ReBCO at BNL

Ramesh Gupta
for
BNL and Collaborators

4th Workshop on Accelerator Magnets in HTS (WAMHTS-4)

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Components of BNL HTS Magnet Program

Significant Ongoing HTS Project:

- HTS/LTS hybrid dipole test results (just concluded, MANY quenches)

Commissioning of 10 T background field facility for HTS/Nb_3Sn racetrack coils: new, unique, rapid-turn-around, lower-cost, available to anyone

Major HTS Project, Just Started:

High field (25 T), large aperture (100 mm) HTS solenoid for IBS, Korea

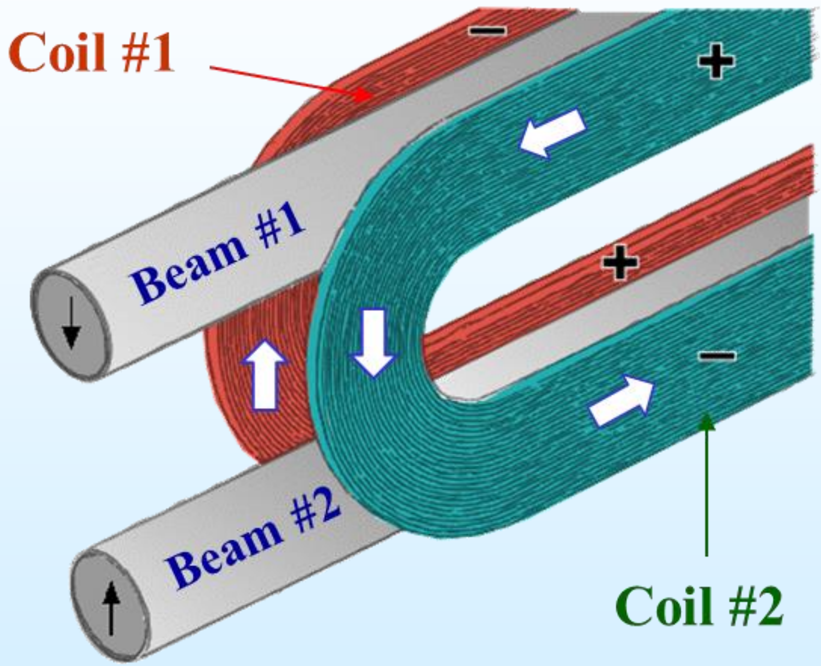
- Need to build a well protected facility magnet - open work, please join
- Need significant ReBCO (5-8 km, ~12 mm wide) - open to all vendors

Designs for high field HTS magnets

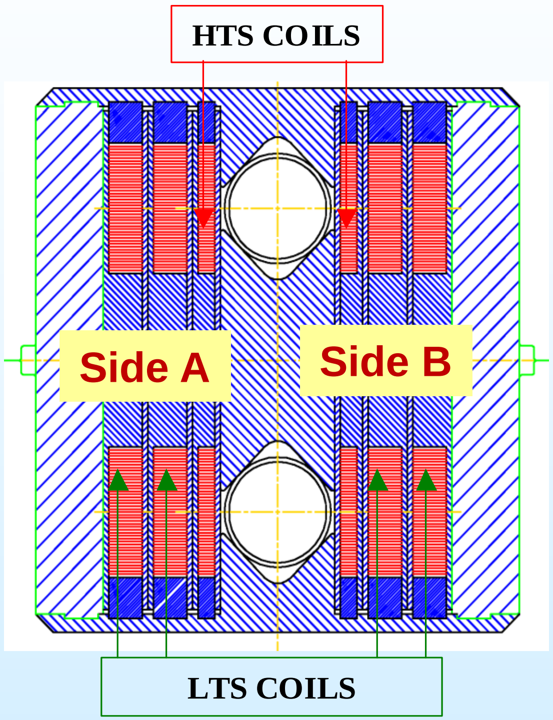
- Conductor friendly magnet designs

Common Coil Design for Colliders

Principle: Innovate magnet designs to make the best use of the strength of new conductors



Modular Design



- Simple, large bend radii, conductor friendly design to allow many technologies
- Allows various HTS cables with essentially no degradation : CORC, Roebel, ...
- Easier segmentation between the HTS & LTS coils; easier stress management
- Modular design : attractive for performing novel and systematic magnet R&D

Slide from ASC2006

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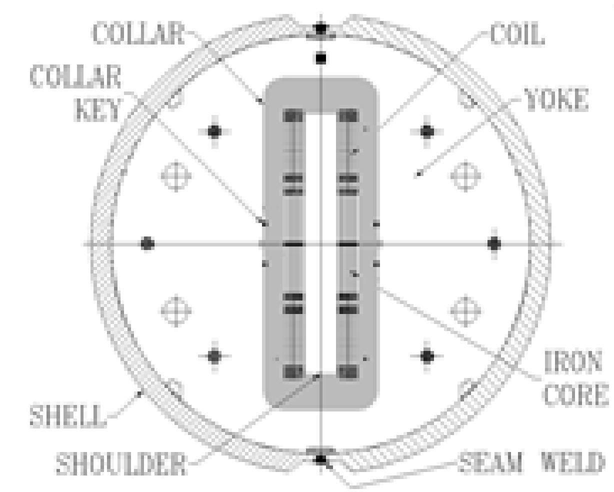
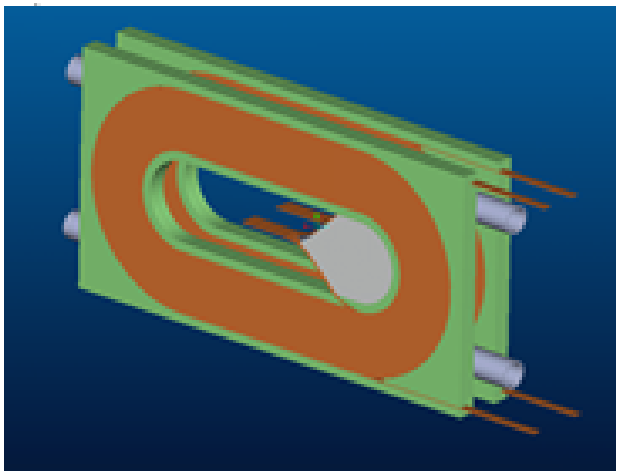
Basic Features of BNL Nb_3Sn 10^+ T React & Wind Common Coil Dipole





- 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

The Background Field Nb_3Sn Dipole

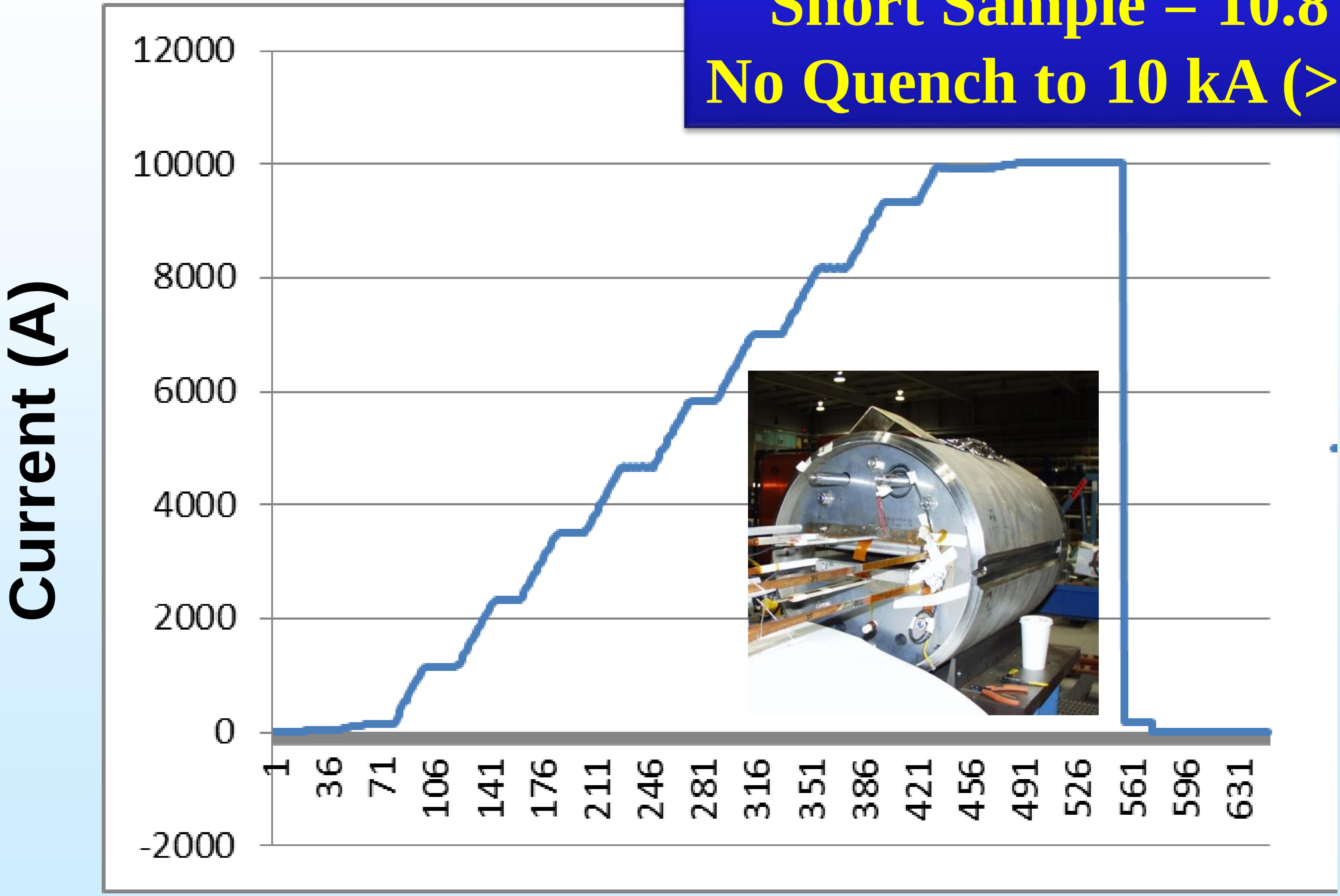
- **The Nb_3Sn BNL common coil dipole DCC017 reached the computed short sample field (100%) in 2006.**
- **However, it has been sitting for over 10 years with no special storage.**

