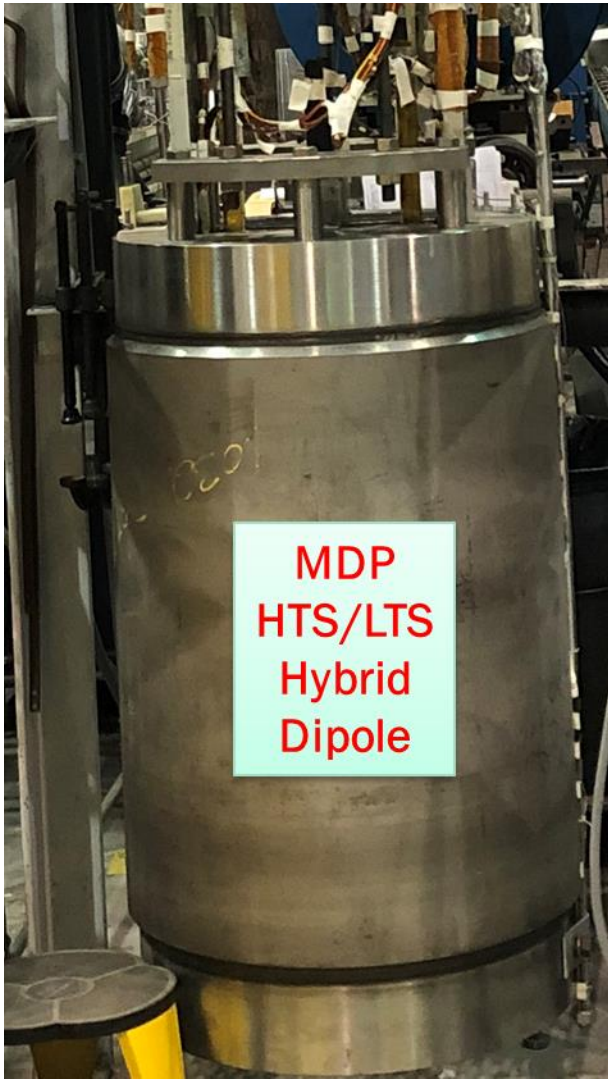
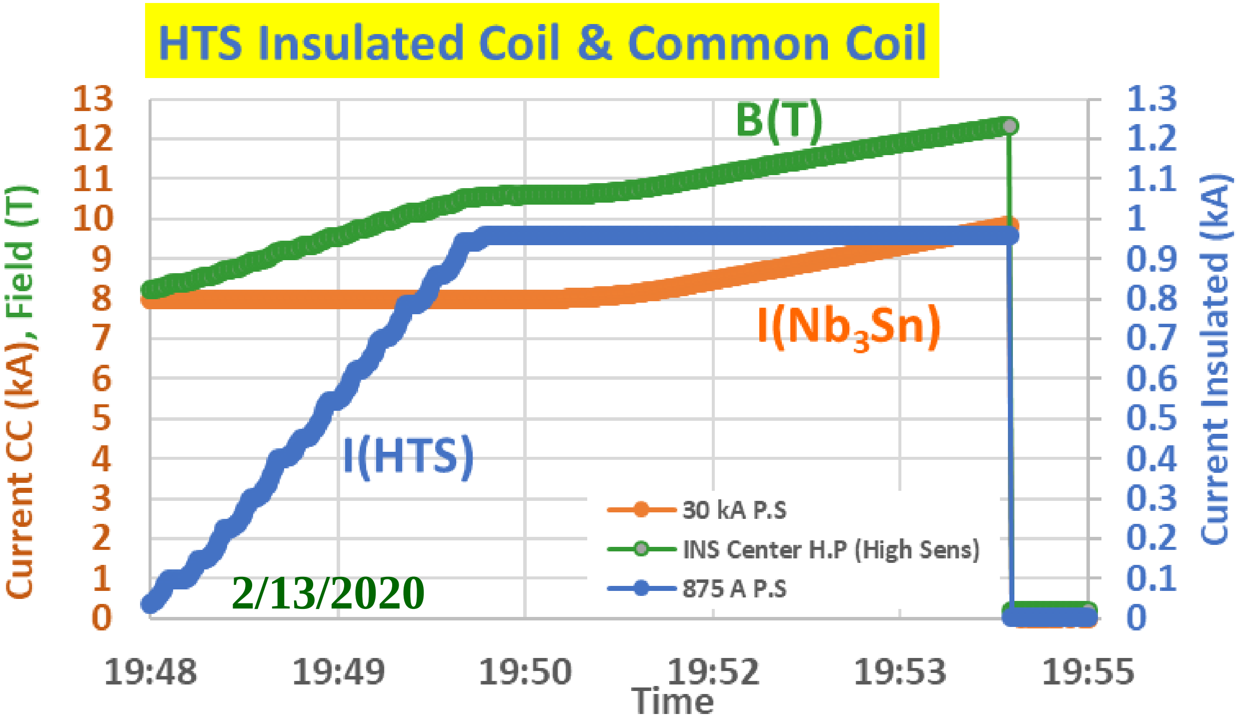
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

12 T HTS/LTS Hybrid Dipole Test Results



Ramesh Gupta, K. Amm, P. Joshi,
S. Joshi, W. Sampson, A. Ben Yahia

LTSW/HFSW2020, Berkley, CA



CONTENTS

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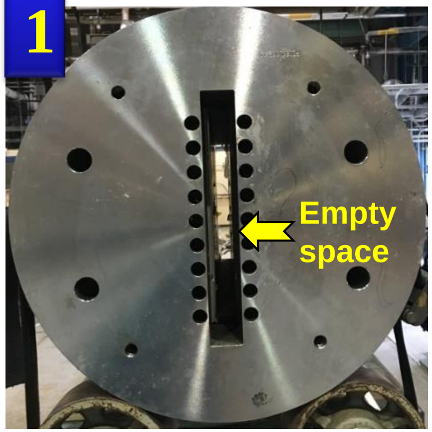
  - Overview of the rapid-turn-around test facility
  - 12 T HTS/LTS hybrid dipole (plus more) in <9 months
- Hybrid Dipole Design and Test Results
  - Two Nb_3Sn/HTS hybrid dipoles (HTS from SuperPower)
- Summary

Rapid-turn-around Facility for Magnet Technology Development

Five Simple Steps/Components

- 10 T, Nb_3Sn Dipole with a large open space for high field coil & cable testing
- Slide coil(s) in the magnet
- Coils become an integral part of the dipole magnet
- Magnet with new coil(s) ready for testing

1



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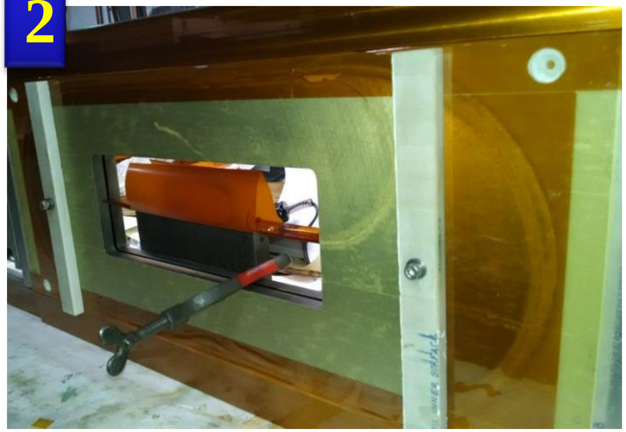

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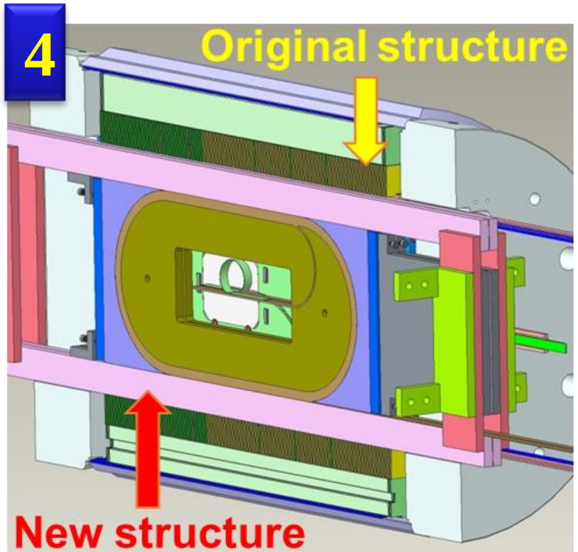

5

What can this unique 10^{+} T dipole do for your R&D?

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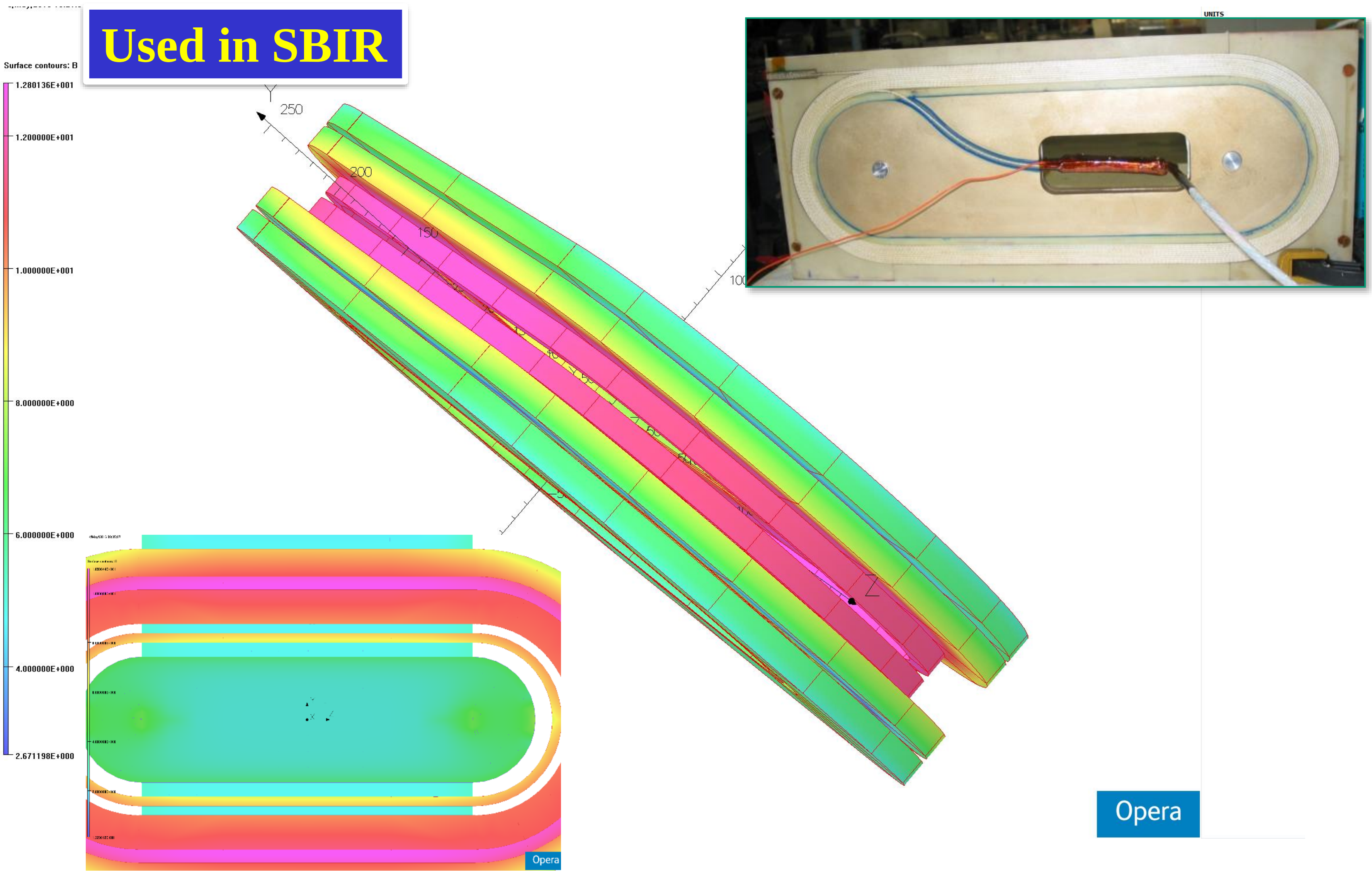
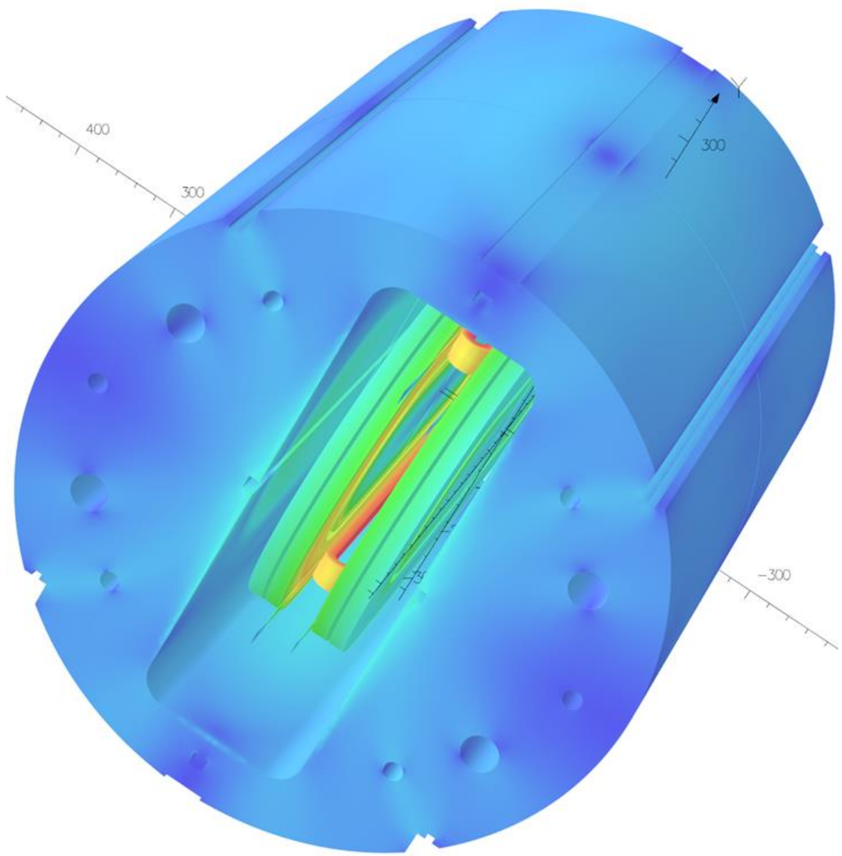
Test Insert Coils in Background Field (configuration #1)

