R&D for High Field Magnet Technology

Ramesh Gupta
Superconducting Magnet Division
Brookhaven National Laboratory

US Particle Accelerator School
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Present Magnet Design and Technology

Tevatron Dipole

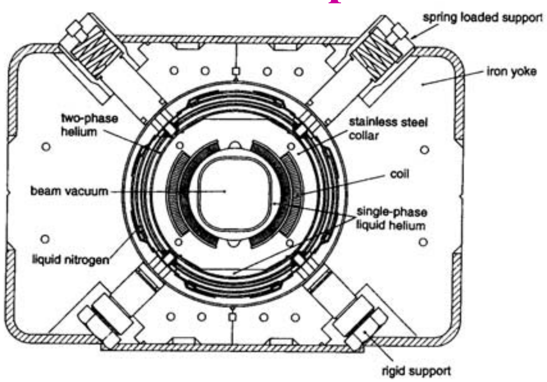
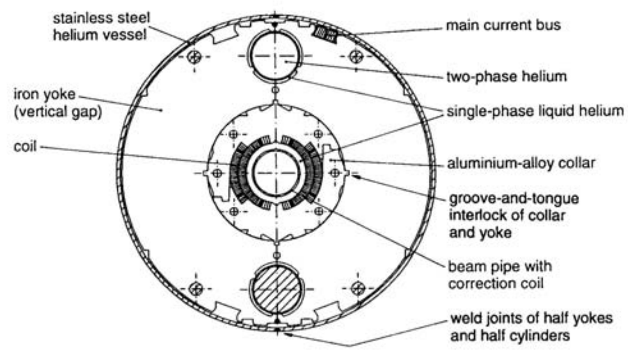
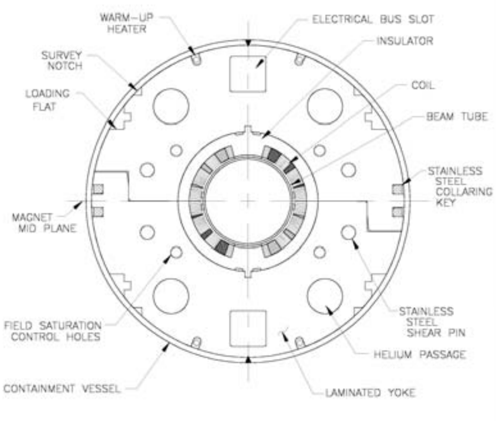


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

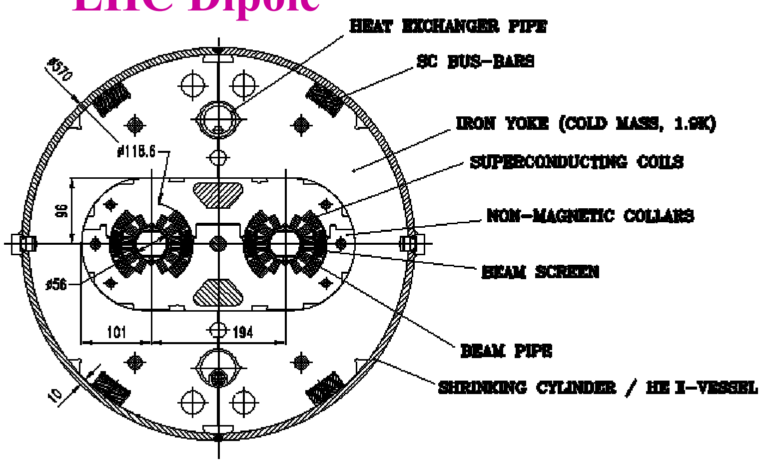
HERA Dipole



RHIC Dipole



LHC Dipole



1.8 K operation

- All magnets use Nb-Ti Superconductor
- All designs use cosine theta coil geometry
- The technology has been in use for decades.
- The technology has reached the limit and can't produce 10^{+} T field magnet.

Scope of This Presentation

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

However, high field magnet technology is a vast and complicated subject. Here are some essential topics that will not be covered in this presentation:

•Mechanical Analysis: Support structure and internal stress analysis is very important in the high field magnet design

•Tooling & construction: An important aspect of the high field magnet engineering

•Quench protection of the cryogenic design

Challenges with High Field Magnet Technology

- High field superconductors and high field magnets present several new challenges, in addition to those that are present with any superconducting magnets, which makes the high field magnet technology very demanding.
- The present high field technology is in R&D stage must use brittle superconductors that are stress/strain sensitive. The conductor performance degrades significantly if it subjected to certain stress/strain value.
- This basic fact guides the high field technology, both in design and in manufacturing.
- The coils are vacuum impregnated, and the magnet is designed and constructed in such a way that the conductor are not subjected to excessive stress/strain under large Lorentz forces (or during high temperature reaction and cool down).

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 magnets for accelerator application.
- It is produced in quantities that even today one can make R&D and specialty magnets. We hope that the Nb_3Sn production can be scaled-up in future 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 cases in a decade or so. 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 not available in quantities to make R&D coils.

Two Technologies for Brittle High Field Superconductors

The material become 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.

Wind & React Vs React & Wind Approach (1)

React & Wind approach eliminates the need to deal with the differential thermal expansions between various materials of coil modules during high temperature reaction process. The issues become more critical as magnets get longer.

- Wind & React technology will require a number of long furnaces; React & Wind does not.
- In Wind & React approach, the integrated build-up of differential thermal expansion and 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.

Wind & React Vs React & Wind Approach (2)

- 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.

- React & Wind approach appears 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 in 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 in developing conductor designs, 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.

Conductor R&D for React & Wind Approach

• Bend strain issue is much more critical for React & Wind designs. Nb_3Sn superconductor made with different manufacturing technologies may have quiet different bend strain properties.

Study differences between Modified Jelly Role, Internal Tin, Powder in Tube.

R&D for increasing bend strain tolerance in each (new design?).

• Reaction process is important. Sintering between wires within the cable must be avoided.

Need more R&D on the treatment of cable before high temperature reaction and on the design of reaction spool, etc.

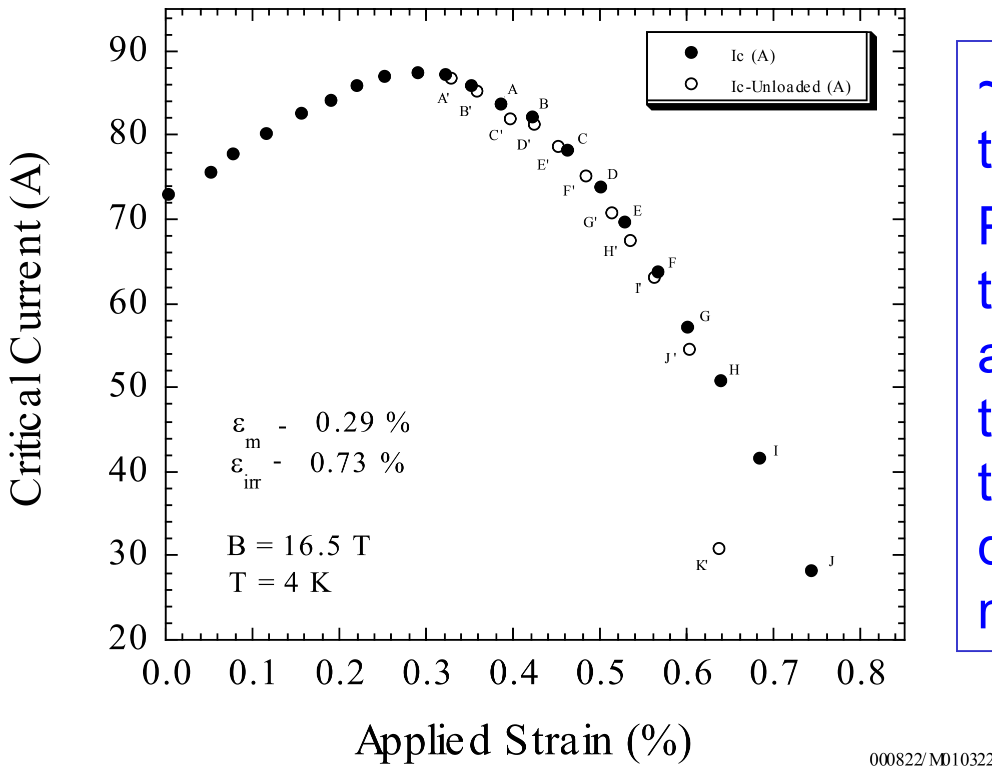
• Are there alternatives to Rutherford cable that may be more suitable for carrying high currents?

Axial Strain Studies

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

It is generally thought that axial strain produces similar internal deformation as bending strain (however, some debate).

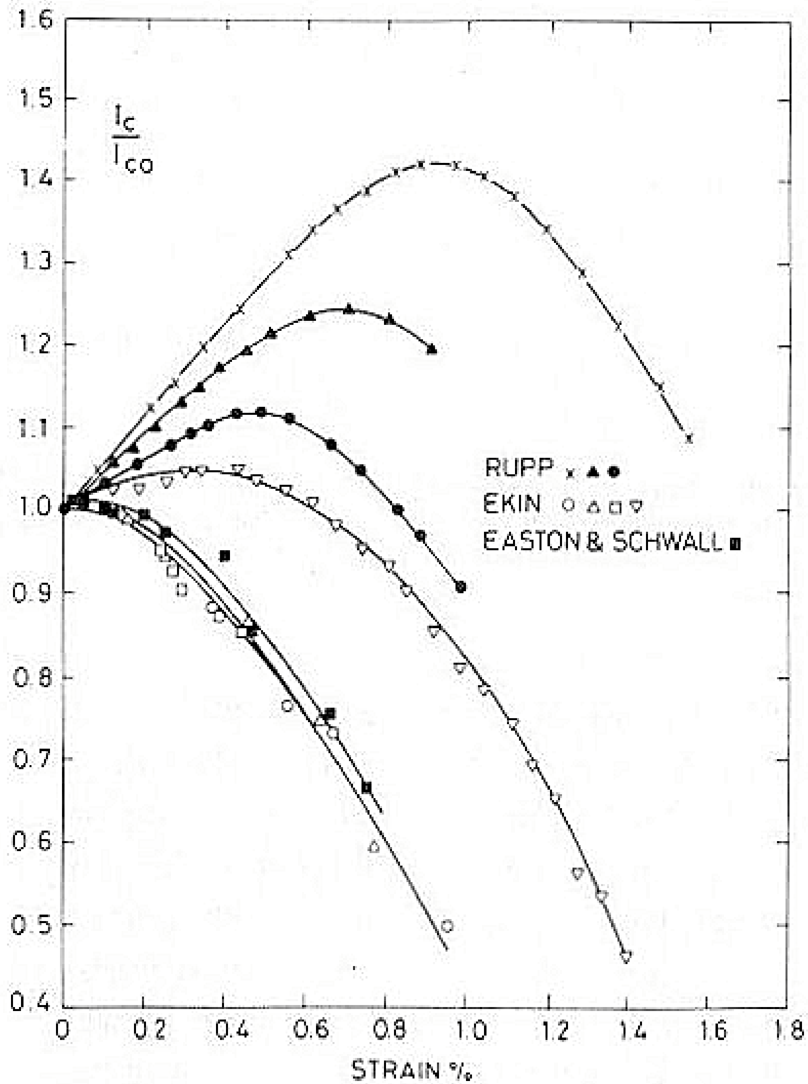
J. Ekin, N. Cheggor, et al, NIST.

