U.S. MAGNET DEVELOPMENT PROGRAM

BNL Update and conductor needs

MDP collaboration meeting, May 01, 2024

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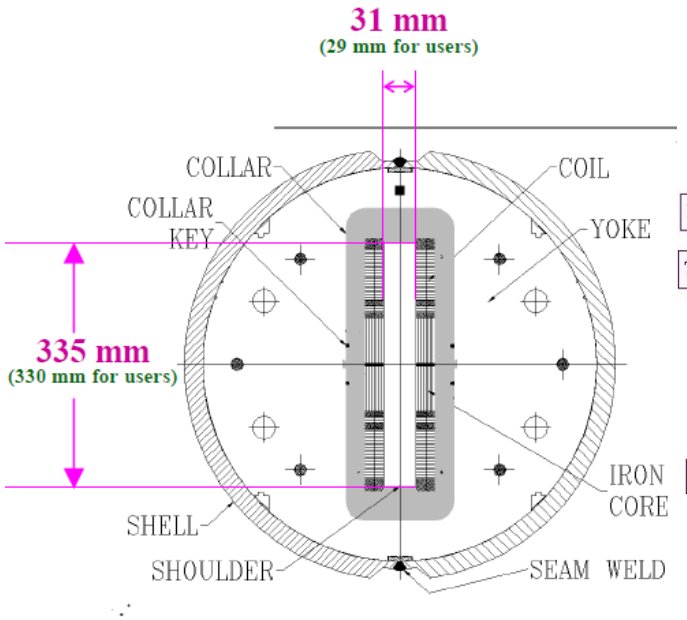
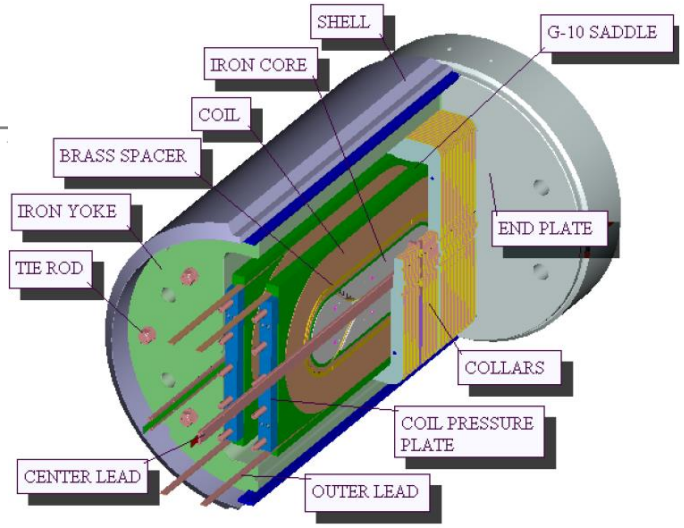
On behalf of scientific and technical staff at BNL

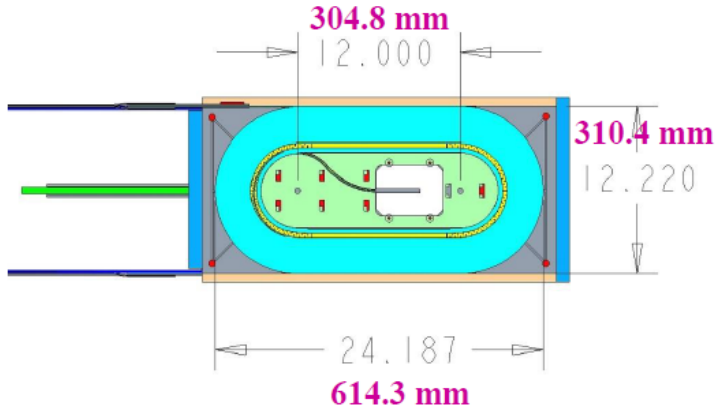
Brookhaven National Laboratory

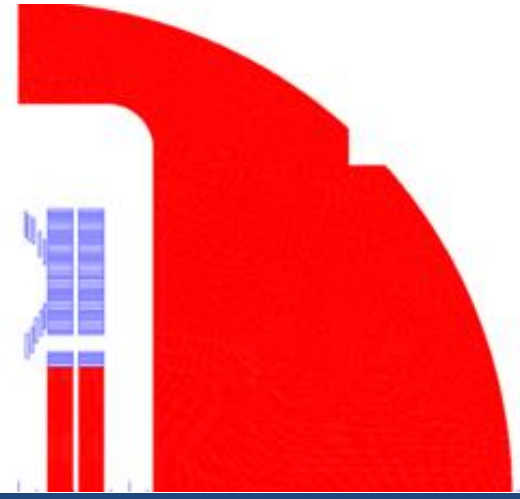
Introduction

- General Motivation
  - HTS/LTS hybrid towards high field magnet
  - Quench protection: detection, energy extraction
  - Stress management
- 2023 Highlights: 4 cold tests
  - HTS CORC insert coil test (BNL/ACT/LBNL), December 2022/July 2023
  - HTS tape insert coils (2 coils) test (BNL/KEK/LBNL), December 2023/March 2024
  - Nb_3Sn Wax impregnated BigBox + BNL HTS tape insert coil test (PSI/BNL), April 2023
- Outlook for 2024









Acknowledgement

- BNL: Anis B Yahiya, Febin Kurian, Piyush Joshi, Ramesh Gupta, Kathleen Amm, technical staff and others
- ACT: Danko V D Laan, Jeremy Weiss, Zachary Johnson
- LBNL: Reed Tyber, Maxim Marchevsky, Xiaorong Wang, Tenming Shen and others
- PSI: Douglas M Araujo, Bernard Auchmann, Michael Daly
- KEK: Mukesh Kumar, Masami Iio and others

HTS CORC insert coil test
December 2022/July 2023

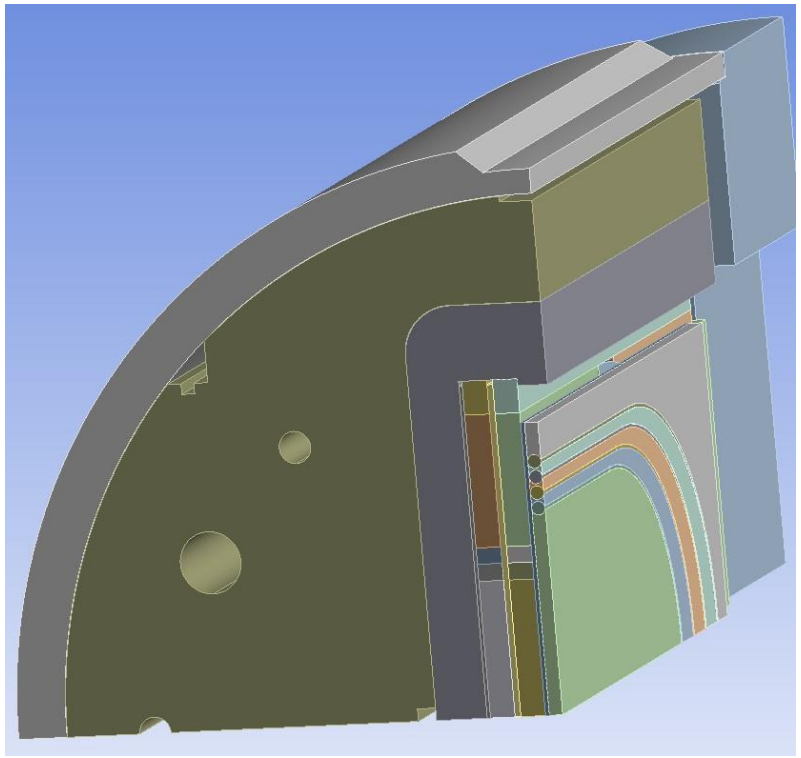
Thanks to colleagues at BNL, ACT, and LBNL

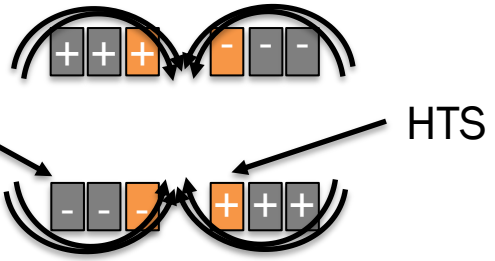
Motivation

- ~20T class magnet requires HTS: 12-15 T LTS + 5-8 T HTS.
- Energize HTS+LTS in series, HTS must 10-20 kA at 20 T⇒ Je of 400 to 600 A/mm^2 at 20 T ⇒ CORC cables.
- 2023 cold testing of MDP coil: “In-field quench studies of a long CORC cable” in the background field of common coil dipole via one 8-turn HTS coil (S-turn in to flip the polarity).

