BNL Experience with NI Coils

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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

High Field, Large Aperture HTS NI Solenoid for Axion Search at CAPP/IBS

Center for Axion and Precision Physics Research (CAPP),, Institute for Basic Science (IBS),. Daejeon, South Korea

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

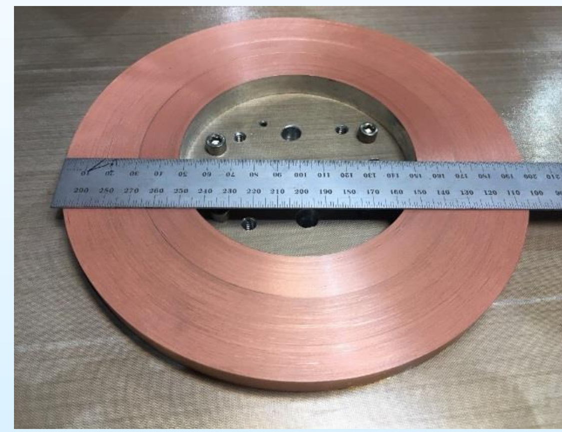
- High field solenoid magnets: B (B^4)
- High volume magnets/cavities: V (V^2)

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

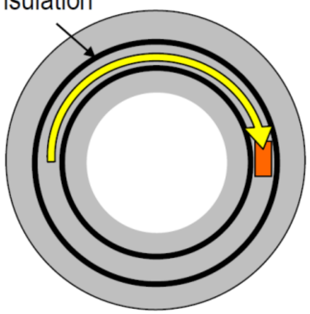


Relaxed field quality and slow ramp rate allows the use of *No-Insulation* windings to (a) tolerate defect in HTS tapes, and (b) expected to offer a more reliable quench protection

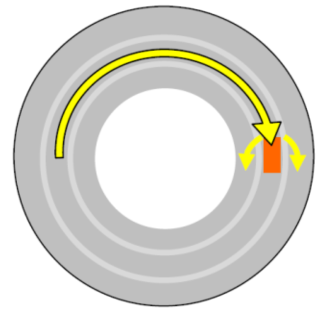
No Insulation Approach to Magnet Protection (slides courtesy S. Hahn)

No-Insulation HTS Winding Technique

INS: Difficulty in Protection



NI: "Quench Current Bypass"



- Slow normal zone propagation in HTS
  - ➔ Slow quench detection
- Larger enthalpy (stability margin) of HTS
  - ➔ Difficulty in "activate-heater" protection

- "Automatic bypass" of quench current through turn-to-turn contacts

REF: S. Hahn, D. Park, J. Bascuñán, and Y. Iwasa, "HTS Pancake Coil without Turn-to-Turn Insulation," *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 1592 – 1595, 2011.

S. Hahn
<shahn@fsu.edu>

No-Insulation HTS Magnet
WAMHTS-3, Lyon, France (September 11, 2015)

5/18

No Protection Device: No-Insulation HTS Magnets

Seungyong Hahn

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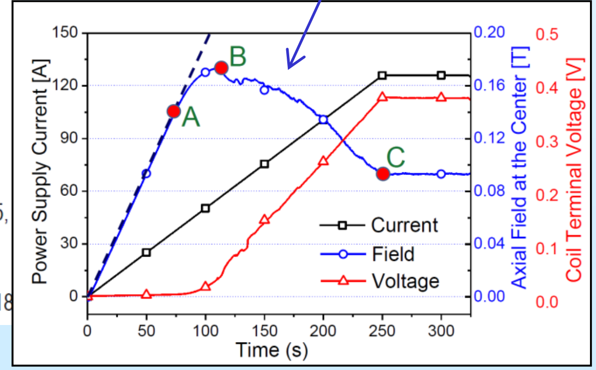
WAMHTS-3
Lyon, France

September 11, 2015

A decrease in field implies that more and more turns are getting shorted



Successfully demonstrated to work in small coils, but not yet in big coils at 4K

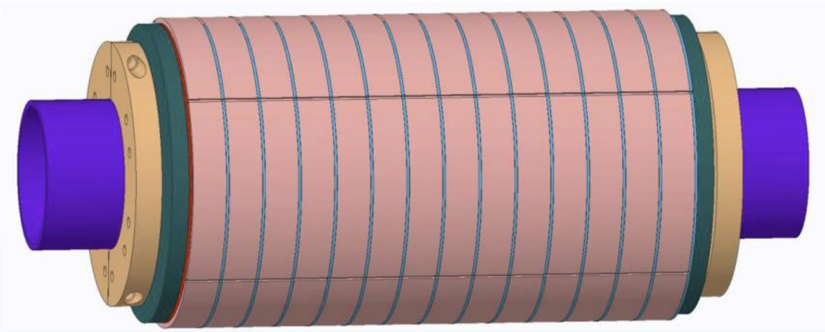
Major Design Decisions (1)

- **No-insulation winding**
  - ➢ Better tolerance to defects (it's still an R&D conductor) and hopefully better quench protection
- **Single layer coil design**
  - ➢ To avoid unbalanced Lorentz forces
- **12 mm wide tape**
  - ➢ To (a) reduce impact of hairline defects, (b) help in quench protection and fewer coils (cost reduction)
  - ➢ Piece length > 100 m (*<u>not =100m</u>*) for cost reduction (each pancake needs ~300 m)

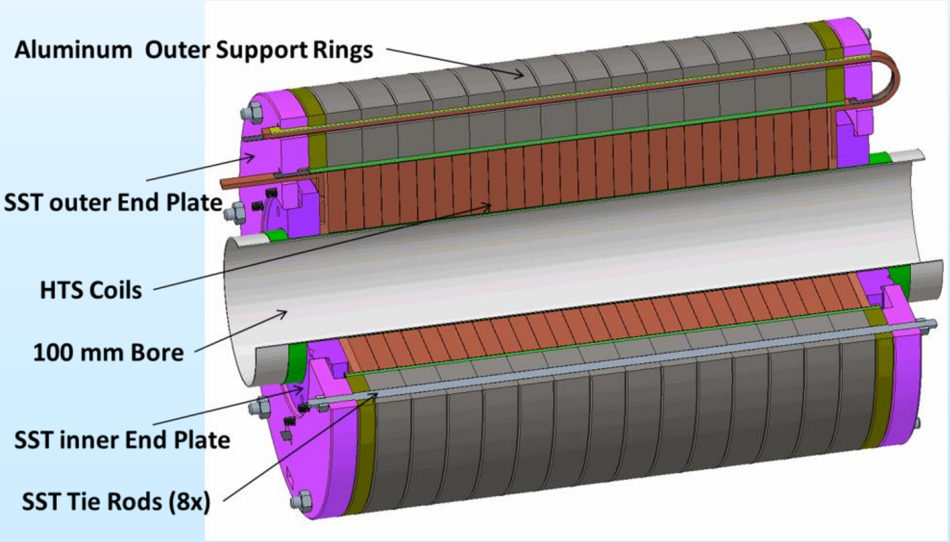
Major Design Decisions (2)

- Electrical margin > 50% (Note: NOT =)
  - ➢ Tight spec on I_c is a "*mirage*" as there is a large variation in I_c margin within HTS coil even for a 100% uniform conductor
- Low spec on minimum I_c
  - ➢ Design is limited by the mechanical properties
- Mechanical margin > 50%
  - ➢ 50 μm Hastelloy and 20 (10+10) μm Cu chosen
- No multi-width coils
  - ➢ Smaller width increases J_c and J X B stresses

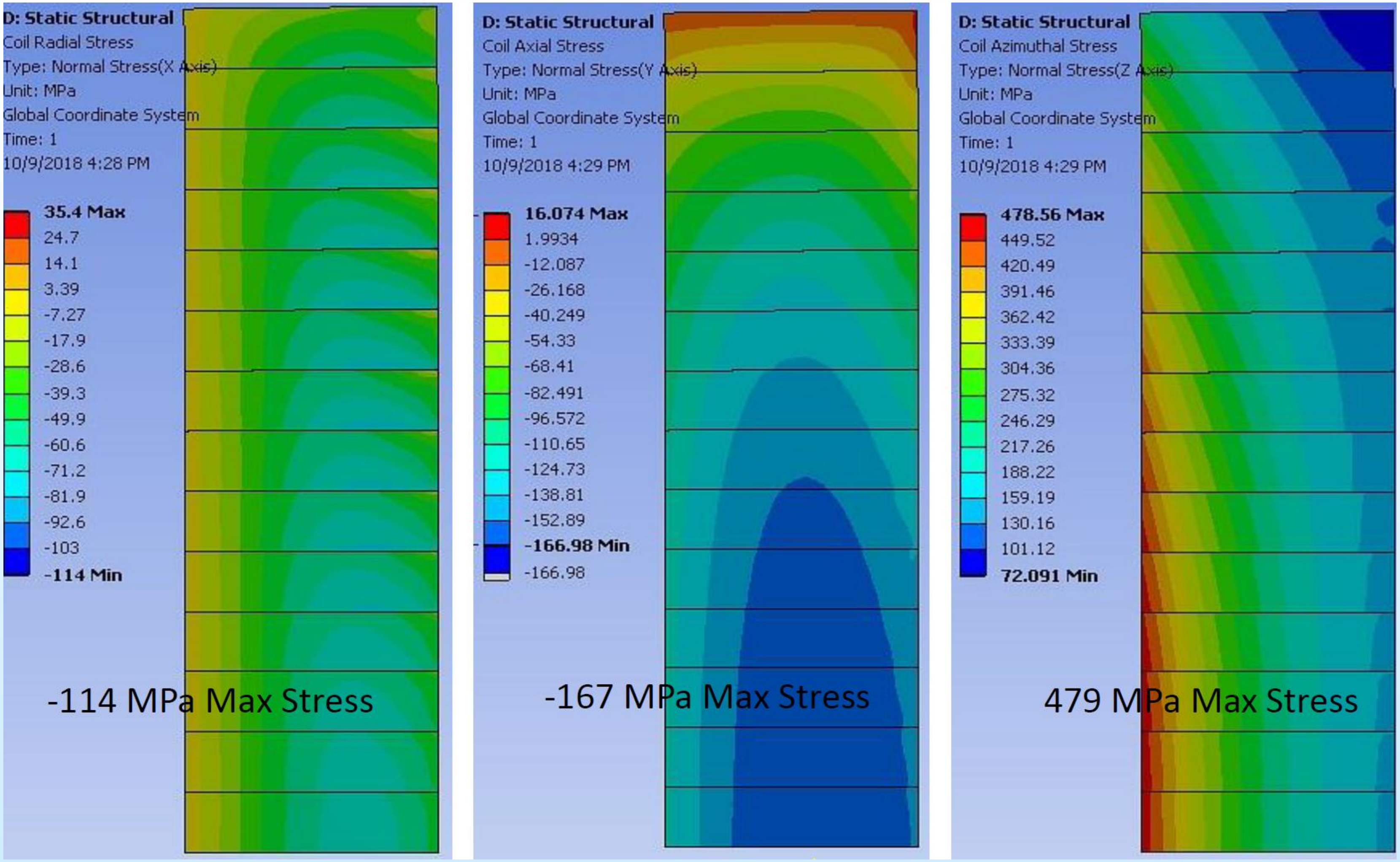
IBS HTS Solenoid Design Summary



- 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



Orthogonal Coil Stresses (@4 K, 25 T)



