HTS/LTS High Field R&D Dipole

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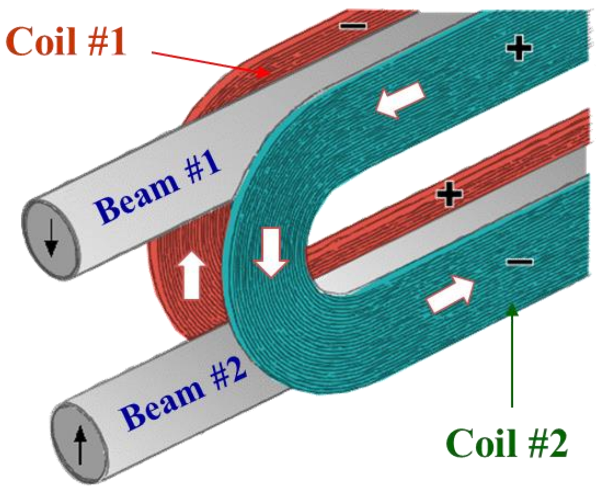
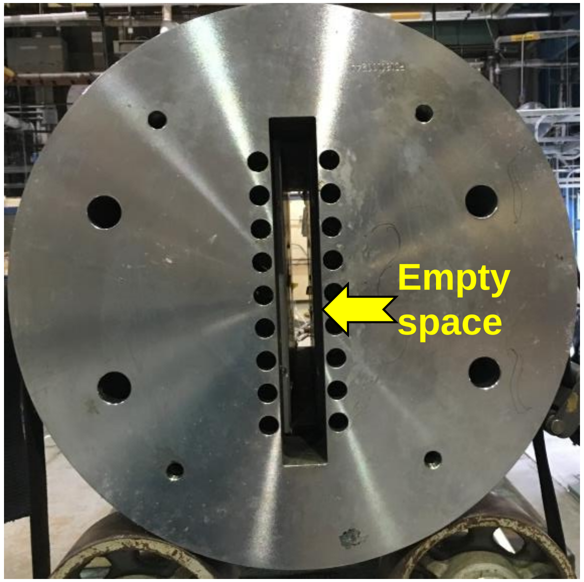
2020

Background

- *For high field (~20 T) dipoles for hadron colliders, HTS/LTS provides the most economical and viable path now*
  - *Use expensive HTS where field is high and relatively less expensive LTS (Nb_3Sn) where field is moderate*
- *Whereas HTS/LTS hybrid solenoids have been built and tested, no significant field hybrid dipoles have been*
- *Hybrid dipoles with coated conductors pose quench protection and field quality challenges. We compare field parallel Vs field perpendicular cases on HTS coil at 4 K*
- *This presentation summarizes significant developments, including test results of a 12.3 T hybrid dipole*

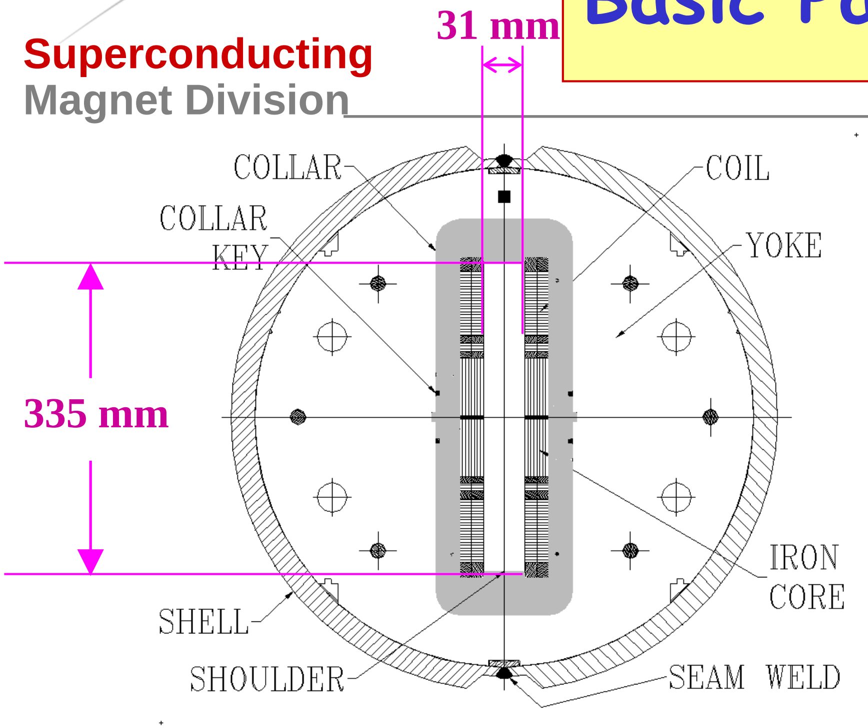
A Unique Background-field Dipole

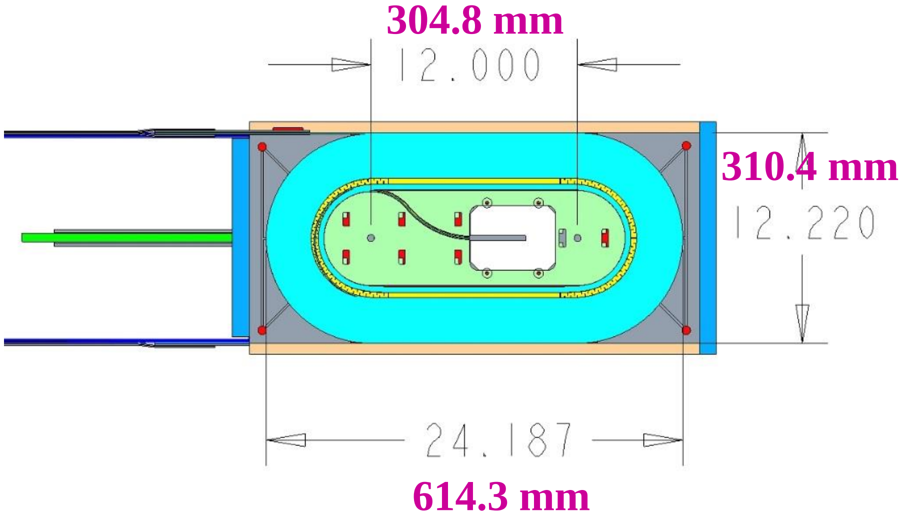




- ➢ Two hybrid dipole tests thanks to a unique Nb_3Sn background field common coil dipole
- ➢ Structure specifically designed to provide a large open space (31mm wide, 335mm high)
- ➢ New HTS coils can be inserted for testing them with up to ~10 T Nb_3Sn LTS coils
- ➢ HTS coils come in direct contact with the Nb_3Sn coils, making it a hybrid structure
- ➢ A new coil test becomes a new magnet test
- ➢ A rapid-turn around and a low-cost test

Basic Parameters of Dipole DCC017



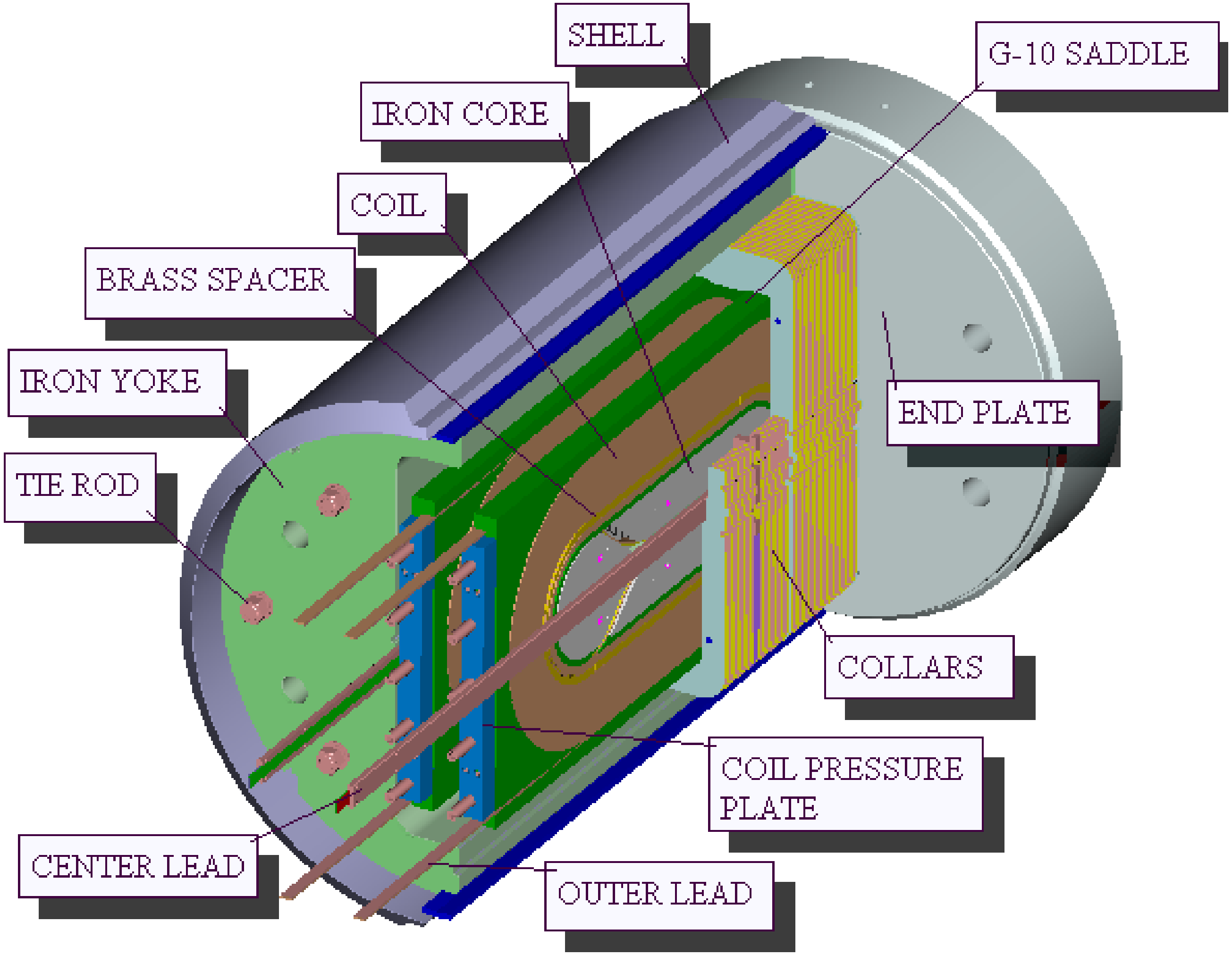


- Two layer, 2-in-1 common coil design
- 10.2 T bore field, 10.7 T peak field at 10.8 kA short sample current
- **31 mm horizontal aperture**
- **335 mm vertical aperture**
  - **A unique feature for testing insert coils or cables**
- **977 mm magnet length (overall)**
- 0.8 mm, 30 strand Rutherford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

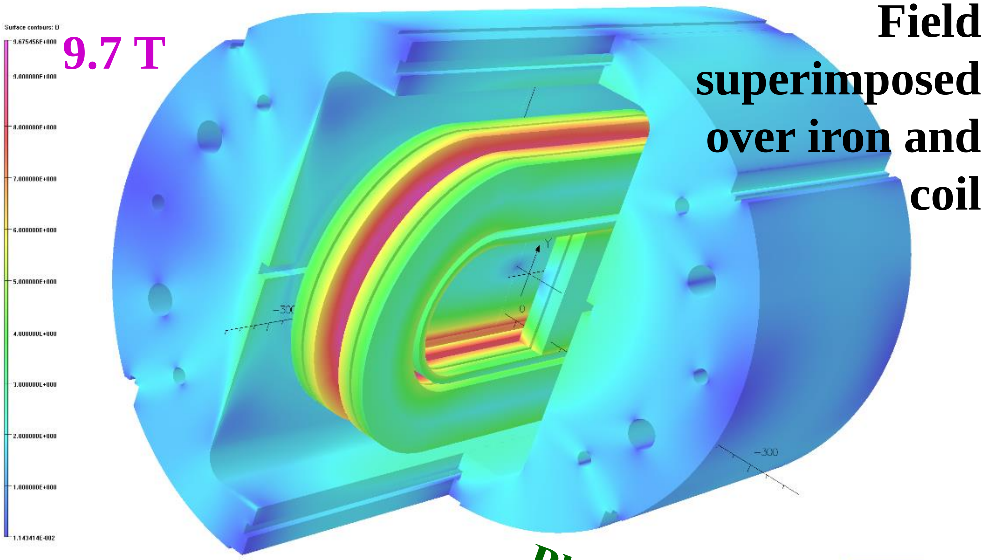
Detailed Design Parameters of DCC017

MAJOR PARAMETERS OF REACT & WIND COMMON COIL DIPOLE DCC017

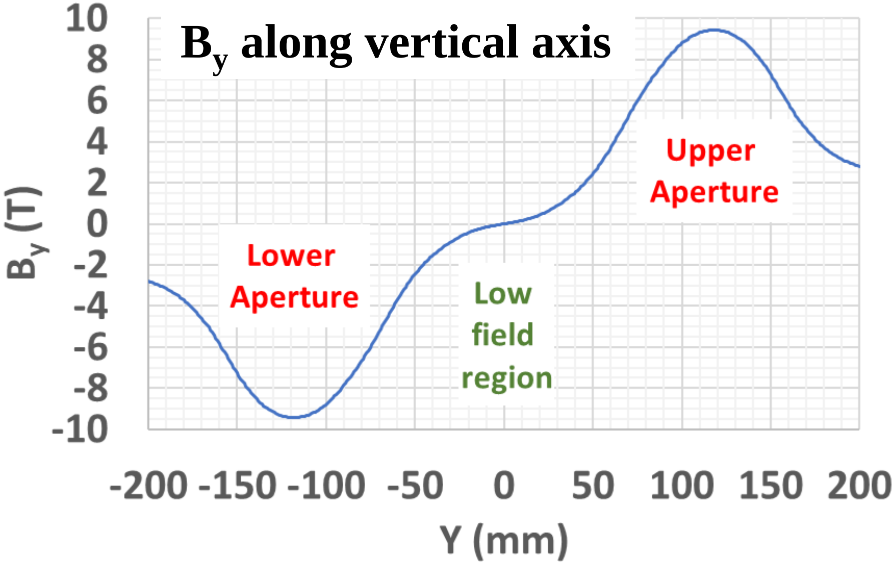
Magnet design	2-in-1 common coil dipole with racetrack coils
Conductor type	Nb_3Sn
Magnet technology	React and wind
Horizontal coil aperture (clear space)	31 mm
Vertical coil aperture (clear space)	335 mm
Separation between the magnetic center of the upper and lower aperture	236 mm
Number of layers	Two
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

