React and Wind Magnet Technology

Program Plans and Special Conductor Requirements

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Outline of the Presentation

- Motivation behind "React and Wind" Approach
- ***Special Requirements for "React & Wind"***

  Conductor/Cable Issues - dialogue with industry
- Program Experience (BNL and Fermilab)
- Program Plans (BNL and Fermilab)
- Update on React & Wind HTS
- Summary

Motivations for React & Wind Approach

• 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.

• 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.

Flexible cable approach is an example of working on conductor/cable design and common coil on magnet design.

• 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?

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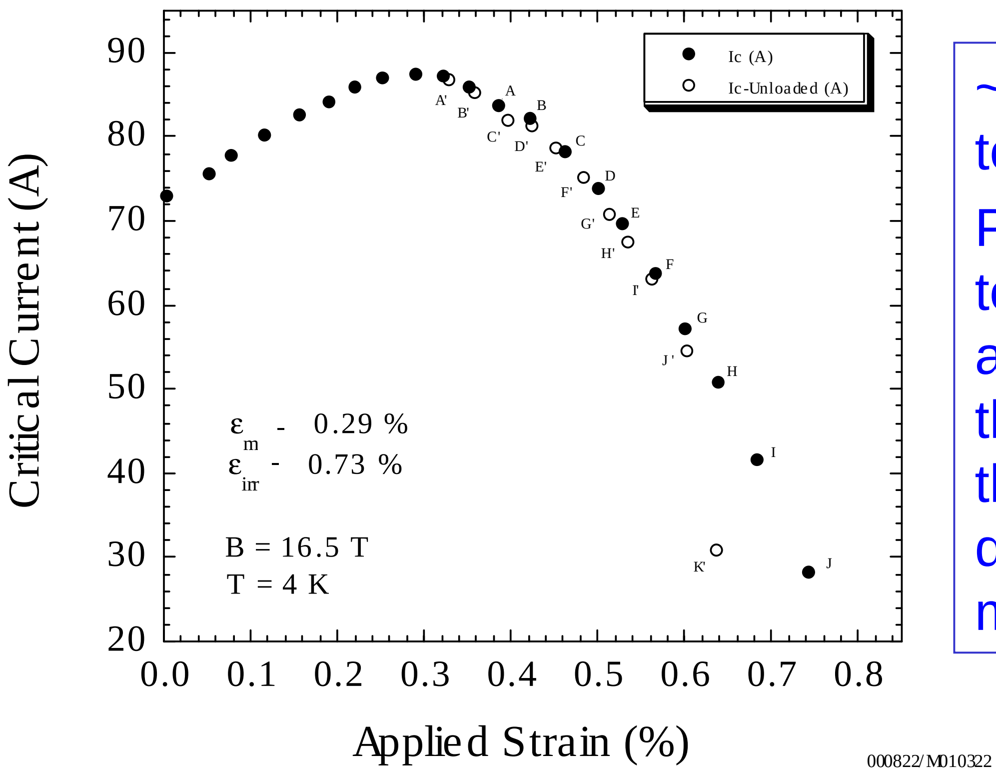
Axial Strain Studies

High niobium density (50% nca) Nb_3Sn (Oxford)

J. Ekin, N. Cheggor, et al, NIST, LTSW '01



~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).

A direct bend strain study is, however, more relevant for accelerator magnets.

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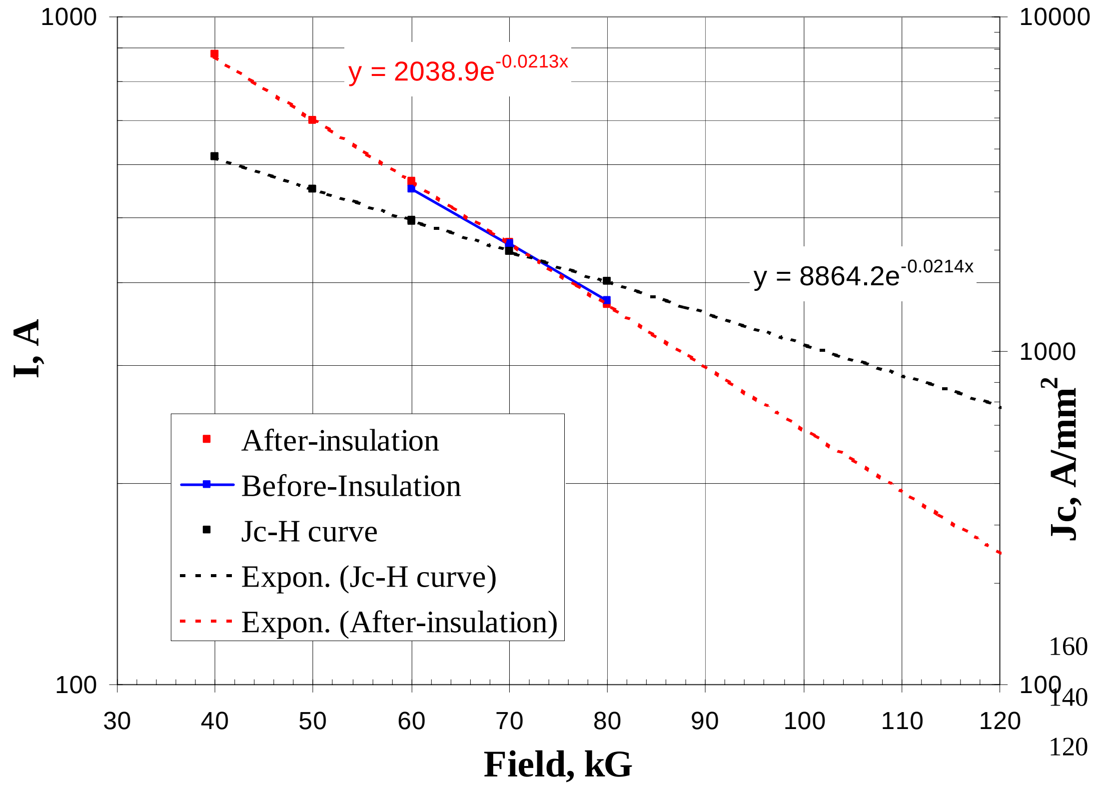
Bending Strain in 6x1 Cable
(Cable made with 0.33mm ITER Strand)



Arup Ghosh, BNL, LTSW'01

Cable made with Mobil 1 coated strand. After Heat Treatment, cable insulated with 25 mm Kapton film.

Bending strain degradation:

None in I_c till 8T.

