HTS pancake coil winding experience at BNL

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June 8, 2023

Muons Magnets Working Group@CERN

HTS Magnet Program at BNL

- A wide ranging HTS magnet R&D at BNL
  - Solenoids, dipoles, quadrupoles, racetrack coils, cos θ coils, curve coils, clover-leaves coils, ...
  - A wide range of operating temperature and fields
- No. 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 equivalent)

This presentation will be limited to 2G HTS pancake coils

For a broader presentation on HTS coil and magnet R&D at BNL, please visit:
https://wpw.bnl.gov/rgupta/wp-content/uploads/sites/9/2023/04/HTS-BNL-CERN-04-17-2023.pdf

HTS Splice-joints at BNL (1)

A large number of HTS splices (several hundreds to => 1,000) have been made at BNL. They are needed because:

- long enough tapes were/are not available to make a single pancake coil; so multiple segments were needed
- to make a double pancake coil from two single pancakes (almost all HTS coils at BNL were wound as single pancake)
- to connect a double pancake to another double pancake and coils to leads (all leads had HTS at the starting point)

Essentially all HTS spice joints were made with Indium solder (~215º C). We rarely had issues with the splices.

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HTS Splice-joint at BNL (2)

- 2G HTS tape typically has conductor on one side only. To keep splice resistance low, splice HTS side to HTS side.
- Winding of each pancake coil was made such that the conductor side was always on the inside of the coil.
- This allowed HTS to HTS side for splicing the two single pancake coils at the coil i.d. to make a double pancake.
- Splice within the coil was made HTS to HTS side. Most single pancake coils had one joint (a few had three also; but always an odd number). This brought HTS side on the outside at the coil outer surface. This allowed HTS-to-HTS splice for leads and for connecting two double pancakes.

Most splices have a joint-resistance of <5 nano-ohms, some as low as a few nano ohms and some more (leads)

HTS Splice-joint at BNL (3)

Two types are geometries are used in making splices between the coils – perpendicular and diagonal or spiral. Perpendicular:

Perpendicular splices are made with several pieces of tapes. They are used for connecting two pancakes or external leads.

HTS Splice-joint at BNL (4)

In diagonal or spiral splice, a tape run from one pancake to another pancake. This has been lately used, wherever possible.

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 24, NO. 3, JUNE 2014

Test Results of High Performance HTS Pancake Coils at 77 K

S. L. Lalitha, *Member, IEEE*, W. B. Sampson, and R. C. Gupta

Brookhaven National Laboratory

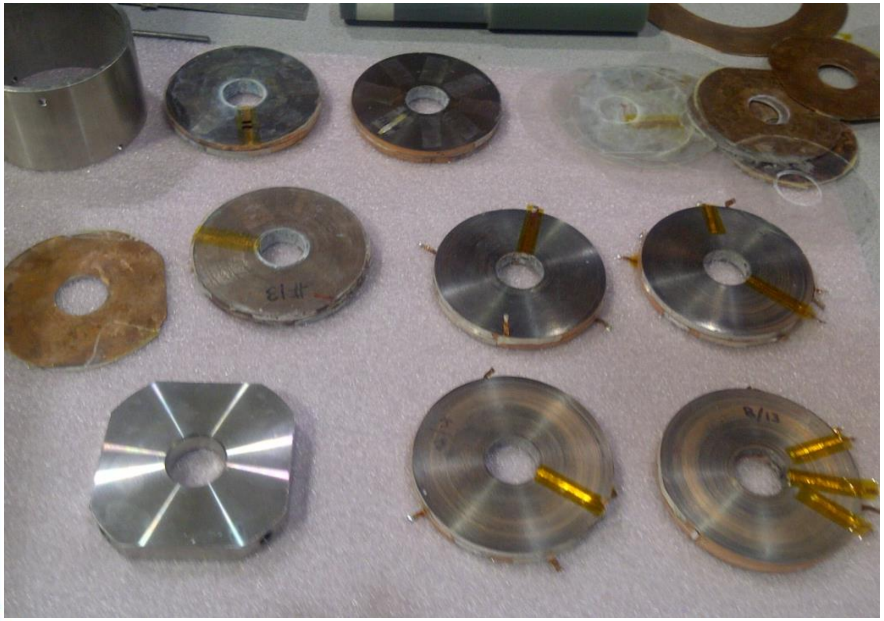
High Field HTS Solenoids

Several Programs:

- 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

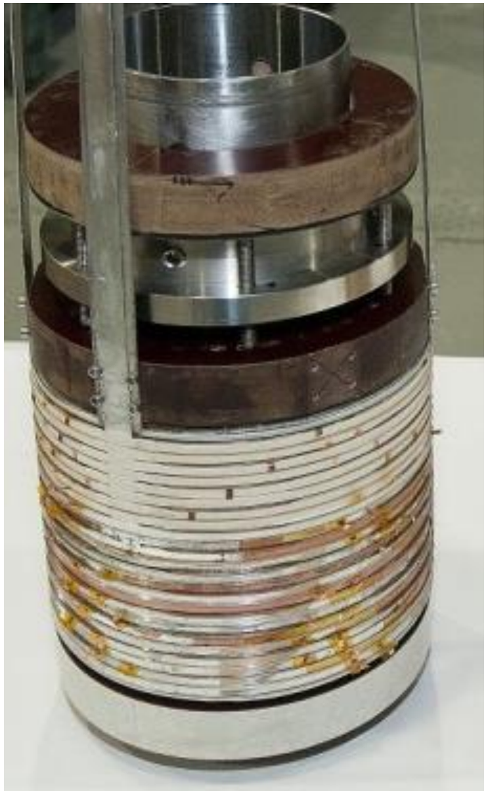
High Field Solenoids Program with PBL

- Two SBIRs for 25 mm and 100 mm coils, with original intend to generate 10-12 T field each, for a combined field of 22 T
- HTS tape is co-wound with insulating stainless-steel tape (now called MI) to reduce hoop stress
- SS tape also helps in quench protection



pancakes

Insert solenoid



Outsert solenoid

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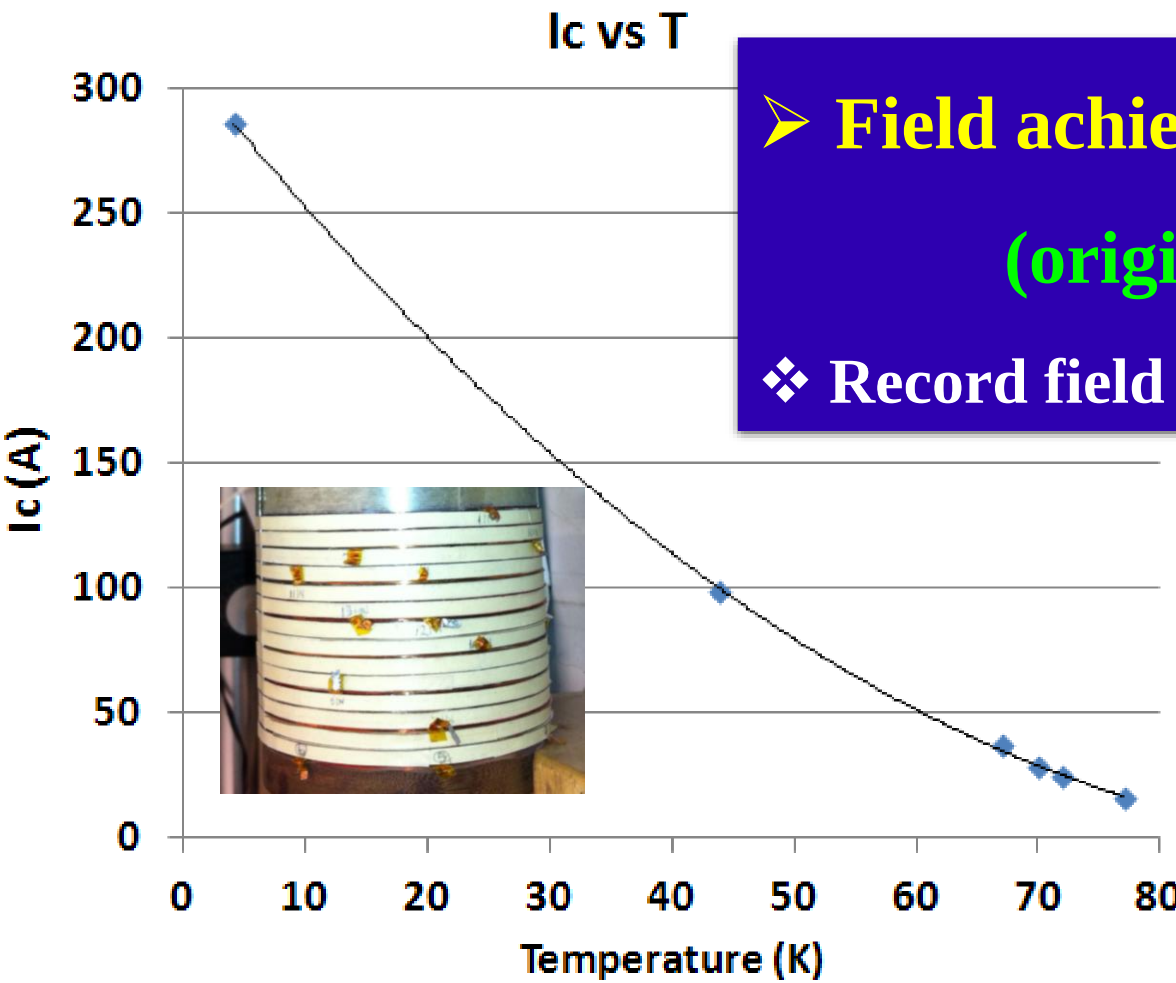
16 T HTS Solenoid (2012)

(and a wide range of operating temperature)



- **Field achieved: ~16 T**

  (original target: 10-12T)

- **Record field HTS solenoid in 2012**

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

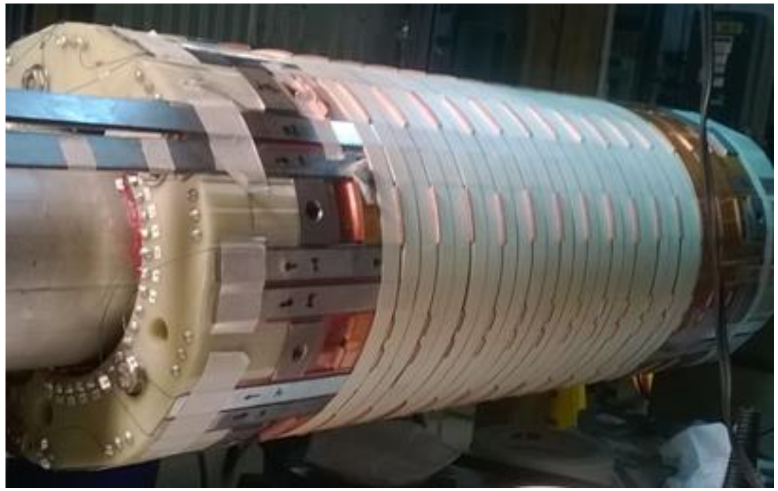
PBL/BNL SBIR

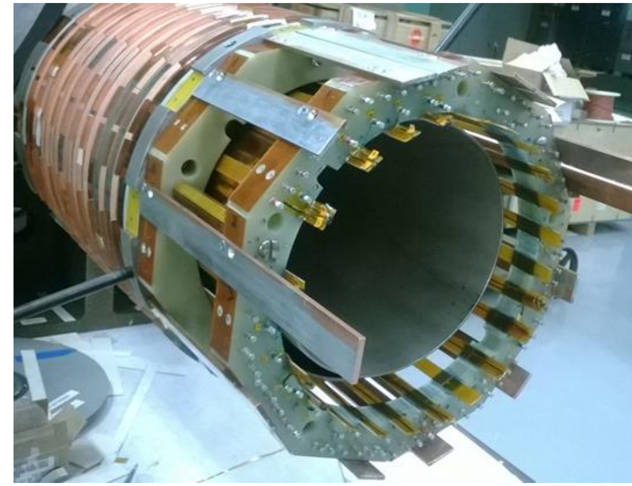
Insert solenoid: 14 pancakes, 25 mm aperture

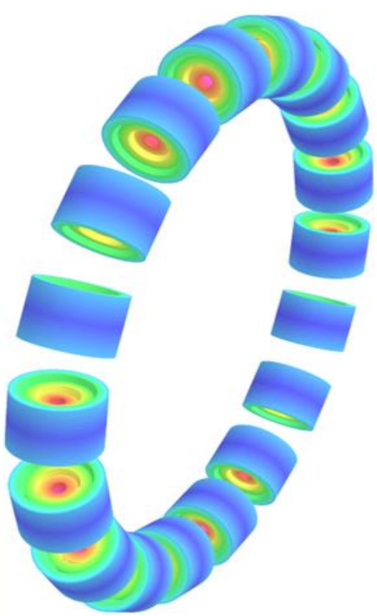
High Field HTS Solenoid for SMES (arpa-e)

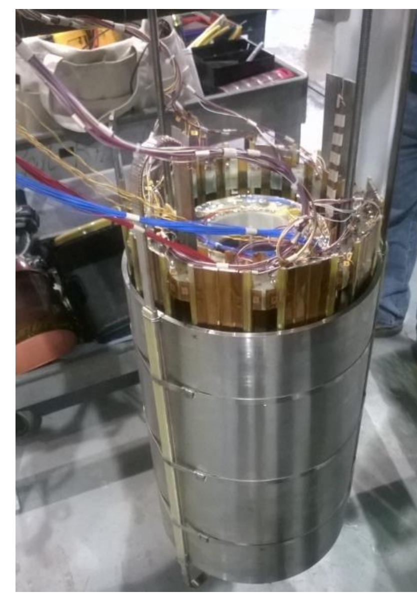
100 mm,
25 T

2-layer
coil design

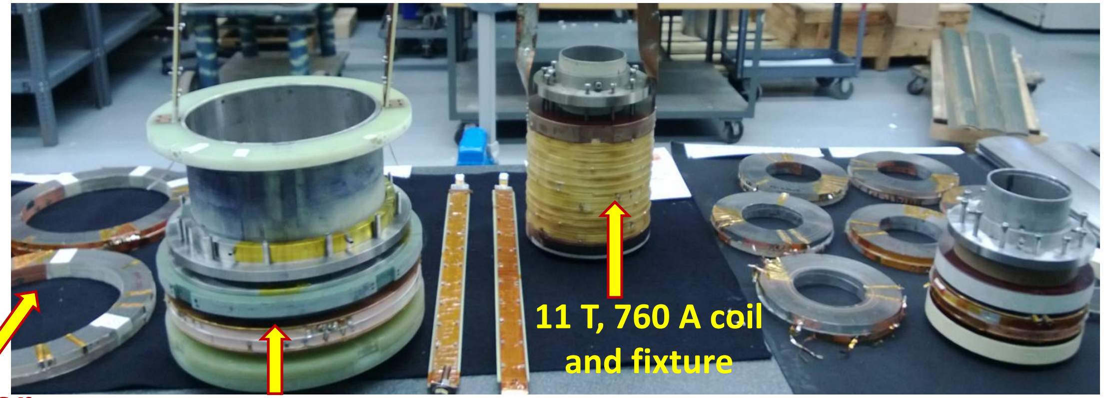






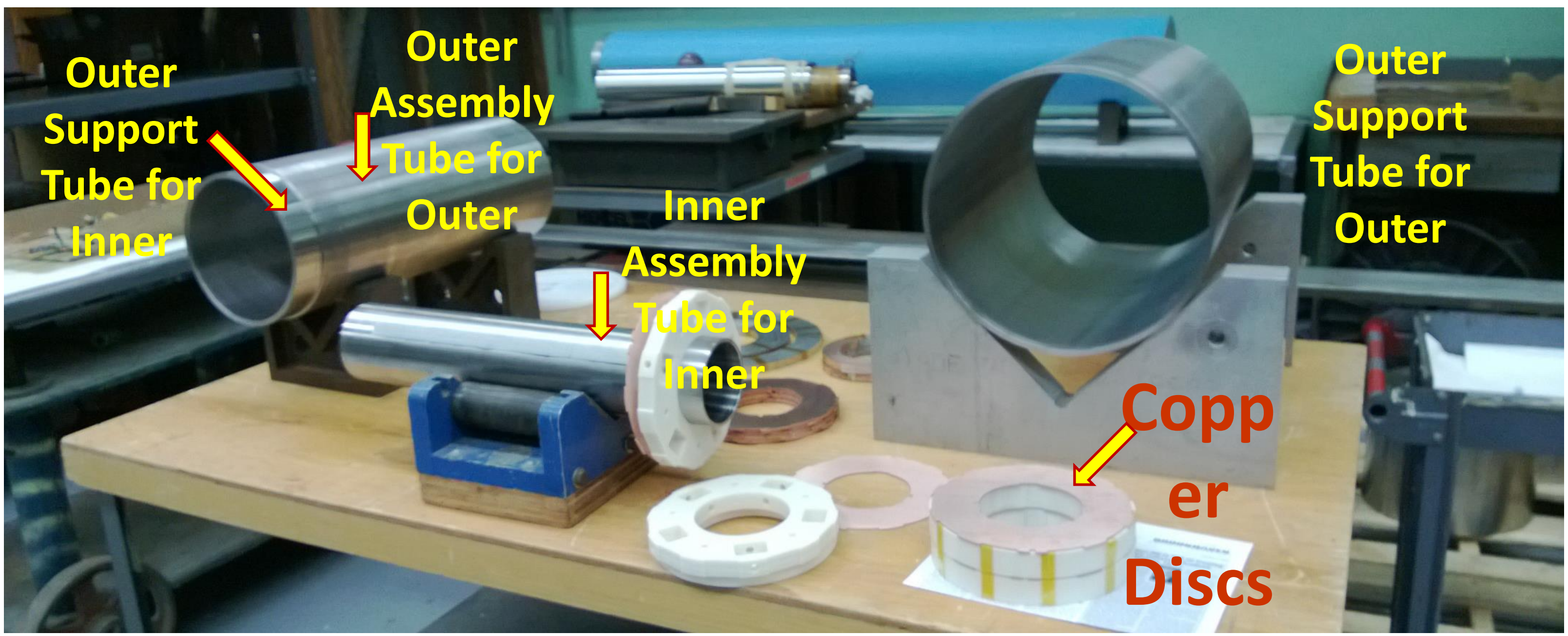


Parts of 25 T HTS Solenoid for SMES arpa-e (with ABB, SuperPower & UoH)