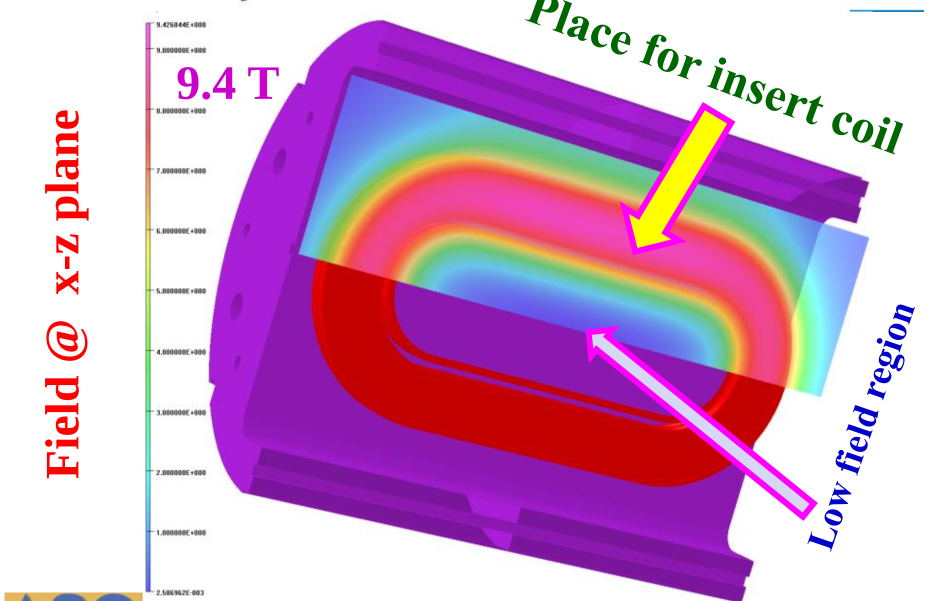


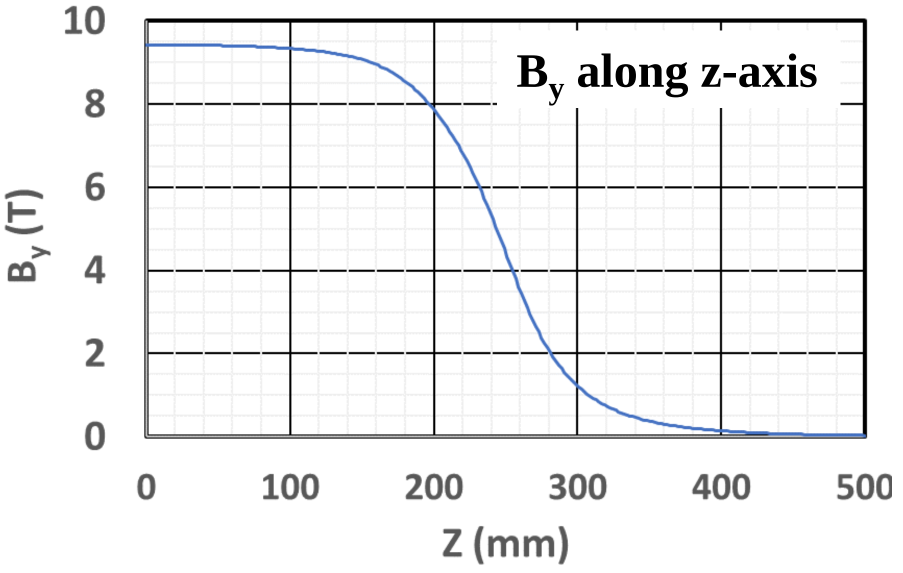
Magnetic Fields at 10 kA



Field superimposed over iron and coil







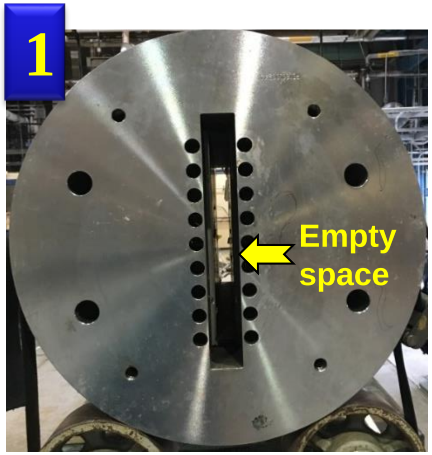
Magnet R&D Approach and HTS/LTS Hybrid Magnet Design & Construction

Rapid turn-around, Low cost R&D Approach

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



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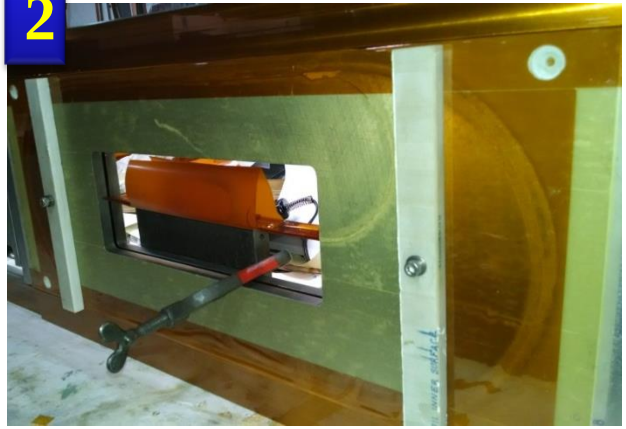

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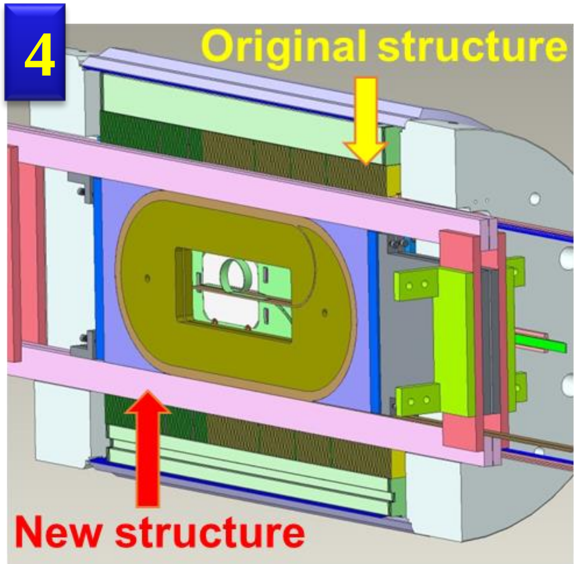

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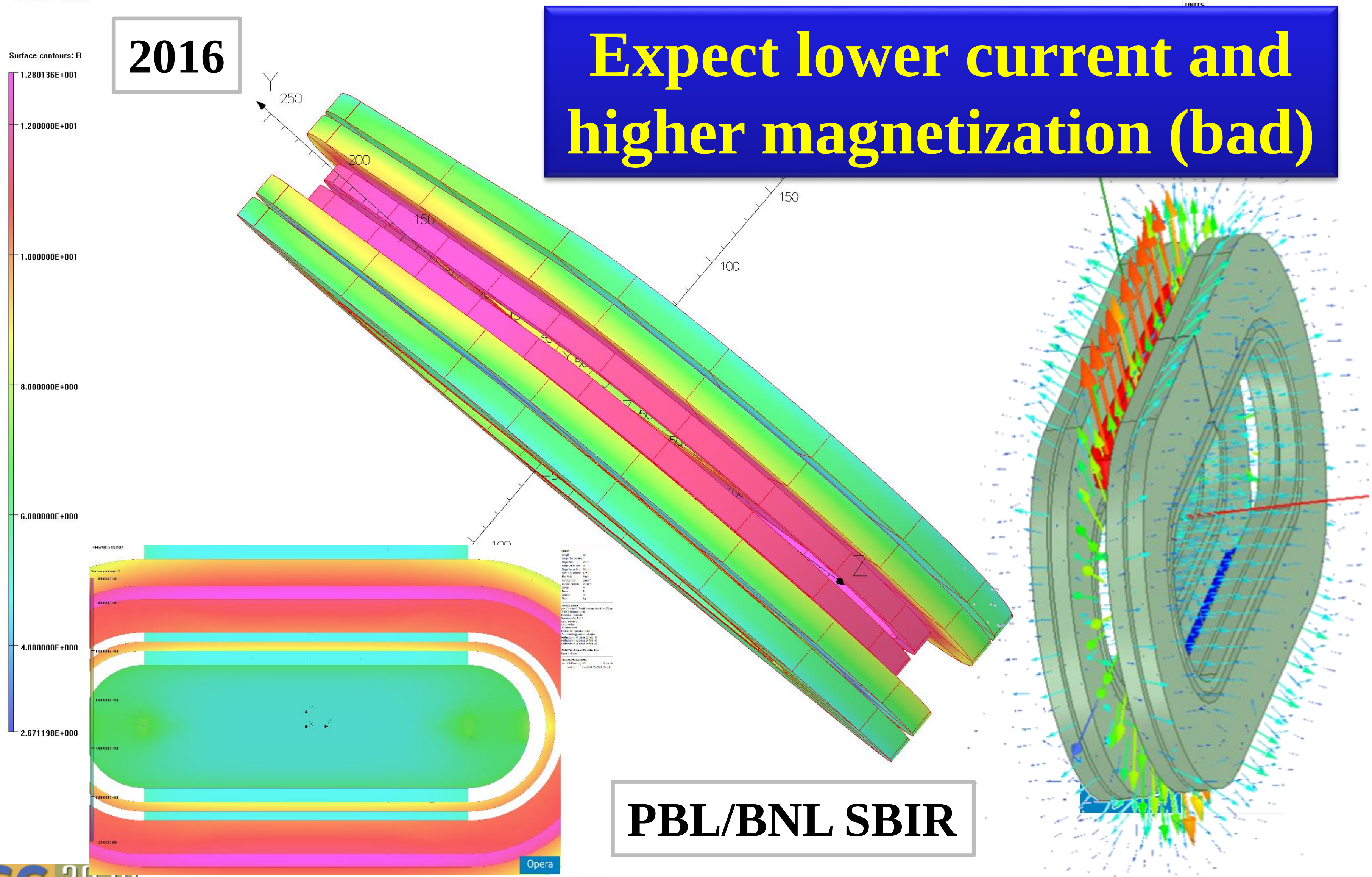
HTS/LTS Hybrid Program Overview

- *HTS/LTS Hybrid Dipole Design and Construction*
  - ➢ ***Field primarily parallel on the wide face of HTS tape***
  - ➢ ***Earlier study for field primarily perpendicular (PBL/BNL SBIR collaboration, results reported at MT25 in 2016)***
- *Quench Tests*
  - ➢ ***This study: many quenches in LTS coils dumping a large amount of energy in inductively coupled HTS coils***
  - ➢ ***Earlier study (2016): many quenches in HTS coils***
  - ✓ ***HTS & LTS coils remained protected in both cases***
- *Magnetization studies of HTS coils*
  - ➢ ***HTS coils in hybrid configuration with field from LTS coil (a) primarily perpendicular and (b) primarily parallel***

Test Configuration for Field Primarily Perpendicular to the Wide Face of the Tape