Will it work?

- **YES, IT DID! Ramped many times. Did many test runs in last couple of weeks. Didn't quench up to the 92.5% short sample.**
- **It keeps going, and going, and going, as long as the leads allow.**
- **Very comforting news, indeed! Isn't it?**

Powering of Nb_3Sn Common Coil Dipole After a Decade

Short Sample = 10.8 kA
No Quench to 10 kA (>92%)

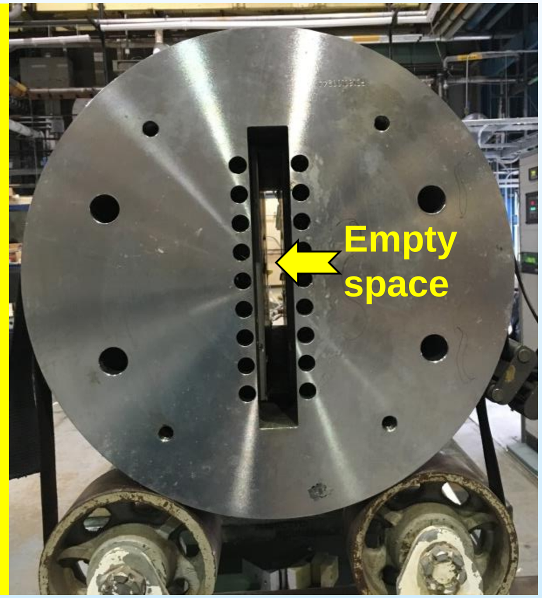


HTS/LTS Hybrid Dipole

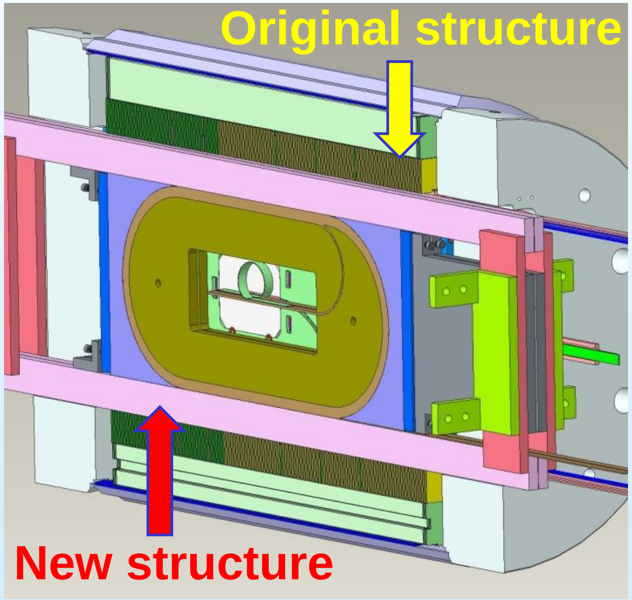
A unique feature of BNL 10T Nb_3Sn common coil dipole:

Large space in magnet for inserting "racetrack coils" without any disassembly

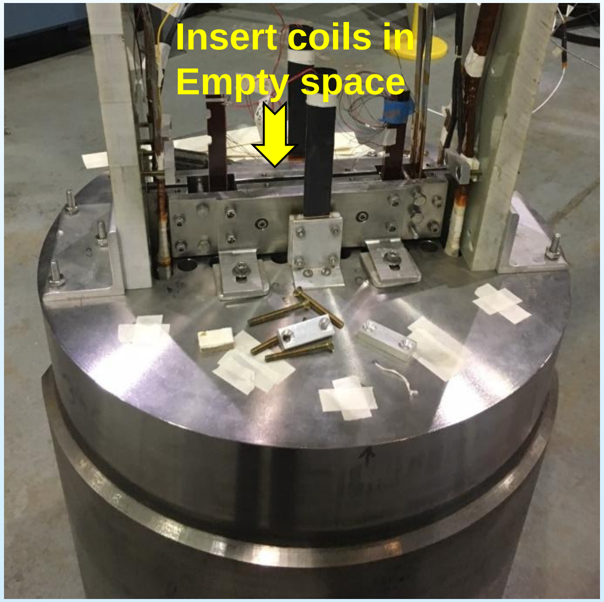
- Basic R&D and demo and try new technology with rapid around at a low cost



BNL Nb_3Sn common coil dipole DCC017 without insert coils



New HTS coils slide inside the existing Nb_3Sn coils. New coils become integral part of the magnet



HTS coils inside Nb_3Sn dipole - early experience of HTS/LTS hybrid coils

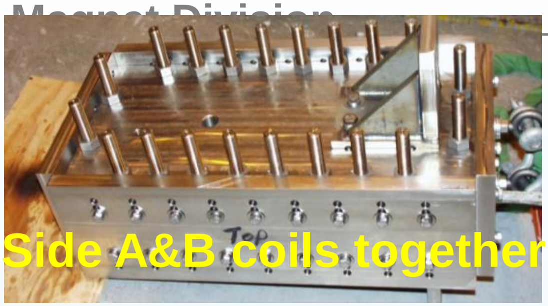
Small Aperture R&D Magnet

- **Common coil design offers an option where the aperture can be made small *"to do initial evaluation of the high field magnets R&D at a much lower cost and efforts*".**

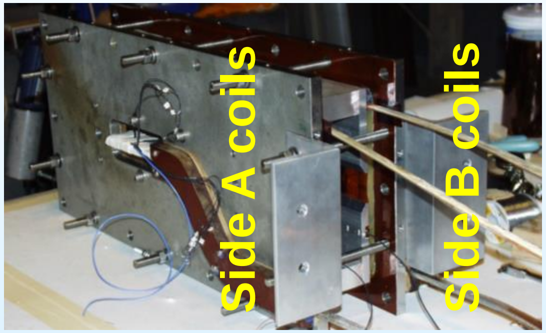
- **Natural question: how much of these low aperture results are applicable to "the magnets with real aperture?"**

- **The answer depends on how these small aperture magnets are designed & built. Let's examine different scenarios.**

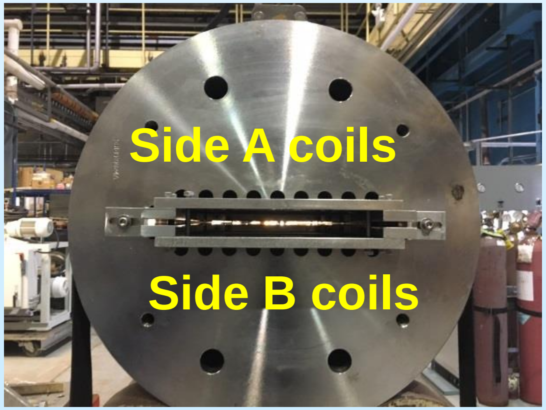
Relevance of Aperture in Magnet R&D



All coils in a single structure



Structure separating coils



Visible space between left and right insert coils inside DCC017

- If the design is such that one side of coils are independent of the other side of coils, then how much does it matter that how far they are, as long as the individual set of coils are subjected to the same level of field & stresses.
- Compare this with using the results of R&D between the long magnets & the short magnets
- Yes, long magnets give complete results. But if we were relying only on them then what would have been the cost of developing technology; or examine different options; or how much R&D we would have been able to do?
- Common coil design with an option of doing R&D with smaller aperture takes the value of subscale magnet R&D to the next dimension.

Ambitious Goals of the PBL/BNL STTR

- Study the HTS tape magnetization in real coils for field parallel and field perpendicular configurations
- Build HTS/LTS (ReBCO/Nb_3Sn) hybrid dipole and test at 4K in the limited SBIR/STTR funding (~1M$)
  - ✓ Yes we essentially managed this task, thanks to …

> - High Speed Pictorial Tour of the Hardware
> - Followed by the Initial Test Results
> - Is this the first significant hybrid dipole?