~480 MPa Max Stress

-114 MPa Max Stress | -170 MPa Max Stress |

Radial + **Axial** + **Azimuthal**

Mechanical Properties of the Conductor

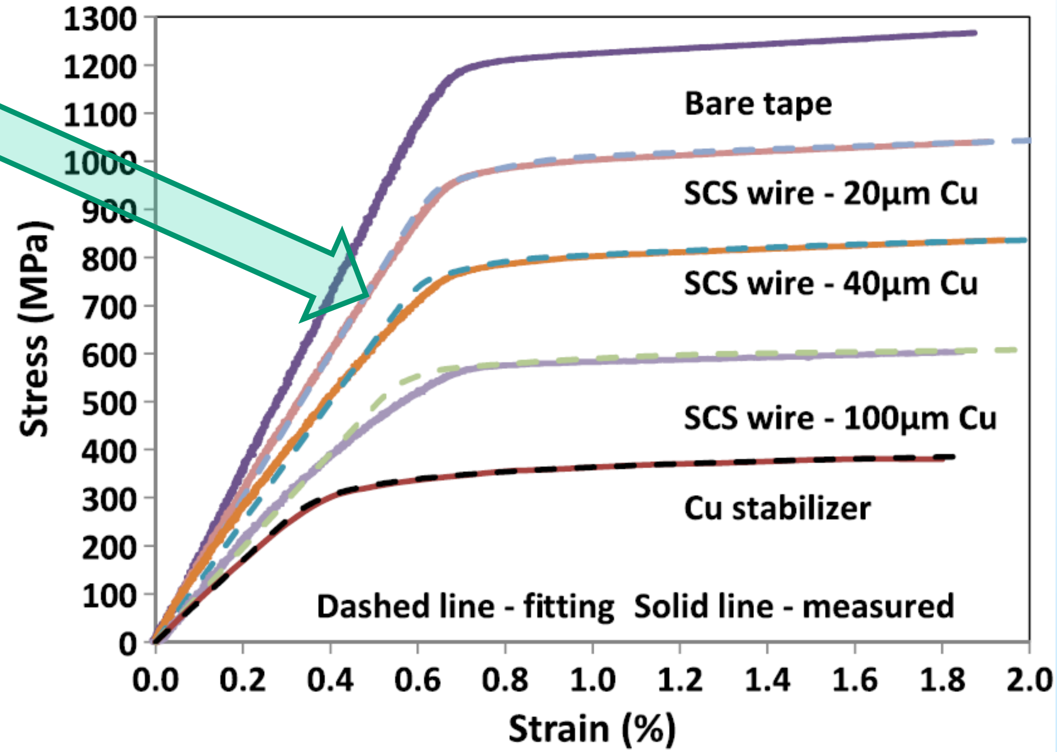
Requirement of Azimuthal stresses of ~500 MPa is met with 2G Tape having 50 micron Hastelloy and 20 micron Copper

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

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 26, NO. 4, JUNE 2016 8400406

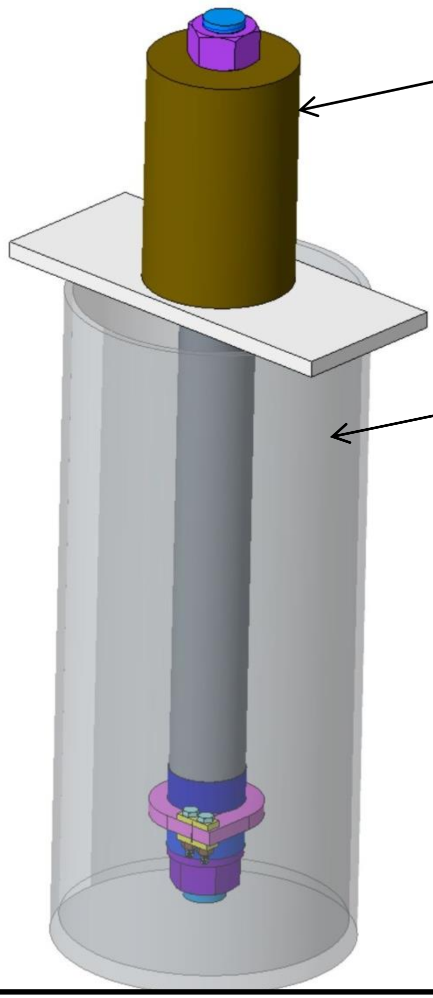
Stress–Strain Relationship, Critical Strain (Stress) and Irreversible Strain (Stress) of IBAD-MOCVD-Based 2G HTS Wires Under Uniaxial Tension

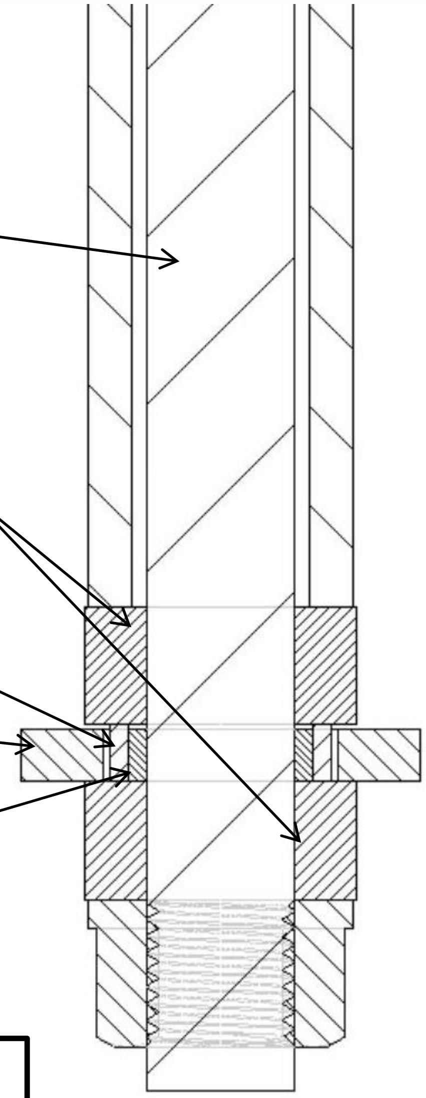
Y. Zhang, D. W. Hazelton, R. Kelley, M. Kasahara, R. Nakasaki, H. Sakamoto, and A. Polyanskii



Courtesy: SuperPower

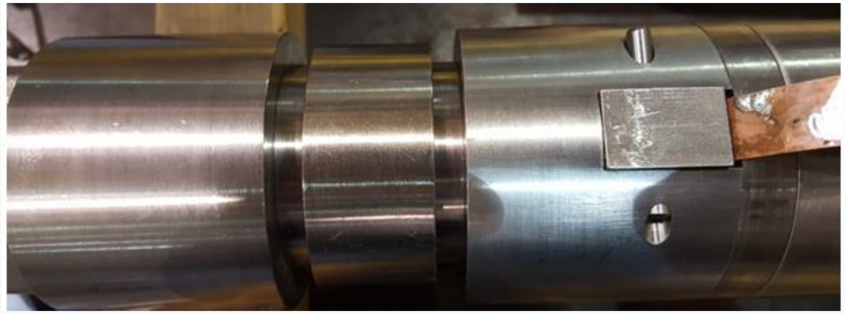
Apparatus to Apply up to 300 MPa Load on the Narrow Side (design needs 170 MPa)





Source of Load on Narrow Side: B_r

Test Setup to Vary Load on the Narrow Edge During the 77 K Test



ENERPAC RCH-302 Hollow Plunger Cylinder

Voltage taps to Multimeter

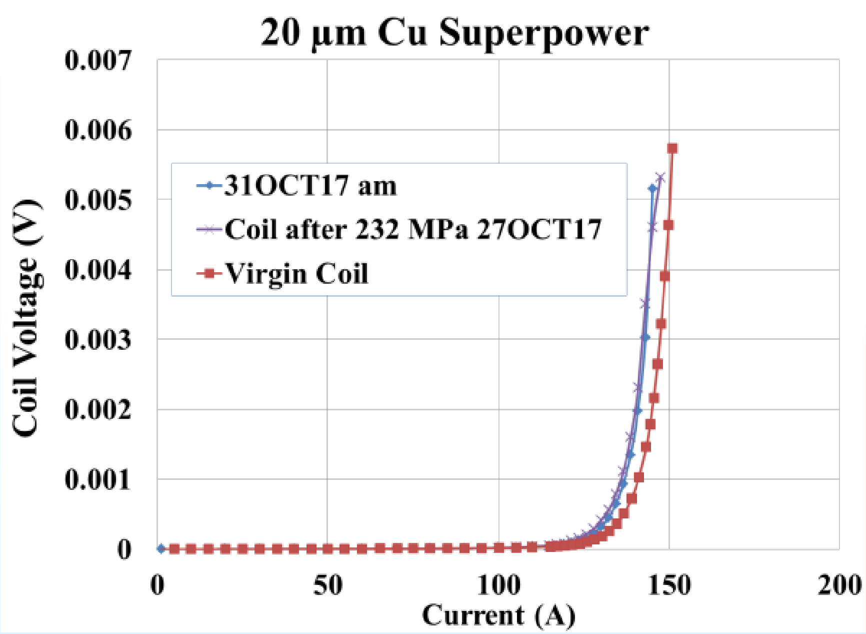
To ENERPAC P-80 Hydraulic Steel Hand Pump

