BNL Experience with Nb_3Sn

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History and Flavor of Nb_3Sn R&D at BNL

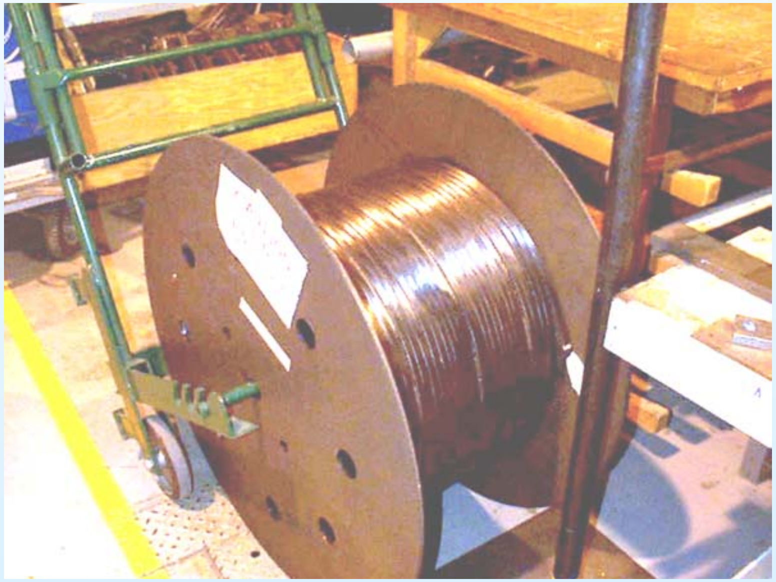
- Started NB_3Sn magnet R&D in late 60's (Sampson)
  - Perhaps first lab in the world to do it for accelerator magnets
- Made magnets with both Nb_3Sn tape and Nb_3Sn cable
- Used both "Wind & React" and "React & Wind" Technology
- Made both Nb_3Sn dipoles and quadrupoles
- Developed a variety of new designs that are useful for Nb_3Sn magnets
- Made both cosine theta and racetrack (block coil) type Nb_3Sn magnets

… and have both "good" and "learning experiences" with brittle Nb_3Sn

Thus BNL has a long history with various aspects of variety of Nb_3Sn Technology.

Focus of this presentation will be what we are doing now
and to outline our future direction for Nb_3Sn technology.

Nb_3Sn Reaction Facility at BNL

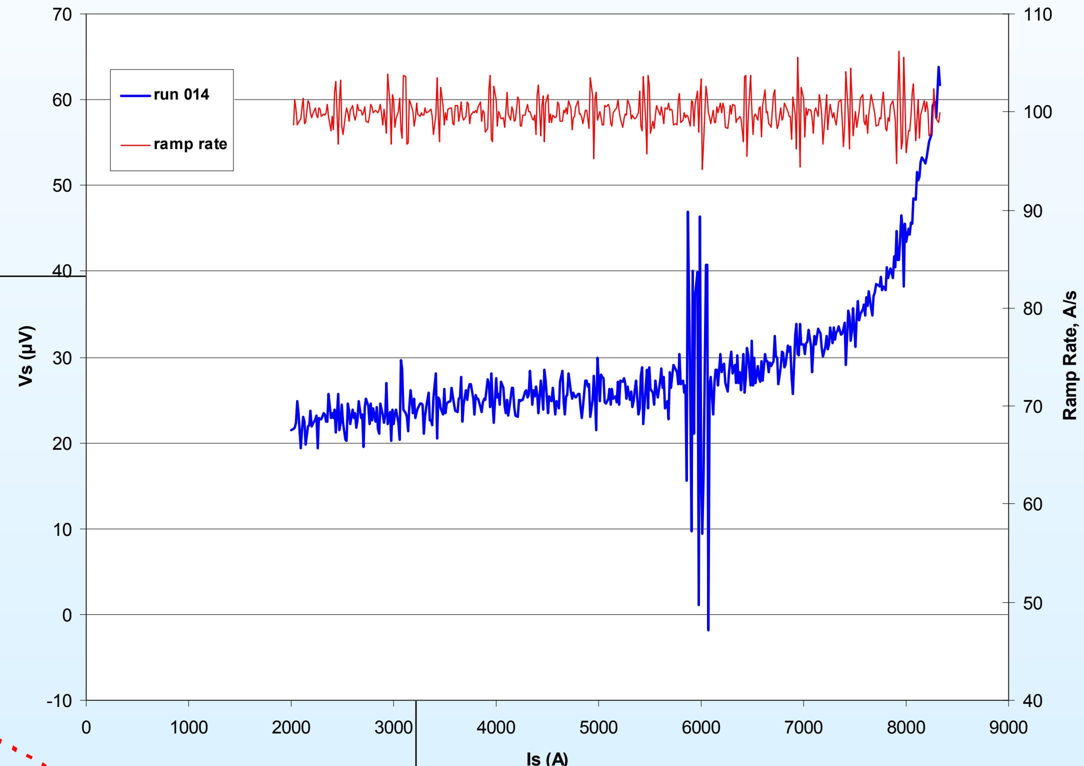


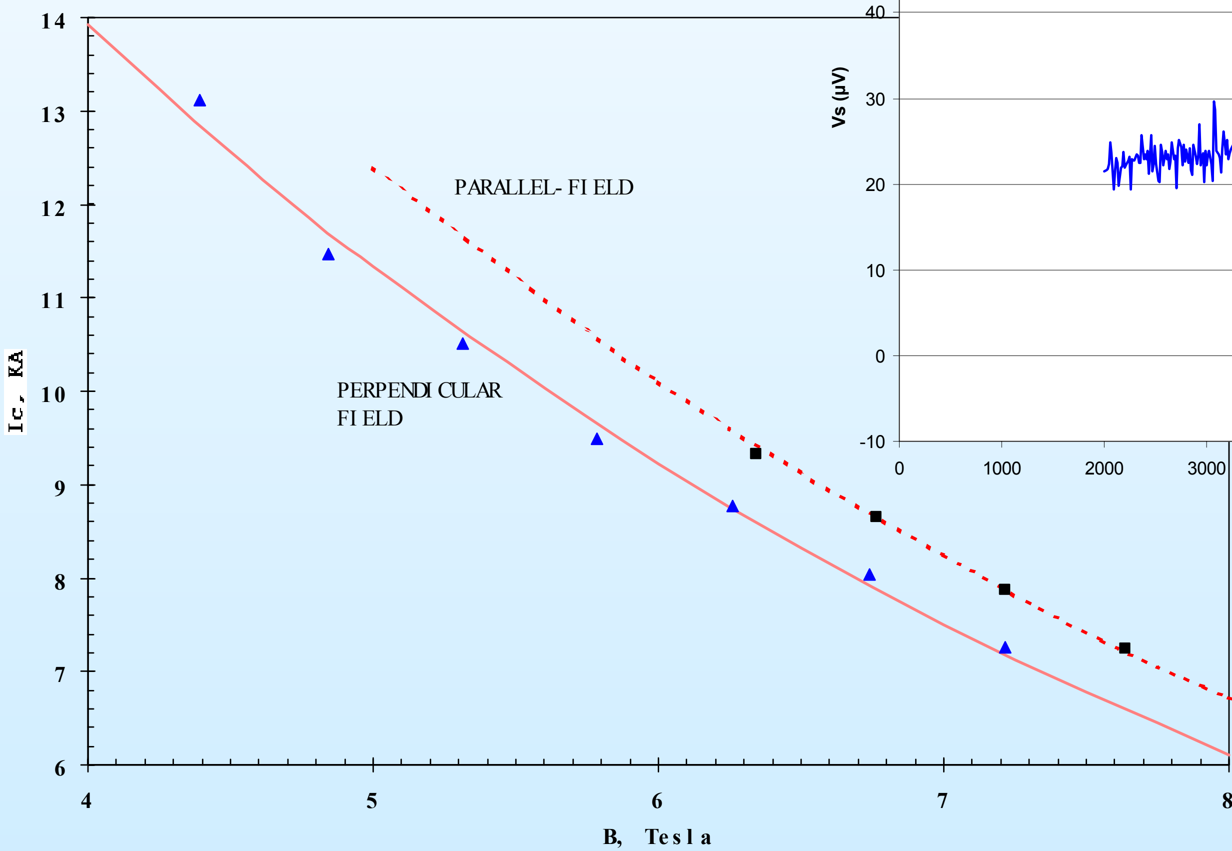
Nb_3Sn cable after reaction.

Large (1.5 m^3) reaction furnace at BNL.

It was used for making full length Nb_3Sn magnets.

Nb$_3$Sn Cable Short Sample Test at BNL (Arup Ghosh)





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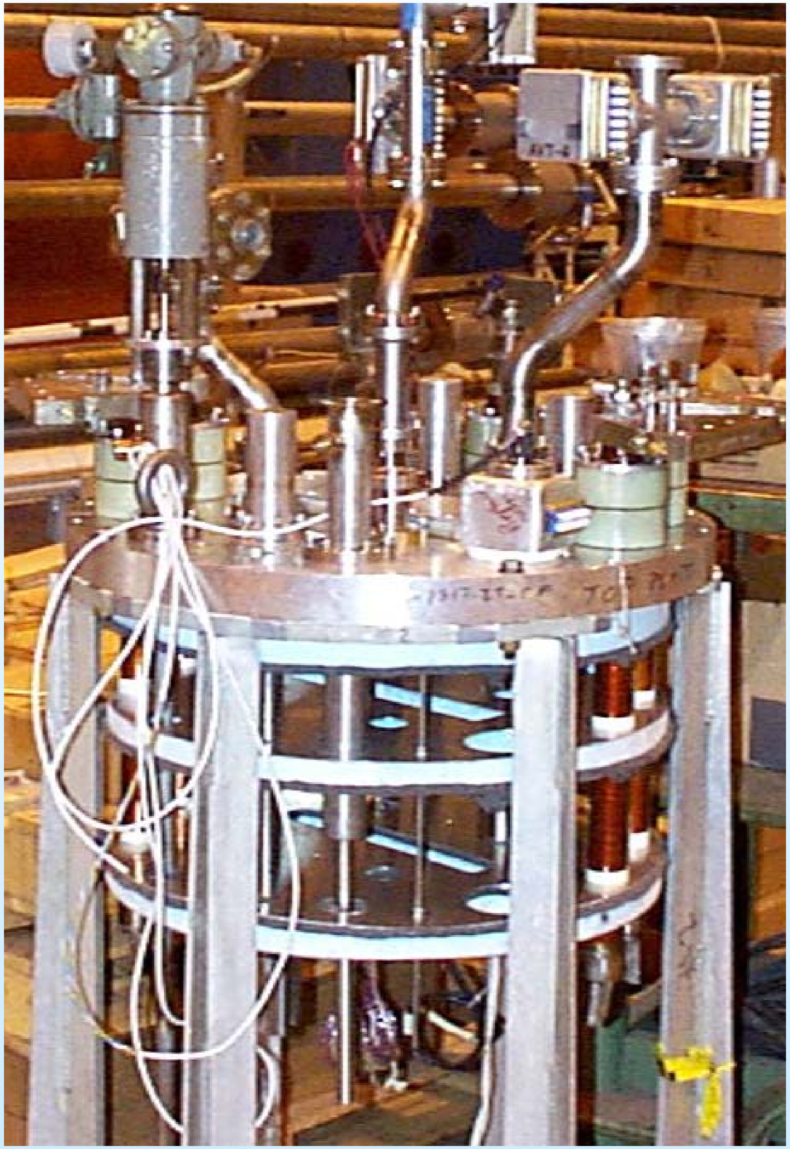
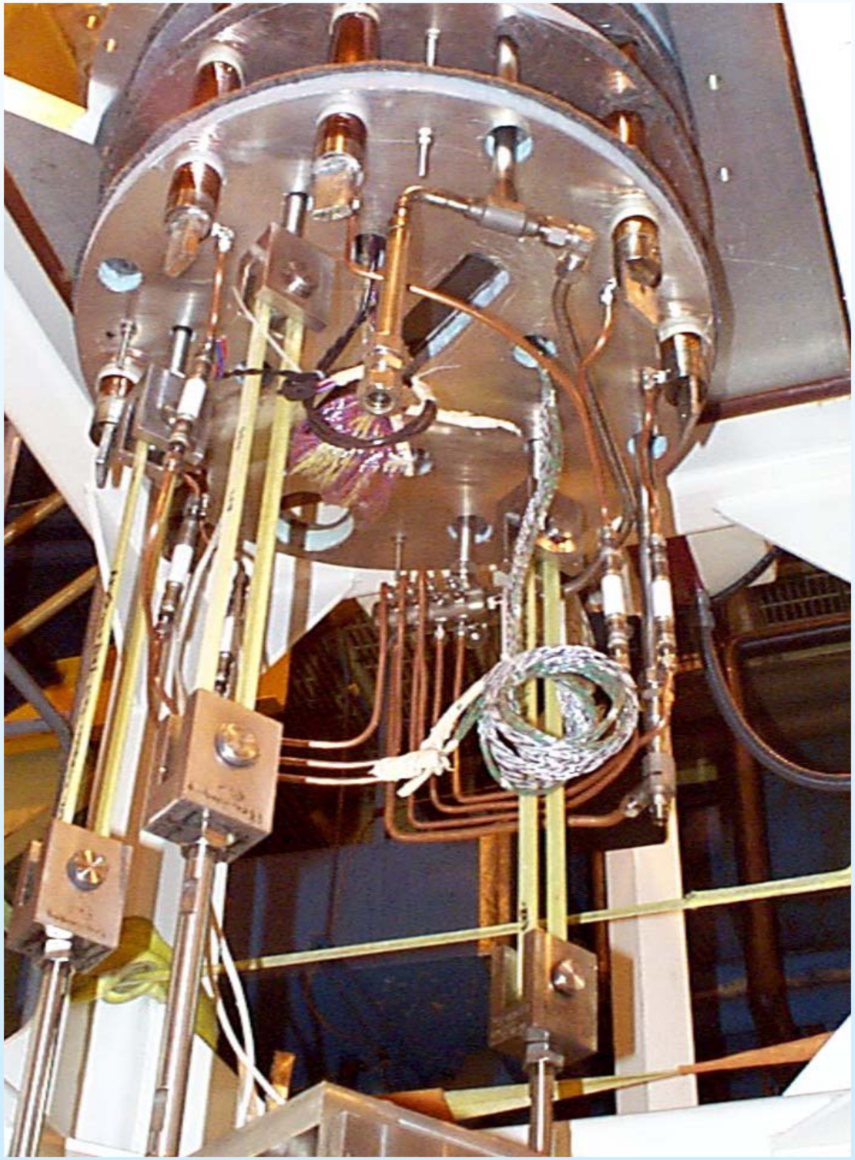
New Top Hat and Commissioning of High Current Test Facility





BNL Perspective on Nb_3Sn R&D

Nb_3Sn magnet technology is not yet at a stage that the full length accelerator magnets can be made for a machine soon

Explore new designs that may be more suitable for Nb_3Sn technology

Despite a few remarkable success, Nb3Sn is still far from a mature technology. Based on the experience of developing NbTi technology and based on the complexities and "unknown" nature of a number of issues involved, we need a systematic and a "Rapid-turn-around" R&D program for a period of time

a "rapid-turn-around", "cost effective" program to study "one issue at a time"

React & Wind Approach

BNL opts for further developing "React & Wind" technologies and designs

Advantages of "React & Wind" Approach

- Eliminates the need to deal with the differential thermal expansions of various materials of coil modules during high temperature reaction.
- Allows one to use a variety of insulation and other materials since the coil and associated structure are not subjected to the high reaction temperature.
- Appears more adaptable for building long magnets by extending present manufacturing techniques and tooling.