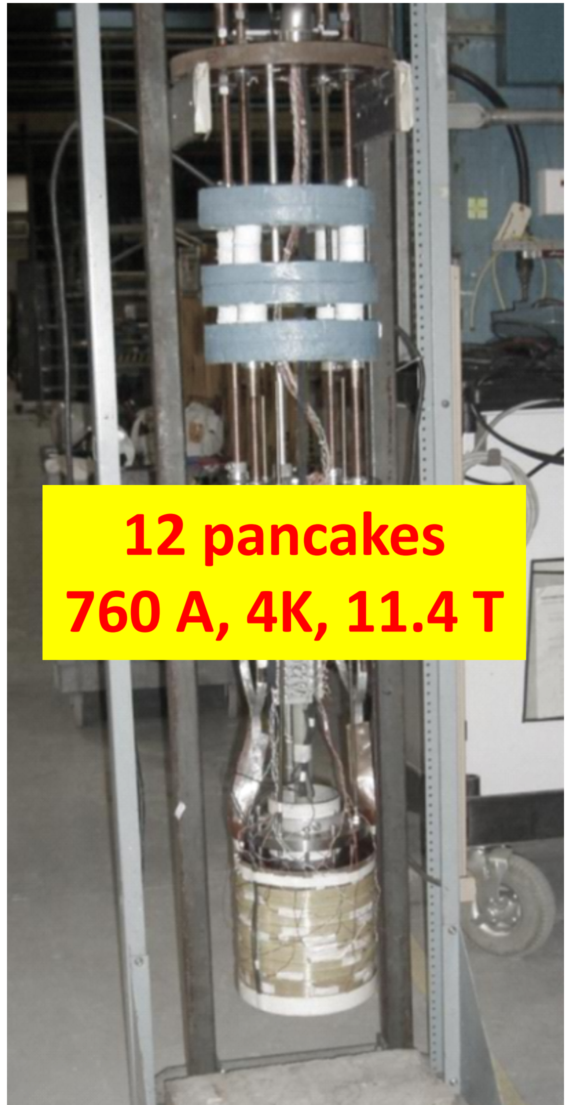


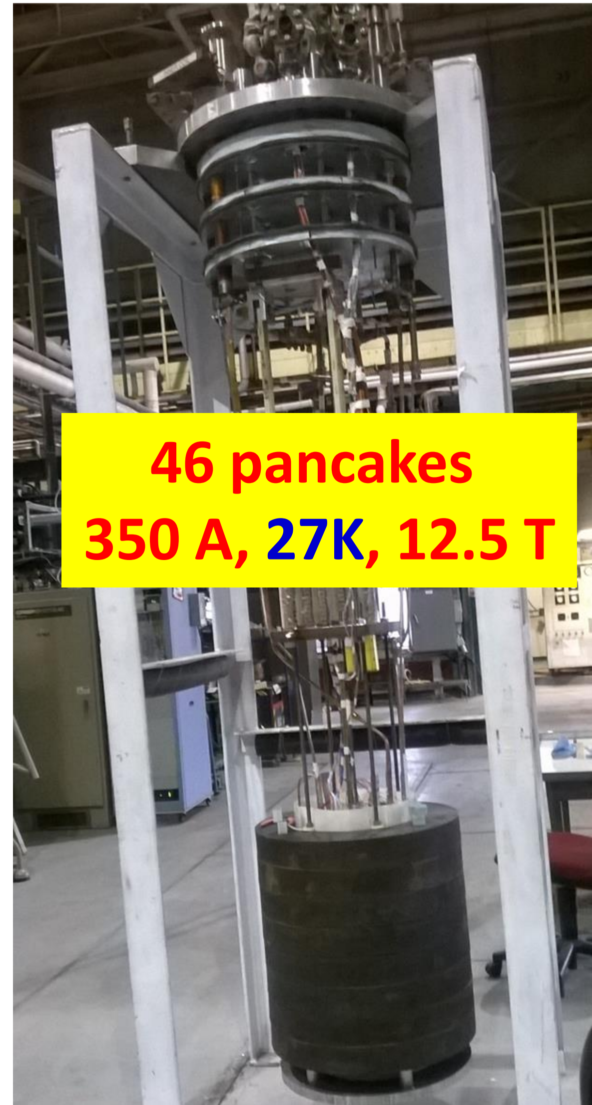
Pancake coils: inner and outer

77 K Test Fixture for outer



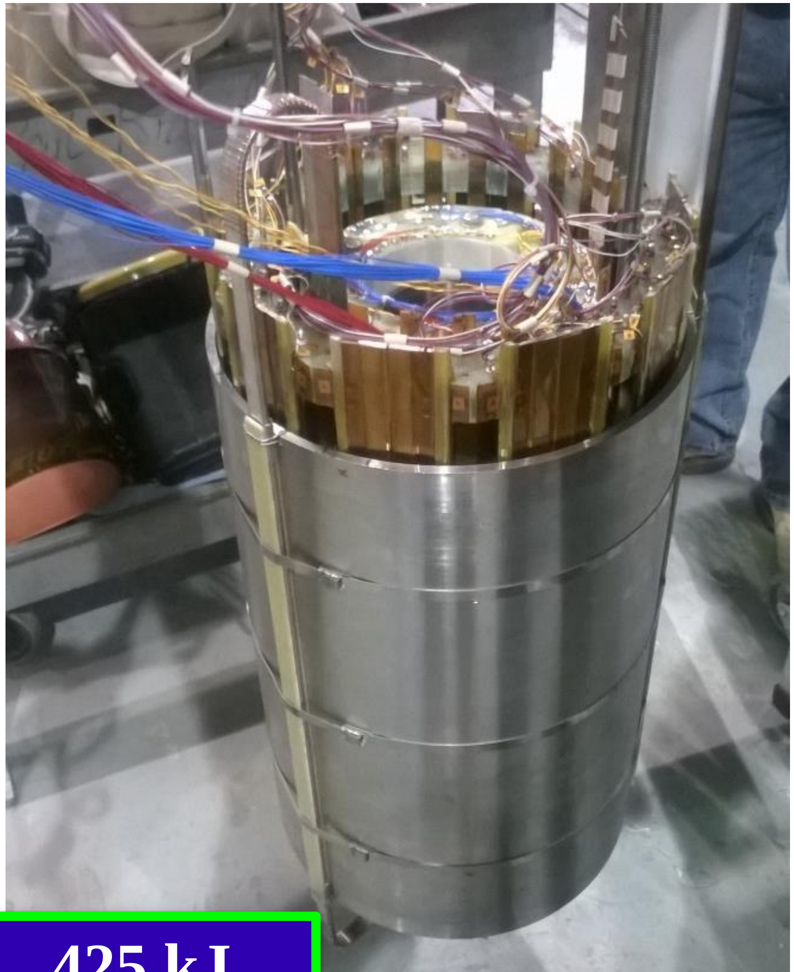
HTS SMES Coil High Field Tests





Peak fields higher

HTS Solenoid for SMES with Record Performance



425 kJ
id:102 mm
od:303 mm

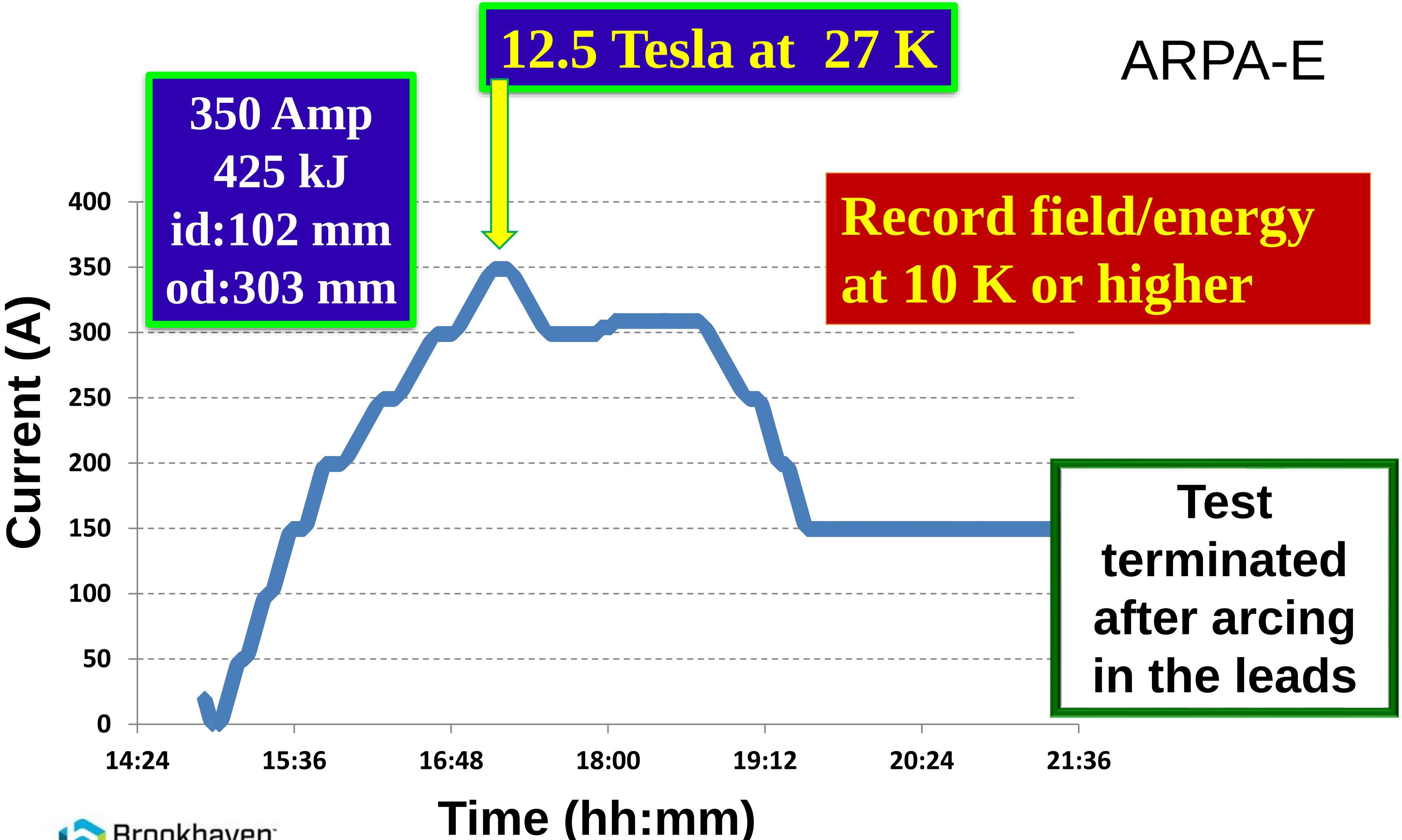
- **Reached a critical field of 12.5 T at 27 K (new record over >10 K in a magnet of this size)**
- **Test terminated due to the electrical issues**

Amount of ReBCO HTS Used:

Over 6 km, 12 mm wide from SuperPower

- **Design Field: 25 T@4 K**
- **Bore: 100 mm**
- **Stored Energy: 1.7 MJ**
- **Hoop Stresses: 400 MPa**

SMES Coil Test
Critical Current Reached at 27 K



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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 #1 (32 channels, 1kV)

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

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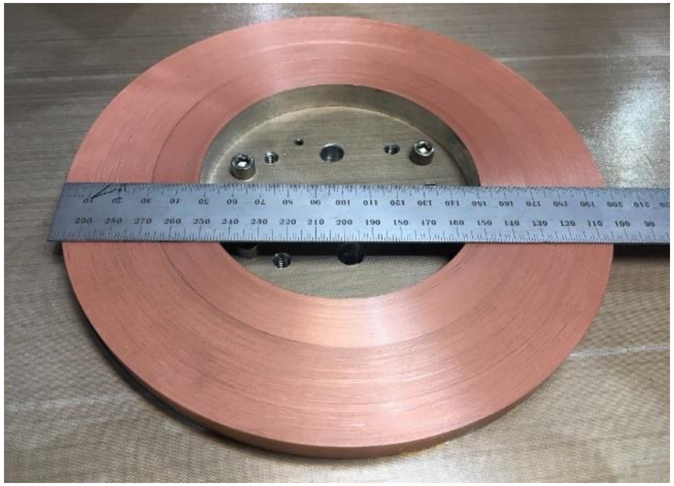
HTS Solenoid for IBS (Korea)

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

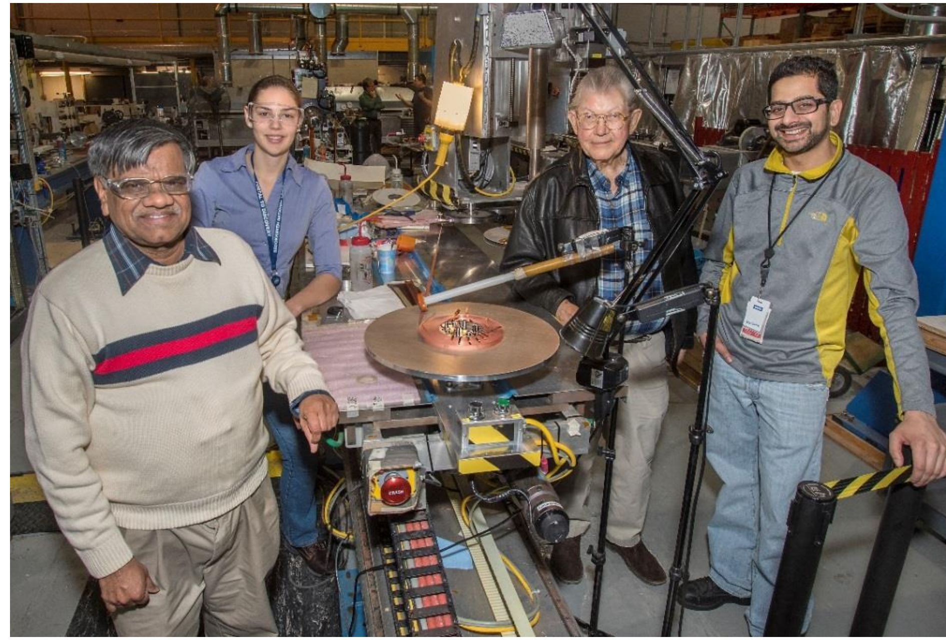
Stresses: J X B X R

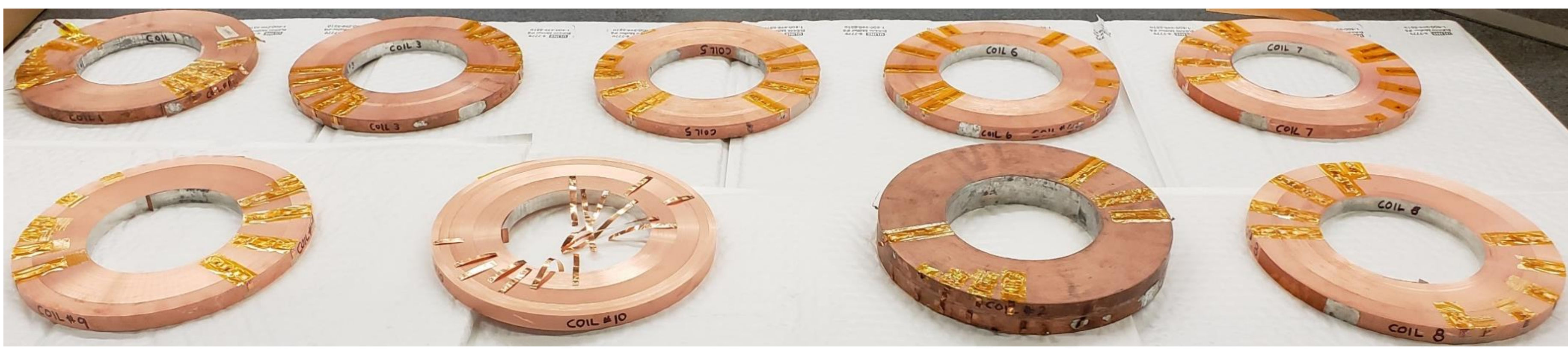


- ❑ Field quality: ~10%
- ❑ Ramp-up time: up to 1 day

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 No-Insulation (NI) HTS Pancake Coils for IBS with BNL Universal Coil Winder





