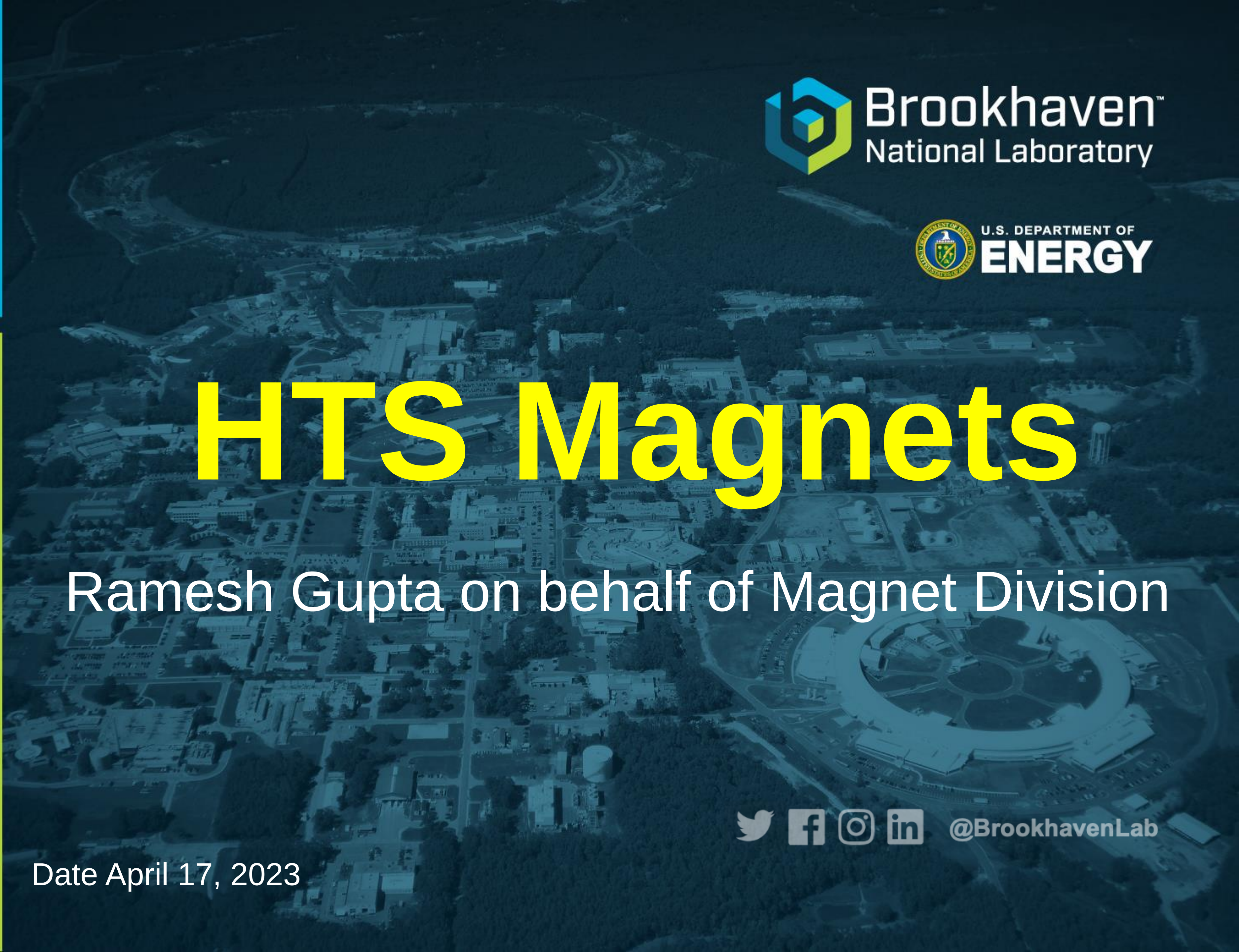


Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

HTS Magnets

Ramesh Gupta on behalf of Magnet Division

@BrookhavenLab

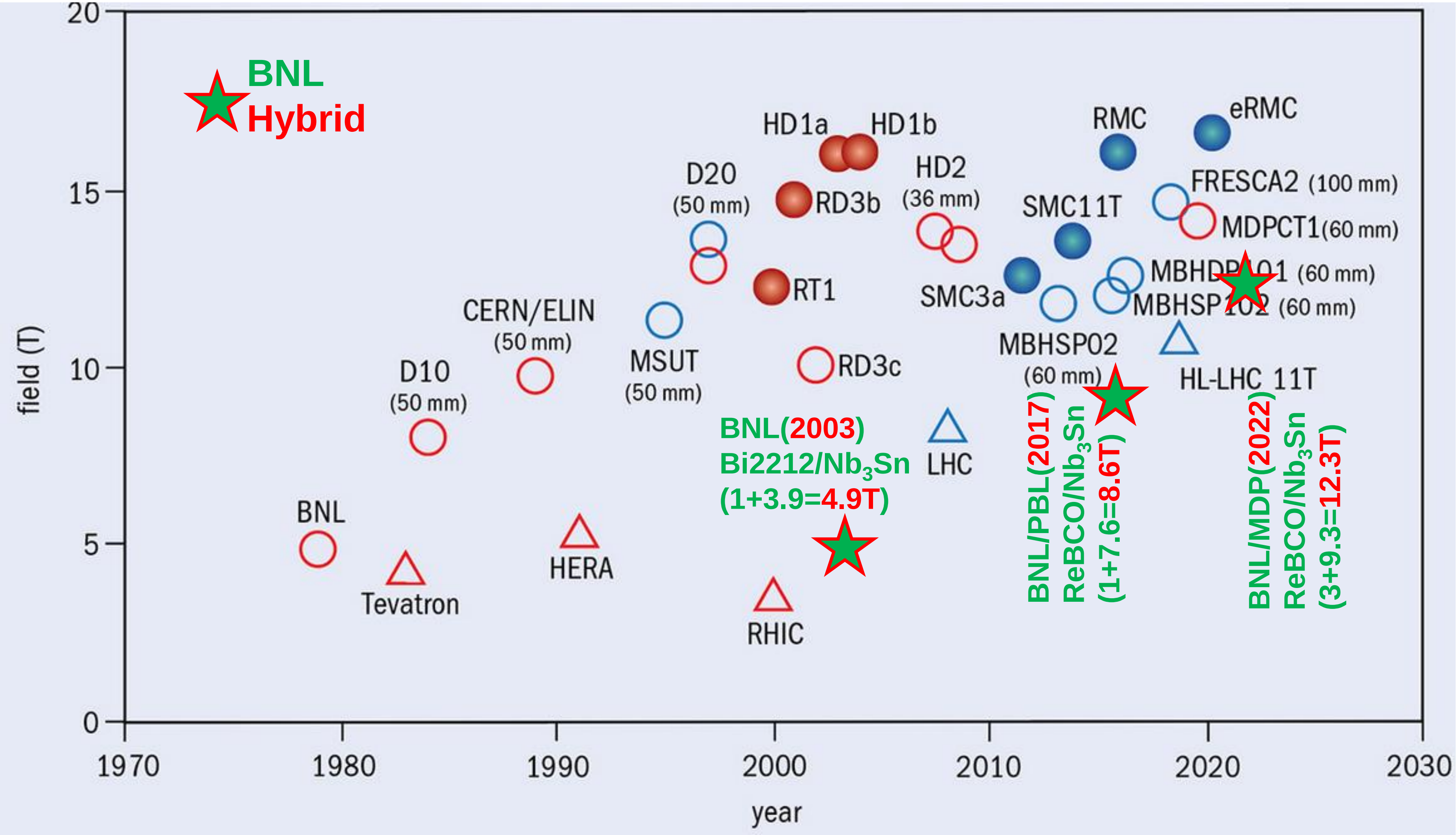
Date April 17, 2023

Overview

- **BNL history with HTS magnet R&D**
- **Some thoughts on future HTS conductors and future HTS magnet designs (10$^+$ year)**
- **Some thoughts on HTS magnet R&D approach with a long-time horizon**

Updated Bottura (CERN) Chart

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

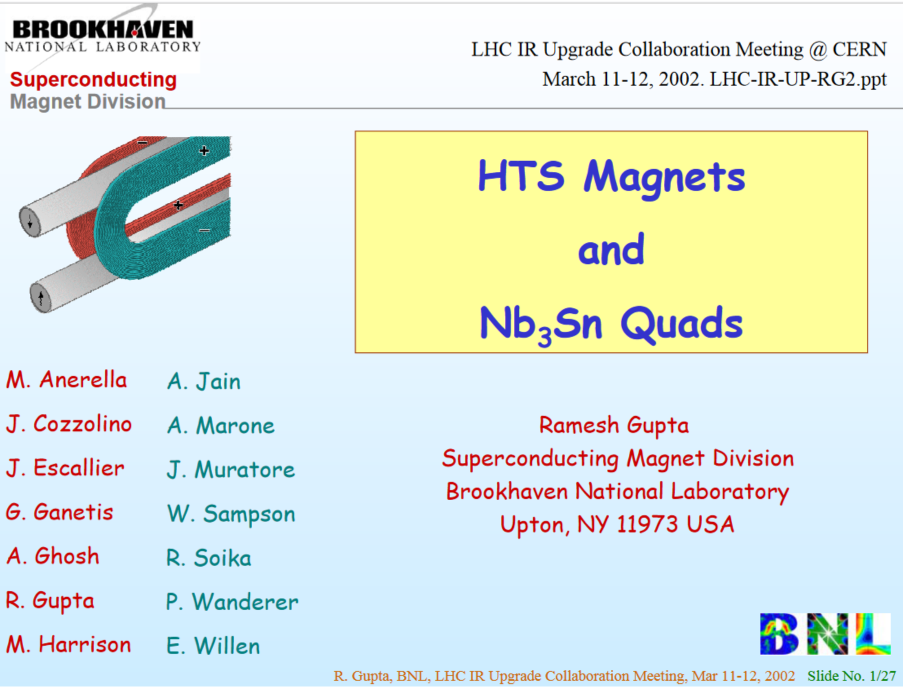


***moved to primarily HTS solenoids in between 2008-2020**

My Early Interaction with CERN on HTS Magnets

LHC IR Upgrade Collaboration Meeting
CERN, Building 112/4-B10
SL Division, CH-1211 Geneva. Switzerland
March 11-12, 2002

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



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Superconducting Magnet Division

LHC IR Upgrade Collaboration Meeting @ CERN
March 11-12, 2002. LHC-IR-UP-RG2.ppt

HTS Magnets and Nb_3Sn Quads

M. Anerella	A. Jain
J. Cozzolino	A. Marone
J. Escallier	J. Muratore
G. Ganetis	W. Sampson
A. Ghosh	R. Soika
R. Gupta	P. Wanderer
M. Harrison	E. Willen

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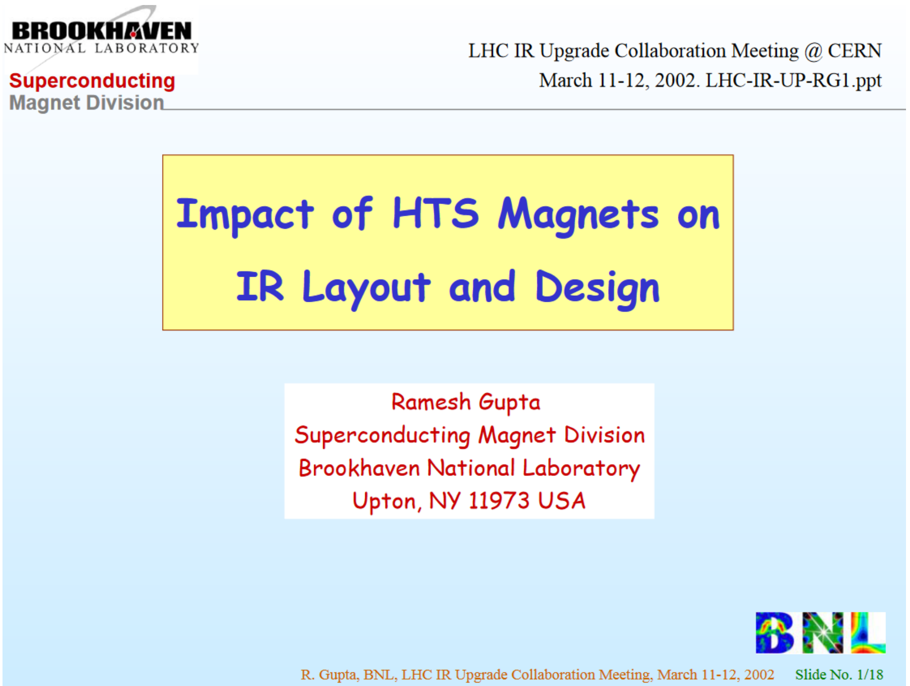
R. Gupta, BNL, LHC IR Upgrade Collaboration Meeting, Mar 11-12, 2002 Slide No. 1/27



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LHC IR Upgrade Collaboration Meeting @ CERN
March 11-12, 2002. LHC-IR-UP-RG1.ppt

Impact of HTS Magnets on IR Layout and Design

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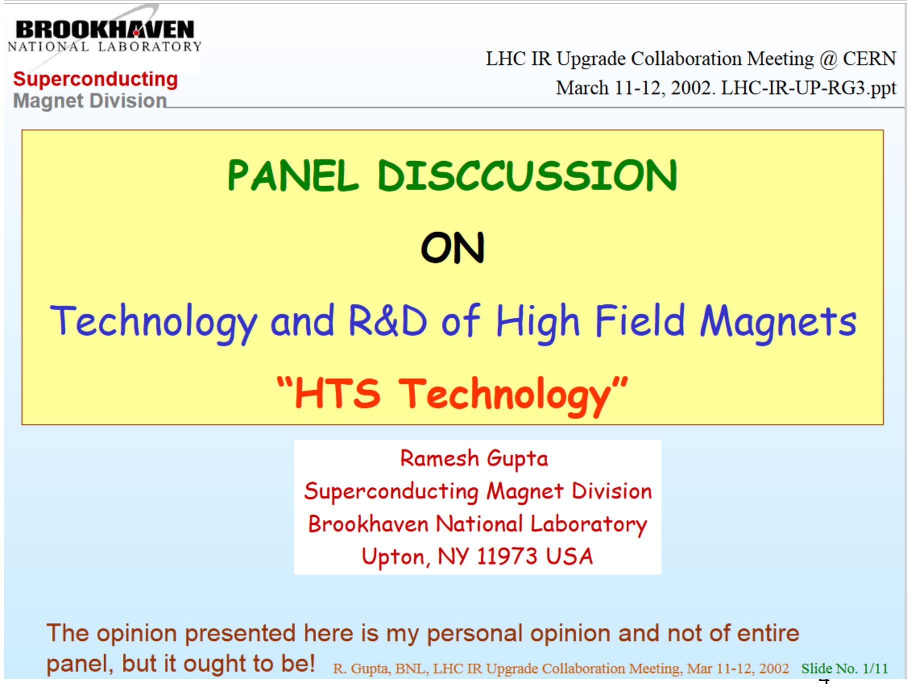
R. Gupta, BNL, LHC IR Upgrade Collaboration Meeting, March 11-12, 2002 Slide No. 1/18



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Superconducting Magnet Division

LHC IR Upgrade Collaboration Meeting @ CERN
March 11-12, 2002. LHC-IR-UP-RG3.ppt

PANEL DISCCUSSION ON Technology and R&D of High Field Magnets "HTS Technology"

Ramesh Gupta
Superconducting Magnet Division
Brookhaven National Laboratory
Upton, NY 11973 USA

The opinion presented here is my personal opinion and not of entire panel, but it ought to be!

R. Gupta, BNL, LHC IR Upgrade Collaboration Meeting, Mar 11-12, 2002 Slide No. 1/11

HTS Magnet Program at BNL

- **1st US national lab to start HTS magnet R&D (over 20 years ago)**

  Opted the approach of demonstrating capabilities of HTS to create new opening, 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**
  - **Solenoids, dipoles, quadrupoles, racetrack coils, cos θ coils, curve coils, clover-leaves coils, ...**
  - **A wide range of operating temperature and fields**

- **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)**

Brookhaven National Laboratory

Early Years of HTS R&D at BNL

Common Coil Magnets With HTS Tapes

Early work with Bi2223 Tapes

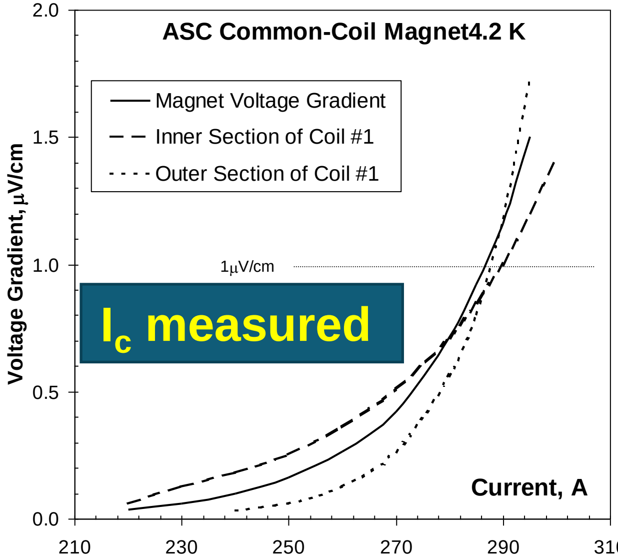
2000

Status of HTS tape coils at BNL

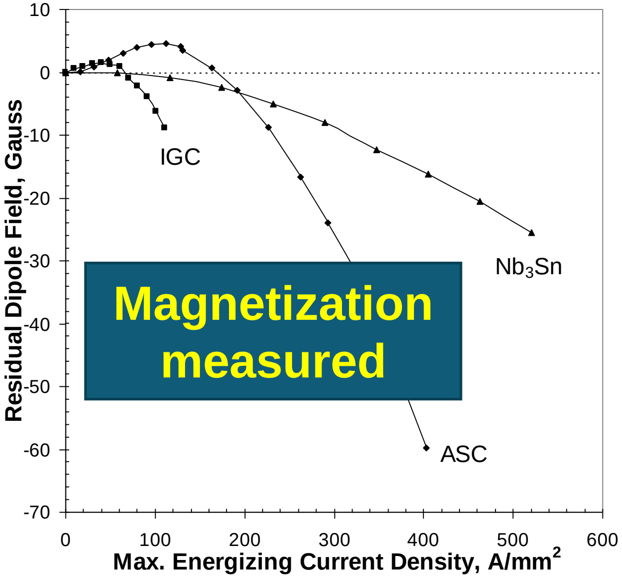
	Size, mm	Turns	Status
Nb_3Sn	0.2 x 3.2	168	Tested
IGC	0.25 x 3.3	147	Tested
ASC	0.18 x 3.1	221	Tested
NST	0.20 x 3.2	220	Under construction
VAC	0.23 x 3.4	170	Under construction

Two HTS tape coils in common coil configuration

Field harmonics measured

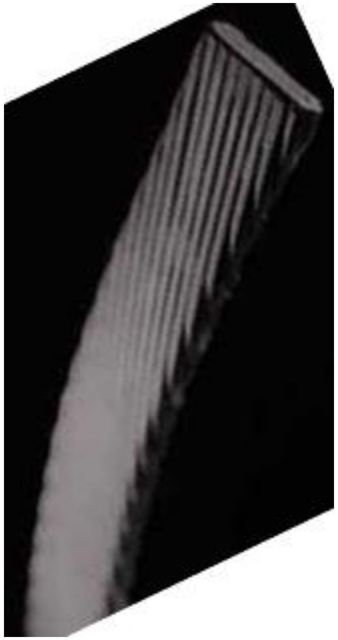


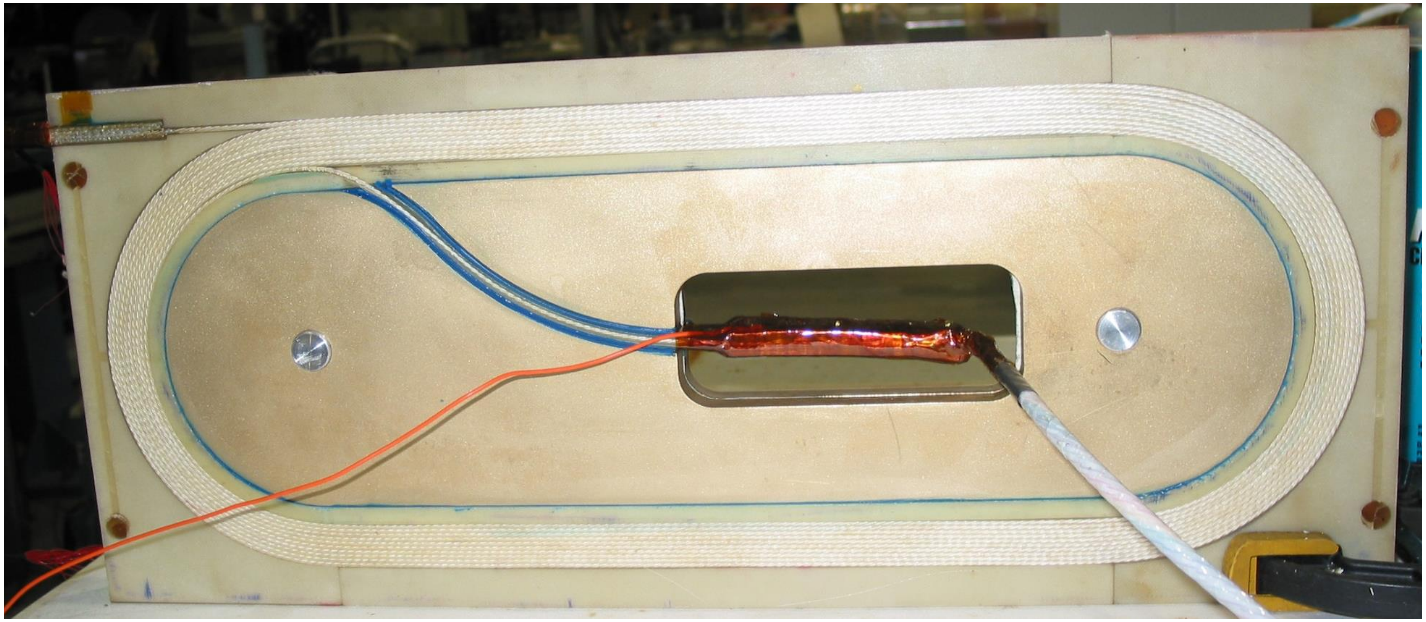
I_c measured



Magnetization measured

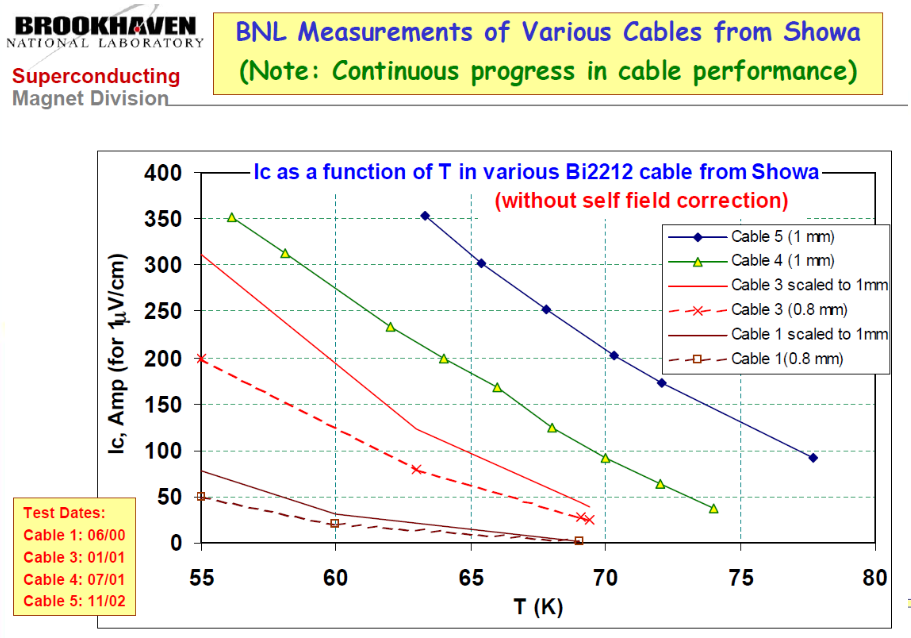
Racetrack coil made with *React & Wind Bi2212* Rutherford cable for the common coil dipole





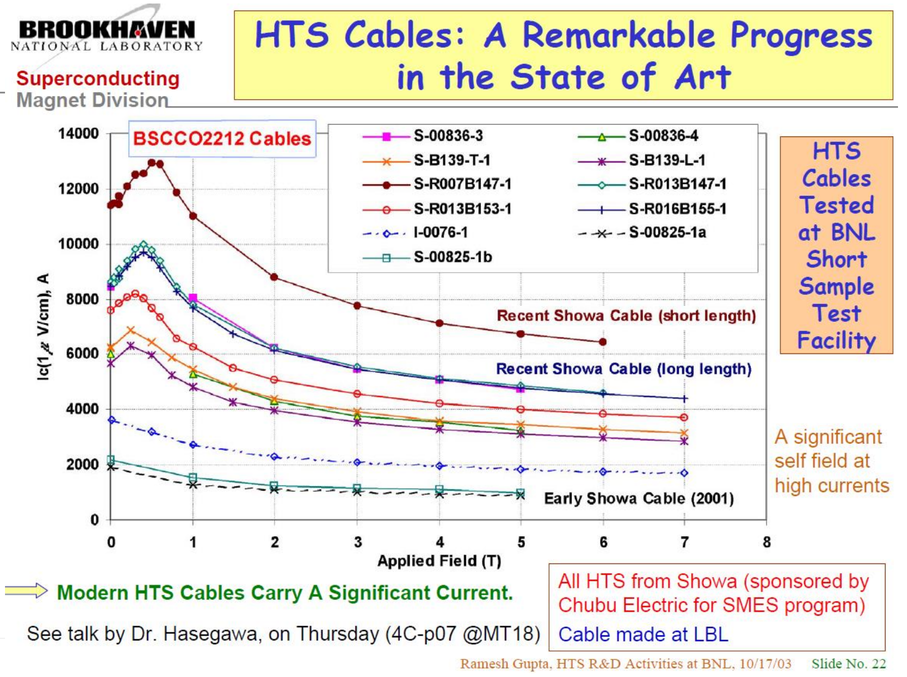
BNL led a wide collaboration on exploring HTS in accelerator magnets (no funds transferred): Bi2212 wire from Showa (Japan) => properties of reacted wire measured at BNL, unreacted Bi2212 Rutherford cable made at LBNL, Bi2212 Rutherford cable reacted at Showa, properties of reacted cable measured at BNL, HTS coils with "pre-reacted Bi2212 Rutherford cable" made at BNL, Bi2212 coils measured at BNL between 77 K and 4K, Bi2212/Nb_3Sn hybrid dipole built and tested at BNL

- **BNL low budget HTS program has been highly leveraged with collaborators.**



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

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



HTS Cables: A Remarkable Progress in the State of Art

HTS Cables Tested at BNL Short Sample Test Facility

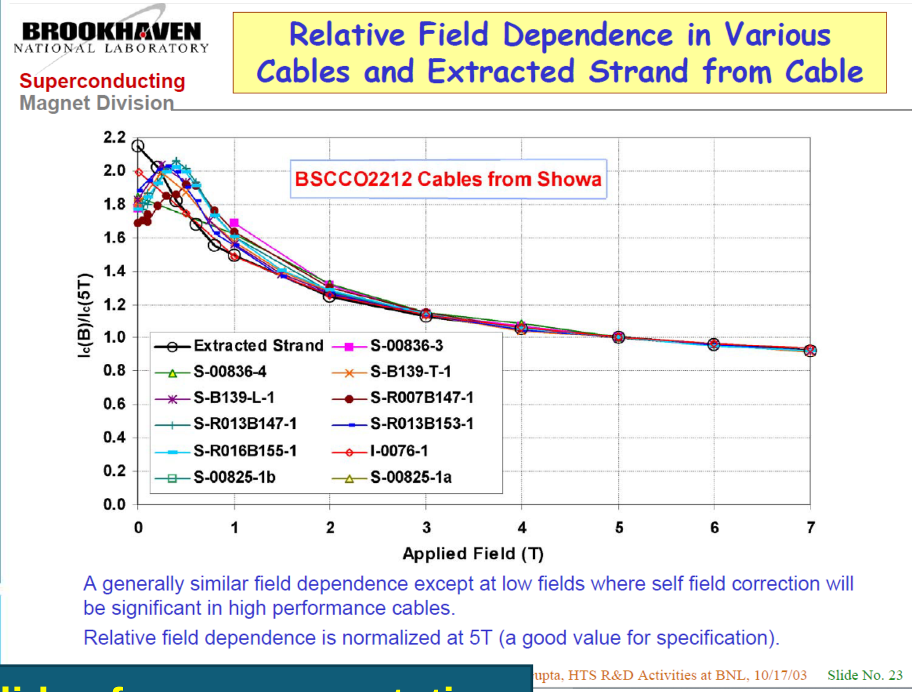
A significant self field at high currents

Modern HTS Cables Carry A Significant Current.

