry by extending most present techniques. Once the proper tooling is developed and the cable is reacted, most remaining steps in industrial production of magnets remain nearly the same in both Nb-Ti and Nb₃Sn magnets.
- Since no specific component of “React & Wind” approach appears to be length dependent, demonstration of a particular design and/or technique in a short magnet, should be applicable in long production magnet (except for mechanical, quench protection, etc.).
 - » **So, there is some good news for “React & Wind” also !!!**

React & Wind The Bottom Line

- “React & Wind” technology has some major advantages.
- But “React & Wind” also has some major serious questions.

Develop design and technology and prove by a magnet test.

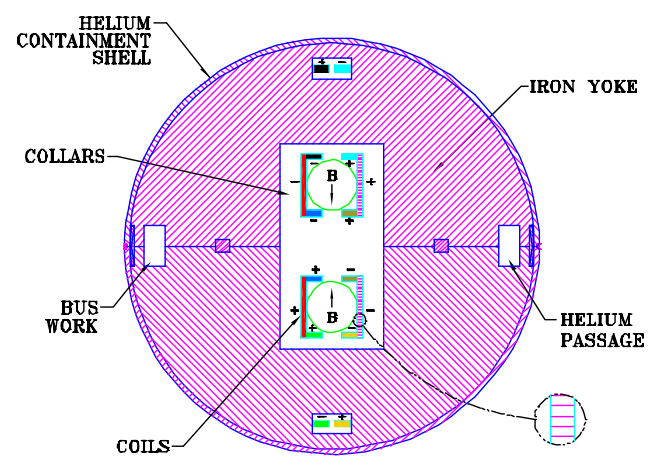
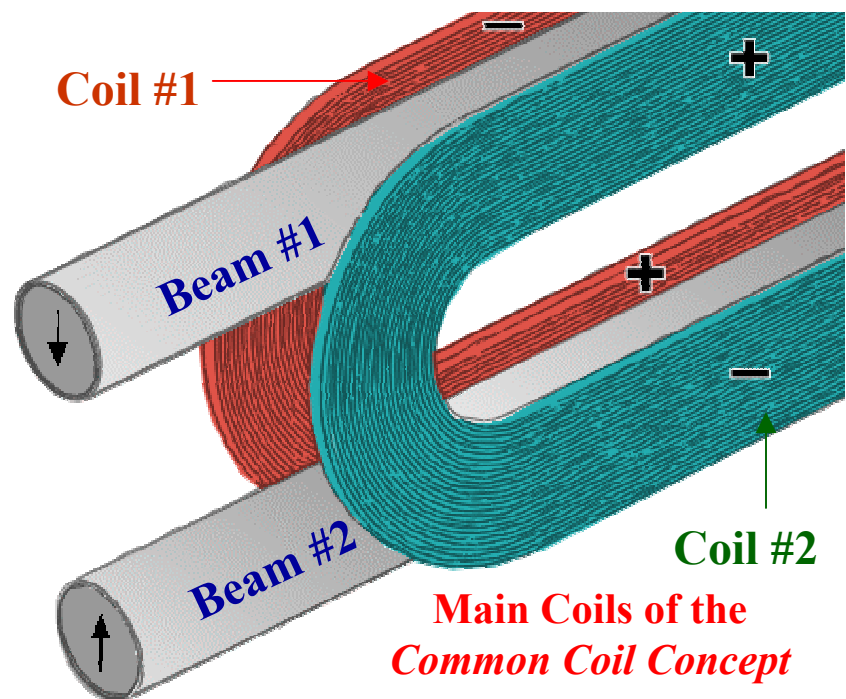
Let experiment be the supreme arbiter to determine if “React & Wind” can be a viable technology for future high field Nb_3Sn accelerator magnets?

Many slides follow that summarize our efforts in developing magnet designs and manufacturing techniques in an attempt to bring about a positive outcome.

Common Coil Design for "React & Wind" Approach

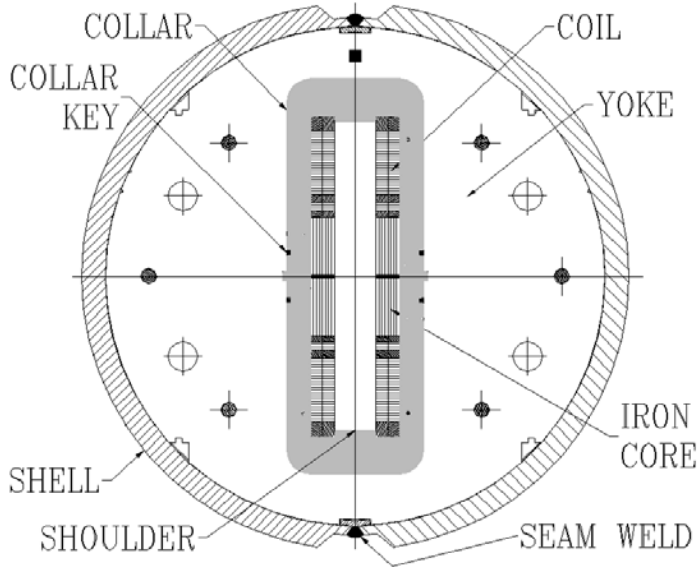
A 2-in-1 Dipole Design with Simple Geometry and Large Bend Radii

- Bend radius is determined by the separation between two beams rather than the aperture itself.
- A conductor friendly design with flat racetrack Coils. No complex 3-d ends.
- The design is particularly suitable for "React & Wind" Approach.

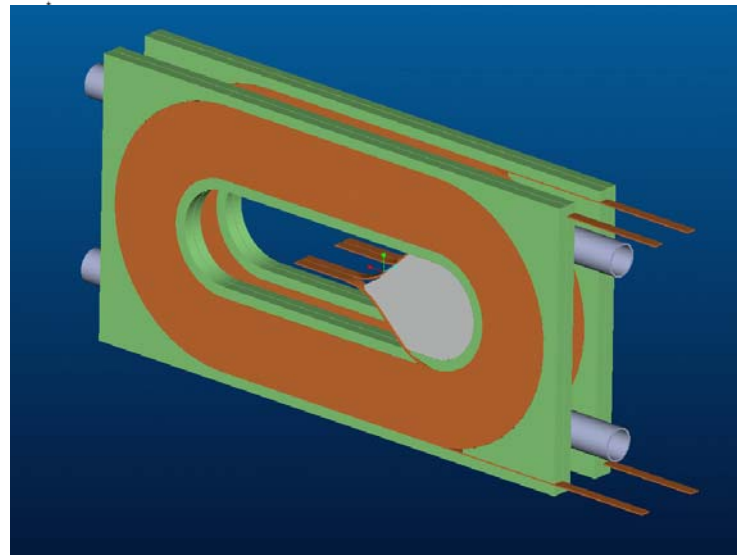


A complete cross-section of a common coil dipole.