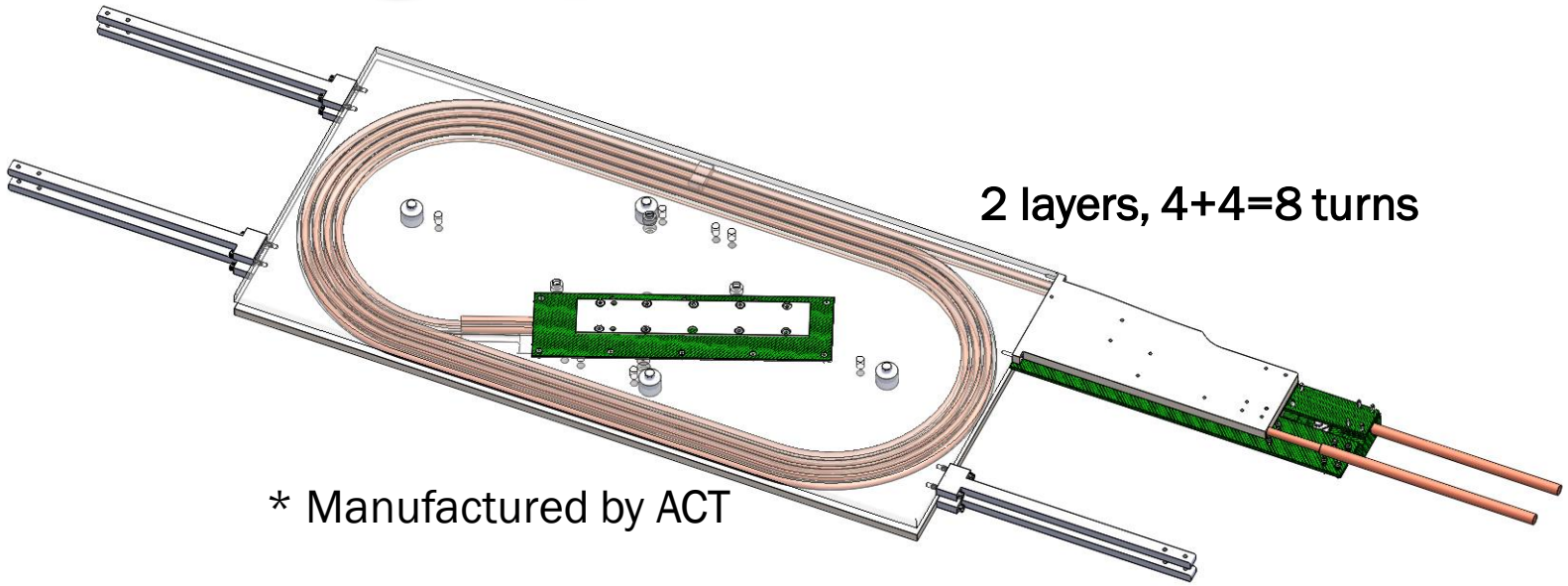
- Outlook: 2024 cold testing of STTR coil: High field Demo (12-13 T with 9 T from LTS).
  - “Demonstration of a high field HTS/LTS hybrid dipole” with two sets of double pancake coils made with 6+8 turns (total 28 turns) of CORC cable.