See talk by Dr. Hasegawa, on Thursday (4C-p07 @MT18)

All HTS from Showa (sponsored by Chubu Electric for SMES program)
Cable made at LBL

Ramesh Gupta, HTS R&D Activities at BNL, 10/17/03 Slide No. 22

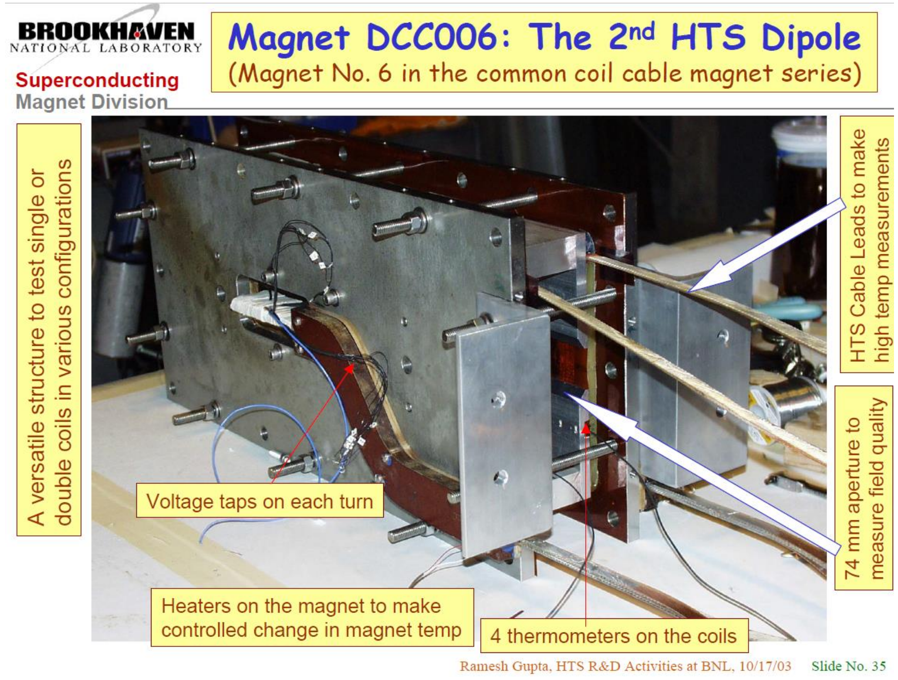


Relative Field Dependence in Various Cables and Extracted Strand from Cable

A generally similar field dependence except at low fields where self field correction will be significant in high performance cables.

Relative field dependence is normalized at 5T (a good value for specification).

upta, HTS R&D Activities at BNL, 10/17/03 Slide No. 23



Magnet DCC006: The 2nd HTS Dipole
(Magnet No. 6 in the common coil cable magnet series)

A versatile structure to test single or double coils in various configurations

HTS Cable Leads to make high temp measurements

74 mm aperture to measure field quality

Voltage taps on each turn

Heaters on the magnet to make controlled change in magnet temp

4 thermometers on the coils

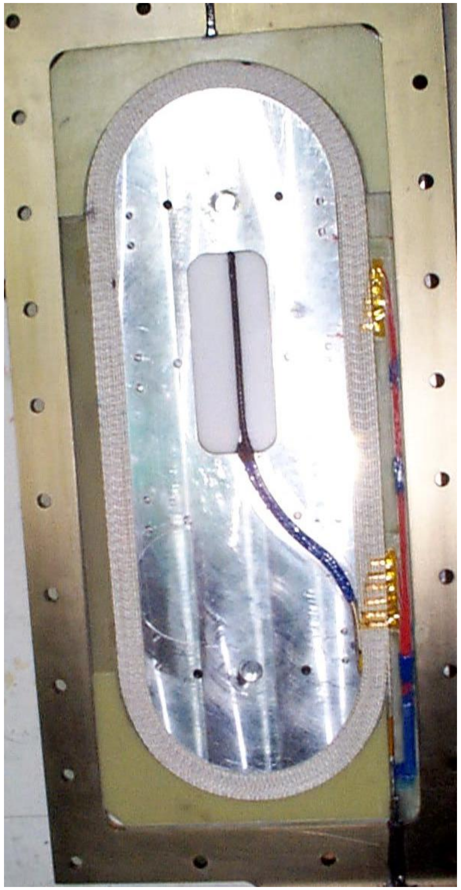
Ramesh Gupta, HTS R&D Activities at BNL, 10/17/03 Slide No. 35

Slides from a presentation at Showa (Japan) in 2003

Early HTS Coils and Magnets at BNL

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

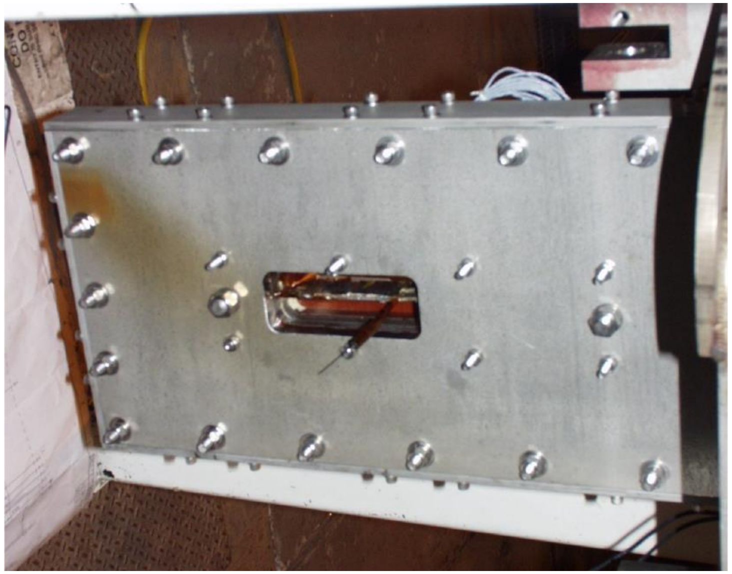
Bobbin to Vacuum Impregnated Coil

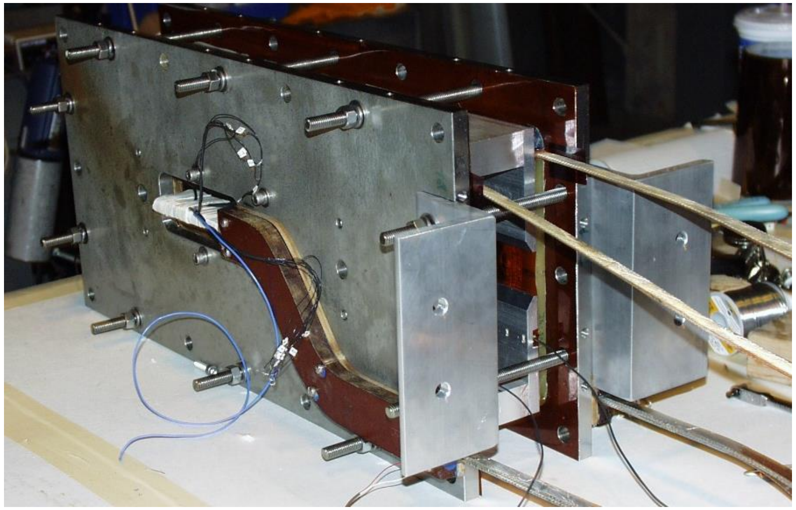


Bi2212 Cable Coil

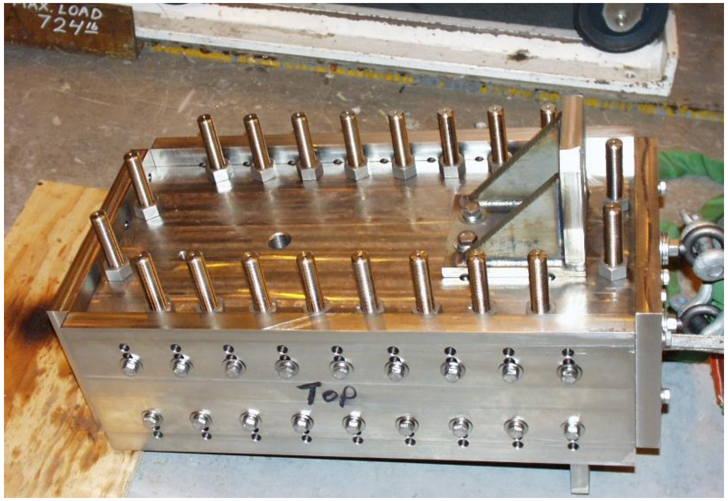
HTS Cable Coils in support structure

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

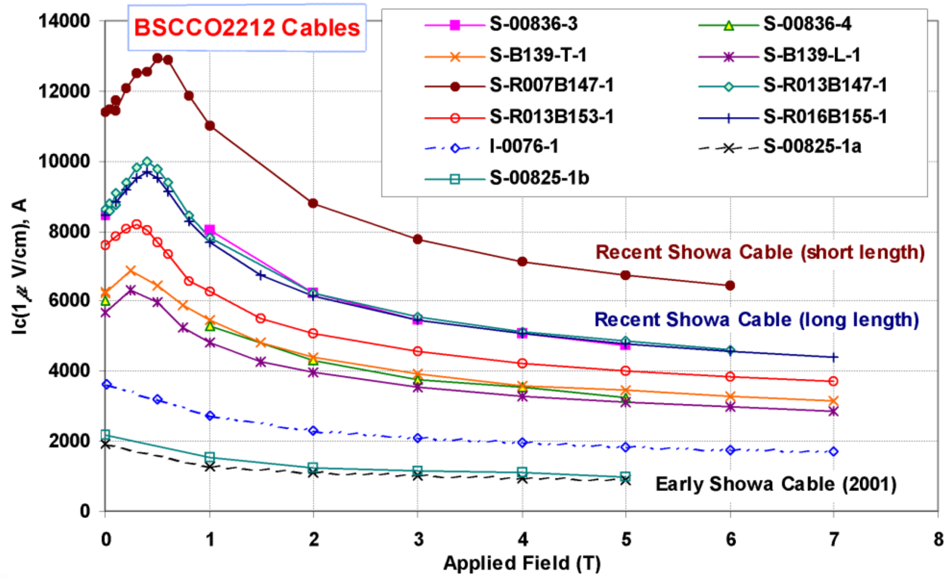




Bolted structures have benefit for easy reassembly (good for R&D)

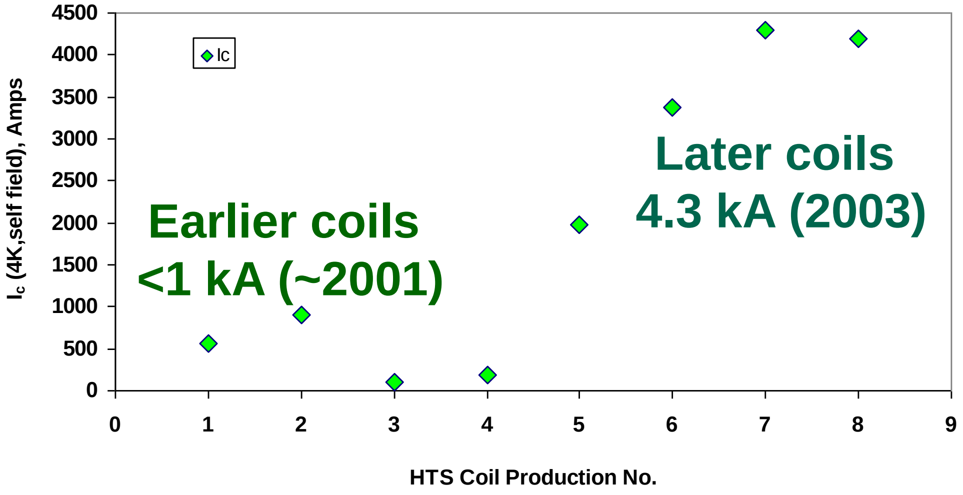


Progress in Bi2212 Cables, Coils and Magnet



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



Earlier coils
<1 kA (~2001)

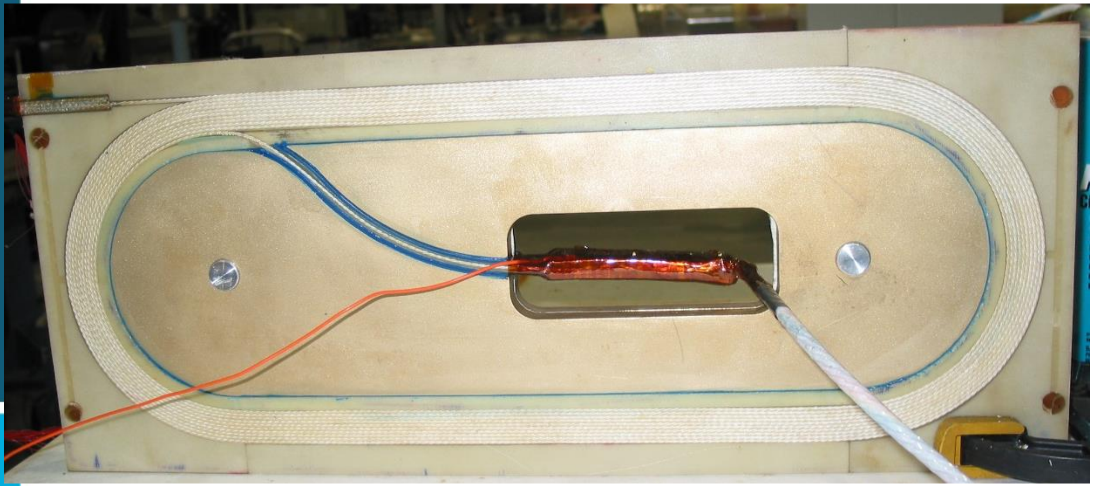
Later coils
4.3 kA (2003)

A Learning Experience

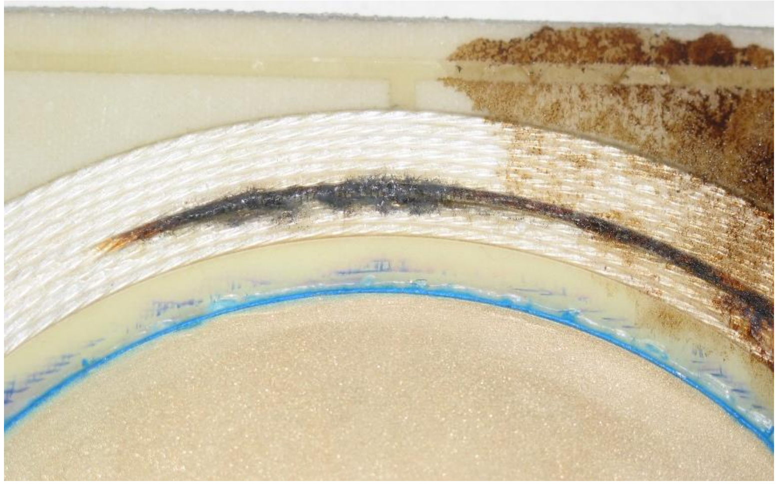
(shared with community)

- 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

High Field HTS/LTS Hybrid Dipole

(with ReBCO)

2G HTS Coils for Hybrid Dipole

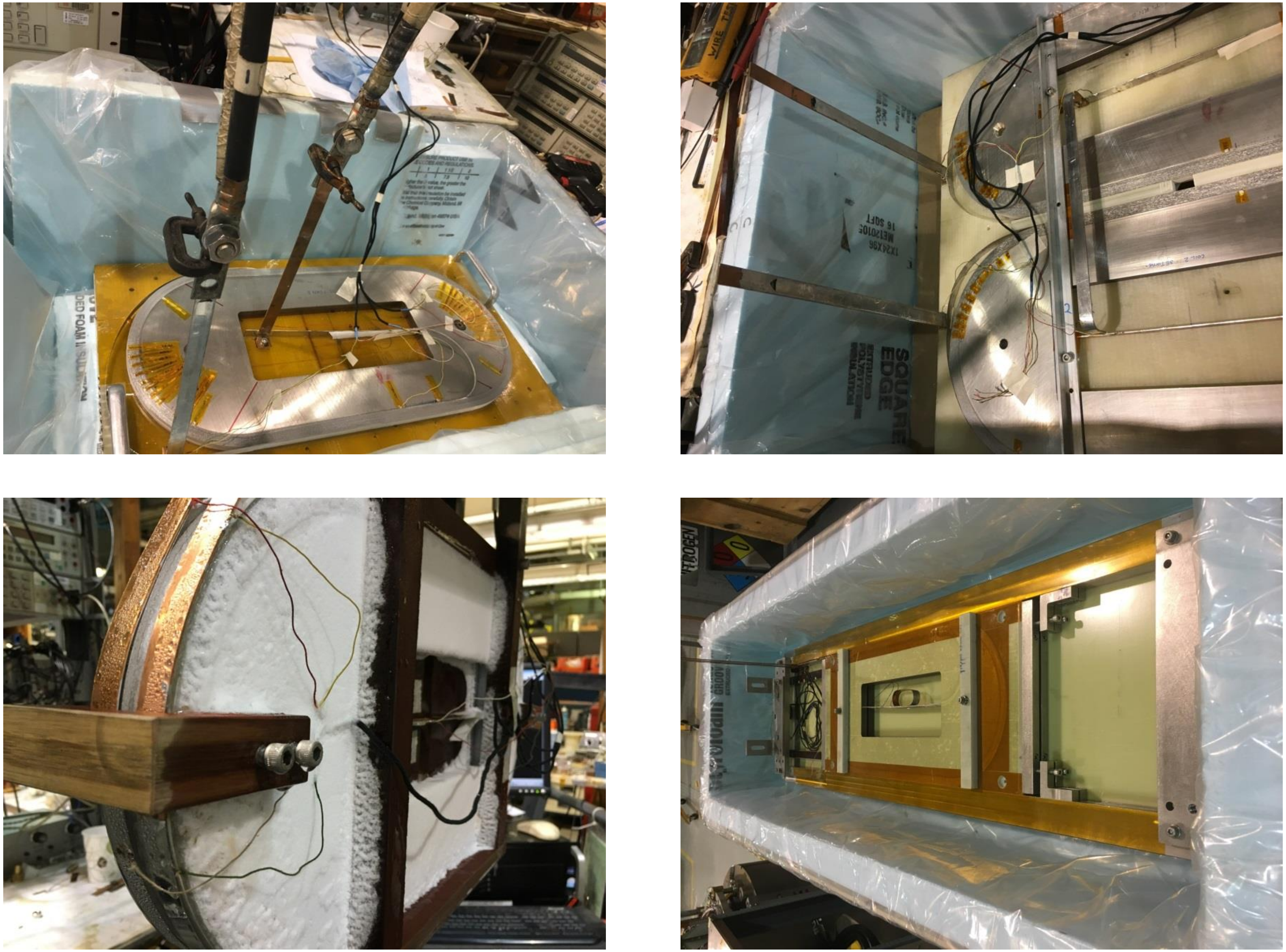
PBL/BNL
SBIR

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

Insulation:
- **Nomex**

Two coils used ~300 meters of 4 mm equivalent

77 K HTS Coil Tests in Various Configurations



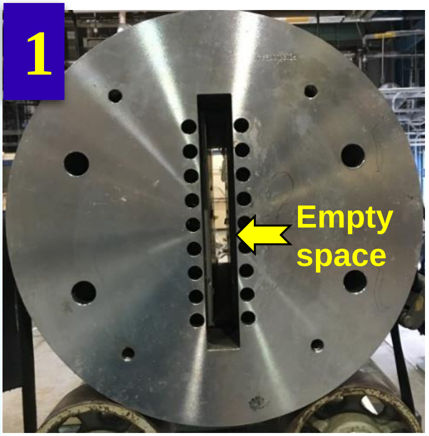
77 K tests provide a unique QA in HTS coils

Commissioning of 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

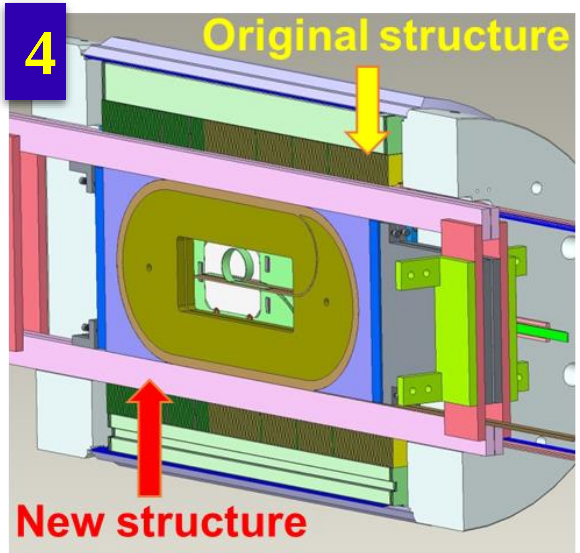
1



2

3

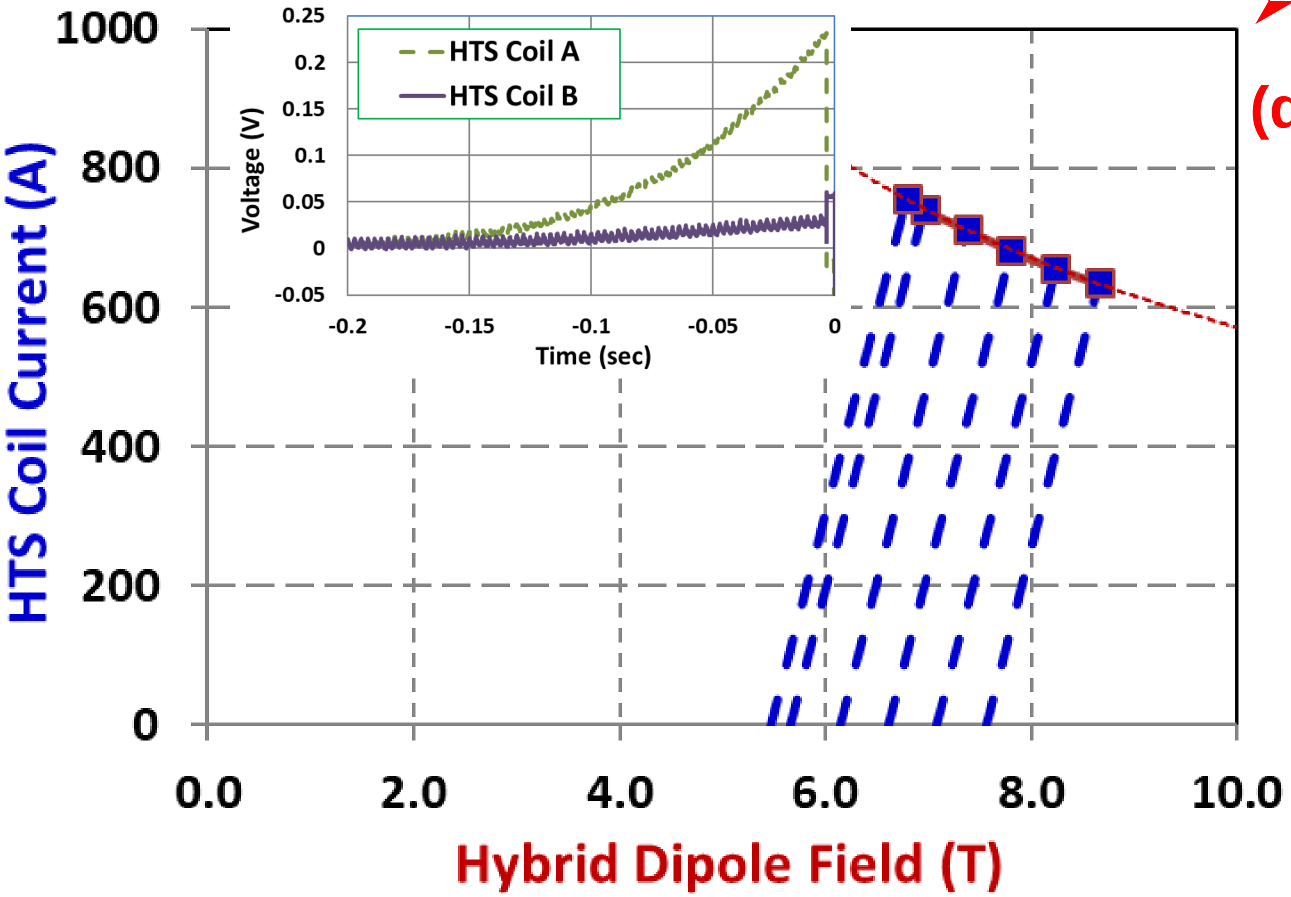
4



5

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)

