3rd INTERNATIONAL WORKSHOP
on Cooling Systems for High Temperature
Superconductor Applications

GE Research Center
1 Research Circle
Niskayuna, NY 12309

October 15, 2019—October 17, 2019

BNL experience with HTS magnets and coils

Ramesh Gupta
on behalf of
SMD@BNL

A pictorial tour

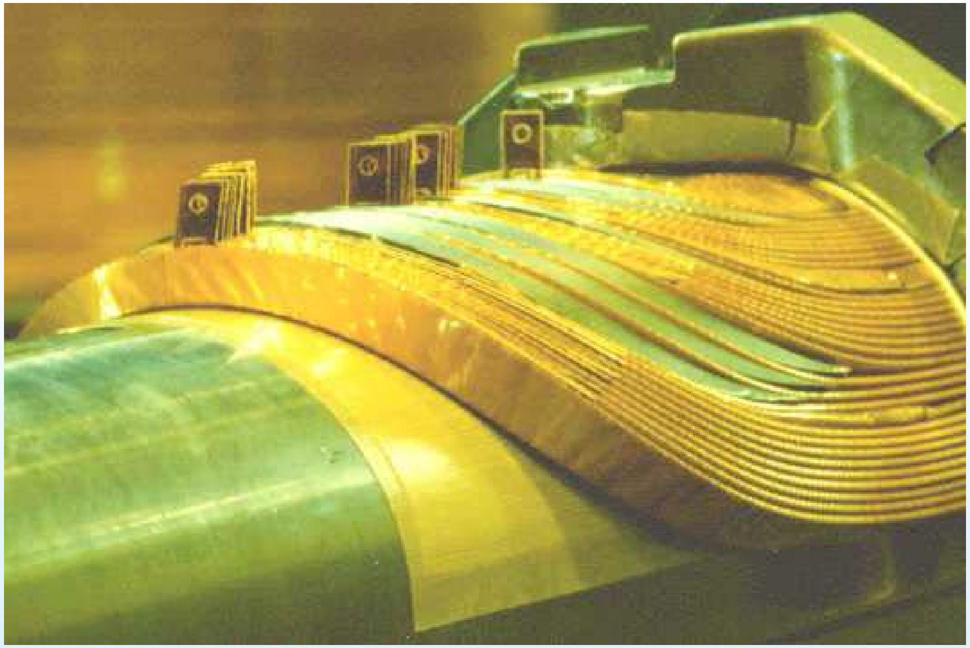
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

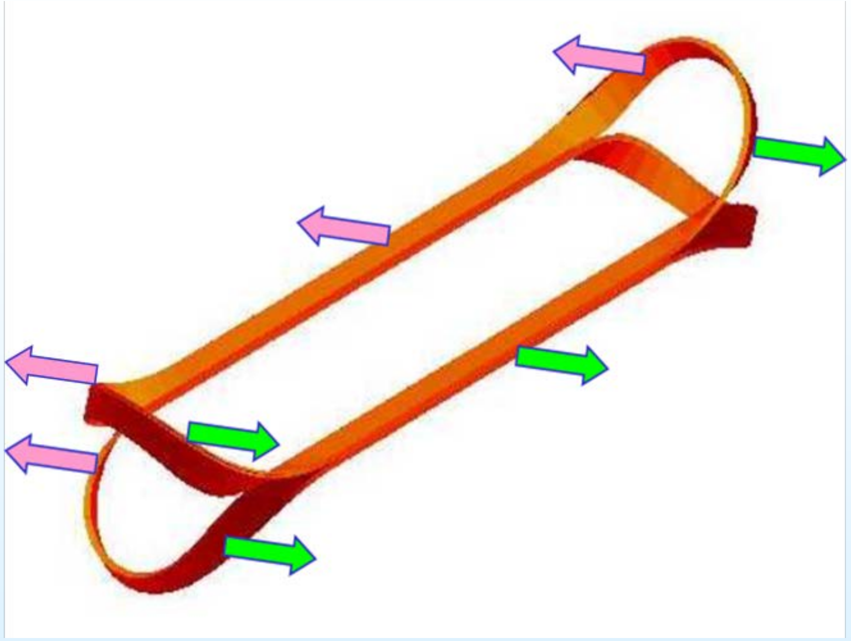
Office of Science
U.S. DEPARTMENT OF ENERGY

Highlights of the HTS Magnet Program at BNL

- **First US national lab to start HTS magnet R&D (over 20 yrs ago)**
  - **Opted the approach of demonstrating capabilities of HTS to create new opening and create excitement, rather than waiting for the conductor to get matured before starting magnet R&D**
- **A wide ranging HTS magnet R&D at BNL**
  - **High field, high temperature and the middle course**
  - **Solenoid, racetrack, cosine theta, curve coils, clover-leaves, ...**
- **Number of HTS coils and magnets designed, built and tested**
  - **Well over 150 HTS coils and well over 15 HTS magnets**
- **HTS used: Bi2223, Bi2212, ReBCO, MgB_2 – wire, cable, tape**
- **Amount of HTS acquired: Over 60 km (4 mm tape equivalent)**

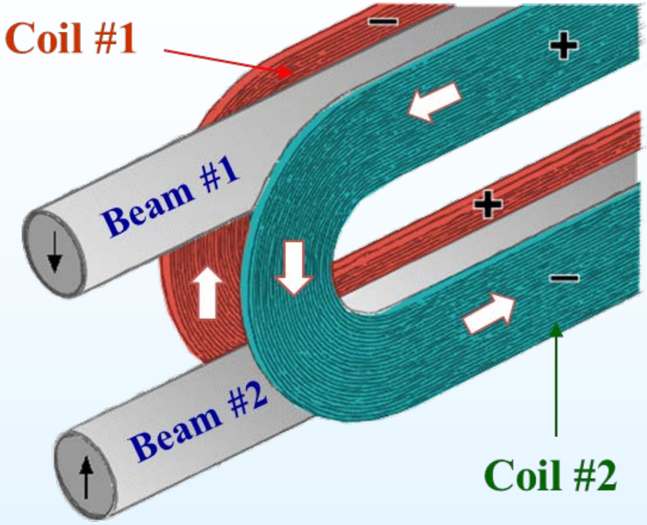
Convectional Designs for Accelerator Magnets

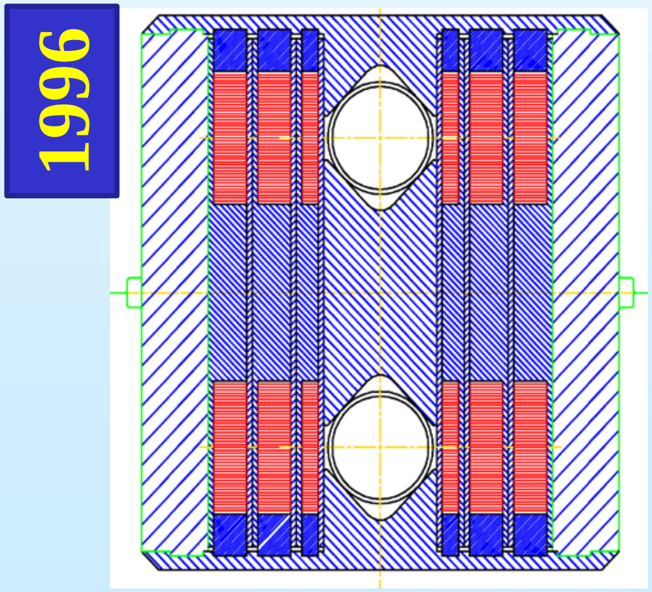




- **Have complex end geometry with tight bend radius**
- **Large Lorentz forces cause strain on the conductor**
- **Design not friendly for high field HTS magnets**

A High Field Collider Dipole Design for HTS Coils





- Common coil 2-in-1 design with large bend radii (determined by the spacing between the two bores rather the size of the bore itself)
- Conductor friendly simple racetrack coils
- Coils move as a unit under large Lorentz forces
- Replaceable coil modules for flexible, low cost, systematic R&D

Superconducting Magnet Division @BNL started working on it in 1996

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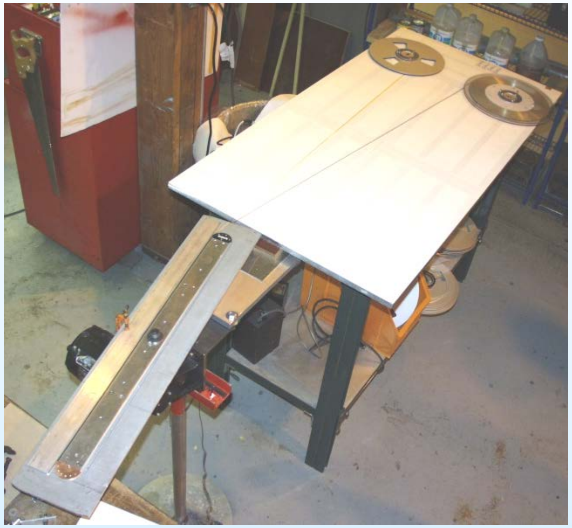
Superconducting Magnet Division

Common Coil Magnets With HTS Tape

Bi2223 Tapes

1998

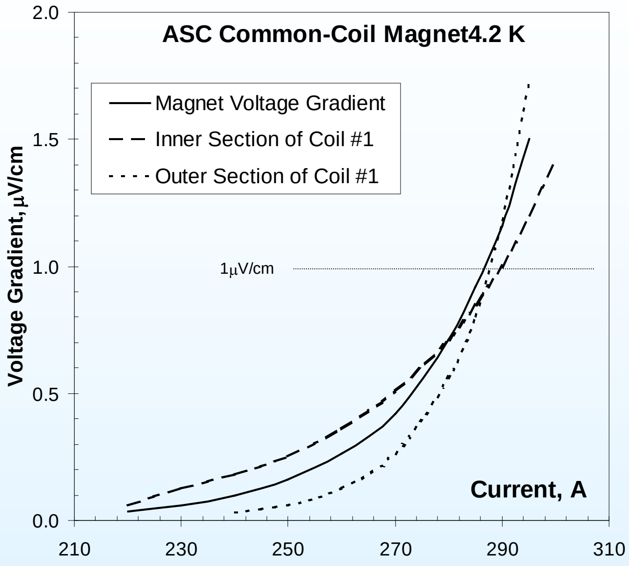


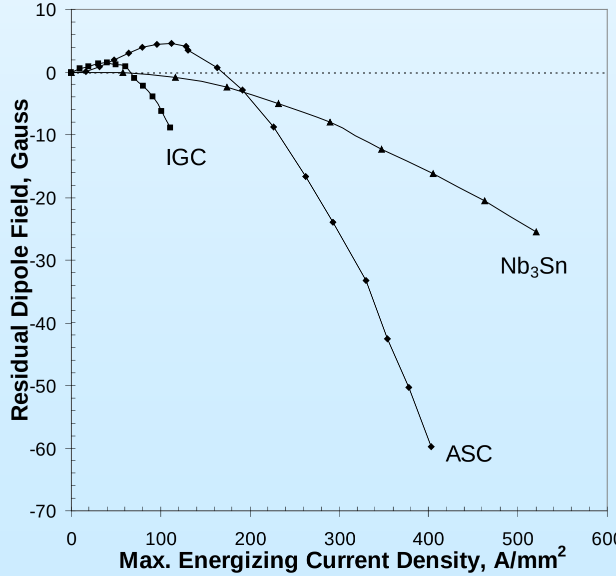
2000

Two HTS tape coils in common coil configuration

Status of HTS tape coils at BNL

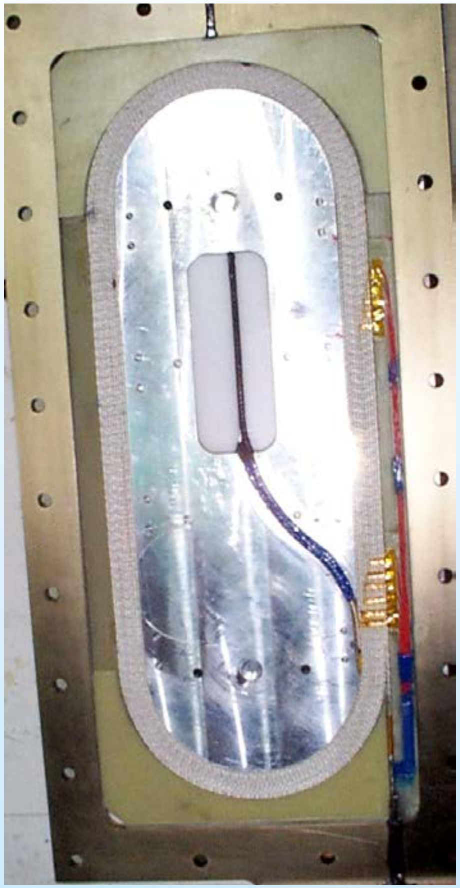
	Size, mm	Turns	Status
Nb_3Sn	0.2 x 3.2	168	Tested
IGC	0.25 x 3.3	147	Tested
ASC	0.18 x 3.1	221	Tested
NST	0.20 x 3.2	220	Under construction
VAC	0.23 x 3.4	170	Under construction





HTS Coils and Magnets @BNL (2002)

BNL had built **14** test coils and several HTS magnets by 2002



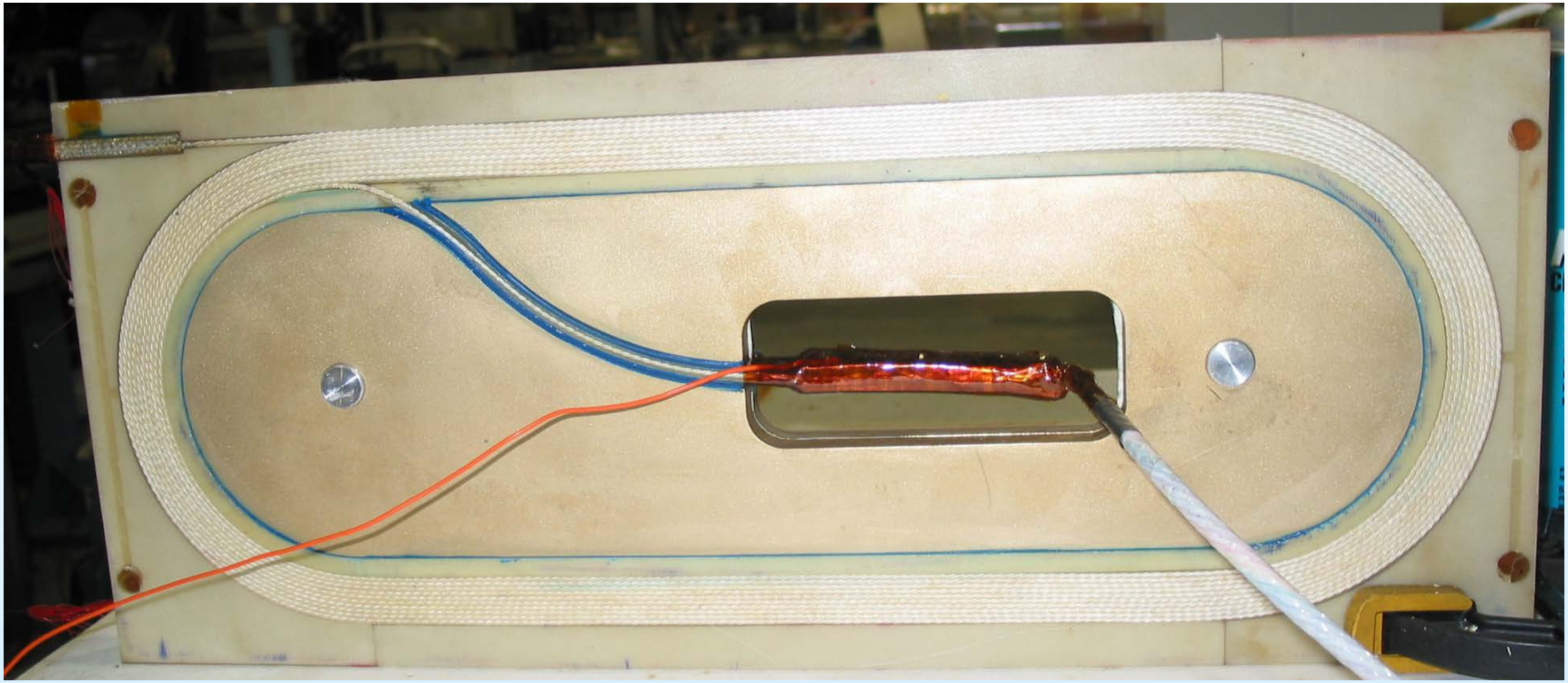
HTS Cable Coil

HTS Cable Coils in support structure

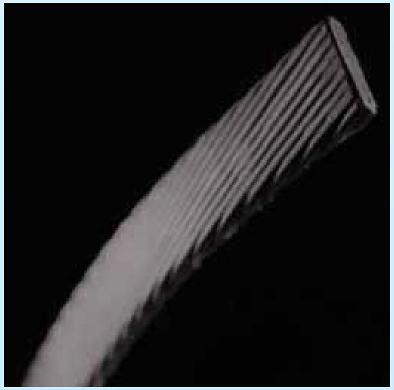
Two HTS tape coils in common coil configuration

Results Reported at MT13 (2003)

Bi2212 Cable Coil for Dipoles



Racetrack coil made with
React & Wind Rutherford cable



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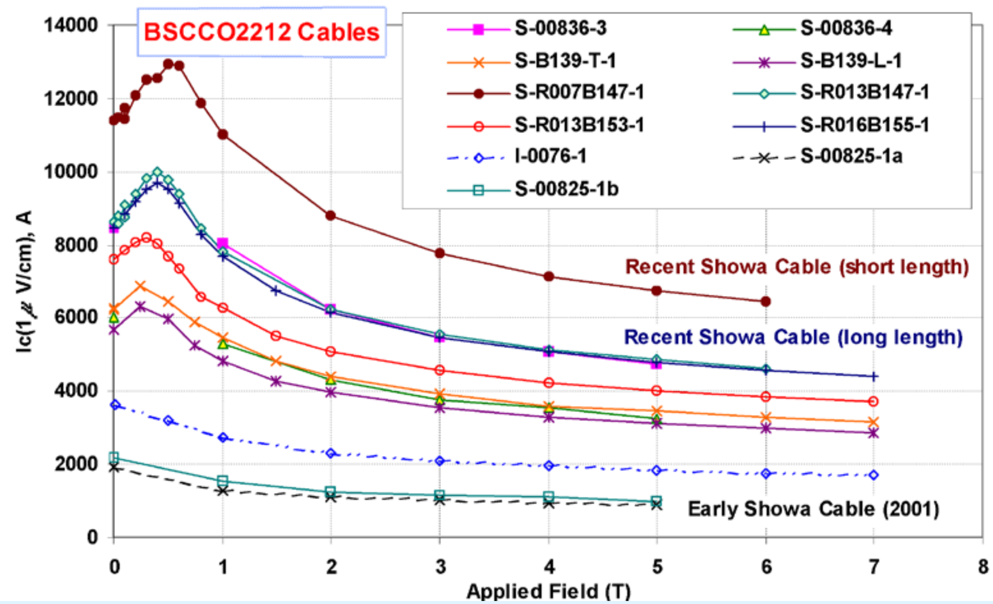
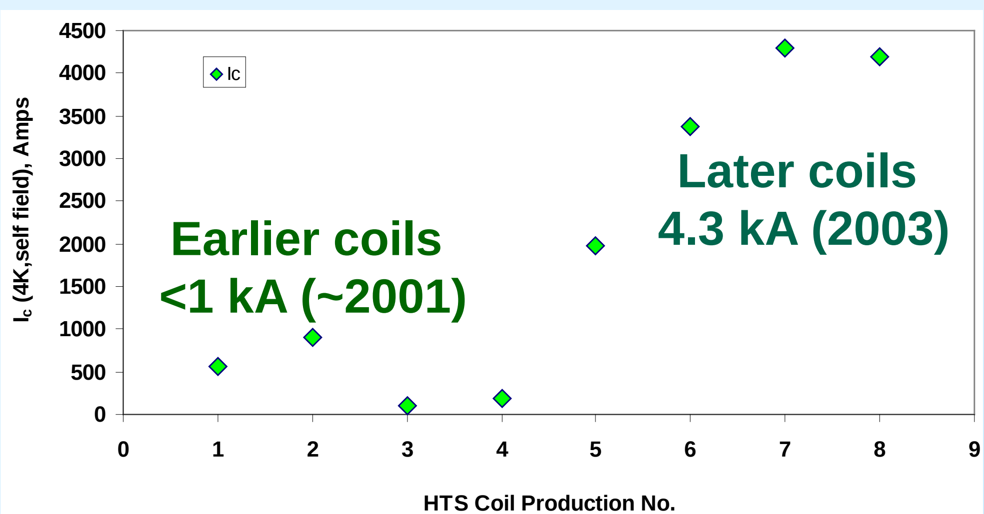
Superconducting Magnet Division