MDP CORC Sample





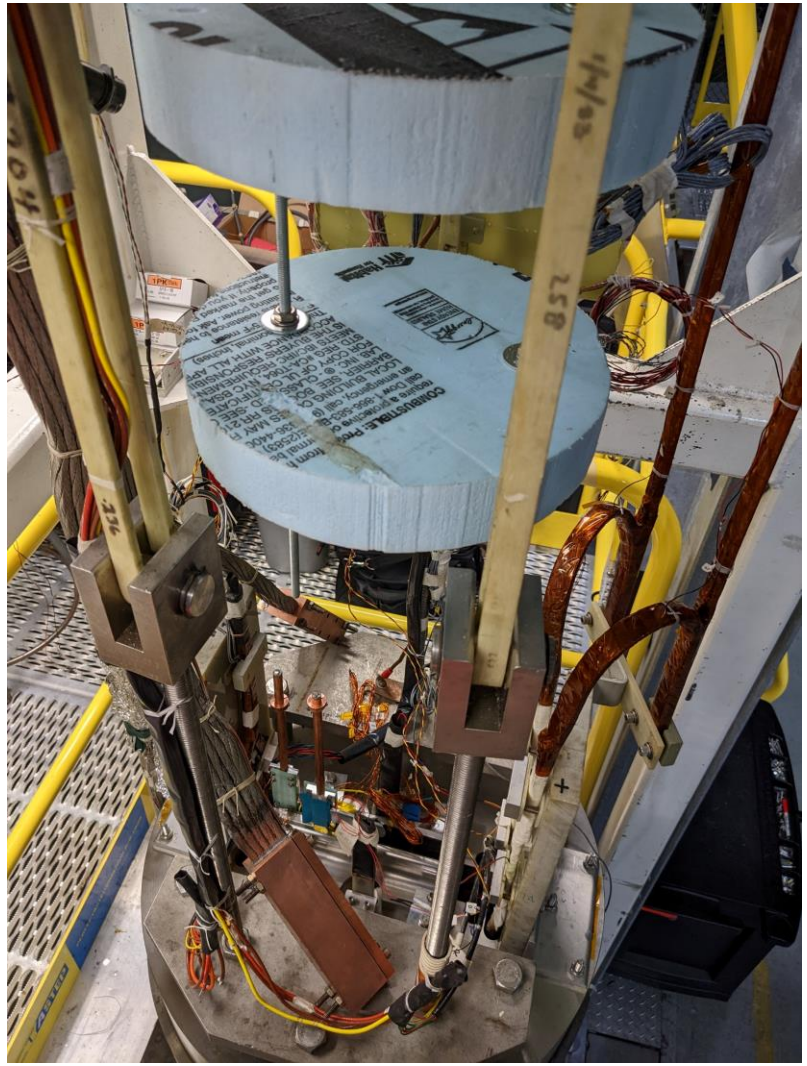
From ACT



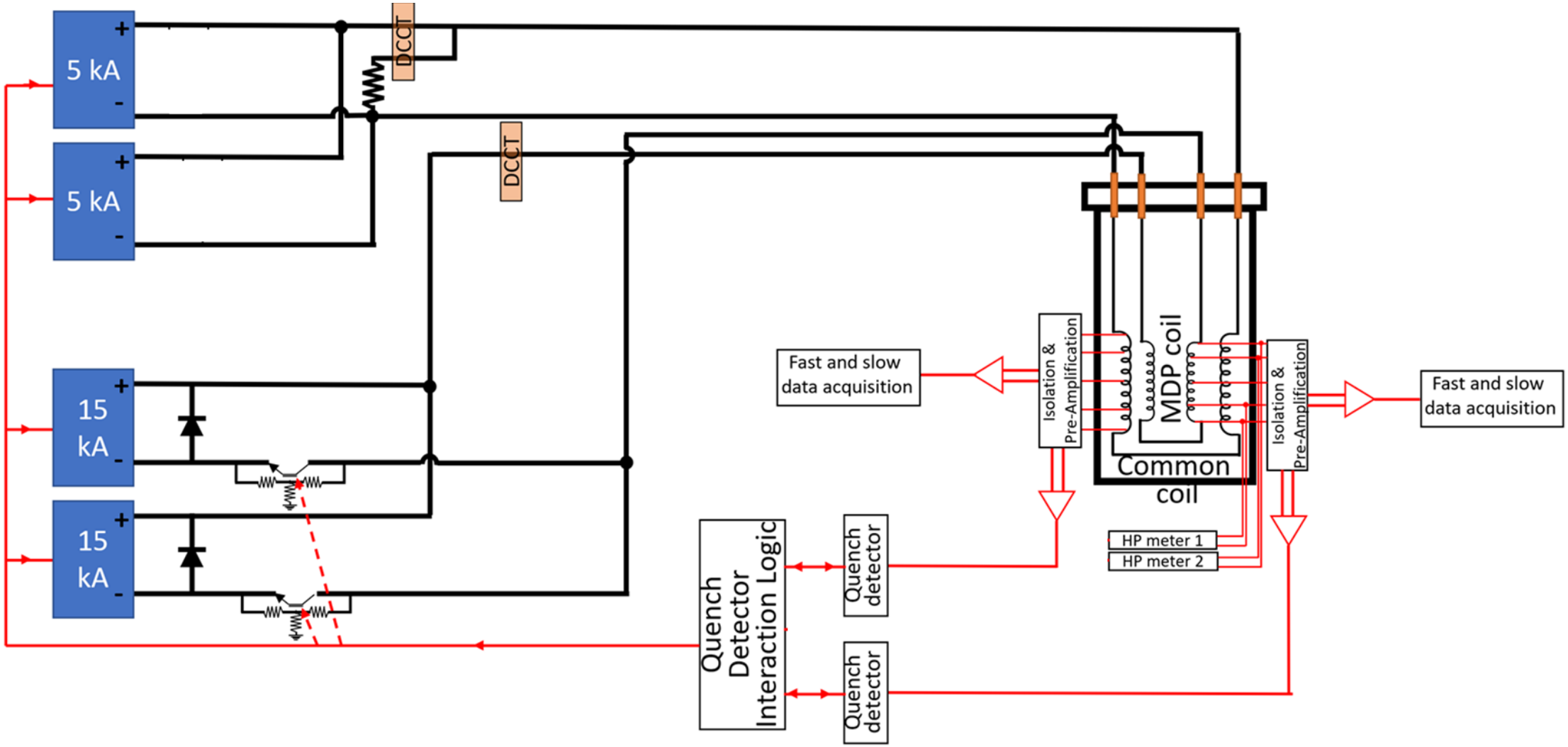
2 layers, 4+4=8 turns

* Manufactured by ACT

Sample Installation

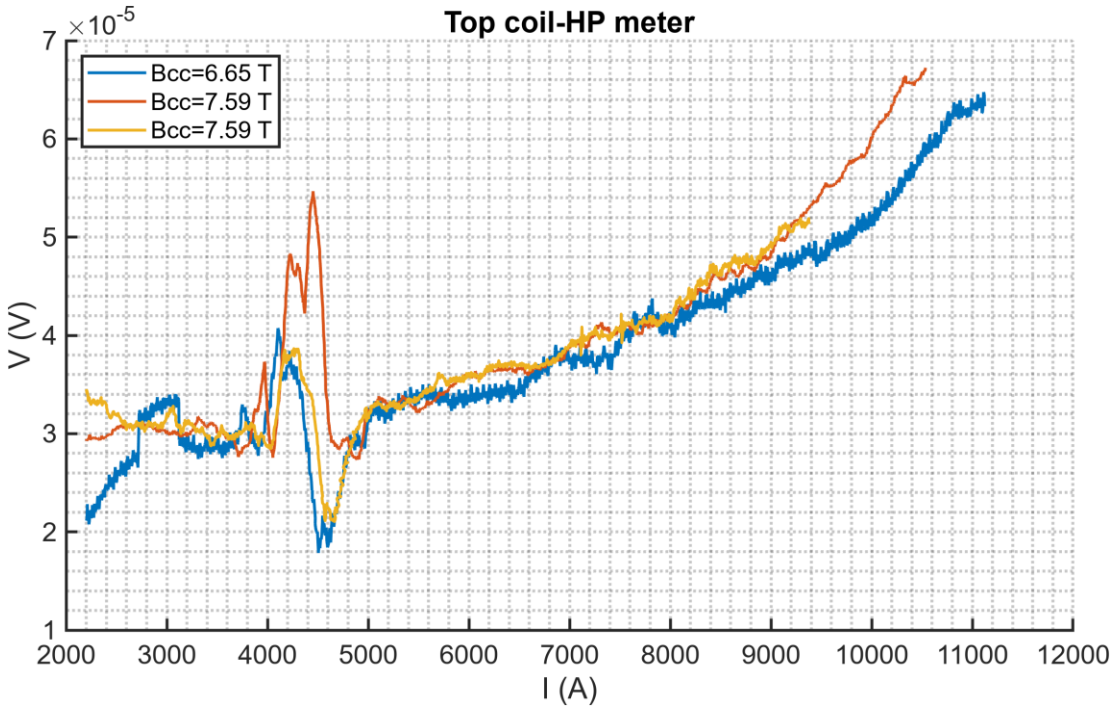


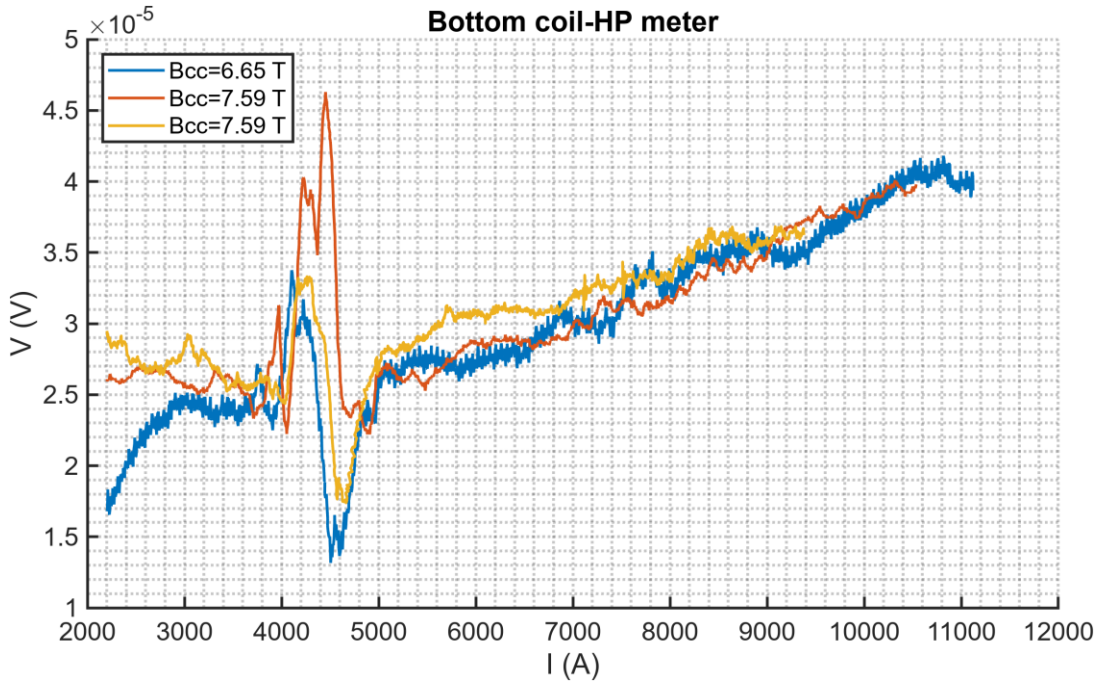
Simplified Power circuit



Voltage vs Current

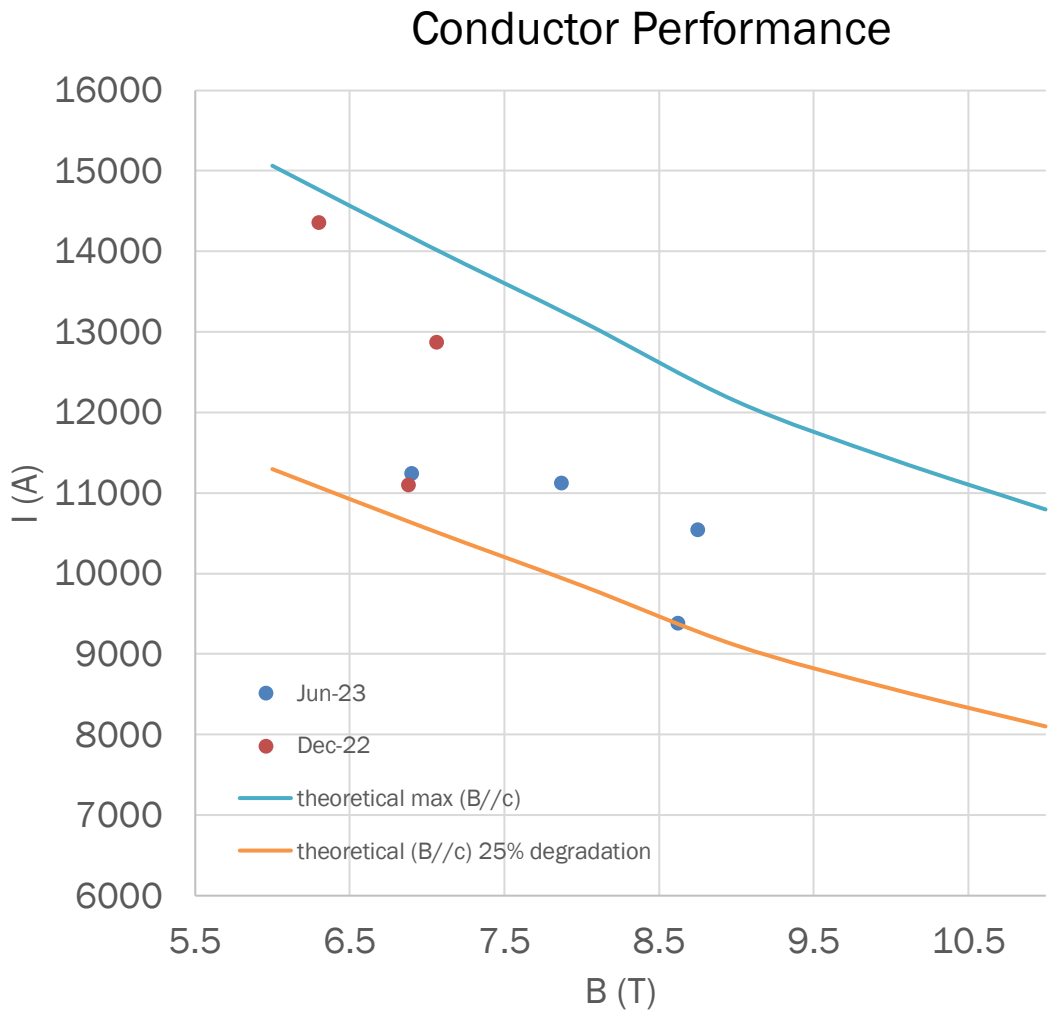
High Voltage precision ~ 1 μV
Low sampling rate (167 ms)





Coil performance summary

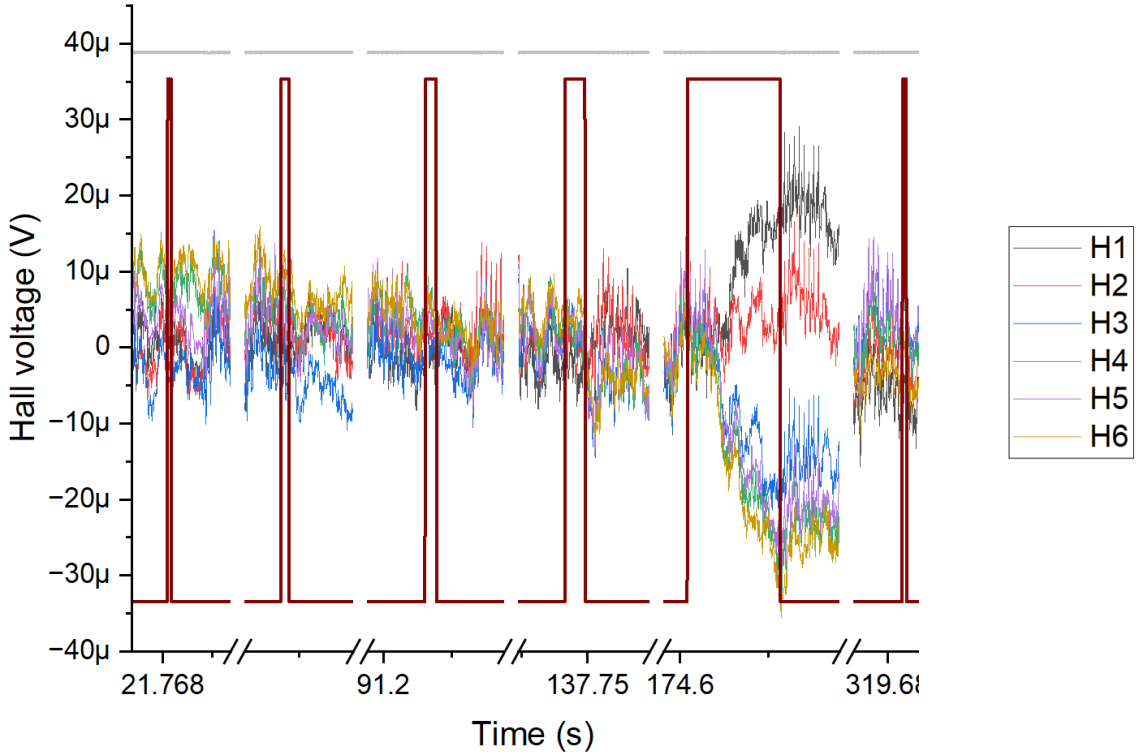
Exp	I_{CC} (A)	I_{MDP} (A)	B_{CC} (T)	B_{MDP} (T)	B_{total} (T)	Pulse Energy (J)
1	6041	11241	5.7	1.236	6.9	
2	7042	11125	6.647	1.22	7.87	
3	8040	10544	7.59	1.16	8.75	
4	7042	8996	6.648	0.989	7.637	$2*(2)^2*10*0.1$
5	7040	5496	6.648	0.604	7.25	$2*(2)^2*10*2$