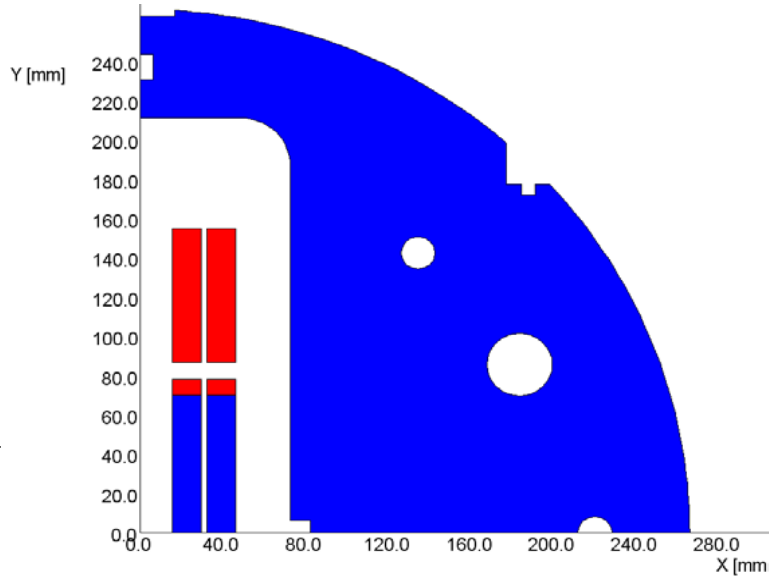
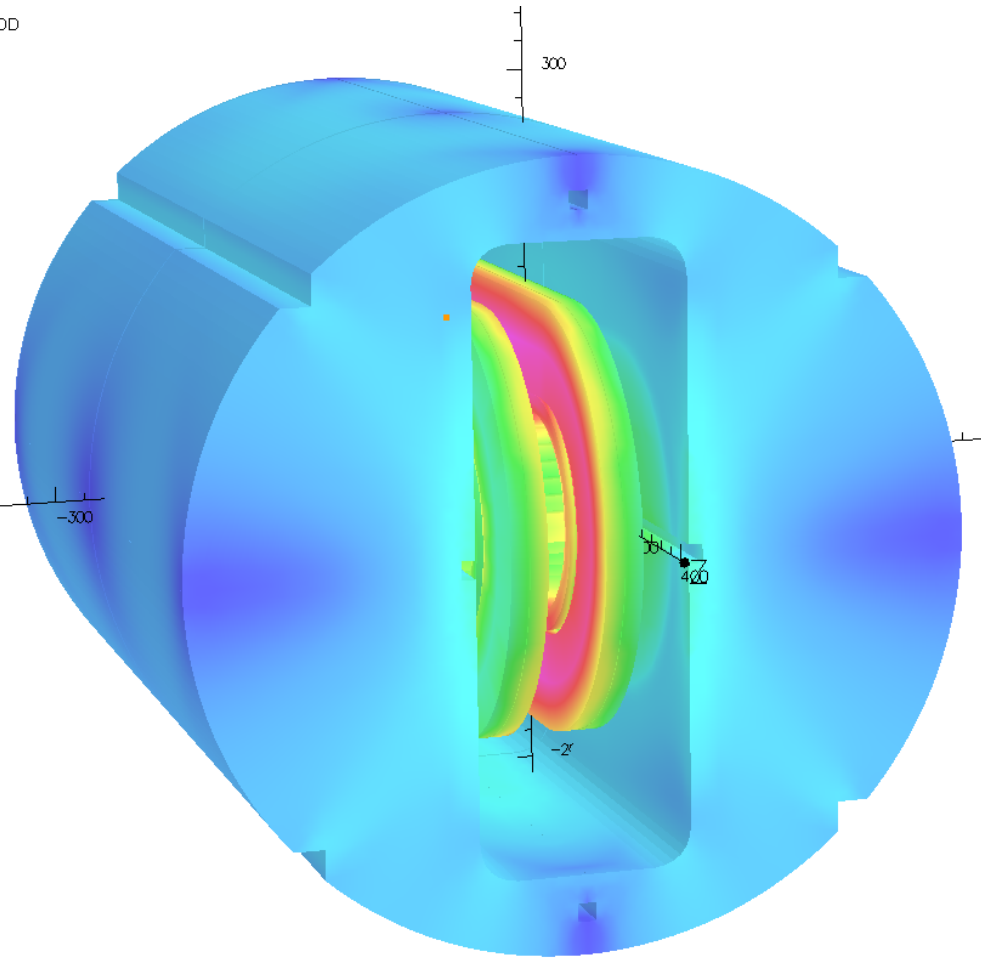
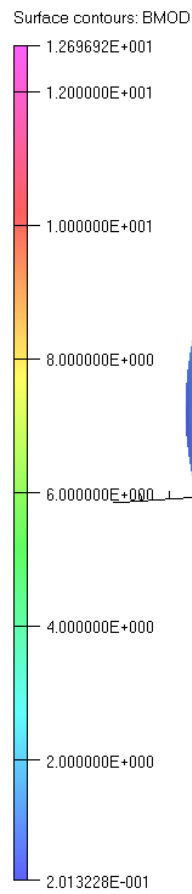
Basic Features of BNL Nb₃Sn 10⁺ T React & Wind Common Coil Dipole



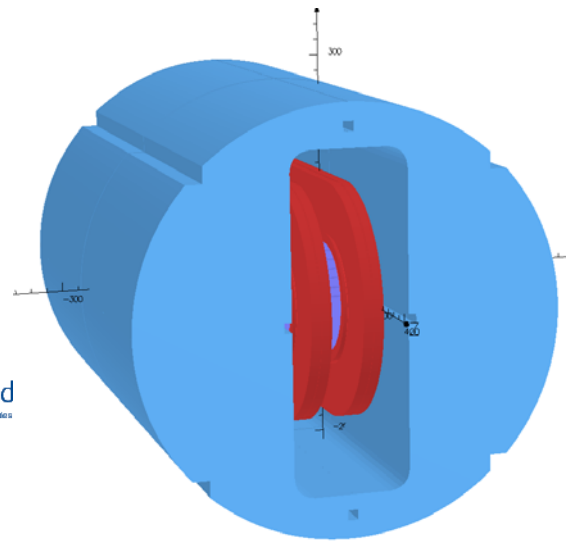
- Two layer, 2-in-1 common coil design
- 10.2 T bore field, 10.7 T peak field at 10.8 kA short sample current
- 31 mm horizontal aperture
- Large (338 mm) vertical aperture
 - » **A unique feature for coil testing**
- Dynamic grading by electrical shunt
- 0.8 mm, 30 strand Rutherford cable
- 70 mm minimum bend radius
- 620 mm overall coil length
- Coil wound on magnetic steel bobbin
- One spacer in body and one in ends
- Iron over ends
- Iron bobbin
- Stored Energy@Quench ~0.2 MJ