Progress in Bi2212 Cables, Coils and Magnet





A Continuous Progress

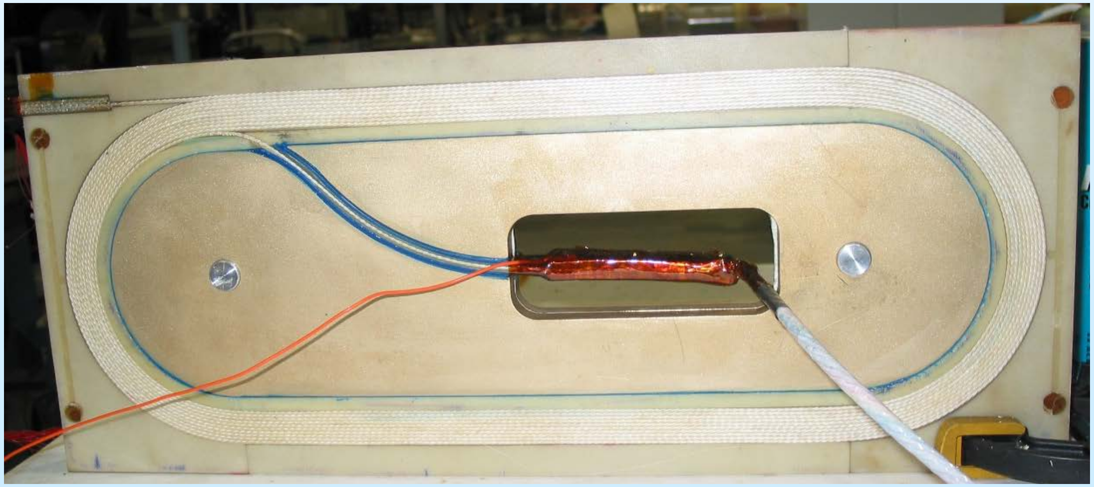
MT18 (2003)

Coil / Magnet	Cable Description	Magnet Description	I_c (A)
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing Common coil configuration	560
CC007 DCC004	0.81 mm wire, 18 strands		900
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	2 HTS coils (mixed strand) 74 mm spacing Common coil	94
CC011 DCC006	0.81 mm wire, 2 HTS, 16 Ag		182
CC012 DCC008	0.81 mm wire, 18 strands	Hybrid Design 1 HTS, 2 Nb_3Sn	1970
CC023 DCC012	1 mm wire, 20 strands	Hybrid Design 1 HTS, 4 Nb_3Sn	3370
CC026 DCC014	0.81 mm wire, 30 strands	Hybrid Common Coil Design 2 HTS, 4 Nb_3Sn coils (total 6 coils)	4300
CC027 DCC014	0.81 mm wire, 30 strands		4200

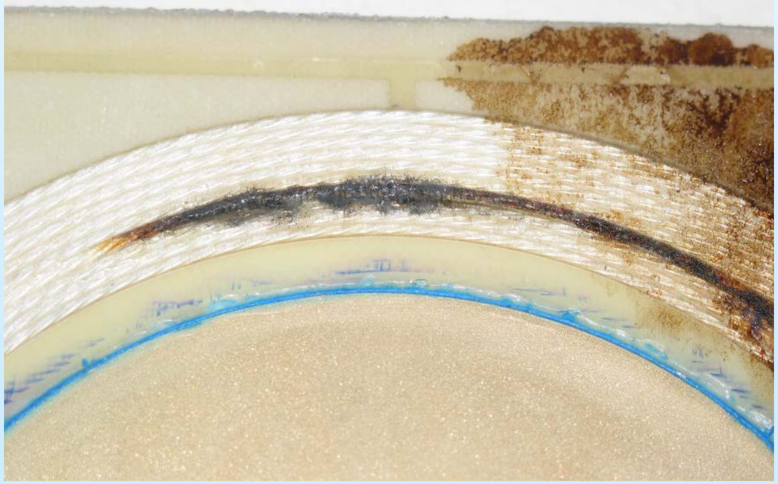
A Learning Experience

- To learn, perhaps one has to burn! And we certainly did that!!
- In magnet DCC014 one of the two HTS coils was damaged (burnt-out) during the test after two quenches.
- The quench protection (as used in LTS coils) was unable to protect the high current HTS coil at 4K.
- Now, of course, we do things differently.
- This particular program was stopped after this test.

(2003)



Before Test



After Test

Round 2 (SBIR with PBL 2014-2017)

High Field HTS/LTS Hybrid Dipole

2G HTS Coils for Hybrid Dipole

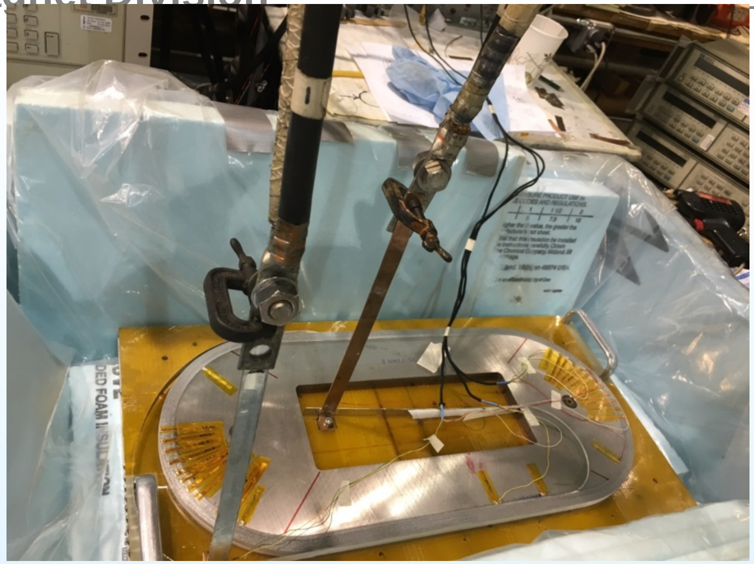
PBL/BNL
SBIR

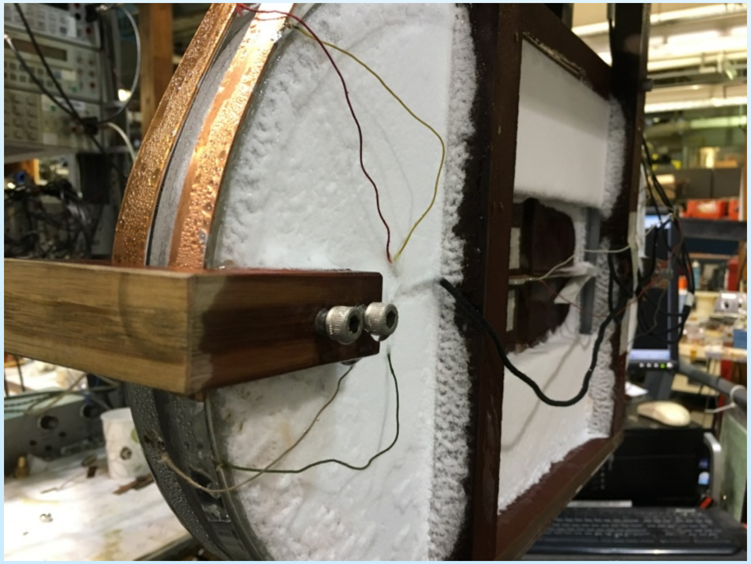
Conductor:
- **12 mm 2G ASC tape**

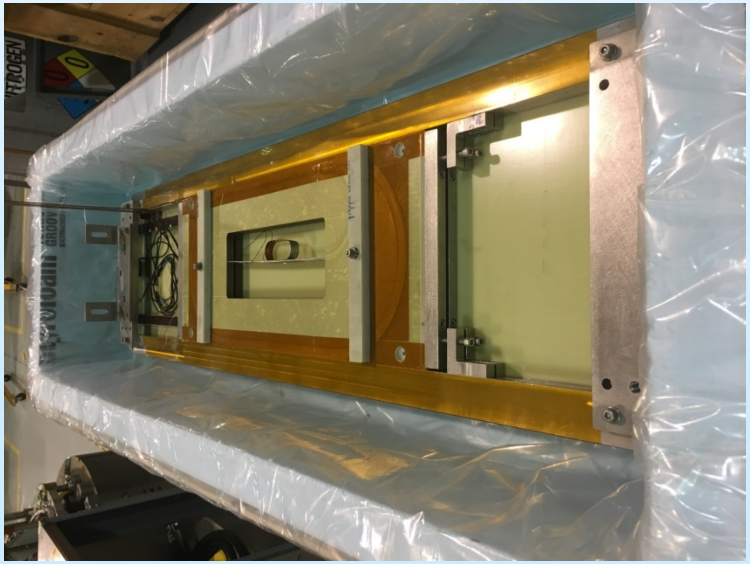
Insulation:
- **Nomex**

Two coils used ~300 meters of 4 mm equivalent

77 K Test HTS Coils in Various Configurations







77 K tests provide a unique QA in HTS coils

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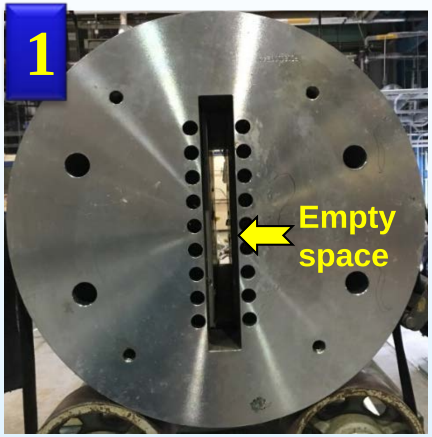
Magnet Division

HTS/LTS Hybrid Dipole with a 10 T Nb_3Sn React & Wind Dipole

Five Simple Steps/Components

1

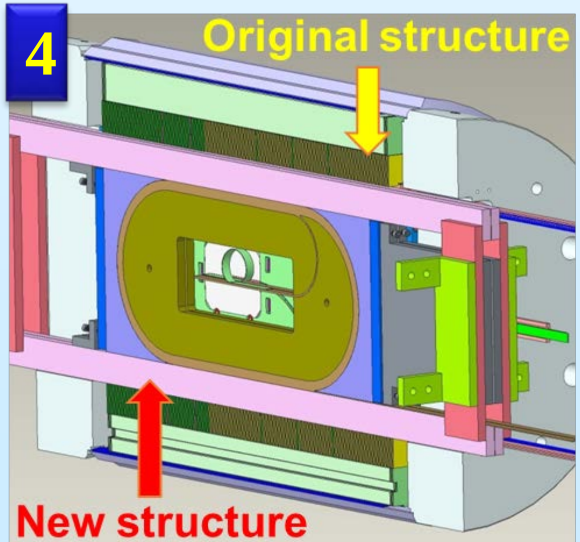


2

1. Magnet (dipole) with a large open space
2. Coil for high field testing
3. Slide coil in the magnet
4. Coils become an integral part of the magnet
5. Magnet with new coil(s) ready for testing

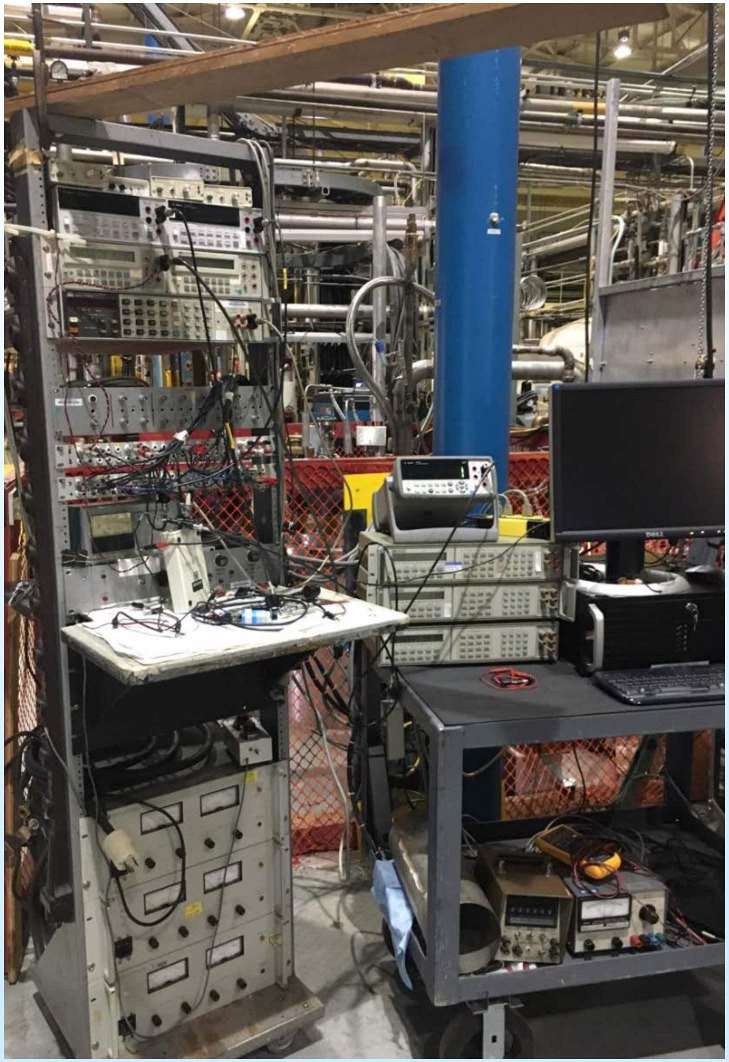
3

4



5

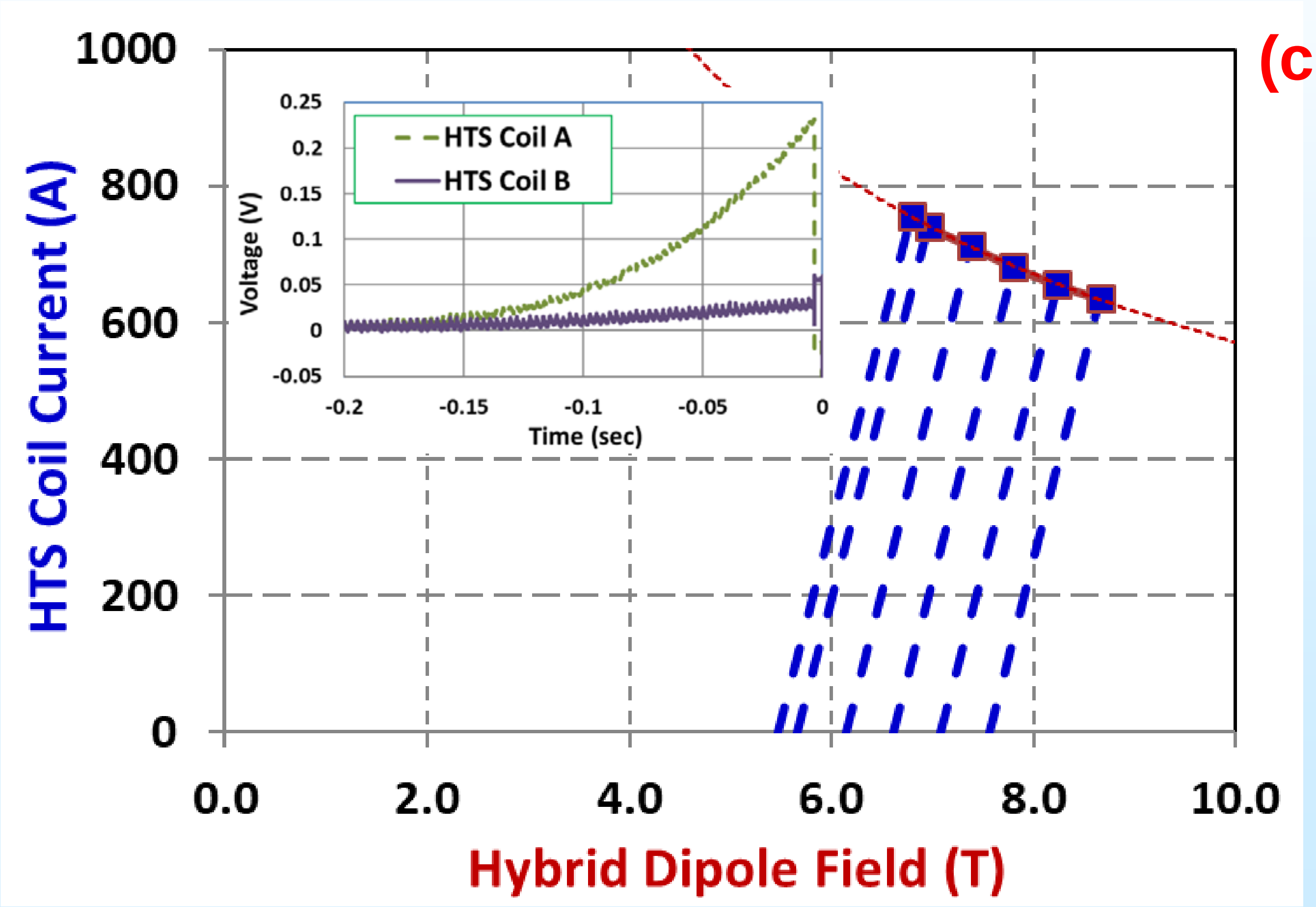
Quench Protection



- **BNL advanced quench protection with fast energy extraction**
- **Quench protection system was designed to protect both the main magnet coils and insert coils (including HTS coils)**

HTS/LTS Hybrid Dipole Test (Round 2, Year 2016)

YBCO coils ramped up till they quenched with different background field from Nb_3Sn coils



Several quenches.