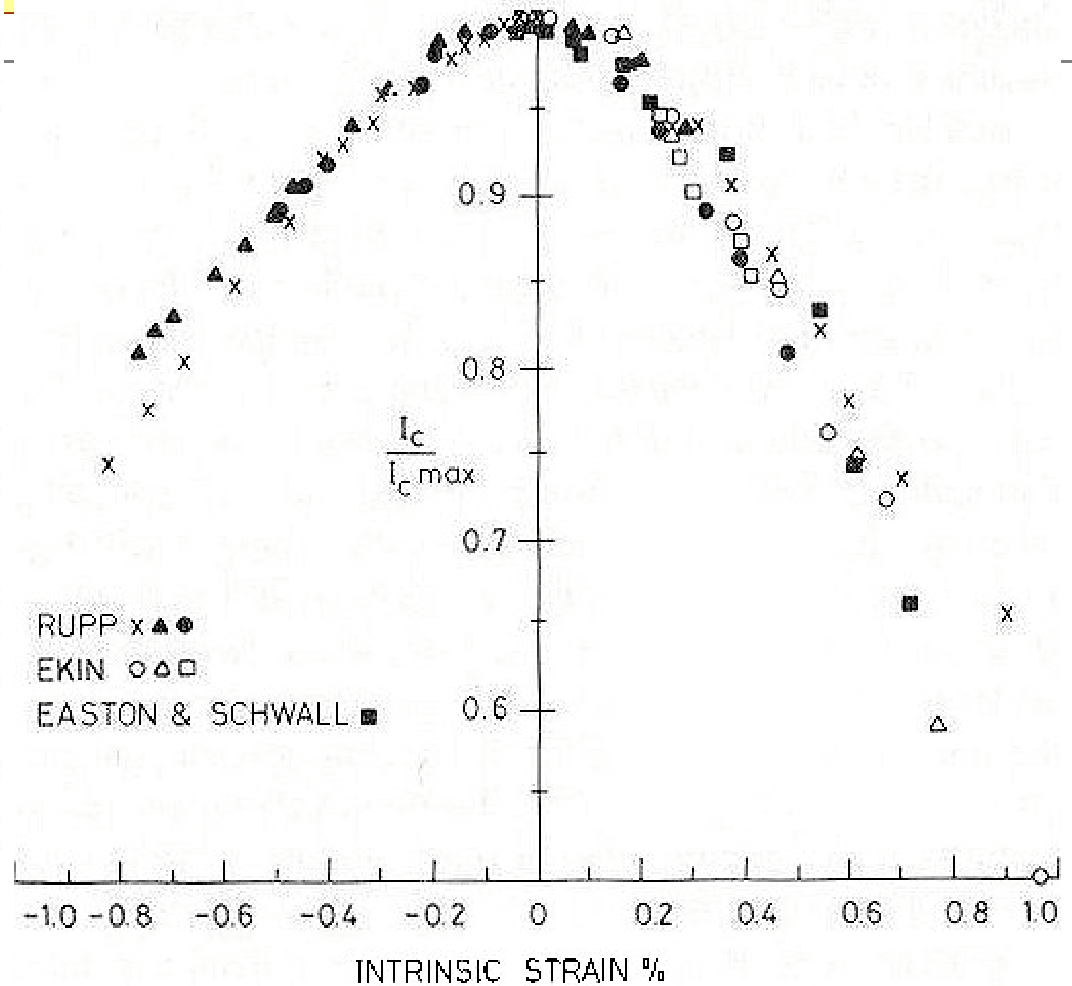


~0.3 % axial strain seems to be acceptable.

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).

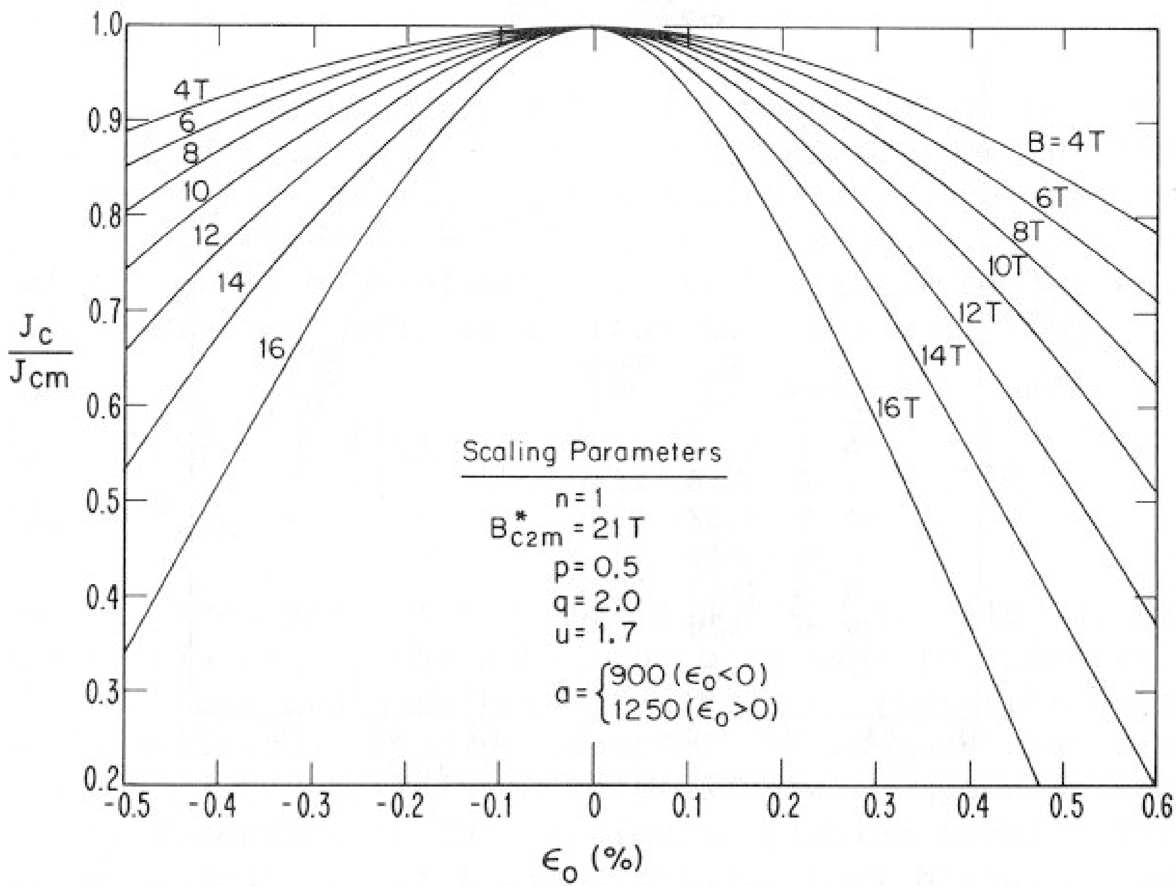
Strain Dependence





Source: M.N. Wilson, Superconducting Magnets

Strain and Field



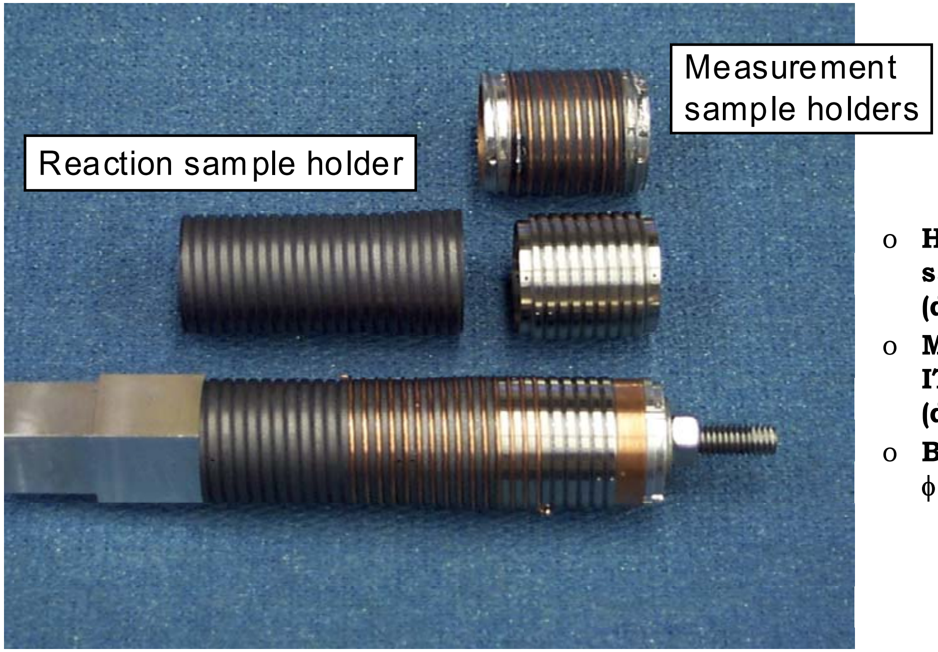
Relative critical-current density J_c/J_{cm} as a function of intrinsic strain $\varepsilon_o (\equiv \varepsilon - \varepsilon_m)$ for different magnetic fields, evaluated using Eq. (3) and the typical set of scaling parameters indicated in the figure.

Source: J.W. Ekin, in "Filamentary A-15 Superconductors", edited by Suenaga and Clark

Bend Strain Studies at Fermilab

Fermilab has made a number of studies on bend strain tolerance on wire and some on cable. Most of them have been reported earlier.

