High Field HTS Magnet Program at BNL

Ramesh Gupta

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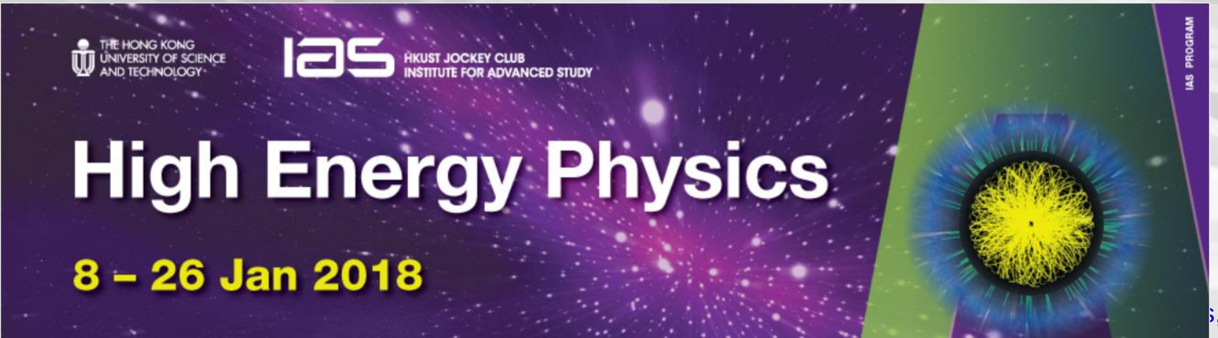
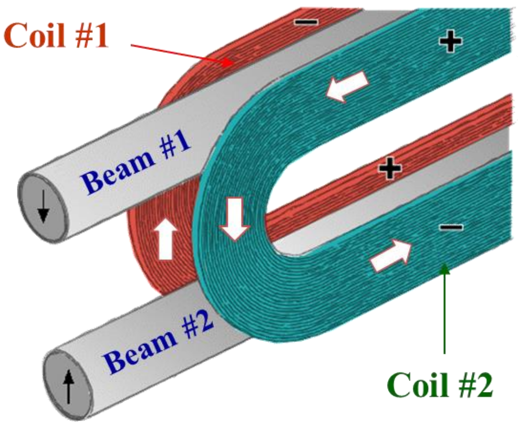
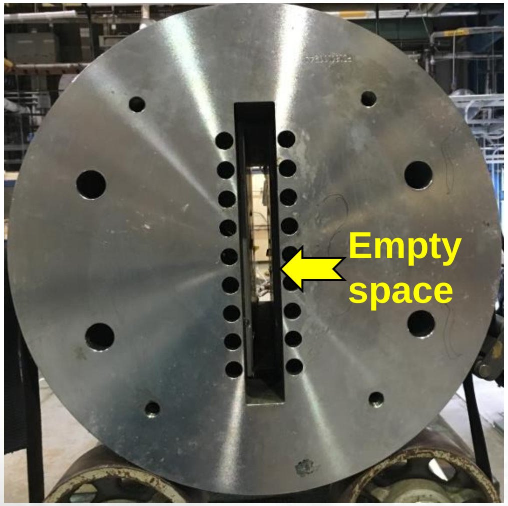


Recent HTS Magnet Programs at BNL

- ***Demonstration of HTS/LTS hybrid common coil dipole***
  - ***Use more expensive HTS where field is high and less expensive LTS (Nb_3Sn and/or NbTi) where field is low (part of PBL/BNL STTR program)***
  - ***A cost-effective, rapid turn-around R&D program/facility***
- ***High Field (25 T), Large Aperture (100 mm) HTS Solenoid***
  - ***HTS subjected to high field and high stresses***
  - ***Part of "Dark Matter Axion Search Program" at IBS, Korea. This magnet must be a reliable user magnet***

Unique BNL Common Coil Dipole

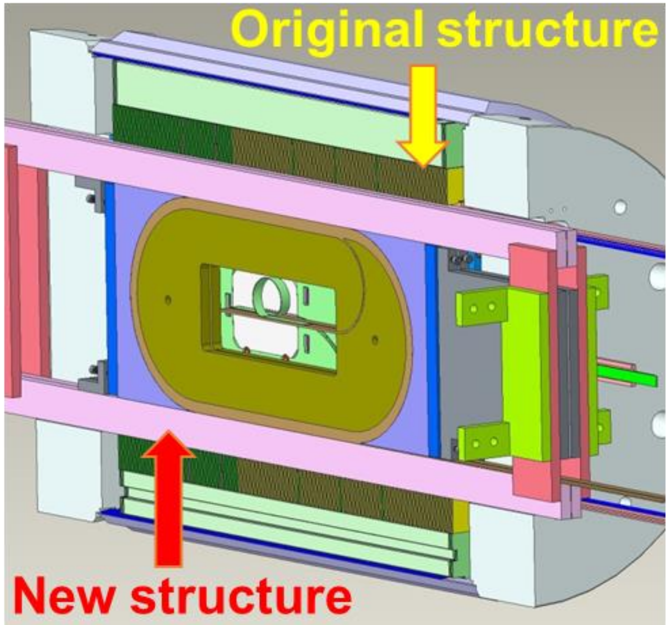




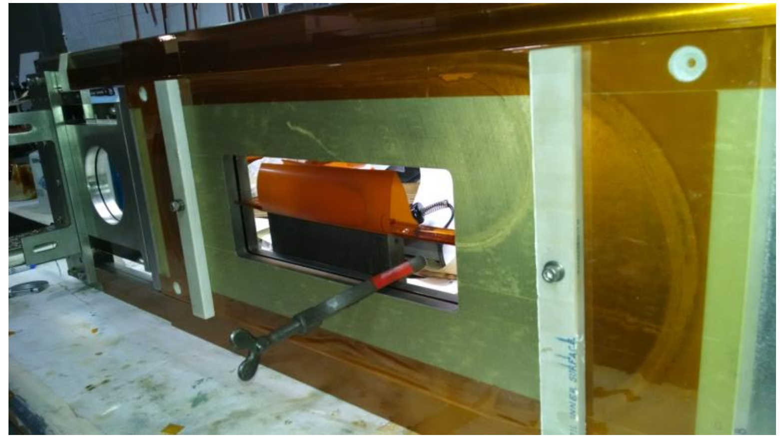
- Common coil 2-in-1 dipole design with simple racetrack coils that are common to both apertures
- Record demonstration of "React & Wind" technology
- Structure specifically designed to provide a large open space (31 mm wide, 338 mm high)
- New racetrack coils can be inserted in the magnet without requiring any disassembly or reassembly
- New insert coils become an integral part of the magnet. Coil tests become magnet tests
- Rapid-turn-around (<2 years), lower cost approach (allowed HTS/LTS hybrid dipole (<2 years, <1M$)

HTS/LTS Hybrid Dipole Structure

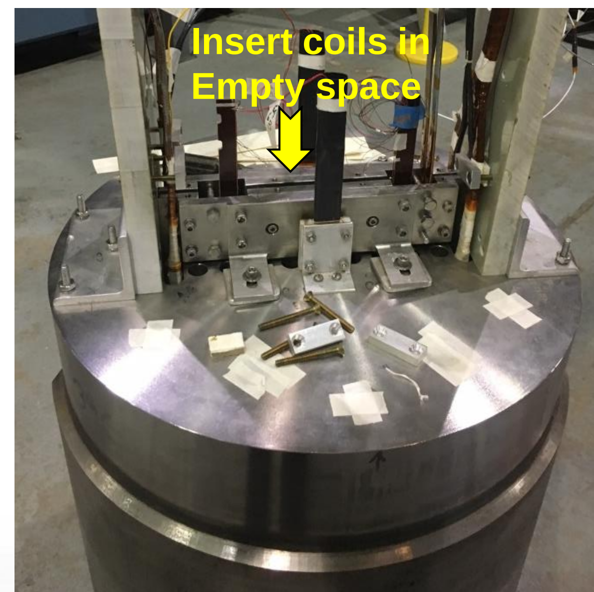
Design



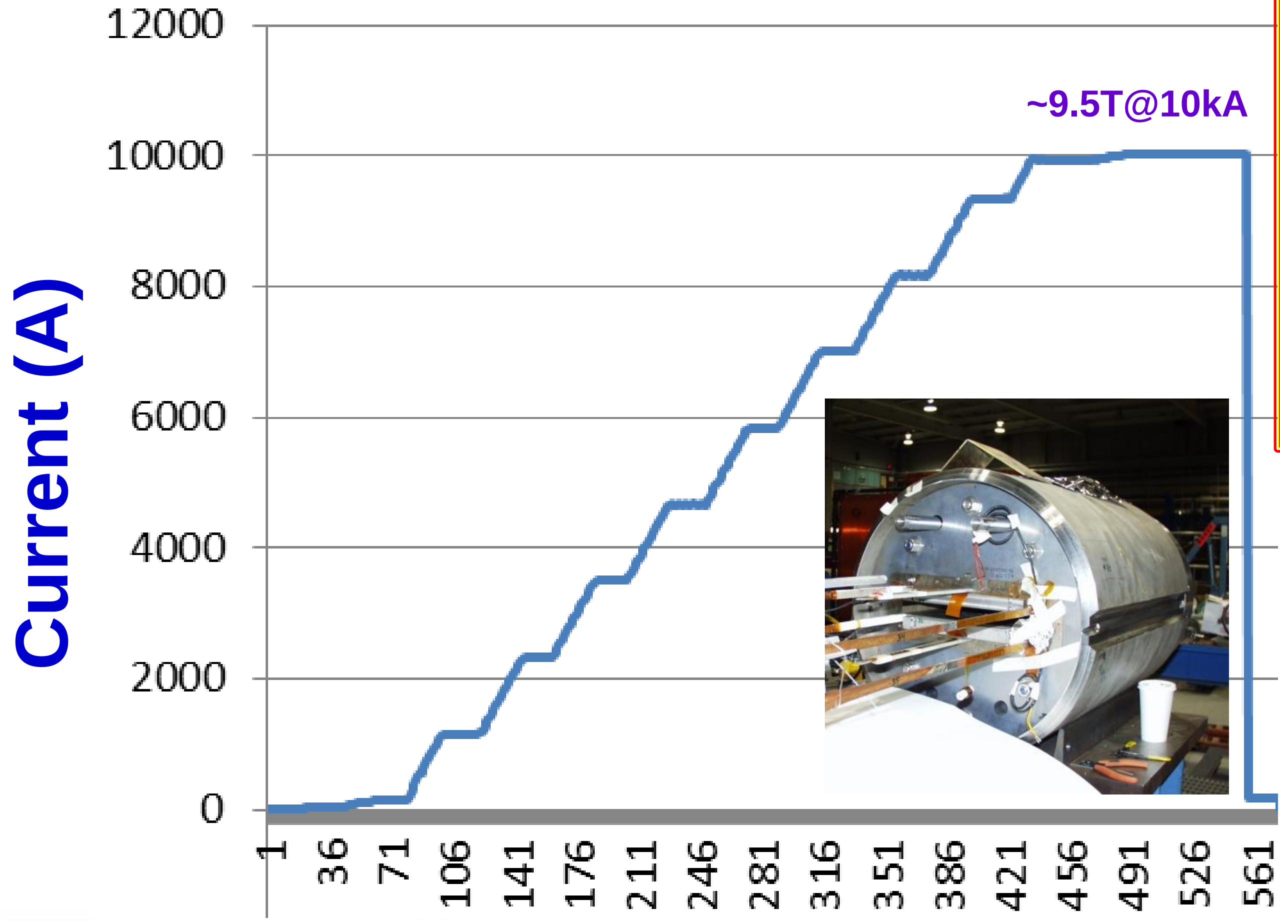
New HTS coils slide inside the existing Nb_3Sn coils and become an integral part of the structure



A pair of HTS insert coils



Retest of Nb_3Sn Common Coil Dipole After a Decade



A display piece of Nb_3Sn

"React & Wind" technology

for dipole

Worked well when tested again after a decade

- **Short Sample: 10.8 kA (reached during 2006 test)**
- **Retest: No quench to 10 kA (>92% of short sample)**

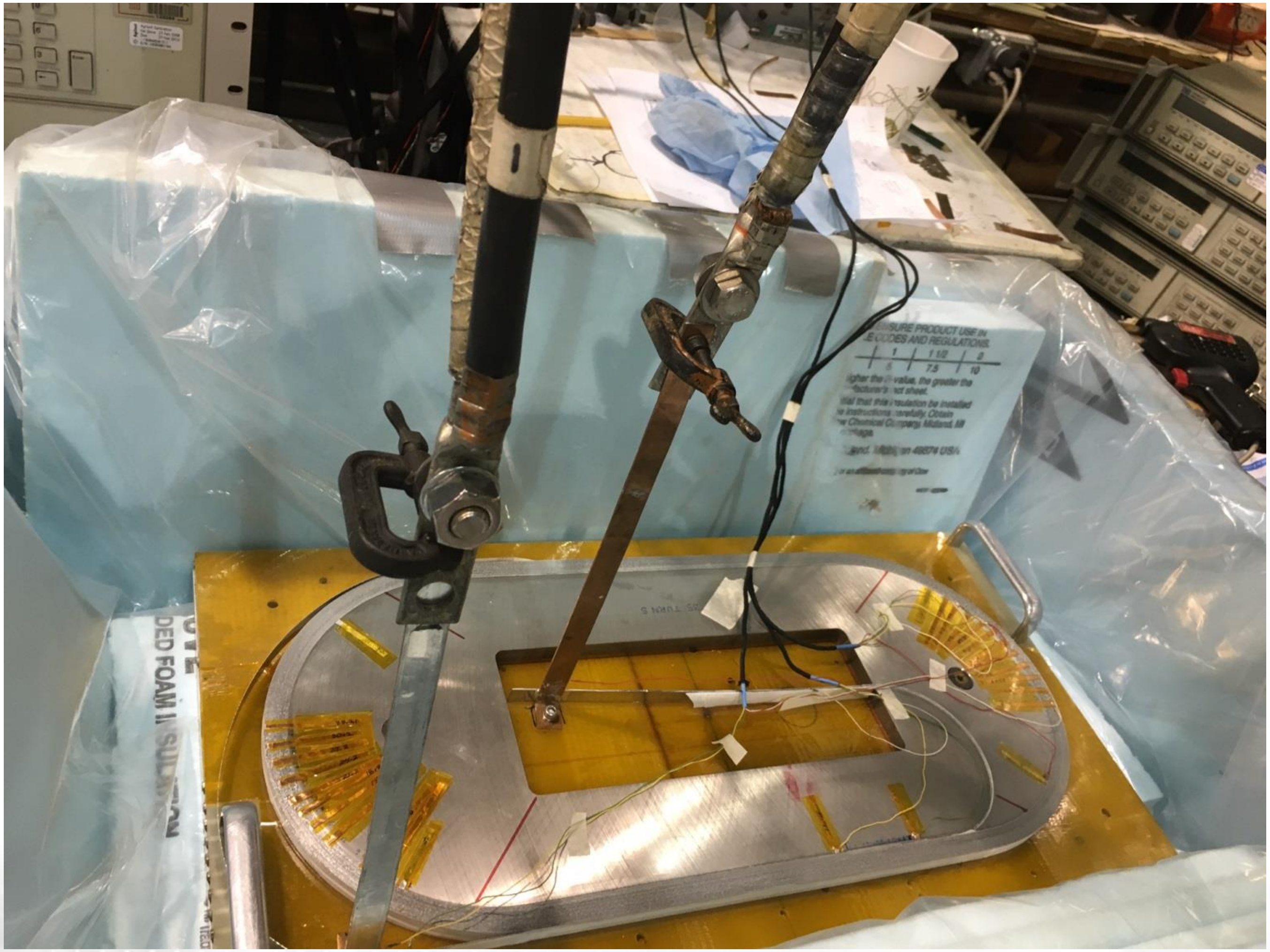
HTS Coil Winding (two coils wound)