LN_2 Dewar

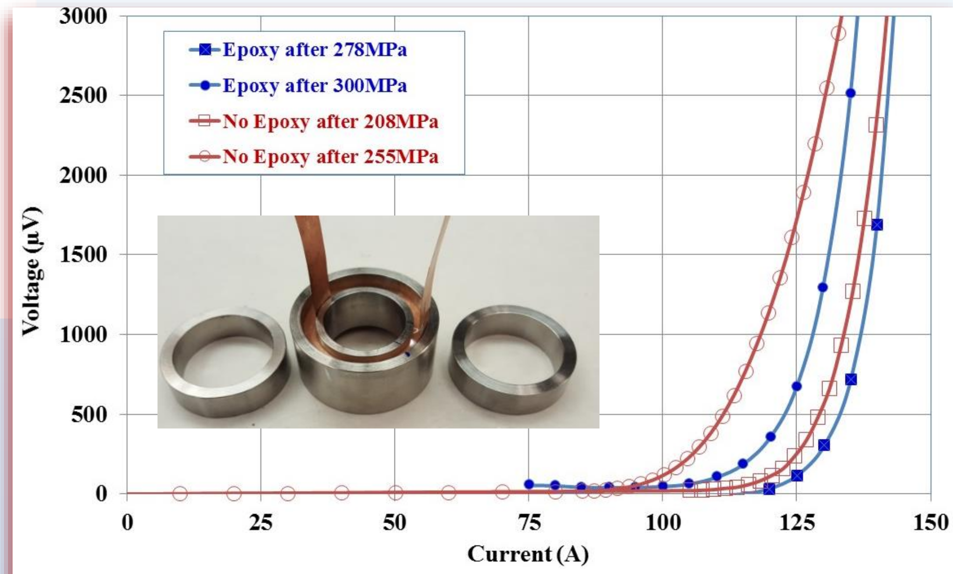
Current Leads

Load varied while testing

Experimental Results of the Load on the Narrow Edge (need >170 MPa)



- **Studies show that painting the surface of the coil with epoxy helps**
- **It reduces the point/local load on an individual tape**
- **We have >50% margin**



Meets the requirements of 170 MPa on the narrow side

- ➢ **Cyclic studies performed**

Tapes with 40 and 65 microns copper and also from the other vendors were tested as well

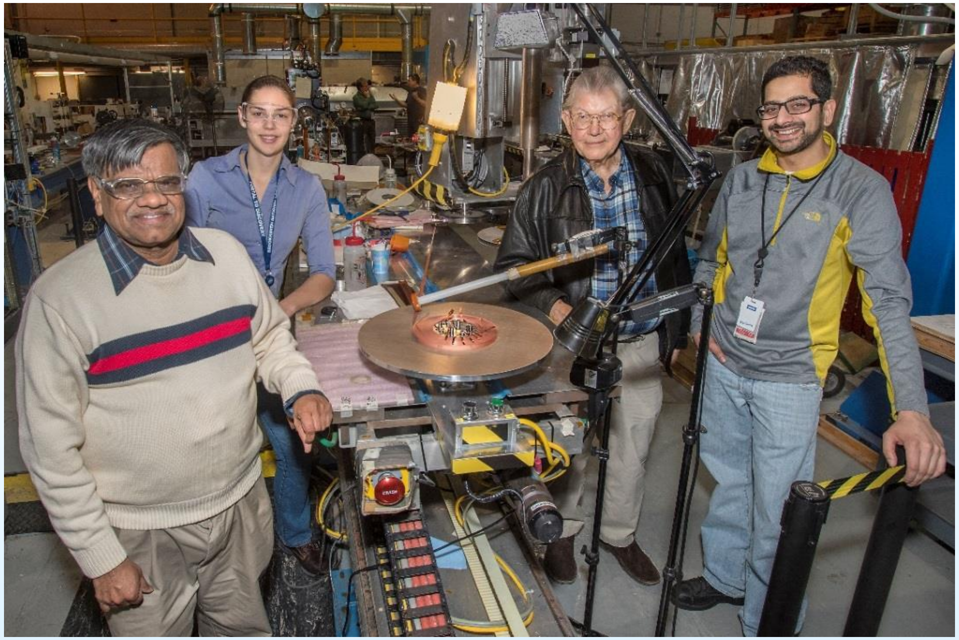
Load should be distributed over the coil surface and not accumulate on the narrow side of one tape

Coil Construction and Test Results

BNL Experience with HTS Magnets

- BNL has been working on HTS coil and HTS magnet technology almost from the beginning (about two decades)
- BNL has made coils with all type of HTS (Bi2212, Bi2223, ReBCO MgB_2) in a variety of forms (wire, tape, cable)
- BNL has experience in making coils with over 60 km of HTS (4mm tape equivalent)
- BNL has made over 100 HTS coils and over 20 HTS magnets in a variety of geometry – dipole, quadrupole, solenoid, curved coils
- BNL has made coils with a variety of insulations - inorganic, stainless steel and no-insulation

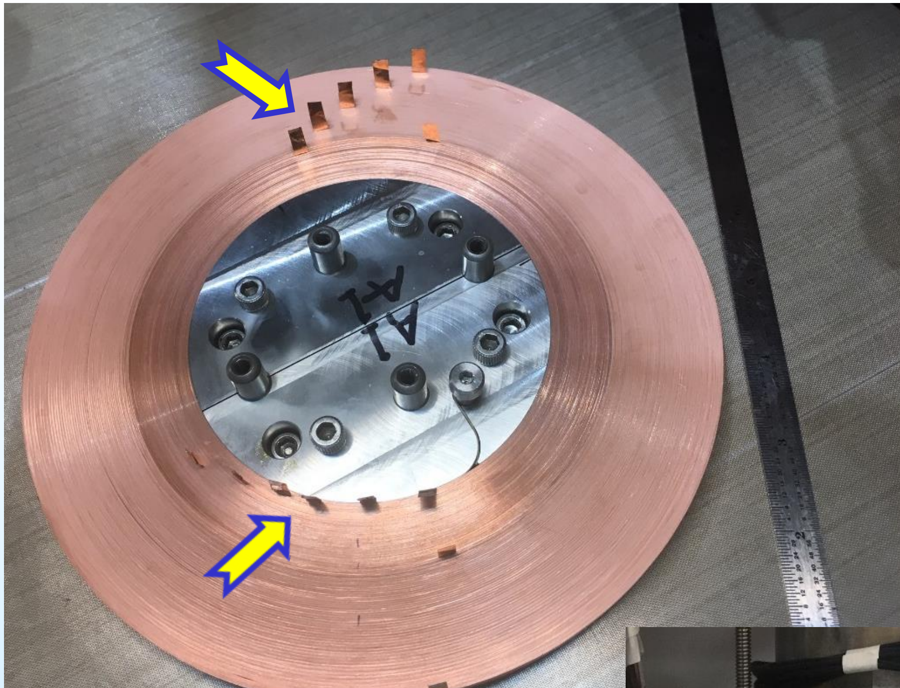
Winding of IBS NI HTS Coils with BNL Universal Coil Winder

