The IBS 25 T Large Bore Magnet

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Contents

- Status of the large bore, high field HTS solenoid for IBS (focus will be on the test results)
  - Summary of the basic design and design choices
  - 77 K test results (10 coils tested, 14 wound, 28 needed)
  - 4 K test results (many quenches and a variety of tests)
- PBL/BNL SBIR on an innovative design of 25 T HTS solenoid for neutron scattering (one slide)
- BNL at USMDP (two slides)

CAPP/IBS Axion Target Plan

Axion dark matter is partially converted to a very weak flickering Electric (E) field in the presence of a strong magnetic field (B)

Scanning Rate:

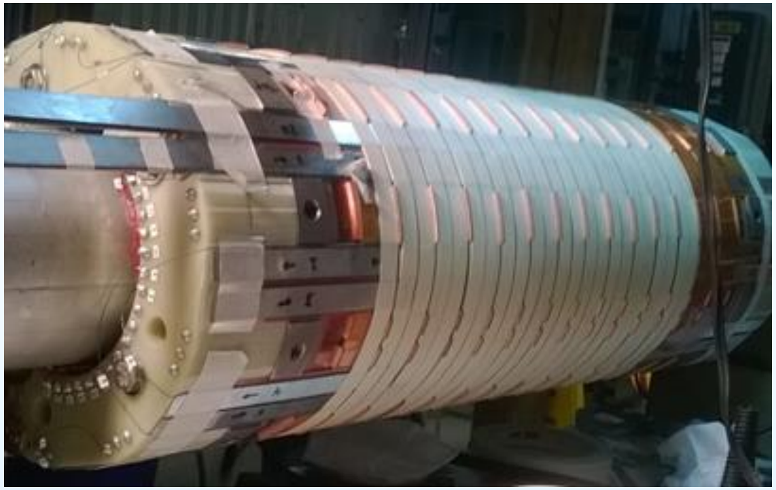
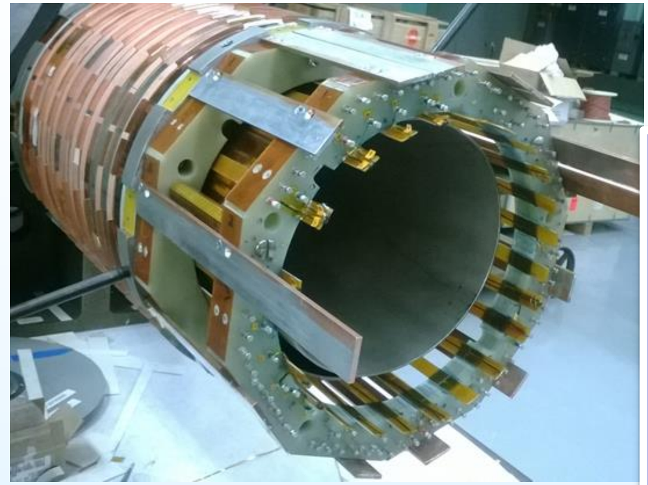
$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \mathrm{GHz}}{year}\left(g_{a\gamma\gamma}10^{15}\,\mathrm{GeV}\right)^4 \left(\frac{5\ \mathrm{GHz}}{f}\right)^2 \left(\frac{4}{SNR}\right)^2 \left(\frac{0.25\ \mathrm{K}}{T}\right)^2$$

$$\times \left(\frac{B}{25T}\right)^4 \left(\frac{c}{0.6}\right)^2 \left(\frac{V}{5l}\right)^2 \left(\frac{Q}{10^5}\right)$$

High field, large volume : key to targeted breakthrough

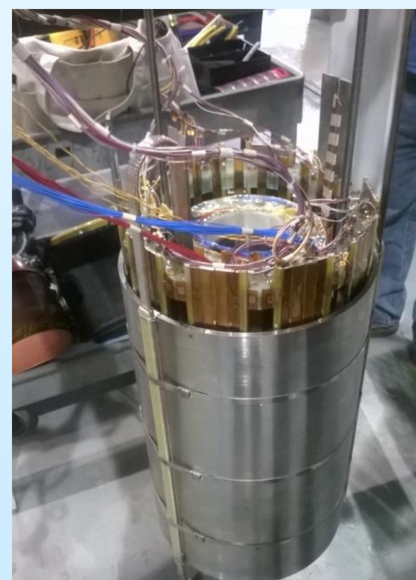
- High field solenoid magnets: B (B^4)
- High volume magnets/cavities: V (V^2)

Starting Point of the Design SMES: 25 T, 100 mm

Reached Expected 12.5 T at 27 K (record for SMES)

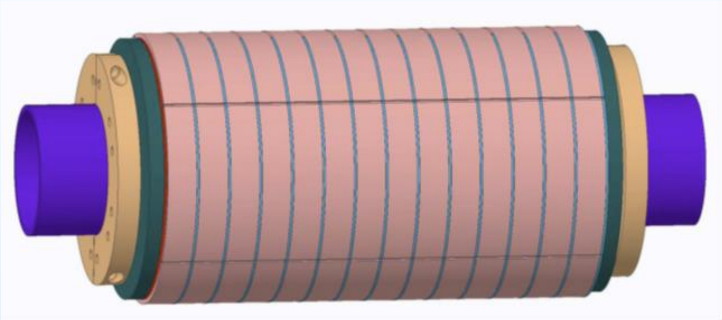




Design Requirements of IBS Solenoid

- High Field : 25 T (must use HTS; it's all HTS)
- Large Volume: 100 mm bore, +/-100 mm long

Stresses: J X B X R

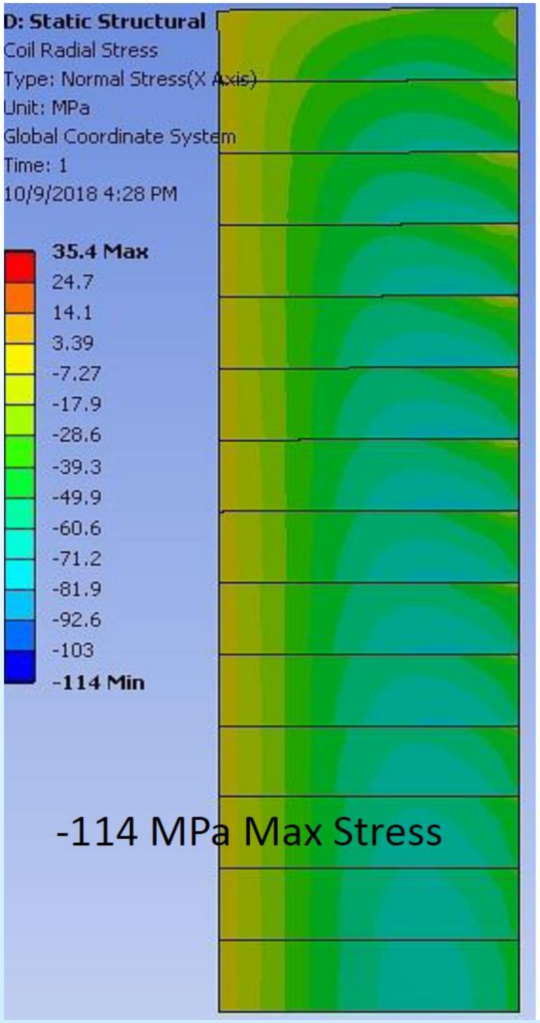


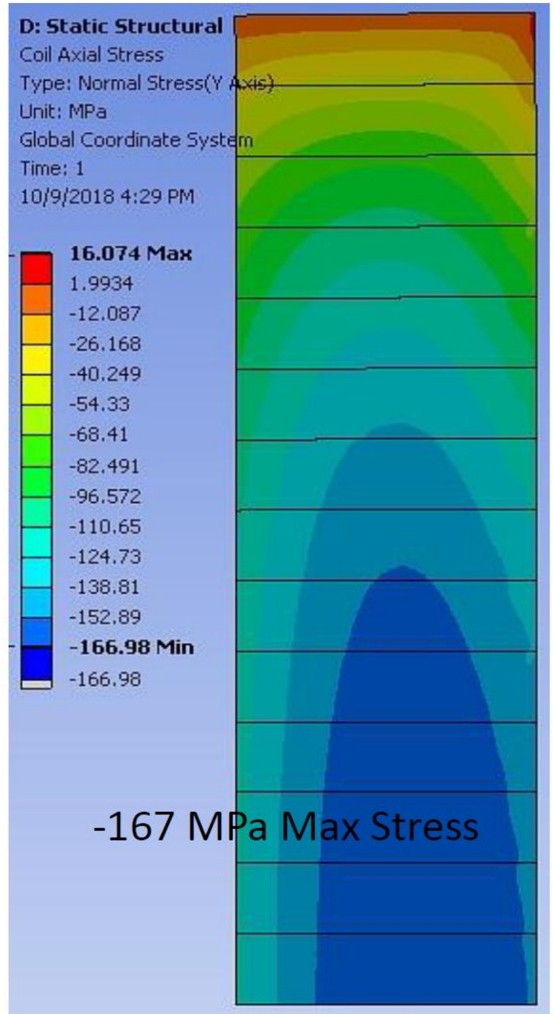
- Field quality: ~10%
- Ramp-up time: up to 1 day

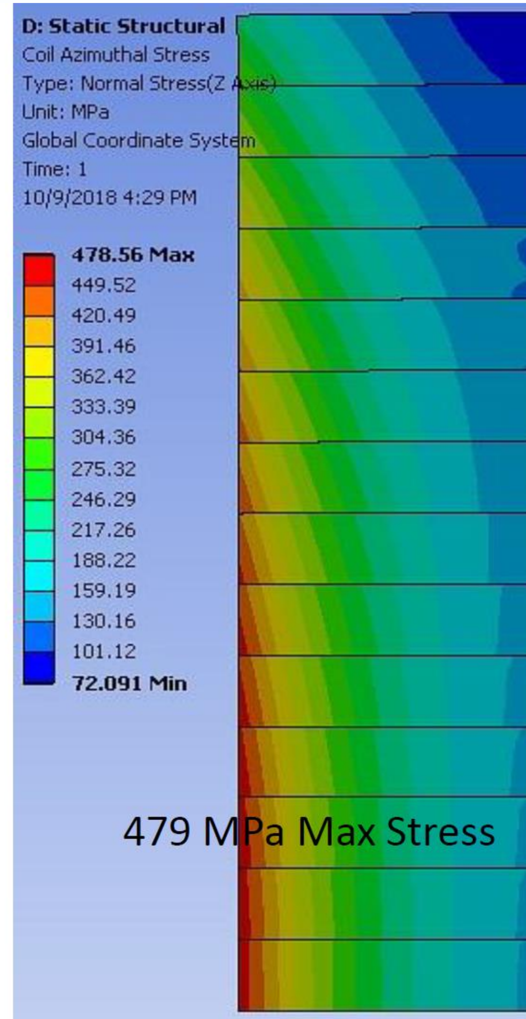
Relaxed field quality and slow charging

Relaxed field quality and slow ramp rate allows the use of *No-Insulation* windings to (a) tolerate defect in HTS tapes, and (b) expected to offer a more reliable quench protection

Orthogonal Coil Stresses (@4 K, 25 T)







~480 MPa Max Stress

-114 MPa Max Stress

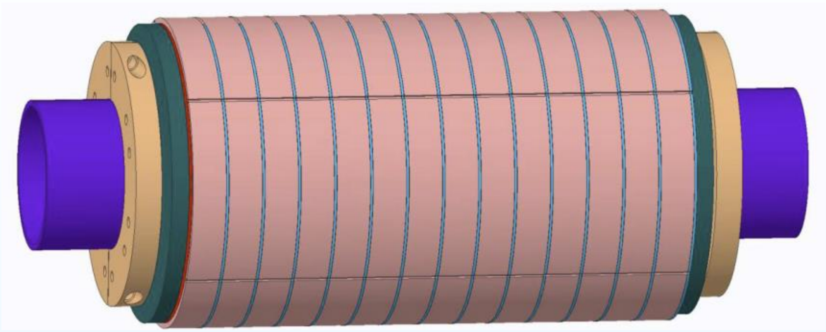
Radial +

-170 MPa Max Stress

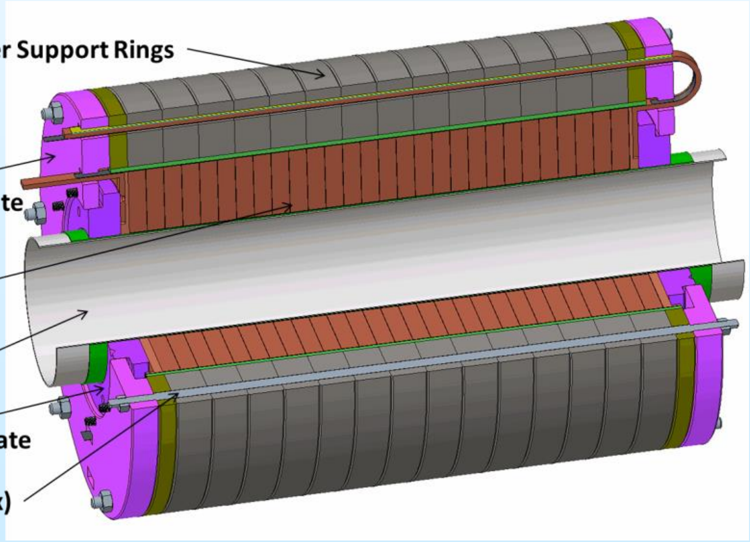
Axial +

Azimuthal

IBS HTS Solenoid Design Summary



- Design Field: 25 T
- Operating Temperature: ~4 K
- Cold Bore: 100 mm
- Coil i.d.: ~105 mm
- Coil o.d.: ~200 mm
- Single Layer
- Conductor: 12 mm wide ReBCO (50 μm Hastelloy, 20 μm Cu)
- Conductor per Pancake: ~300 m
- Number of Pancakes: 28
- Current: ~450 A
- Coil Current Density: ~500 A/mm^2
- Stored Energy: ~1.3 MJ
- Inductance: ~13 Henry
- Maximum Hoop Stress: ~480 MPa
- Maximum Axial Stress: ~180 MPa
- Outer Support Ring: High Strength Aluminum Rings



Conductor Requirements and Status

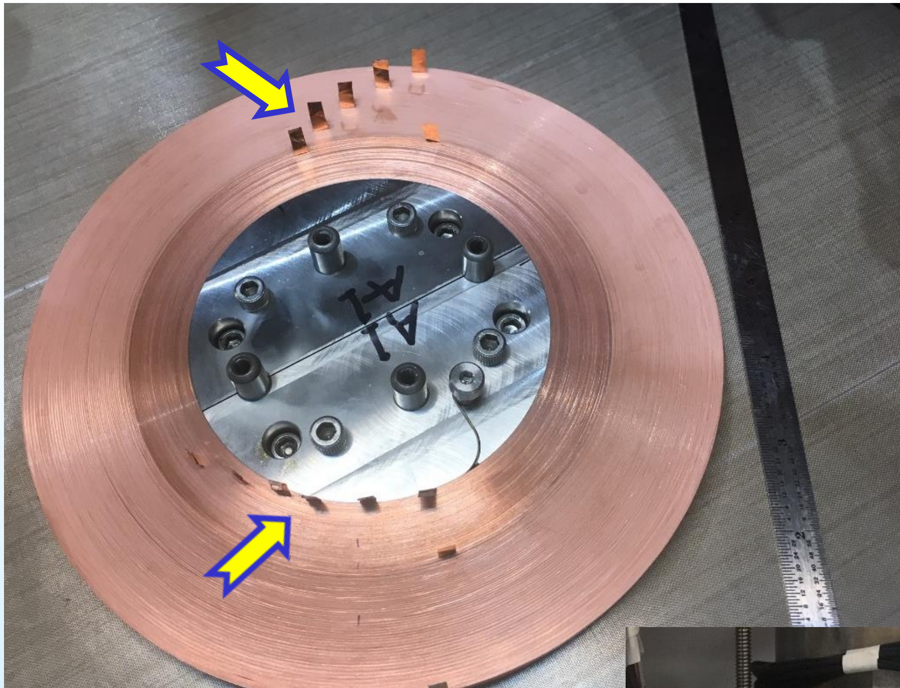
- I_c(8T,4K) >675A (50% margin)
  - 50 micron Hastelloy, 20 micron Copper
  - Design and conductor specs are governed by the mechanical properties (50% margin) and not by the electrical properties

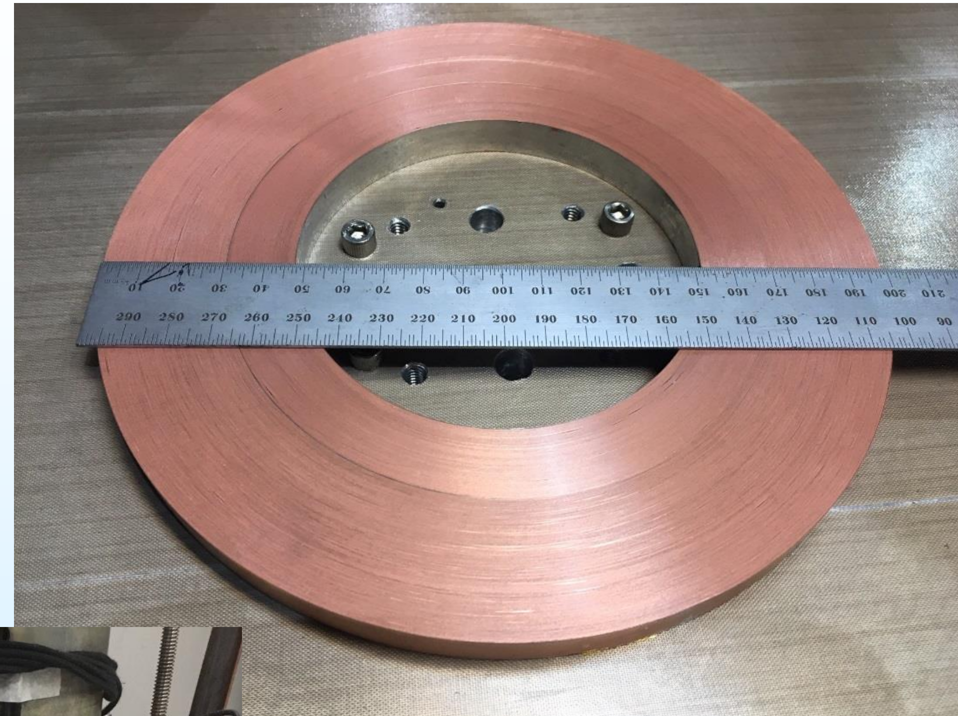
- Need a significant quantity of 2G HTS (ReBCO) tape
  - 9 km, 12 mm wide