Conductor:
- **12 mm ASC tape**

Insulation:
- **Nomex**

Two coils used ~300 meters of 4 mm equivalent

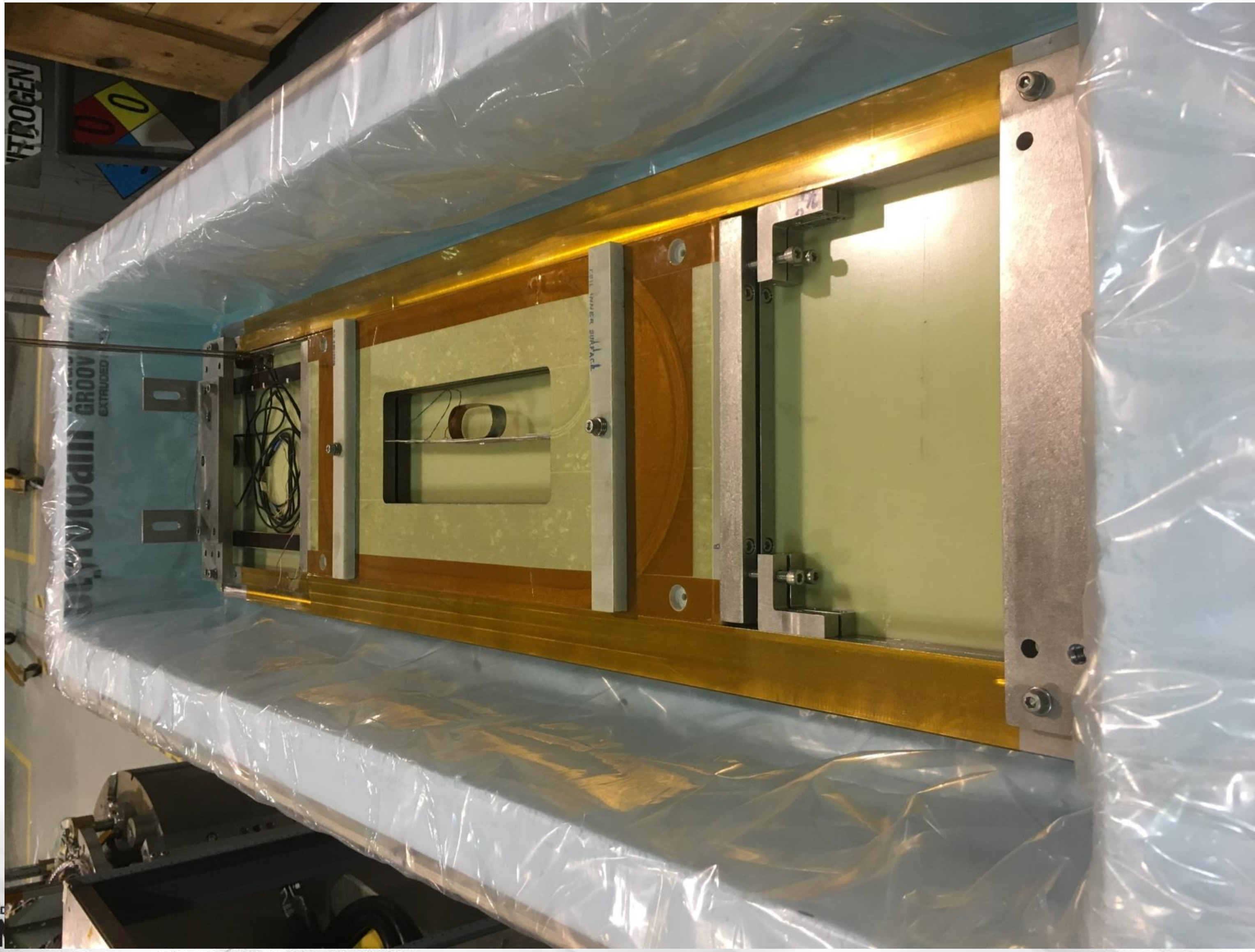
Single Pancake HTS CoilsTesting



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

Two HTS Coils Getting Assembled in the Metal Frame

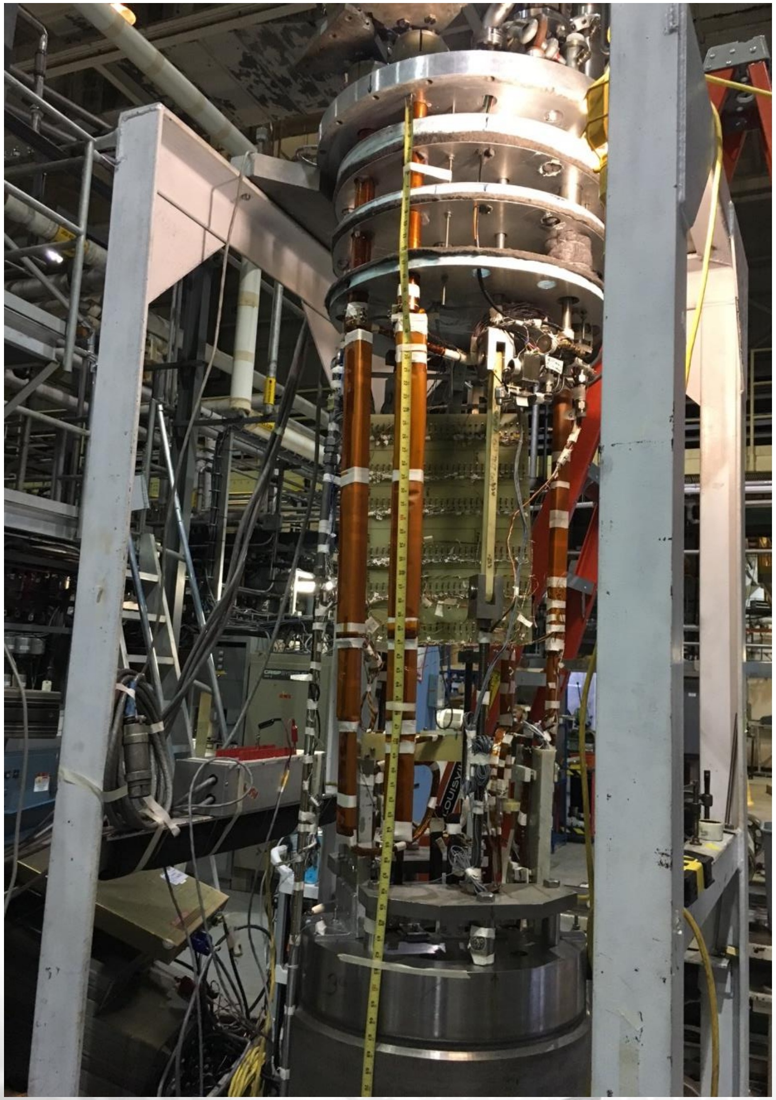
77 K Pre-test of Two HTS Coils Assembled as in Common Coil



HTS Coils Installed inside the Magnet

HTS/LTS Hybrid Dipole Quench Test Results

Challenges with the HTS/LTS Hybrid Dipole



- **Large coupling between HTS/LTS coils**
  - ➢ **Maximum current in HTS: ~800 A**
  - ➢ **Maximum current in Nb_3Sn: ~10 kA**
- **Protection of the HTS coils at 4 K**
- **Quench protection of HTS coils in HTS/LTS hybrid configuration**

Questions:

- **Can HTS coil survive quenches without significant degradation?**
- **Can HTS coils be operated like the LTS coils?**

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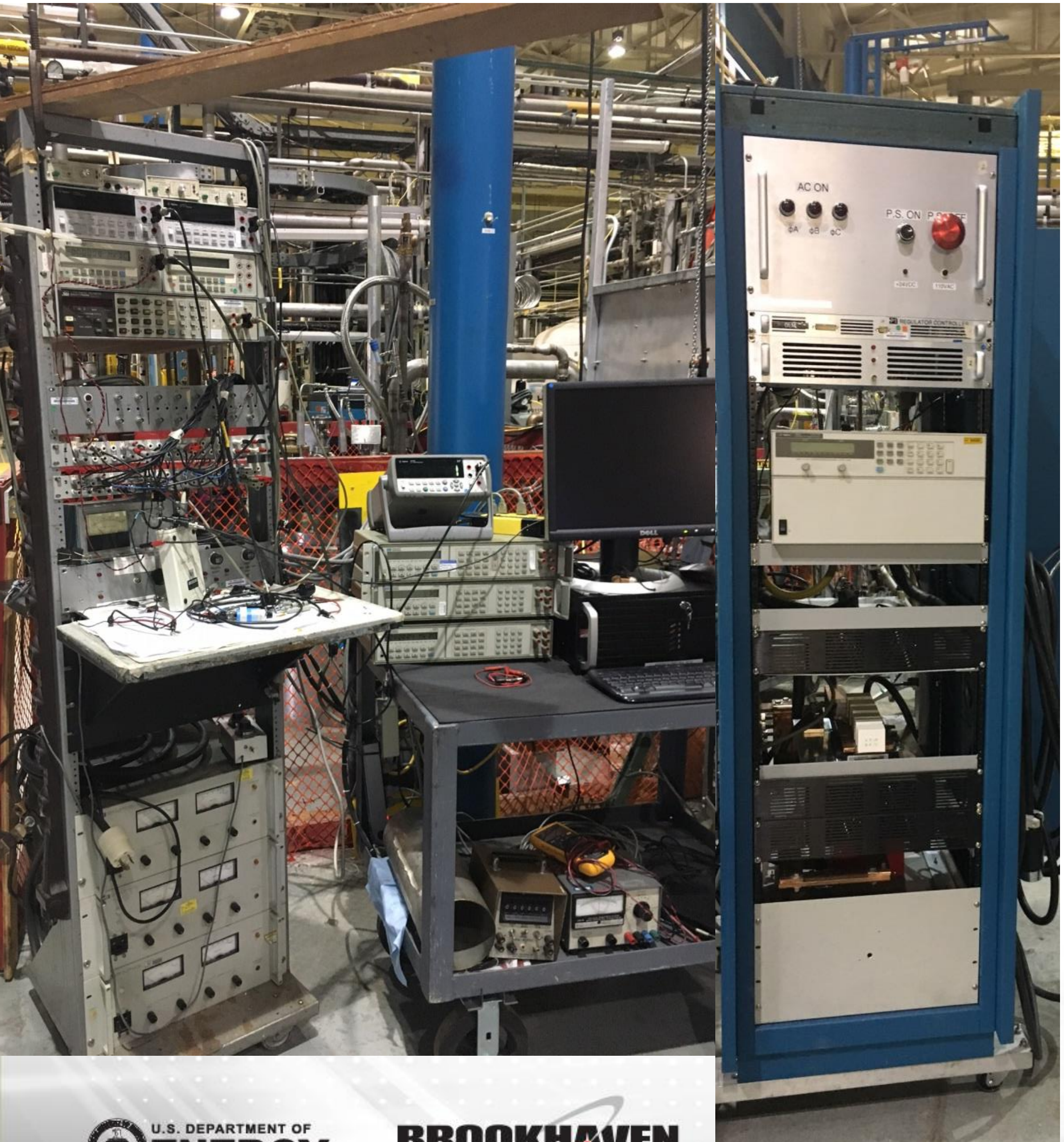
HTS/LTS Hybrid Operation and Quench Protection



- **HTS & LTS powered separately**
- **Common quench platform; fast energy extraction from both coils**
- **Quench detection response time: < 5 msec**
- **Coil current interruption: < 10 micro-second after detection**
- **HTS coil shut-off: a few msec**
- **High power IGBT switches**
- **Electronic threshold for quench detection: ~100 micro-volts**
- **HTS Quench threshold : 5 mV**
- **HTS coils were actually tested in more brutal conditions: ~200 mV (like LTS coils)**

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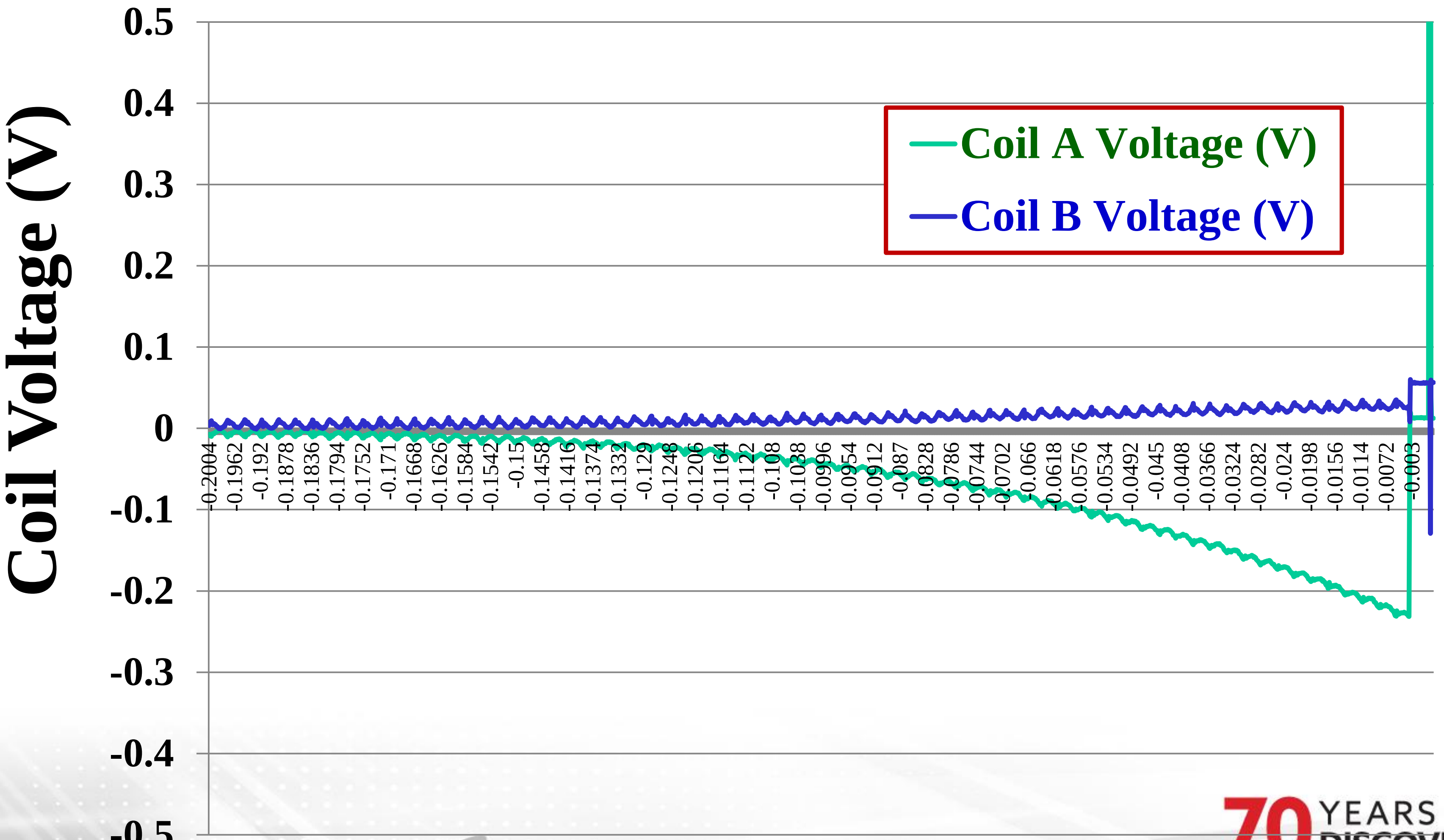
HTS coils operated like LTS coils