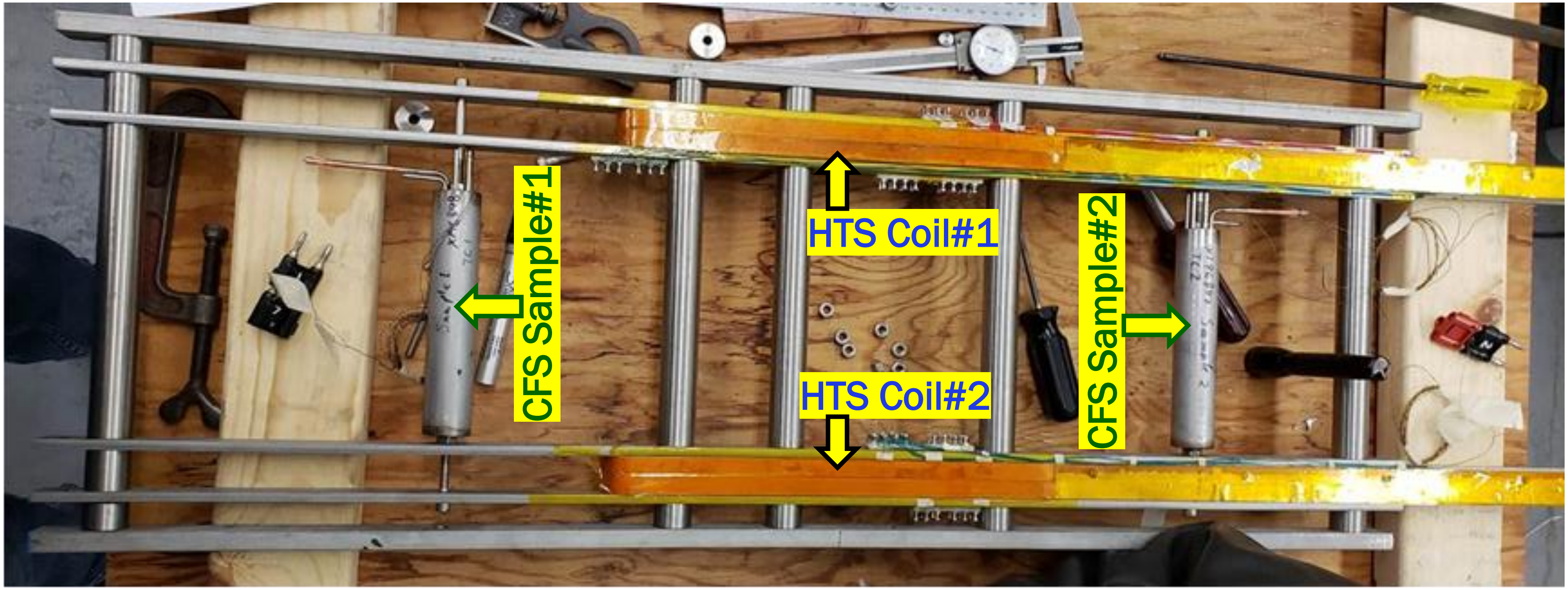
No damage and no degradation

Encouraging results

Quench threshold 0.2 V (just like in LTS)

Multi-test Platform (four tests in one go)

Test holder ready to be inserted in DCC017

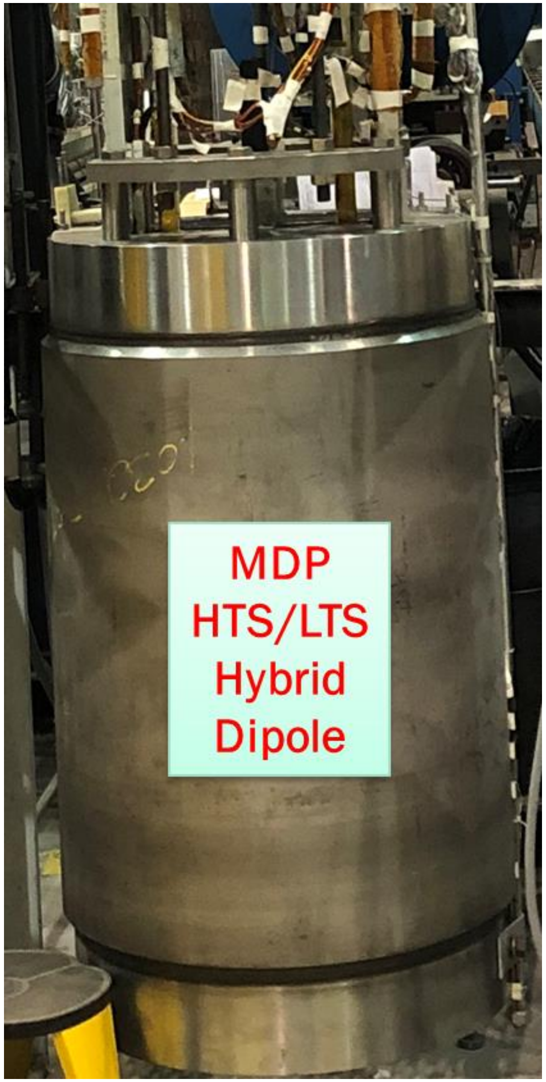


Two HTS coils for testing in field parallel configuration

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

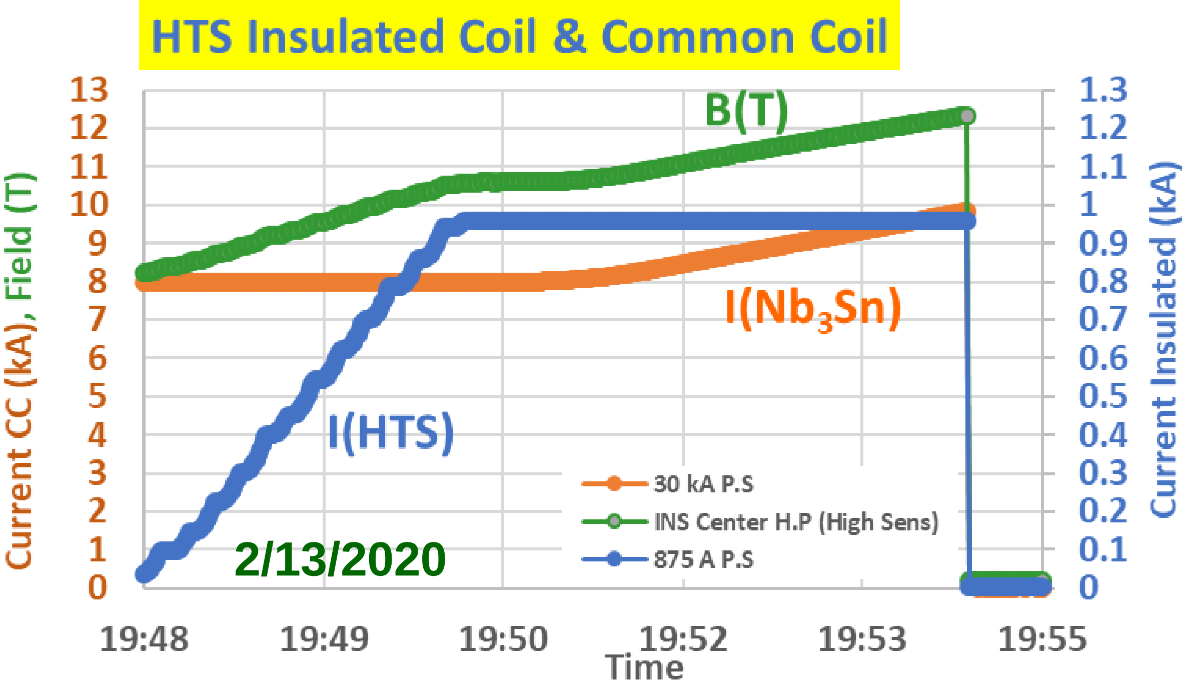
HTS/LTS Hybrid Dipole Test

(creating a record 12.3 T hybrid dipole field)



Test sequence:

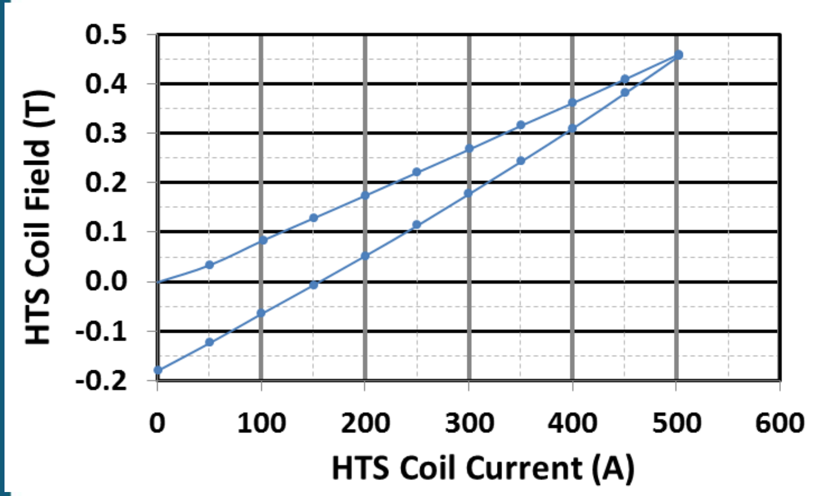
- ➢Nb_3Sn ramped to 8 kA (~8 T)
- ➢HTS ramped to 950 A
- ➢Nb_3Sn ramped to quench (~10 kA) creating a record ~12.3 T hybrid field (~3 T from HTS)



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

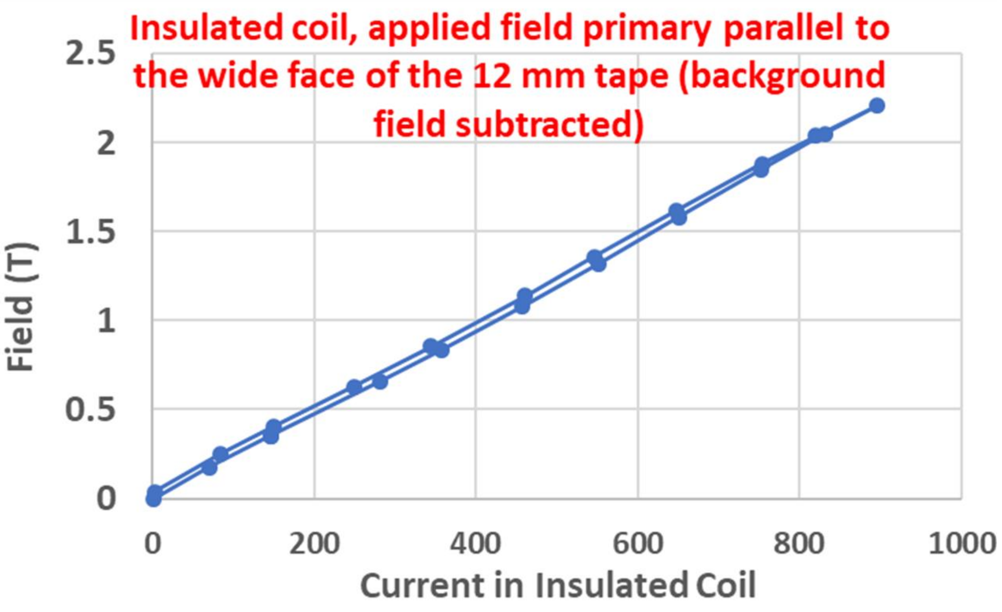
Field perpendicular (2016)

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

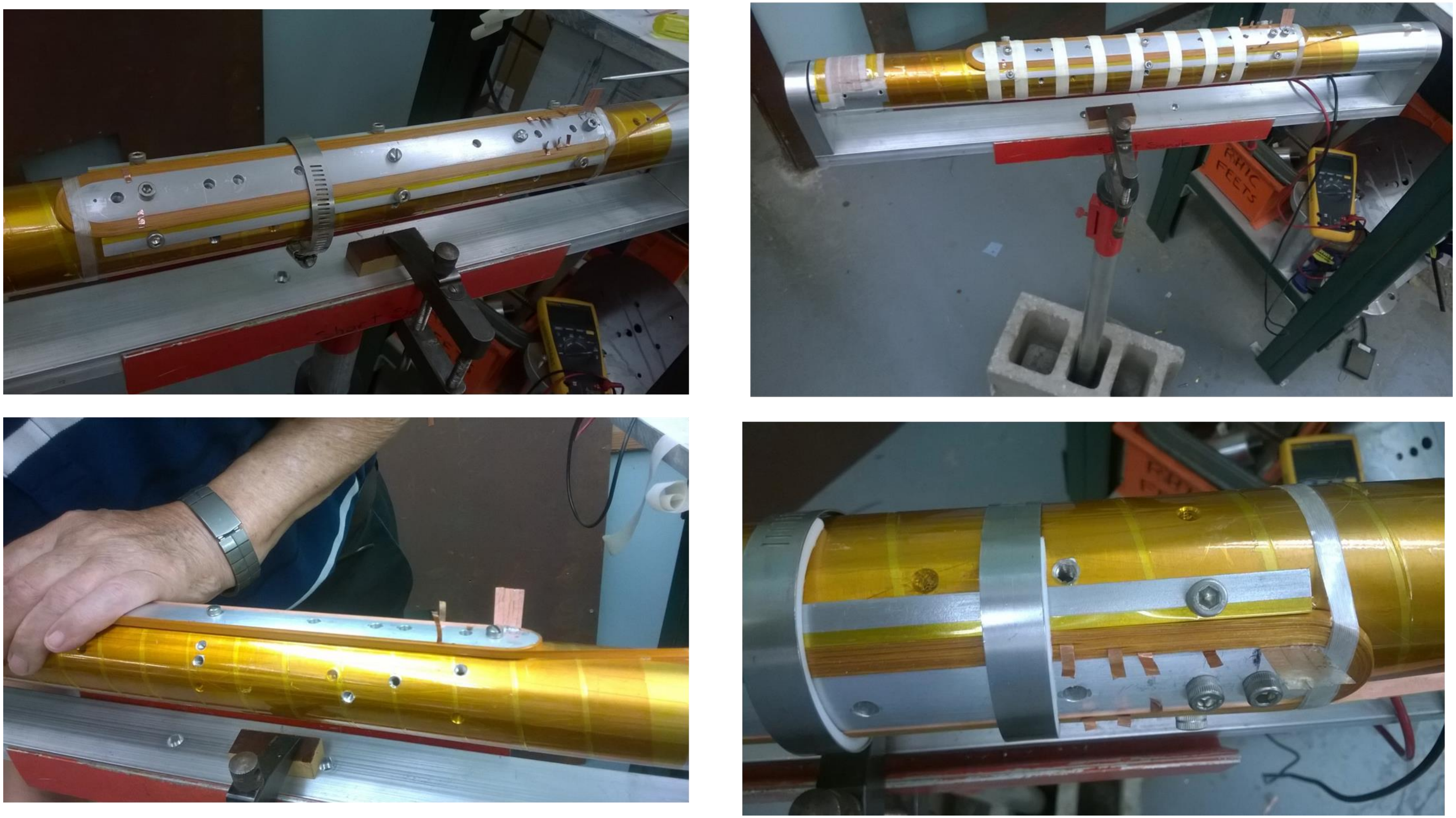
Field parallel (2020)



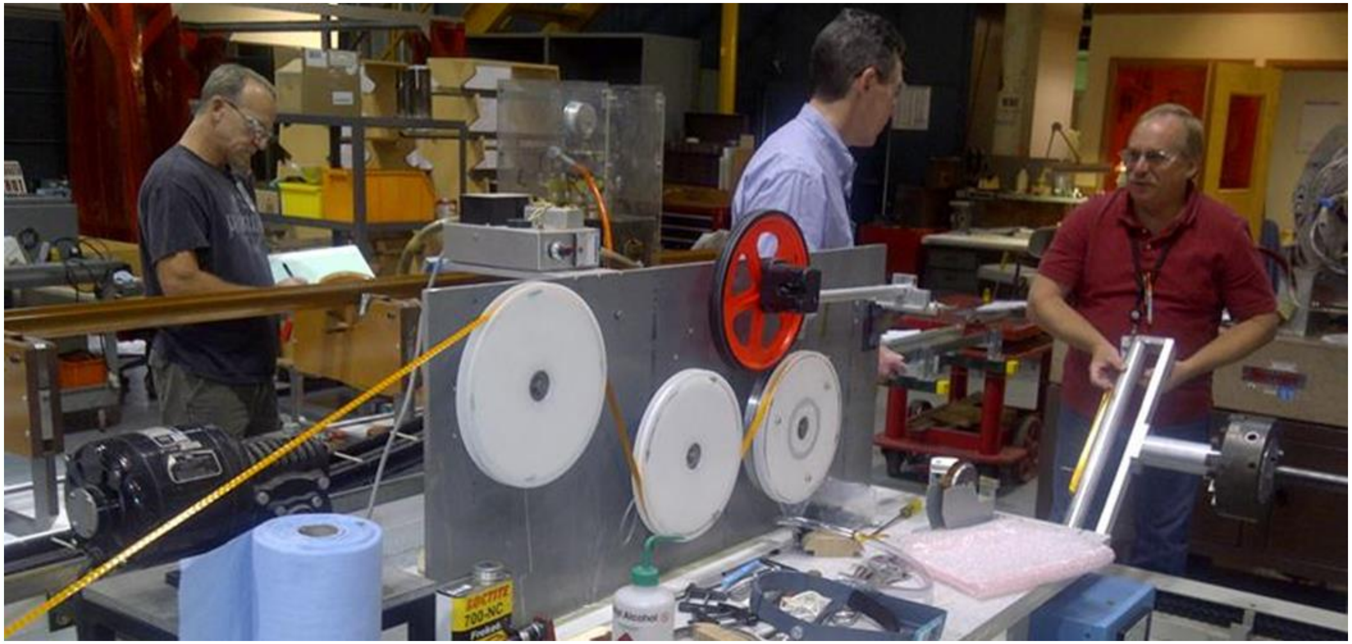
Order of magnitude reduction in the magnetization when the field is primarily parallel to the HTS tape

Other Geometries of HTS Dipole Magnets

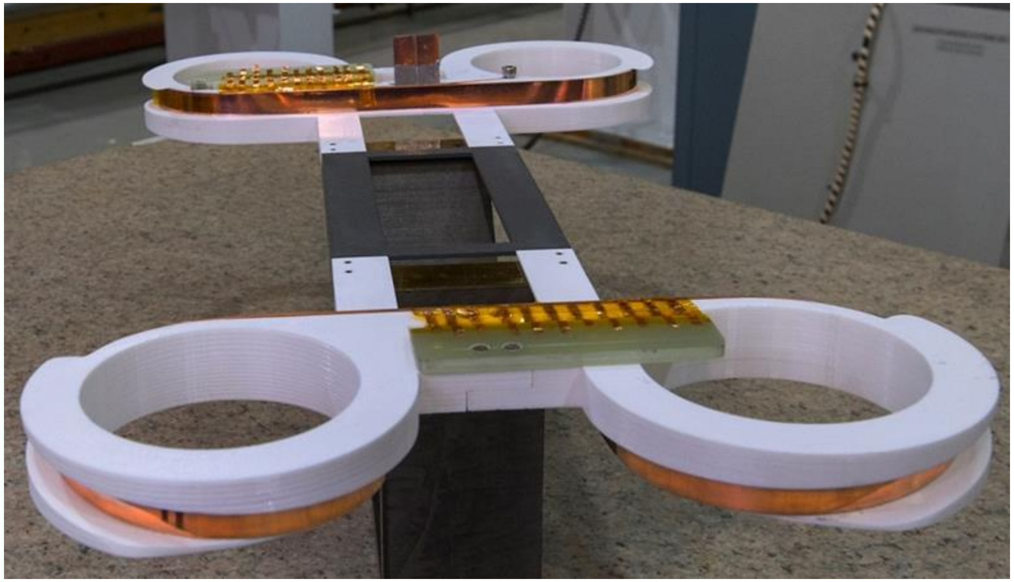
Cosine Theta Coil with 4 mm 2G HTS Tape - PBL/BNL SBIR (1)

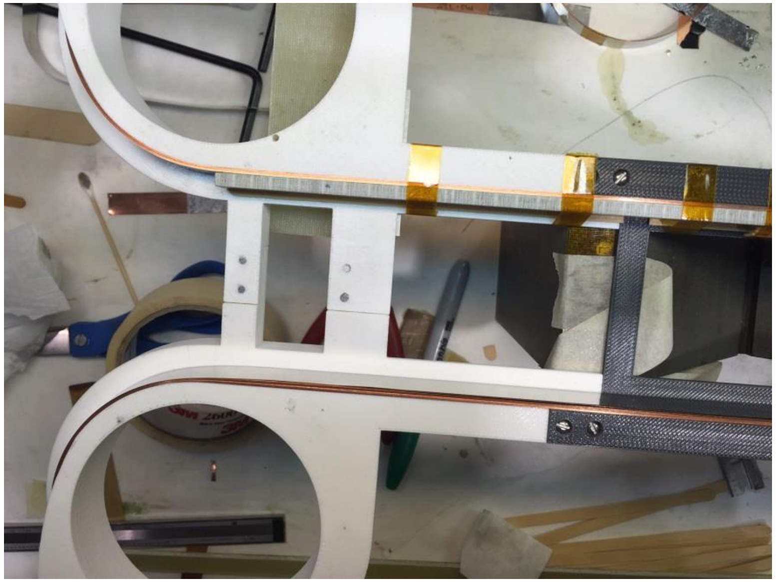


Cosine Theta Coil with 12 mm 2G Tape PBL/BNL SBIR (2)