Challenge: Must learn to deal with brittle pre-reacted material

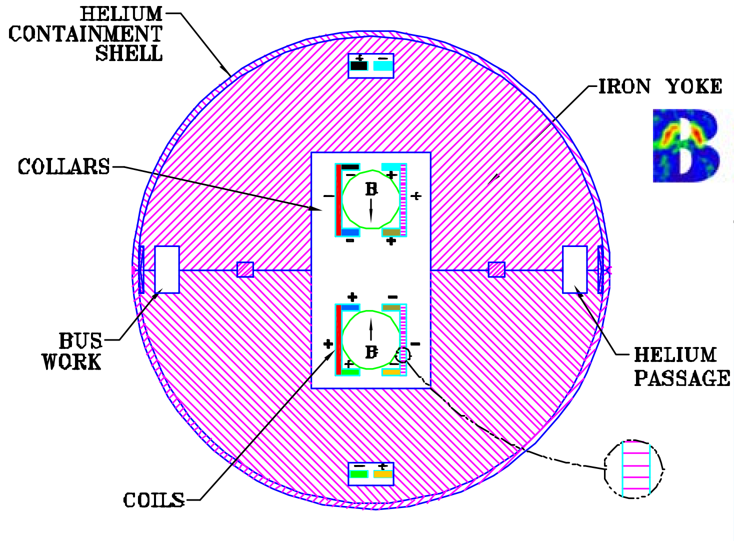
Guiding Principle of BNL's Nb_3Sn Program

Develop designs and technologies that can use brittle materials without causing significant degradation.

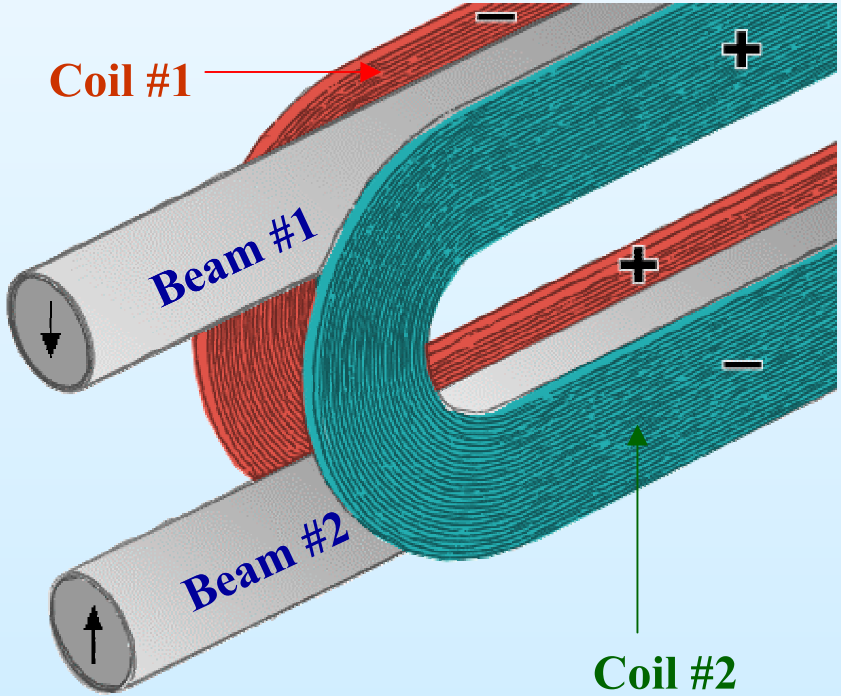
Nb_3Sn --limited experience in building R&D magnets; none in building long magnets

$\Rightarrow$ pursue various options at this stage in a systematic and cost effective manner.

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 (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**



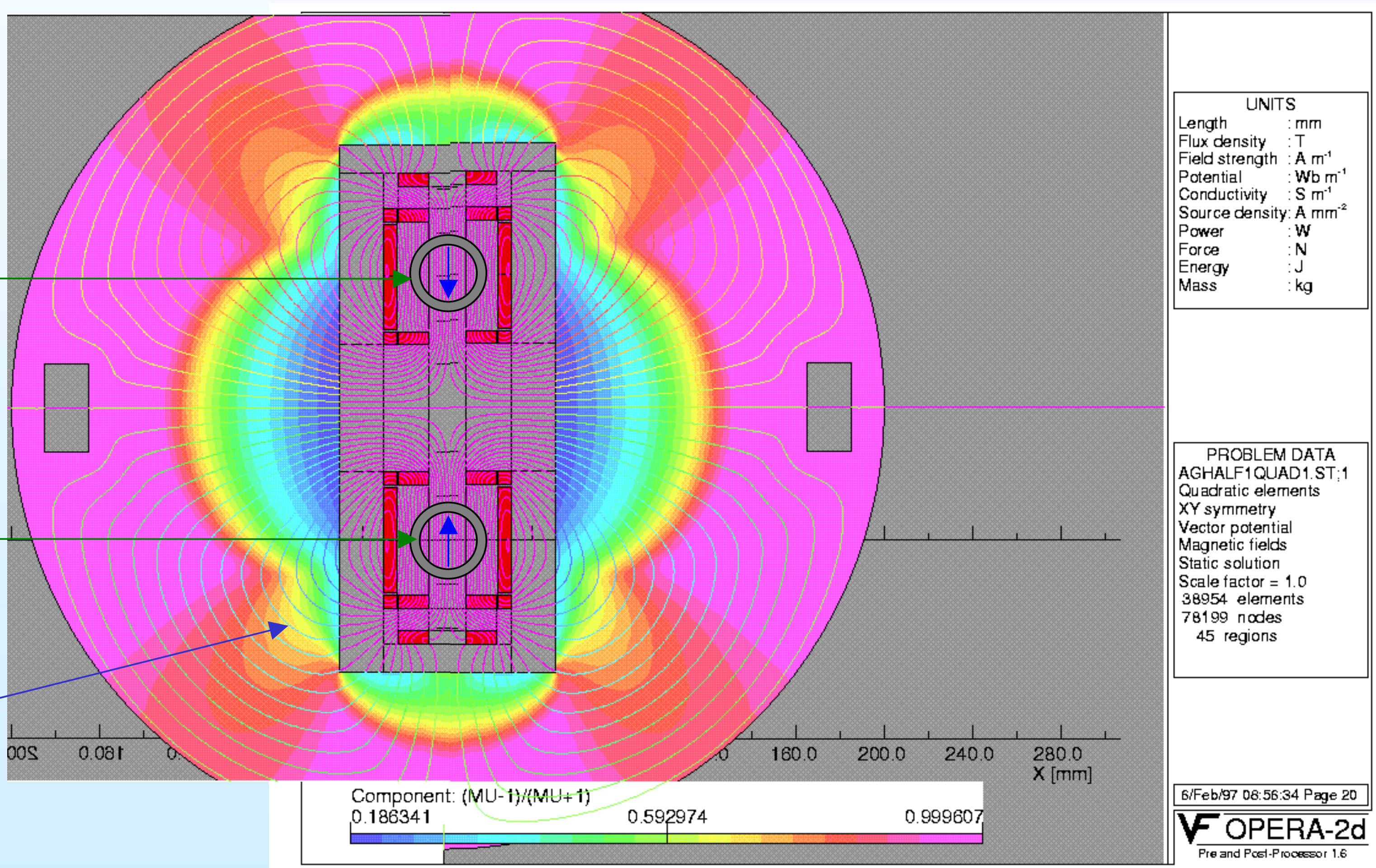
Main Coils of the *Common Coil Design*

Field Lines at 15 T in a Common Coil Magnet Design

Aperture #1

Aperture #2

Place of maximum iron saturation



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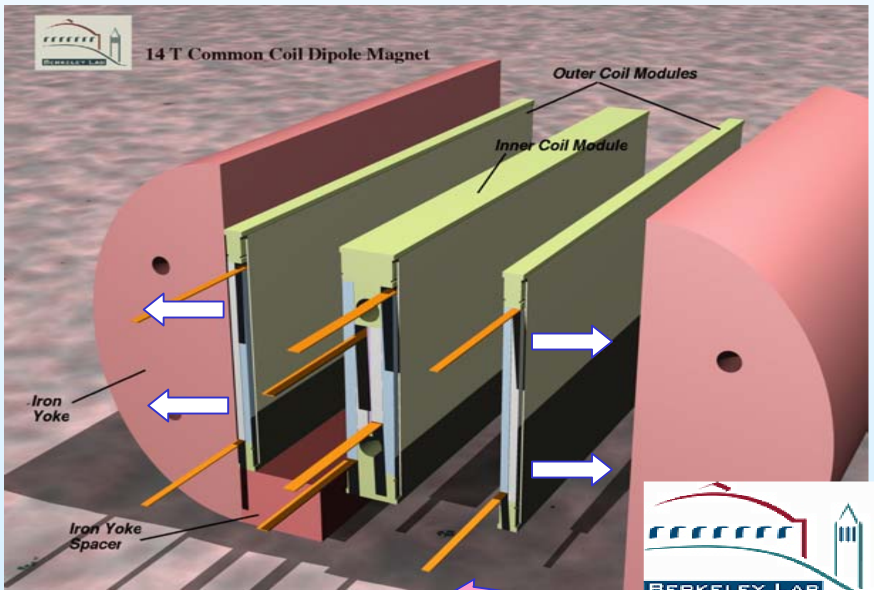
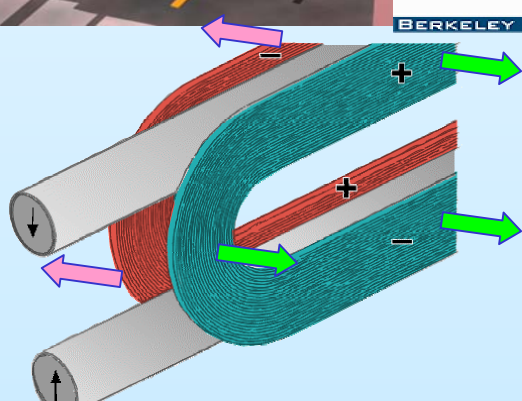
Common Coil Design in Handling Large Lorentz Forces in High Field Magnets

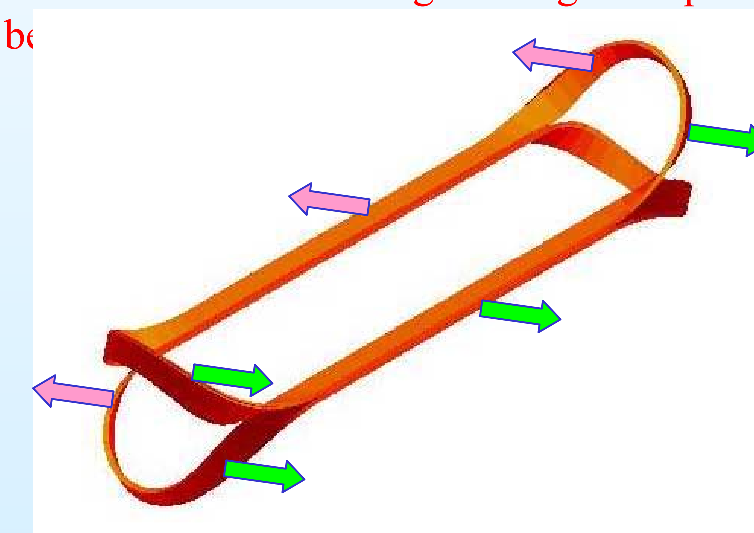
In common coil design, geometry and forces are such that the impregnated solid volume can move as a block without causing quench or damage. Ref.: over 1 mm motion in LBL common coil test configuration).



Horizontal forces are larger

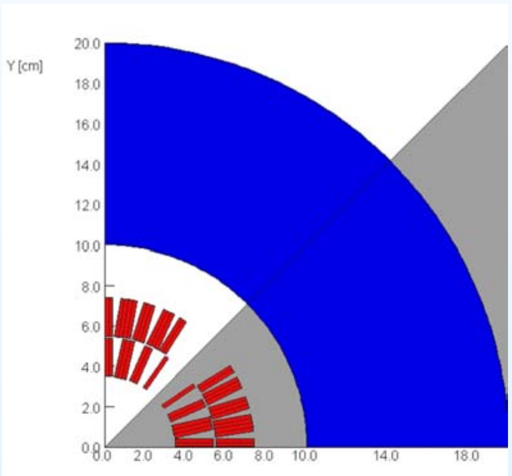


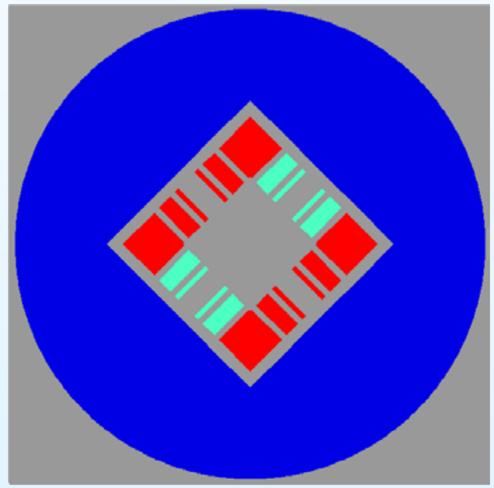
In cosine theta designs, the geometry is such that coil module cannot move as a block. These forces put strain on the conductor at the ends and may cause premature quench. The situation is somewhat better in single aperture block design, as the conductors don't go through complex be

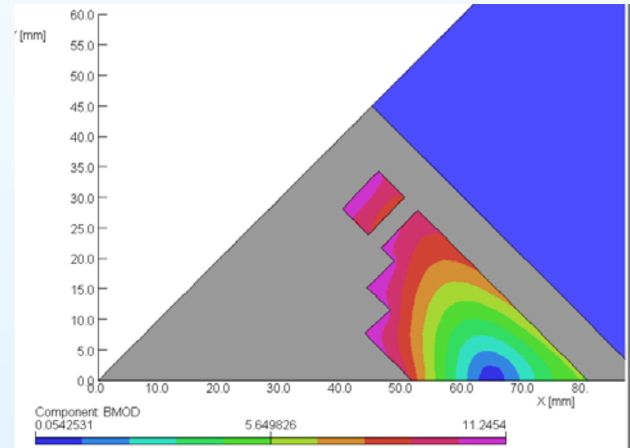


We must check how far we can go in allowing such motions in the body and ends of the magnet. This may significantly reduce the cost of expensive support structure. Field quality optimization should include it (as was done in SSC and RHIC magnet designs).