2016

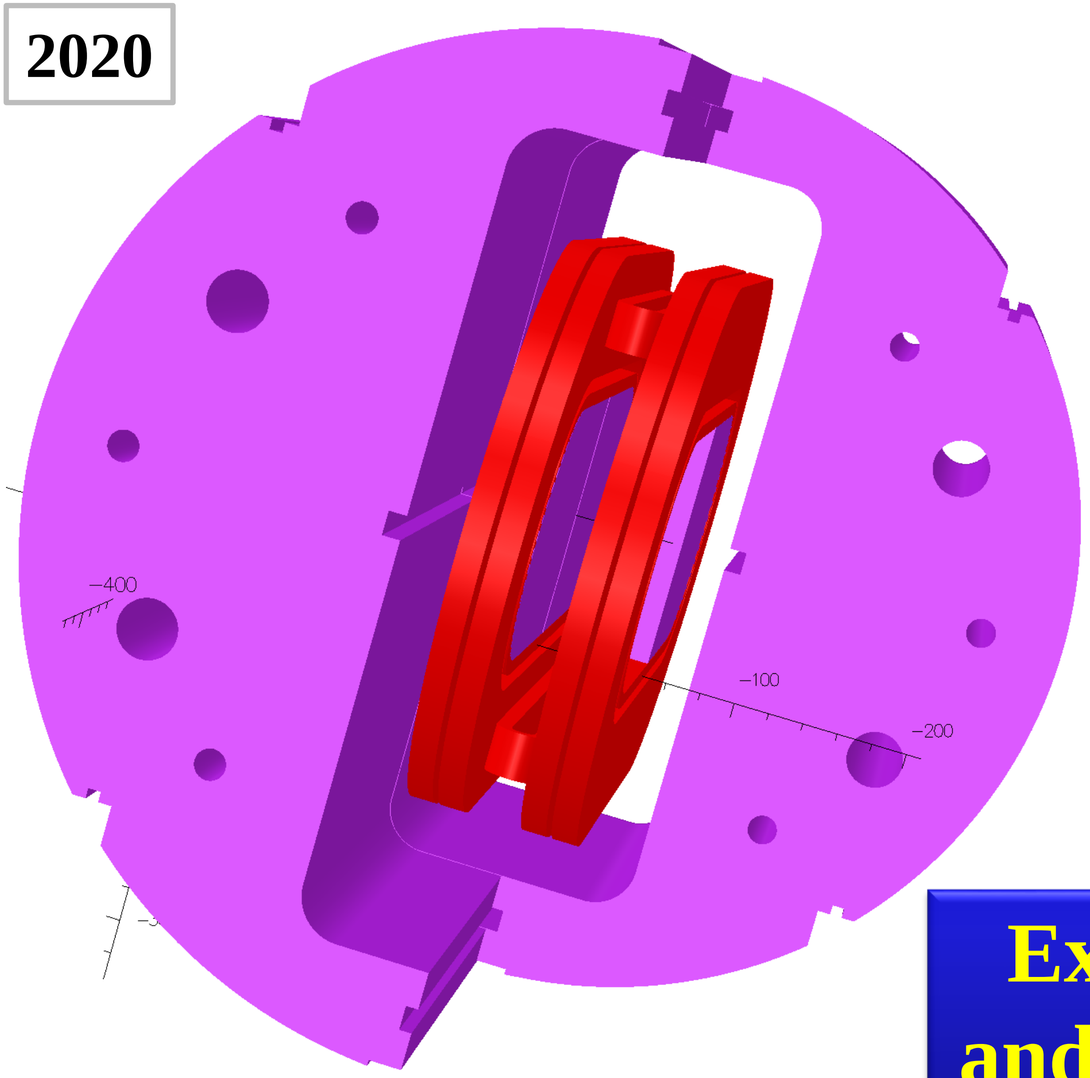


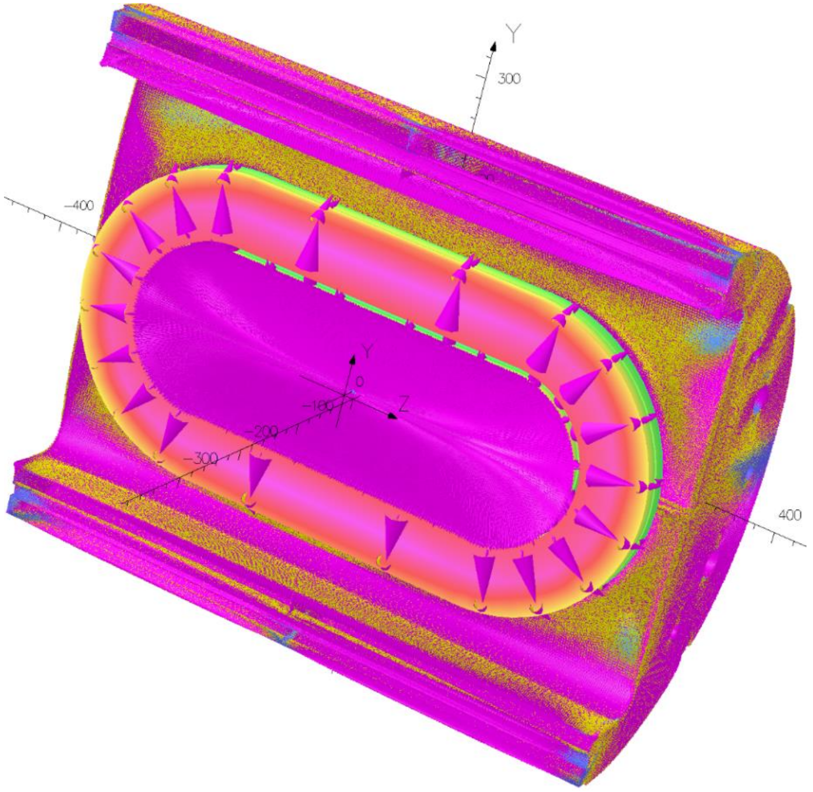
Expect lower current and higher magnetization (bad)

PBL/BNL SBIR

Test Configuration for Field Primarily Parallel to the Wide Face of the HTS Tape

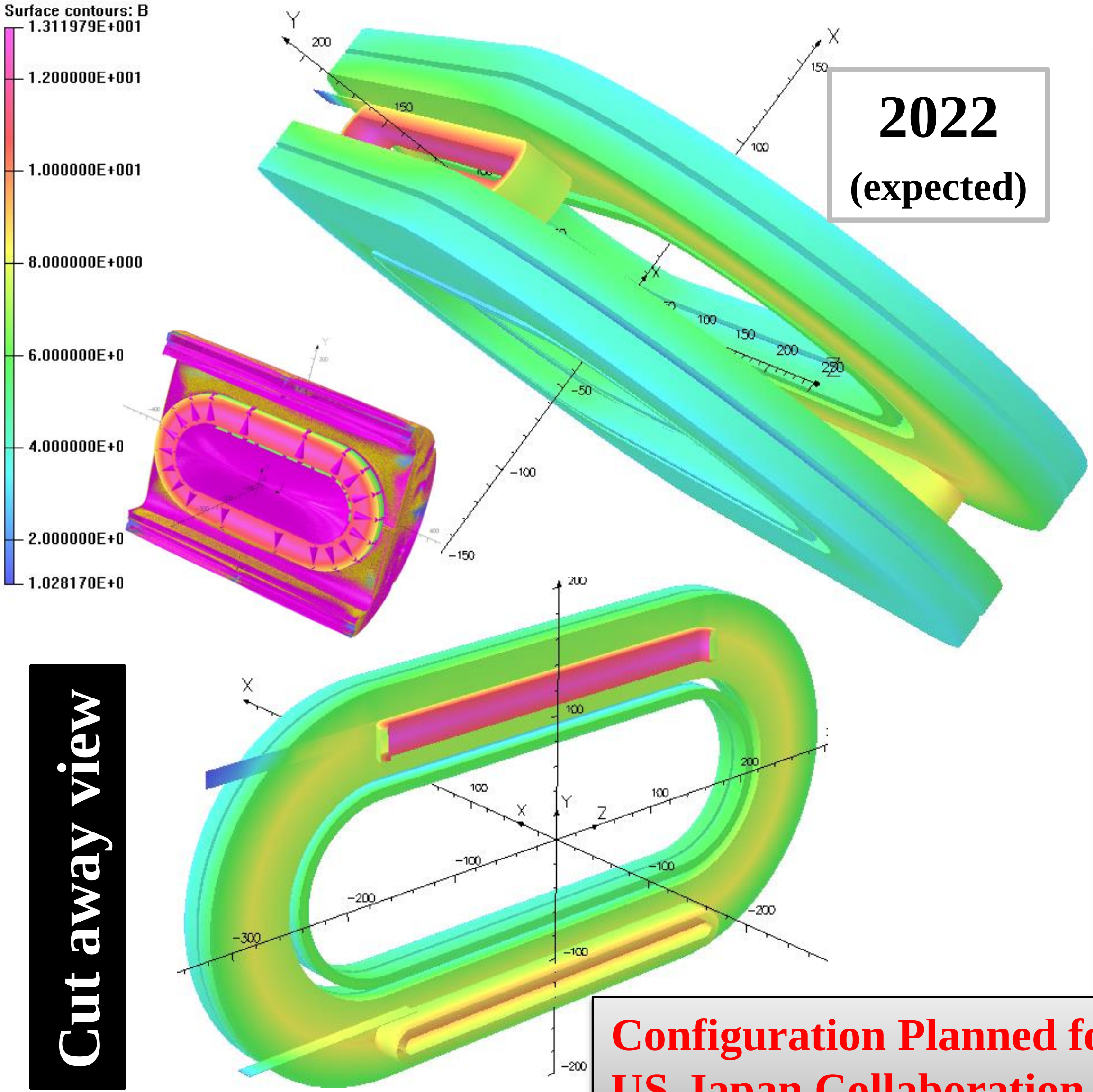
2020





Expect higher current and lower magnetization

Configuration for Both (field parallel & field perpendicular) Tested Together



2022
(expected)

Cut away view

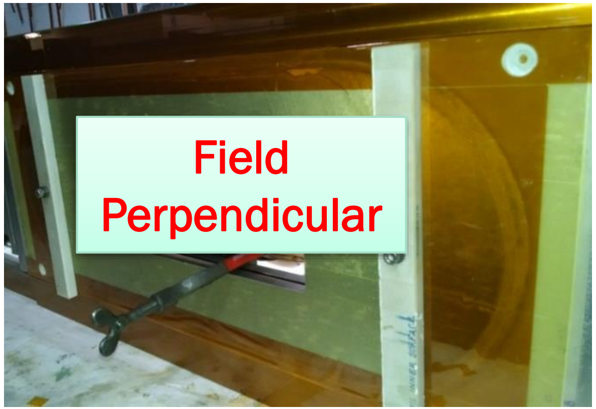
Configuration Planned for US-Japan Collaboration

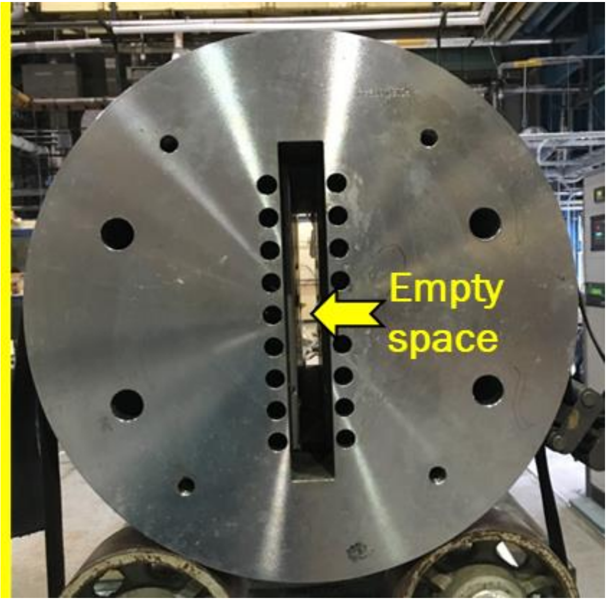
Two HTS insert coils in two bores (apertures) of the common coil dipole

(a) Upper bore: Field primarily parallel

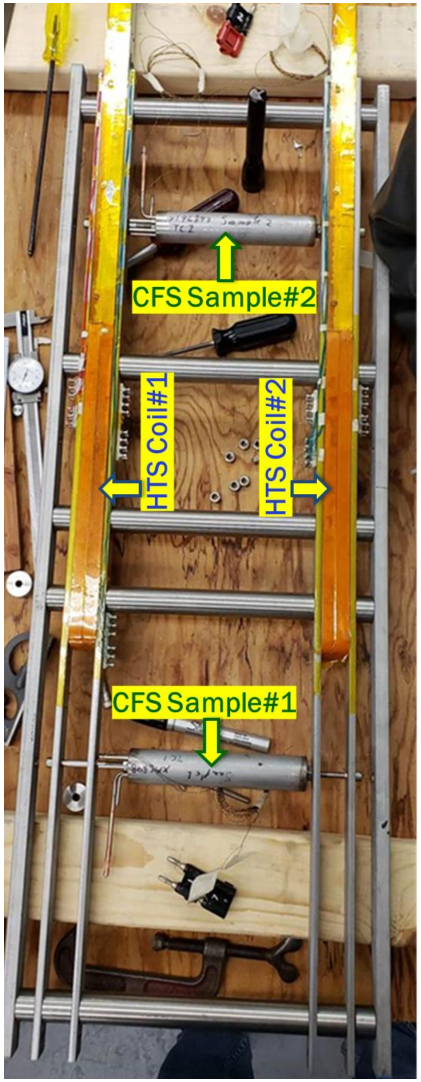
(b) Lower bore: Field primarily perpendicular

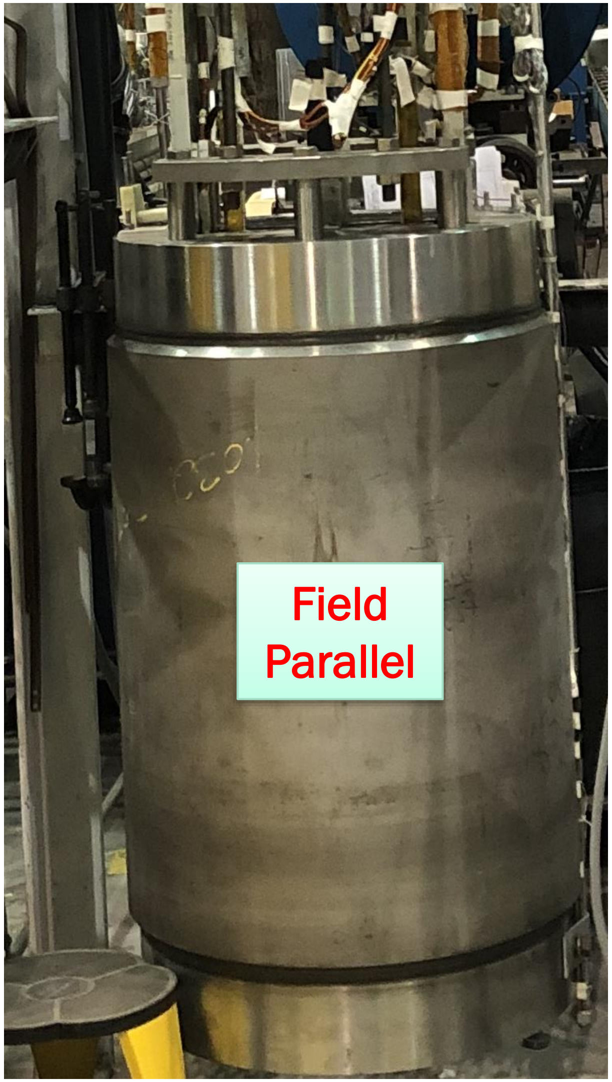
HTS/LTS Hybrid Dipole Configurations
Perpendicular (left), Parallel (right)





Test carried out under SBIR Program with PBL (2016)

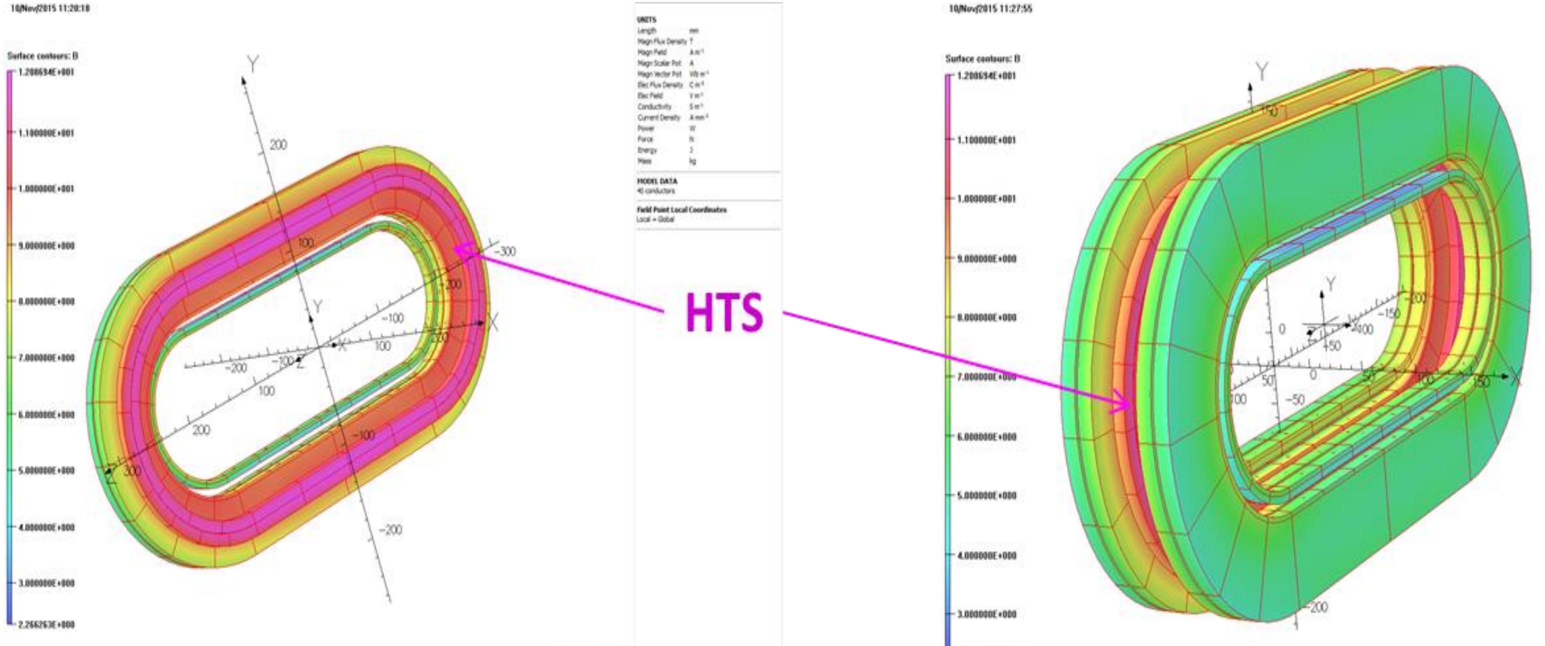




Test under Magnet Development Program (2020)