- **No training**

(compare to LTS)

No damage and no degradation

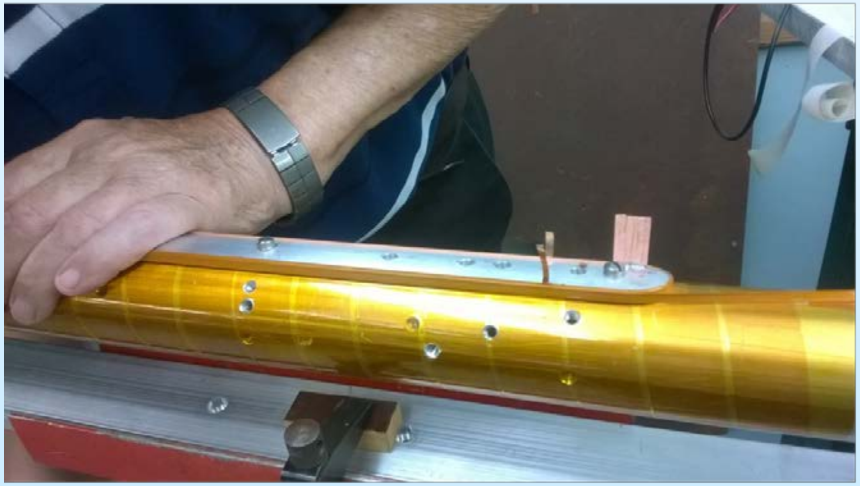
<u>Encouraging results</u>

Quench threshold 0.2 V (just like in LTS)

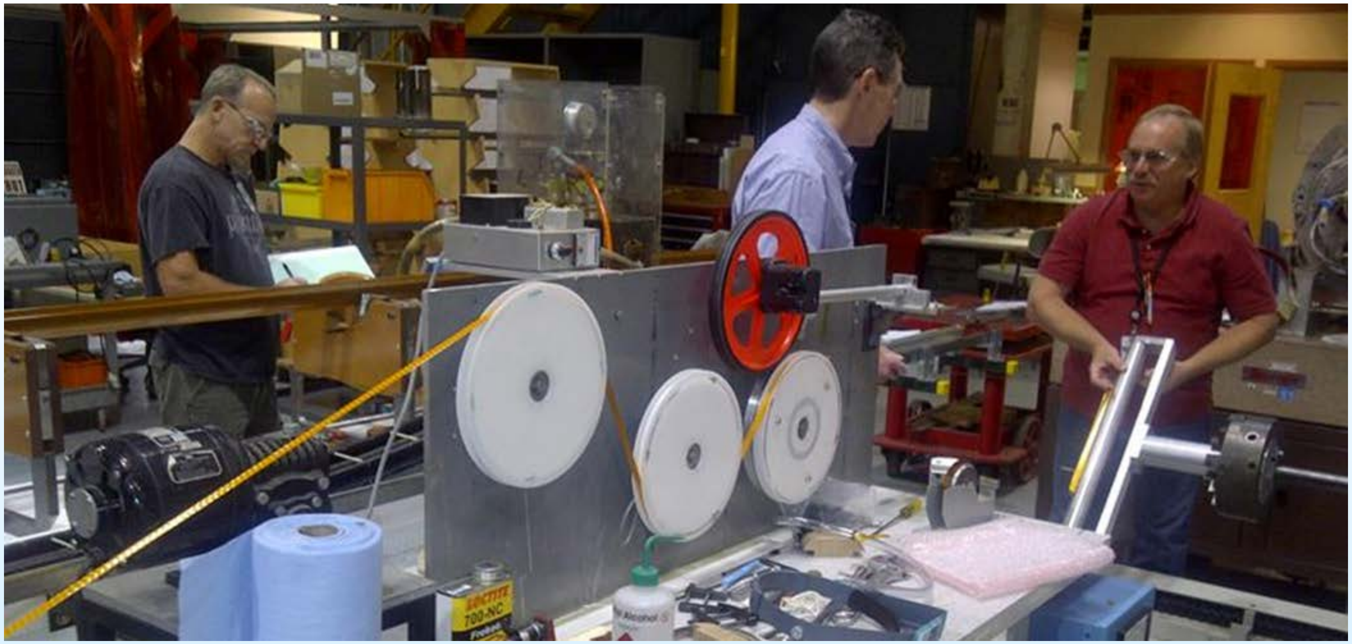
New HTS Coils being Prepared for yet another Hybrid Dipole Magnet Test

Other Geometries for HTS Dipole Magnets

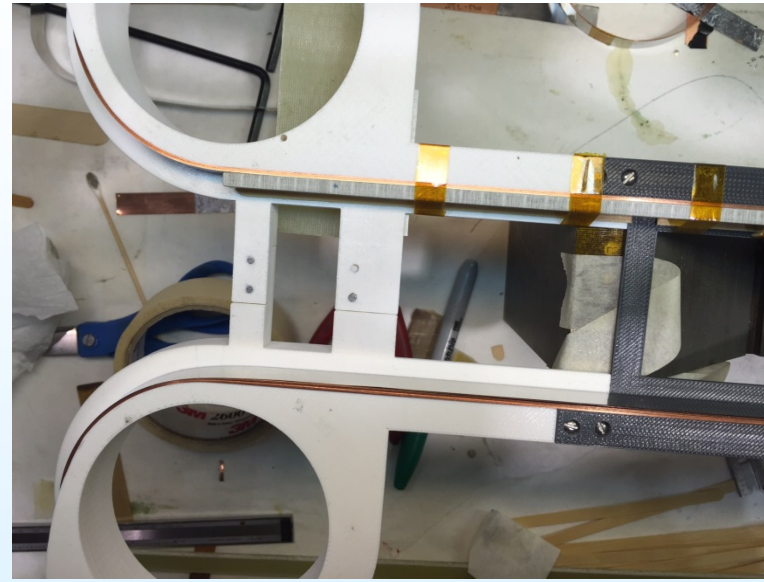
Cosine Theta Coil with 4 mm 2G HTS Tape - PBL/BNL SBIR (1)



Cosine Theta Coil with 12 mm 2G Tape PBL/BNL SBIR (2)

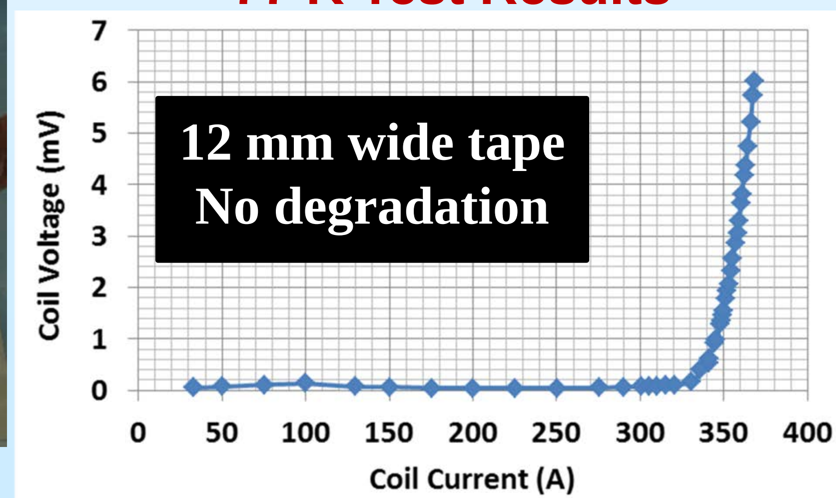


Demonstrations of the Dipole Coil Overpass/Underpass e2P/BNL SBIR



SBIR withe2P

77 K Test Results

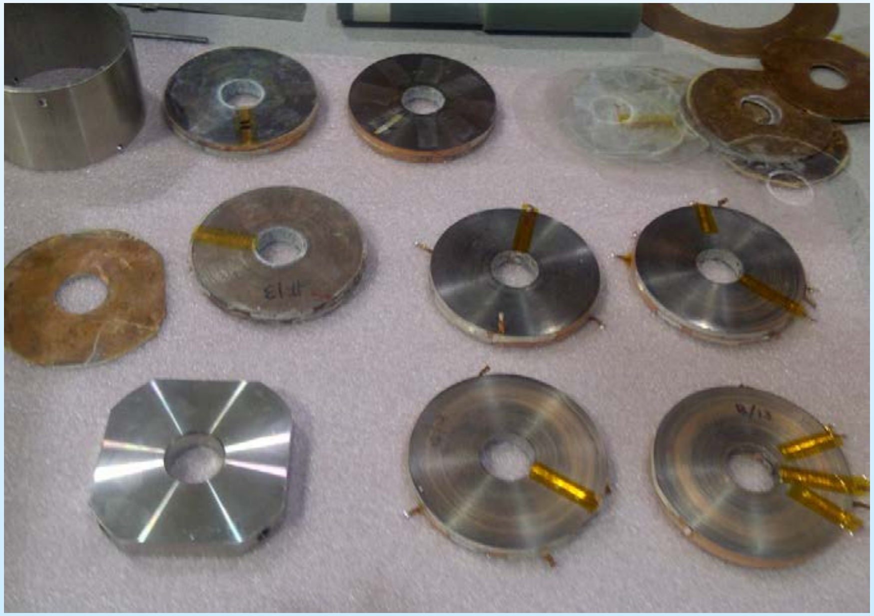


High Field HTS Solenoids

- Two Phase II SBIR with Particle Beam Lasers (PBL) for Muon Collider
- ARPA-E SMES Solenoid
- IBS 25 T, 100 mm No-insulation coils for Axion search
- High Field Solenoid for Neutron Scattering

High Field Solenoids with PBL

- Two SBIRs for 25 mm and 100 mm coils, each to generate 10-12 T field for a combined field of 22 T
- HTS tape is co-wound with insulating stainless steel tape to reduce hoop stress
- Also to help in quench protection



pancakes

Insert solenoid

Outsert solenoid

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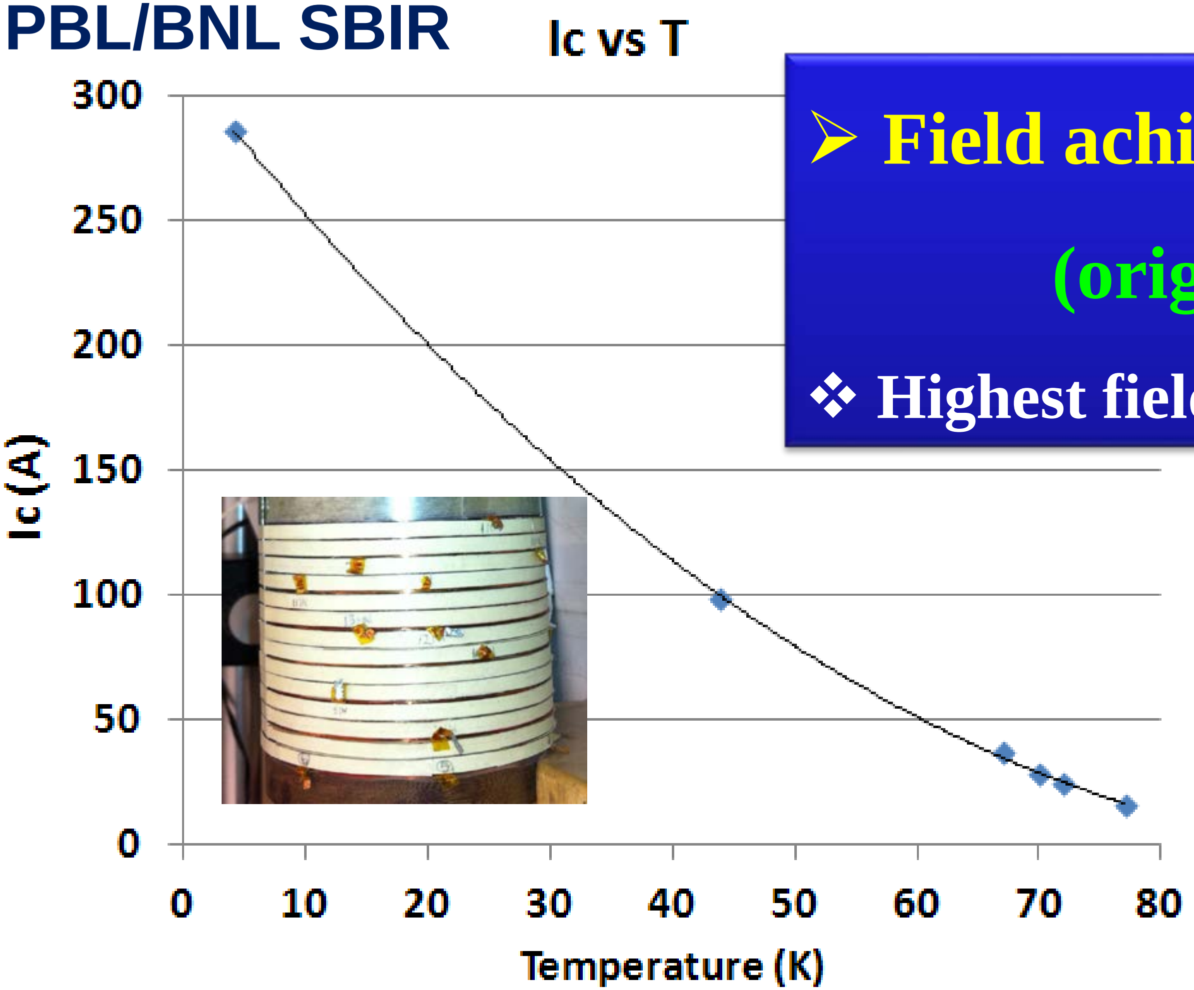
16 T HTS Solenoid (2012)

(plus a wide range of operating temperature)

PBL/BNL SBIR



- **Field achieved: ~16 T**

  (original target: 10-12T)

- **Highest field HTS solenoid in 2012**

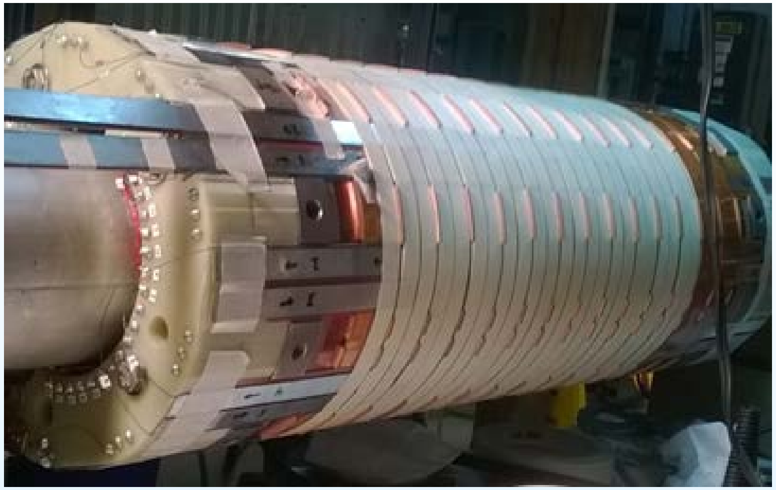
Overall J_o in coil: >500 A/mm^2 @16 T

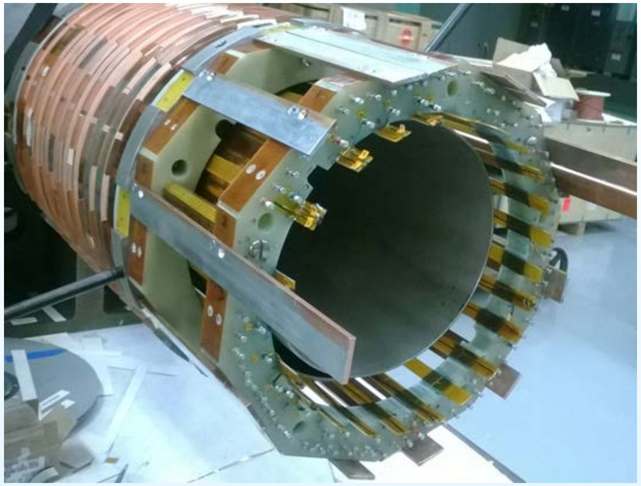
Insert solenoid: 14 pancakes, 25 mm aperture

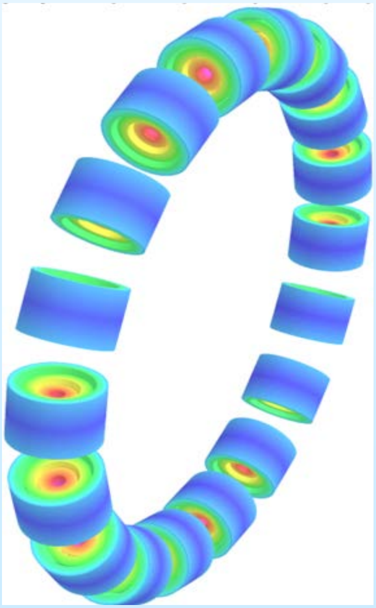
High Field HTS Solenoid for SMES (funded by ARPA-E)

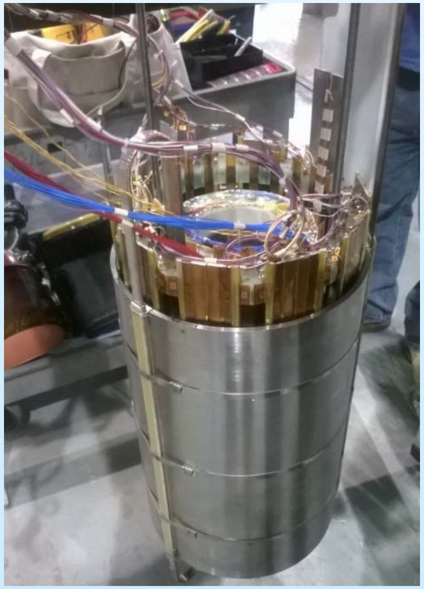
100 mm, 25 T

2-layer coil design

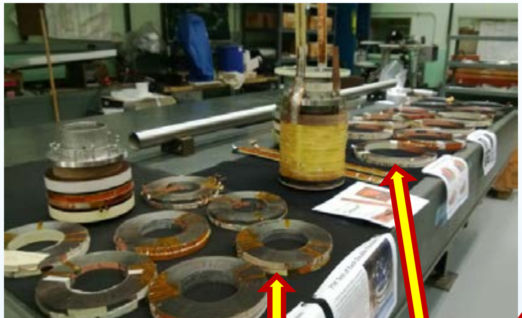


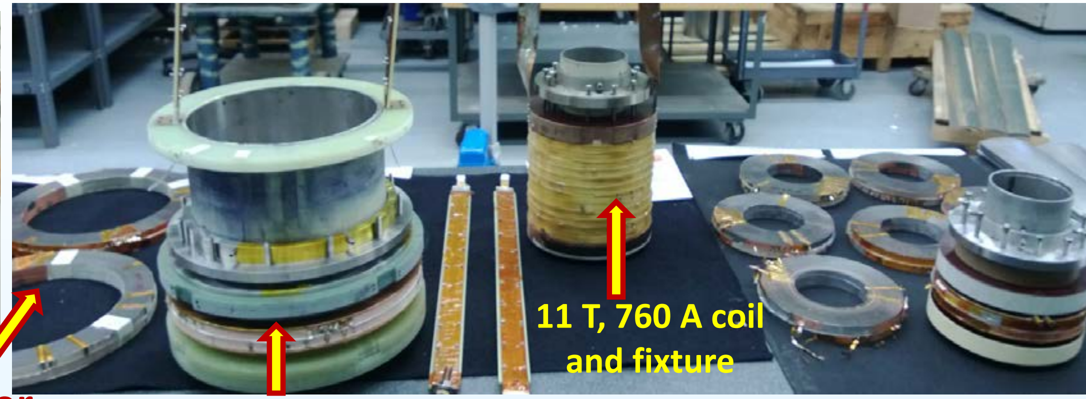






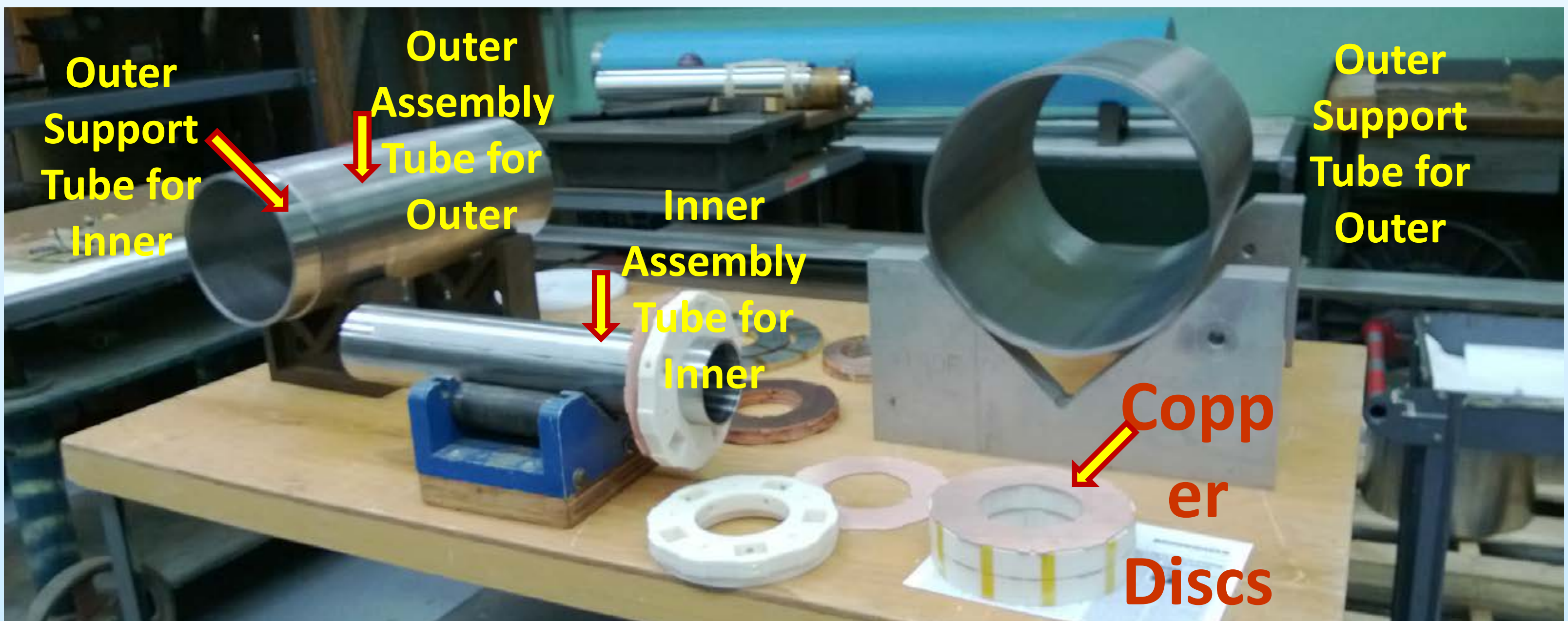
Parts of 25 T HTS Solenoid for SMES arpa-e (with ABB, SuperPower & UoH)