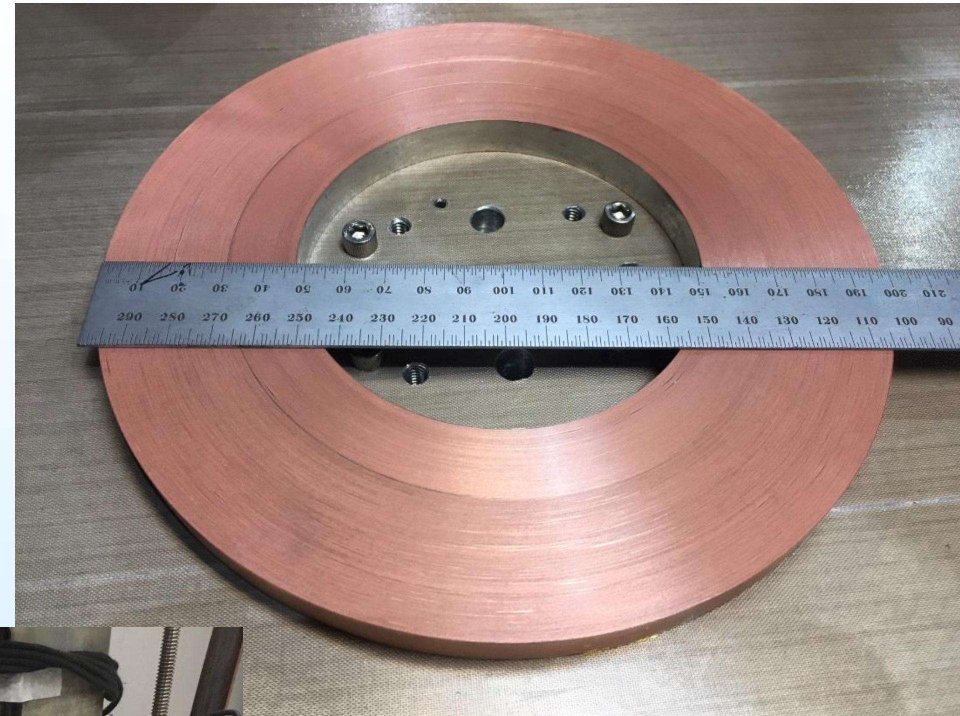


16 coils wound

~5 km of 12 mm tape used

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





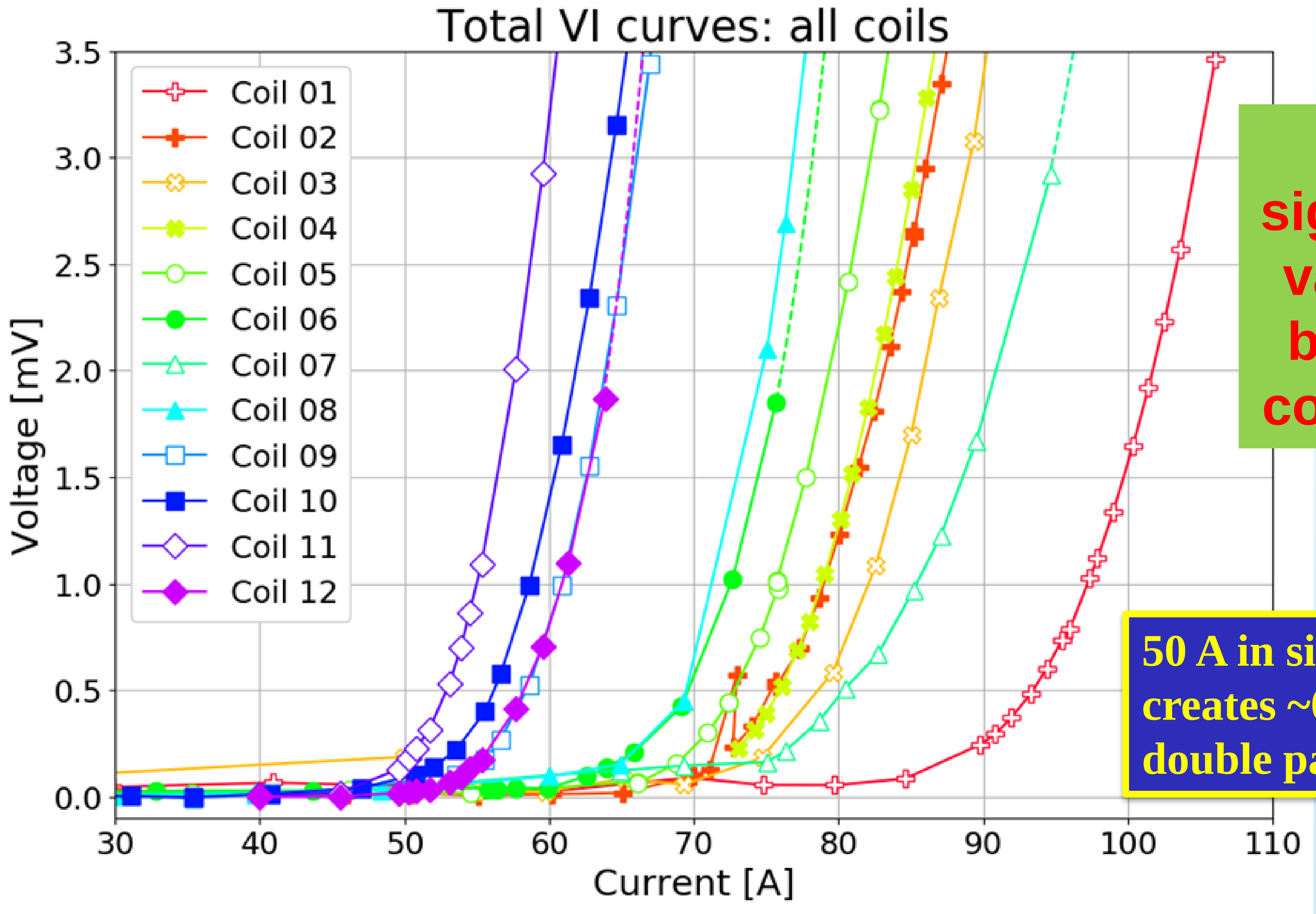
Major parameters:

- 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

77 K (LN2) Test of 12 Pancake coils

(coils 1-6 tested as single pancakes and 7-12 as double pancakes)

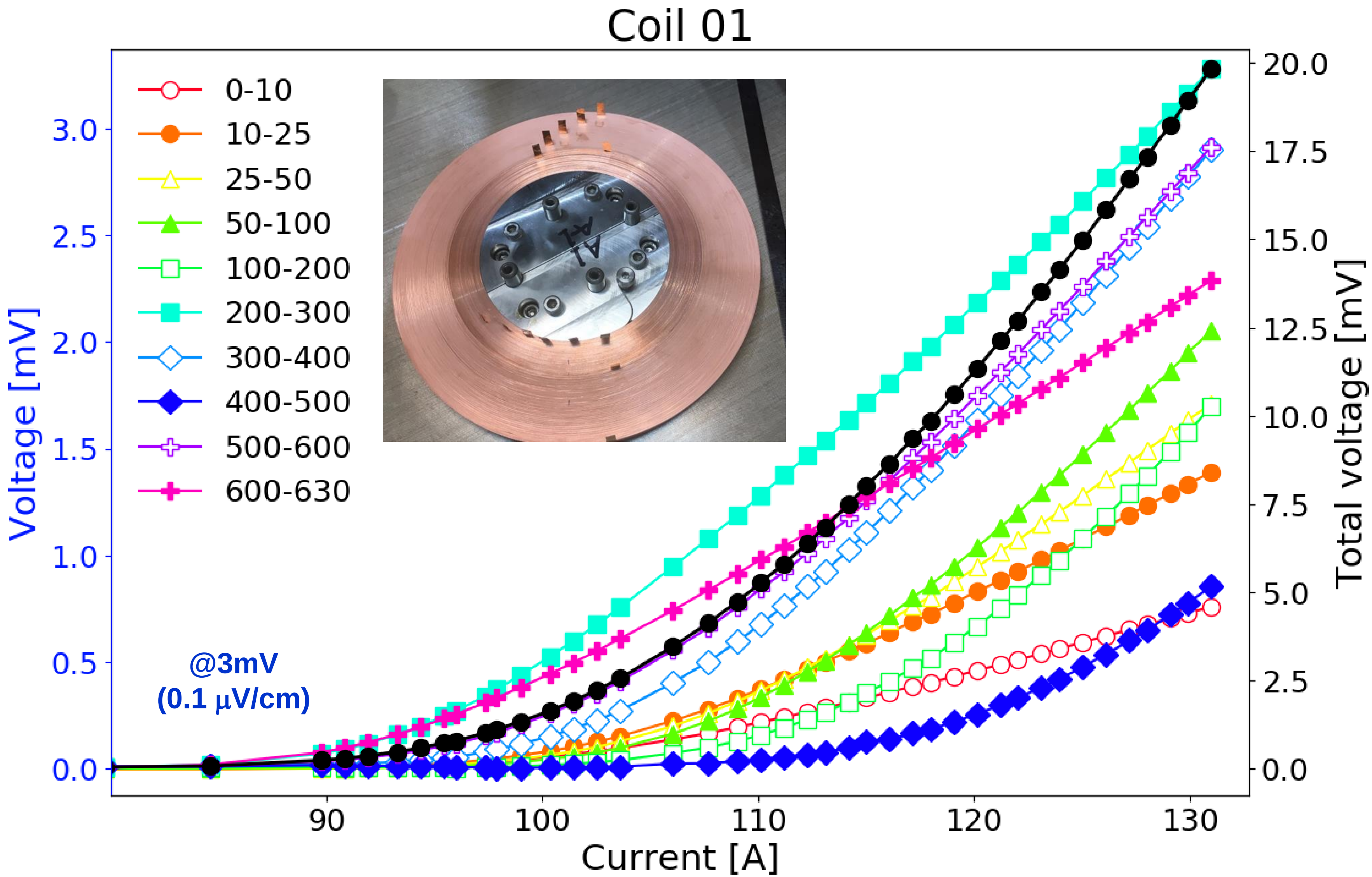


A significant variation between coil to coil

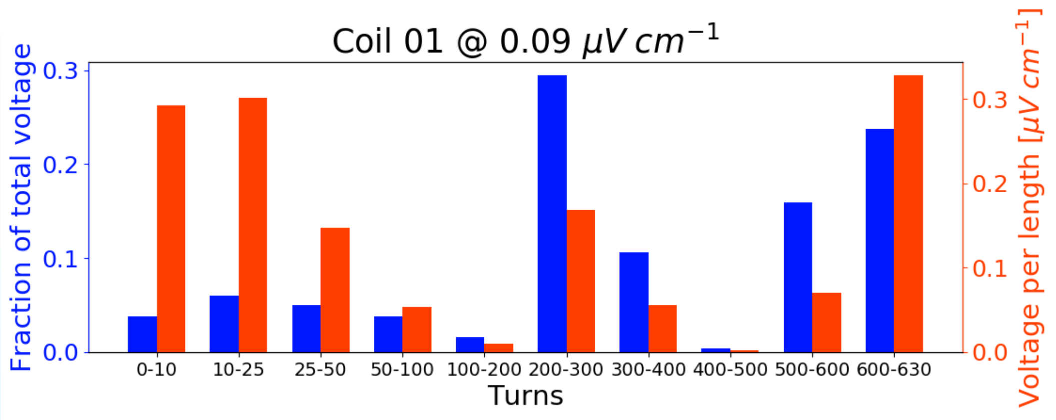
50 A in single pancake creates ~0.5 T and in double pancake ~1 T