- SuperPower has delivered 5 km of 12 mm wide tape (easily exceeding I_c margin)

Coil Construction and Test Results

IBS Coil - Well Instrumented
(two single pancakes spliced to a double pancake)





Major parameters:

- i.d. : 105 mm
- o.d. : 200 mm
- Turns: ~1250 (DP)
- 600 meters of tape (12 mm wide)

A large number of v-taps are key to our detailed investigations during the test and how the performance of the conductor within the coil changes after certain event and to decide if more measurements needed then

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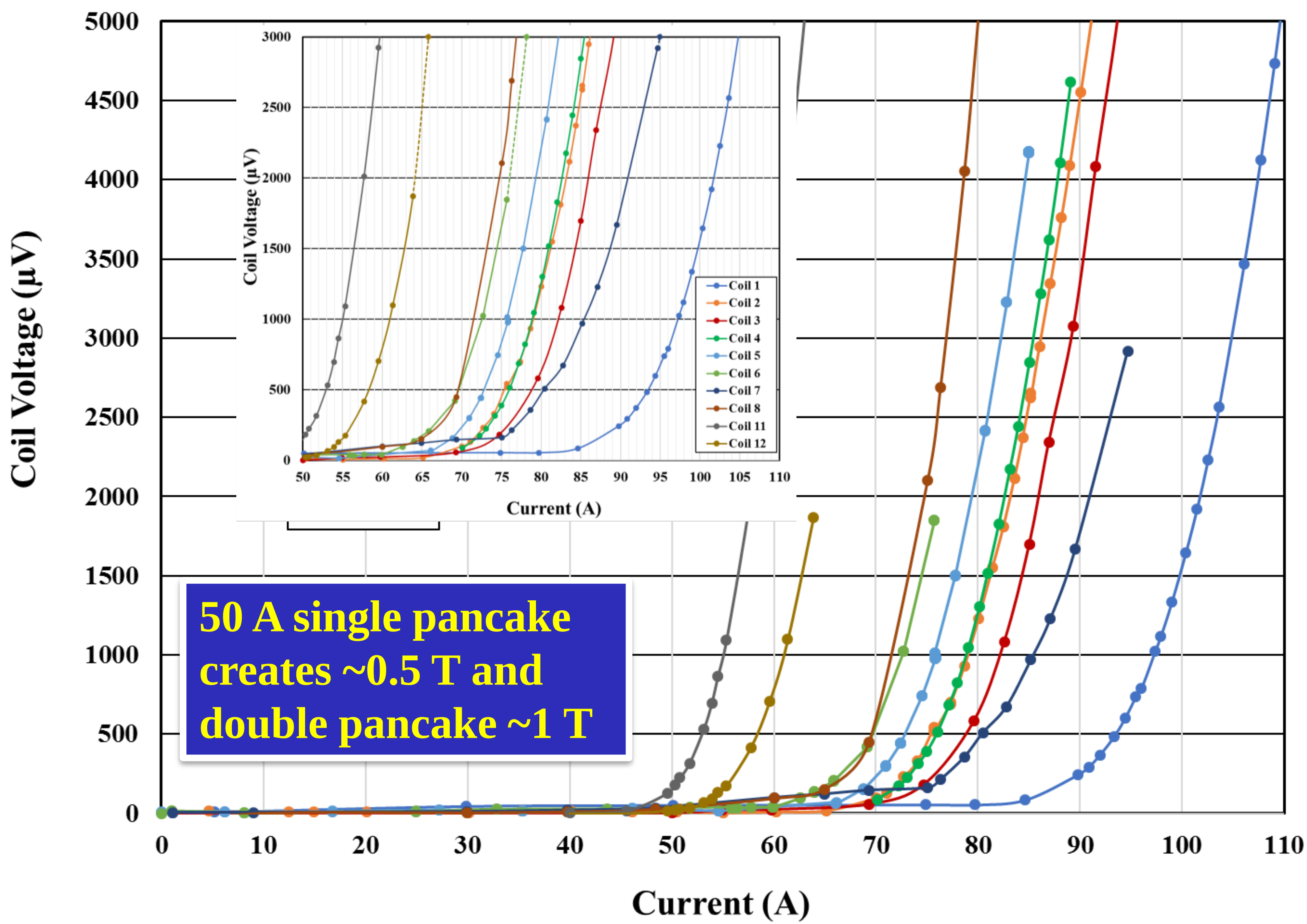
77 K (LN2) Test of 10 Pancake coils

(1-4 tested as single pancakes and the rest double)



A significant variation between coil to coil

@3mV (0.1 µV/cm)

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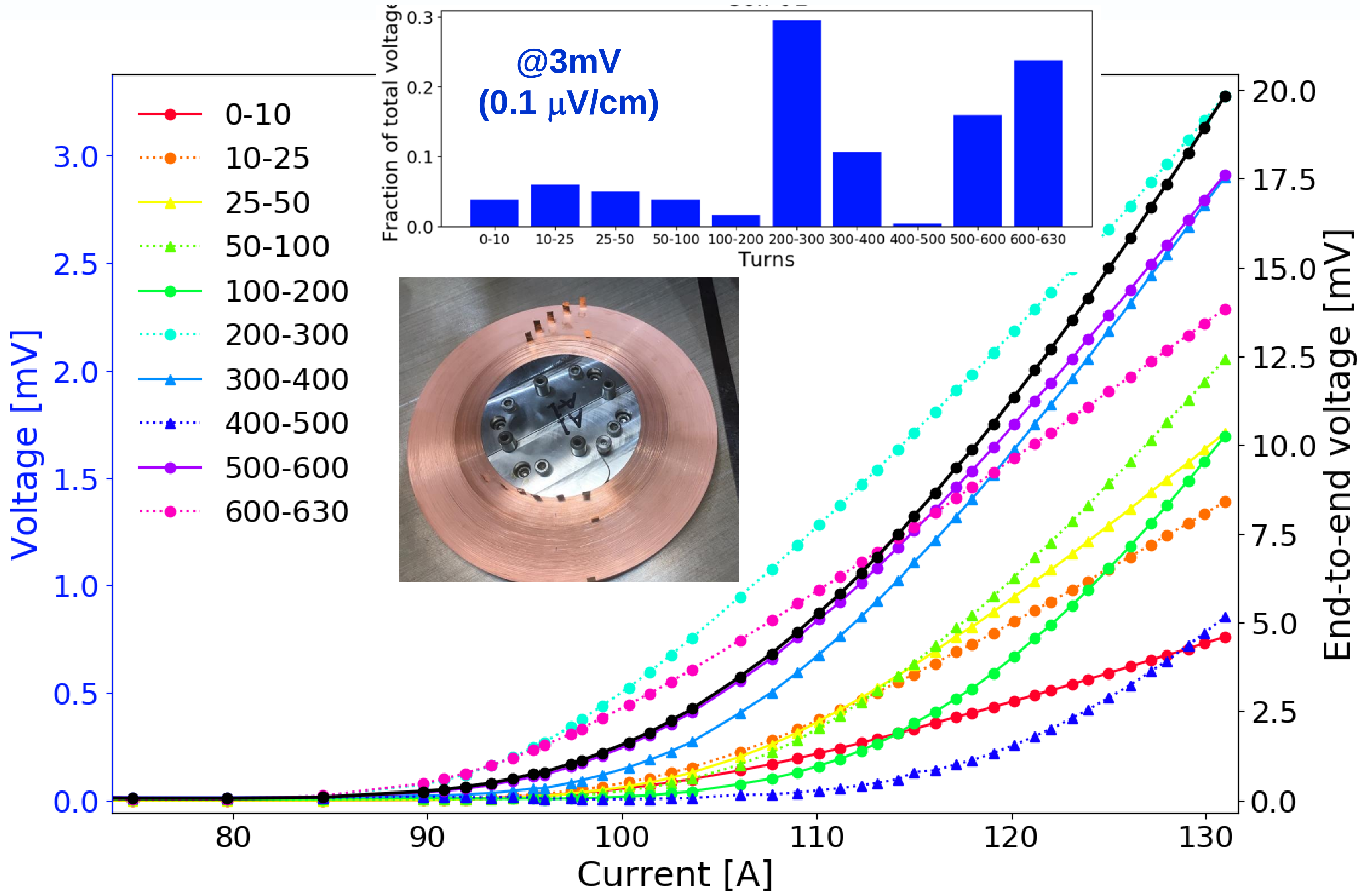
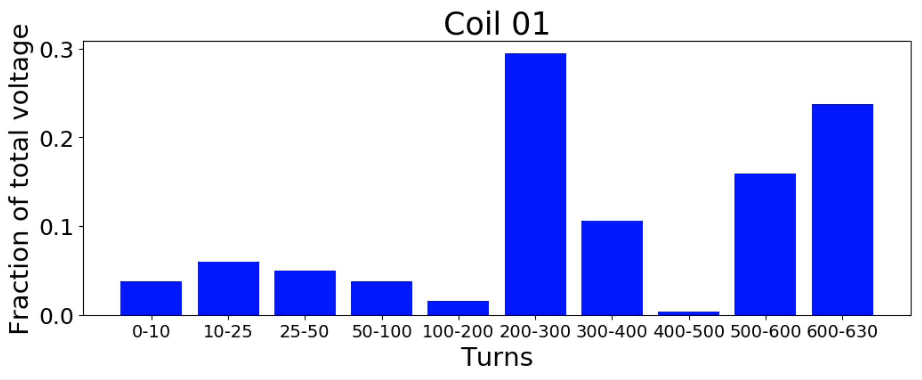
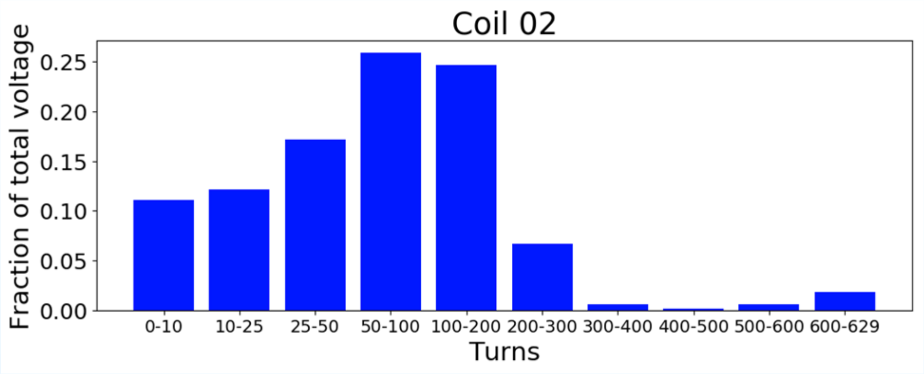
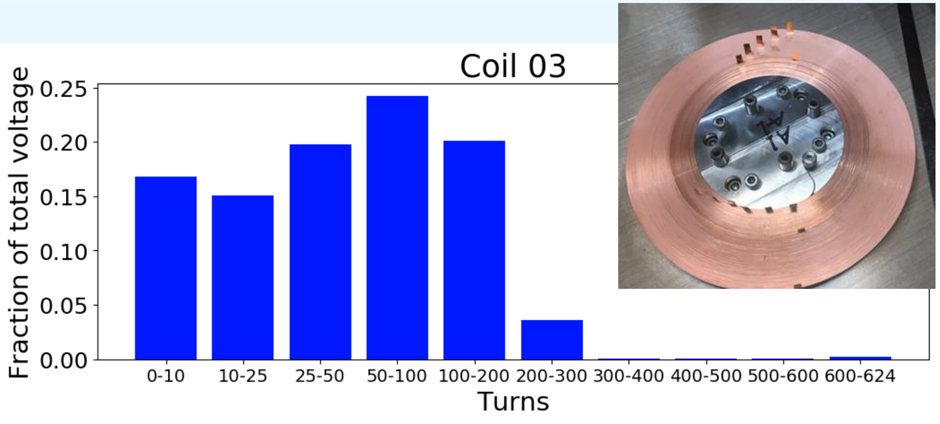
Details of the 77 K Test Results (Sectional Voltage in Coil #1)

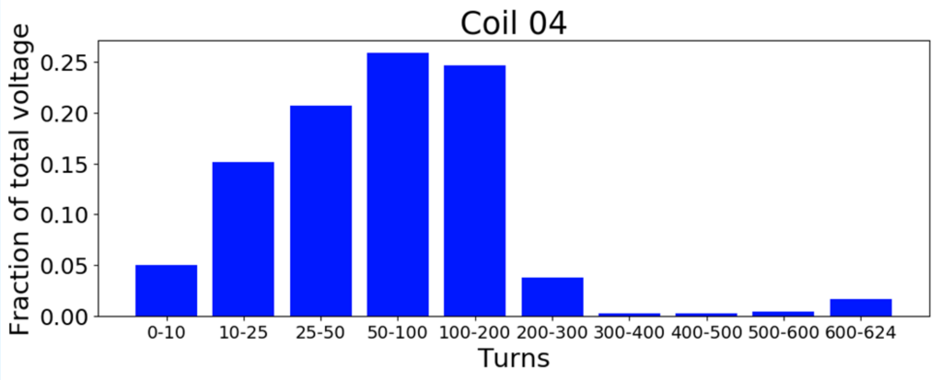


Distribution of Voltage @77K within the Pancake Coils #1 to Coil #4









Note: A significant coil to coil variation

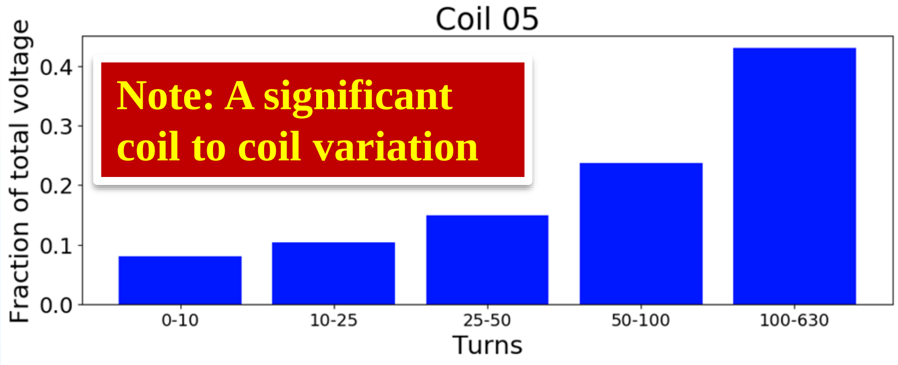
@3mV (0.1 μV/cm)

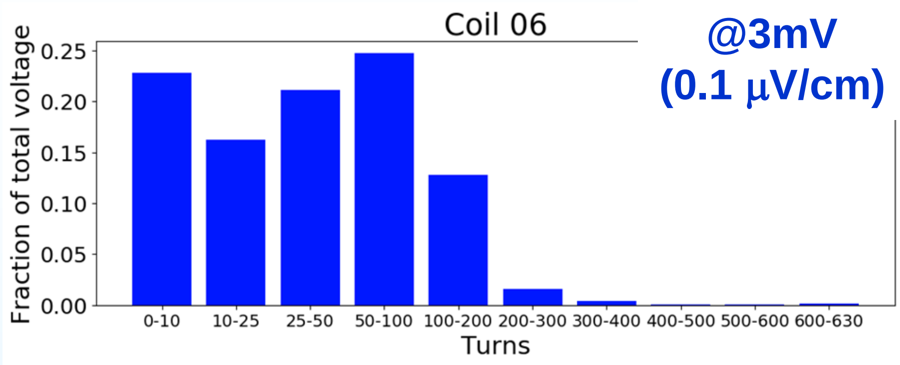
Measurements in single pancake test configuration

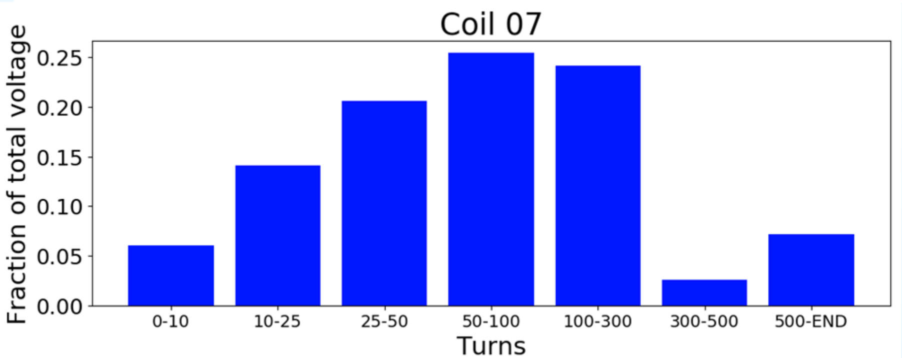
Distribution of Voltage @77K within the Six Other Pancake Coils