Magnetic Design Features

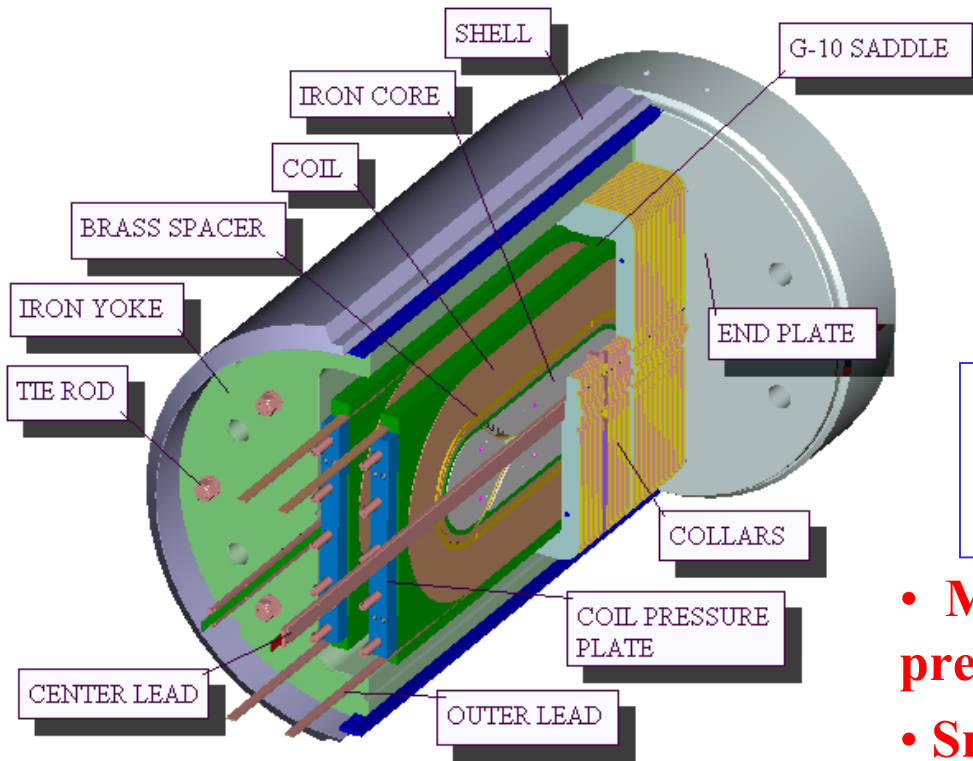


Vector Field
software for electromagnetic des



Peak field in ends lower than the peak field in straight section despite iron over ends (end spacer and iron bobbin)

Mechanical Design Features



Main components of support structure:

- **Stainless steel collar: 13 mm thick**
- **Rigid yoke: 534 mm o.d.**
- **Stainless steel shell : 25 mm thick**
- **End plate: 127 mm thick**

In common coil design, the Lorentz forces and their influence on coil, particularly in end region, is different from other designs.

- **Magnet is designed for almost no cold pre-stress (horizontal, vertical or axial)**
- **Small warm vertical load is applied to account for differential thermal expansion**
- **Inflatable bladder to keep coil outward**
- **Keepers (SS) to lock coil to collars**
- **End plates (SS) were circumferentially welded to shell**

The original support structure was designed for 40 mm, 12.5 T dipole. Choice of conductor, etc. made it 31 mm, 10.2 T dipole. It is ok for 13.5 T with 3000 A/mm² conductor.

Nb₃Sn High Temperature Reaction

Oil Impregnation Setup



Oil impregnation puts a thin coating on wires of Rutherford cable to avoid sintering during the reaction

Cable was pre-annealed to take out initial thermal expansion and to avoid possible local strain during high temperature reaction.

Large (1.5 m³) reaction furnace



Used for reacting long lengths of Nb₃Sn cable

Bending Strain

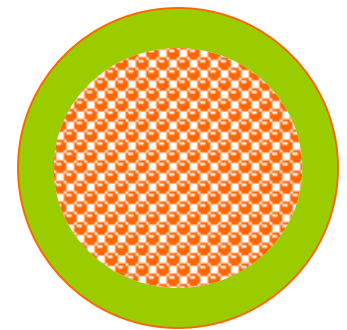
It is very important to keep bending strain low in “React & Wind”

- Sintering of wires in cable during the heat treatment should be avoided as that would increase strain in Rutherford cable by about a factor of two
- Cable should be reacted on a drum that is about twice the bend radius as this reduces bending strain by a factor of two (split difference between body and ends)
- In bending strain calculations, area of superconductor filament should be used rather than the diameter of wire as this makes a difference of ~30%.



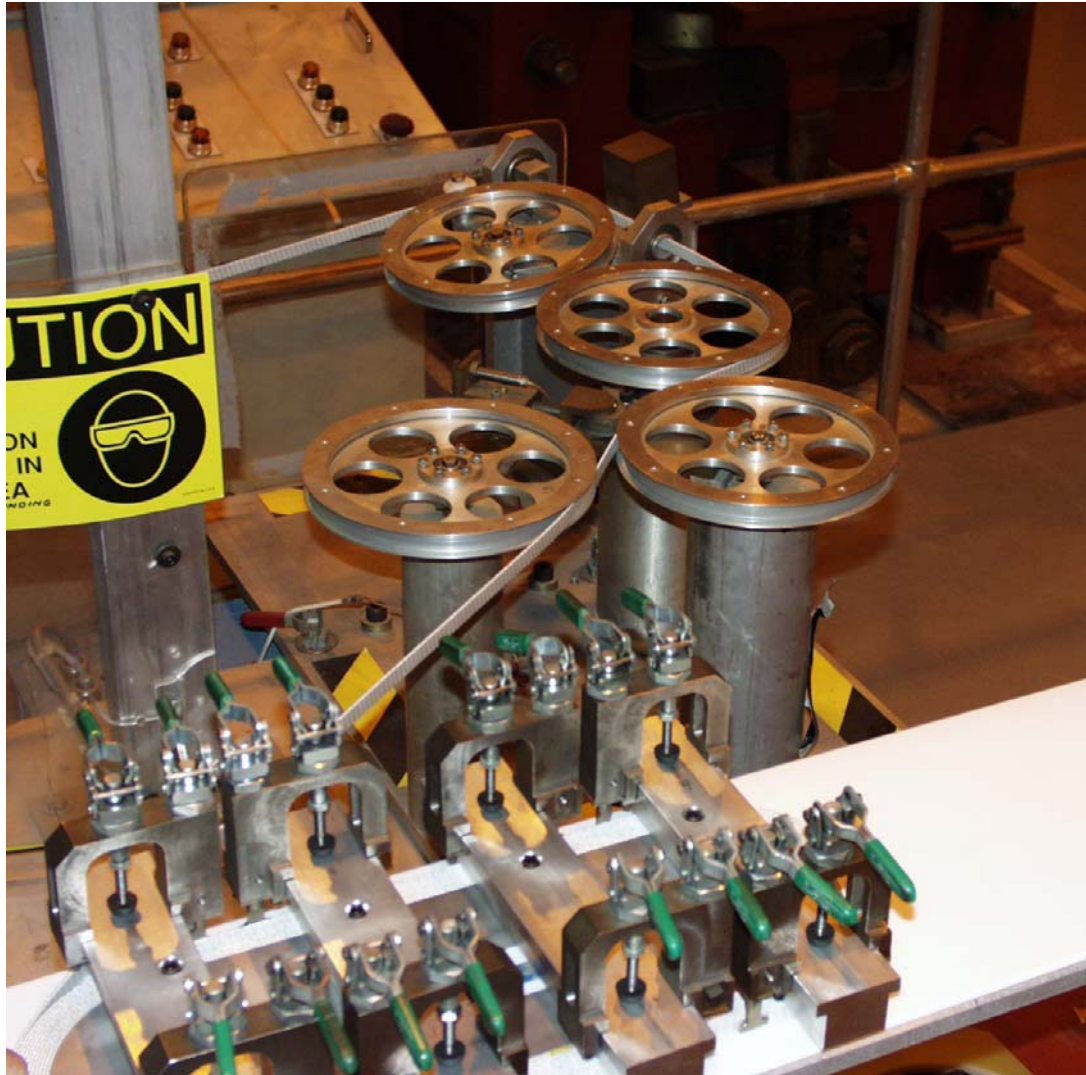
All of above make a large accumulated difference.