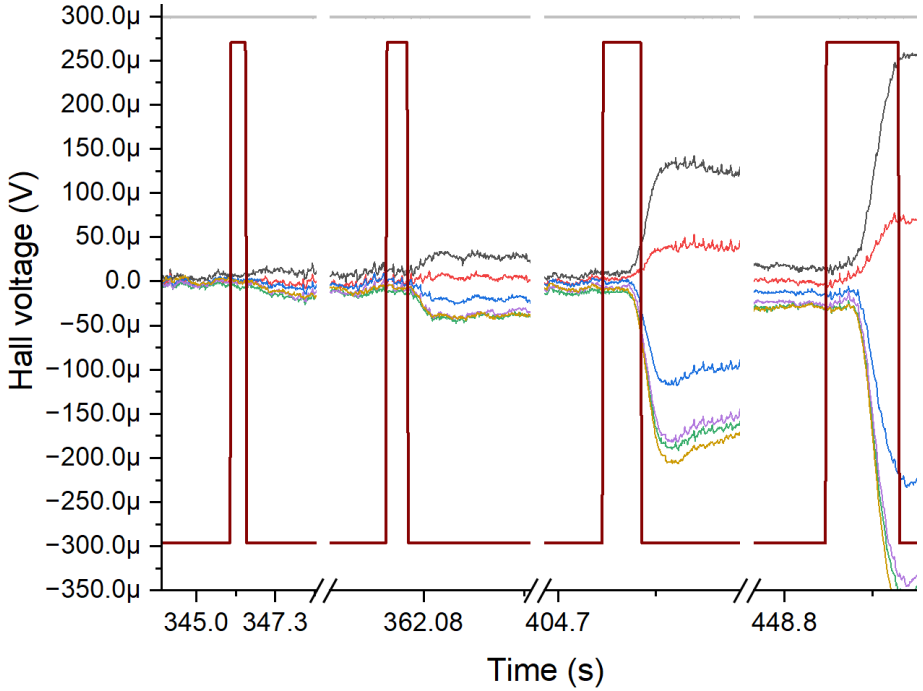


Hall Arrays as quench detection technique ?

Reed Tyber

Icc=7042A, Imdp=5496A,
Bcc=6.65T, Bmdp=0.6T,
Btot=7.25T





I_{heater} = 1 A: 100 ms, 300 ms, 500 ms, 1000 ms, 5000 ms, 2A(100 ms) I_{heater} = 2 A: 300 ms, 500 ms, 1000 ms, 2000 ms (Q)

Summary

- Corc based insert + Nb3Sn outsert was energized to combined peak field of 8.75 T.
- Validation of independent powering and energy extraction circuitry.
- Quench detection
  - Higher detection voltage threshold + low validation time works better than low detection voltage + higher validation time.
  - Low voltage detection using HP meters: not suitable for quench protection.
  - Hall voltages due to current sharing between tapes should be investigated further.
  - Fiber broke
  - Couldn’t set acoustic set up properly

HTS tape insert coils (2 coils) test December 2023/March 2024

Thanks to colleagues at BNL, KEK, and LBNL

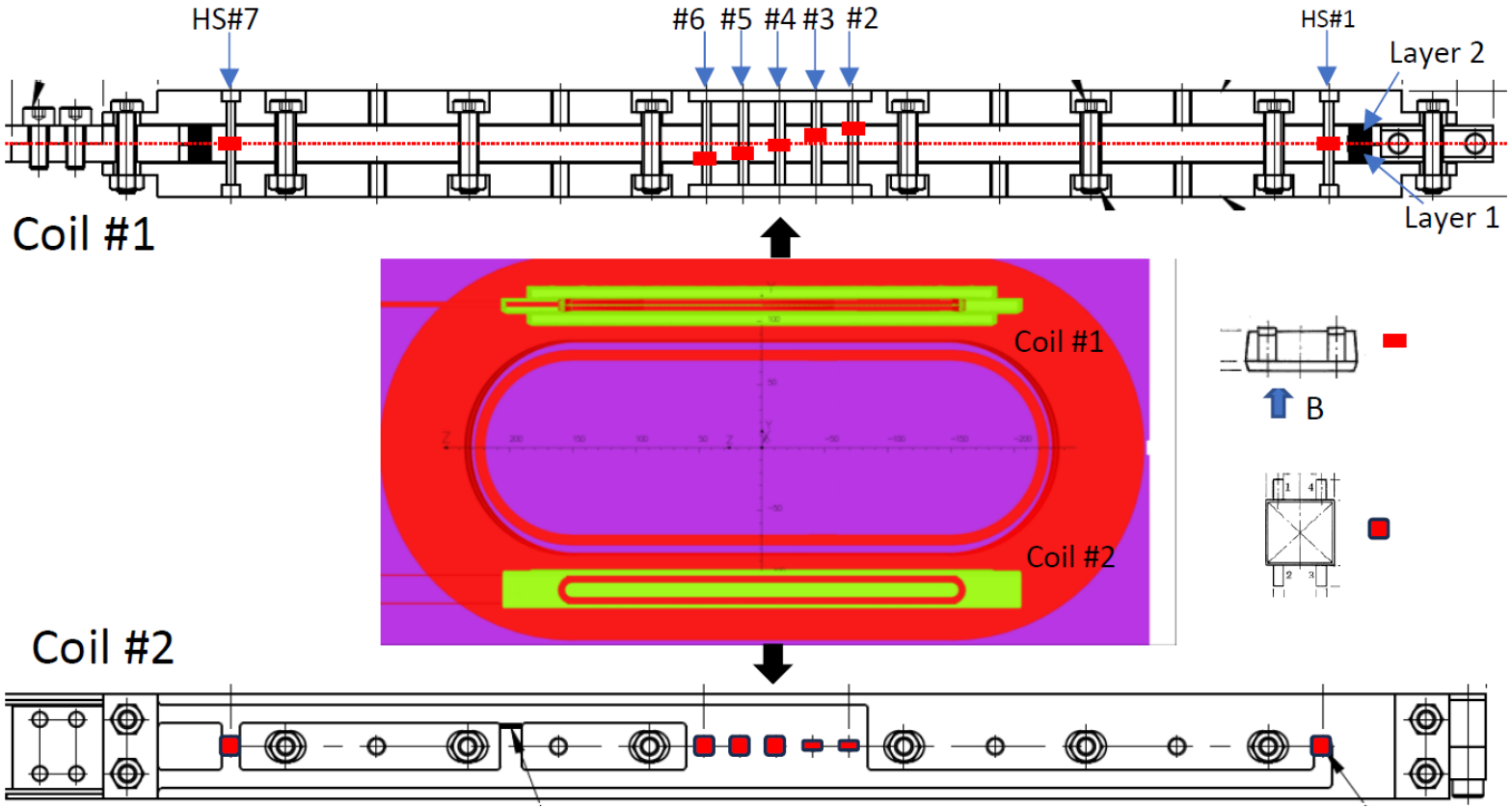
- Partially funded by MDP.
- Tested by Febin/Piyush.

