U.S. MAGNET DEVELOPMENT PROGRAM

Test of HTS Tape Coil in a Hybrid Dipole
(HTS tape aligned in favorable direction)

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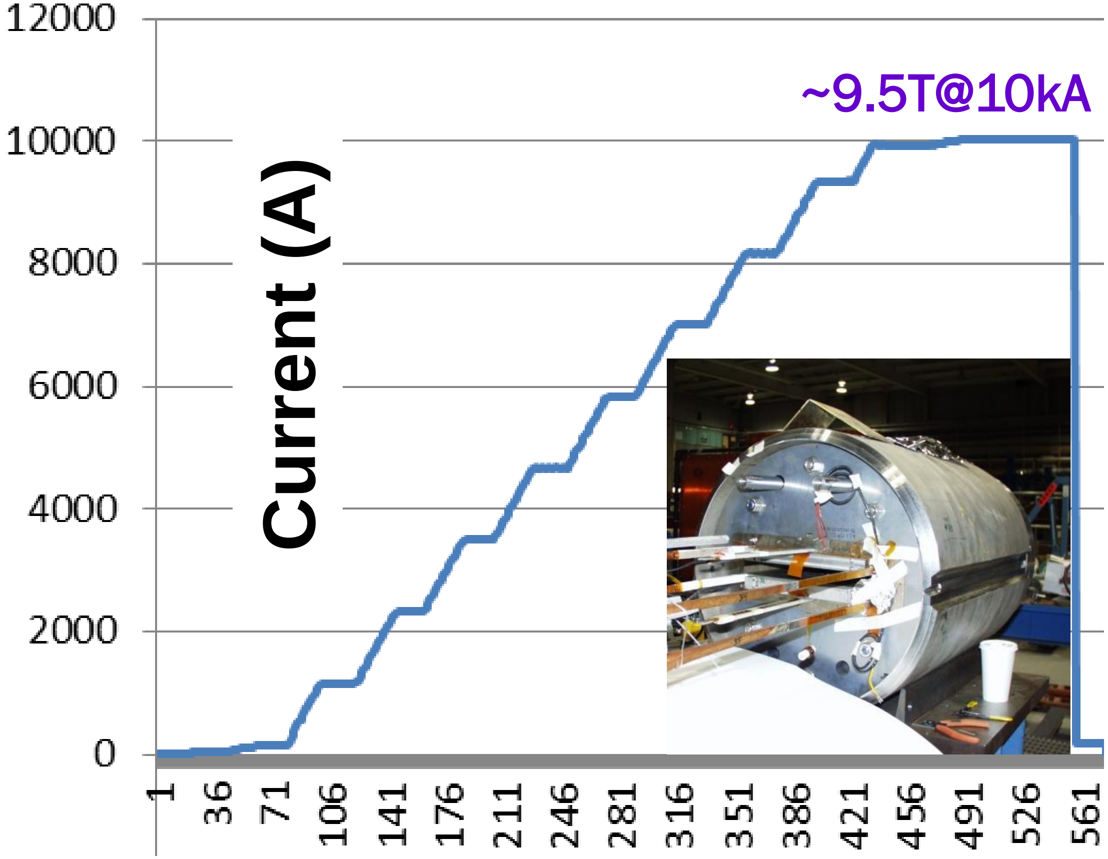
Overview

- Main goal of this test is to perform field error measurements of the HTS coils with tape aligned primarily in field parallel direction.
- Other important goal of this test run is to demonstrate that the common coil dipole DCC017 can be used as a test facility for repeatedly testing insert coil in the background field
- Another technically important goal is to perform quench protection studies of HTS coils HTS/LTS hybrid structure
- Two apertures allows us testing two types coils (on separate power supplies). We are taking advantage of that to perform certain studies with no-insulation coil, in addition to the coils made with nomex insulation (total four coils – two double pancakes).

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)**

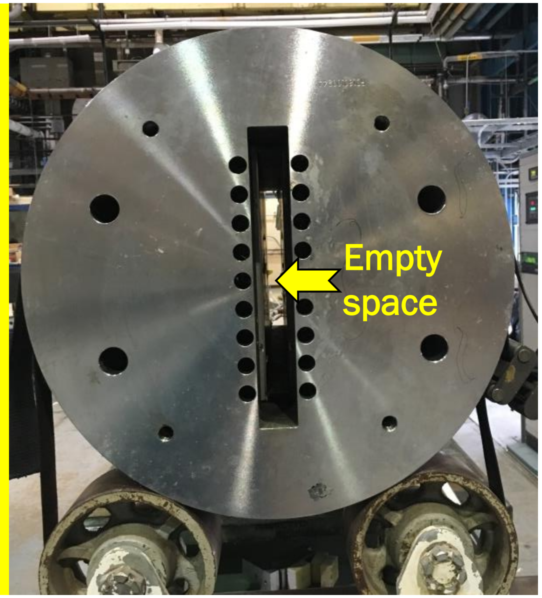


- This time we will ramp to the maximum field and allow stable operation up to 10 kA
- In addition, we will have a 850 Amp P/S and another 4 kA P/S
- Separate control and data collections for HTS coils and LTS coils

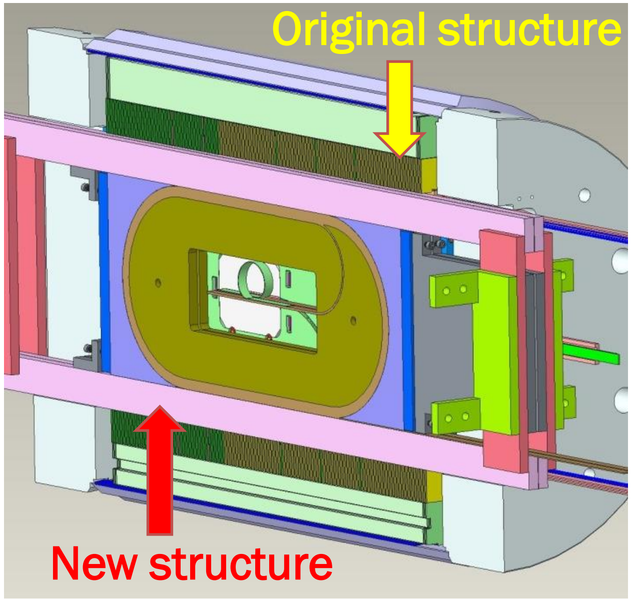
PBL/BNL STTR on HTS/LTS Hybrid Dipole

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

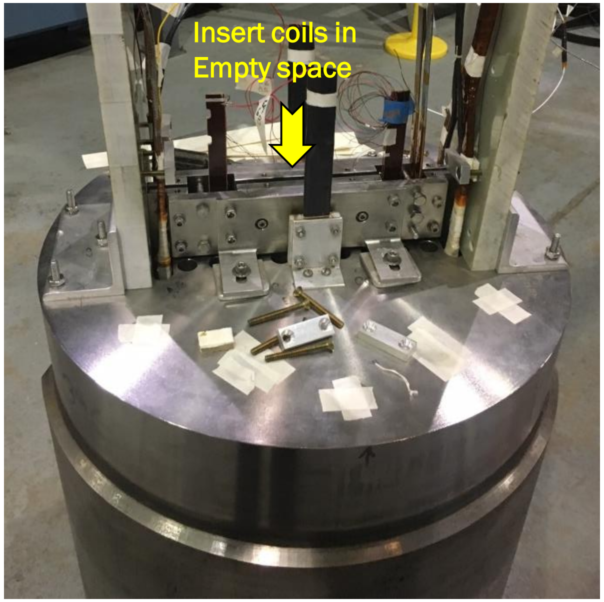
STTR Phase II for (1) Demonstration and protection of High field HTS/LTS hybrid dipole (2) measurement of field ~~parallel and~~ perpendicular field quality



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

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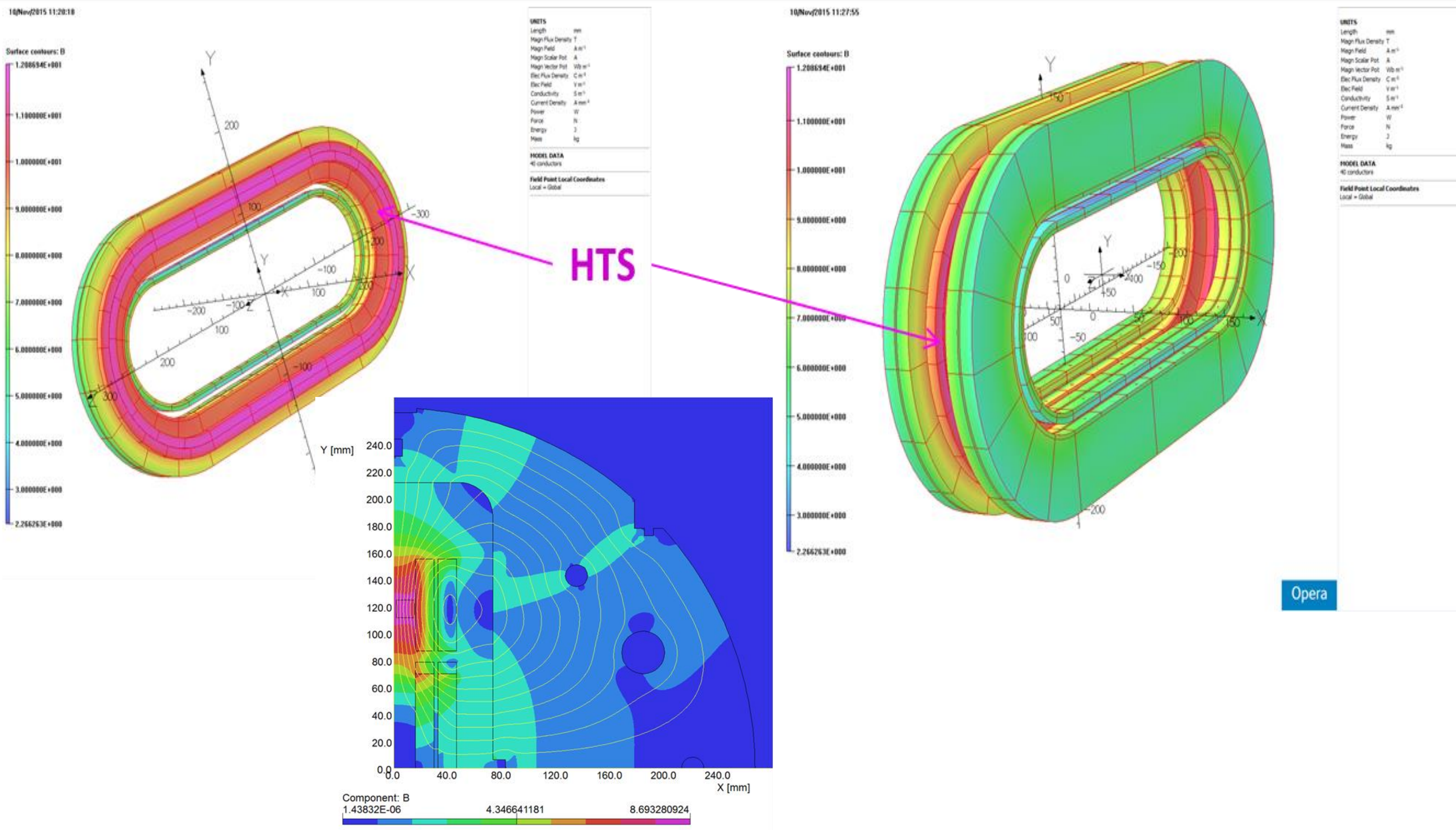
Last Test: HTS/LTS Hybrid Dipole Model (field on HTS coils primarily perpendicular)