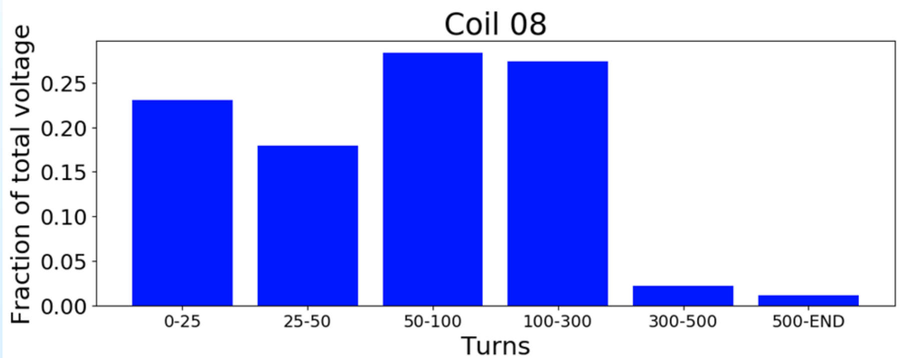
Note: A significant coil to coil variation

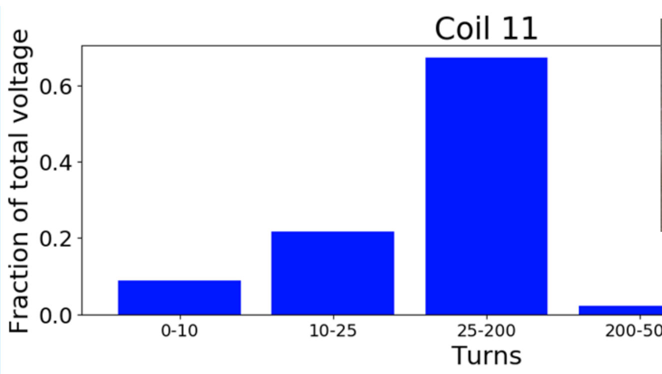
@3mV (0.1 μV/cm)

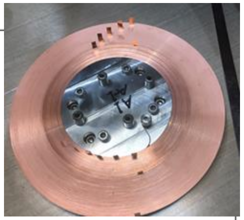


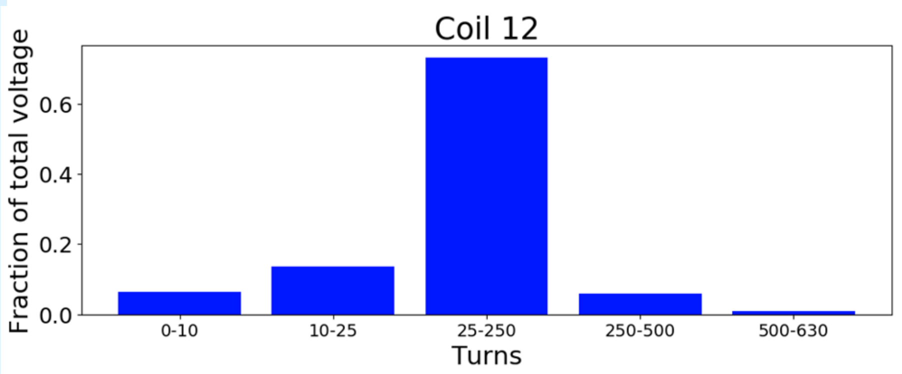






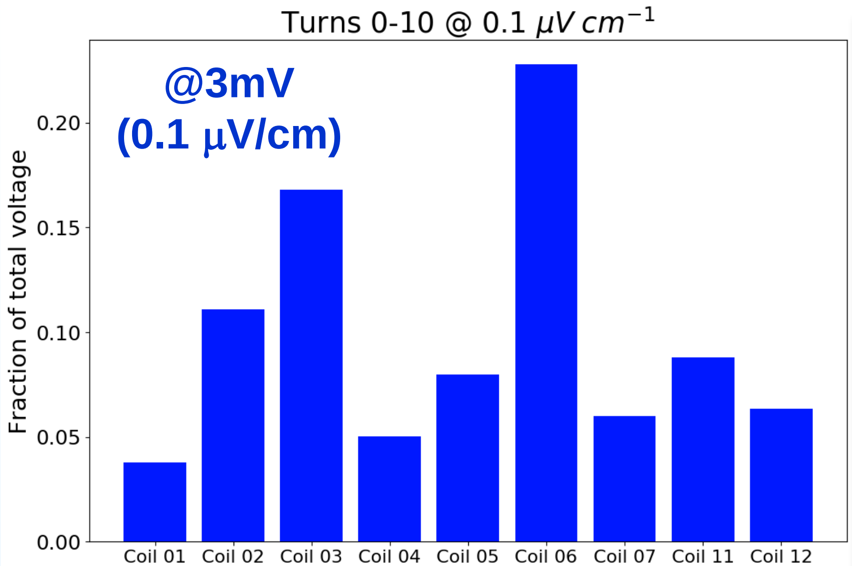


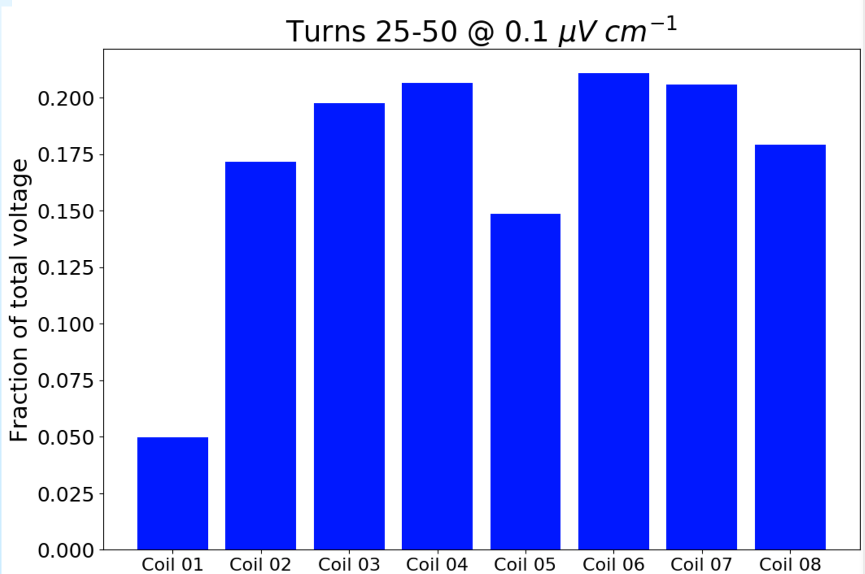




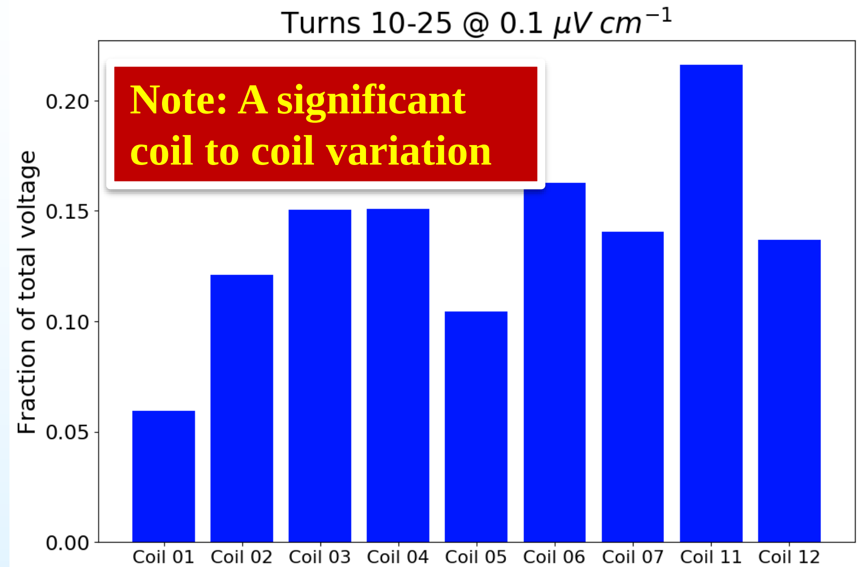
Measurements in double pancake test configuration

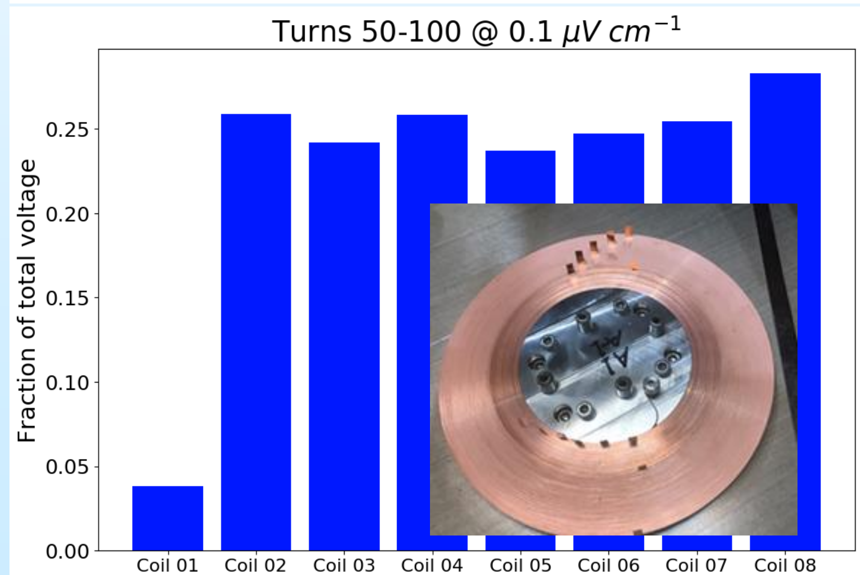
Variation in the Voltage @77K within a set of turns of different Coils



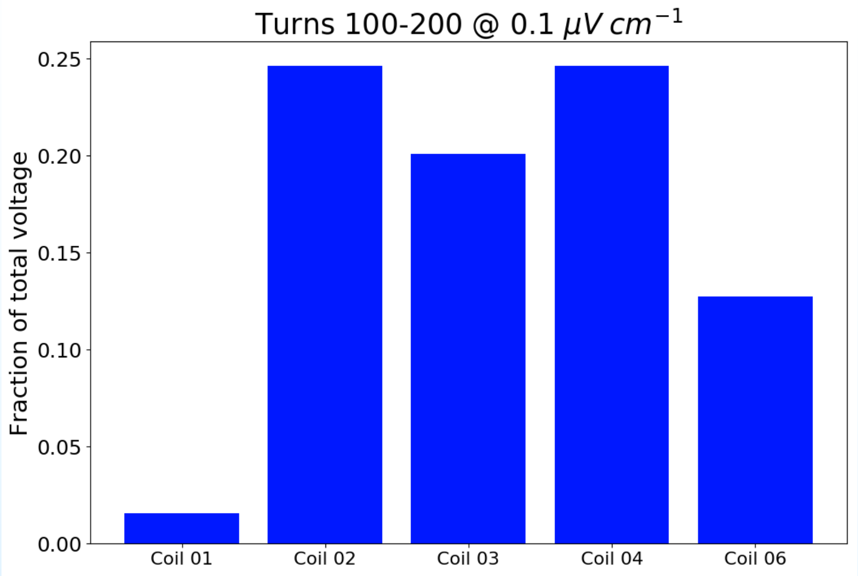


Turns: 0-10, 10-25, 25-50 & 50-100

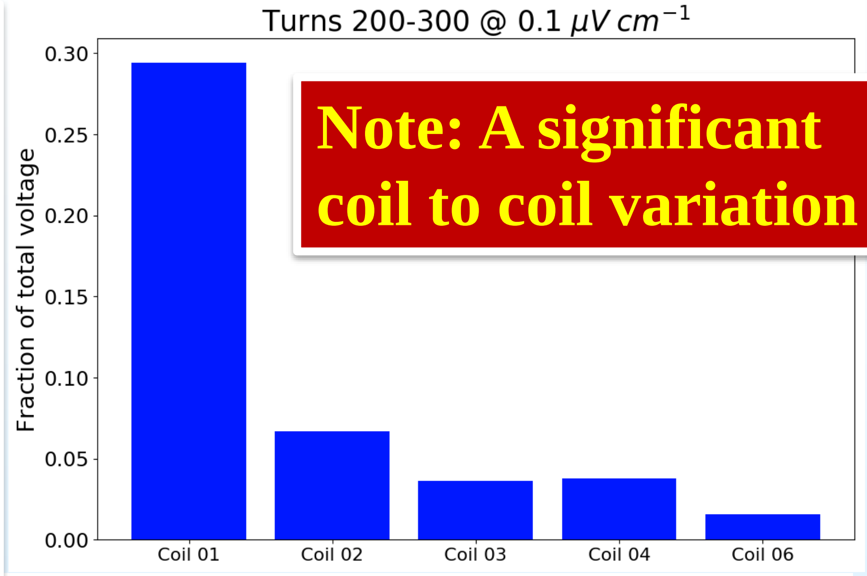




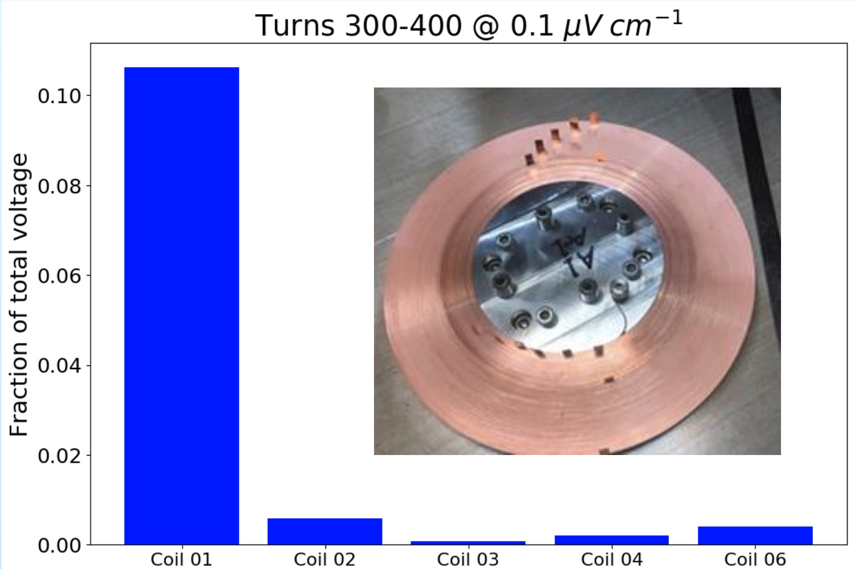
Variation in the Voltage @77K within a set of turns of different Coils

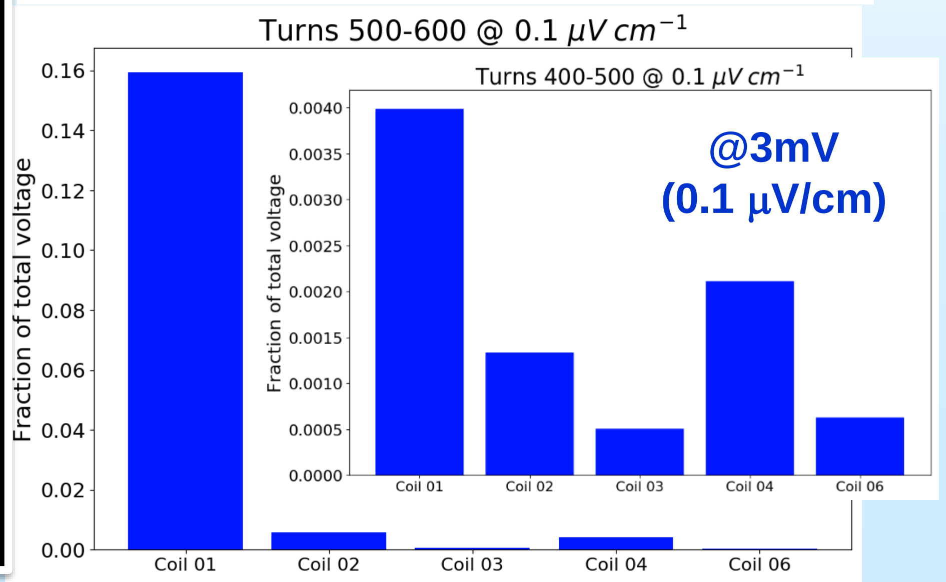


Turns: 100-200, 200-300, 300-400, 400-500 & 500-600

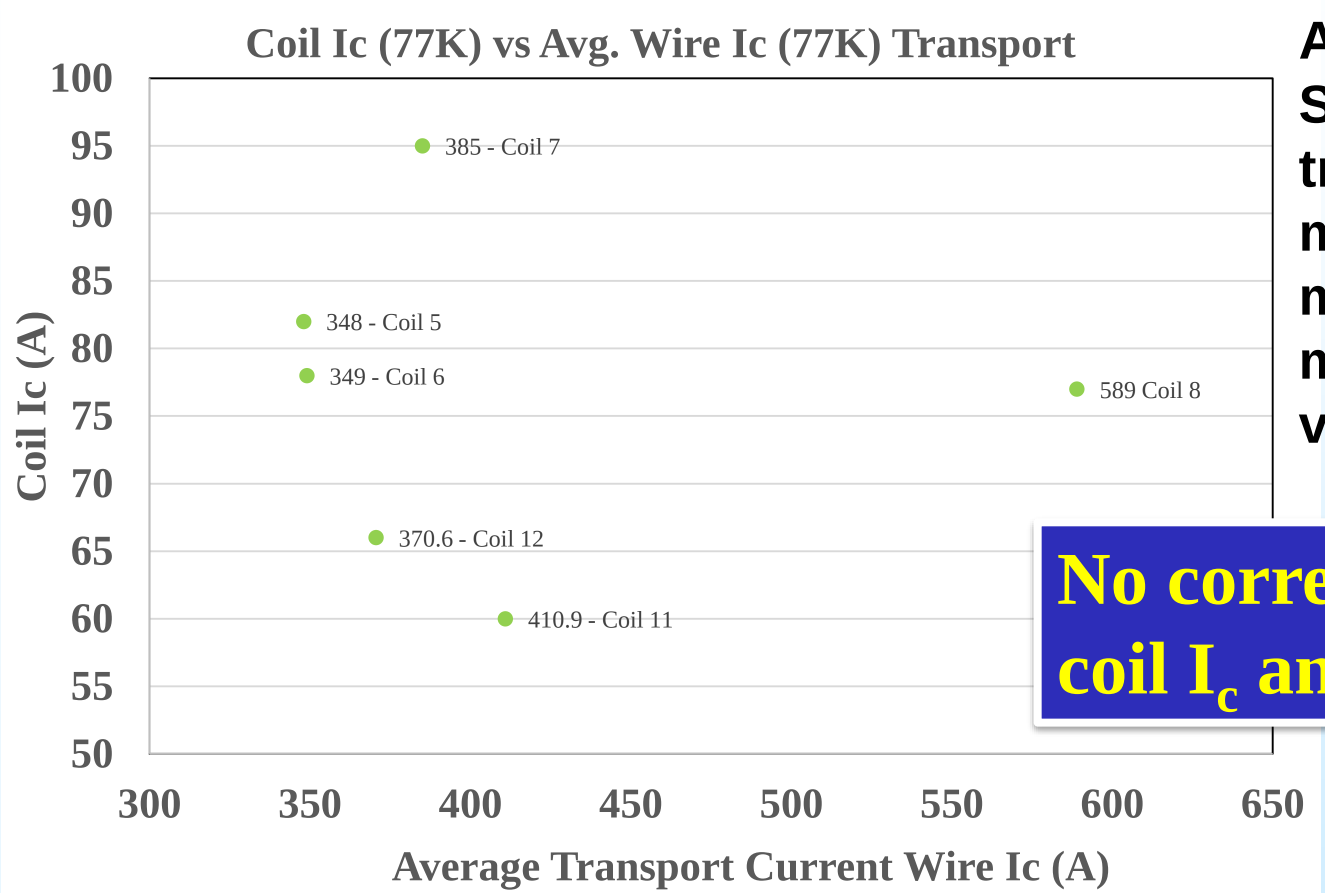


Note: A significant coil to coil variation





Correlation between Coil I_c (@77K) and Wire I_c (77K, self-field, average current)