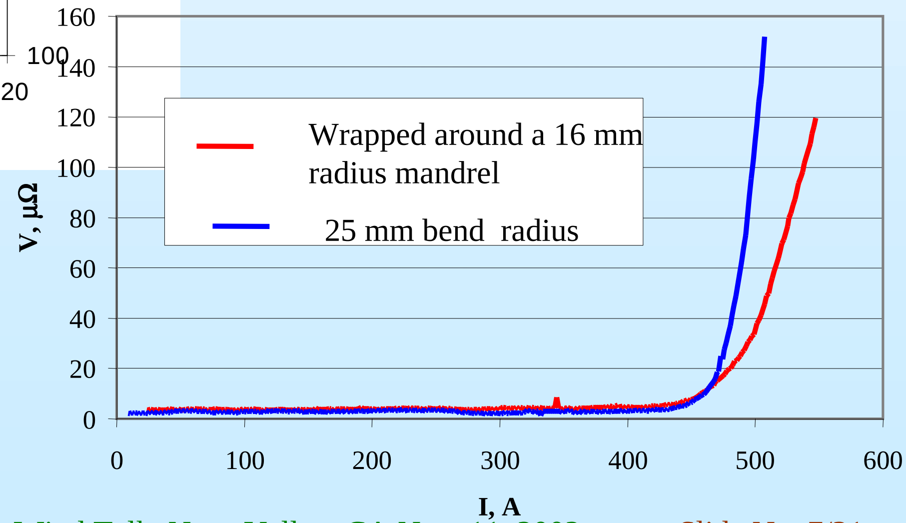
Observed degradation in n-value:

Small for 0.66% (R=25 mm)

Noticeable for ~1% (R=16 mm)

N-value @ 8T ~ 30 for 25 mm bend radius.

When bent around a 16 mm radius mandrel Jc does not change but the n-value drops to ~ 25, indicating a degradation.

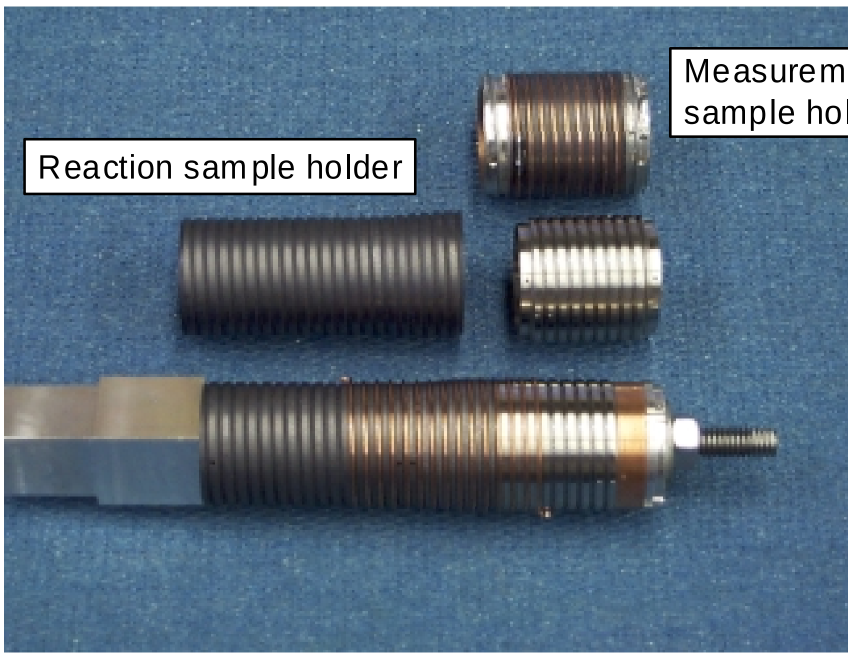


- **Performance of high Jc wire?**

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 $\phi 1 < \phi 2$**

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Results from Fermilab

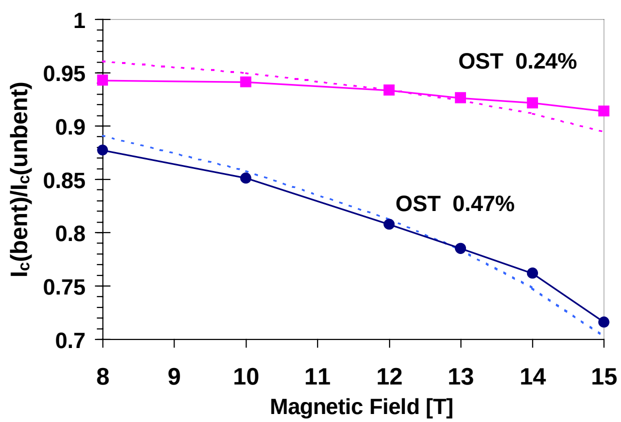
Larger bending degradation in high J_c wires as compared to low J_c wires

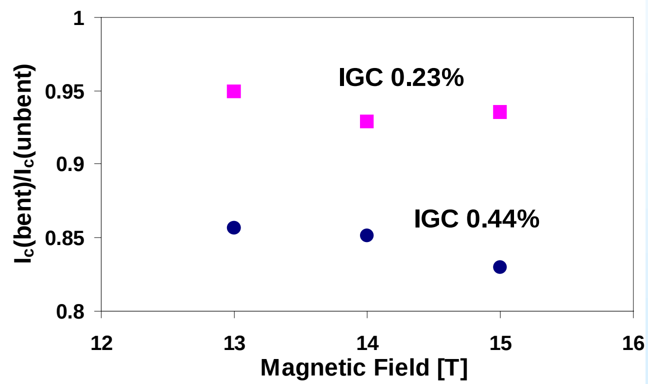
- **Degradation depends on the wire manufacturing process**

Courtesy:

E. Barzi

Bending degradation of High-Jc wires





- 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

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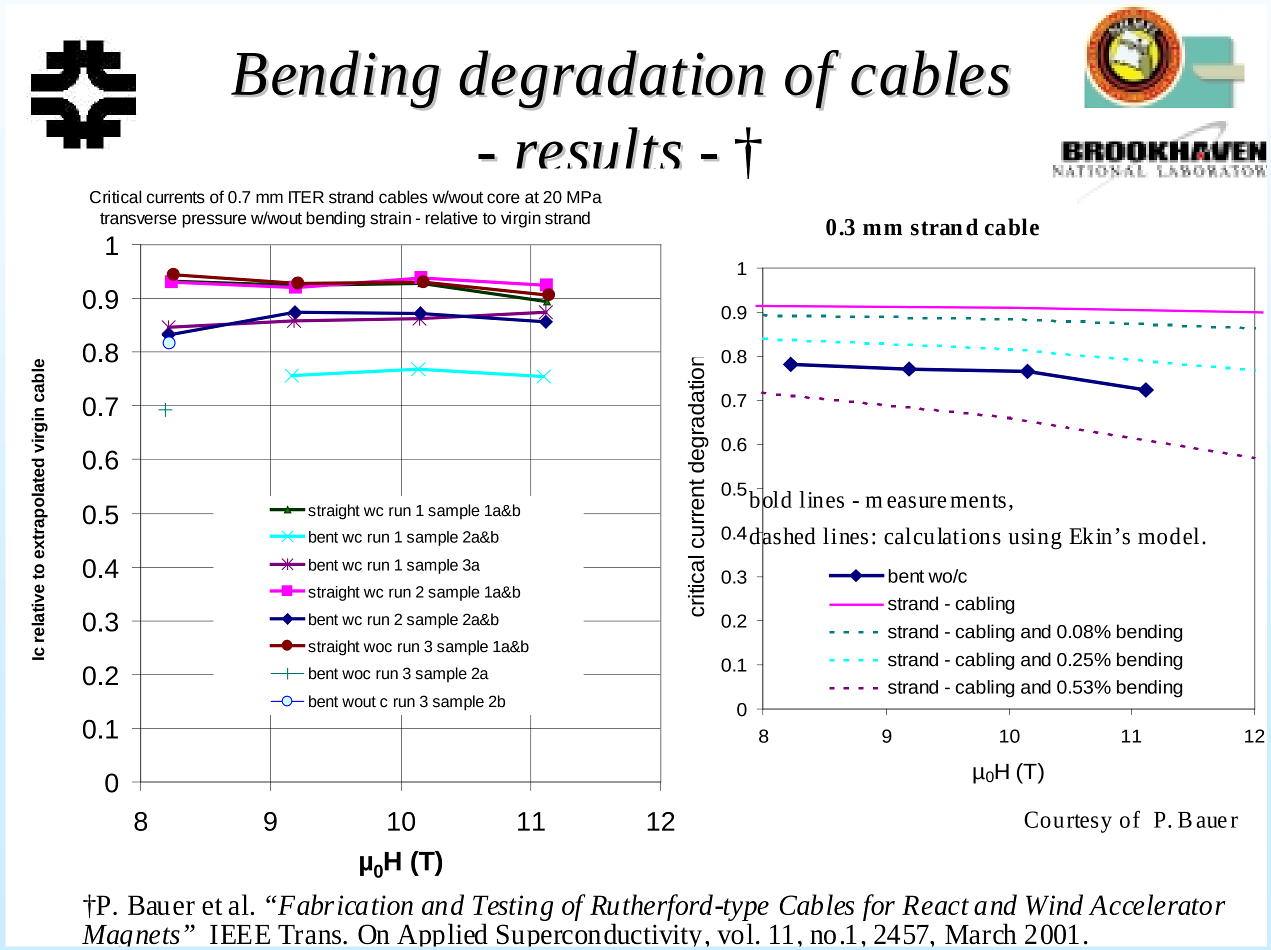
Results from Fermilab on Cable