HTS/LTS Hybrid Magnet Quench Test Results

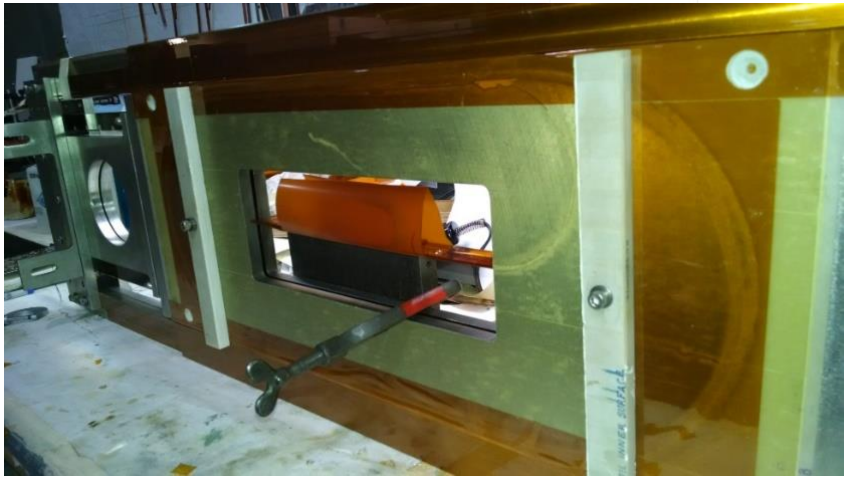
HTS/LTS Hybrid Dipole Test (2016)
(field on HTS coils primarily perpendicular)

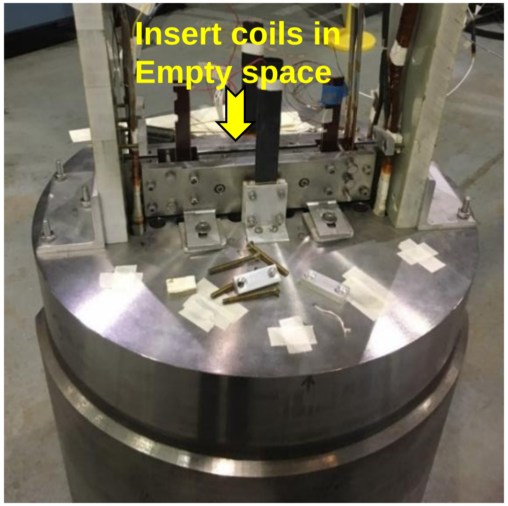


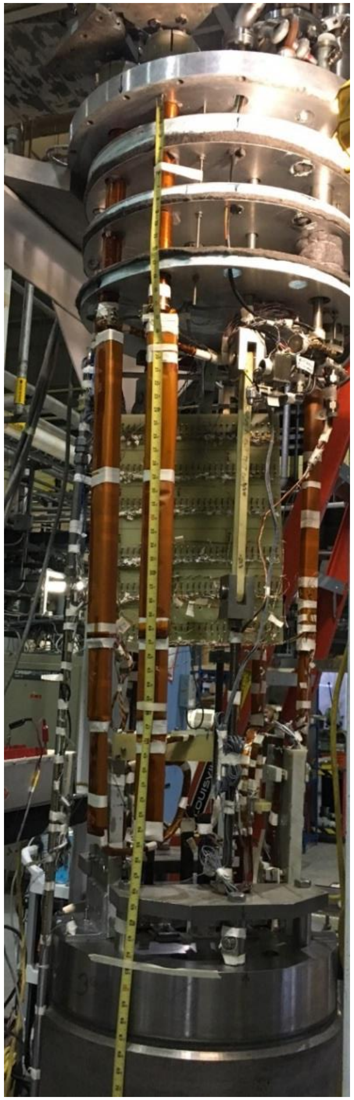
UNITS	
Length	mm
Magn Flux Density	T
Magn Field	A m⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Wb m⁻¹
Elec Flux Density	C m⁻²
Elec Field	V m⁻¹
Conductivity	S m⁻¹
Current Density	A mm⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA
40 conductors

Field Point Local Coordinates
Local = Global

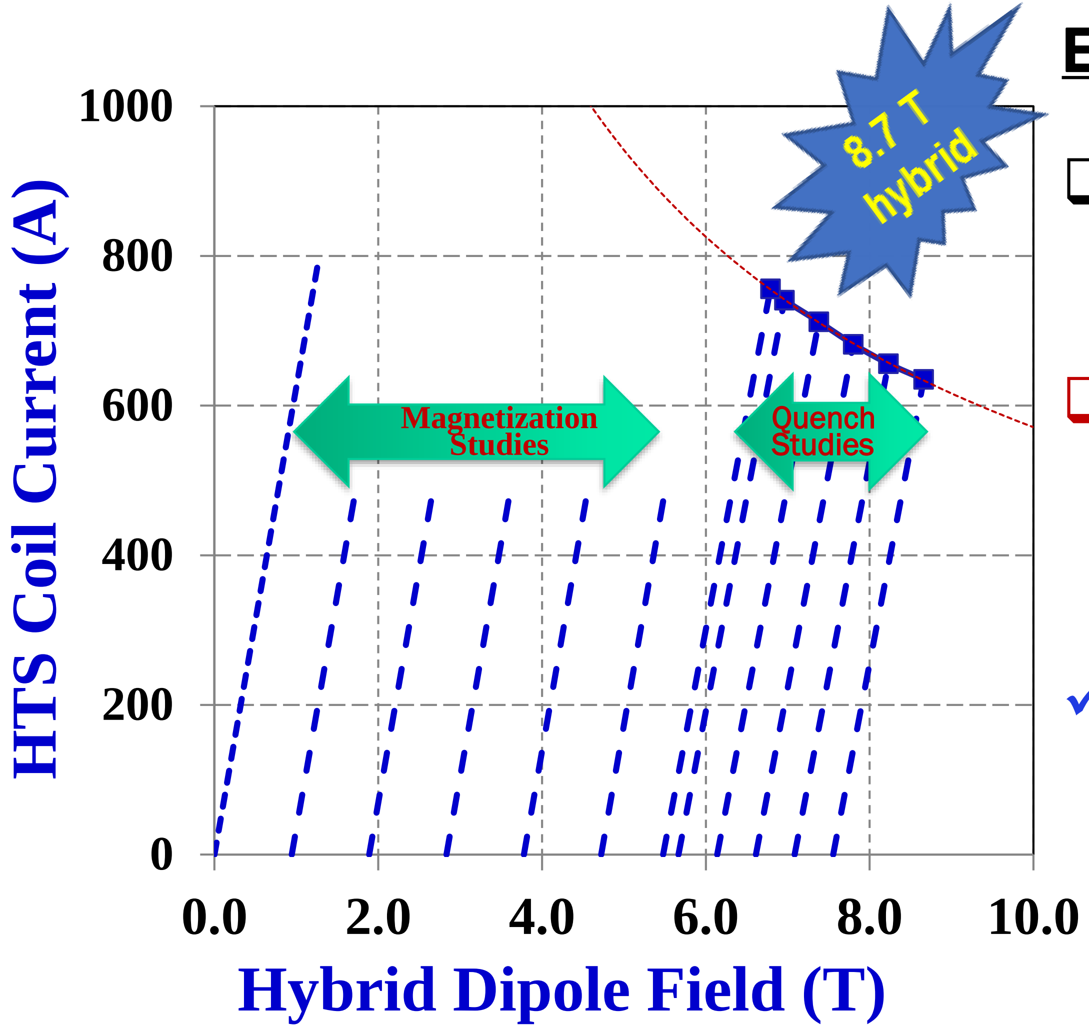






HTS/LTS Hybrid Dipole Test (2016)

(new HTS insert coils with existing Nb_3Sn magnet coil)



Encouraging Results:

- ☐ HTS coils were ramped to quench, just like LTS coils
- ☐ HTS coils had no training, no degradation despite **"several quenches"**
- ✓ Significant demonstration. 8.7 T was the highest field HTS/LTS hybrid dipole magnet at that time (2016)

➢ **Performance limited by the leads (not by the coils)**

Reported at MT25

HTS/LTS Hybrid Operation and Quench Protection Approach

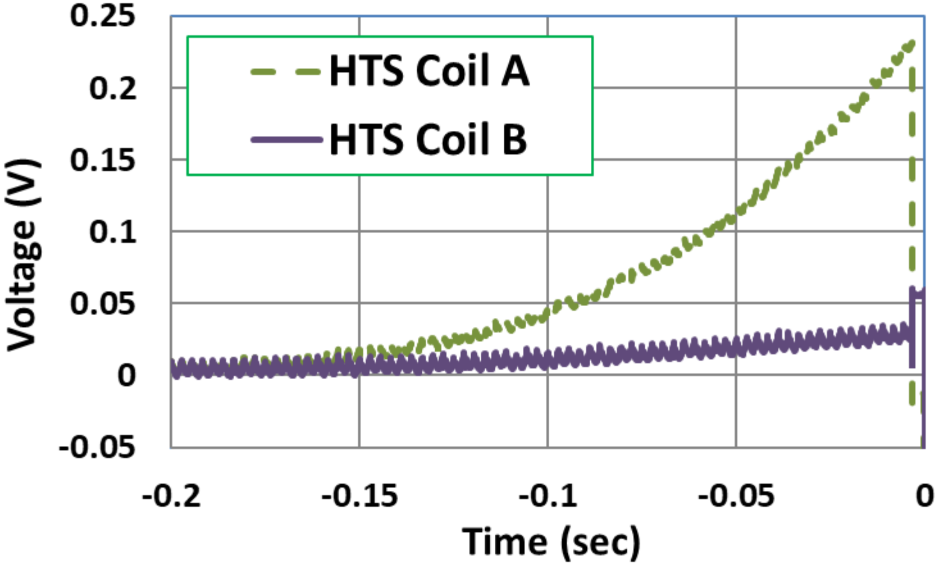
- HTS coils and LTS coils are powered separately
- Common quench platform
- Quench detection response time: < 5 msec; Coil current interruption: < 10 micro-second after detection
- In case of LTS quench, HTS is rapidly discharged before discharge of LTS is initiated
- LTS discharge is achieved by very high-speed switching sequence of dump resistors using IGBT switches

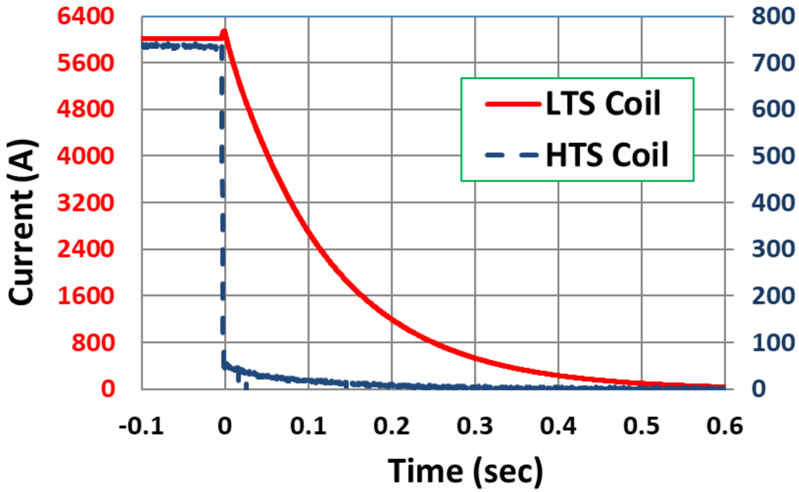
Slides in this presentation explaining this strategy in use

Quench Protection of HTS Coils in HTS/LTS Hybrid Magnet (2016)

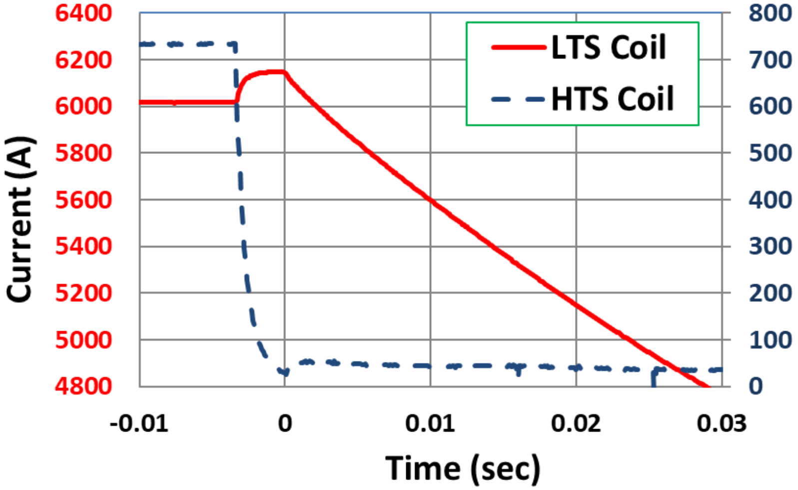
HTS coils operated like LTS coils

- Significant voltage in HTS coils





Energy extraction from HTS coils prior to shutting of the LTS coils



- Coupling between HTS & LTS coils
- LTS coil never quenched during these tests
- Next Question: Will HTS coils survive the quenches in inductively coupled LTS coils with larger stored energy? (wait for 2020)