From worse case of 1.2% to a relative change of 0.21% in bending strain.



Coil Winding

Things to Avoid

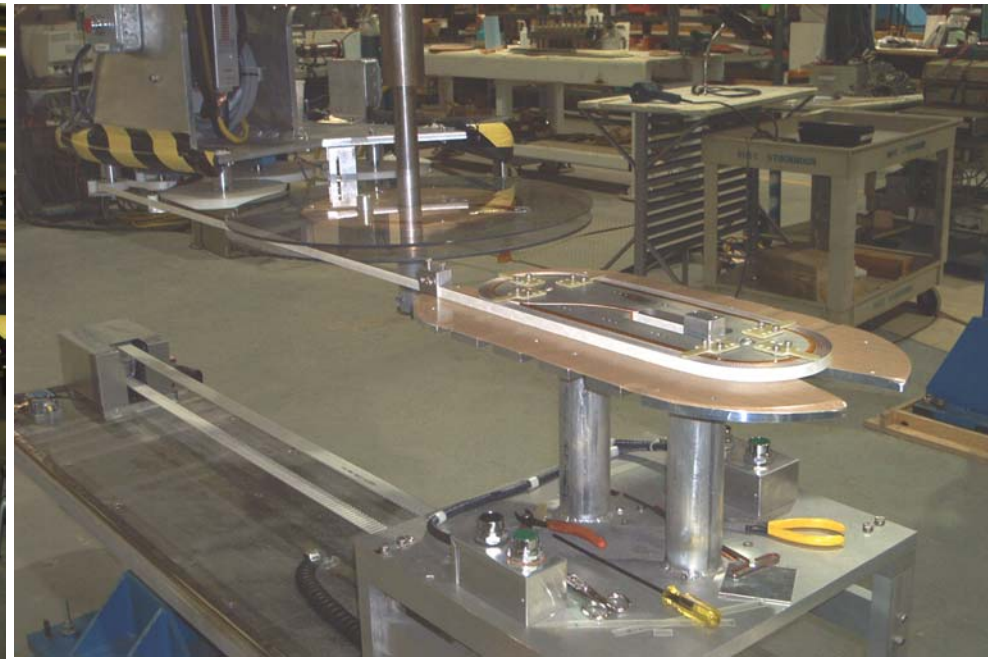


**Avoid guide spools with
small bend radius**

Avoid reverse bend

**Minimize manual
handling and manual
control**

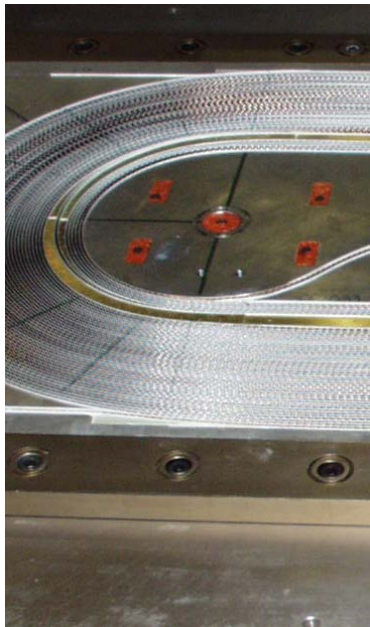
Automatic Coil Winder : A Key Component in Developing "React & Wind" Technology



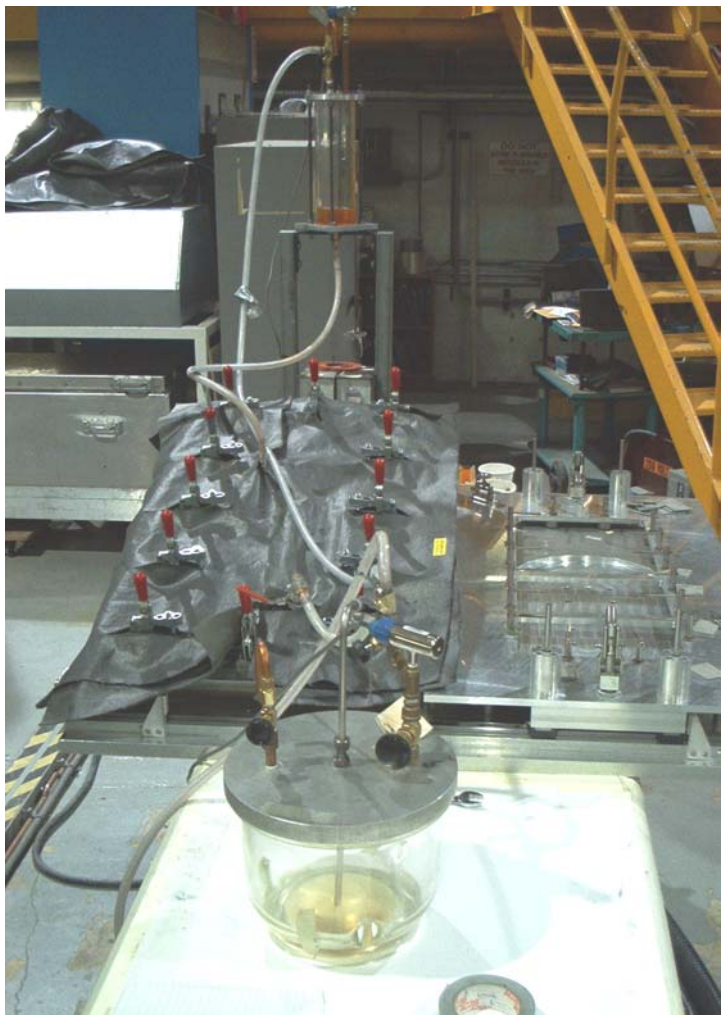
Each part and step in this new automatic coil winder is carefully designed to minimize the potential of bending degradation to brittle superconductors during the winding process. The machine is fully automated and computer controlled to minimize uncontrolled errors (human handling). All steps are recorded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

Dealing With Brittle Conductor

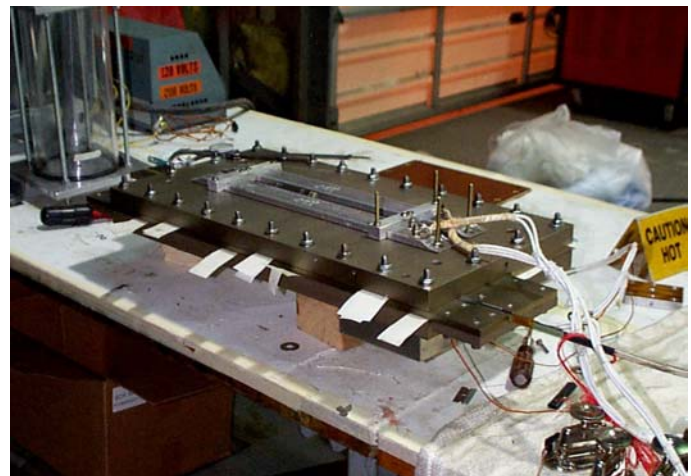
- End spacers are slit over many places to make it some what elastic in bending direction to help it conform to actual coil shape.
- In general, conductor is not forced.
- Bend in splice region is pre-fabricated. Gentle reverse bend and inner splice are in low field region in a common coil design.