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

Courtesy:

P. Bauer



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**

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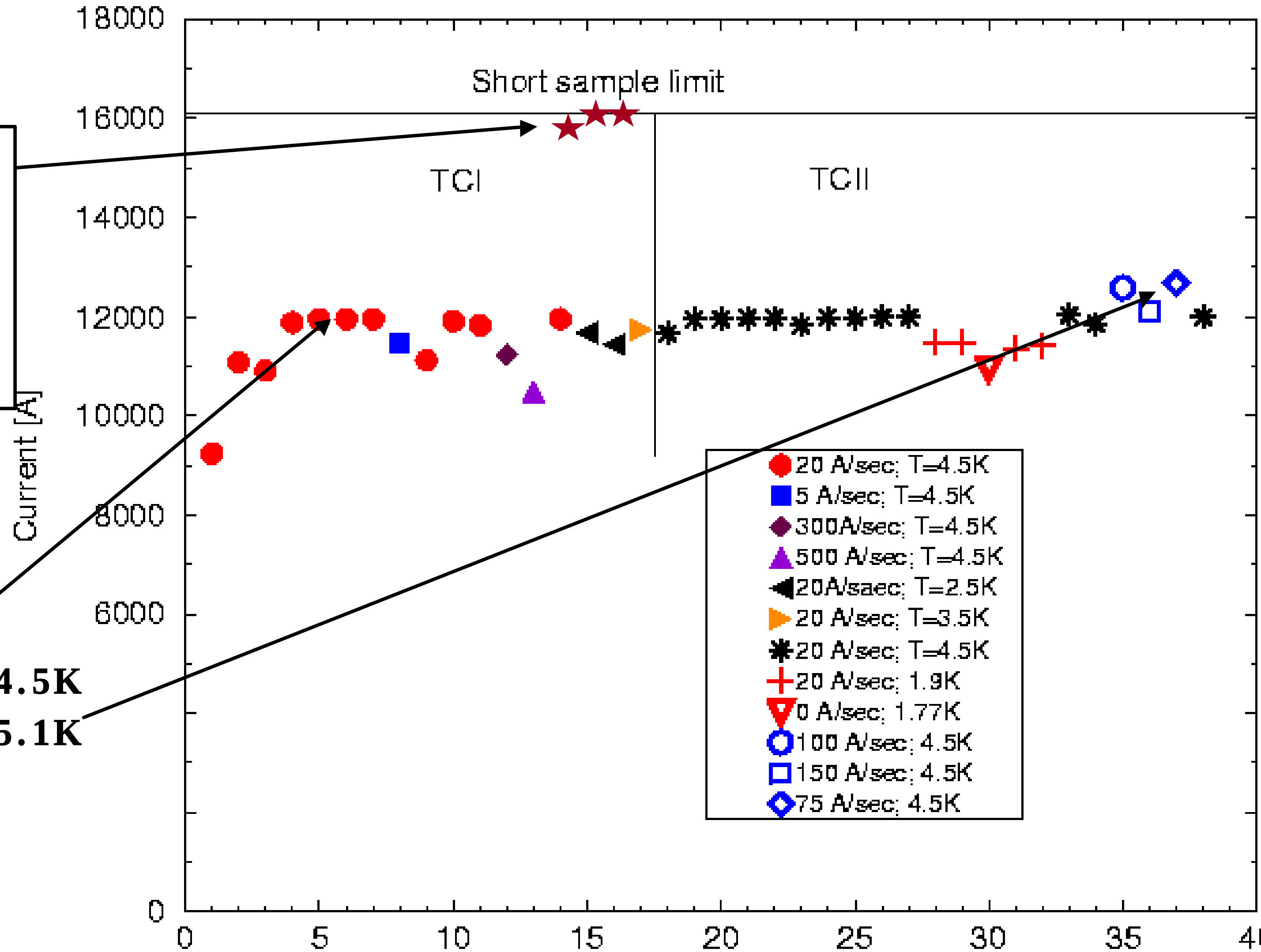
Quench history

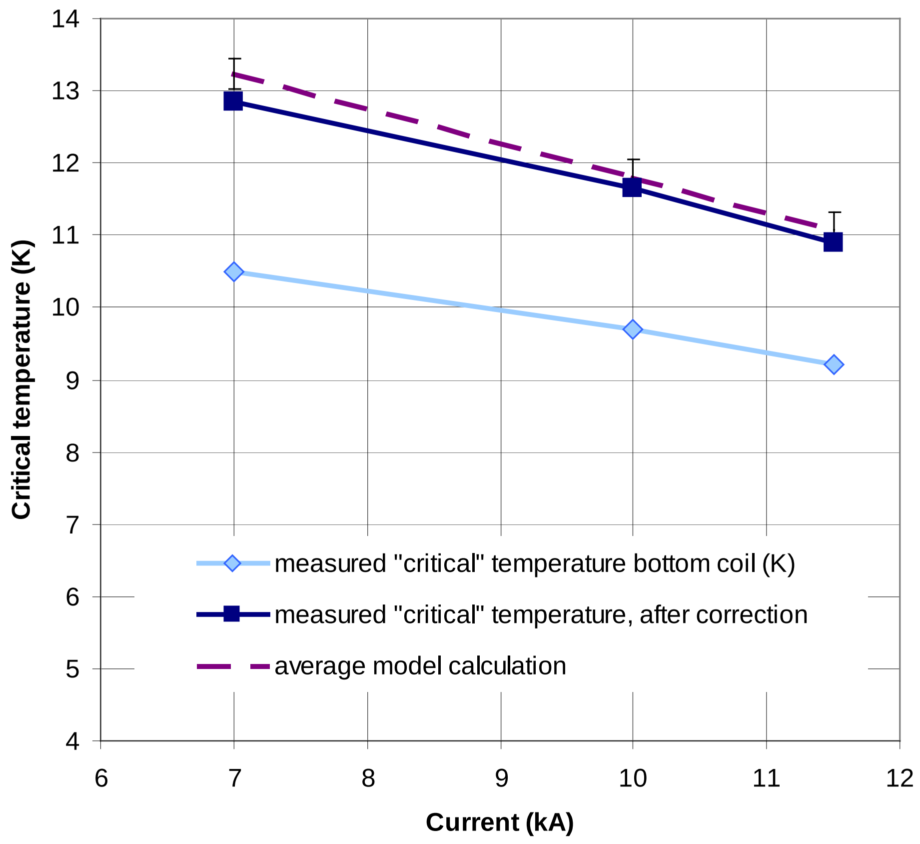
Computed Ic from measurement of the critical temperature of the cables facing the spot heaters ~ 97%