Copper discs between double pancake

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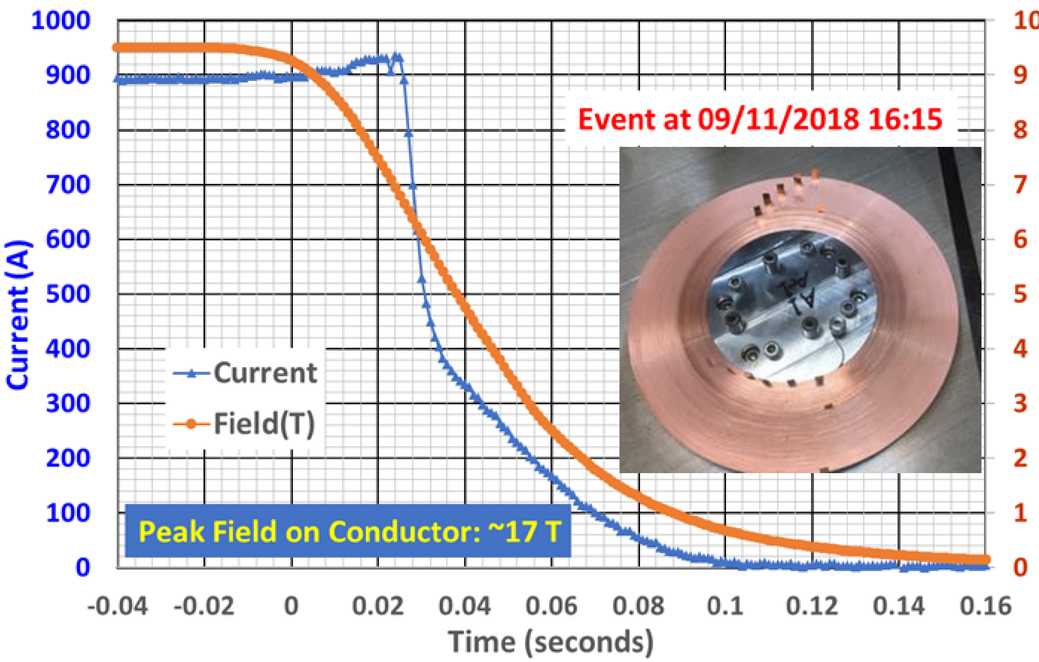
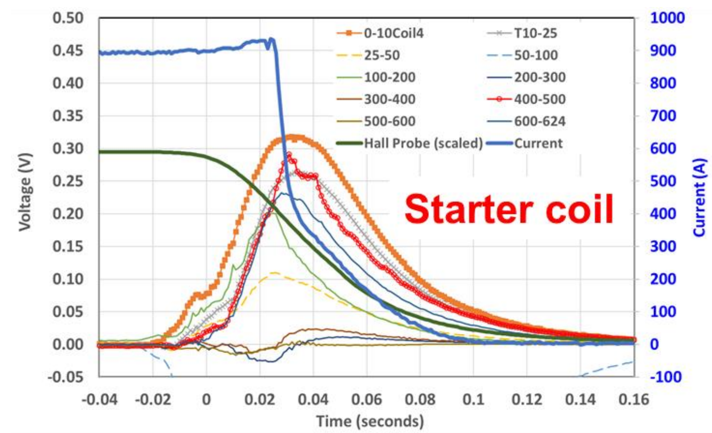
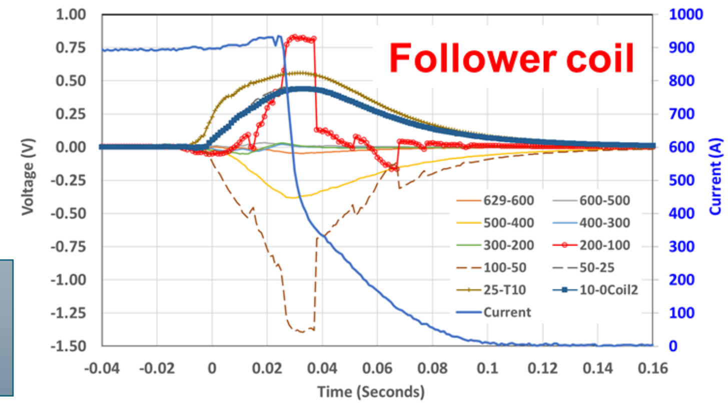
Quench Scenario in Large No-Insulation Coil
(fast 4K propagation within coil and coil-to-coil)







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**

HTS/LTS Hybrid Dipole

(with ReBCO)

2G HTS Pancake Coils for Hybrid Dipole

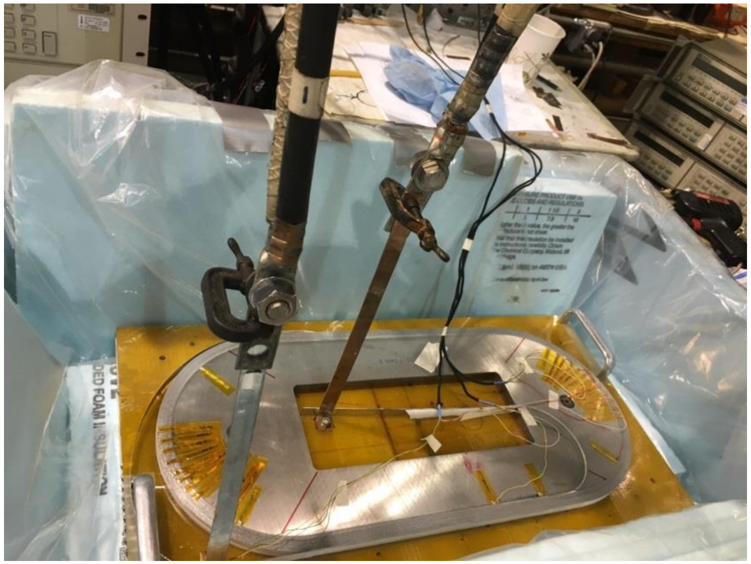
PBL/BNL
SBIR

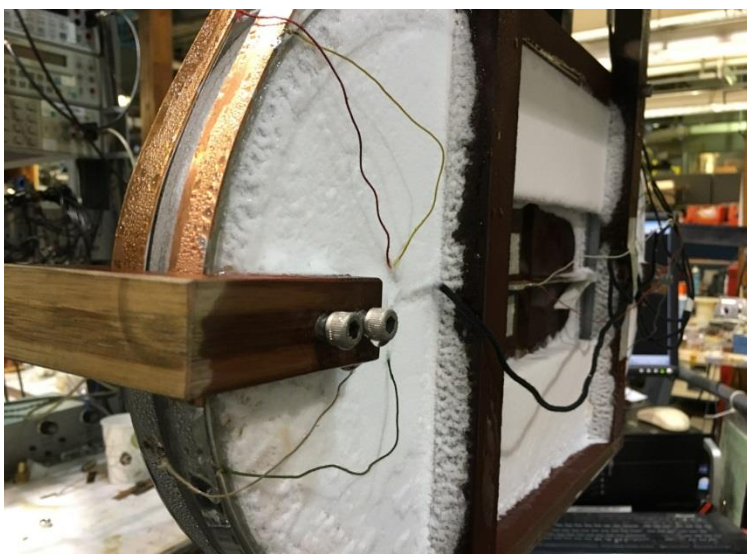
Conductor:
- **12 mm 2G ASC tape**

Insulation:
- **Nomex**

Two coils used ~300 meters of 4 mm equivalent

77 K HTS Coil Tests in Various Configurations

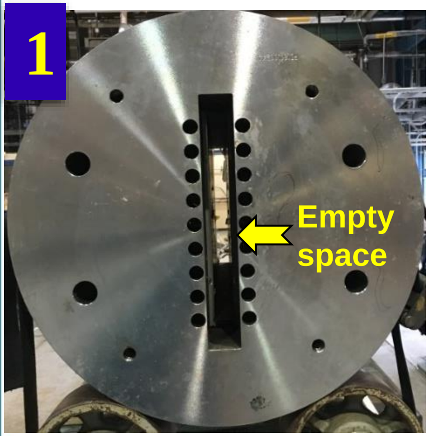




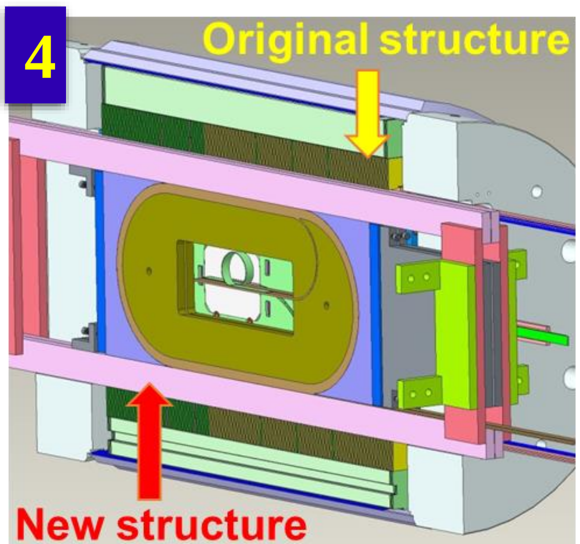
77 K tests provide a unique QA in HTS coils

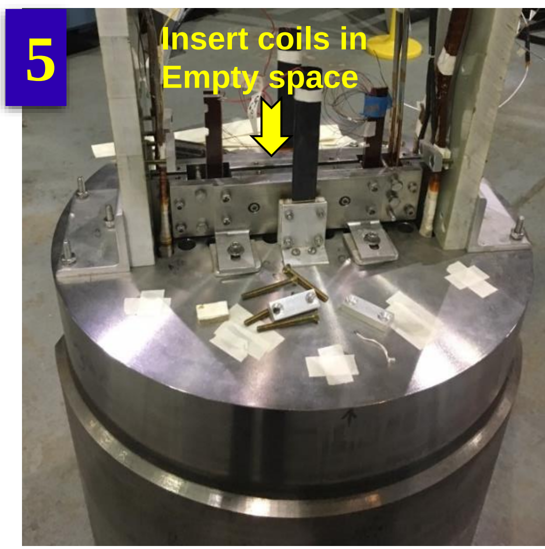
A New Low cost, Rapid-turn-around R&D Approach with a 10 T Nb_3Sn React & Wind Dipole

Five Simple Steps/Components



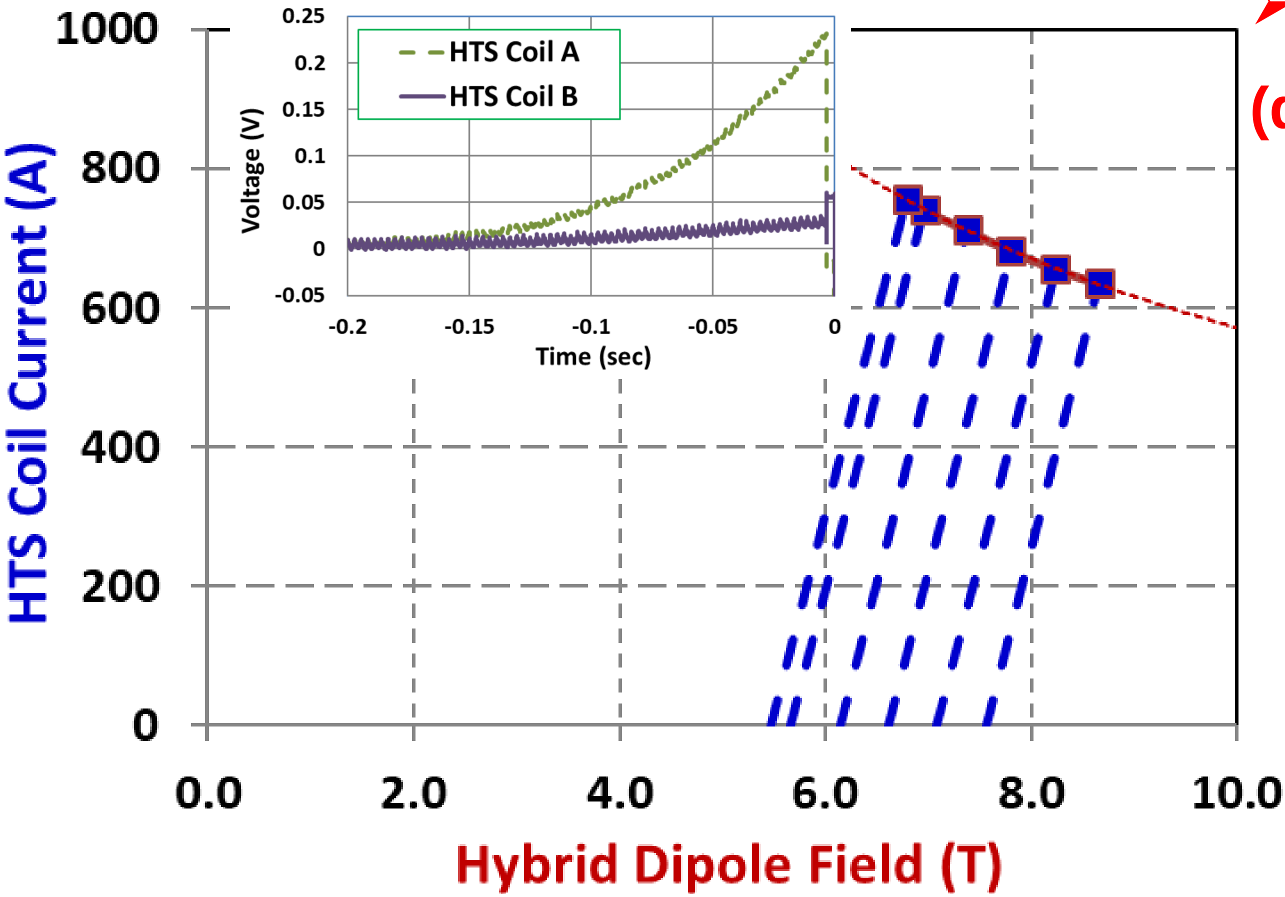
1. Magnet (dipole) with a large open space
2. Coil for high field testing
3. Slide coil in the magnet
4. Coils become an integral part of the magnet
5. Magnet with new coil(s) ready for testing





HTS/LTS Hybrid Dipole Test (2016)

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



Several quenches.

