U.S. MAGNET DEVELOPMENT PROGRAM

BNL experience related to HTS accelerator magnets

MDP Videoconference on May 15, 2019

Ramesh Gupta

Brookhaven National Laboratory

BNL at USMSP

- BNL is glad to join US magnet development program…
- Funding is in place in May FIN plan, which means we can start working soon.
- Key memorandum is being signed, if not done already.
- The initial scope of work for this year was planned to do (a) quench studies on CORC cable and (b) magnetization studies of HTS tape coils (field primarily parallel to the wider face), both in the background field of BNL 10 T common coil dipole.
- A detailed plan for will be presented in a future presentation for your feedback. We are already in discussion with LBL and ACT.
- The purpose of this presentation is to review previous BNL HTS magnet programs related to accelerators. We are open to sharing experimental data for better scientific understanding.

HTS Dipole and Quadrupole Magnet Programs at BNL for Accelerators

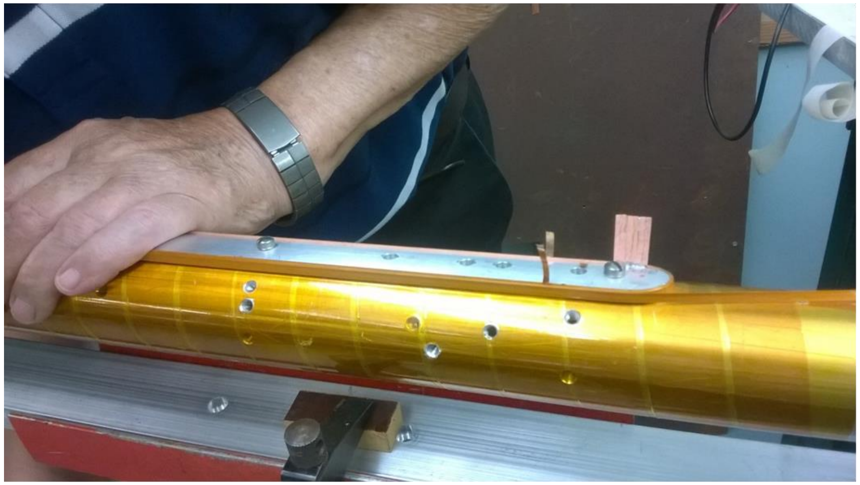
- Hybrid Dipole with CORC® Cable (Phase II SBIR)
- High field hybrid collider dipole (Phase II STTR)
- Overpass/Underpass HTS dipole (Phase I SBIR)
- Curved dipole with the ReBCO tape (Phase II SBIR)
- High radiation HTS Quadrupole for FRIB (FRIB/DOE)
- Bi2223 HTS tape common coil dipole (DOE)
- HTS magnet for NSLS (BNL Project)
- HTS quadrupole for RIA (funded by DOE)
- Bi2212 Rutherford cable Common Coil Collider Dipole (DOE)
- Cosine theta dipole with 4 mm YBCO/ReBCO tape (SBIR)
- Cosine theta dipole with 12 mm YBCO/ReBCO tape (SBIR)

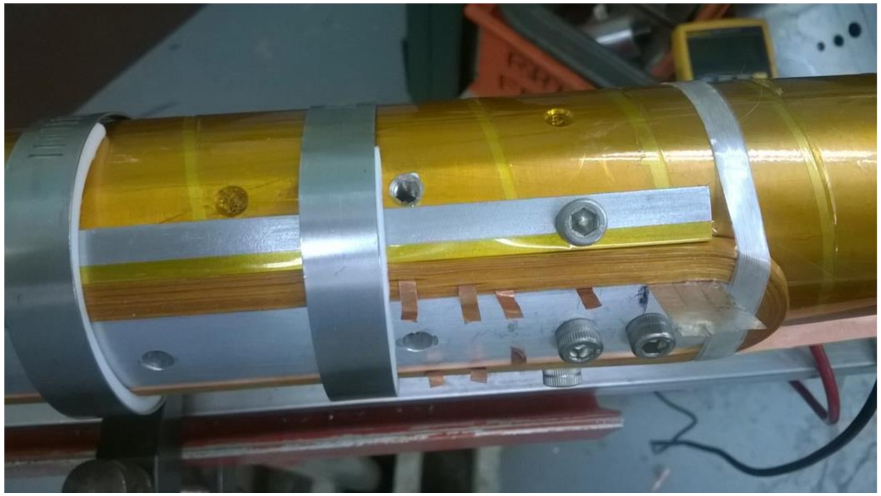
BNL can make a significant contribution to the US MDP for developing high field HTS accelerator magnet technology with the above and other high field HTS solenoid programs

Overview

- The goal of this presentation to (re)familiarize everyone with some of these programs to help collaboration to benefit from that experience

Cosine Theta Coil with 4 mm HTS Tape - SBIR Phase I (1)





Cosine Theta Coil with 4 mm HTS Tape - SBIR Phase I (2)

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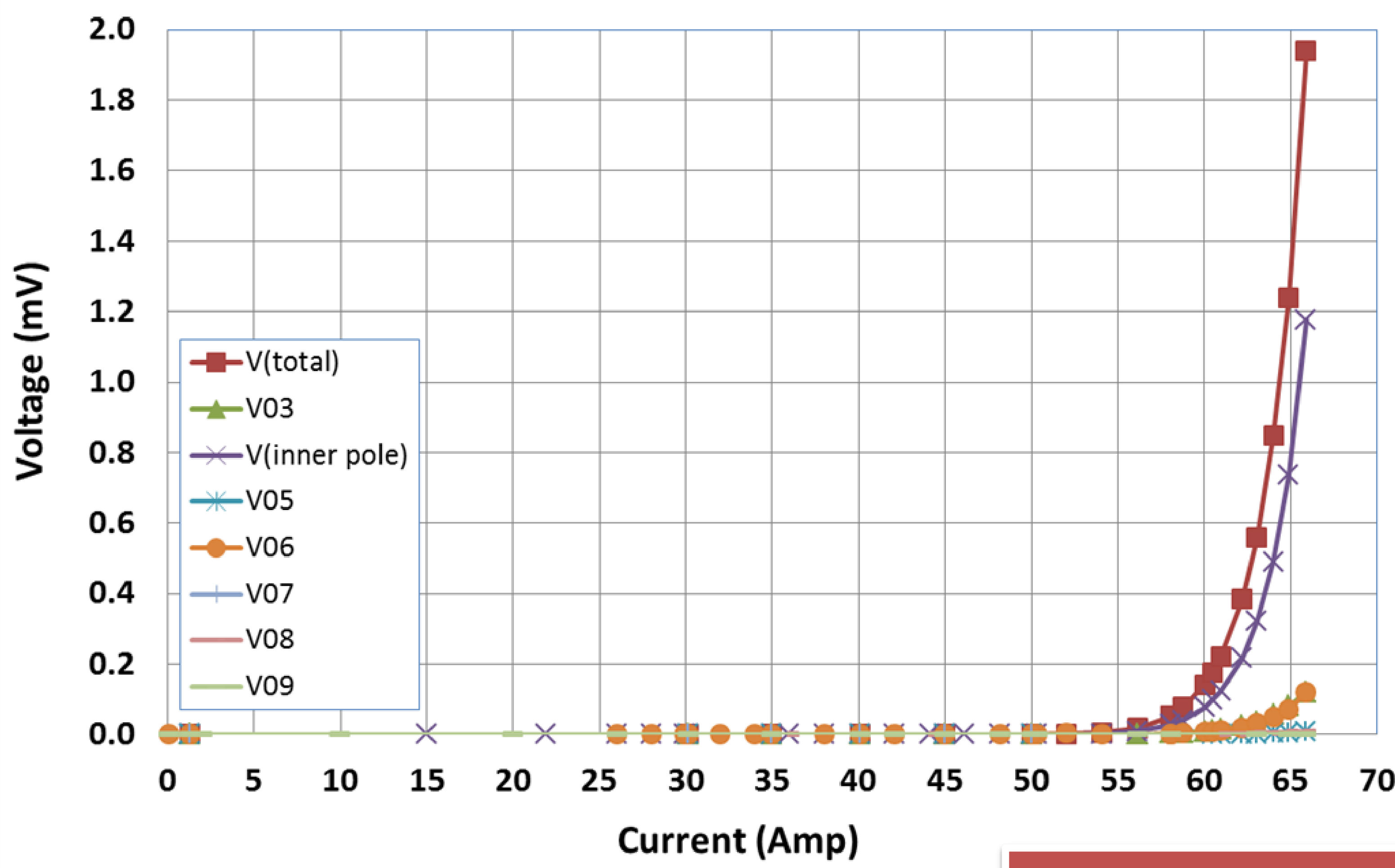
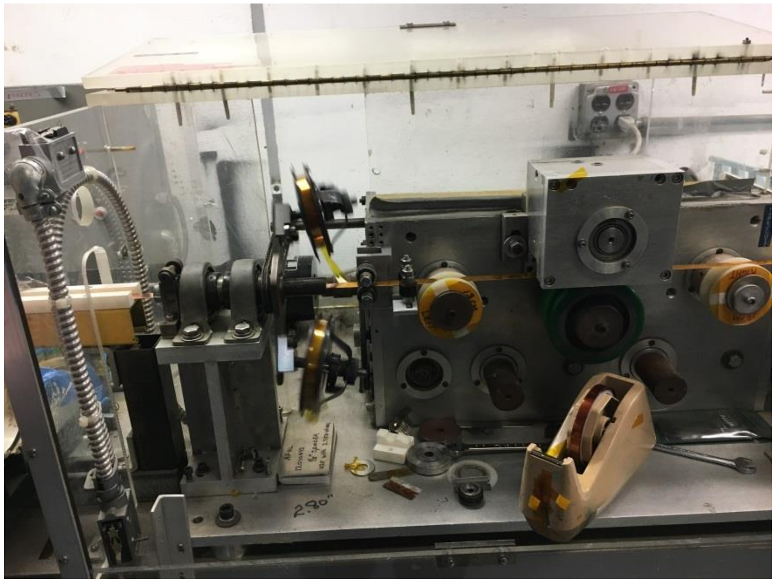
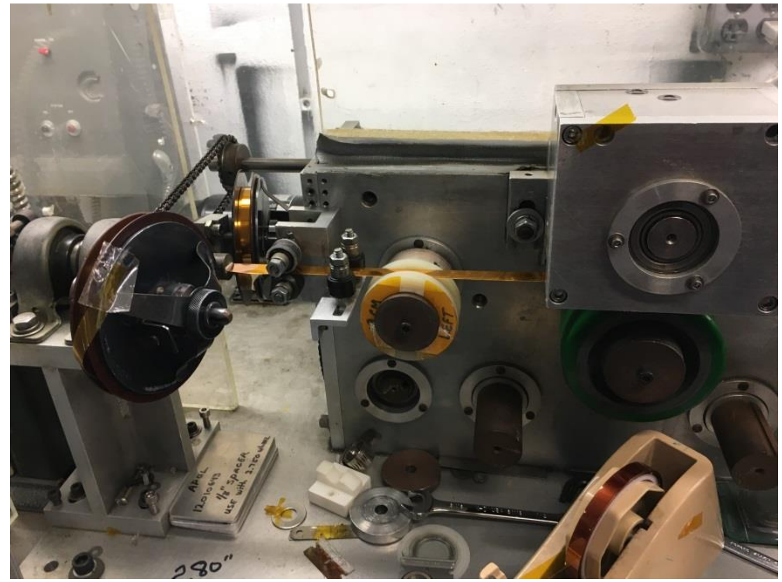