Bending degradation of wires



- **HT on reaction sample holder (diam = $\phi 1$)**
- **Measurement on ITER sample holder (diam = $\phi 2$)**
- **Bending is given by $\phi 1 < \phi 2$**

10/28/02 G. Ambrosio - Conductor R&D at Fermilab for Nb3Sn React-and-Wind 6

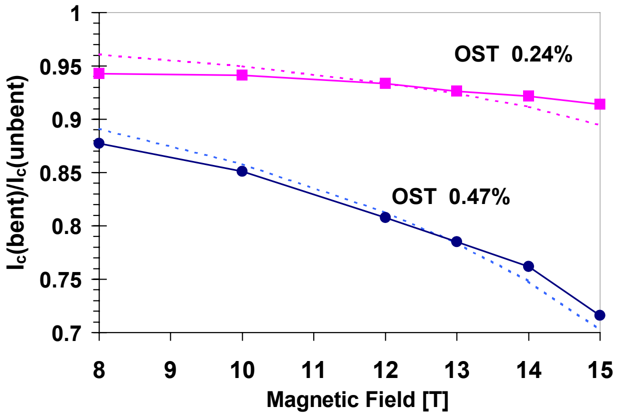
Results from Fermilab

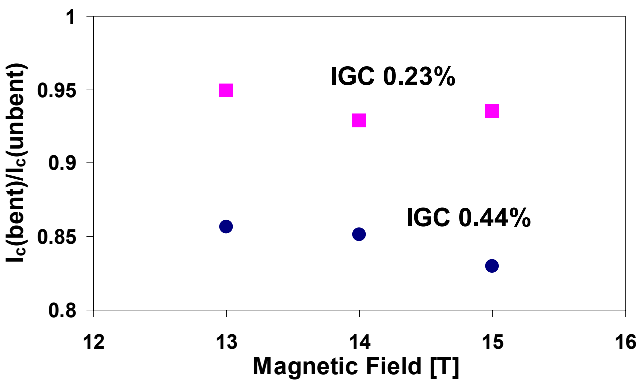
Larger bending degradation in high J_c wires as compared to low J_c wires

•Degradation depends on the wire manufacturing process

Bending degradation of High-Jc wires

Courtesy:
E. Barzi





- diameter: 0.7 mm
- Jc = 1904 A/mm2 @ 4.2K 12T
- Copper: 47 %
- twist pitch: 13 mm
- subelements: 54
- "thick" Nb barrier

- diameter: 0.7 mm
- Jc = 1676 A/mm2 @ 4.2K 12T
- Copper: 38 %
- twist pitch: 13 mm

The critical current degradation due to bending of 0.7 mm wires is 5-7 % @ 12T, 0.24% ε_{max} for IGC (IT) and OST (MJR)

Courtesy of E. Barzi

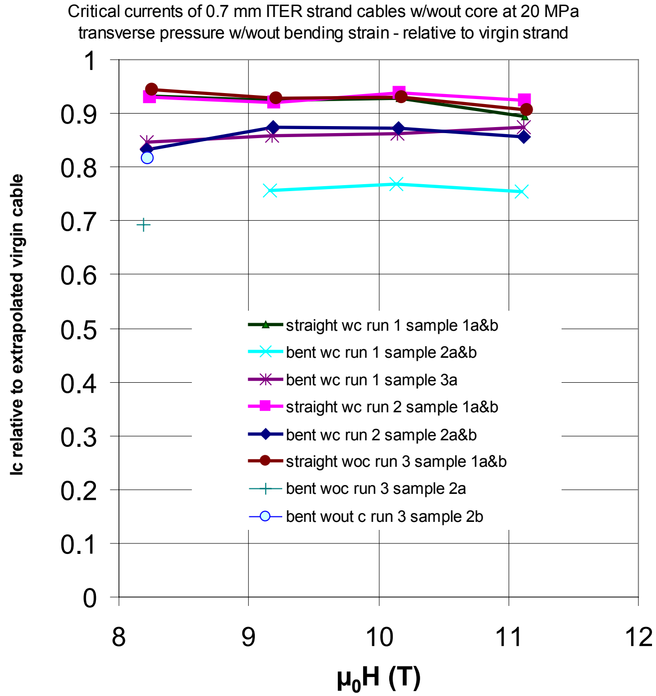
Results from Fermilab on Cable

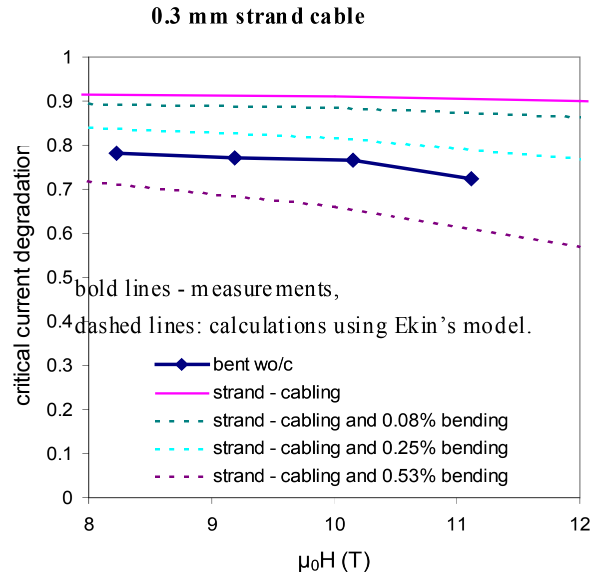
Useful studies; we need more such studies for various bending parameters for various cables/wire/heat treatment, etc.

Bending degradation of cables - results - †

Courtesy:

P. Bauer





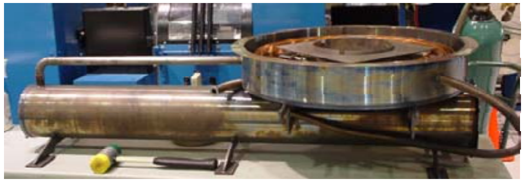
Courtesy of P. Bauer

†P. Bauer et al. *"Fabrication and Testing of Rutherford-type Cables for React and Wind Accelerator Magnets"* IEEE Trans. On Applied Superconductivity, vol. 11, no.1, 2457, March 2001.

Reaction Spool and Tooling at Fermilab

Assembly procedure - 1

- **Synthetic oil is used in order to prevent sintering between the two layers of wires in the cable,**
  - **Some synthetic oil is used during cabling,**
  - **More synthetic oil is added before heat treatment**
- **Cable is reacted inside a retort**
  - **Single layer spool,**
  - **A gap is left between the core of the spool and the first turn**



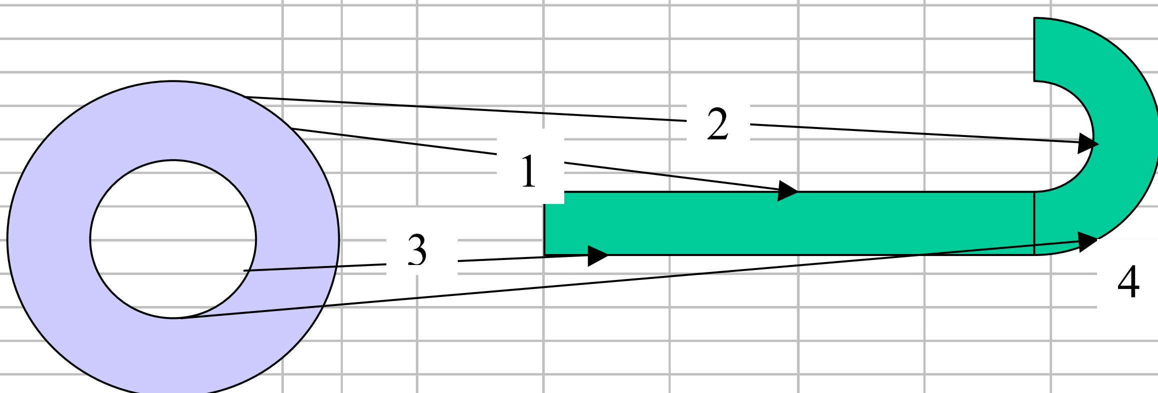
Strain in the Racetrack coil

Strain in the OST cable used in the 2nd Racetrack

			innermost coil turn		outermost coil turn	
Wire			***OST***	***OST***	***OST***	***OST***
strand diameter	*d*	mm	**0.7**	**0.7**	**0.7**	**0.7**
outer filam. diam / strand diam.			0.88	0.88	0.88	0.88
outer filament diameter	ϕ	mm	*0.616*	*0.616*	*0.616*	*0.616*
starting radius (in the spool)		mm	**253.5**	**253.5**	**180**	**180**
final radius (in the magnet)			**infinite**	**90**	**infinite**	**132.3**
Max strain (strand diameter)	$\varepsilon1$	%	0.121	**0.221**	**0.171**	0.062
Max strain (sintered strands)	$\varepsilon2$	%	0.260	**0.472**	**0.366**	0.132
Position			**1**	**2**	**3**	**4**

$$\varepsilon_1 = \frac{\phi}{2}\left(\frac{1}{R_2} - \frac{1}{R_1}\right)$$

$$\varepsilon_2 = \frac{\phi + d}{2}\left(\frac{1}{R_2} - \frac{1}{R_1}\right)$$

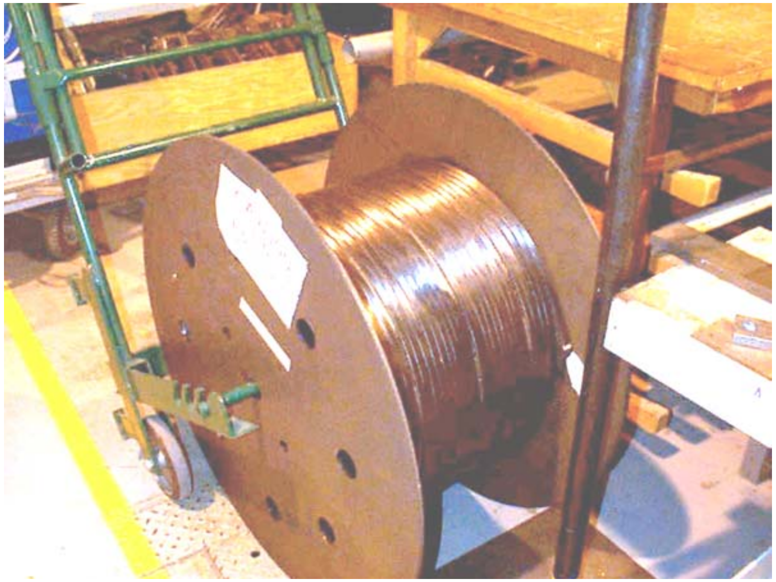


Reaction Process at BNL

- BNL has four reaction spools. The bending radii of small spool (on left) happens to be twice the minimum bend radius of our common coil design.
- Below (right) is a oil impregnation setup to vacuum impregnate the cable before reaction to minimize the chances of sintering.

Nb_3Sn Reaction Facility at BNL

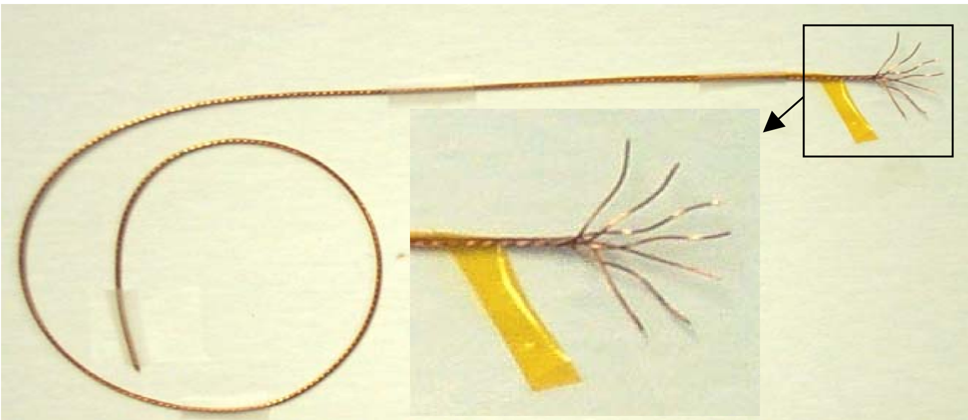
Large (1.5 m^3) reaction furnace at BNL.
It was used for making full length Nb_3Sn magnets.