Cross sections for LHC Upgrade Quad







Cosine theta X-section (with improved technology for ends)

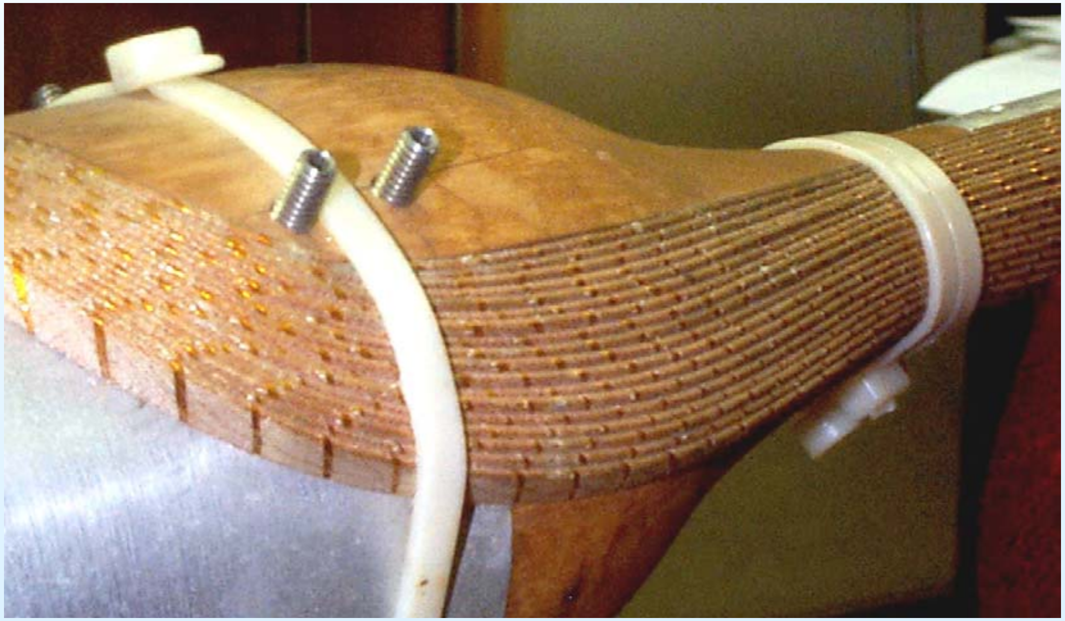
Simple Racetrack New End Designs

High Performance Racetrack Quads

Ends drive the conceptual design of "React & Wind Magnets"

Ends for Cosine theta Magnets

Earlier Design: Dogbone Ends (~20 years ago) :



A series of 32 mm aperture Nb3Sn dipoles were made for SSC (Palmer, et.al)

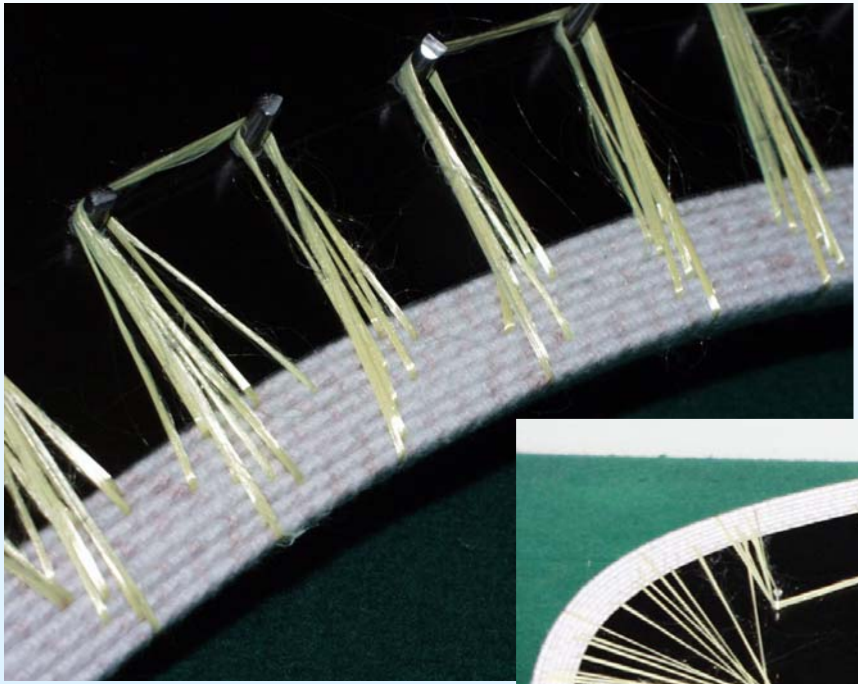
All magnets had a single flow: cable was too strained in the transition reason

Lessons learned:

During early R&D phase with expensive material, make one magnet at a time

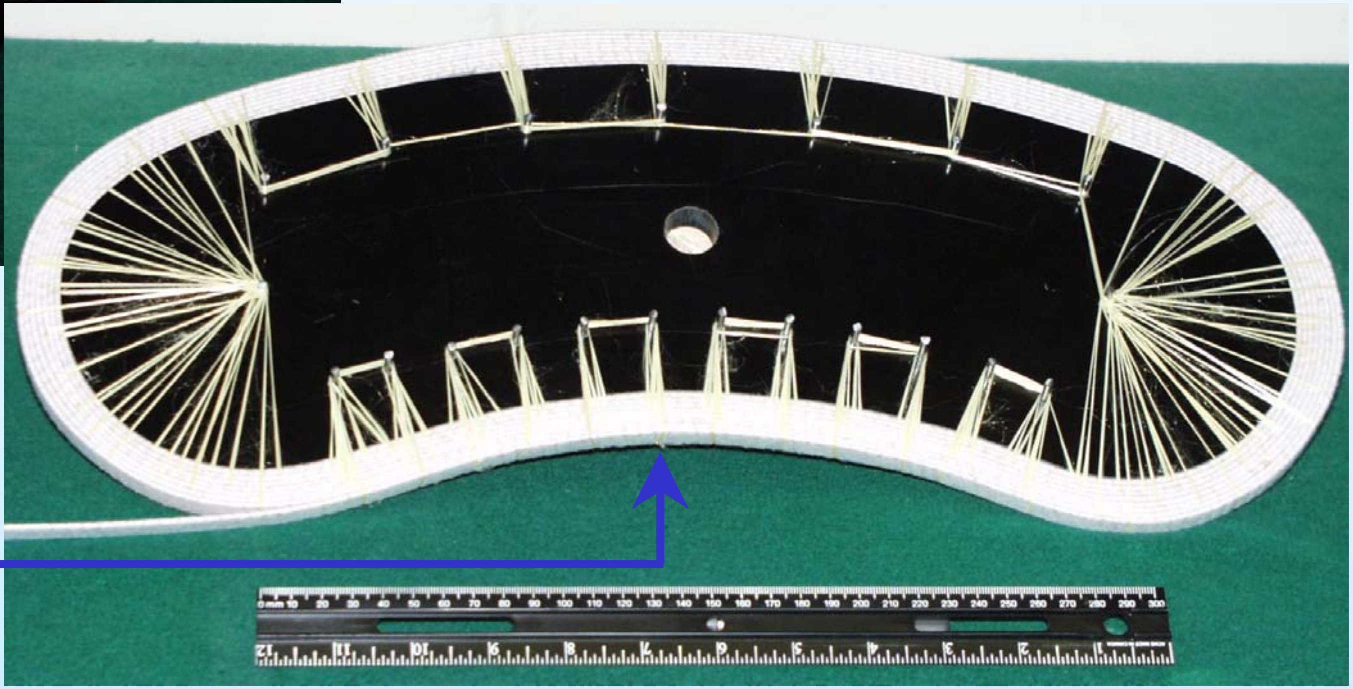
Develop technology to avoid above problem

Technique to Implement Complex Bends in React & Wind Magnets



Hold cable in place using Kevlar strings during winding (John Escallier)

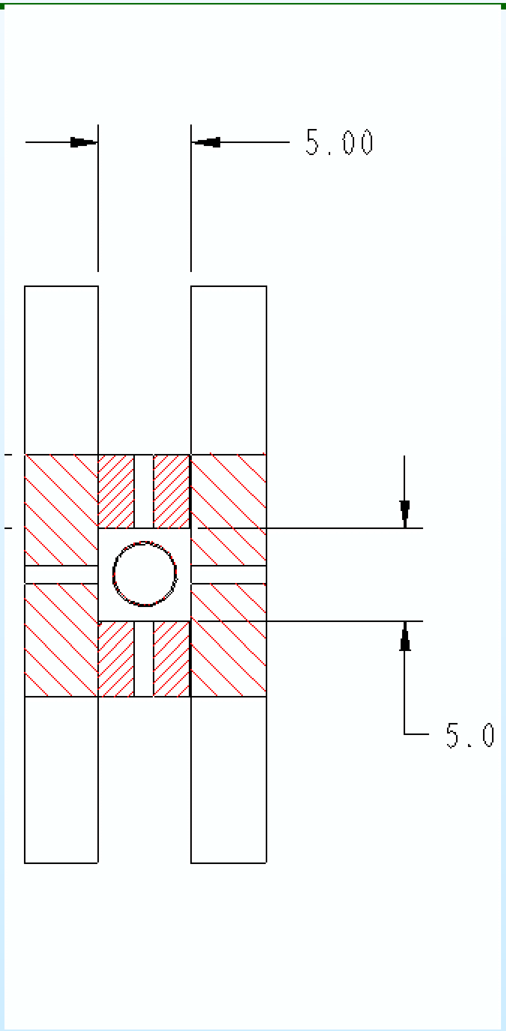
Now being used in common coil dipoles also as it makes highly compacted coils

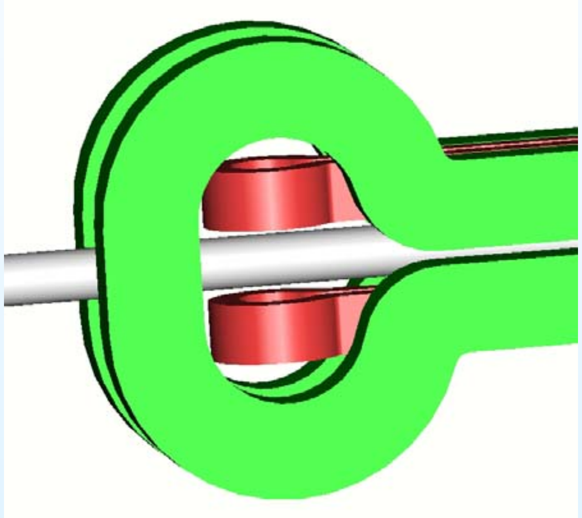


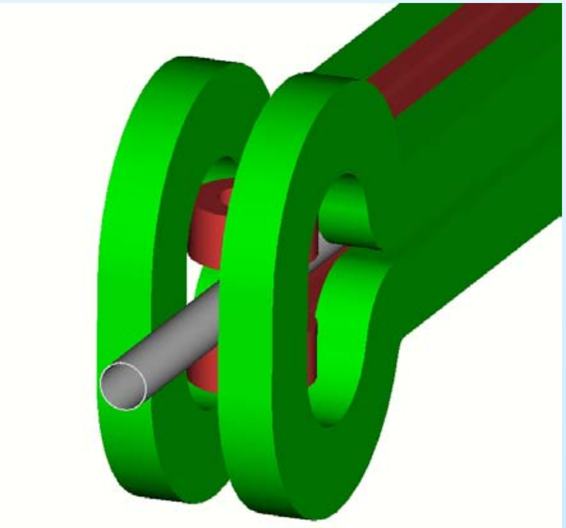
Reverse curvature

New End Design Concepts

Flat Coil Ends: Nested Coils

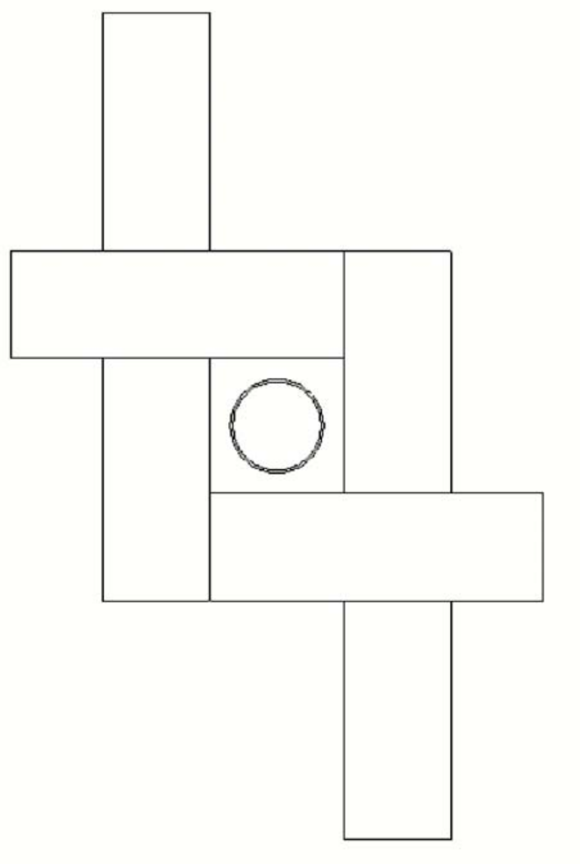


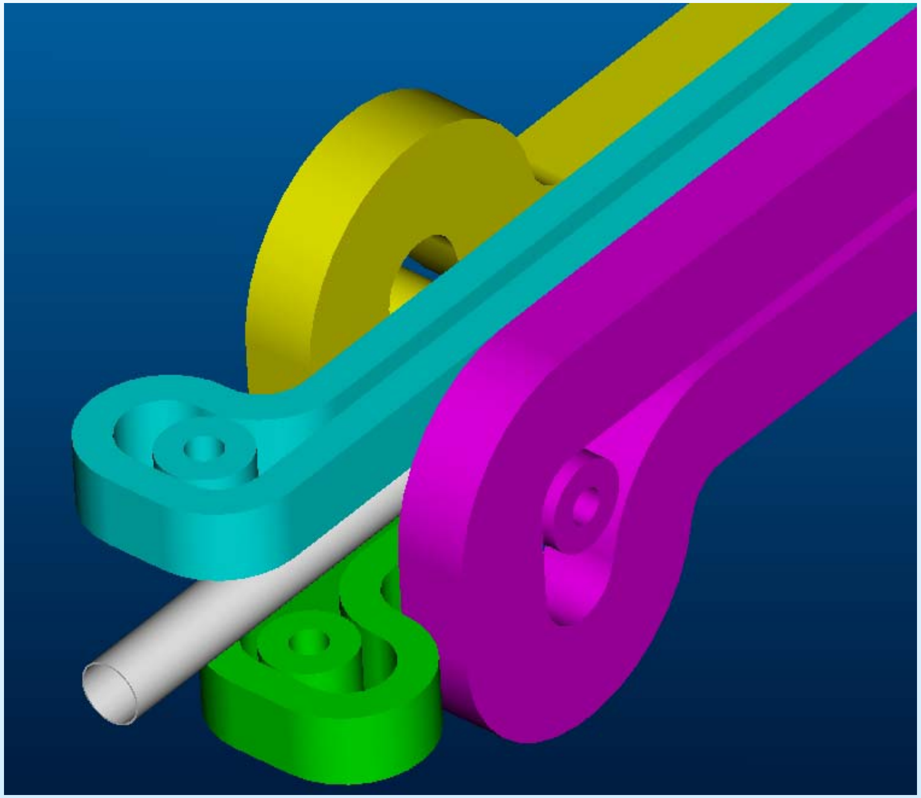




New End Design Concepts (contd.)

