



# US-Japan HTS/LTS Hybrid Program and Possible Benefits and Studies for MDP

### Ramesh Gupta For US-Japan HEP Collaboration



November 8, 2023

### Upcoming US-Japan HTS/LTS Hybrid Magnet Test and it's Wider Benefit to Magnet Science and to MDP

• Main goals of the upcoming US-Japan test:

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- > Examine ceramic insulation on HTS tape in high field magnets
- > Test high field HTS/LTS hybrid dipole magnet
- > Field error (magnetization) studies with the orientation of tape
- All above are relevant to MDP and hence the reason for its interest
- In addition, MDP is (or should be) interested in wider magnet science, so that these results can applied more widely, such as:
  - Understanding the test results and validating the models
  - There is an interest in operating HTS at higher temperature
- A range of BNL programs (magnet designs and experimental studies) in past decades have been doing that. Examples follow with a proposal for MDP to support additional tests of these coils

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## **Key Features of Various HTS/LTS Hybrid Programs**

- PBL STTR : 8.7 T, HTS coils in common coil configuration with field perpendicular to wide face of HTS tape
- MDP: 12.3 T, two HTS coils in two bores, both with field parallel to wide face of HTS tape (one NI, another insulated)
- US-Japan (upcoming): Potentially even higher field, two identical HTS coils in two bores - one primarily field parallel and another primarily field perpendicular configuration.
   KEK coils used 4 mm wide tape (PBL & MDP used 12 mm)



### Work Performed Under US Programs



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errors to be expected in the HTS Magnets

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19:49

19:52

19:53

19:55

### Intermediate Structure for taking HTS/LTS Hybrid to Higher Field





- Intermediate structure removes the local stress/strain concentration which may have limited Nb<sub>3</sub>Sn coils in the MDP from getting higher field.
- HTS coils with intermediate structure were inserted in common coil and made two trips to cold test. The hybrid test was not performed.
- Similar structure in US-Japan test, with smaller coils (another attempt).





#### **MDP HTS coils with intermediate structure**



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## **Configuration of US-Japan HTS/LTS Hybrid Test**



Two identical HTS insert coils from KEK in two apertures of the BNL common coil dipole:

- **One Bore: field primarily parallel**
- Another bore: field primarily perpendicular

#### **Systematic experimental studies:**

- Expect (a) significantly higher current in HTS coils, and (b) significantly lower magnetization in field parallel orientation as compared to the field perpendicular.
- This test should provide a variety of useful experimental data on hybrid magnets and on using HTS in accelerators



### 12 mm wide HTS Tape Coil Tests at 77 K (PBL STTR) (details for US-Japan tests to be presented by Febin)

Test Sequence of HTS Coils at 77 K

(trapped field create field errors)



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## 12 mm wide HTS Tape Coil Tests (PBL STTR)

#### Two Successive Runs to 200 Amp (77 K)



between subsequent runs

(~0.2 T or ~10%)

#### **Exponential decay**

Time (second)

8

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## Importance of Quantifying Performance of HTS Coils with Field Angle in the Magnet

- Performance of HTS tape and the field errors created by HTS coils depends strongly on the field angle. We must quantify it via experiments and extrapolates in various conditions via models.
- It has been known for a while that you can design HTS/LTS magnets to take advantage of this (or suffer from the consequences). PBL has a patent on it – it helps it in making its commercialization case.
- Others, including CERN and Texas A&M, have developed special designs to take advantage of it.



### US-Japan Studies to Measure the Impact of Changing Screening Currents as a Function of Position & Time

Locations of Hall probes (marked by X)



Screening currents change as a function of field and field angle. >This should impact the local field distribution Field configuration is different for Hall probes at two ends (dipole + solenoid)

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Bill Sampson measured the change in field over time, mostly with one Hall probe at the center
 Several Hall probes will take those studies to the next level!



### Can Trapped Field be Removed by Transient Cycle? (Recent 77K US-Japan test, see more by Febin)

#### Coil 2: Power Trip



#### Near zero trapped fields after trip

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# Wider Magnet Science Program for Developing Accelerator Magnets

Technical research work that we need to do to evaluate if HTS or

HTS/LTS hybrid magnets are viable for accelerators:

- Field quality
- Operation at higher temperature
- Quench protection, ...



### **Measurement of Field Harmonics in HTS Dipole (MT17, 2001)**





Now we are doing magnetization measurements which are less expensive and with some modeling give some indication of what will be the impact in accelerator magnets

 $\mathbf{\sigma}$ 

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## **HTS Magnet Programs with Wide Operating Range**

- BNL HTS programs covered wide operating range and magnet type
  - High Field HTS/LTS hybrid dipole @4K
  - SMES solenoid (12.5 T@27K, 25 T @4K)
  - Medium field FRIB quad (1G: 30K-40K, 2G 40-50K)
  - Many more (Please visit: <u>https://wpw.bnl.gov/rgupta/</u>)
- We are proposing MDP to support medium temperature (>4 K) tests as there has been recent interest in operating HTS coils at higher temps. They should also validate new promising models

#### Examples follow to help elevate some concerns



Connection from the bottom of the leads at top-hat to the coil with HTS tape (backed by copper) to allow testing in a wide temperature range





## **HTS Magnet Tests with Wide Operating Range (SMES)**

Connection from the bottom of the leads at top-hat to the coil with HTS tape (backed by copper) to allow testing in a wide temperature range





## **HTS Magnet Tests with Wide Operating Range (FRIB)**





### **Testing Models Over Wide Operating Range**

HTS tape performance and dependence on field angle varies by about an order of magnitude over the operating range. This provides a good challenges and test of the computer model. We need experimental data to test and validate the models

#### Modelling the Magnetization in HTS Tape



R. Gupta et al, Design, construction, and test of HTS/LTS hybrid dipole, IEEE Transactions on Applied Superconductivity, 28(3), 4002305, 2018

Courtesy: Ye Yang and Tengming Shen, LBL



Benchmark



- Upcoming US-Japan test of hybrid dipole should be very interesting.
- 77 K test results to be present in details next by Febin Kurian.