No measurable degradation

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





Part of an same STTR

77 K tests show no degradation in conductor performance

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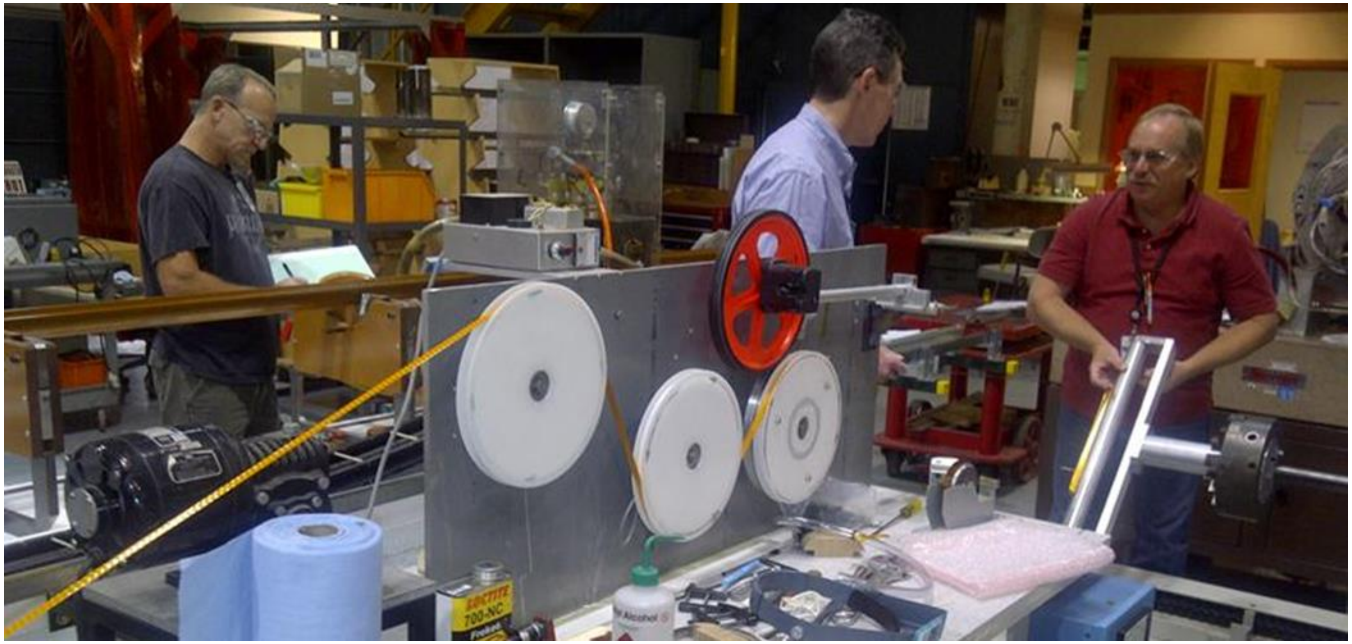
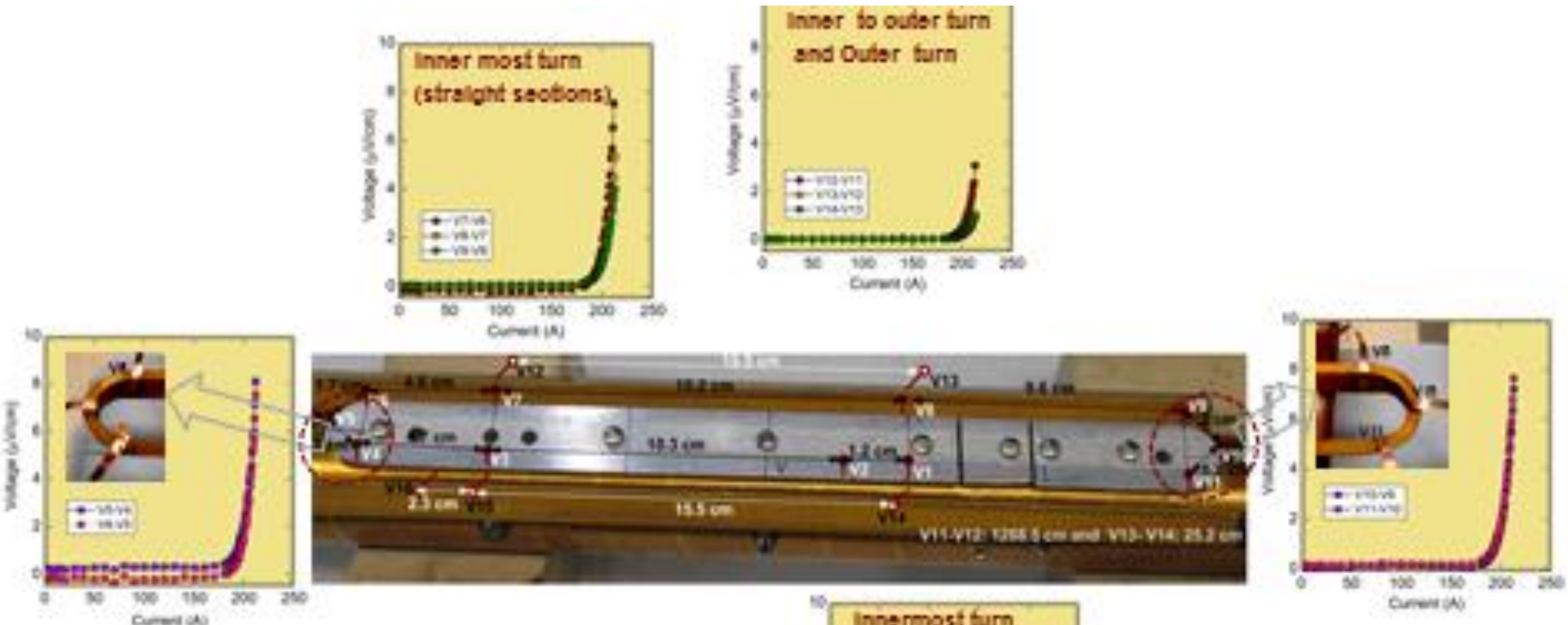
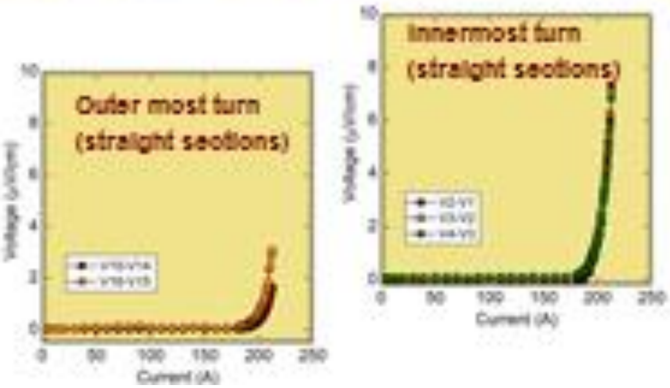
Cosine Theta Coil with 12 mm HTS Tape - SBIR Phase I (1)



Cosine Theta Coil with 12 mm HTS Tape - SBIR Phase I (2)





No measurable degradation

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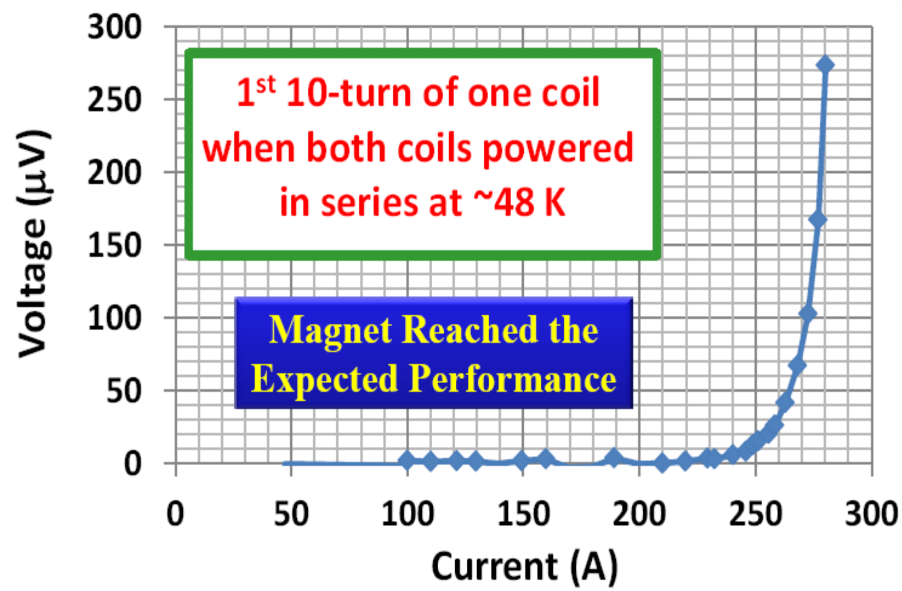
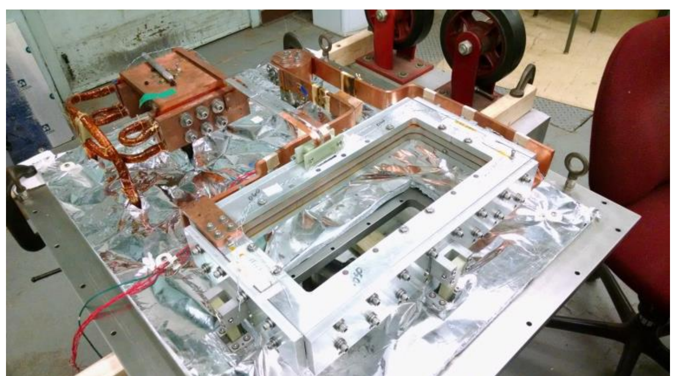
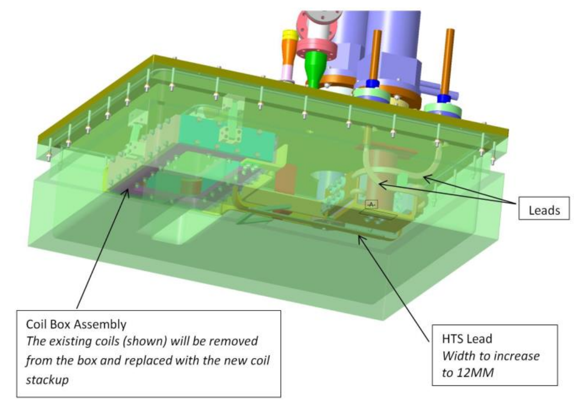
HTS Curved Coil with Cryo-cooler (SBIR Phase II with Muons, Inc.)







SBIR on CORC Cable with ACT (Phase I and Phase II)

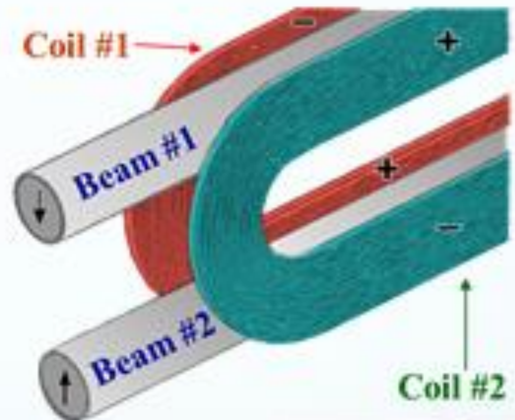
CORC® cables for Common Coil accelerator magnets

CORC® cables are ready for the next step

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

Common Coil magnet ideal for CORC® cables

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



Proposed program to Department of Energy

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

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Advanced Conductor Technologies LLC
www.advancedconductor.com

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CORC Cable Test at BNL (Phase I SBIR with ACT)