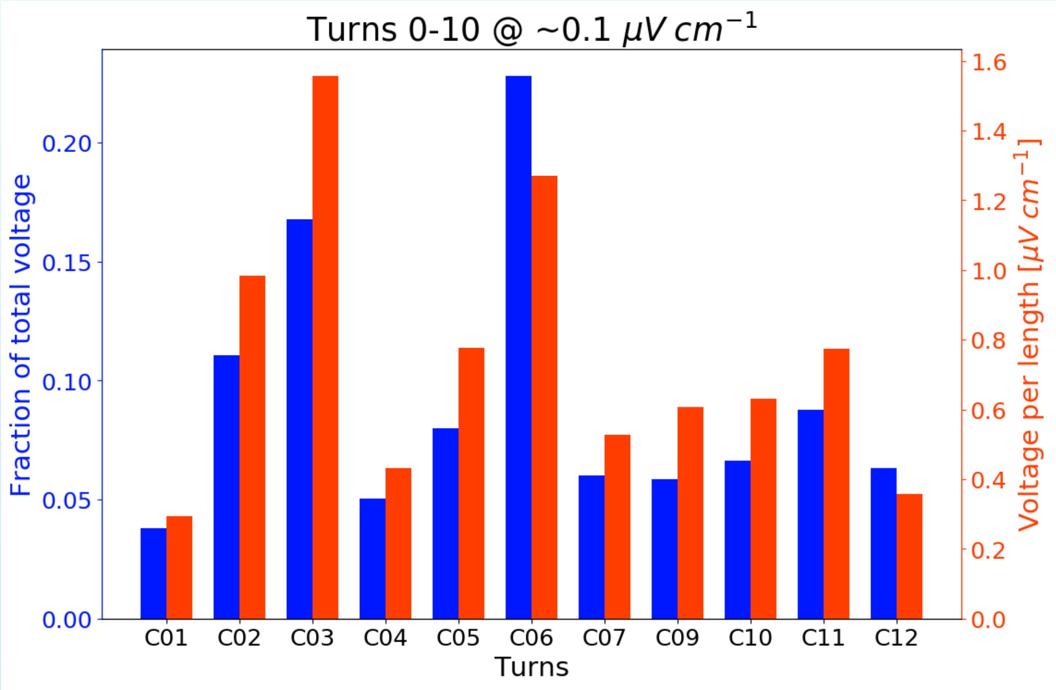
@3mV (0.1 μV/cm)

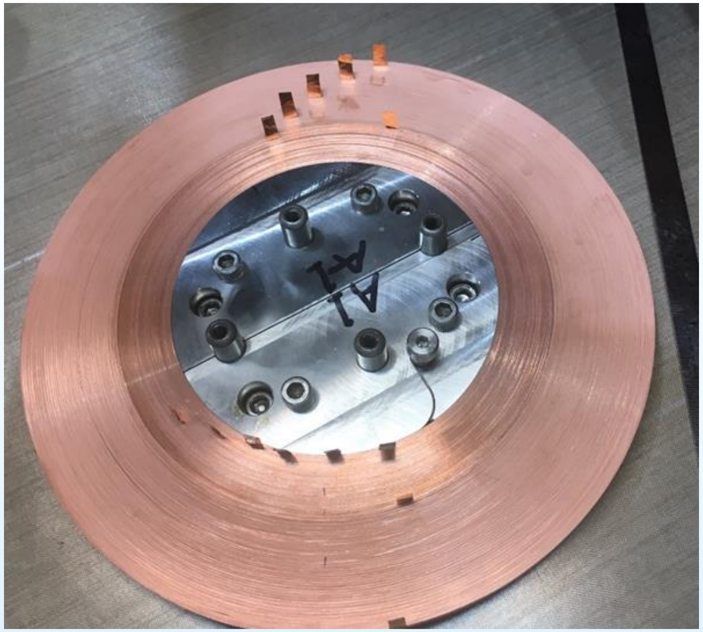
Details of the 77 K Test Results (Sectional Voltage in Coil #1)



Details of the 77 K Test Results (Sectional Voltage in Coils)







Backup slides for a detailed analysis of 77 K test results for twelve coils

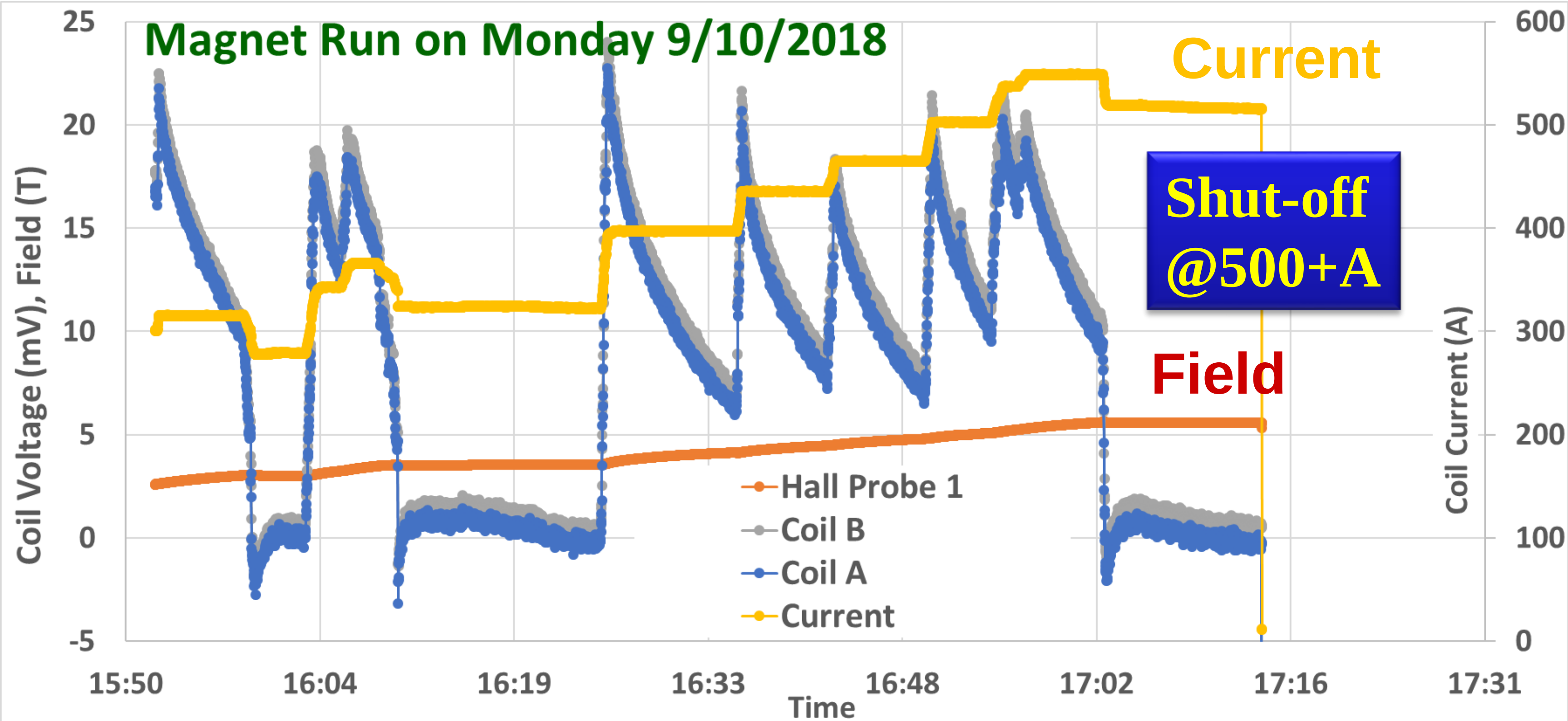
Coil Tests in Helium

IBS Double Pancake Coil Runs with Helium

- **Two sets of runs of R&D coils (including defect simulation with heaters) were carried out in 2017 (not presented here)**
- **Two sets of runs of the IBS double pancake "*production coil*" were carried out from 9/10 to 9/14 and from 10/16 to 10/18. First test run was extensive and discussed 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-offs at various currents**
  - **Many high current quenches or runaways**
  - **Sudden over-current tests**
  - **Helium runout tests**

Attempt to create a series of fault scenarios

Monday Run Summary

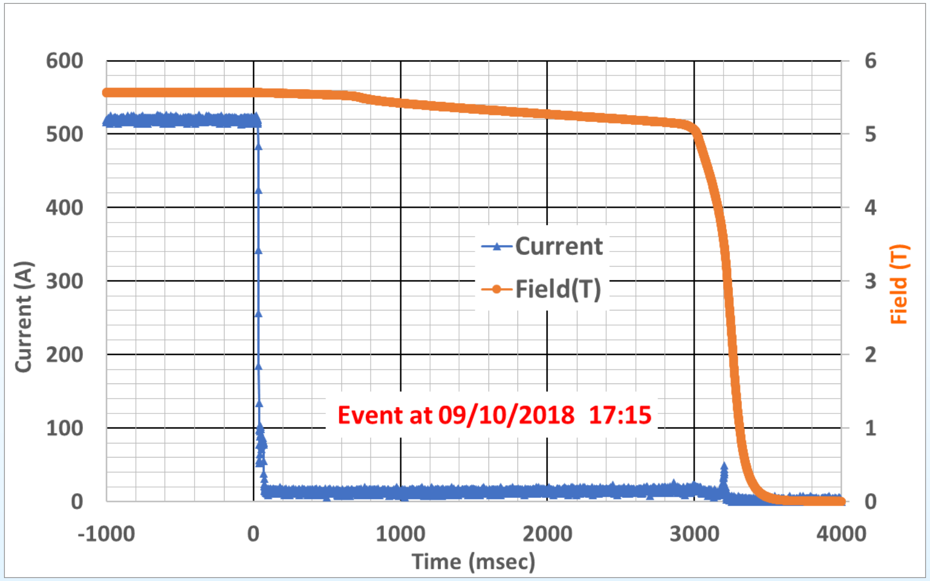


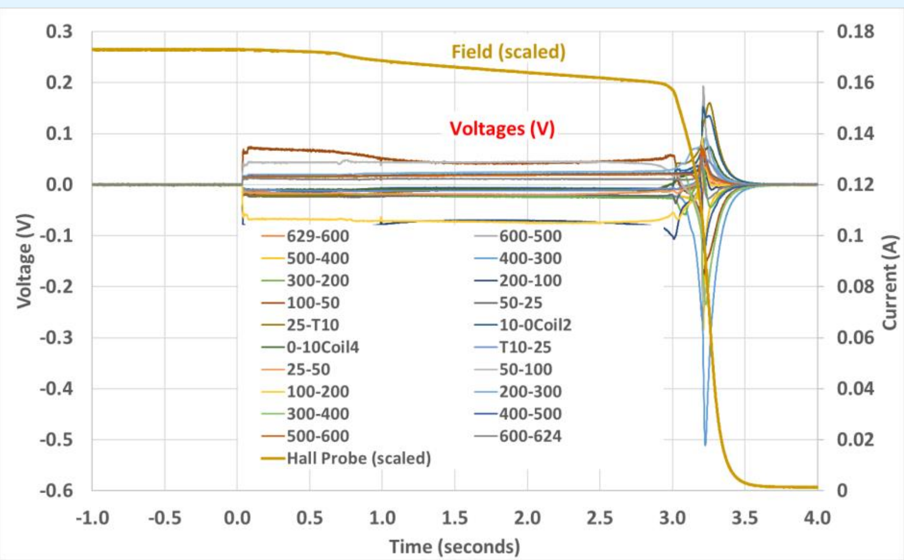
Shut-off may cause an eventual thermal runaway (quench)