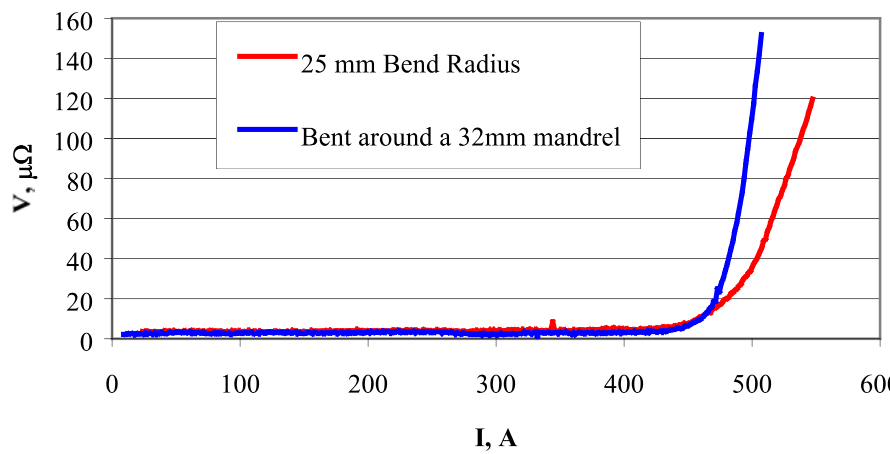
Nb_3Sn cable after reaction.

6-around-1 Flexible Nb_3Sn Cable

The cable used for the coil was made of 0.33 mm diameter wires wound into a 6-around-1 cable of 0.99 mm diameter.



Nb3Sn 6x1 cable
NSC-013-RD5



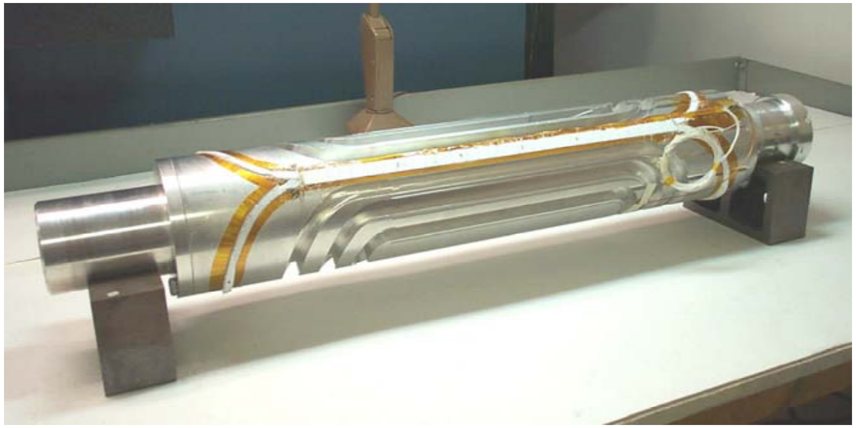
N-value @ 8T ~ 30

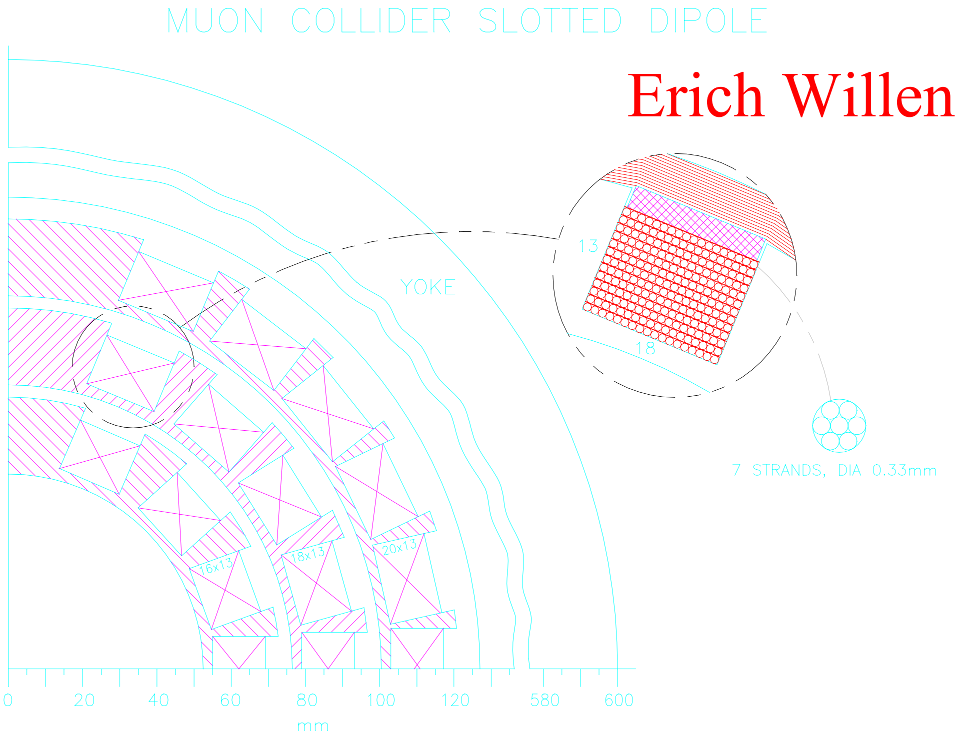
When bent around a 32mm diameter mandrel Jc does not change but the n-value drops to ~ 25

Willen & Ghosh, BNL

Magnets with Flexible Wire

Recently flexible pre-reacted Nb_3Sn 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)