- **No training**

(different from LTS)

No damage and no degradation

Encouraging results

Quench threshold 0.2 V (just like in LTS)

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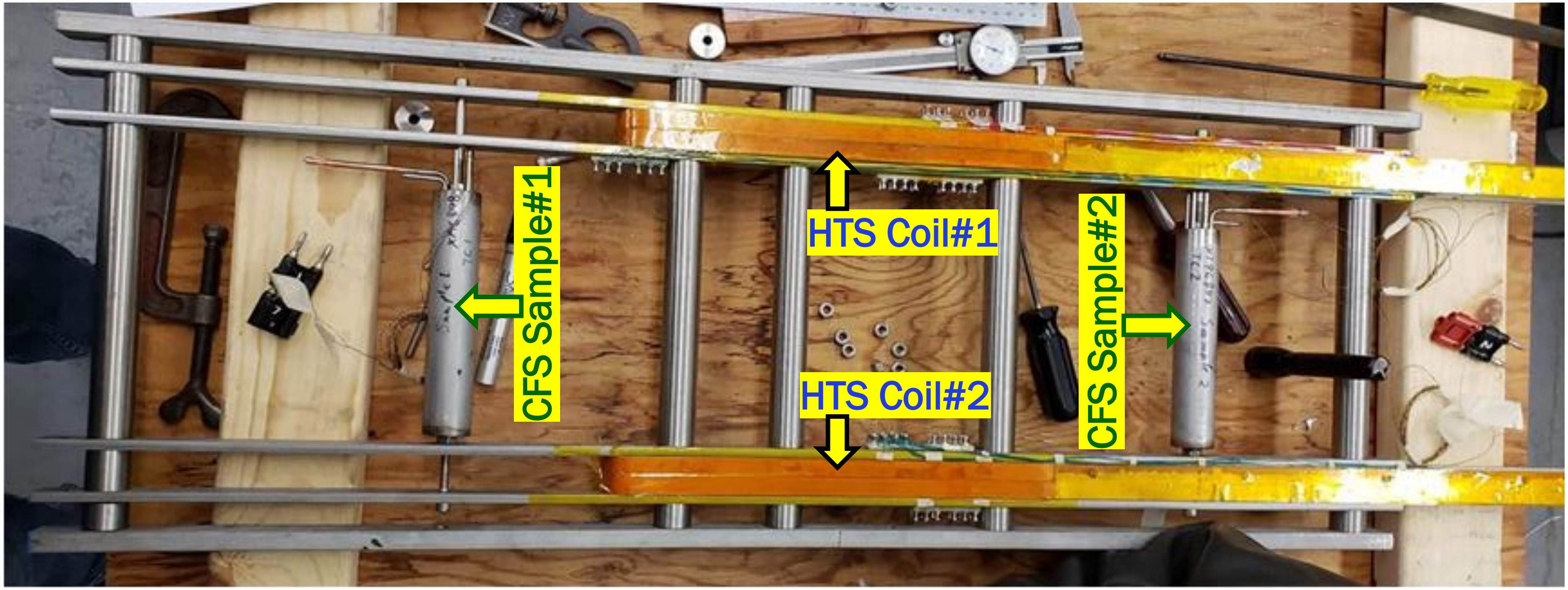
High Field HTS/LTS Hybrid Dipole Test (2020)

Test holder ready to be inserted in DCC017



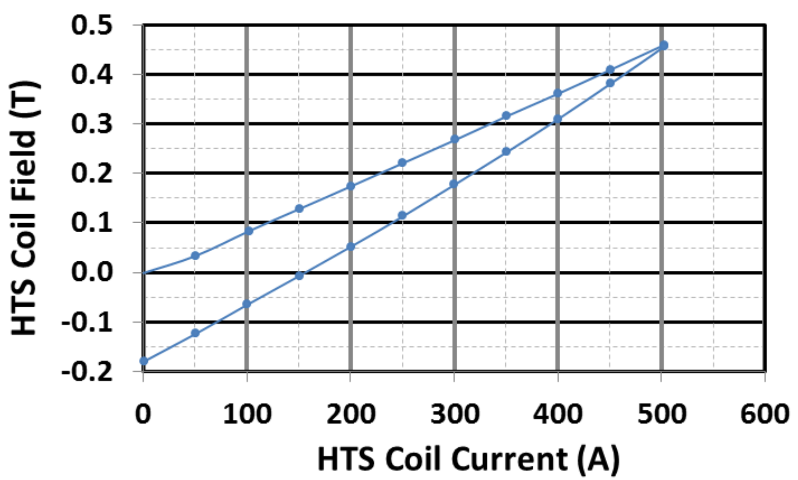
Two HTS coils for testing in field parallel configuration

(also included, two HTS cable samples from the fusion community)

Comparison between Field Perpendicular and Field Parallel Magnetization @2T Dipole Field

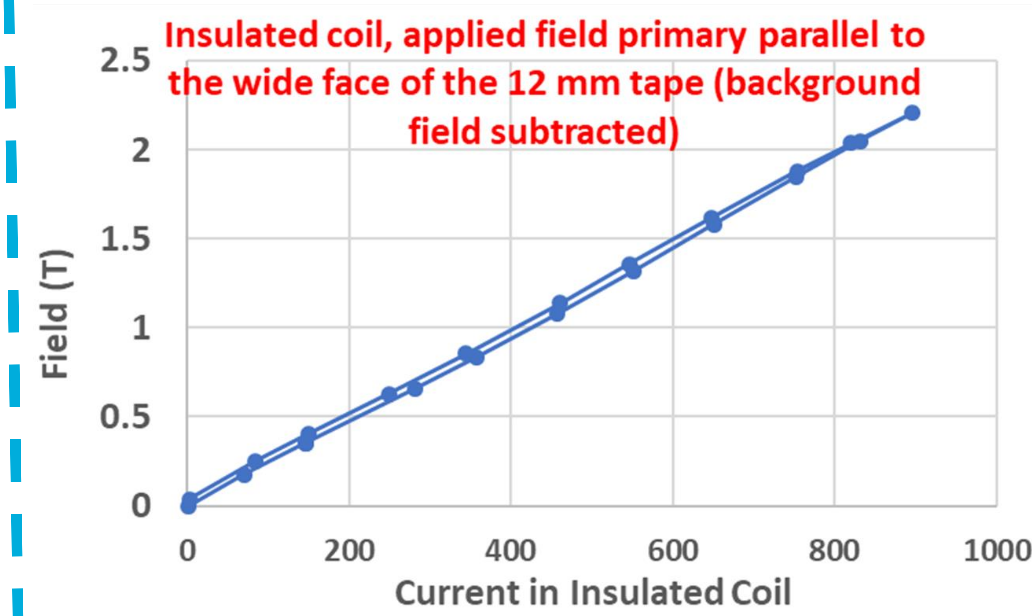
Field perpendicular (2016)

Additional field from the HTS coils in up and down ramp (Field from LTS coil subtracted)



A large remnant field (-0.2 T) due to magnetization in tape

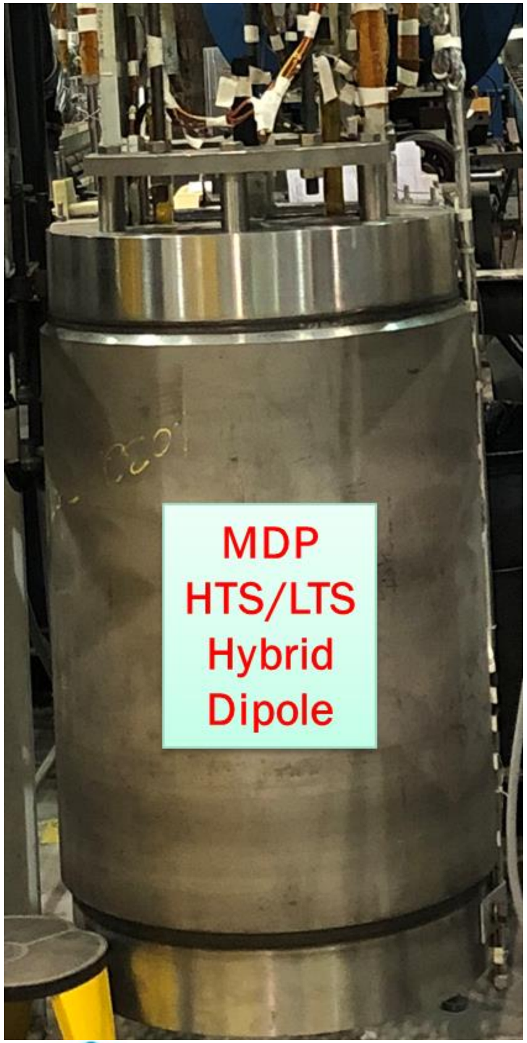
Field parallel (2020)



Order of magnitude reduction in the magnetization when the field is primarily parallel to the HTS tape

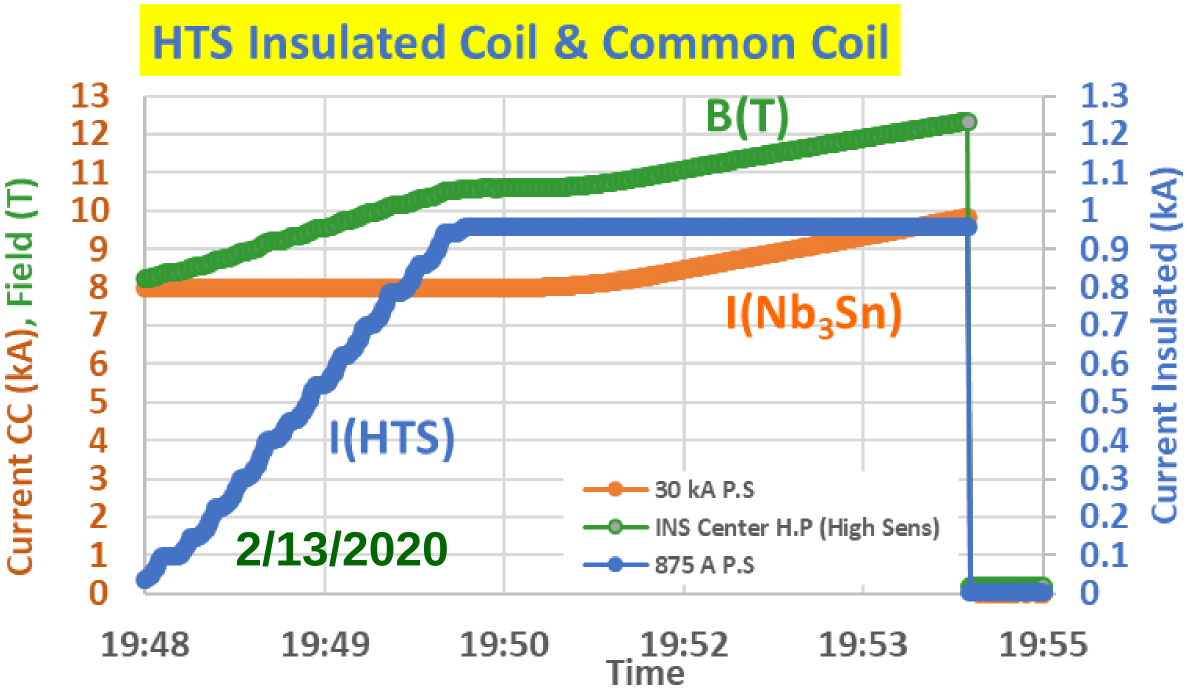
HTS/LTS Hybrid Dipole Test

(creating a record 12.3 T hybrid dipole field)



Test sequence:

- Nb_3Sn ramped to 8 kA (~8 T)
- HTS ramped to 950 A
- Nb_3Sn ramped to quench (~10 kA) creating a record ~12.3 T hybrid field



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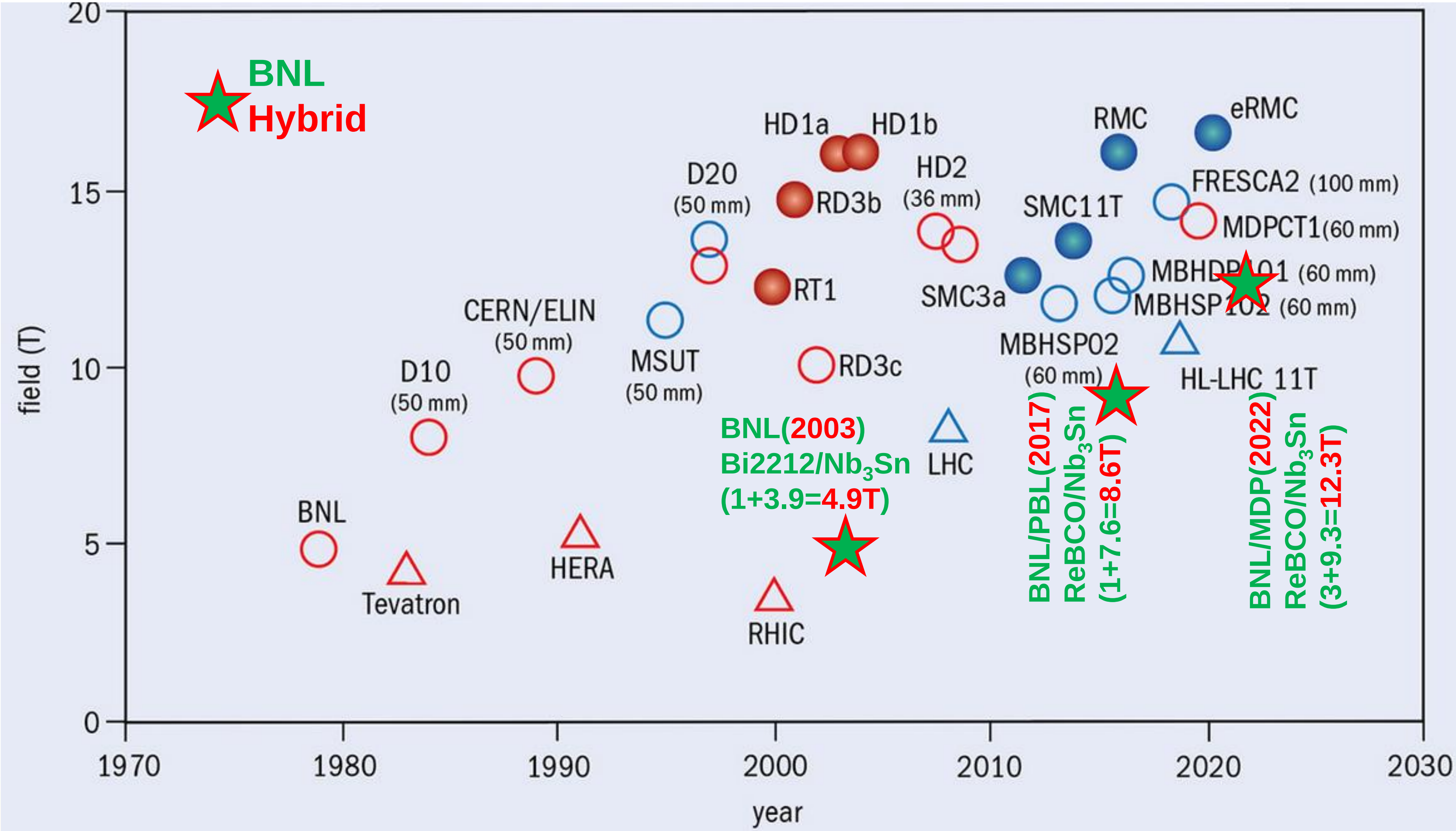
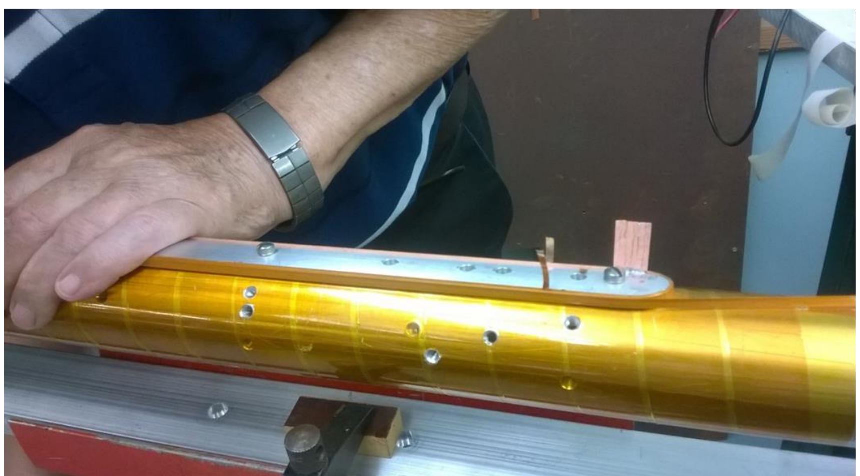
Updated Bottura (CERN) Chart

(includes BNL HTS/LTS hybrid R&D dipoles)