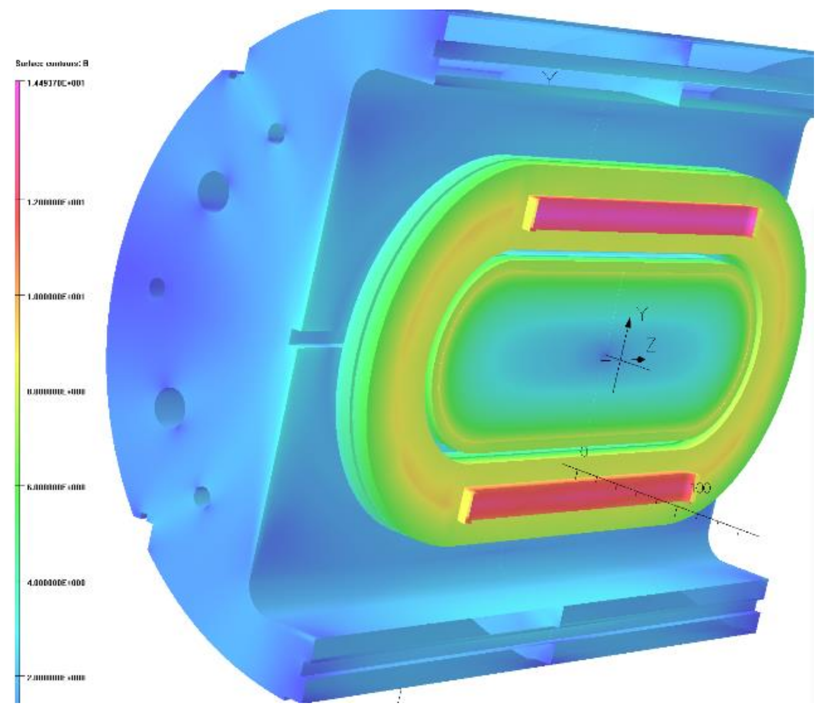
Used in SBIR



Test Insert Coils in Background Field (configuration #2)

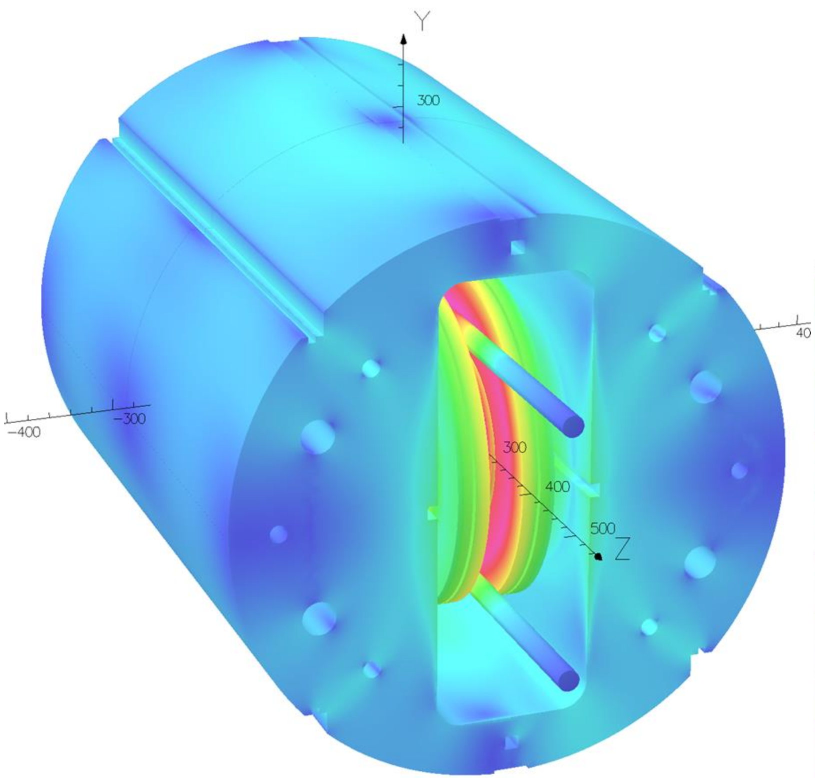
Used in MDP

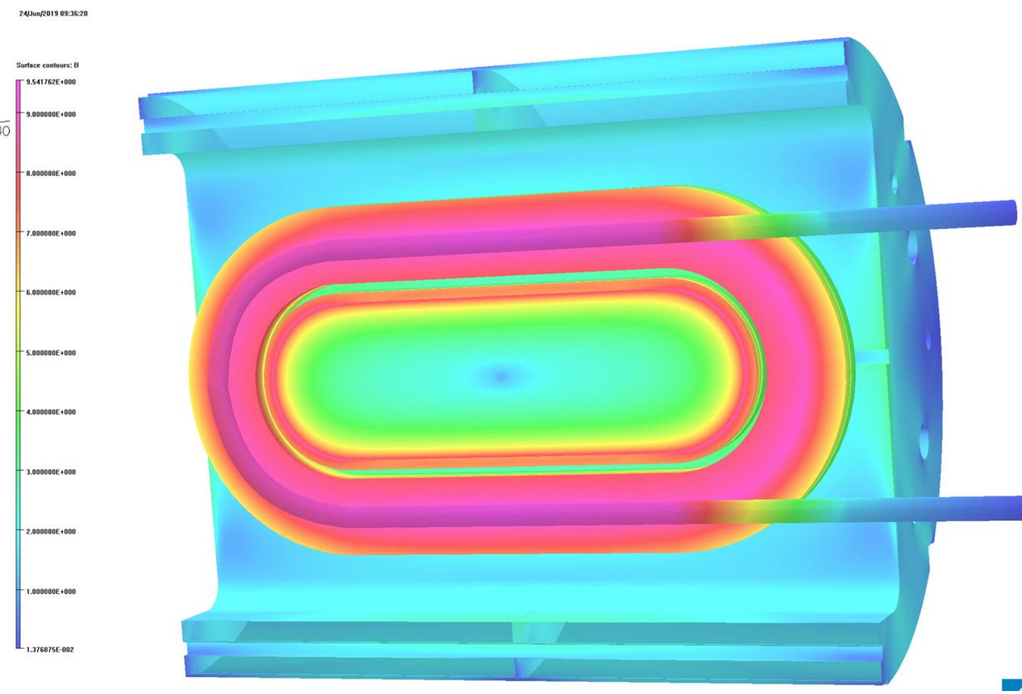




Test Cable (including those requiring high bend radius)

To be used in INFUSE (funded)



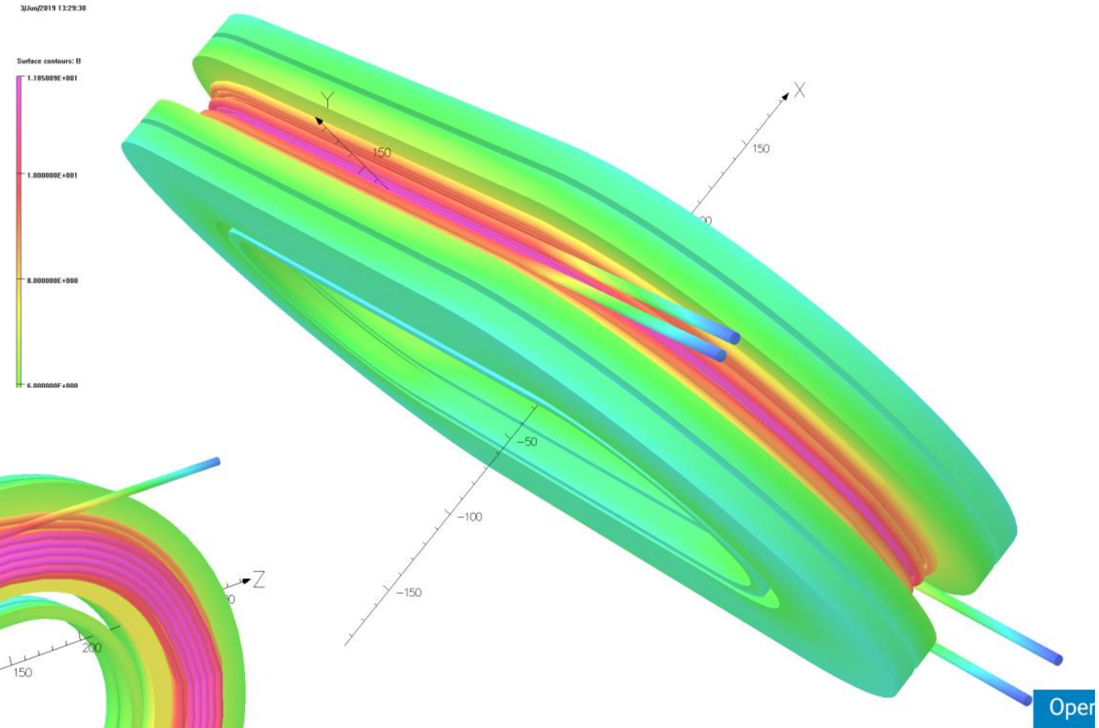


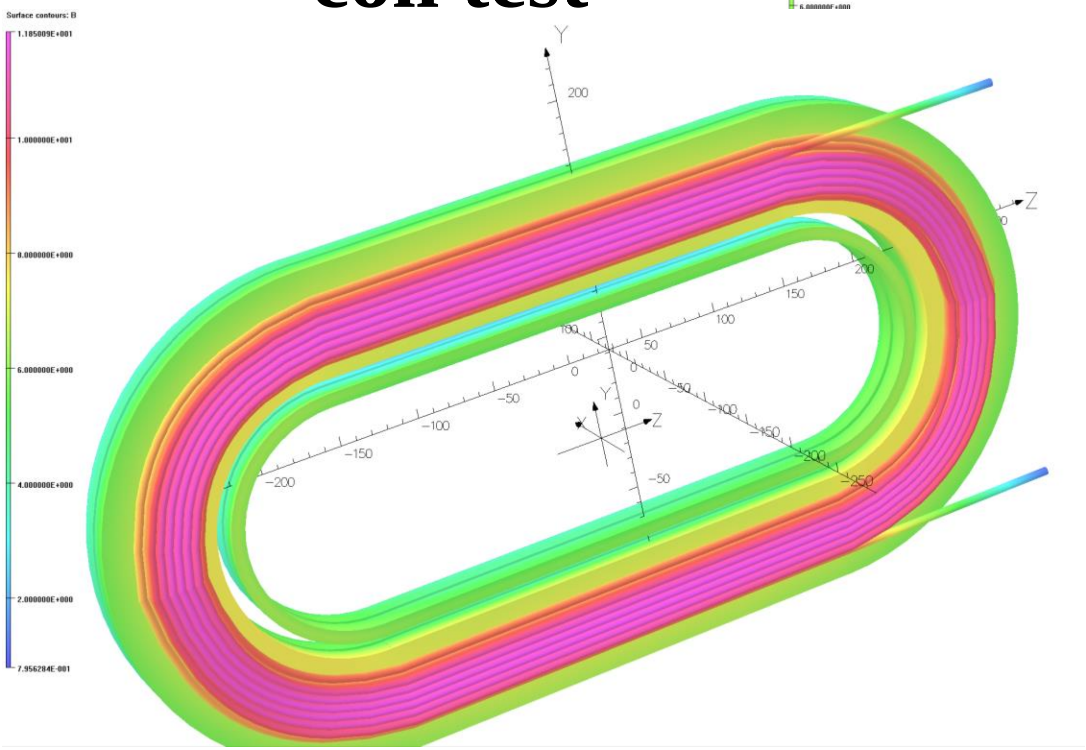
Allows large bend radii

Multi-turn Cable Test Configurations

To be used in MDP and in SBIR (both funded)

Multi-turn cable => coil test

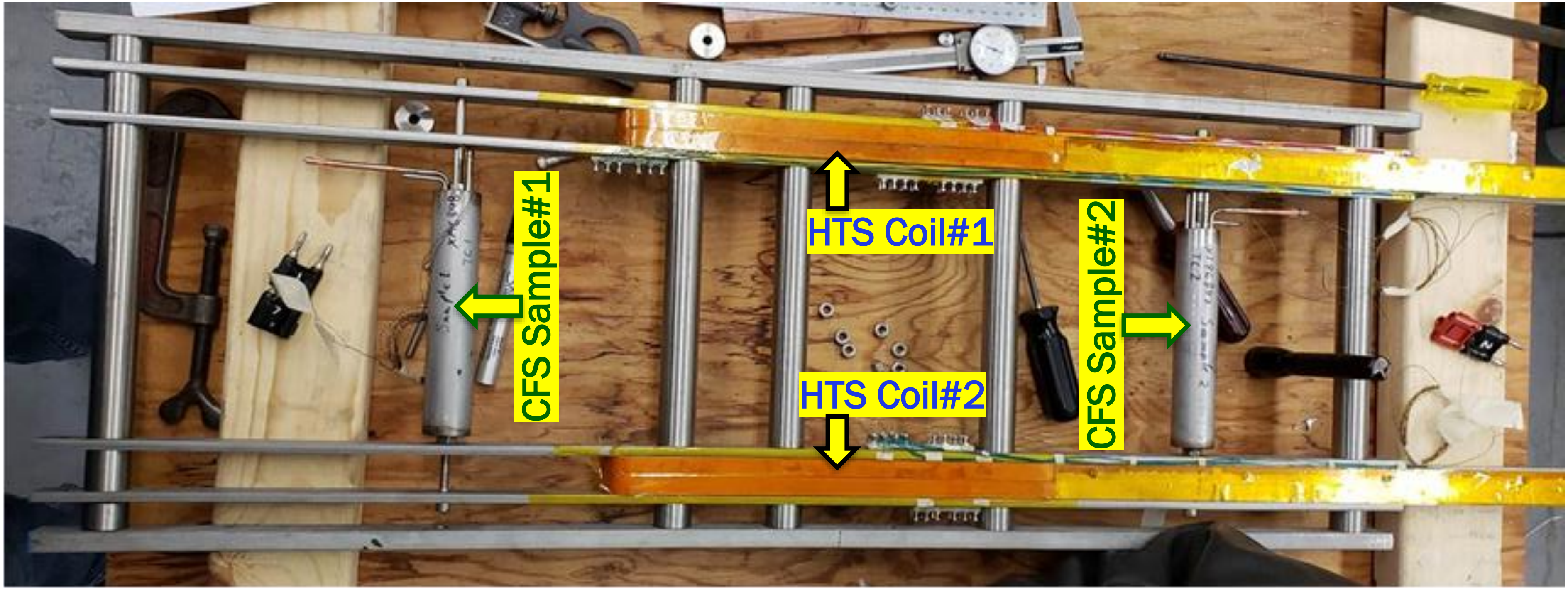




Large length of cable in high field

Multi-test Platform (four tests in one go)

HEP Working with the Fusion Community



Test results in <3 months from the first mention, thanks to the unique test platform @BNL (*existing*), MDP test and the Fusion Business Development funds provided by the BNL.

