HTS/LTS Hybrid Dipole Test
MDP Video meeting on January 29, 2020

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Contributions from

Work presented here and the work being performed now is thanks to many individuals, including:

Bill Sampson, Shresht Joshi, Anis Ben Yahia, Piyush Joshi, Bill McKeon, Sonny Dimaiuta, Denny Sullivan, Peter Galioto, Pat Doutney, Mike Anerella, John Cozzolino, Ray Ceruti, ...
Main goal of this test is to perform field error measurements of the HTS coils with tape aligned primarily in field parallel direction.

Another technically important goal is to study high field HTS/LTS hybrid magnet, particularly the quench and mechanical studies.

The program benefits from the unique geometry of DCC017, which allows insert coils to be inserted and become integral part of the magnet without disassembling or assembling magnet.

This particular test should be very productive with four tests in one go (a) two tests for two sets of HTS double-pancake coils (both on two separate power supplies in two high field apertures for HEP, and (b) another two independent tests of two HTS cable samples for “fusion community” in other two high field region in the end sections, clear of interference from the straight section.
Four easily accessible high field regions for four independent high field tests

Locations 1 and 2 for HTS coils; Locations 3 and 4 for HTS samples

|B| at y-z plane @10 kA

Basic test (1&2) supported by USMDFP. Additional (3&4) by internal funds.
Testing of HTS Coil Technology @High Fields (rapid turn-around, low cost)

Five Steps:
1. Magnet (dipole) with a large open space
2. R&D 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
HTS Coils Structure Inserted in Nb₃Sn Coils
(addition of CFS samples incorporated later)

CFS Samples between two sets of Nb₃Sn coils in the end region
(clear access, no interference)
USMDP HTS/LTS Hybrid Dipole Test in February 2020 (4 tests in one go)

A simple fixture is inserted inside the BNL Nb$_3$Sn Common Coil Dipole DCC017 (without disassembling the magnet) to test insert coils, in addition to the cable samples, in a high background field.

HEP Working with the Fusion Community
Magnet Test Assembly

Test run for inserting fixture in the magnet

Fixture inside the common coil dipole

Top

Bottom
Fixture inside the magnet

HTS coils and samples inside

HTS/LTS Hybrid Dipole

Zoo of leads
Run Plan and Instrumentation
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 Nb₃Sn 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.
Hall Probes for Magnetization Measurements

Two Hall probes (redundancy) at the center and one at the edge (at the request of Mike Sumption) in the base coil with turn-to-turn insulation after the BNL/LBL/OSU test planning meeting.

Note: planned test is magnetization studies in insulated coil only. Everything else is exploratory (extra at very small cost).

| AVT5-a | Insulated Coil - Center Hall sensor 1 |
| AVT5-b | Insulated Coil - Center Hall sensor 1 |
| AVT5-c | Insulated Coil - Center Hall sensor 1 |
| AVT5-d | Insulated Coil - Center Hall sensor 1 |
| AVT5-e | Insulated Coil - Center Hall sensor 2 |
| AVT5-f | Insulated Coil - Center Hall sensor 2 |
| AVT5-g | Insulated Coil - Center Hall sensor 2 |
| AVT5-h | Insulated Coil - Center Hall sensor 2 |
| AVT5-j | Insulated Coil - Edge Hall sensor |
| AVT5-k | Insulated Coil - Edge Hall sensor |
| AVT5-l | Insulated Coil - Edge Hall sensor |
| AVT5-m | Insulated Coil - Edge Hall sensor |
| AVT5-n | Non-Insulated Coil - Center Hall sensor 1 |
| AVT5-p | Non-Insulated Coil - Center Hall sensor 1 |
| AVT5-r | Non-Insulated Coil - Center Hall sensor 1 |
| AVT5-s | Non-Insulated Coil - Center Hall sensor 1 |
| AVT5-t | Non-Insulated Coil - Center Hall sensor 2 |
| AVT5-u | Non-Insulated Coil - Center Hall sensor 2 |
| AVT5-v | Non-Insulated Coil - Center Hall sensor 2 |

Two Hall probes (redundancy) at the center only in the No-insulation coil.
A v-tap after every 10 turns in each of four pancake coil
Two “insulated pancake coils” with 16 v-taps and two “No-insulation pancake coils” with 10 v-taps