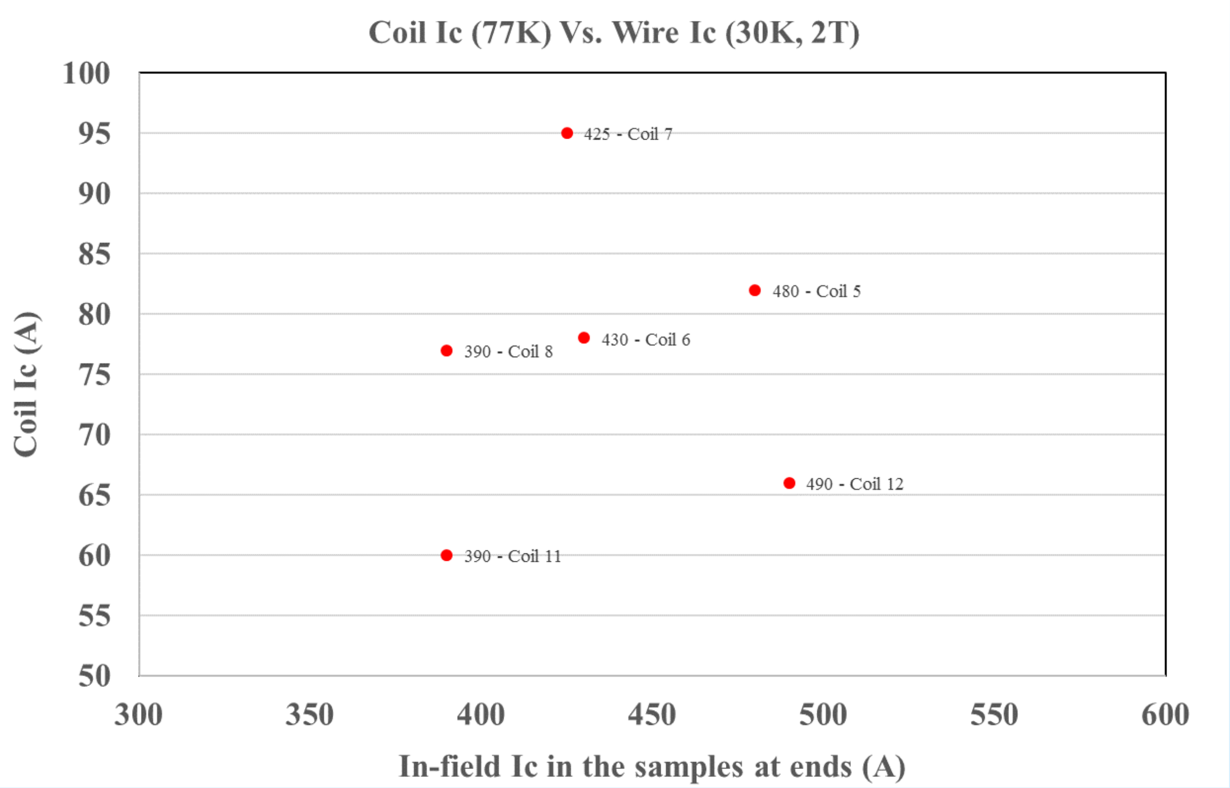
As a part of contract, SuperPower provided transport current measurements to meet certain spec on minimum and variation.

No correlation between coil I_c and conductor I_c

BNL suspected a poor correlation and, therefore, put a loose spec on self-field wire I_c for QA purpose only.

Correlation between Coil I_c (@77K) and Wire I_c (77K, self-field, average current)

- As a part of contract, SuperPower also measured and provided Ic (30K, 2T) measurements from the samples cut at two ends.
- That has a good correlation with Ic(high field 4K).
- However, often a significant variation was found between the two ends.



Poor correlation between coil I_c (77, self-field) and conductor I_c (30K, 2T) from two ends

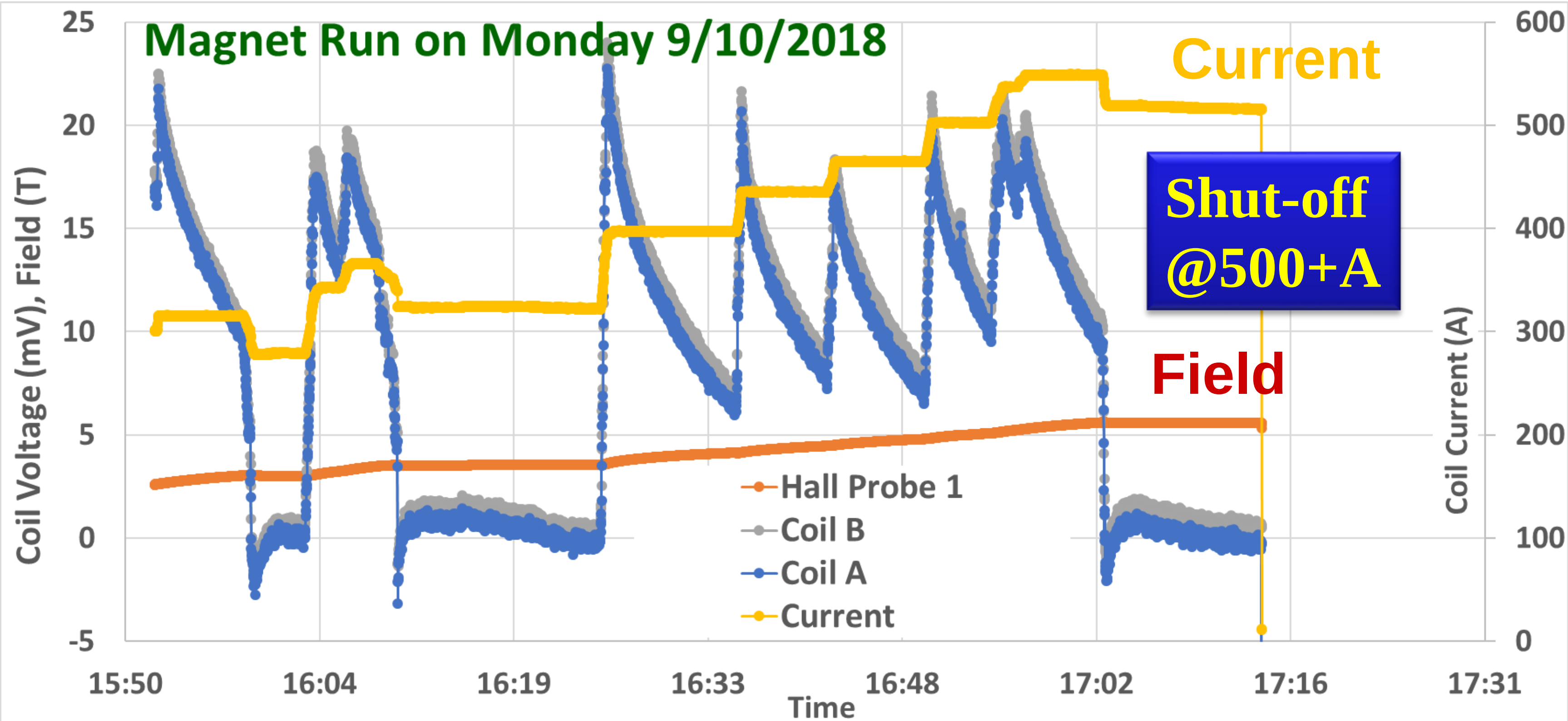
IBS Double Pancake Coil Runs with Helium

- Two set of runs of R&D coils (including defect simulation with heaters) were carried out in 2017 (not presented here)

- Two test runs of the IBS double pancake "*production coil*" were carried out with Helium from 9/10 to 9/14 & from 10/16 to 10/18. First test run was extensive and presented here:
  - Many test runs over the design current of 450 Amps
  - Several test runs at the stress level of 25 T solenoid
  - A large number of shut-off at various currents
  - Many high current quenches or runaways
  - Sudden over-current tests
  - Helium runout tests

Attempt to create different fault scenarios

Monday Run Summary

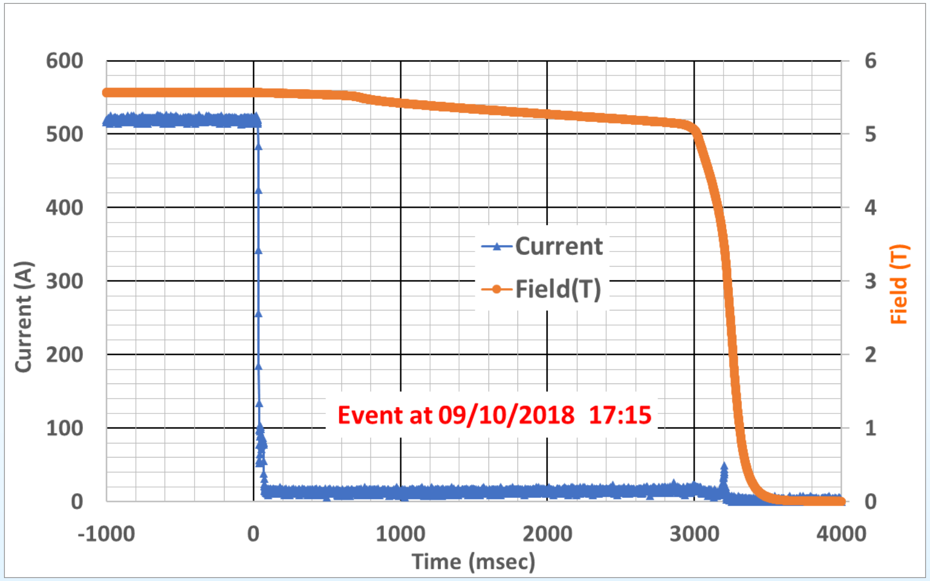


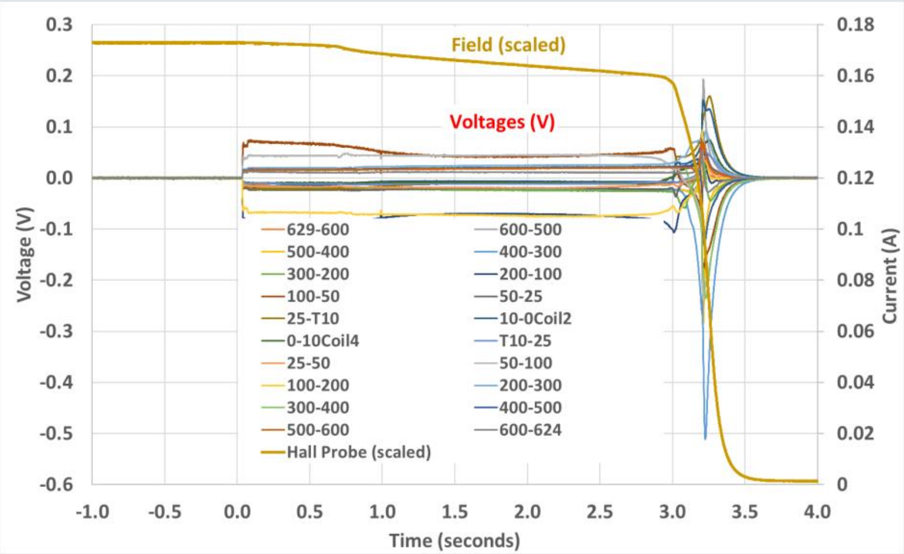
Shut-off may cause an eventual thermal runaway (quench)

- **As a part of the study a large number of shut-off (over 30) performed. This gives an early indication, depending on whether coil runs away or not, on how close we are to the limit (more discussion in the next slide)**

  - **Do these shot-offs create excessive shielding currents?**

Discussion on Shut-off @550 Amp
(a large number of shut off tests at different currents)

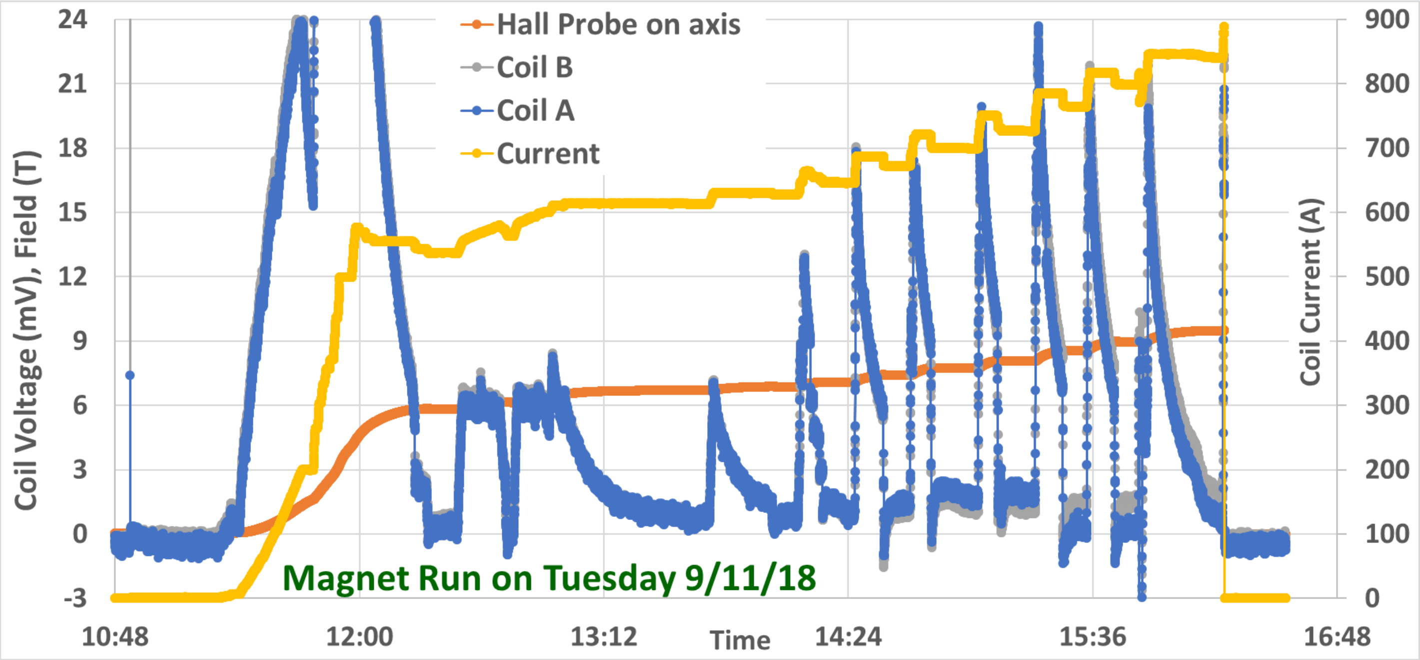




- In No-insulation coils, in addition to the circulating current, the current may flow across the turns (sideways), providing an extra protection
- These sideways current keep flowing even after the power supply shut-off and decay slowly in No insulation coils
- These sideways current heat-up the coil and depending on the contact resistance and on how close one is to the critical surface, may or may not quench the coil (thermal runaway)
  - In our case, we found that it runs away at 450 Amps or more
  - At high currents it runs away within a few hundred milli-seconds
  - At 550 A, it took about 3 seconds
  - During this period resistive voltage kept increasing the temperature