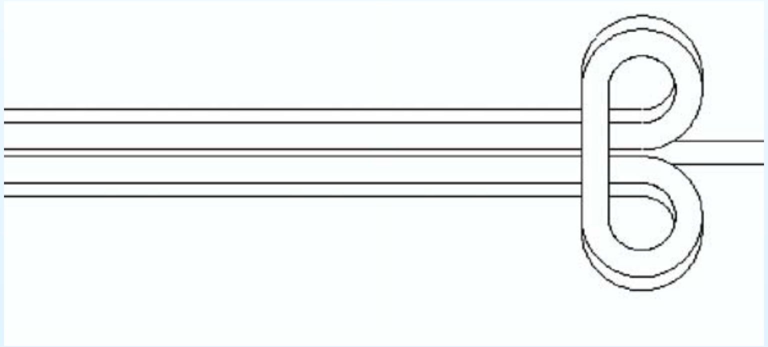
Flat Coil Ends: Sideway Overlap

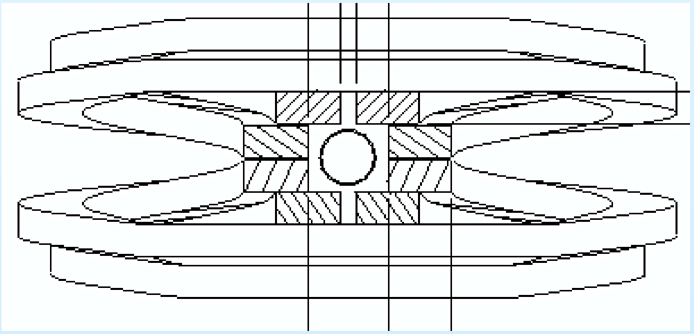


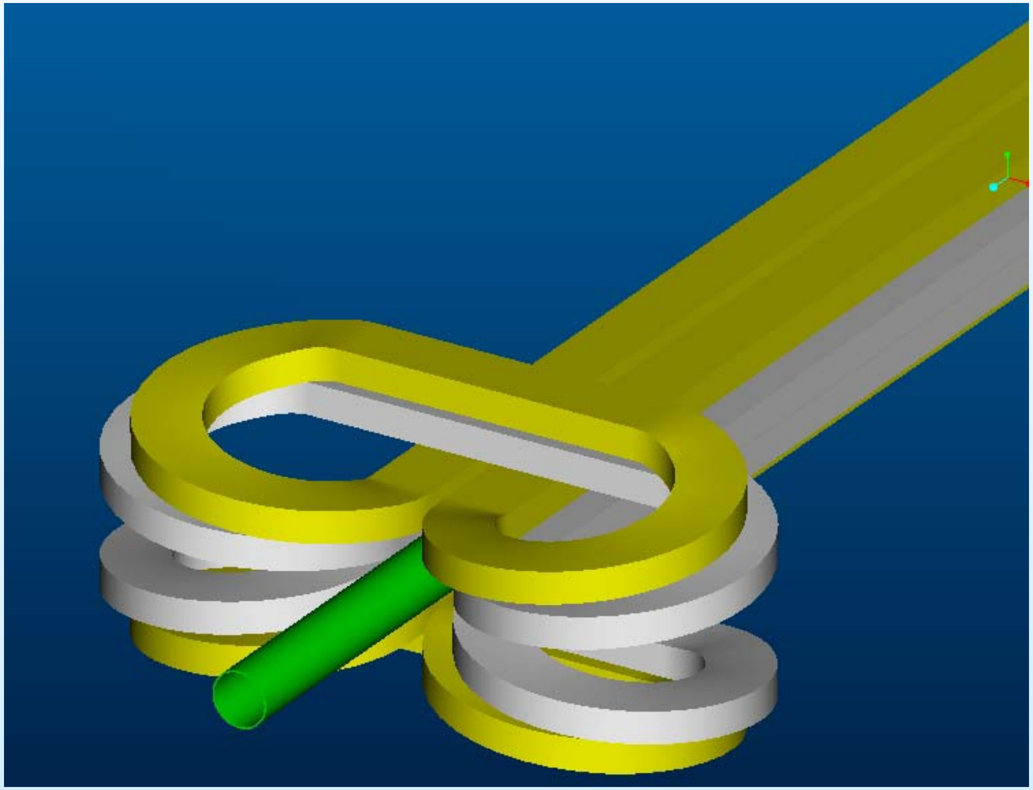


New End Design Concepts (contd.)

Overpass/Underpass (Clover Leaf) Ends: NO Reverse bend needed





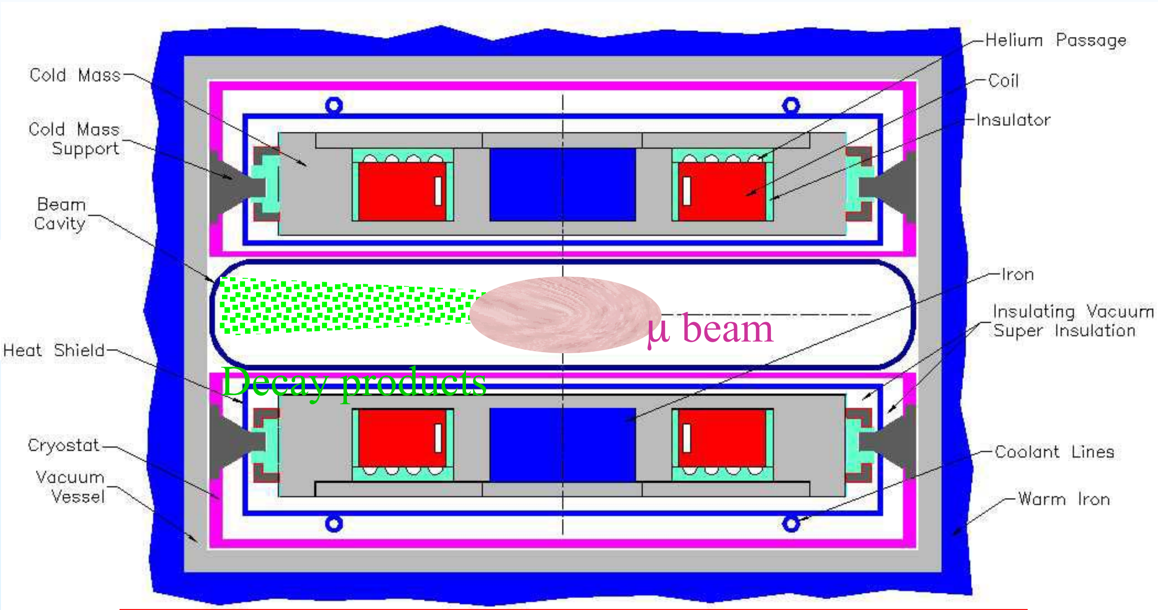


Magnet Design for ν Factory

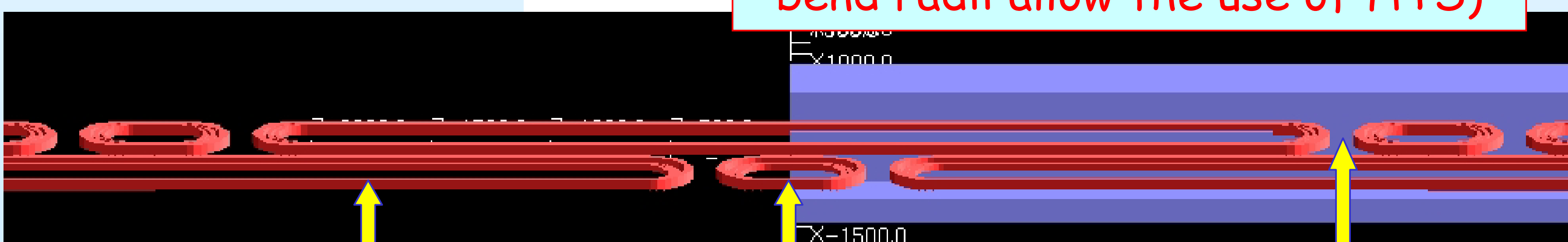
Decay products clear superconducting coils

Compact ring to minimize the environmental impact
(the machine is tilted)

Need high field magnets & efficient machine design



(simple racetrack coils with large bend radii allow the use of HTS)



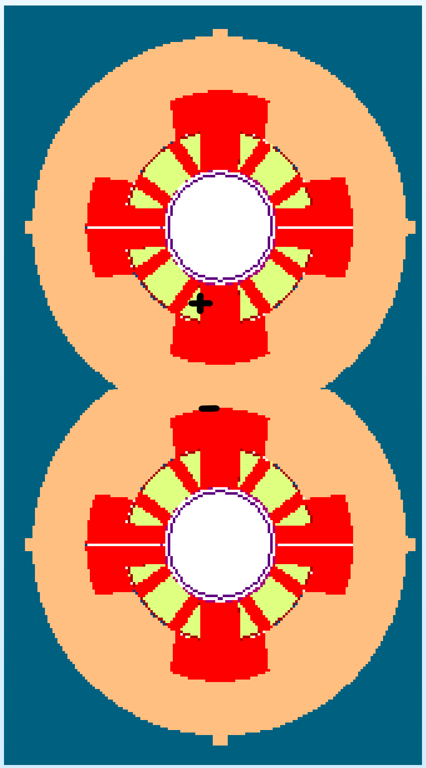
Normal Coils Dipole

Reverse Coils Skew Quad

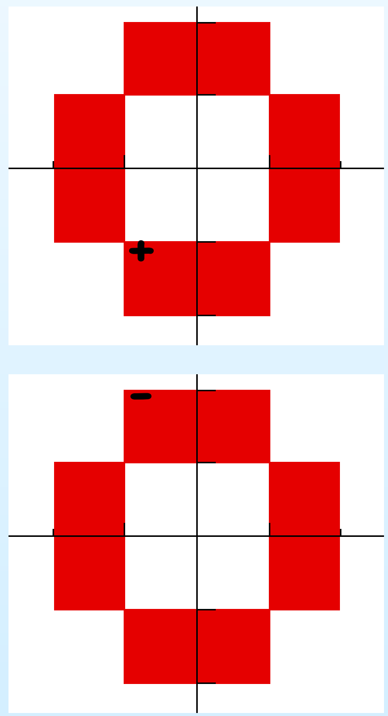
One Coil 1/2 & 1/2

VLHC-2 Interaction Region Magnet Design Concept

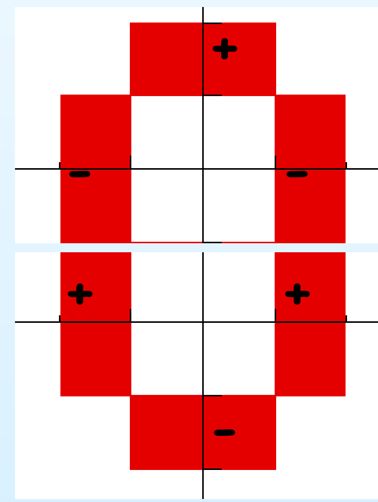
Conventional 2-in-1 cosine theta design



Panofsky 2-in-1 quad design



Modified Panofsky Quad with no spacing



(Bo not zero)

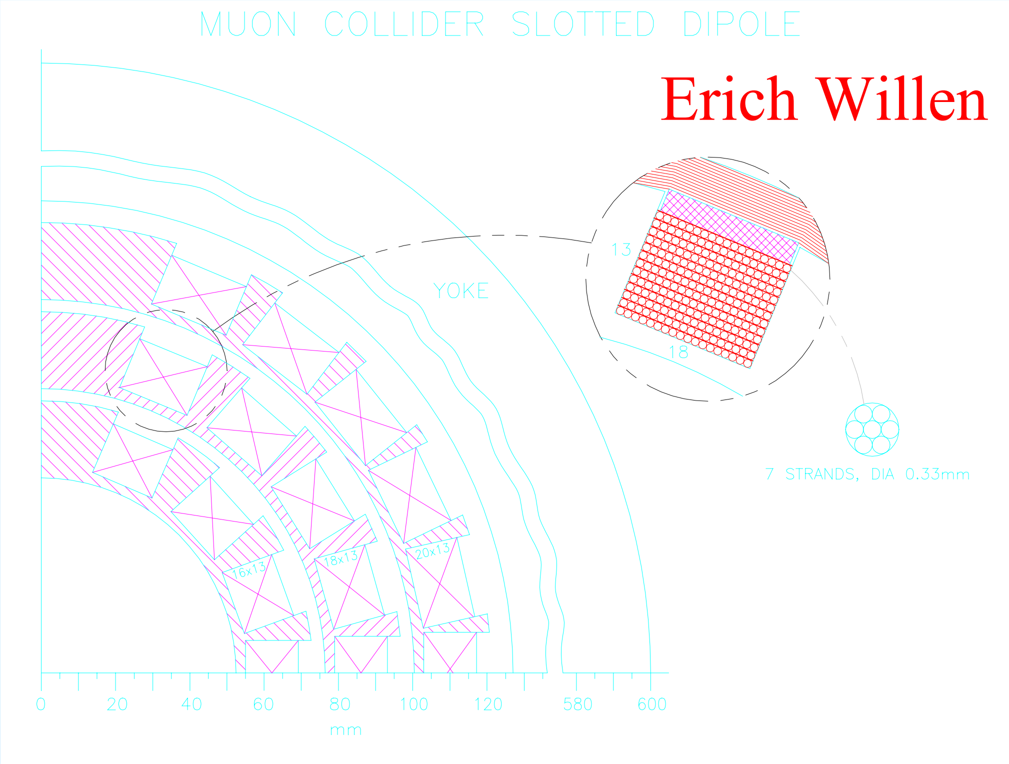
Support structure and middle conductor is removed/reduced. This reduces spacing between two apertures significantly.

Spacing depends on the conductor and support structure requirements

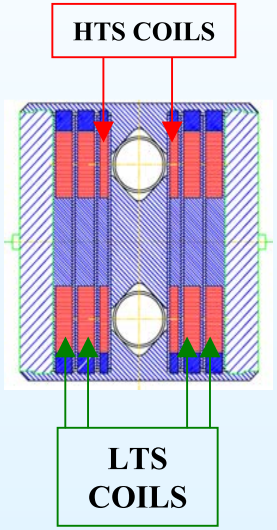
Magnets with Flexible Wire

Recently flexible pre-reacted Nb3Sn wire has become available. BNL is trying to use that in magnets in magnets that require small bend radii in the ends (example LHC IR upgrade and muon collider)

- The Lorentz forces are contained in the individual blocks and do not pile up on the midplane as in conventional cos Θ magnets



Common Coil Magnet R&D at BNL



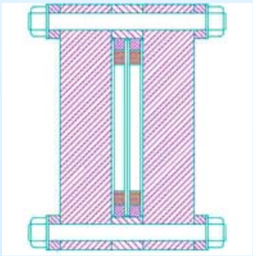
Primary Goal of the Program:

Design and build a ~12 Tesla,

"React & Wind" Common Coil Magnet

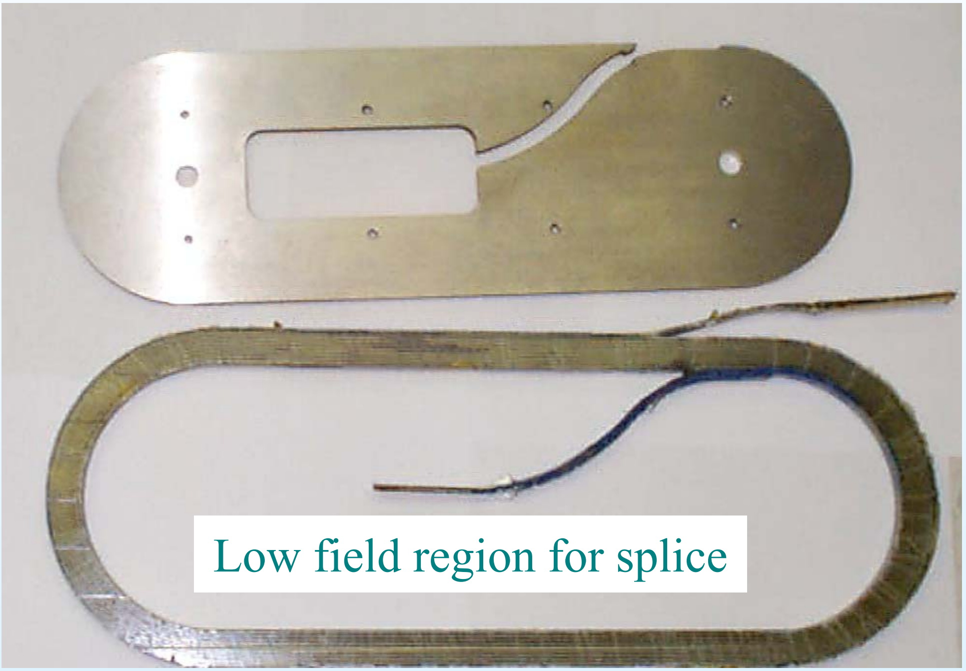
R&D Plan to Develop Technology:

A "*mini 10-turn magnet R&D program*" to systematically develop and test new ideas, designs and technologies in a time and cost effective manner.