Rapid-turn-around Factcheck

11/7/2019: email from Charlie Sanabria (first information sought):
…. we've been particularly interested in AC losses. Do you think we could aim to perform some preliminary characterization ...

2/7/2020: Cooldown for test (2 samples inside the magnet) started

2/15/2020: Test completed with several runs (~1 dozen) with useful data, including some ~9 T to ~2 T in ~0.12 sec (~50 T/sec)

Budget: No cost to CFS - Courtesy Business Development Funds by BSA/BNL plus DOE MDP funding to BNL (received <9 months ago)

Rapid-turn-around Feedback

Charlie Sanabria <charlie@cfs.energy>
To Gupta, Ramesh C; Amm, Kathleen
Mon 2/17

You replied to this message on 2/17/2020 8:56 AM.

Dear Ramesh and collaborators,

It was great working with you last week, and seeing how exciting your results were. I think our results were equally exciting. It is a lot more data than we expected, and we are extremely grateful for it. Looking forward to future collaborations.
From all of us at CSF, thank you!

Charlie Sanabria
Commonwealth Fusion Systems
Magnet Systems Engineer
501 Massachusetts Ave
Cambridge, MA 02139
Work: +1(617) 253-5348
Cell: +(703) 409-5534
cfs.energy

INFUSE Funds for Testing HTS Cables in Background Fields and for other R&D for Fusion

https://infuse.ornl.gov/news/first-2020-rfa-call/

INFUSE Innovation Network for Fusion Energy

What Is INFUSE? | Topic Areas | Lab Capabilities | Library | Submission

INFUSE funds national labs for using its resources for fusion work

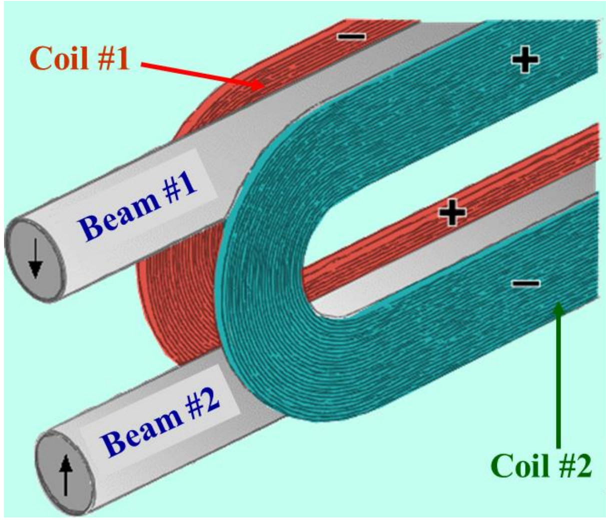
The first FY2020 INFUSE RFA Call opens on February 24. Proposals are due on the INFUSE submission site by Friday April 10. The five topical areas remain the same; however, restrictions on the number of proposals in any area have been relaxed. The eligibility criteria were also revised and the maximum size of the awards has increased. Please visit the INFUSE website for more details on the latest changes.

Helpful Links

- FES HomePage
- Oak Ridge National Laboratory
- Princeton Plasma Physics

Brookhaven National Laboratory
Superconducting Magnet Division

Making of the Unique Facility



- Common coil dipole DCC017 built and tested in 2006 to demonstrate "React & Wind" Nb_3Sn Technology.
- Dipole had a unique design allowing a large open space for insert coil testing
- PBL/BNL SBIR in 2016 demonstrated it
- The recent MDP test (Feb 2020) proves rapid-turn-around, low cost capability (Kathleen Amm's presentation later today)

PBL Team: Ron Scanlan, Bob Palmer, Erich Willen, Bob Weggel, Steve Kahn, Jim Kolonko, Del Larson, …

Also had: Al Garren and David Cline

Hybrid Dipole Design and Test Results

HTS/LTS Hybrid Magnets Design

Aperture #1

HTS coil size: 9 mm X 25 mm

HTS No. of turns: 92 (2 X 46)

Insulation: Nomex

LTS coil size: 27 mm X 85 mm

LTS No. of turns: 90 (2 X 45)

Insulation: Nomex

Bore size: 13 mm X 25 mm

Aperture #2

HTS coil size: 9 mm X 25 mm

HTS No. of turns: 142 (2 X 71)

Insulation: No Insulation (NI)

LTS coil size: 27 mm X 85 mm

LTS No. of turns: 90 (2 X 45)

Insulation: No Insulation

Bore size: 13 mm X 25 mm

NI coils were wound with "low tension" and this test was partly meant to simulate multi-tape cable providing added protection by current sharing.

It was also meant to test if "field" can be made to track the "current".

Overriding Test Objectives (a view from 30,000 ft)

MDP R&D test is to continue the HTS/LTS hybrid dipole technology work performed under a previous PBL/BNL SBIR

- SBIR test was for the case when the field was primarily perpendicular to the wide face of the tape; MDP test is when it's primarily parallel (=> expect much lower magnetization)
- SBIR test was for the case when HTS coil survived multiple quenches in itself; MDP test is to find out if HTS coil will survive when LTS coil, with much larger energy, quenches
- SBIR test achieved 8.7 Tesla hybrid field (record at that time), MDP test to find out if it can be increased significantly without destroying the HTS coils in the event of a quench

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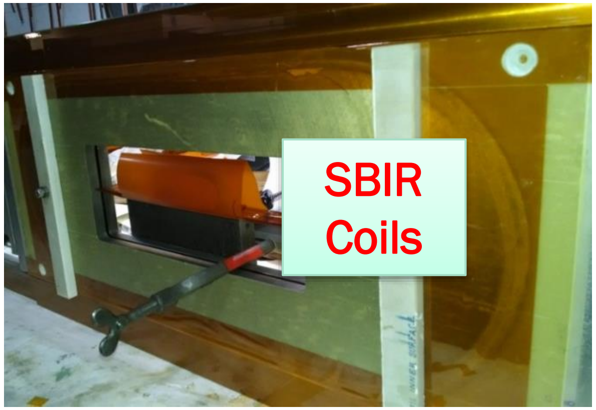
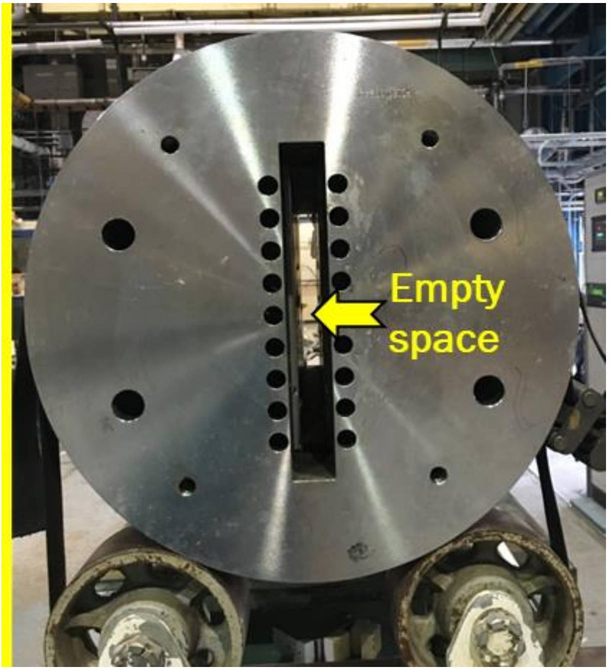
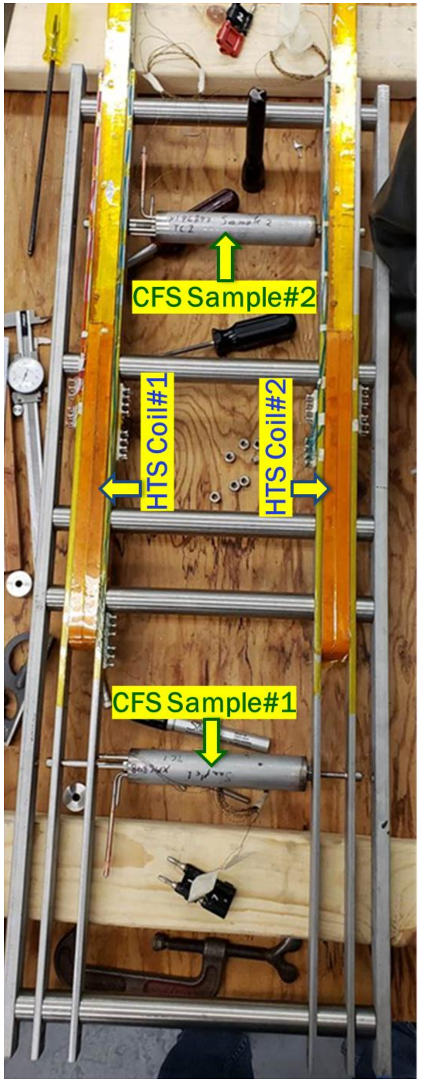
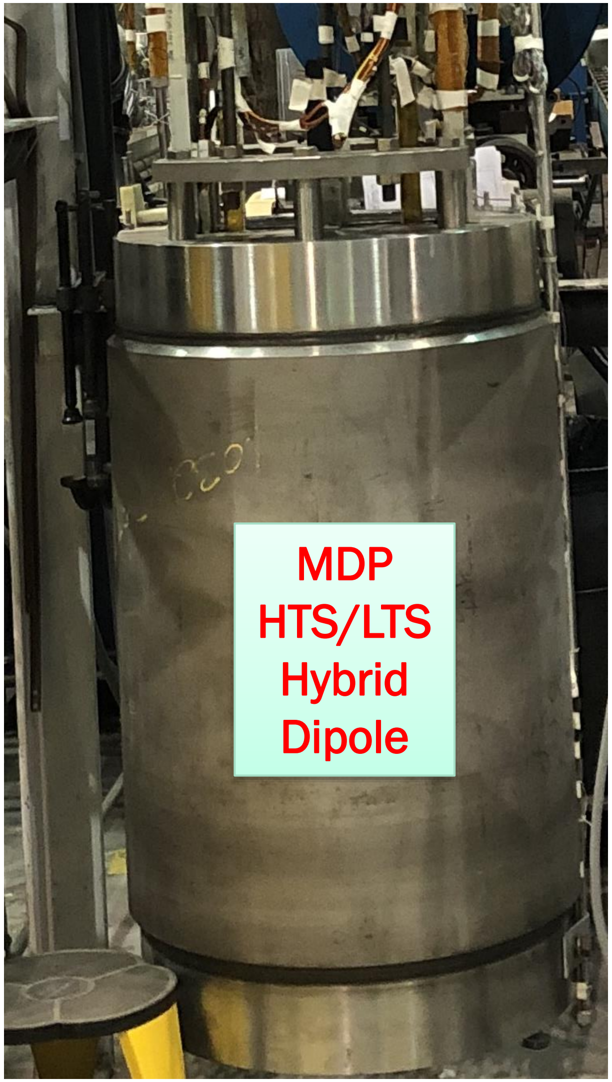
HTS/LTS Hybrid Dipole (1) (SBIR & MDP)

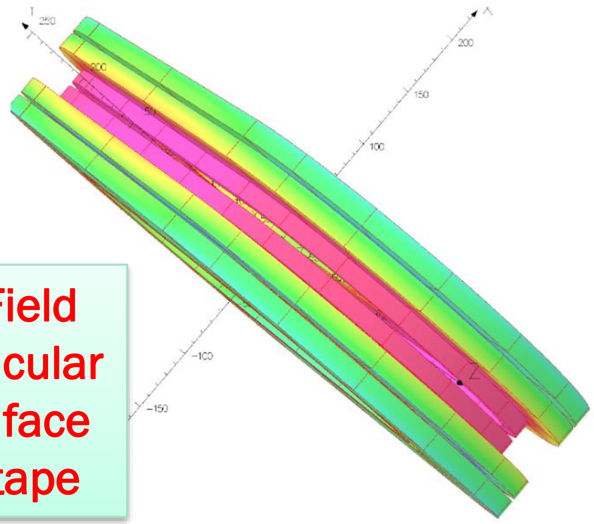




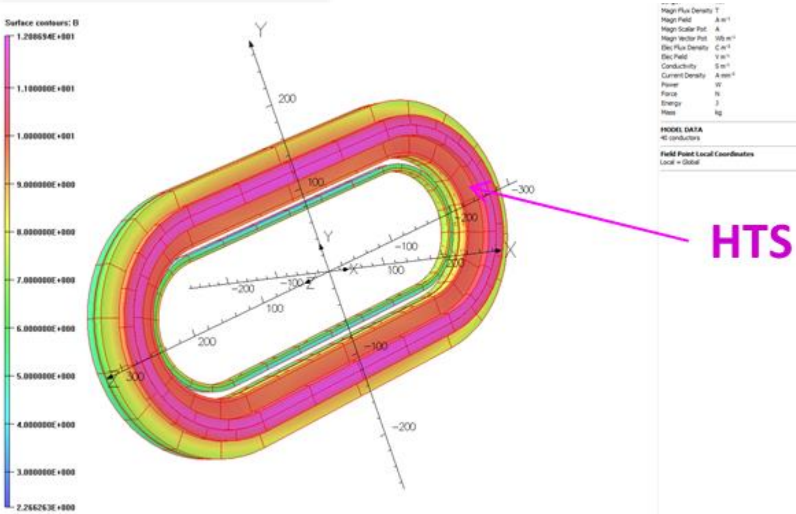


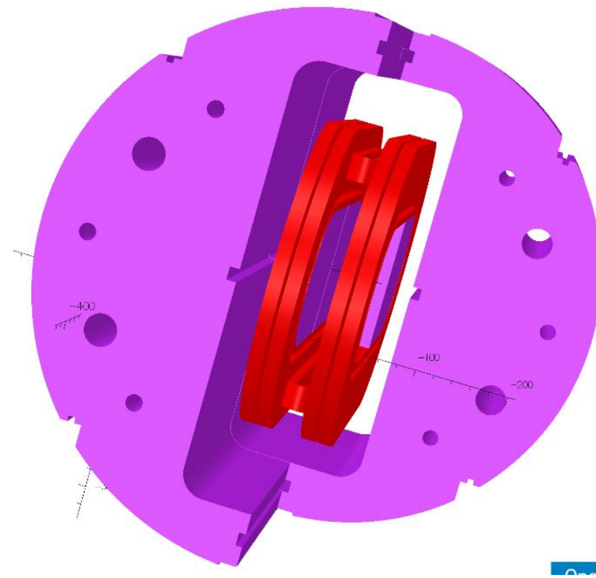


HTS/LTS Hybrid Dipole (2) (SBIR & MDP)