HTS Coil Winding (1)

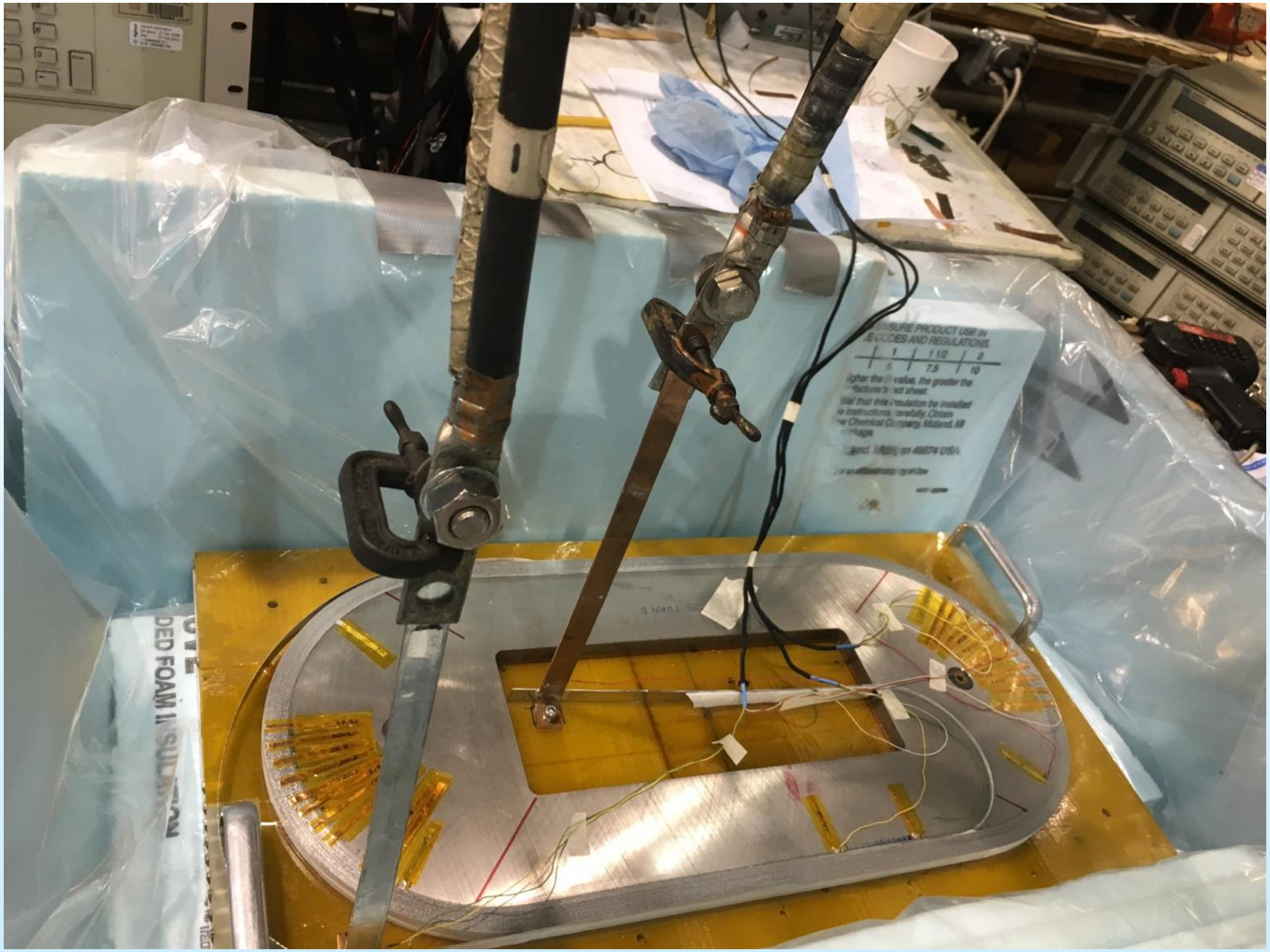
Coil wound with the 4-ply ASC tape and Nomex insulation. 35X2 turns. Two coils use ~300 meters of 4 mm equivalent.

HTS Coil Winding (2)

Many v-taps for detailed 77 K test study and diagnostics

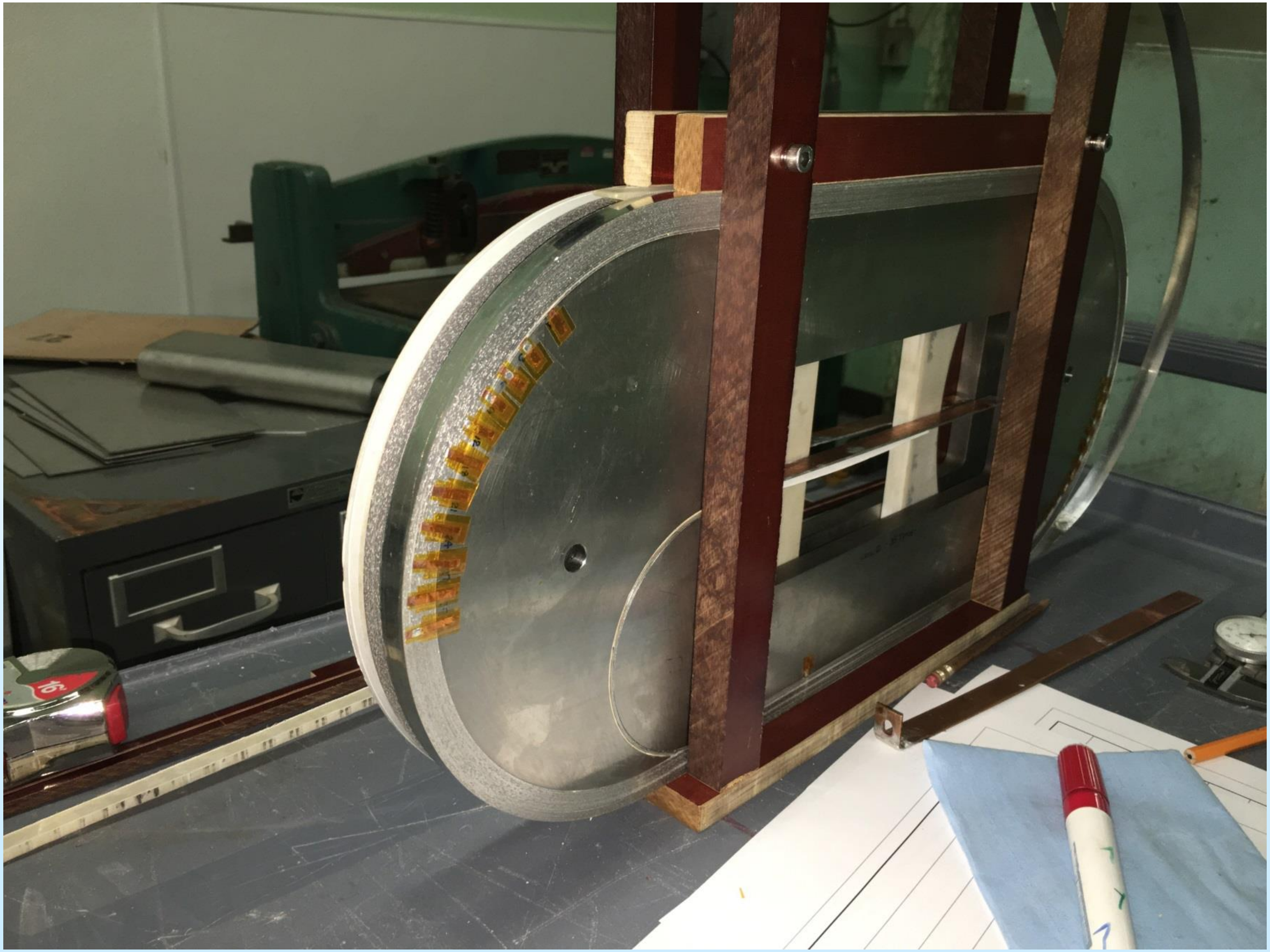
Everything looks OK under the microscope

Single Pancake HTS Coil Tests (2)



In HTS coils, low cost 77 K testing with a large number of v-taps, reveals a lot (2 coils, 2 tests)

Two HTS Coils Assembled in the Common Coil Configuration



½ inch aperture

All Cleared by a Young Scientist

Hall probe installed for magnetization measurements at 77 K

Common coil configuration to study field perpendicular case

HTS Common Coil Magnet (just out after 77 K test)