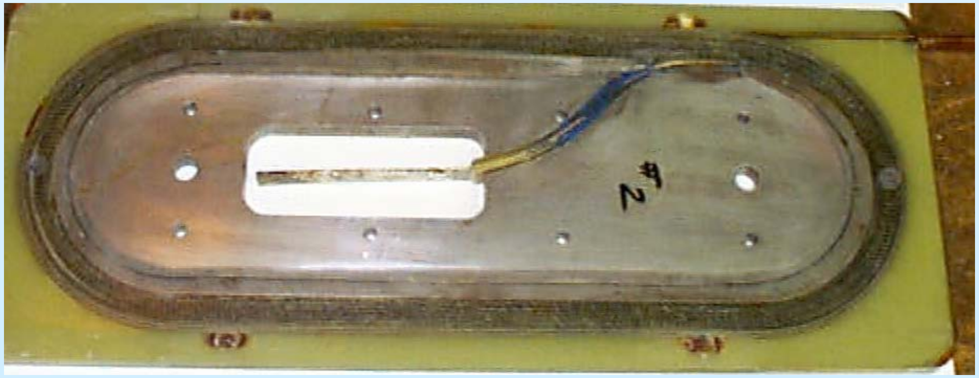
Due to lower cost, we can afford to built many coils and afford to see some destroyed in an attempt to understand and develop new technology and find a limit of others.

The Bobbin and the 10-turn Coil



The bobbin
(the coil is wound on it)

The first 10-turn practice coil
(removed from bobbin after impregnation)



The complete cassette module
(vacuum impregnated coil in bobbin)

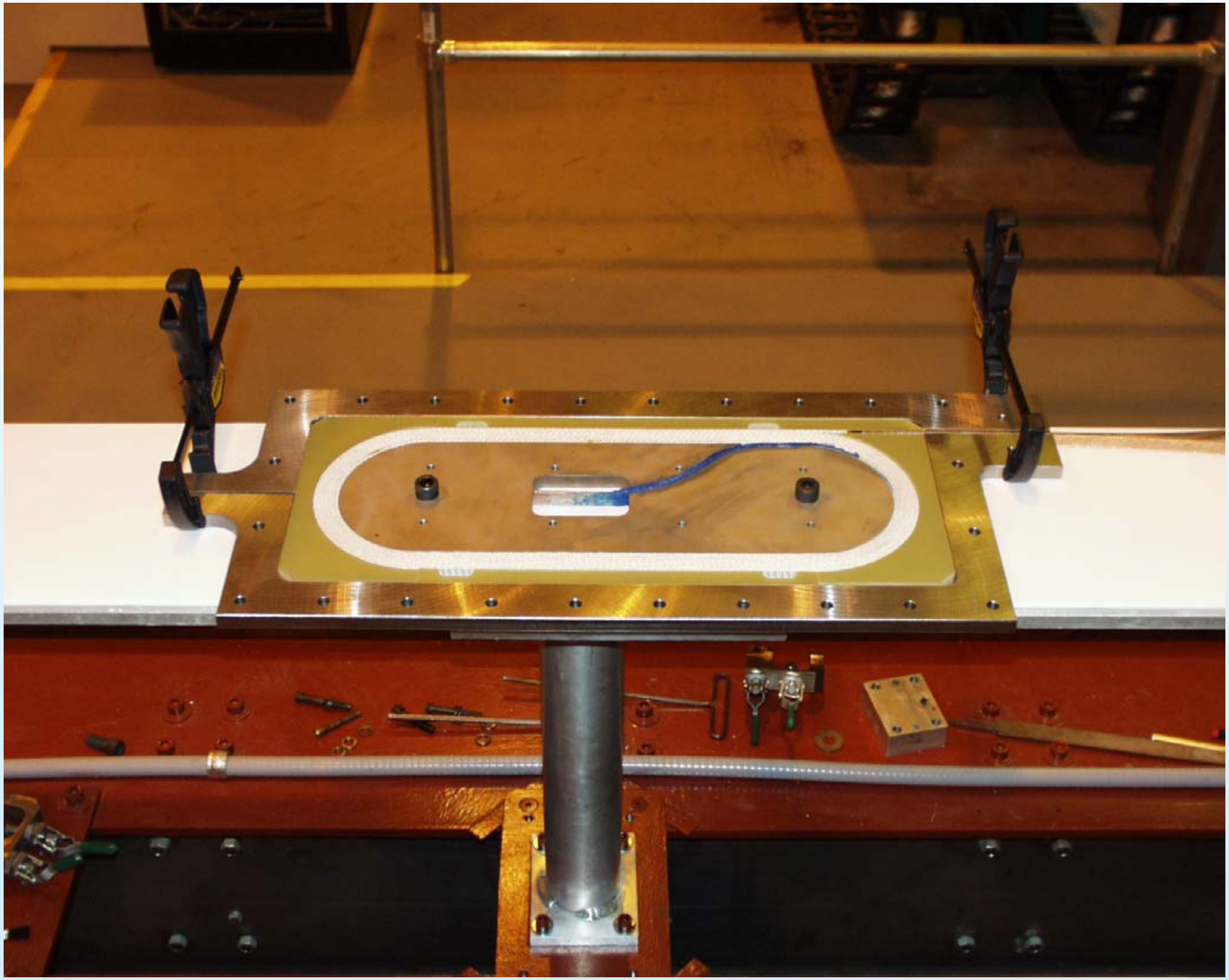
In the next generation package, bobbin will not be a part of the final product.

Nb_3Sn Cable Coming Out of Spool

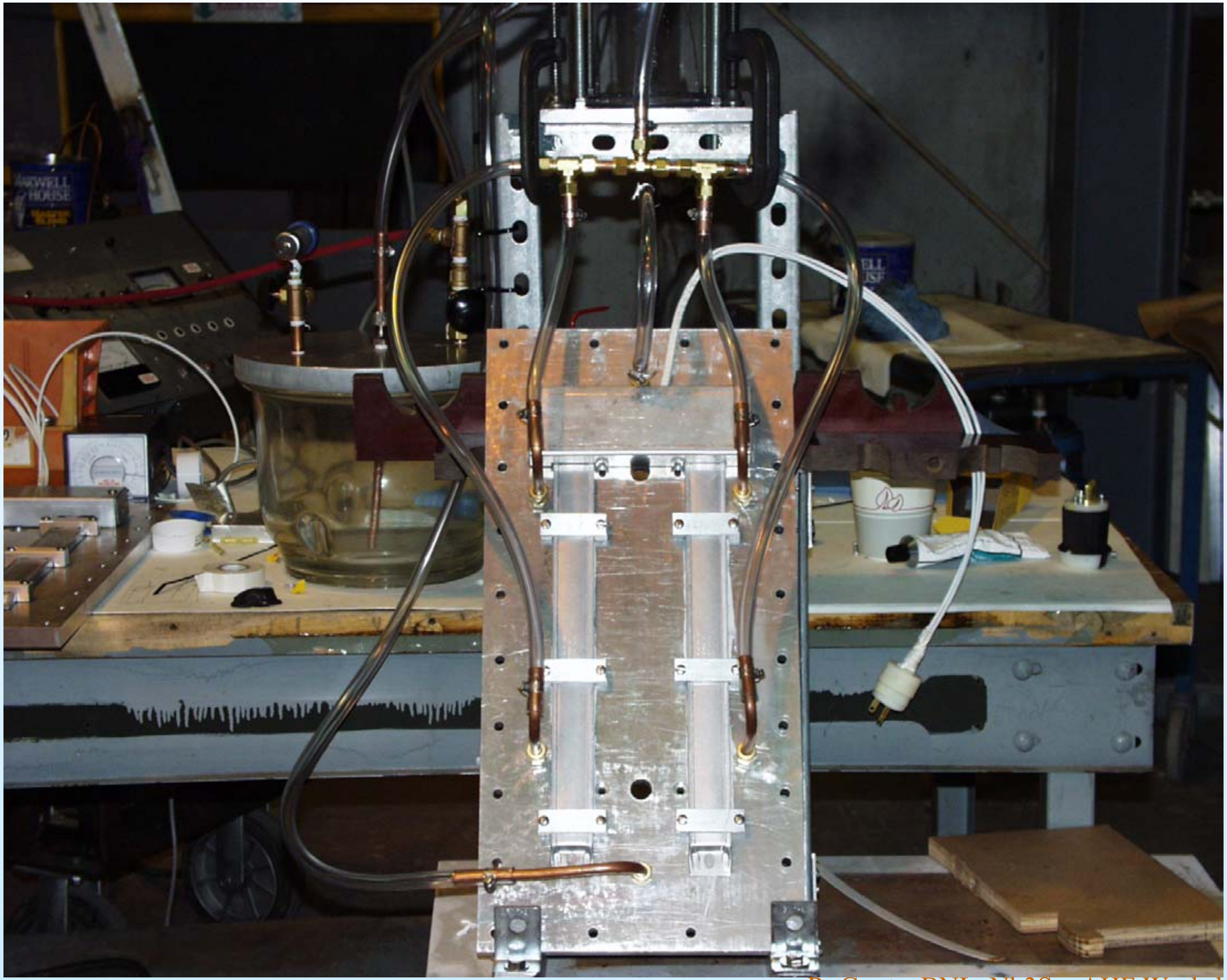
The coil is wound like a regular NbTi coil, of course with proper care (e.g., lower tension). This should help establish procedure, care (cost) required for Nb_3Sn magnets.

This scheme has been replaced due to reverse bend, etc.

10-turn Coil Being Prepared for Vacuum Impregnation

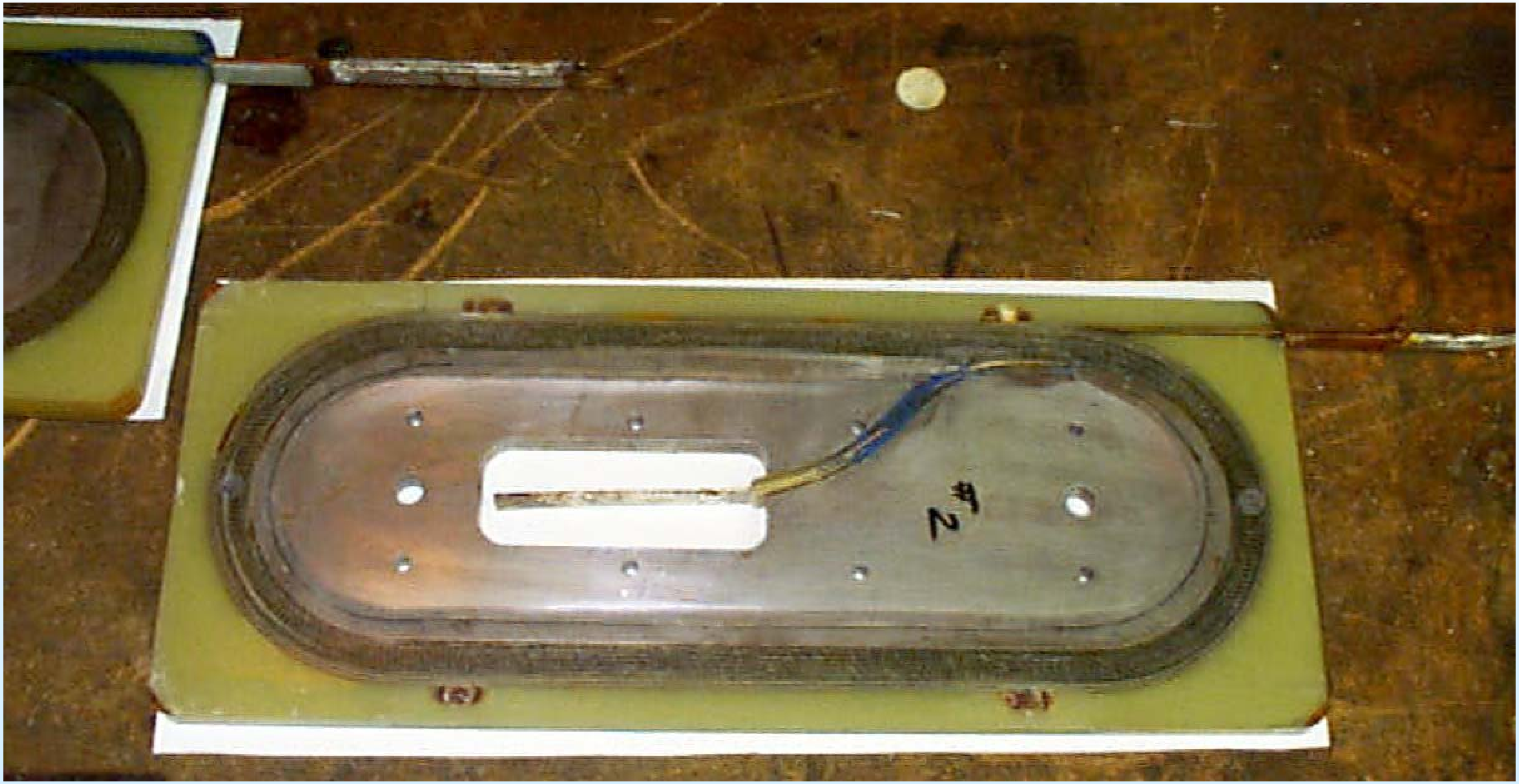


Vacuum Impregnation Setup



Several upgrades to this

Vacuum Impregnated Coils



Vacuum impregnated coils made after "react and wind" technique.

This picture was taken after the coils were tested and removed from the support structure.

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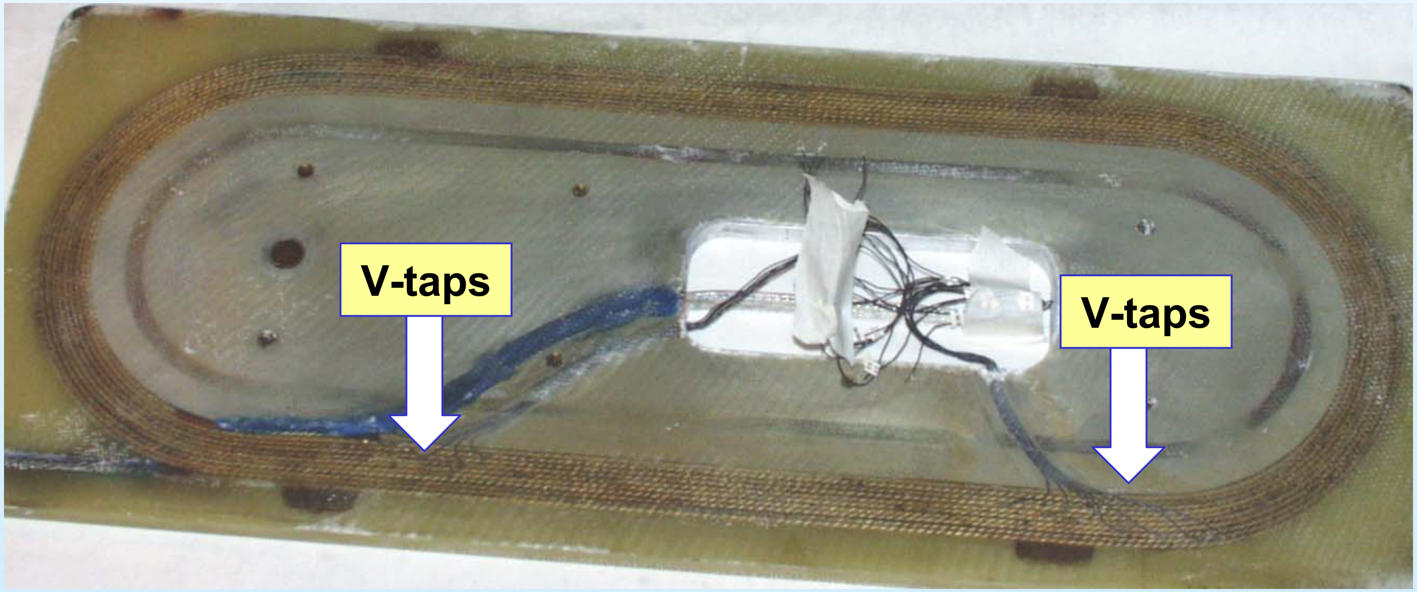
Voltage Taps, etc.