Other Geometries of HTS Dipole Magnets

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



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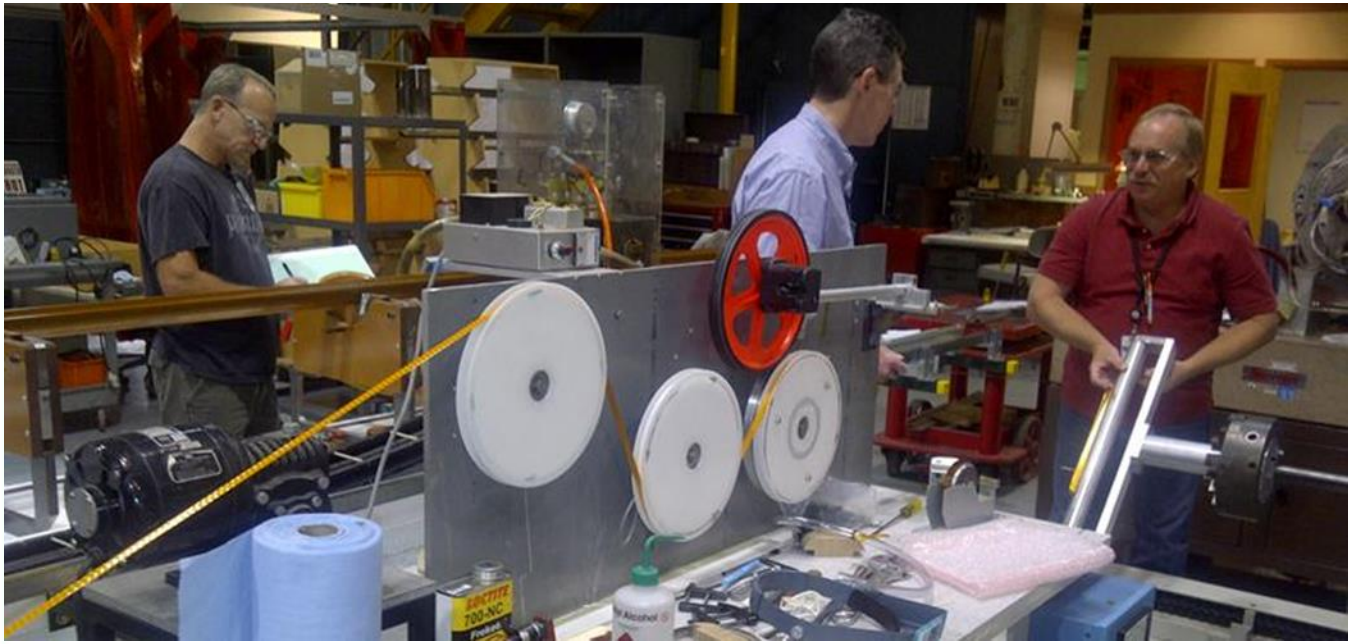
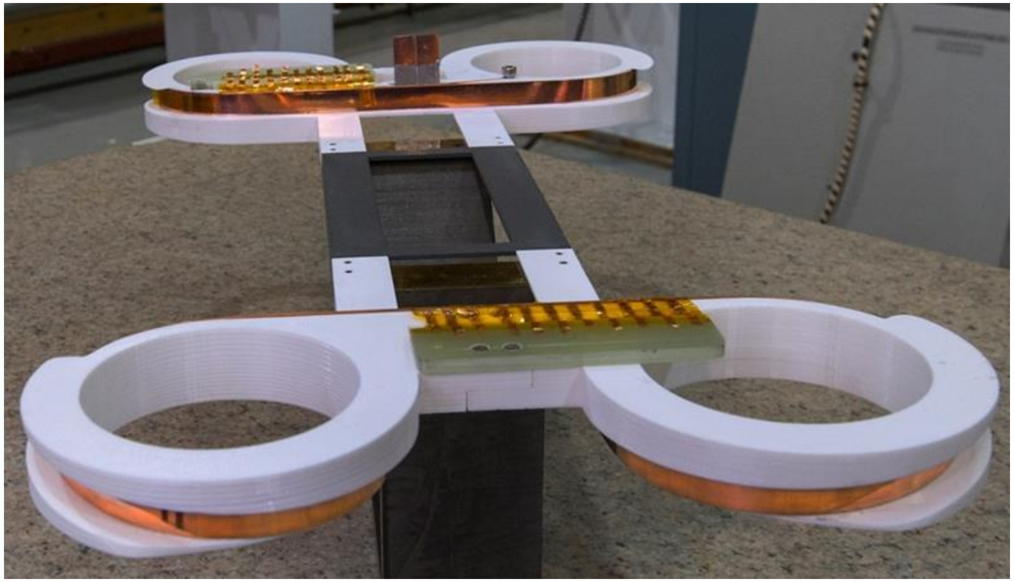
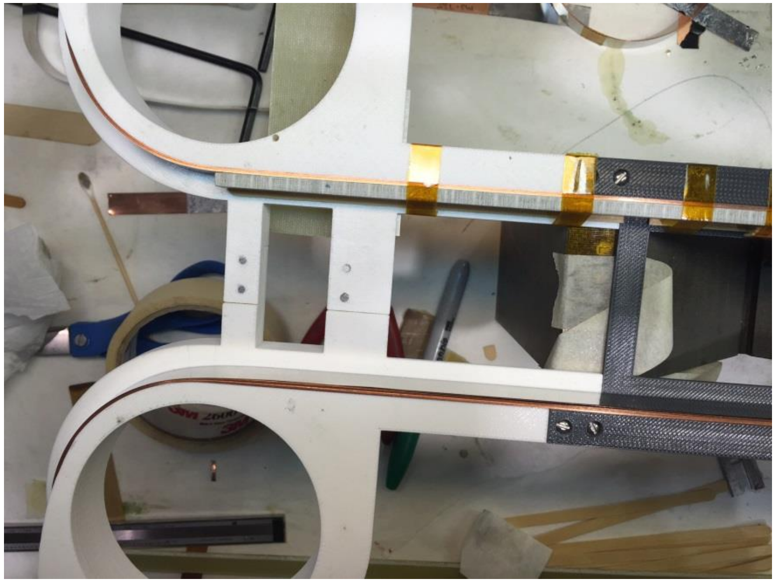
Cosine Theta Coil with 12 mm 2G Tape PBL/BNL SBIR (2)

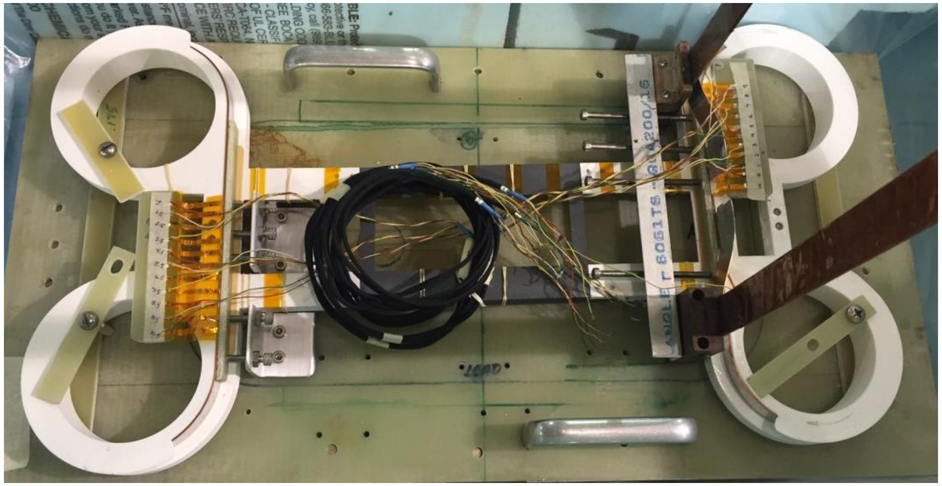


Demonstrations of the Dipole Coil Overpass/Underpass e2P/BNL SBIR

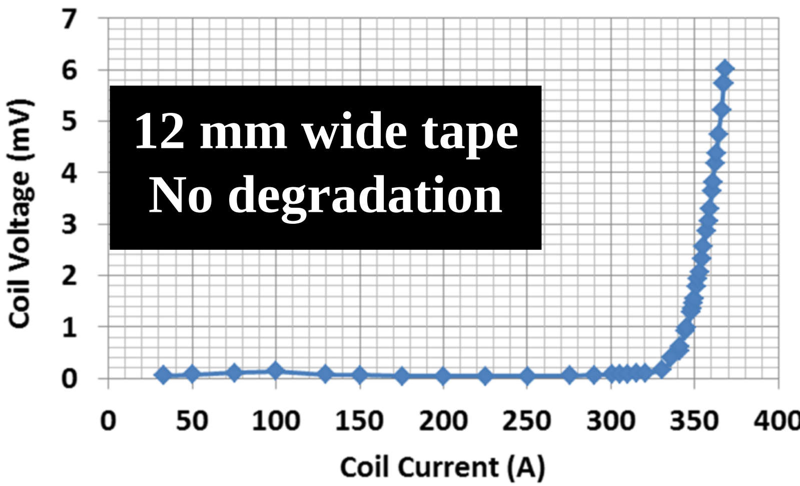




SBIR withe2P



77 K Test Results



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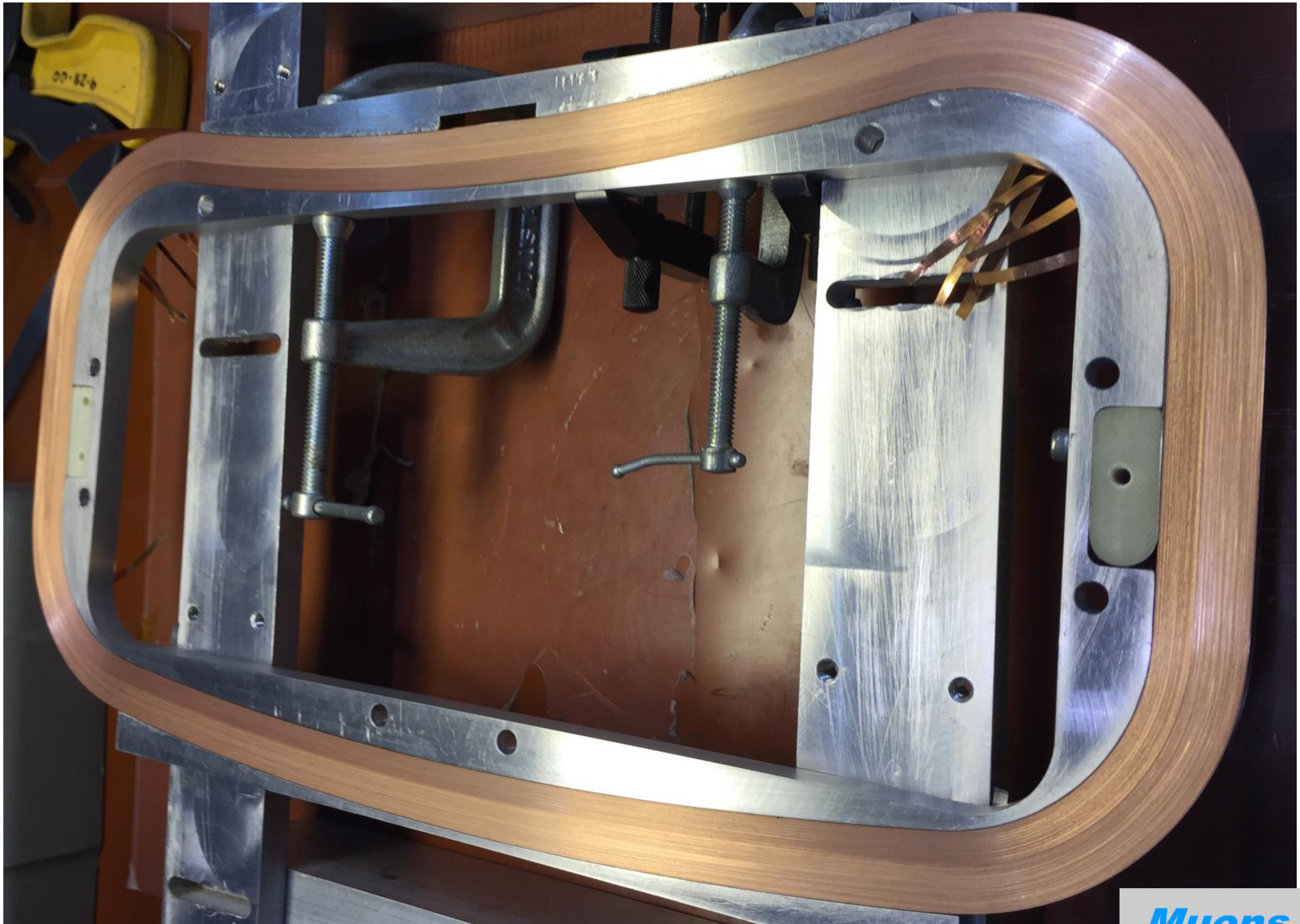
Curved HTS Coil for FRIB (SBIR)



HTS coil with
“reverse curvature”

National Laboratory

Muons, Inc.

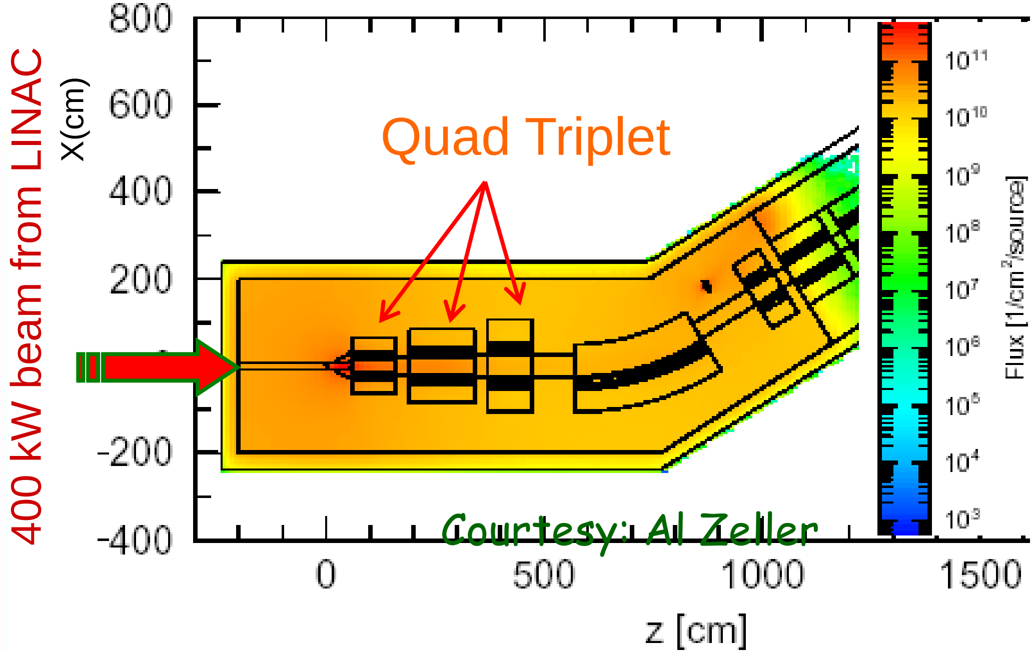
HTS Quadrupole R&D for the Facility for Rare Isotope Beams (FRIB) 2003-2014

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

FRIB was earlier referred to as RIA (Rare Isotope Accelerator)

Fragment Separator Quadrupole for FRIB

(2003)



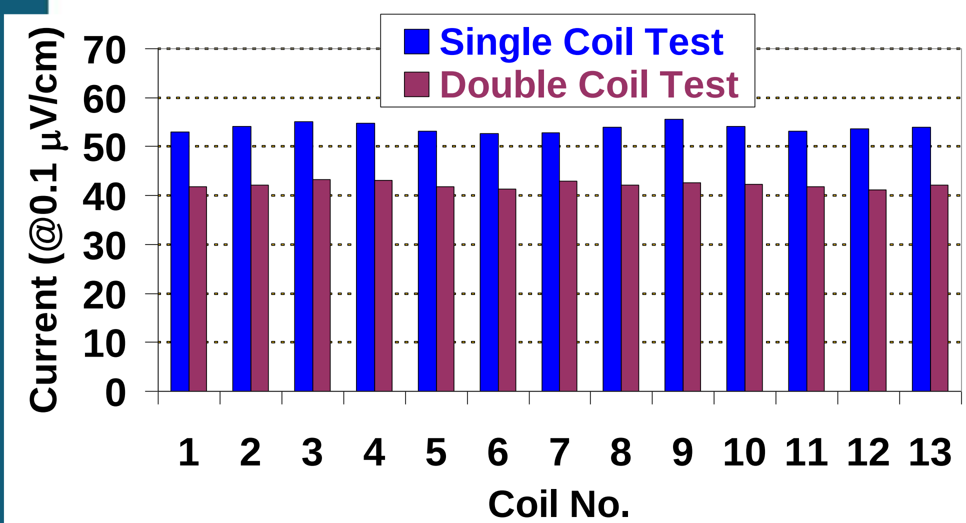
- **Up to 400 kW of beam power hits the target.**
- **Quad triplet in the fragment separator is exposed to very high radiation and heat loads.**
- **~15 kW is deposited in the first quadrupole itself.**

- **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**

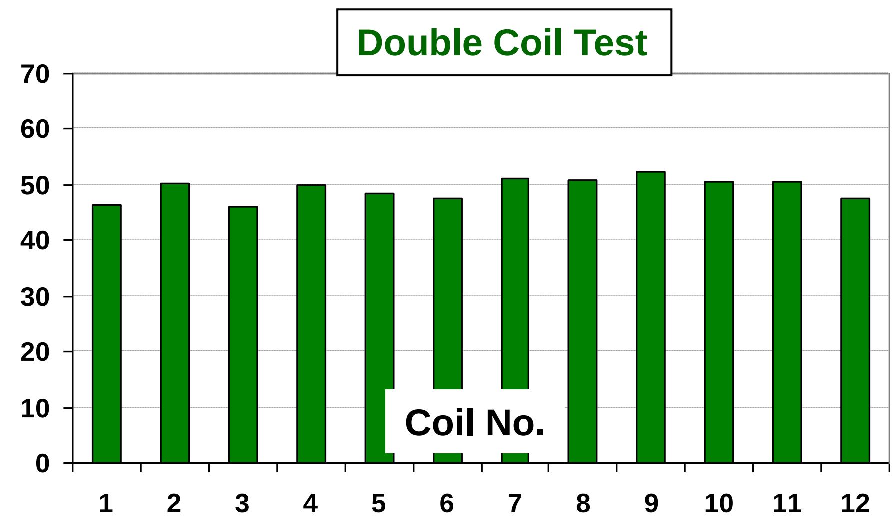
77 K Test of Coils Made with ASC 1st Generation (Bi2223) HTS