Tuesday Run Summary

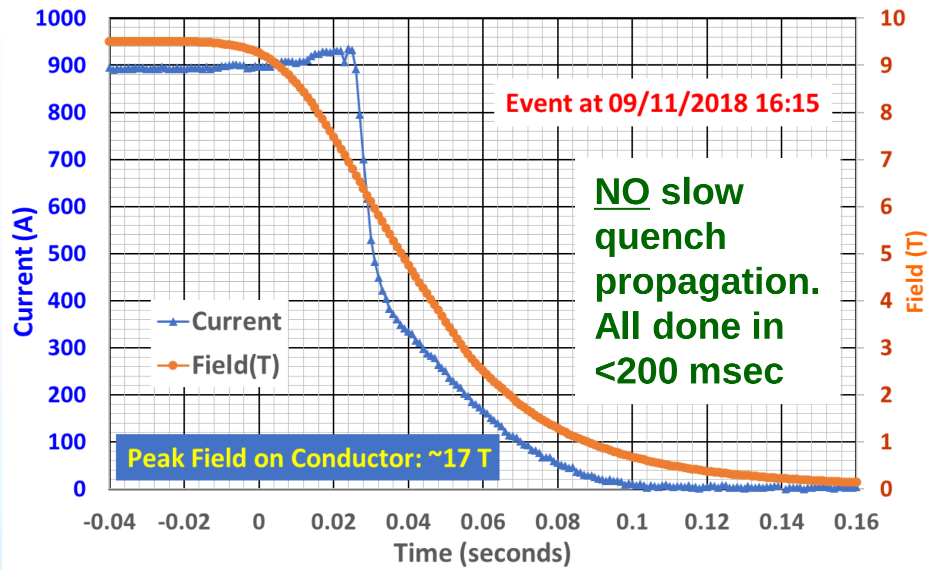
- Keep increasing current to see how high it could go (as in LTS)
- Quenched in going from 850 A to 900 A (design: ~450 A)
- Bore field ~9 T, Peak field ~17 T (high peak stresses: B x I)

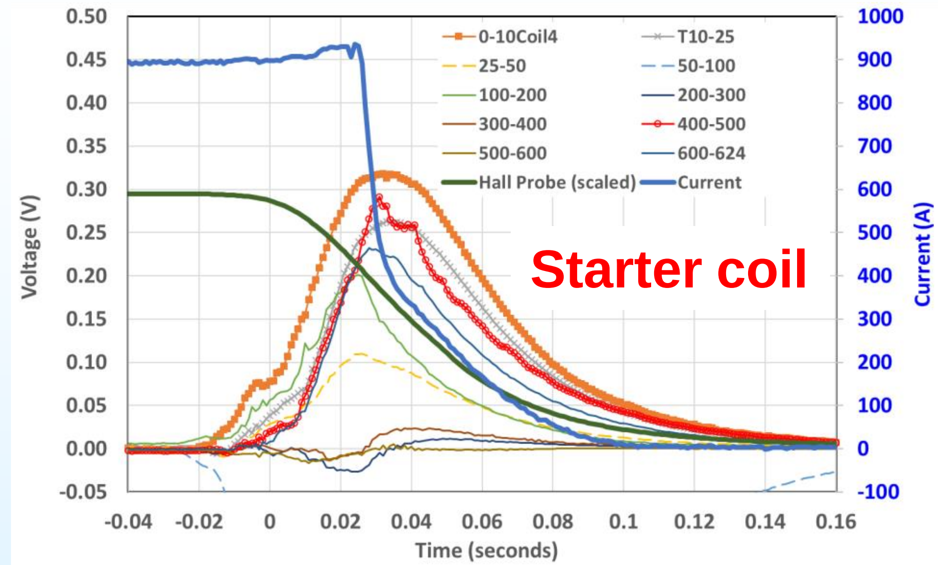


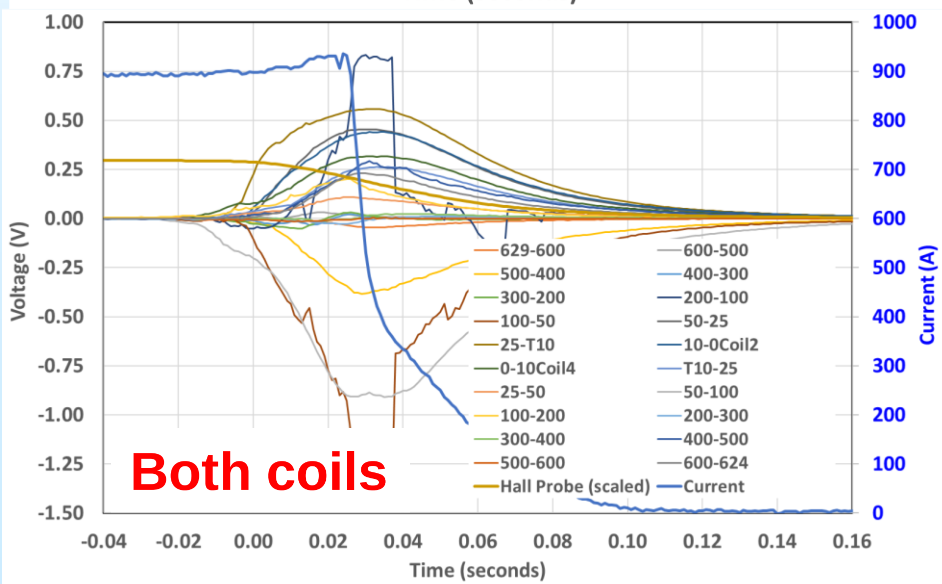
850 Amp in a double pancake, creates similar peak stresses and similar stored energy per pancake as in the 25T IBS solenoid

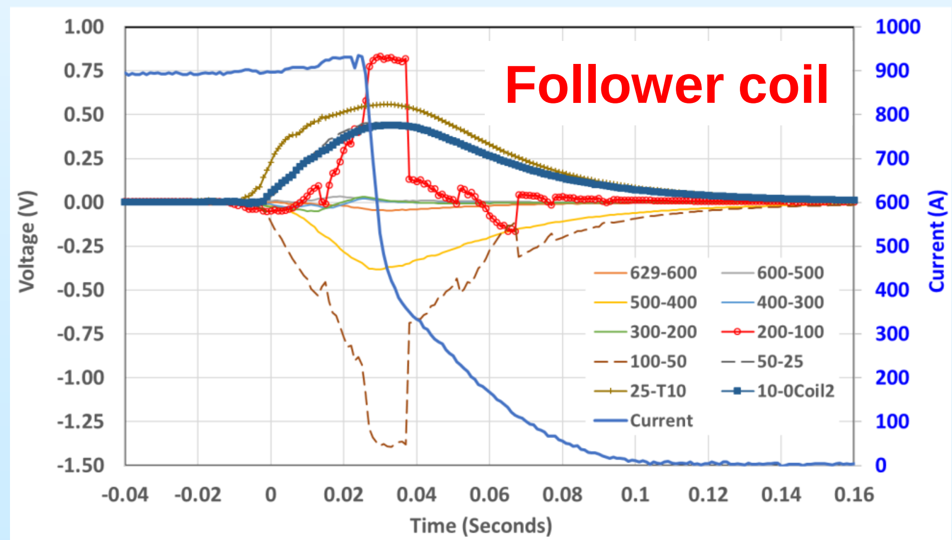
➢ **Quench discussed in more details in the next slide**

Discussion on Quench at High Current (Tuesday 9/11/2018)

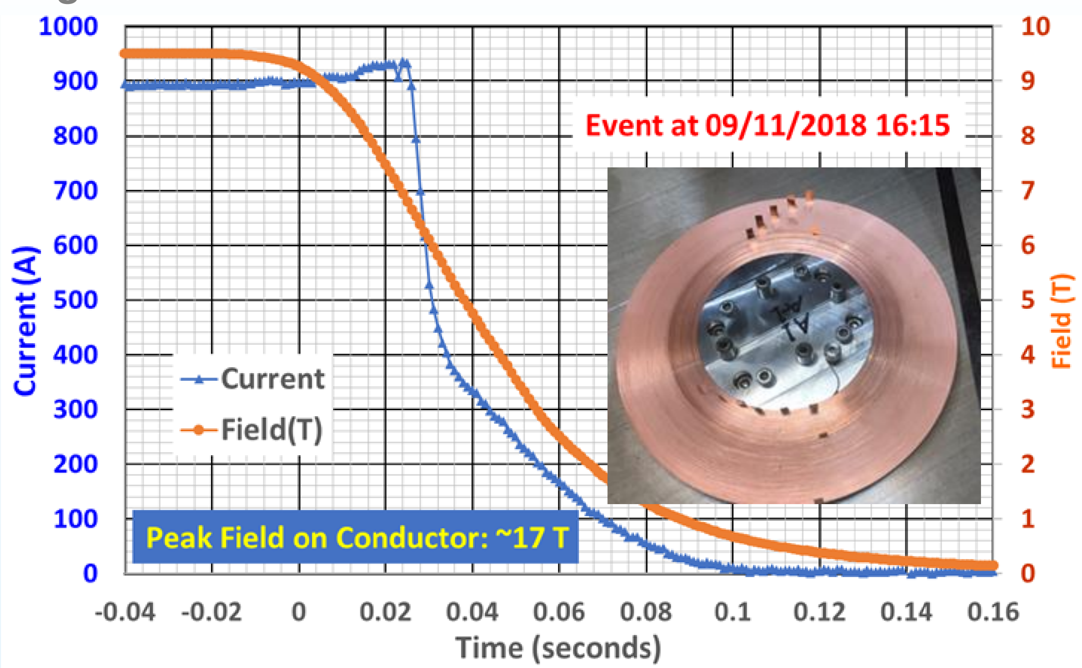


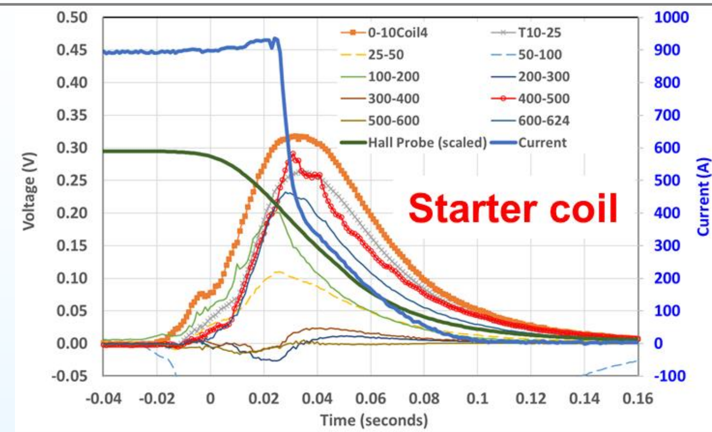


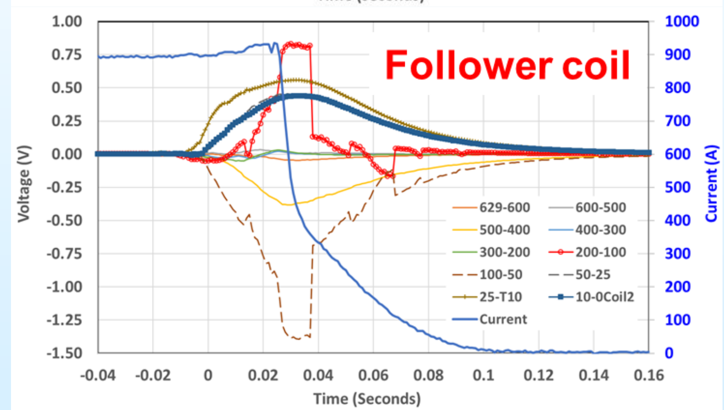




Quench Scenario in Large No-Insulation Coil (fast 4K propagation within coil and coil-to-coil)



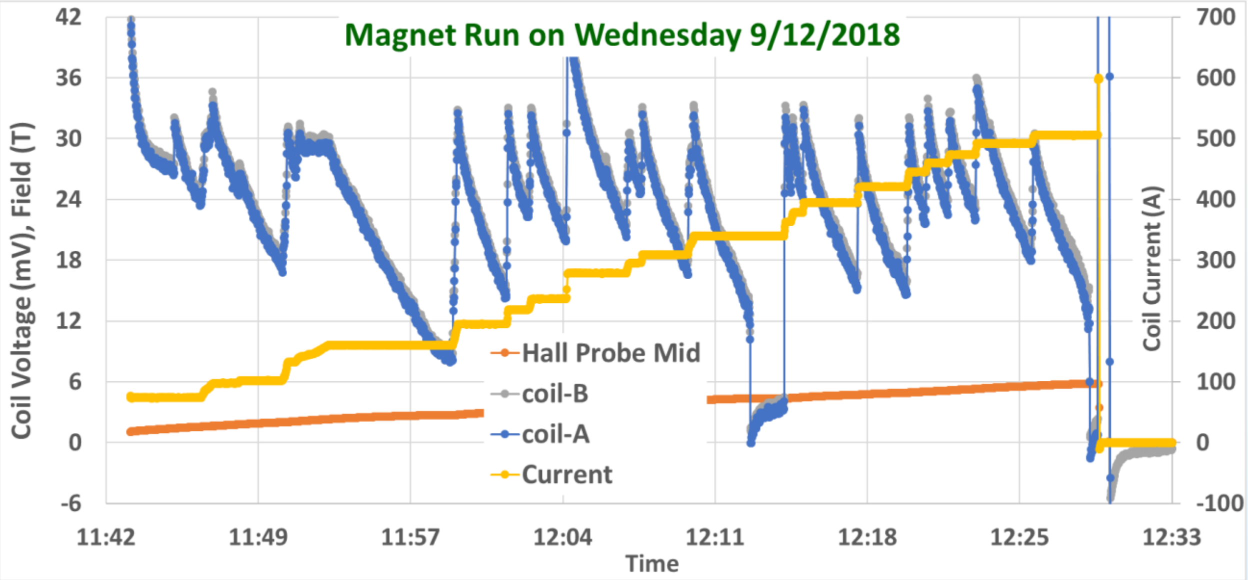


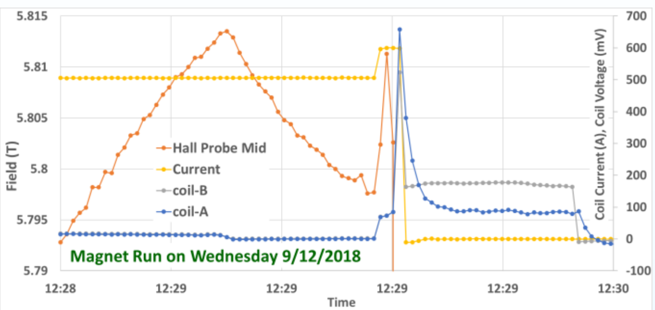


Large No-Insulation HTS coil became normal in <200 msec (even faster than in many LTS magnets)

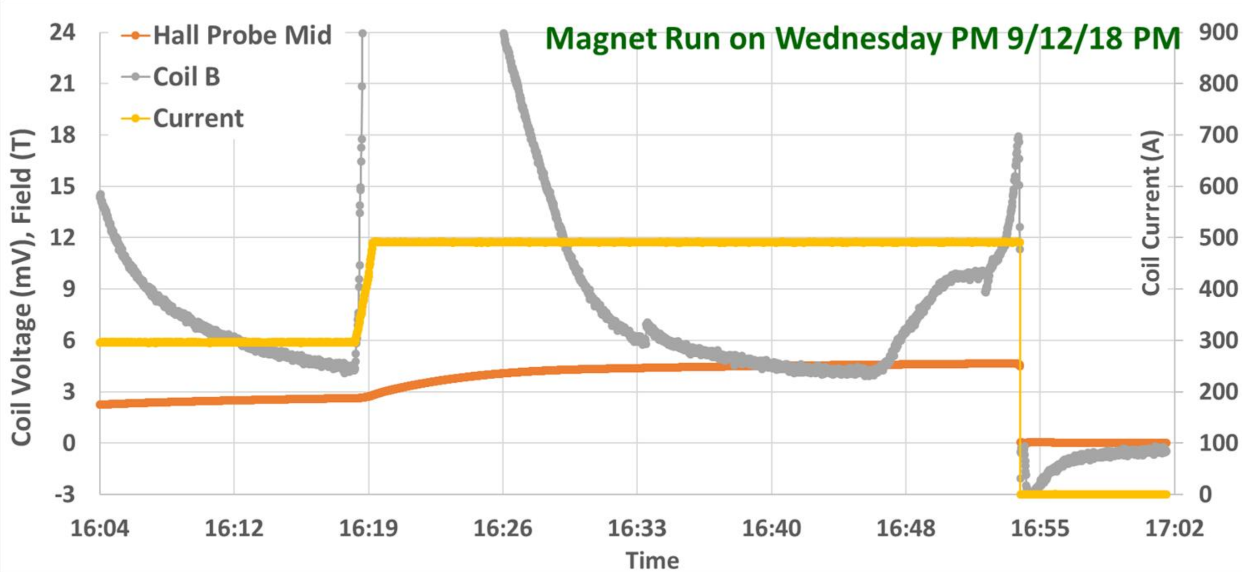
- Large number of voltage-taps gives a detailed insight of what is happening
- Within a pancake: fast propagation due to resistive heating through contact resistance between turns when the current flows across (not around) in a “No-insulation” coil
- Pancake to pancake: fast propagation due to inductive coupling of the drop in local field
- The mechanism seems scalable to long solenoids made with many pancake coils

Wednesday Run Summary
(unusual events – not expected during normal operation)