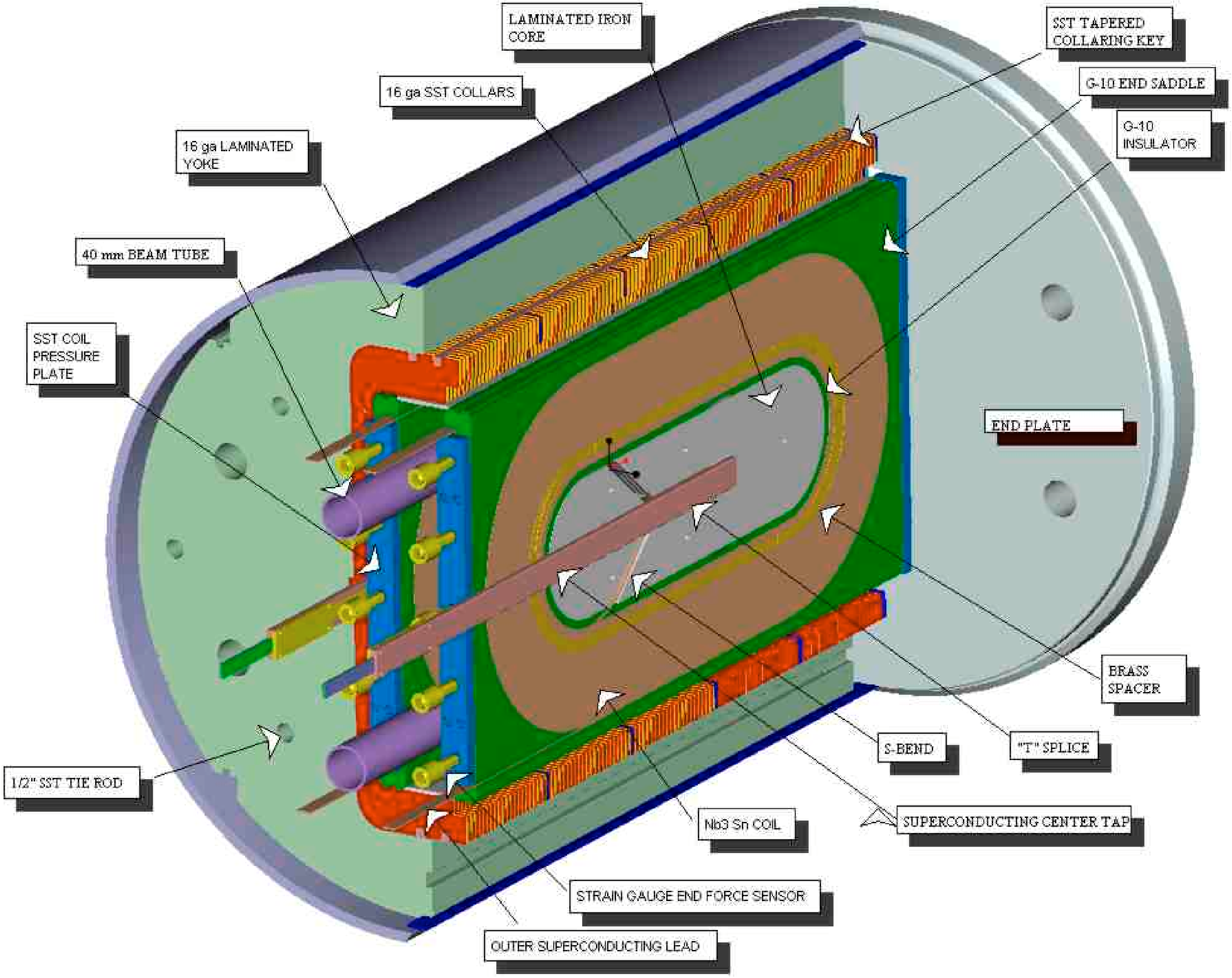




Erich Willen

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

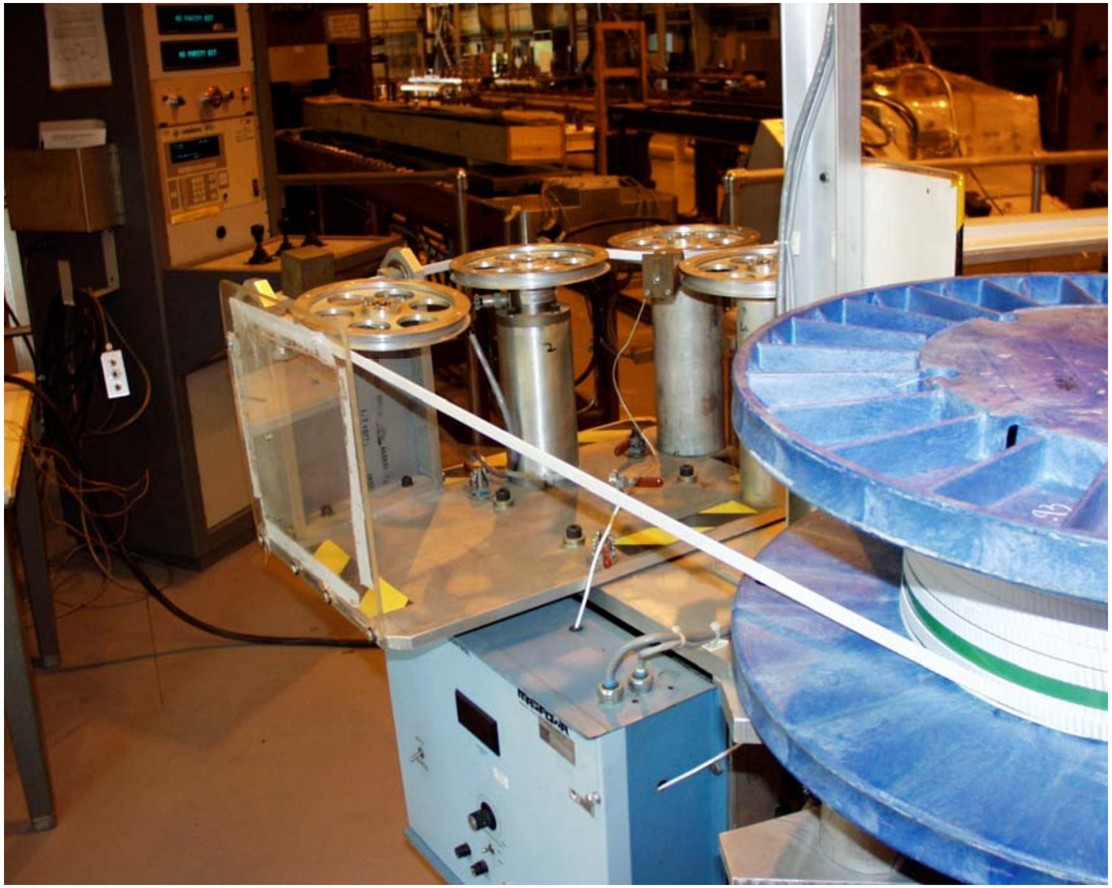
BNL 12 T Nb_3Sn Common Coil Background Field Dipole



Nb_3Sn conductor for both inner and outer layers is provided by OST

Rutherford Cable Magnet Technology

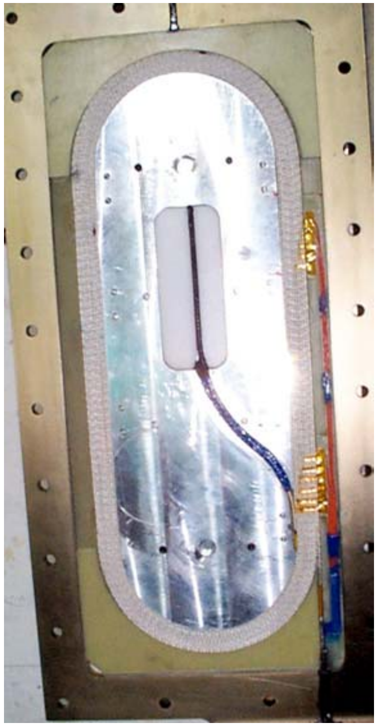
The present high field magnet R&D is primarily being carried out with Rutherford cable.



Nb_3Sn cable coming out of spool to wind the coil. In the case of "React & Wind" technology, one has to be careful not to damage the superconductor during the manufacturing process.

10 Turn Coil Program

GOAL: Experimentally test an item, beginning to end, in ~1 month.



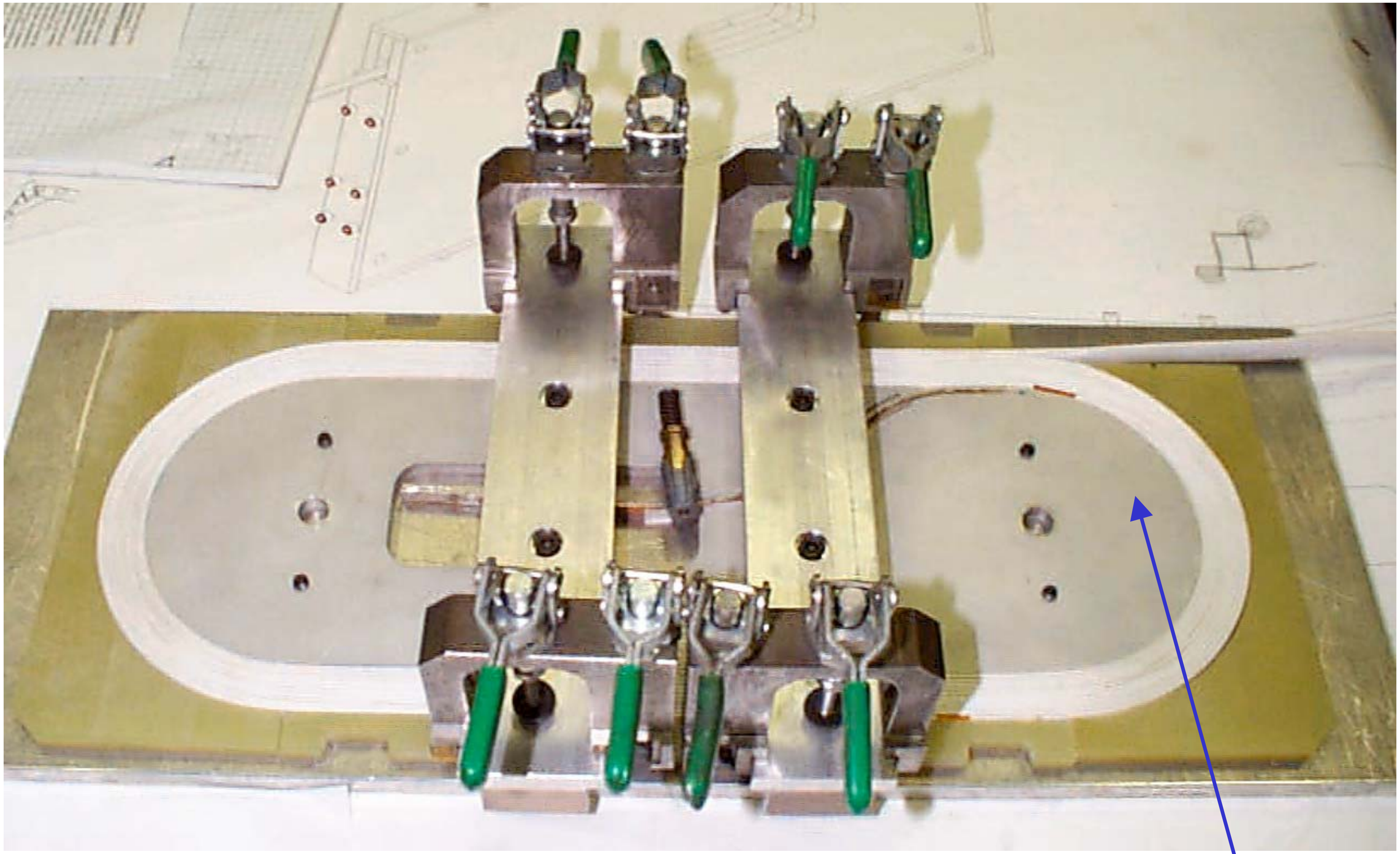
The construction should be as simple as possible and cost should be as low possible.

Rapid turn-around encourages test of new ideas and allows iterations in them. It scientifically evaluates the validity of old biases and the limit of present technologies.

In an atmosphere of limited funding, *"designing a magnet R&D program"* is just as important as designing a magnet. It sets the tone and nature of R&D.

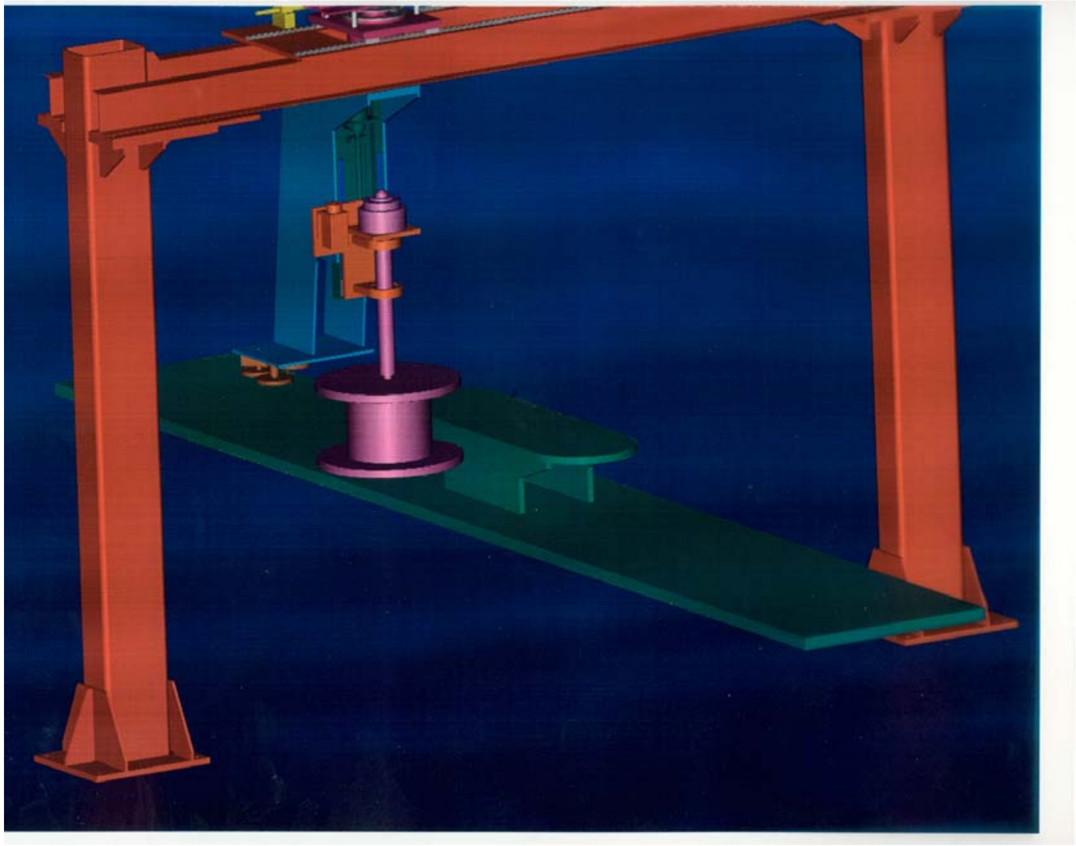
Such a program is must for HTS magnet development given the state of technology and the cost of conductor.