Field Parallel Configuration (2020)

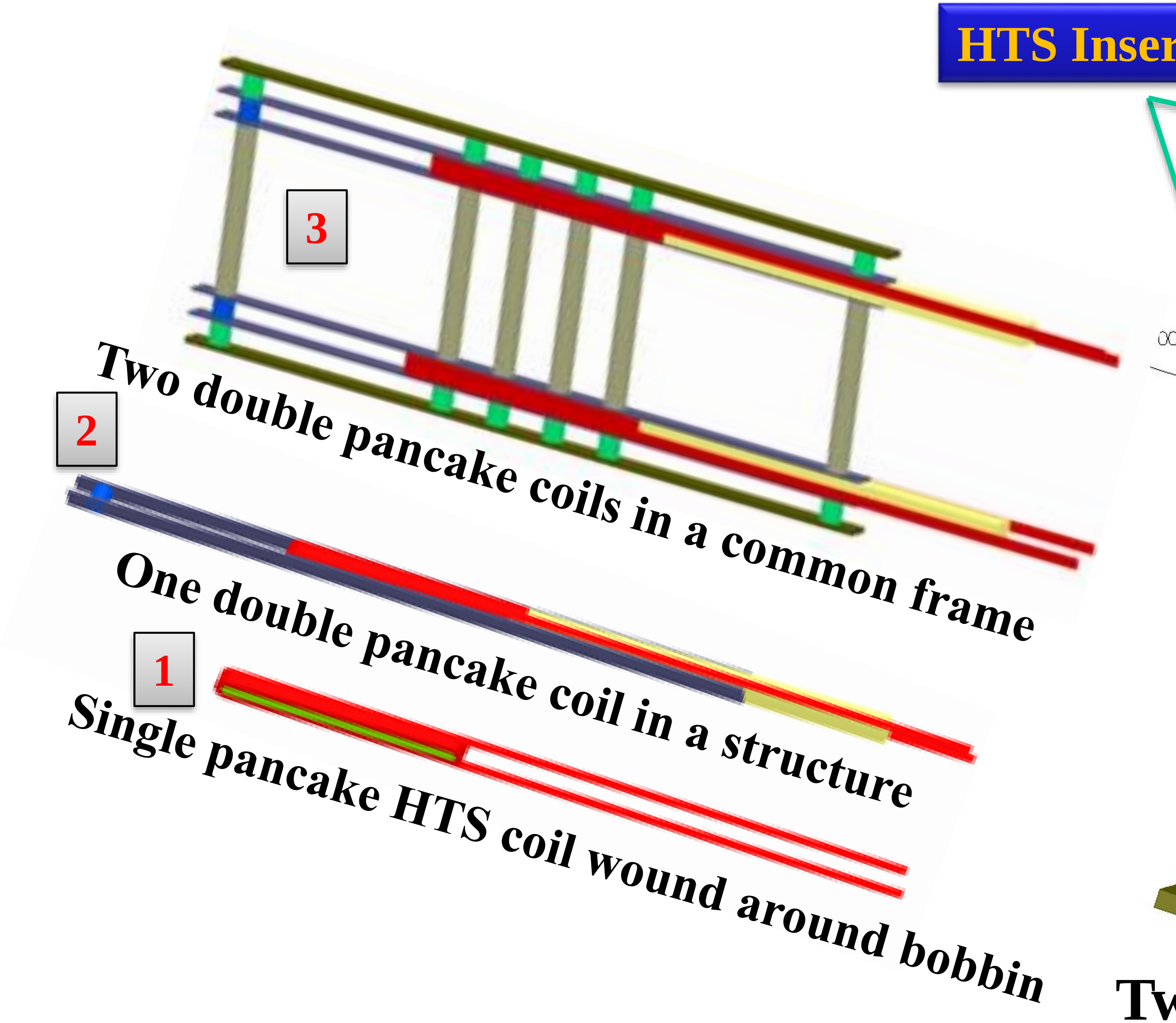
- **Expect higher current in HTS Coils**
- **Expect higher HTS/LTS hybrid fields**
- **Expect lower magnetization in HTS coils**

Coils wound with 12 mm HTS Tape in Different Stages of Construction

ReBCO tape from SuperPower

HTS Insert Coil Structure Concept

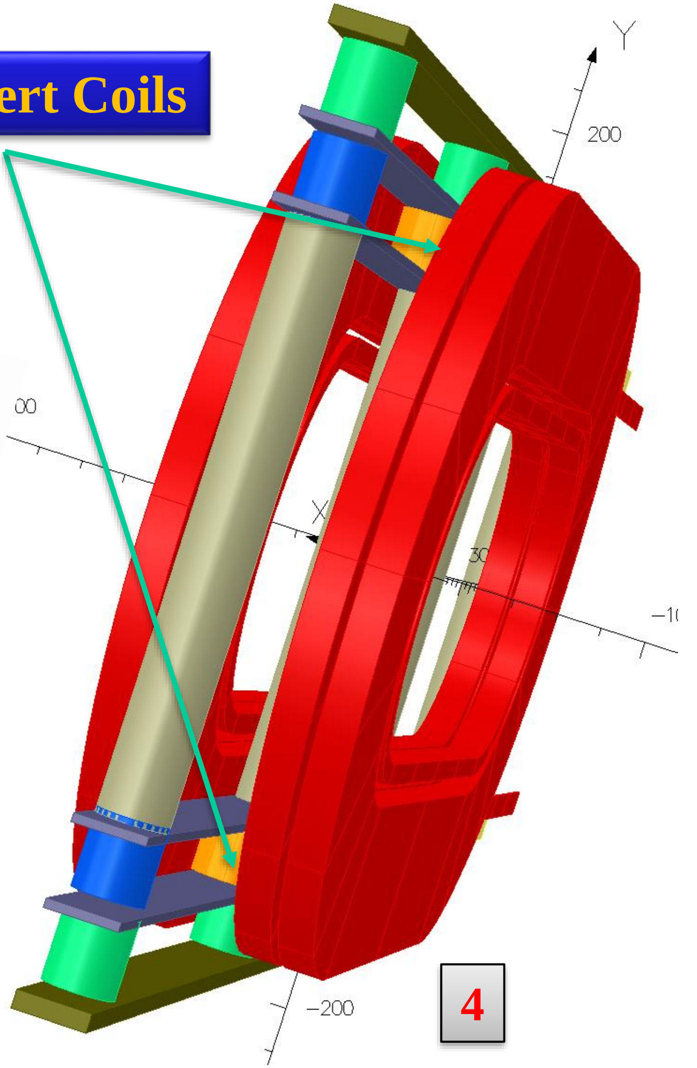
(two HTS coils in the 2-in-1 Nb$_3$Sn common coil dipole)



Two double pancake coils in a common frame

One double pancake coil in a structure

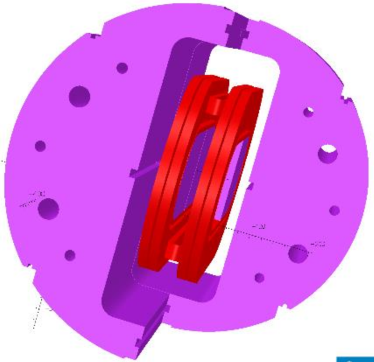
Single pancake HTS coil wound around bobbin

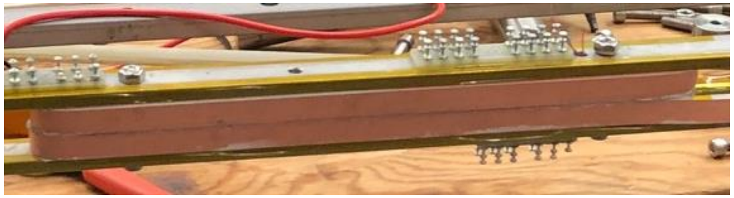


HTS Insert Coils

Two coils in two aperture

Field Parallel Hybrid Magnet Tests
(two apertures allow two variations in one go)





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)

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)

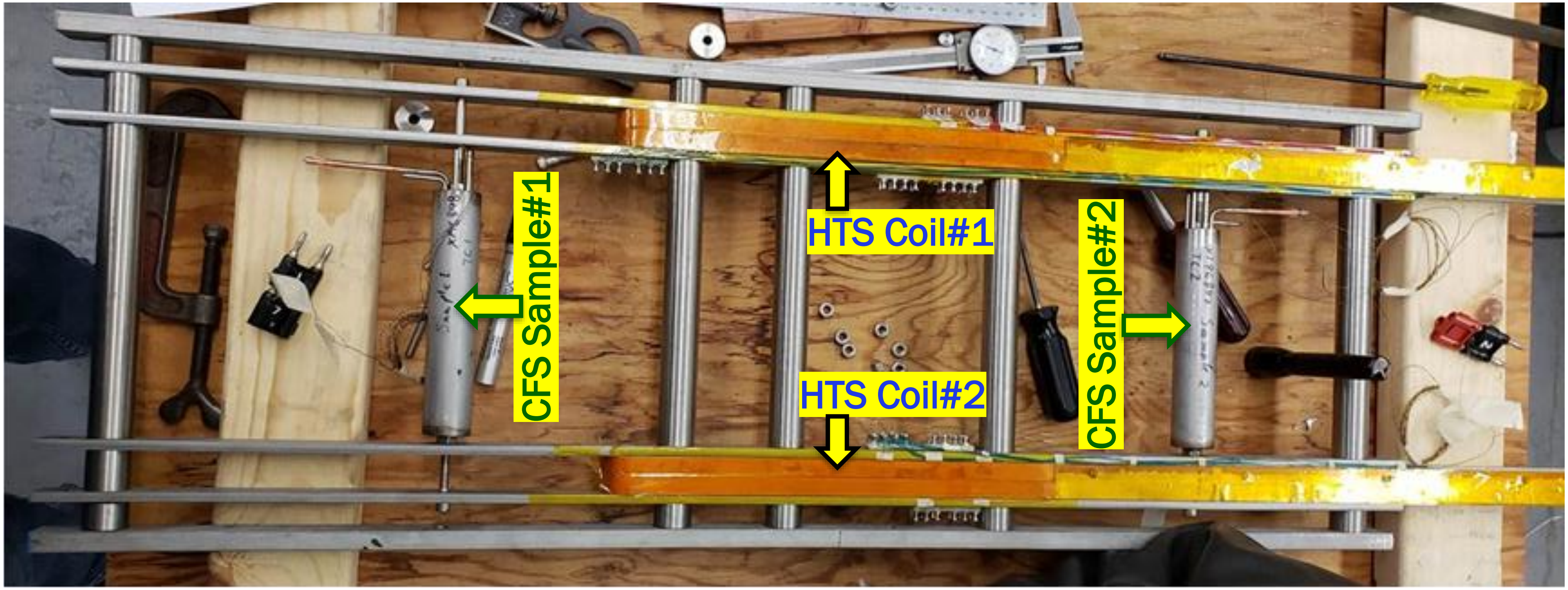
LTS coil size: 27 mm X 85 mm

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

Bore size: 13 mm X 25 mm

Multi-test Platform (four tests in one go)

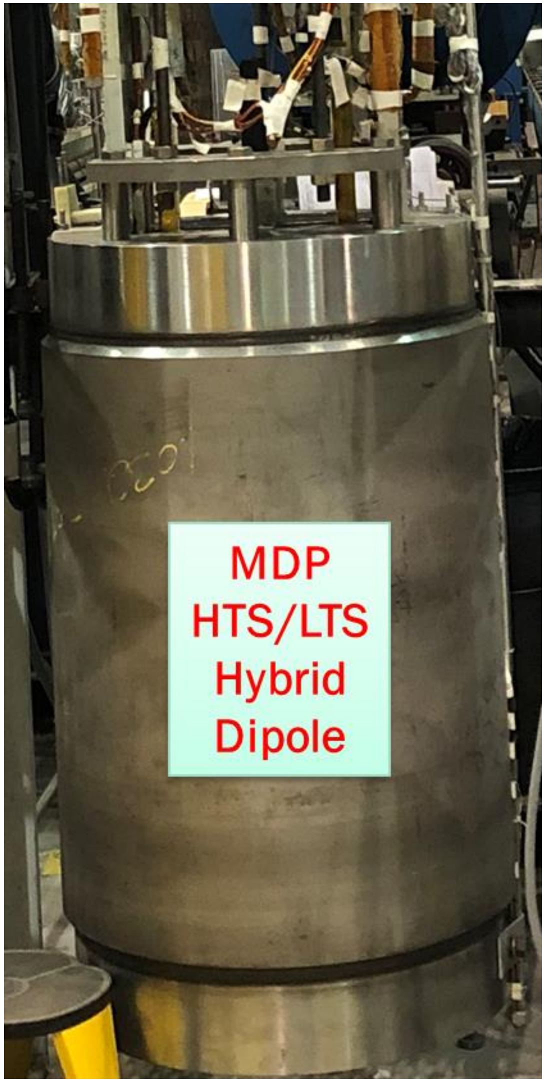
Test holder ready to be inserted in DCC017