- ❑ Significant voltage in HTS coils: >0.2 Volts



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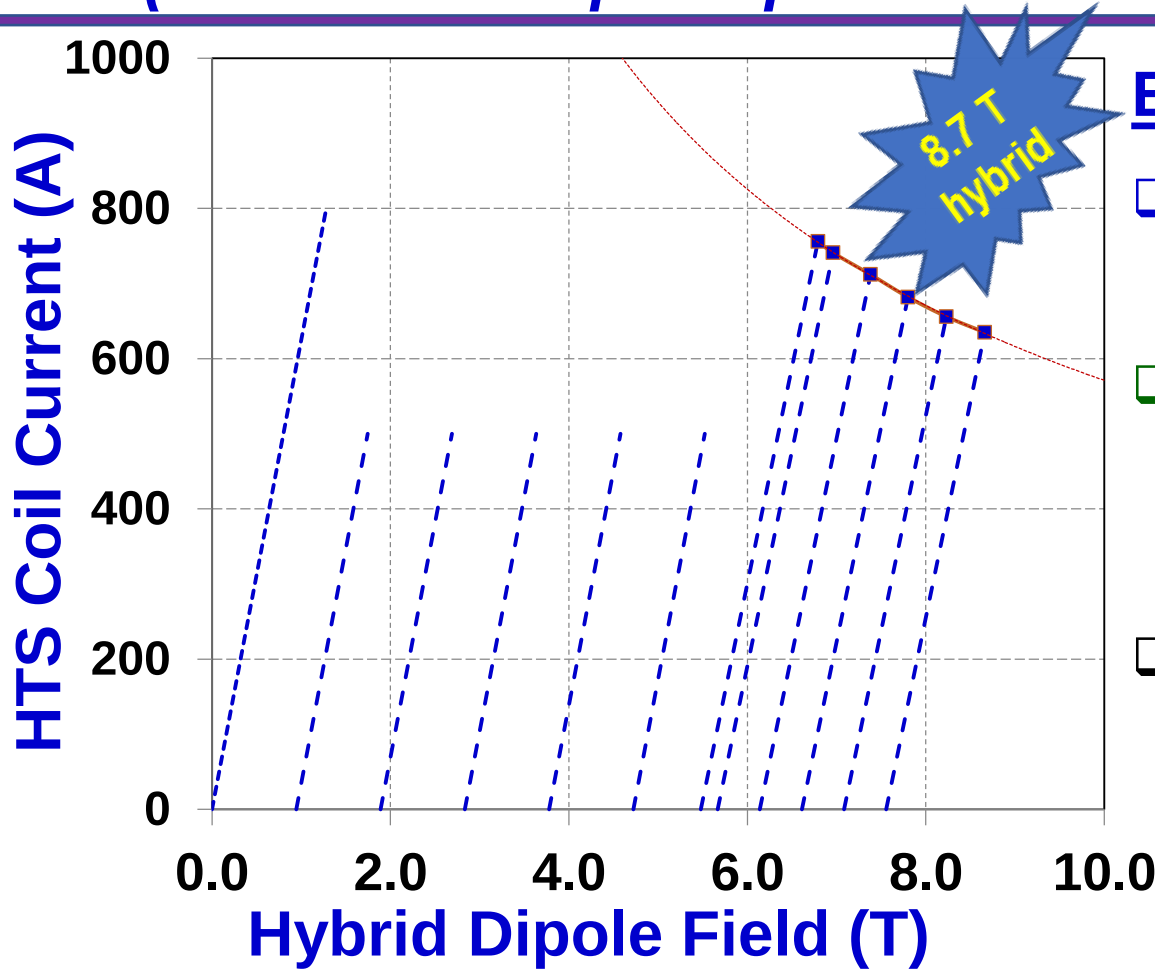
Operation of HTS/LTS Hybrid Dipole
(HTS coils ramped-up in different fields of Nb_3Sn coils)



Encouraging Results:

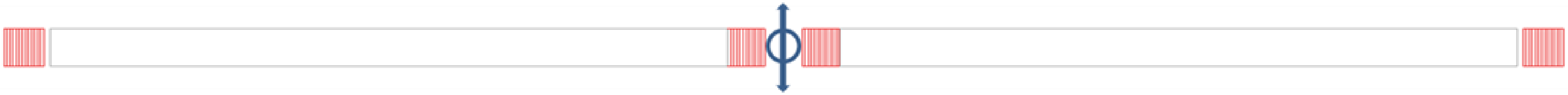
- ❑ HTS coils were ramped to quench, just like LTS coils
- ❑ No degradation in HTS coils despite a number of quenches
- ❑ Significant demonstration. 8.7 T may be the highest field HTS/LTS hybrid dipole magnet

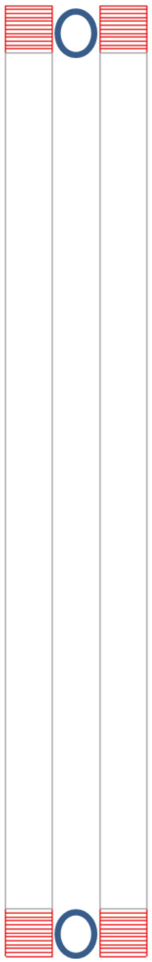
- ➢ Performance limited by the leads (not by coils)
- ➢ ~14 T possible with new HTS tapes, in favorable direction

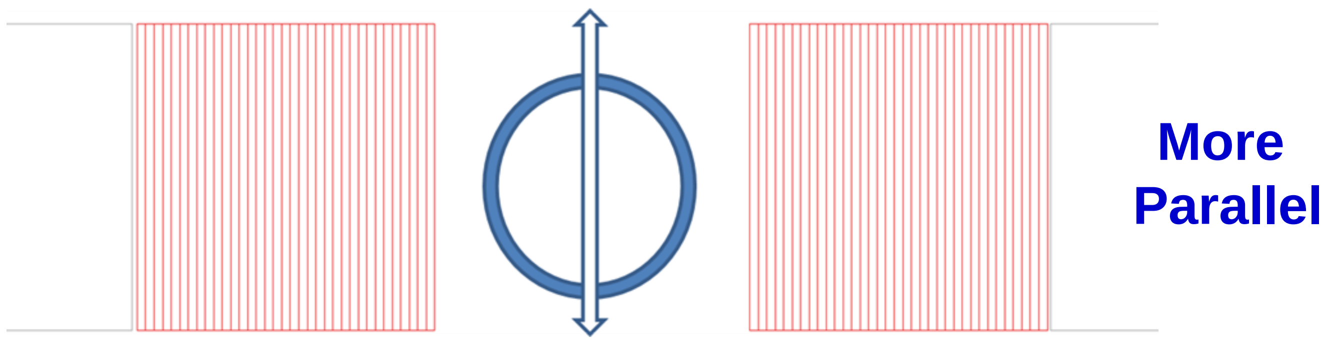
Magnetization studies in magnets made with the HTS tapes

(Hall probe measurements)

Coil and Magnet Cross-section for Measurements

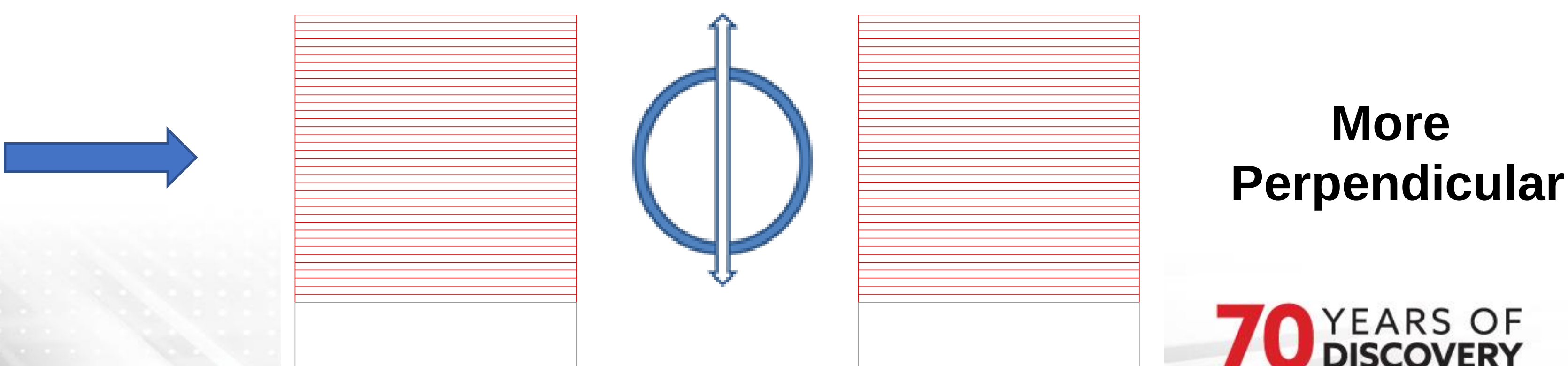






Square cross-section was chosen so that two coils can be placed in two configurations (a) with field **more parallel** or