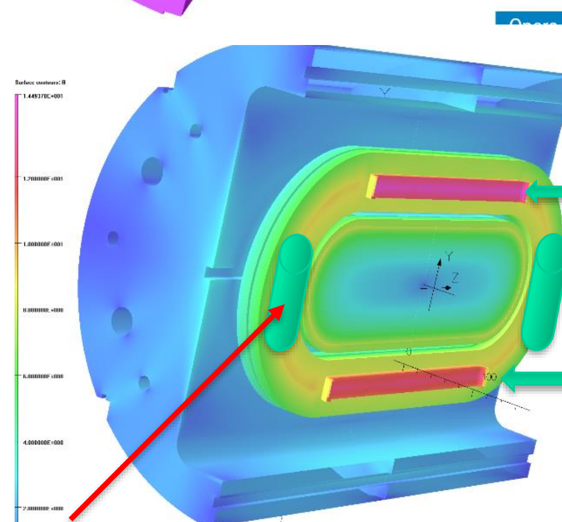


SBIR : Field Perpendicular on wide face of HTS tape





MDP Field Parallel on HTS coils

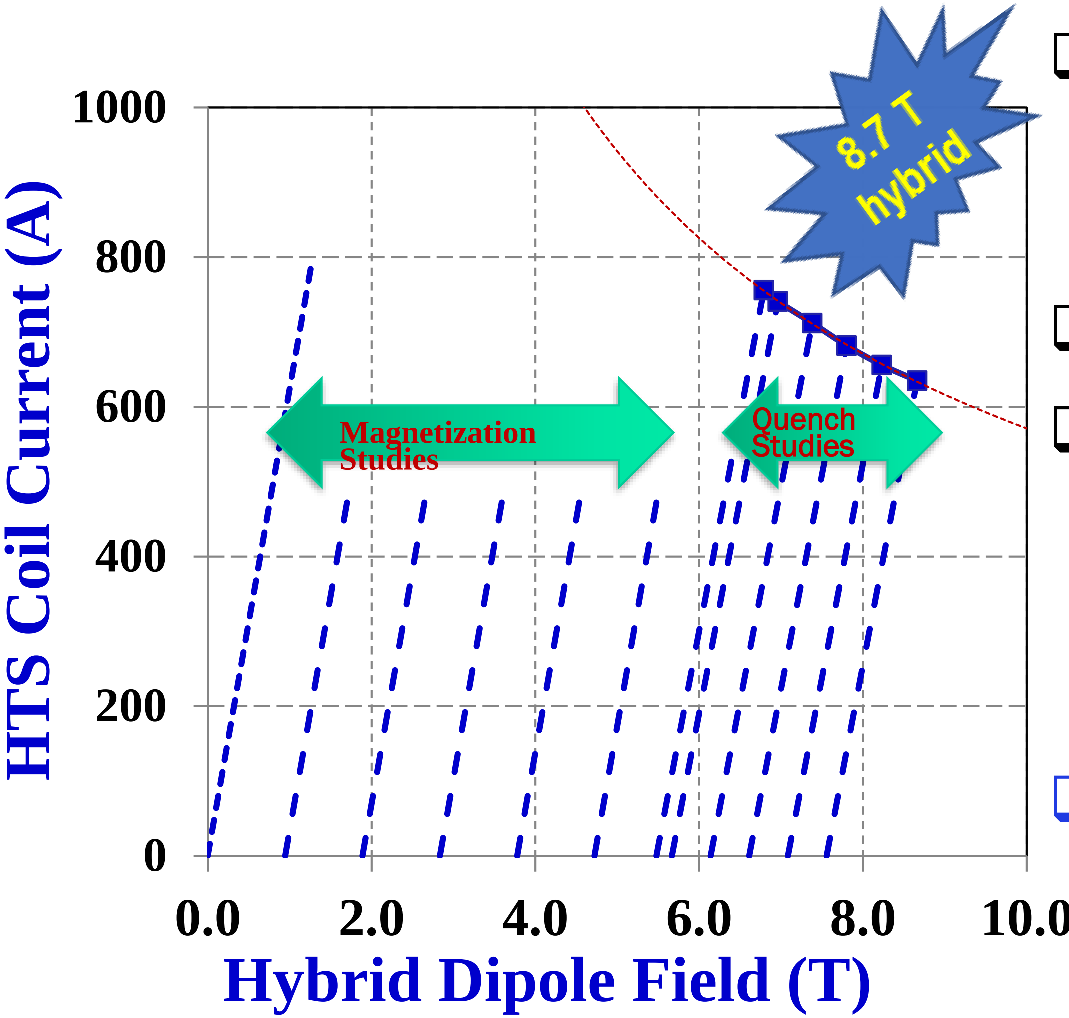


HTS Coil#1

HTS Coil#2

CFS Sample

PBL/BNL SBIR 2016 Test
HTS/LTS Hybrid Dipole Structure

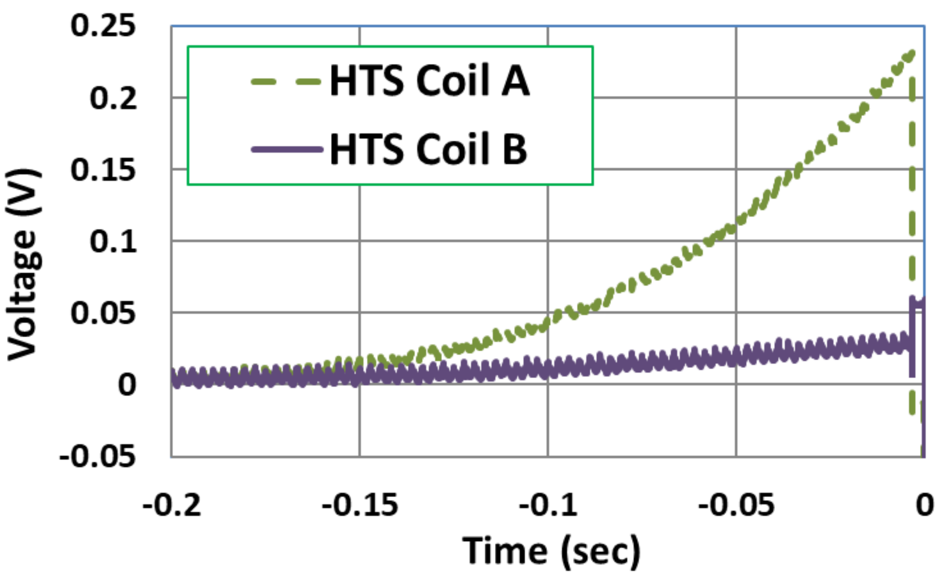


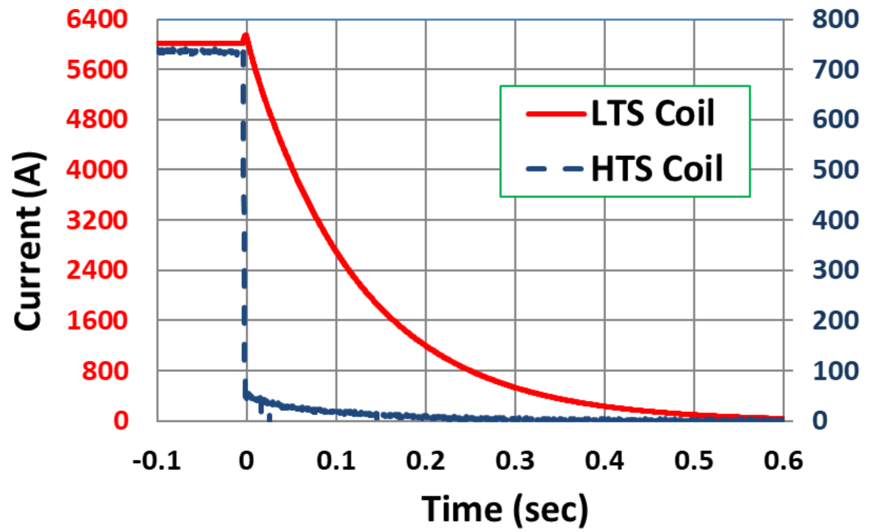
- HTS coils in hybrid dipole were ramped multiple times to quench, just like LTS.
- NO training
- No degradation in HTS coils despite a number of quenches.

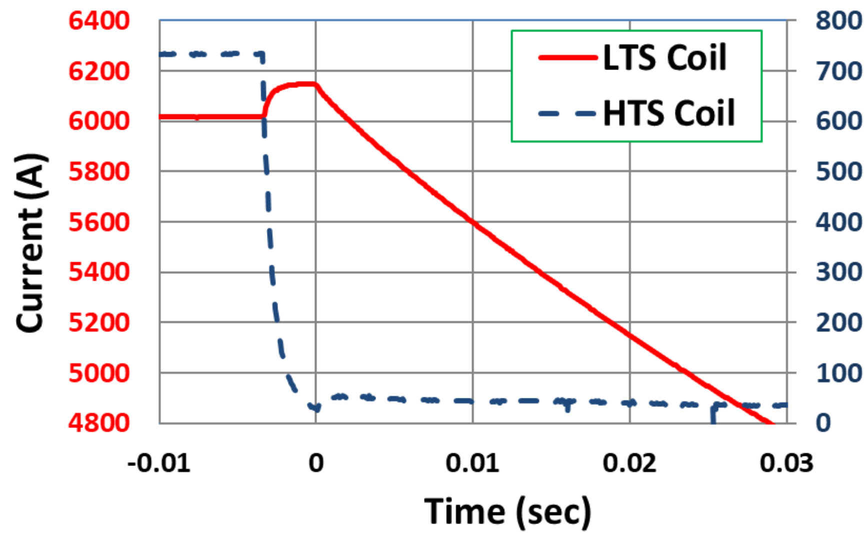
- Field due to conductor magnetization estimated by taking difference between up and down ramps.

Quench Protection of HTS Coils in HTS/LTS Hybrid Magnet

HTS coils were operated like the LTS coils
(significant voltages allowed till quench even on the HTS coils)







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

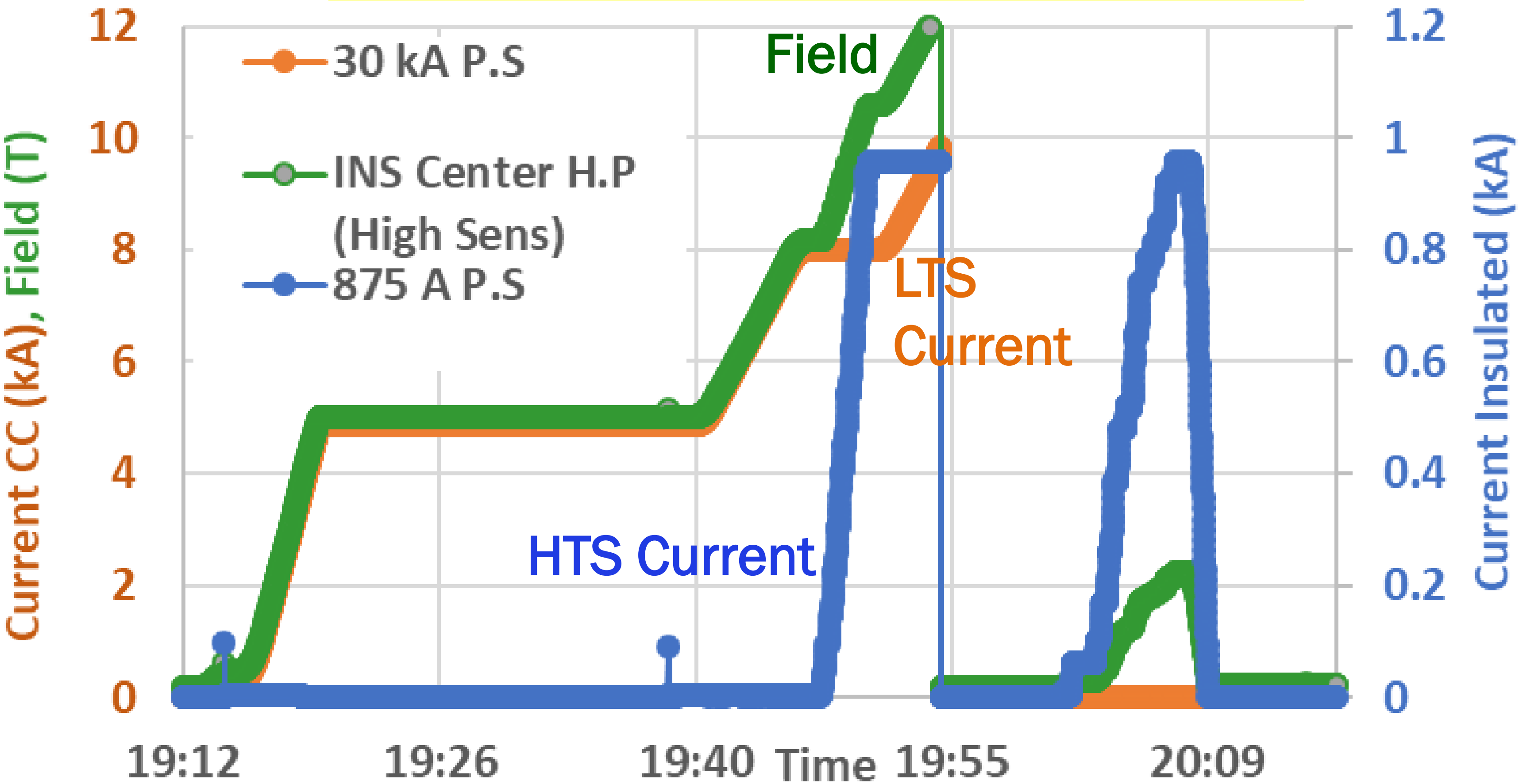
Results of the HTS/LTS hybrid dipole

(test performed two weeks ago)

MDP HTS/LTS Hybrid Dipole (magnet reached 12.2 T, HTS coils survived)