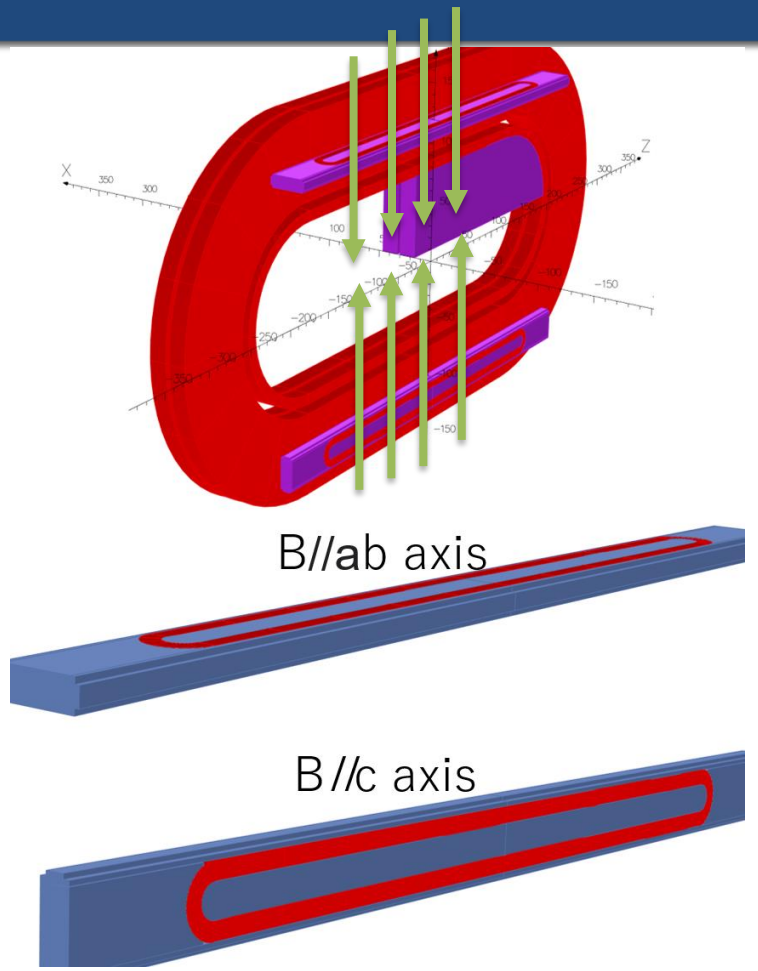
Motivation

- Radiation resistant superconducting magnet for the pion capture solenoid
  - Ceramic coated REBCO tapes.
- Magnetization of HTS pancake with background magnetic field parallel and perpendicular to the tapes.
- LTS/HTS hybrid demonstrator for the pole coil

Set up (I)

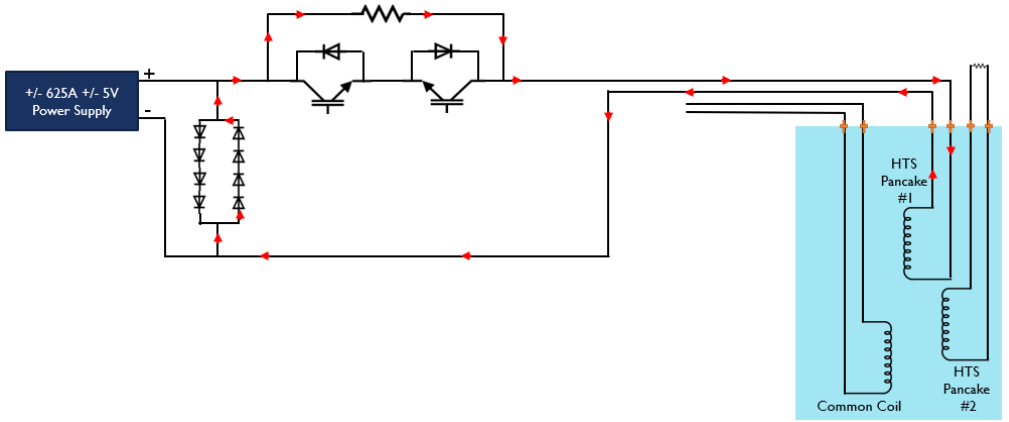
**Slide courtesy Mukesh Dhakarwal, KEK*



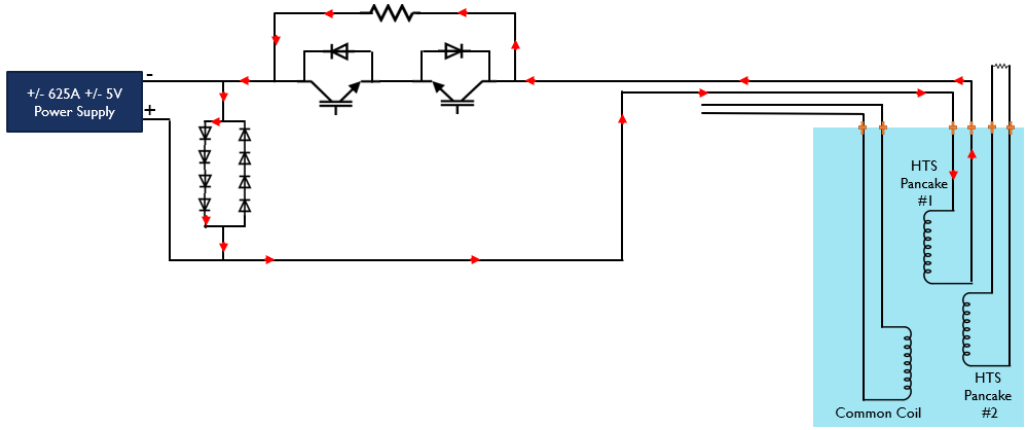


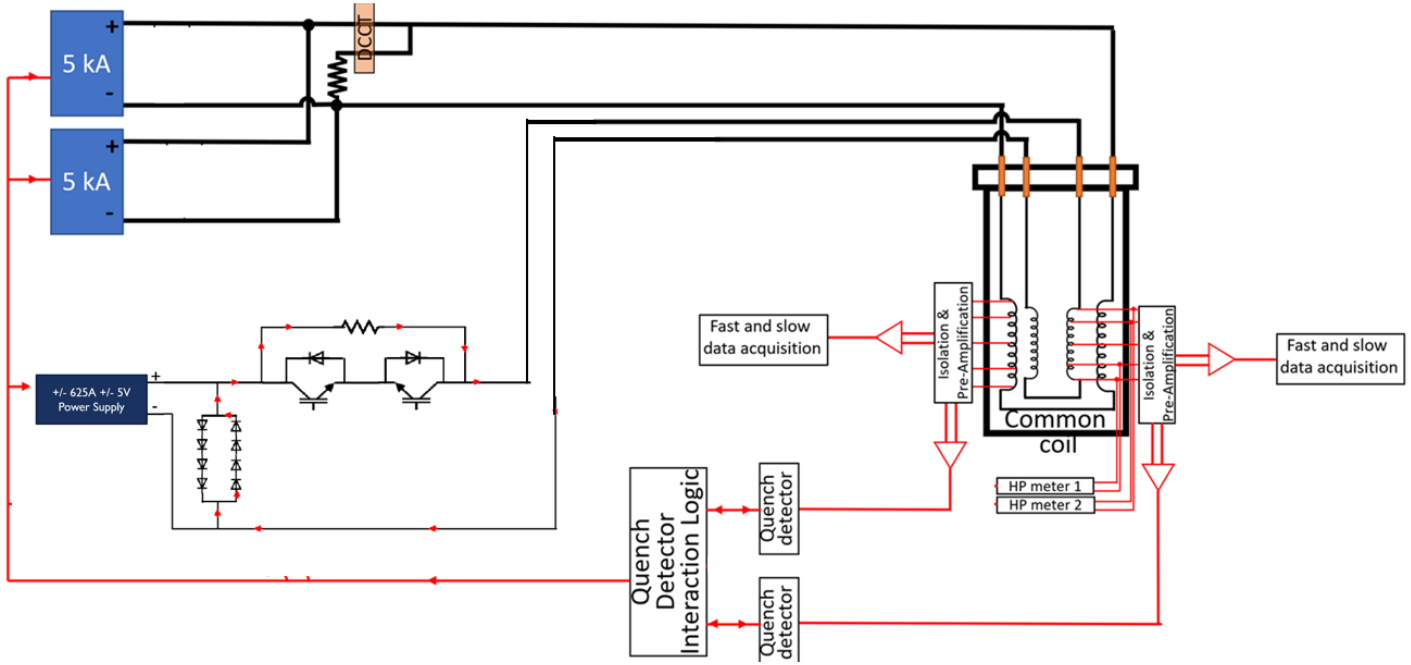
Set up (II)