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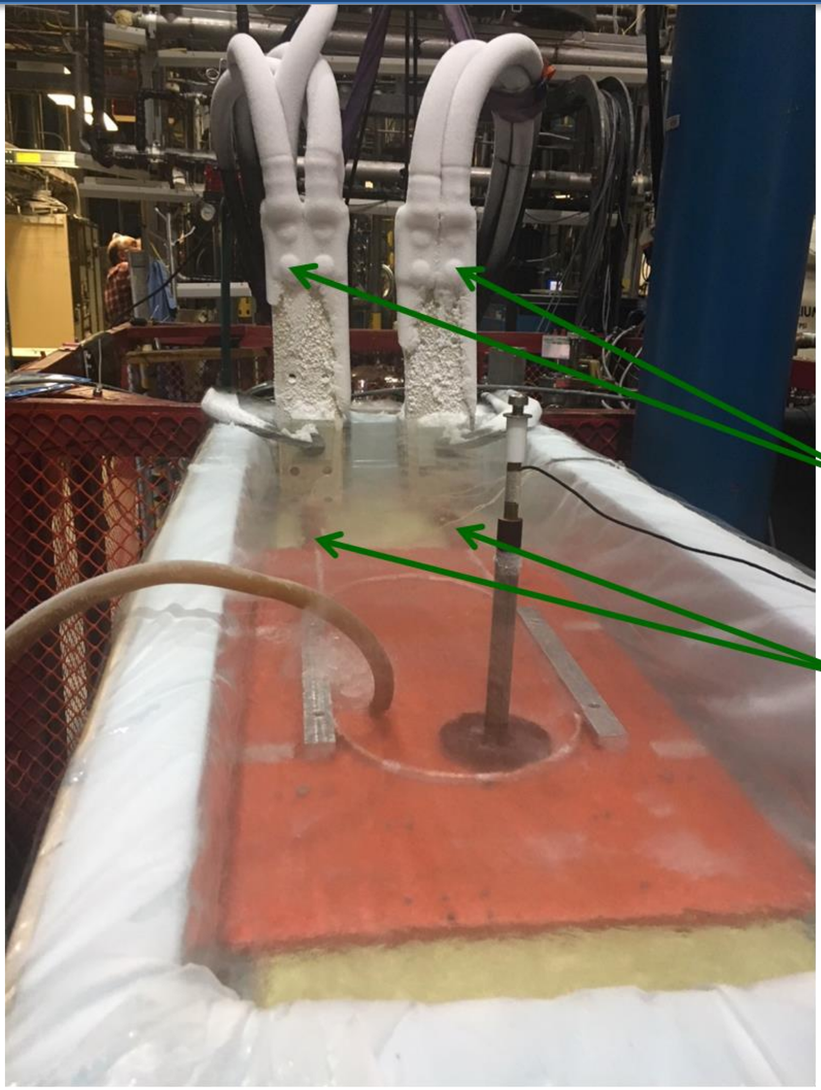
CORC Test Setup

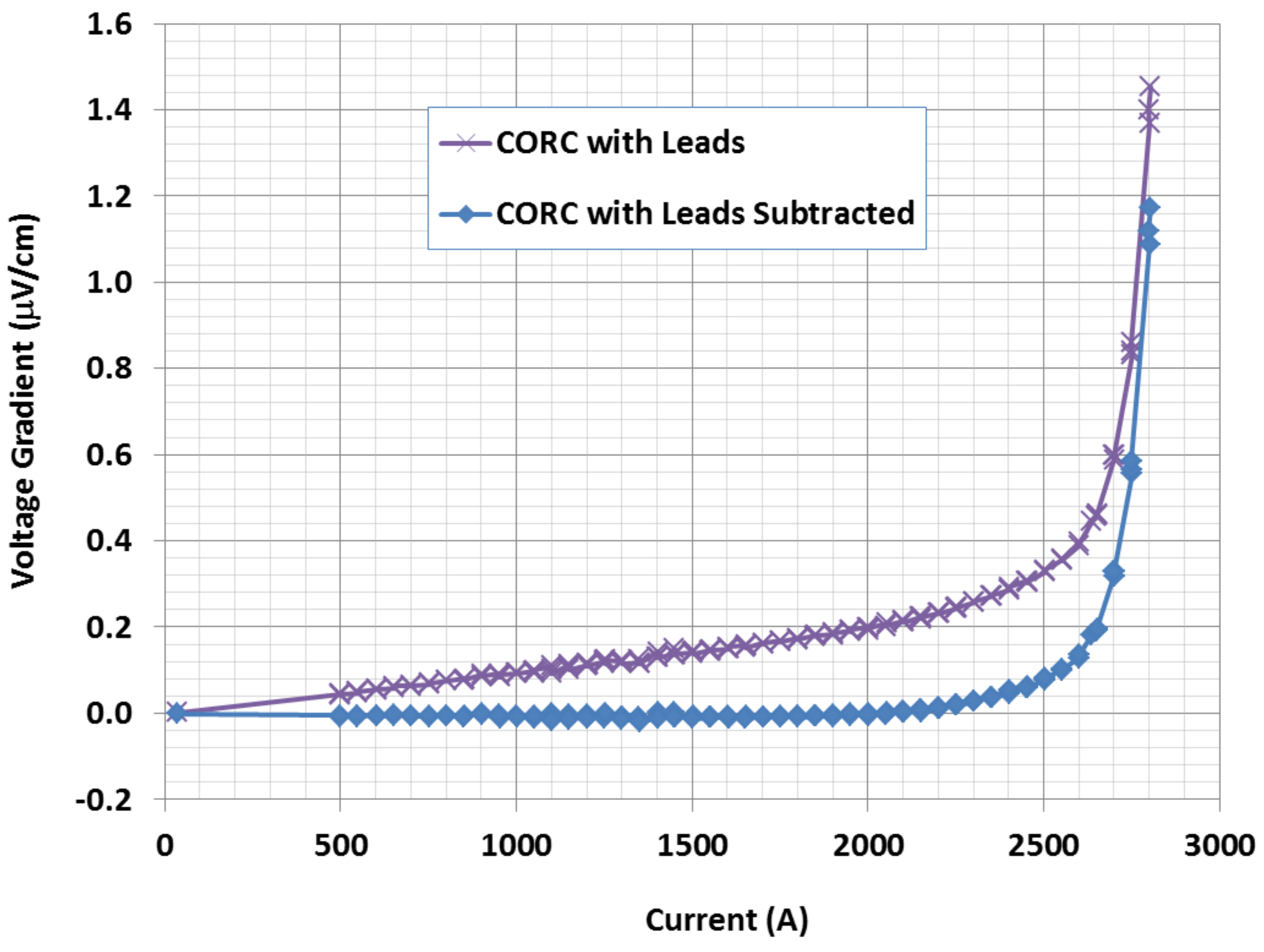


Heavy leads and significant part of the current feed in LN2 to minimize resistive lead voltage (~10 mV out of >300 mV, assuring most coming from CORC)

Additional v-taps on the back

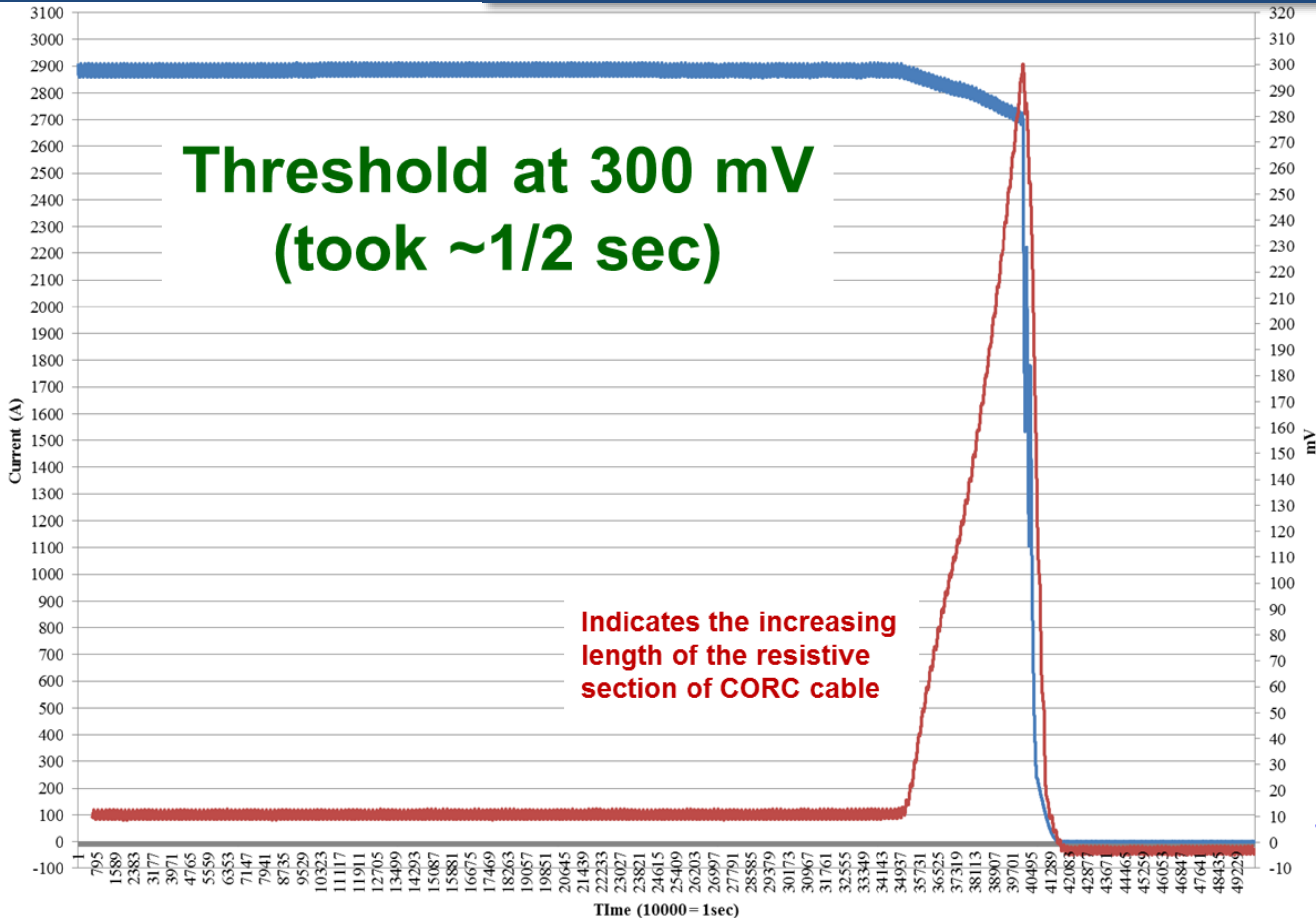
Original v-taps

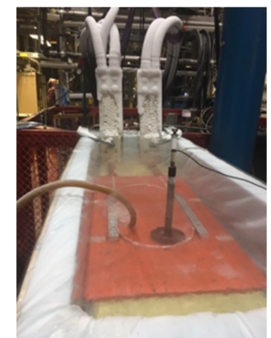
Measurements at the original V-taps



Measurements at the additional v-taps on the leads (data recorded with fast logger every 100 microsec)

77 K Test to ~3000 A





Lead resistive voltage: ~10mV

Power supply feedback slow
(not able to maintain constant current)

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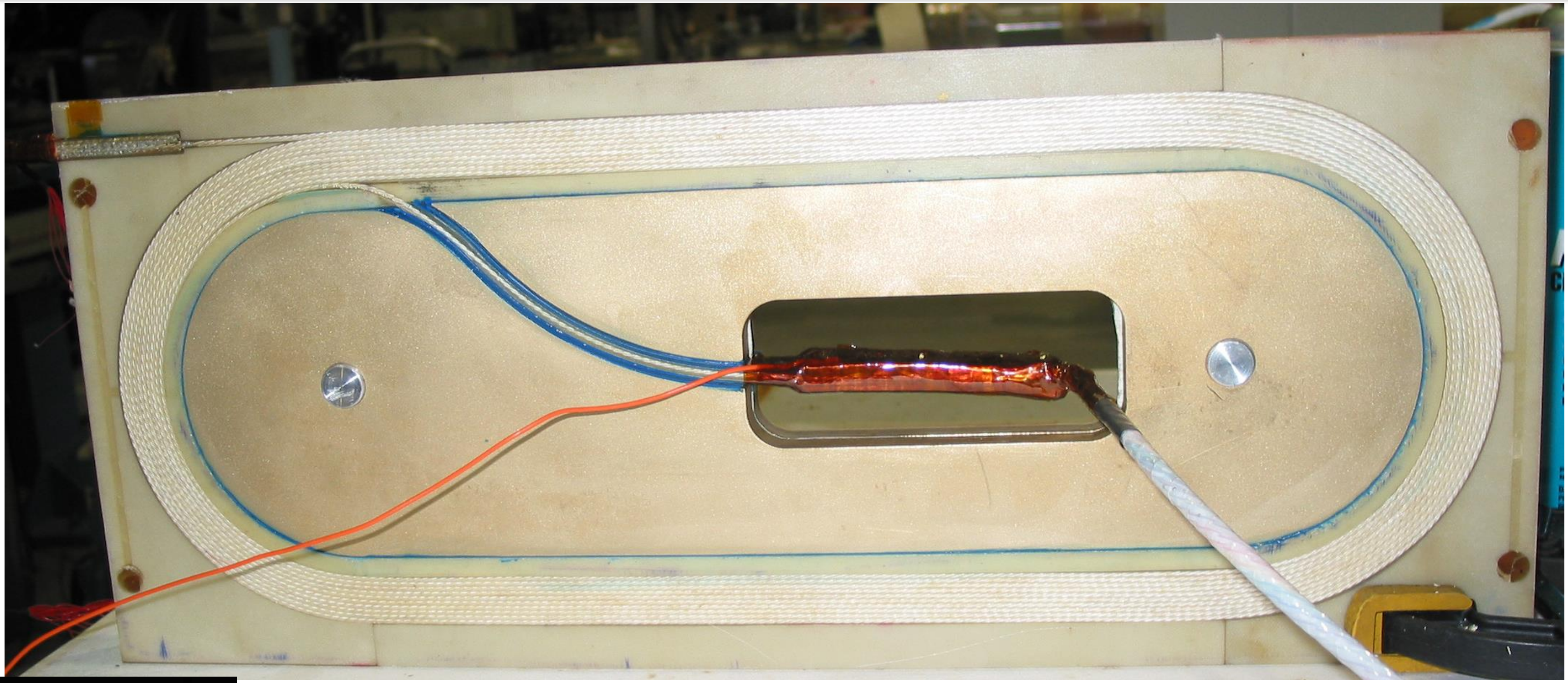
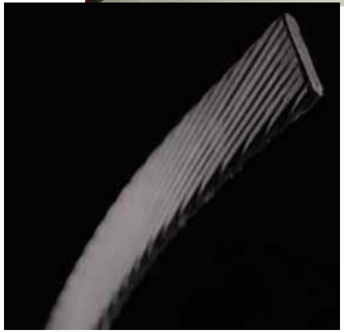
HTS Coil with Bi 2212 Rutherford Cable (React & Wind)





Several Bi2212 cable racetrack R&D coil built and tested at BNL.