Cost-effective Sign of Our Sponsors Carved

Coils Placed Side-by-Side for 77 K Test

This configuration allows Field Parallel Magnetization Measurements

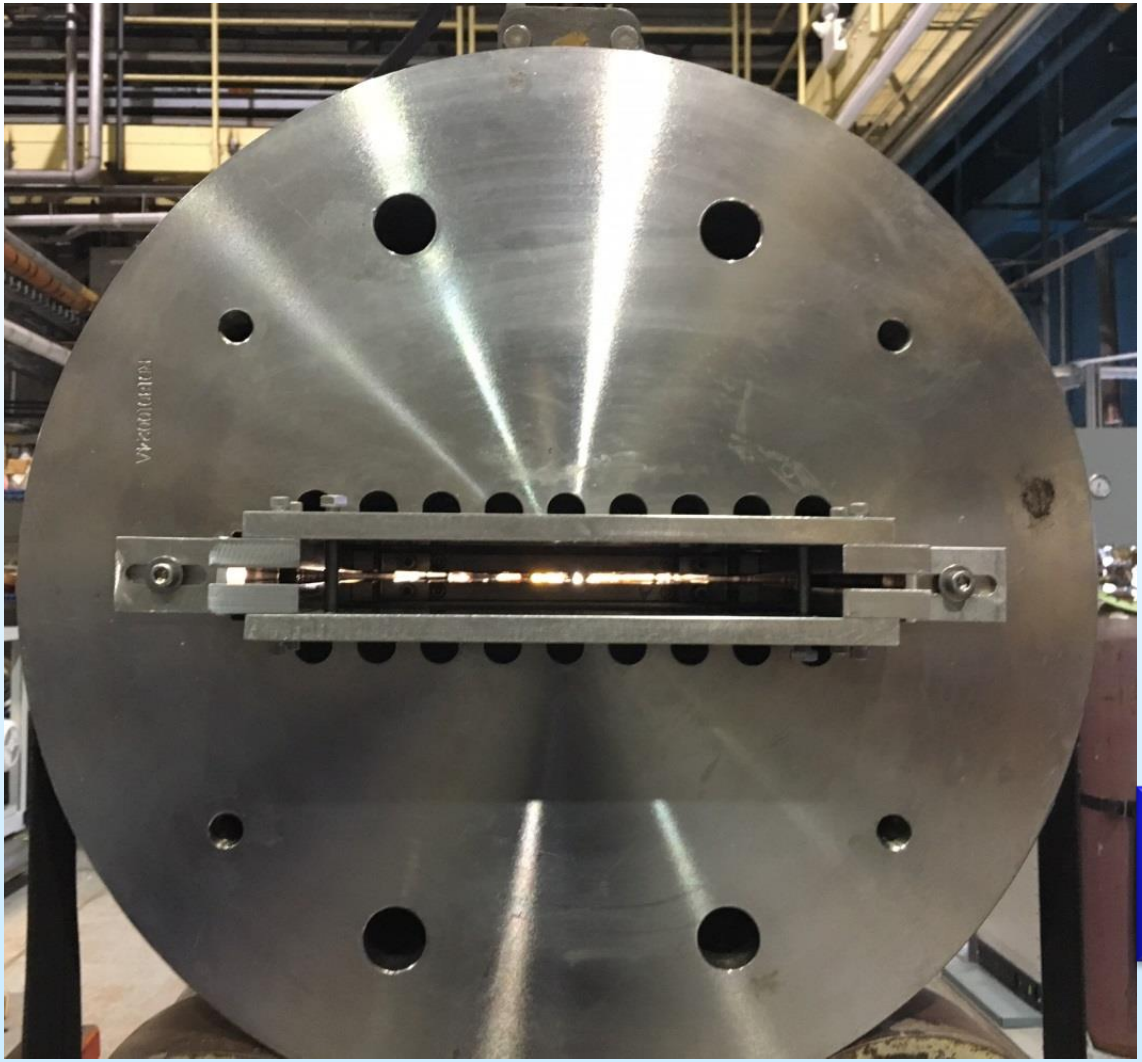
Coil cross-section was made square to compare similar geometries for field parallel (this case) and field perpendicular (previous case)

Dry Run for Final Assembly

Dry run to see that the metal frame structure will fit inside the common coil magnet opening

Metal part fabrication was coordinated and purchased by PBL (saves on overhead)

Metal Structure Inserted



Further check to see that the two pancake coils can be separated out by ~1/16" after the installation

(You can see light through the end of the gap

Two HTS Coils Getting Assembled in the Metal Frame

Internal Splice Made (flexible to allow separation)

Close-up of Flexible Splice

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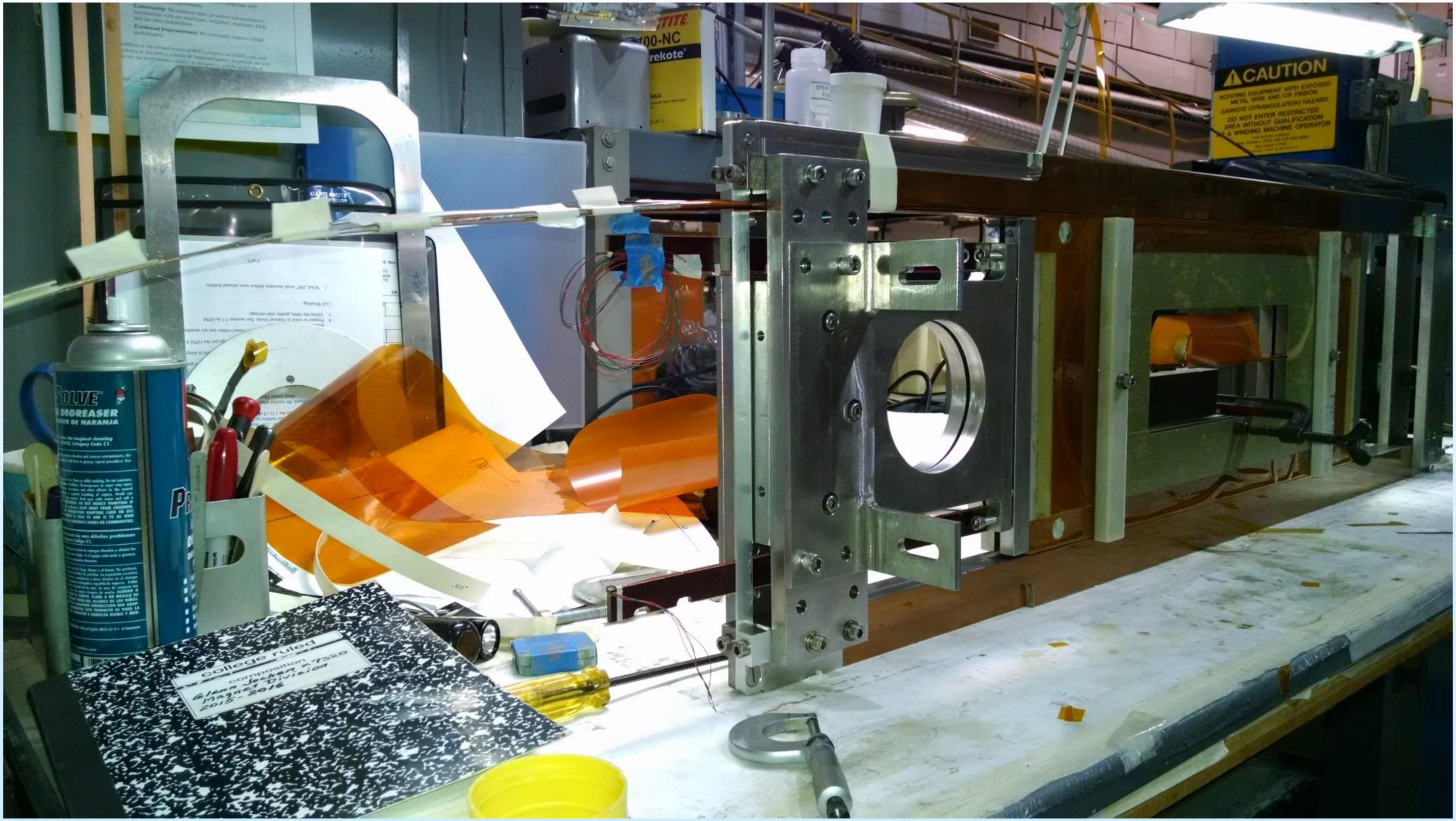
HTS Common Coil Assembly Ready with Current Leads Installed



Here Comes Our Latest and Longest Cryostat

(generously sized to serve whole body assembly)