I_q = 71% @ 20A/s 4.5K
I_q = 78% @ 75A/s 5.1K
Local degradation

Temperature margin in the innermost turn

- Current kept at constant value
  - I = 7, 10, 11.5 kA
- Spot heater was connected to a DC power supply
  - Heater current was raised very slowly
- Temperature was recorded by adjacent sensor
- ANSYS model was used to compute the temperature in the hot spot
- Generation temperature was computed taking into account the bending degradation
  - Several models used (range shown by error bar)



Possible cause of local degradation

- **Inspection of cable leftovers**
  - four bumps in a 5” long region repeated every 44”
    - the print is less and less sharp as the regions move away from the beginning of the cable
    - it is the print of the copper shims used to have a smooth transition from the first to the second turn
    - bottom coil leftover: 10 bumps (the cable was much longer)
    - top coil leftover: 6 bumps (the cable was six turn long)
    - <u>some bumps should be in the winding of the top coil</u>

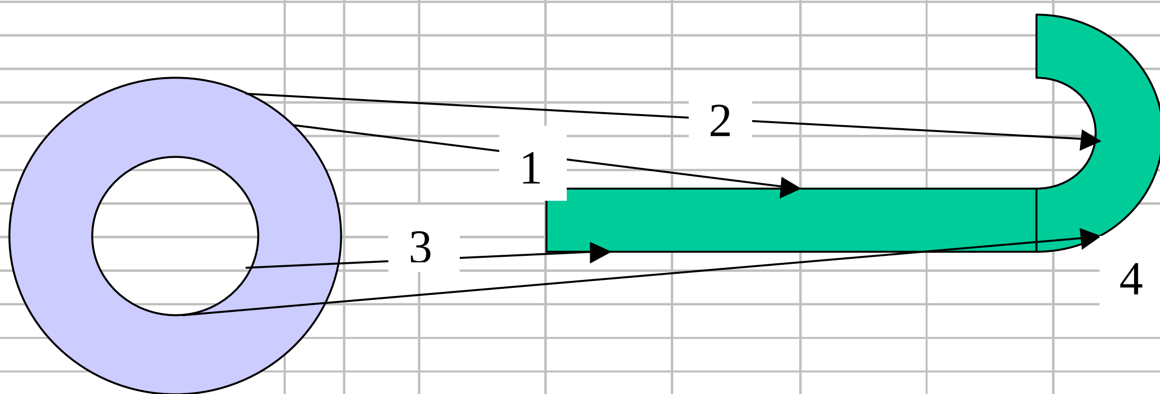
Strain in the Racetrack coil

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)	$\varepsilon 1$	%	0.121	**0.221**	**0.171**	0.062
Max strain (sintered strands)	$\varepsilon 2$	%	0.260	**0.472**	**0.366**	0.132
Position			**1**	**2**	**3**	**4**

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

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



Technological model winding

Status and plans

- The technological model has been completed
  - Some small modifications end parts
- We are practicing with:
  - The inner splice
  - The instrumentation
- The tensioners have been modified
- The cable for both coils has been reacted
- The winding of the first model will begin soon

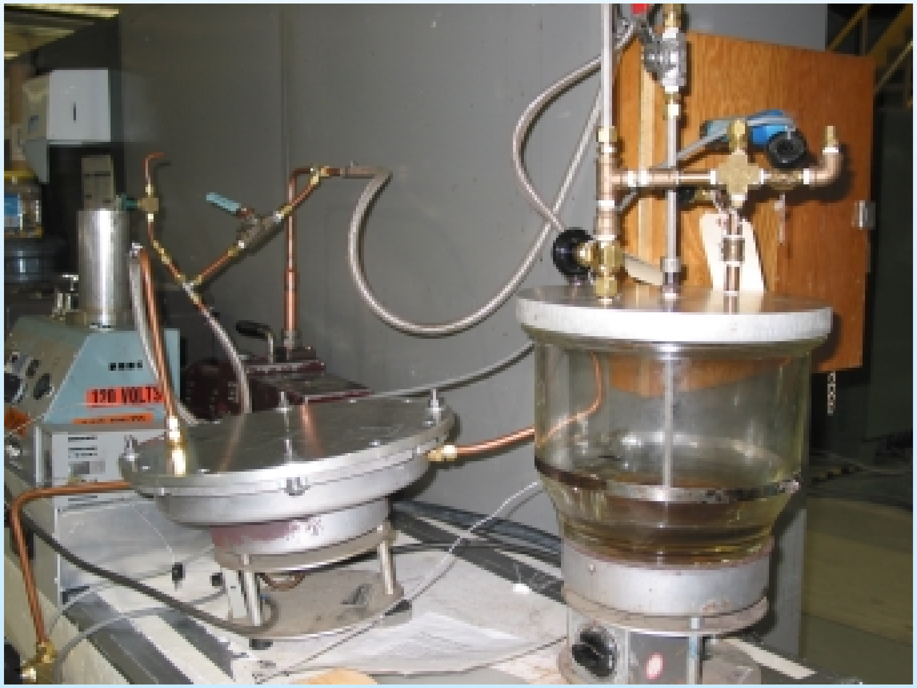
React & Wind Program at BNL and at FNAL

- React & Wind programs at BNL and Fermilab have some similarities but mostly they are complementary.
- This is an ideal case as we do not want to repeat every thing but it is healthy (perhaps necessary) to have more than one group working on a new and technologically challenging R&D. Some time little details and biases make or break a critical item and hence may cast an incorrect impression on the viability of the entire technology. In this connection, a recent visit by Giorgio Ambrosio of Fermilab to BNL was quiet useful.
- Fermilab (in collaboration with LBNL) has worked more on the conductor and cable issue and BNL on 10-turn coil rapid turn around program.
- Fermilab uses 0.7 mm wire in their common coil magnet design with a minimum bend radius of 90 mm. BNL uses 0.8 mm wire in our common coil design with minimum bend radius of 70 mm (more aggressive approach).

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 new oil impregnation setup (made after Giorgio's suggestions) to vacuum impregnate the cable before reaction to minimize the chances of sintering.