Minimum bend radius 70 mm; Cable thickness ~1.6 mm.

Bending strain 1.4% or 0.7% depending on whether the wires in the cable are sintered or not.

Bi2212 Ruther Coils and Magnets

TABLE II

COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. I_c IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

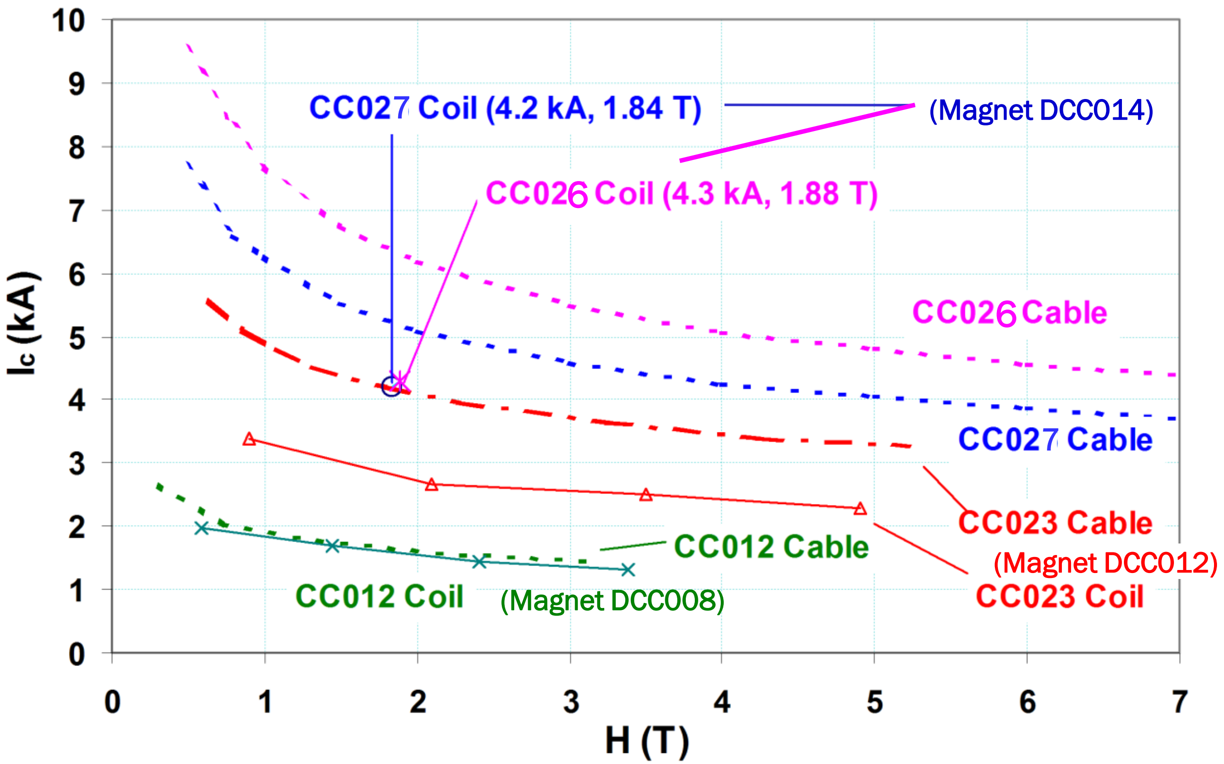
Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands	Common coil configuration	900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	2 HTS coils (mixed strand)	94	91 [41]	0.023
CC011 DCC006	0.81 mm wire, 2 HTS, 16 Ag	74 mm spacing Common coil	182	177 [80]	0.045
CC012 DCC008	0.81 mm wire, 18 strands	Hybrid Design 1 HTS, 2 Nb_3Sn	1970	212 [129]	0.66
CC023 DCC012	1 mm wire, 20 strands	Hybrid Design 1 HTS, 4 Nb_3Sn	3370	215 [143]	0.95
CC026 DCC014	0.81 mm wire, 30 strands	Hybrid Common Coil Design	4300	278 [219]	1.89
CC027 DCC014	0.81 mm wire, 30 strands	2 HTS, 4 Nb_3Sn coils (total 6 coils)	4200	272 [212]	1.84

Five Accelerator Type R&D Magnets

HTS from Showa
Cables made at LBL
All React & Wind

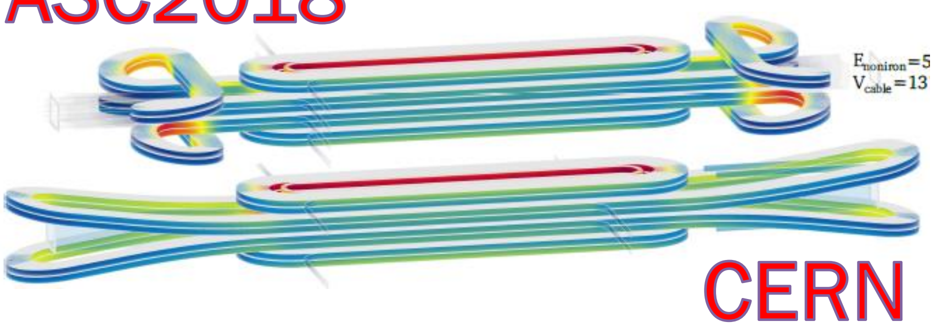
Bi2212/Nb_3Sn Hybrid Dipole

HTS/LTS Hybrid Magnets (background field provided by Nb_3Sn)



Freeway Overpass/UnderPass (or clover-leaf) Ends

ASC2018



- HTS test coil wound in Phase I with e2P/BNL SBIR

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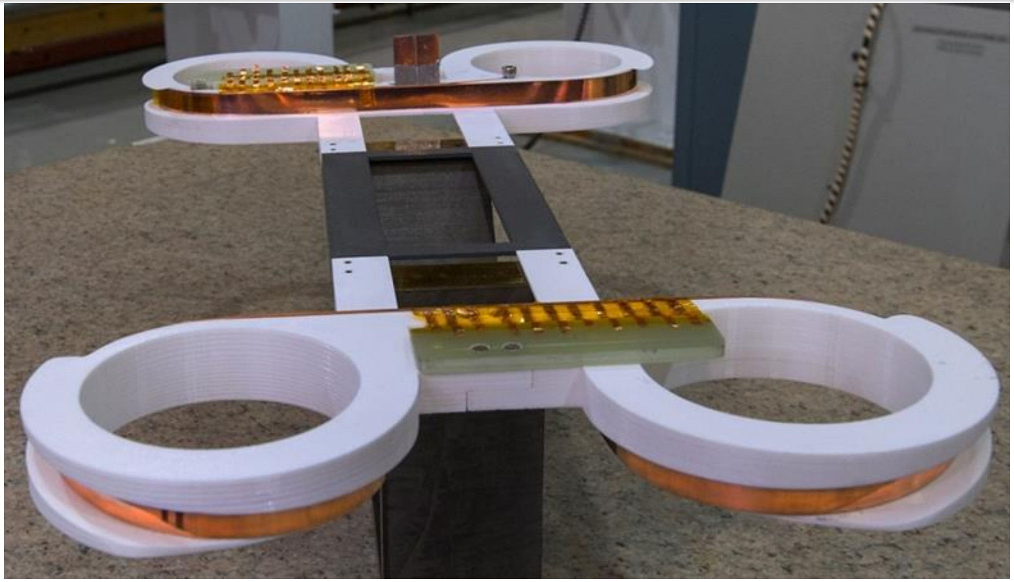
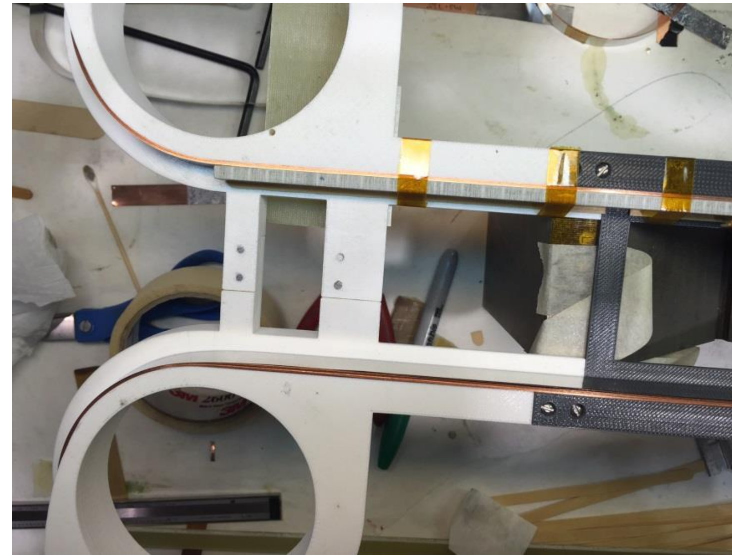
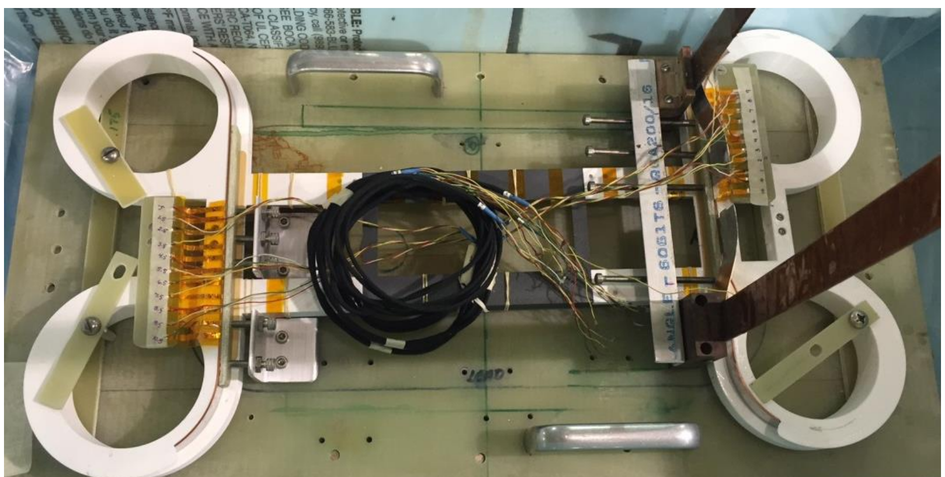
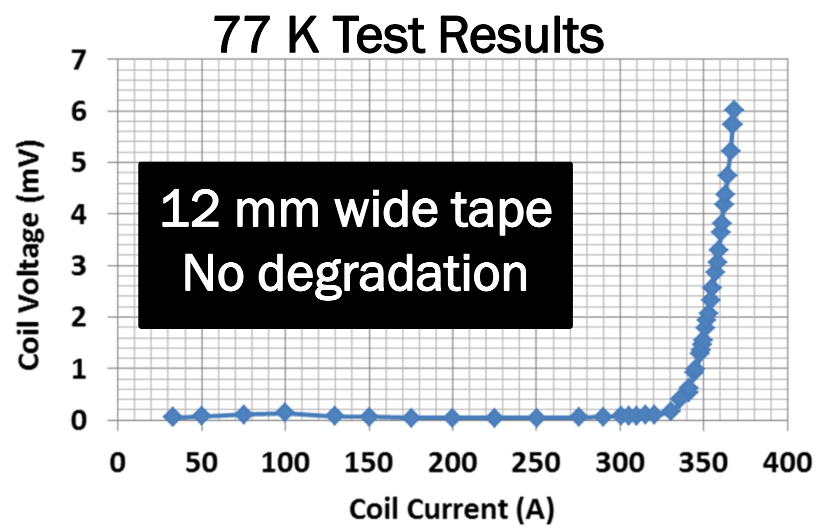
Demonstrations of the Overpass/Underpass in Phase I