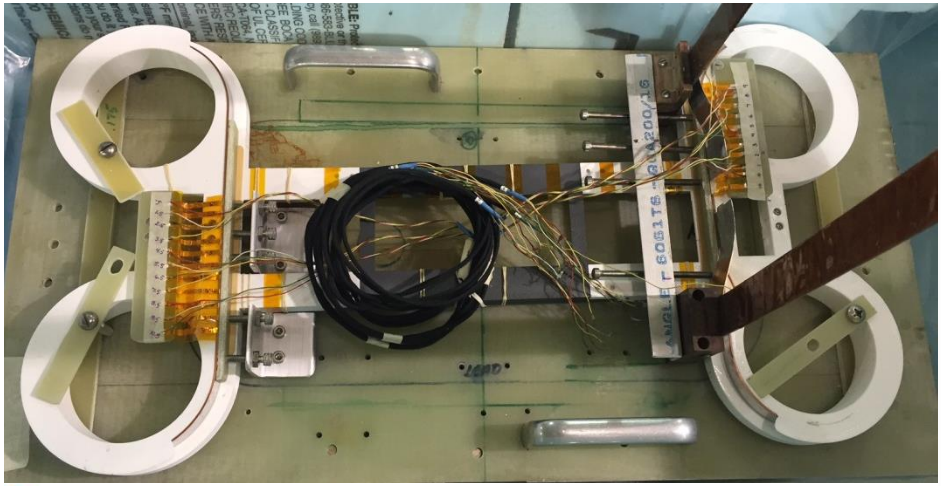


Demonstrations of the Dipole Coil Overpass/Underpass e2P/BNL SBIR

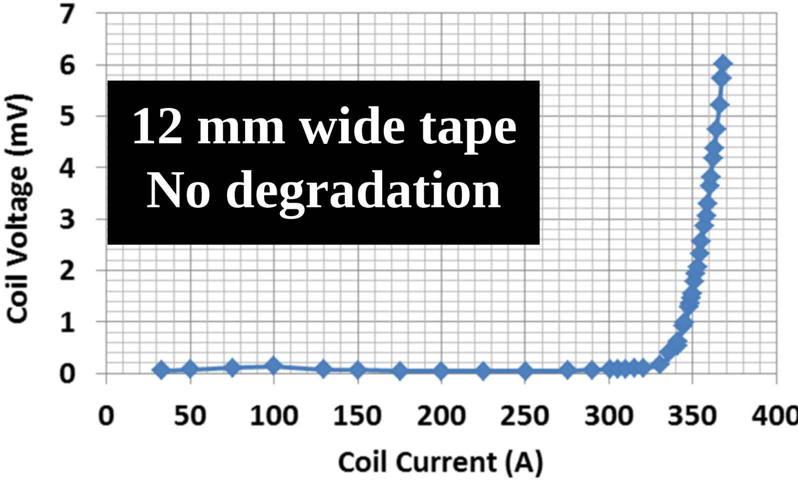




SBIR withe2P



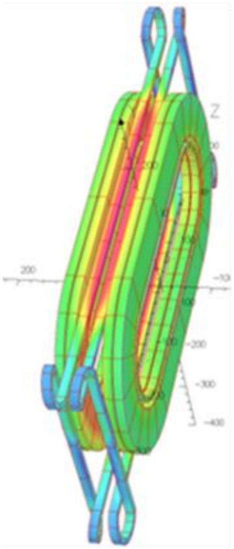
77 K Test Results

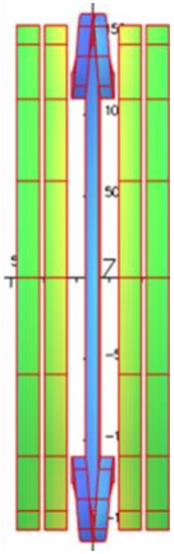


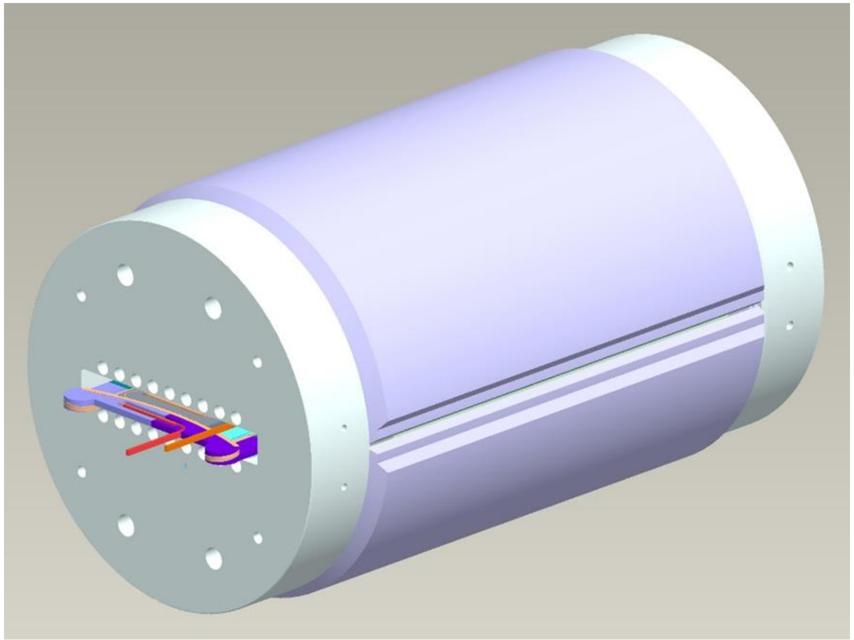
12 mm wide tape
No degradation

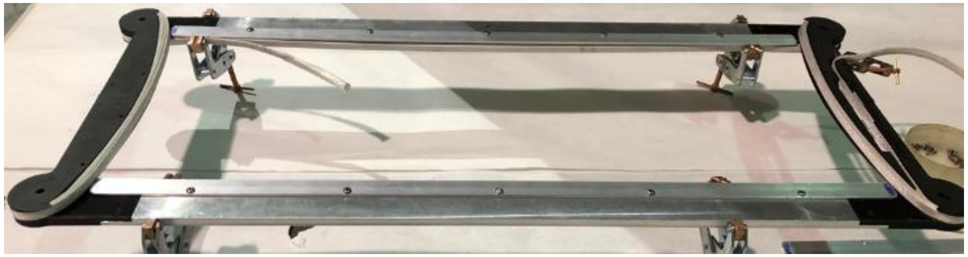
Brookhaven
National Laboratory

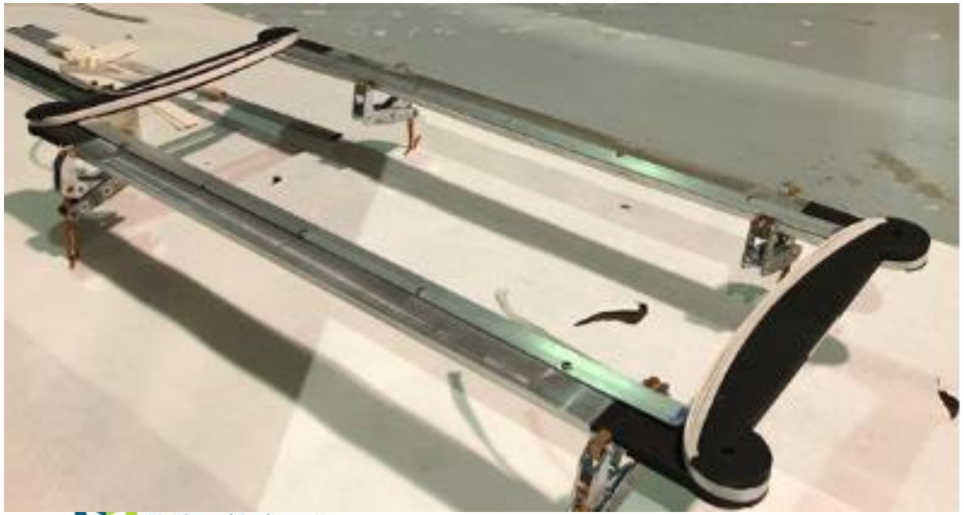
PBL
Overpass/ Underpass
STTR











ReBCO Cable for Accelerator Magnets

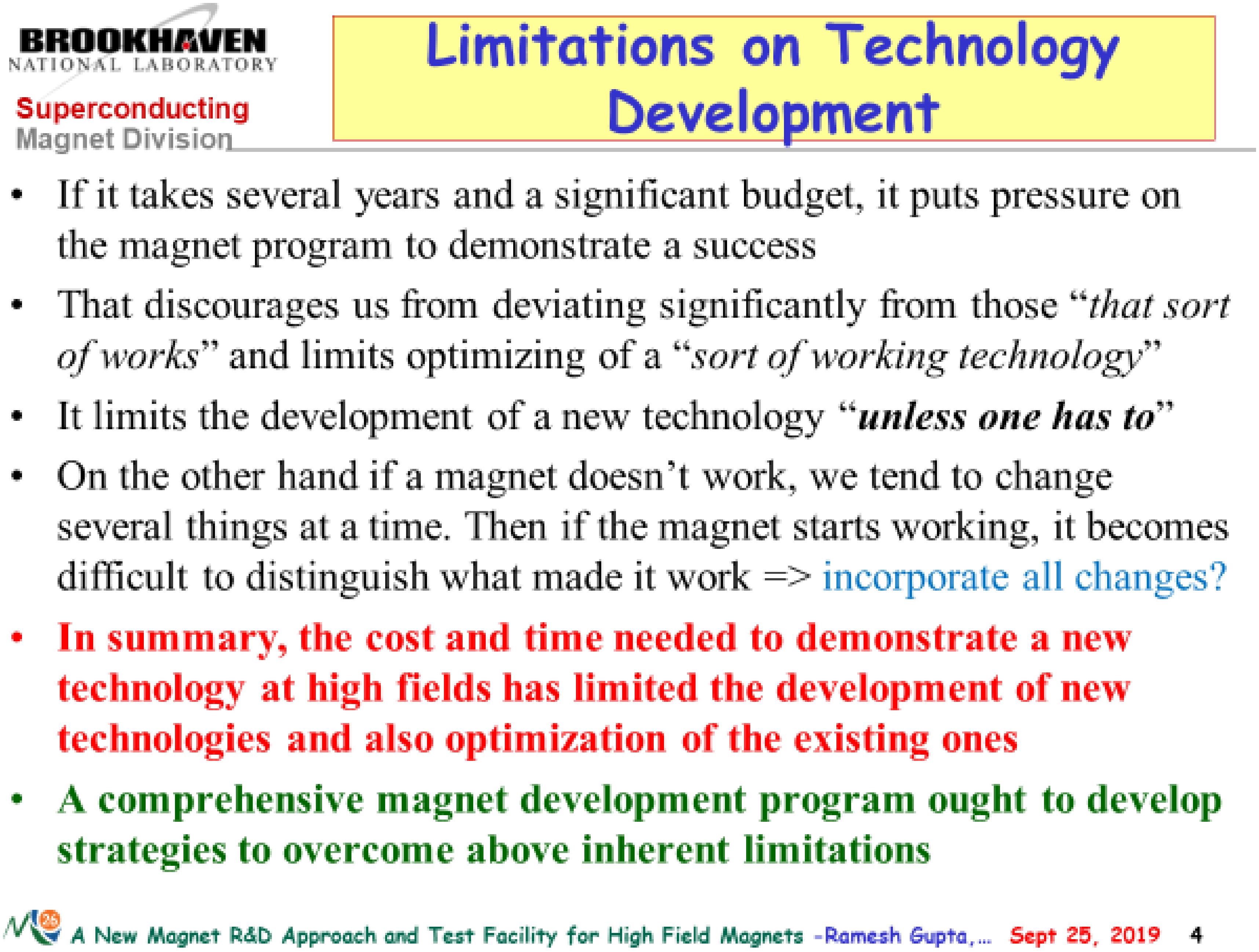
ReBCO comes in tape form and that poses several challenges:

- 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



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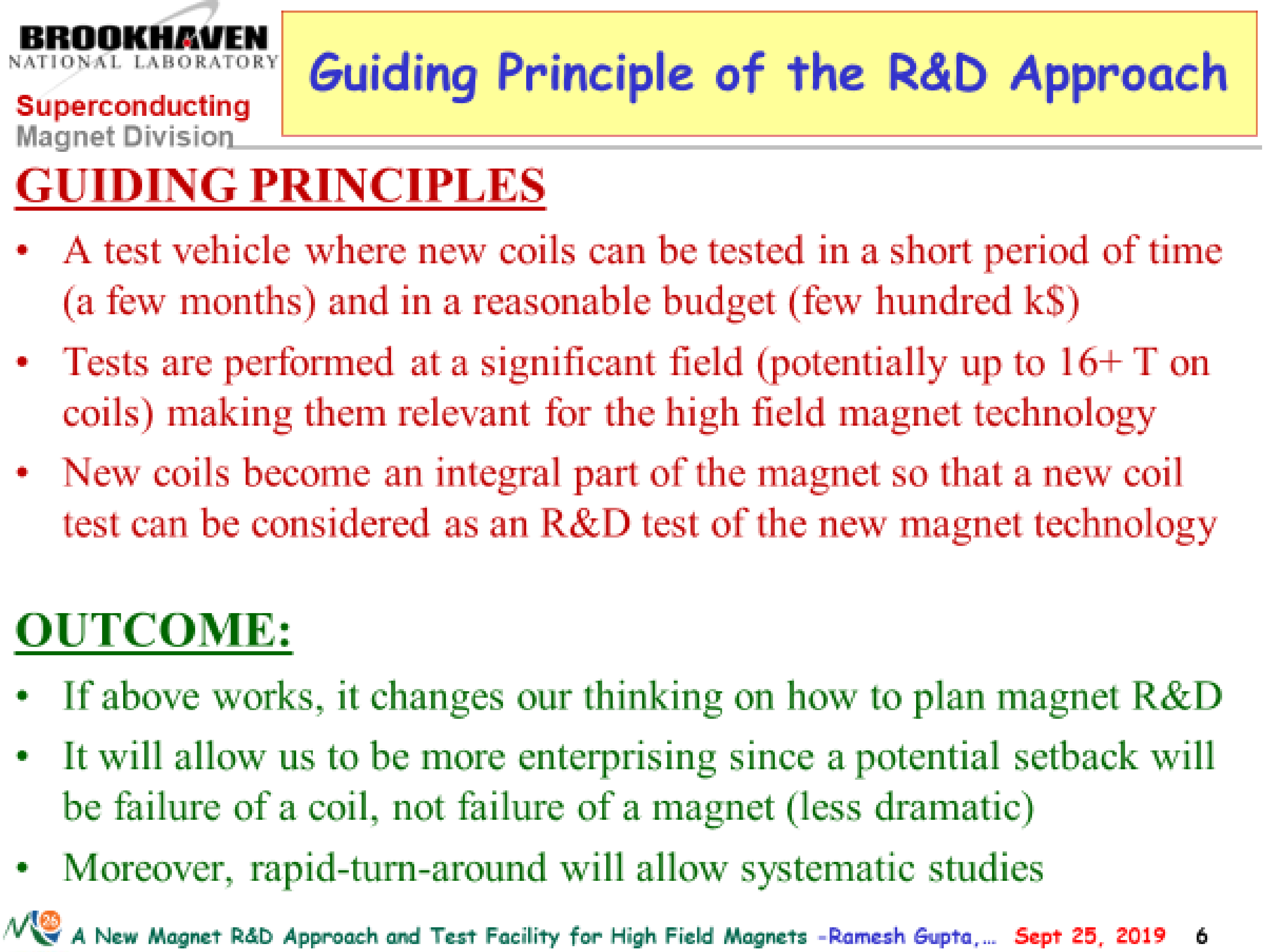
Limitations on Technology Development

- If it takes several years and a significant budget, it puts pressure on the magnet program to demonstrate a success
- That discourages us from deviating significantly from those "*that sort of works*" and limits optimizing of a "*sort of working technology*"
- It limits the development of a new technology "***unless one has to***"
- On the other hand if a magnet doesn't work, we tend to change several things at a time. Then if the magnet starts working, it becomes difficult to distinguish what made it work => incorporate all changes?
- **In summary, the cost and time needed to demonstrate a new technology at high fields has limited the development of new technologies and also optimization of the existing ones**
- **A comprehensive magnet development program ought to develop strategies to overcome above inherent limitations**

A New Magnet R&D Approach and Test Facility for High Field Magnets -Ramesh Gupta,… Sept 25, 2019 4

https://wpw.bnl.gov/rgupta/wp-content/uploads/sites/9/2023/02/wed-afor13-02-presentation.pptx



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Guiding Principle of the R&D Approach

GUIDING PRINCIPLES

- A test vehicle where new coils can be tested in a short period of time (a few months) and in a reasonable budget (few hundred k$)
- Tests are performed at a significant field (potentially up to 16+ T on coils) making them relevant for the high field magnet technology
- New coils become an integral part of the magnet so that a new coil test can be considered as an R&D test of the new magnet technology

OUTCOME:

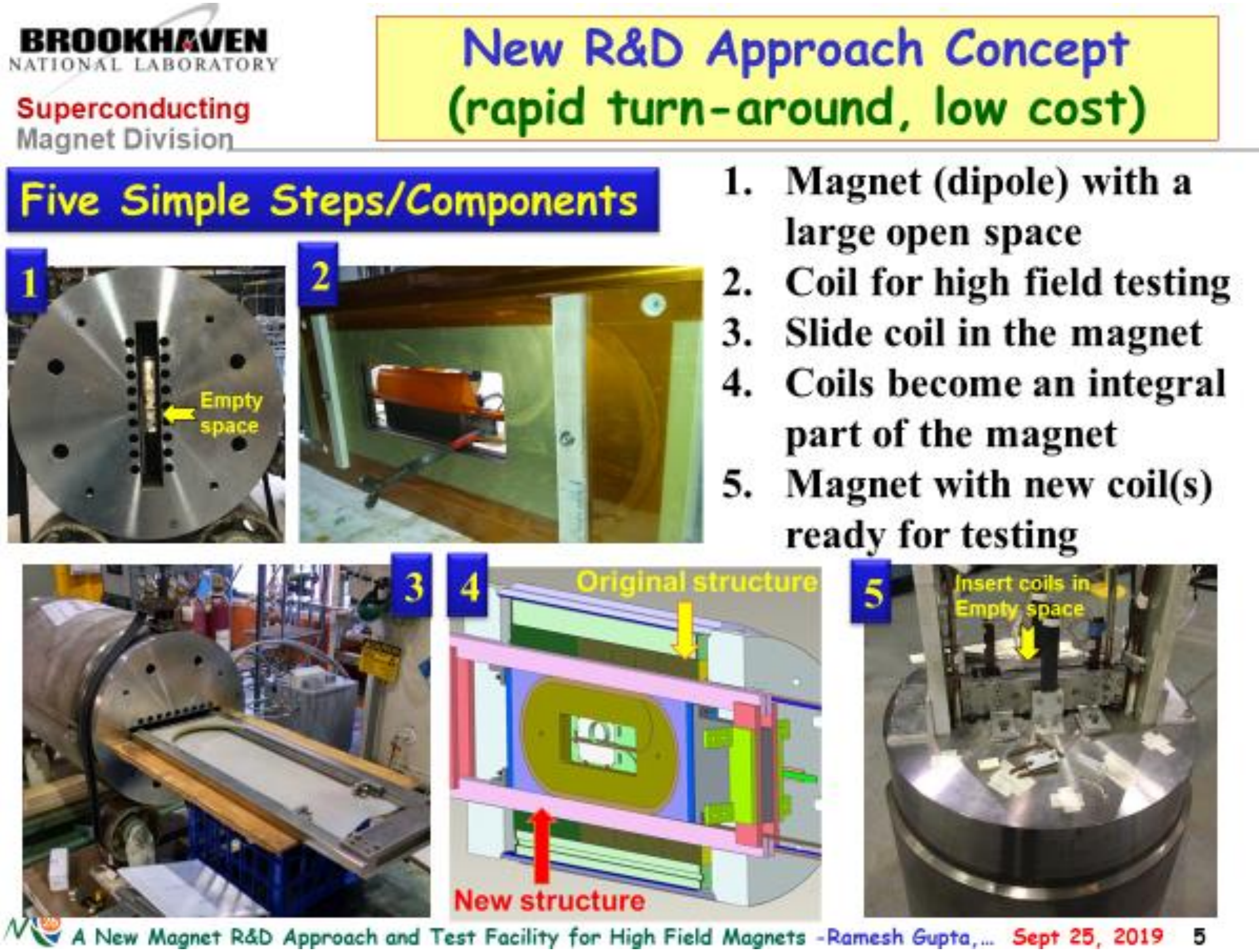
- If above works, it changes our thinking on how to plan magnet R&D
- It will allow us to be more enterprising since a potential setback will be failure of a coil, not failure of a magnet (less dramatic)
- Moreover, rapid-turn-around will allow systematic studies

A New Magnet R&D Approach and Test Facility for High Field Magnets -Ramesh Gupta,… Sept 25, 2019 6

https://wpw.bnl.gov/rgupta/wp-content/uploads/sites/9/2023/02/wed-afor13-02-presentation.pptx

Some thoughts for making such a facility quickly at CERN

(includes using existing 16 T Nb_3Sn coils)



BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

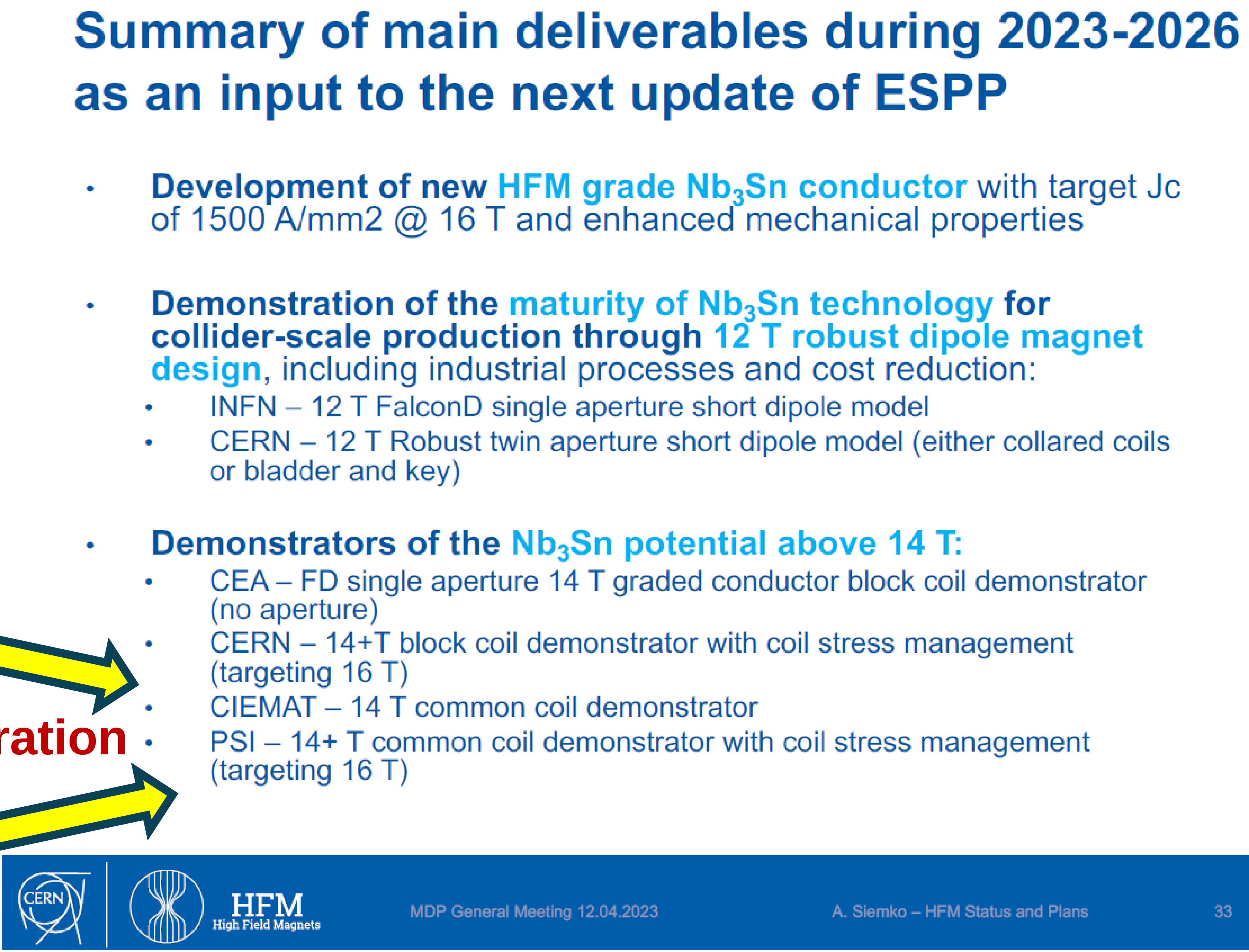
New R&D Approach Concept (rapid turn-around, low cost)

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

A New Magnet R&D Approach and Test Facility for High Field Magnets -Ramesh Gupta,... Sept 25, 2019 5

https://wpw.bnl.gov/rgupta/wp-content/uploads/sites/9/2023/02/wed-afor13-02-presentation.pptx



Summary of main deliverables during 2023-2026 as an input to the next update of ESPP

- **Development of new HFM grade Nb_3Sn conductor** with target Jc of 1500 A/mm2 @ 16 T and enhanced mechanical properties
- **Demonstration of the maturity of Nb_3Sn technology for collider-scale production through 12 T robust dipole magnet design**, including industrial processes and cost reduction:
  - INFN – 12 T FalconD single aperture short dipole model
  - CERN – 12 T Robust twin aperture short dipole model (either collared coils or bladder and key)
- **Demonstrators of the Nb_3Sn potential above 14 T:**
  - CEA – FD single aperture 14 T graded conductor block coil demonstrator (no aperture)
  - CERN – 14+T block coil demonstrator with coil stress management (targeting 16 T)
  - CIEMAT – 14 T common coil demonstrator
  - PSI – 14+ T common coil demonstrator with coil stress management (targeting 16 T)

Collaboration

HFM
High Field Magnets

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

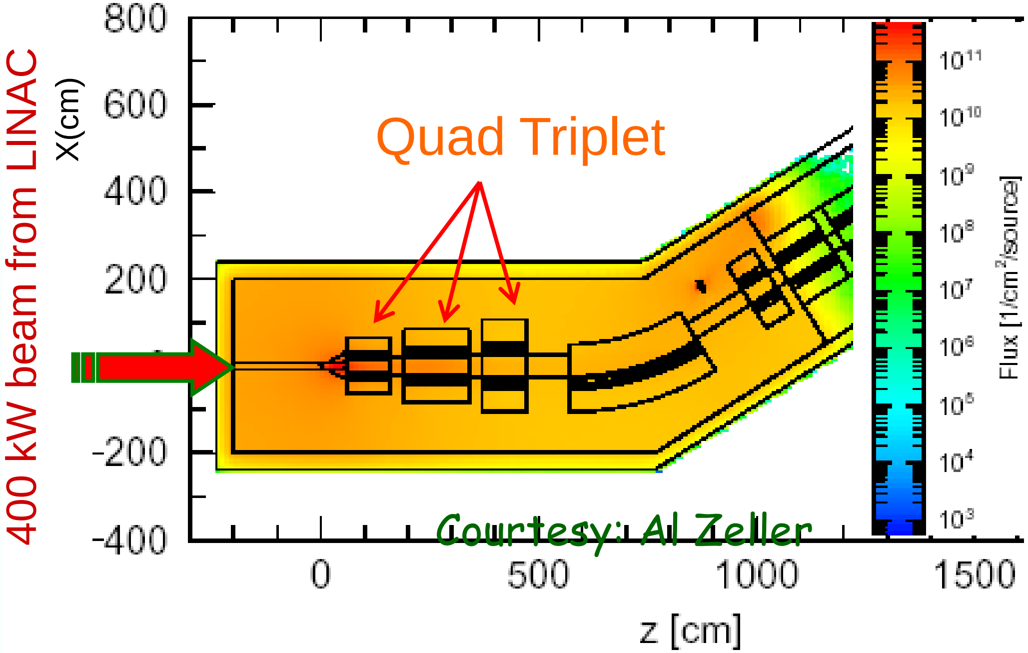
2003-2014

- **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)



400 kW beam from LINAC

Quad Triplet

Courtesy: Al Zeller

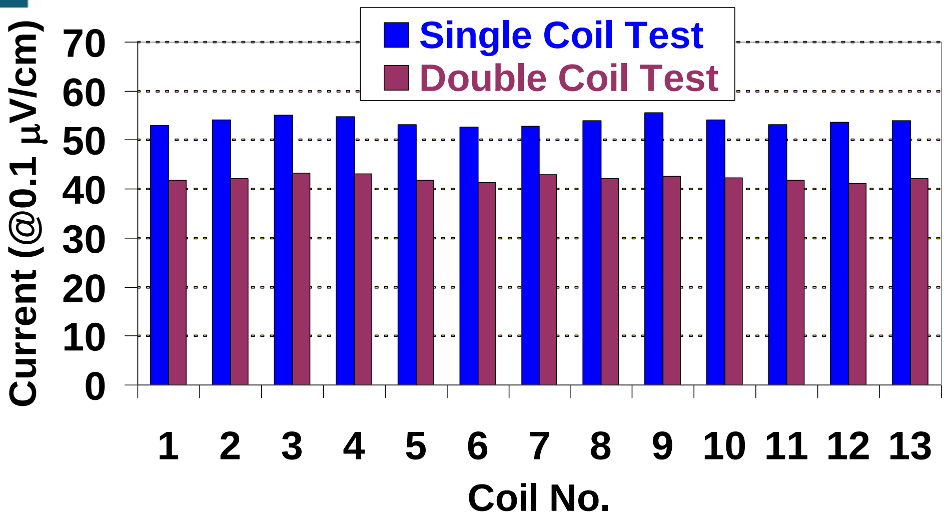
- **Up to 400 kW of beam power hits the target.**
- **Quad triplet in the fragment separator is exposed to very high radiation and heat loads.**
- **~15 kW is deposited in the first quadrupole itself.**

- **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**

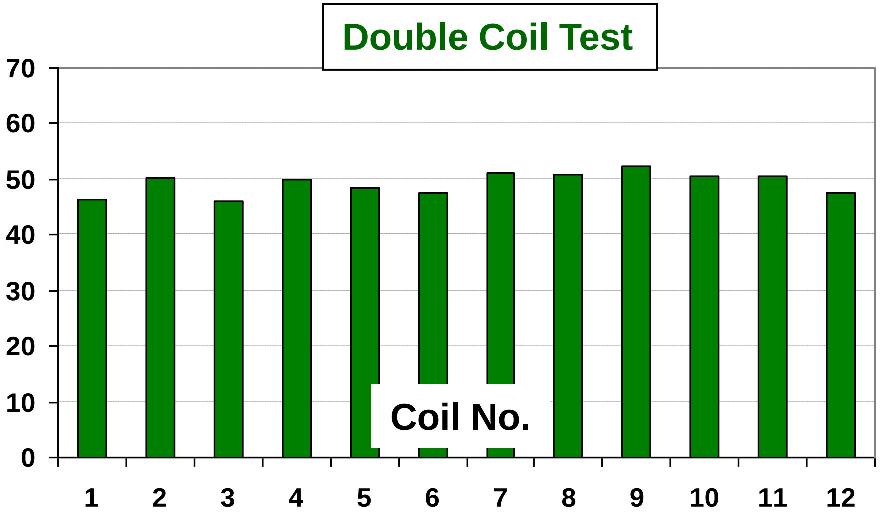
77 K Test of Coils Made with ASC 1st Generation HTS