Construction & Test Results

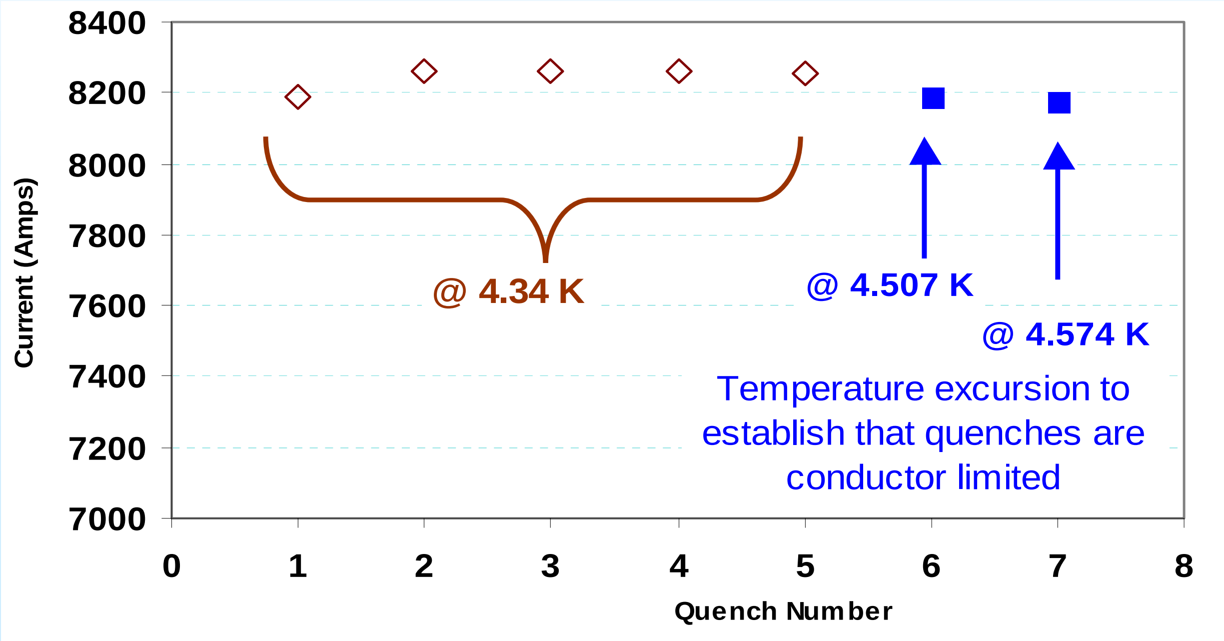
BNL has made nineteen 10-turn coils using "React & Wind" Technology with Nb3Sn & HTS cable. Nine tests have been carried out so far.

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.

A Perfect Test Result of a "React & Wind" Test Magnet:

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 Nb3Sn with respect.

Next in 10-turn Coil Program

- Make two coils with high performance vacuum impregnated cable.

- React cable on a spool that has about twice the radius of that in the magnet coil. This lowers the effective bend strain by a factor of two.

- Eliminate the machine insulation step and be extra watchful in rest of the construction to avoid any potential of damage/degradation.

- Make one coil with almost no instrumentation (to minimize the potential of damage) and other with as much instrumentation as possible (to help locate the problem spot). We have been putting one voltage tap each turn.

- We hope that the above coils produce good results=> retain 12T design.
- A still poor performance would indicate that though we did not exceed the bend strain tolerance in ITER conductor, we did in the high performance Nb_3Sn. In that case, build two 10-turn coils with a lower bend strain design. A good performance in the last two coils point to a required modification in the 12 T design with a lower bend strain.

Experience with Rapid Turn Around Program

We have been arguing for rapid turn around program for about ~5 years.

In last 2-3 years, we have made 20 test coils with brittle pre-reacted material (15 with Nb_3Sn cable and 5 with HTS cable) and tested 10+ test magnets in a cost effective magnet program.

The program has been successful in producing what it was expected to:

- Aggressive magnet R&D - generating both good and bad results (learning experiences).

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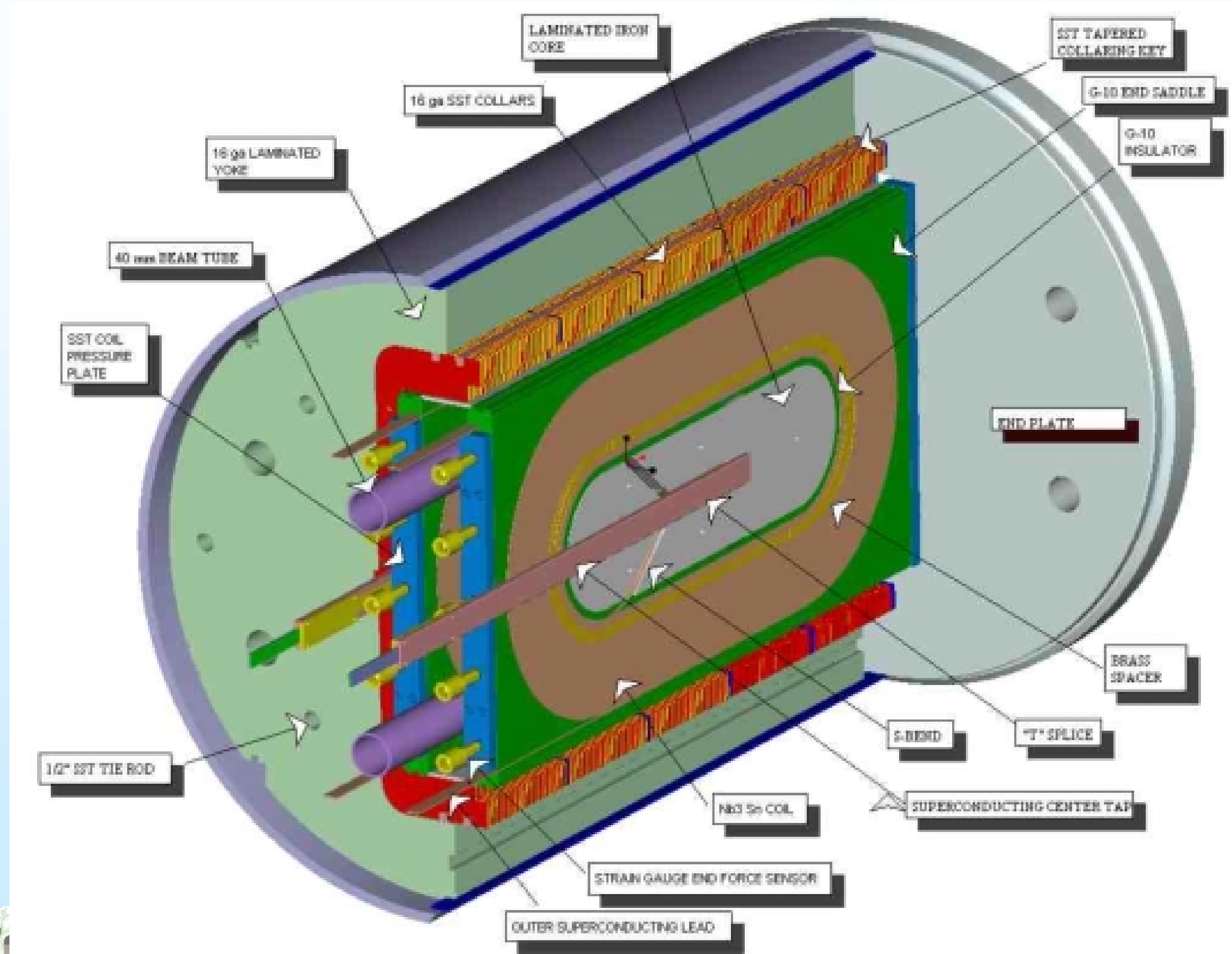
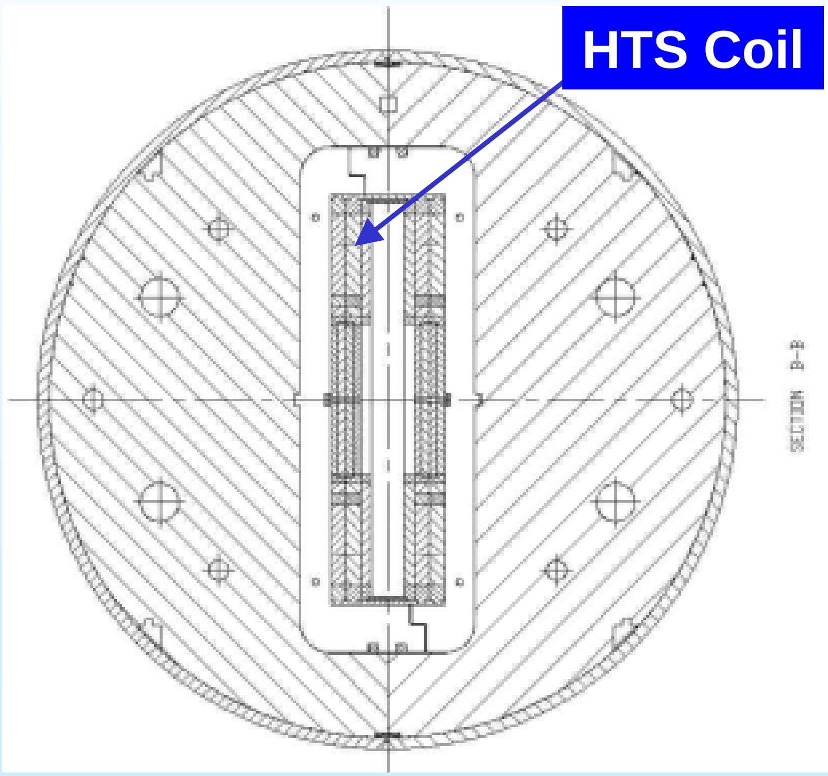
BNL 12 T Nb_3Sn Common Coil Background Field Dipole