SBIR with e2P





PBL/BNL STTR on HTS/LTS Hybrid Dipole

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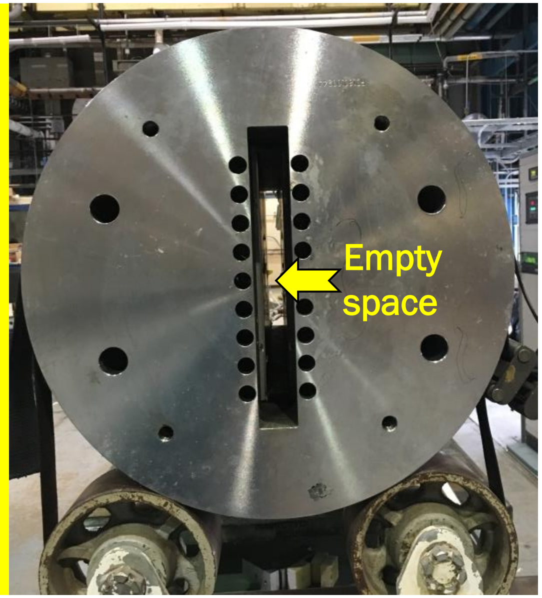
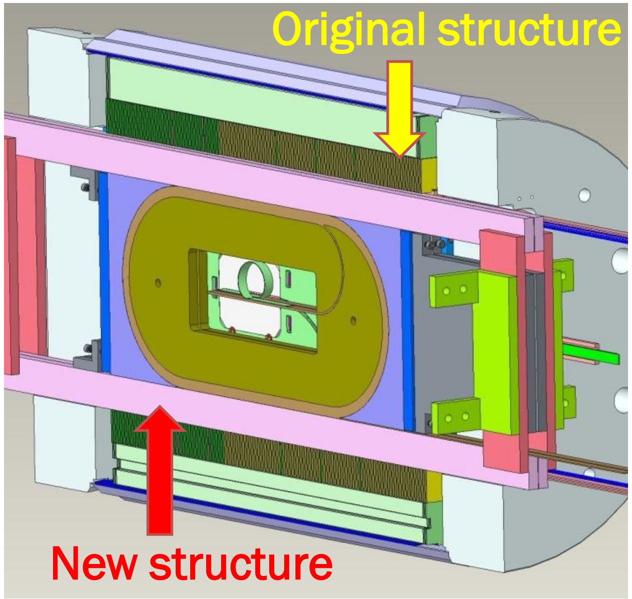
A unique feature of BNL's common coil dipole: large open space for inserting & testing "coils" without any disassembly (rapid around, lower cost)

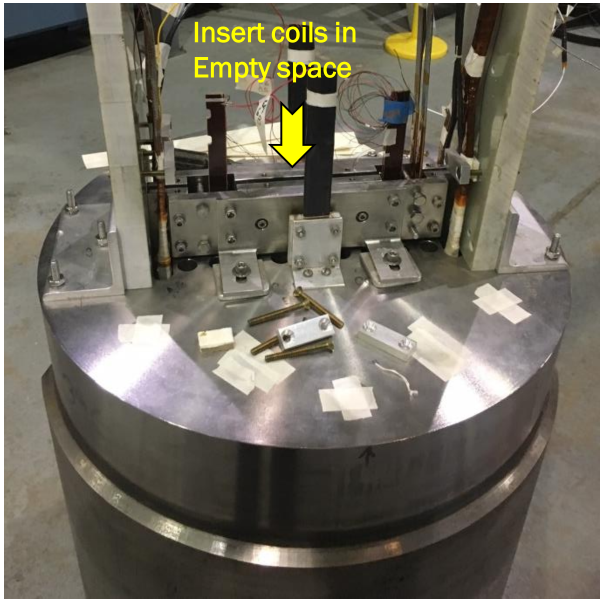
STTR Phase II for (1) Demonstration and protection of High field HTS/LTS hybrid dipole (2) measurement of field ~~parallel and~~ perpendicular field quality



BNL Nb_3Sn common coil dipole DCC017 without insert coils



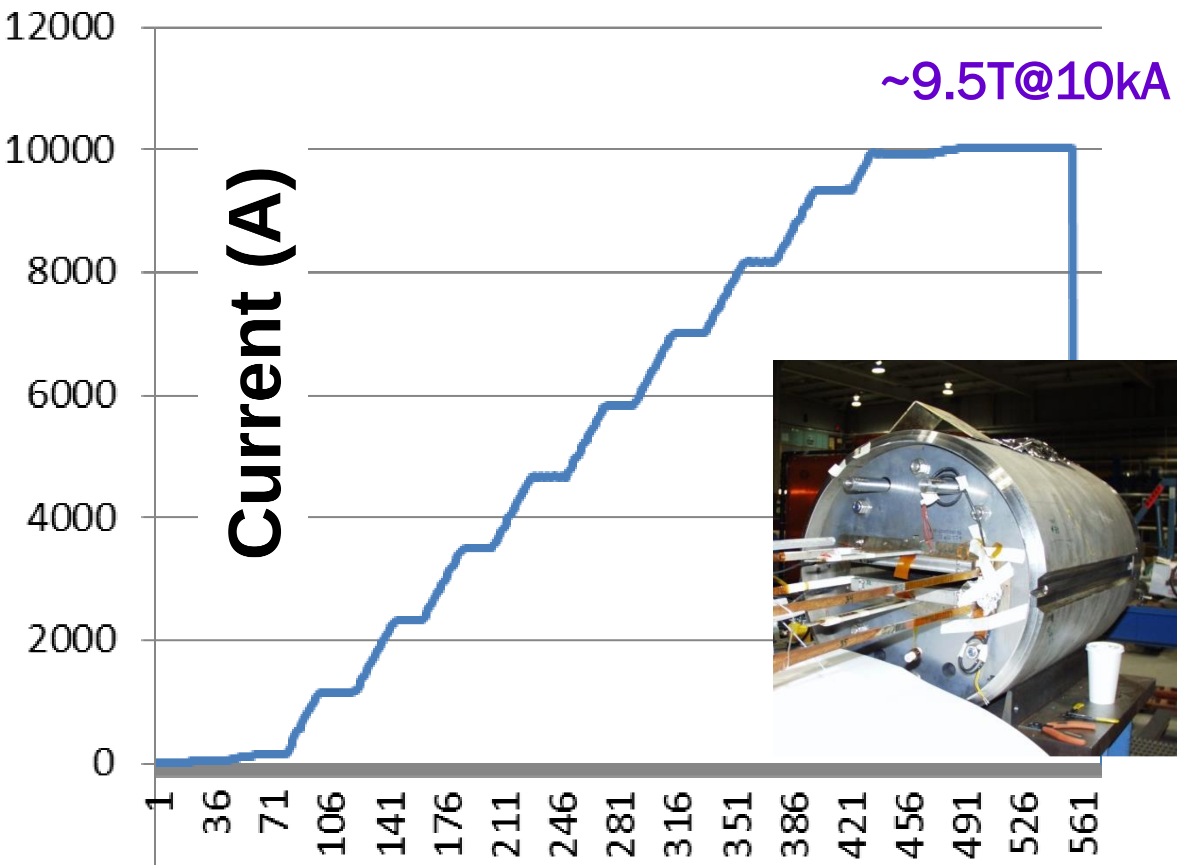
New HTS coils with the existing Nb_3Sn coils and become part of the magnet



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

Retest of Nb_3Sn Common Coil Dipole After a Decade

- **Short Sample: 10.8 kA/10.2 T (reached during 2006 test)**
- **Retest: No quench to 10 kA/9.5 T (>92% of quench, leads limited)**



A reliable magnet for test facility

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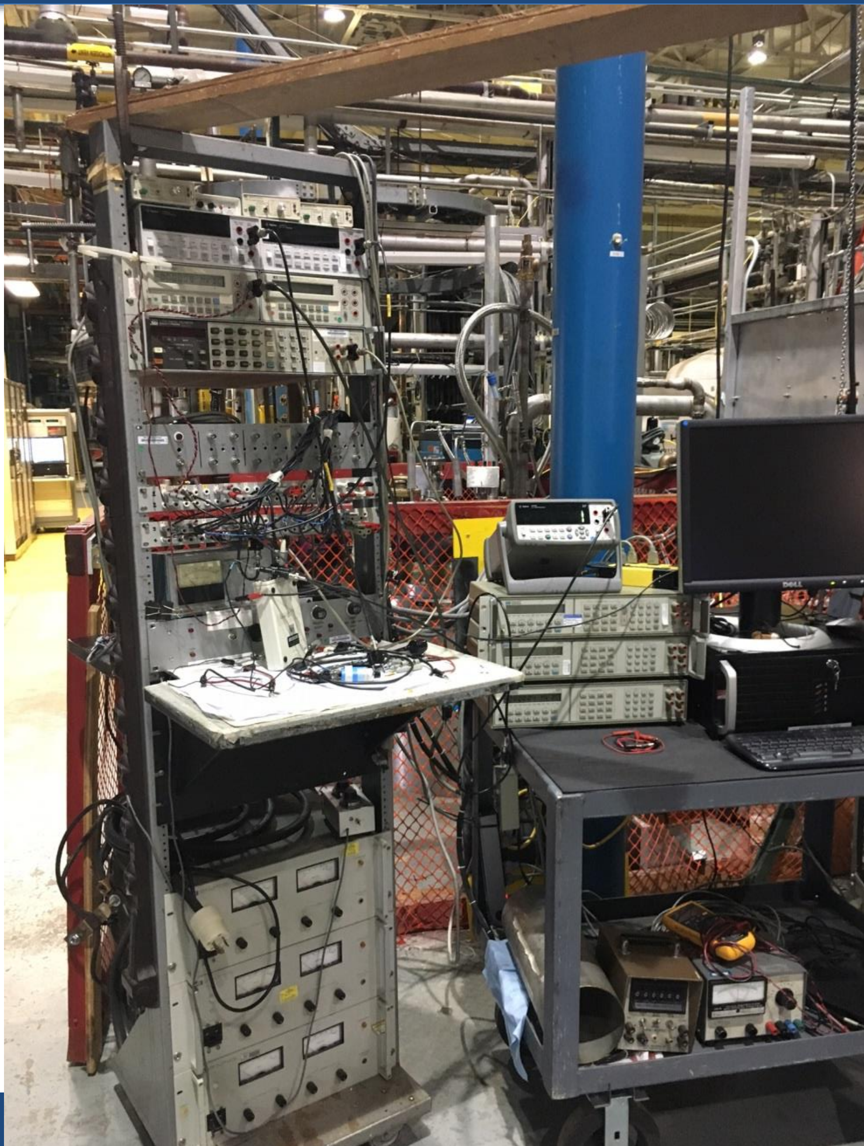
HTS Quench Protection