(b) **more perpendicular** to the wide face of the HTS tape

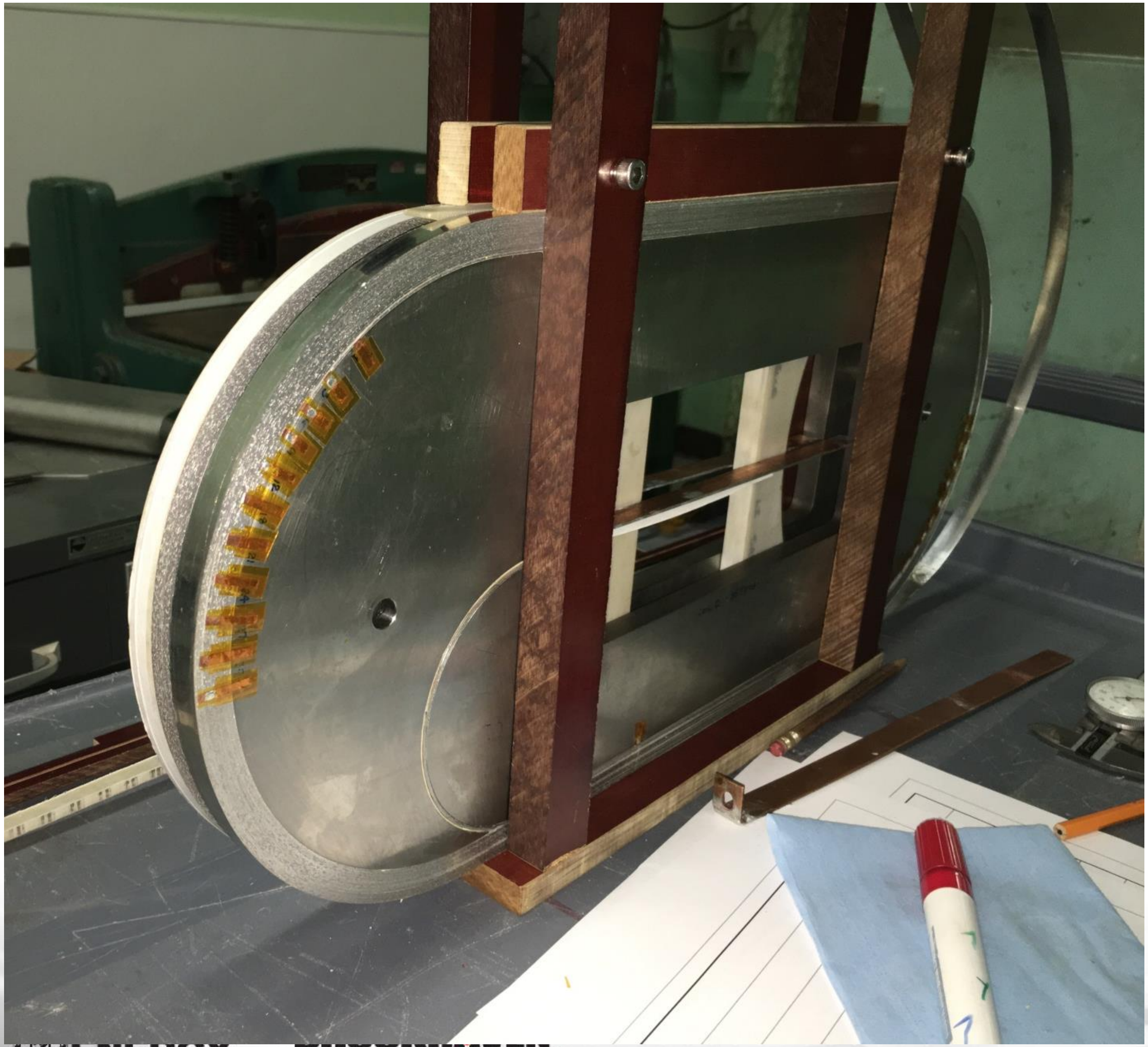


Coils Placed Side-by-Side for 77 K Test

½ inch aperture

This configuration allows (more) Field Parallel Magnetization Measurements

Two HTS Coils Assembled in Common Coil Configuration



½ inch aperture

This configuration allows (more) Field Perpendicular Magnetization Measurements

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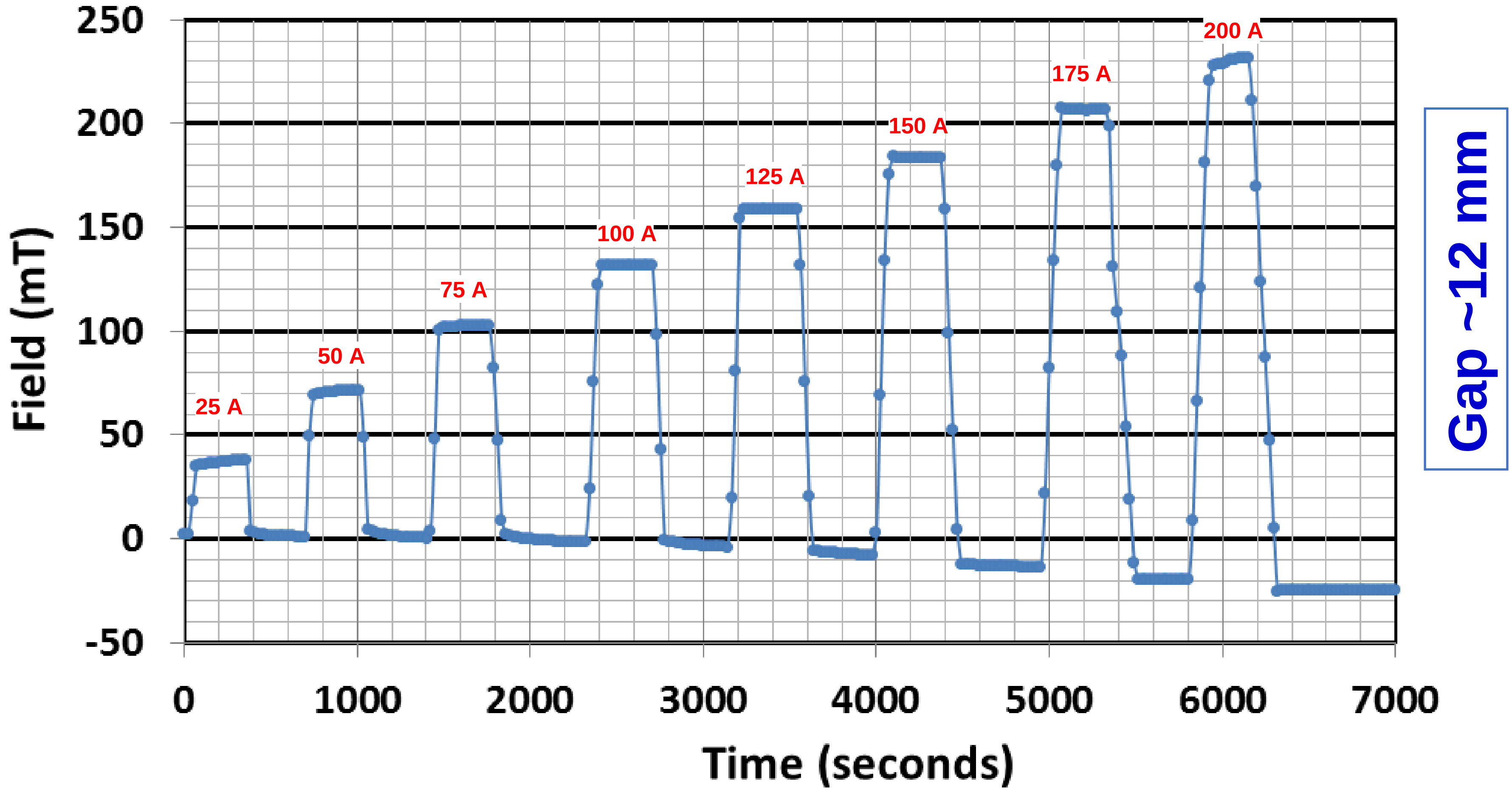
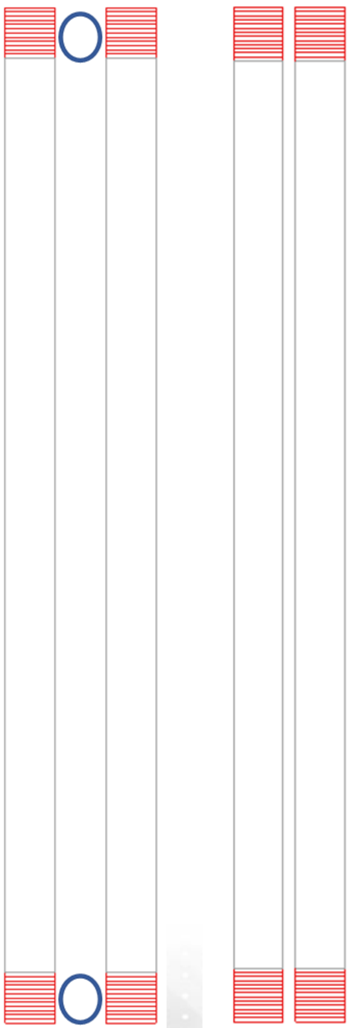
Test Sequence of HTS Coils at 77 K
0 → 25 → 0 → 50 → 0 → 75 → 0, …

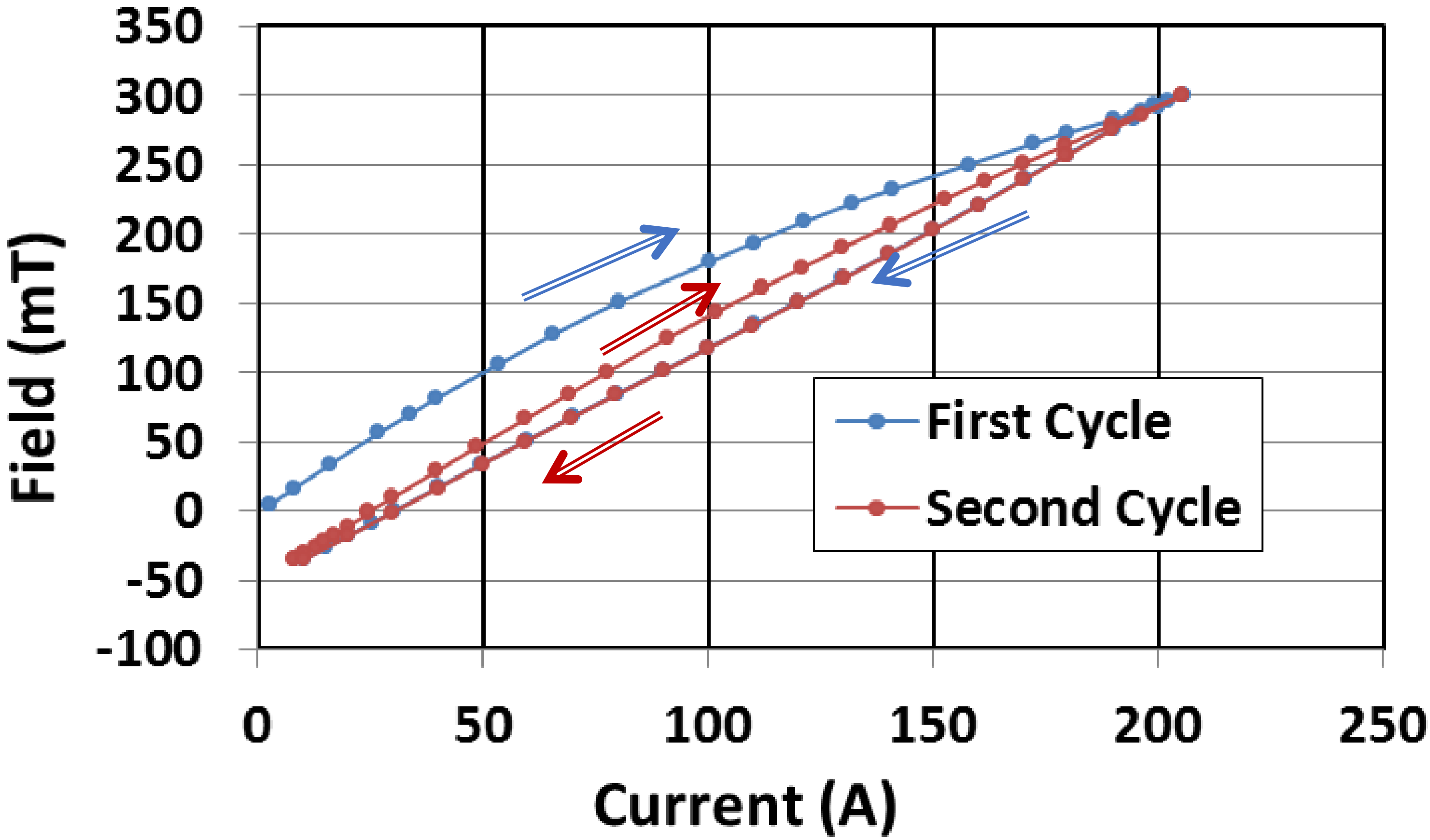


Common coil configuration (field perpendicular, more magnetization)

Two Successive Runs to 200 Amp (77 K)



0 → 200 → 0 → 200 → 0

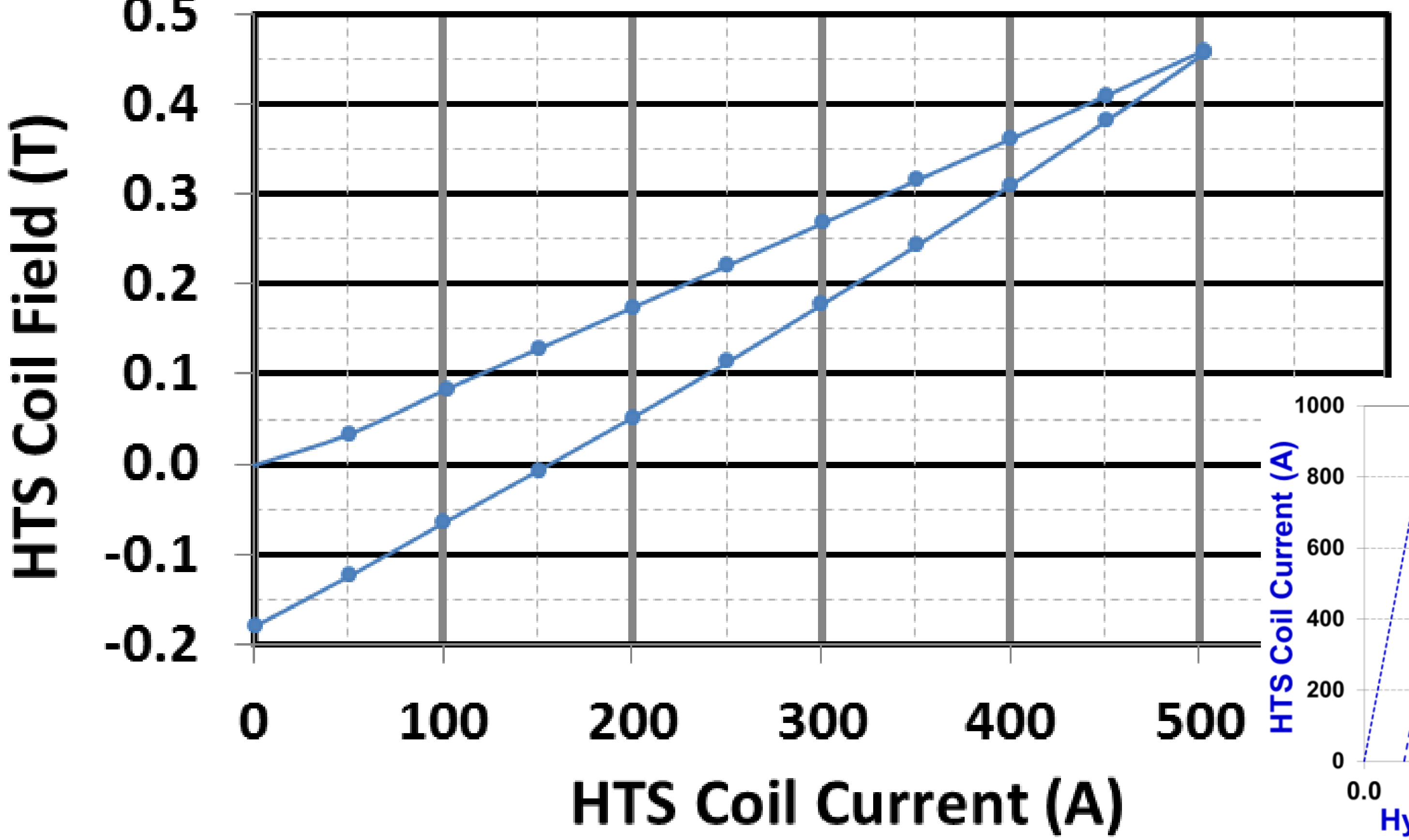


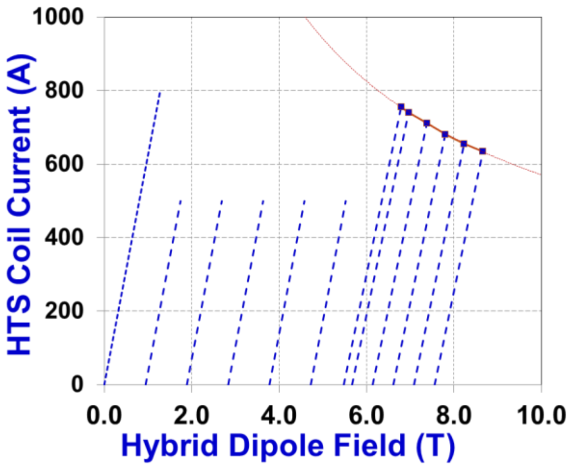
Gap ~3 mm

4 K   Measurements

Test Run at 4 K (in 2 T background field from Nb_3Sn coils)

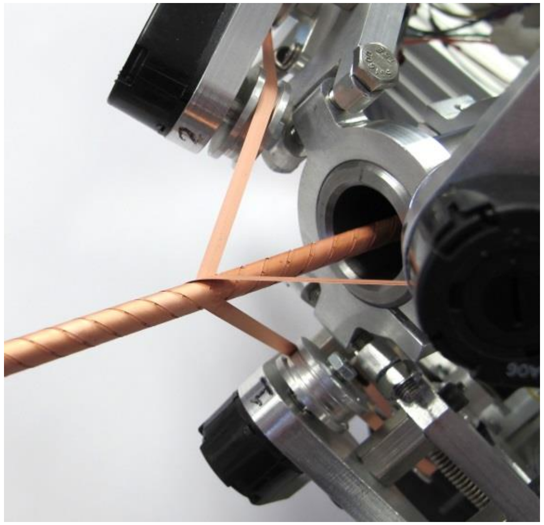
Additional field from the HTS coils in up and down ramp (offset to start from zero to start up-ramp)