# **Extra Slides**



# Magnetization Studies as a Function of Temperature (self field only, no applied field above ~4 K)



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- Intermediate temperature is obtained by putting some liquid Helium at the bottom of the Dewar and let the temperature get stabilized.
- It has been done many times in the past at BNL. We will have thermometers at the bottom and top of the HTS coils to assure a temperature gradient within a couple of degrees.
- This data should help validate the models and should be helpful for future studies as higher temperature options gets considered time to time.
- Added cost should be evaluated and maybe MDP can support extended studies (this and others)



# Background

- During the last HTS/LTS hybrid test, the maximum performance of 12.3 T was limited by the LTS coils, and not by the HTS coils.
- Moreover, it was <u>NOT</u> limited by Nb<sub>3</sub>Sn coils themselves, as they by themselves worked well. Performance got limited when Nb<sub>3</sub>Sn coils were energized together with the HTS insert coils.
- Theory:  $Nb_3Sn$  coils were stress/strain limited locally (no intermediate structure to manage or distribute the stresses).
- This question/issue is important in all high field  $Nb_3Sn$  magnets.
- All new inserts are planned with intermediate structures. This PSI/BNL test was became a test to overcome the stress limit.
- It allowed higher peak field in DCC017 coils (10.7 T =>  $\sim$ 12 T)
- More interesting what was observed accidently (magnet survived).







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Science

## From ASC2006 Paper on DCC017



High field Nb<sub>3</sub>Sn coils should include strain as a parameter in such plots

Stress-managed Common Coil

-Ramesh Gupta

USMDP General Meeting, May 10, 2023

## A Lingering Issue until the Recent PSI/BNL Test



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Ramesh Gupta, K. Amm, P. Joshi, S. Joshi, W. Sampson, A. Ben Yahia LTSW/HFSW2020, Berkley, CA



Even though a record 12.3 T hybrid field was obtained, the performance was not limited by HTS coils. It was limited by the Nb<sub>3</sub>Sn coils in every HTS/LTS combination.

Smaller HTS coils were in direct contact with the larger Nb<sub>3</sub>Sn coils with no structure in between. This meant a local discontinuity or stress/strain from the pressure of HTS coils on Nb<sub>3</sub>Sn coils.



HTSW/LTSW 2020

#### HTS Insert Coil Structure in Frame Concept for US-Japan Test (two HTS coils in the 2-in-1 Nb<sub>3</sub>Sn common coil dipole)



## A Unique Background-field Dipole for Magnet R&D

- $> Nb_3Sn$ , common coil 2-in-1 dipole that allows two insert coils in two aperture
- Structure is designed to provide a large open space (~30 mm X 335 mm)
- New insert coils can be tested in the background field of up to 10 T (+ self-field)
- The insert coils come in direct contact with the existing Nb<sub>3</sub>Sn coils and therefore become an integral part of the magnet (e.g., HTS/LTS hybrid dipole)
- Facilitates a rapid-turn around, low-cost R&D approach for high field magnets
  The approach has already been successfully demonstrated in several tests



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## **Two Previous HTS/LTS Hybrid Dipole Tests** (Either Field Perpendicular or Field Parallel)



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#### HTS Magnetization Studies (with no background field)

800

Superconducting Magnet Division 2 1.5 0.5 Field [T] -200 200 -600 -400 400 600 -0.5 -1 -1.5 Current [A]

- 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

-First cycle -Second cylce -3rd cycle HTSW/LTSW 2020 Magnetization Measurements of HTS Coil -Ramesh Gupta May 25, 2022 28



Superconducting Magnet Division 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



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Magnetization Measurements of HTS Coil

-Ramesh Gupta



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#### Suggested Location of Hall Probes in KEK HTS Coils (double pancake)



Possible Locations (marked by X) of Hall probes: at the center, and at two edges of each pancake (5 locations) in SS, and one at each end (2 location). Total 7 Hall probes



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### Field on the Coil (All calculations at 100 A)



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Magnetization Measurements of HTS Coil

-Ramesh Gupta May 25, 2022



### **Field on Patch**

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### Field on Coils at the End



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#### Magnetization Measurements of HTS Coil

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### Patch at the Middle of the Coils



TIJW/LIJW LULU

magnetization measurements of FID con

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MUY CO, CUEC JT

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### Feld along z-axis (Hall Probe at z=150 mm)

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## Field along y-axis (Hall Probe Locations)

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## Field along y-axis (Hall Probe Locations)

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### Field along x-axis @y=112.5

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### **Current Ramps Used for Magnetization Experiments**

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### Hall Probe Measurements for Magnetization Cycle

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### Hall Probe Measurements for Magnetization Cycle





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### Hall Probes One Side (low current and high current)

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### Hall Probes Other Side (low current and high current)

ow current (Orange) High current (Blue)

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### Low current (blue), High current (orange)



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### Low current, High Current

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### Decay of Residual Field after Power Supply Shut-off

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