We put at least one voltage taps on each turn

Given the aggressive R&D nature of the program we instrument is as much as we can to locate the weak spot (remember we are pushing beyond the safe limit).

Technicians have done a superb job as they have put hundreds of voltage taps and lost only one so far (open) and we do not believe that they have damaged any coil.



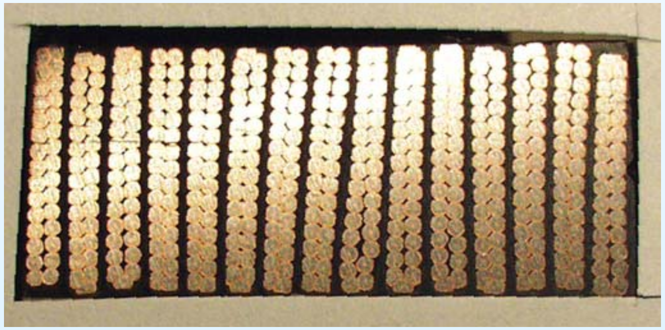
Recently, we have also started putting two quench heaters on each coil.

Insulation Test & Development

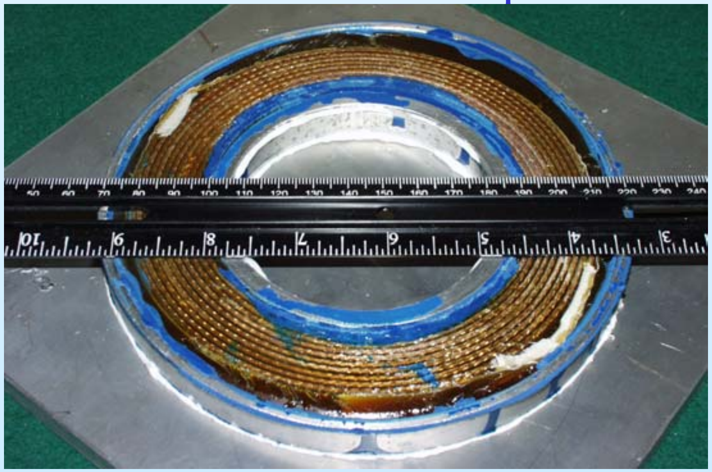
Insulation tapes as thin as 50 microns

Impregnated nomex insulation

10-turn fiberglass insulation test setup

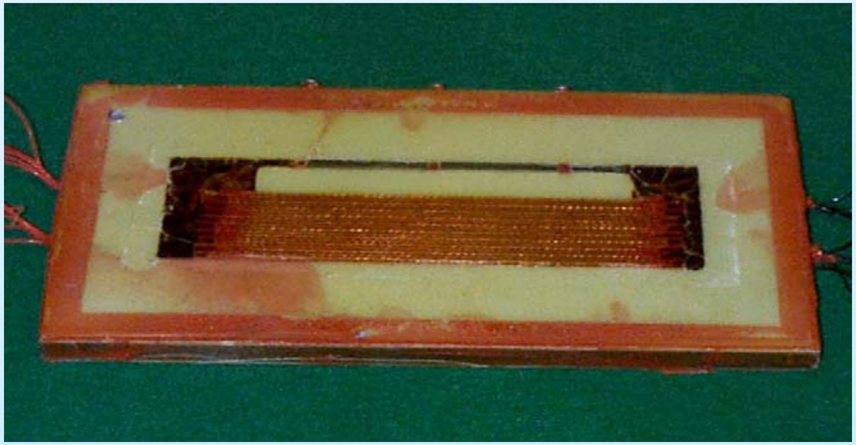


Insulation test setup



Braided insulation on reacted cable

Insulation Hi-pot test sample

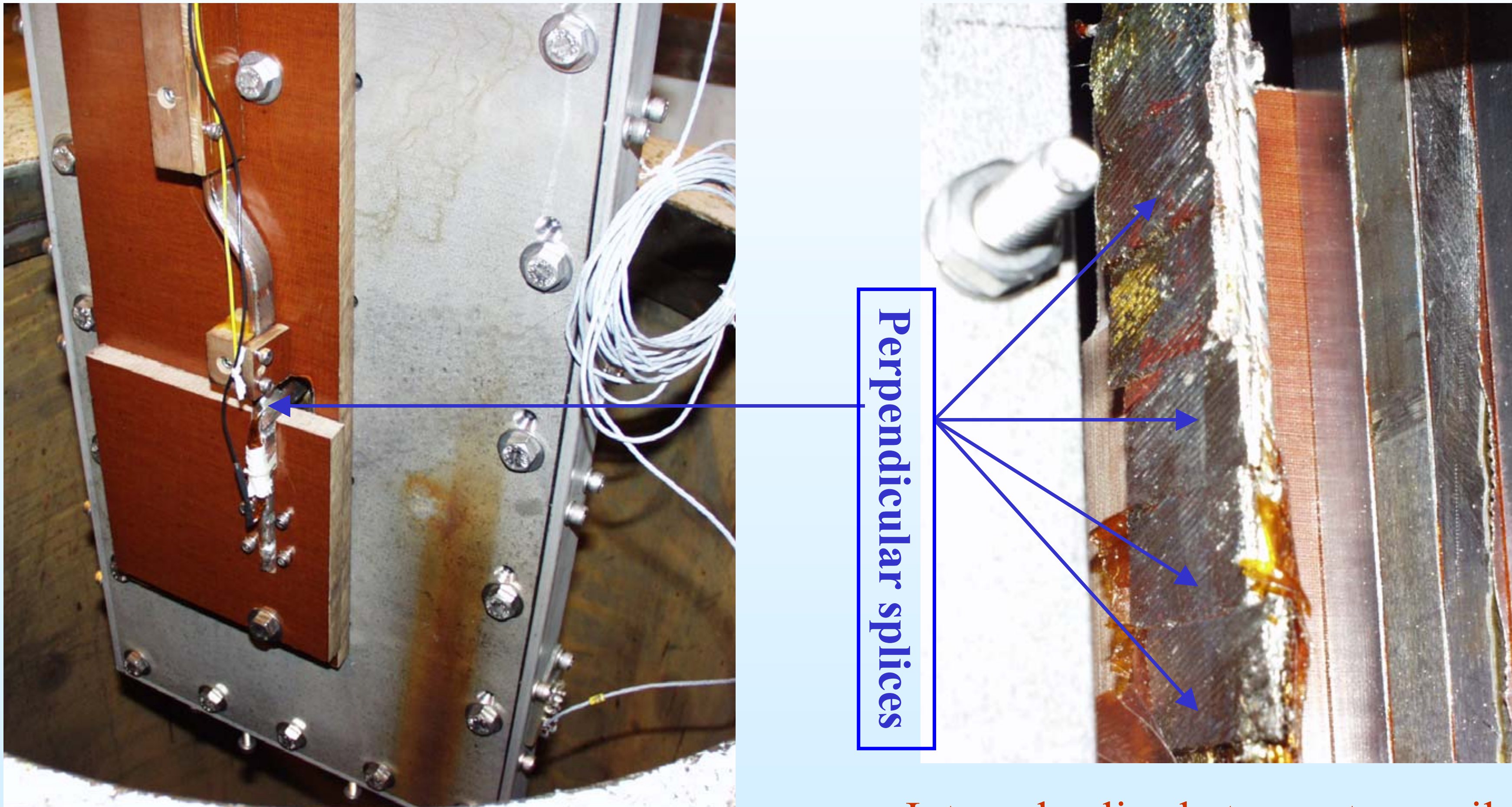


Coils in Support Structure

Two coils in a support structure

Internal Splice in Common Coil Design

(splices are perpendicular and are in low field region)



Splice for a single coil test (perpendicular splice take out the current to outside lead)

Internal splice between two coils in a common coil configuration (note several perpendicular splices)

Support Structures (three)

Early Support Structure (4 T)

Simple used in low current testing

New Versatile Support Structure (9T)

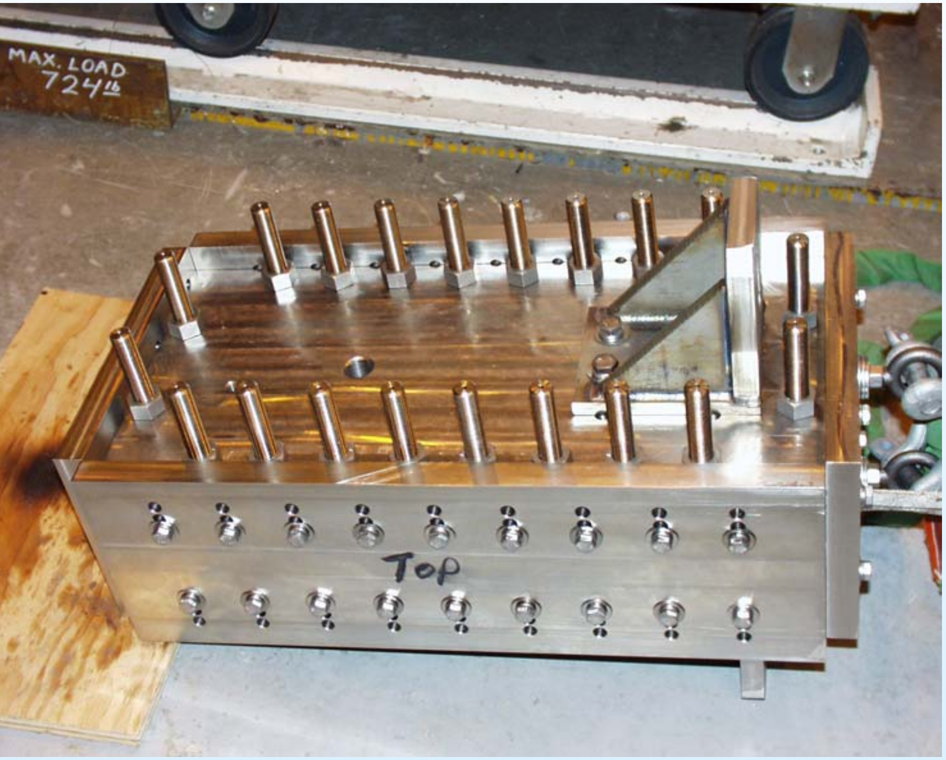
Can take one to six coils with multiple power supplies in various configurations

Allows HTS coil testing in background field

Future Support Structure (12 T)

Still in conceptual stage. Would be versatile and allow HTS coil testing in high background field

9 T Support Structure



Versatile: Can test from one to six coils with three different currents.

Good for testing HTS coils in background field.

Construction & Test Results

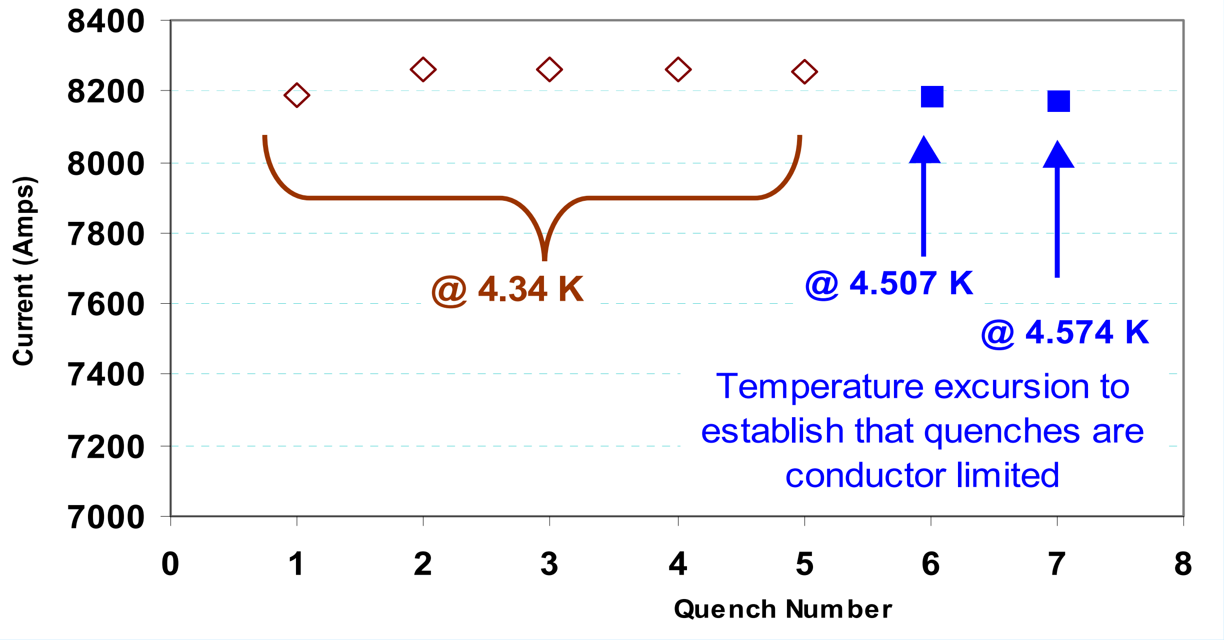
BNL has made nineteen 10-turn coils using "React & Wind" Technology with Nb3Sn & HTS cable. Nine tests have been carried out so far.

In two tests we had problem, the same problem.

Thank God it was a serious problem -– only 10-20% of short sample – as serious problems are generally easier to locate and fix. We blame it on the cable getting highly damaged from a wire mesh during reaction. FNAL points to similar excuse in one case.

Test results of other magnets were very gratifying.

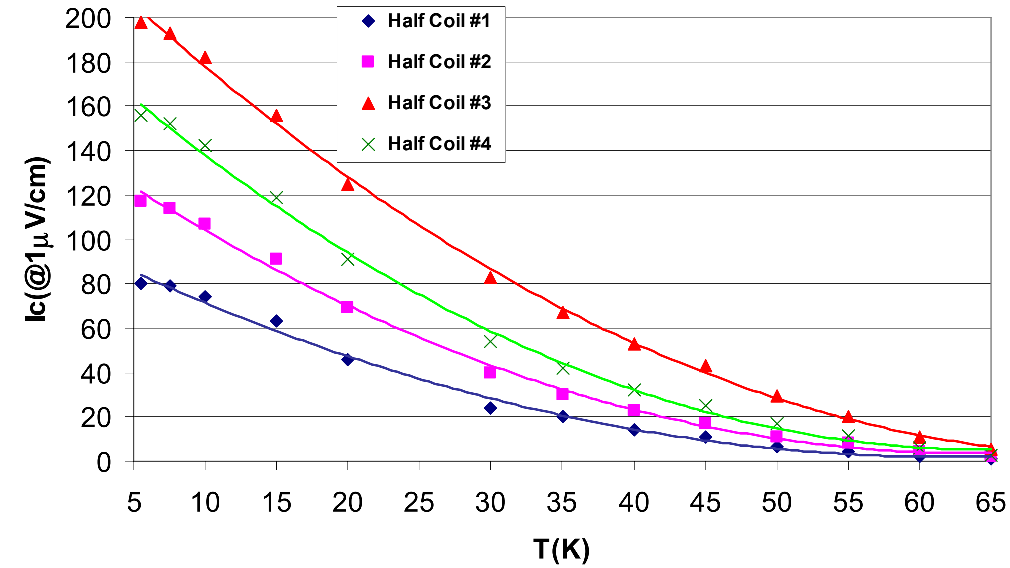
In the last test with ITER cable (one after shown or right), the magnet went to cable short sample on first quench itself.