HTS Coil Test in HTS/LTS Hybrid Dipole Structure

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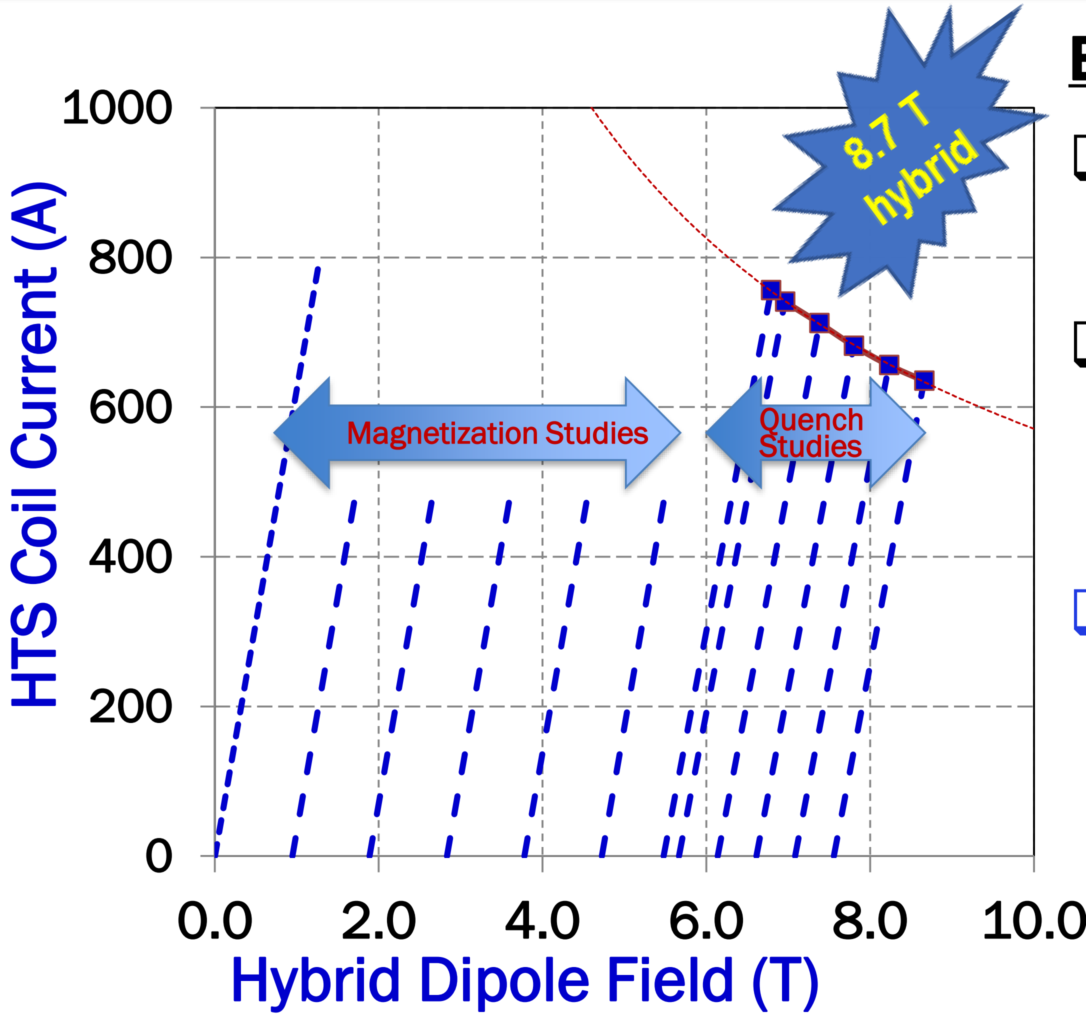
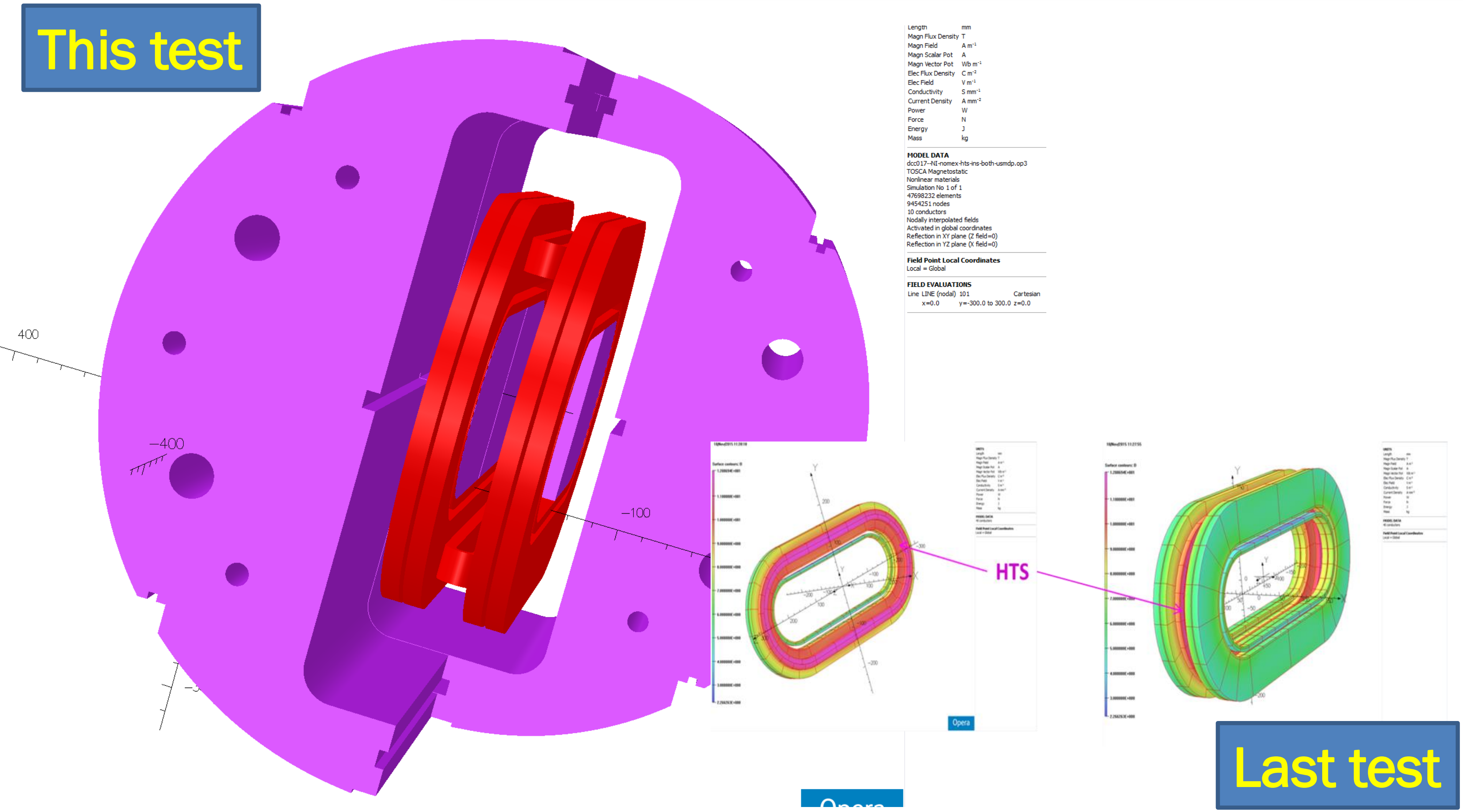


Encouraging Results:

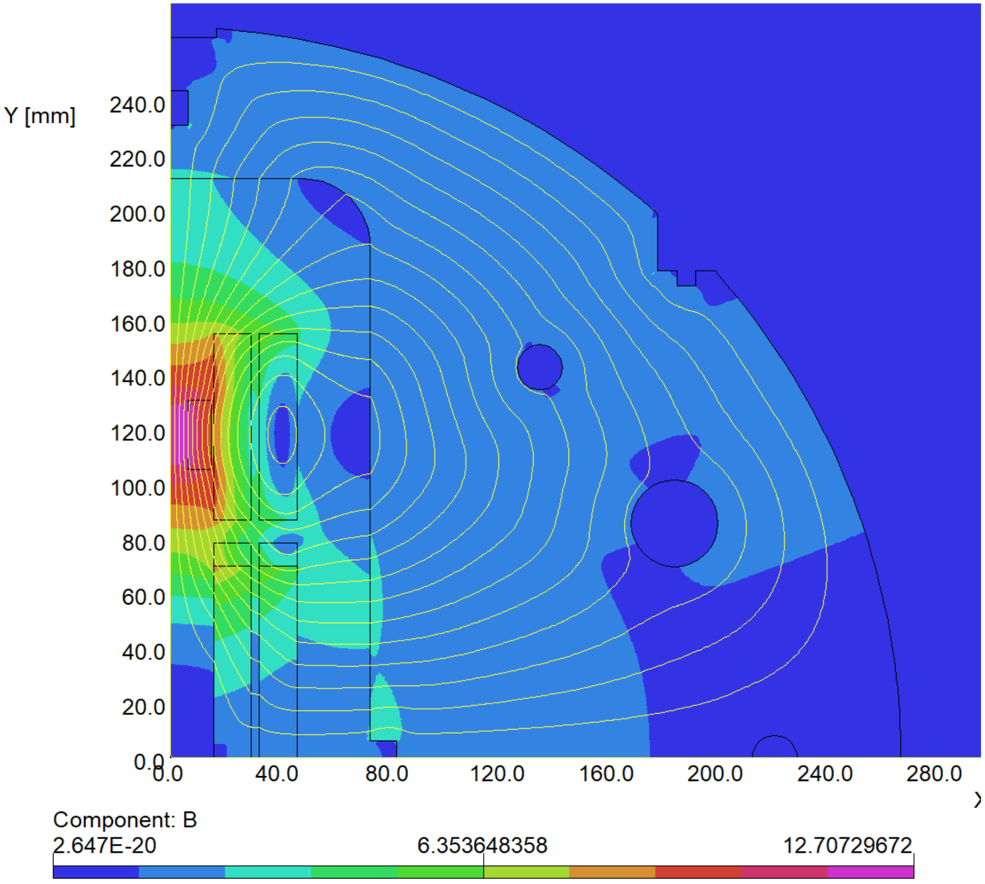
- ❑ HTS coils were ramped to quench, just like LTS coils.
- ❑ No degradation in HTS coils despite a number of quenches.
- ❑ In many of these runs, the field was measured with Hall probe during up and down ramp. The difference is primarily due to conductor magnetization.

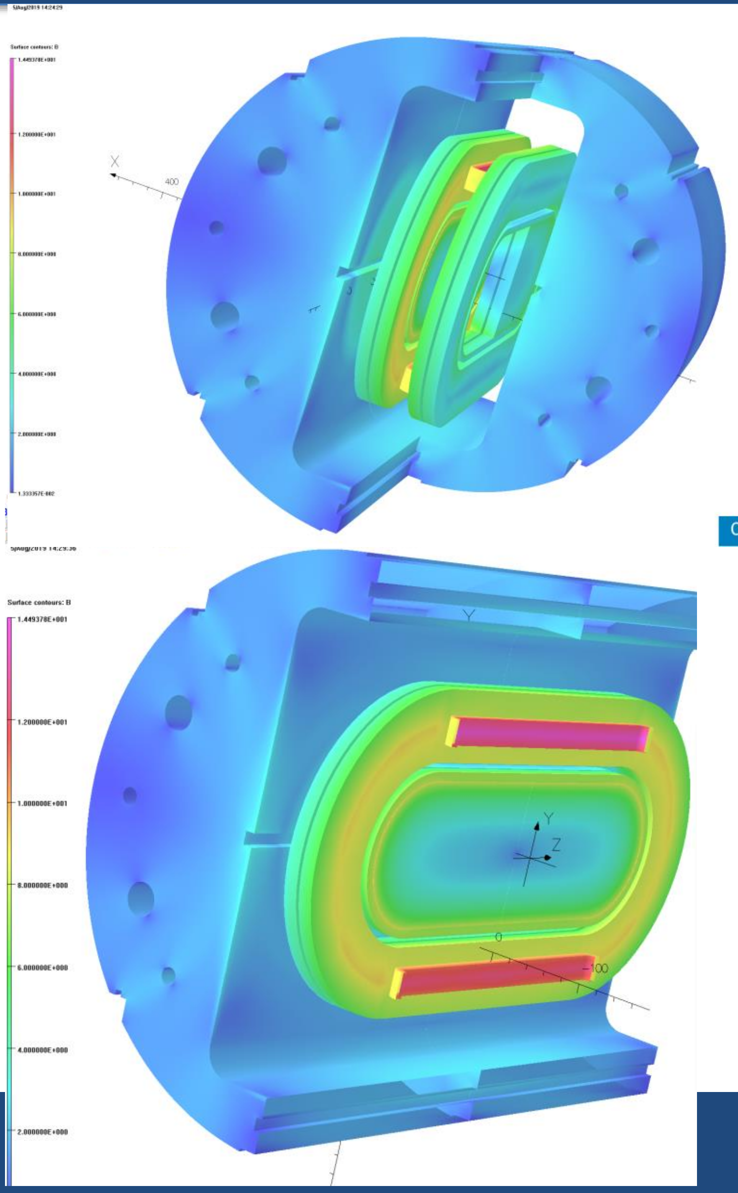
This test: USMDP Studies (field on HTS coils primarily parallel)