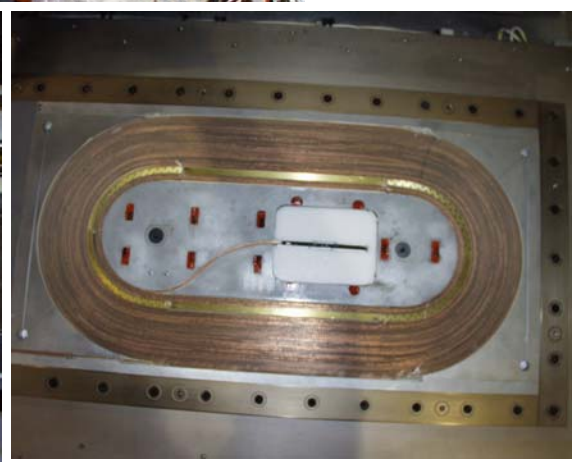
Racetrack Coil Modules and Vacuum Impregnation



Coil impregnation fixture

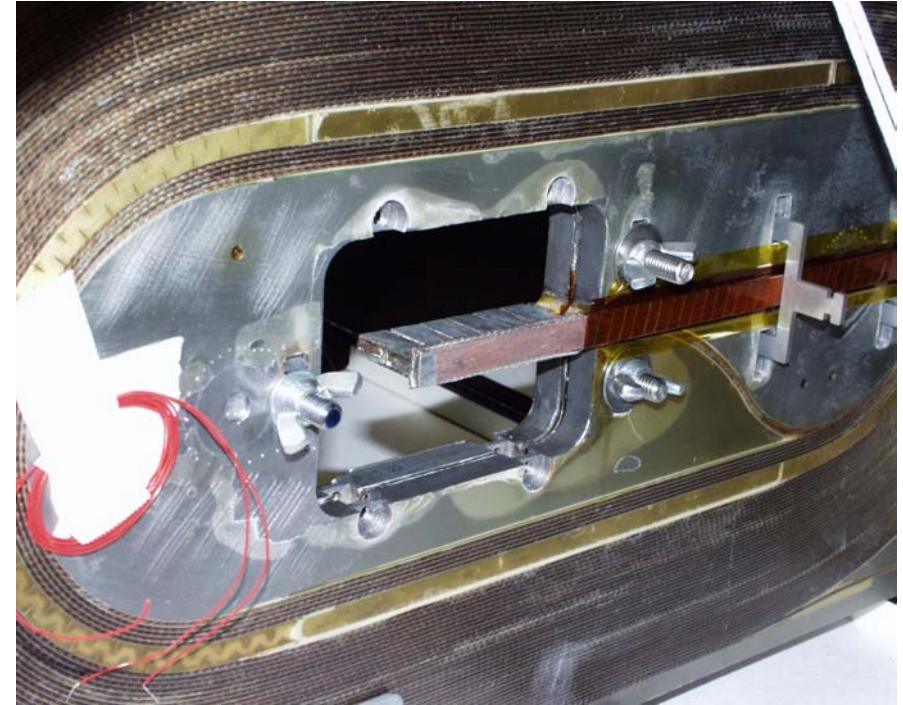
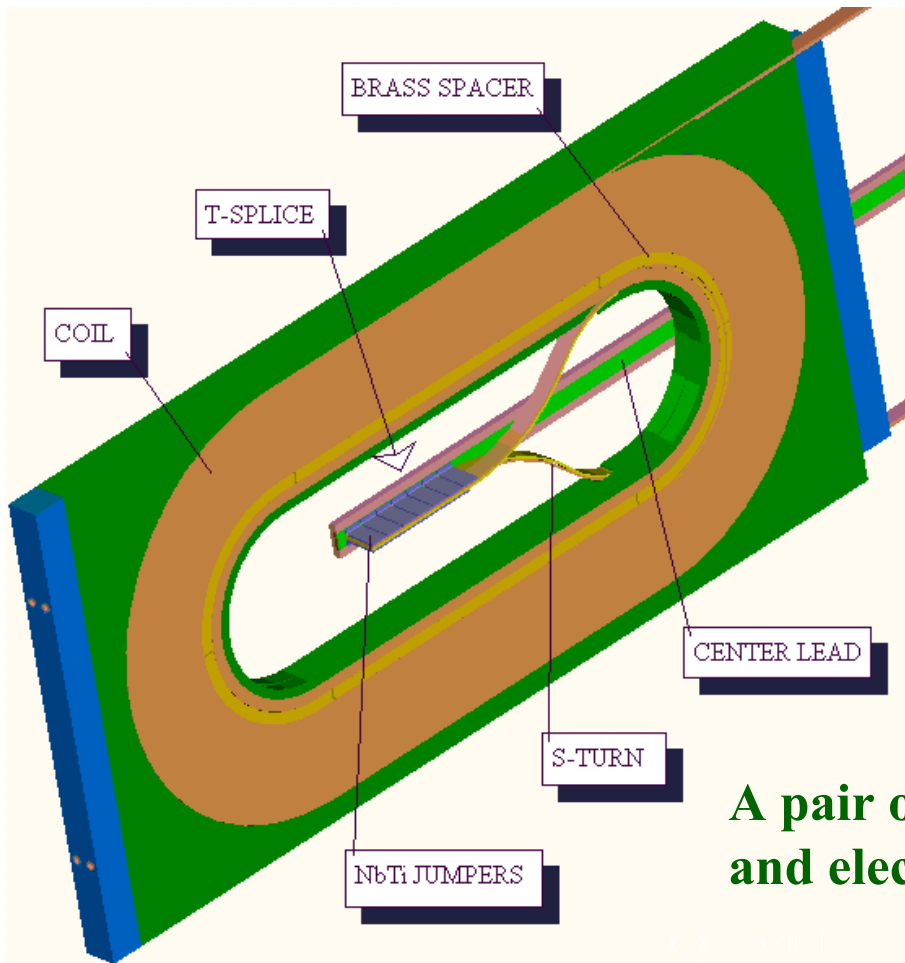