Pancake coils: inner and outer

77 K Test Fixture for outer



Brookhaven National Laboratory
Superconducting Magnet Division

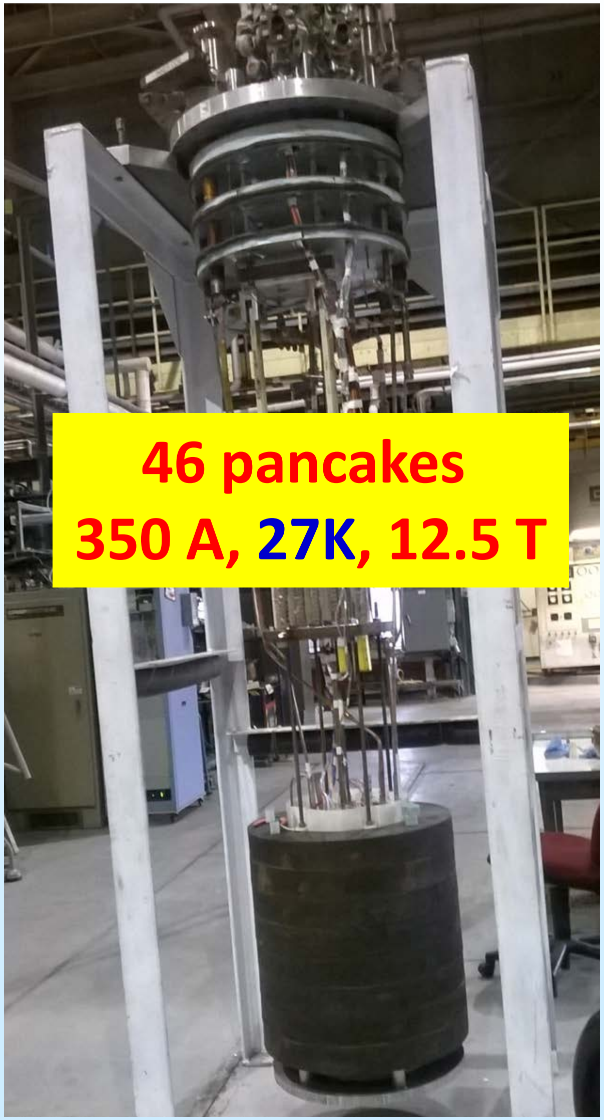
Advanced Quench Detection System with Fast Energy Extraction

- Fast energy extraction in larger magnets creates high voltages as "L" increases
- Develop electronics that can tolerate high isolation voltage (>1 kV)
- Divide coils in several sections

Cabinet #2 (32 channels, 1kV) (expandable to 64 and 3kV)

Cabinet #1 (32 channels, 1kV)

HTS SMES Coil High Field Tests



Peak fields higher

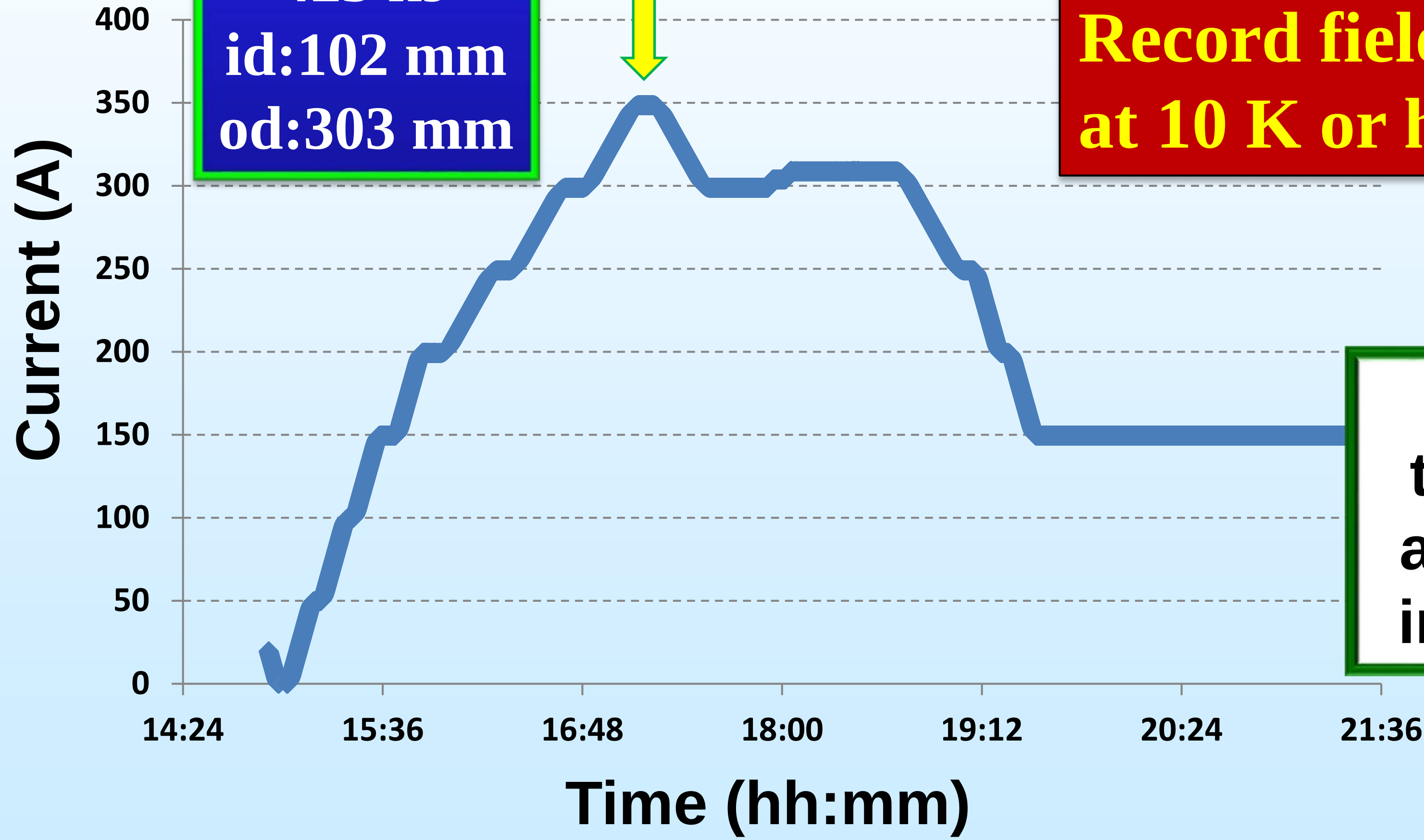
SMES Coil Test
Critical Current Reached at 27 K

12.5 Tesla at 27 K

ARPA-E

350 Amp
425 kJ
id:102 mm
od:303 mm

Record field/energy at 10 K or higher



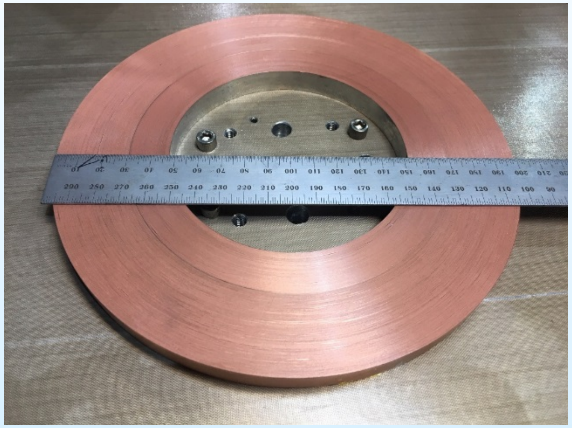
Test terminated after arcing in the leads

HTS Solenoid for IBS (Korea)

- High Field : 25 T (must use HTS; it's all HTS)
- Large Volume: 100 mm bore, +/-100 mm long

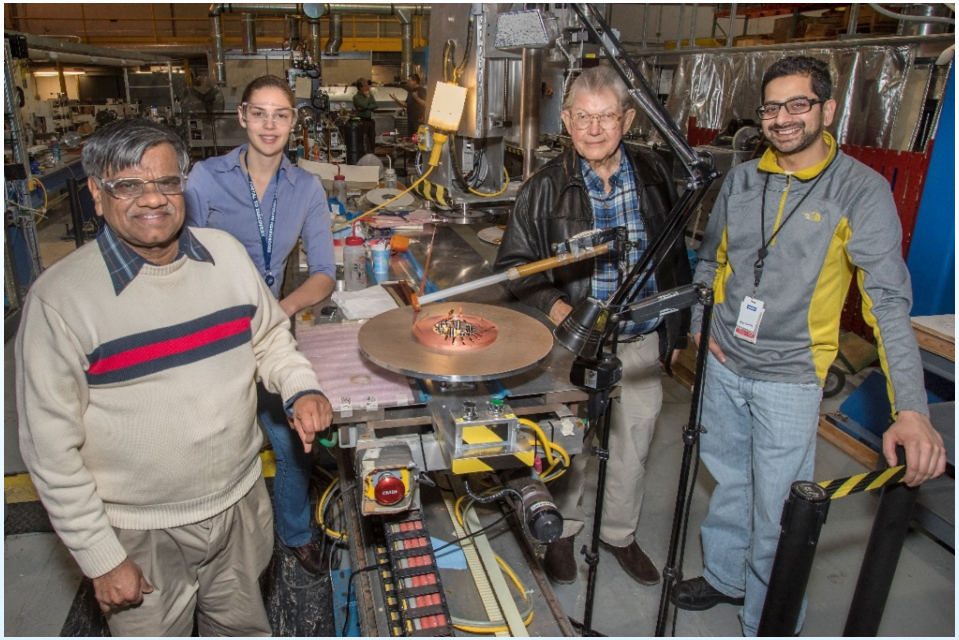
  Stresses: J X B X R

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



Relaxed field quality and slow ramp rate allows the use of *No-Insulation* windings to (a) tolerate defect in HTS tapes, and (b) expected to offer a more reliable quench protection

Winding of IBS NI HTS Coils with BNL Universal Coil Winder



16 coils wound

~5 km of 12 mm tape used

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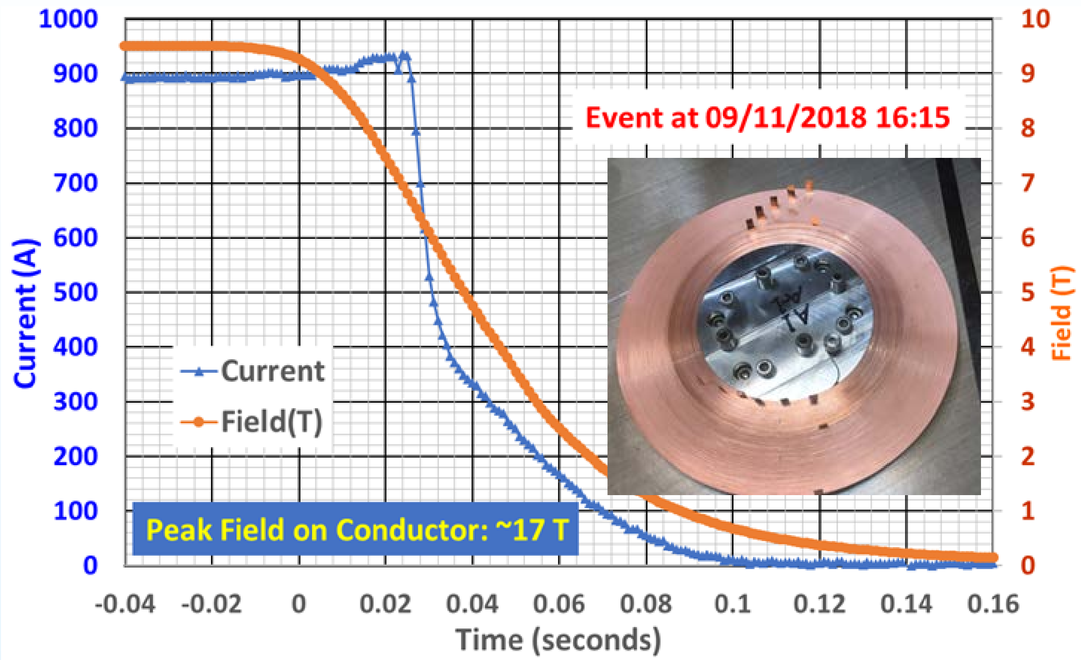
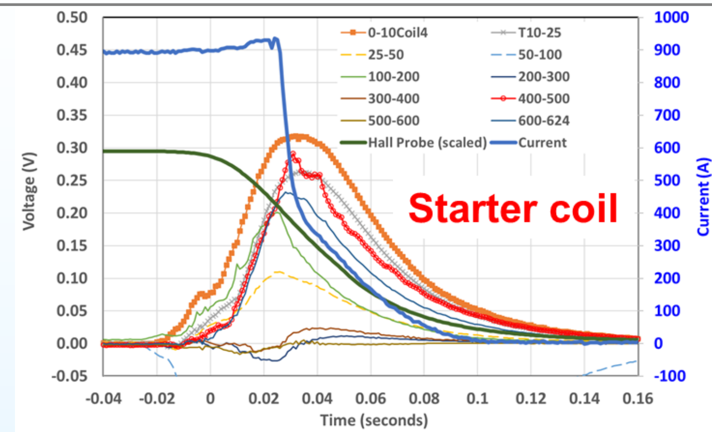
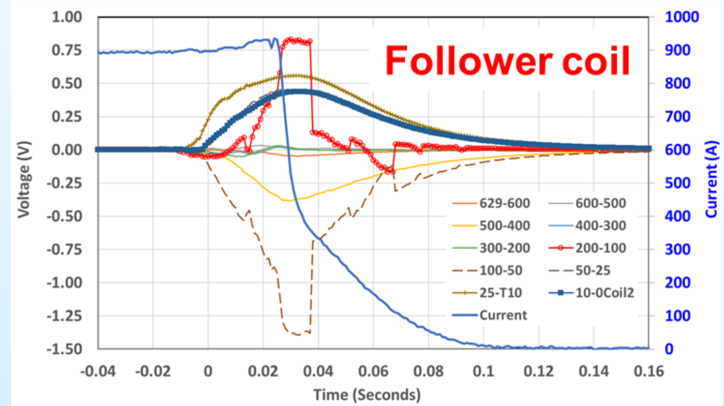
Quench Scenario in Large No-Insulation Coil (fast 4K propagation within coil and coil-to-coil)



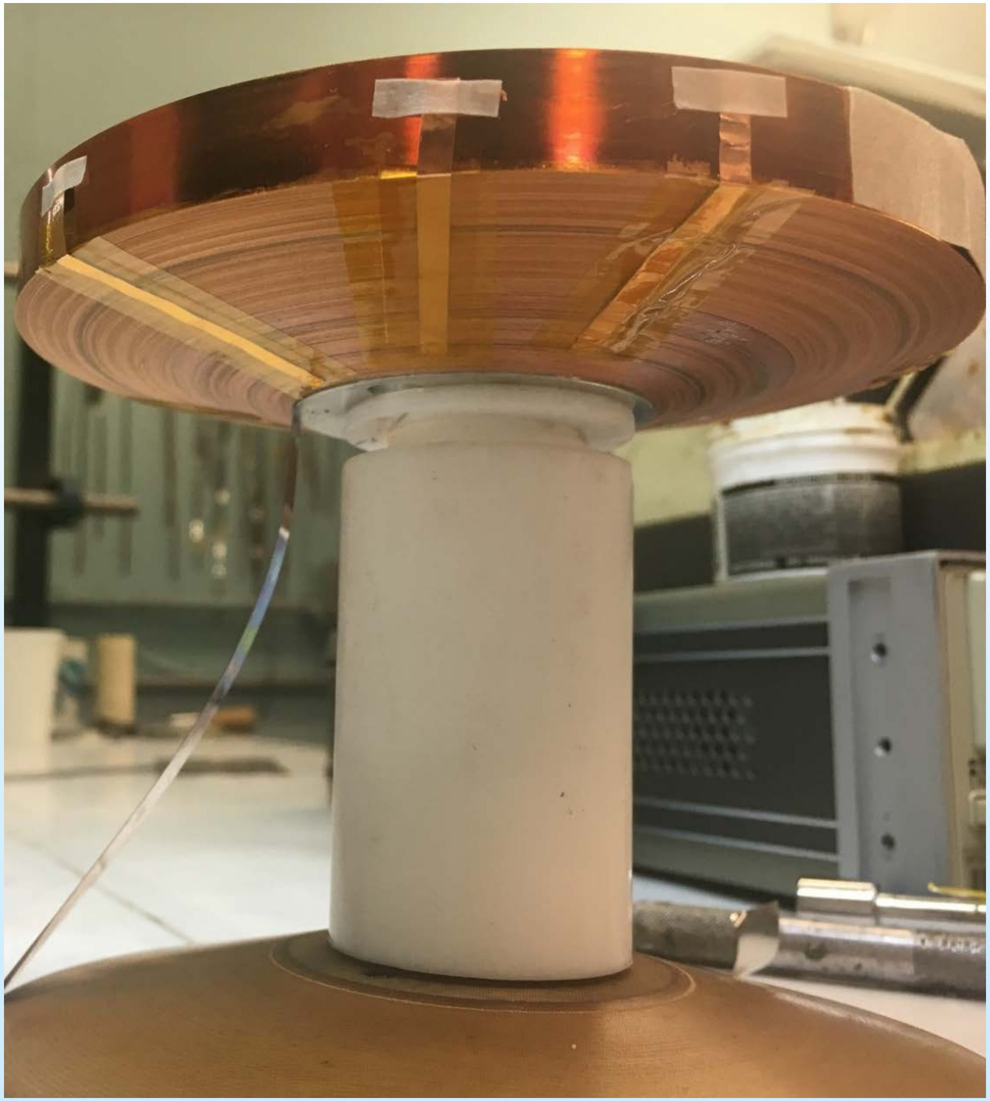




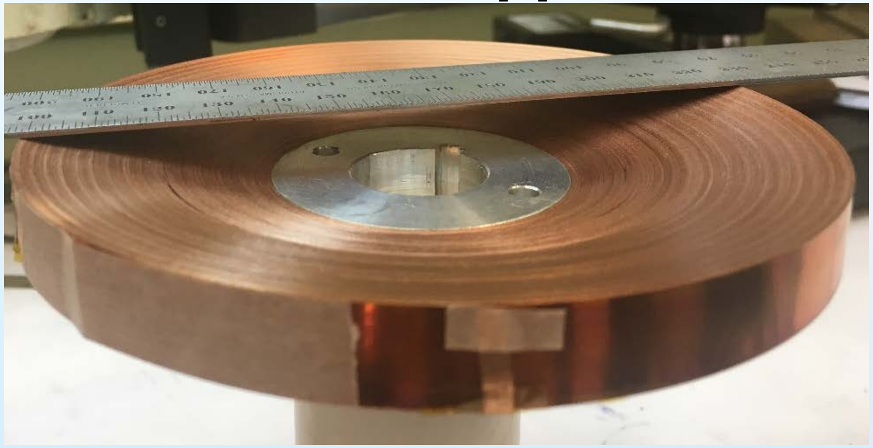
Large No-Insulation HTS coil became normal in <200 msec (even faster than in many LTS magnets)