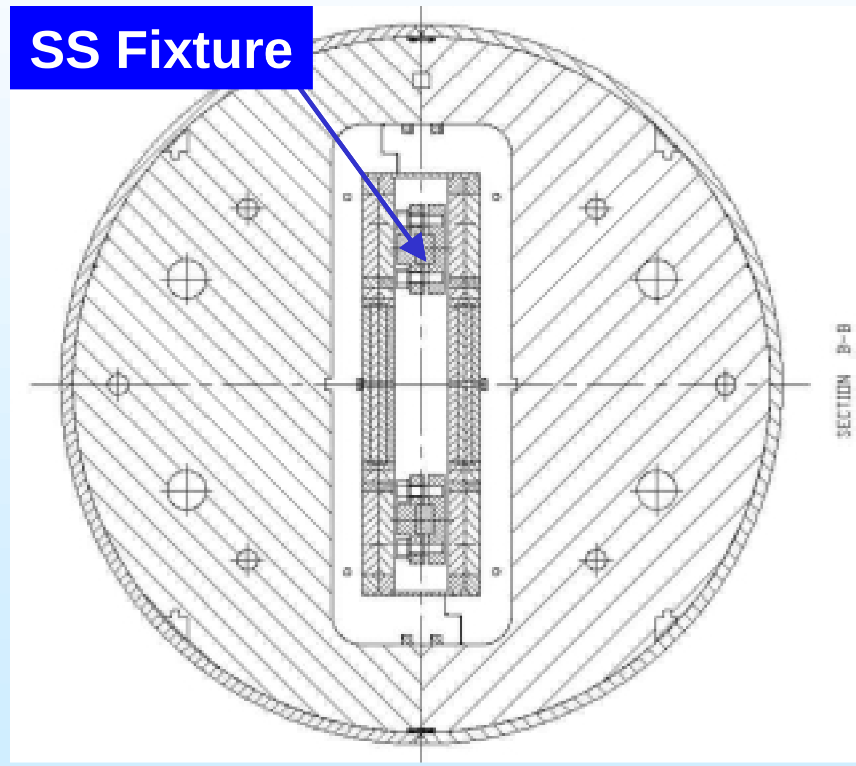
Nb_3Sn conductor for both inner and outer layers is provided by OST

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

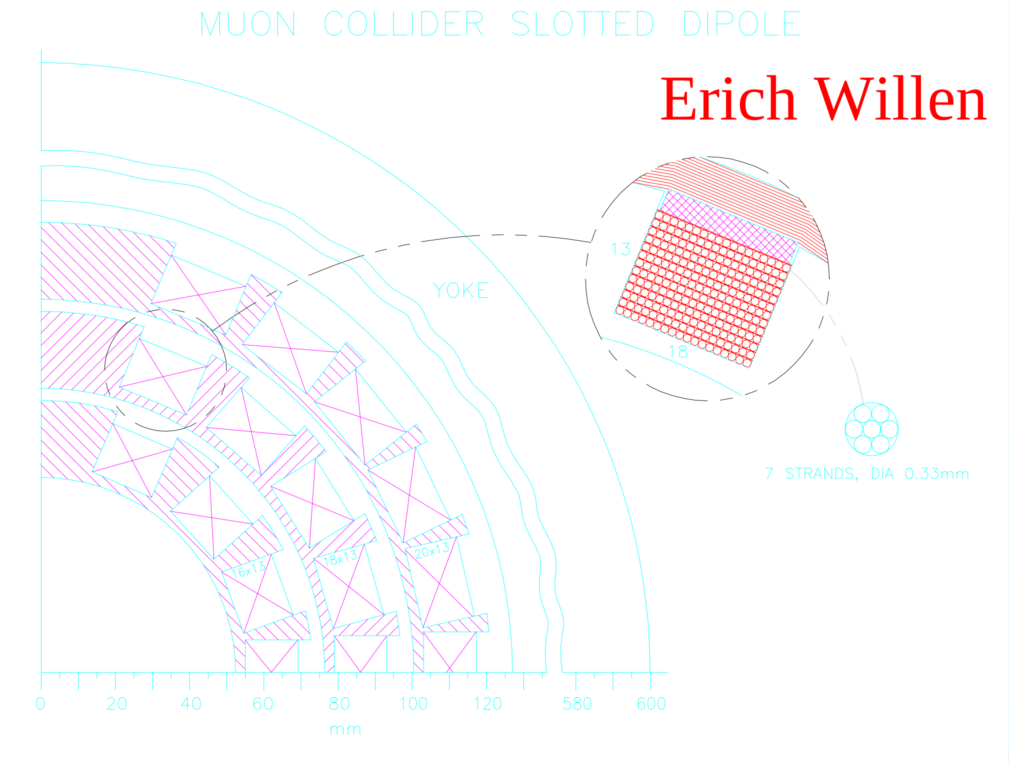


Short sample test configuration

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)

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



Progress in BSCCO2212 at Showa
(Investment in HTS and Current Capacity)