2/13/20

HTS Insulated Coil & Common Coil



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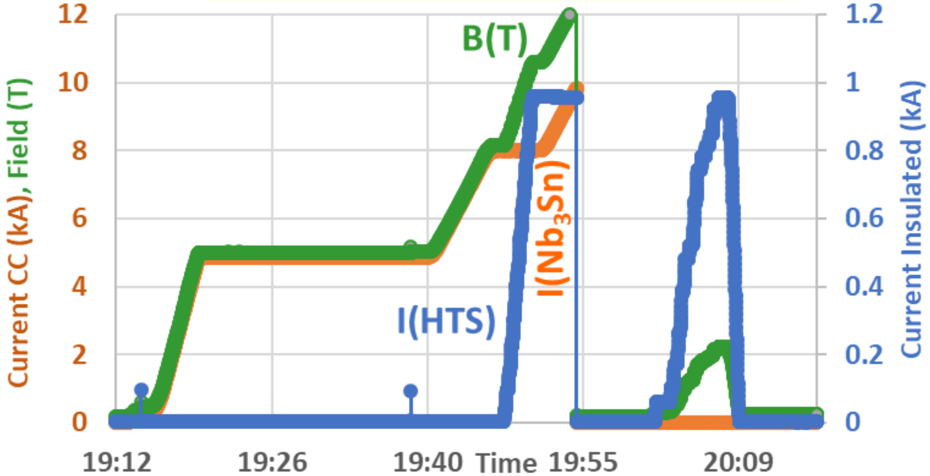
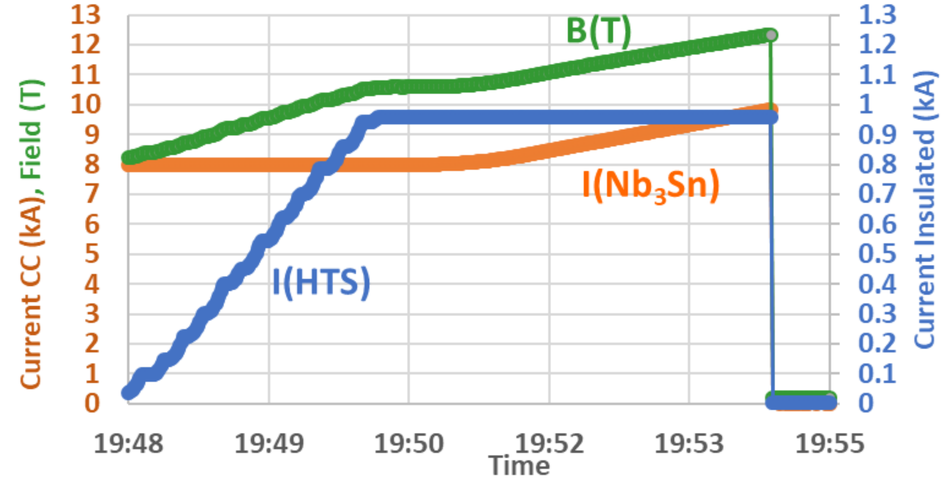
More Details of the 12.2 T HTS/LTS Hybrid Dipole Test

HTS Insulated Coil & Common Coil

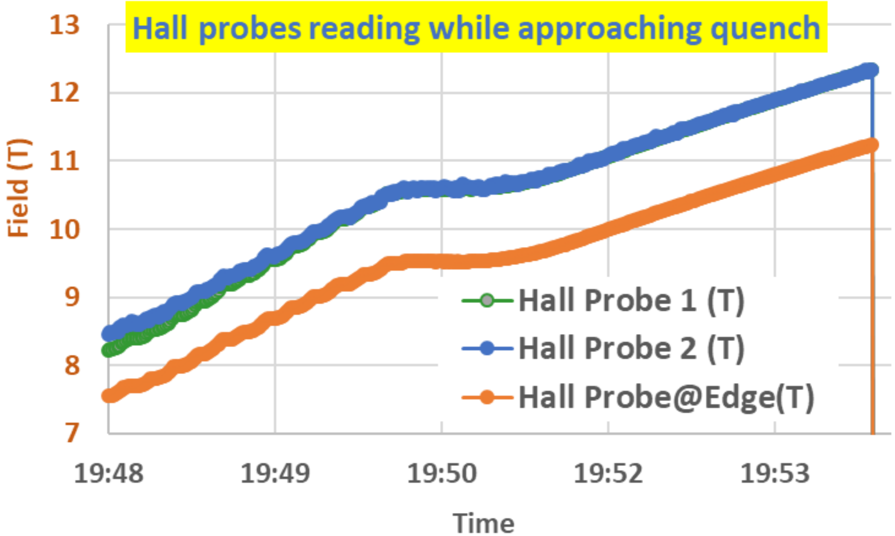


HTS Insulated Coil & Common Coil

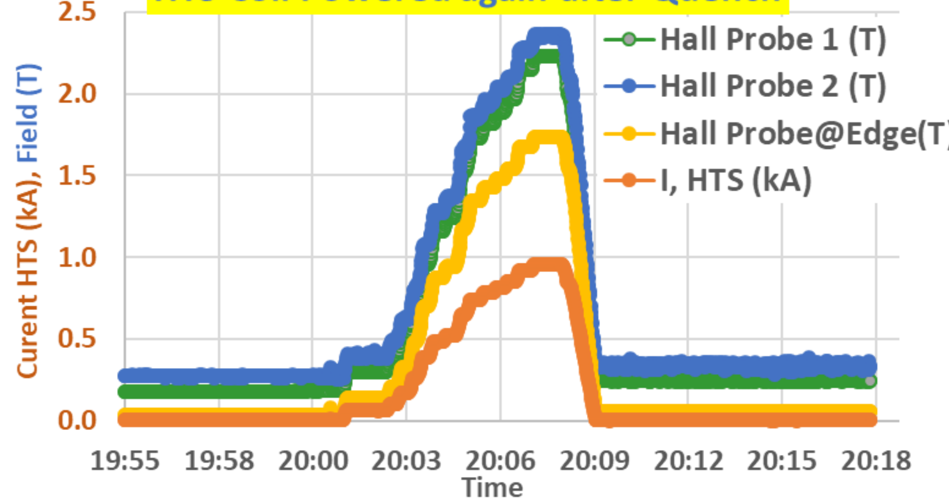


Magnetization Studies

Hall probes reading while approaching quench



HTS Coil Powered again after Quench



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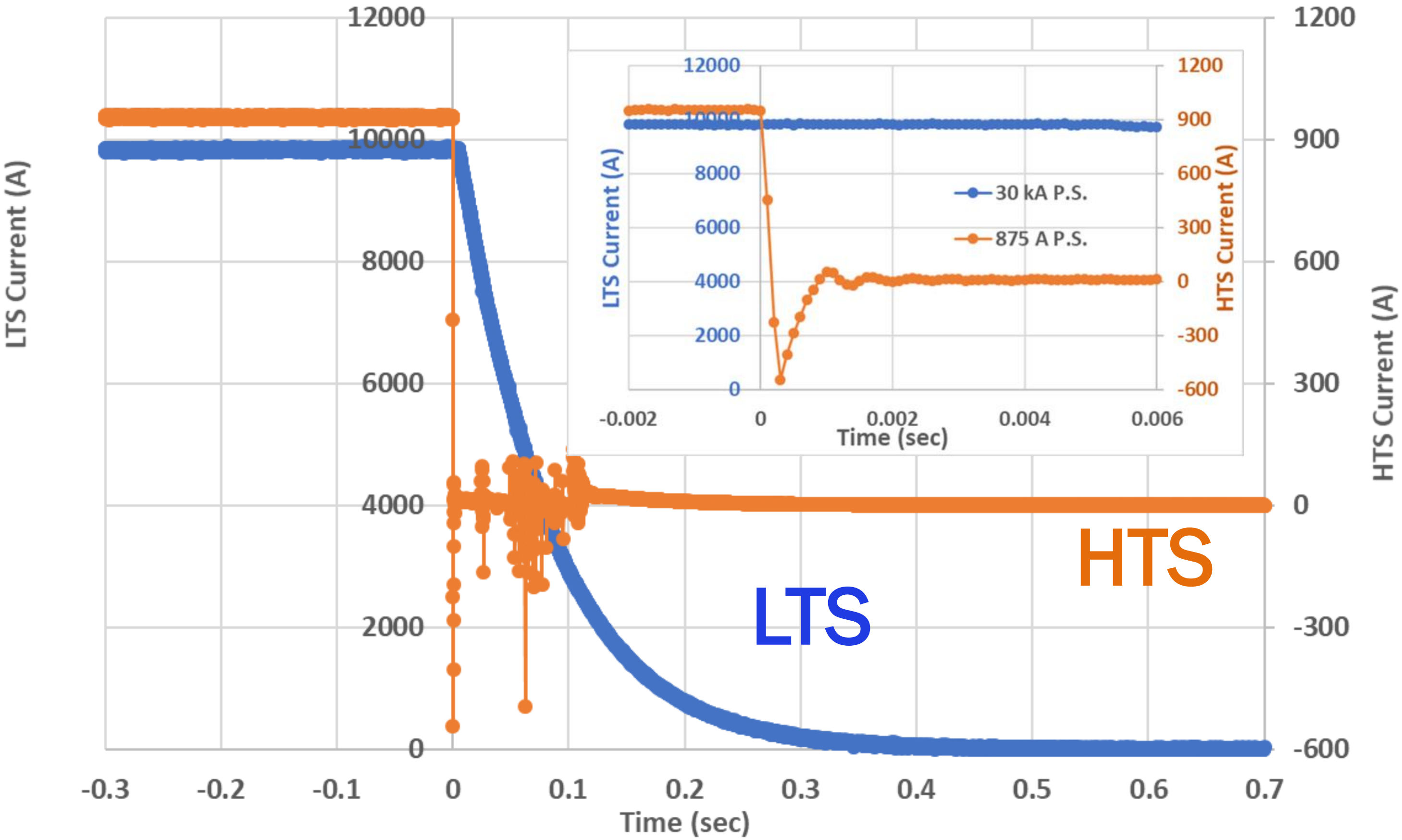
2020 12 T HTS/LTS Hybrid Dipole

Major concern was: what happens if LTS coil quenches and dumps large energy on HTS coils? Will HTS coils survive?



Energy extraction from LTS coils starts after HTS coils are deenergized, protecting HTS coils

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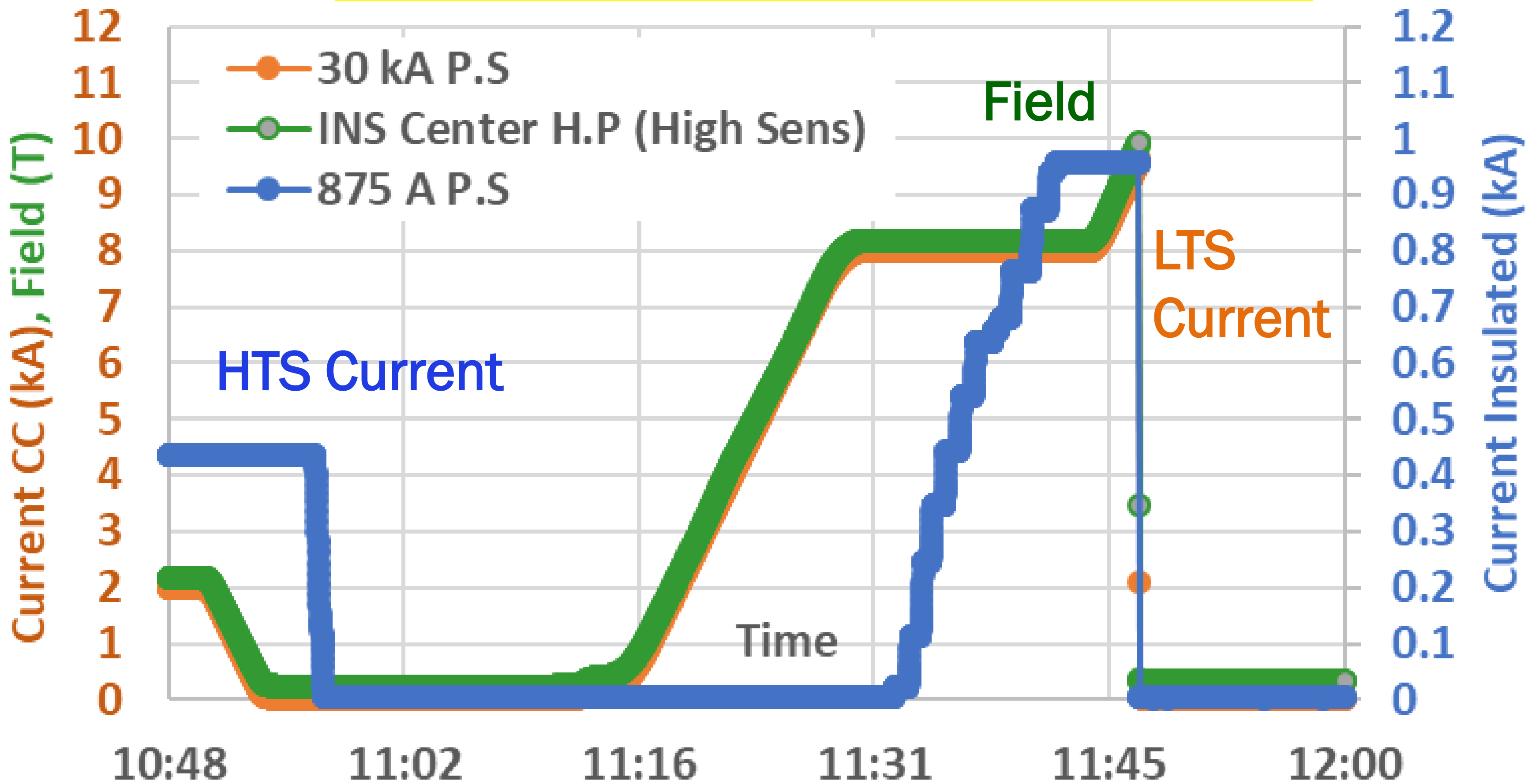
MDP HTS/LTS Hybrid Dipole Test (test repeated next morning, hybrid survived)