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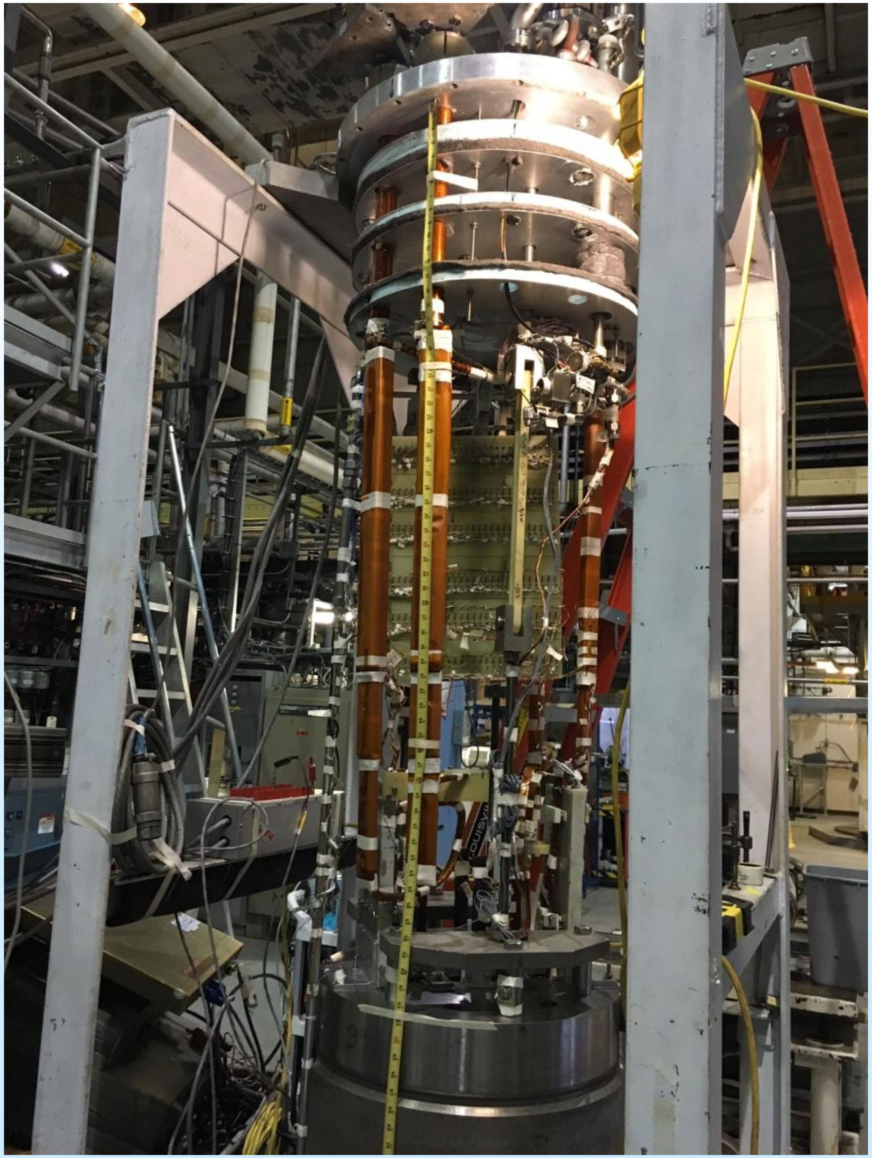
77 K Pre-test of Two HTS Coils Assembled as in Common Coil

HTS allows such pre-tests before the more expensive 4 K Tests

HTS Coils Installed inside the Magnet

Magnet with the Top-hat



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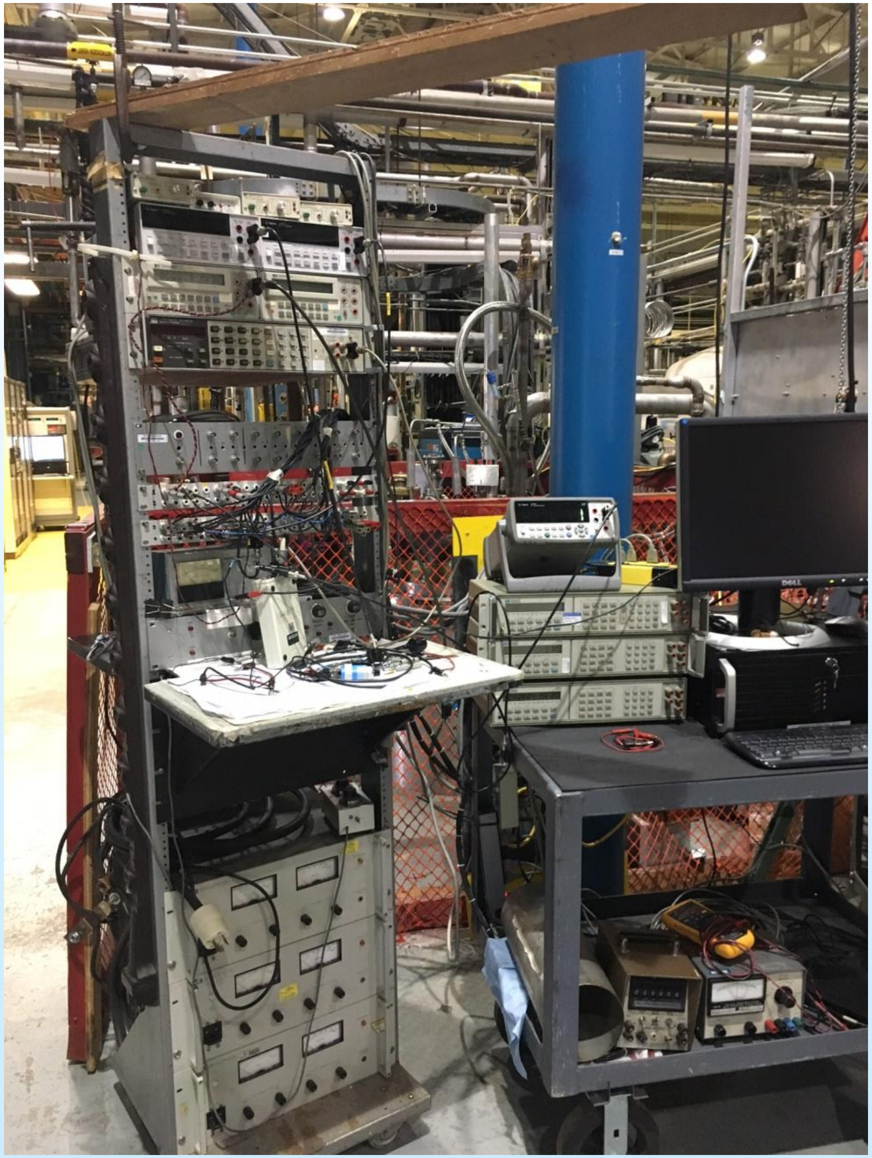
HTS Quench Protection