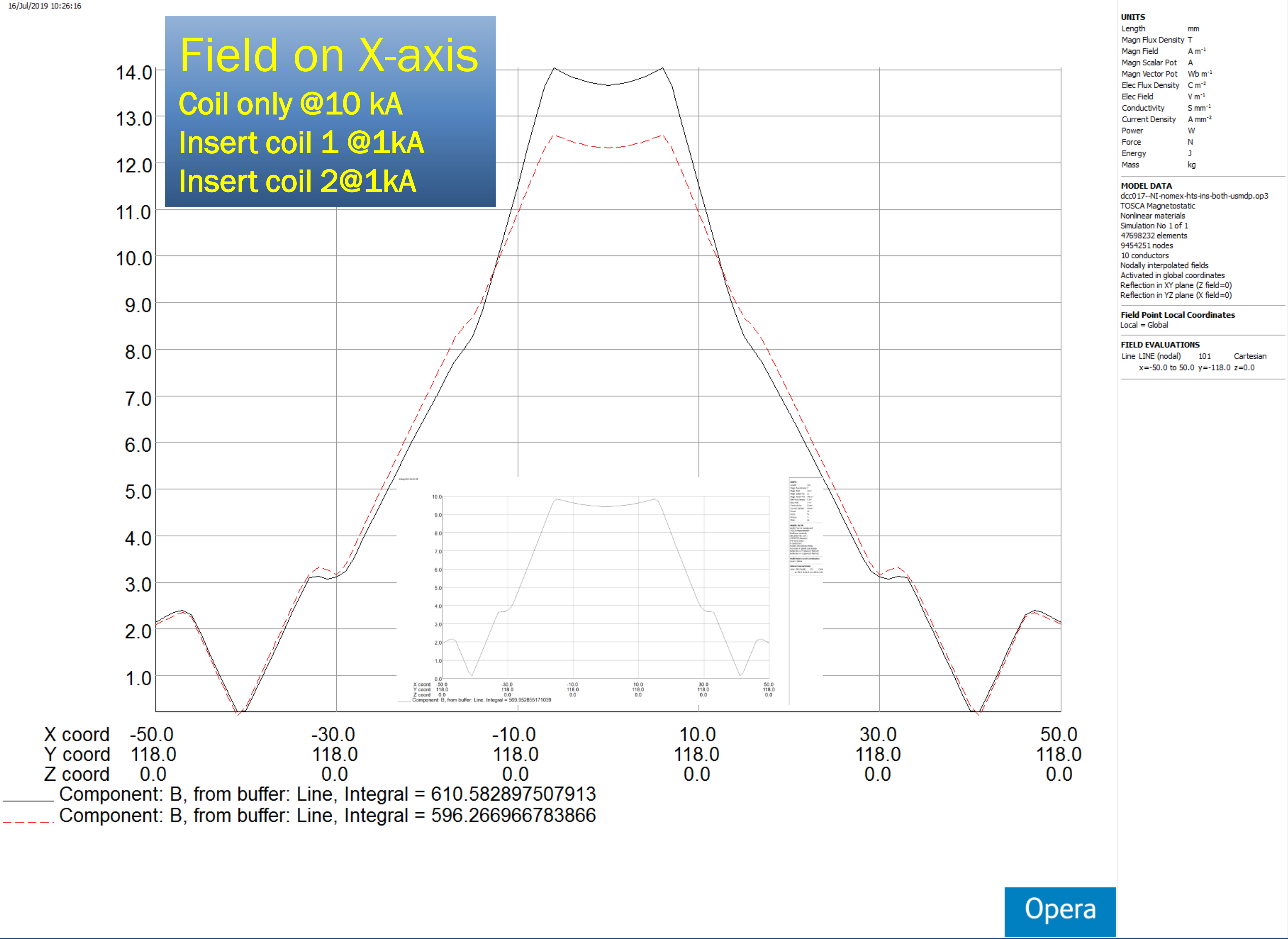


Field in Hybrid Dipole

Field primarily parallel to the wide face of HTS tape

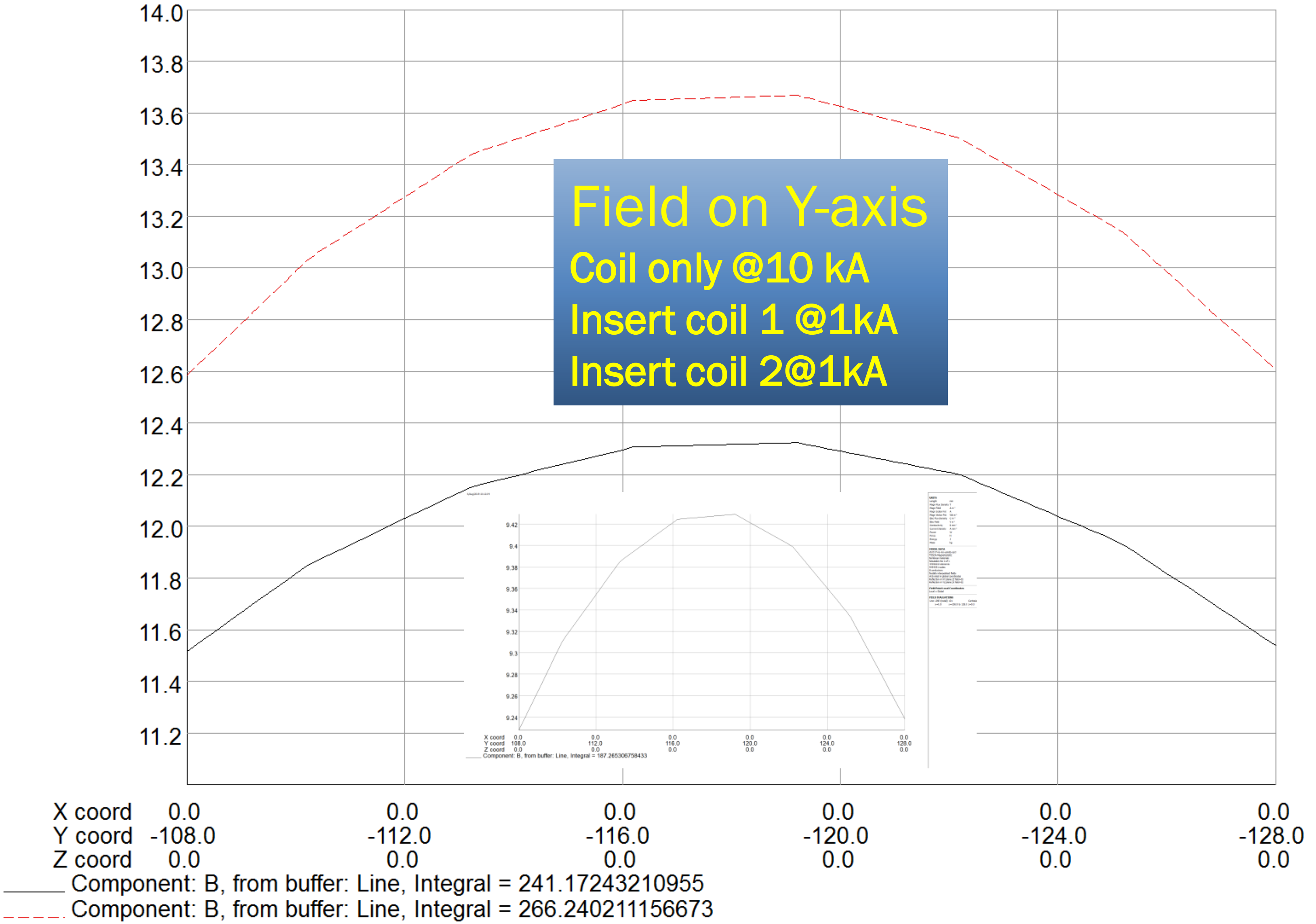






16/Jul/2019 10:26:16
Field on X-axis
Coil only @10 kA
Insert coil 1 @1kA
Insert coil 2@1kA
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
X coord -50.0 -30.0 -10.0 10.0 30.0 50.0
Y coord 118.0 118.0 118.0 118.0 118.0 118.0
Z coord 0.0 0.0 0.0 0.0 0.0 0.0
Component: B, from buffer: Line, Integral = 610.582897507913
Component: B, from buffer: Line, Integral = 596.266966783866
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 mm-1
Current Density A mm-2
Power W
Force N
Energy J
Mass kg
MODEL DATA
dcc017--NI-nomex-hts-ins-both-usmdp.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
47698232 elements
9454251 nodes
10 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in YZ plane (X field=0)
Field Point Local Coordinates
Local = Global
FIELD EVALUATIONS
Line LINE (nodal) 101 Cartesian
x=-50.0 to 50.0 y=-118.0 z=0.0
Opera

16/Jul/2019 10:20:32



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	$S\ mm^{-1}$
Current Density	$A\ mm^{-2}$
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA

dcc017--NI-nomex-hts-ins-both-usmdp.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
47698232 elements
9454251 nodes
10 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in YZ plane (X field=0)

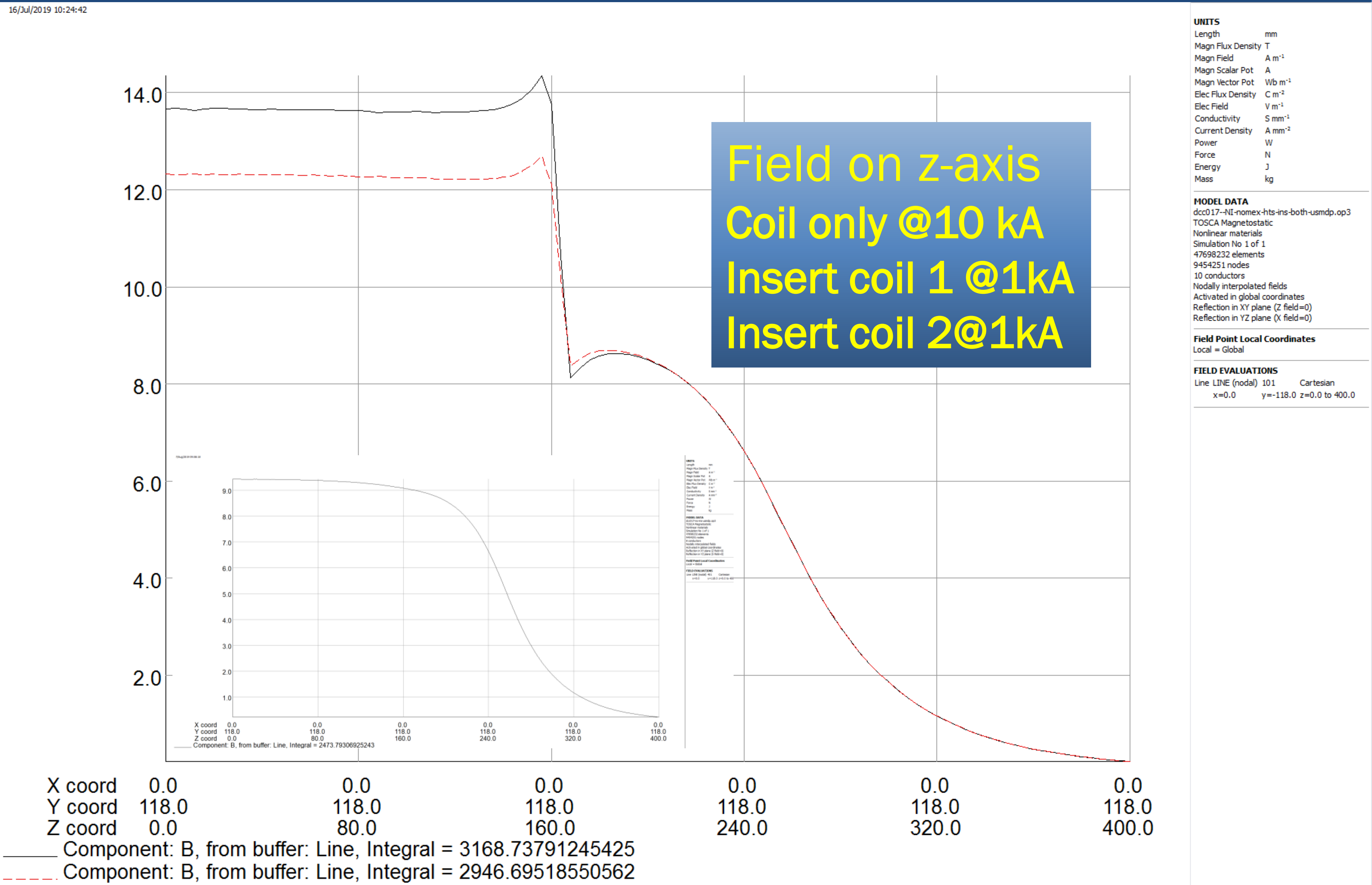
Field Point Local Coordinates

Local = Global

FIELD EVALUATIONS

Line LINE (nodal) 101 Cartesian
x=0.0 y=108.0 to 128.0 z=0.0

Opera



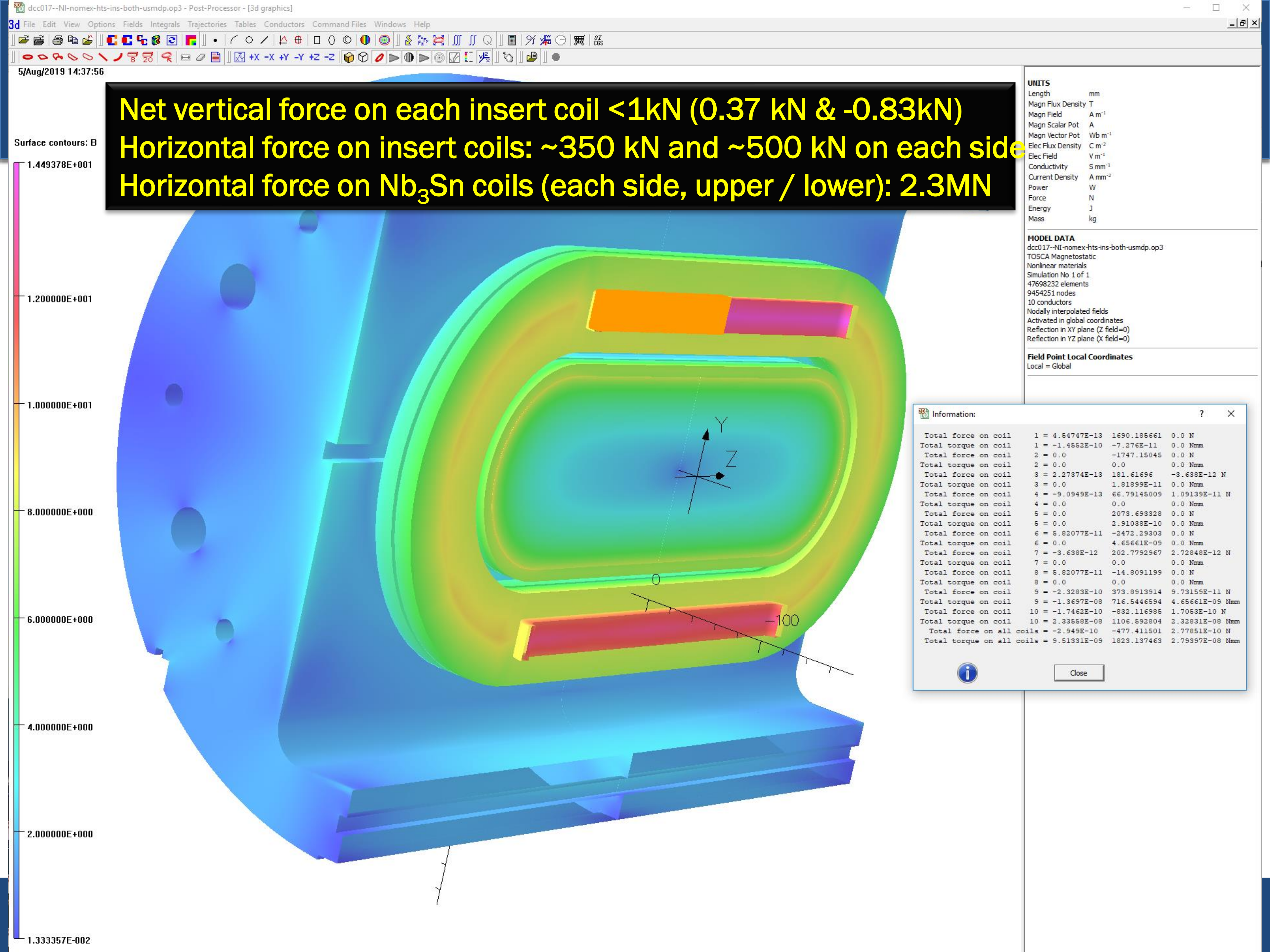
16/Jul/2019 10:24:42
14.0
12.0
10.0
8.0
6.0
4.0
2.0
Field on z-axis
Coil only @10 kA
Insert coil 1 @1kA
Insert coil 2@1kA
X coord 0.0 0.0 0.0 0.0 0.0 0.0
Y coord 118.0 118.0 118.0 118.0 118.0 118.0
Z coord 0.0 80.0 160.0 240.0 320.0 400.0
Component: B, from buffer: Line, Integral = 3168.73791245425
Component: B, from buffer: Line, Integral = 2946.69518550562
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 mm⁻¹
Current Density A mm⁻²
Power W
Force N
Energy J
Mass kg
MODEL DATA
dcc017--NI-nomex-hts-ins-both-usmdp.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
47698232 elements
9454251 nodes
10 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in YZ plane (X field=0)
Field Point Local Coordinates
Local = Global
FIELD EVALUATIONS
Line LINE (nodal) 101 Cartesian
x=0.0 y=-118.0 z=0.0 to 400.0