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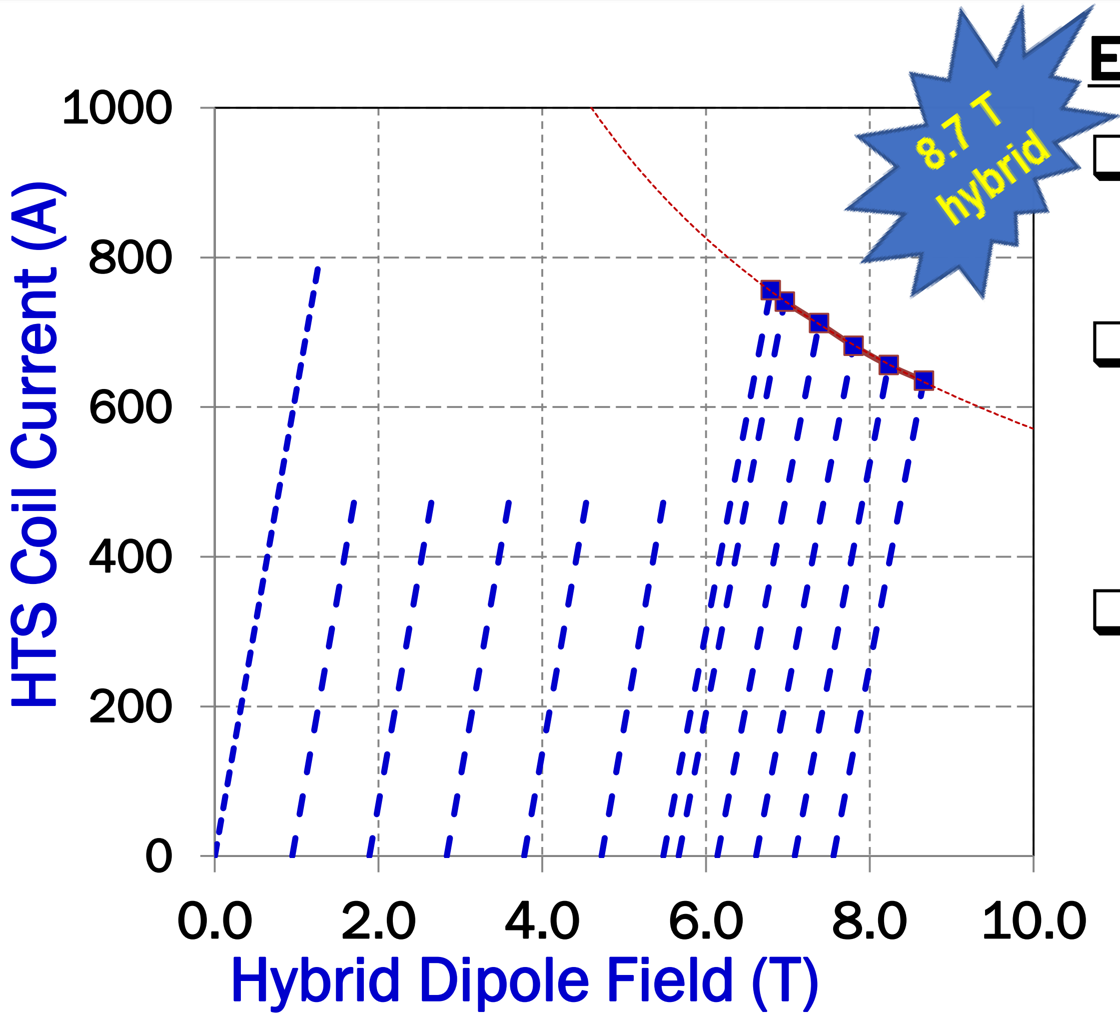
HTS Coil Quench Test in HTS/LTS Hybrid Dipole Structure



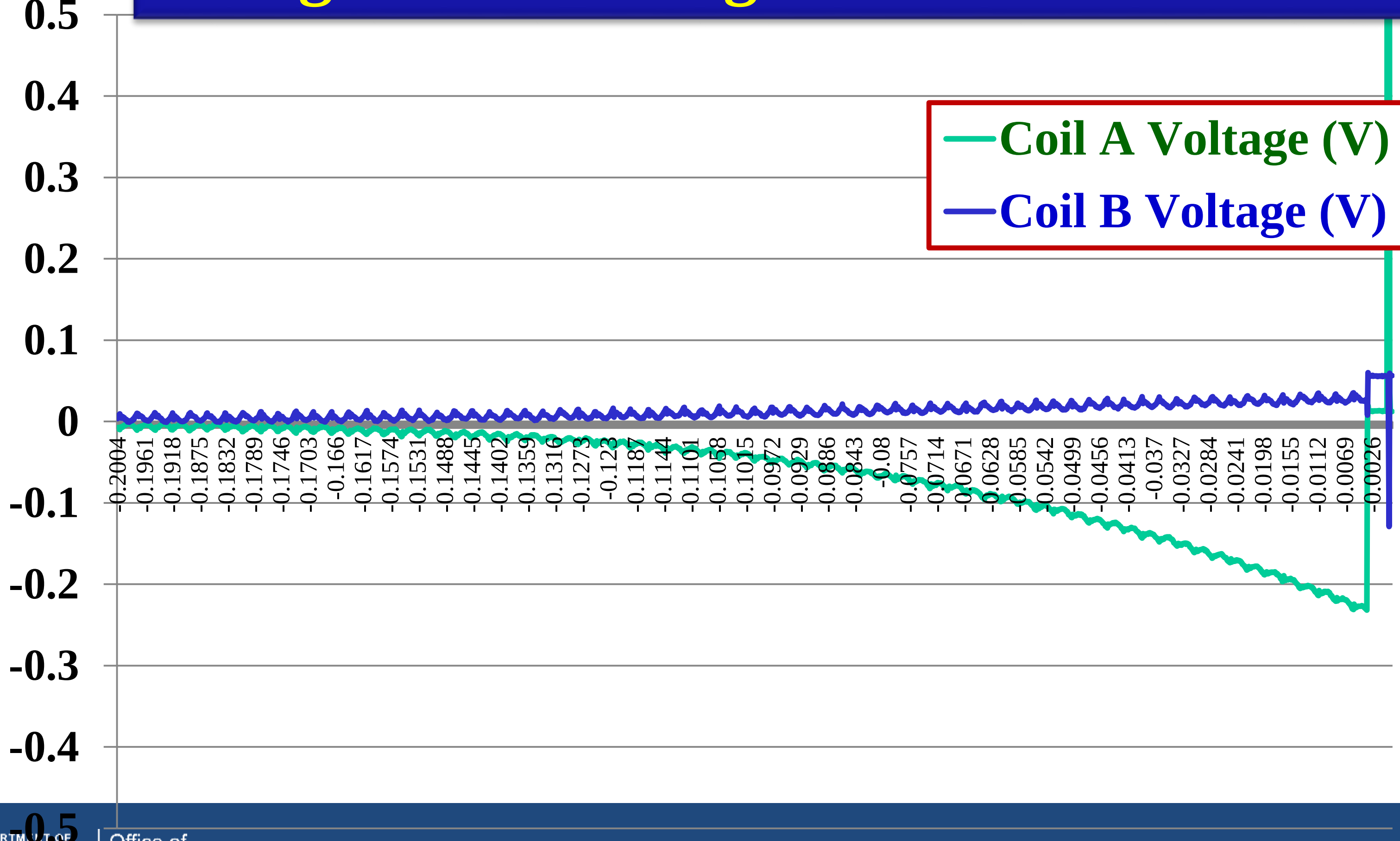
Encouraging Results:

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

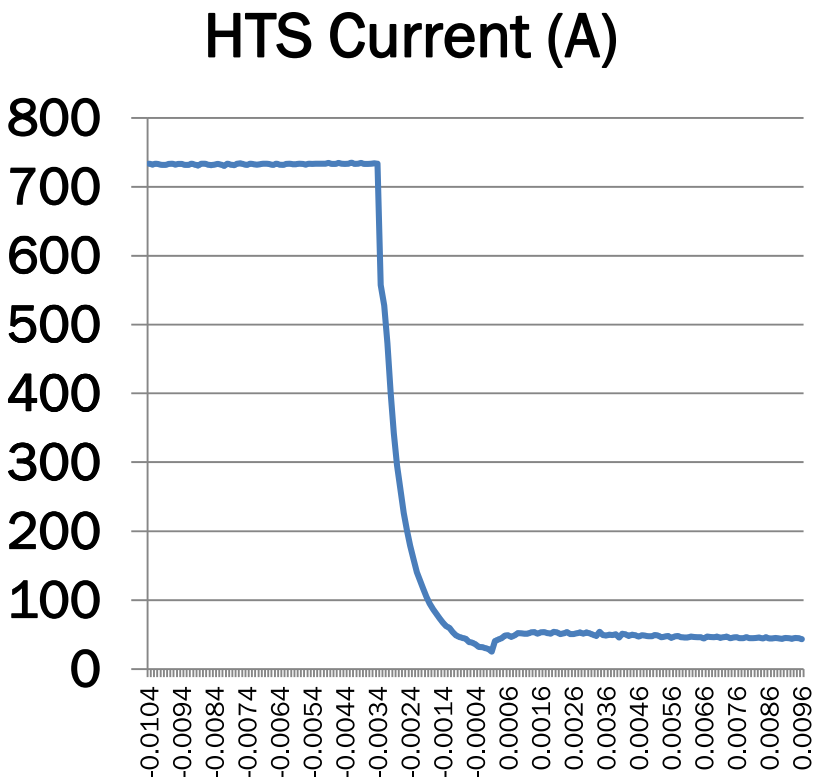
Operation of HTS Coils

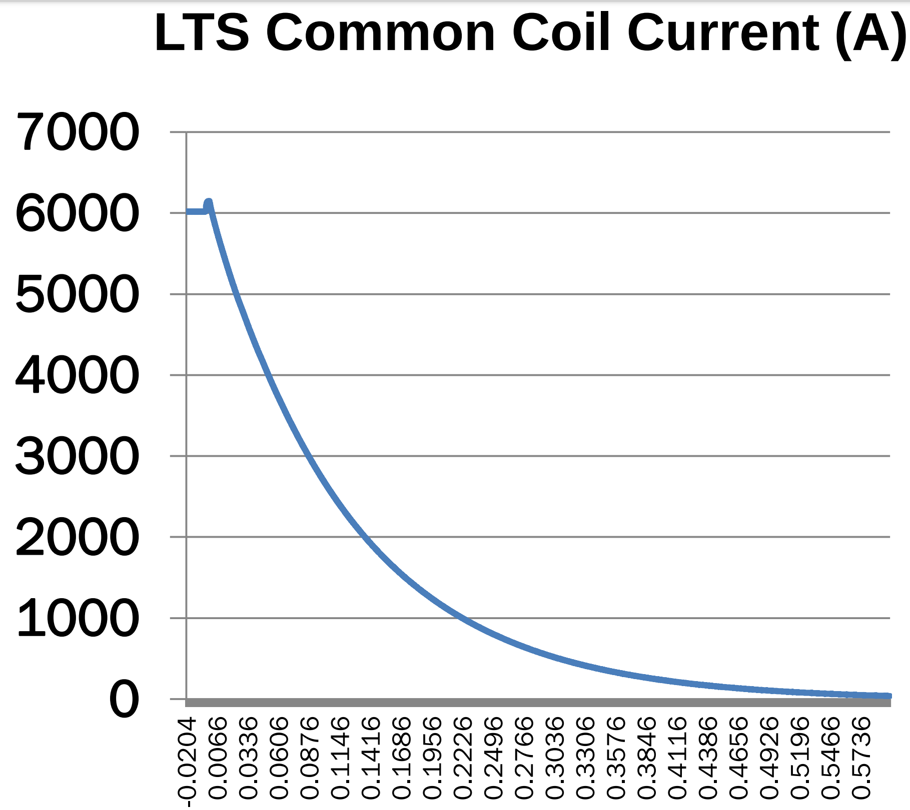
HTS coils operated like LTS coils

- ❑ Significant voltage in HTS coils: >0.2 Volts



HTS and LTS Currents (just before and after the quench)





Separate power supplies and separate energy extraction for HTS and LTS coils
HTS and LTS coils have different inductances and different characteristics