- ➢ **Each single coil uses ~200 meter of tape**

13 Coils made HTS tape in year #1

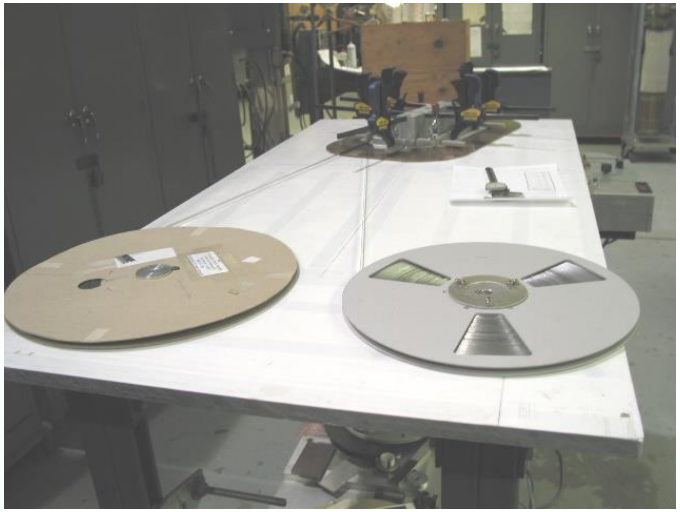


12 coils with HTS tape in year #2

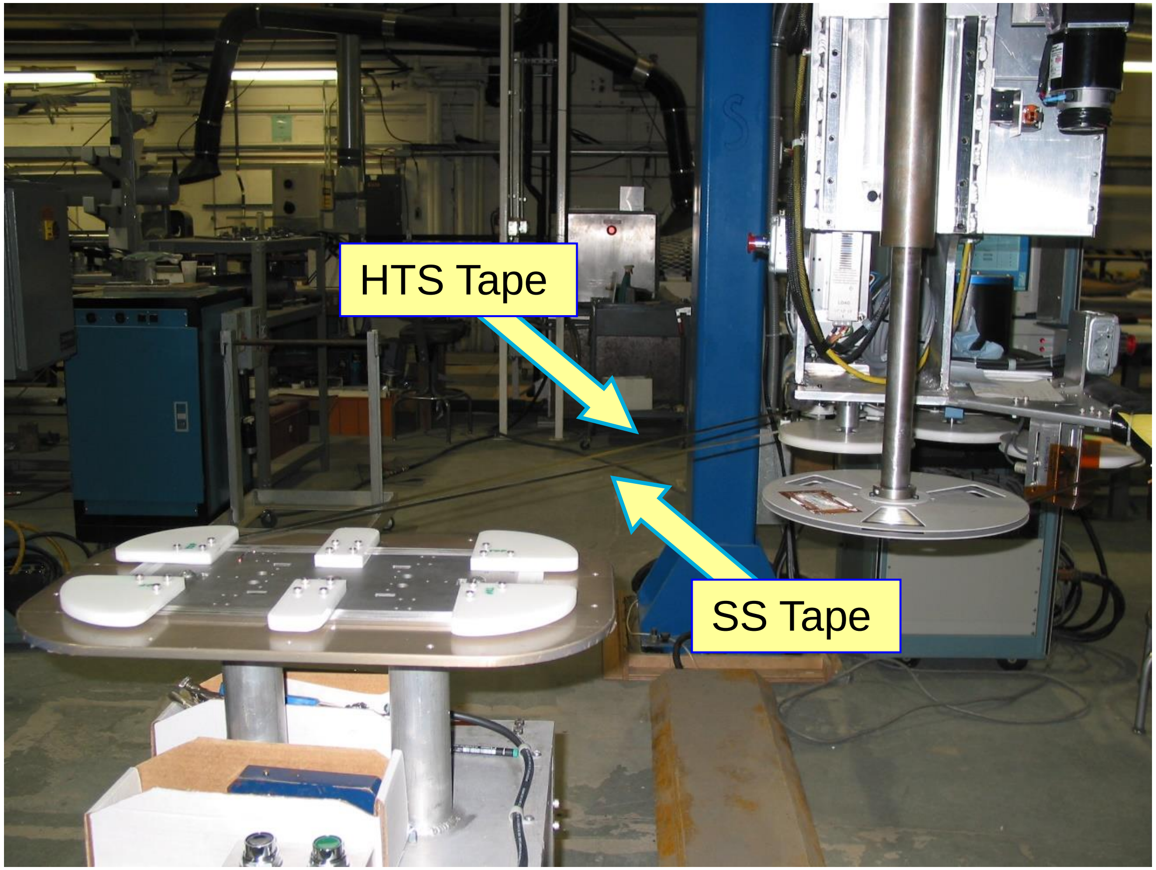


Note: A uniformity in performance of a large number of HTS coils

HTS Pancake Coil Winding

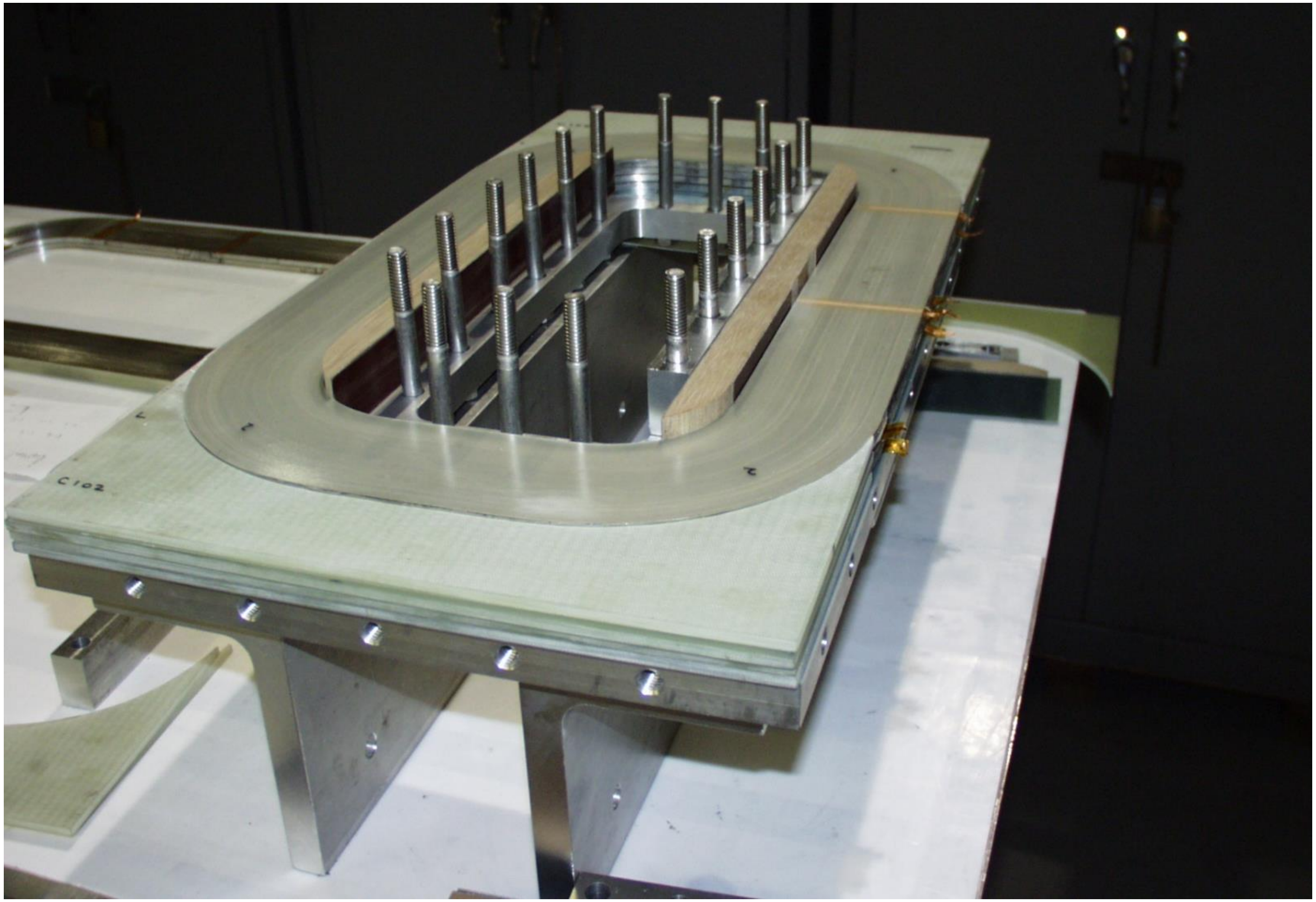


Earlier coils wound with manual controls



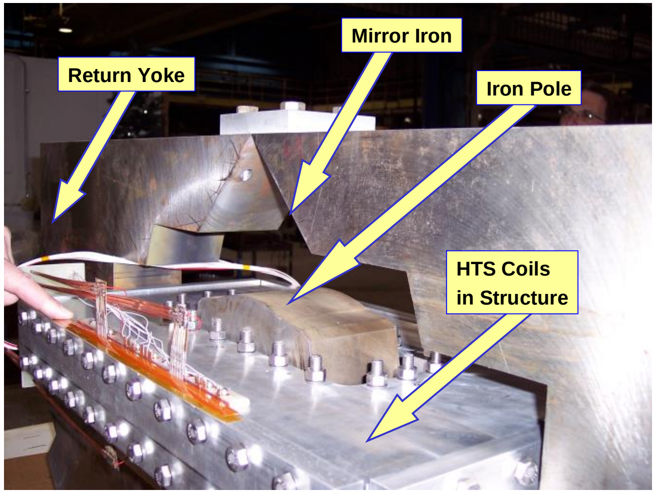
Later coils wound with a computer controlled winding machine (universal coil winder)