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

13 Coils made HTS tape in year #1

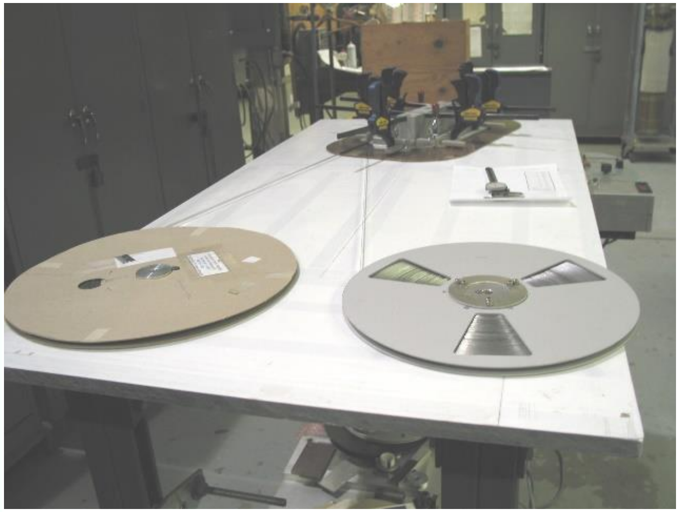


12 coils with HTS tape in year #2

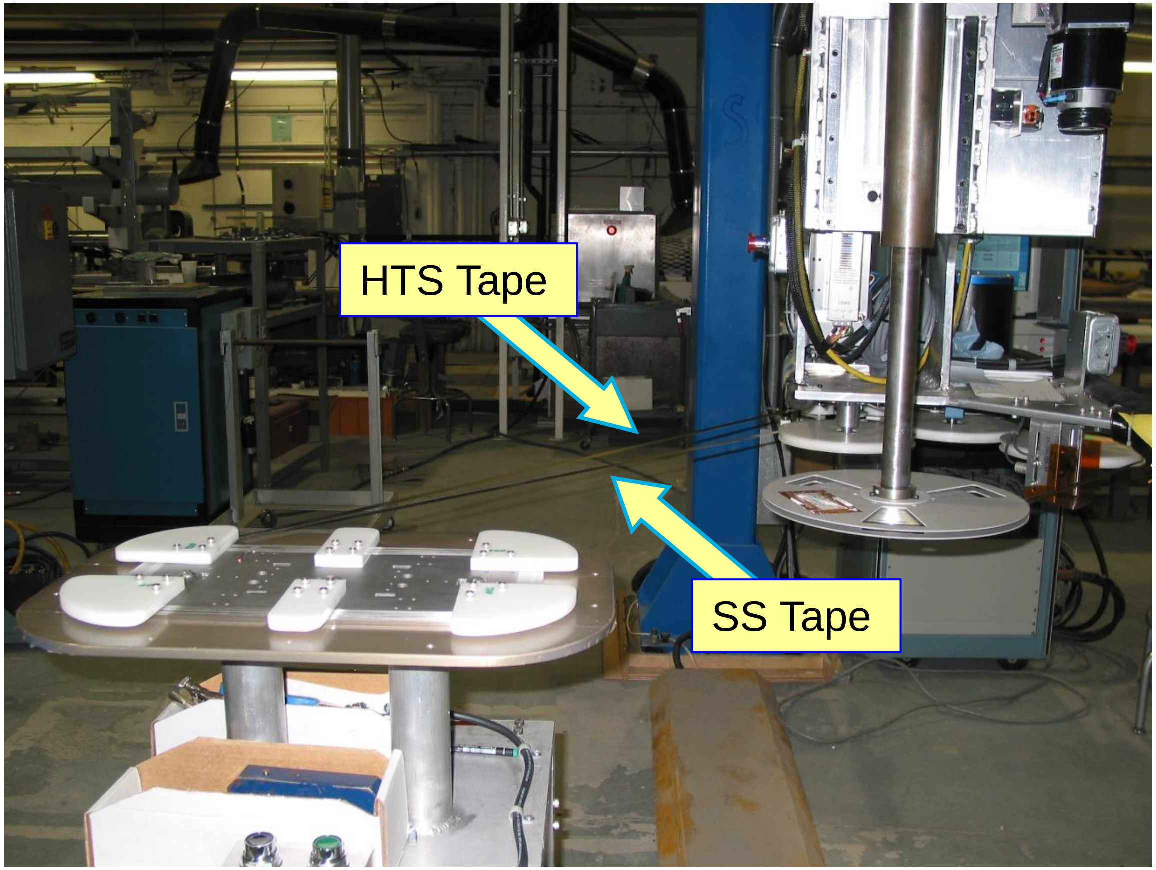


Note: A uniformity in performance of a large number of HTS coils

HTS Coil Winding

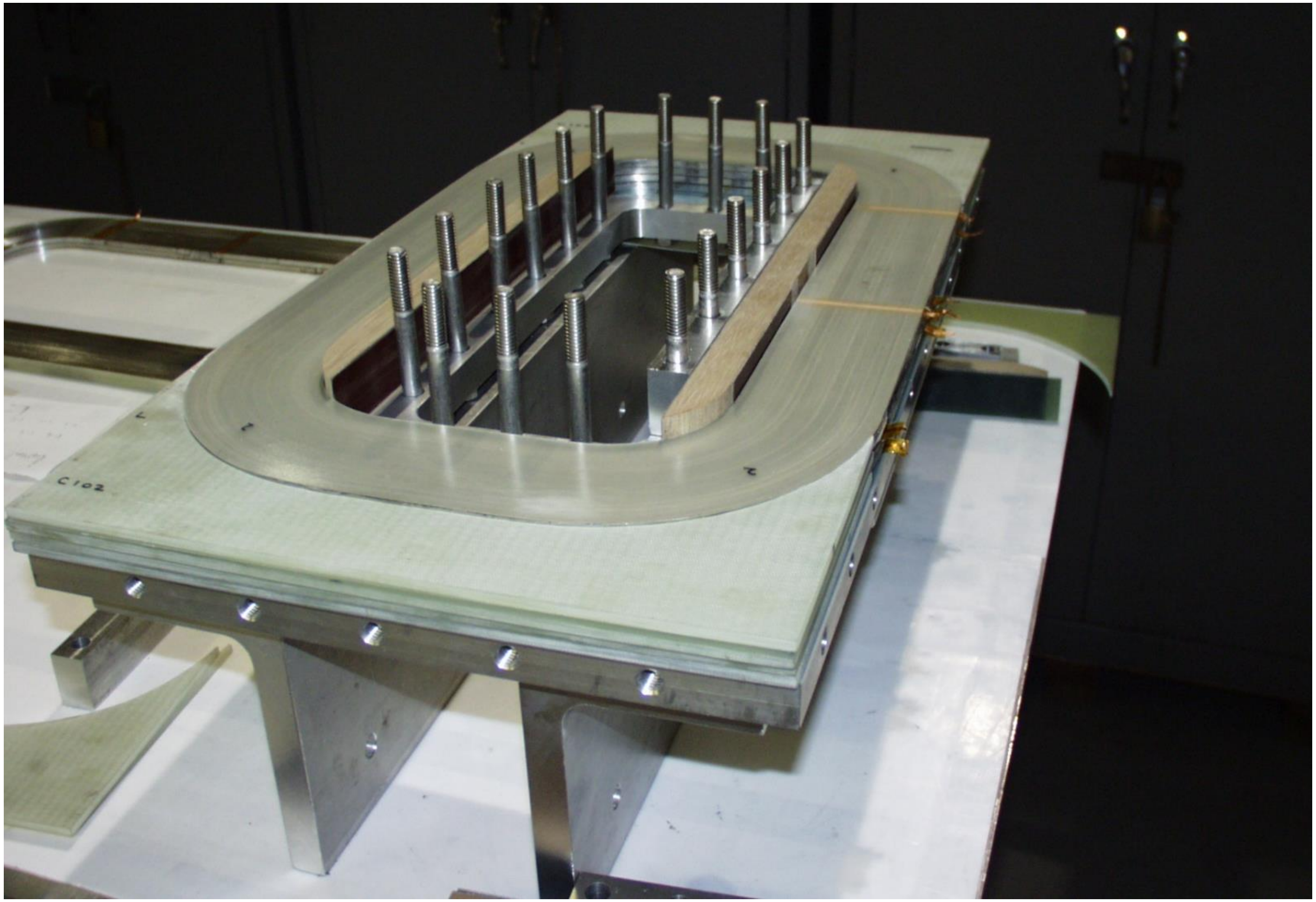


Earlier coils wound with manual controls



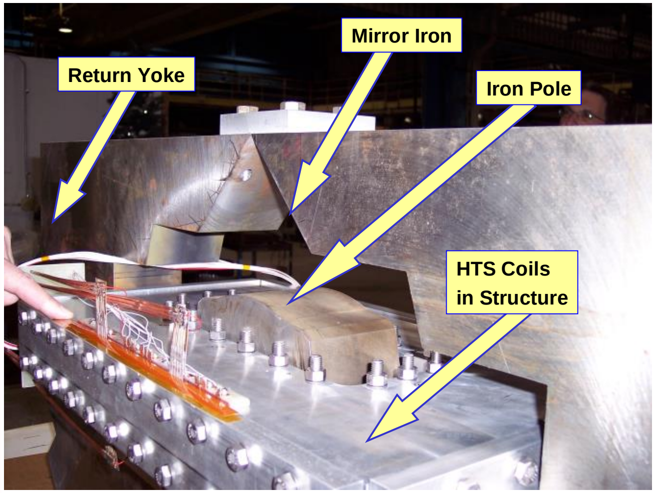
Later coils wound with a computer controlled winding machine (universal coil winder)

Assembled Coils with Internal Splice



Three pairs of coils during their assembly a support structure

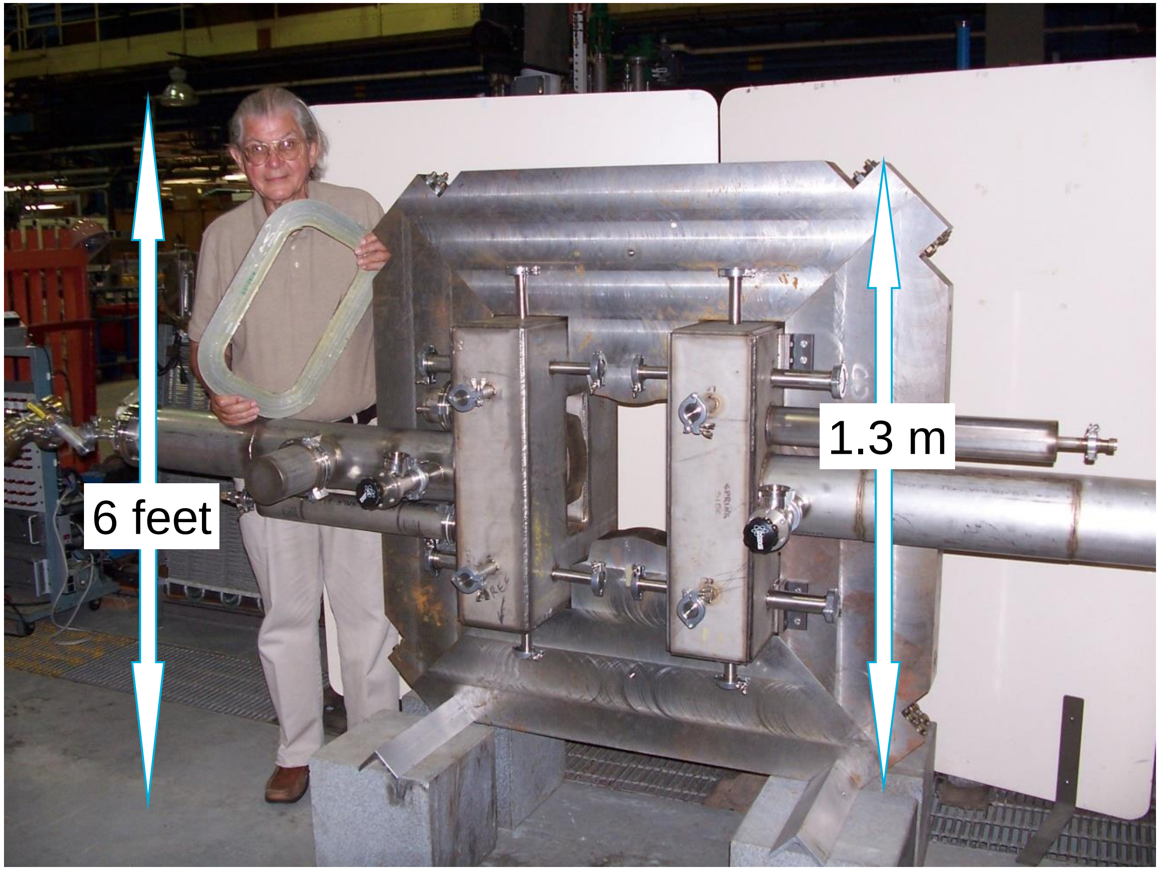
1st Generation HTS Quad



Mirror cold iron

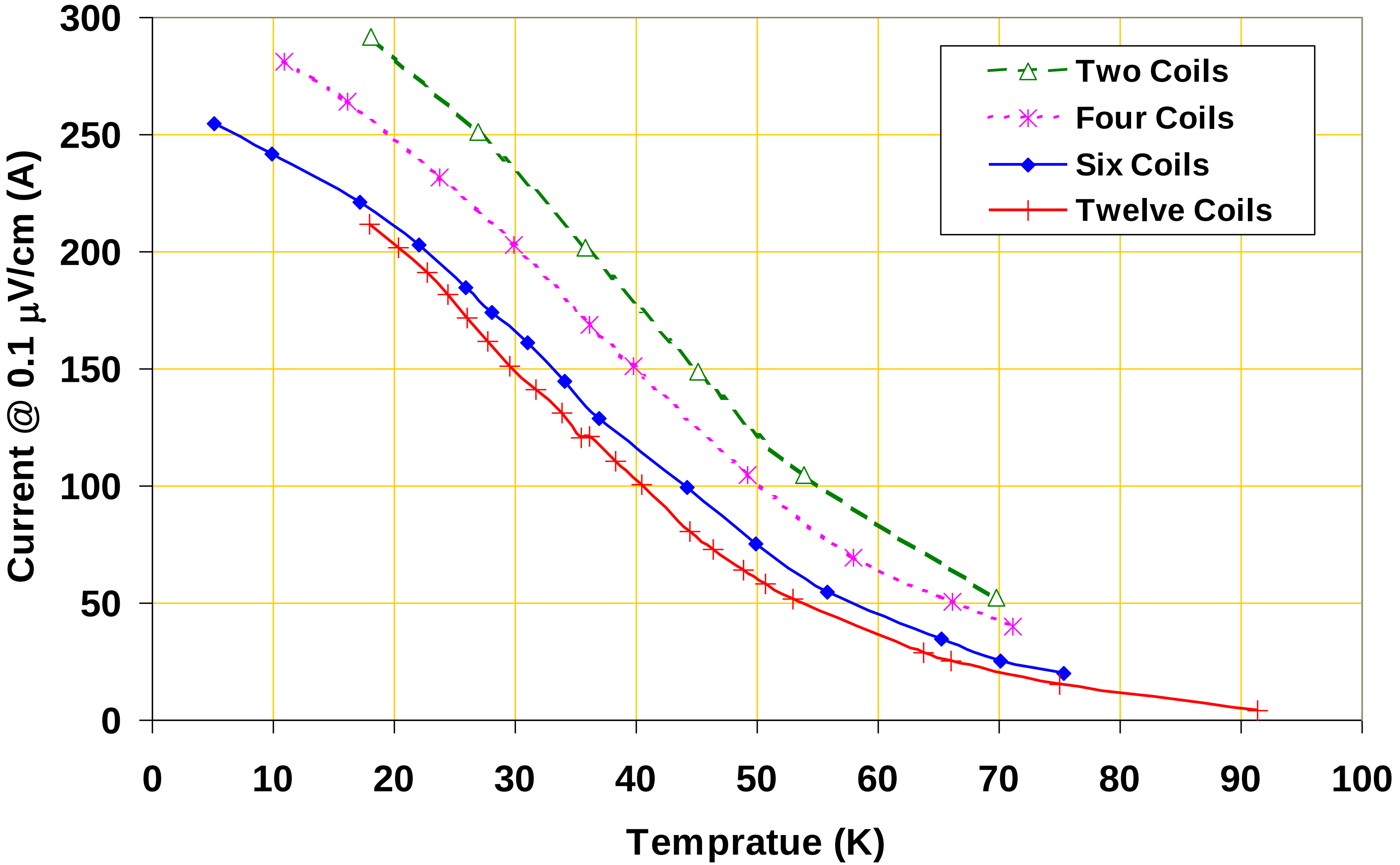
Mirror warm iron

Three magnet structures, built and tested



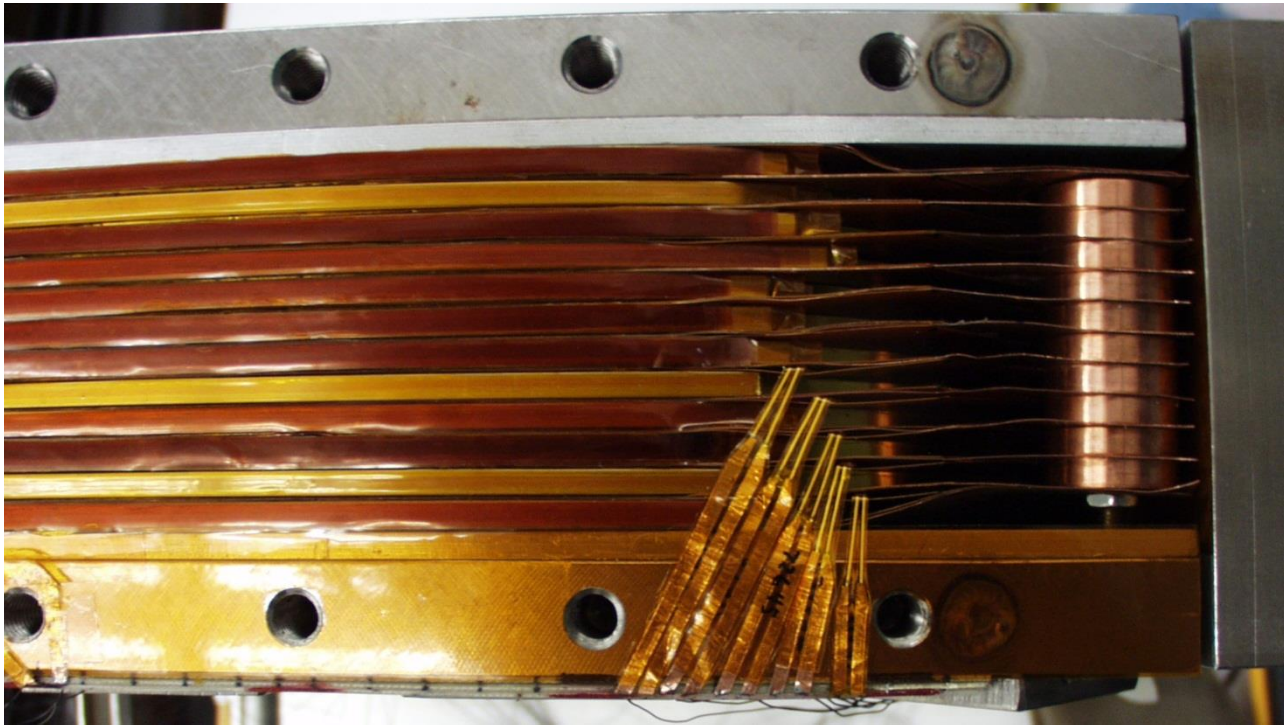
Warm Iron Design to Reduce Heat Load

Summary of First Generation HTS Quad Tests



Operation over a large temperature range- only possible with HTS

Energy Deposition Experiments

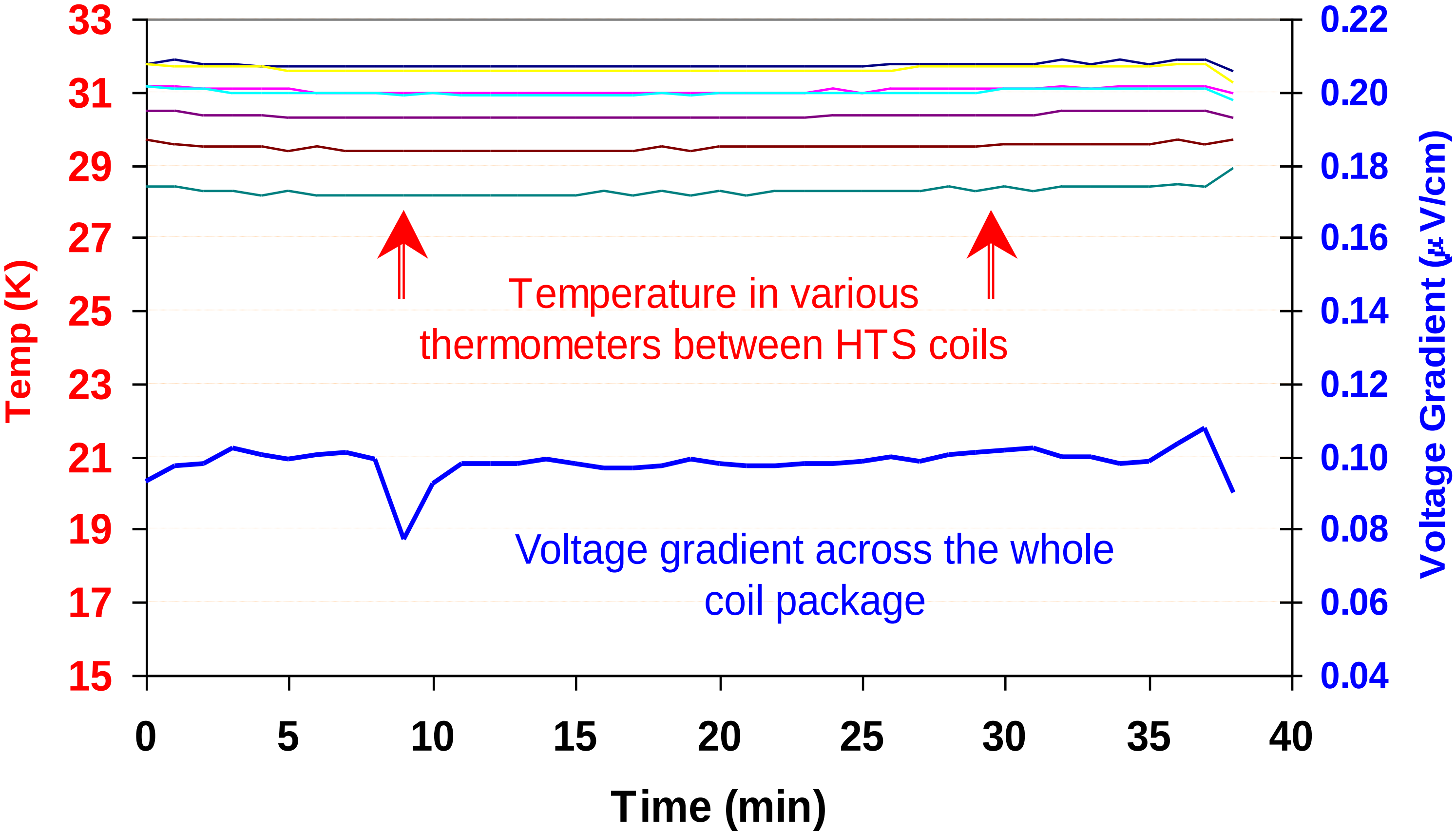


Stainless steel tape heaters for energy deposition experiments

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



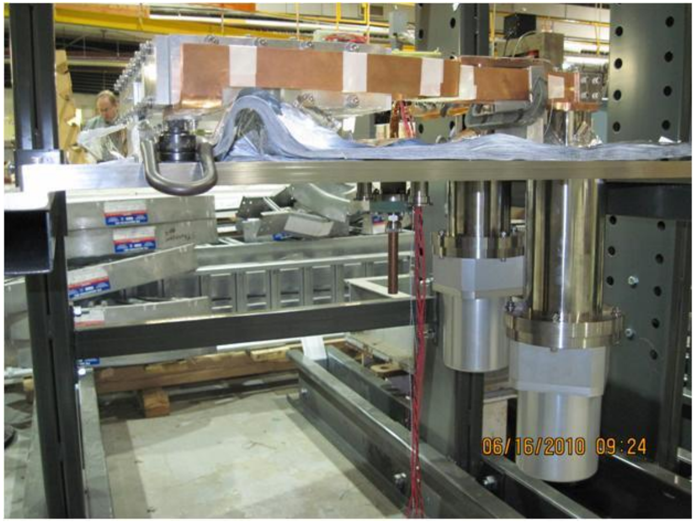
Voltage spikes are related to the noise

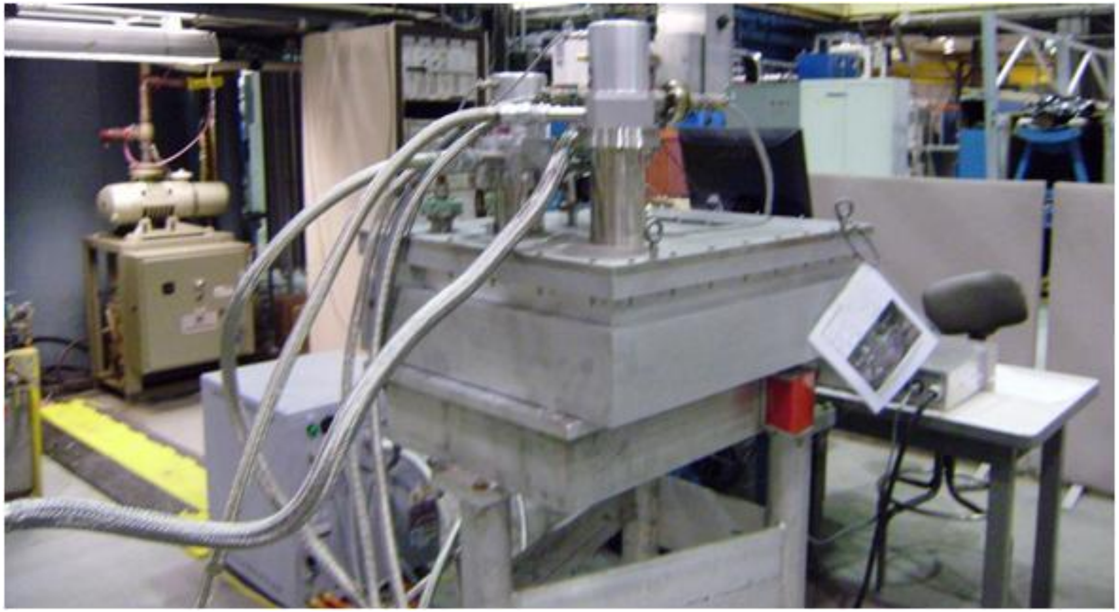
Transition from 1st Generation to 2nd Generation

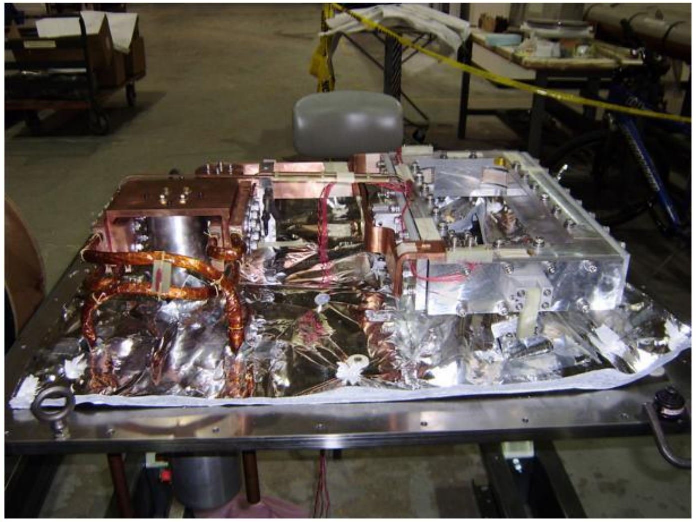
(both conductor and magnet design)

- Project name changed from RIA to FRIB (site specific)
- Took advantage of the transition time to introduce cryo-cooler