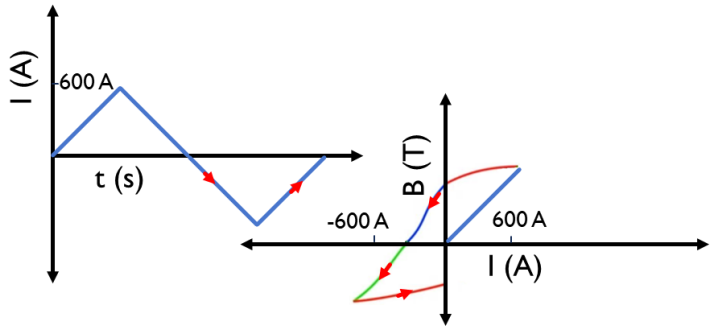
Quench during positive cycle



Quench during negative cycle







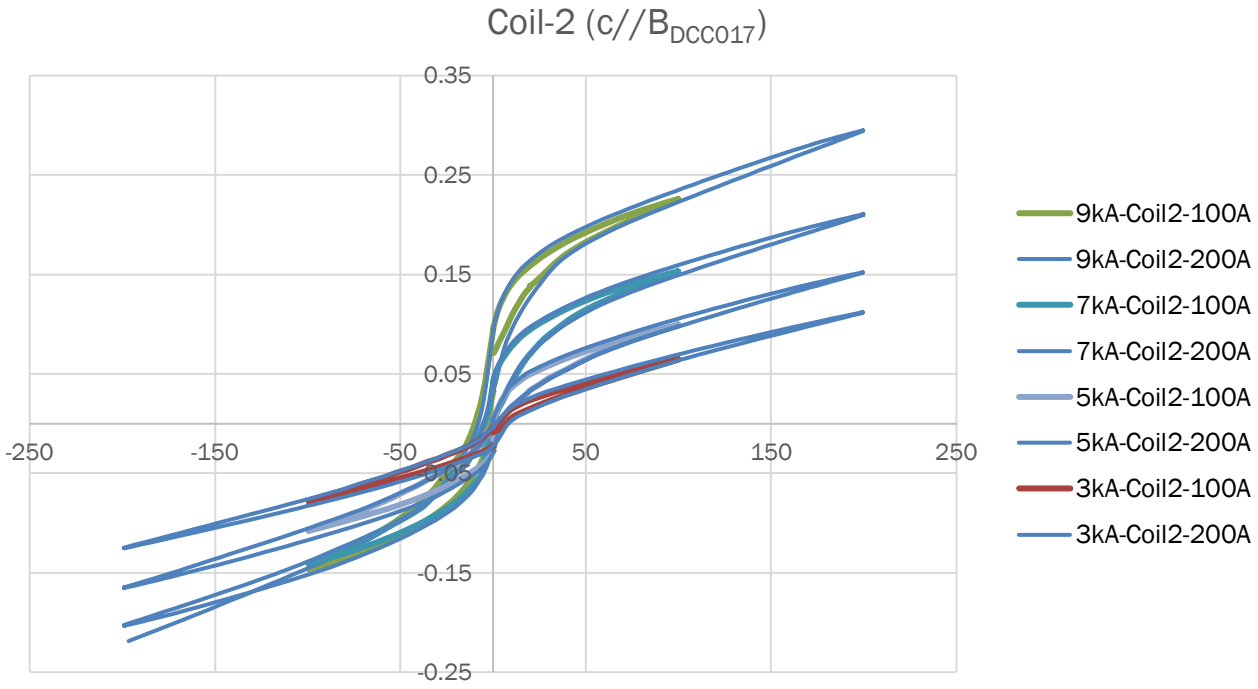
Measured cases

Magnetization Measurements	Coil 1	Coil 2
Background Field → 0T	100 A-500 A	100 A & 300 A
I_{cc}=1kA (0.98T)	100 A, 200 A & 500A	200 A & 350 A
I_{cc}=3kA (2.94T)	100 A , 200 A & 500 A	100 A, 200 A
I_{cc}=5kA (4.87T)	100 A, 200 A	100 A, 200 A
I_{cc}=7kA (6.72T)	-	100 A, 200 A
I_{cc}=9kA (8.64T)	-	100 A, 200 A

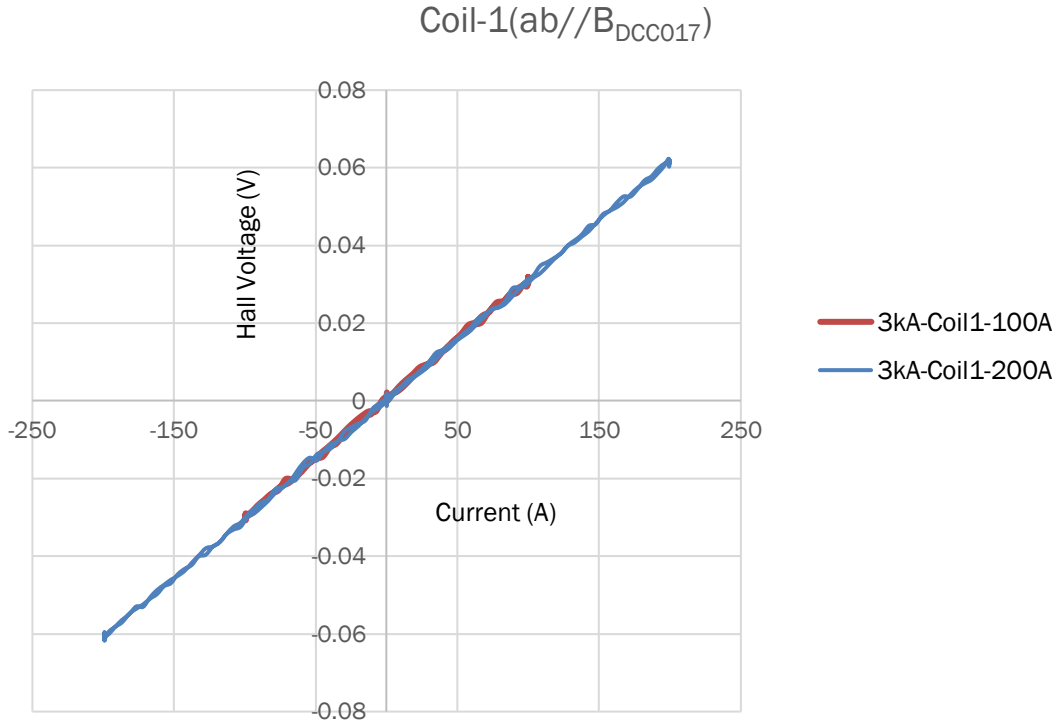
AC cycle – FEM vs Experiment	Coil A	Coil B
I_{cc}=1kA (0.98T)	100A	100A
I_{cc}=3kA (2.94T)	200 A & 500 A	-
I_{cc}=5kA (4.87T)	200 A & 500 A	100 A

Quench Current test	Coil A	Coil B
Quench 4.87T Background Field	1243.18 A	-

Magnetization Measurements



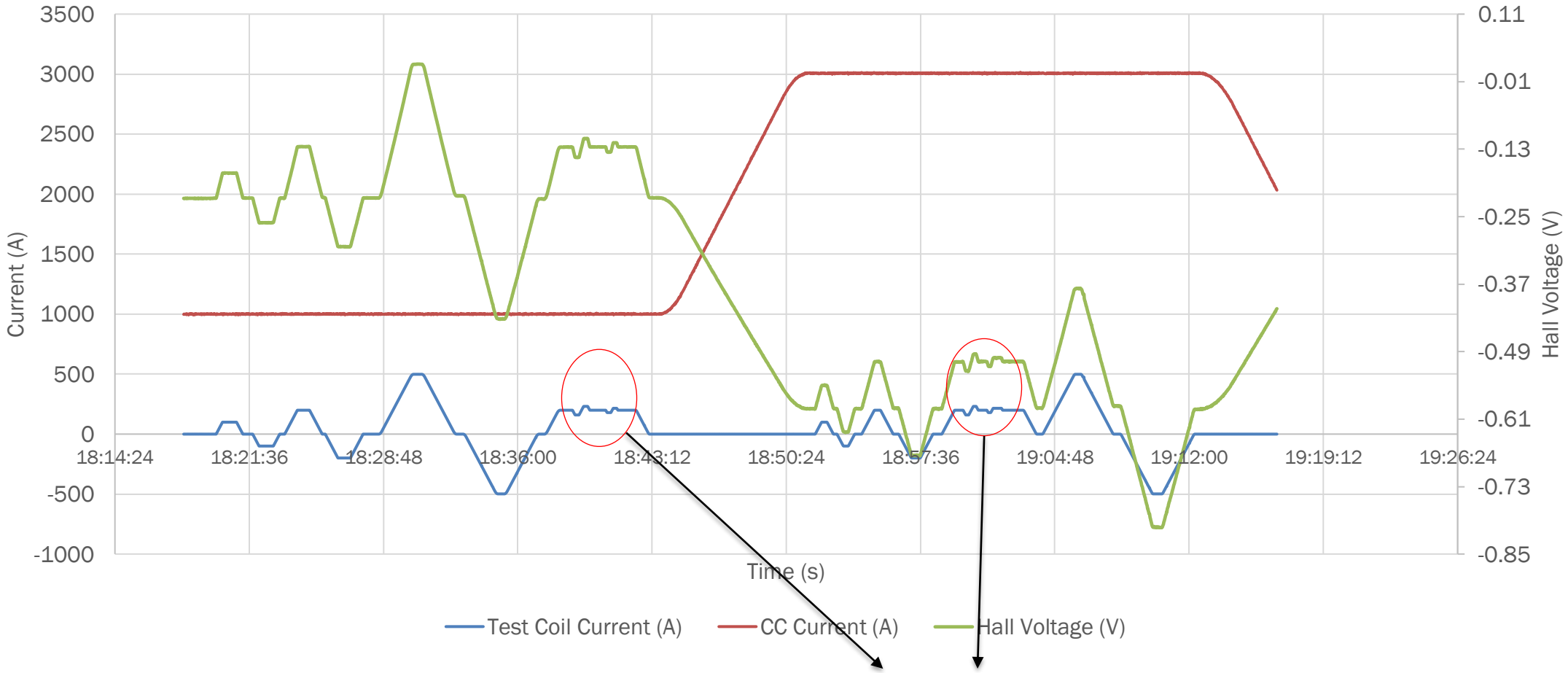
Background current ramped from 9kA → 3kA, coil current ramped to 100A and then 200A (Background field is not substracted)



Background current 3kA, coil current ramped to 100A and then 200A (background field subtracted)