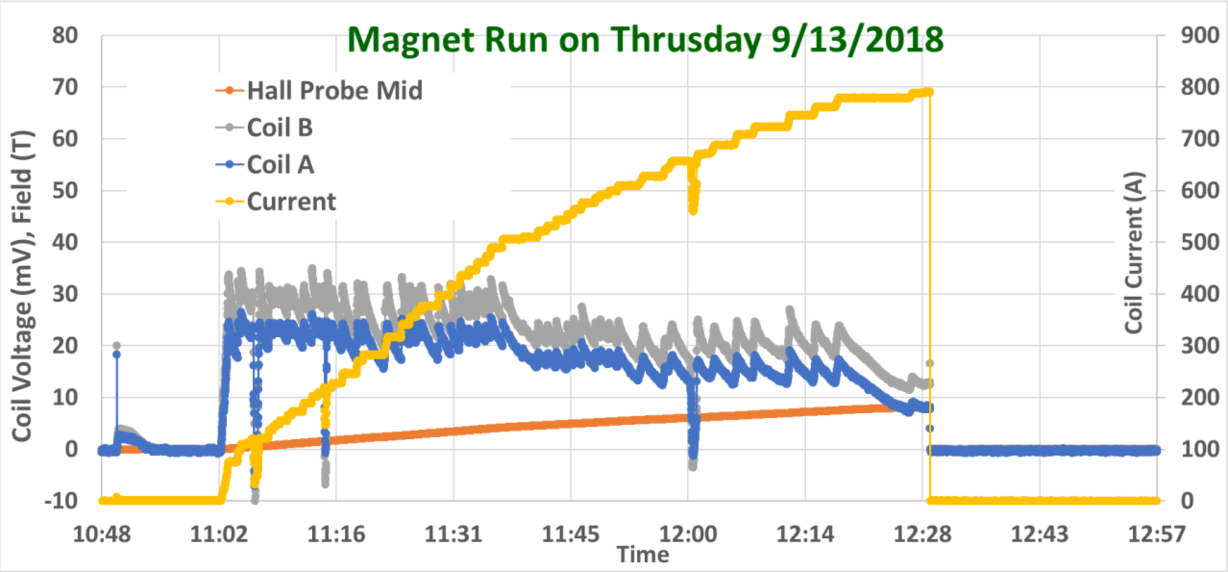




1. **Sudden increase in current due to coupling of two power supplies**
2. **Running out of Helium at the end of the day**

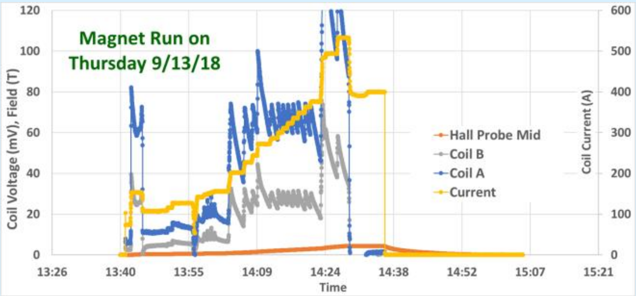


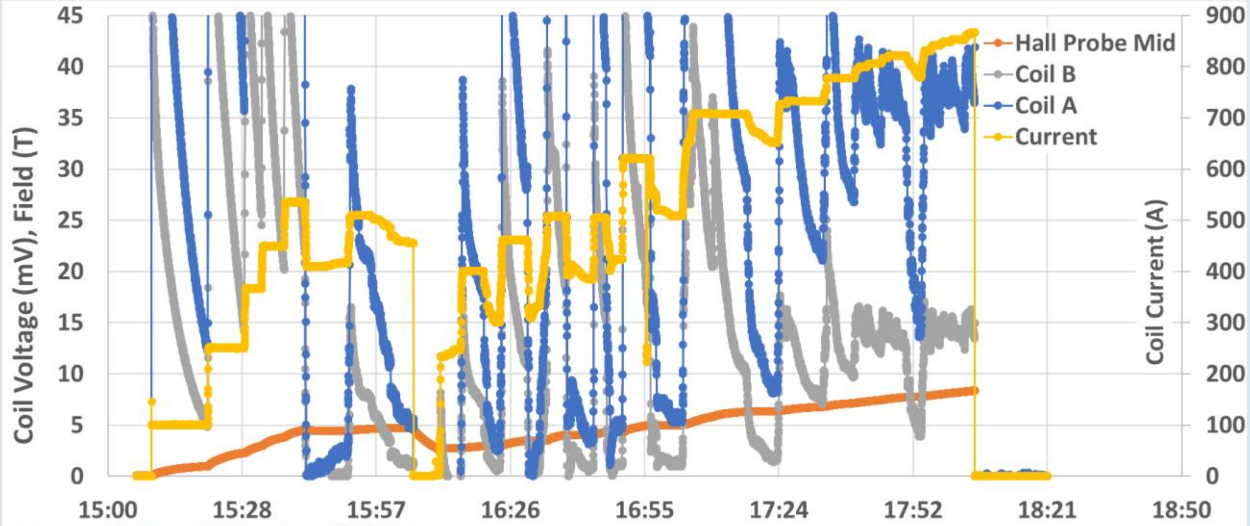
Thursday Run Summary



Two more quenches at 800-850 A (design: ~450 A)

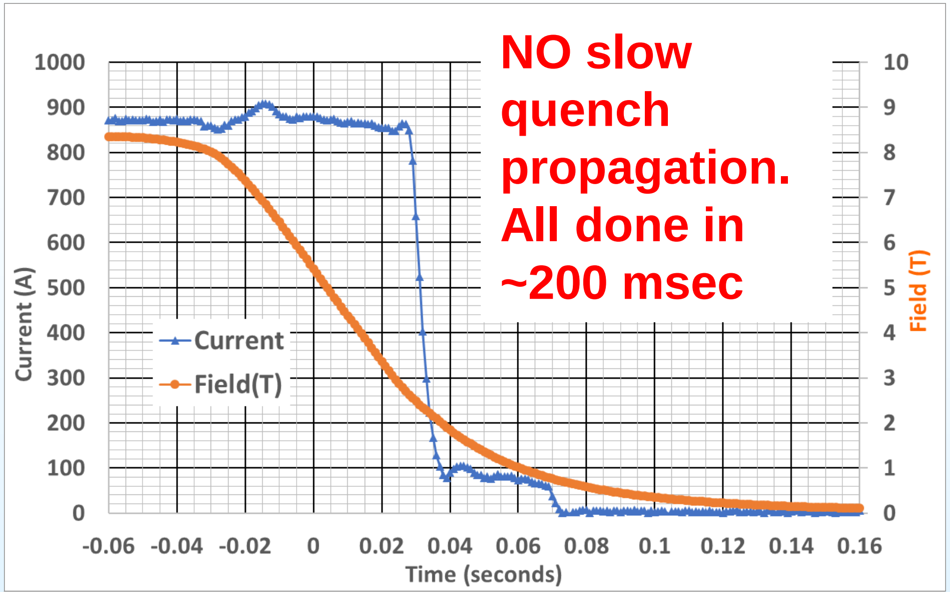
..and a shut-off near design current

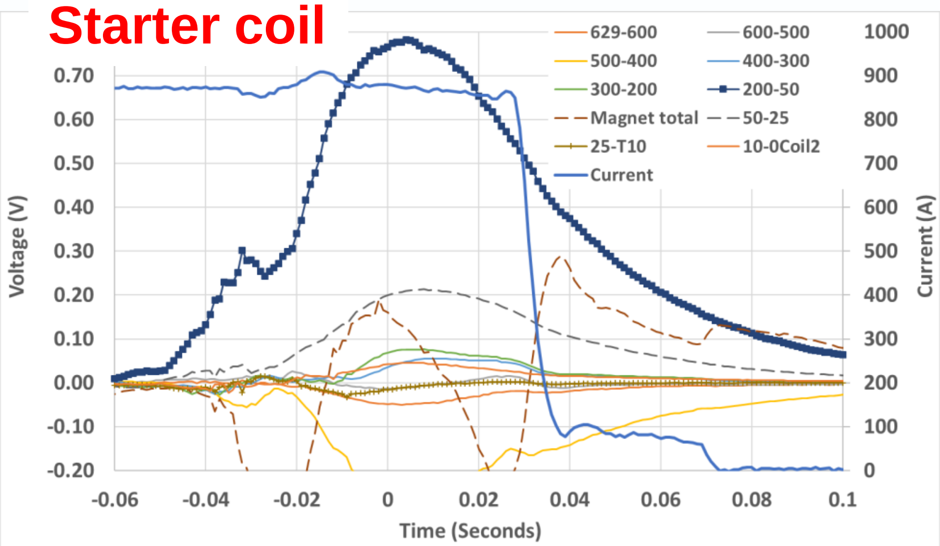


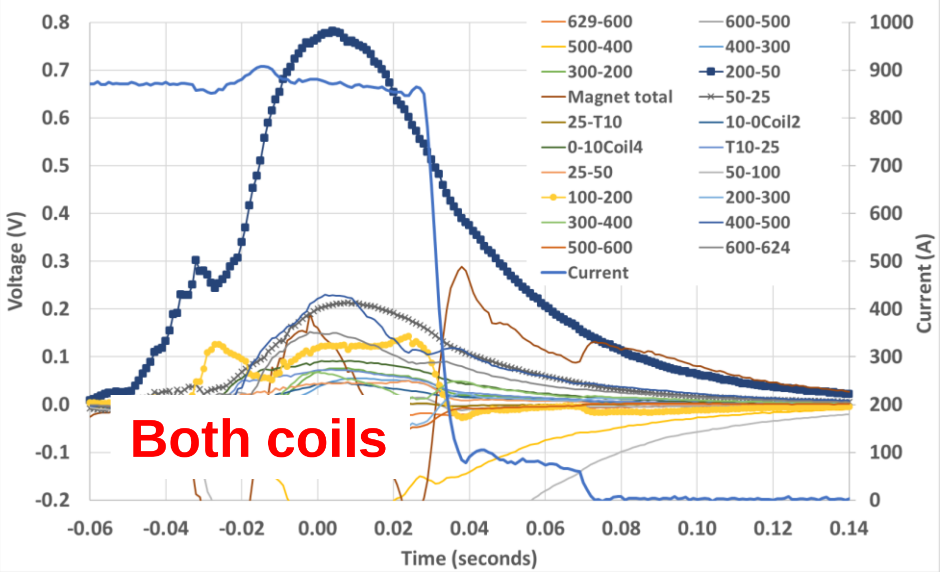


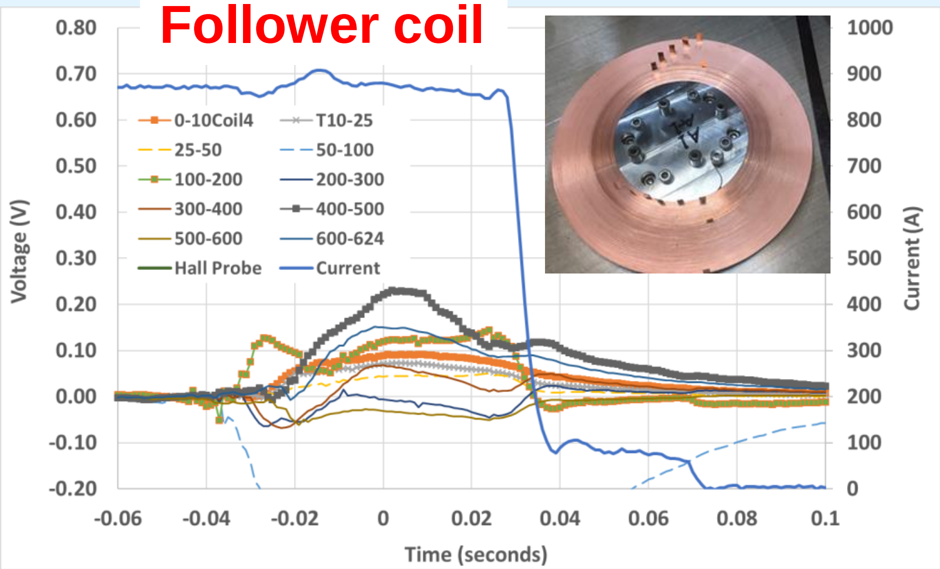
Magnet Run on Thursday 9/13/18

Discussion on 4K Quench Propagation in Large No-Insulation Coil at ~850 A

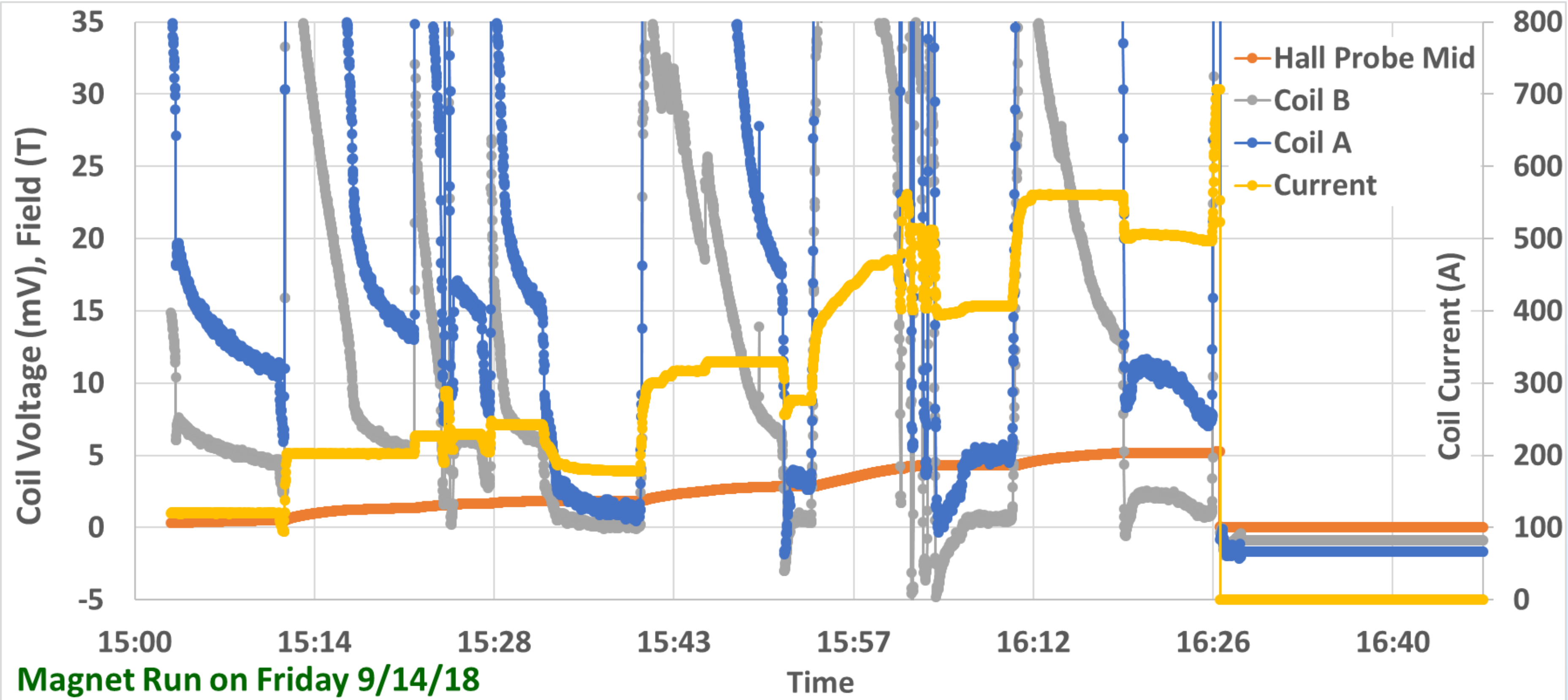








Friday Run Summary



- **Higher temperature operation mostly in Helium gas environment**

Key Takeaway from the Quench Studies in Large NI HTS Coils

- Conventional HTS thinking: Slow quench propagation velocities in HTS. This implies energy getting deposited in a small area for long enough to possibly degrade and even permanently damage the conductor locally.
- One conventional solution: Large fast acting heaters. Challenge in HTS - large and varying thermal margin across the magnet.
  - Recent results in the "No-Insulation Windings" point to a very different scenario ➔ quench propagation is fast within a pancake between the adjacent turns (as indicated by the large number of v-taps) and also the propagation is fast to the adjacent pancakes.
  - BNL 4 K results in large aperture, high field/high stress double pancake coils are so far encouraging.
  - We need to properly understand the other results/concern with more diagnostics (v-taps) and demonstrate a working solution.