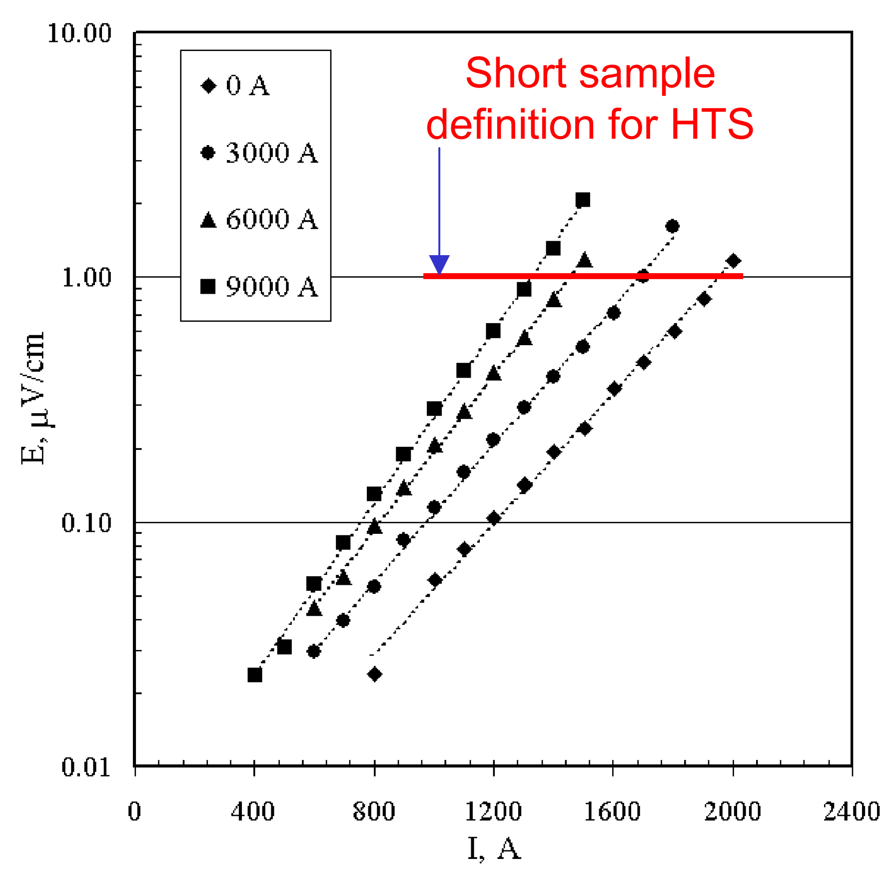
Lessons learned: Treat it with respect. But may be given time and effort we can make it work in full scale magnets.

HTS Test Results

BNL has been able to make test coils and test magnets (accelerator type) with HTS cable and HTS Tape. The test results have been quiet promising – no significant degradation observed.



Temperature dependence of critical current in HTS coils. (for current per 0.8 mm diameter wire, divide by 2).



HTS coil with various current in Nb_3Sn coils

12 Tesla Magnet Program

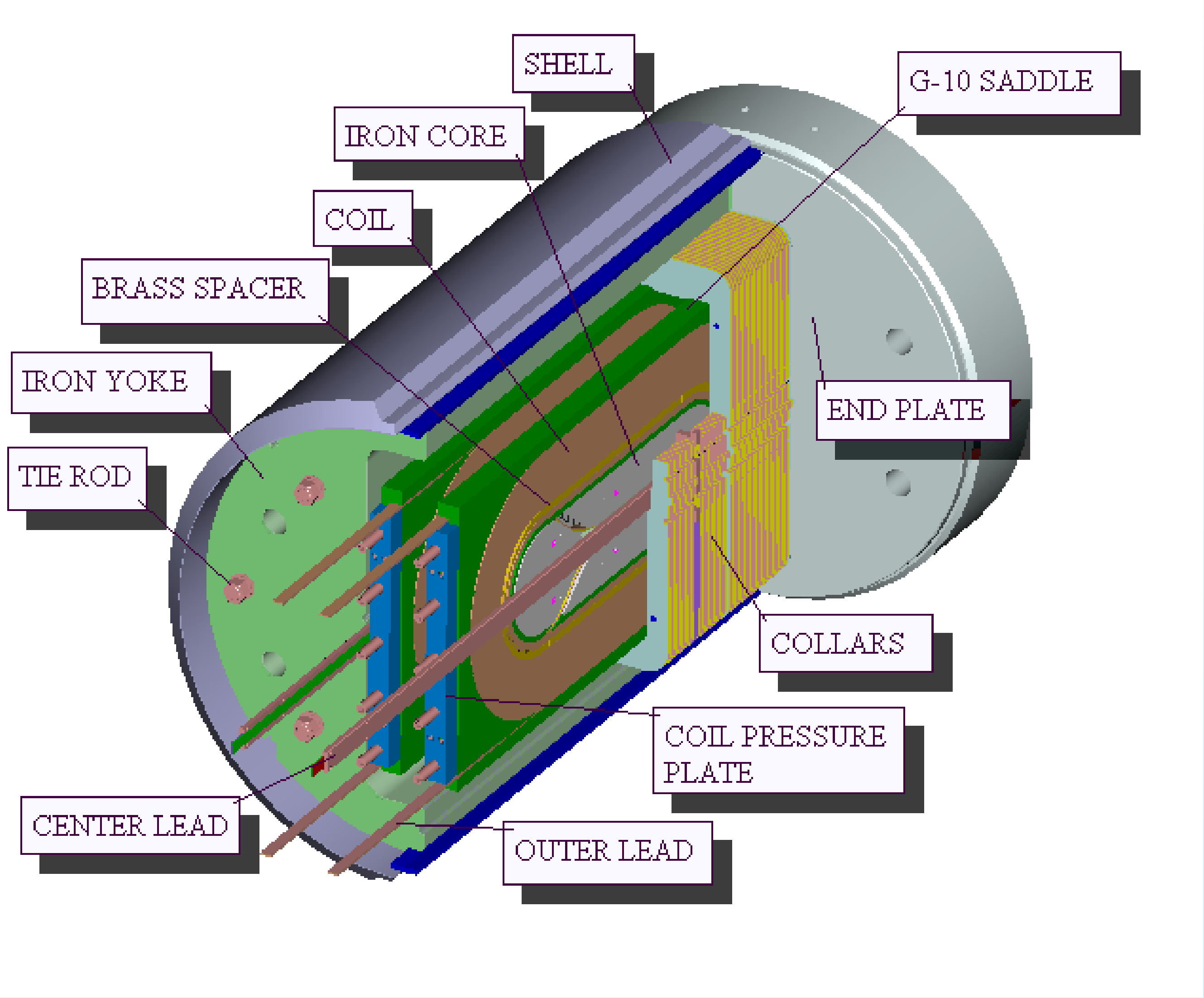
- *Design to develop technology for a "React and Wind" Nb_3Sn High Performance Prototype Magnet for future accelerators*
- *12 Tesla background field will also allowing testing short sample and insert coils*
- *Associated Coil Production tooling designed to handle delicate conductors*
- *Continue to pre-check validity of the design and associated technology with the 10-Turn Nb_3Sn coil program running in parallel*

Design Features

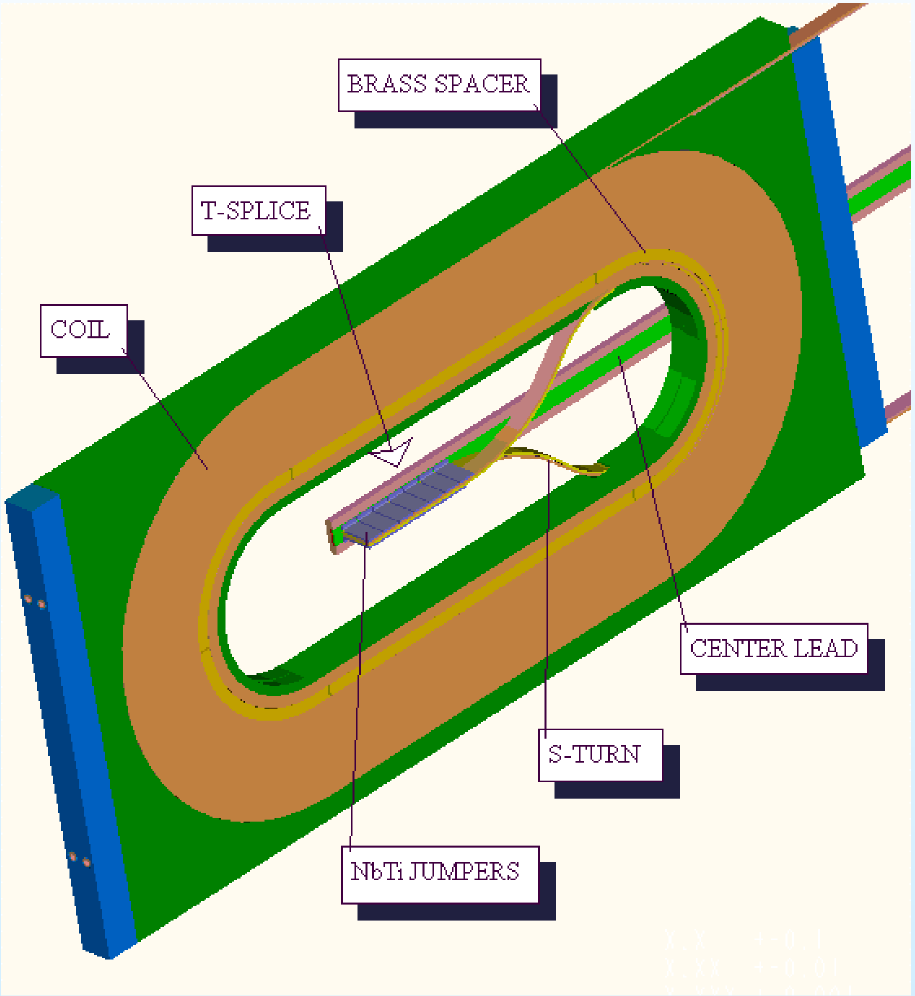
Four 45-Turn epoxy vacuum impregnated high-performance Nb_3Sn coils made using "React and Wind" methods

- .002 in. thick fiberglass cable insulation - half overlap wrapping scheme
- Kawasaki High Manganese stainless steel collars with tapered keys
- 16 ga. ultra low carbon steel yoke laminations and coil core laminations
- 1 in. thick stainless steel outer shell. 5 in. thick stainless steel end plates
- Rectangular 44mm wide coil aperture
- Containment structure designed to support high Lorentz forces

Cut-away View of the 12 T Magnet



Coil with T-Splice



T-Splice allows relative adjustment in current between two coils

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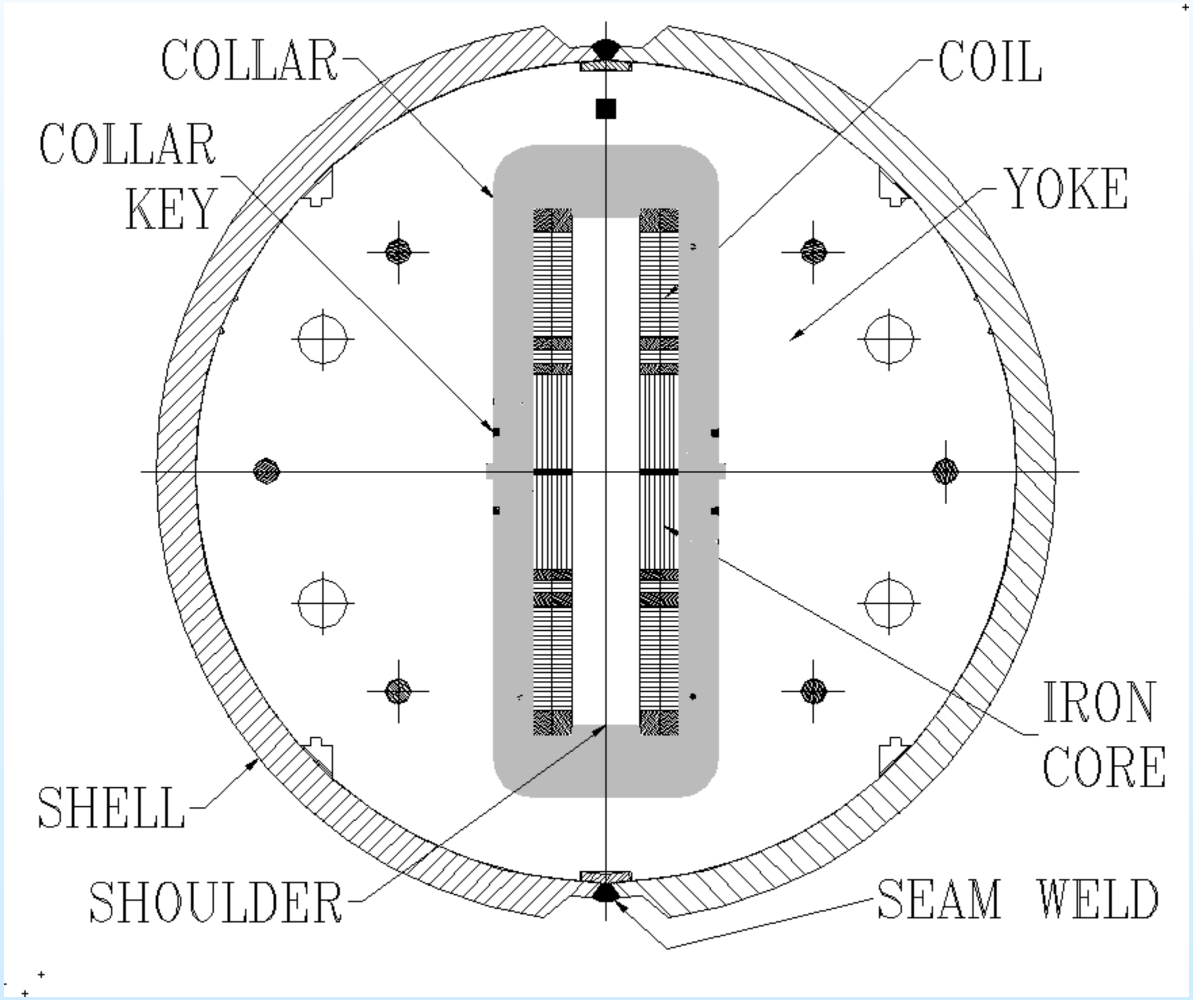
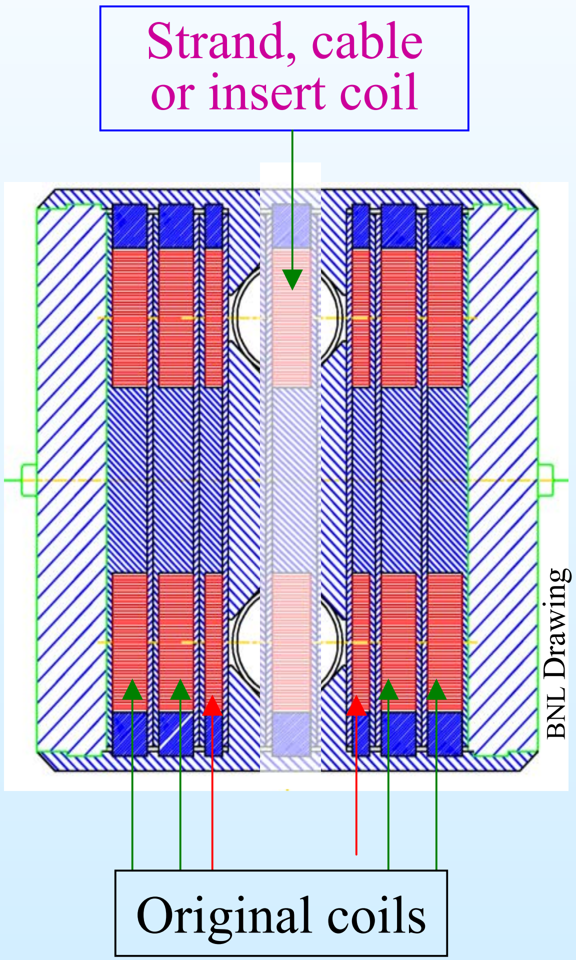
Magnet Division