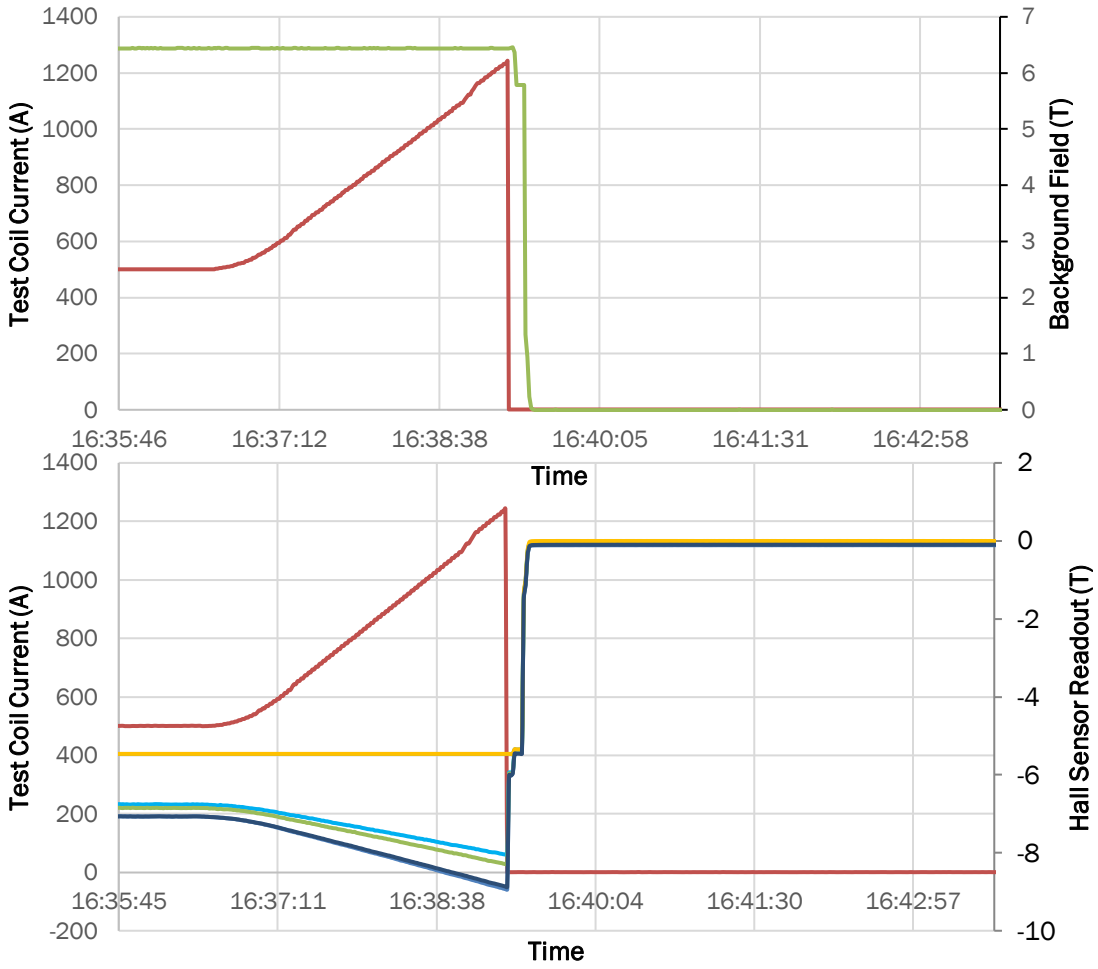
Reduction in magnetization when the background field is parallel to wide face

Hall Voltage response to Combined Field



AC cycle measurements for comparison with Simulation done by LBNL

Quench Under Background Field



Test Coil-1 (ab//B_{DCC017})

Subsequent quenches indicate degraded performance to around **553A**

At a background field around 6T Test coil quenched at 1243 A current (**8.8T total field**)

Summary

- Pole coil HTS coil and Nb_3Sn LTS coil were energized in hybrid combination creating 8.8 T magnetic field.
  - Coil A degraded to half its performance after first few quenches=> damaged tapes?
- Magnetic measurements were performed to understand distribution of bult magnetization in HTS coil.
- Complete analysis in progress.

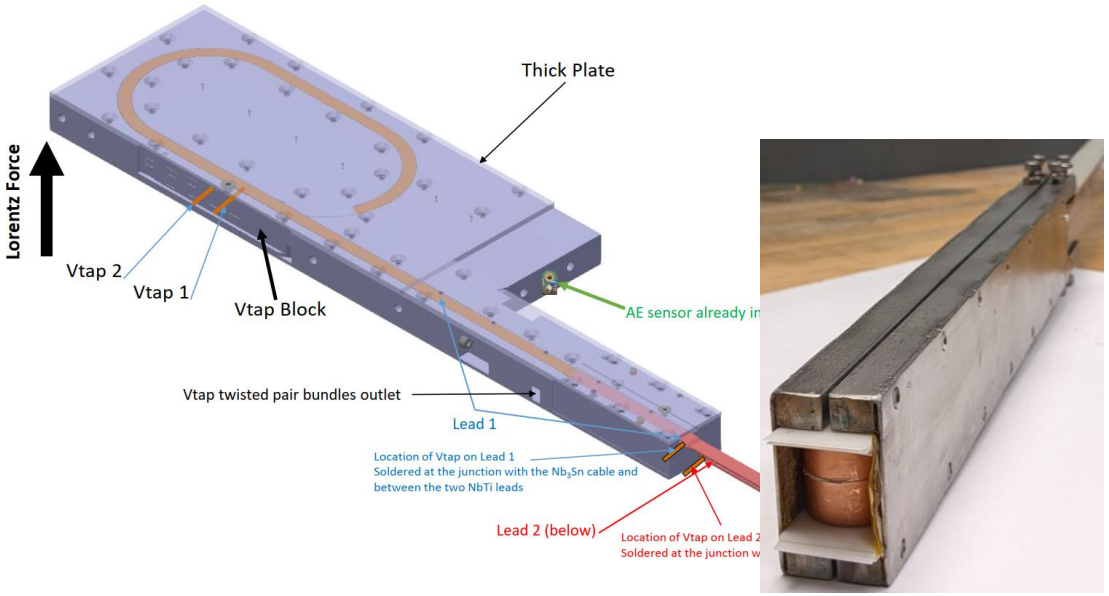
*Contact Febin for more information !

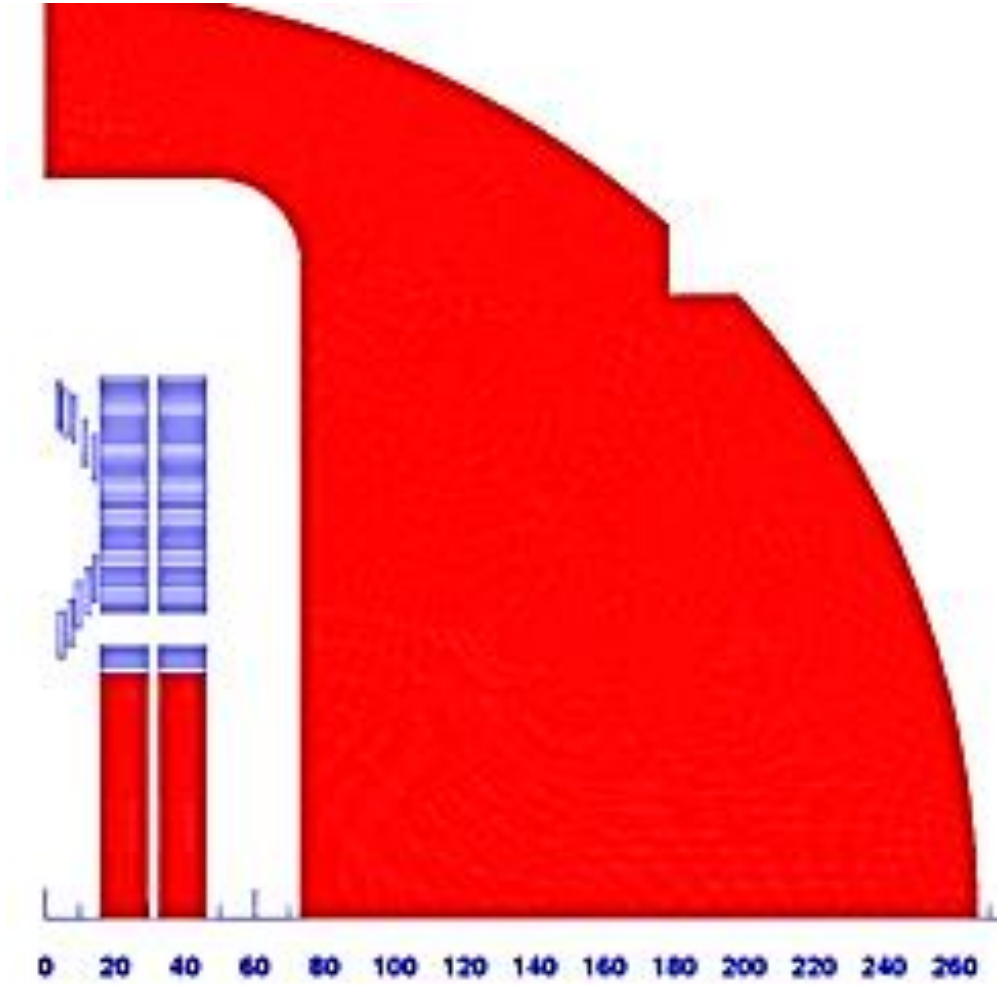
Nb3Sn Wax impregnated and HTS tape insert coil test April 2023