Cryo-cooler based HTS Magnet R&D





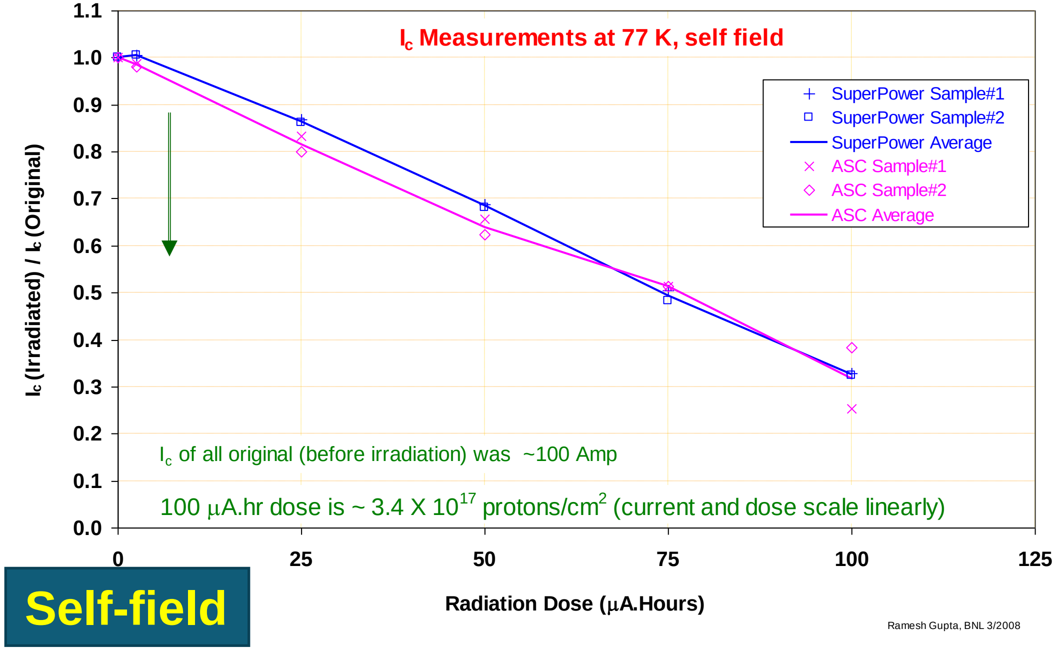


- **Coils reached <40 K (goal was 40-50 K)**
- **Cryo-coolers turned-on at 5 pm in the evening before leaving and coils cooled to the desired at 8:30 am in the morning.**
- **Good test bed for HTS coil technology – No Helium, no personnel, turn on cryo-cooler the evening before and start experiment in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

Second Generation Quadrupole for FRIB

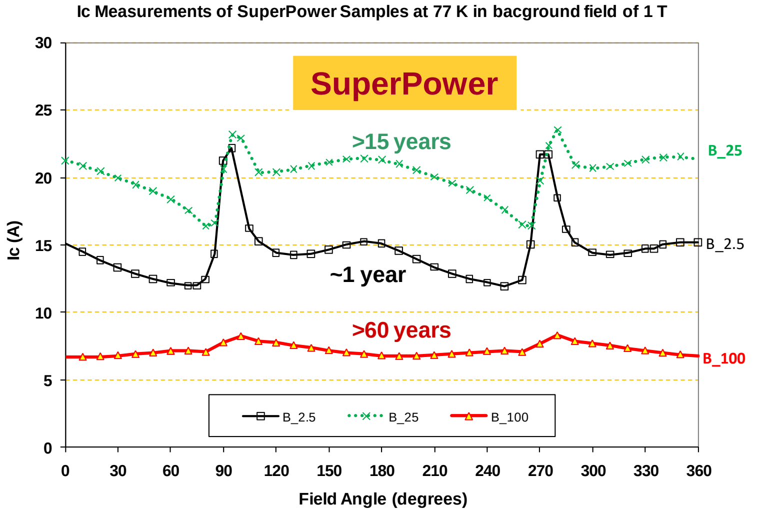
Radiation Damage Studies @BNL in 2G HTS from SuperPower & ASC (measurements @77K in self-field and in 1 T Applied Field)

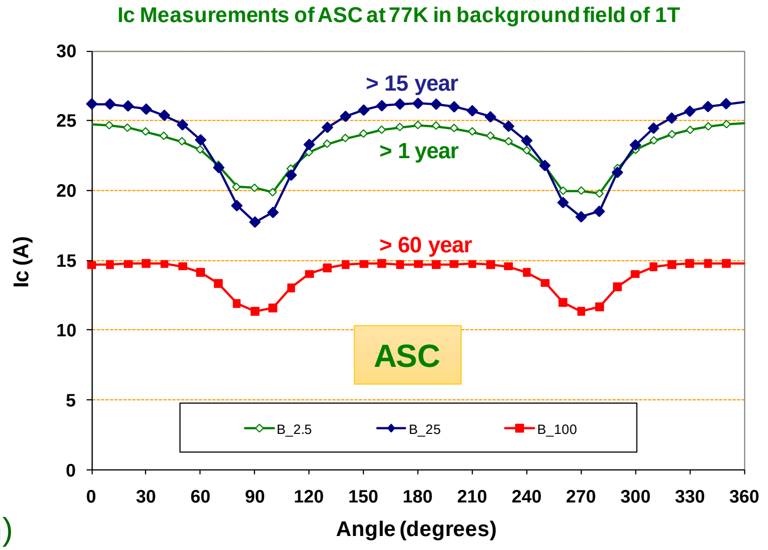
- Self-field radiation damage is found to be similar in samples from both ASC and SuperPower.
- A significant difference in the change in-field anisotropy between SuperPower and ASC tapes.
- Based on these studies, 2G HTS seems to survive FRIB radiation (Zeller, Ronningen, MSU).



Self-field

1 T applied field





Brookhaven National Laboratory

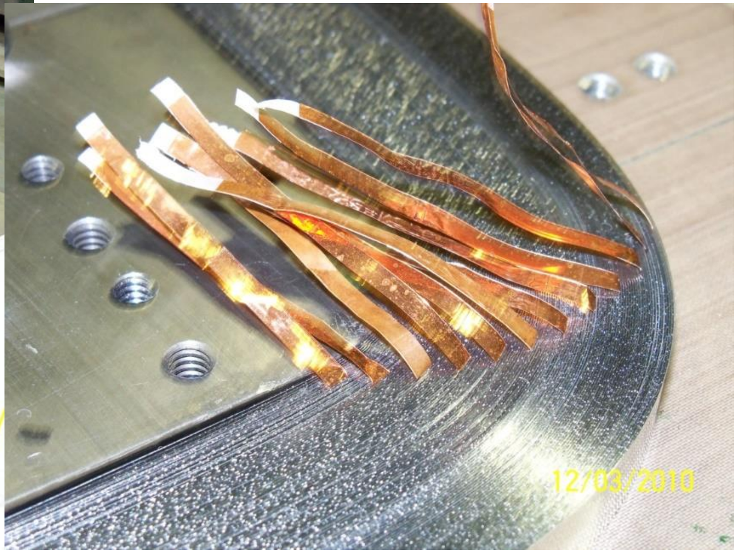
10% damage after 30 years (Zeller & Ronningen)

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

4 coils made with SuperPower Tape

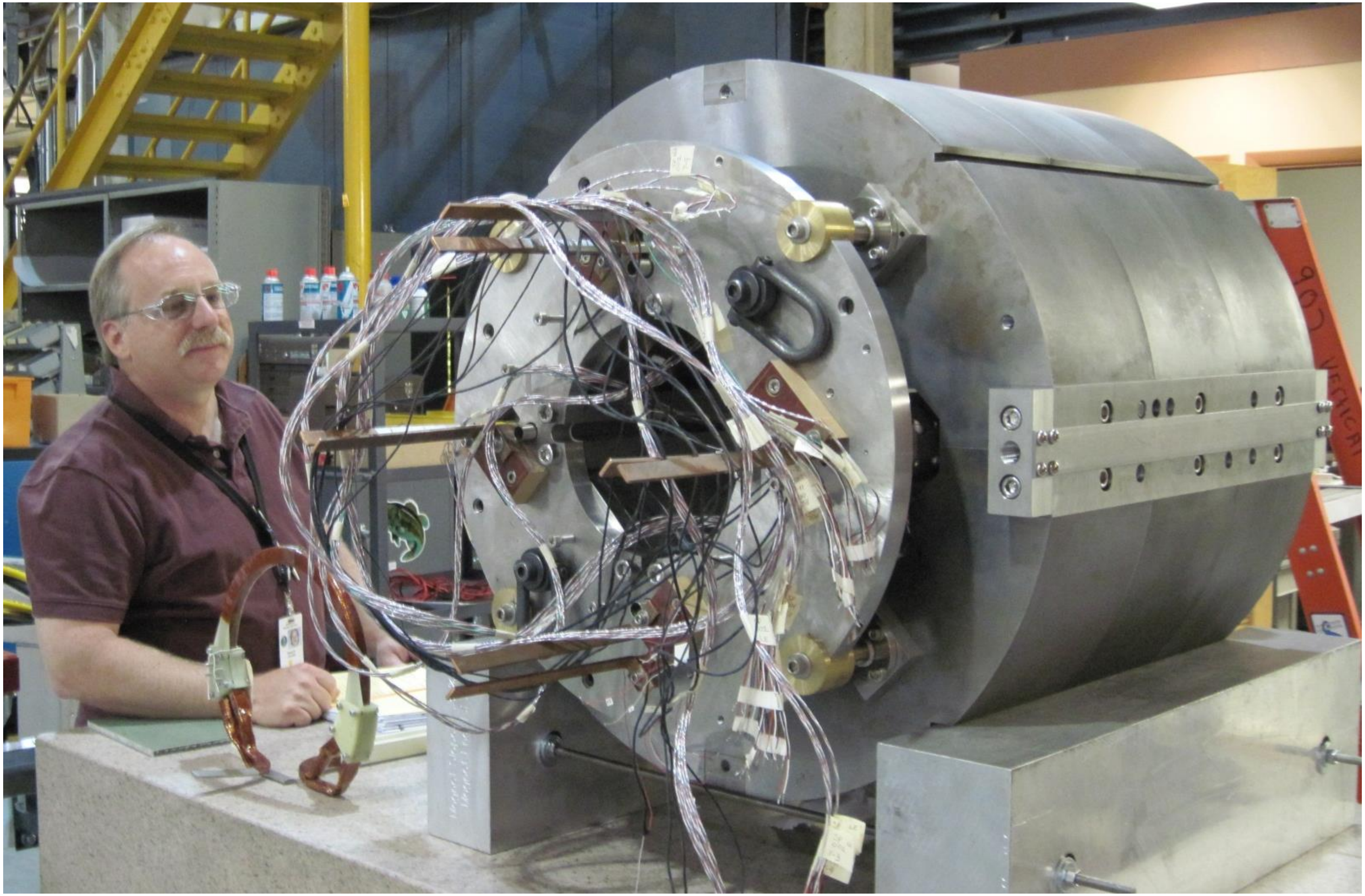
and

4 coils made with ASC

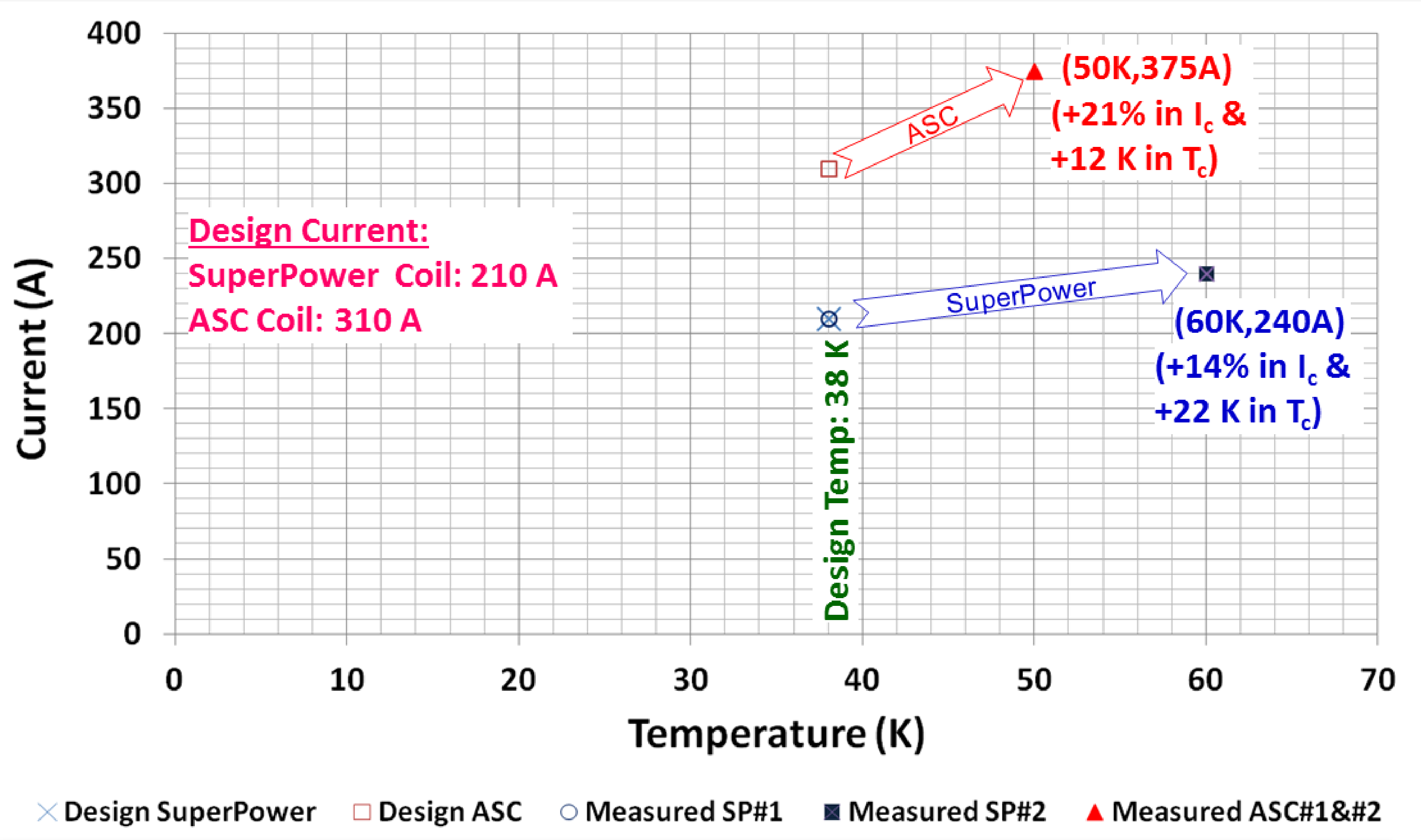


(~9 km of standard 4 mm equivalent used)

Completed 2G HTS Quad for FRIB



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



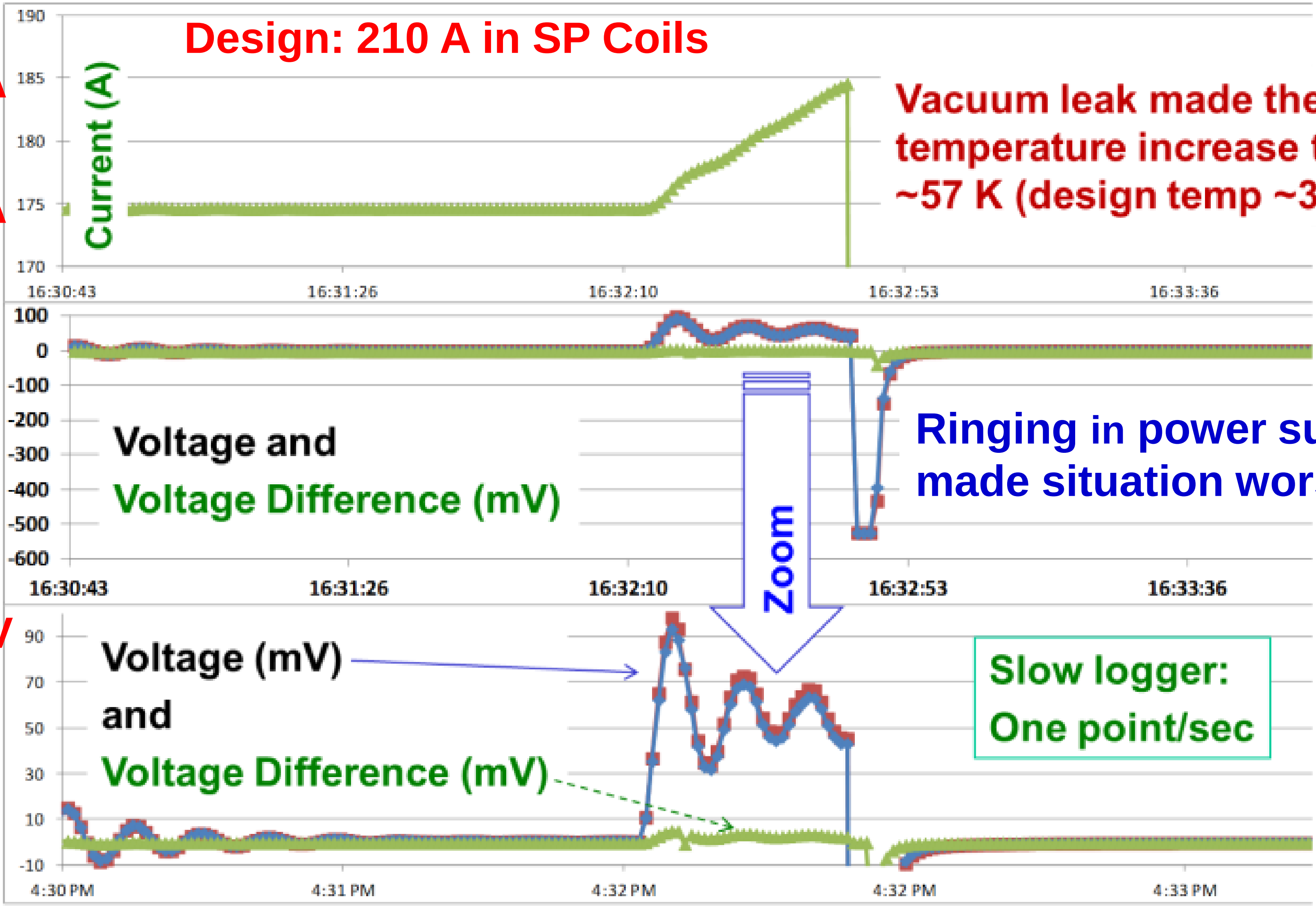
Design Current:
SuperPower Coil: 210 A
ASC Coil: 310 A

(50K,375A)
(+21% in I_c &
+12 K in T_c)

(60K,240A)
(+14% in I_c &
+22 K in T_c)

Provides robust operation against local and global heat loads

Protection of HTS Magnet during an Operational Accident Near Design Current



185A

175A

90mV

Design: 210 A in SP Coils

Vacuum leak made the temperature increase to ~57 K (design temp ~38 K)

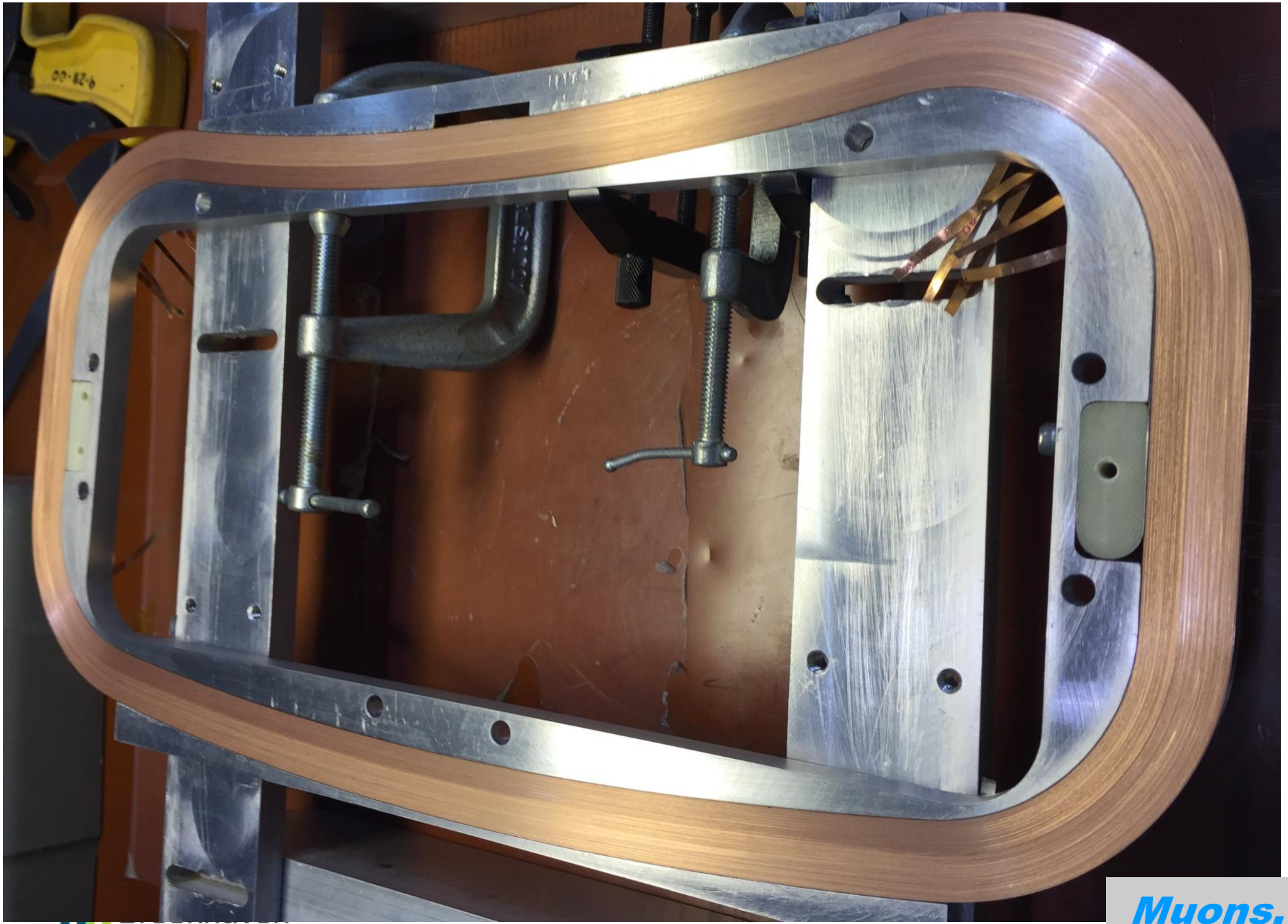
Voltage and Voltage Difference (mV)

Ringing in power supply made situation worse

Voltage (mV) and Voltage Difference (mV)

Slow logger: One point/sec

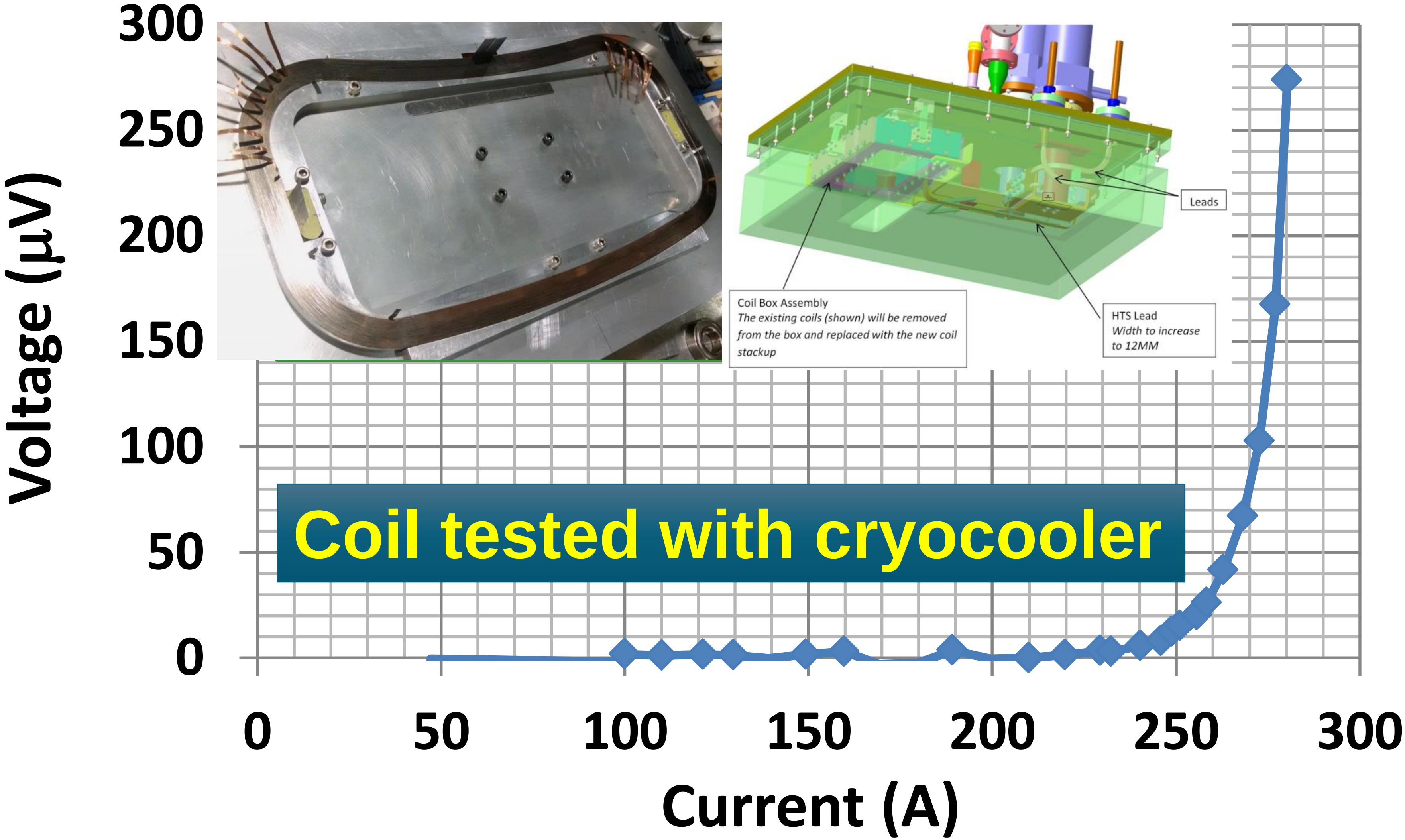
Curved HTS Coil for FRIB (SBIR)



HTS coil with “reverse curvature”

Muons, Inc.