Assembled Pancake Coils with Internal Splices

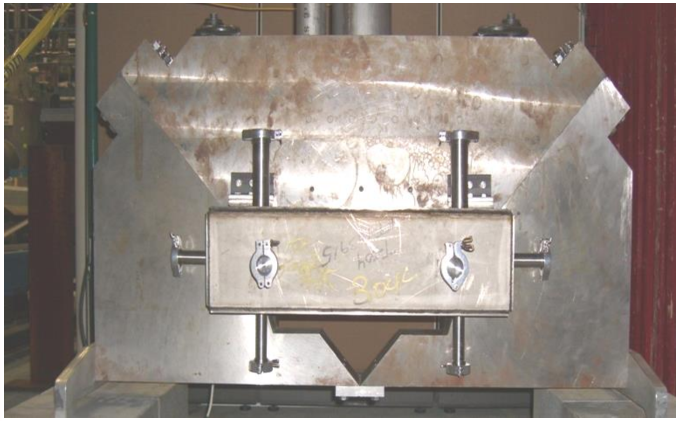


Three pairs of coils during their assembly a support structure

1st Generation HTS Quad

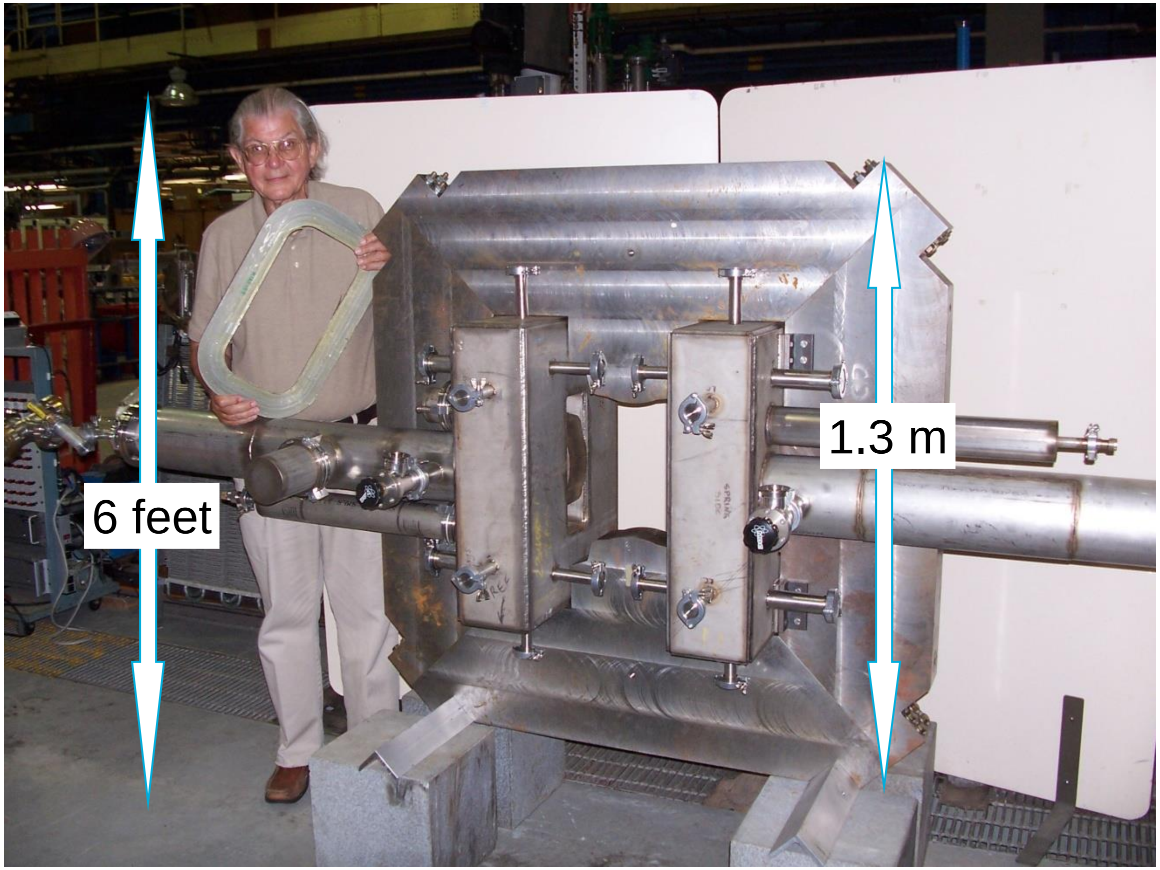


Mirror cold iron



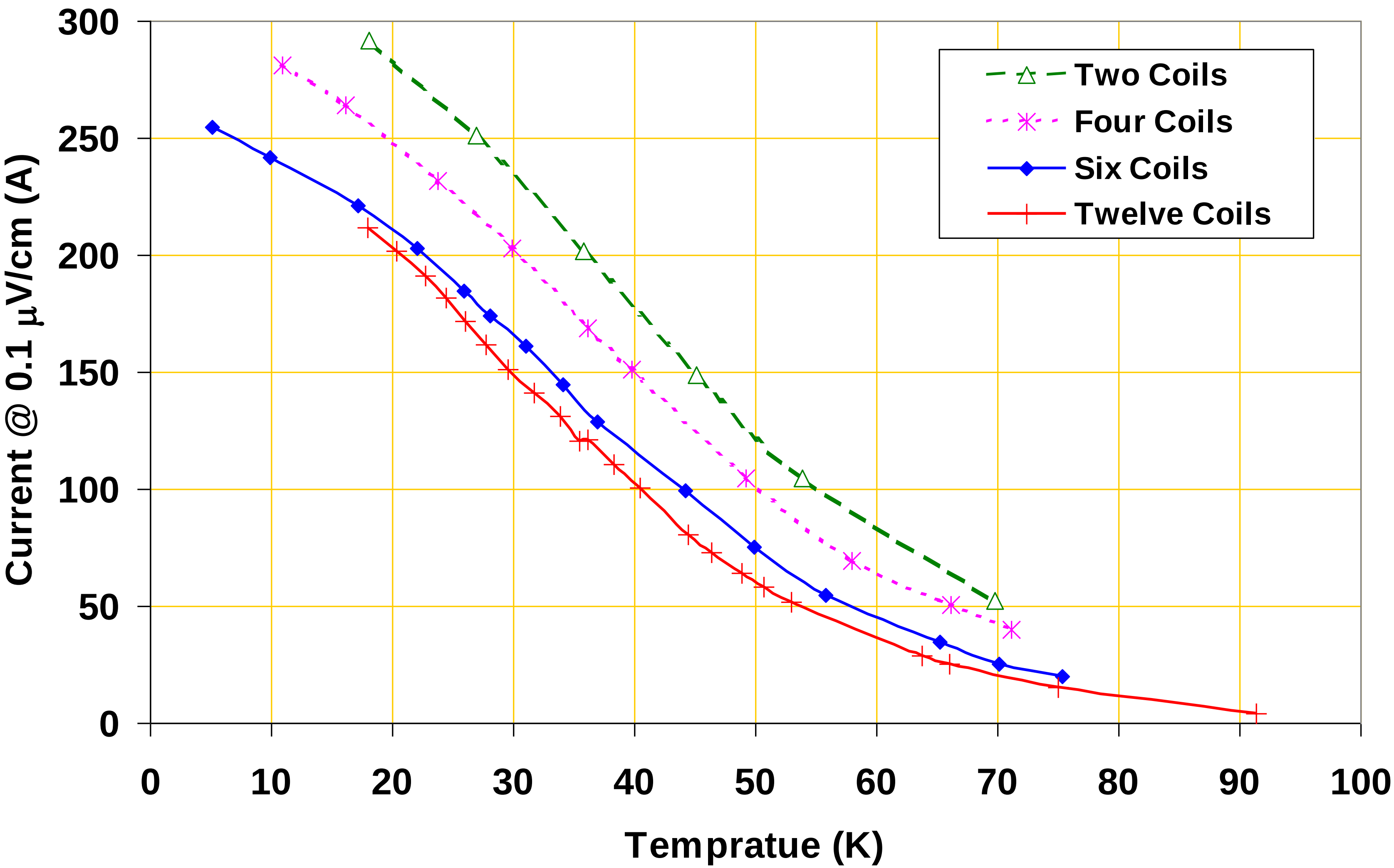
Mirror warm iron

Three magnet structures, built and tested



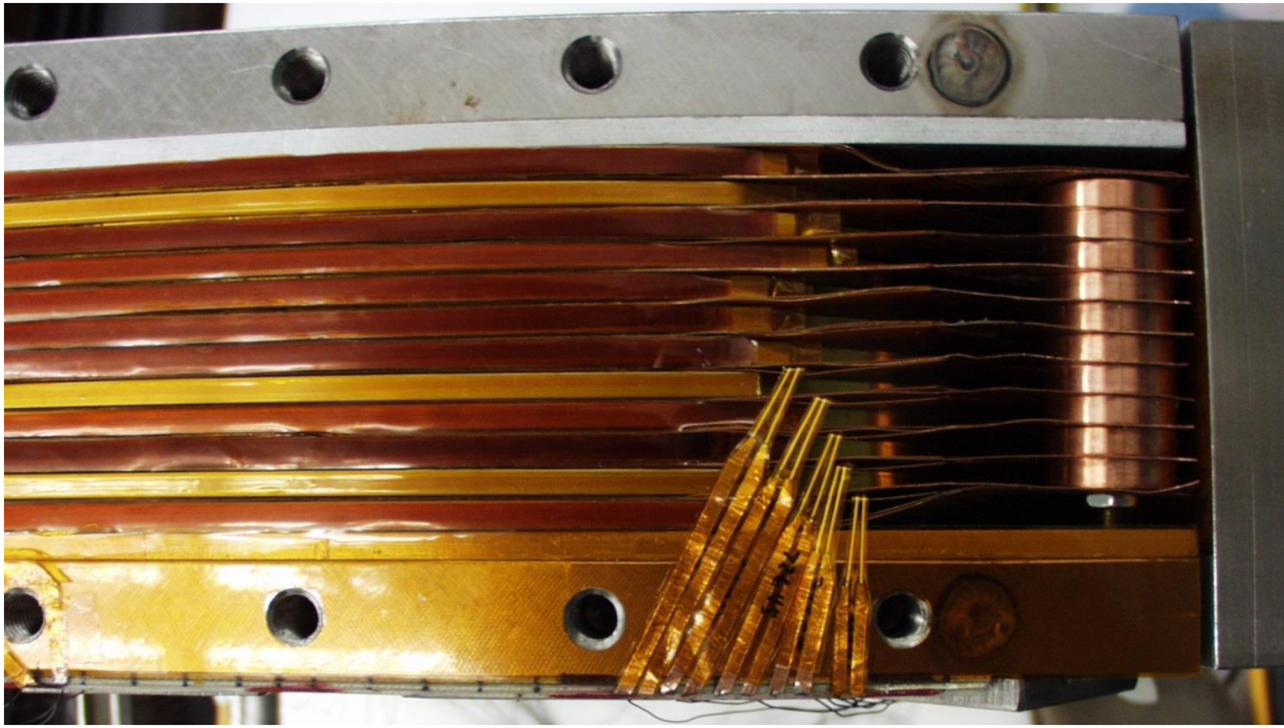
Warm Iron Design to Reduce Heat Load

Summary of First Generation HTS Quad Tests



Operation over a large temperature range- only possible with HTS

Energy Deposition Experiments

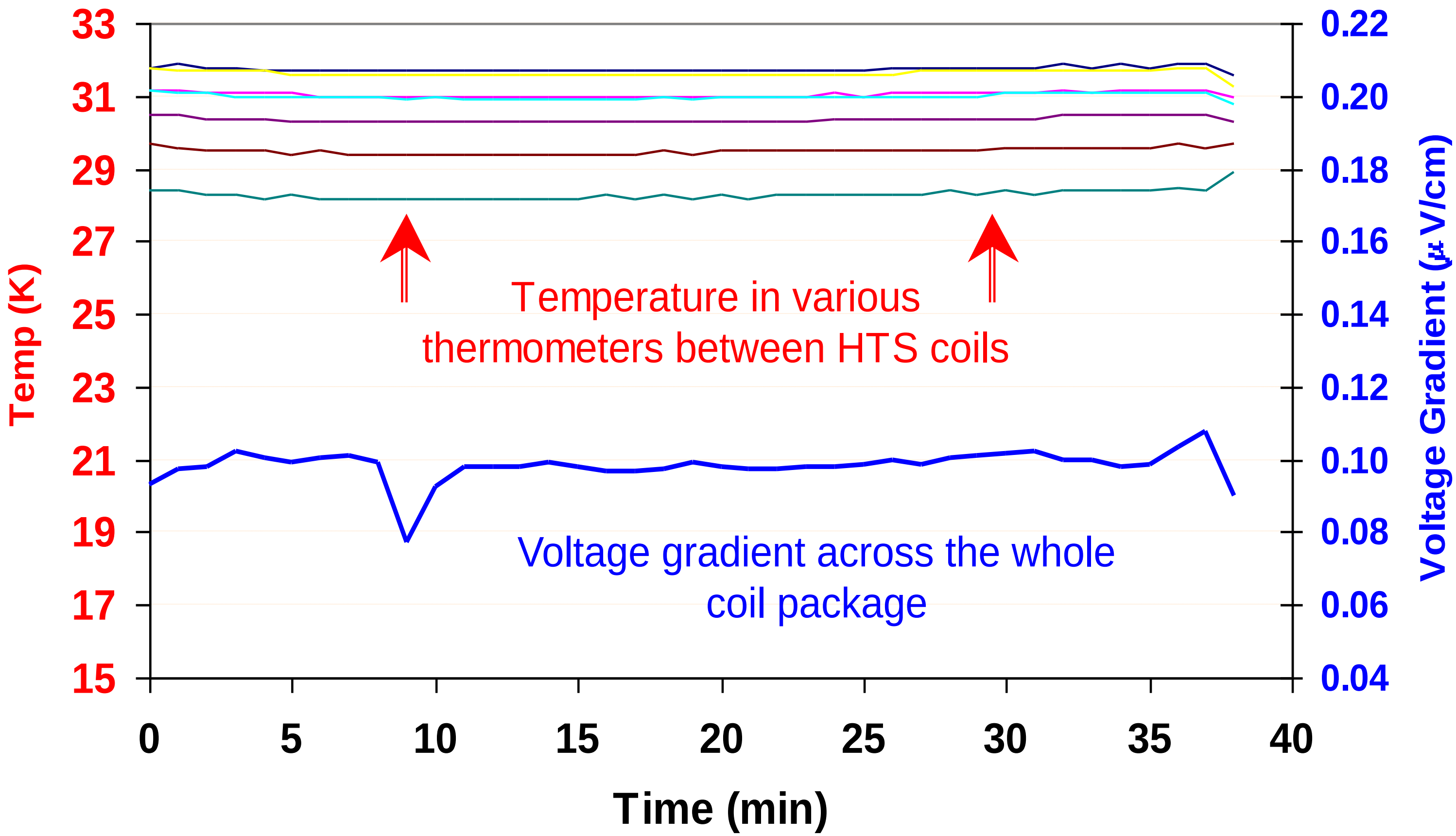


Stainless steel tape heaters for energy deposition experiments

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

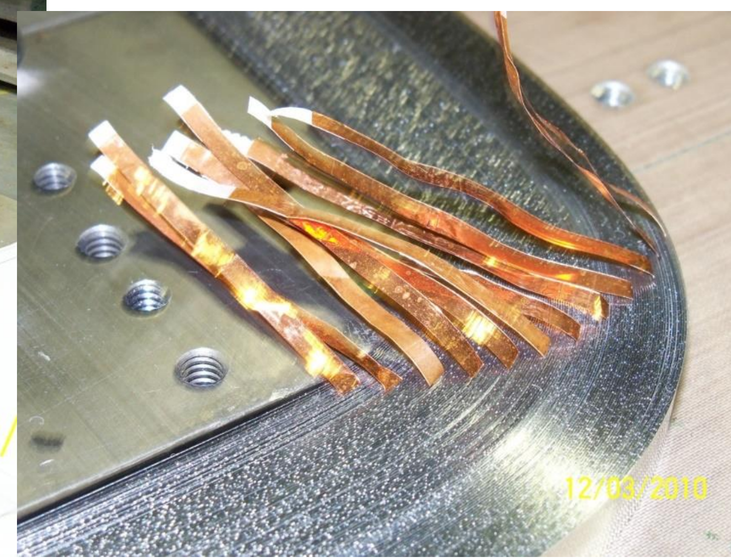
Second Generation Quadrupole for FRIB

HTS Coils for FRIB with the 2nd Generation (2G) HTS Tape from ASC and SuperPower

4 coils made with SuperPower Tape

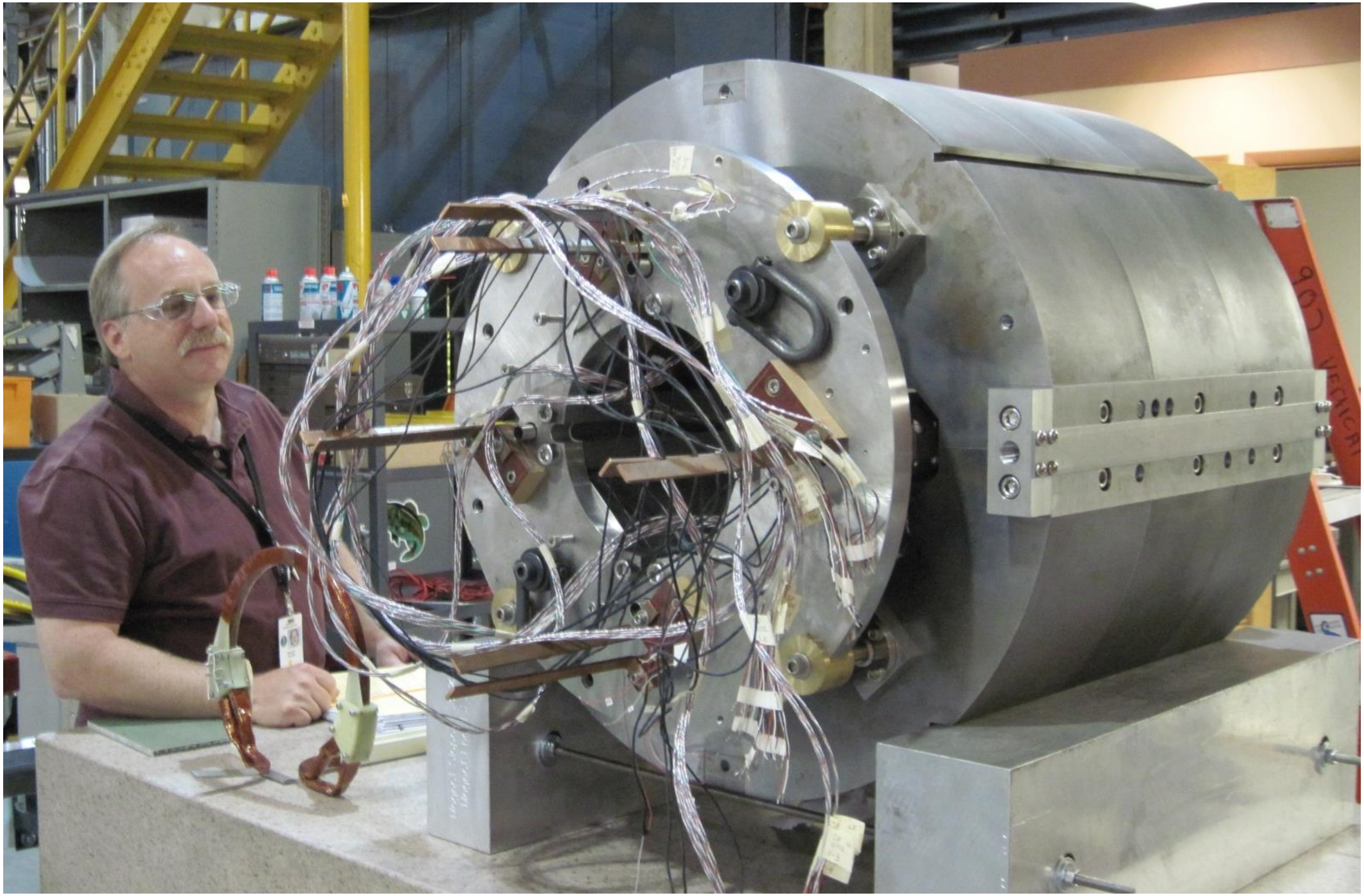
and

4 coils made with ASC



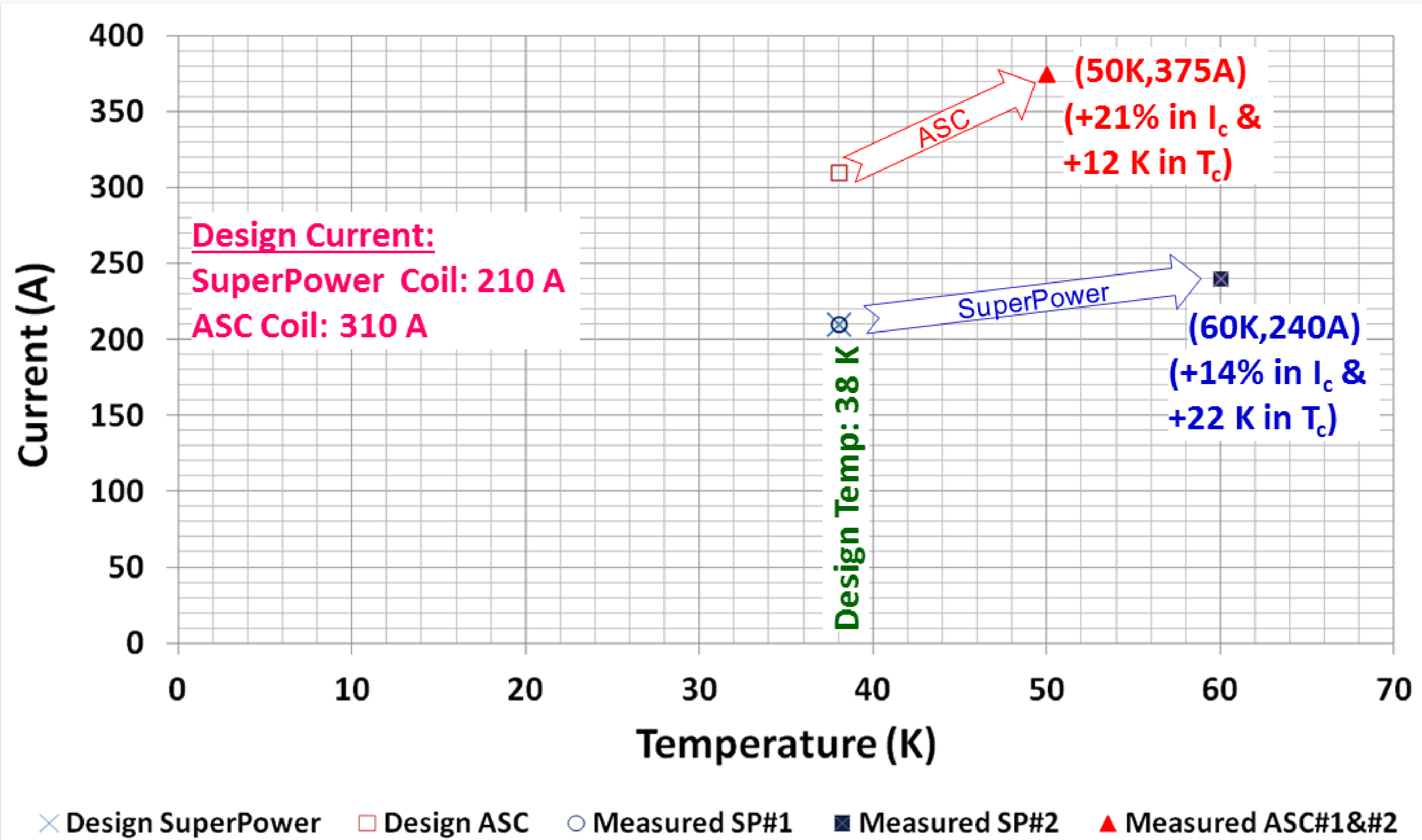
(~9 km of standard 4 mm equivalent used)

Completed 2G HTS Quad for FRIB



Brookhaven National Laboratory

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



Provides robust operation against local and global heat loads

ReBCO Cable for Accelerator Magnets

ReBCO comes in tape form and that poses several challenges:

- A local defect, not always detected at 77 K QA test of ReBCO tape, could cause an irrecoverable damage to the accelerator magnet coils, when operated at high fields and/or high stresses. This challenge is faced in fusion magnets as well.
- Tape conductors (rather than round wire) create field errors that may be too large for accelerator magnets. Similarly, tape conductors cause large losses that may be too much for fusion devices.
- Quench protection of the large high stored energy HTS magnets is a major issue for the accelerator magnets. This is also a major issue for the large fusion devices.

High current HTS cables are essential to deal with the above issues.