Opera

Net vertical force on each insert coil <1kN (0.37 kN & -0.83kN)

Horizontal force on insert coils: ~350 kN and ~500 kN on each side

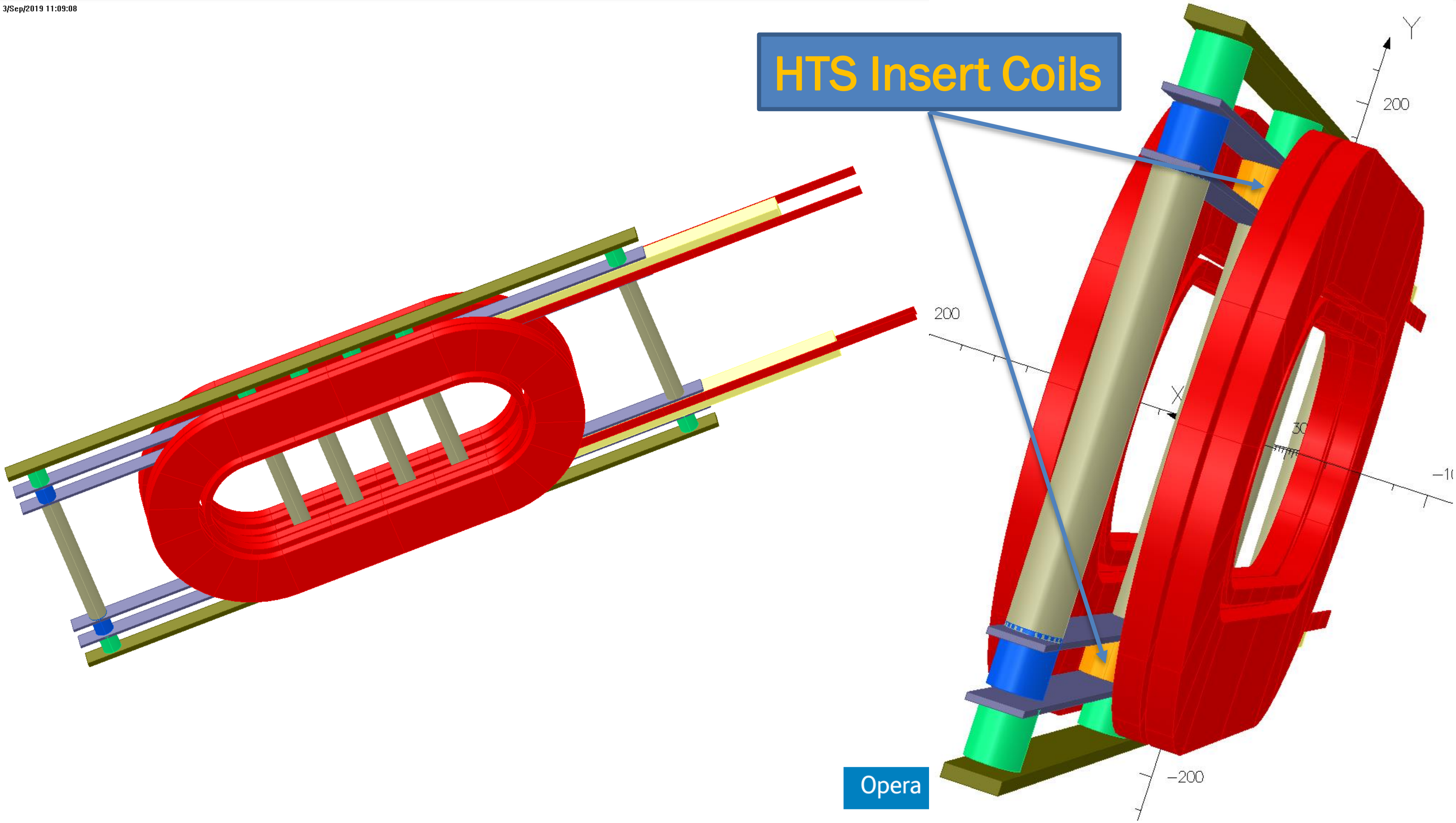
Horizontal force on Nb_3Sn coils (each side, upper / lower): 2.3MN



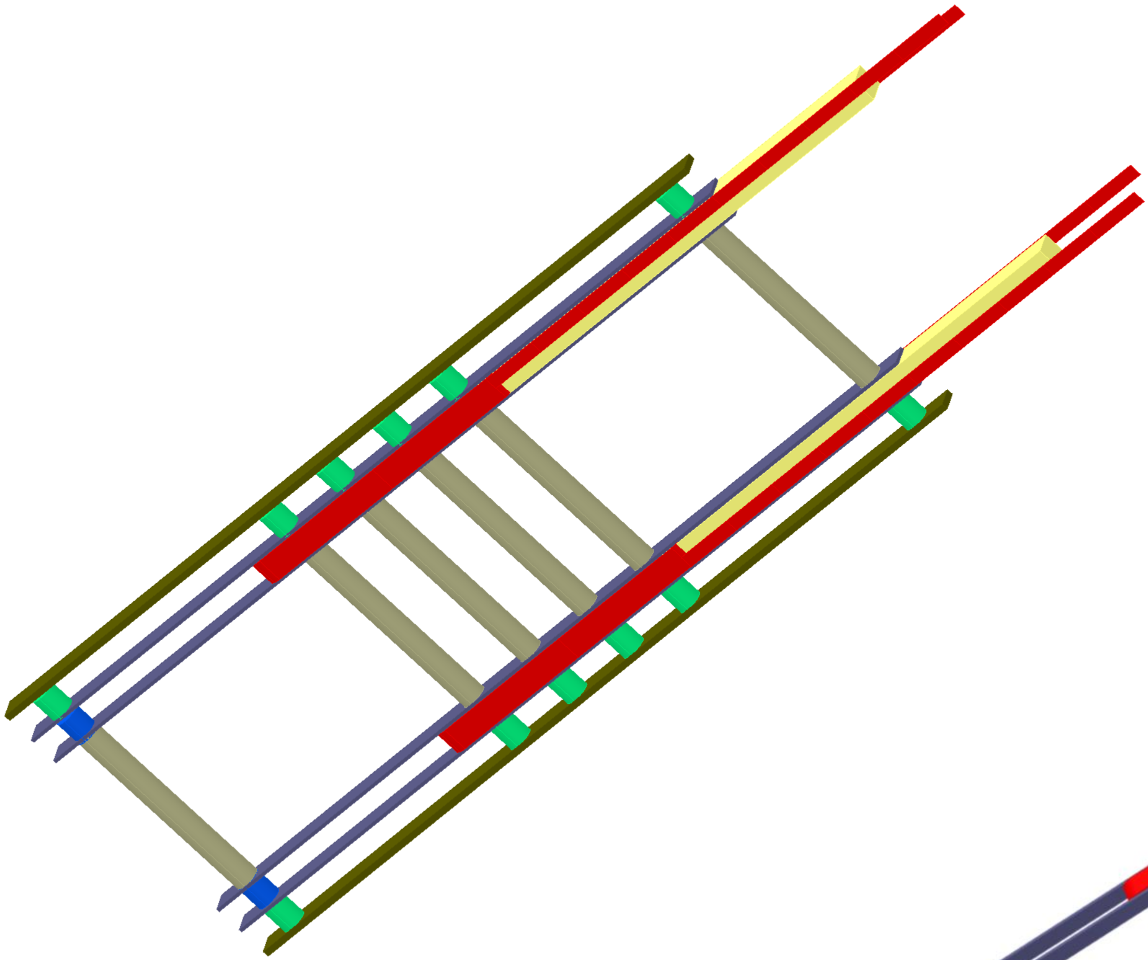
Structure holding the insert coils

- Simple independent structures for the two insert coils.
- Single pancake HTS coils are wound under low tension. They move out in the middle after winding. Push them in as much as possible by bobbin in the middle pushing out axially.
- The coils will be inserted in a structure as tightly as possible (5-10 mil clearances).
- Since the net vertical forces on each of them are small (<1 kN) no significant structure is required to contain that. We need spacer and structure to keep them in place and located within the magnet.
- Major forces on the HTS insert coils are horizontally outward. We rely on the HTS coils to make contact to Nb_3Sn coils with outer structure containing net Lorentz Forces.
- When HTS coils are moved horizontally outward by Lorentz forces, they are pushed axially inward. These are small movement and coils should be fluffy (loose) enough to deal with them. Axial Lorentz force is in opposite direction and tries to move the coils outward.
- A conceptual structure (or rather holder) is shown in next few slides.