Two HTS coils for testing in field parallel configuration

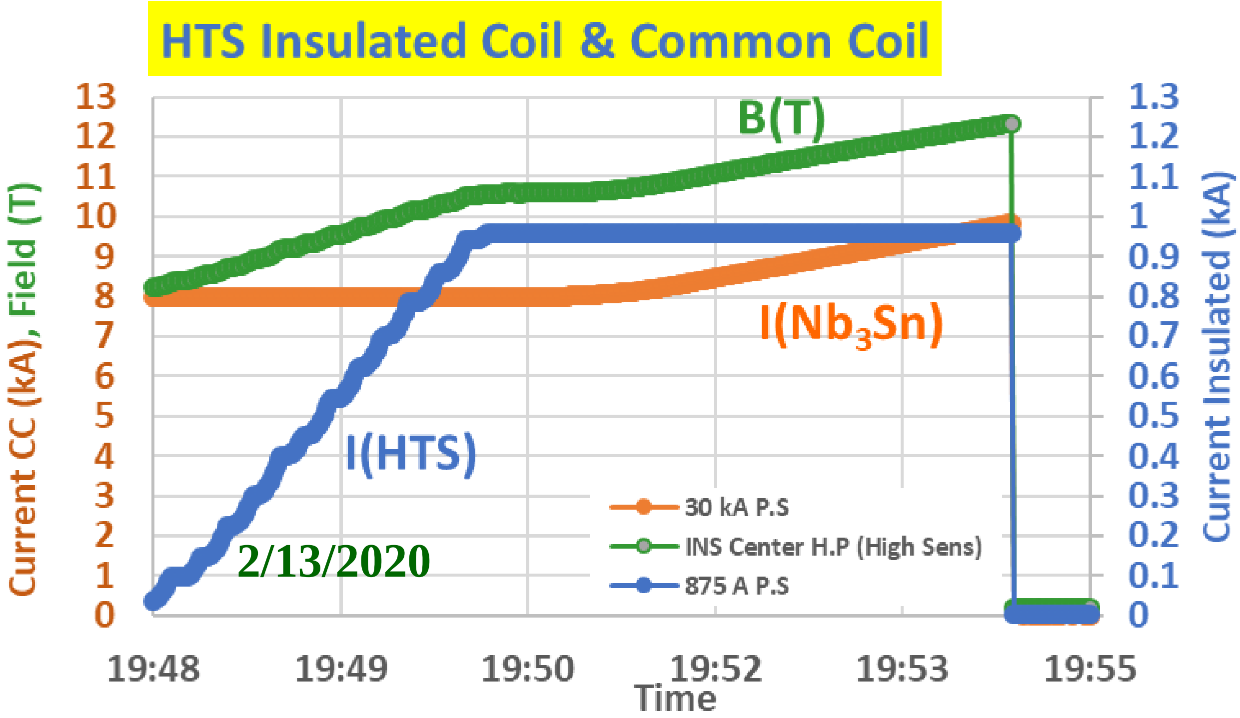
(also included, two HTS cable samples from the fusion community)

HTS/LTS Hybrid Dipole Test
(creating a record 12.3 T hybrid dipole field)



Test sequence:

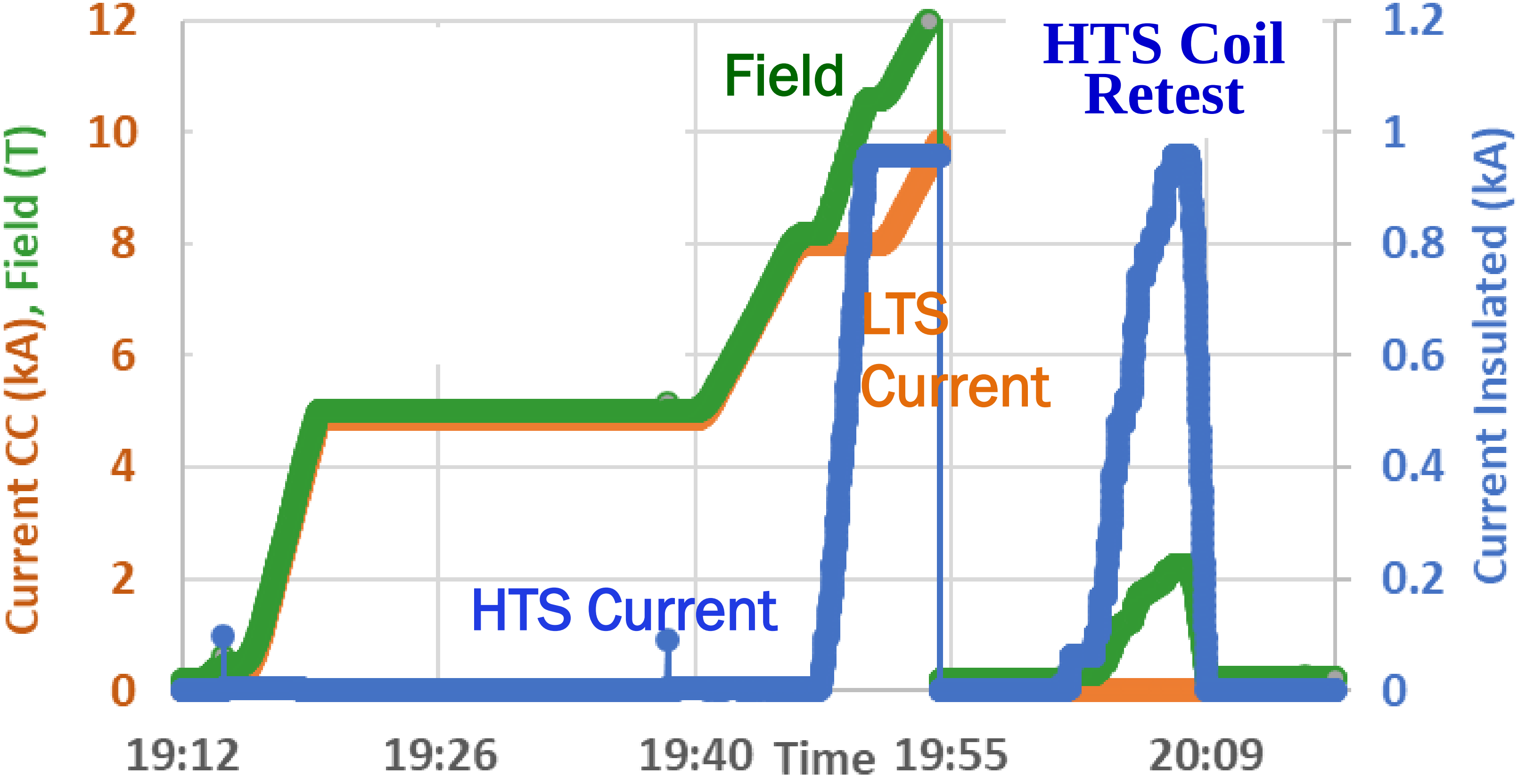
- Nb_3Sn ramped to 8 kA (~8 T)
- HTS ramped to 950 A
- Nb_3Sn ramped to quench (~10 kA) creating a record ~12.3 T hybrid field (~3 T from HTS)



Full Hybrid Dipole Test Sequence
(magnet reached 12.3 T, HTS coils survived)

2/13/20

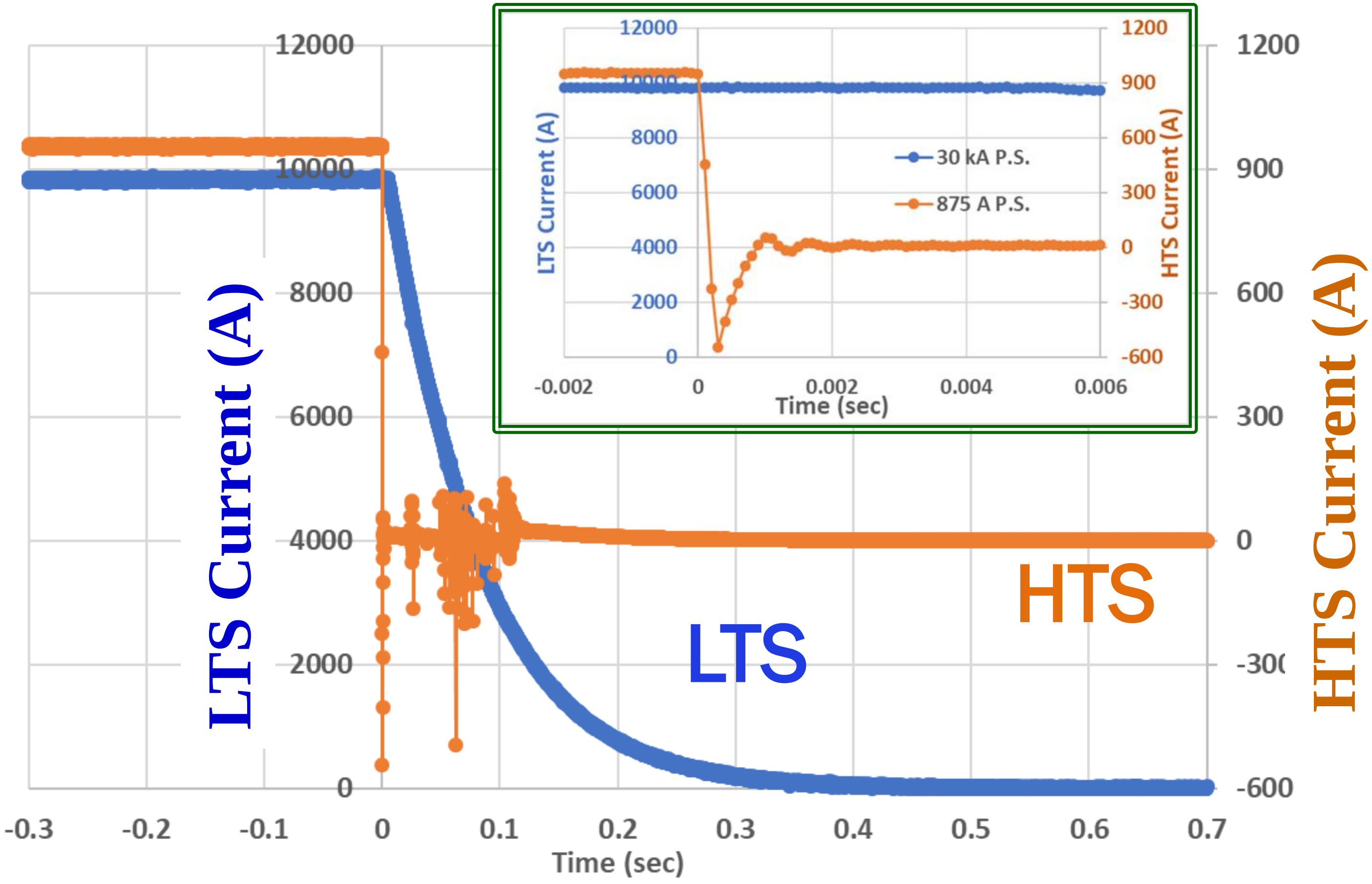
HTS Insulated Coil & Common Coil



HTS coil was quickly retested to check if it survived the quench (large stored energy from the LTS coil was dumped in to the HTS coil)

Quench Protection of HTS/LTS Hybrid Dipole when LTS Quenches

Major concern was: what will happen if LTS coil quenches, and dumps large energy on HTS coil? Will HTS coil survive?

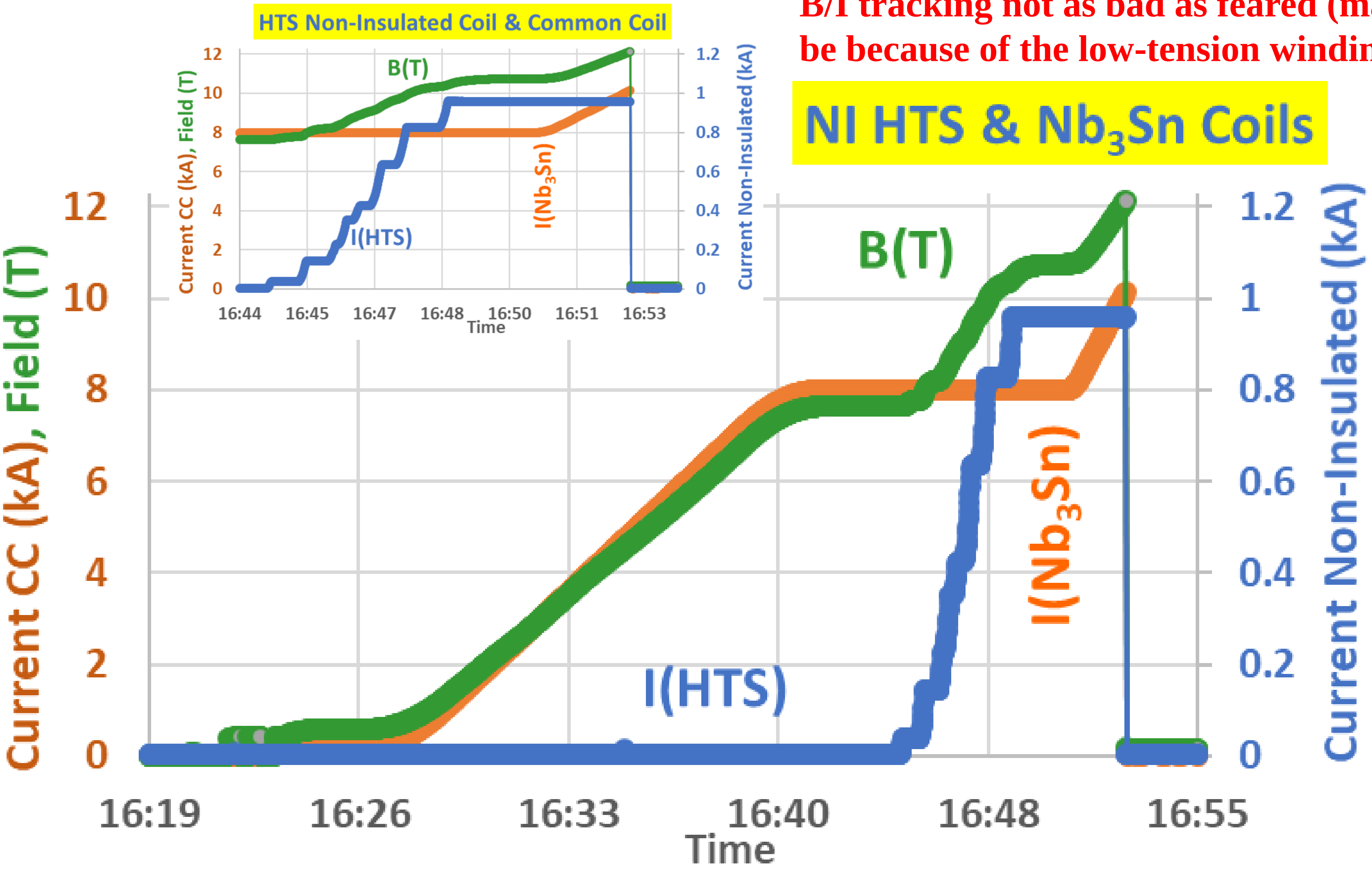


Energy extraction from the LTS coils starts after the HTS coils are rapidly deenergized (see inset), protecting HTS coils