Before
Impregnation



After
Impregnation

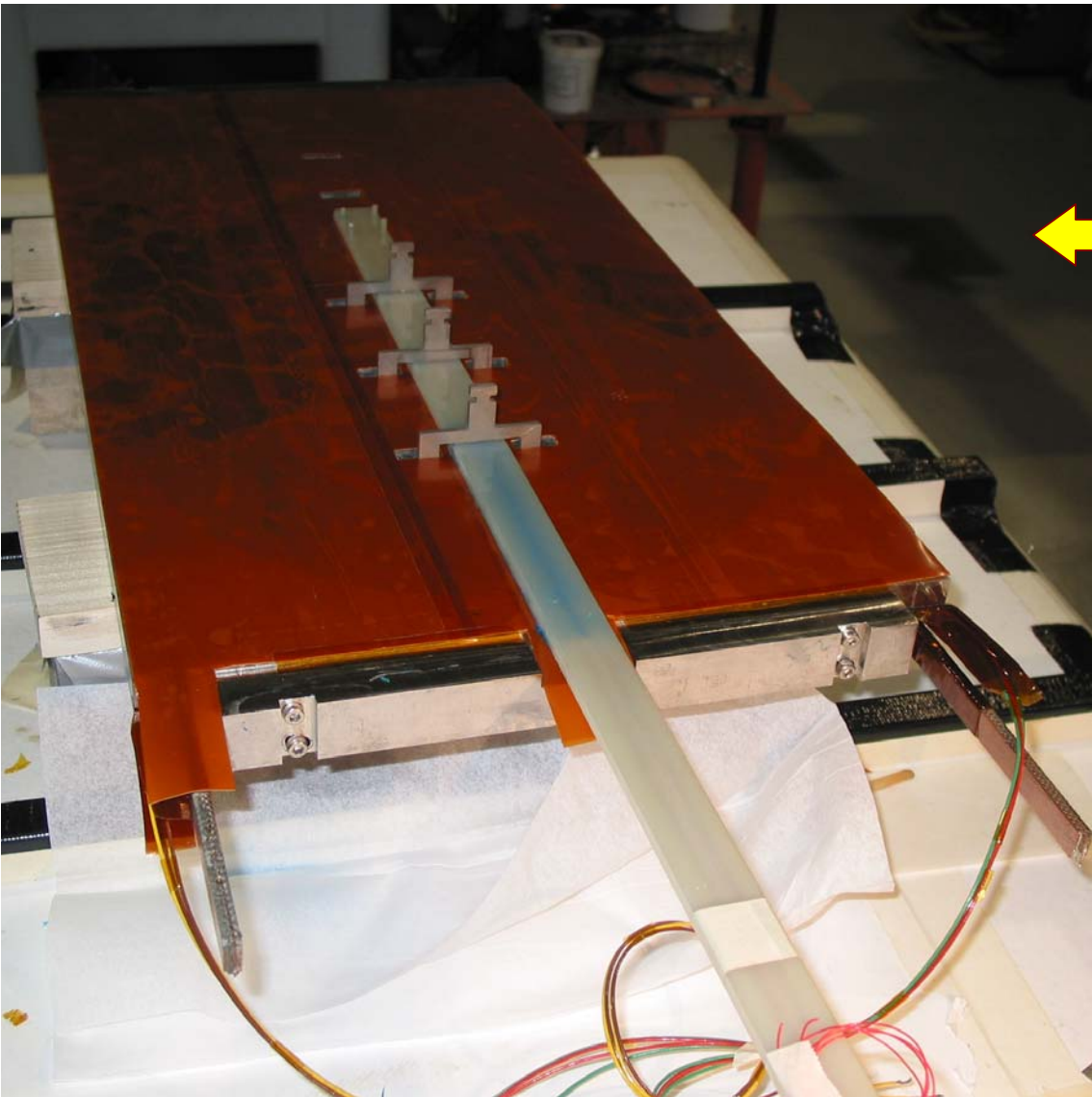
Splice Between A Pair of Coils



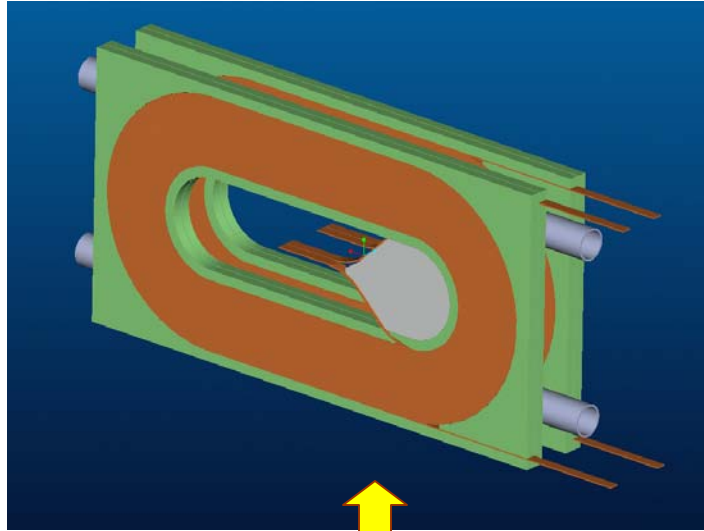
A pair of similar coils spliced properly oriented and electrically connected to make one side

Perpendicular Nb-Ti splice in low field region.

Complete Module for One Side



A completed coil module consisted of two coils, shunt lead, quench heaters, etc.



Two Pairs of Coil Modules in Common Coil Configuration

BNL Nb₃Sn React & Wind Common Coil Dipole DCC017 During Final Assembly



DCC017 at Vertical Test Facility



Magnet has very little instrumentation

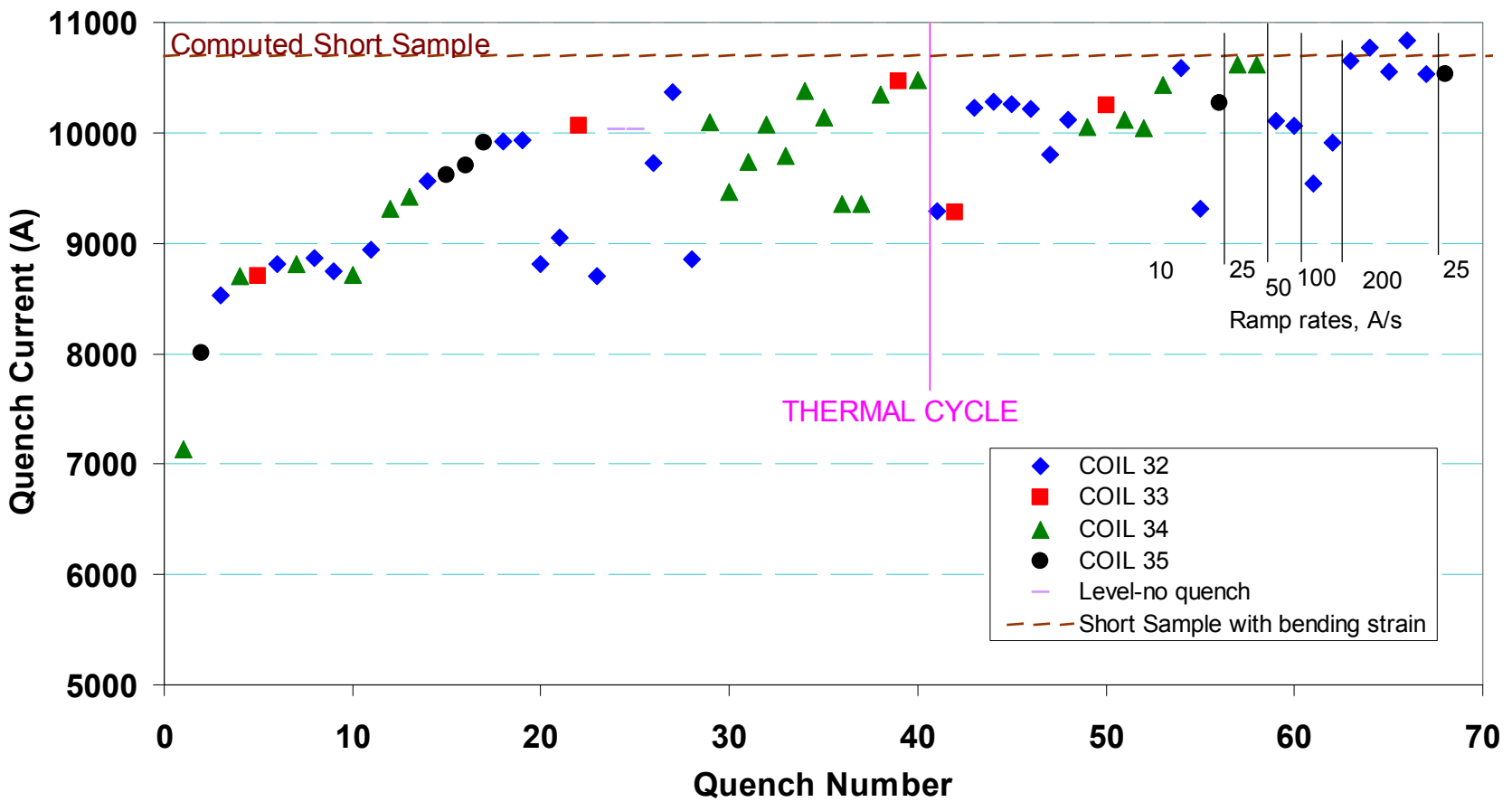
- **No strain gauges**
- **No voltage taps between the turns**