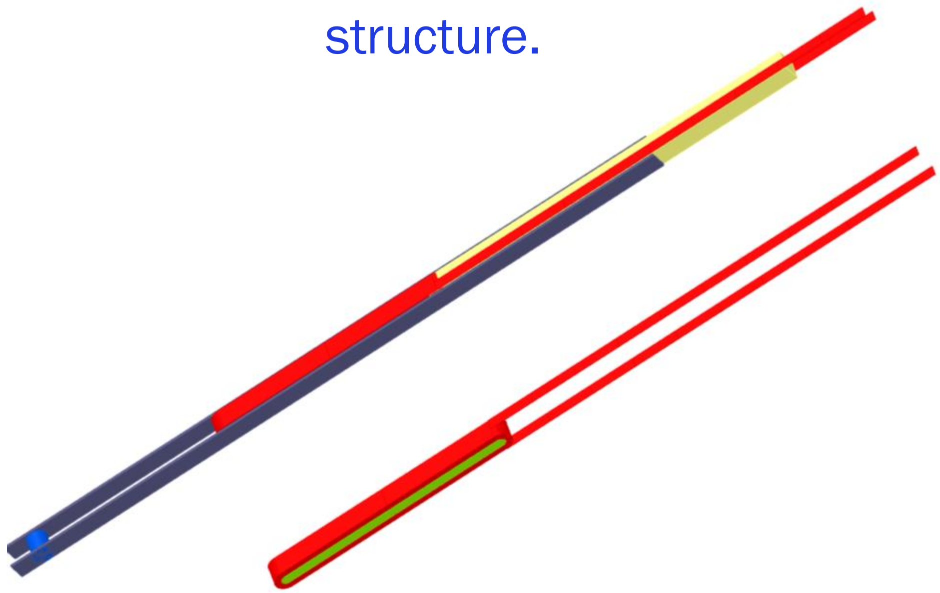
HTS Coils Structure Inserted in Nb3Sn Coils



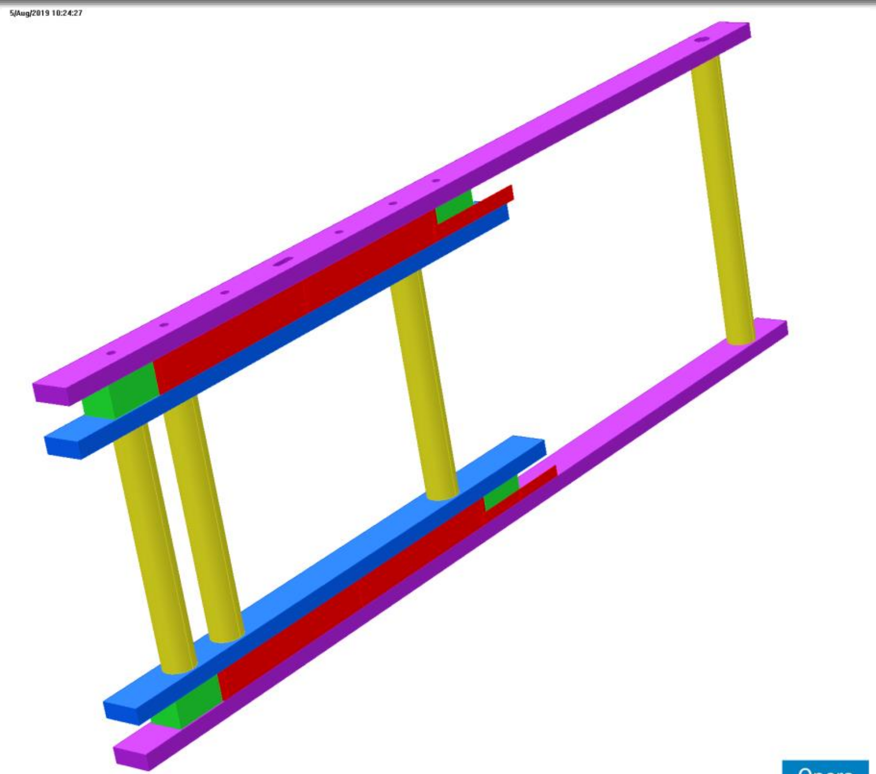
HTS Coils in Conceptual Structure

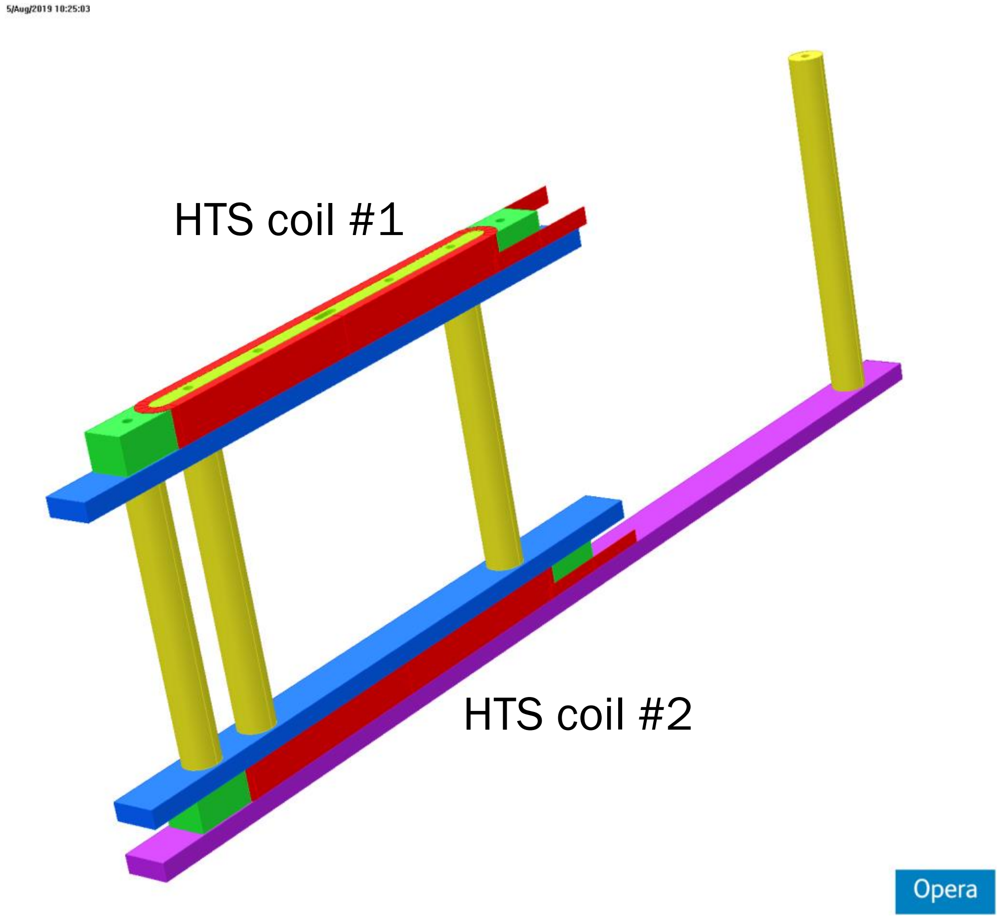


- Each coil in their own structure, separated by the spacers.
- Major forces are horizontal. HTS coils lean on LTS coil and rely on the common coil support structure.



Schematic of the Structure





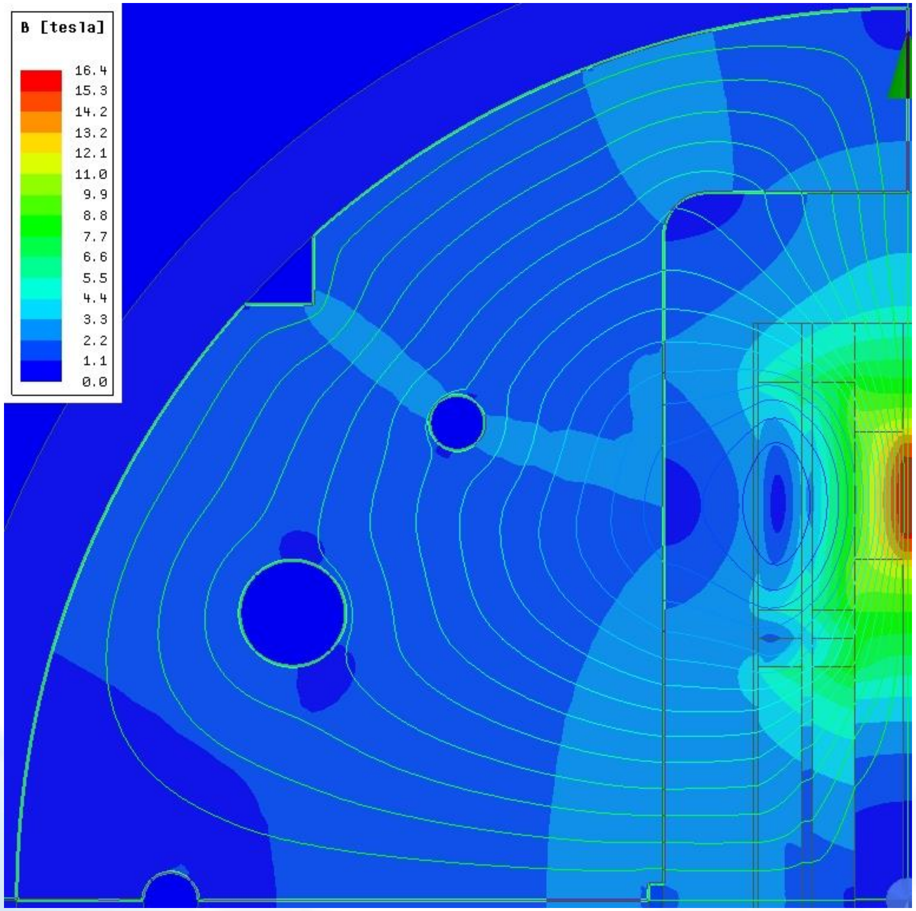
- Each coil in their own structure, separated by the spacers.
- Major forces are horizontal. HTS coils lean on LTS coil and rely on the common coil support structure.