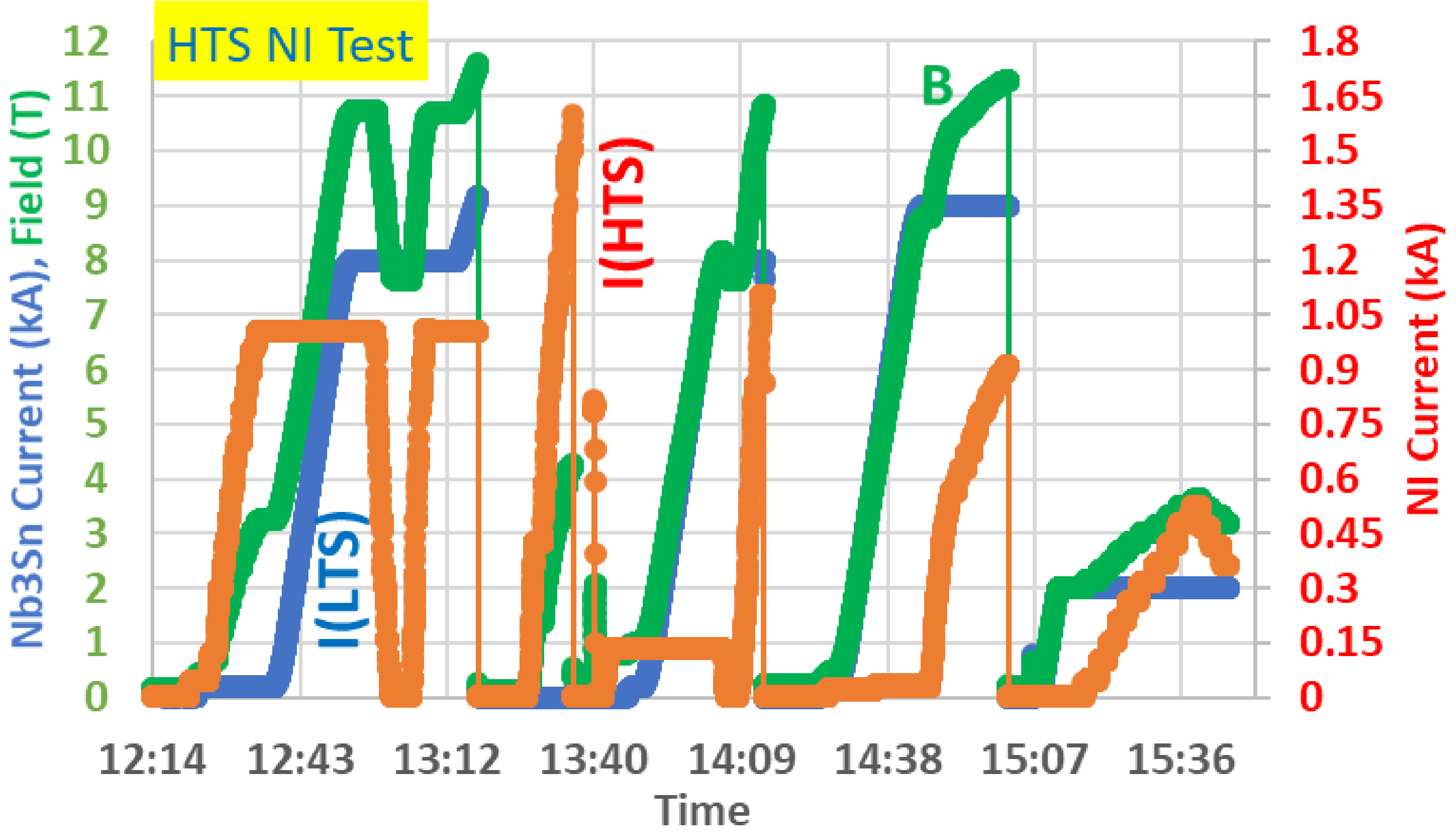
ReBCO/Nb_3Sn Hybrid Dipole with NI Coils

B/I tracking not as bad as feared (may be because of the low-tension winding)

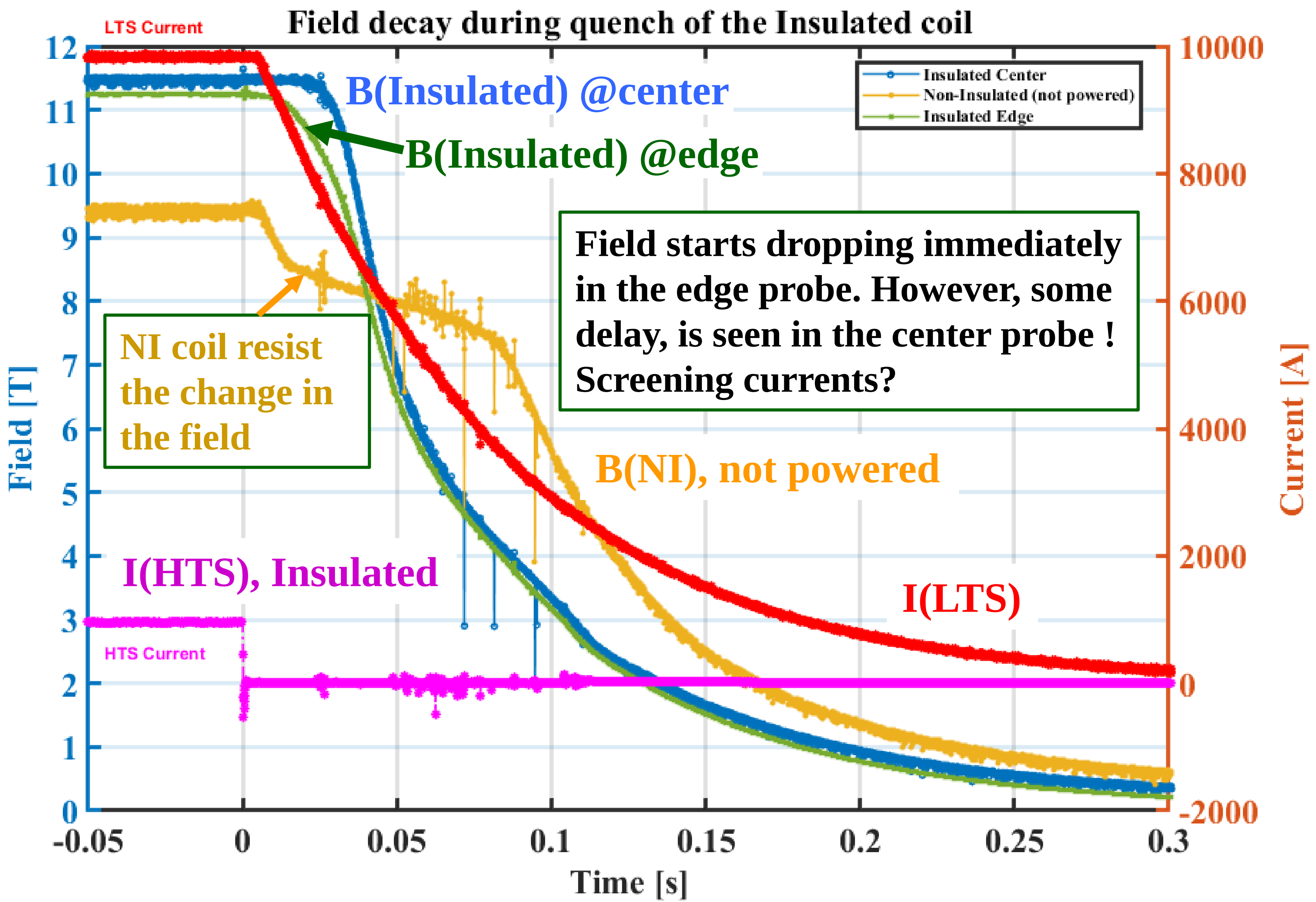
NI HTS & Nb_3Sn Coils



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



Insulated HTS Coil Energized with LTS Coil (No-Insulation HTS coil not powered)



B(Insulated) @center

B(Insulated) @edge

Field starts dropping immediately in the edge probe. However, some delay, is seen in the center probe ! Screening currents?

NI coil resist the change in the field

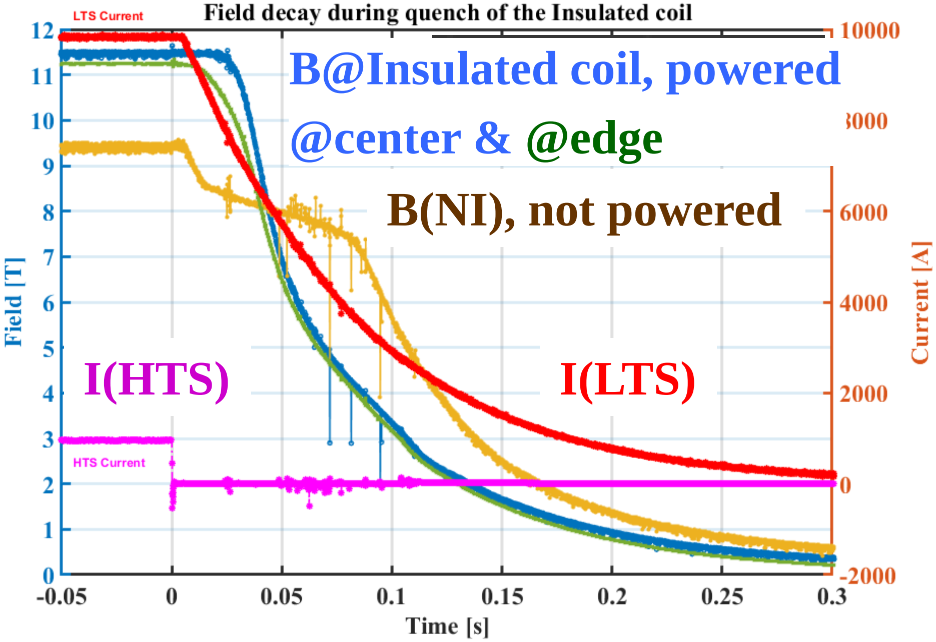
B(NI), not powered

I(HTS), Insulated

I(LTS)

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

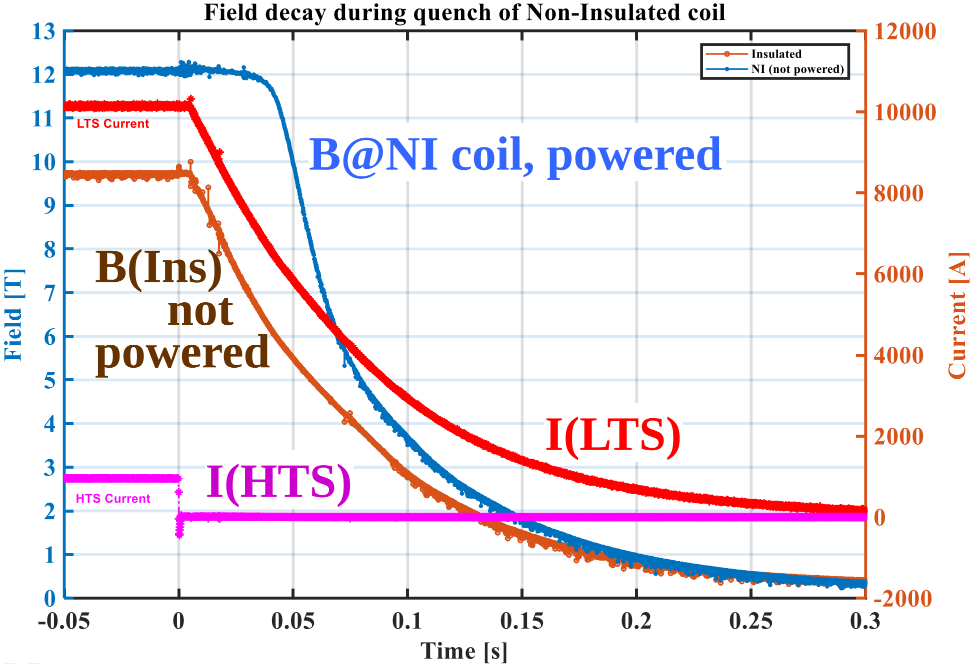
Insulated Coil



Notes:

- B drop at the center of insulated coil (powered) starts with some delay after shutting both HTS and LTS coils
- B drop at the center of NI coil (not powered), first resist the change and then drops slowly

Non-Insulated (NI) Coil



Notes:

- B drop at the center of NI coil (powered) starts with a delay of 0.04 seconds after shutting both HTS and LTS coils (compare this to 0.02 in case of insulated coil)
- B drop at the center of Insulated coil (not powered) is immediate

Quenches in HTS/LTS Hybrid Dipole

Experience with many quenches in LTS coil in a hybrid dipole.

Quench system protected the HTS coils despite a large energy transfer from LTS coils to HTS coils due to inductive coupling.