- **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)

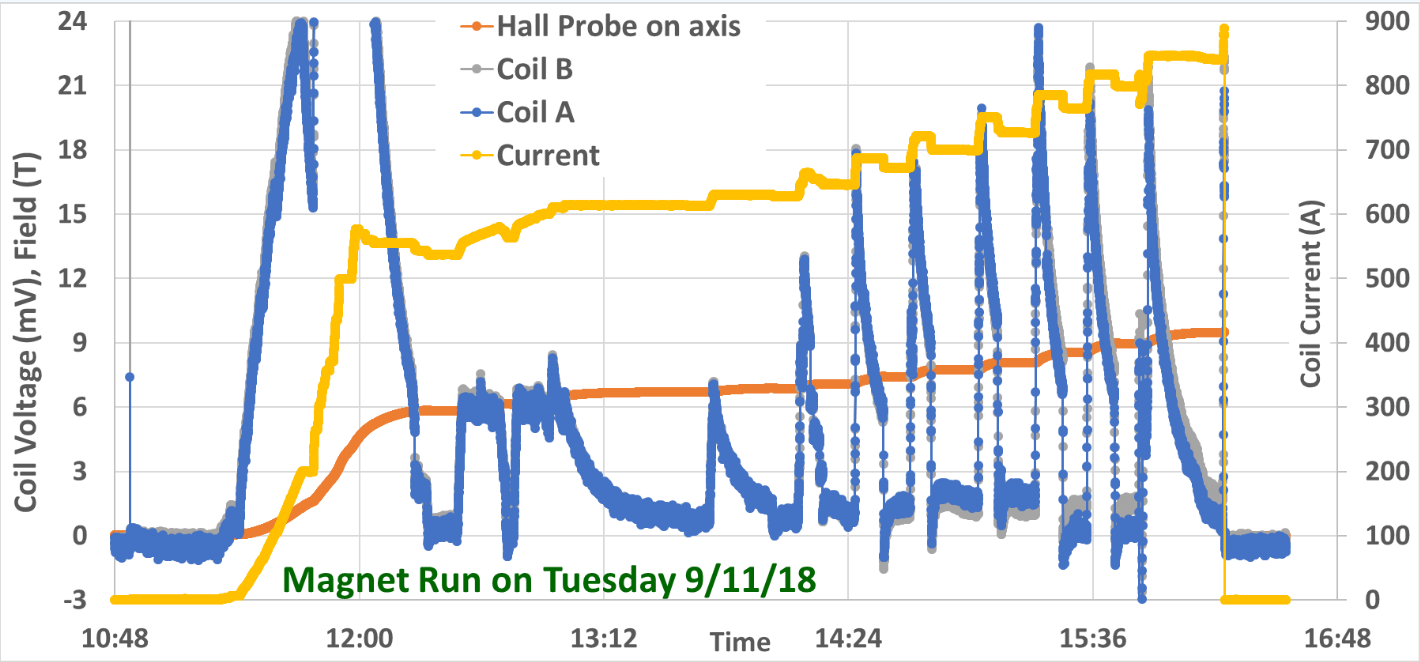




- **In No-insulation coils, in addition to the circulating current, the current may flow across the turns (sideways), providing an extra protection**
- **These sideways current keep flowing even after the power supply shut-off and decay slowly in No insulation coils**
- **These sideways current heat-up 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

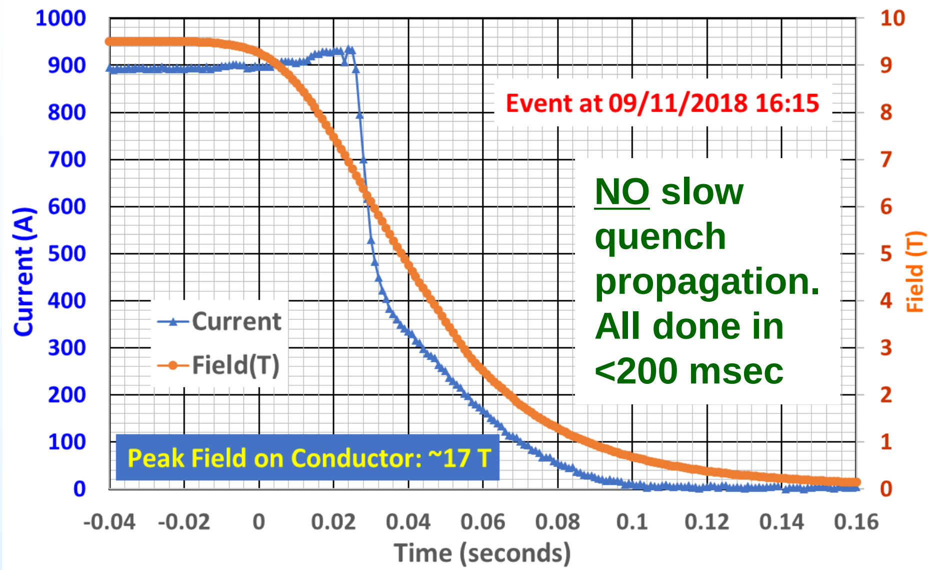
- Keep increasing current to see how high it could go (as in LTS)
- Quenched in going from 850 A to 900 A (design: ~450 A)
- Bore field ~9 T, Peak field ~17 T (high peak stresses: B x I)

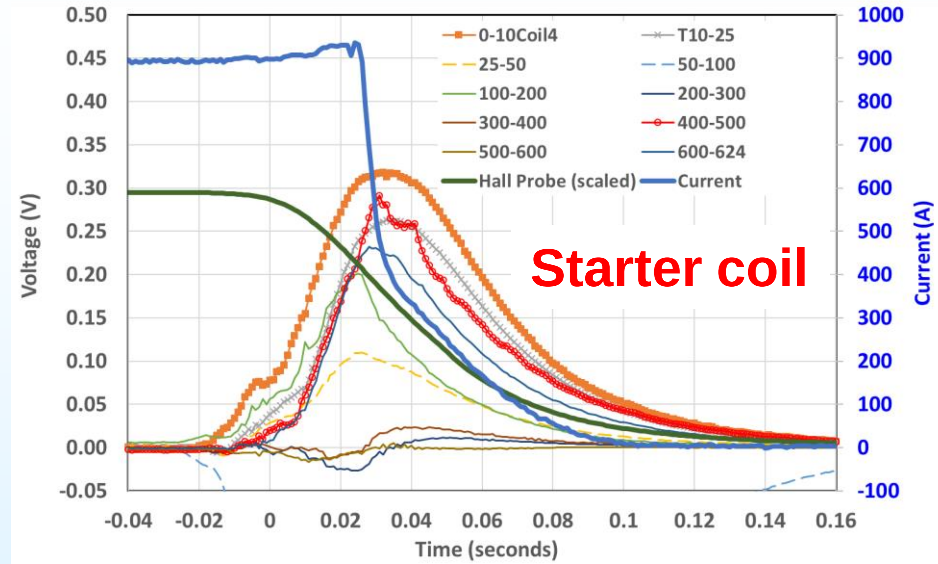


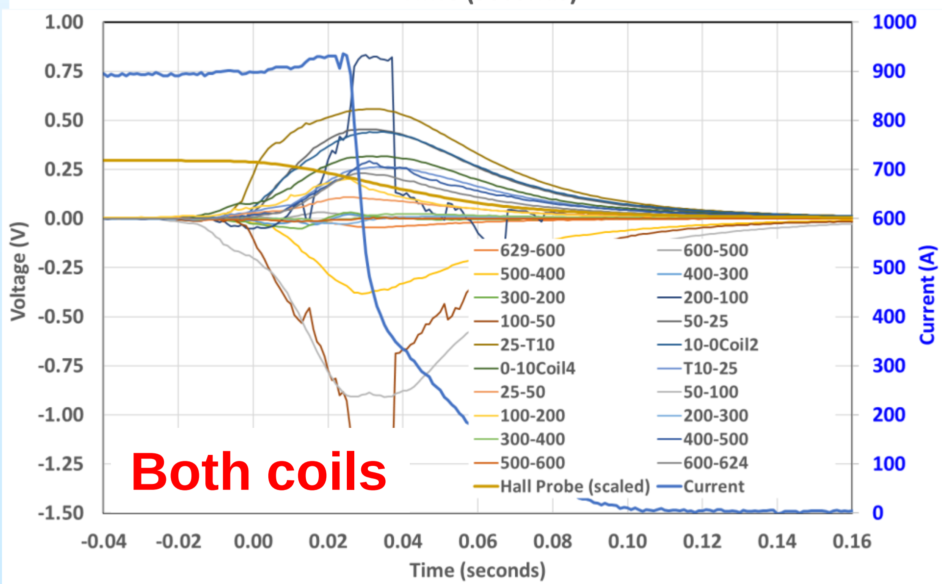
850 Amp in a double pancake creates similar peak stresses and similar stored energy per pancake as in the 25T IBS solenoid