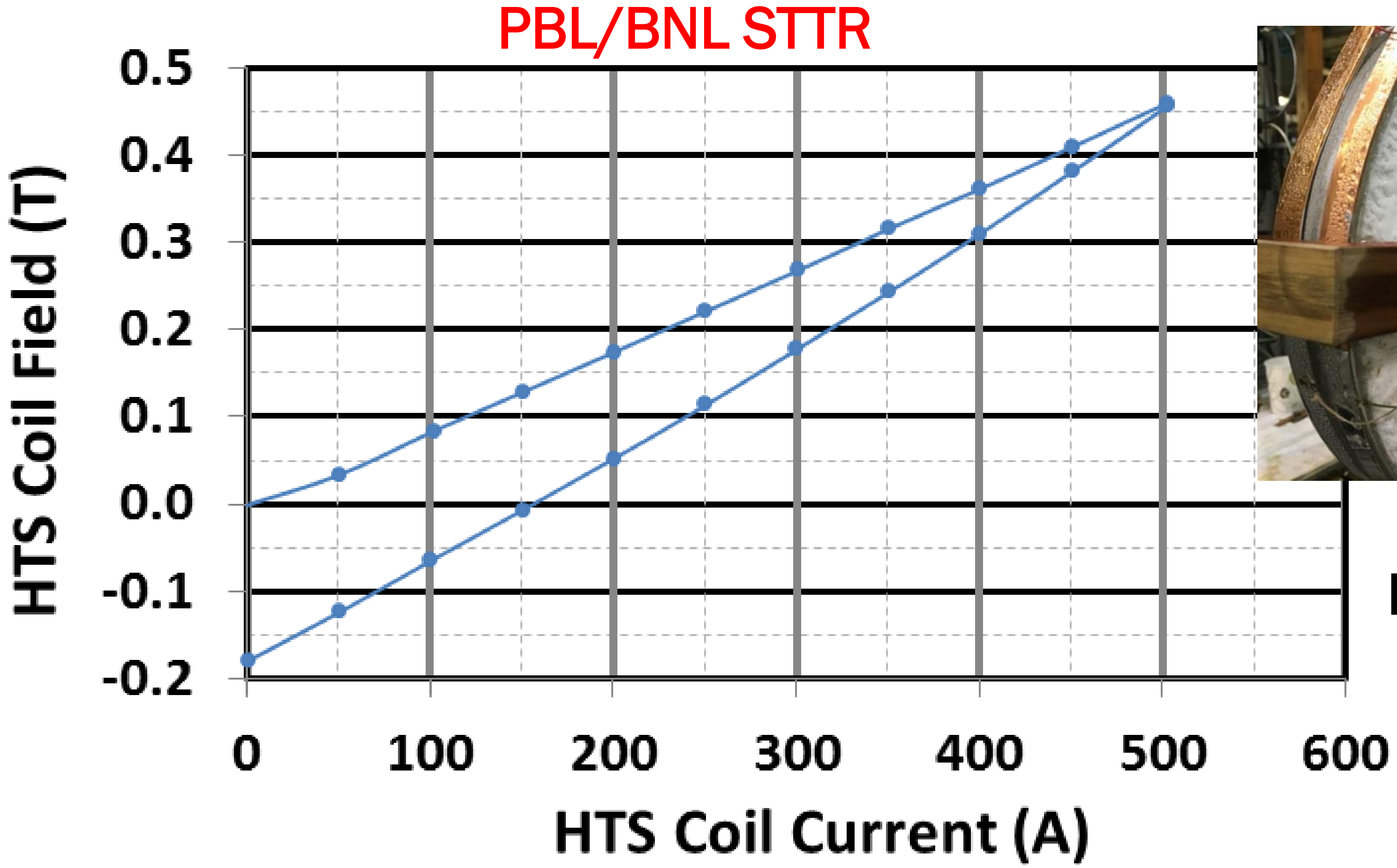
Magnetization studies in high field at 4 K in magnets made with the HTS tapes

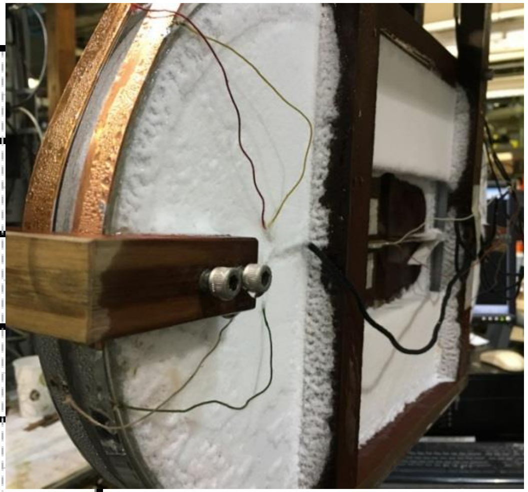
(Hall probe measurements)

- A select data presented in a couple of slides.
- A significantly more data available.

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

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

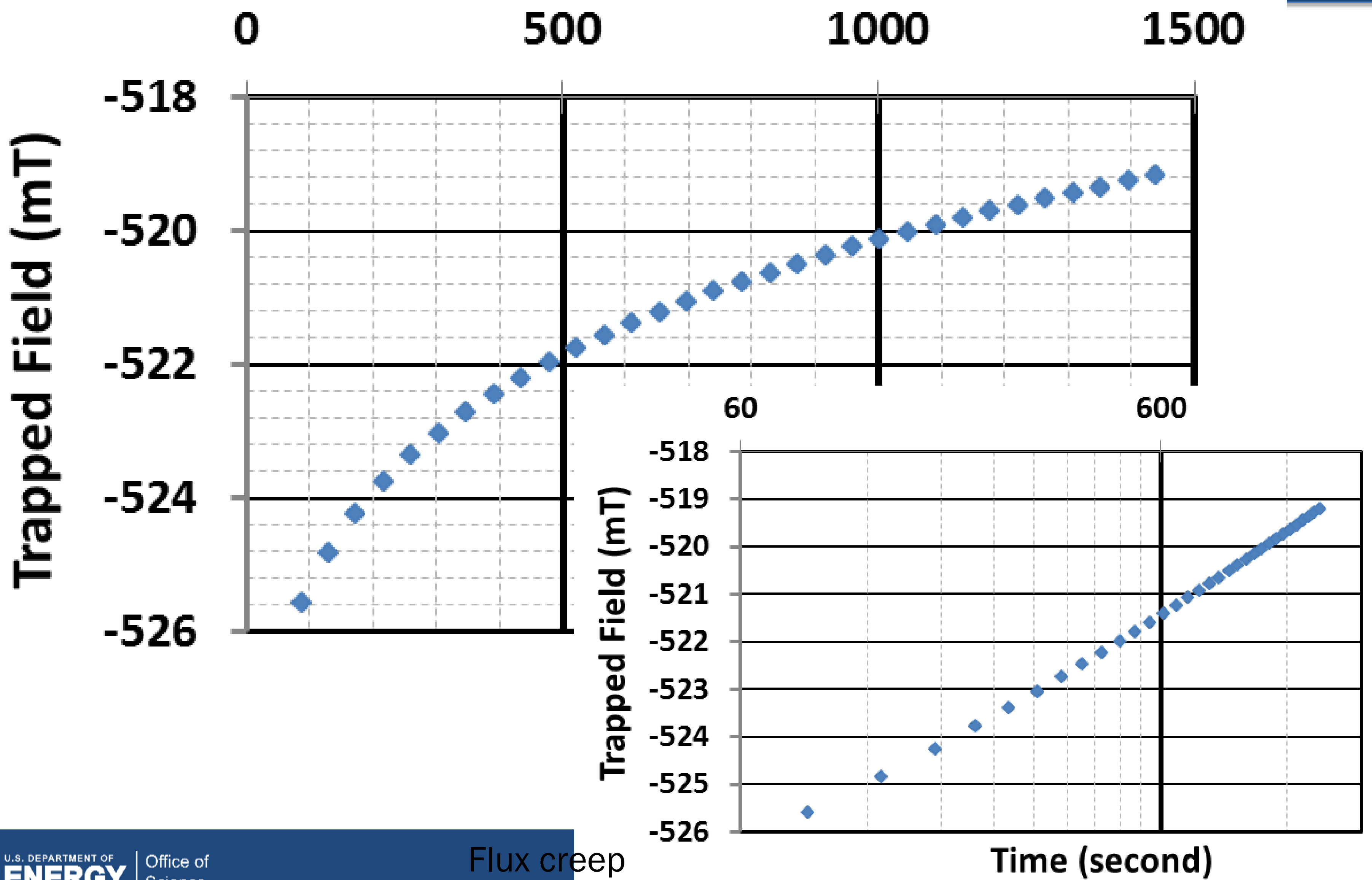




field perpendicular configuration

Decay of Trapped Field

(after the final run to ~8.7 T hybrid field @ 4 K)



Flux creep

Summary and Conclusions

- **With it's vast and unique experience with various HTS, BNL can provide a strong contribution to US high field Magnet Development Program, particularly in the area of HTS magnets**
- **With a unique team experienced in large scale magnet productions in partnership with industry for superconducting colliders, BNL can help develop HTS magnets that industry can build**
- **BNL common coil magnet provides immediately a unique fast turn around, low cost magnet development test facility**
- **BNL can make unique and significant contributions by providing answers to key basic science and technology within a year**

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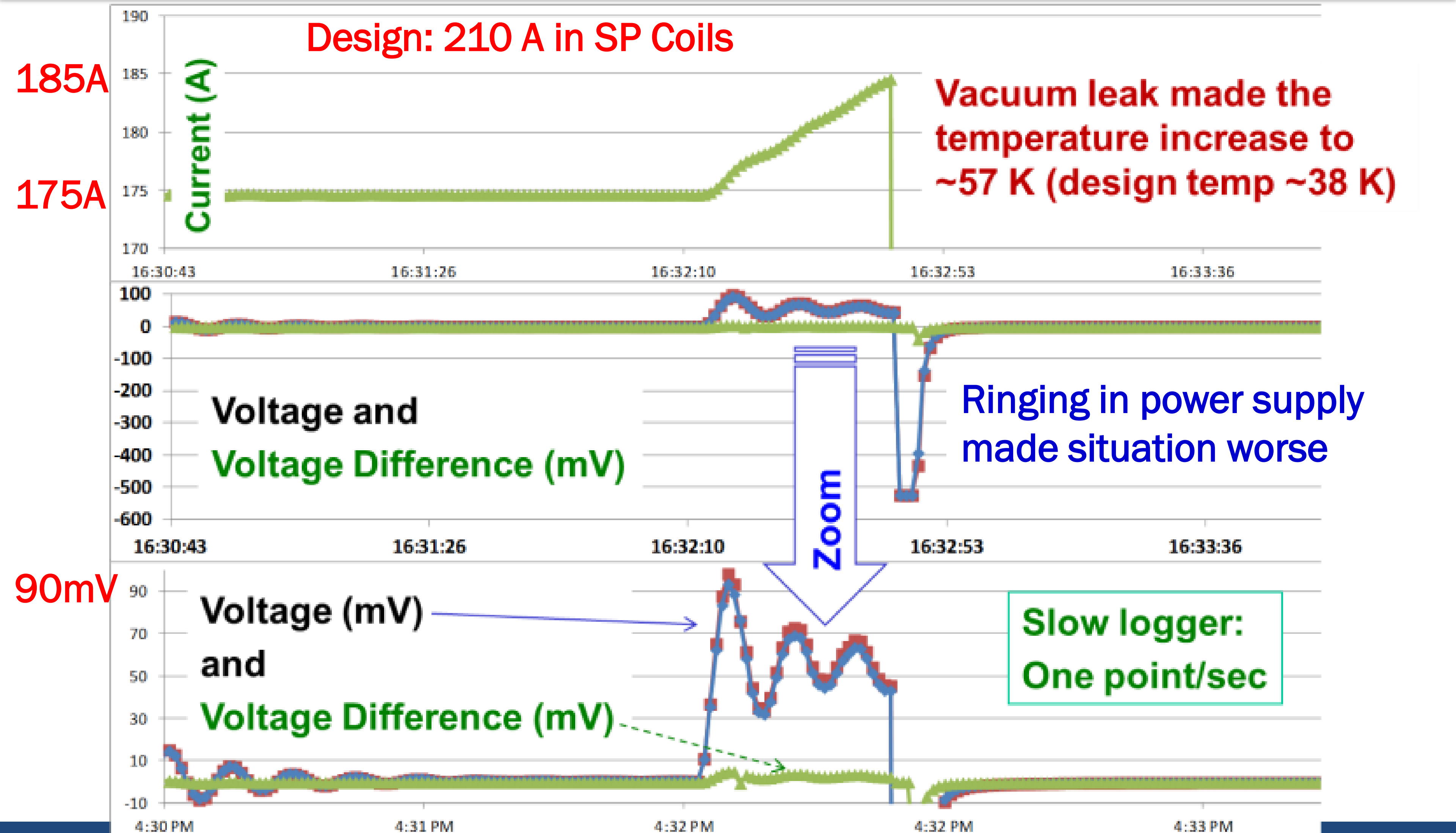
Extra Slides on FRIB Quench Studies