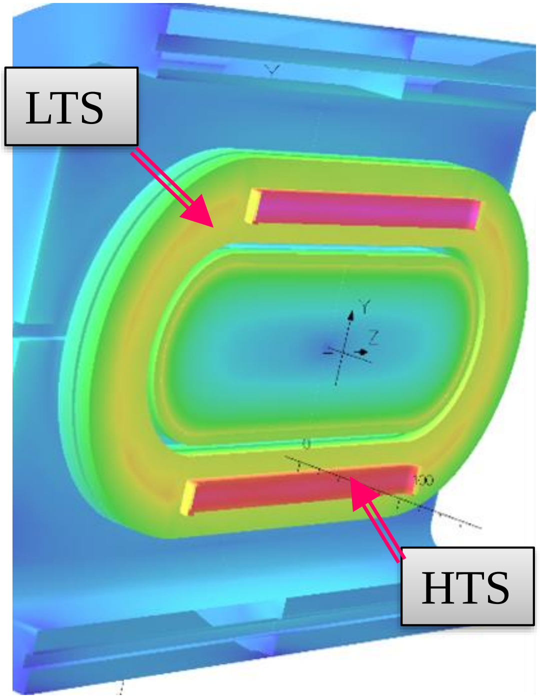
I=0 (HTS)

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**

One HTS coil was partly damaged when accidently the HTS power supply circuit was left open during one of the LTS coil shut-off

- ➢ Lesson relearned - high induced voltage create arcing

Summary and Observations from the Quench Tests (2)

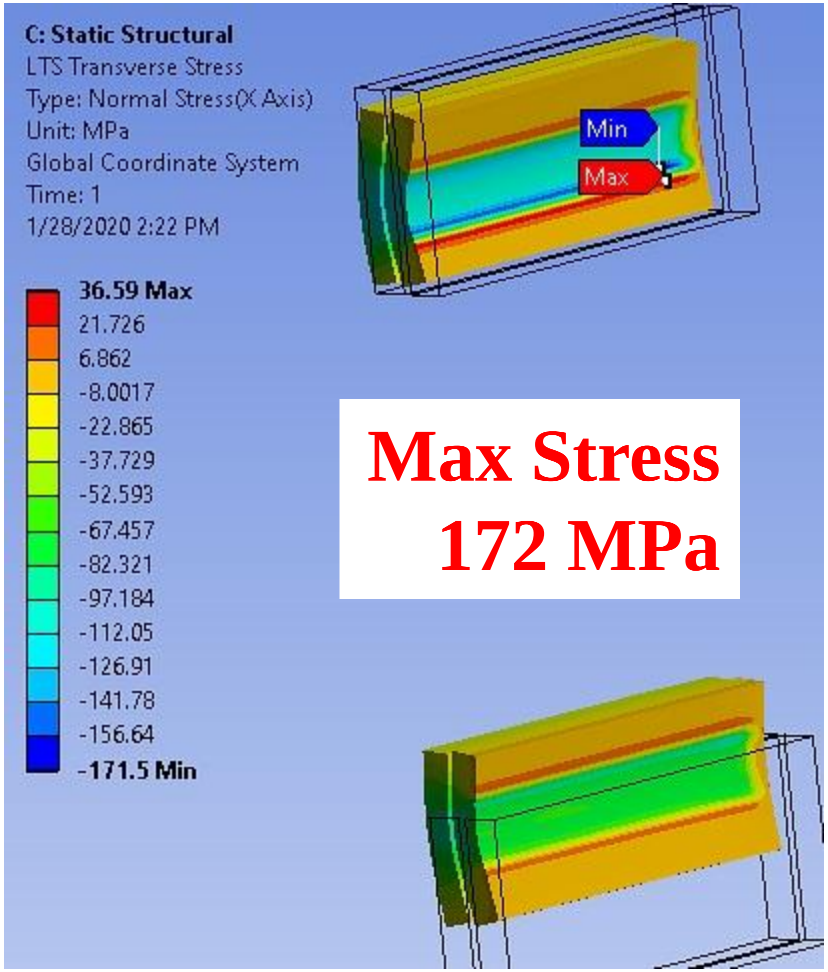


- ☐ Note that the HTS coils didn’t have their own independent support structure. When they were energized, they leaned on the LTS coils for support. It creates a pinching stress on the LTS coils at the corners where HTS coils rest.
- ☐ Several combinations of currents in the HTS coils and the LTS coils were tried. In all cases, LTS coils quenched (sometimes a little before short sample).

The hypothesis is that the quench is caused by the strain from the pinching forces. To minimize that either include a relatively thicker structure on the HTS coil to contain the Lorentz forces, or at least a thinner structure on the HTS to distribute/dilute the local stress/strain.

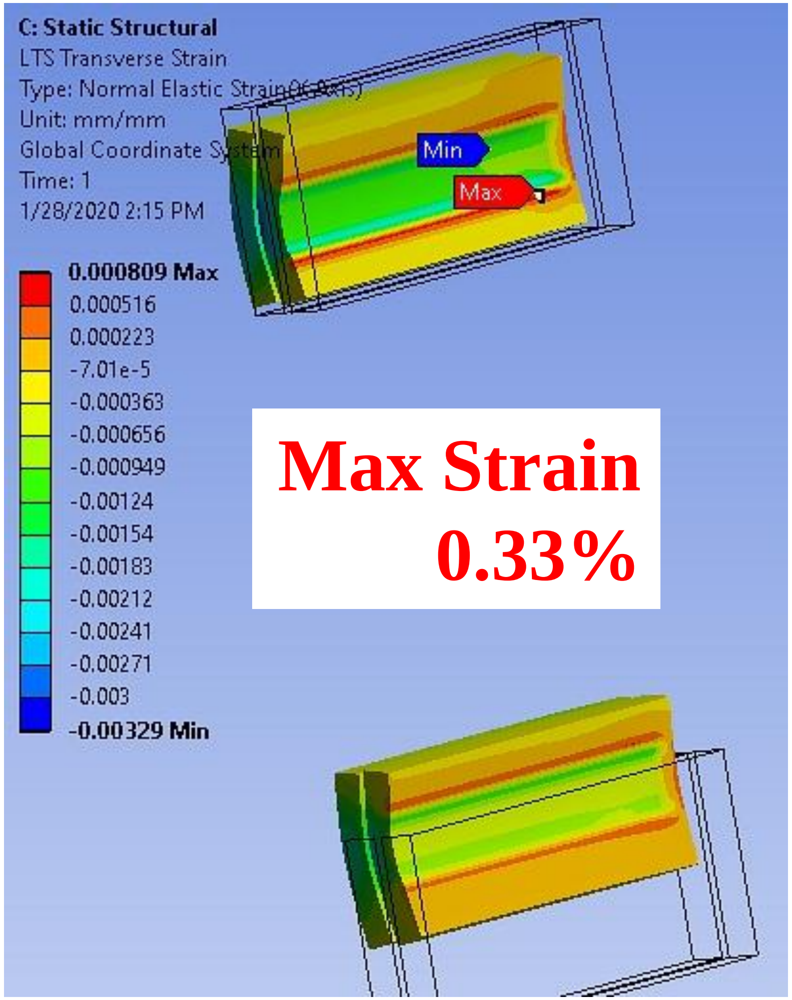
ANSYS Run Transverse Stress and Strain from Nb_3Sn 10 kA, HTS 2 kA

Stress and Strain on the LTS Coils from the HTS



C: Static Structural
LTS Transverse Stress
Type: Normal Stress(X Axis)
Unit: MPa
Global Coordinate System
Time: 1
1/28/2020 2:22 PM

Max Stress
172 MPa



C: Static Structural
LTS Transverse Strain
Type: Normal Elastic Strain(X Axis)
Unit: mm/mm
Global Coordinate System
Time: 1
1/28/2020 2:15 PM

Max Strain
0.33%

Hybrid Magnet Test Results

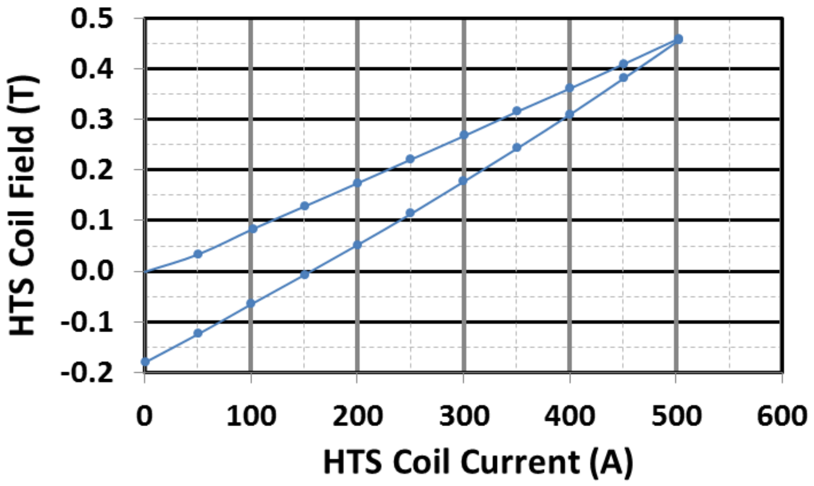
HTS Coil Magnetization

- Expect smaller conductor magnetization and hence field errors in a configuration when the background field is primarily parallel to the wide face of the HTS tape rather than perpendicular

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

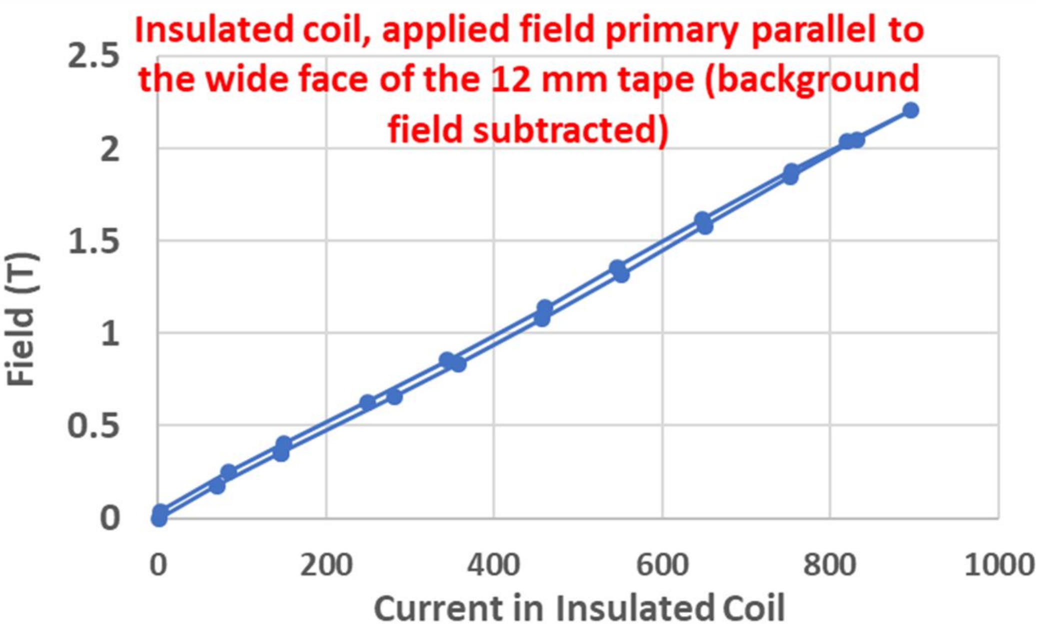
Field perpendicular (2016)

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)


Insulated coil, applied field primary parallel to the wide face of the 12 mm tape (background field subtracted)

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

Both coils have the same Nomax insulation but 12 mm wide tape from different sources

Summary and Discussion (1)

- ➢ **Encouraging results for HTS/LTS hybrid dipoles with a record 12.3 T hybrid field**
  - ❑ **~9.3 T from Nb_3Sn coils and ~3 T from ReBCO coils**
- ➢ **HTS coils remained protected despite a large energy dump from inductively coupled LTS coils quenching**
- ➢ **Earlier results showed that it was possible to protect quenching HTS coil themselves**
  - ❑ **Key to HTS quench protection strategy at BNL is the advanced quench protection system and discharging HTS coils fast before LTS coils shut off starts**
- ➢ **Magnetization effects become an over order of magnitude smaller when the applied field is primarily parallel to wide face of HTS tape rather than perpendicular to it**

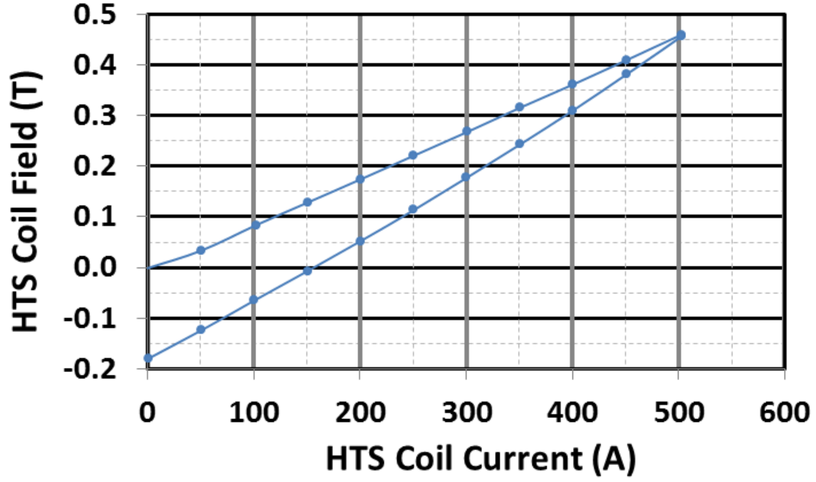
Summary and Discussion (2)

- As encouraging these results are these tests still involved short HTS coils with a relatively small inductance and stored energy. The challenge increases as the HTS coils play a larger role with more stored energy.
- The coils used in the two hybrid dipoles were wound with single HTS tape and the test used two independent power supplies for HTS and LTS. Future dipoles are likely to use coils made with HTS cables, operating in series with the LTS coils.
- Common coil dipole DCC017, with a large opening, has played a key role in carrying out the hybrid dipole program with a rapid-turn-around R&D at a low cost. The hybrid dipole test in 2016 was carried out within 2 years under an SBIR and the recent test was carried out under US MDP within 9 months.

Extra Slides

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

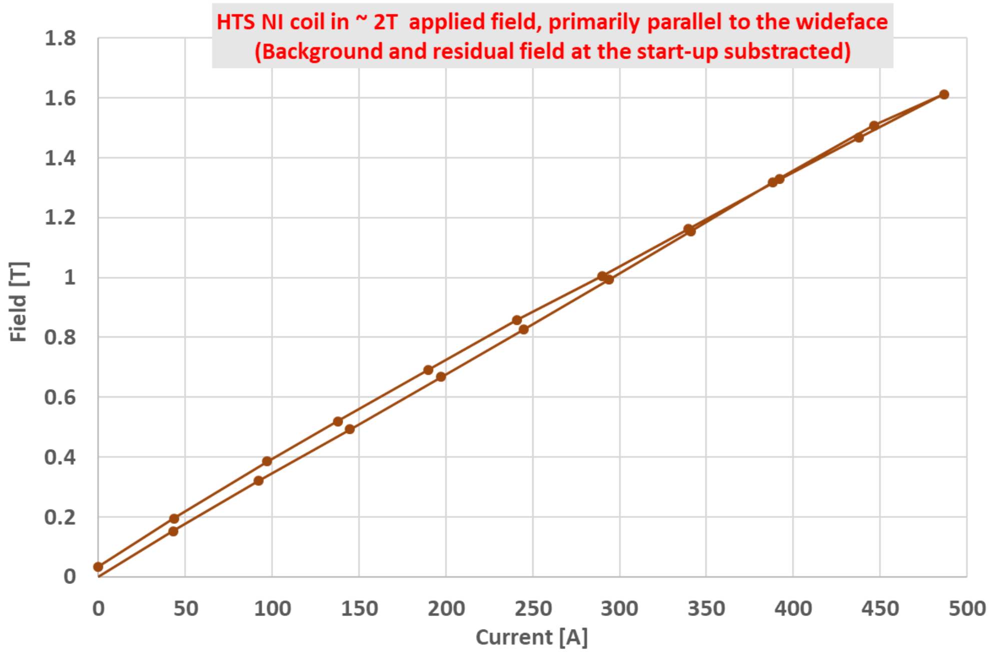
Field perpendicular (2016)



Nomax insulation and 12 mm wide HTS tape from **ASC**

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

Field parallel (2020)



No-Insulation and 12 mm wide HTS tape from **SuperPower**

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