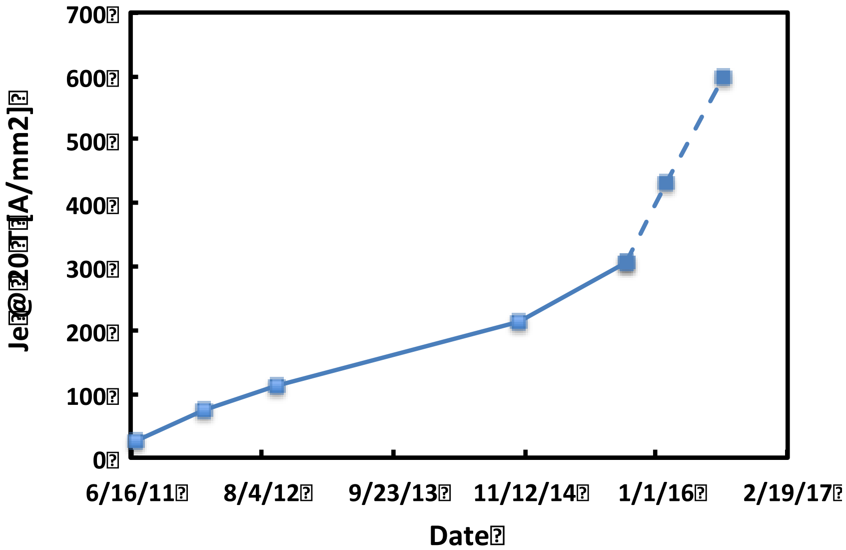


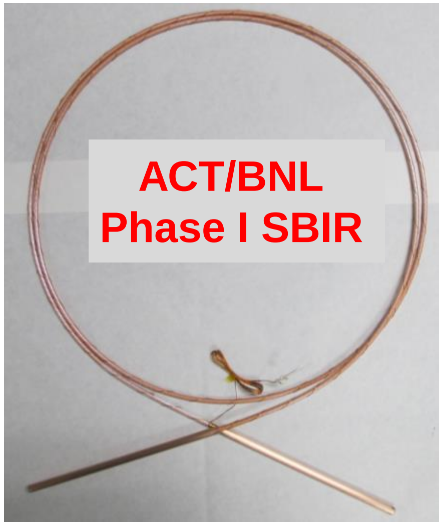


SBIR on High Field Hybrid Dipole with High Current CORC® Cable

CORC® Cable for Accelerator Magnets
High J_e and High I_c



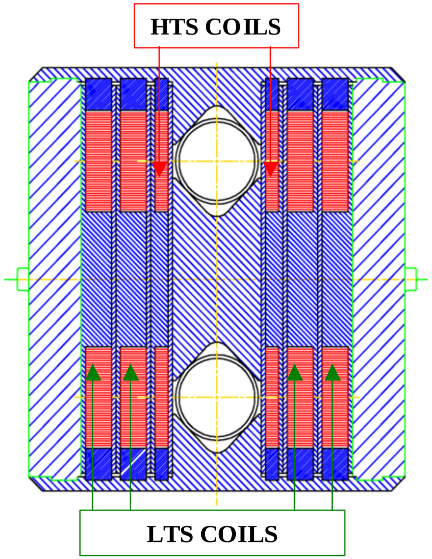




- **J_e of >500 A/mm^2 at 20 T for ~10 kA already available (part of ACT/BNL SBIR; 400 A/mm^2 was the promised target)**
- **J_o of ~1000 A/mm^2 at 20$^+$ T for 10-20 kA cable in a few years?**

Phase I SBIR (funded) on High Current CORC® Cable in Accelerator Magnets

- High I_c, high J_e CORC® cable requires large bend radii - common coil design allows that
- HTS CORC® cable coil can be powered in series with LTS Rutherford cable coil
- Same high current provides easier operation and easier quench protection
- Partially transposed CORC® cable also helps in reducing magnetization-induced field errors associated with the high strength ReBCO tape
- Demonstration of a proof-of-principle dipole with insert coil CORC® cable coil running in series made with Nb_3Sn BNL common coil dipole is possible within the budget of Phase II



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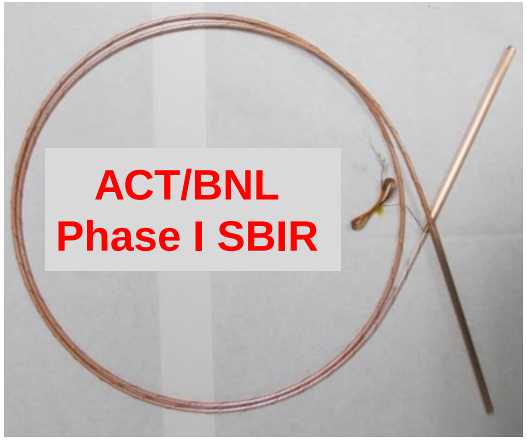
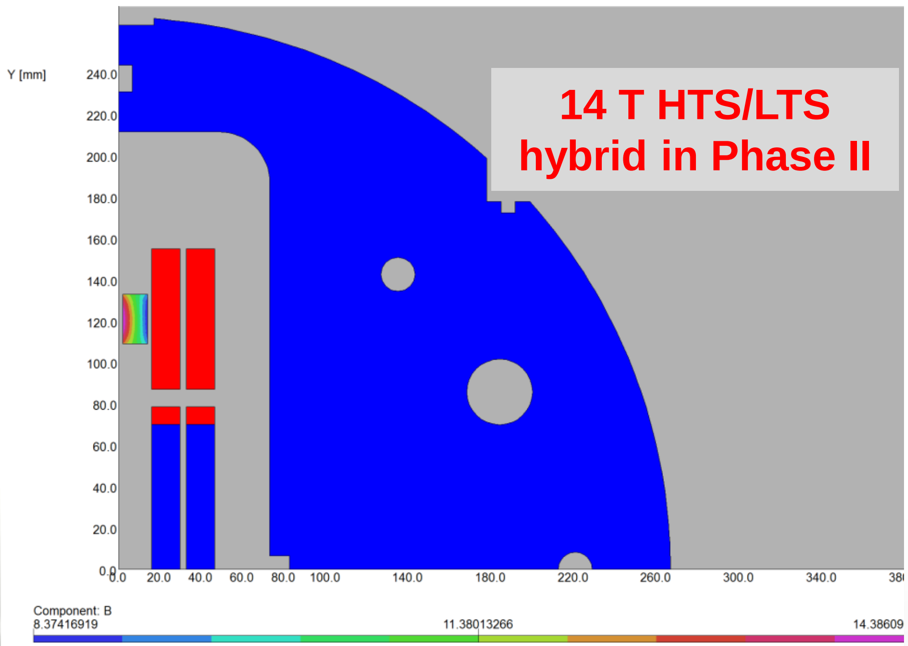
SBIR Main Tasks and Plans on the Demonstration of HTS/LTS Hybrid Dipole with the CORC® Cable



Phase I (funded)

- Make high cable suitable for Phase II
- Test CORC cable at ACT and at BNL
- Develop Phase II design for HTS/LTS hybrid



Phase II (if funded)

- Make CORC cable for two coils
- Wind two double pancake coils
- Assemble HTS/LTS hybrid dipole
- Test 14 T HTS/LTS hybrid dipole
- Develop 20 T HTS/LTS design

High Field, Large Aperture HTS Solenoid for Axion Dark Matter Search

IBS Solenoid and High Field Collider Dipoles

Differences:

Geometry

- IBS: Solenoid
- Collider: Dipole

Field Quality

- IBS: ~10^{-2}
- Collider Dipoles: 10^{-4}

Similarities

High Field

- IBS: 25 T operational
- Next generation dipoles: 15 – 25 T

High Stresses on Conductor/Coils

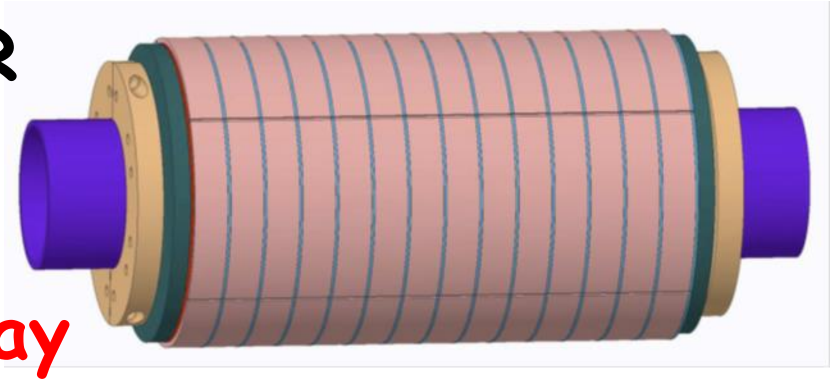
- IBS design: ~500 MPa
- Next generation dipoles: 200 - 300 MPa

Experience from building a high field, large bore HTS solenoid for IBS should be partly useful to developing high field HTS collider dipole technology

Requirements for the IBS Solenoid

- High Field : 25 T (must use HTS)
- Large Volume: 100 mm bore, +/-100 mm long

  Stresses: J X B X R



- Field quality: ~10%
- Ramp-up time: up to 1 day

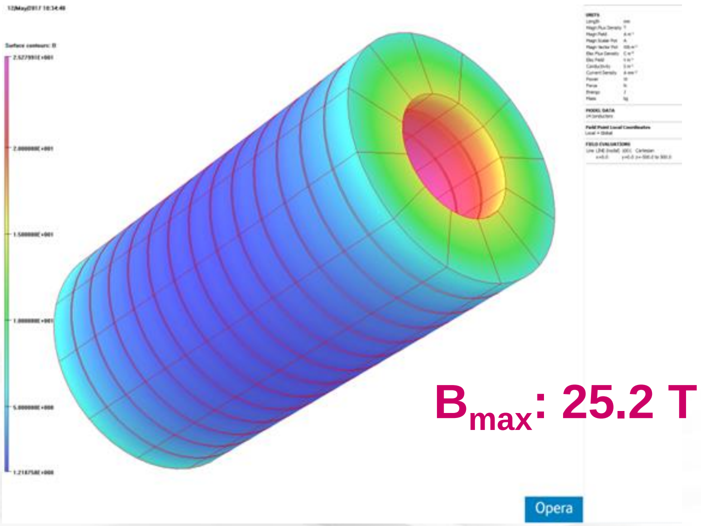
  Relaxed field quality and slow charging

- User magnet: robust design, large Margin

Relaxed field quality & slow ramp rate allows no-insulation scheme for a more robust protection and higher reliability

Design Choices for IBS Solenoid

- No Insulation Coil (no insulation between turn-to-turn)
  - Bypasses current from one turn to the next turn in the event of a quench
  - Takes benefit of the relaxed field quality and slow charging time
- Single Layer Design
  - In "No Insulation" case, there could be an unbalanced force situation between the two layers when the current is bypassed
- Conductor: High Field, High Strength, 12 mm wide 2G ReBCO Tape
  - 50 μm Hastelloy, 20 μm copper, advanced pinning
- Critical Current Margin : 30-50% @4K
  - High performance at high fields
  - Need ~10 km of 12 mm wide tape
- Stress/Strain Margin : 30-50%



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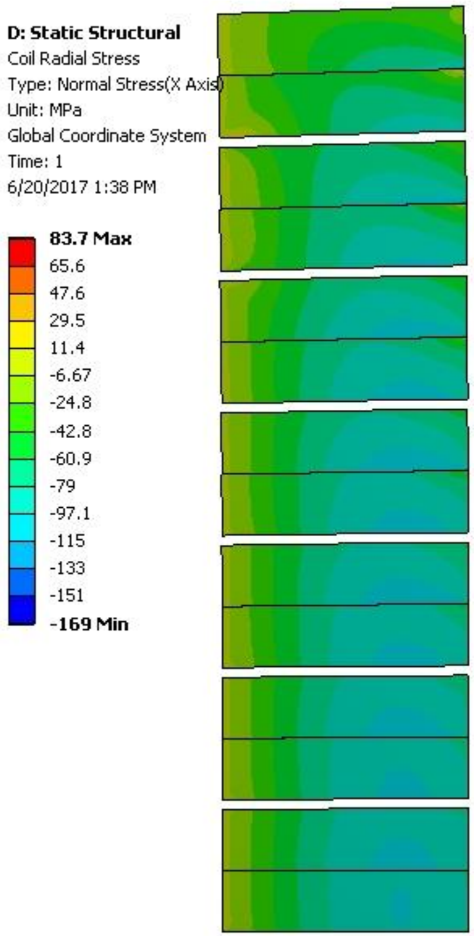
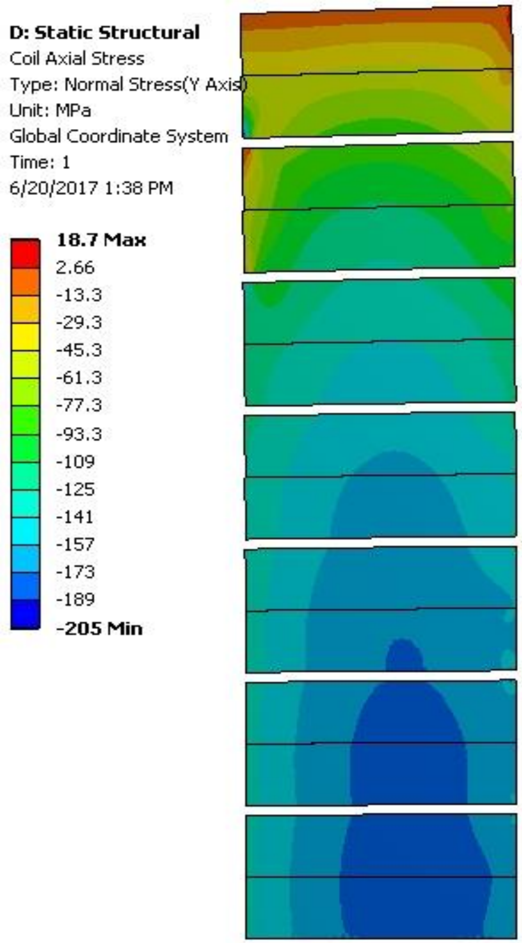
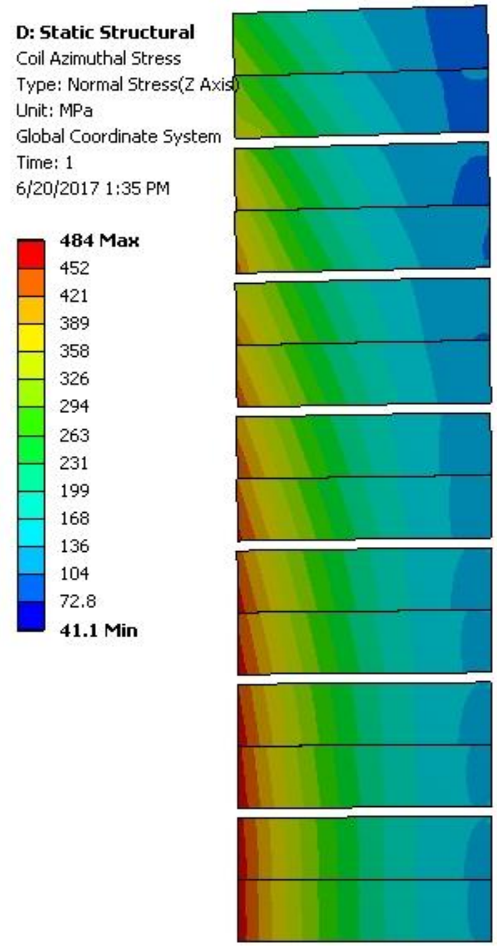
Orthogonal Coil Stresses (MPa) @ 4 K, 25 T