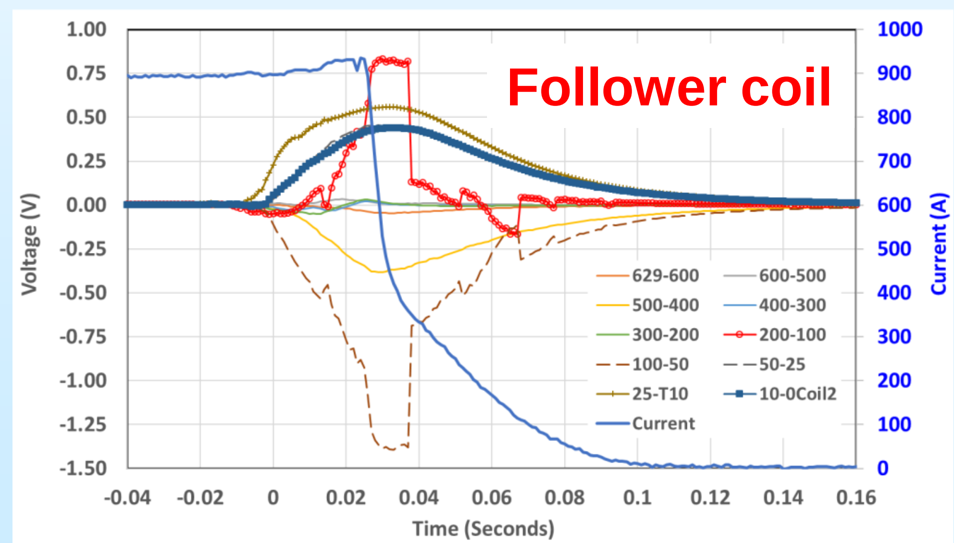
➢ Quench discussed in more details in the next slide

Discussion on Quench at High Current (Tuesday Run: v-taps help in analysis)

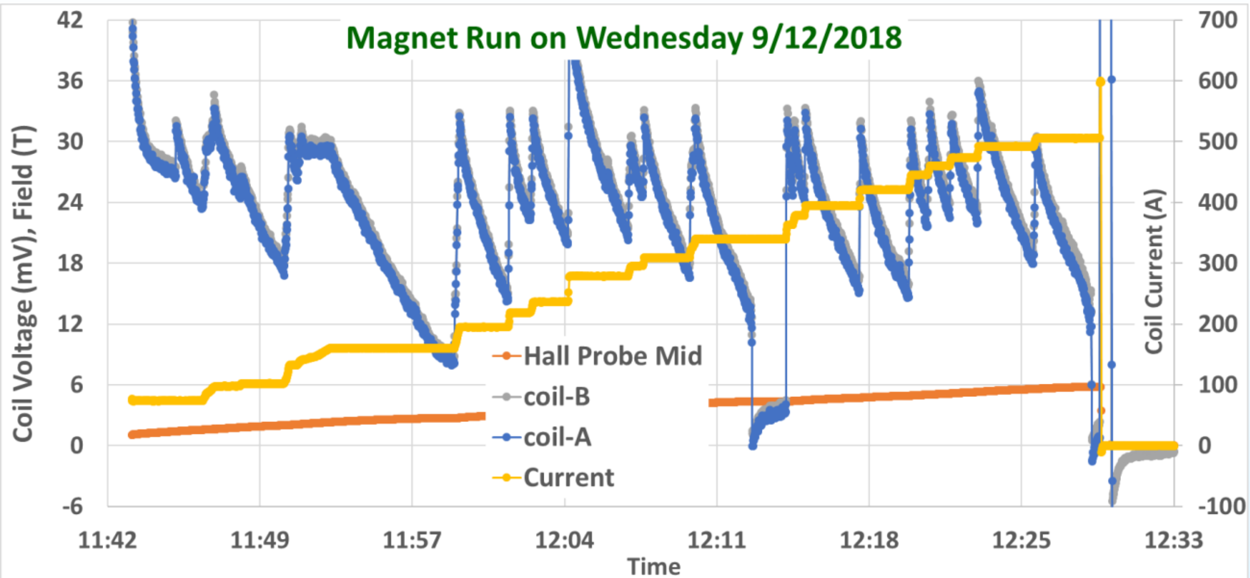


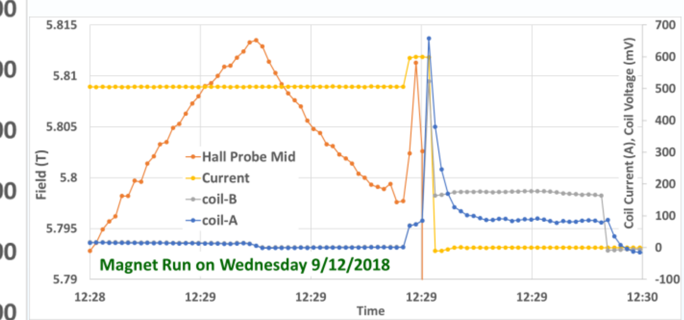




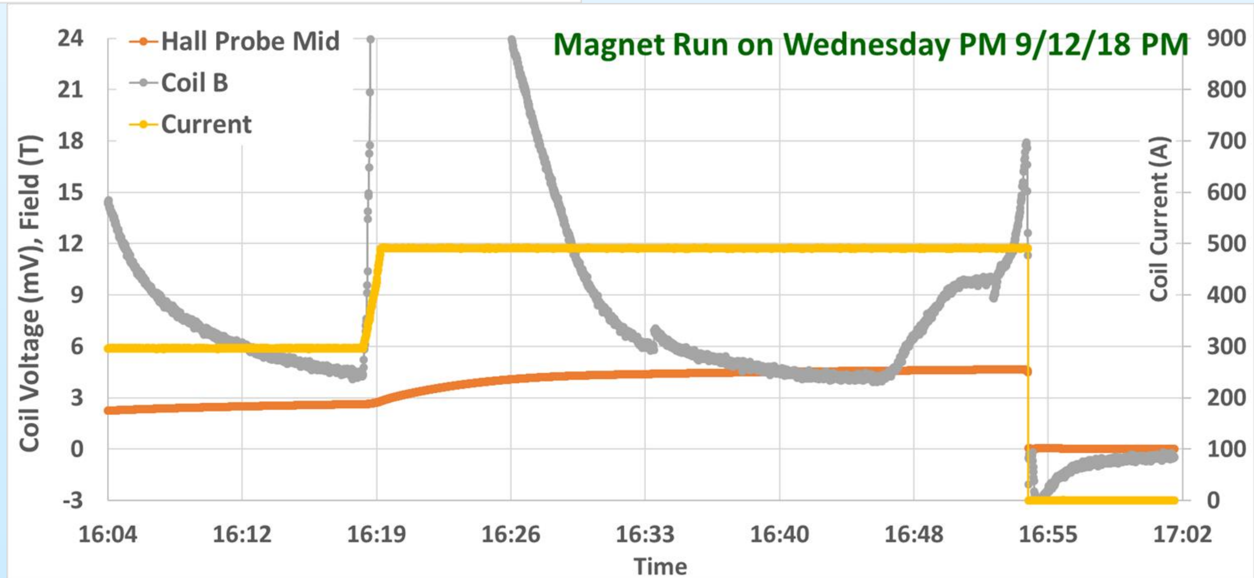


Wednesday Run Summary
(unusual events – not expected during normal operation)

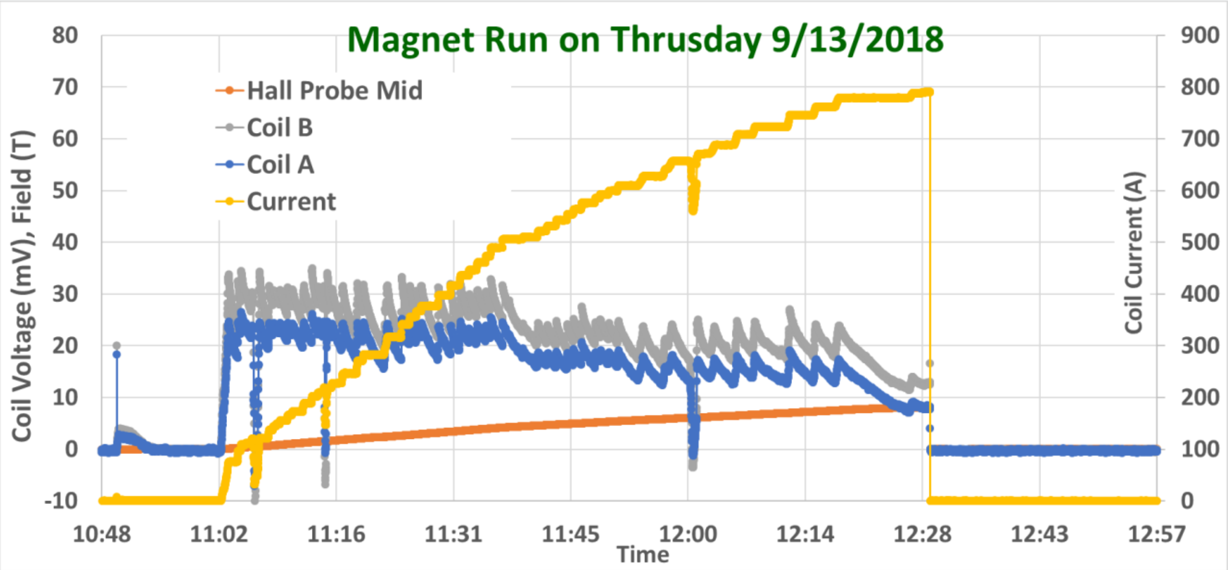




1. **Sudden increase in current due to coupling of two power supplies**
2. **Running out of Helium at the end of the day**