Thanks to colleagues at BNL and PSI

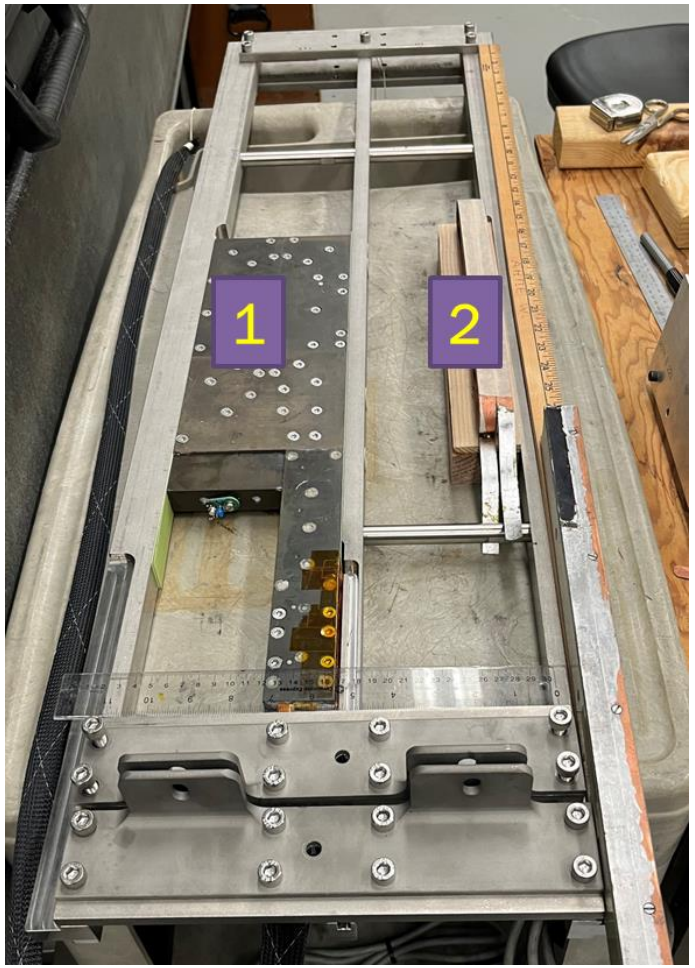
Motivation

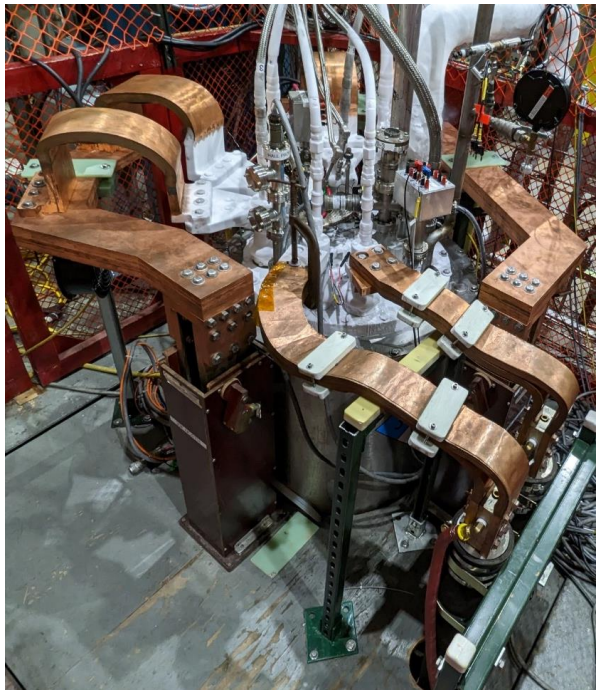
- Wax impregnated coil technology,
- Pole coil for field quality in common coil
  - Stress-managed structures,
  - Record HTS/LTS hybrid field, and

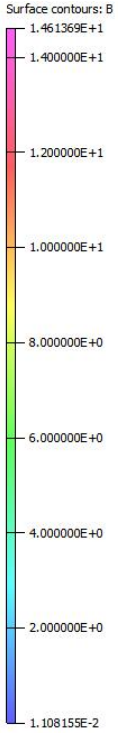




Set up


1
2




Surface contours: B
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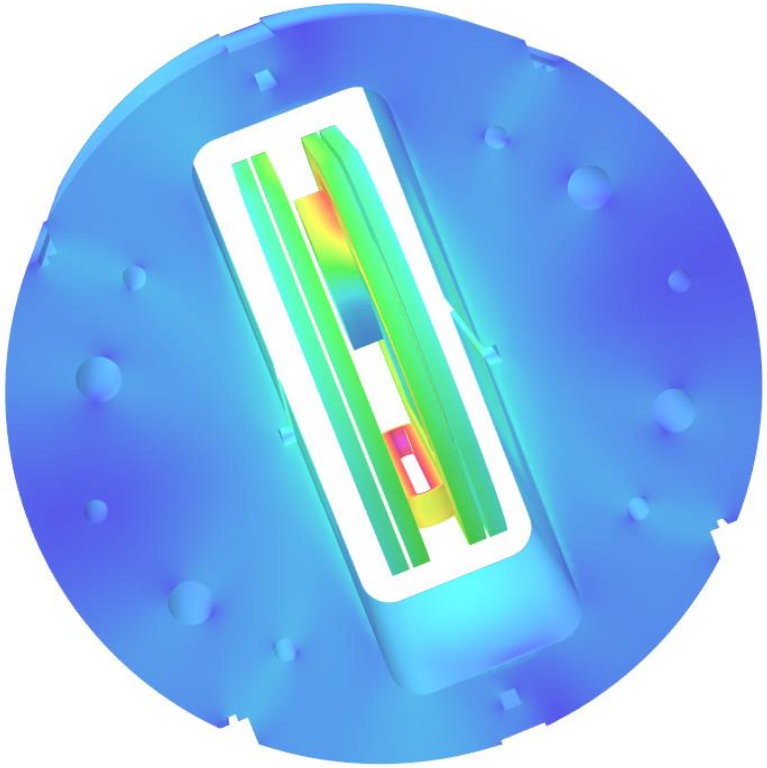
1.400000E+1
1.200000E+1
1.000000E+1
8.000000E+0
6.000000E+0
4.000000E+0
2.000000E+0
1.108155E-2

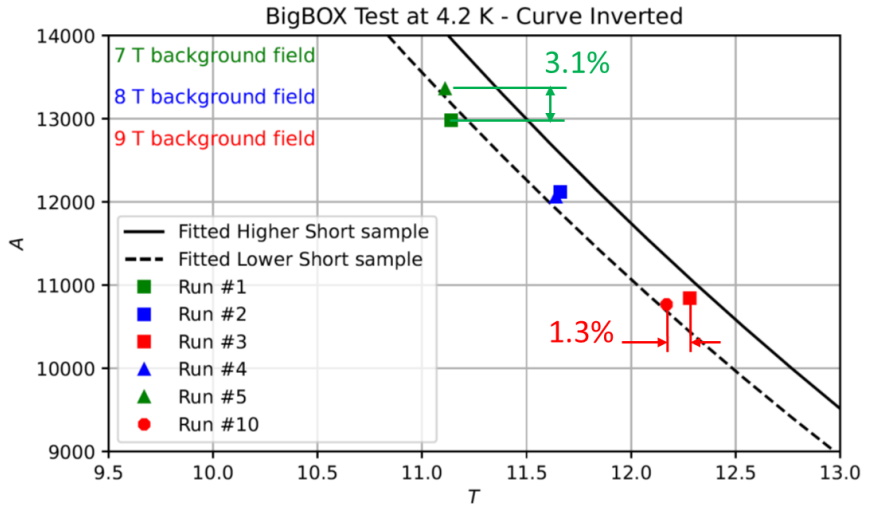


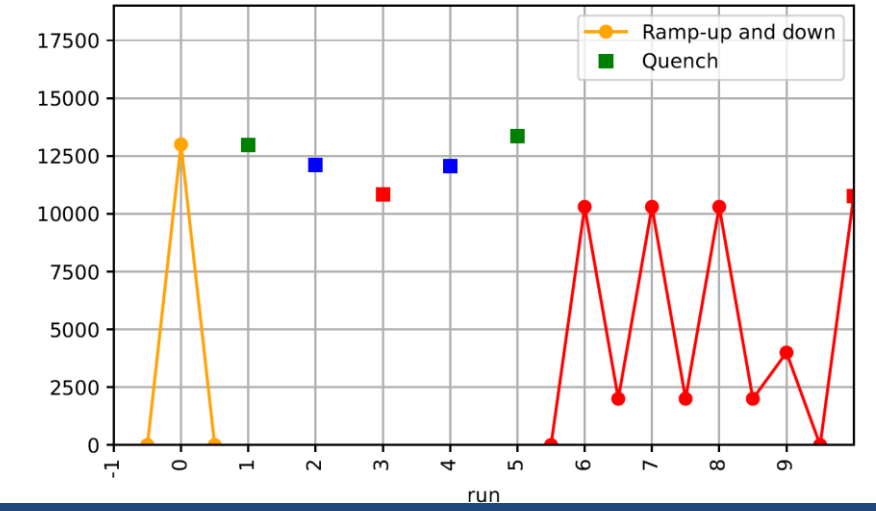
Results

- Design, manufacturing and testing of a mechanically and magnetic coupled racetrack stress-managed demonstrator with no training behavior => roadmap towards ultimate field stress-managed common coils.
- No noticeable training/degradation (limited to 11 electromagnetic cycles, 2 thermal cycles).

- Outlook
  - LTS/HTS hybrid (pole) coil testing in 2024 ?

**Plots courtesy Douglas, PSI*





* Araujo, D. M., Auchmann, B., Brem, A., Daly, M., Hug, C., Michlmayr, T., ... & Milanese, A. (2024). Assessment of Training Performance, Degradation and Robustness of Paraffin-Wax Impregnated Nb 3 Sn Demonstrator under High Magnetic Field. IEEE Transactions on Applied Superconductivity.

Upcoming milestones, R&D issues, and conductor needs

- Upcoming:
  - LTS/HTS hybrid test: STTR coil
    - "Demonstration of a high field HTS/LTS hybrid dipole" with two sets of double pancake coils made with 6+8 turns (total 28 turns) of CORC cable.
    - High field Demo (12-13 T with 9 T from LTS).
  - LTS/HTS hybrid test with double layer pancake insert
- Reviewing Conductor needs => will be updated

- R&D issues
  - Achieve higher fields
    - DCC017 was energized to 8.5-9 kA= 8-8.5 T.
      - Power circuit for Common coil outsert magnet has been upgraded => could DCC017 be energized to 10 kA= 9.44 T ?
      - Energy Extraction circuit: IGBT + external dump resistors
    - Manufacture and test new coils with higher fields + stress managed structures
  - Improve quench detection
    - Cold electronics
    - Acoustic technique, ultrasonic waveguide
    - Fiber optics (Rayleigh scattering)
  - Magnetization studies
    - Ramp rate dependence
    - Other conductors + coil configurations

Extra slides

Other coil quenches