Protection of HTS Magnet During an Operational Accident Near Design Current



Snap Shot of the Event (Quench?) that Triggered the Shut-off

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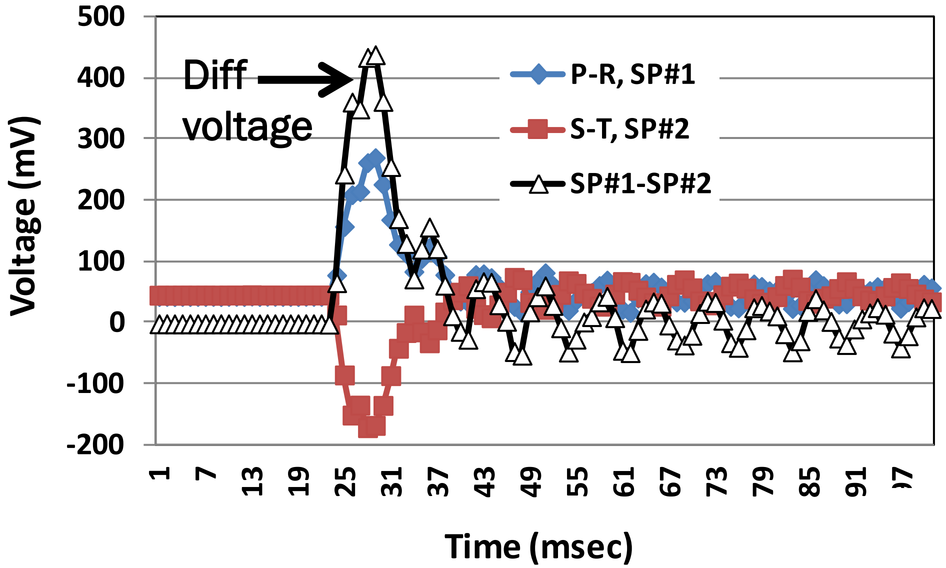
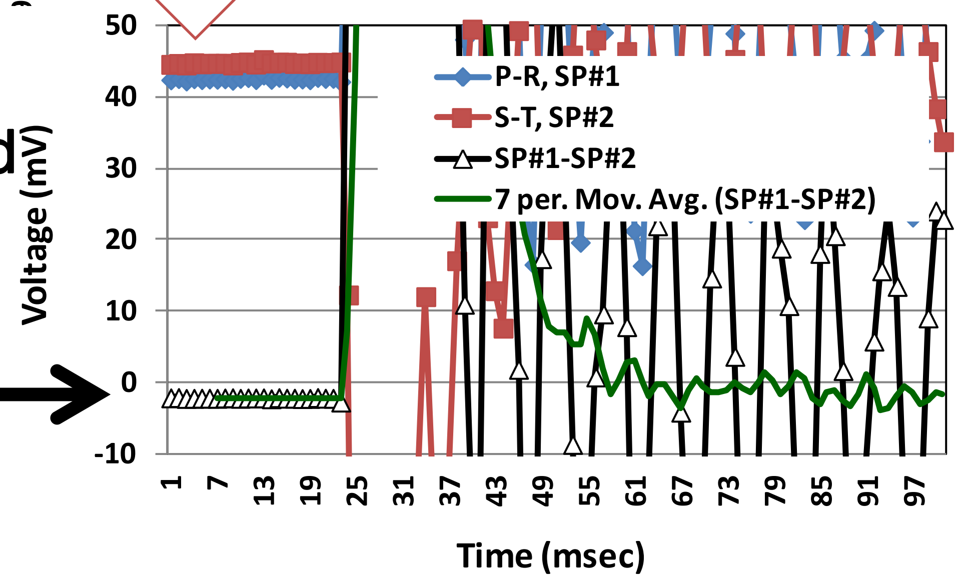


Fast data logger:
One point/msec

Large inductive voltage in individual coils (ramp)



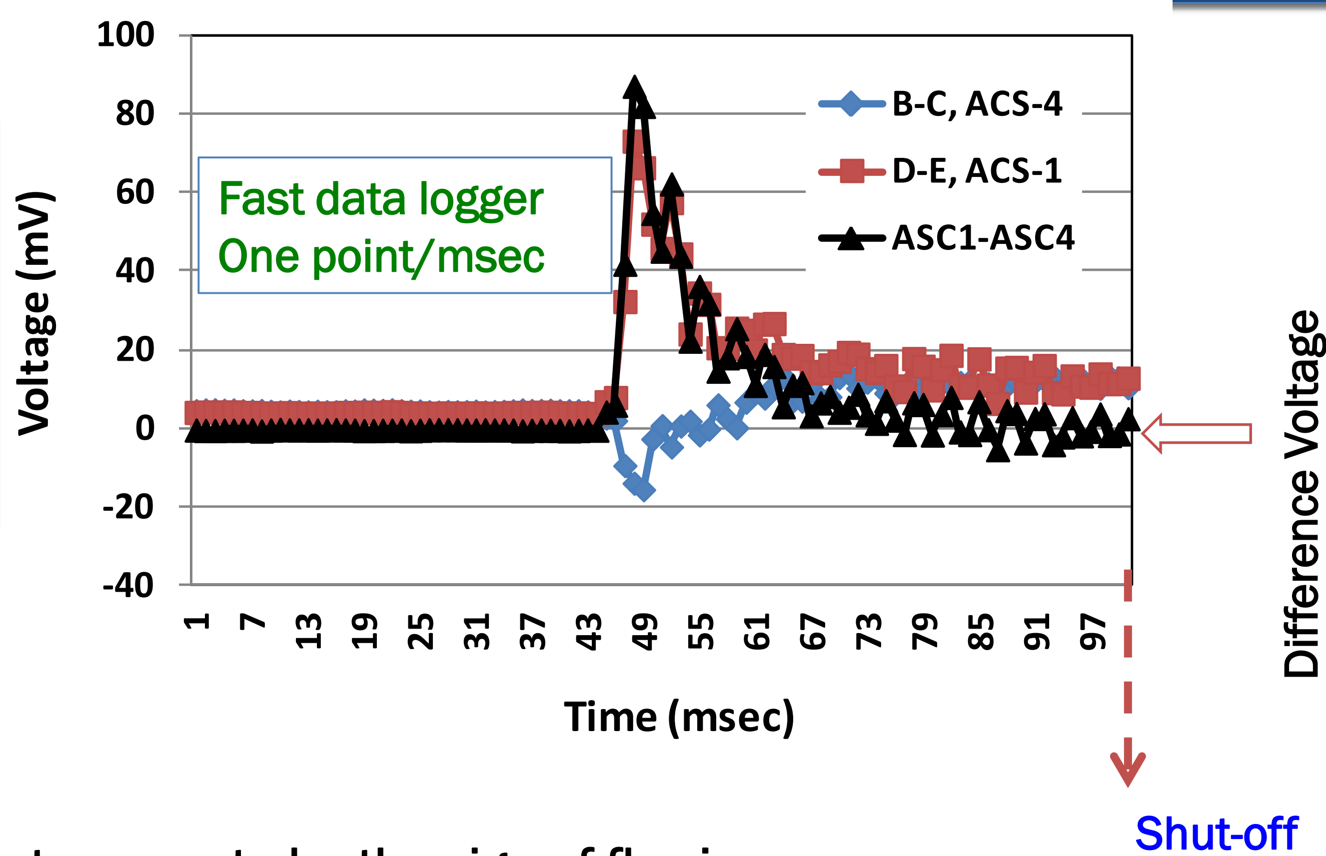
Small quench detection threshold (2 mV) kept during the ramp by monitoring difference voltage

No degradation in coil performance after the event

Event (Quench?) while ASC Coils were held at 382 A (design: 310 A) at ~50 K (design: 38 K)

Snap Shot of the Event in ASC Coils (individual and difference voltages)

Event at (a)12 K above the design temperature and (b) at 24% above design current



- This and previous event appear to be the sign of flux jump
- This exceeded quench threshold, triggered shutoff & energy extraction

No degradation in coil performance observed

Operation Well Beyond the Quench Detection Threshold Voltage (~ mV)

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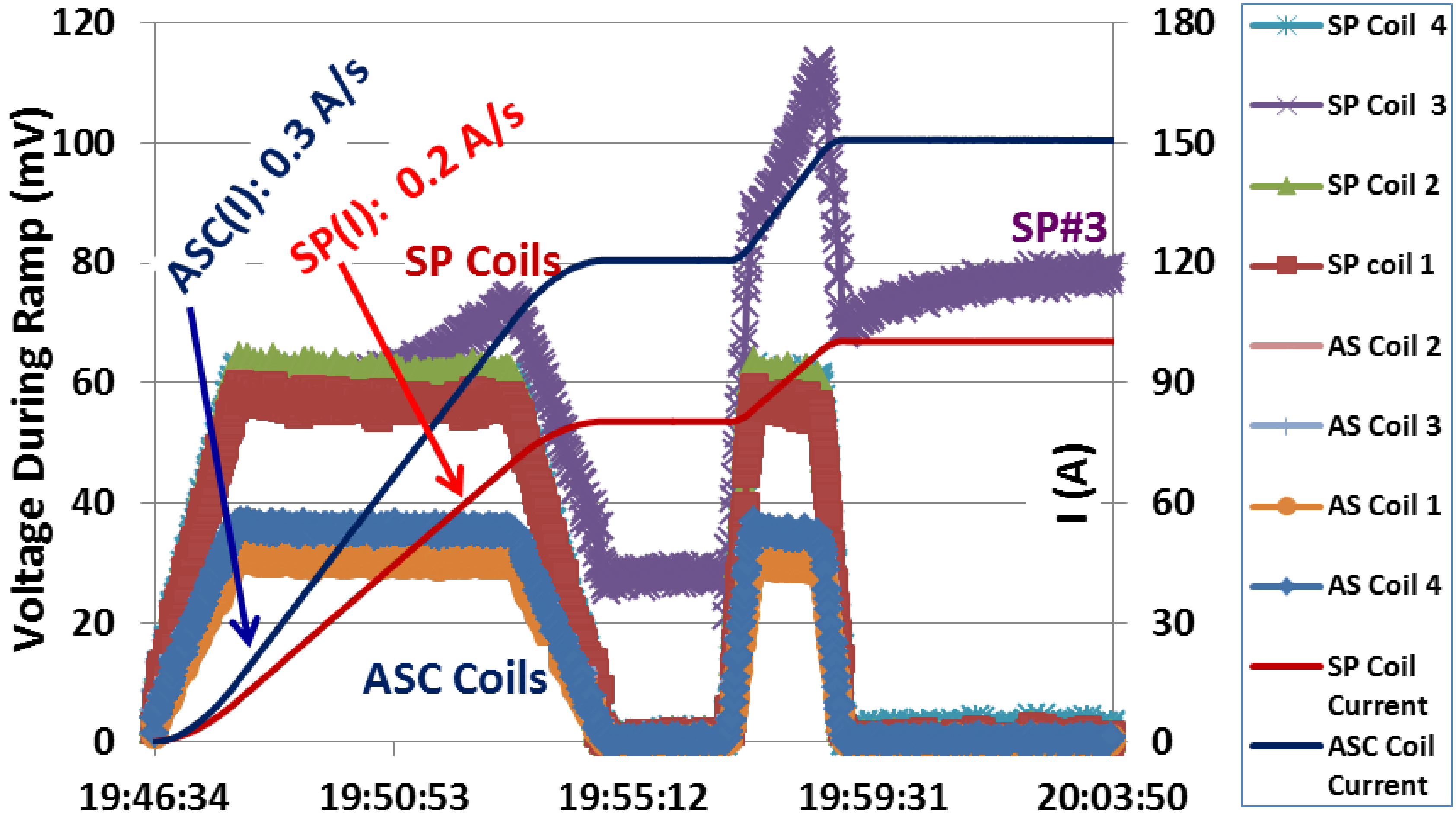

Test temperature: ~67 K
(ASC to 150 Amp; SP to 100A)

Operated at about two order of magnitude beyond the quench detection threshold. No degradation in coil performance observed.