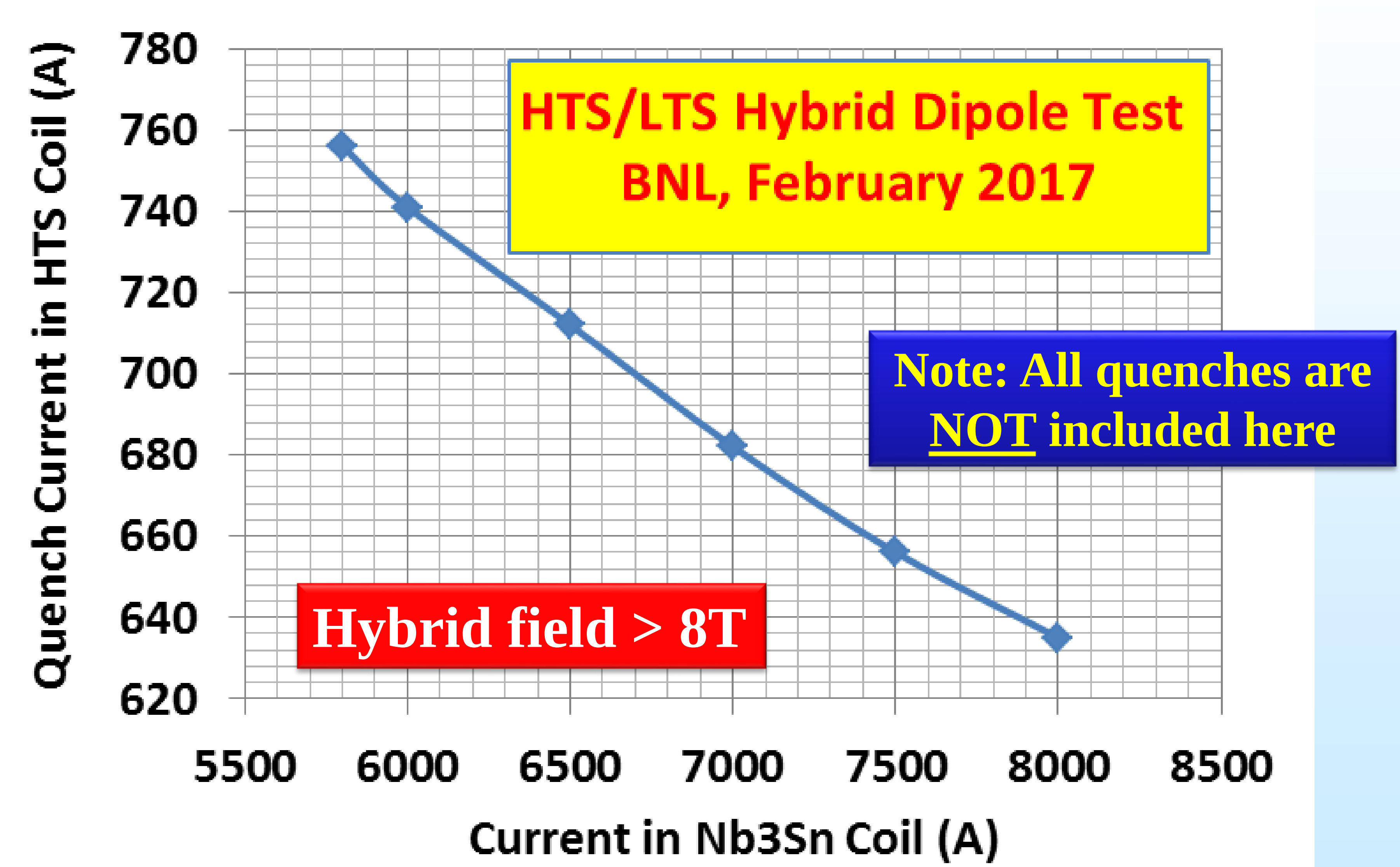


HTS/LTS Hybrid Dipole Tests at 4K

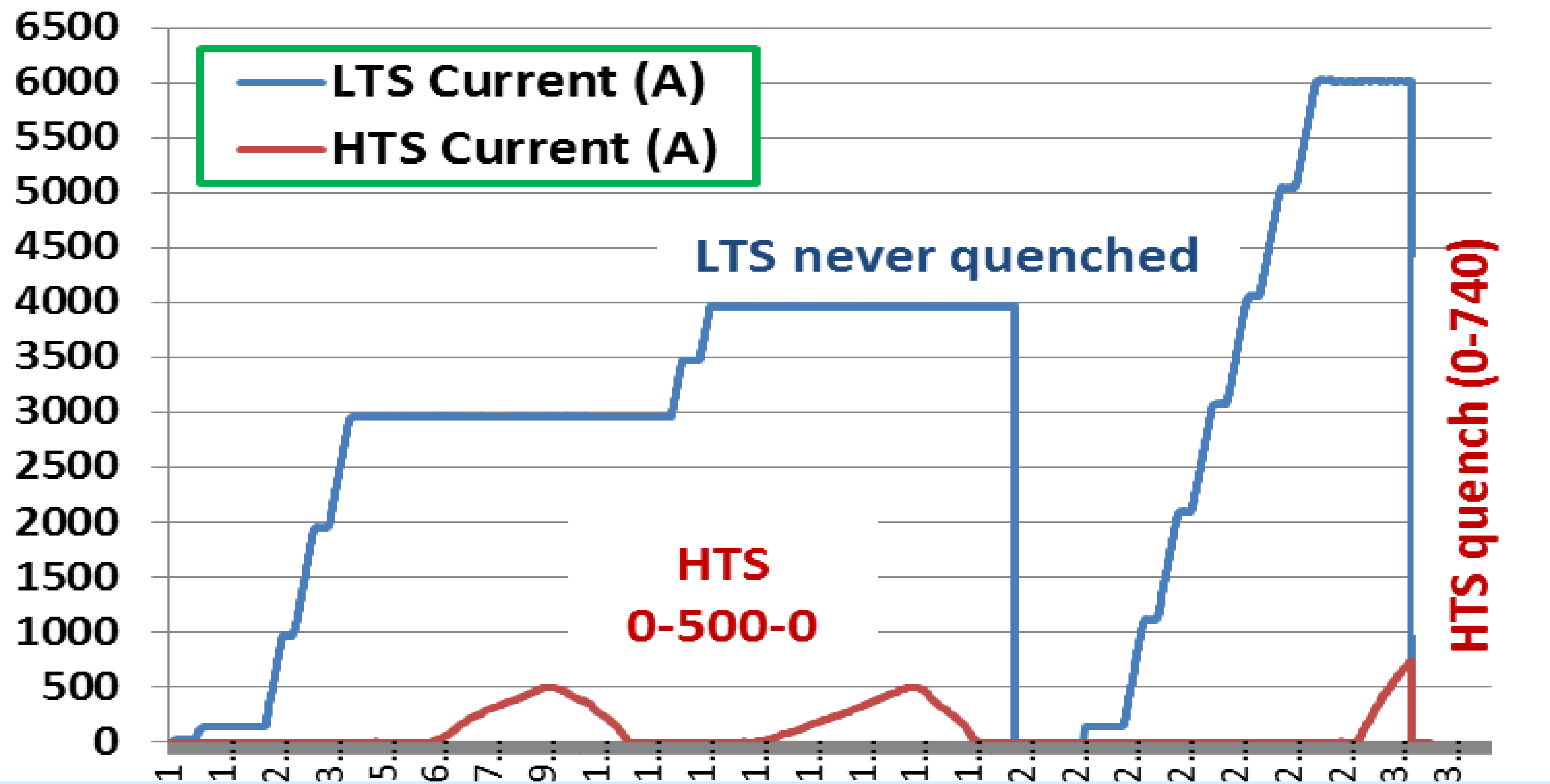
- Initial low current test on LTS/HTS coupling to experimentally set quench protection parameters
- Perform quench and magnetization studies
  - First do typical up and down ramps in HTS 0 A => 500 A => 0 A with field in LTS fixed at various levels (0 to 8000 A)
  - Fix current in LTS and change current in HTS till it quenches
  - Two hall probes in two apertures (cross-verification, unique feature)

HTS coil quenched many times.
NO damage or degradation observed.

Can You Believe That There is a Slide Like This

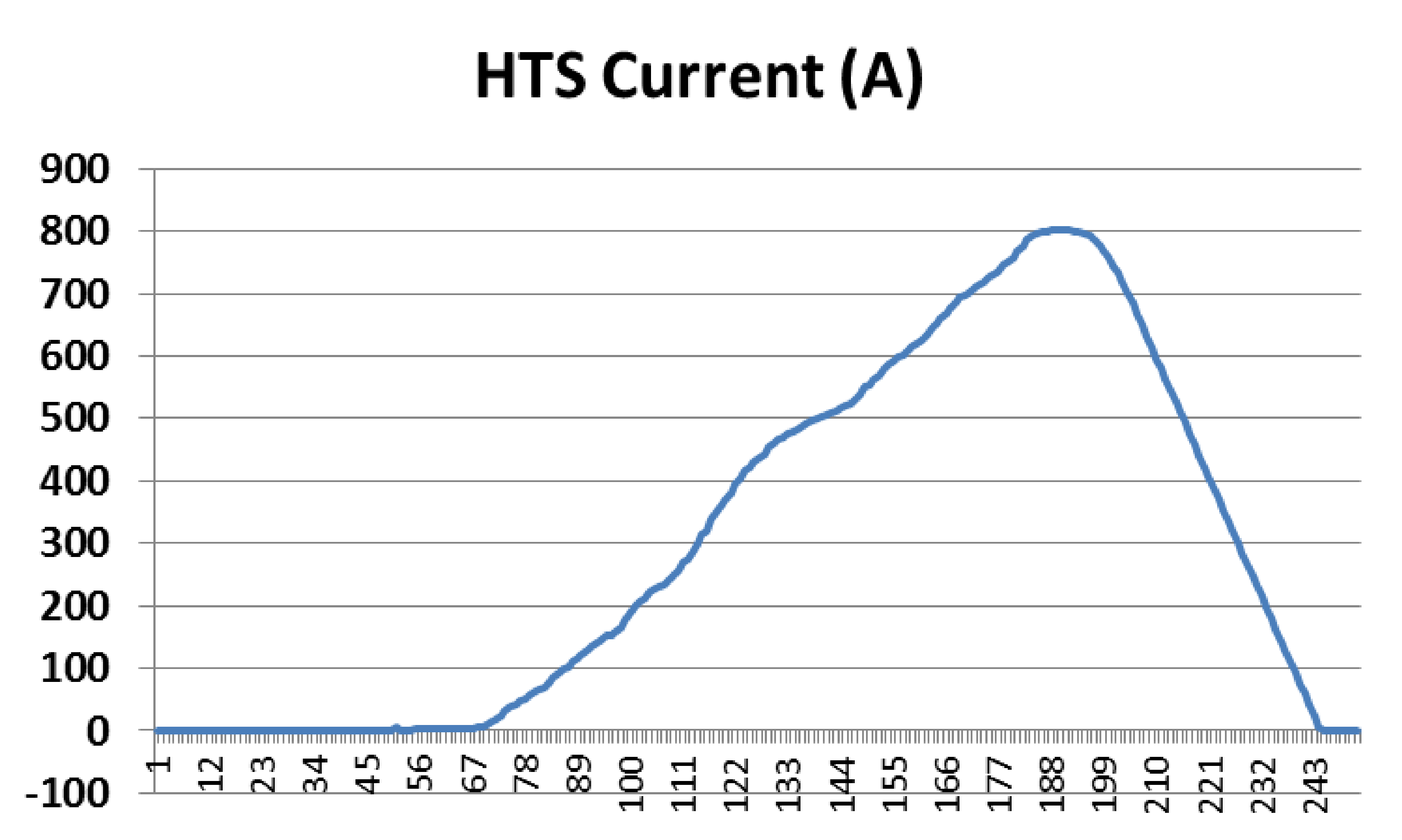


Another Plot



- Test was repeated again after the quench.
- No degradation in performance observed.