Voltage taps between each coil

- **No energy extraction**

Strip heaters for quench protection

Quench Plot of BNL React & Wind Common Coil Dipole DCC017

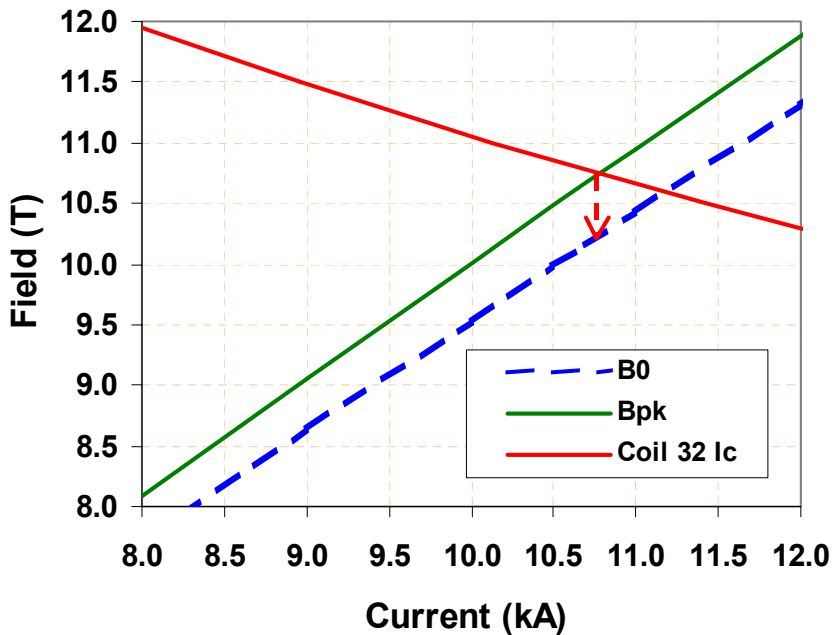
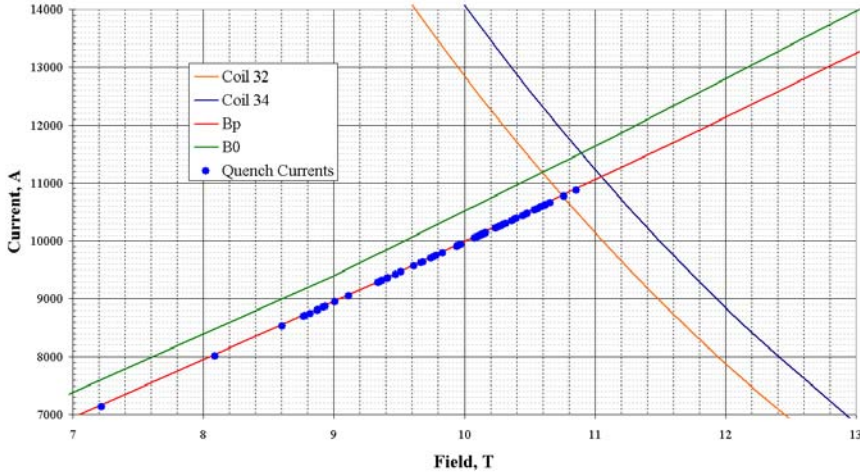


- Magnet reached short sample after a number of quenches
- ✓ Reasonable for the first technology magnet
- No significant ramp rate dependence

$I_c = 10.8 \text{ kA}$
 $B_{pk} = 10.7 \text{ T}$
 $B_{ss} = 10.2 \text{ T}$

Load-line and Peak Field Line with Extracted Strand Measurements

DCC017 Strand Data (including Bending Strain) and Magnet Load Line T=4.5K



- Magnet reached short sample based on the measurements of the extracted strand of the two types of cables used in coils.
- Magnet did not have any energy extraction system. There was a concern if there could be strain degradation due to thermo-mechanical effects. No conclusive evidence based on limited information.
- Magnet had practically no pre-stress on the coil (horizontal, vertical or axial). No experiment are planned to determine if pre-stress could improve the performance.
- Relative (internal) deflections of coils could have been $\sim 100 \mu\text{m}$. Absolute deflections much higher (\sim a factor of two).

Limitations of Nb₃Sn “React & Wind”

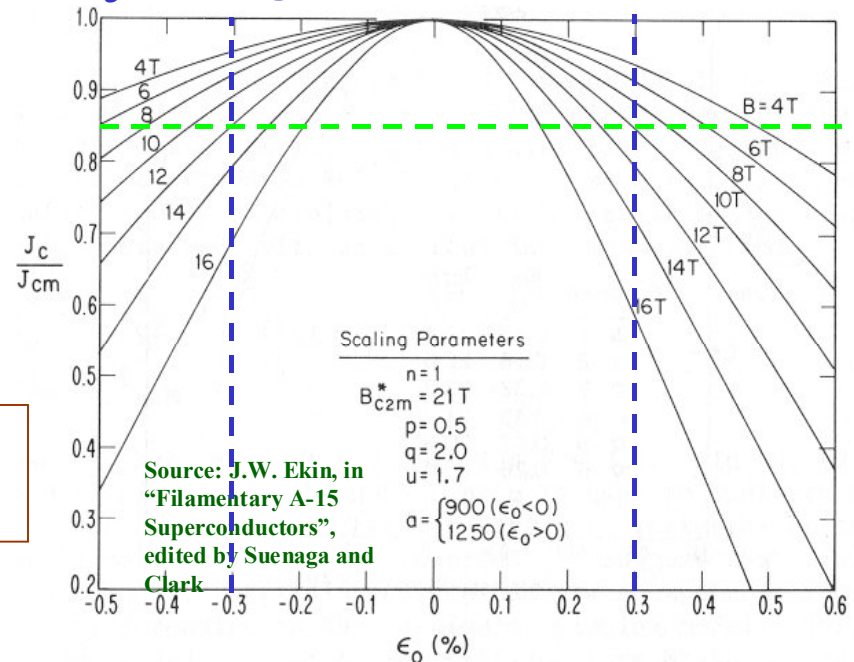
Acceptable bending strain is an important consideration in determining the highest possible field in “React & Wind” Nb₃Sn magnets.