Not for Distribution

Not for Distribution

Progress in BSCCO2212 at Showa
(Progress in I_c and It's Uniformity)

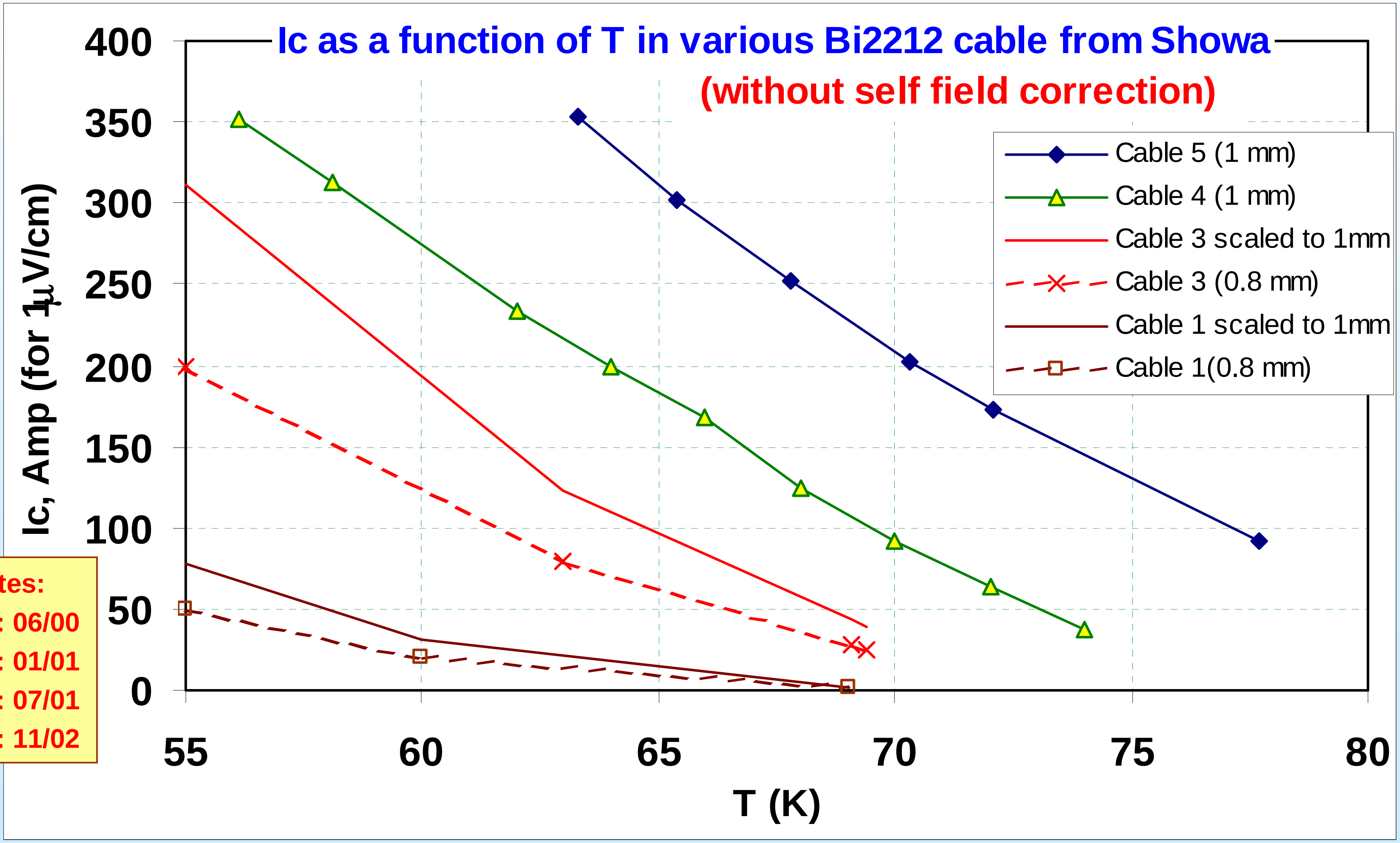
Tested at BNL also (Cable 5)

Not for Distribution

Not for Distribution

BNL Measurements of Various Cables from Showa
(Note: Continuous progress in cable performance)

Extrapolated 4 K performance of 20 strand cable (#5) (wire dia = 1 mm) :
~5 kA at high fields and ~9 kA at zero field



Test Dates:
Cable 1: 06/00
Cable 3: 01/01
Cable 4: 07/01
Cable 5: 11/02

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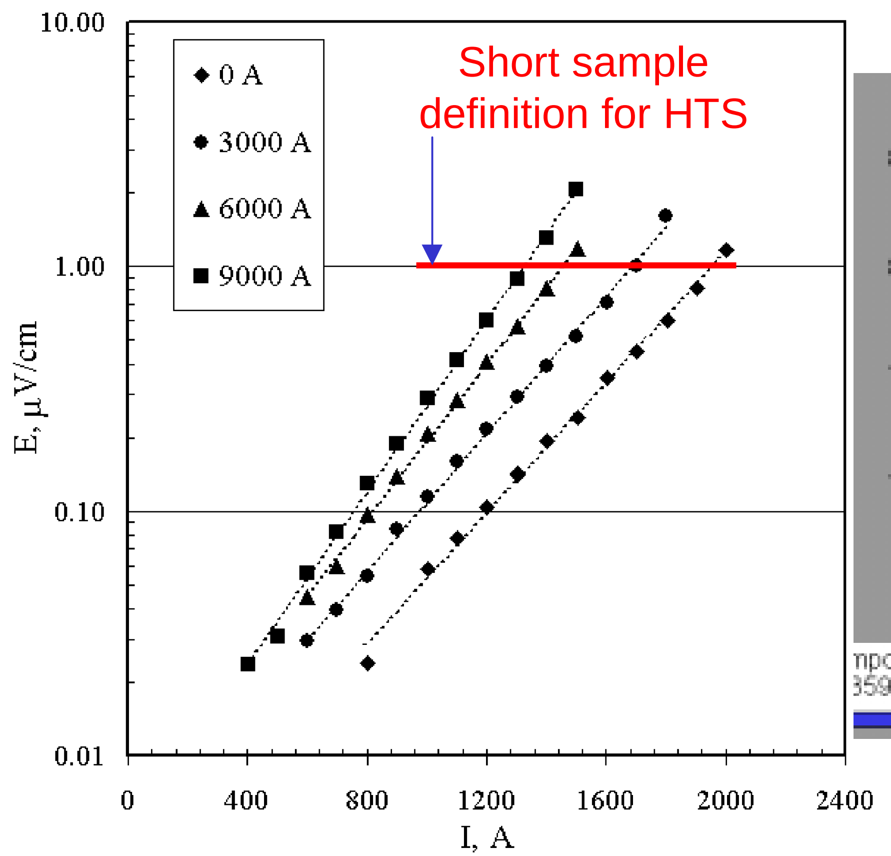
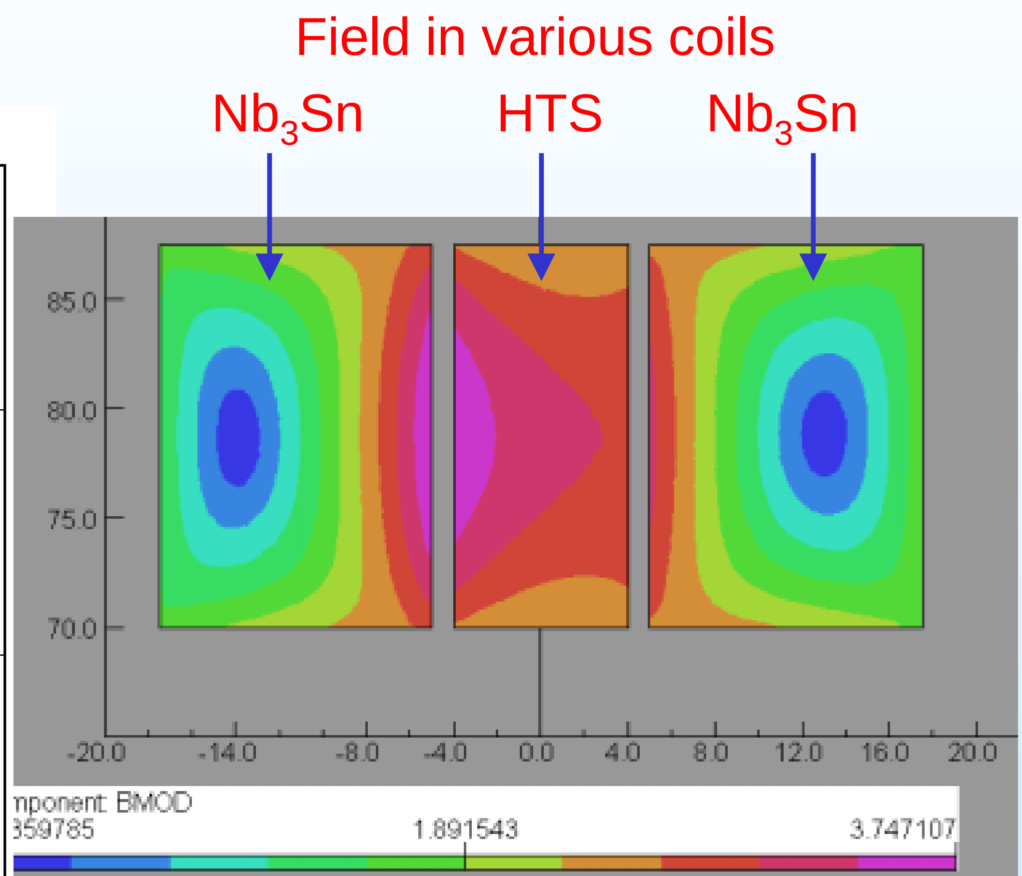
Performance of HTS Coil in the Background Field of Nb_3SN Coils