Only HTS Coil Powered



(HTS coil powered multiple times to 800 A)

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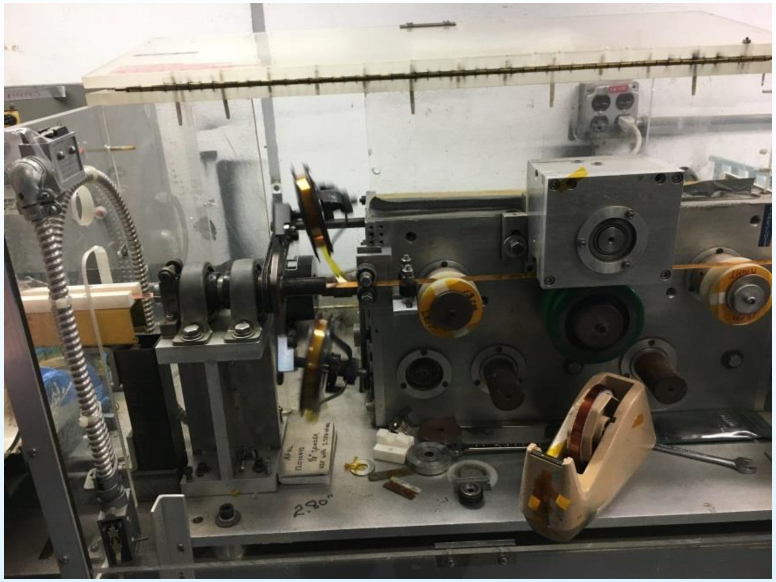
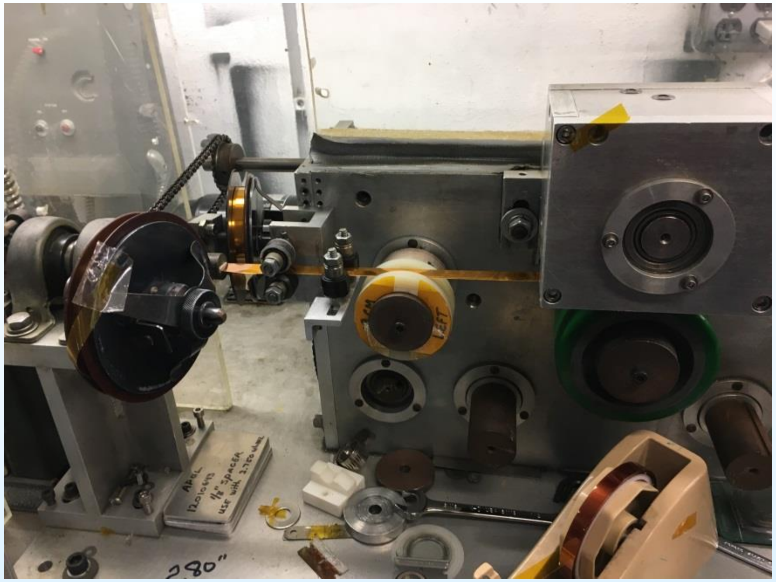
Kapton-Ci Insulation on ReBCO Tape (and Making a NbTi Type Cured Coil)



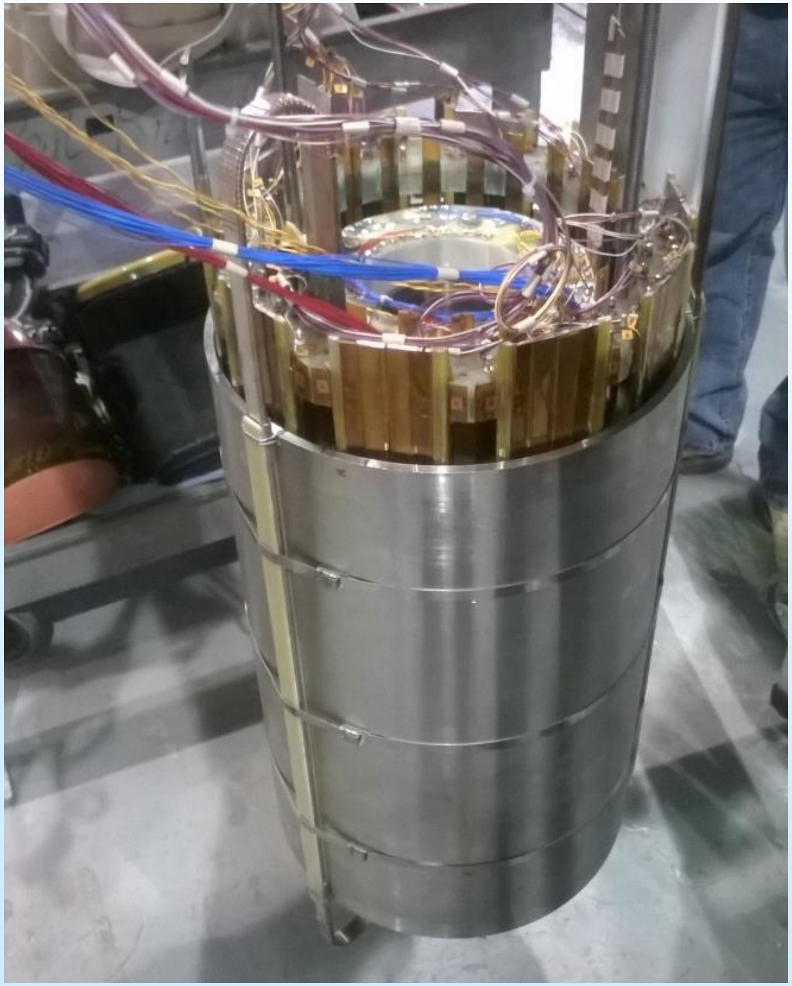


Part of the same STTR

77 K tests show no degradation in conductor performance

HTS Solenoid for SMES

Solenoid for IBS is based on the solenoid for SMES



- **Field: 25 T@4 K**
- **Bore: 100 mm**
- **Stored Energy: 1.7 MJ**
- **Hoop Stresses: 400 MPa**
- **Conductor: HTS (2G)**

ReBCO Used:

~6 km, 12 mm wide from SuperPower

- **Reached a critical field at 27 K: 12.5 T (new record for magnets operating over >10 K in a solenoid of similar sizes)**
- **Test terminated after arcing in leads at ½ of above field – NO quench problem.**

Requirements for IBS Solenoid ***Very Relaxed***

- ❑ Field quality: few percent (OK)
- ❑ Ramp-up time: days (OK)
- ❑ NO Insulation coil envisioned

Sensitivity of search => B^2 * Volume

- ➢ **Good first application to prove that HTS can produce high fields and can deal with high stresses**

Welcome discussions and collaboration

Conductor Requirement for IBS Solenoid

- Need significant ReBCO tape in 2 years
  - ~12 mm wide, 5-8 km (actual amount will depend on the performance/price)
  - All HTS wire suppliers welcome
  - May use 2 conductor suppliers
  - Preferred performance > 800 A@4K (any direction)

Conductor Friendly Dipole Designs

(three slides)

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Example: C5 Dipole

CORC Cable for Common Coil Collider Dipole

May be P5 recommendations can be satisfied by C5 Dipole

CORC® cables for Common Coil accelerator magnets

CORC® cables are ready for the next step

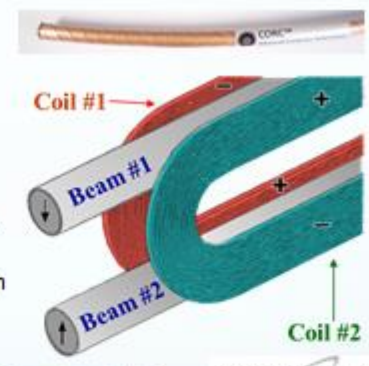
- R&D for their application into magnets
- Cable bending diameter > 100 mm
- Cable J_e(20 T) > 400 A/mm²
- Operating current > 10,000 A (20 T)

Common Coil magnet ideal for CORC® cables

- Conductor friendly design
- Performance determined by coil separation, not cable bending diameter
- Allows for large bending diameters > 250 mm

Proposed program to Department of Energy

- Teaming with Ramesh Gupta (BNL)
- 10 T LTS Common Coil outsert magnet
- Phase I SBIR funding requested to develop 5 T CORC® insert magnet



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Summary

CORC® cables with bending diameter > 100 mm

- Demonstrated J_e(20 T) = 309 A/mm²
- On track to reach J_e(20 T) > 600 A/mm²
- No new CORC® cables measured at high field after Oct. 2015 due to decommissioning of large-bore magnet at NHMFL
- CORC® cables are ready for conductor friendly accelerator magnets such as Common Coil magnets