HTS Solenoid for Neutron Scattering (PBL/BNL SBIR, Phase I funded)

Ultimate requirements of the experiment:

- A high field (25 T) magnet with wide opening (both horizontally and vertically) to maximize the range of angles for incoming neutrons and minimize the blockage of scattered neutrons

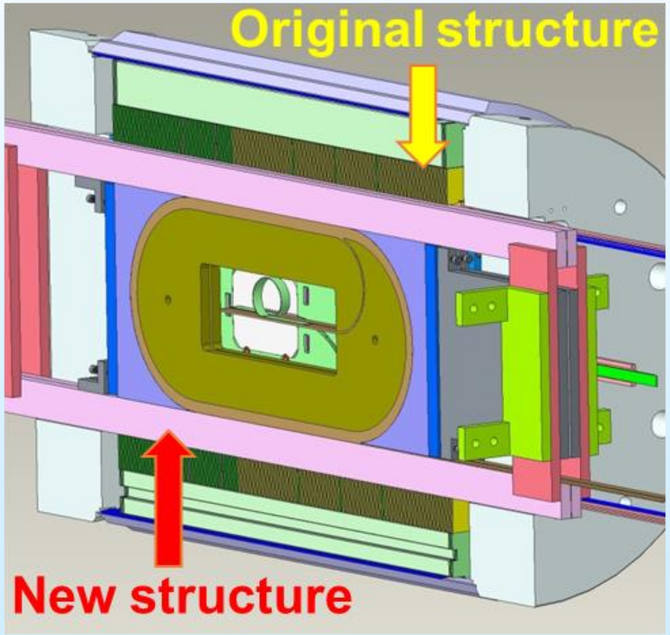
PBL/BNL SBIR:

- Develop innovative designs and technologies with large opening angles that could revolutionize the capabilities of neutron diffraction
- Specifically exploit the concept of the open-midplane design (developed under HEP) and a conical-bore design
- HTS conical coil to be built and tested at 77 K in Phase I
- Proof-of-principle magnet to be demonstrated in Phase II, if funded

Possible BNL Contributions to US MDP (1)

A unique facility to carry out high field Magnet Development Program
(cost effective and rapid turn around program)

Can be further upgraded as a part of USMDP



New HTS coils slide inside the existing Nb_3Sn coils and become an integral part of the structure

A pair of HTS insert coils

Possible BNL Contributions to US MDP (2)

- ❖ **Contribution to ReBCO Dipole R&D thanks to a large HTS experience**
  - ❑ **Leveraging and drawing benefits from other HTS magnet programs**

- ❖ **Common Coil Dipole as a unique background field magnet where insert coils become part of the magnet for technology development**
  - ❑ **Leveraging advanced quench protection and electrical system**

- ❖ **Contribution to developing magnet designs that can be built reliably and cost-effectively for the next generation collider**
  - ❑ **Leveraging unique experience of the staff in building large scale production of RHIC magnets and with an operating collider on site**

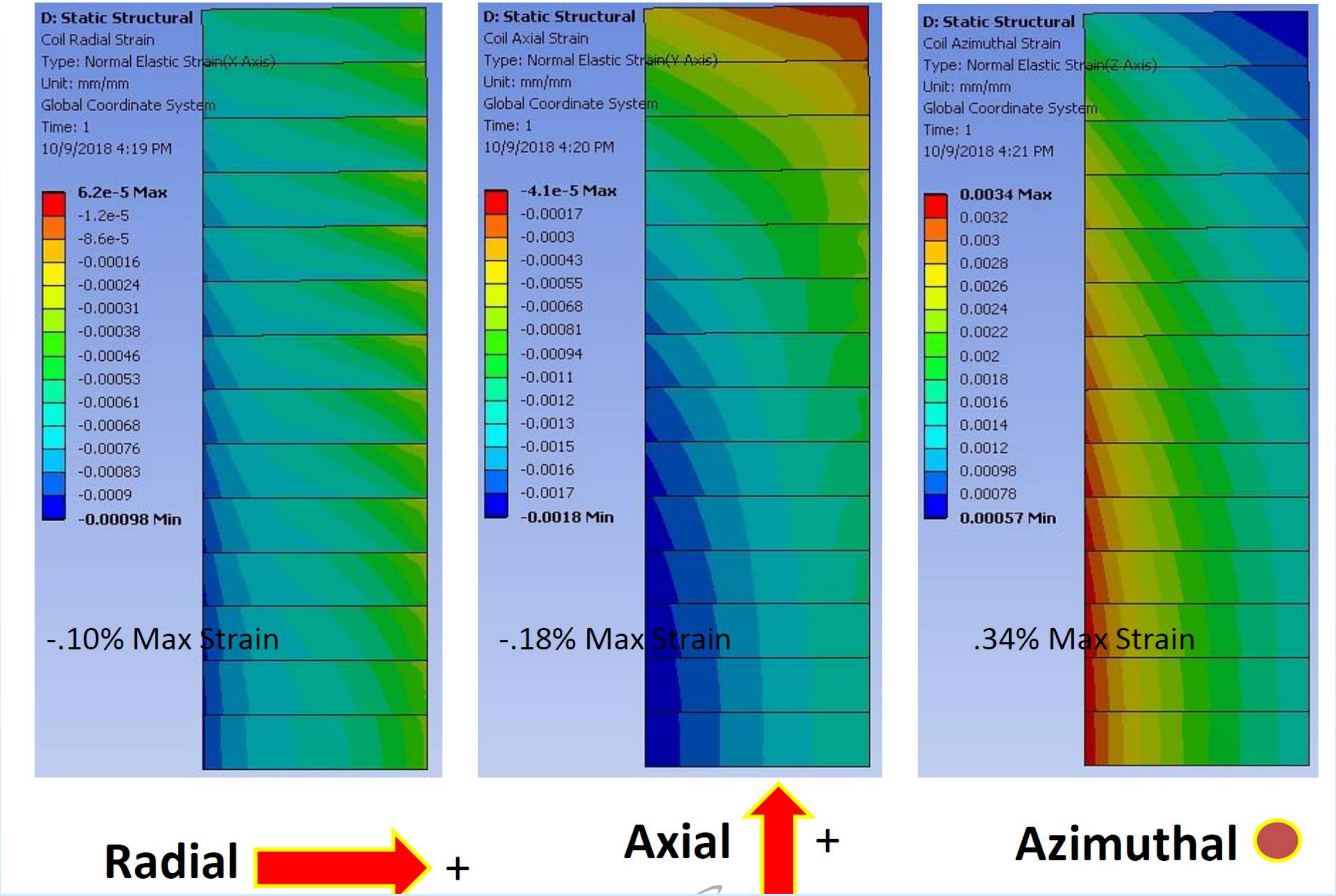
One specific topic under discussion: Quench study of small CORC® cable coil in 10+T hybrid dipole (BNL/LBNL/ACT collaboration)

Summary

- Slow ramp rate and relaxed field quality in IBS 25 T, 100 mm bore HTS solenoid allows the use of No-insulation winding (courtesy S. Hahn)
- Four sets of 4 K test runs with many voltage taps in two sets of coils. A large number of v-taps provide useful information for extensive analysis
- IBS double pancake coil was subjected to several quenches (runaway). The test run also included simulation of various accidents. The coil was able to reach high field in the next run, implies no major degradation
- The quench propagation in this large no-insulation coil is fast, both within pancake and pancake-to-pancake. Our understanding of the process is that it should be scalable to longer magnet many pancakes
- Since the project has been planned to proceed in a step-by-step manner (testing of 1 DP, 3 DP, 7 DP before the final 14 DP), we will be able to review the intermediate test results and make adjustments, if necessary
- (Not presented here but available for discussion - many more tests on R&D double pancake coil, including simulation of defects and events)

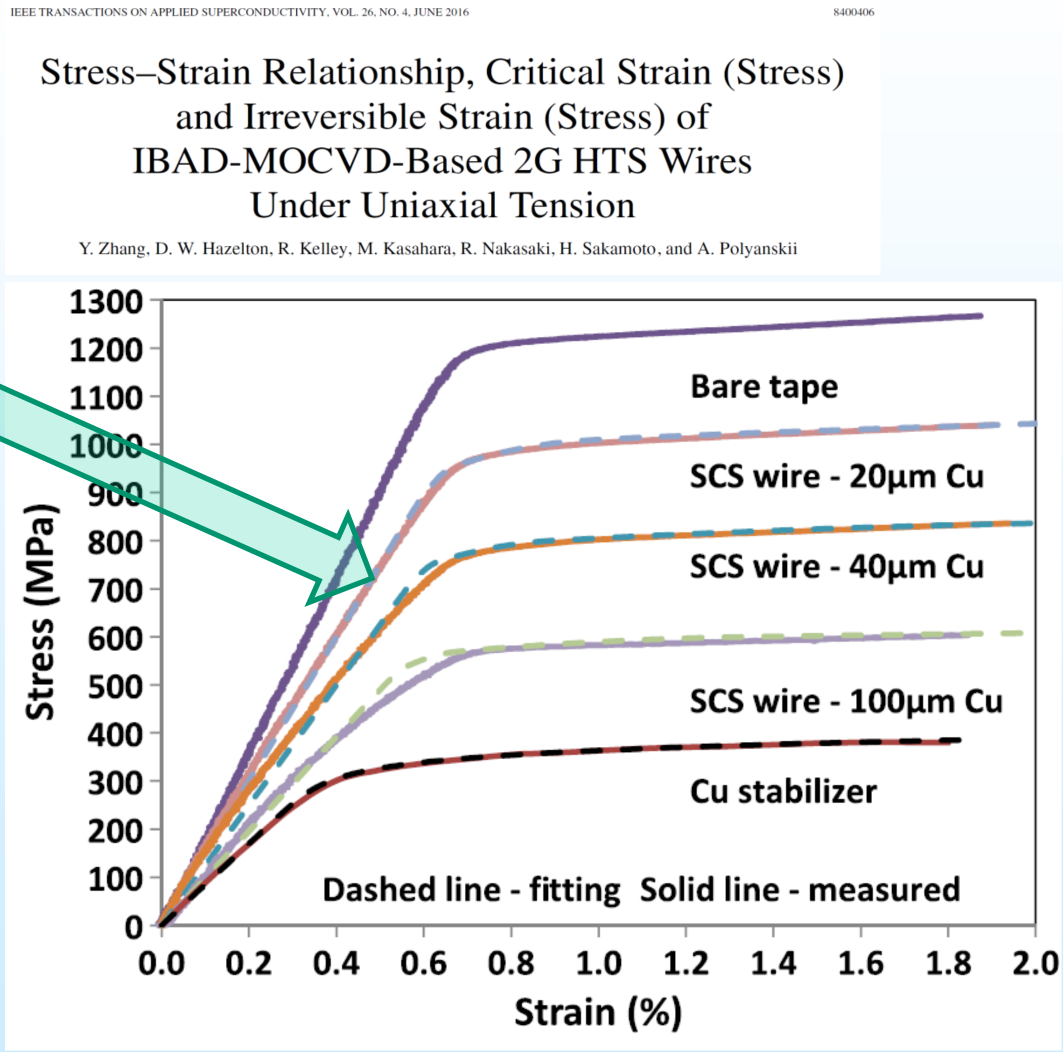
Extra Slides

Orthogonal Coil Strains @4K, 25 T



Mechanical Properties of the Conductor

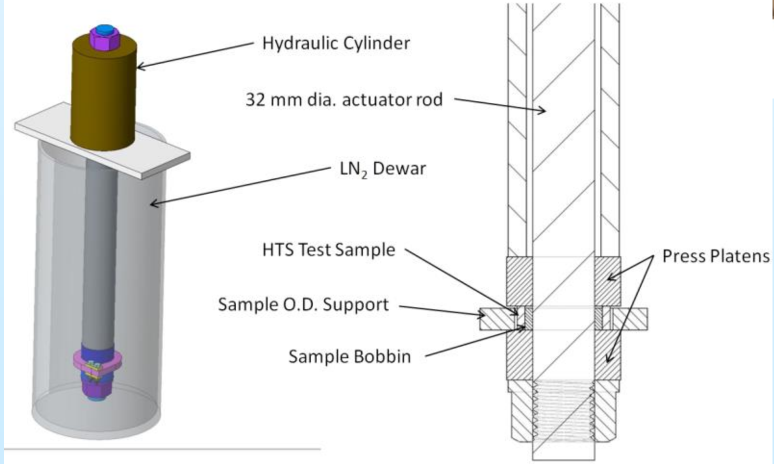
Requirement of Azimuthal stresses of ~500 MPa is met with 2G Tape having 50 micron Hastelloy and 20 micron Copper

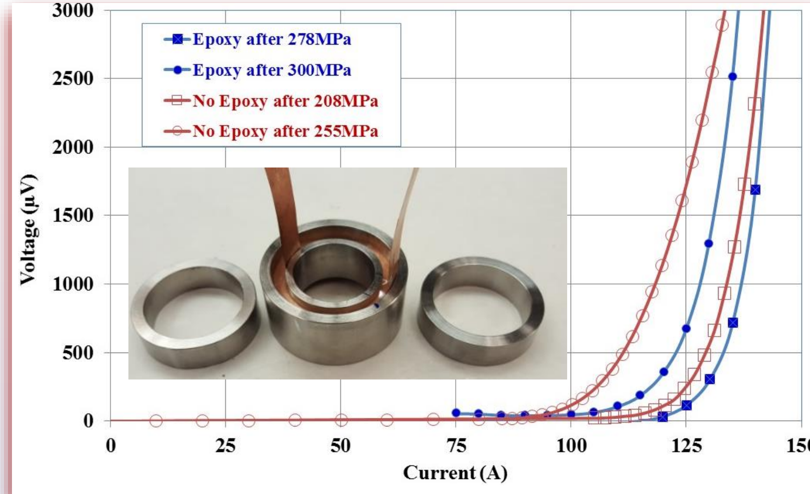


Meeting requirement of ~200 MPa on the narrow side of the tape needs to be checked as no such data is available

Courtesy: SuperPower

Ability of the Conductor to Withstand Load on the Narrow Edge

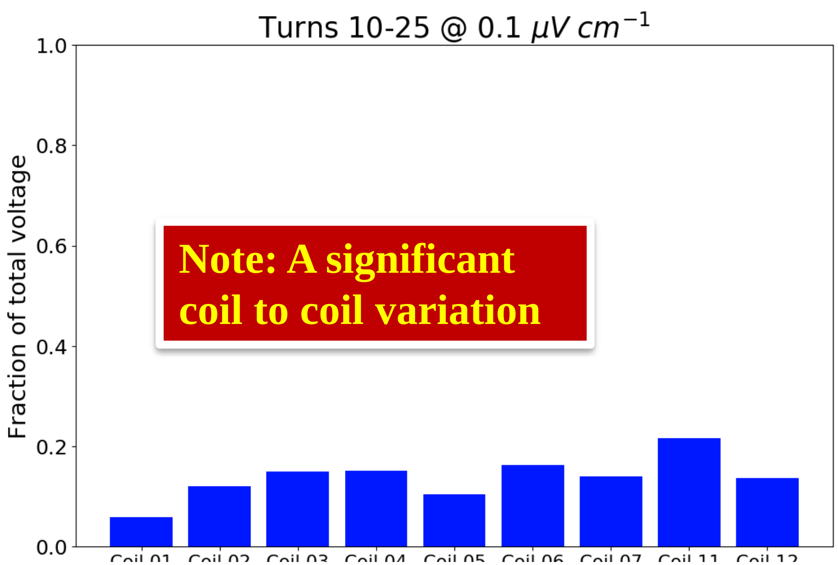


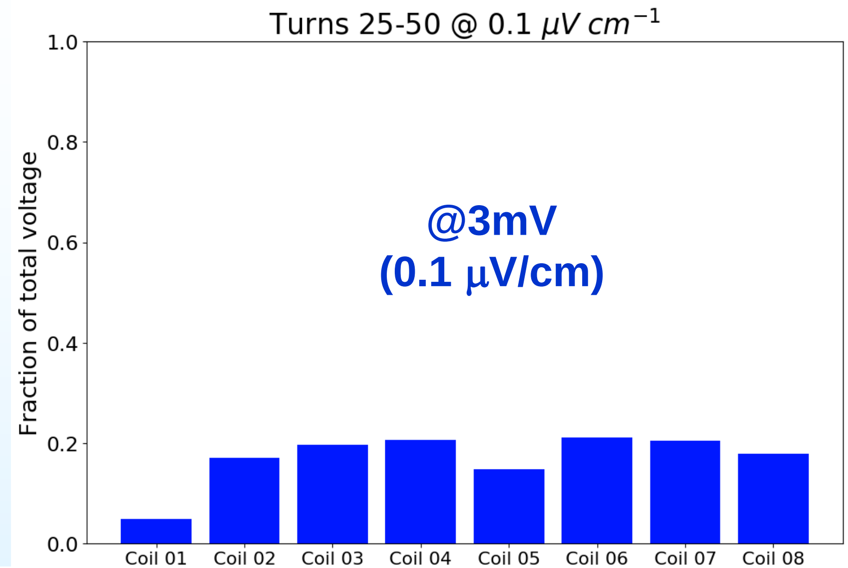


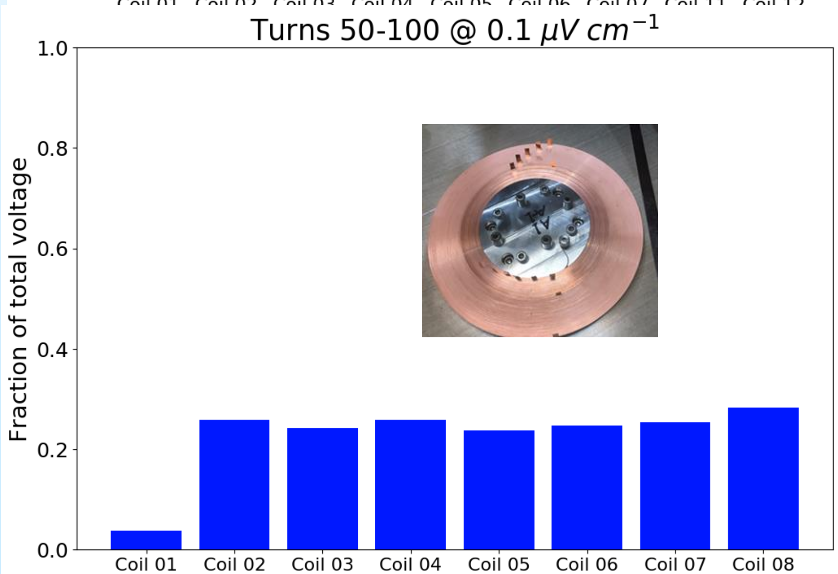
Special apparatus was designed and built to make sure that coil can withstand these large axial loads (~200 MPa)on the narrow face of HTS tape