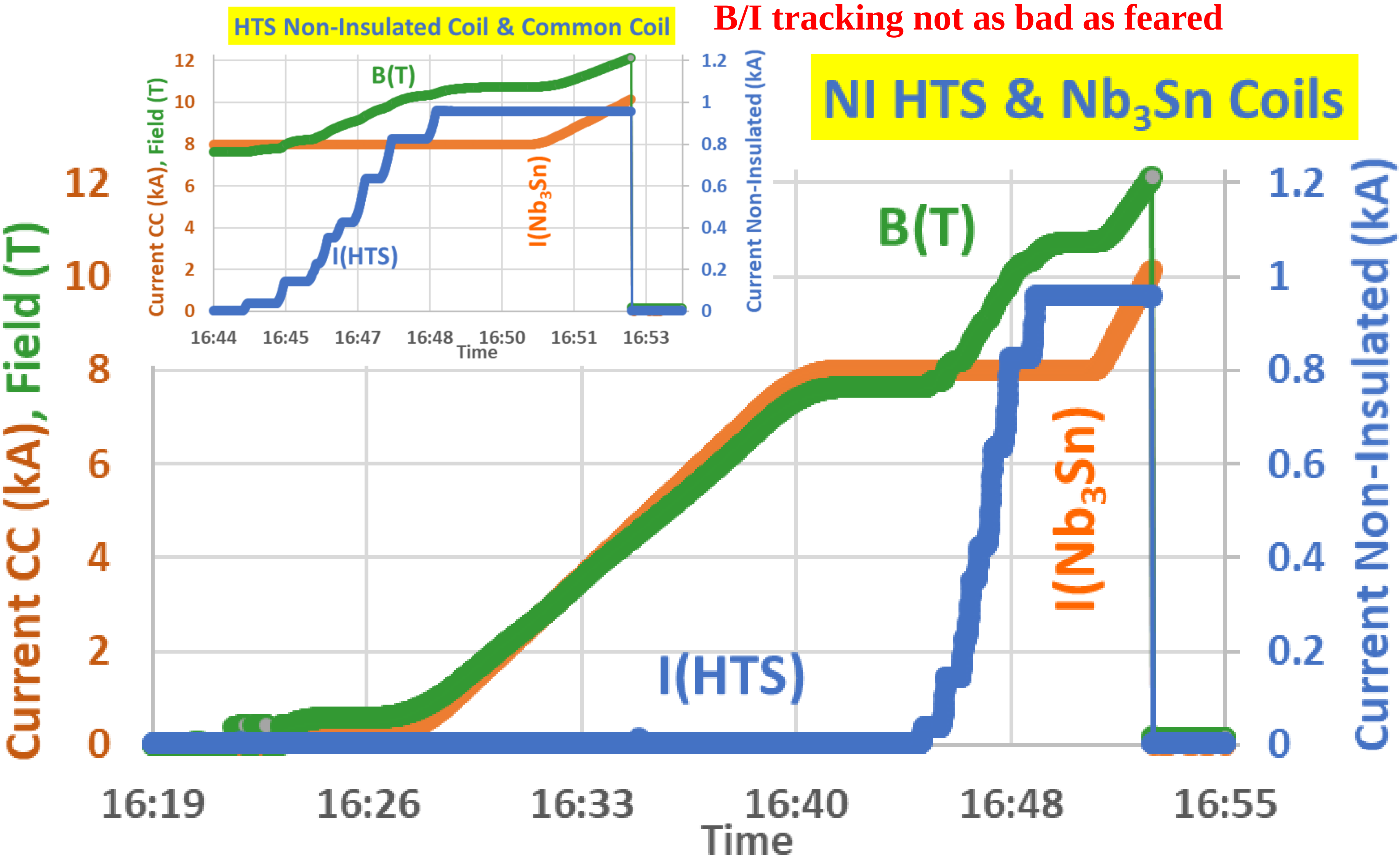
2/14/20

HTS Insulated Coil & Common Coil

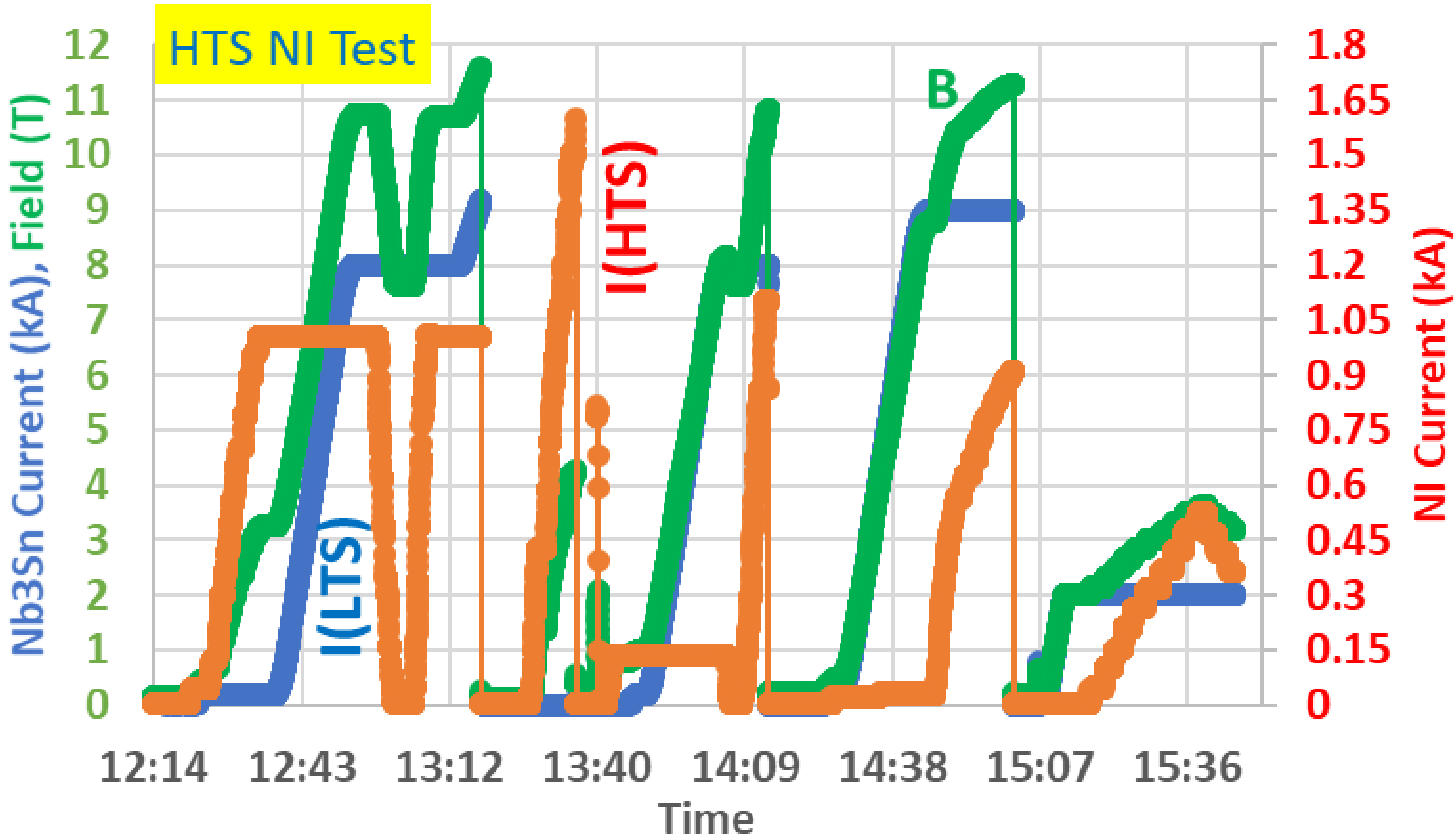


ReBCO/Nb_3Sn Hybrid Dipole with NI Coils

B/I tracking not as bad as feared

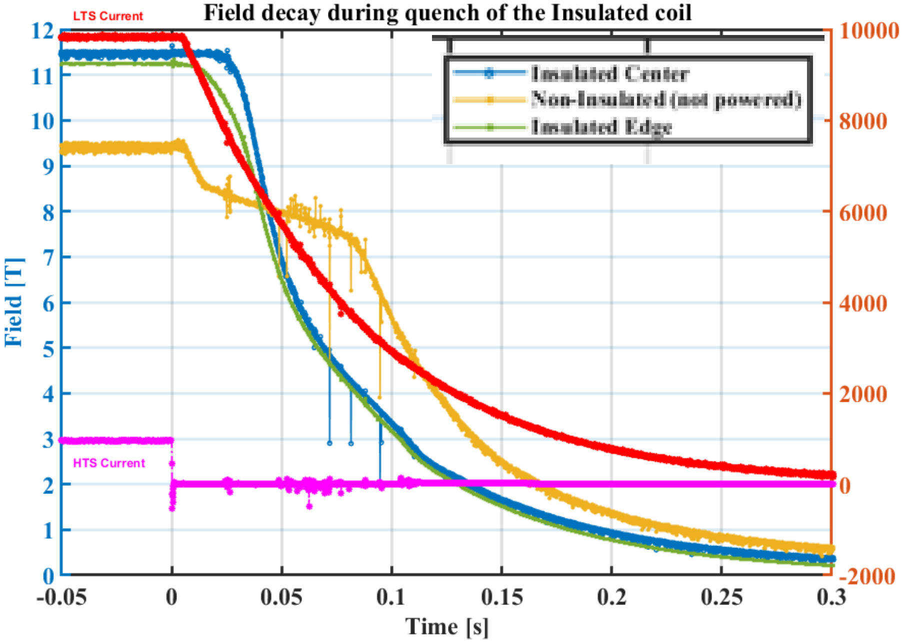


More HTS/LTS Hybrid Dipole Run till Quench with Higher Current Power Supply



Comparison of Insulated and NI HTS Coils (unique test from 2-in-1 hybrid dipole)

Insulated Coil



I(LTS)

I(HTS), insulated coil

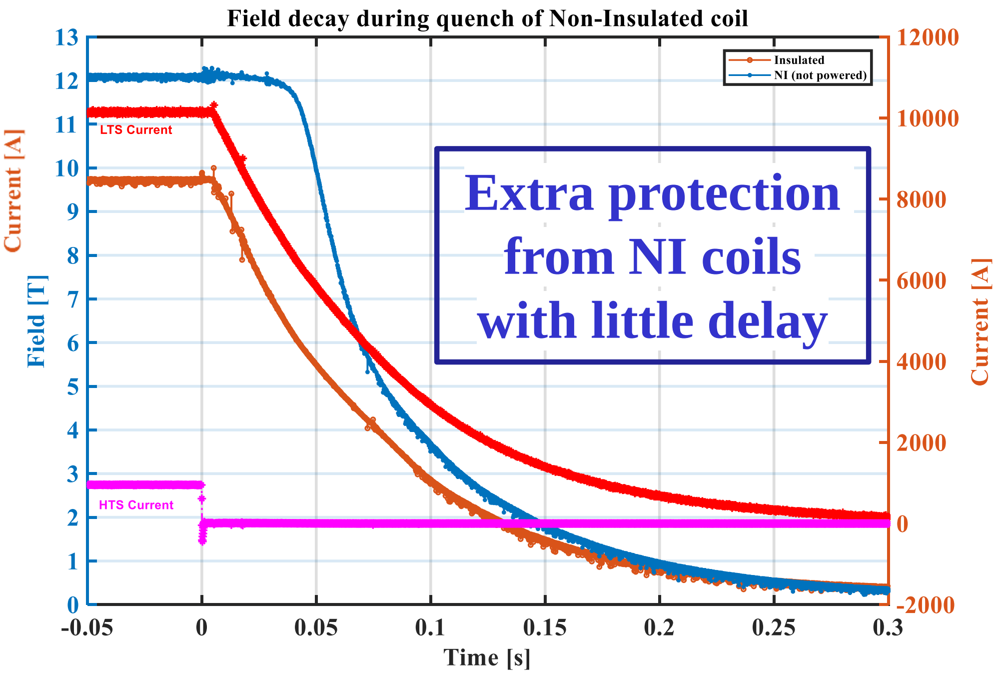
B at the center of insulated coil

B at the edge of insulated coil

B at the center of NI coil (not powered)

Very interesting results from NI coils

Non-insulated Coil



I(LTS)

I(HTS), non-insulated coil

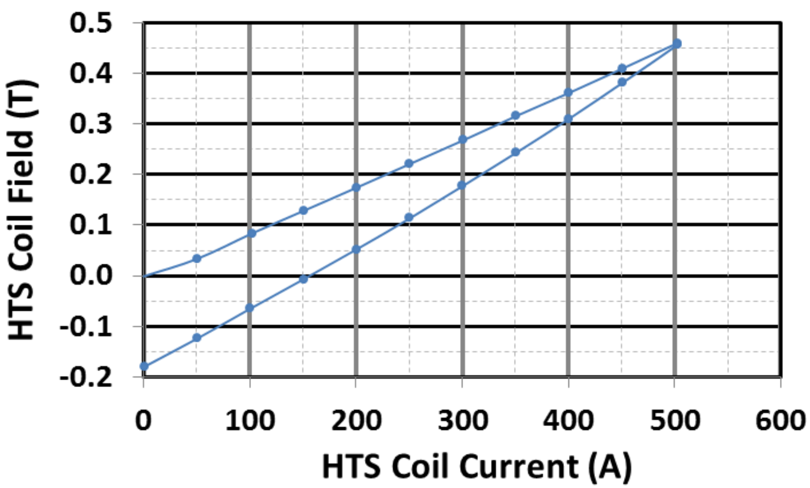
B at the center of non-insulated coil

B at the center of insulated coil (not powered)

Magnetization Measurements

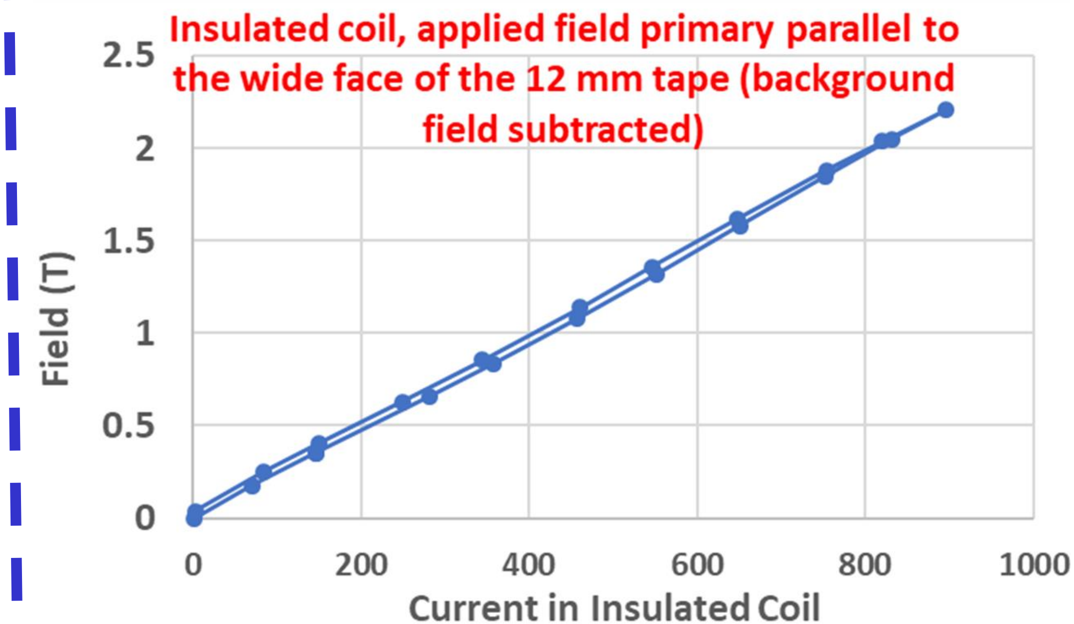
Magnetization Studies @2T Dipole Field

Field perpendicular (2016 SBIR)



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

Field parallel (2020 MDP)



Significant reduction in magnetization from HTS coils when field is primarily parallel to the wide face