CORC® wires with bending diameter < 50 mm

- Demonstrated J_e(20 T) = 145-210 A/mm²
- On track to reach J_e(20 T) > 300 A/mm² (Twente test next week)
- CORC® wires with thinner substrates and J_e(20 T) > 1,000 A/mm² on the horizon
- CORC® wires now wound into high-field solenoid and CCT insert magnets

CORC® magnet feeder cables now available

- CORC® feeder cables incorporated in 32 T REBCO magnets at NHMFL

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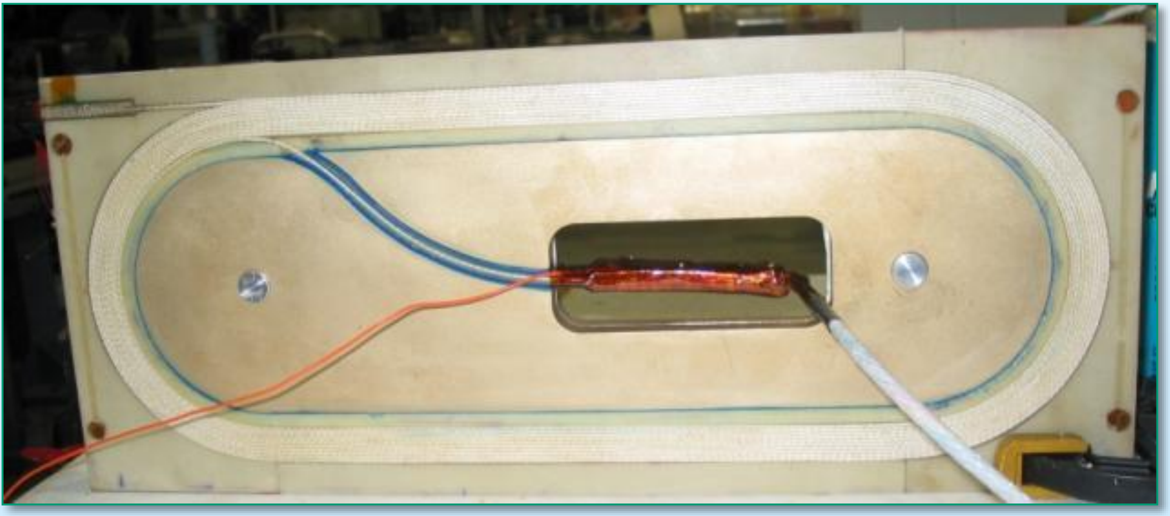
- **High current HTS coils running in series with Nb_3Sn coils provides a magnet with easier operation and easier protection**
- **6 mm CORC® cable is a factor of 2 higher in J_e than the smaller 3 mm diameter cable, has less wastage, lower cost, …**

Common Coil Design for React & Wind HTS Cable Coils

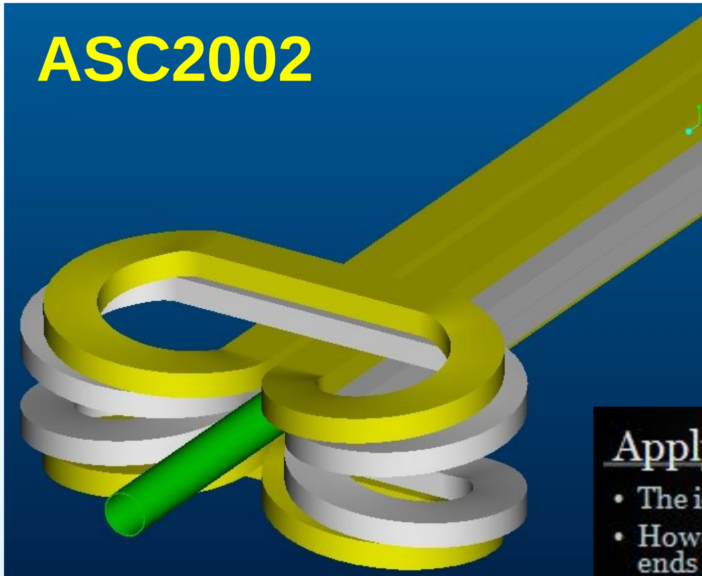
- **Due to large bend radius, the common coil design allows both "Wind & React" and "React & Wind" technologies**
- **For Bi2212 cable, it offers another option (real coils)**
- **Also works with the cable mentioned by SuperPower and CERN yesterday**



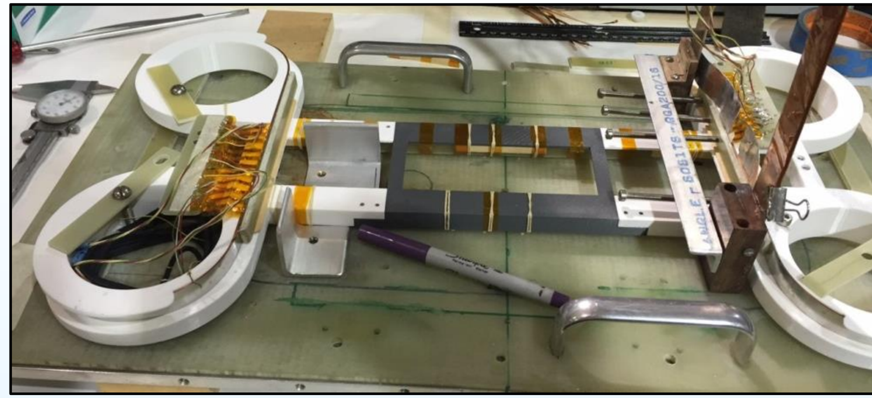
BNL "React & Wind" Bi2212 coil
8 coils, 5 magnets, 4.3kA (10/03)

BNL "React & Wind"
10 T Nb_3Sn Dipole

End Design for Block Coils

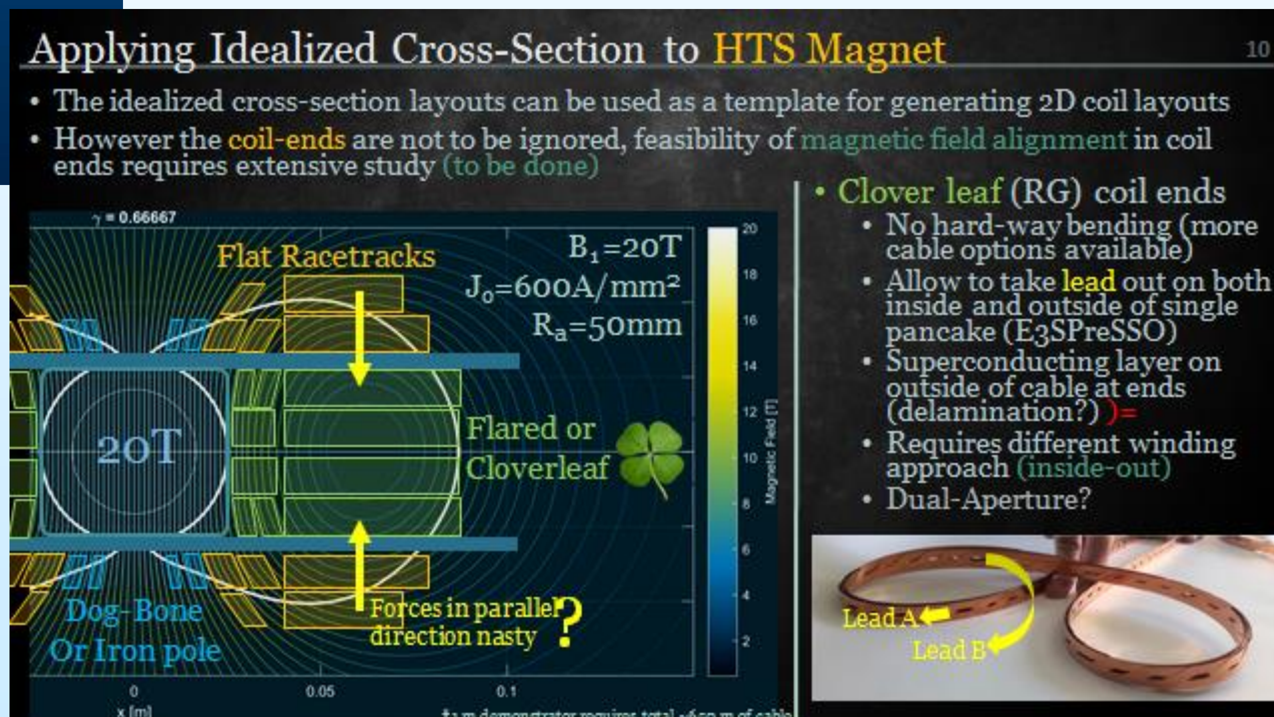


HTS Coils made in e2P/BNL Phase I SBIR



- Shorter ends
- Conductor friendly

New STTR proposal for Nb_3Sn with PBL



SUMMARY

- **Testing of Hybrid HTS/LTS dipole.**
- **Commissioning of the rapid turn-around, lower-cost test facility for racetrack coils should be useful to everyone around the word.**
- **High field (~25 T), large aperture (100 mm), HTS solenoid for IBS**