Measured electrical Resistance of HTS coil in the background field provided by various Nb3Sn coils in the magnet DCC008R





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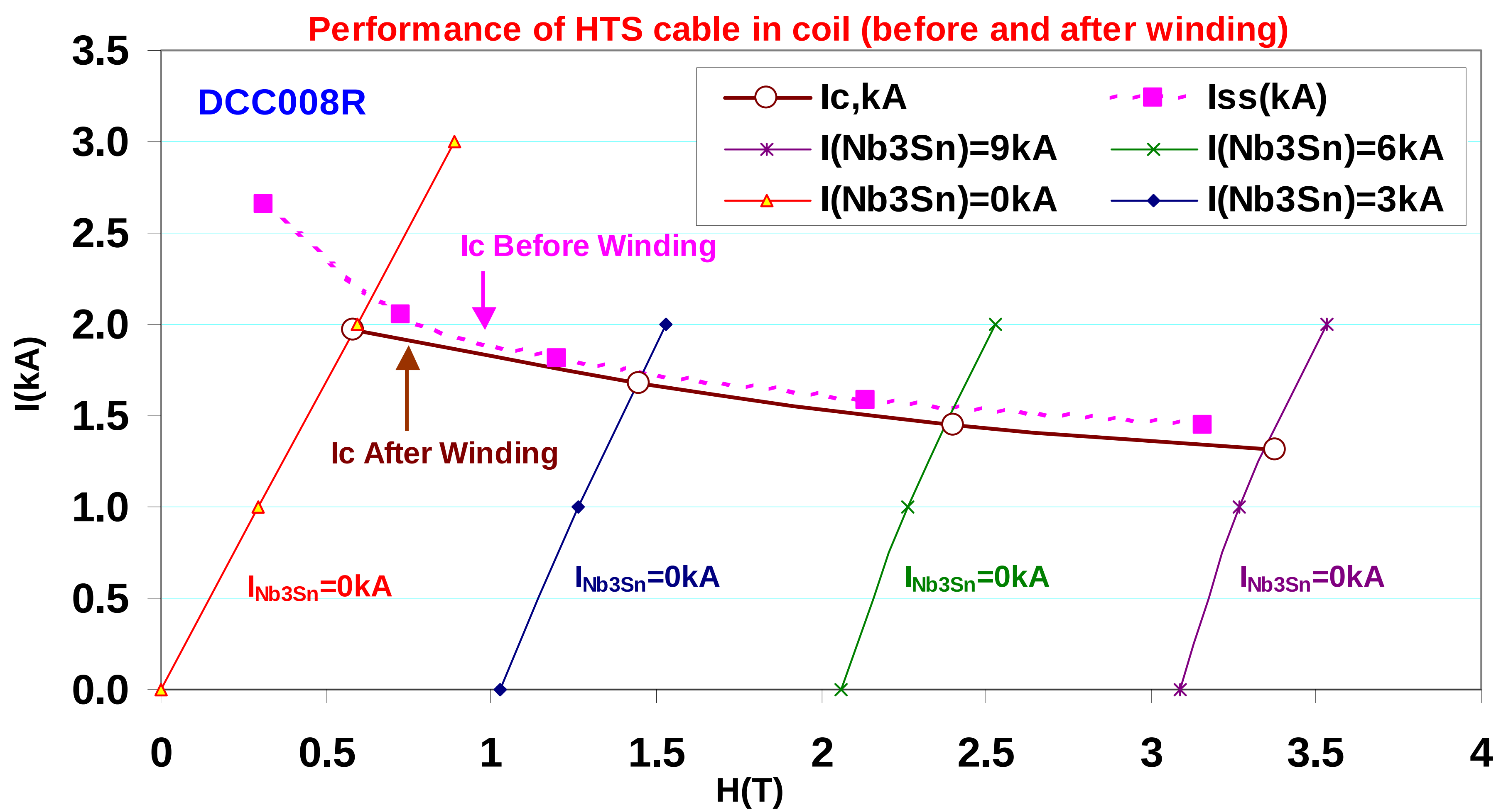
Performance of HTS Coil in the Background Field of Nb_3SN Coils



HTS coil was subjected to various background field by changing current in "React & Wind" Nb_3Sn coils (HTS coil in the middle and Nb_3Sn on either side)

Summary

- React and Wind approach has a potential to offer a significant advantage in developing Nb_3Sn magnet technology that is scalable for large scale production of long magnets.

- The performance of Nb_3Sn React & Wind magnets with ITER has been impressive in low to medium field magnets.

- We need to do more conductor and magnet R&D to demonstrate similar success with high performance Nb_3Sn in high field React and Wind magnets.

- React & Wind HTS conductor and magnet program continue to show progress.