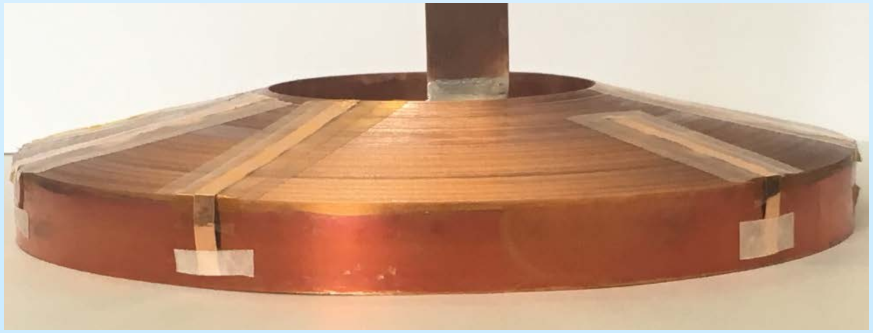
- Large number of voltage-taps gives a detailed insight of what is happening
- Within a pancake: fast propagation due to resistive heating through contact resistance between turns when the current flows across (not around) in a "No-insulation" coil
- Pancake to pancake: fast propagation due to inductive coupling of the drop in local field
- The mechanism seems scalable to long solenoids made with many pancake coils

PBL/BNL SBIR for Neutron Scattering Solenoid (conical shape HTS coils)



- Goal: 25 T solenoid with a large opening
- Successful coil winding and 77 K testing in Phase I
- Next Phase II application



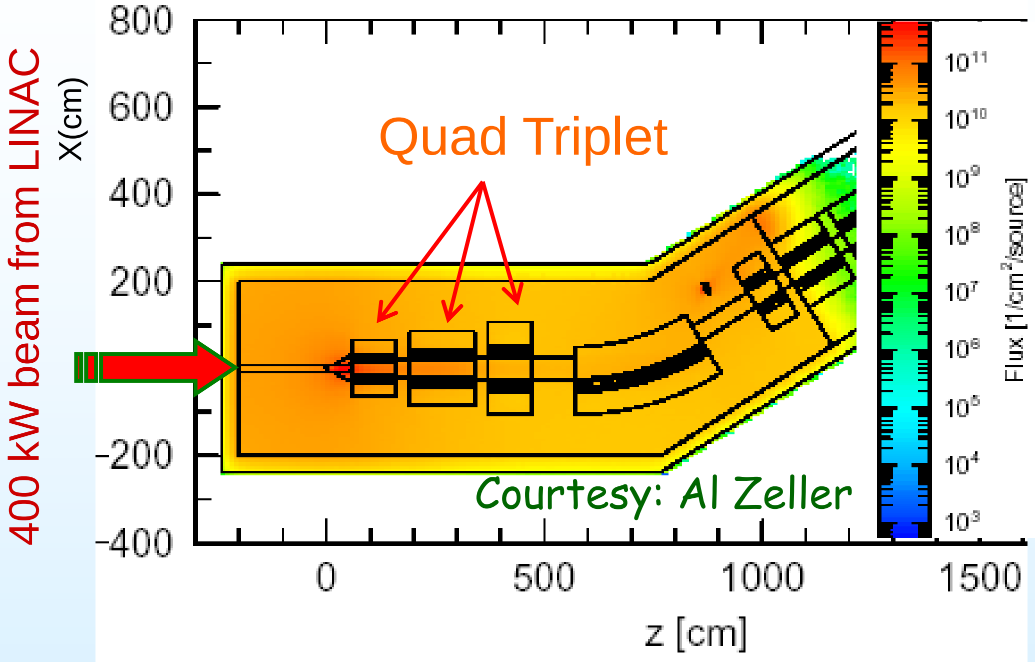


- **Medium field (2-3 T), medium temperature (30-50 K)**
- **Very large heat and radiation loads**

HTS Quadrupole R&D for the Facility for Rare Isotope Beams (FRIB)

Fragment Separator Quadrupole for FRIB

(2003)



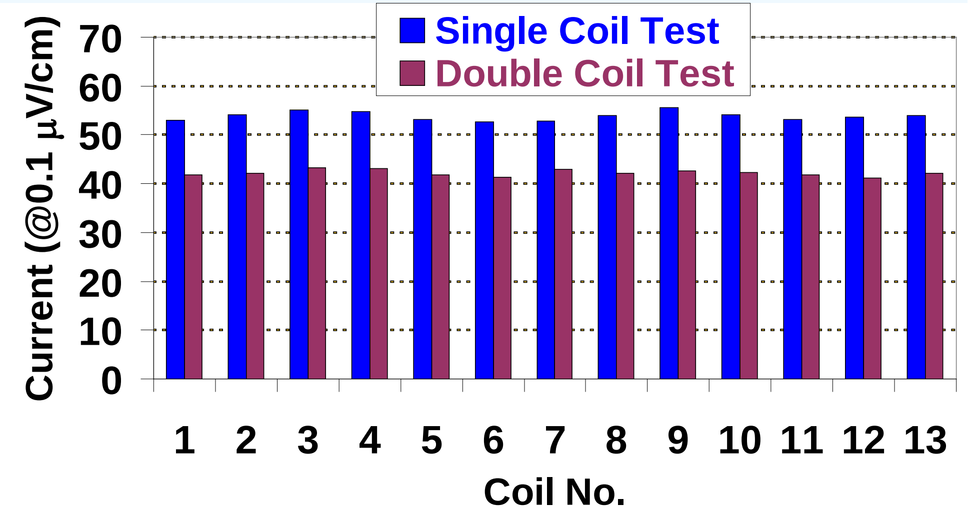
- Up to 400 kW of beam power hits the target.
- Quad triplet in the fragment separator is exposed to very high radiation and heat loads.
- ~15 kW is deposited in the first quadrupole itself.

- **Conventional superconductors and insulators can't tolerate such heat and radiation loads**
- **BNL performed a significant R&D on HTS quadrupoles with stainless steel insulation**
- **1st generation with 2213 tape and 2nd with ReBCO tape**

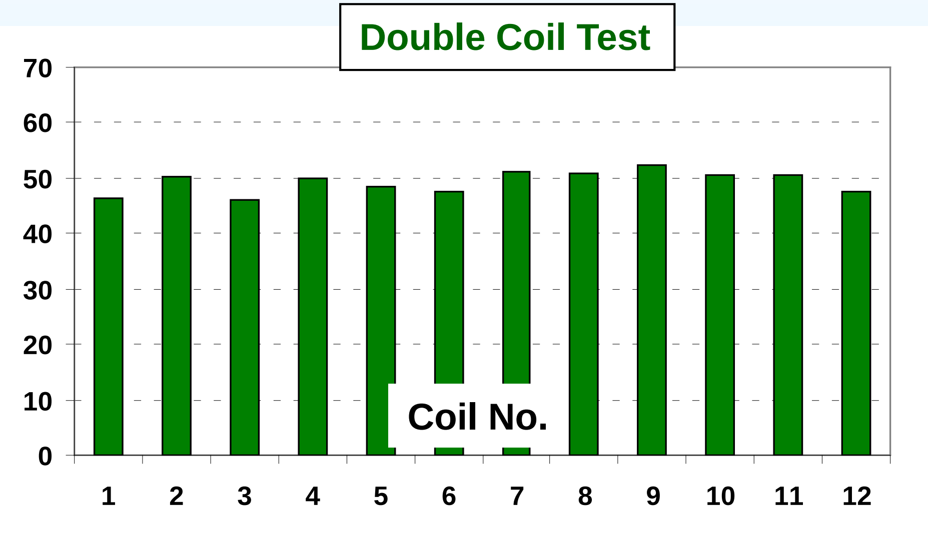
77 K Test of Coils Made with ASC 1st Generation HTS

- Each single coil uses ~200 meter of tape

13 Coils made HTS tape in year #1

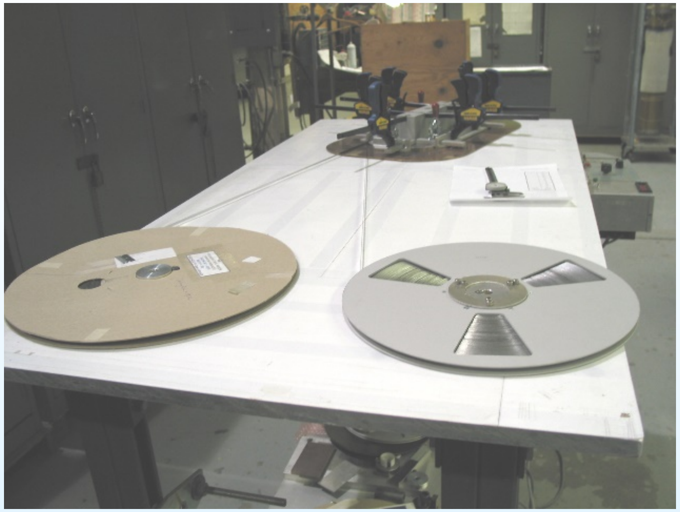


12 coils with HTS tape in year #2

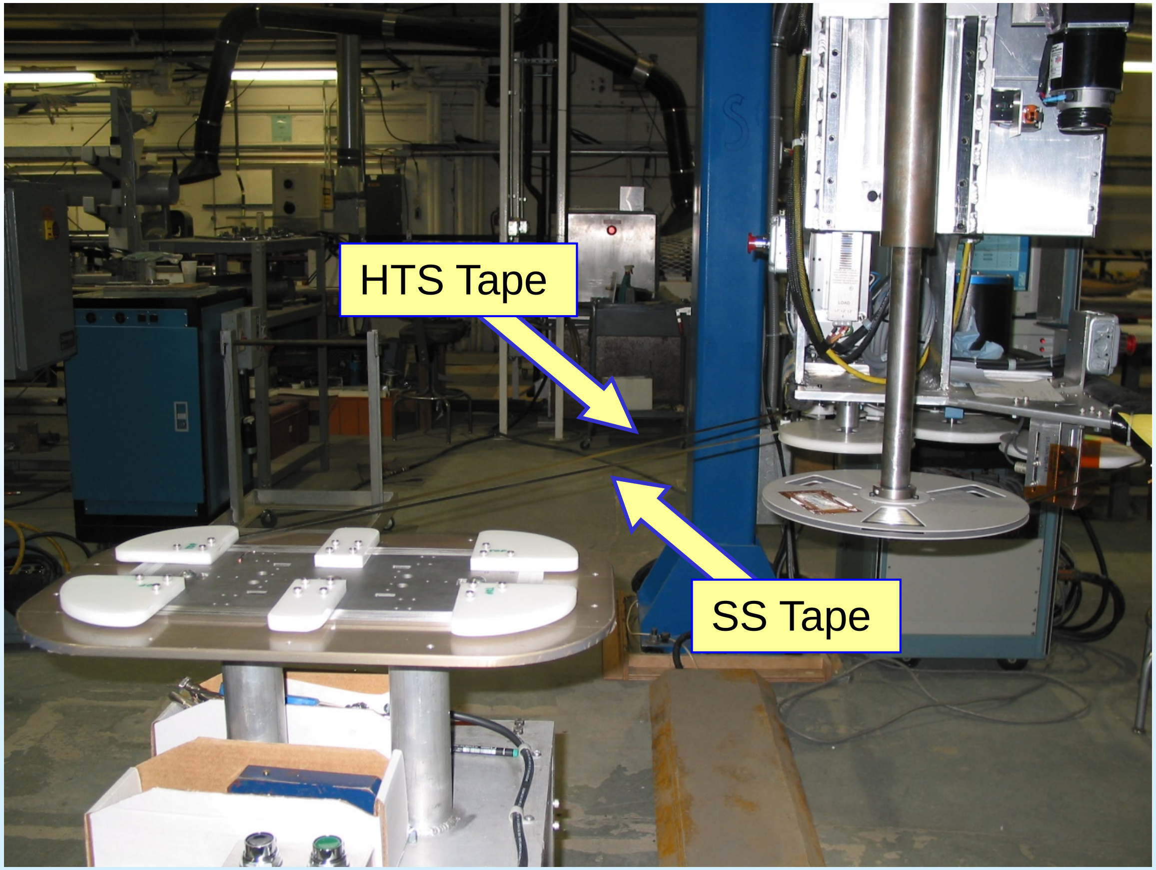


Note: A uniformity in performance of a large number of HTS coils

HTS Coil Winding

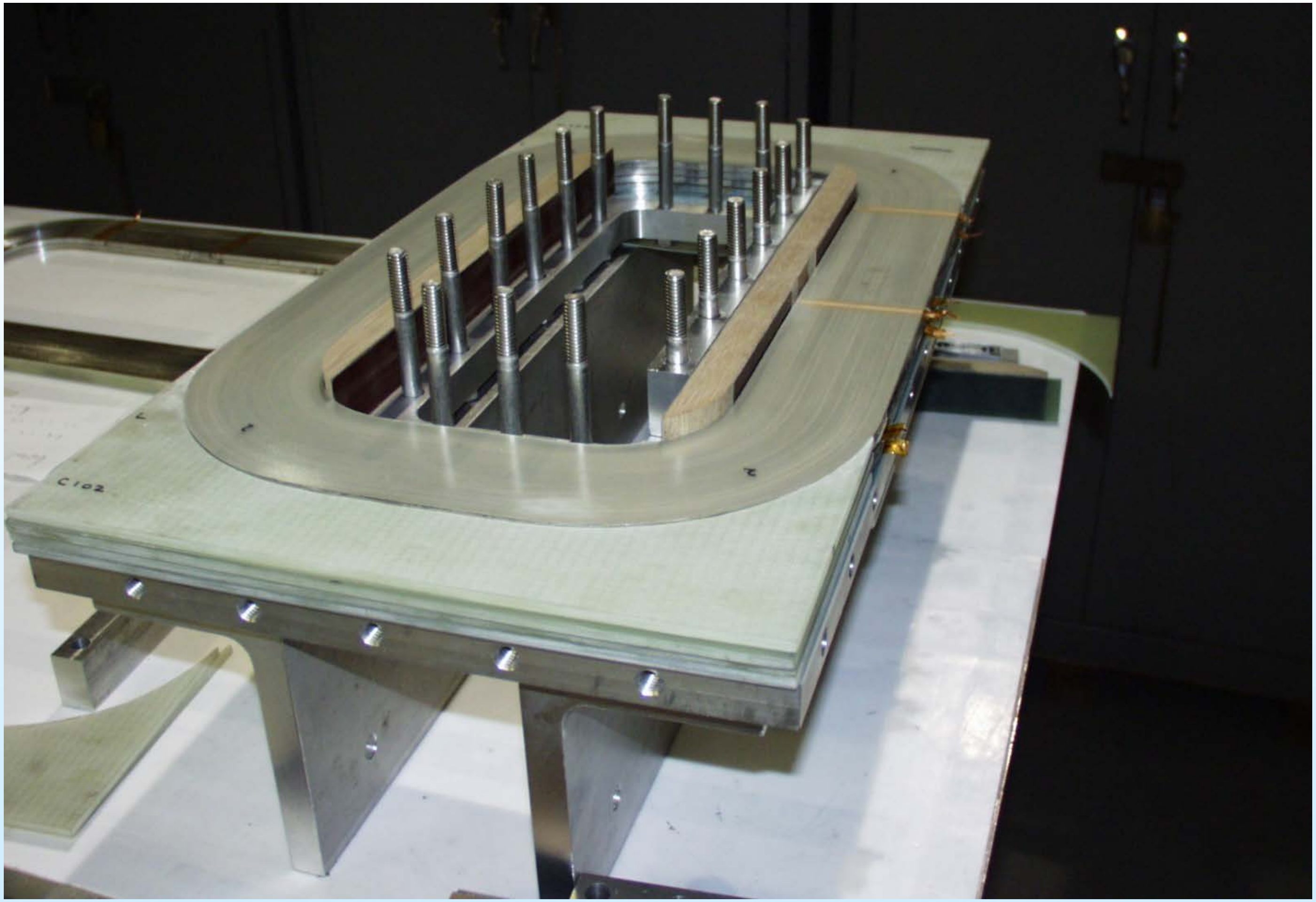


Earlier coils wound with manual controls



Later coils wound with a computer controlled winding machine

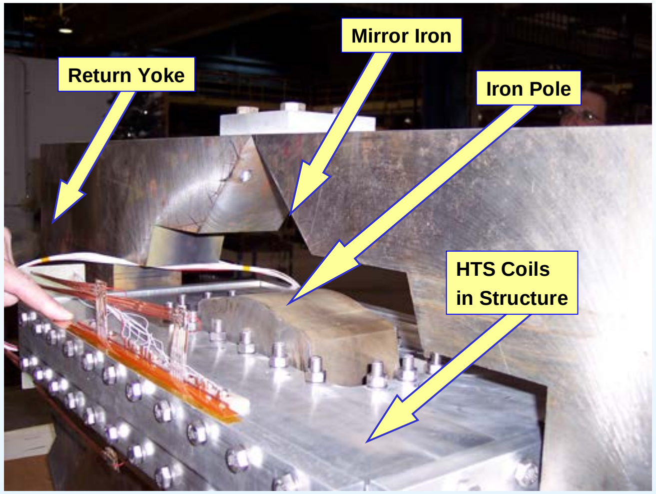
Assembled Coils with Internal Splice



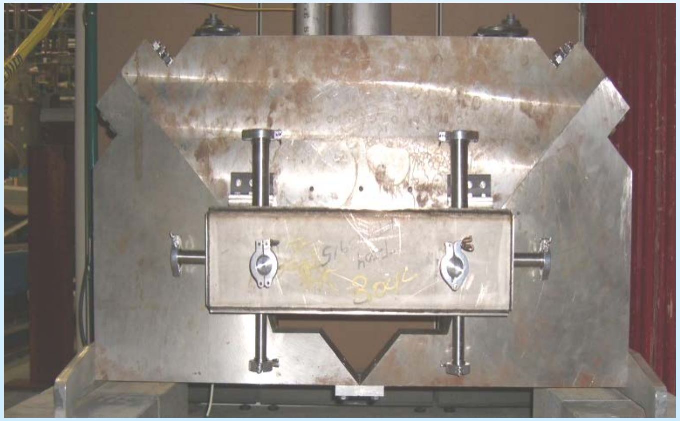
Three pairs of coils during their assembly a support structure