A Short Racetrack Coil for Common Coil Magnet R&D



Al Bobbin (70 mm radius)
(also used, Fe, SS and brass bobbins)

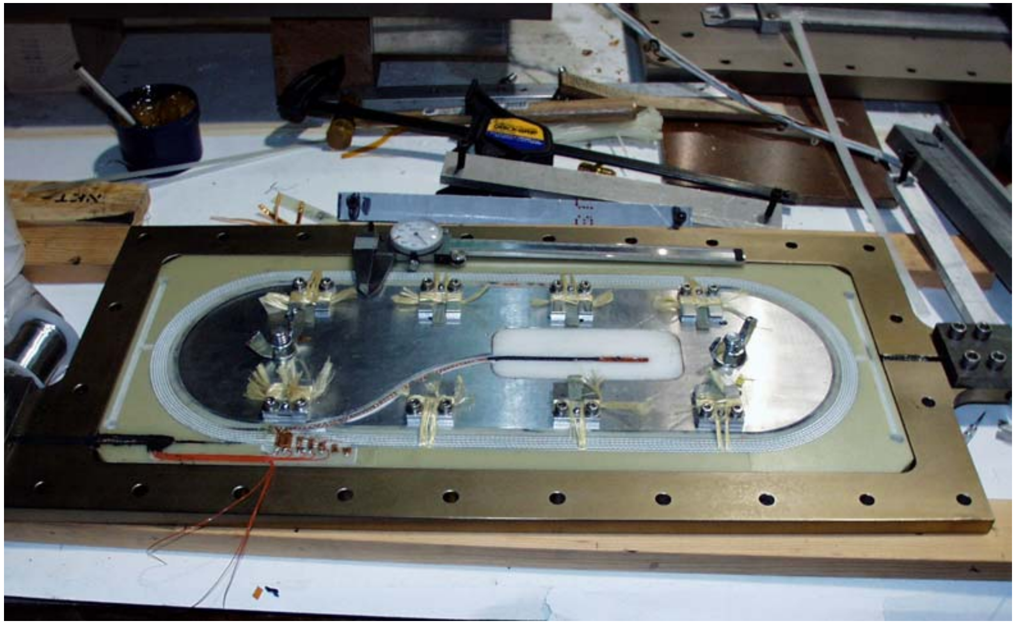
New Versatile Coil Winder Now Under Design



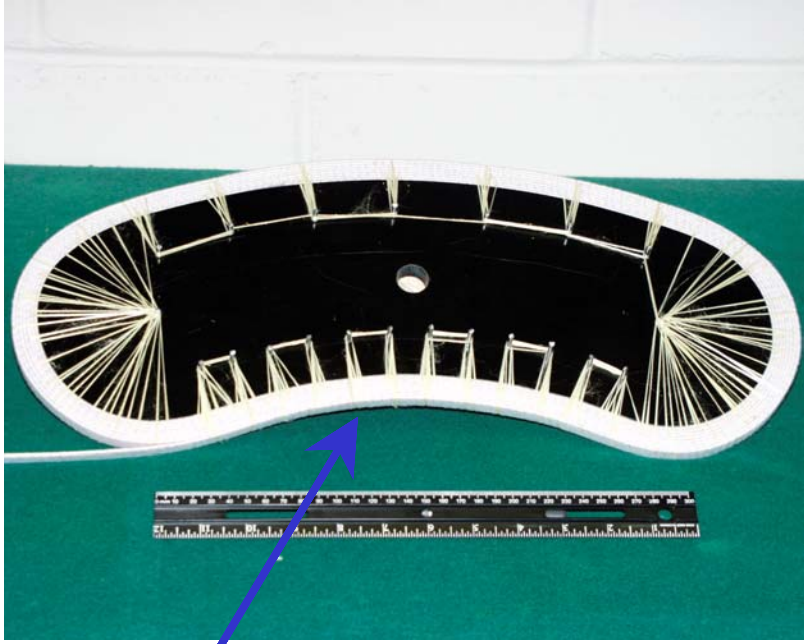
The new winder will be used in winding future HTS and Nb_3Sn coils. This versatile winder will handle brittle materials better and will wind coils having different number of turns in various geometries.

Use of Kevlar Strings

Kevlar strings make well compressed coils with brittle materials in shapes that were thought to be difficult before