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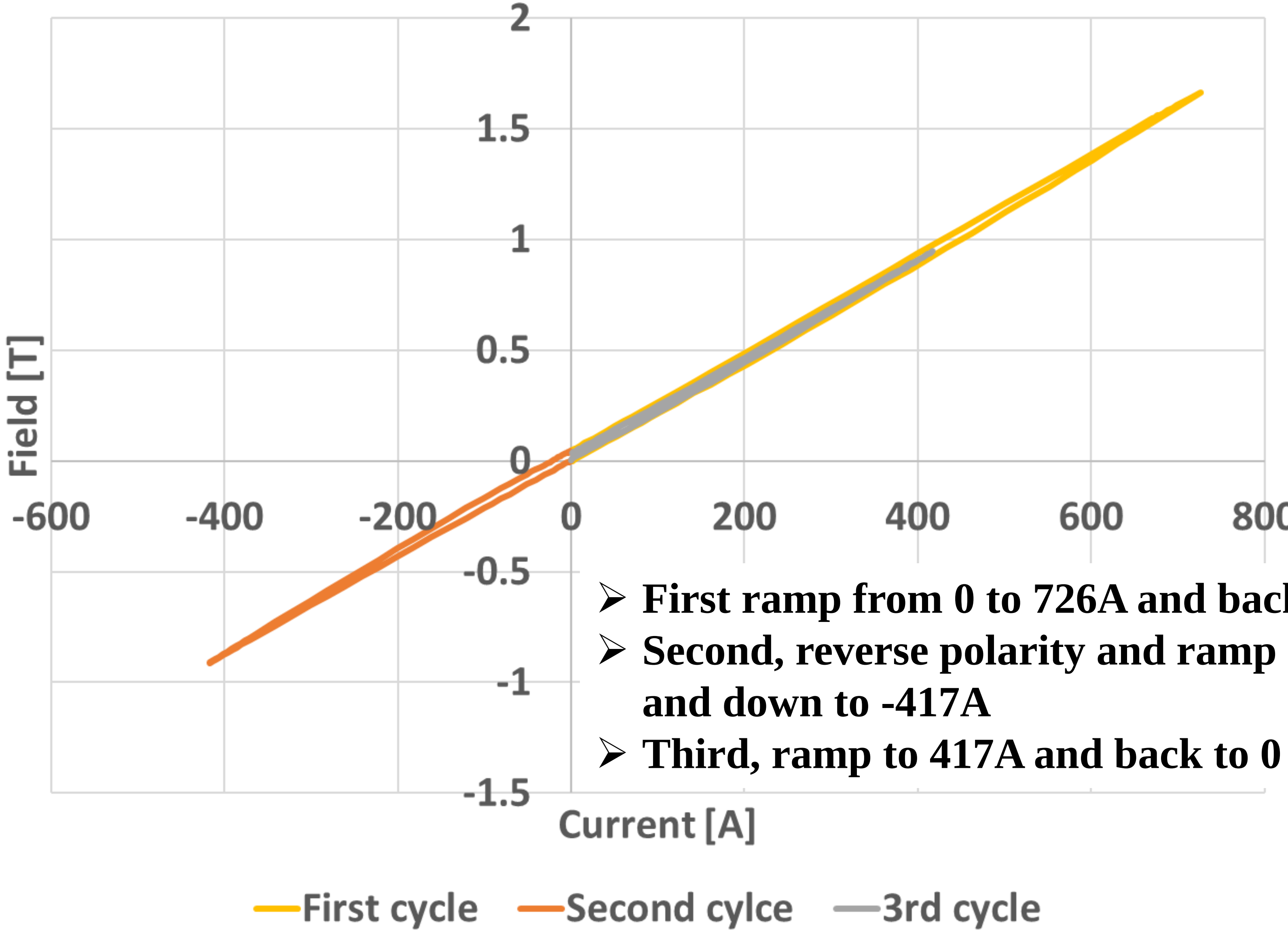
HTS Magnetization Studies (with no background field)



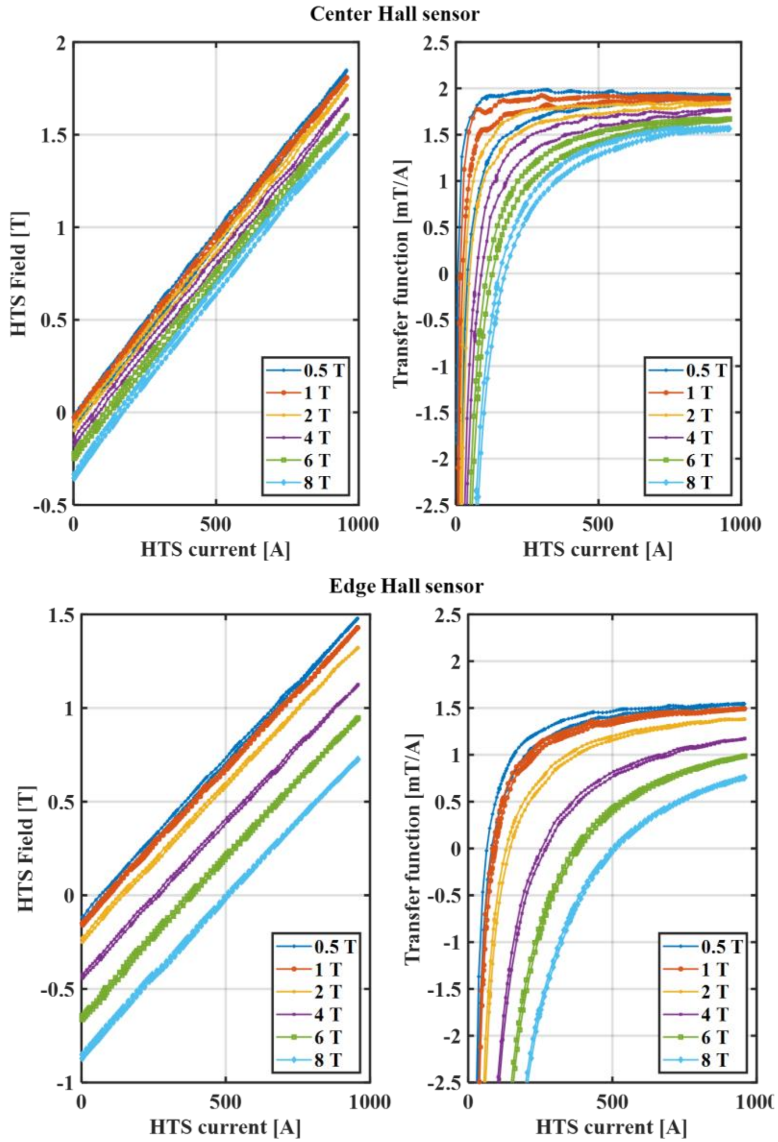
- First ramp from 0 to 726A and back to 0
- Second, reverse polarity and ramp up and down to -417A
- Third, ramp to 417A and back to 0

HTS Magnetization Studies (background field primarily parallel)

HTS/LTS Hybrid Tests:

- Hold LTS coils at 500 A, 1 kA, 2 kA, 4 kA, 6 kA, and 8 kA. For each background field from LTS, HTS coil is ramped up to 950 A and then back to 0

- The field is measured at two locations: at the center and also at the edge of the double pancake of the insulated coil



Thanks to our staff at BNL

Work presented here was the result of many people working very hard - late hours day after day.

They came over weekend, worked late hours for weekdays continuously (usually till 10 pm) and were back early morning next day.

Thank you for this opportunity to present their hard work...

SUMMARY

- A unique 10 T, Nb_3Sn dipole background field facility is available NOW for cable and insert coil testing (see Kathleen's presentation for a wider perspective and future plans)
- Since, insert coils become a part of the magnet, coil test becomes a magnet test, but at a lower cost and at a shorter turn around
  - could this be called a disruptive component of the program planning (which is increasing becoming an integral part of the strategy) for developing breakthrough technologies
- Two 12 T HTS/LTS hybrid dipole (plus more) in <9 months
- Advance quench protection worked in protecting HTS coils in a significant size HTS/LTS hybrid dipole
- Measured field errors due to magnetization are significantly lower when the field is primarily parallel to the wide face of HTS tape rather than perpendicular

Extra Slides

An Alternate Approach to Magnet Technology Development

When there were more funds to develop and demonstrate magnet technology (SSC and RHIC days), we used to argue about the applicability of short magnet test results in building long magnets

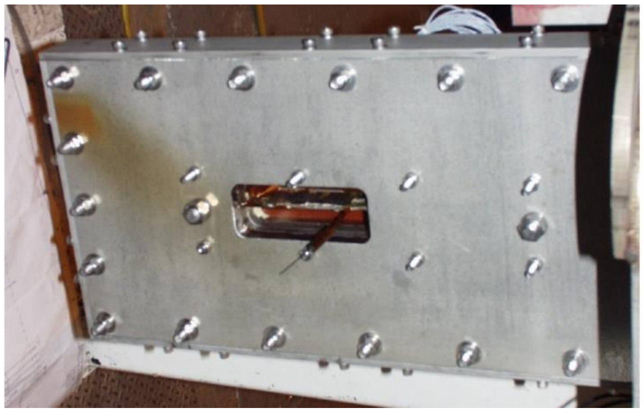
- ❑ We accepted the benefits of short magnet R&D as they could be built and tested cheaper and faster (relatively speaking) and we could afford to change one or fewer parameters at a time to identify issues and to develop magnet technology
- ❑ Now short high field R&D magnets take so long and are so expensive to build (relatively speaking) that we can't afford even them. Then we have to find an alternate R&D approach

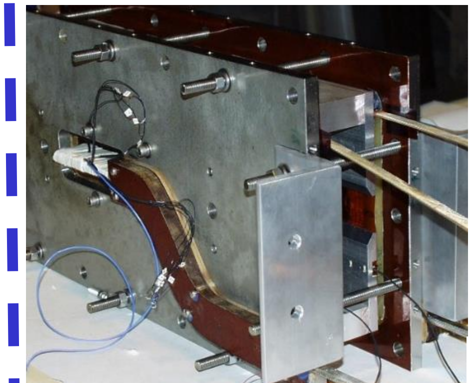
The results of the alternate approach should be largely (even if not completely) applicable to real magnets and the test vehicle be robust

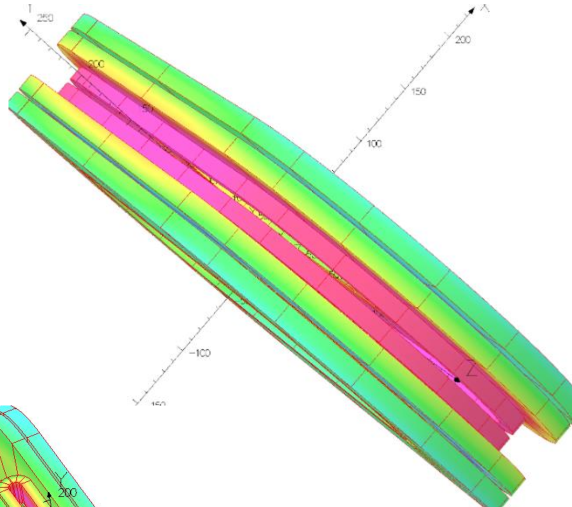
Proof-of-Principle Test of the Technology
Where does the size of the magnet aperture really matters and where it matters less?

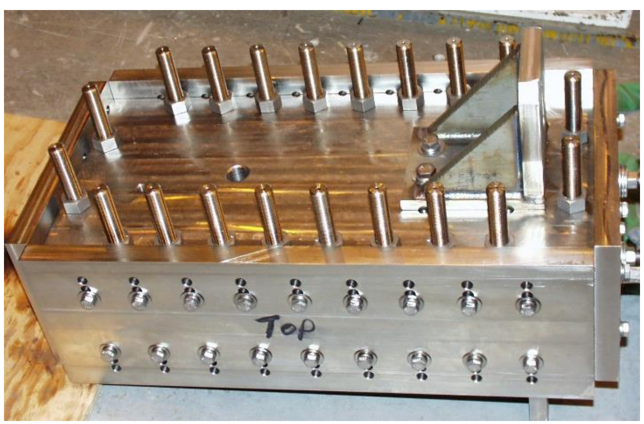
<u>NOT VALID</u> (structure relies on clamping two sides)

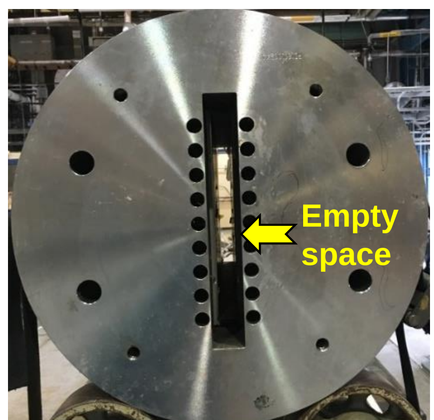
Two sides of the coils are free to move independently.
If stresses and fields on the insert coil of small aperture can simulate that of larger aperture, results should be valid for technology development

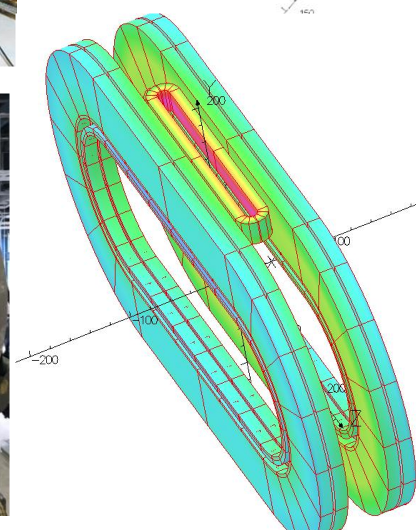








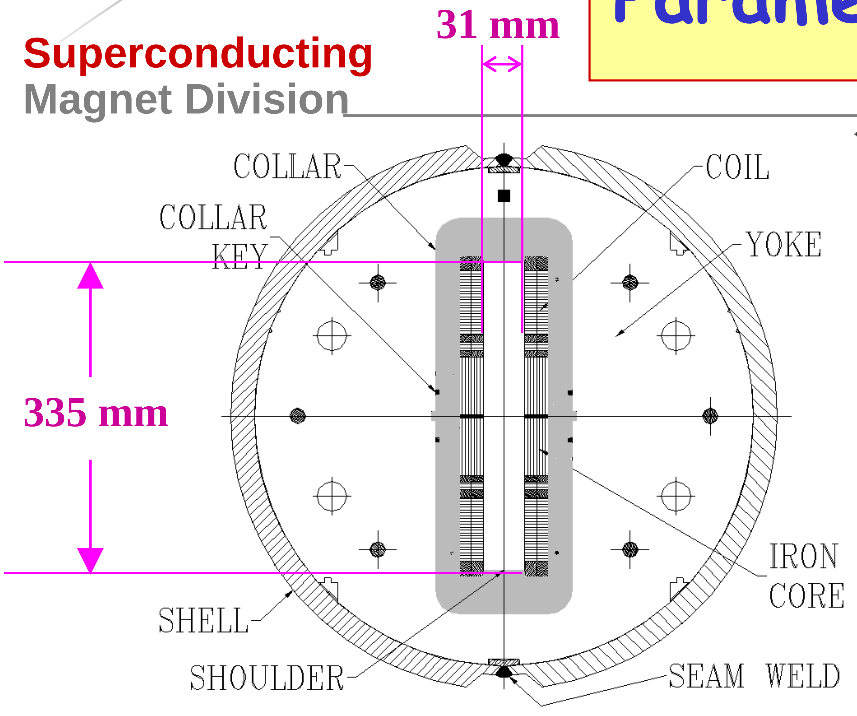


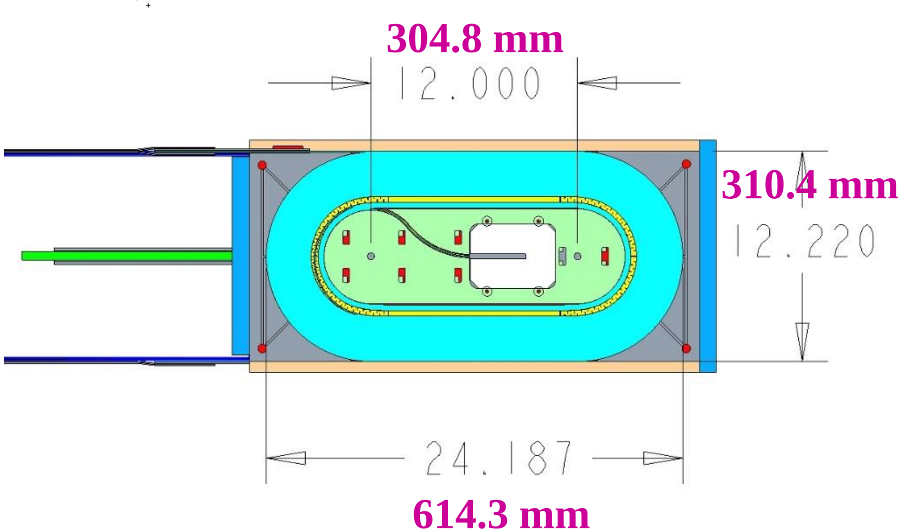


Empty space

Left side is free from the right side (doesn't know where it is). So, aperture matters less