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



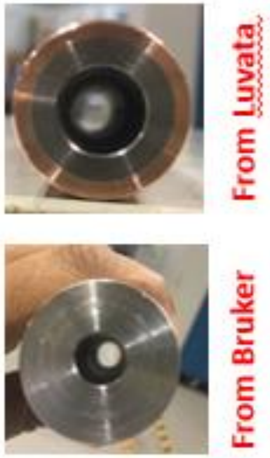
Coil Box Assembly
The existing coils (shown) will be removed from the box and replaced with the new coil stackup

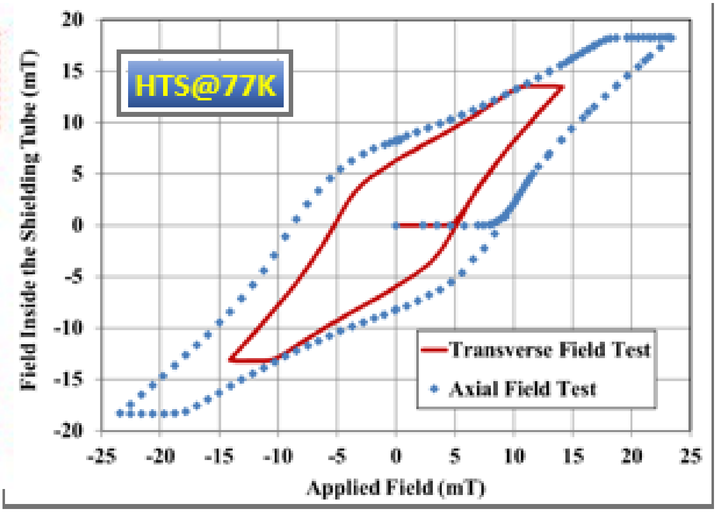
HTS Lead
Width to increase to 12MM

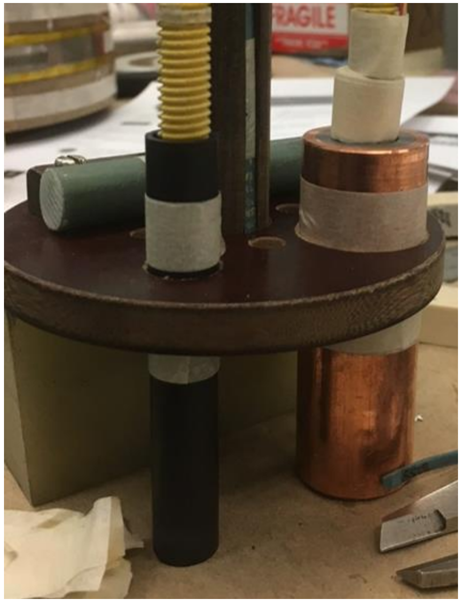
Coil tested with cryocooler

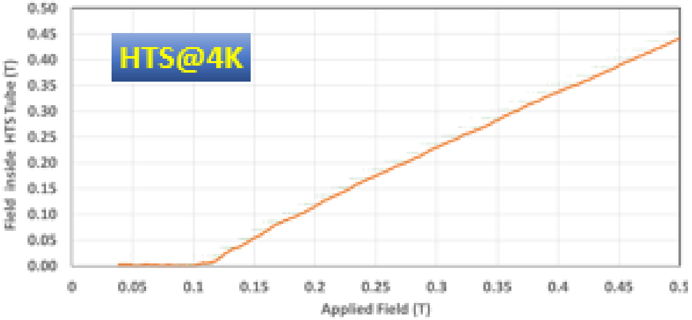
HTS Shielding for EIC (SBIR with PBL)

Collaboration between BNL SMD, BNL MSD, PBL, Bruker, Luvata, and CAN Superconductors (free SC tubes)









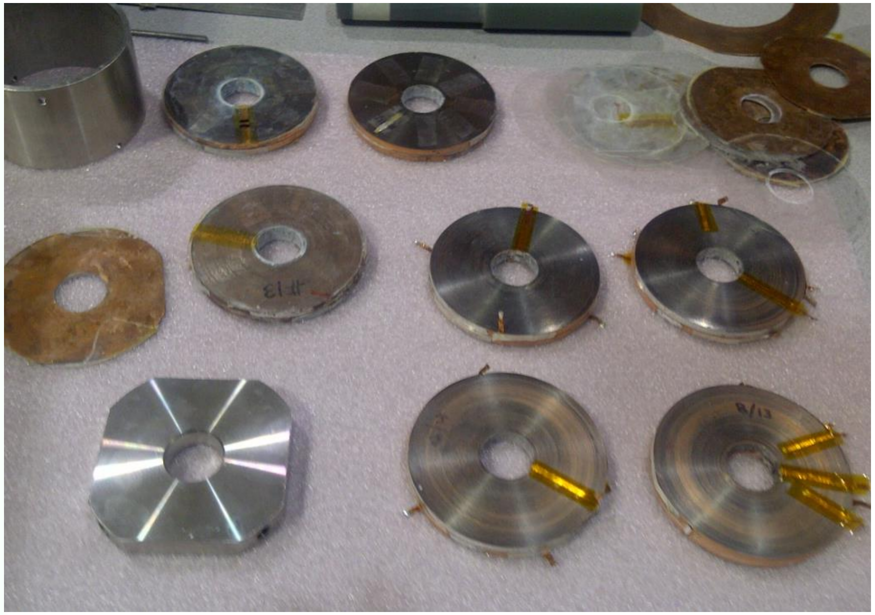
Brookhaven National Laboratory

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

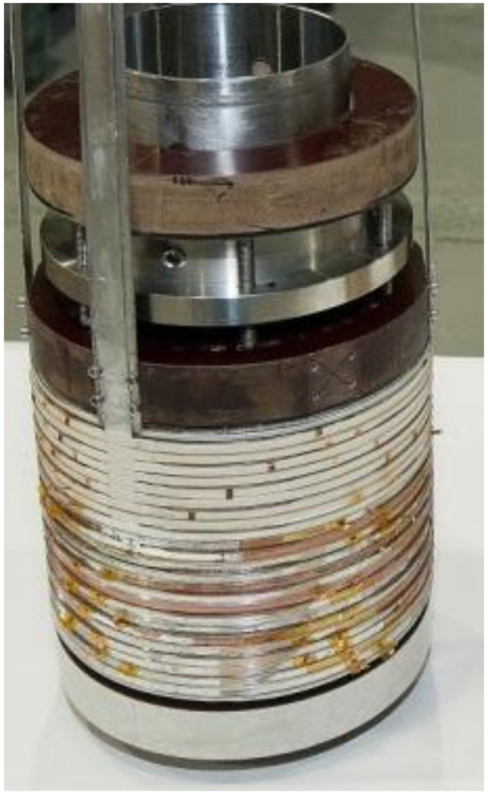
High Field Solenoids with PBL

- 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 (now called MI) to reduce hoop stress



pancakes

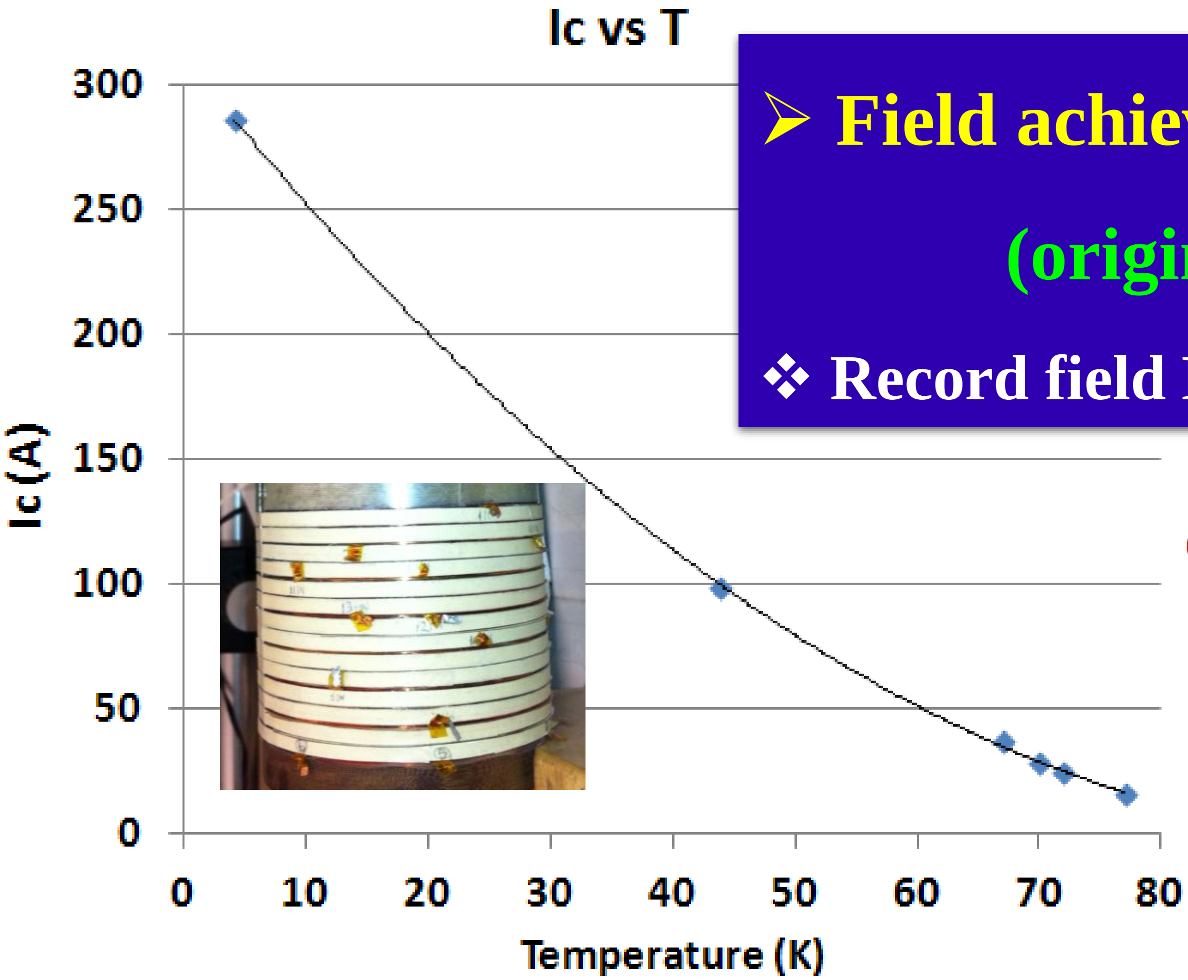
Insert solenoid



Outsert solenoid

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

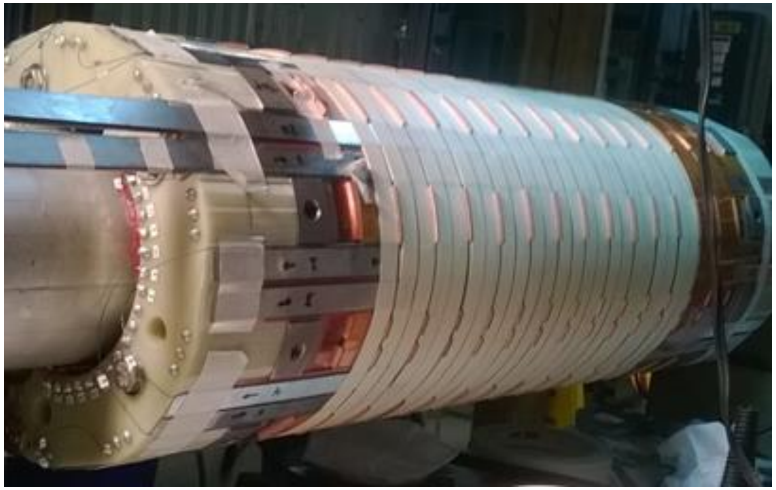
PBL/BNL SBIR

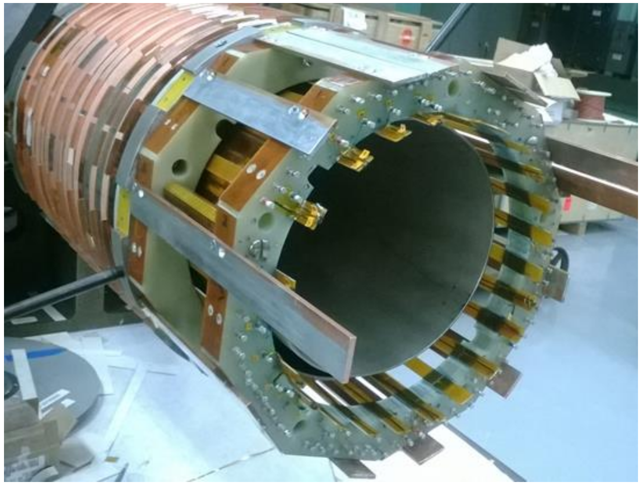
Insert solenoid: 14 pancakes, 25 mm aperture

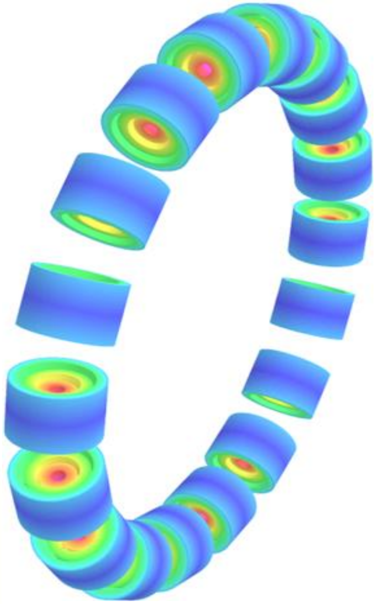
High Field HTS Solenoid for SMES (arpa-e)

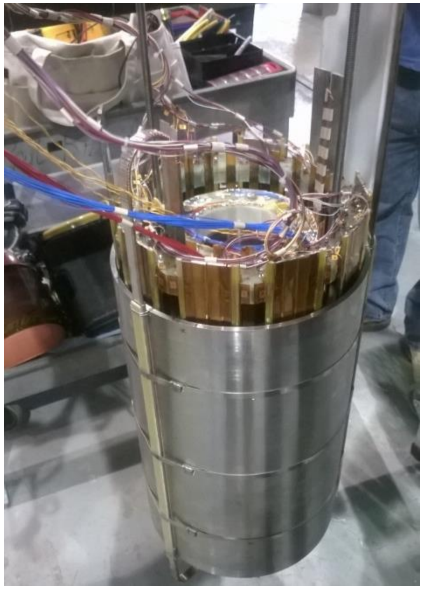
100 mm,
25 T

2-layer
coil design

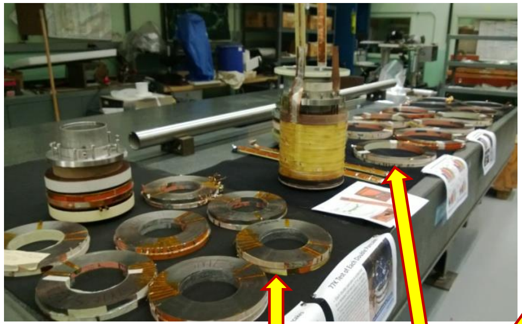




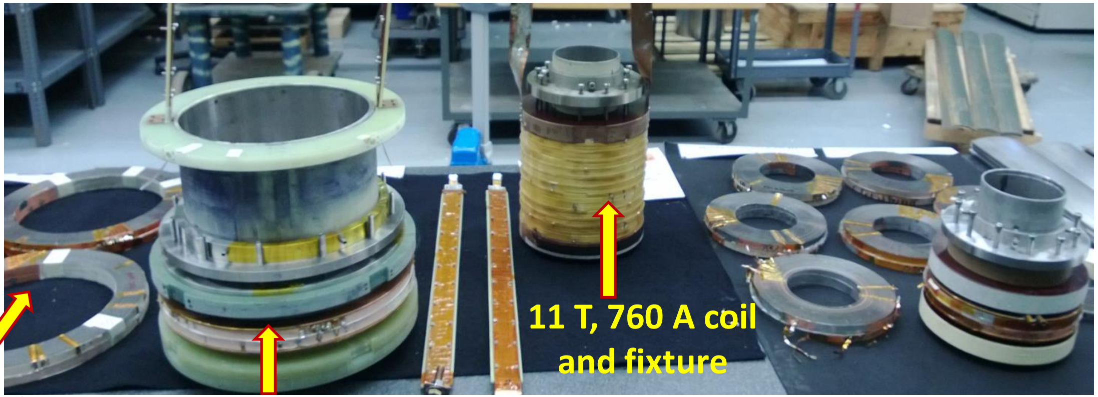




Parts of 25 T HTS Solenoid for SMES arpa-e (with ABB, SuperPower & UoH)

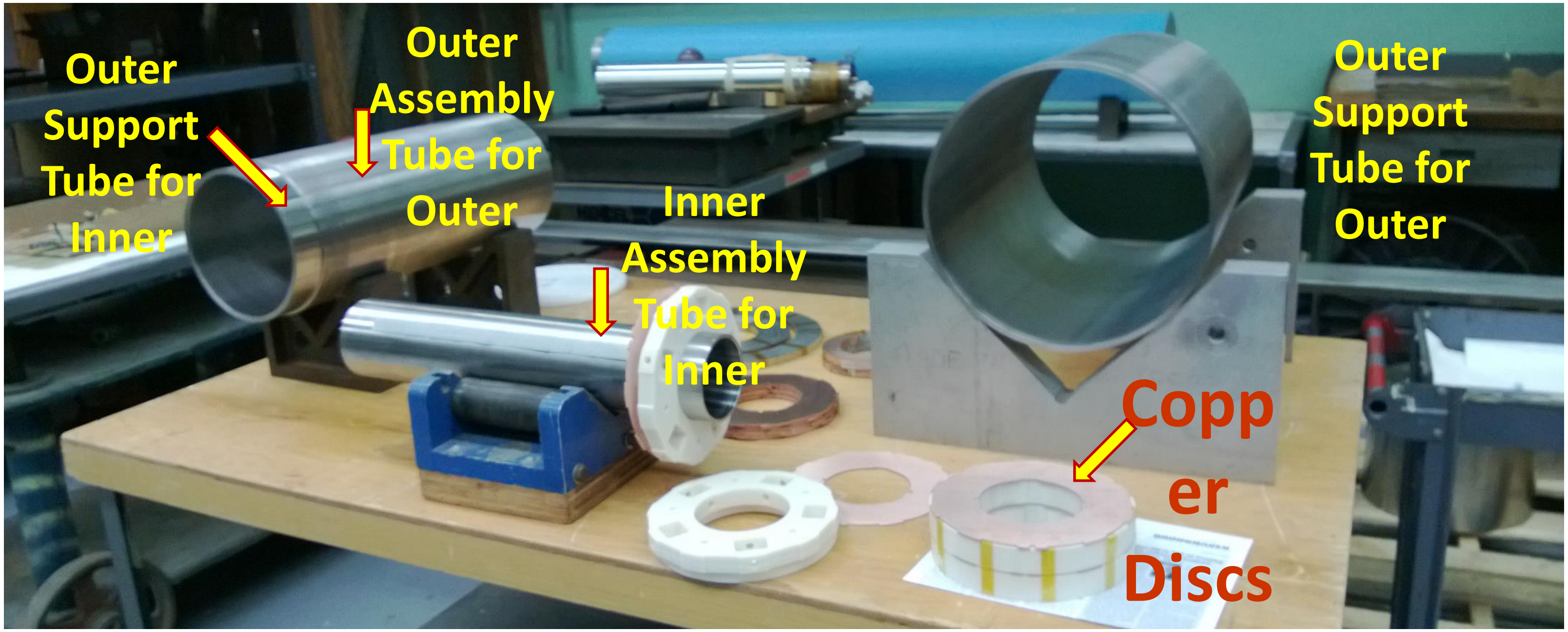


Pancake coils: inner and outer



11 T, 760 A coil and fixture

77 K Test Fixture for outer



Outer Support Tube for Inner

Outer Assembly Tube for Outer

Inner Assembly Tube for Inner

Outer Support Tube for Outer

Copper Discs

Advanced Quench Detection System with Fast Energy Extraction

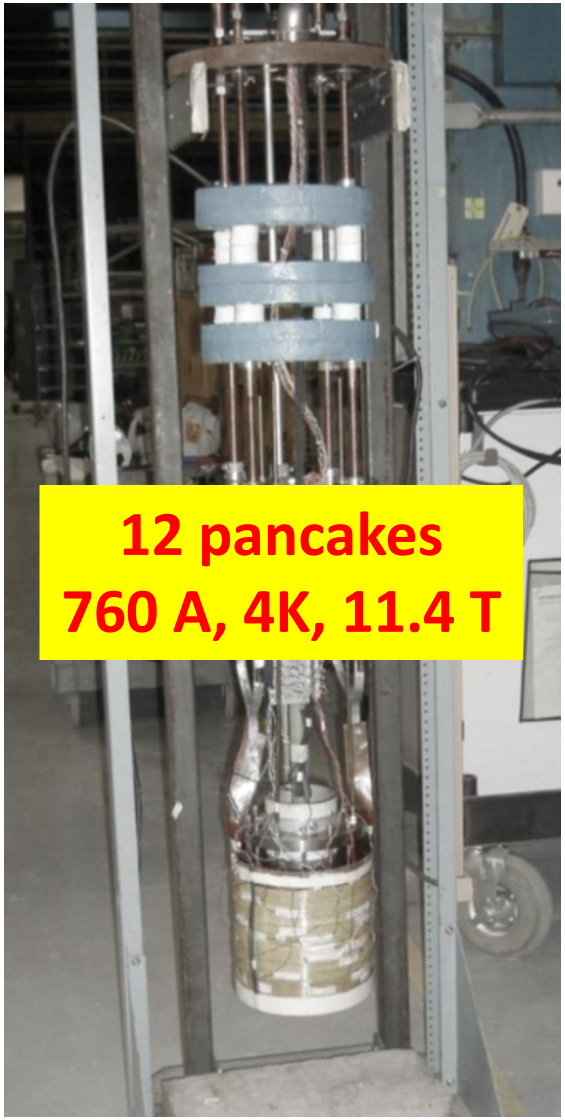
- Fast energy extraction in larger magnets creates high voltages as “L” increases
- Develop electronics that can tolerate high isolation voltage (>1 kV)
- Divide coils in several sections

Cabinet #1 (32 channels, 1kV)

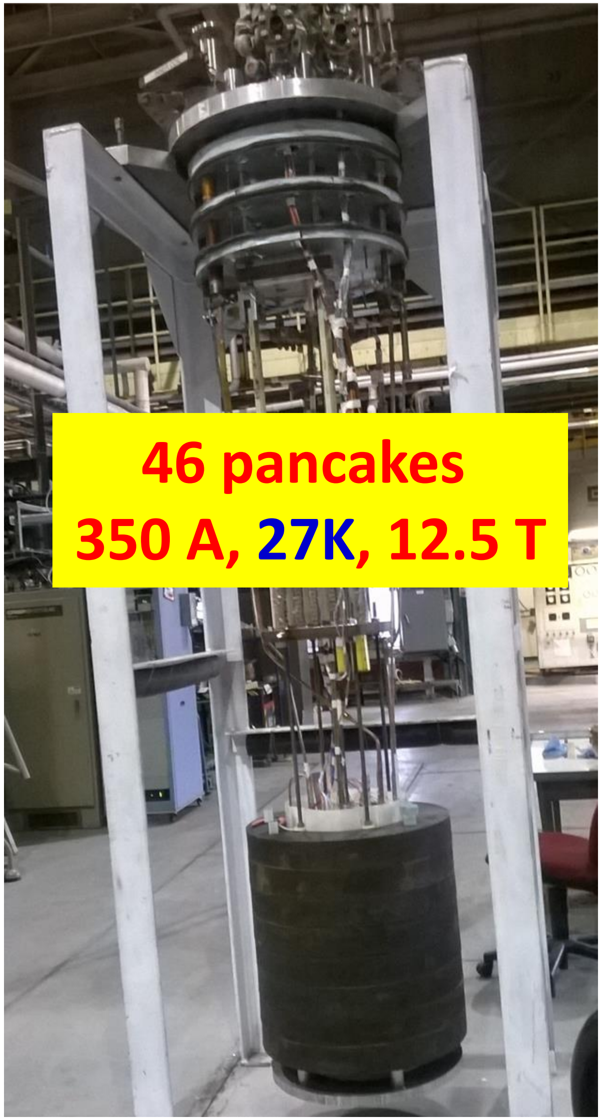
Cabinet #2 (32 channels, 1kV)
(expandable to 64 and 3kV)

HTS SMES Coil High Field Tests

2 pancakes
1140 A, 4K



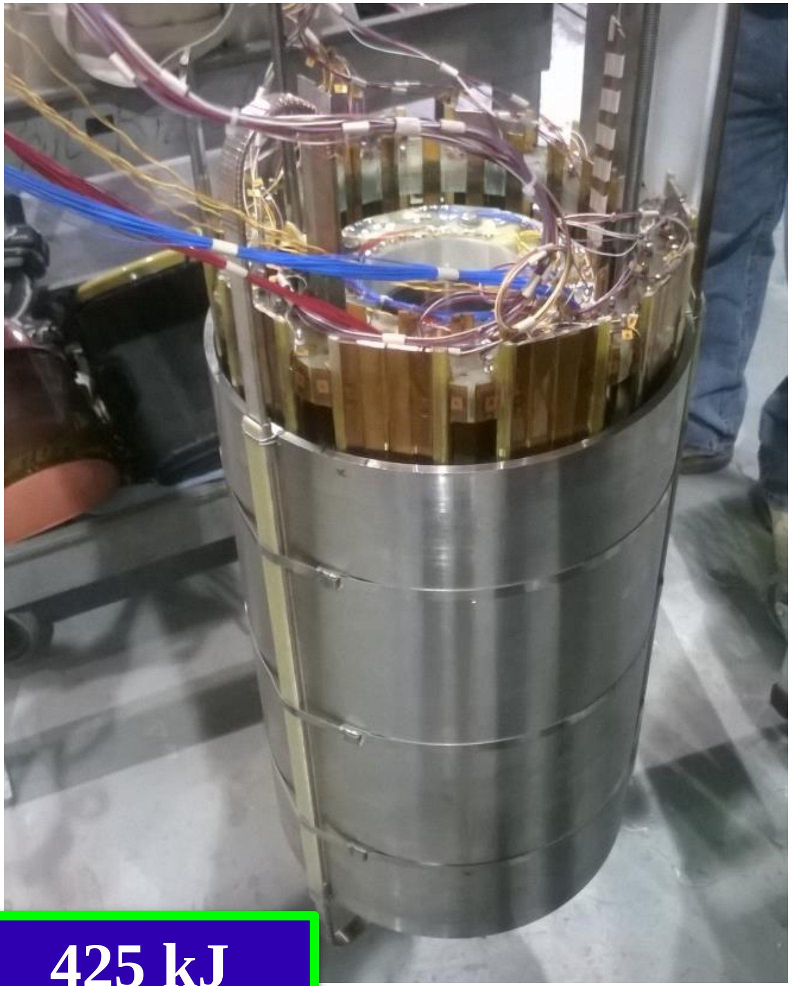
12 pancakes
760 A, 4K, 11.4 T



46 pancakes
350 A, 27K, 12.5 T

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:

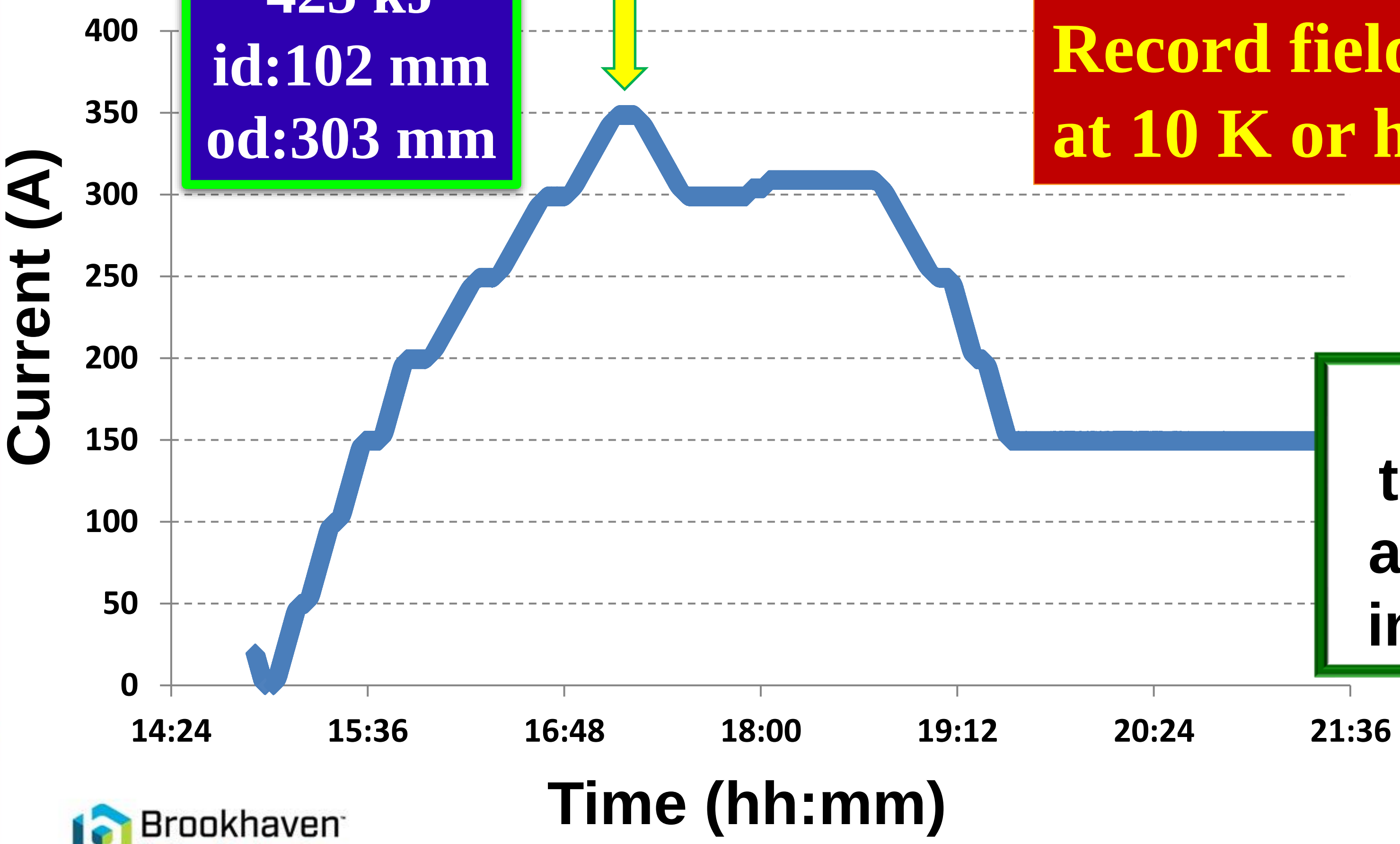
Over 6 km, 12 mm wide from SuperPower

- **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

ARPA-E



12.5 Tesla at 27 K

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

Record field/energy at 10 K or higher

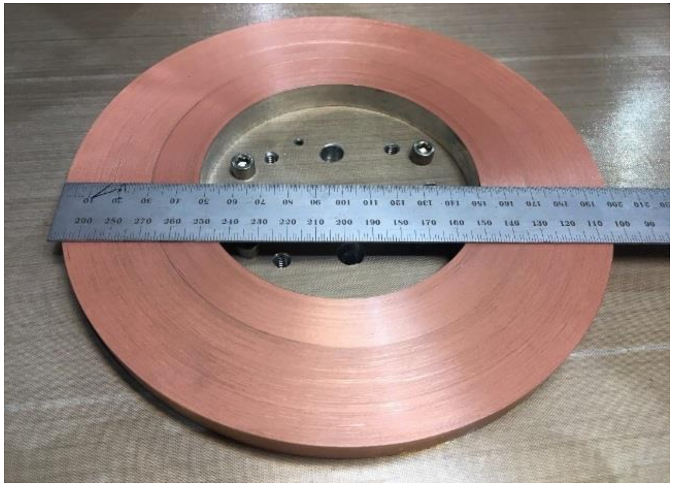
Test terminated after arcing in the leads

HTS Solenoid for IBS (Korea)

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

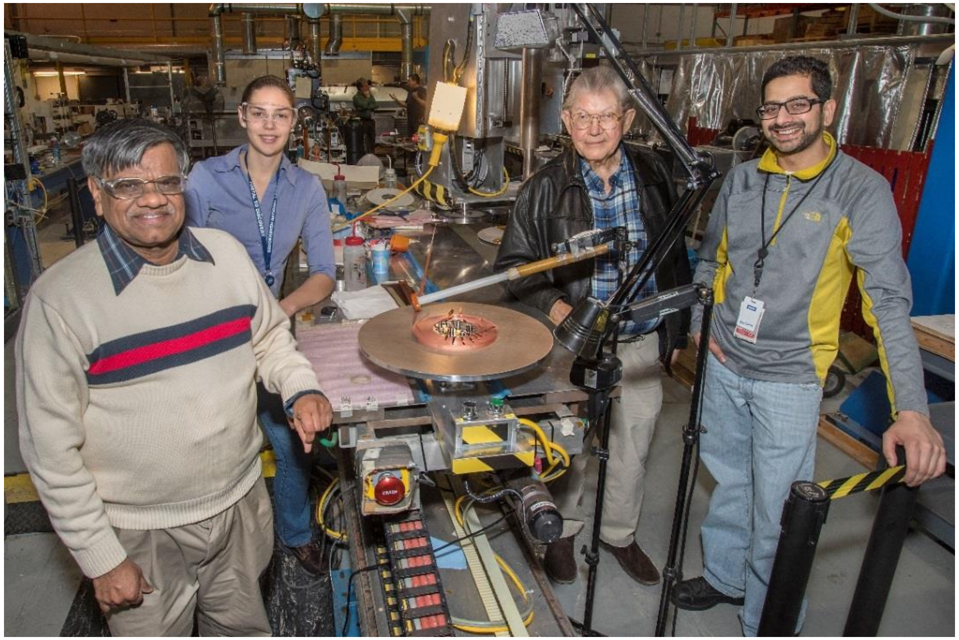
Stresses: J X B X R

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



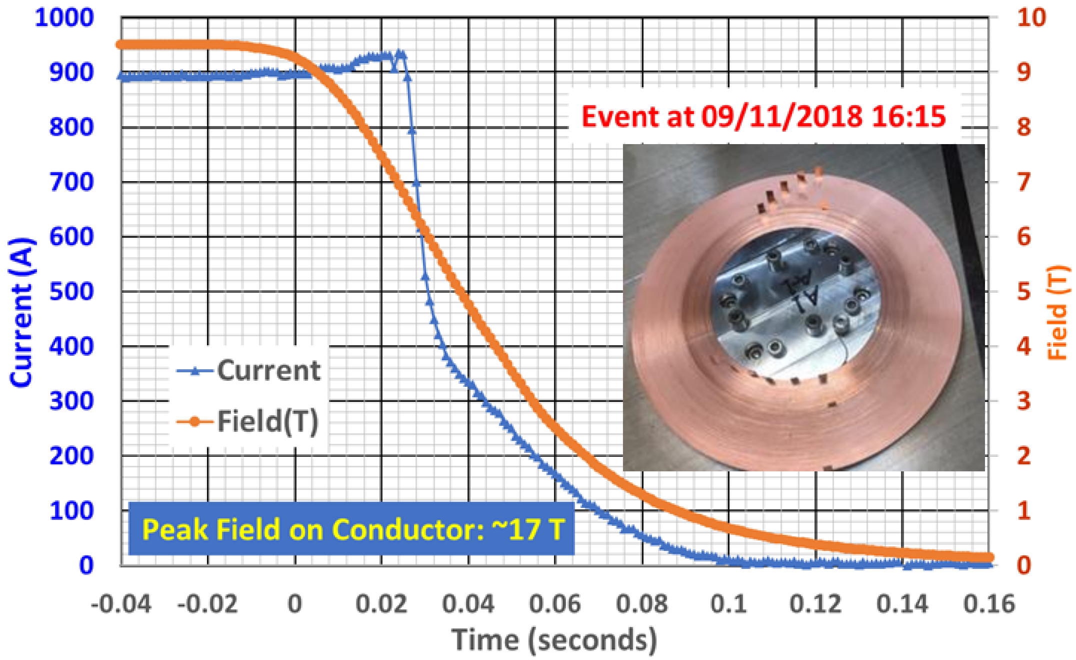
Relaxed field quality and slow ramp rate allows the use of *No-Insulation* windings to (a) tolerate defect in HTS tapes, and (b) expected to offer a more reliable quench protection

Winding of IBS NI HTS Coils with BNL Universal Coil Winder



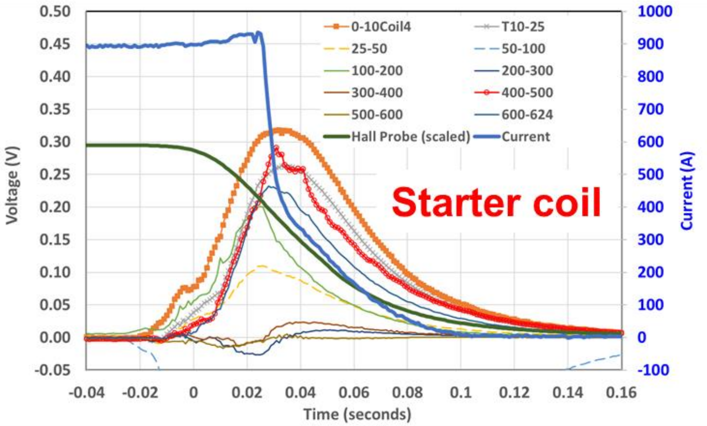
Quench Scenario in Large No-Insulation Coil

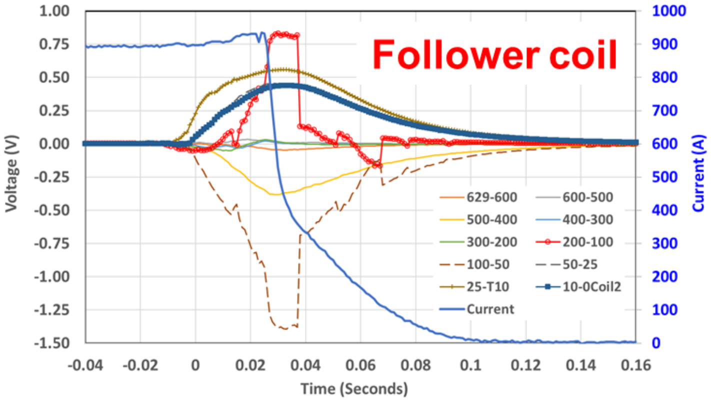
(fast 4K propagation within coil and coil-to-coil)



Event at 09/11/2018 16:15

Peak Field on Conductor: ~17 T

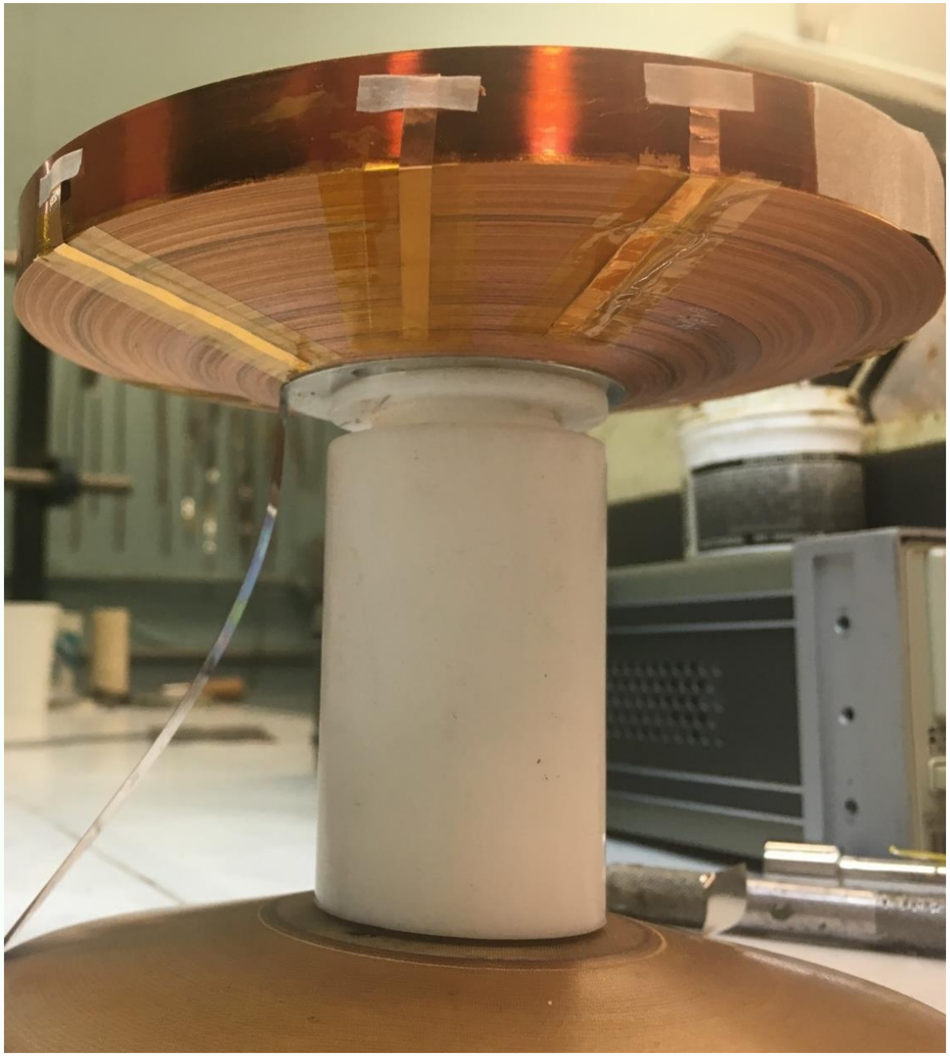




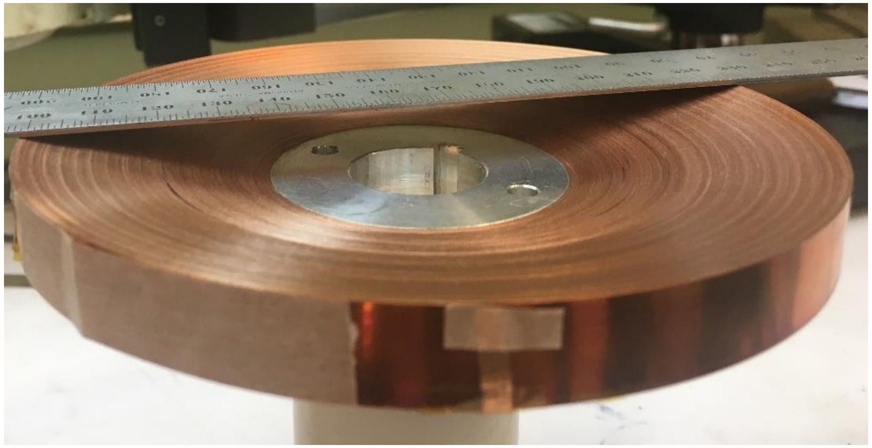
Large No-Insulation HTS coil became normal in <200 msec (even faster than in many LTS magnets)

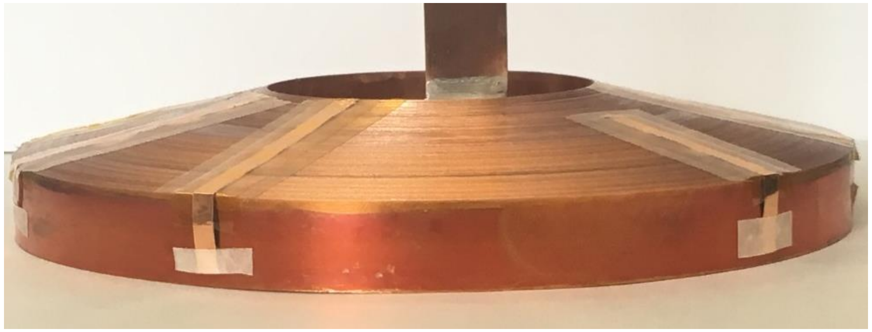
- **Large number of voltage-taps gives a detailed insight of what is happening**
- **Within a pancake: fast propagation due to resistive heating through contact resistance between turns when the current flows across (not around) in a "No-insulation" coil**
- **Pancake to pancake: fast propagation due 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**
- **Phase II not funded**

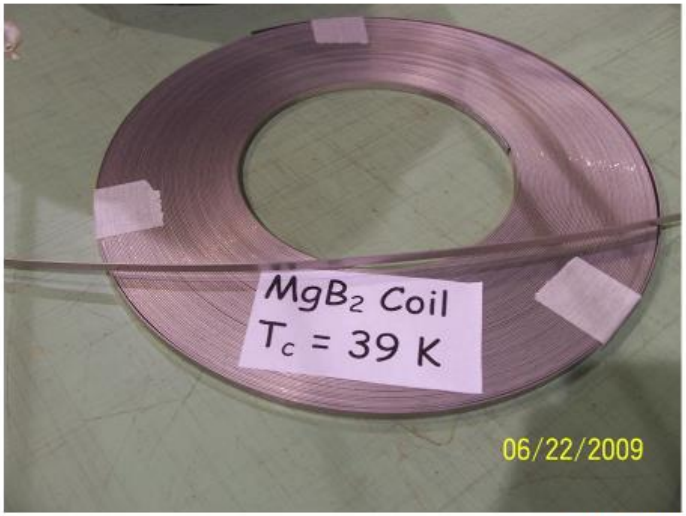




R&D with MgB_2

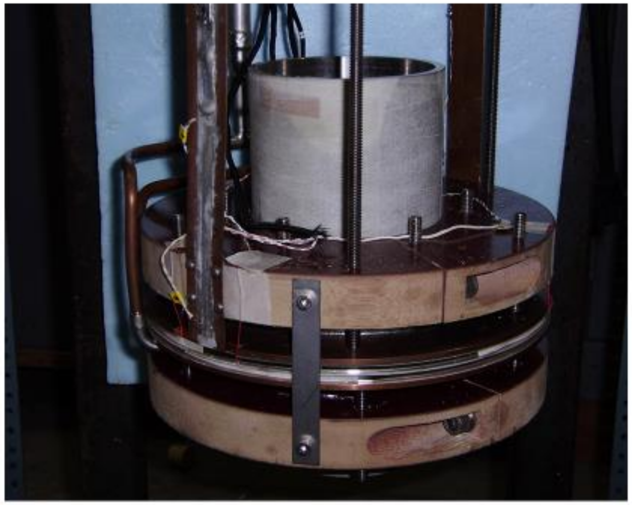
- Collaboration with Columbus, Italy
- Phase I and Phase II SBIR's with HyperTech, Columbus, Ohio, USA

MgB$_2$ Coil with Conductor from COLUMBUS SUPERCONDUCTORS SpA



Coil i.d.
100 mm
Coil o.d.
200 mm
# of Turns
80

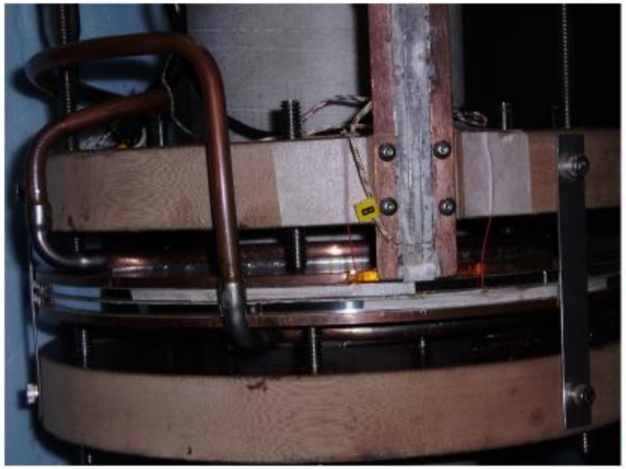
MgB$_2$ Solenoid with Conductor from COLUMBUS SUPERCONDUCTORS SpA



MgB$_2$ Solenoid with a double pancake coil and all instrumentation

Coil i.d.
100 mm
Coil o.d.
200 mm

MgB$_2$ Solenoid with Adjustable Helium Flow to Control (vary) Temperature



- Helium flow is adjusted to vary the temperature
- Top and bottom plates are cooled with the helium gas
- The same technique will be used in HTS solenoid to study the performance as a function of temperature over a wider range

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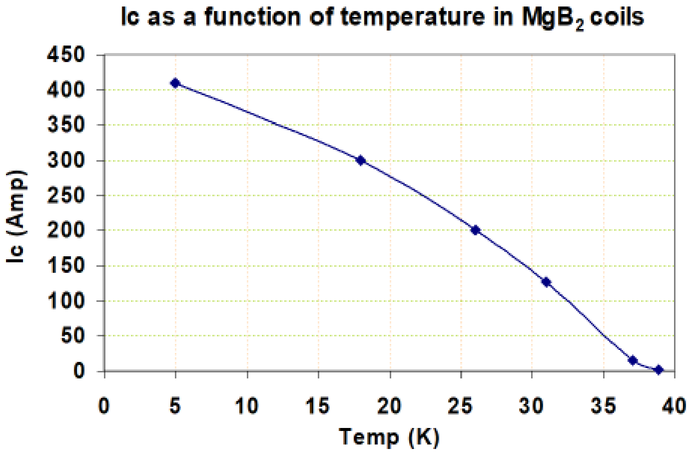
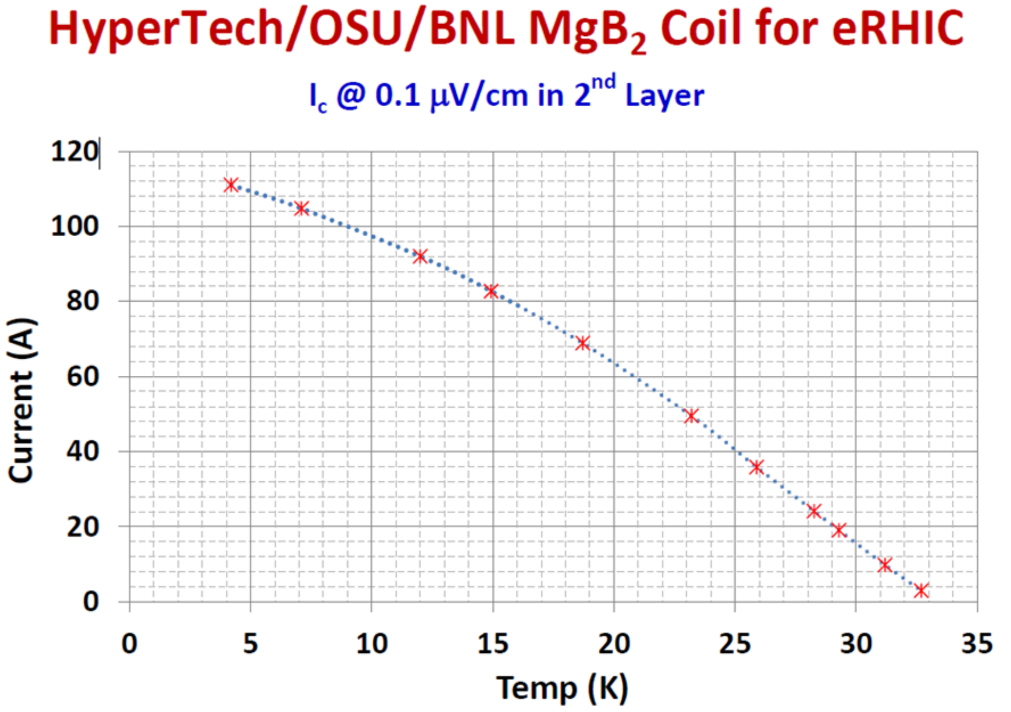
Critical Current as a Function of Temperature MgB$_2$ Solenoid


Ic as a function of temperature in MgB$_2$ coils

Conductor courtesy of COLUMBUS SUPERCONDUCTORS SpA

MgB$_2$ SBIR's with HyperTech



HyperTech/OSU/BNL MgB$_2$ Coil for eRHIC

I_c @ 0.1 μV/cm in 2nd Layer

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 may reduce cryogenic challenges.
- Just summarized BNL R&D experience on a wide-ranging applications.
- Yes, there are many challenges. But are they show-stoppers (time horizon- a few decades of R&D)?
- Let’s find out…

Extra Slides

A Partial List of HTS Programs at BNL

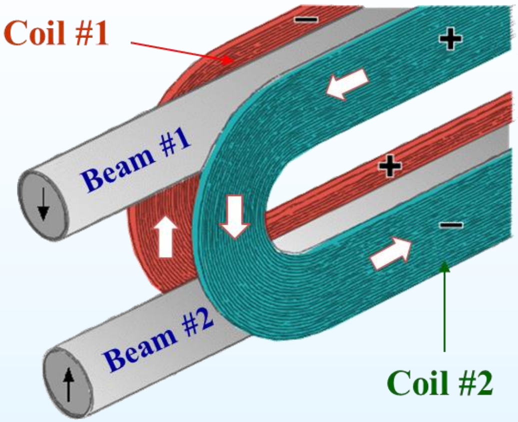
- **HTS/LTS Hybrid dipole with HTS tape (Phase II SBIR)**
- **HTS/LTS hybrid dipole with HTS tape (USMDP)**
- **HTS/LTS hybrid dipole with HTS tape (US-Japan HEP)**
- **Hybrid Dipole with CORC® Cable (Phase II SBIR)**
- **Cosine theta HTS dipole (Two Phase I SBIR)**
- **25 T, 100 mm HTS solenoid for 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)**

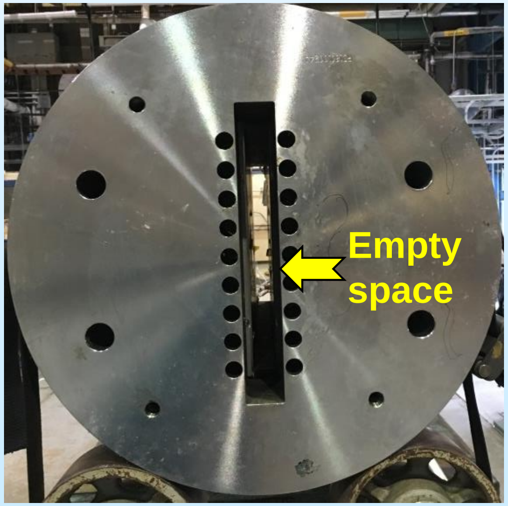
Completed HTS Magnet Programs

- 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.

Brookhaven National Laboratory

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