1st Generation HTS Quad

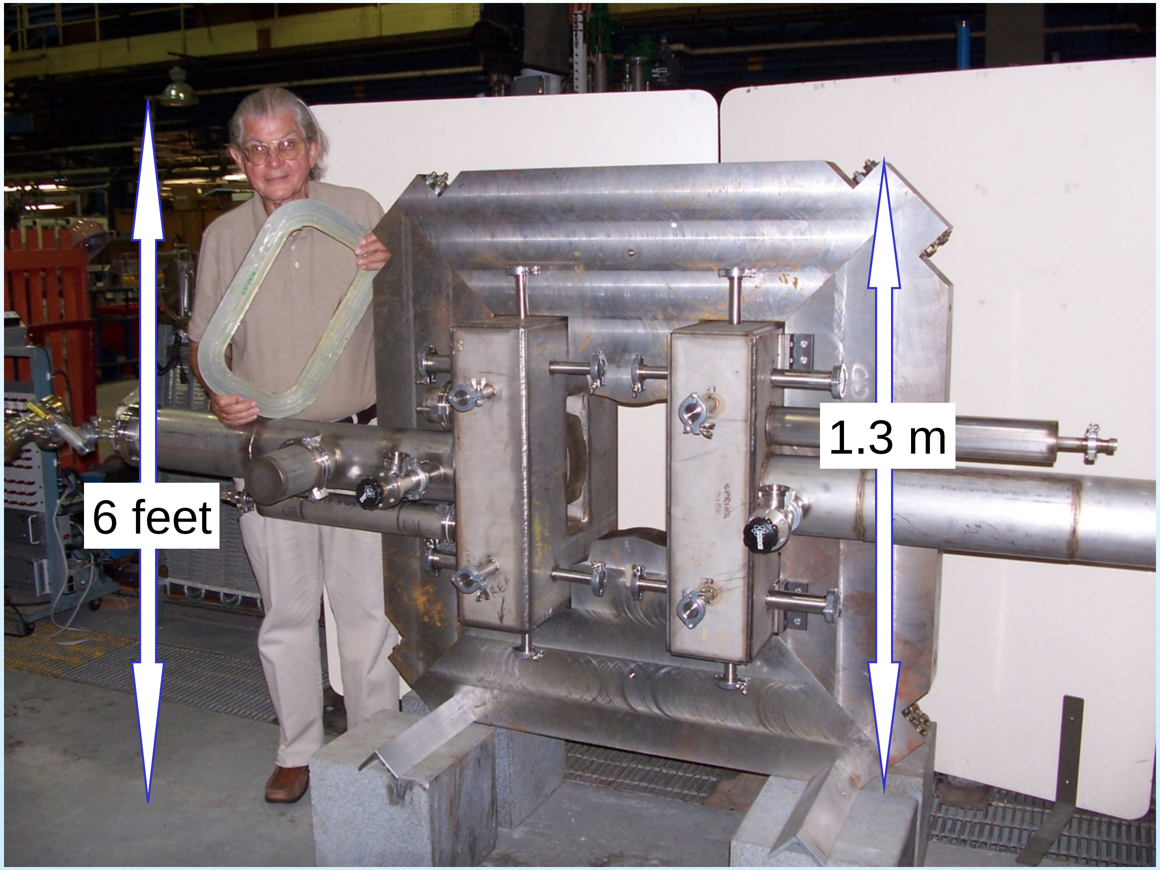
Three magnet structures, built and tested



Mirror cold iron

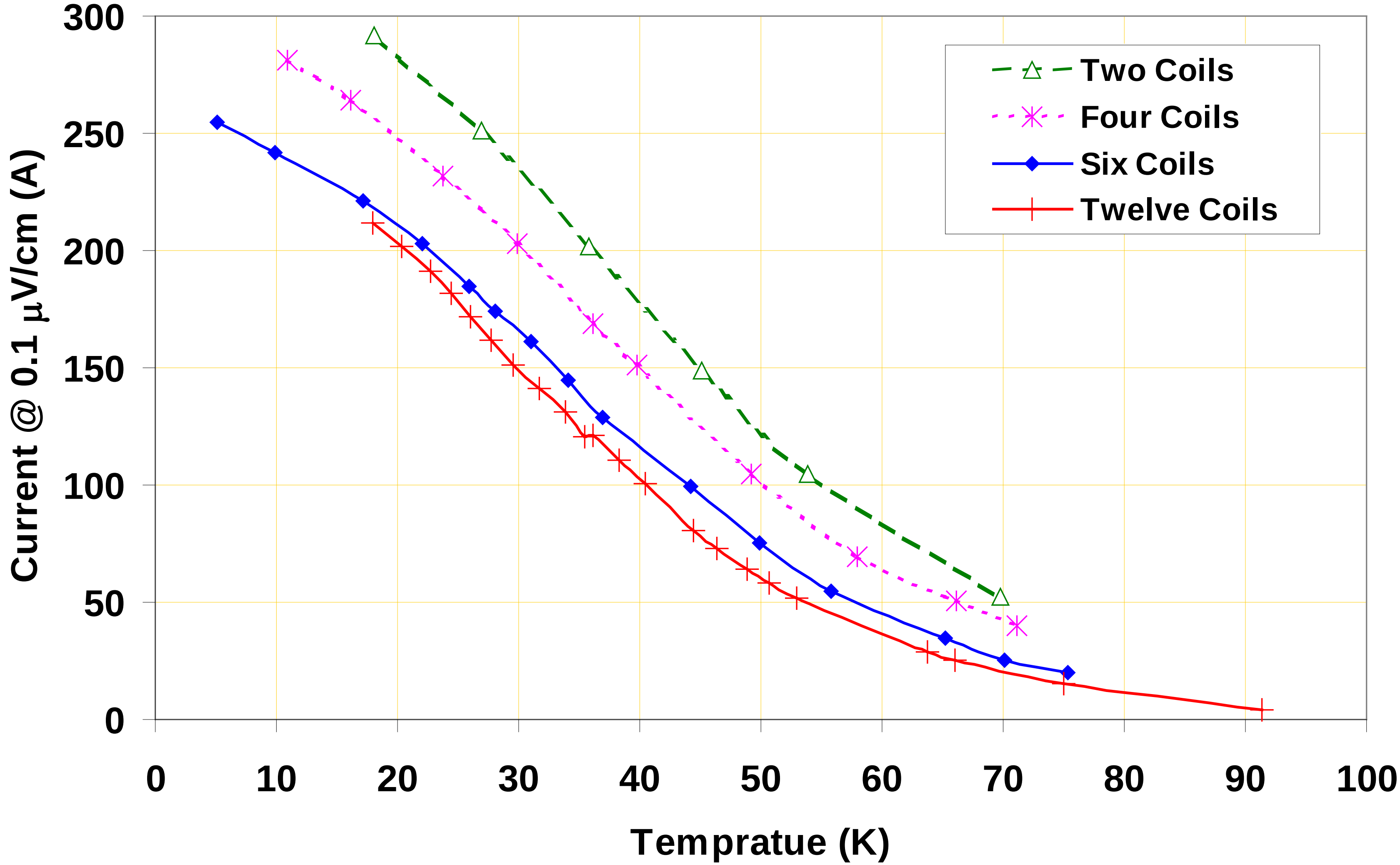


Mirror warm iron



Warm Iron Design to Reduce Heat Load

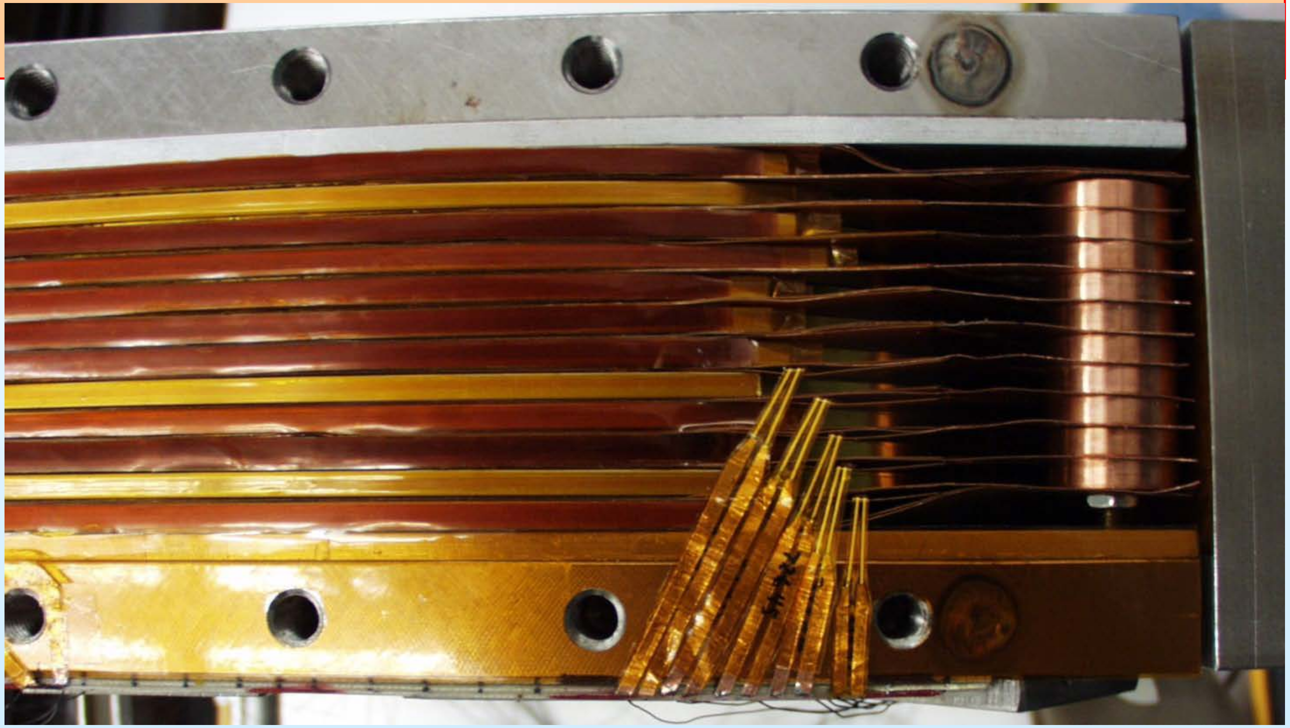
Summary of First Generation HTS Quad Tests



Operation over a large temperature range- only possible with HTS

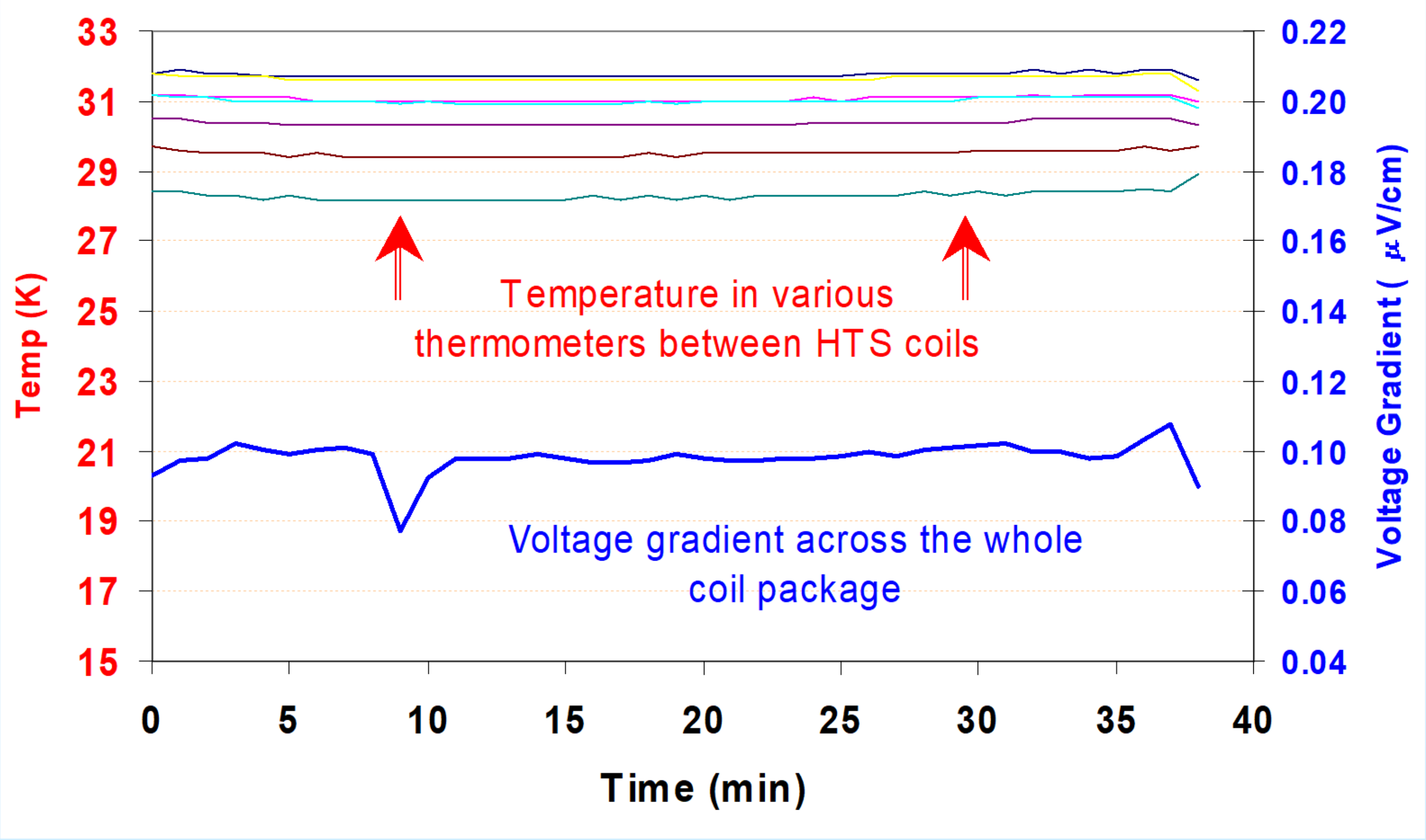
Energy Deposition Experiments

Stainless steel tape heaters for energy deposition experiments



Large Energy Deposition Experiment

Magnet operated in a stable fashion with large heat loads (25 W, 5kW/m^3) at the design temperature (~30 K) at 140 A (design current is 125 A).