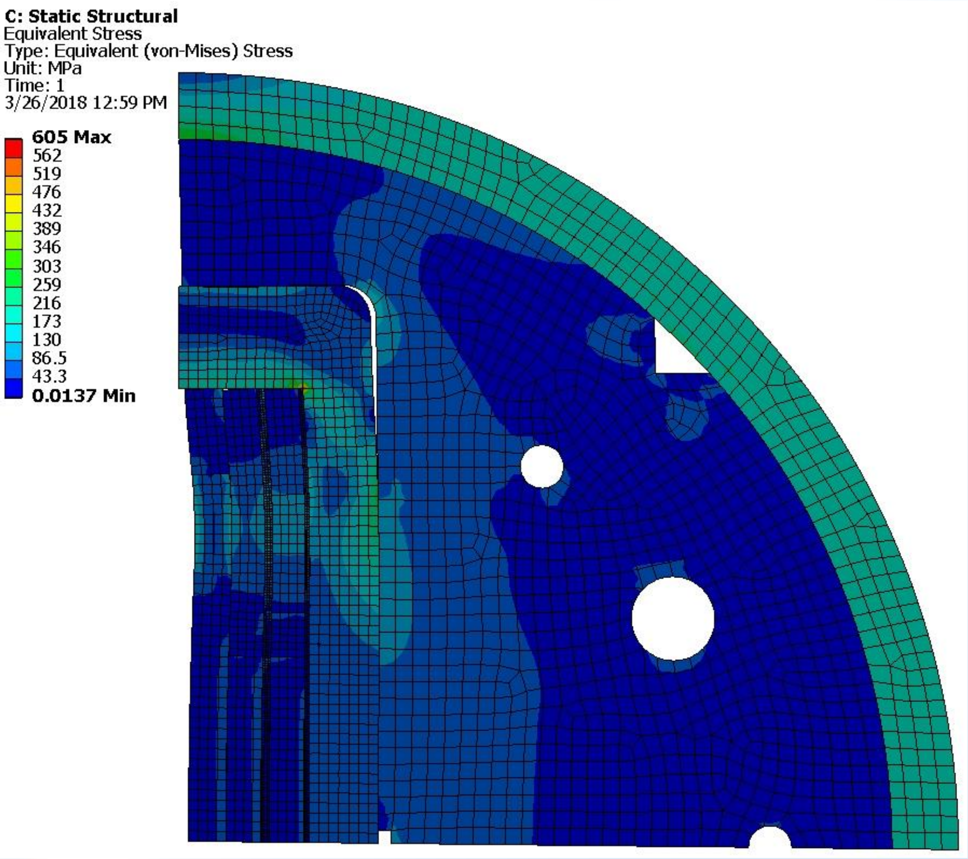
Mechanical Considerations

- Simple structure based on above forces and common coil geometry
- Original common coil structure was designed for higher field/forces (~12 kA?). Common coil design tolerates larges horizontal displacement due to Lorentz forces without causing large strain since the coil move as a whole.
- 2-d ANSYS calculations were performed for CORC insert coil (similar geometry, higher field). Use that as a guideline for now as the ANSYS run with simple modification didn't work and since the forces in the insert CORC coil model were higher.
- Each of the two HTS coils are in their own structures, separated by the spacers to keep them centered at the magnet. As such, there is no structure on HTS coils to contain movement (particularly horizontal displacement) due to Lorentz forces. We allow HTS coils to push against Nb3Sn coils and let the outer structure of the Nb3Sn magnet take the net forces of HTS/LTS hybrid. The net horizontal force on one side of Nb3Sn coil is ~4.6 MN (~0.9 MN from HTS coils) when both HTS coils are energized at 1 kA together with Nb3Sn coils at 10 kA.
  - Question: HTS coils are smaller than LTS coils (both in cross-section and in length), therefore is a discontinuity at the interface. Should we be varied about the local pinching forces (both in the body and in the ends) or we need some sort of pads to distribute?
  - Should we find it out experimentally – i.e. energize the HTS coils till the Nb3Sn coil quench or could it cause a permanent damage to Nb3Sn coils? Assumption is that the coil will quench well before it reaches the mechanical limit. Is it valid? If concern, limit the test to lower field levels. If so, at what level?
- Since the outer structure can't be modified so the plan is to let it reach the experimental limit. Stop the run when the LTS coil quench.
  - Question: Does this plan compromises the Nb3Sn coils? Assumption is that the coil will quench well before it reaches the mechanical limit. Is it valid? If concern, limit the test to lower field levels. If so, at what level?
- HTS coils are smaller than the LTS coils. Therefore, the leads (HTS leads) go through the high field region of common coil magnet. Provide adequate support.

BNL Nb_3Sn Common Coil Dipole DCC017 with HTS Insert Coil

- 480 A/mm^2 in LTS and HTS coils. 14.25 mm wide HTS
  - Magnetic flux density. Equivalent Stress

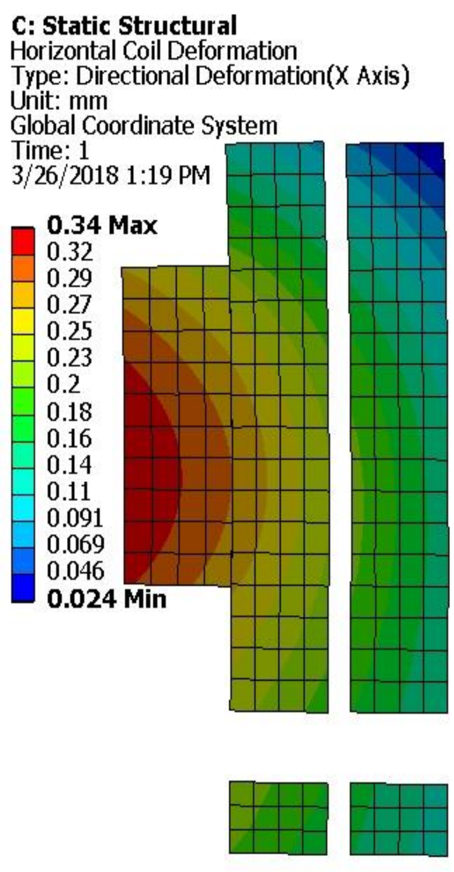


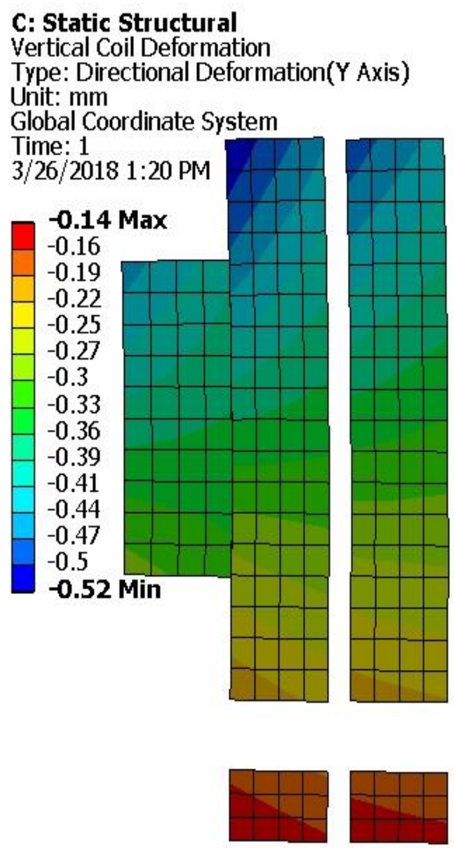


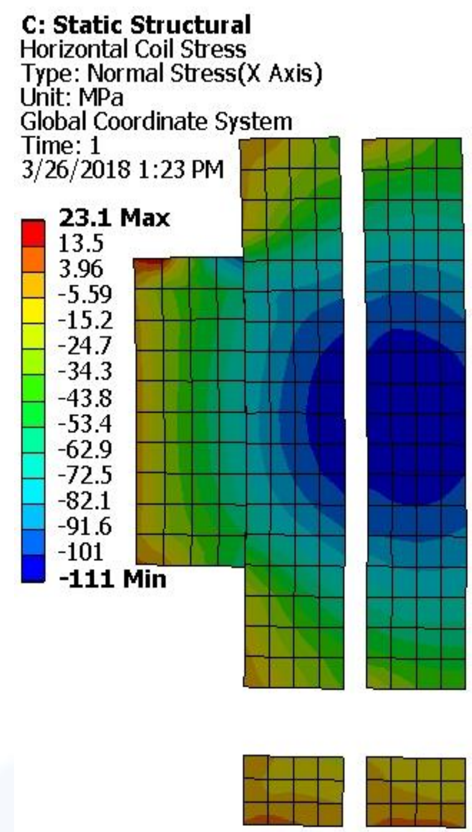
From John Cozzolino
Similar study for CORC Coil Hybrid Test

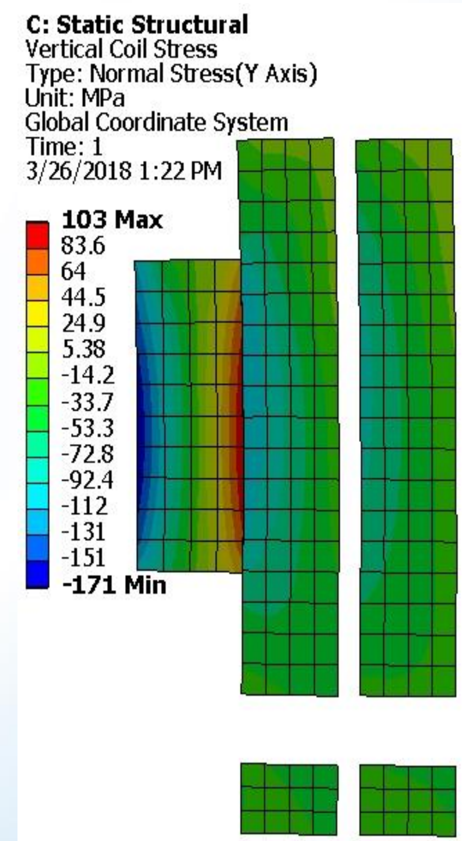
BNL Nb_3Sn Common Coil Dipole DCC017 with HTS Insert Coil

- 480 A/mm^2 in LTS and HTS coils. 14.25 mm wide HTS
  - Coil Deflections and Stresses