484 MPa Max Stress

-100 MPa Max Stress

-205 MPa Max Stress

Azimuthal

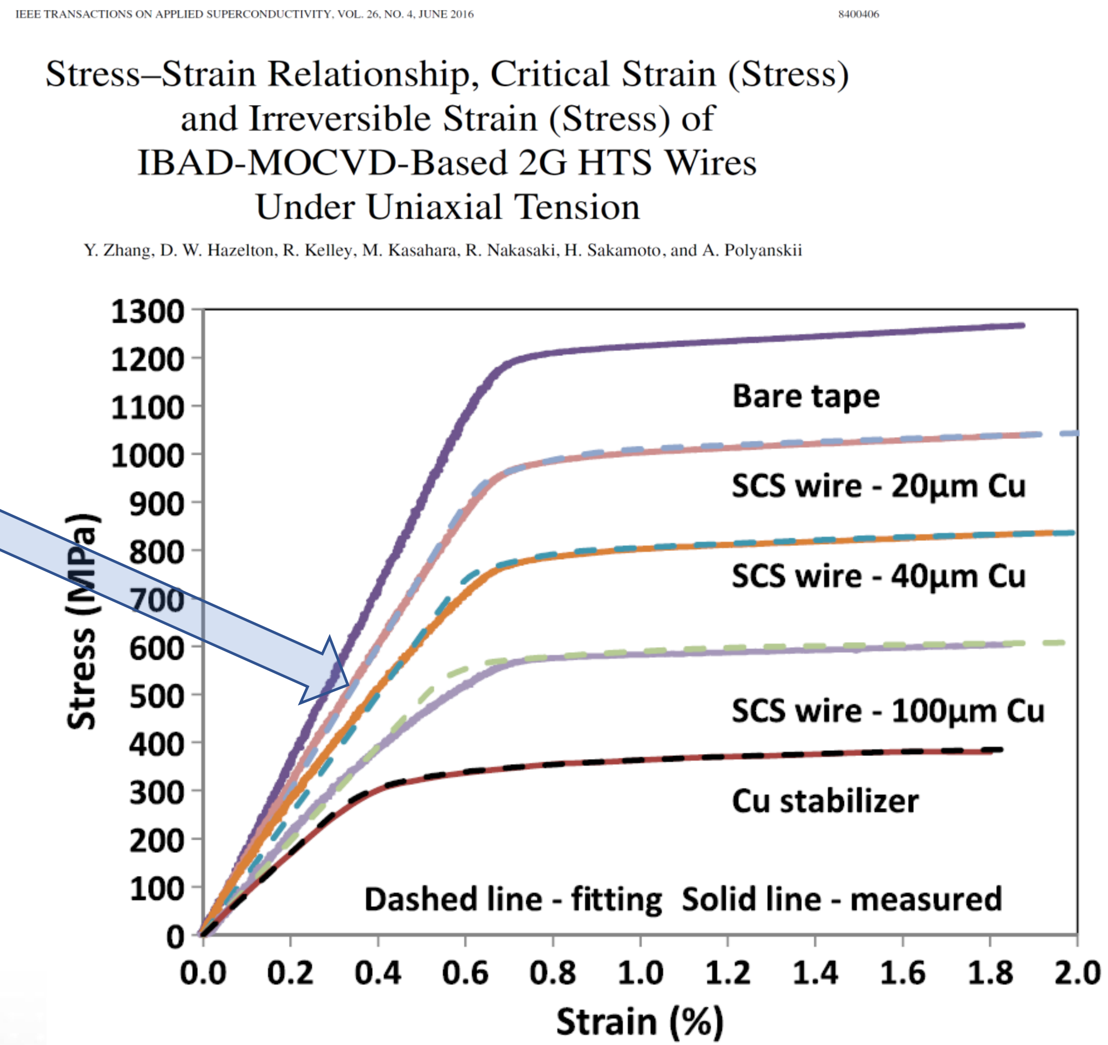
Radial

Axial +

Mechanical Properties of the Conductor

Requirement of Azimuthal stresses of ~500 MPa is met with 2G Tape having 50 micron Hastelloy and 20 micron Copper

Meeting requirement of ~200 MPa on the narrow side of the tape needs to be checked as no such data is available



Courtesy: SuperPower

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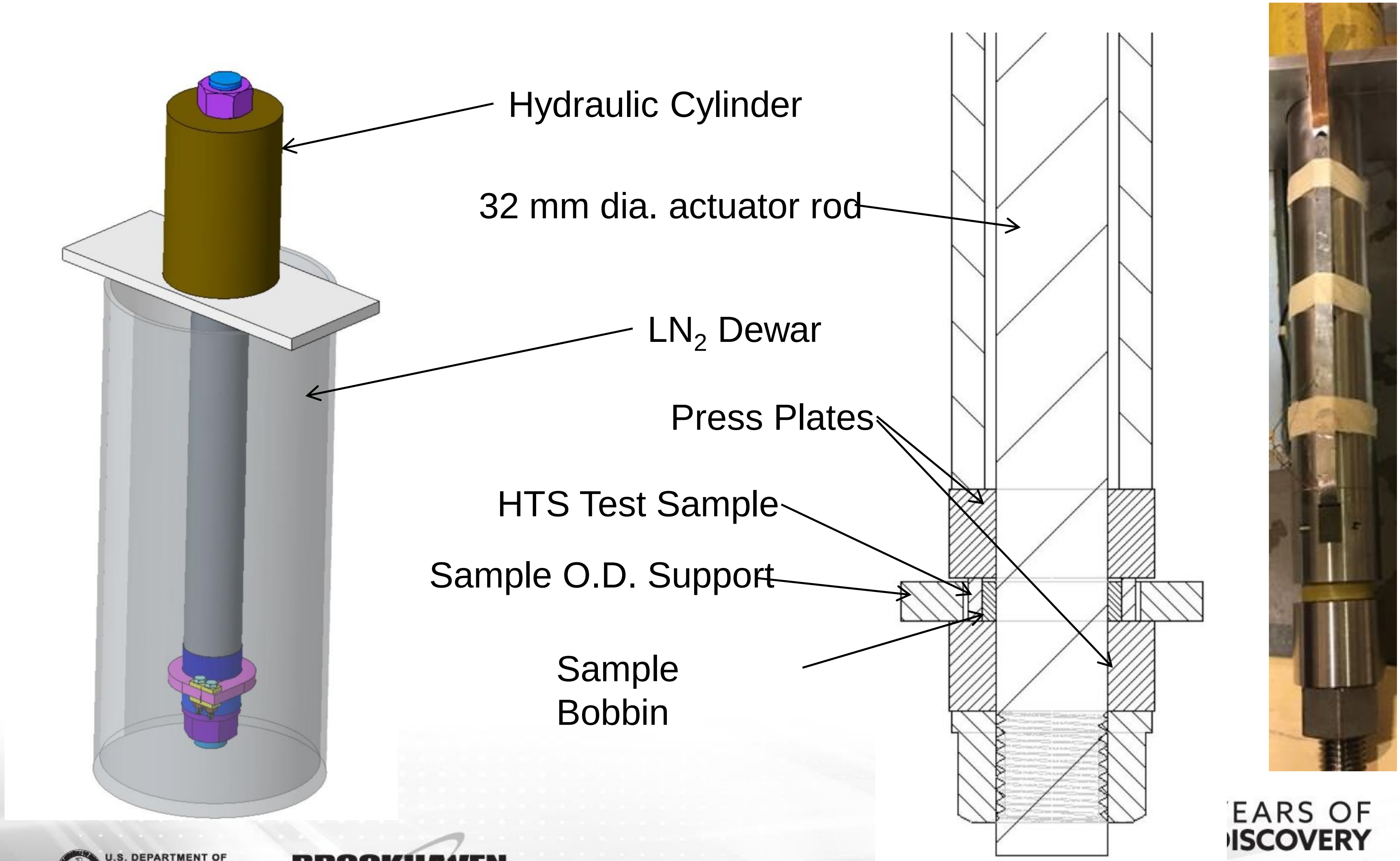
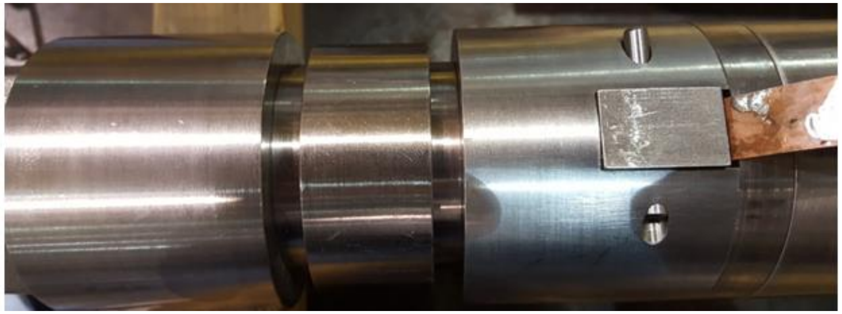
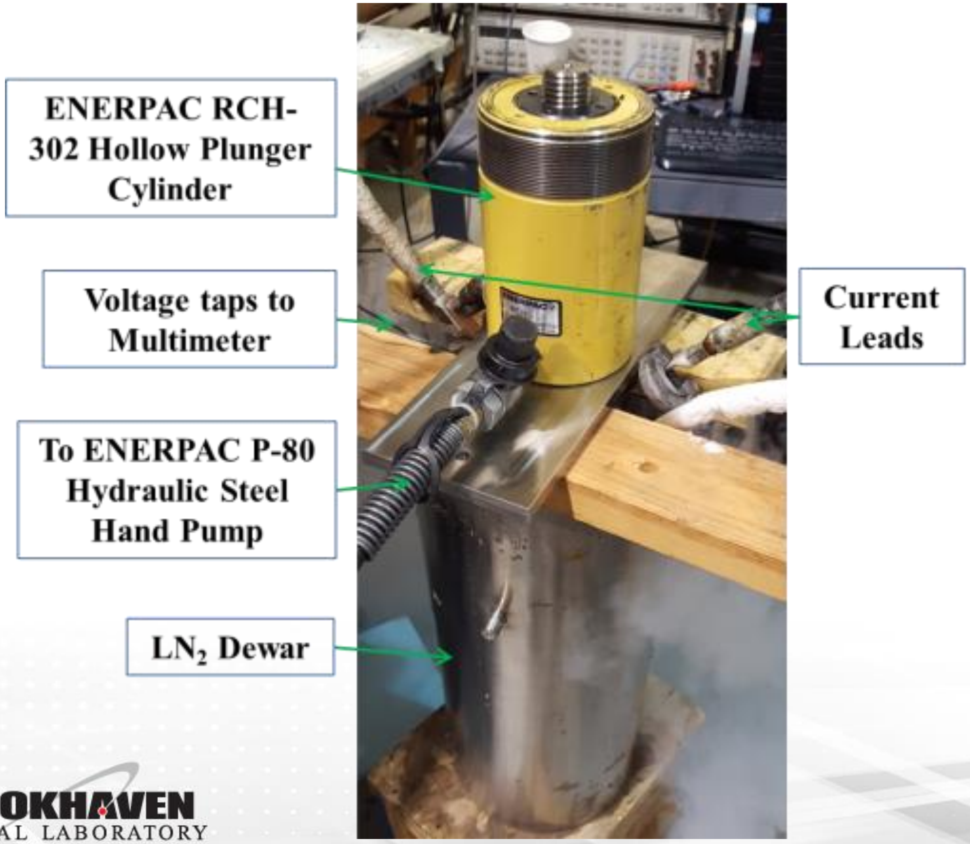
New Apparatus to Apply 300 MPa Load on the Narrow Side (design needs 200 MPa)



Apparatus to Measure High Pressure (300 MPa) on the Narrow Face of the Conductor and Coil





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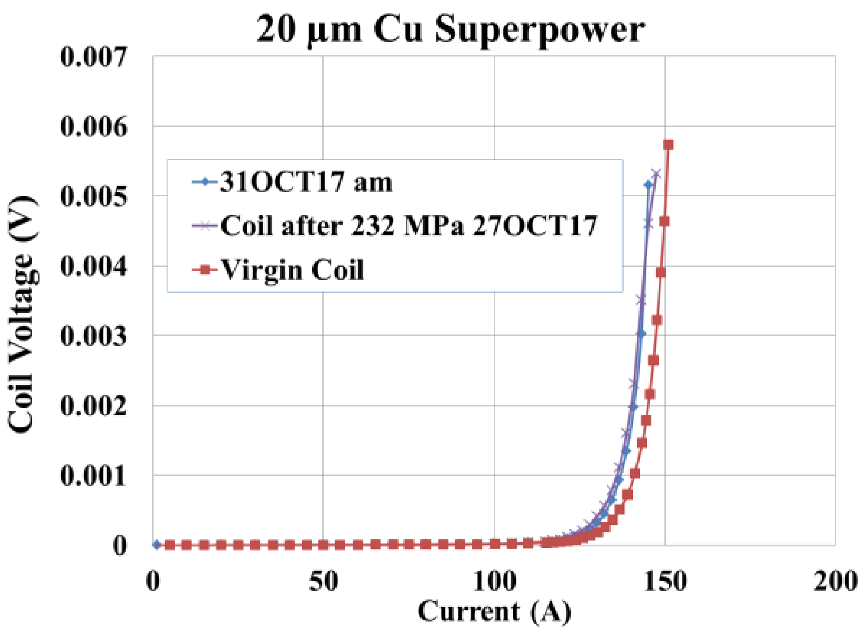
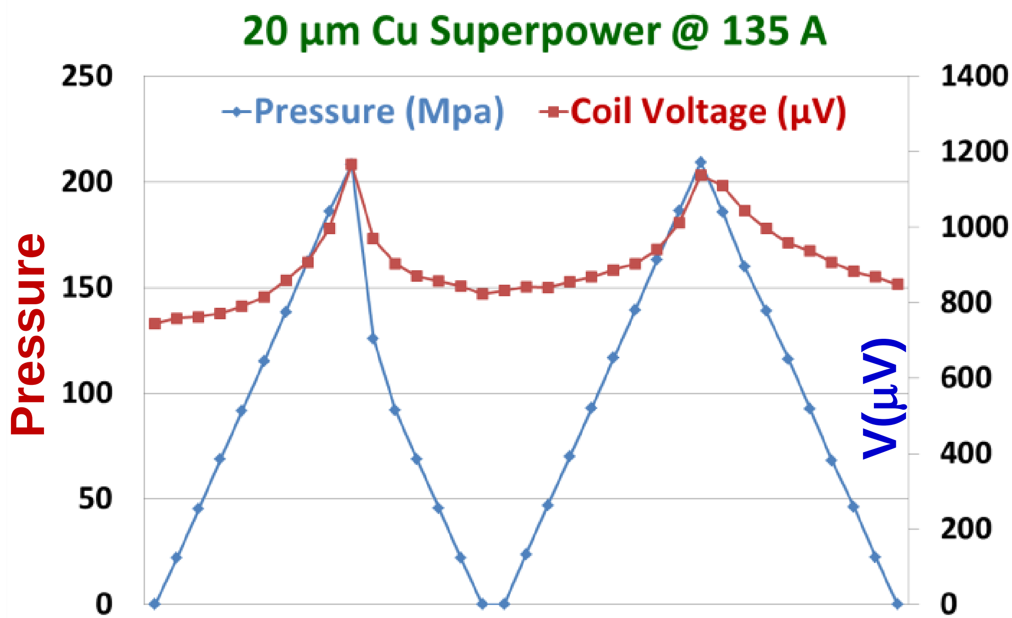
Measurement of the Load on the Narrow Face of HTS Tape (50 μm Hastelloy, 20 μm Copper from SP)