Stable operation for ~40 minutes

Voltage spikes are related to the noise

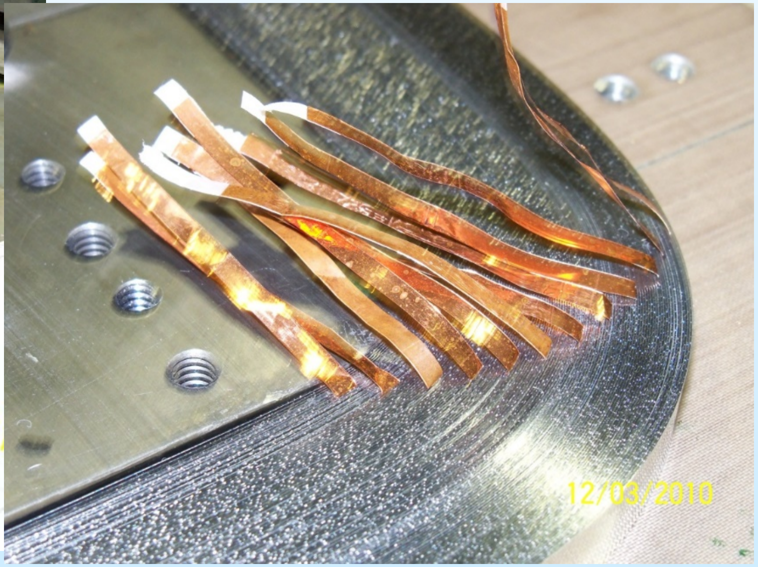
Second Generation Quadrupole for FRIB

HTS Coils for FRIB with the Second Generation (2G) HTS Tape

4 coils made with SuperPower Tape

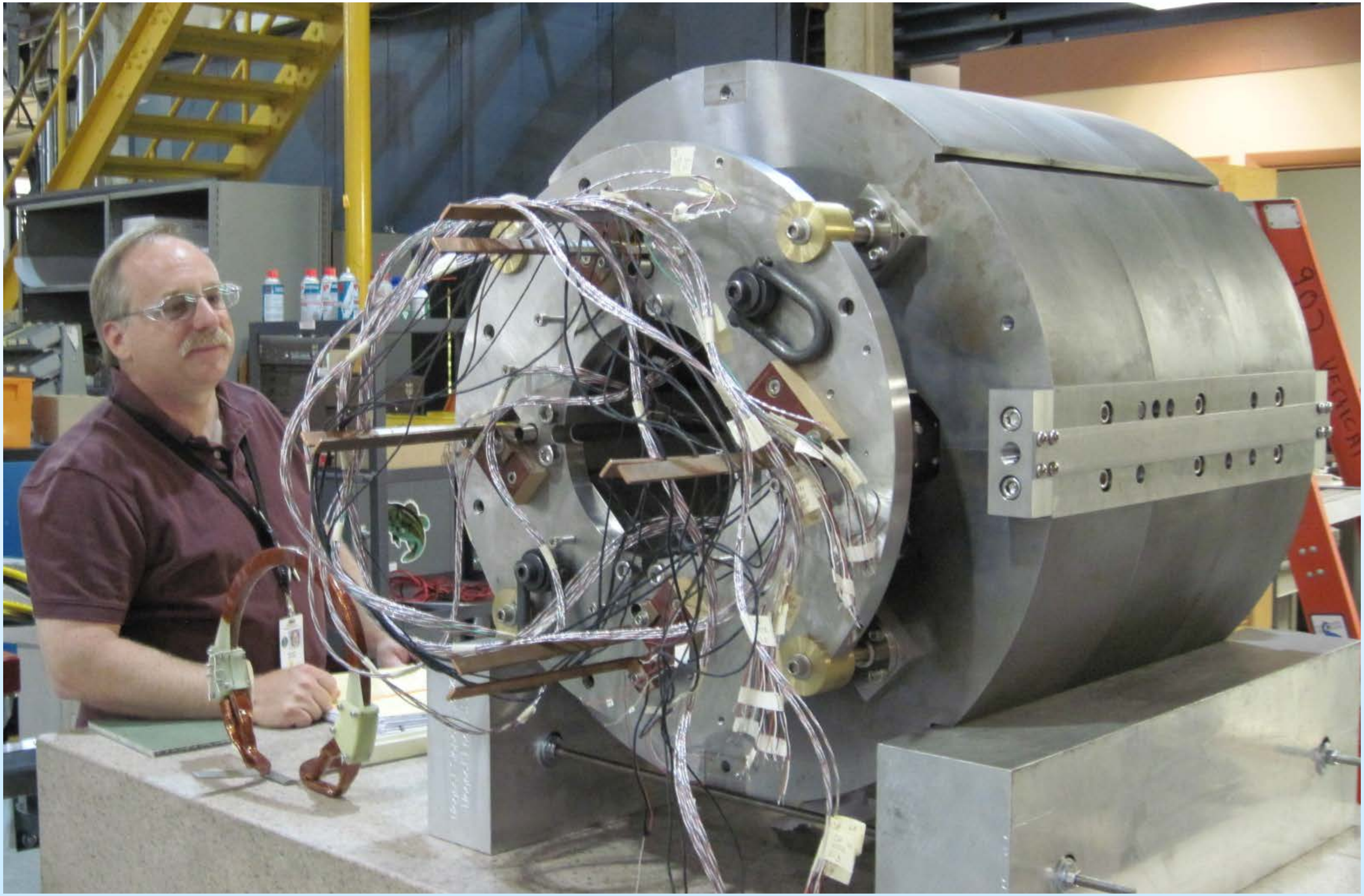
and

4 coils made with ASC

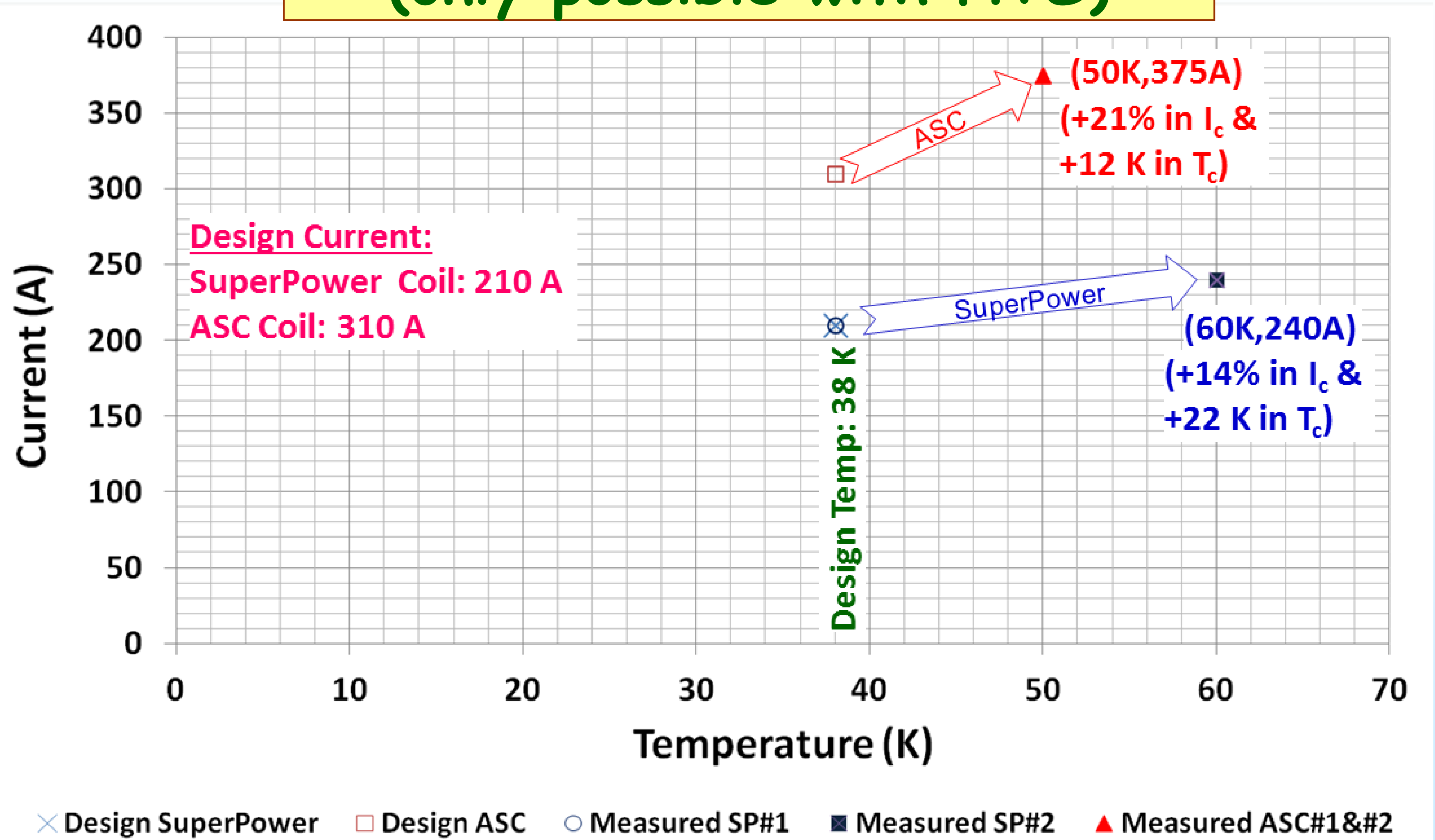


(~9 km of standard 4 mm equivalent used)

Completed 2G HTS Quad for FRIB

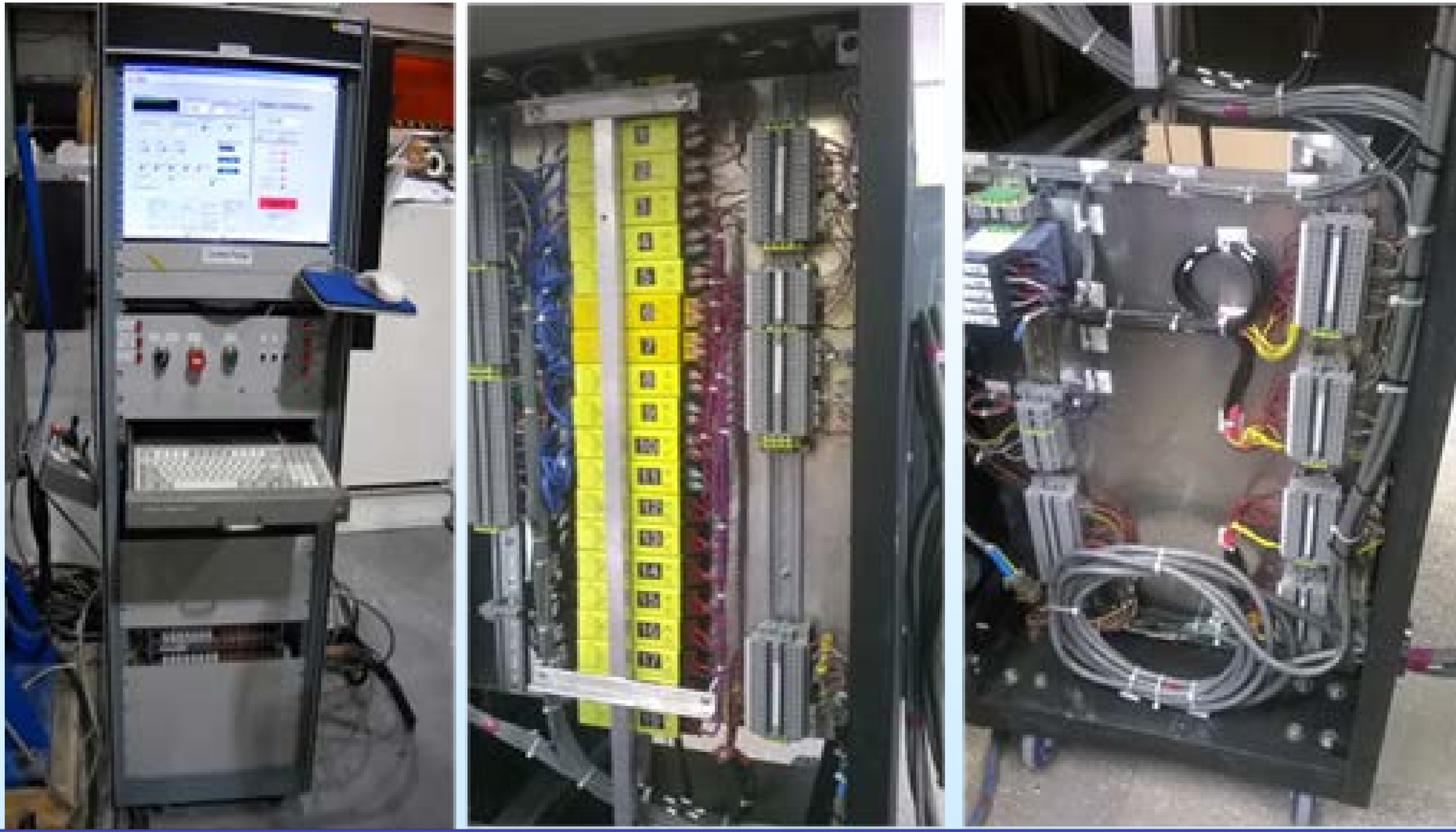


FRIB Quad Test Results Large Temperature Margins (only possible with HTS)



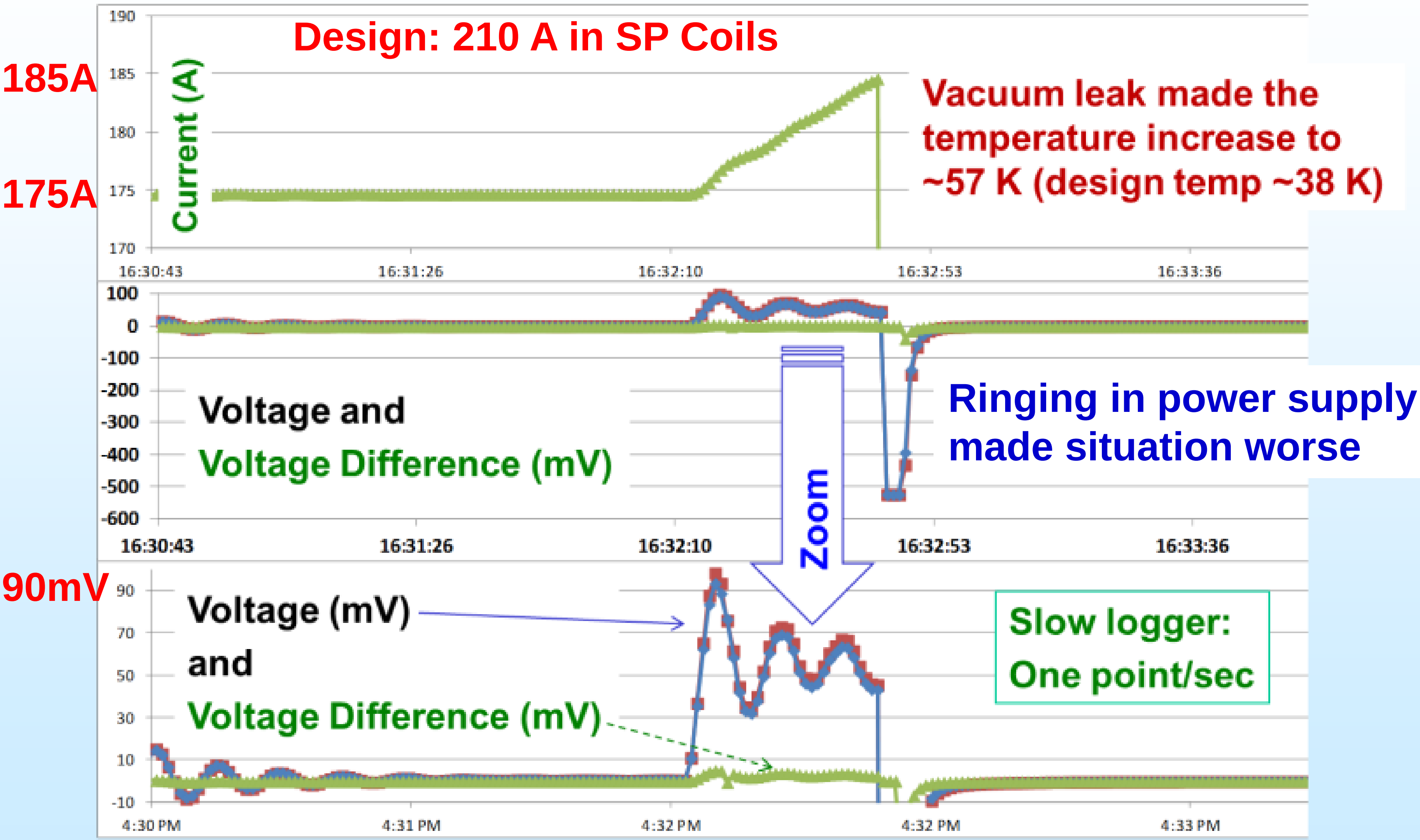
Provides robust operation against local and global heat loads

Advanced Quench Protection Electronics

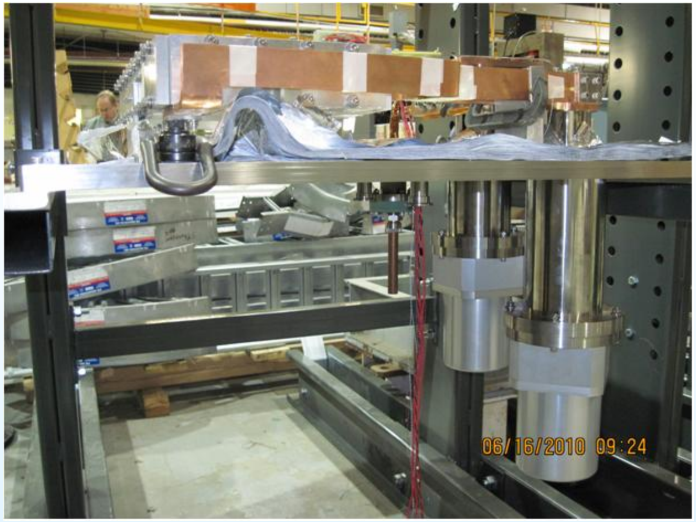


Detects onset of pre-quench voltage at < 1mV and with isolation voltage > 1kV allows fast energy extraction

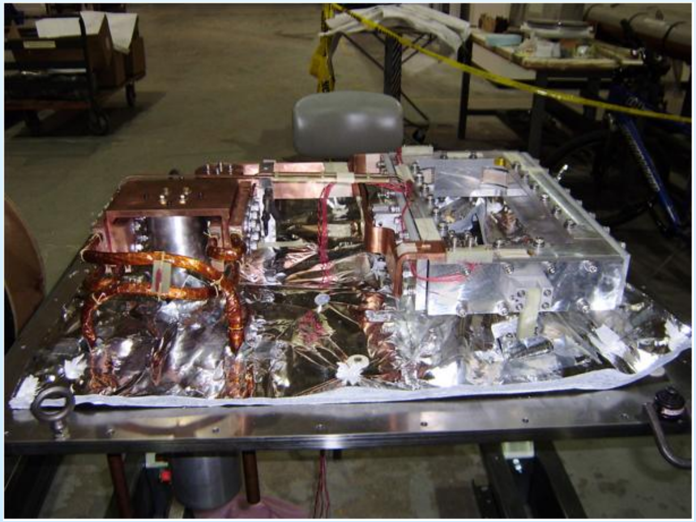
Protection of HTS Magnet During an Operational Accident Near Design Current

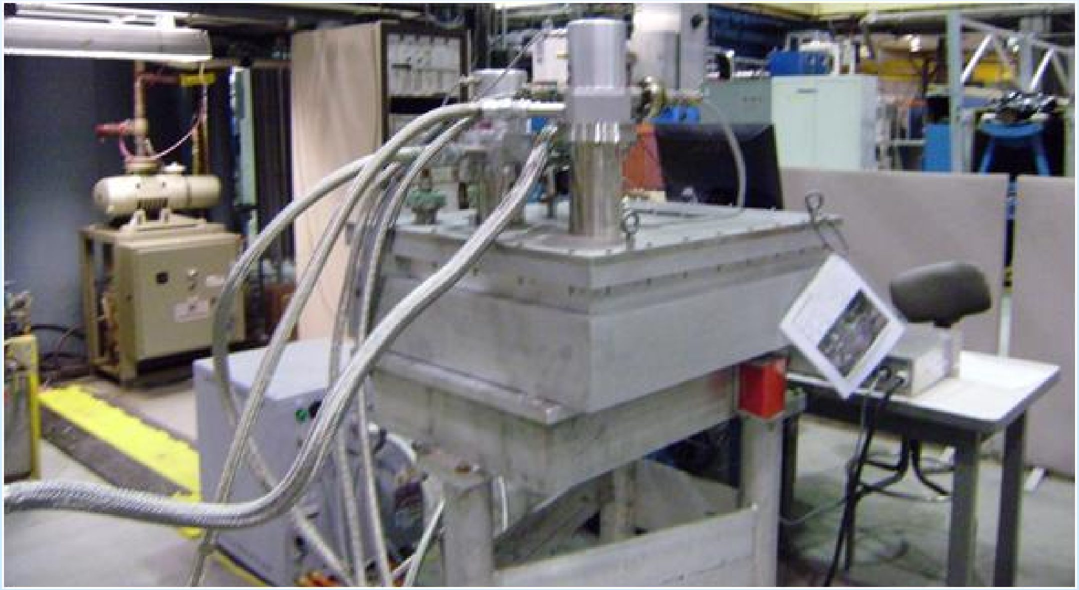


Cryo-cooler based HTS Coil R&D

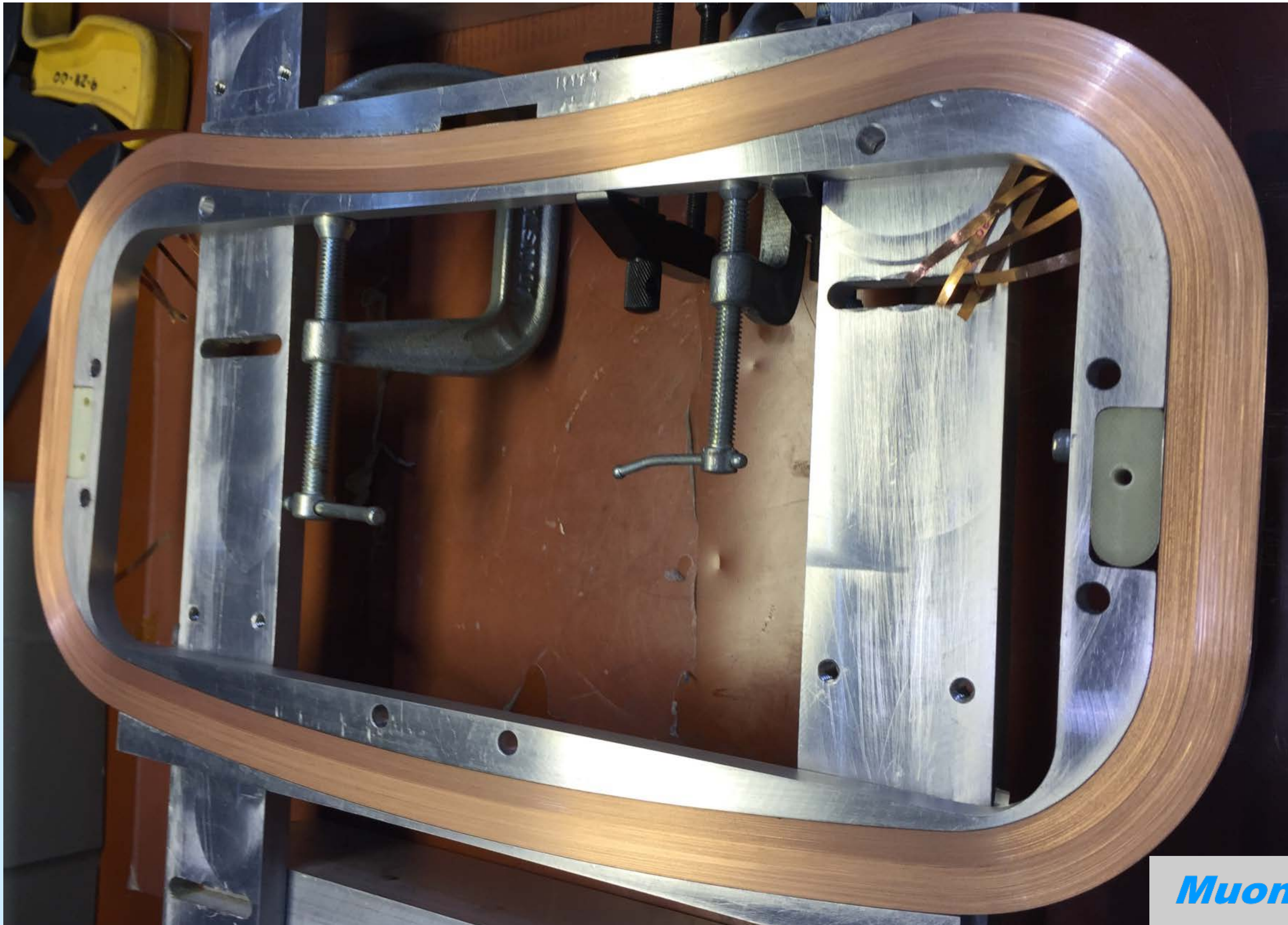


- Coils reached <40 K (goal was 40 to 50 K)
- Cryo-coolers turn-on at 5 pm in the evening before leaving and coils cooled at 8:30 am in the morning.
- Cryo-coolers removed a significant heat efficiently removed at 50 K.