Cross-section of the 12 T Design

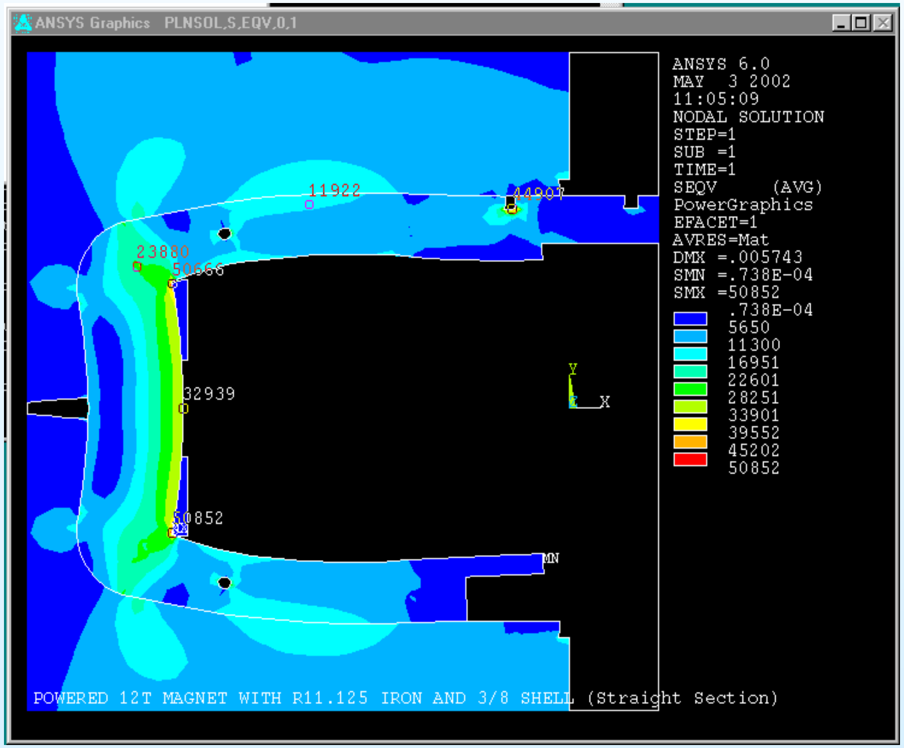


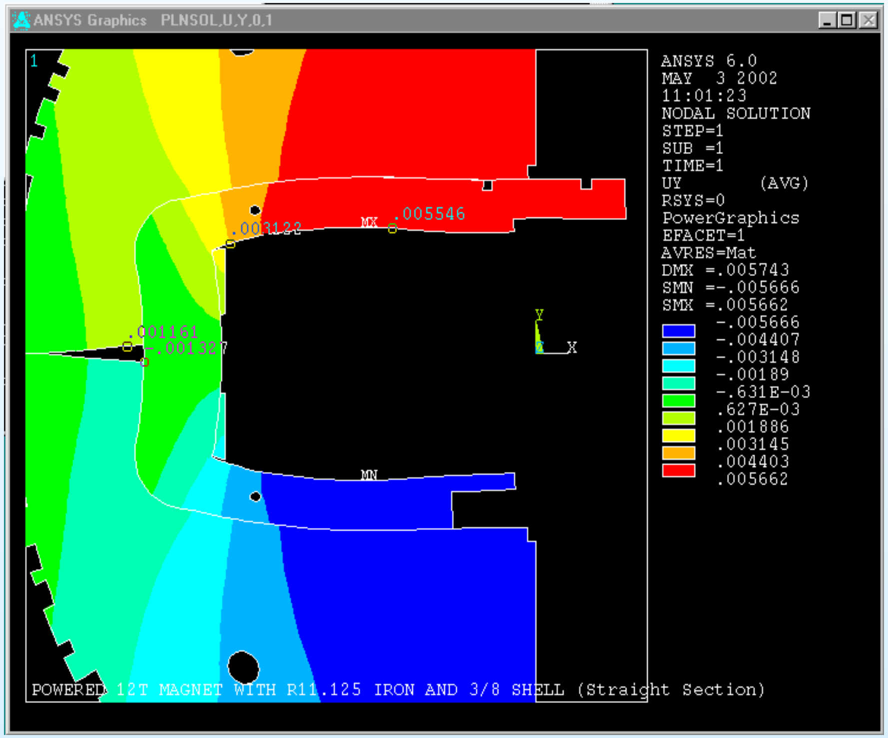
Common Coil Magnet As A Test Facility



- **A Modular Design with a significant flexibility.**
- **Coil geometry is vertical and flat. That means a new coil module having even a different cable width can be accommodated by changing only few parts in the internal support structure.**
- **The central field can be increased by reducing the separation between the coils.**
- **The geometry is suitable for testing strands, cables, mini-coils and insert coils.**
- **Since the insert coil module has a relatively small price tag, this approach allows both *"systematic"* and *"high risk"* R&D in a time and cost-effective way. This might change the way we do magnet R&D.**
- **Can use the successful results in the next magnet.**

Finite Element Analysis of Collars





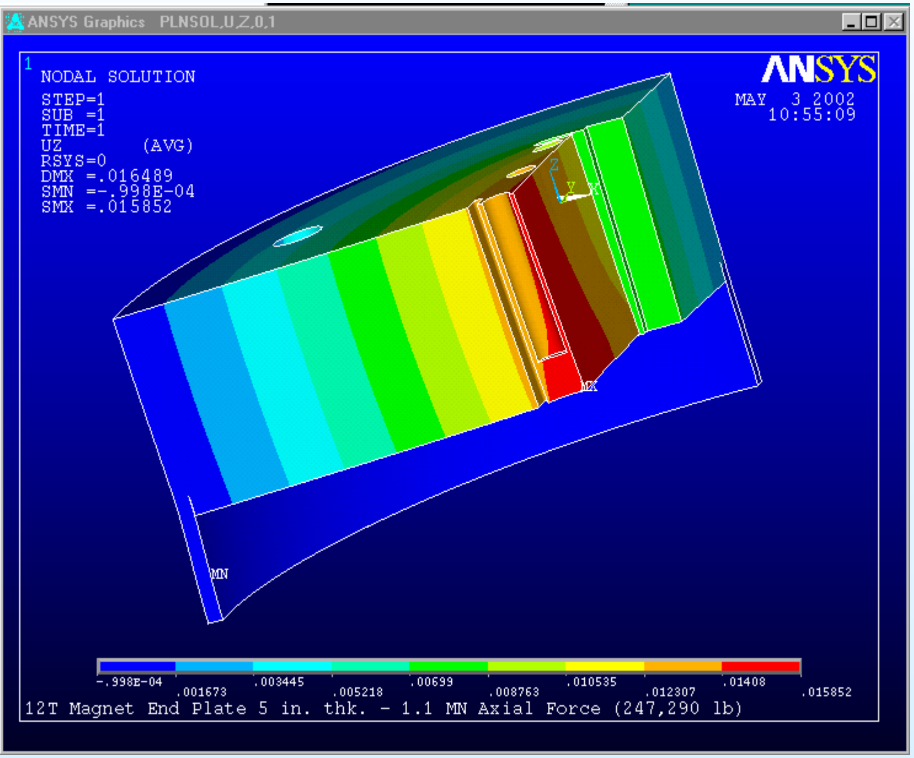
FEM - Collar Stress (psi)

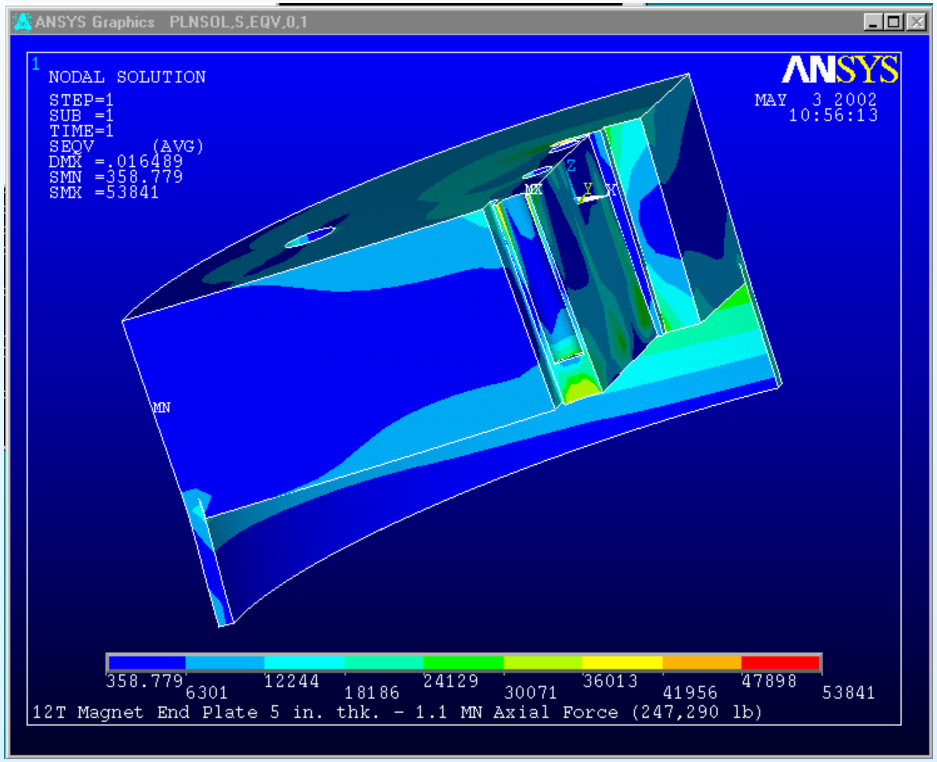
FEM - Collar Deflection (in)

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

FEM Analysis of End Plates





FEM - End Plate Stress (psi)

FEM - End Plate Deflection (in)

12 T Common Coil Tooling

New insulating line for both Nb_3Sn and HTS conductors

•Control cable tension by connecting the pay-out and take-up spools to a load cell.

•Avoids problems associated with monitoring the cable directly.

•Cable position actively actively corrected by photocells that activate motors to jog the spool position laterally

•Provides control while minimizing flexing and direct handling of the cable

The **new winding machine** will tension cable without applying unnecessary flexure

•The coil will shuttle back and forth while the spool translates laterally from an axially fixed gantry

•Spool motion is coordinated so that no conductor re-spooling is required

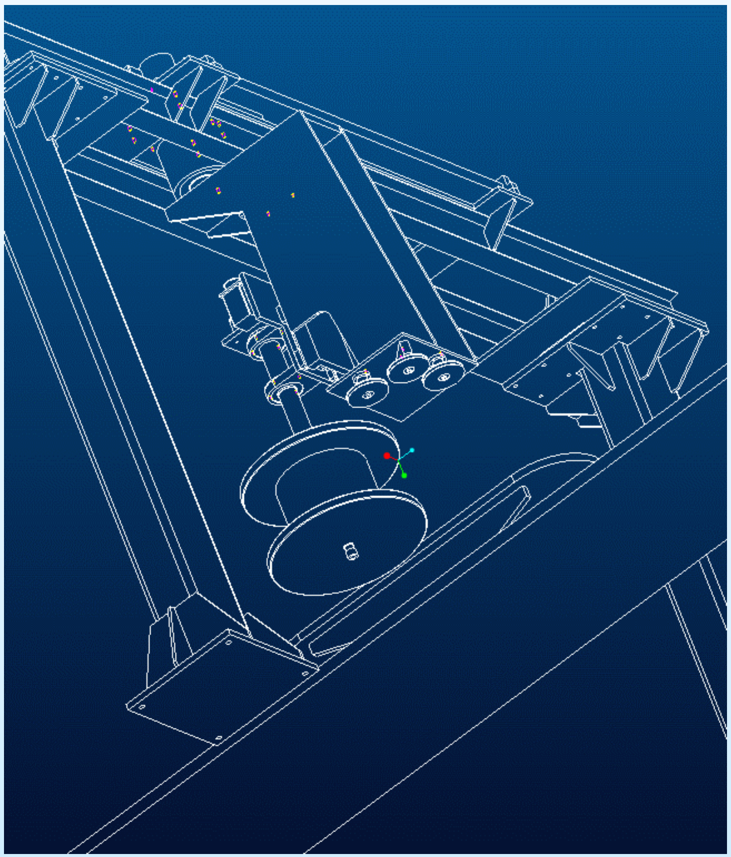
The **new curing station** will reduce coil handling risks.

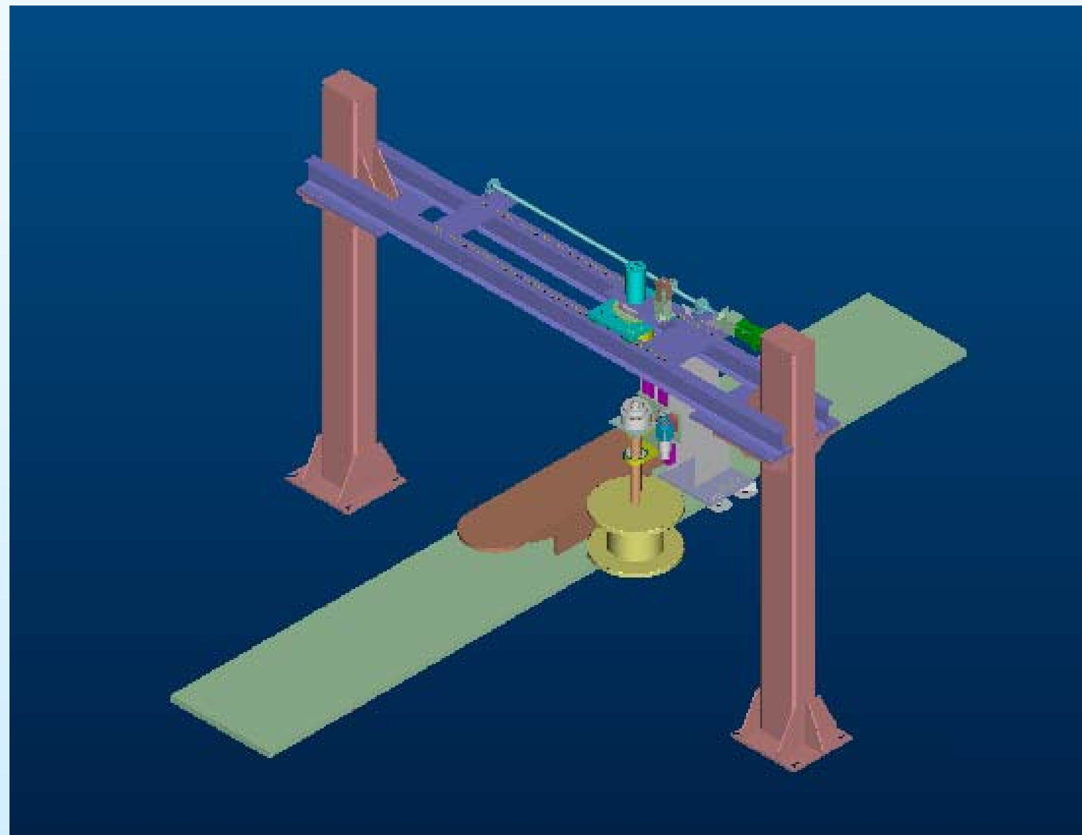
•Will accommodate the Kevlar string clamping scheme and will permit safe removal of clamps once the coil is in the potting fixture.

• It will employ a vacuum bag within a fixed cavity and will have versatility for molding coils of various configurations.

New Versatile Coil Winder Now Under Construction

We are developing and constructing several new toolings to built 12 T magnet with pre-reacted brittle Nb3Sn. This is one example.





CONCLUSION

We have a very exciting, versatile and intellectually stimulating high field magnet R&D program.

Come on, join us.

And yeah, bring in some money. Will you?