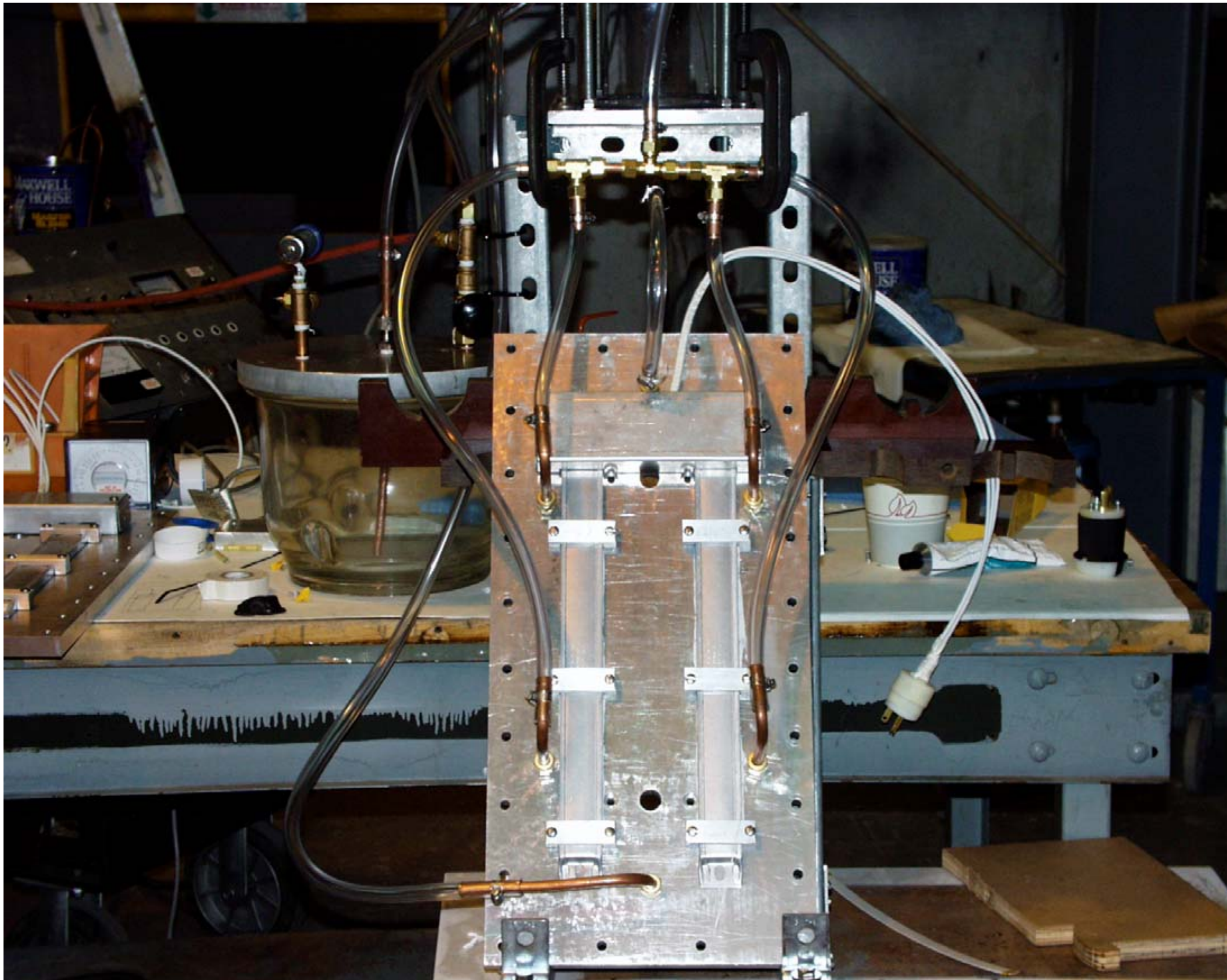


Kevlar clamp setup, coil locked into fixturing

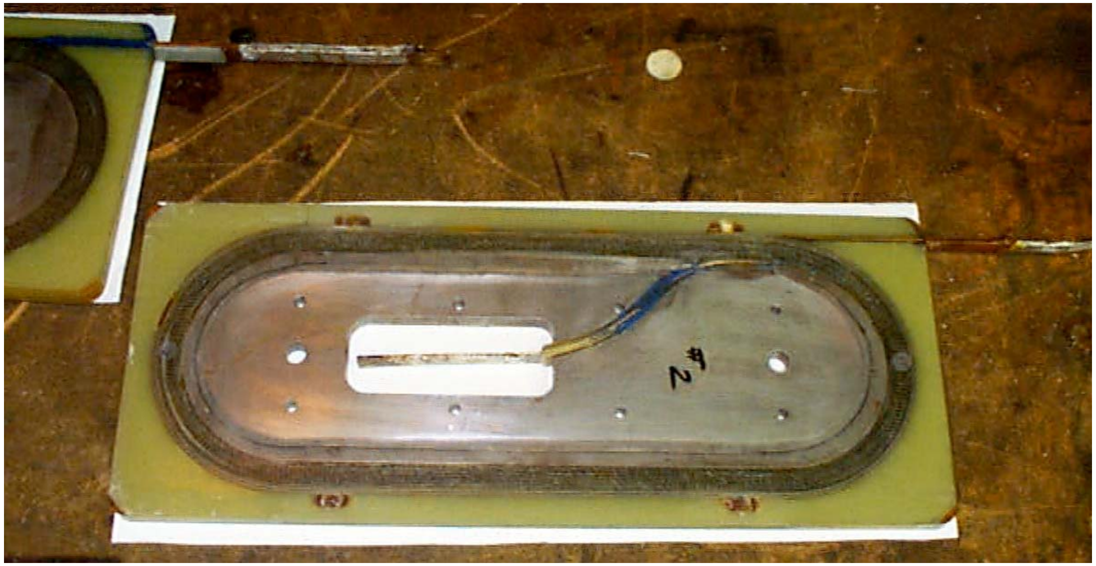


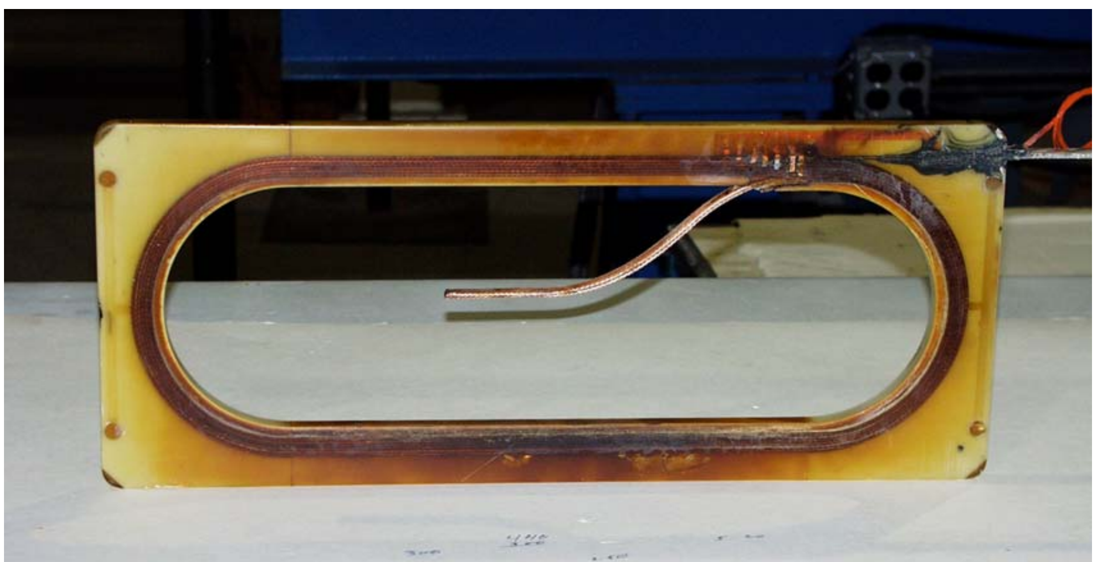
Coils with reverse curvature

Vacuum Impregnation Setup



Vacuum Impregnated Coils



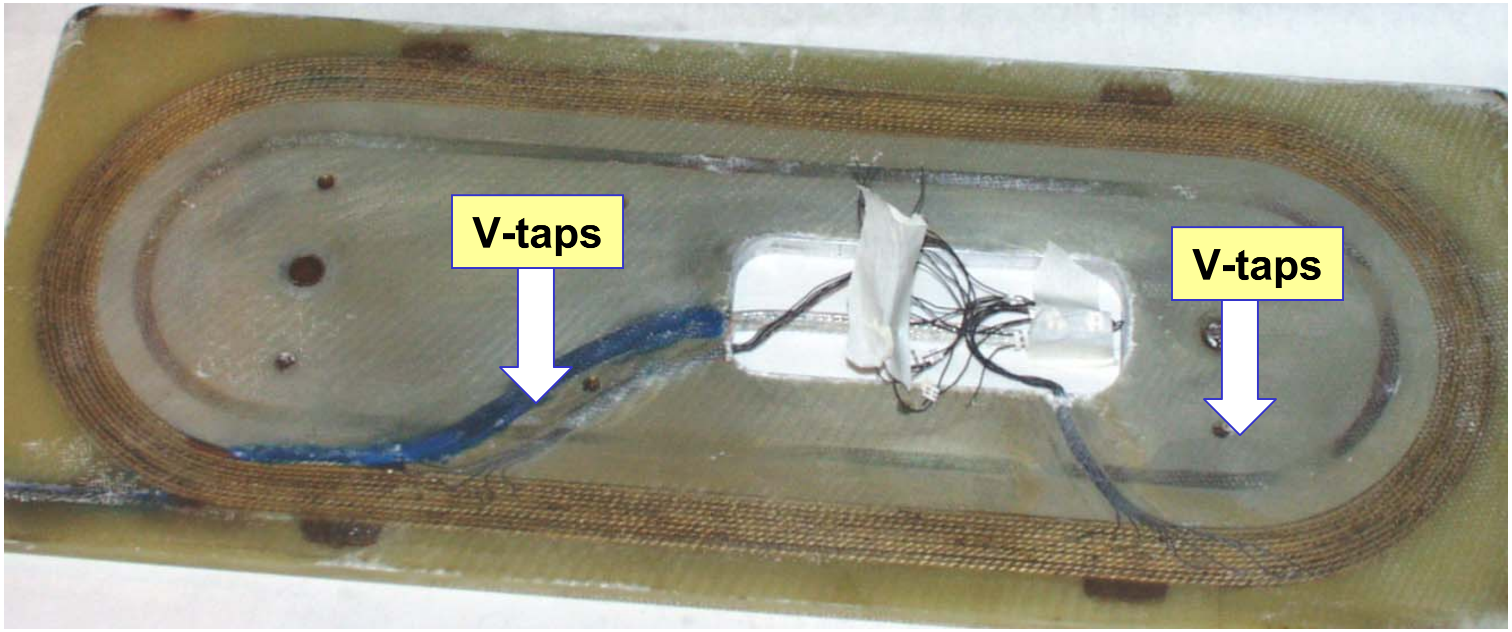


Vacuum impregnated coils made with the "React & Wind" technique.

Voltage Taps, etc.

We put at least one voltage tap on each turn for detailed study

- Given the aggressive R&D nature of the program we instrument as much as we can to locate the weak spot(s)
  - Remember we are pursuing/pushing the new technology
    - It's OK to follow "learn and burn" approach, as long as we learn from it experimentally in a scientific and systematic way



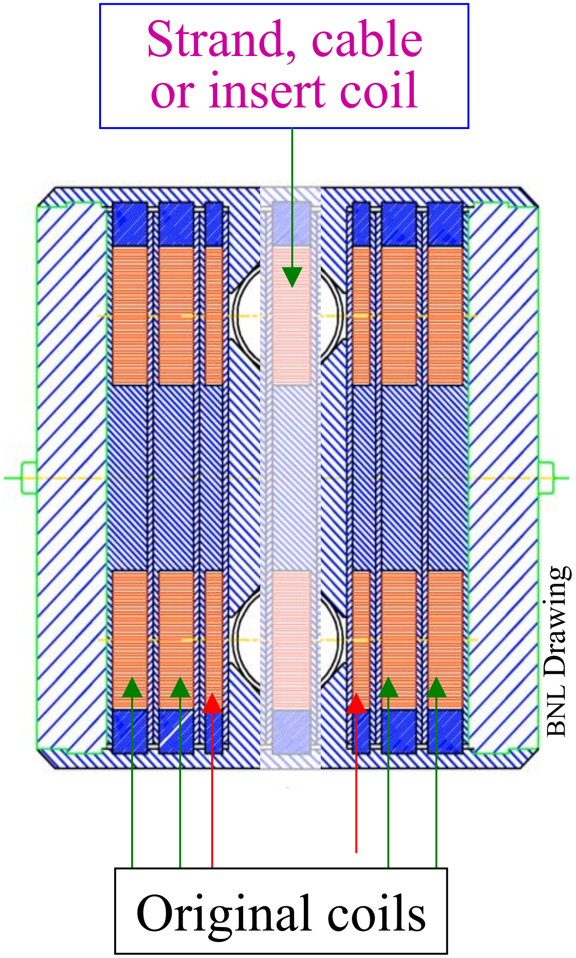
Common Coil Magnet Coils in Support Structure

Coils are heavily instrumented. There is a voltage tap after each turn. Data were recorded from all 26 voltage taps.

Coils are assembled for the most flexible and extensive testing. Four leads are taken out of the cryostat. During the test the coils were powered separately and together in “common coil” and “split-pair solenoid mode”.

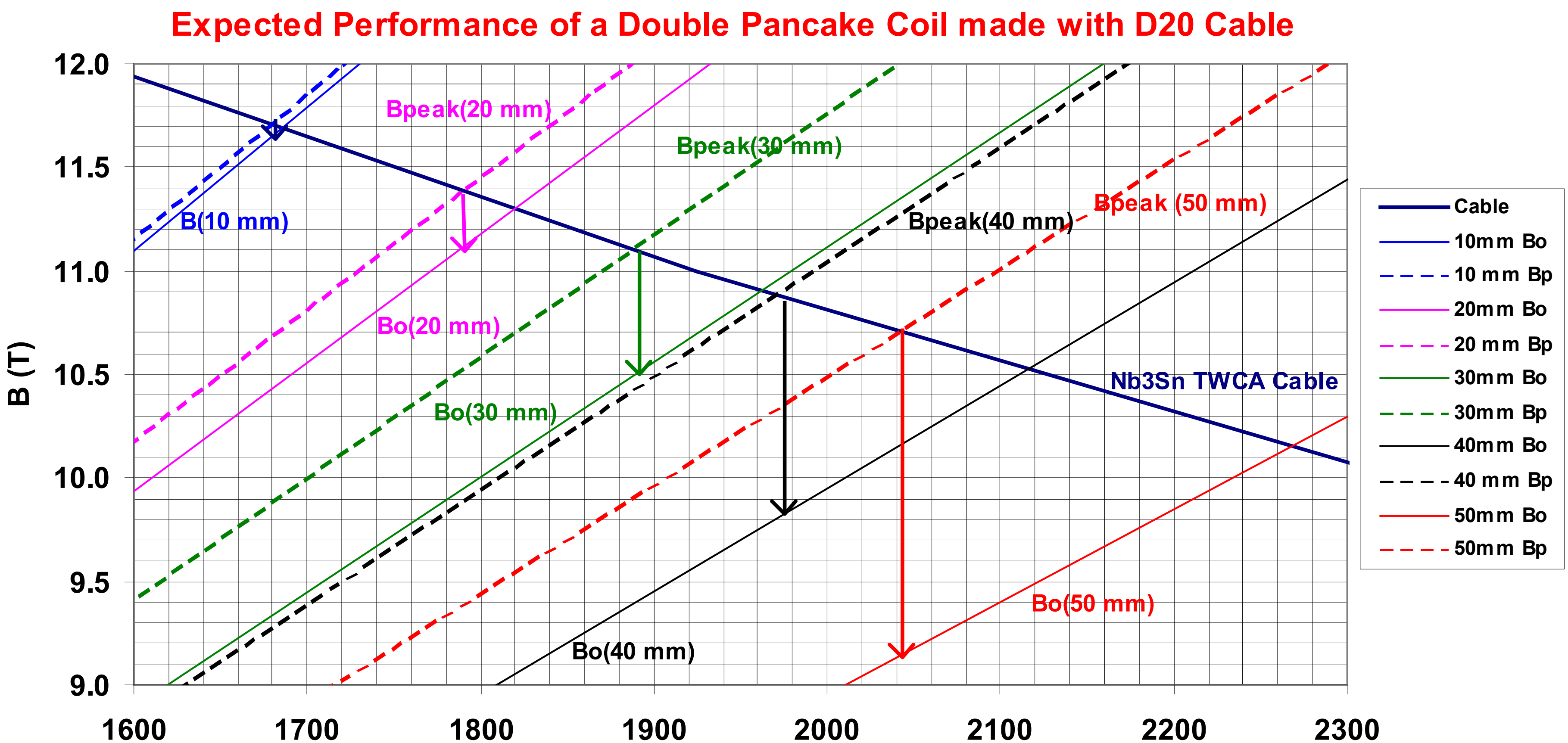
Two Hall probes (between the two coils and at the center of two coils) also recorded the central field.