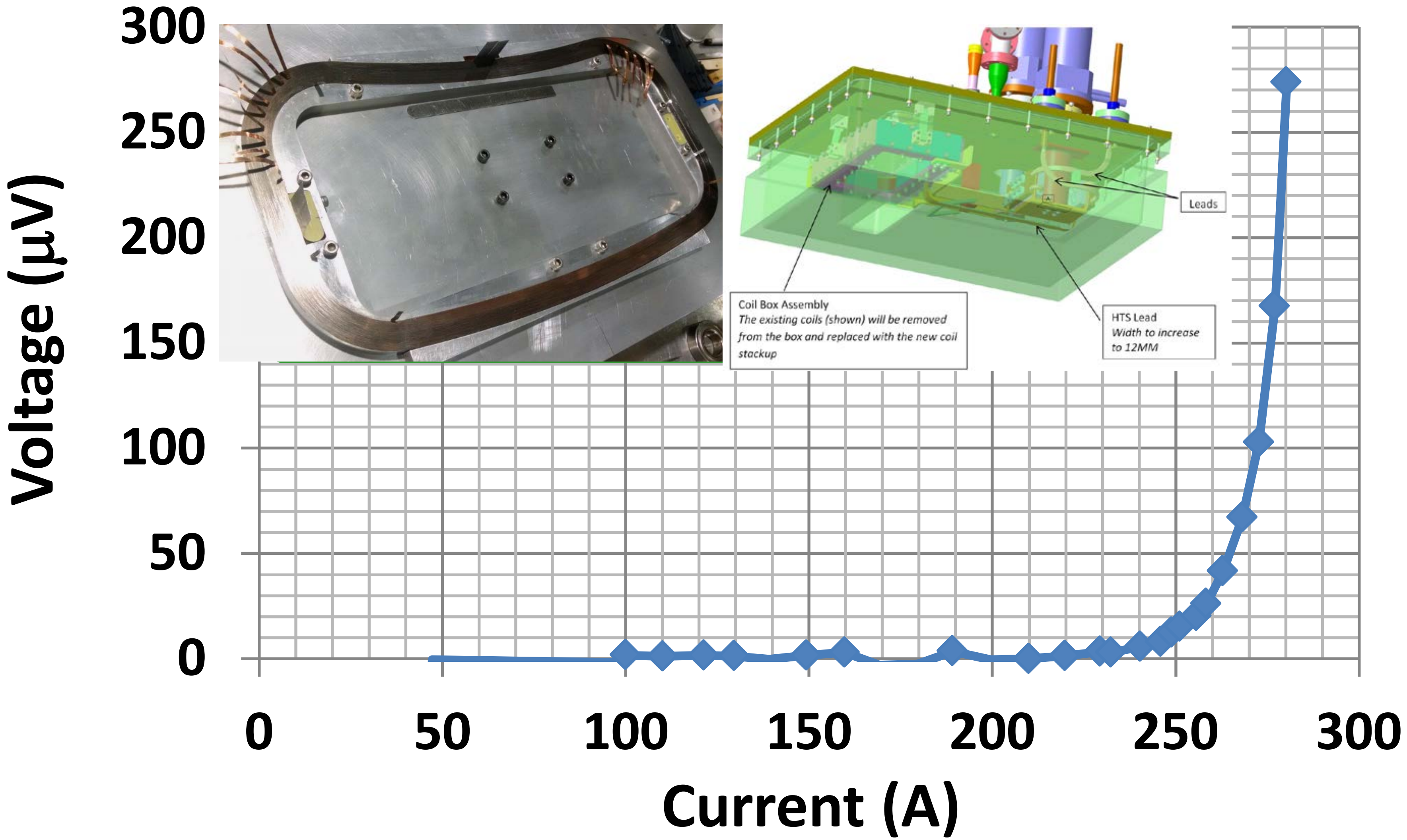
Curved HTS Coil (SBIR)



HTS coil with
"reverse curvature"

Muons, Inc.

Test Results of HTS Curved Coils Reached Expected Performance @48K



Summary and Conclusions

- **HTS magnets provide the opportunities that did not exist before**
- **This is the only superconductor that can work over 20 T, or can work over 20 K, or can take very high heat loads.**
- **Yes there are some challenges but no show stoppers. I just summarized BNL R&D experience on a wide ranging applications.**
- **We are very interested in working with various organizations to contribute to the new applications of HTS technology**
- **With a unique team experienced in large scale magnet productions in partnership with industry, BNL can help develop HTS magnets that industry can build**

Extra Slides

A List of HTS Programs at BNL (old slide)

- 25 T, 100 mm HTS solenoid for IBS, Korea (Work for Others)
- Hybrid Dipole with CORC® Cable (Phase II SBIR)
- High field solenoid for Neutron Scattering (Recent SBIR)
- Passive shielding for Electron Ion Collider (Phase I SBIR)
- Modular racetrack coil quadrupole for EIC (Phase I SBIR)
- 100 mm aperture "12.5 T @27 K" HTS SMES solenoid (arpa-e)
- High field collider dipole (Phase II STTR)
- Curved ReBCO tape dipole (Phase II SBIR)
- MgB_2 solenoid (Phase II SBIR)
- High field open HTS midplane dipole (Phase I SBIR)
- High radiation HTS Quadrupole for FRIB (Collaboration)

Completed HTS Magnet Programs

- 25 mm aperture 16 T HTS solenoid (SBIR)
- 100 mm aperture 9 T HTS solenoid (SBIR)
- HTS quadrupole for RIA (Collaboration with MSU)
- Bi2223 HTS tape common coil dipole (funded by DOE)
- Bi2212 Rutherford cable Common Coil Collider Dipole (DOE)
- HTS solenoid for Energy Recovery Linac (BNL project)
- HTS magnet for NSLS (BNL Project)
- Cosine theta dipole with 4 mm YBCO/ReBCO tape (SBIR)
- Cosine theta dipole with 12 mm YBCO/ReBCO tape (SBIR)
- …and a few others.

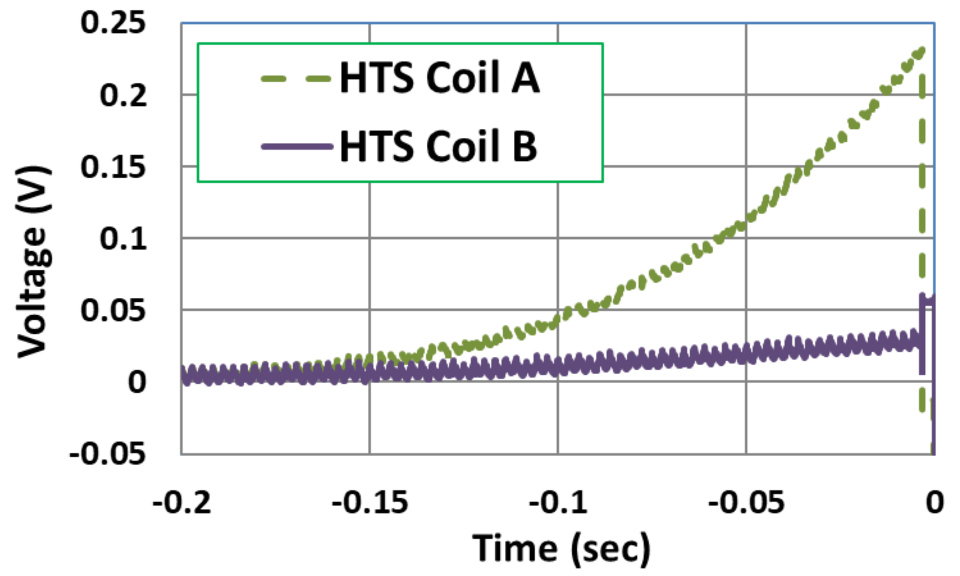
Quench Protection of HTS Coils in HTS/LTS Hybrid Magnet

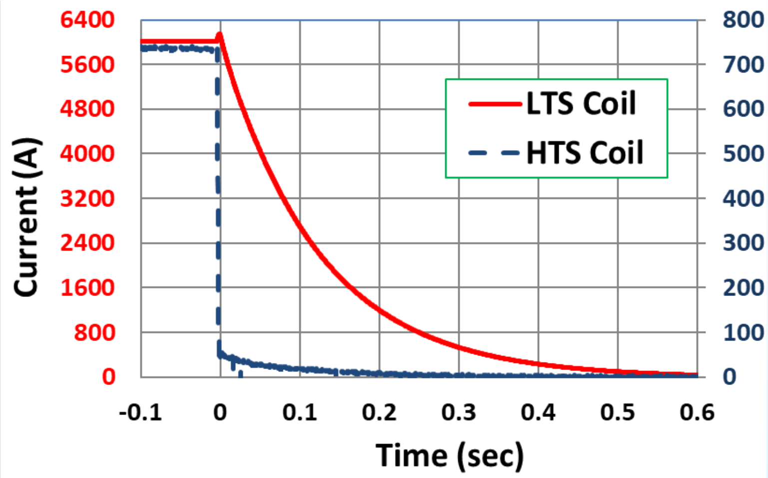
BROOKHAVEN NATIONAL LABORATORY

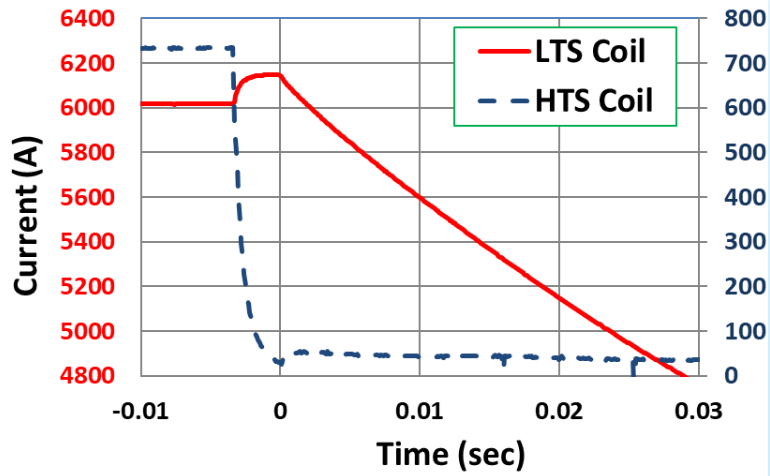
Superconducting Magnet Division

HTS coils operated like HTS coils

Significant voltage in HTS coils

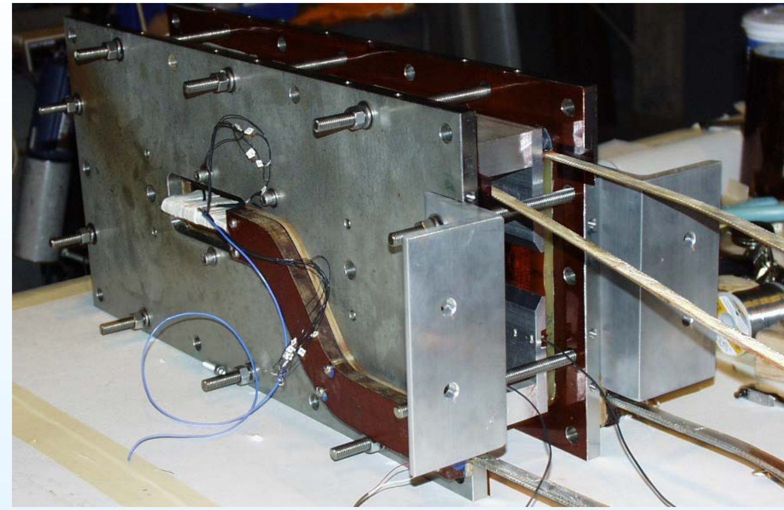




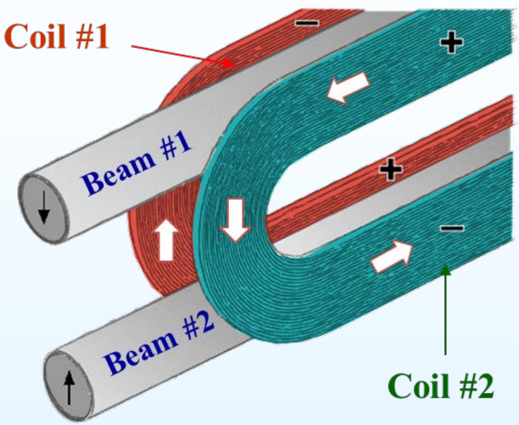


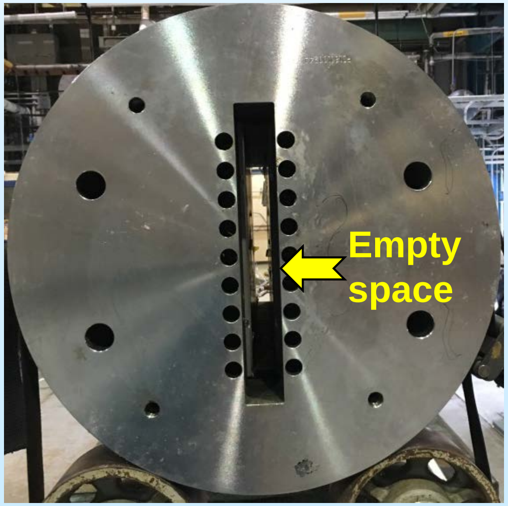
- HTS and LTS coils were operated with different power supplies and had separate energy extraction under a common platform
- Coupling between HTS & LTS

Structures for HTS and HTS/LTS Magnet R&D with Racetrack Coils



Unique BNL Common Coil Dipole

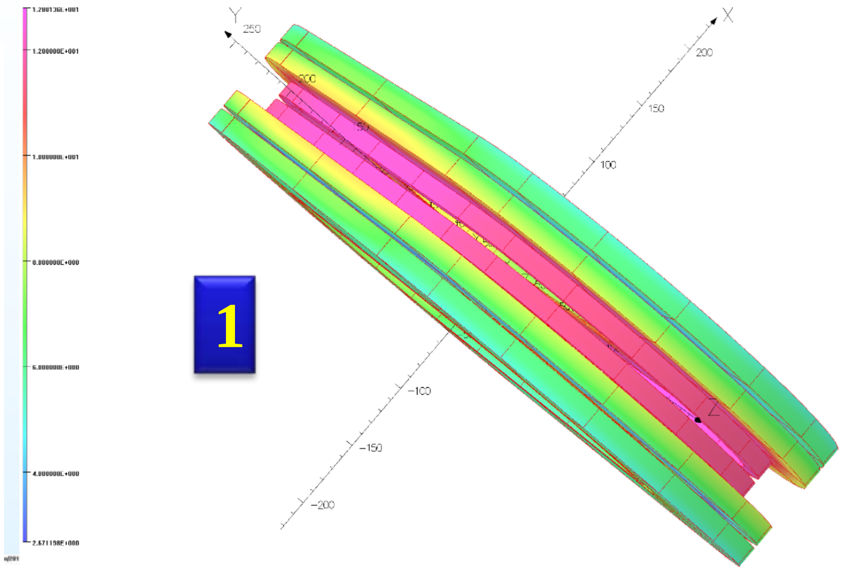


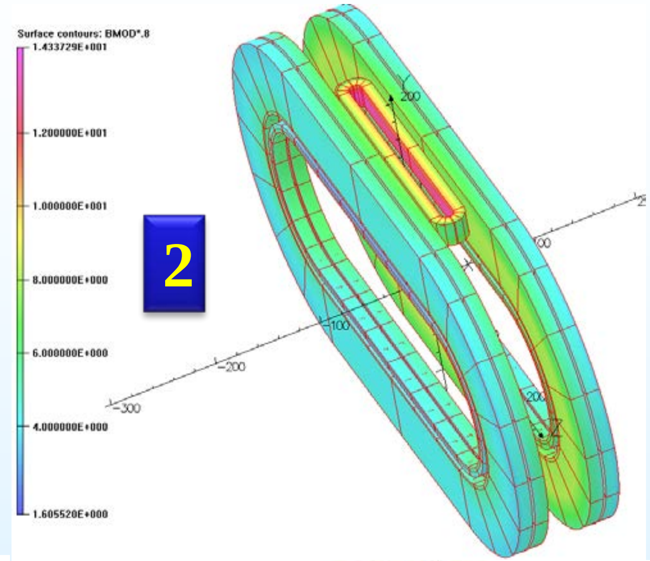


- BNL built a magnet to demonstrate "React & Wind" Nb_3Sn technology in 10+ T dipole
- Structure specifically designed to provide a large open space (31 mm wide, 338 mm high)
- New racetrack coils can be inserted in the magnet without any disassembly or reassembly
- New HTS insert coils become an integral part of the magnet. Coil tests become magnet tests
- Rapid-turn-around, lower cost approach allowed hybrid dipole in DOE/SBIR program

Four Possible Configurations for Insert Coils and the Cable Tests

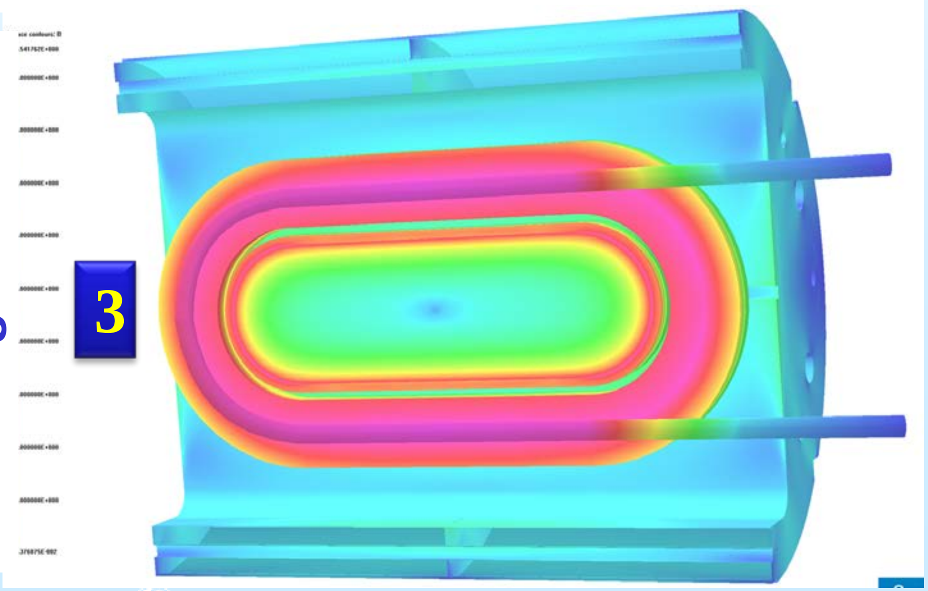
Standard insert coil test configuration

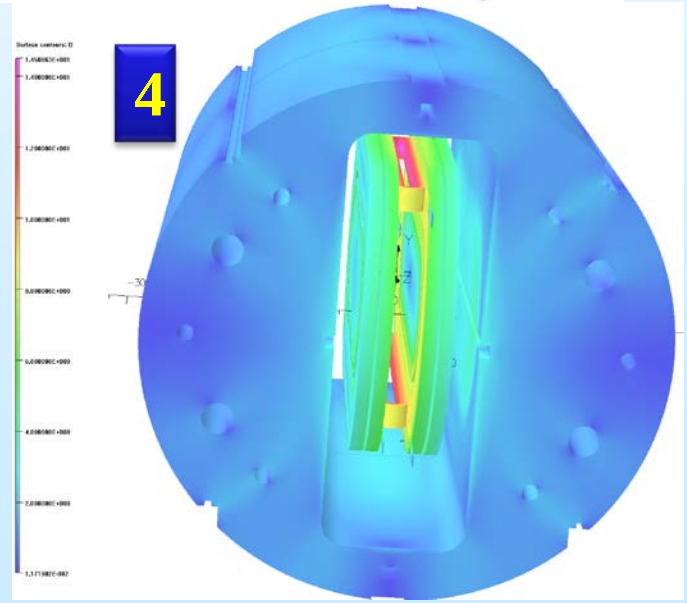




One insert coil in one aperture

Cable test configuration





Two independent insert coils in two aperture