- 0.3% strain may be tolerable for a 12 T design, as it means a 15% drop in J_c and ~4% drop in quench field (bottom line).
- For a similar ~4% drop in quench field, place strain limit to ~0.25% for a 14 T design and ~0.2% for a 15 T design.

Moreover, conductor R&D may reduce bending strain degradation in Nb₃Sn wires.

One can reduce bending strain by using smaller diameter strand and a larger bend radii in design. BNL design was too aggressive: 50% more strain than FNAL.

Maximum strain and maximum field are not necessarily at the same location.



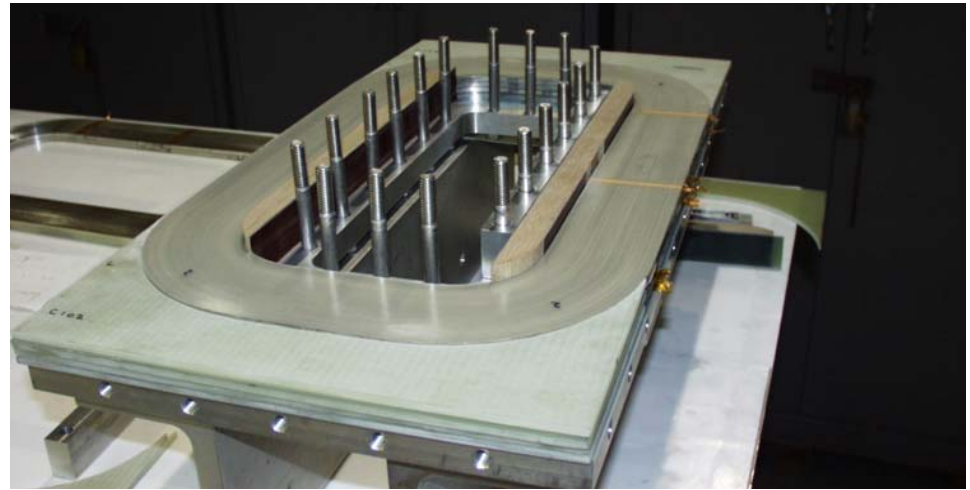
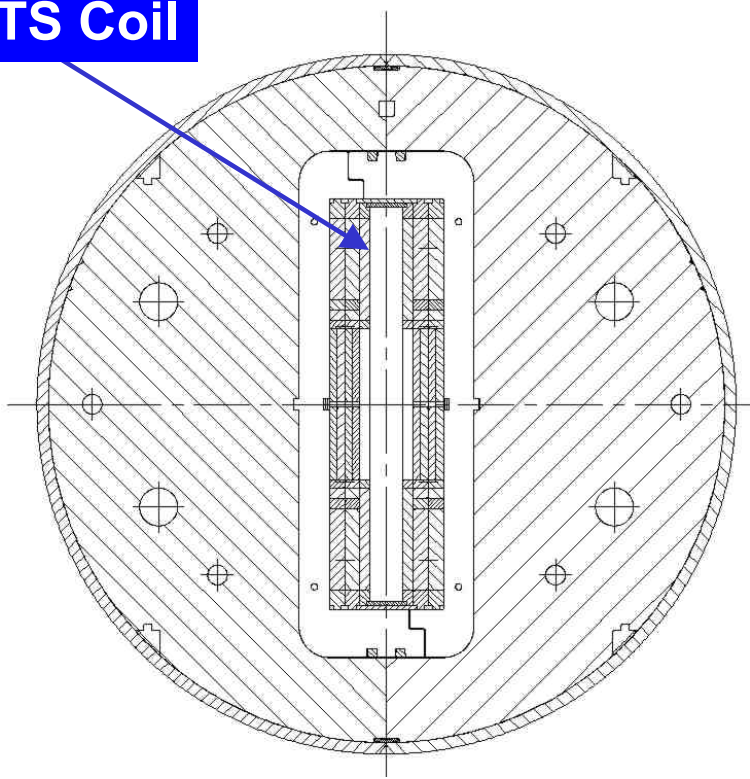
Relative critical-current density J_c/J_{cm} as a function of intrinsic strain $\epsilon_0 (\equiv \epsilon - \epsilon_m)$ for different magnetic fields, evaluated using Eq. (3) and the typical set of scaling parameters indicated in the figure.

A ~15 T magnet should be possible with Nb₃Sn “React & Wind” Technology.

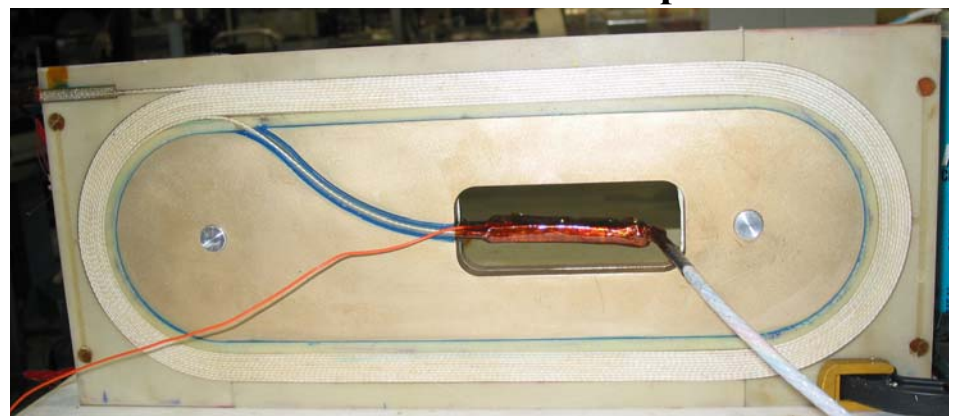
Unique Coil Test Features

A unique feature of this design is a large vertical open space for high field testing of racetrack HTS insert coils without disassembling the magnet.

HTS Coil



HTS coils made with BSCCO tape from ASC



HTS coil made with Rutherford cable from Showa/LBL

HTS insert coil test configuration
(HTS/Nb₃Sn Hybrid magnet)

SUMMARY

- React & Wind is an appealing alternate option for building long length high field Nb₃Sn production magnet.
- The main purpose of this R&D program was to determine if it is viable, i.e.:
“Can React & Wind technology produce high field magnets without damage or significant degradation”?
- Of course, a lot more R&D is still needed to establish it for a true full length accelerator quality magnet. However, the successful construction and test of the magnet DCC017 indicates that, “yes it is a viable technology for high field Nb₃Sn accelerator magnets”.
- It should be possible to make React & Wind accelerator magnets up to a quench field of ~15 T.
- Due to a unique large open space, DCC017 can be used for relatively inexpensive and fast turn around high field insert coil test (or hybrid magnet test) of racetrack coils made with HTS and Nb₃Sn, Nb₃Al, MgB₂, etc.