Common Coil Magnet As A Test Facility



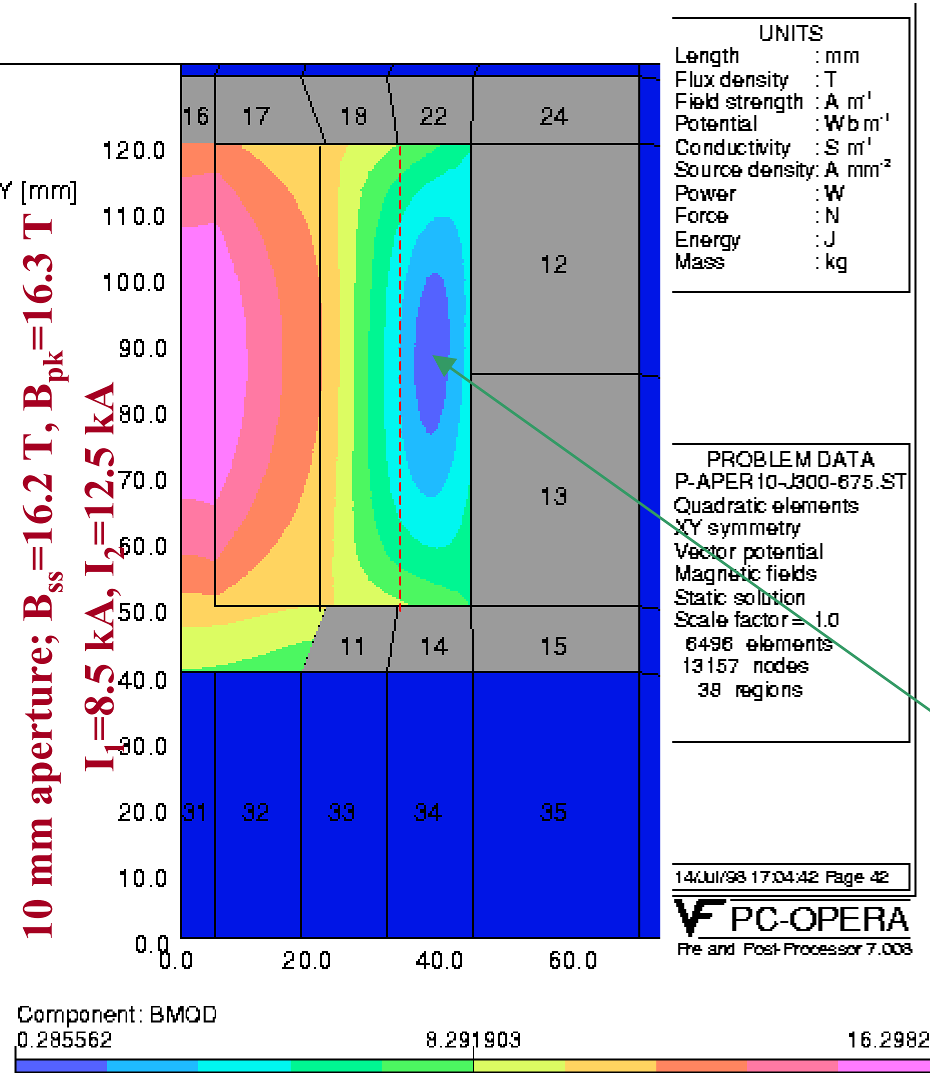
- **A Modular Design with a significant flexibility.**
- **Coil geometry is vertical and flat. That means a new coil module having even a different cable width can be accommodated by changing only few parts in the internal support structure.**
- **The field can be increased by reducing the separation 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.**

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

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

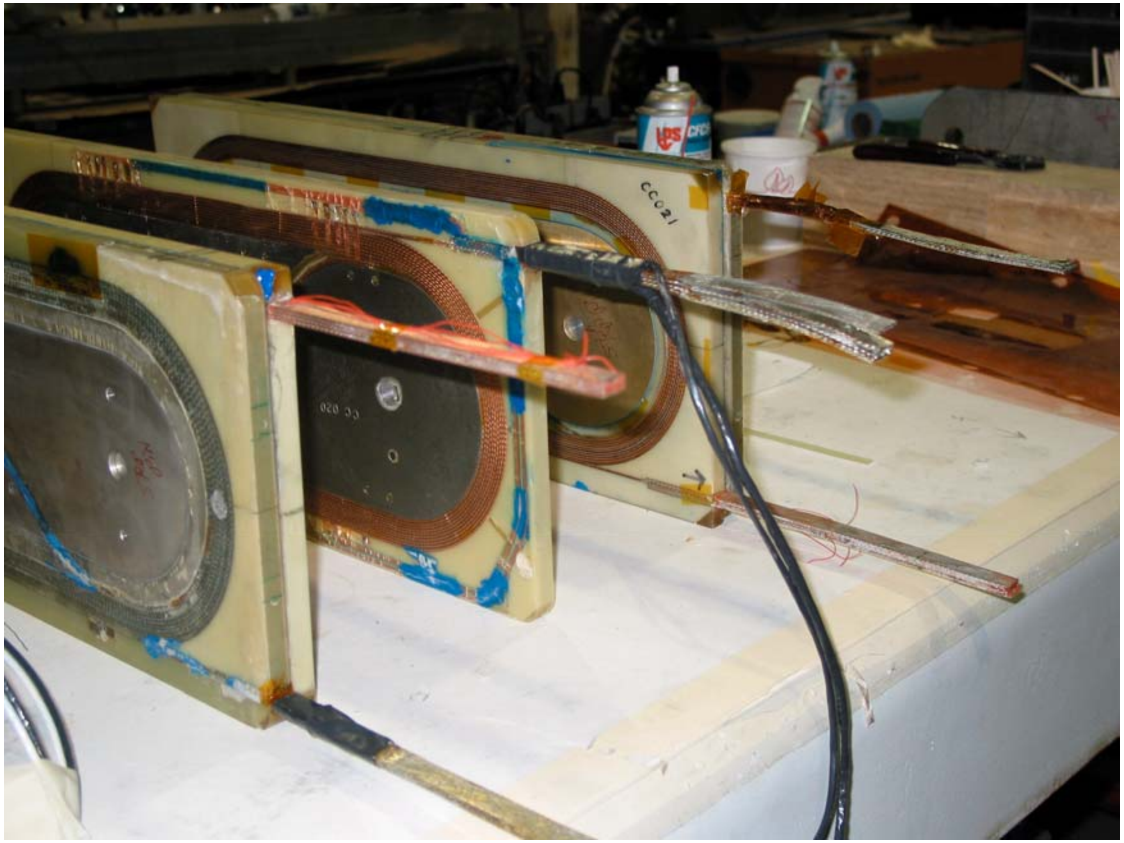
When do we really need a stress management scheme (cost and conductor efficiency questions), and how much is the penalty?

Simulate the future (better J_c) conductor

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Racetrack Coil Cassettes for Rapid Turn Around Magnet R&D Facility



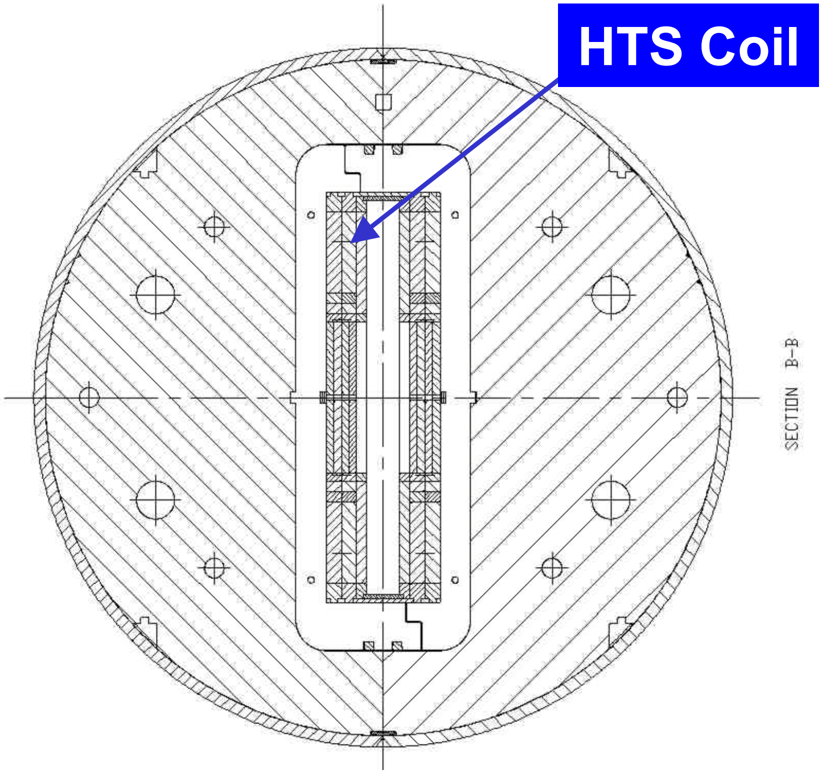
5 cassettes for a magnet test

BNL makes racetrack coils in modular structure. These modules (cassettes) can be mixed and matched for a variety of experiments in a rapid turn around fashion.

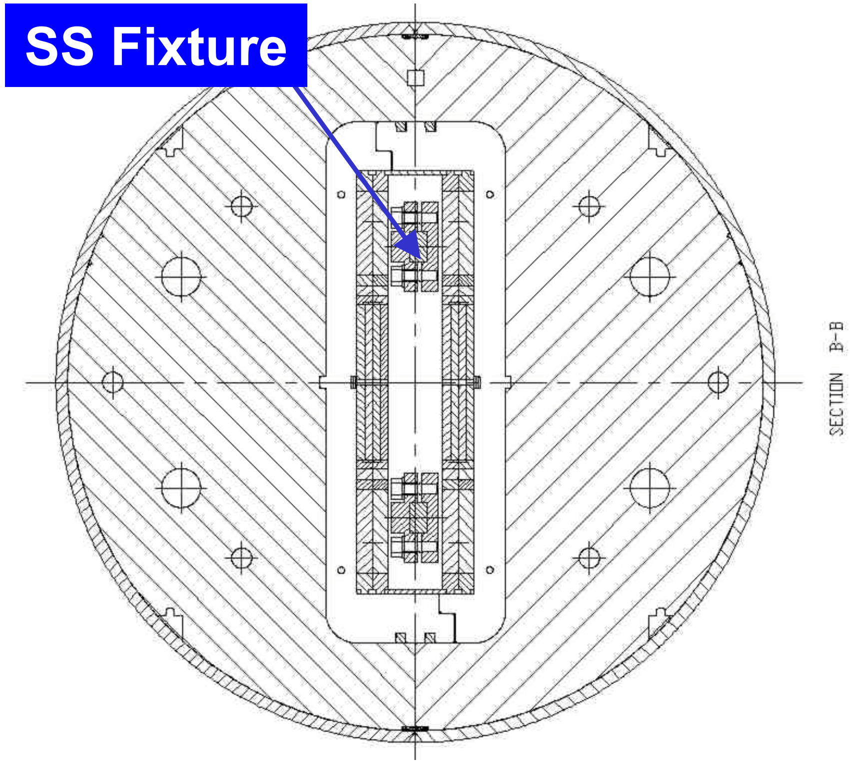
The support structure can accommodate up to six coils.

Insert Coil and Sample Test Scenarios

An interesting feature of the design, which will make it a truly facility magnet, is the ability to test short sample and HTS insert coils without disassembling it.



HTS insert coil test configuration



Short sample test configuration

Summary

• This presentation gave you a basic background of the issues that are critical to "React and Wind" magnet design.

• It also gave a feel of what is involved in developing a high magnet R&D program.

• Some of the topics were more specific to "React & Wind" technology but many other were common to both. For example, in case of "Wind & React" technology one need not worry about bending strain but must concern with the insulation and other structure material that need to go to high reaction temperature.

•High field magnet technology has still not reached a stage that one can use them in large scale application. But we are in a stage that it can be considered for special applications.