- Will that and other development in technologies be sufficient? Fusion community has made a massive investment and is counting on developing a reliable solution.
- Can/should accelerator community partially align its program to benefit from above?

https://wpw.bnl.gov/rgupta/wp-content/uploads/sites/9/2023/02/1MSpeOr3-02-asc2022-gupta.pdf

Summary

- **HTS magnets provide an opportunities that did not exist before.**
- **This is the only superconductor that can work over 20 T or can work over 20 K. This may reduce cryogenic challenges.**
- **Yes, there are many challenges. The question is, “are they show-stoppers?**
- **We need to find out. Let’s take this exciting journey with a longer time frame.**

https://wpw.bnl.gov/rgupta/hts-presentations/

https://wpw.bnl.gov/rgupta/papers-on-hts/

Extra Slides

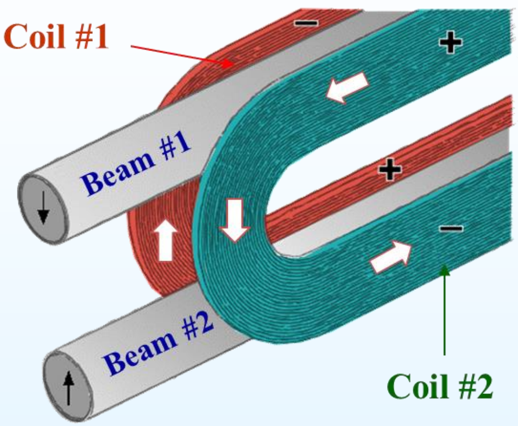
A Partial List of HTS Programs at BNL

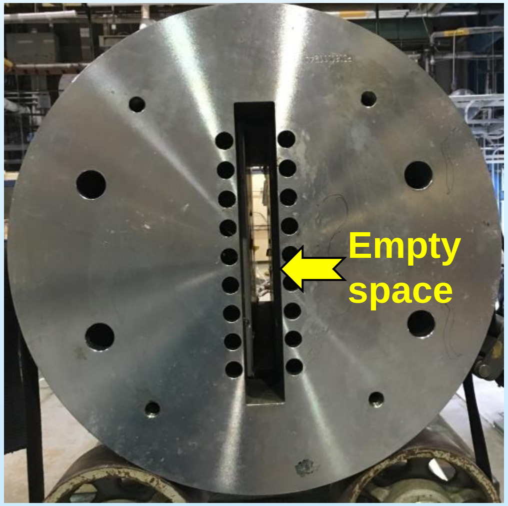
- HTS/LTS Hybrid dipole with HTS tape (Phase II SBIR)
- HTS/LTS hybrid dipole with HTS tape (USMDP)
- HTS/LTS hybrid dipole with HTS tape (US-Japan HEP)
- Hybrid Dipole with CORC® Cable (Phase II SBIR)
- Cosine theta HTS dipole (Two Phase I SBIR)
- 25 T, 100 mm HTS solenoid for IBS, Korea (Work for Others)
- High field solenoid for Neutron Scattering (Phase I SBIR)
- Passive shielding for Electron Ion Collider (Phase I SBIR)
- 100 mm aperture “12.5 T @27 K” HTS SMES (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.

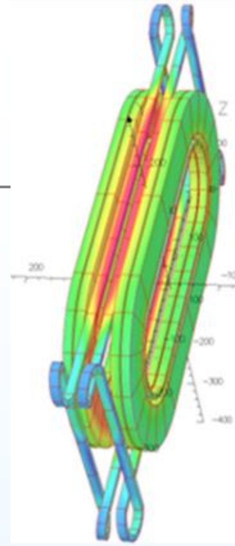
Unique BNL Common Coil Dipole

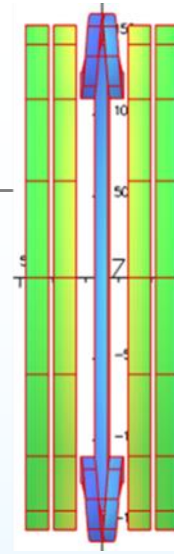


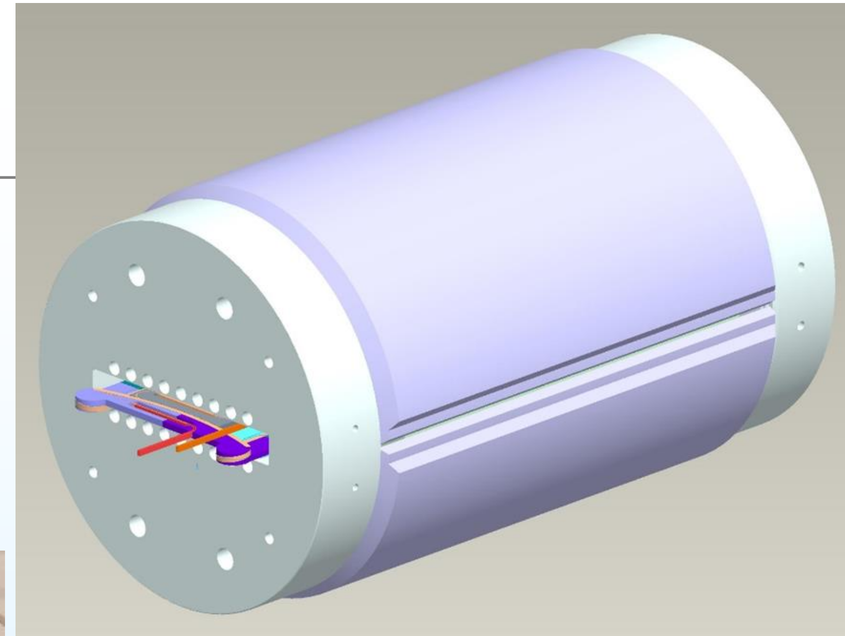


- BNL built a magnet to demonstrate "React & Wind" Nb_3Sn technology in 10+ T dipole
- Structure specifically designed to provide a large open space (31 mm wide, 338 mm high)
- New racetrack coils can be inserted in the magnet without any disassembly or reassembly
- New HTS insert coils become an integral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

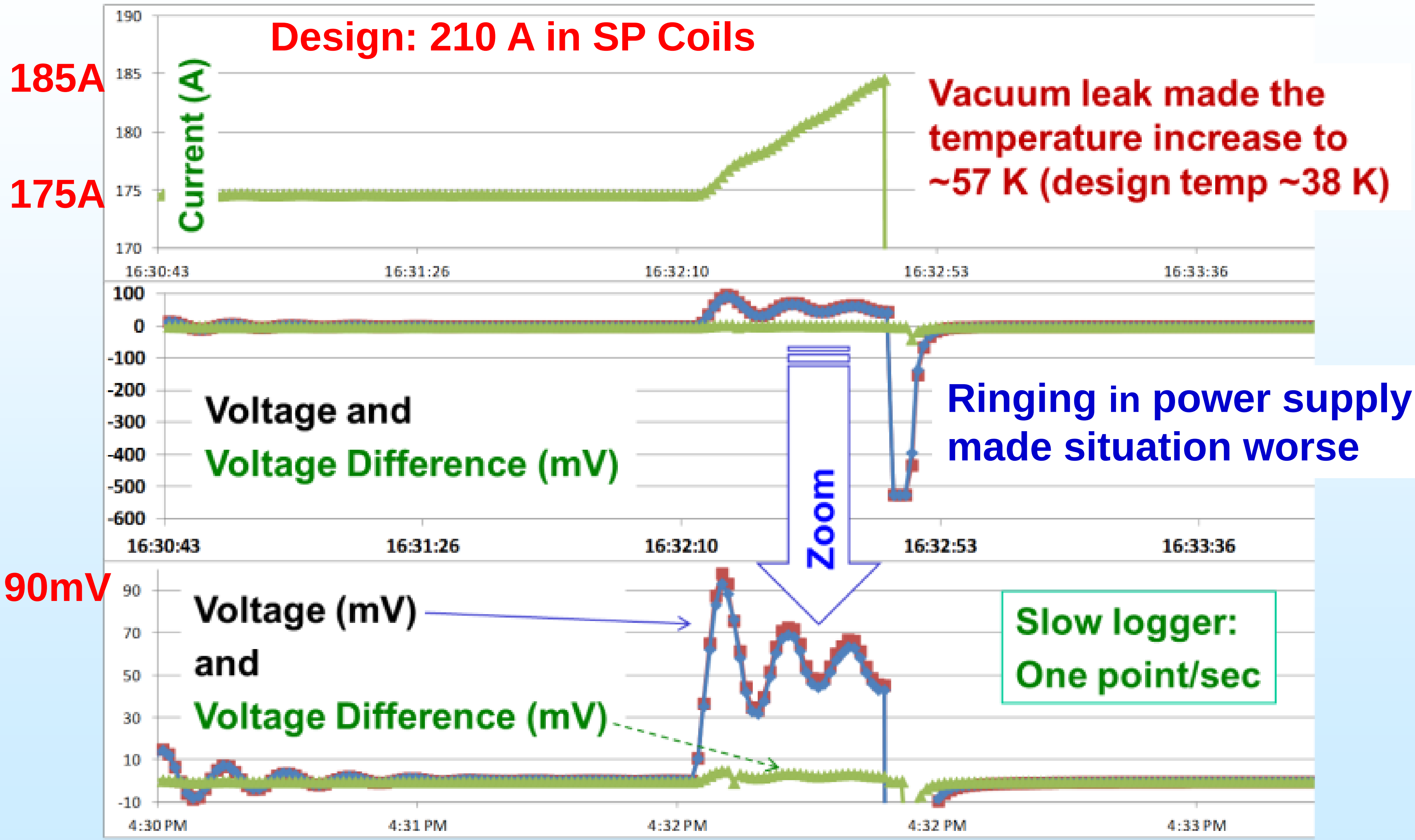
PBL Overpass/ Underpass STTR





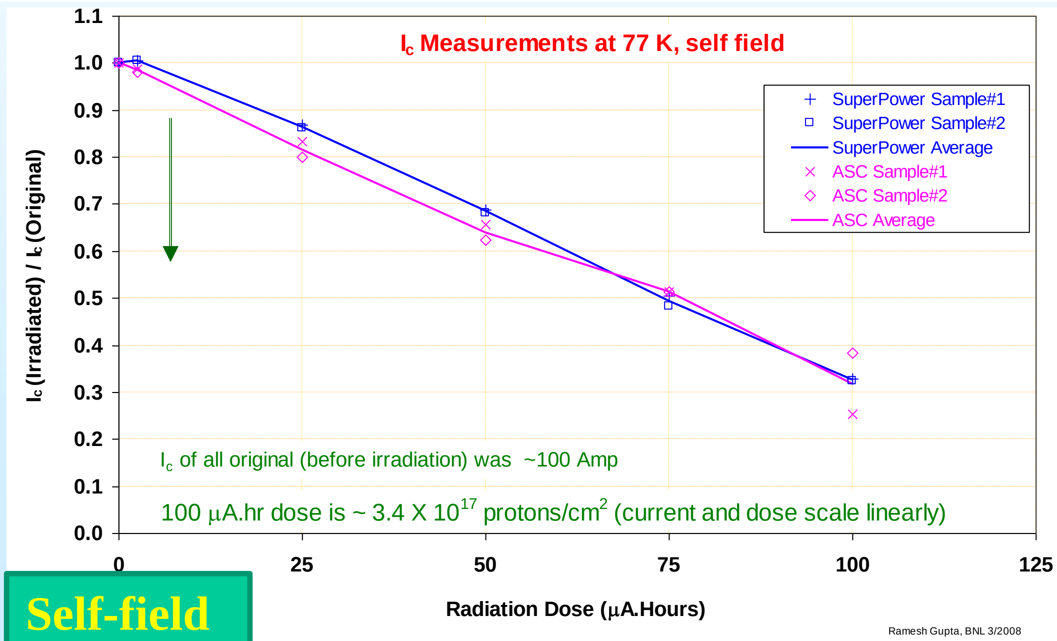


Protection of HTS Magnet during an Operational Accident Near Design Current



Radiation Damage Studies @BNL in 2G HTS from SuperPower & ASC (measurements @77K in self-field and in 1 T Applied Field)

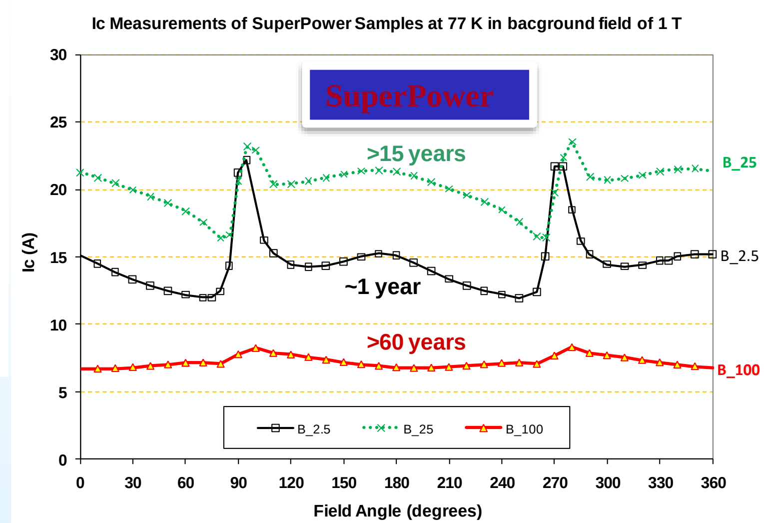
- Self-field radiation damage is found to be similar in samples from both ASC and SuperPower.
- A significant difference in the change in-field anisotropy between SuperPower and ASC tapes.
- Based on these studies, 2G HTS seems to survive FRIB radiation (Zeller, Ronningen, MSU).

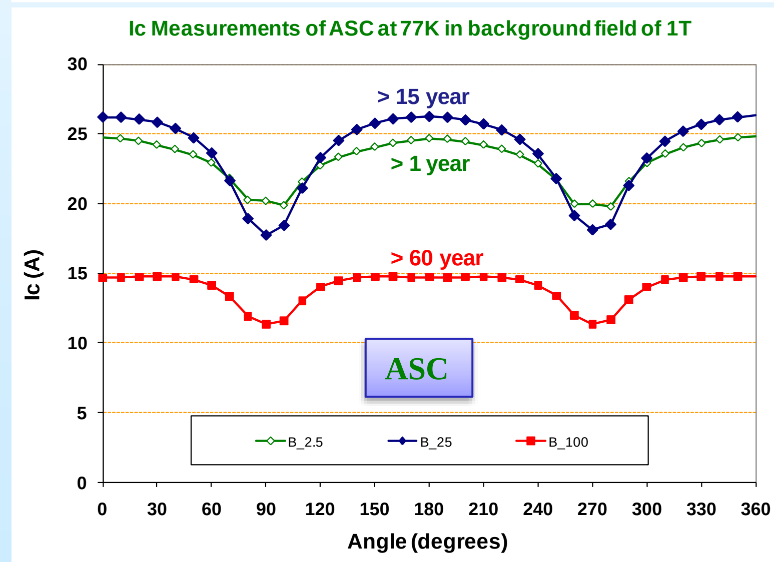


Self-field

10% damage after 30 years (Zeller & Ronningen)

1 T applied field

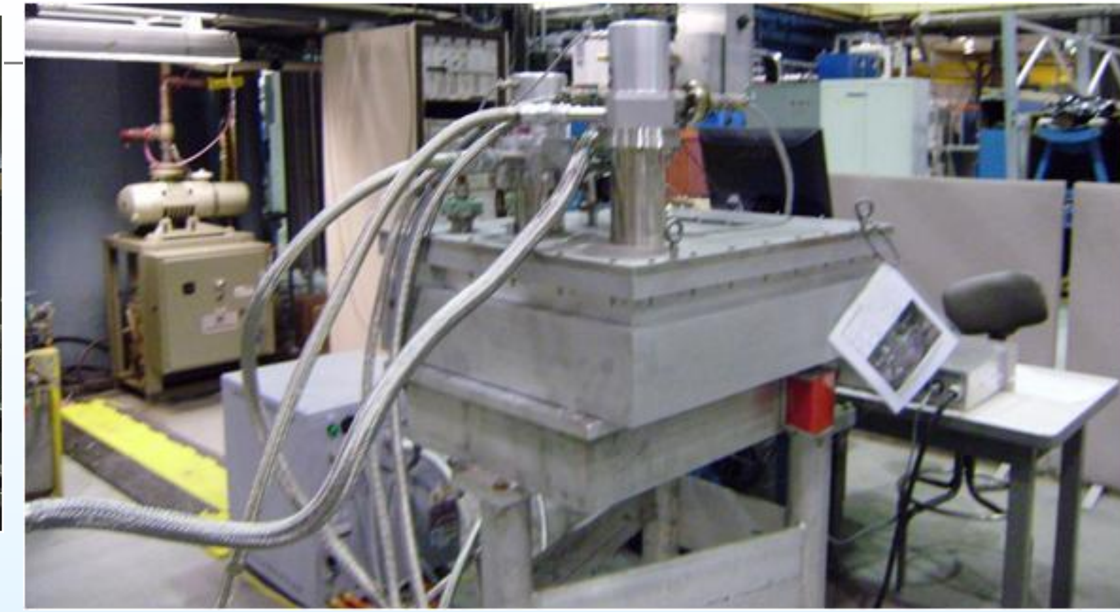




Curved HTS coil (with reverse bend) for Dipoles and Conduction-cooled magnet R&D at BNL

Cryo-cooler based HTS Magnet R&D

Superconducting



- Coils reached <40 K (goal was 40-50 K)
- Cryo-coolers turned-on at 5 pm in the evening before leaving and coils cooled to the desired at 8:30 am in the morning.
- Good test bed for HTS coil technology – No Helium, no personnel, turn on cryo-cooler the evening before and start experiment in the morning…

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