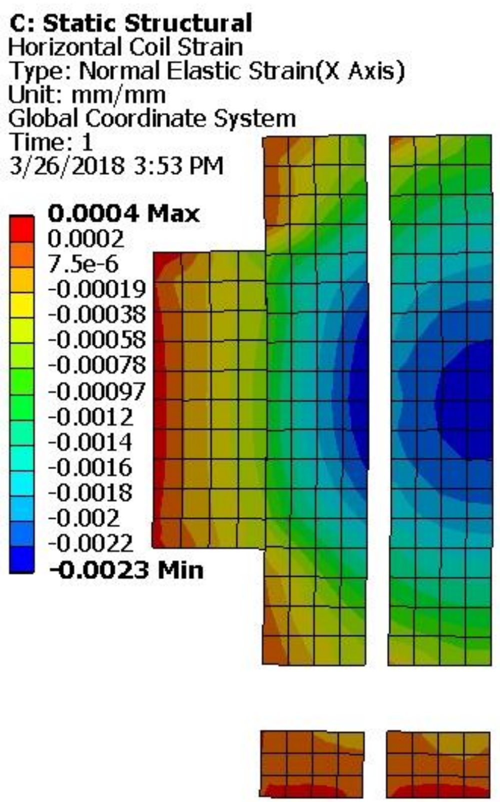


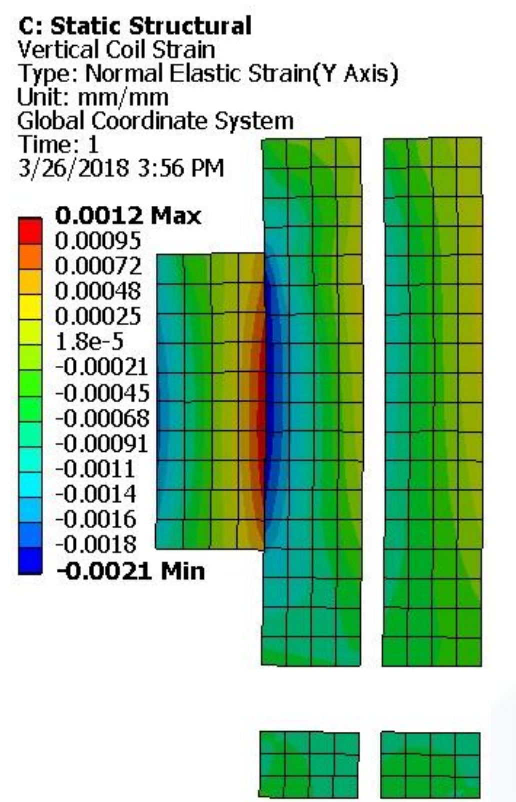


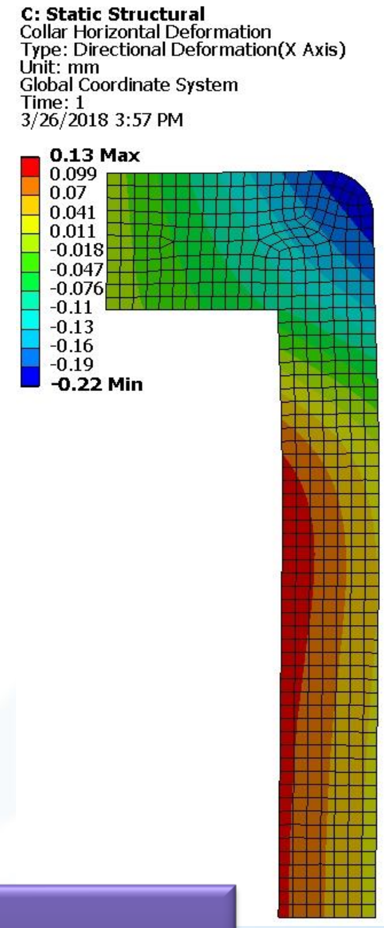
From John Cozzolino
Similar study for CORC Coil Hybrid Test

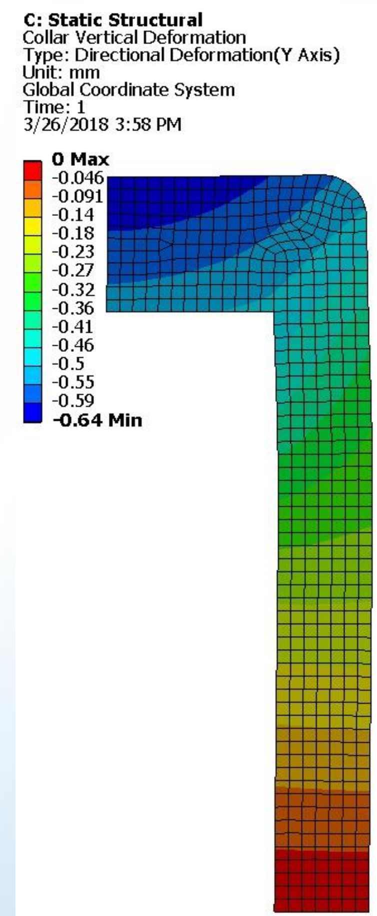
BNL Nb_3Sn Common Coil Dipole DCC017 with HTS Insert Coil

- 480 A/mm^2 in LTS and HTS coils. 14.25 mm wide HTS
  - Coil Strains and Collar Deflections









From John Cozzolino
Similar study for CORC Coil Hybrid Test

Quench Considerations

- Quench protection of HTS coils
- Quench protection of Nb_3Sn coils
  - Do we need to activate strip heaters?
- Quench protection in hybrid structure
  - What happens to HTS coils when LTS coils quench
  - What happens to LTS coils when HTS coils quench

Initial Test Plan (will evolve)

The primary purpose of this test is to do magnetization studies of HTS coils in the background field of Nb3Sn coils.

Equally important is to perform quench studies of HTS/LTS hybrid dipole. In addition we will perform initial investigations of no-insulation coil for accelerator magnet applications. Following are the basic features of the test plan:

<u>HTS Coils Only, one at a time</u>

- Ramp up to 100 Amp and down to 0 A
- Then ramp up to 200 Amp and down to 0 (similarly for 400 Amp, 600 A, and 800 Amp)
- After reviewing above test data, make plan for ramping to higher currents

<u>Nb3Sn Coil Only</u>

- Ramp gradually to 10,000 A (the coil didn't quench at 10,000 A during the last run in 2017 and earlier in 2006 it has reached 10,800 A)

<u>HTS/LTS Hybrid Test</u>

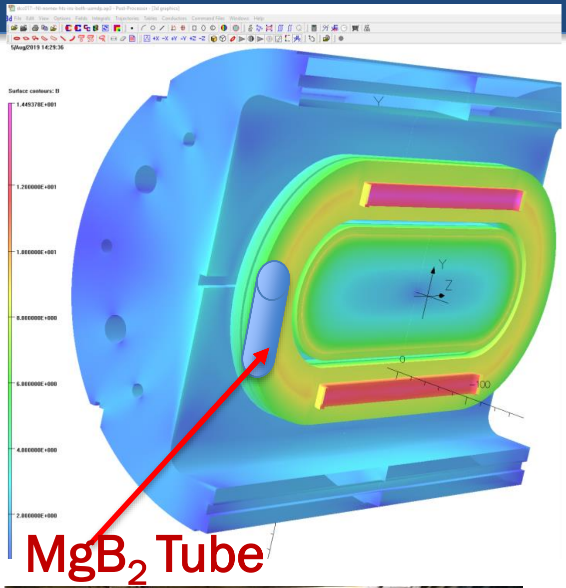
- Interaction between HTS and Nb3Sn Coil – Ramp Nb3Sn and observe HTS coils
- Hold Nb3Sn coils at various currents and ramp HTS coil up and down to whatever current safely possible without quenching (nominal maximum 800 A in HTS coils).
- Start with lower background field from Nb3Sn coils and move to higher
- The values of holding currents in Nb3Sn coils while HTS coils are ramped up and down: 500 A, 1000 A, 2000 A, 4000 A, 6000 A, 8000 A and 10000 A.
- Find out how far the No-insulation coils can be pushed? Nb3Sn coils can't be damaged; HTS can be…
- Can feedback loop provide constant rate of field ramping in "No-insulation" coil (Piyush Joshi)?

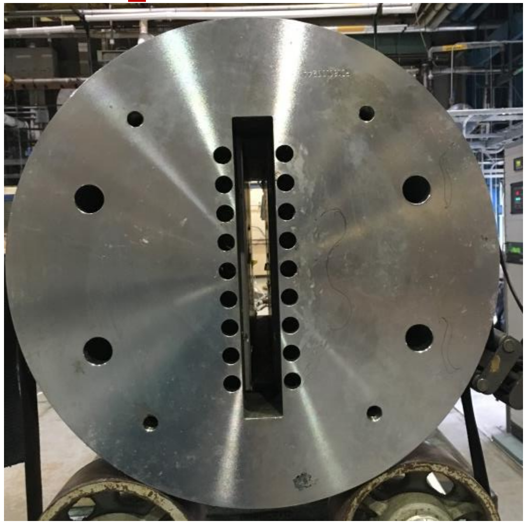
Possible MgB2 Shield Tube Test

If MgB_2 tube is available in time then it can be placed somewhere for shielding experiment as a part of Phase I SBIR with HyperTech.

The place available is towards the end/entrance of the common coil opening.

4K test was not in the plan of the original Phase I proposal but that test can be carried out in a parasitic mode.





Extra Slides

Common Coil Hybrid Magnet Test Goals

Two HTS double-pancake insert coils inside the React & Wind Nb3Sn 2-in-1 common coil dipole DCC017

Main Purpose/Goal:

- Magnetization studies
  - Measure magnetization of insert coils made with HTS tape with field predominately aligned parallel to the wide face.
  - Magnetization is measured with the Hall probe by measuring the field at the center of HTS coils which are centered at the place where the field from Nb3Sn coil is maximum
  - Earlier measurements under SBIR were performed for field predominately aligned perpendicular to the wide face of the tape.
  - Magnetization (particularly in relative terms) is more at lower current/field. Therefore, we don't have to push to the highest fields. Even powering to the same current densities as in last test will be great from the magnetization point of view. However, we can push for the purpose of understanding the quench behavior in HTS coils, particularly in hybrid structure. HTS coils can be compromised to seek the limit and to study quench after the initial magnetization data is taken. LTS coils are part of the magnet which is intended for other usage and can't be put at risk.