<table>
<thead>
<tr>
<th>AVT3-A</th>
<th>Non-Insulated Coils - Coil 1 Turn 71</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVT3-B</td>
<td>Non-Insulated Coils - Coil 1 Turn 60</td>
</tr>
<tr>
<td>AVT3-C</td>
<td>Non-Insulated Coils - Coil 1 Turn 50</td>
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<tr>
<td>AVT3-D</td>
<td>Non-Insulated Coils - Coil 1 Turn 40</td>
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<tr>
<td>AVT3-E</td>
<td>Non-Insulated Coils - Coil 1 Turn 30</td>
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<tr>
<td>AVT3-F</td>
<td>Non-Insulated Coils - Coil 1 Turn 20</td>
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<tr>
<td>AVT3-G</td>
<td>Non-Insulated Coils - Coil 1 Turn 10</td>
</tr>
<tr>
<td>AVT3-H</td>
<td>Non-Insulated Coils - Coil 1 Turn 0</td>
</tr>
<tr>
<td>AVT3-J</td>
<td>Empty</td>
</tr>
<tr>
<td>AVT3-K</td>
<td>Insulated Coils - Coil 1 Turn 46</td>
</tr>
<tr>
<td>AVT3-L</td>
<td>Insulated Coils - Coil 1 Turn 40</td>
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<tr>
<td>AVT3-M</td>
<td>Insulated Coils - Coil 1 Turn 30</td>
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</tr>
<tr>
<td>AVT3-R</td>
<td>Insulated Coils - Coil 1 Turn 0</td>
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<tr>
<th>AVT4-A</th>
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More v-taps at leads, etc.
LTS coils have the original v-taps
Magnetic and Mechanical Models

- Maximum for magnetization test: 8 KA in Nb$_3$Sn coils and 800 A in HTS coils
- The baseline models are for 10 kA in the Nb$_3$Sn coil and 1 kA in two HTS coils
- Also examined HTS coils at 1.5 kA and 2 kA (just in case), for quench studies
Magnetic Model
(Nb3Sn coils @10 kA, HTS coils @1kA)
HTS coils are installed with as low clearance as possible. Horizontal Lorentz forces will bring them in contact with the LTS coils.
Field along vertical axis

By:: NI upper, Nomex lower. Green 1.5kA, Black 1kA, cyan - no Insert; B:: red 1.5kA, blue - No Insert

- HTS 1.5 KA
- HTS 1 kA
- NO HTS

Lower aperture
Upper aperture
B along x-axis in the aperture

Upper NI (Green 1.5kA, black 1kA), Lower Nomex (blue 1.5 kA, red 1kA), cyan - No insert

HTS 2 kA
HTS 1.5 kA
HTS 1 kA
No Insert
B along z-axis

- HTS 2 kA
- HTS 1.5 kA
- HTS 1 kA
- No Insert
The baseline models are for 10 kA in the Nb$_3$Sn coil and 1 kA in two HTS coils. Also examined HTS coils at 1.5 kA and 2 kA (just in case), for quench studies.
Main Question
Can Nb3Sn coils and structure take the transverse Lorentz load (x-axis) coming from the HTS coils powered at high current
ANSYS Run  Field from Nb₃Sn 10 kA, HTS 1 kA
ANSYS Run Transverse Stress and Strain from Nb$_3$Sn 10 kA, HTS 1 kA

LTS Coils
ANSYS Run Transverse Stress and Strain from Nb$_3$Sn 10 kA, HTS 1 kA

HTS Coils

C: Static Structural
HTS Transverse Stress
Type: Normal Stress(Y Axis)
Unit: MPa
Global Coordinate System
Time: 1
1/28/2020 3:53 PM

C: Static Structural
HTS Transverse Strain
Type: Normal Elastic Strain(Y Axis)
Unit: mm/mm
Global Coordinate System
Time: 1
1/28/2020 3:51 PM
ANSYS Run Transverse Stress and Strain from Nb$_3$Sn 10 kA, HTS 2 kA

LTS Coils
ANSYS Run Transverse Stress and Strain from Nb$_3$Sn 10 kA, HTS 2 kA

HTS Coils

C: Static Structural
HTS Transverse Stress
Type: Normal Stress(Y Axis)
Unit: MPa
Global Coordinate System
Time: 1
1/28/2020 3:40 PM

82.819 Max
67.013
51.207
35.401
19.596
3.7896
-12.016
-27.822
-43.628
-59.434
-75.24
-91.046
-106.85
-122.66
-138.46 Min

C: Static Structural
HTS Transverse Strain
Type: Normal Elastic Strain(Y Axis)
Unit: mm/mm
Global Coordinate System
Time: 1
1/28/2020 2:21 PM

0.00036385 Max
0.0002105
5.7162e-5
-9.6181e-5
-0.00024952
-0.00040287
-0.00055621
-0.00070955
-0.00086289
-0.0010162
-0.0011696
-0.0013229
-0.0014763
-0.0016296
-0.0017829 Min
Quench Protection of HTS/LTS Hybrid Dipole
What happens when the energy of HTS coil increases? Or what happens to HTS coils if LTS coil quenches?

Study of coupling between HTS & LTS coils can be a major part of MDP
From Piyush Joshi
Summary

• The magnet has been assembled with HTS coils and CFS samples inserted in the common coil dipole DCC017.

• We are on track for performing the test before the MDP collaboration meeting at Berkeley.

• The main purpose of this test is to measure the magnetization on HTS coils with HTS tape primary in field parallel direction (earlier studies under SBIR program was for field perpendicular direction).

• We will also study the performance HTS/LTS hybrid magnet at high fields (>10 T).

• A unique BNL common coil structure allows four simultaneous tests – two HTS coils and two HTS samples. It should score well with the fusion community in terms of MDP/FES collaboration.