Meets the requirements of ~200 MPa on the narrow side

Tapes with 40 and 65 microns copper and from other vendors were also examined

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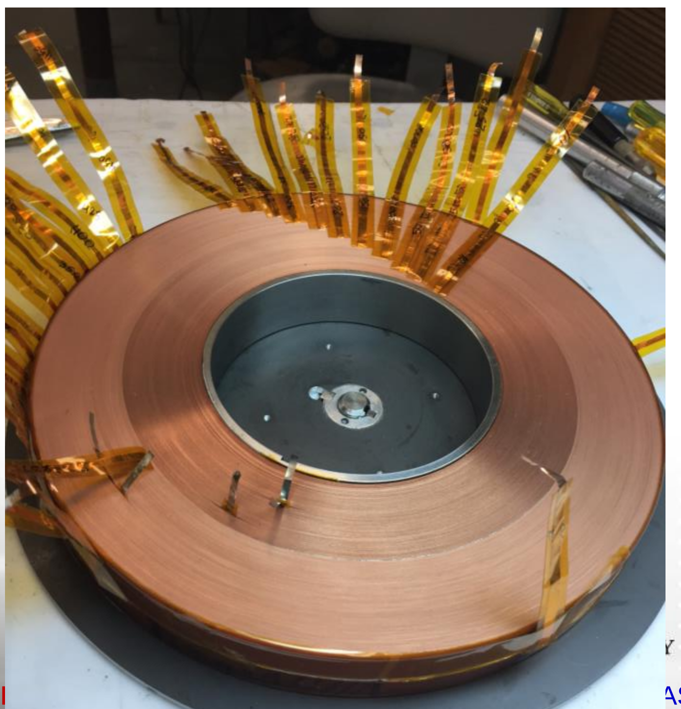
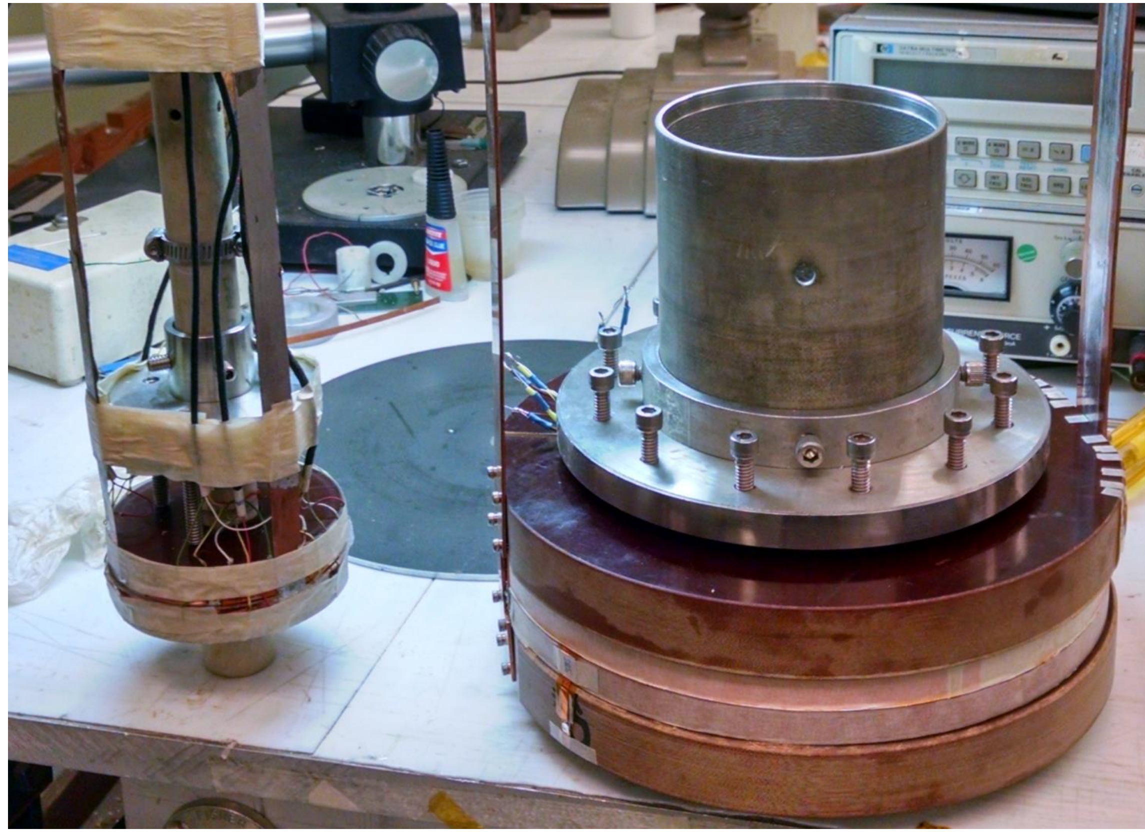
No Insulation Coil Construction and Test Results

No Insulation Double Pancake Coils

To obtain data and 4 K test experience with large "NI" coil early on, a coil wound with ~550 m of 12 mm wide ReBCO tape

- **i.d. = 100 mm**
- **o.d. = 220 mm**
- **Turns = 971**

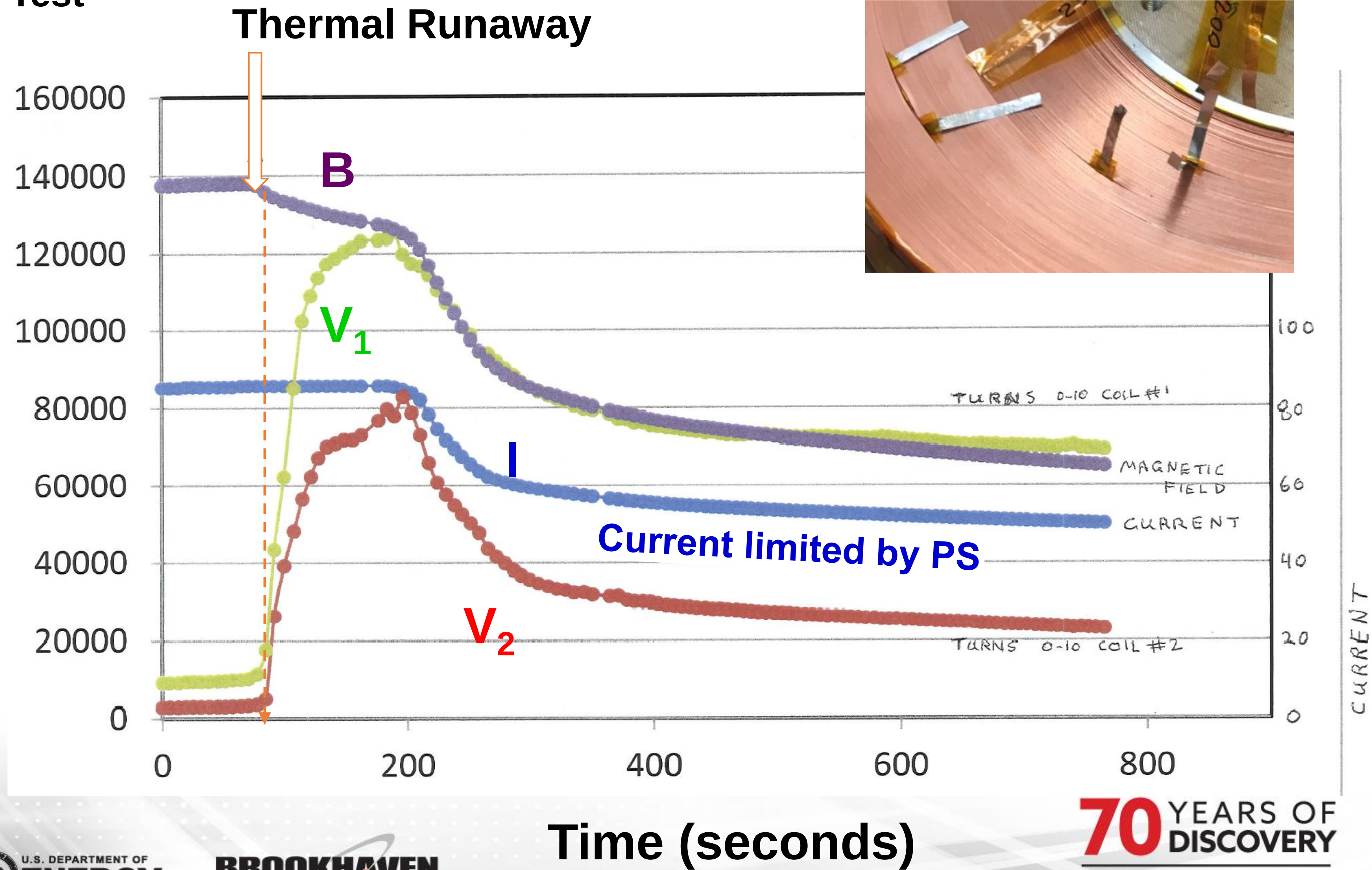




Significant instrumentation (v-taps) and three heaters for simulated defects

B, V and I in No Insulation Coil at Thermal Runaway

77K Test



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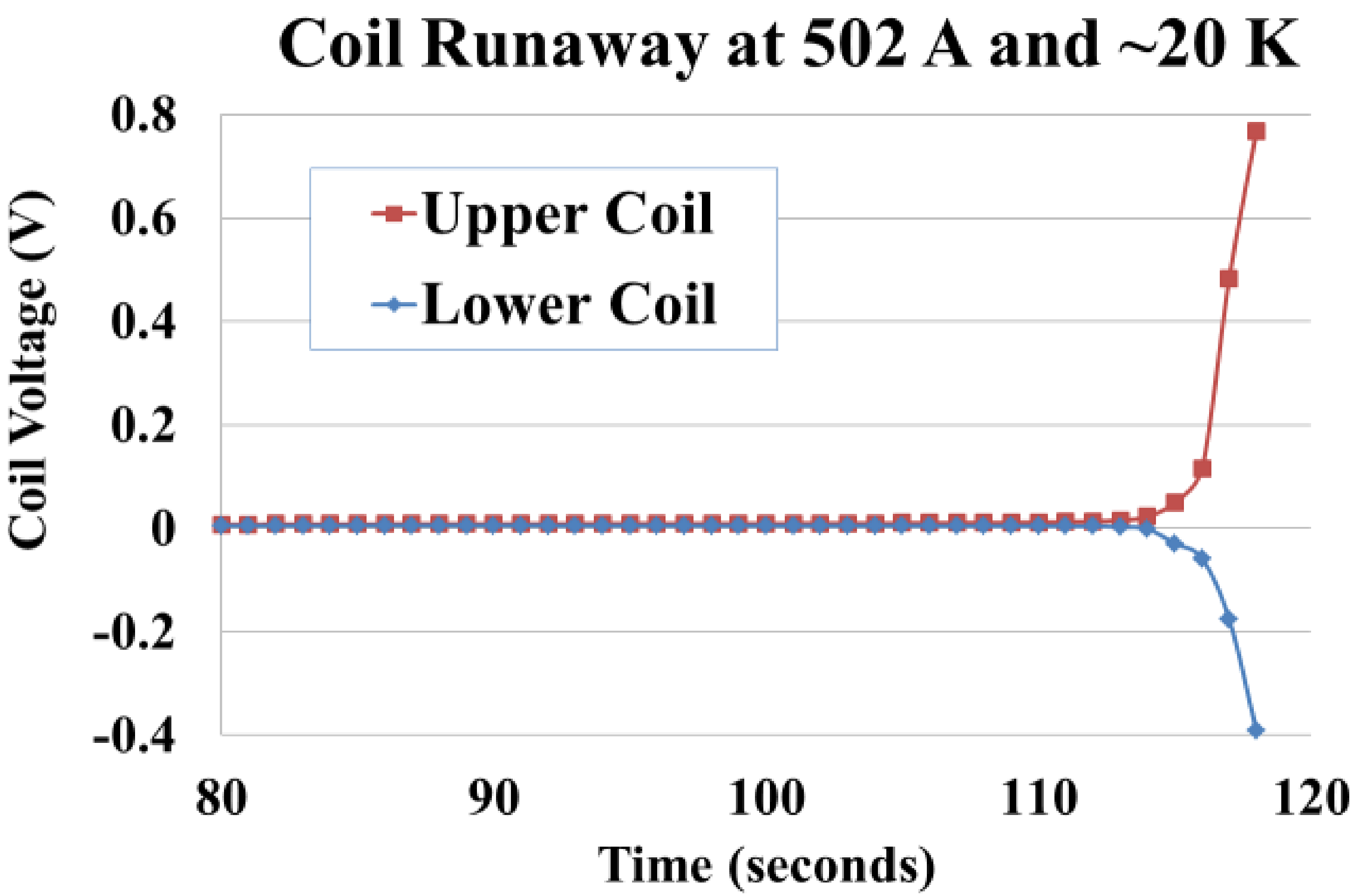
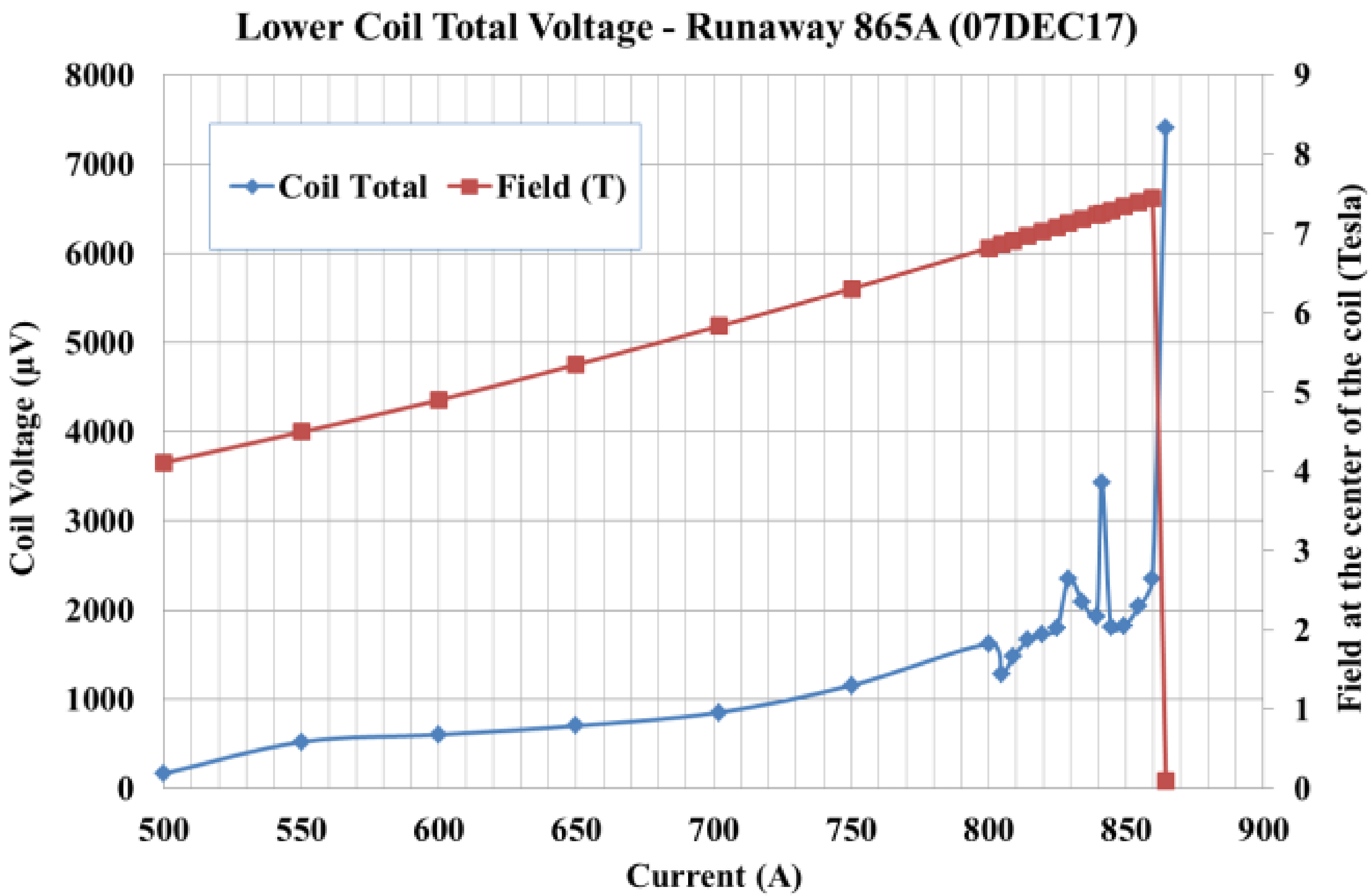
Low Temperature, High Current Testing

Test at Intermediate Temperature (20 K)



- Coil was allowed to runaway unprotected.
- Normal HTS coil would probably have been damaged.