Parameters of BNL Dipole DCC017





- Two layer, 2-in-1 common coil design
- 10.2 T bore field, 10.7 T peak field at 10.8 kA short sample current
- **31 mm horizontal aperture**
- **335 mm vertical aperture**
  - **A unique feature for insert coil or cable testing**
- 0.8 mm, 30 strand Rutherford cable
- 70 mm minimum bend radius
- 85 mm coil height
- 614 mm coil length
- One spacer in body and one in ends
- Iron over ends
- Iron bobbin
- Stored Energy@Quench ~0.2 MJ

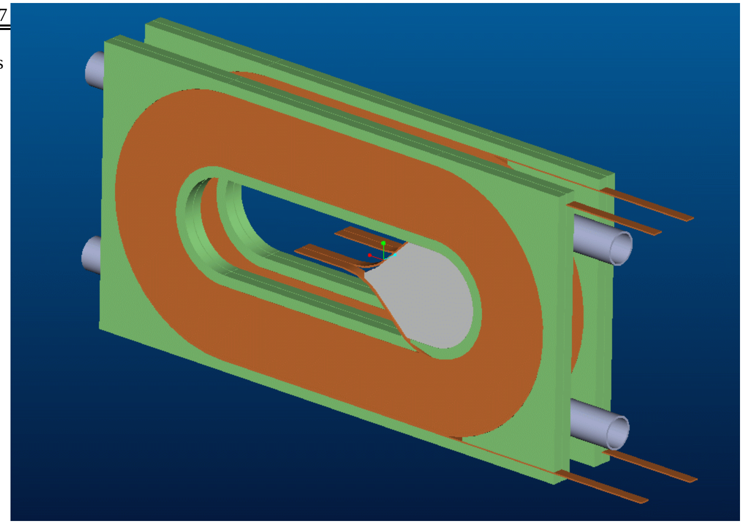
BROOKHAVEN NATIONAL LABORATORY

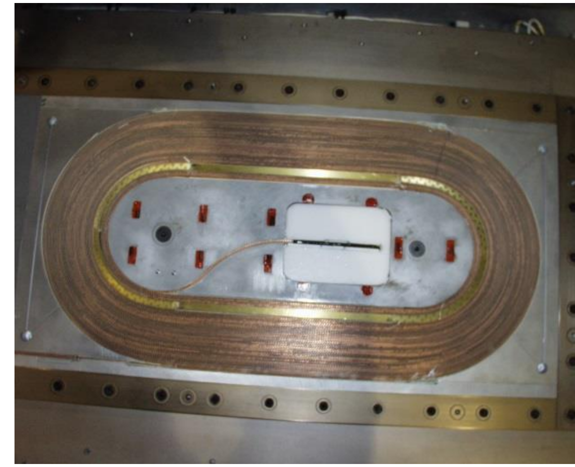
Superconducting
Magnet Division

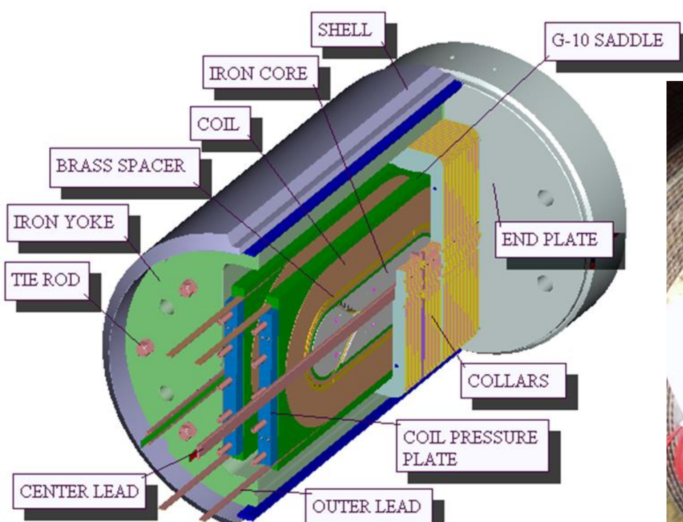
Performance Parameters of DCC017

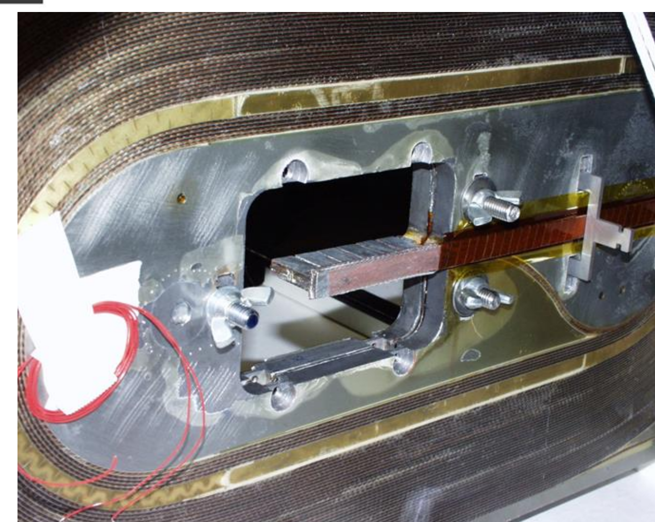
MAJOR PARAMETERS OF REACT & WIND COMMON COIL DIPOLE DCC017

Magnet design	2-in-1 common coil dipole with racetrack coils
Conductor type	Nb_3Sn
Magnet technology	React and wind
Horizontal coil aperture (clear space)	31 mm
Vertical coil aperture (clear space)	335 mm
Separation between the magnetic center of the upper and lower aperture	236 mm
Number of layers	Two
Number of turns per quadrant of single aperture (pole-to-pole)	45 turns in each layer
Coil height (pole-to-pole)	85 mm
Wedge(s) (size and number)	8.5 mm, one in each layer (inner & outer)
End-spacer(s) (size and number)	8.5 mm, one in each layer (inner & outer)
Wire non-Cu J_{sc} (4.2 K, 12 T)	1900 A/mm^2
Strand diameter	0.8 mm
Number of strands in inner and outer cable	30
Cable width (inner and outer layers)	13.13 mm
Cu/Non-Cu ratio in the wire (same for both inner and outer cables)	1.53
Computed quench current (limited by inner)	10.8 kA
Computed quench field @4.2 K	10.2 T
Peak field at quench in inner, outer Layer	10.7 T, 6.1 T
Special electrical feature (not used)	Shunt between layers
Computed stored energy at quench	0.2 MJ
Computed inductance	4.9 mH
Coil bobbin (core) material	Carbon steel
Coil length (overall)	614.3 mm
Coil straight section length	304.8 mm
Coil height (overall)	310.4 mm
Coil inside radius in ends	70 mm
Coil outside radius in ends	155 mm
Coil curing preload - sides	0 N
Coil curing preload – ends	0 N
Insulation thickness between turns	180 μm thick Nomex®
Potting agent	CTD-101K
Thickness of the collar	26.6 mm
Thickness of stainless-steel sheet between inner and outer layers	1.65 mm
Vertical pre-stress applied	17 MPa (low)
Horizontal pre-stress applied	Essentially none
Computed horizontal stress on structure	59 MPa at 10.2 T
Design maximum for horizontal stress	75 MPa
Stainless steel shell thickness	25.4 mm
Thickness of the end plates	127 mm
Yoke outer radius	267 mm
Yoke length	653 mm
Quench protection strip heaters (no energy extraction available during the tests)	25 μm X 38.1 mm, each quadrant, between layers

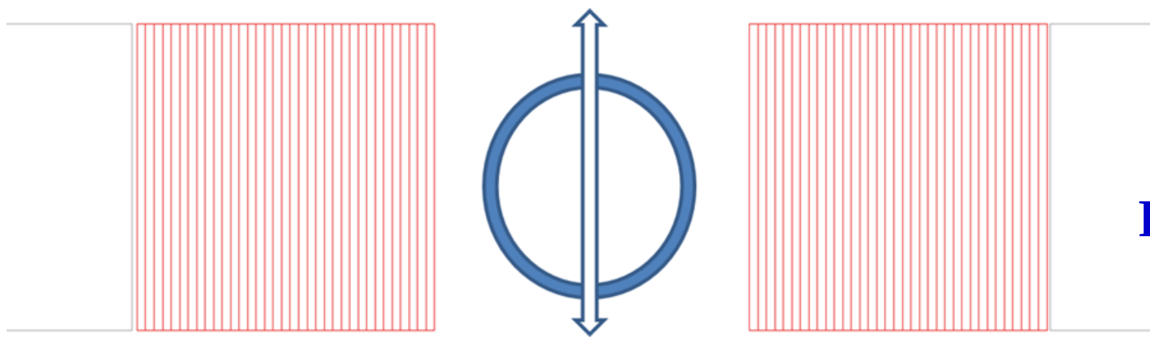






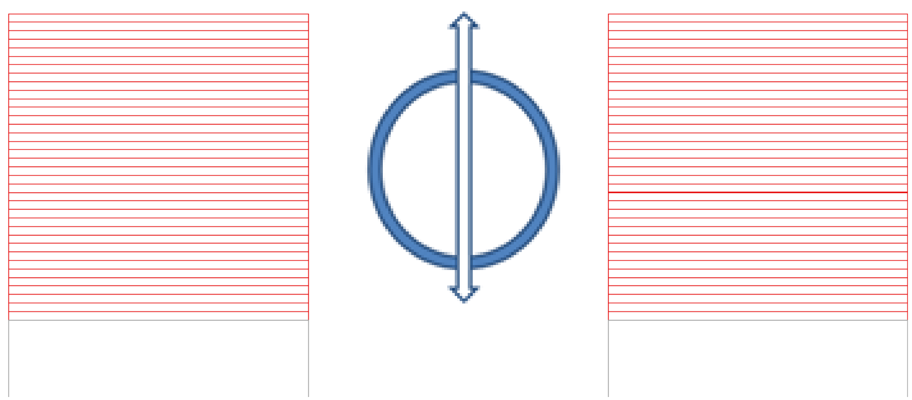


Coil and Magnet Cross-section for Measurements



More
Parallel

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



More
Perpendicular

Run Plan for Magnetization Studies
(almost everything planned in this slide done, perhaps not always be in the order planned)

Magnetization Studies Test Program at 4.5 K.
Purpose: To perform magnetization studies of HTS coils first by themselves and then in the background field of the Nb_3Sn common coil magnet.
During the following tests the magnet field should be measured continuously by the Hall probes and recorded.

1. **HTS Nomex Coil Only** (difference voltage between two HTS pancake coils must remain < 2 mV and attempt should be made that the HTS coil doesn't quench)
   - Ramp up to 100 A and down to 0 A
   - Ramp up to 200 A and down to 0 A
   - Ramp up to 400 A and down to 0 A
   - Ramp up to 600 A and down to 0 A
   - Ramp up to 800 A and down to 0 A

2. **HTS No-Insulation Coil Only** (difference voltage between two HTS pancake coils must remain < 10 mV and attempt should be made that the HTS coil doesn't quench)
   - Ramp up to 100 A and down to 0 A
   - Ramp up to 400 A and down to 0 A
   - Ramp up to 800 A and down to 0 A
   - After review of results of above tests, make plan to ramp to higher currents

3. **LTS (Nb3Sn) Coil Only**
   - Ramp gradually in steps to 10000 A (no quench at 10000 A in 2017 test and it reached 10,800 A in 2006).
   - If magnet trains, we will stop at 5 quenches and limit further operation of the LTS magnet to 90% of the current reached at the 5th quench.
   - If the magnet reaches 10000 A without quench, ramp the magnet to quench and limit further operation of the LTS magnet to 90% of the current reached.

4. **HTS/LTS Hybrid Magnetization Tests**
   - Hold LTS magnet at 500 A, 1 kA, 2 kA, 4 kA, 6 kA, and 8 kA, and for each HTS coil ramp up and down to whatever current safely possible without quenching (800 A nominal max).
   - Reduce current in LTS magnet and perform above steps.

Quenches in HTS/LTS Hybrid Dipole

DATE	TIME	HTS COIL	Nb3Sn Coil (A)	HTS Coil (A)	B, hybrid (T)	B, Nb3Sn + trapped
13-Feb-20	1955	Nomex	9830	955	**12.3 Tesla**	**9.39 Tesla**
14-Feb-20	1157	Nomex	9617	955	**11.96 Tesla**	**9.87 Tesla**
14-Feb-20	1652	NI	10120	955	**12.09 Tesla**	**10.37 Tesla**
15-Feb-20	1318	NI	9171	1000	**11.53 Tesla**	**9.34 Tesla**
15-Feb-20	1336	NI	-	1590	**4.23 Tesla**	**0.27 Tesla**
15-Feb-20	1414	NI	8000	1110	**10.74 Tesla**	**8.1 Tesla**
15-Feb-20	1502	NI	9000	910	**11.23 Tesla**	**9.2 Tesla**

All quenches in LTS coils.

HTS coils seems to tolerate quenches from Nb_3Sn coils (large energy transfer)