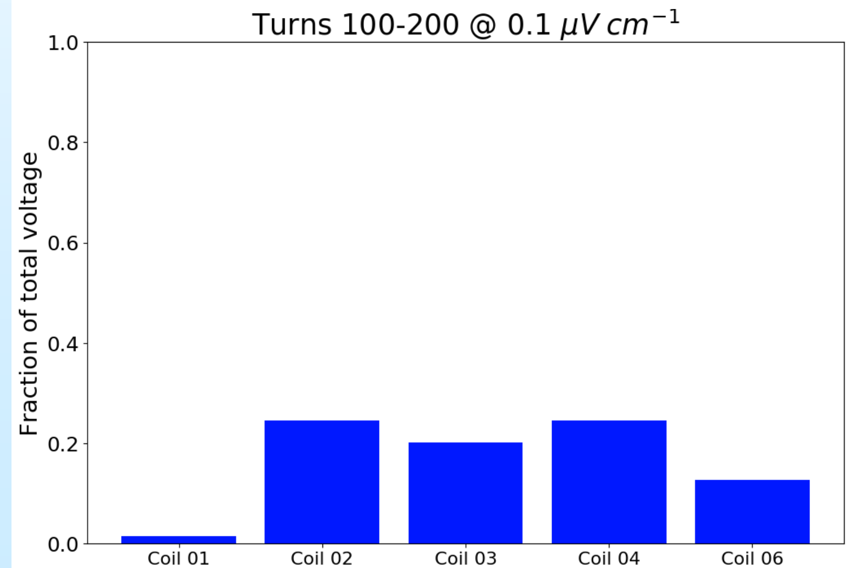
- **Measurements show that SuperPower 2G HTS Tape with 50 µm Hastelloy and 20 µm Cu can**
- **Studies show that painting the surface of the coil with epoxy increases the margin**

Variation in the Voltage @77K within a set of turns of different Coils

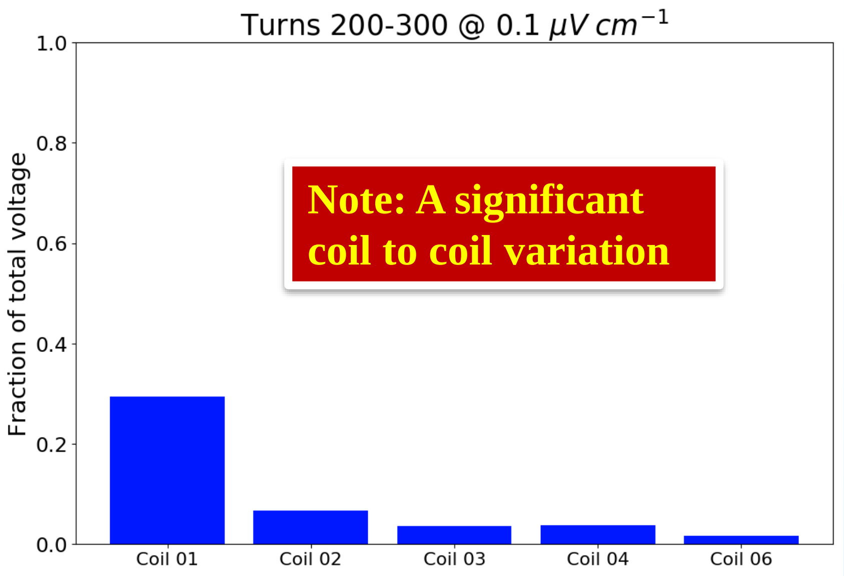


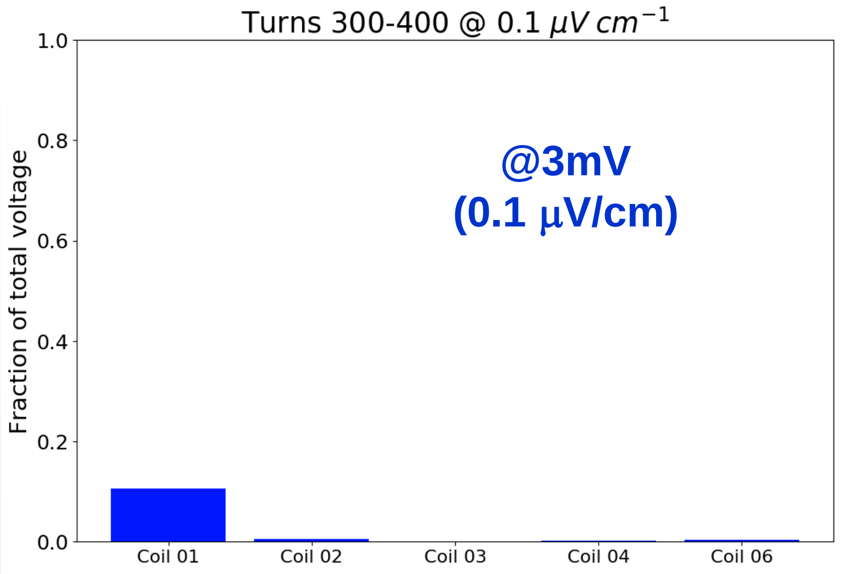


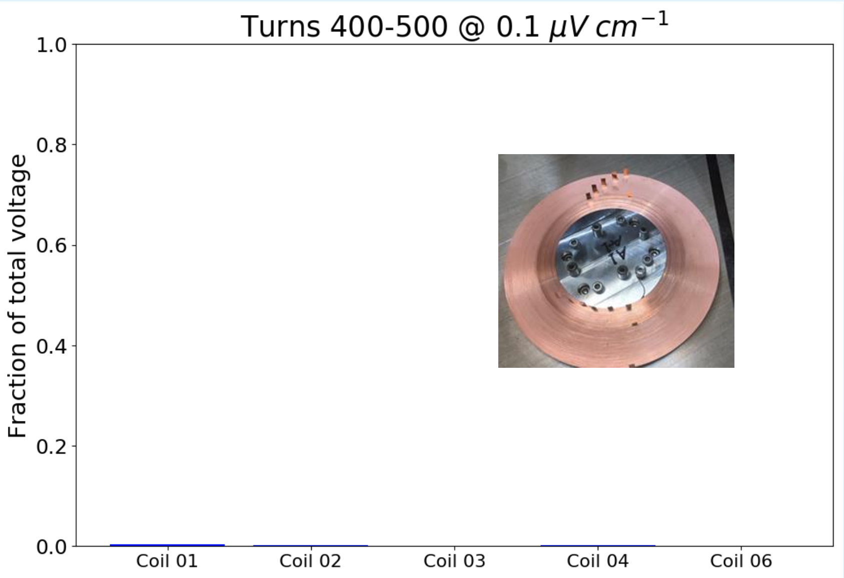


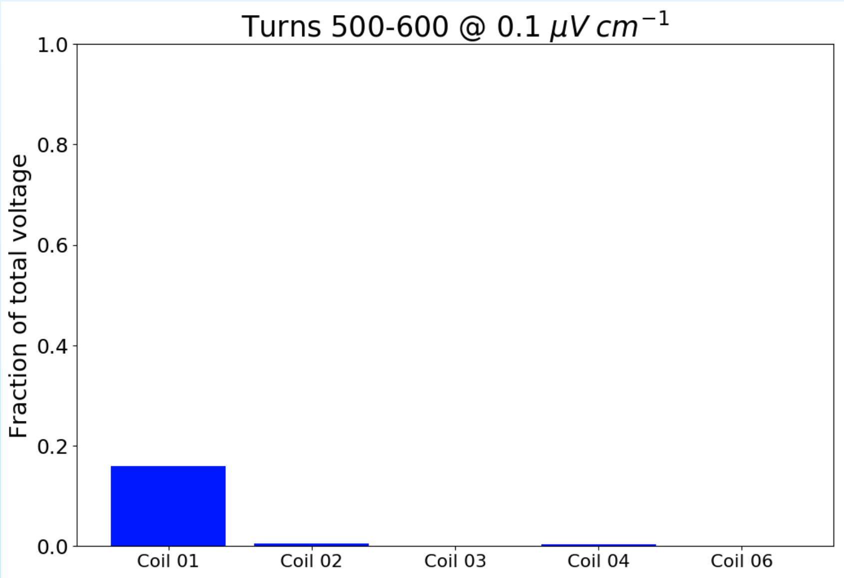


Variation in the Voltage @77K within a set of turns of different Coils

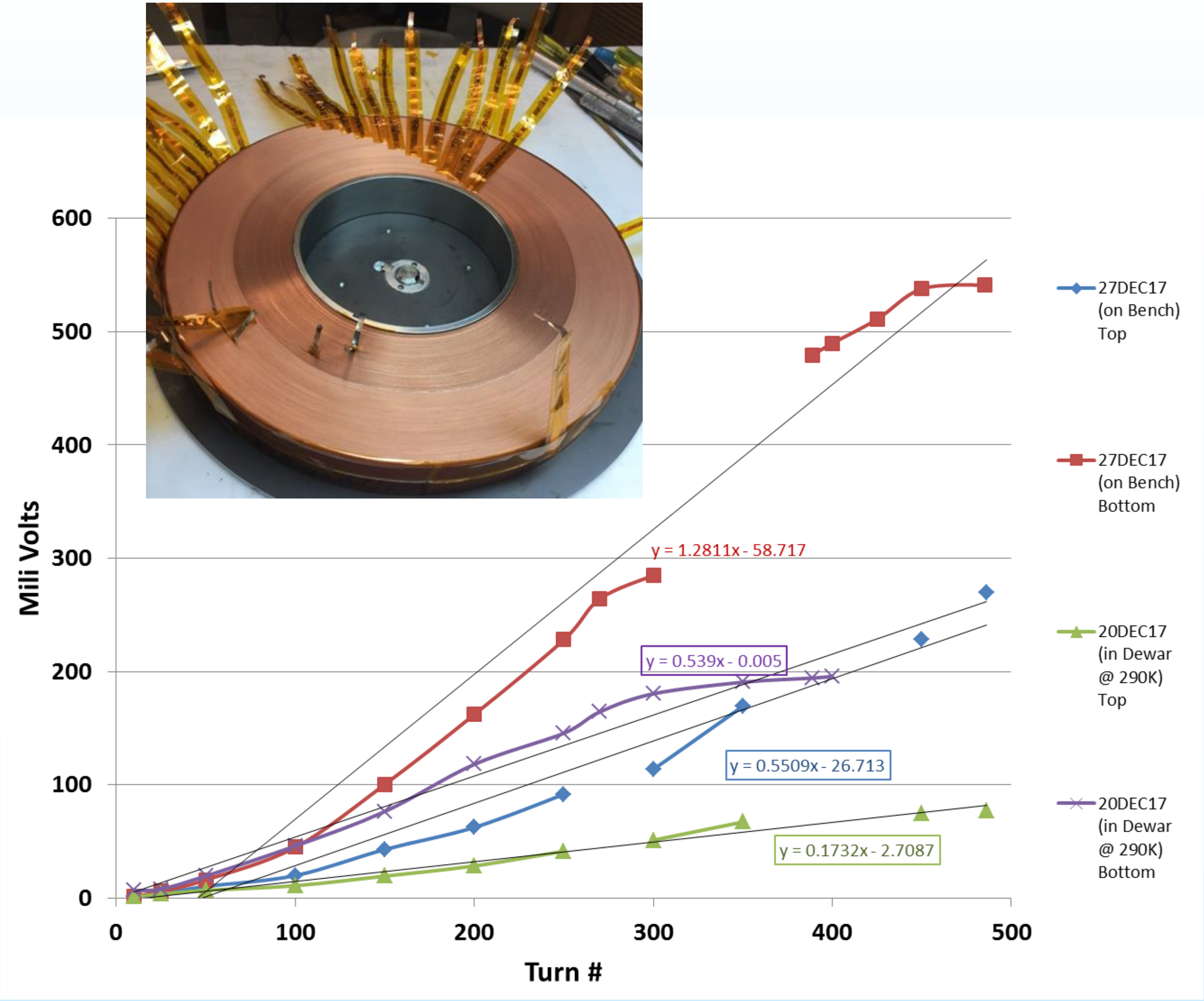






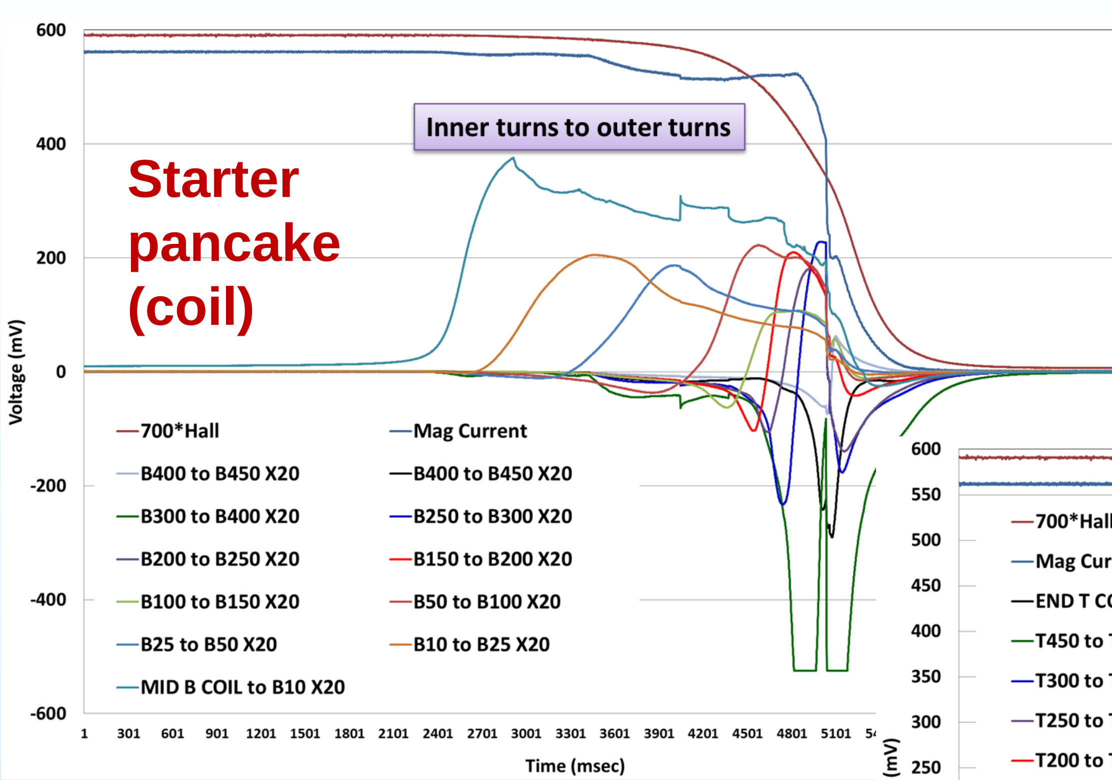


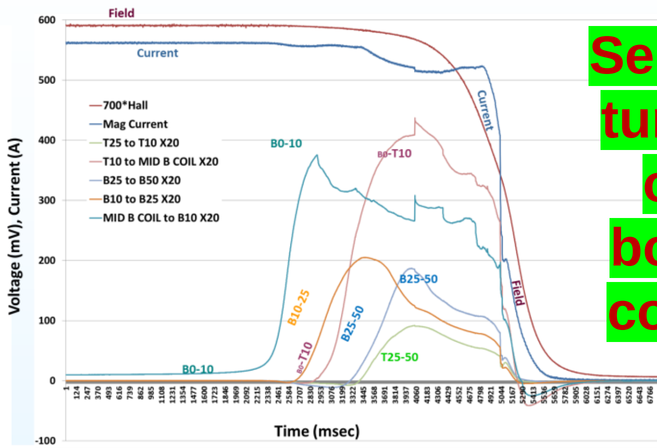
Observed Change in Contact Resistance



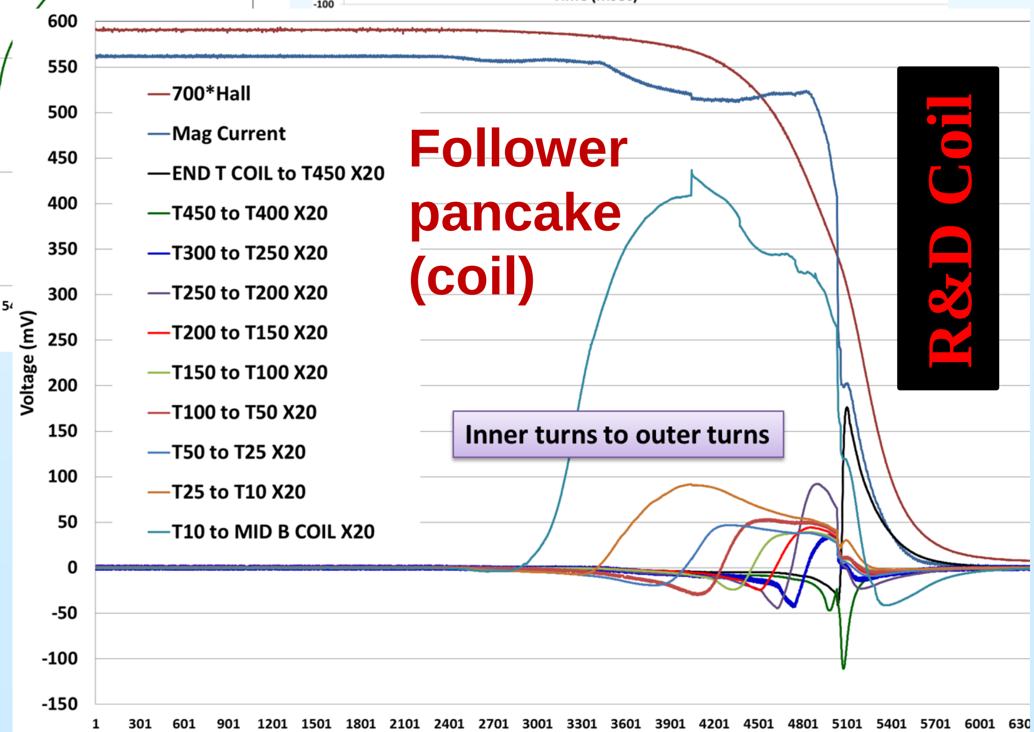
- Large coil (100 mm id, 220 mm od, using >500 m 12 mm tape)
- No epoxy painted on the surface
- Coil was rewound at higher (3X) tension
- Better situation with higher tension.
- Higher tension used in production coils.

Quench Propagation in the Second Series of Double Pancake Tests





Select turns of both coils



R&D Coil

- Quench propagation from the inner turns to the outer turns
- Quench propagation from one pancake (coil) to another pancake (coil) after ~1/2 sec