Test of Large Double Pancake Coil at 4 K

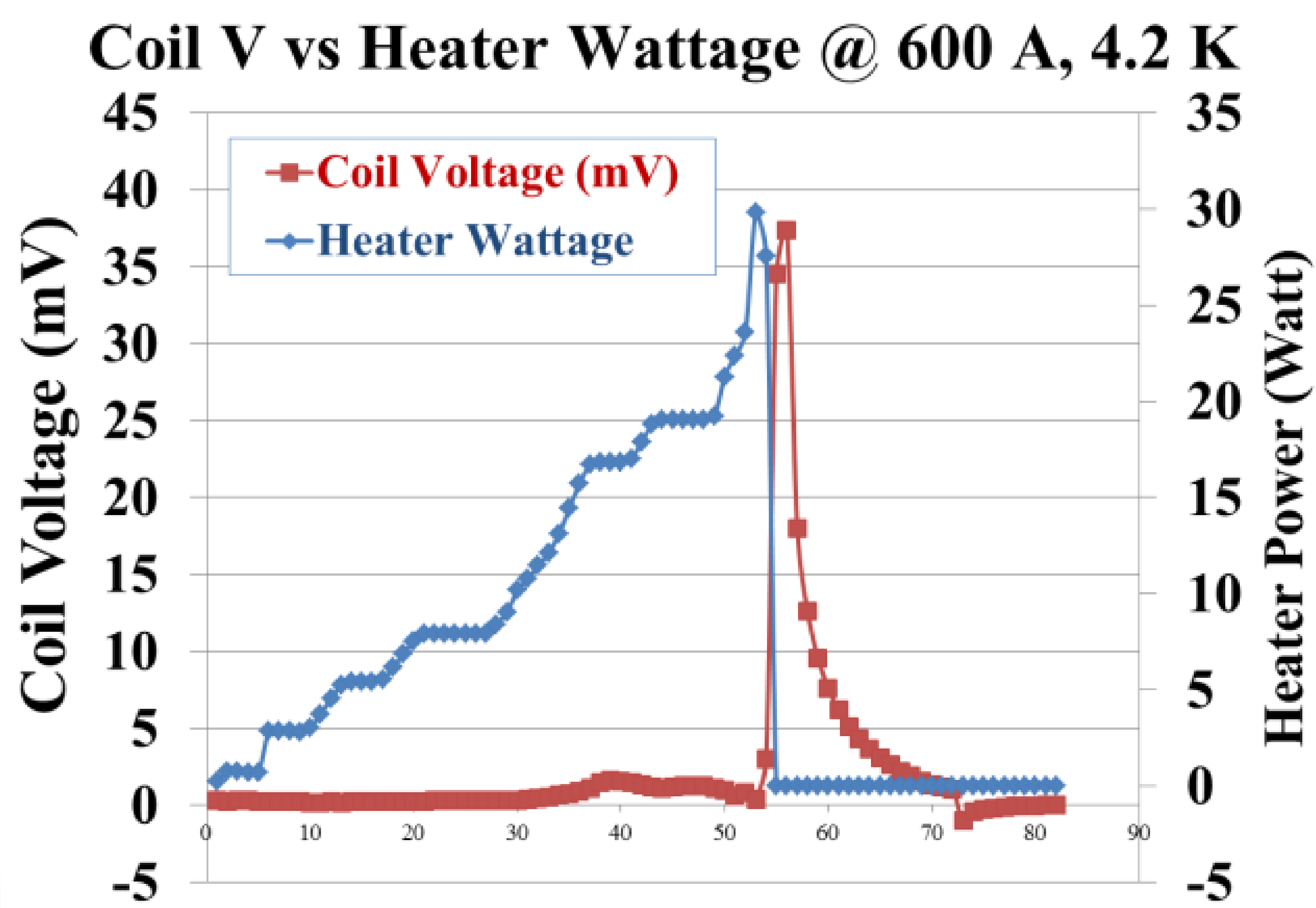


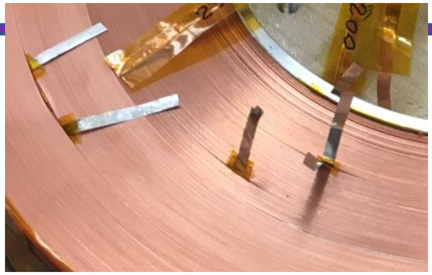
Further tests found no damage in coil

Peak field 11.2 T

Design current: ~500 A

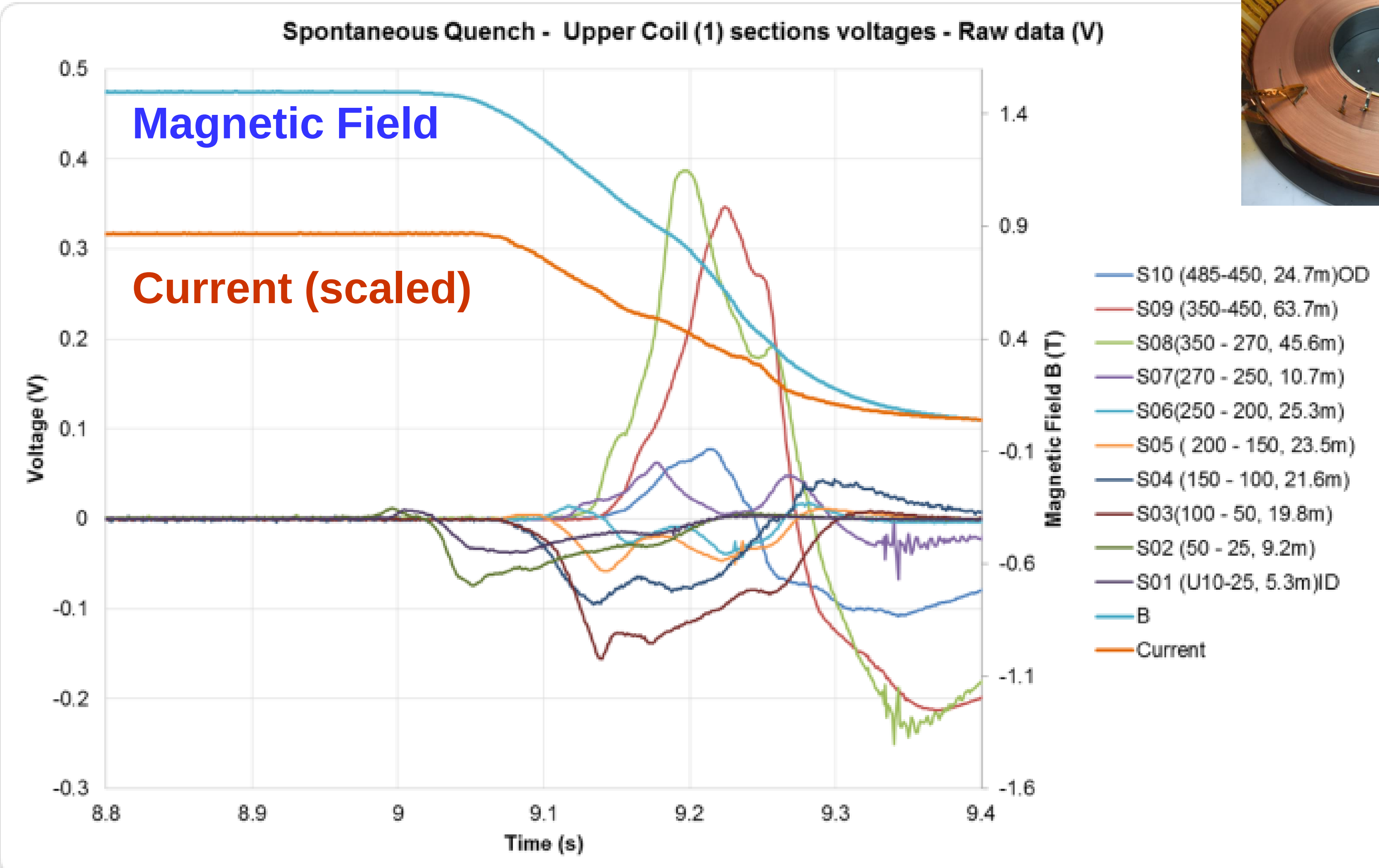
Simulation of Large Local Defects (~30 W)

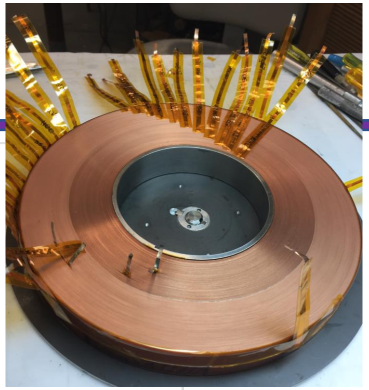




No degradation in the performance of coil observed during further tests

Propagation of Quench Voltage





Summary

- ❖ Encouraging test results from HTS/LTS Hybrid dipole

- ❖ Many LTS type quenches with no degradation in HTS coils

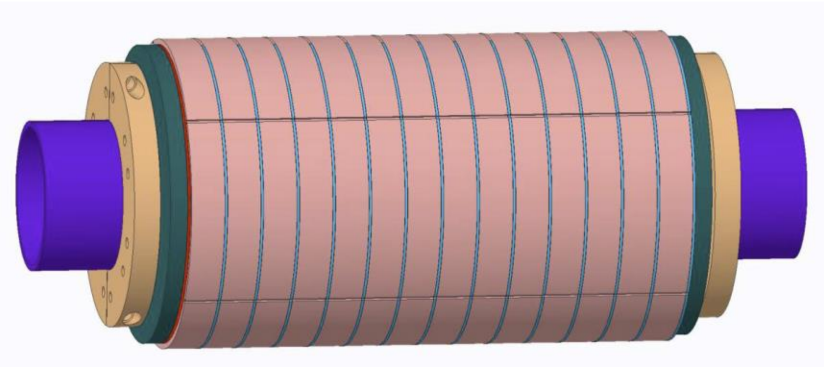
- ✓ A unique rapid-turn-around, low-cost background field coil test facility is commissioned for collaborative use
  - ➢ Insert coils become an integral part of the magnet

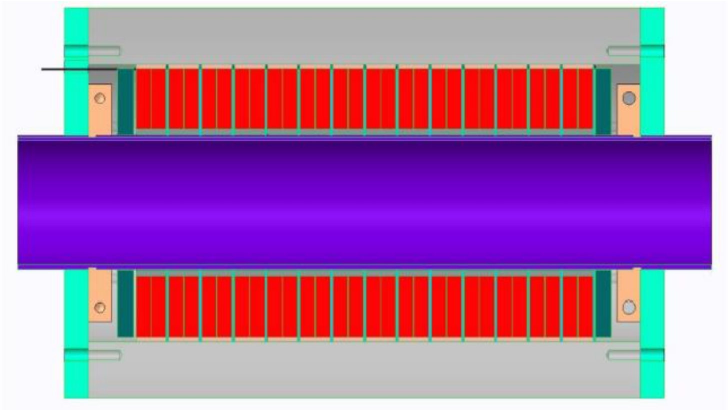
- ❑ Development of high Field, large aperture HTS solenoid for IBS is giving an experience in dealing with very high stresses in HTS magnets.

Backup Slides

Major Parameters of the IBS HTS Solenoid

- **Field: 25 T@4 K**
- **Single Layer**
- **Cold Bore: 100 mm**
- **Coil i.d.: ~118 mm**
- **Coil o.d.: ~200 mm**
- **Conductor: 12 mm wide ReBCO**
- **Current: ~500 A**
- **Current Density: ~550 A/mm^2**
- **Stored Energy: ~1.6 MJ**
- **Max. Hoop Stress: ~500 MPa**





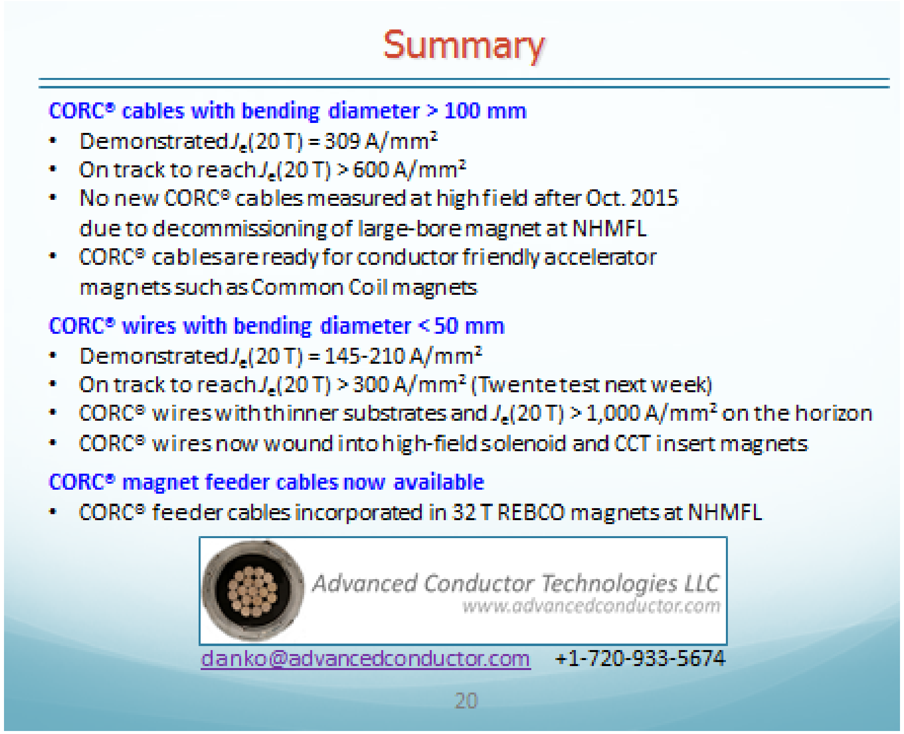
CORC Cable for Common Coil Collider Dipole (C5 Dipole)

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



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

One of the P5 recommendations on high field dipoles may possibly be met with the demonstrate of a hybrid C5 Dipole

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