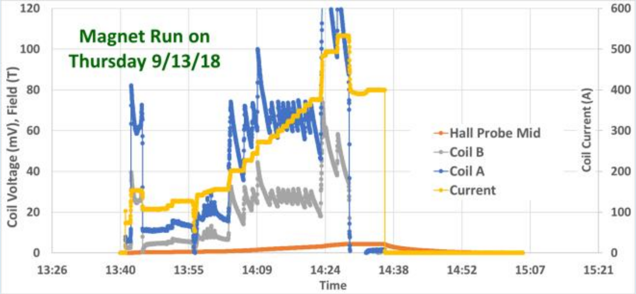


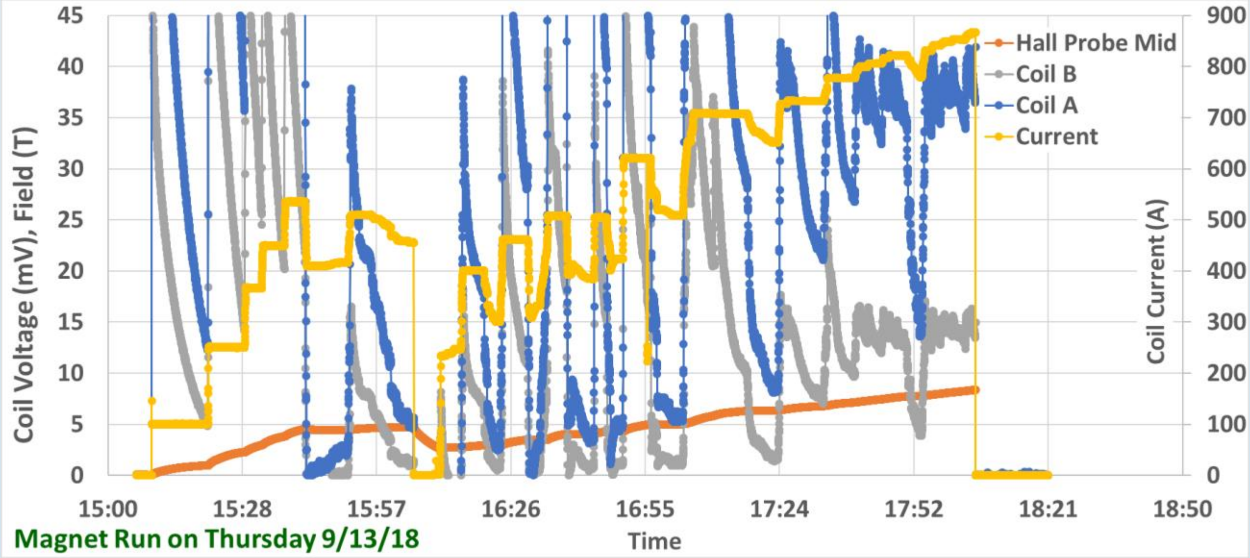
Thursday Run Summary



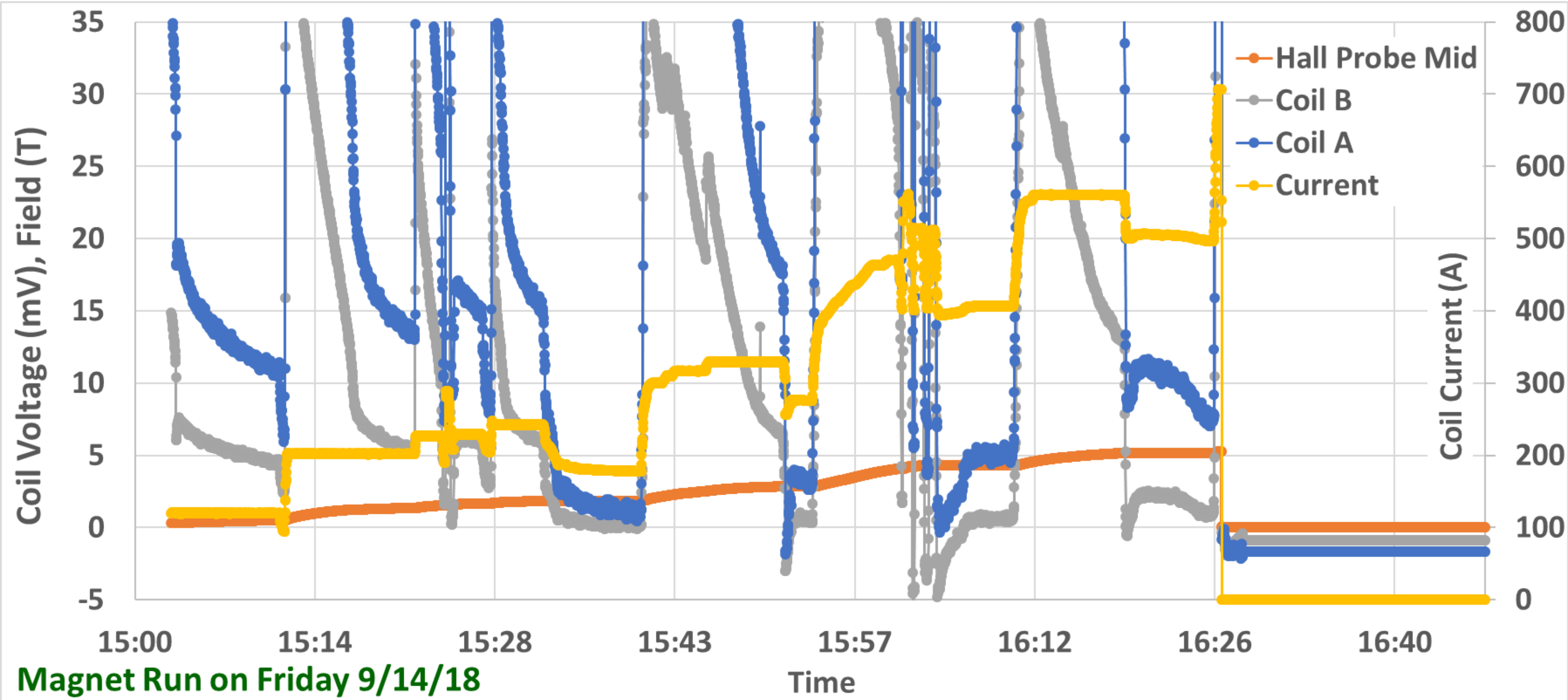
Two more quenches at 800-850 A (design: ~450 A)

..and a shut-off near design current





Friday Run Summary



- Higher temperature operation mostly in Helium gas environment

Overall Summary of four Series of Tests of two Large NI Coils at 4 K

- **Two large coils survived many quenches/thermal runaway at 4 K, 17 T peak field (i.d. 105 mm, o.d. 200 mm, ~600 m of 12 mm wide tape used in each)**
- **Coil survived simulation of a variety of accidents**
- **Maximum current density in coil: ~950 A/mm^2 (design needs ~500 A/mm^2)**
- **Hoop stresses (JXB) over 400 MPa**
- **A large number of v-taps helps understanding of the quench propagation within coil and coil-to-coil**

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.**
- **Conventional Approach: Fast acting heaters. Challenge in HTS magnets to make it work - 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.**

High Field Solenoids for Neutron Scattering

PBL Collaborators:

Bob Weggel, Ron Scanlan, Erich Willen, Steve Kahn, Del Larson and Jim Kolonko

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 (angular opening)

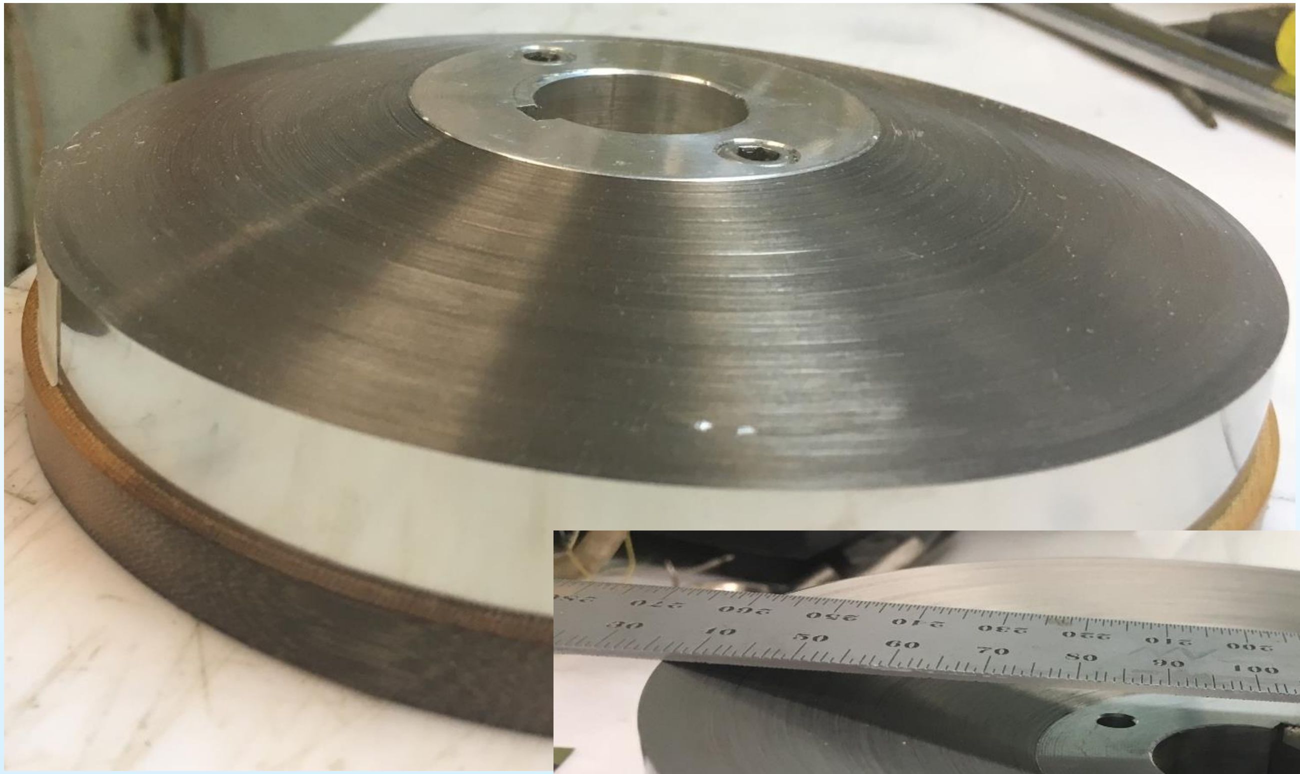
Stated Goals of PBL/BNL SBIR:

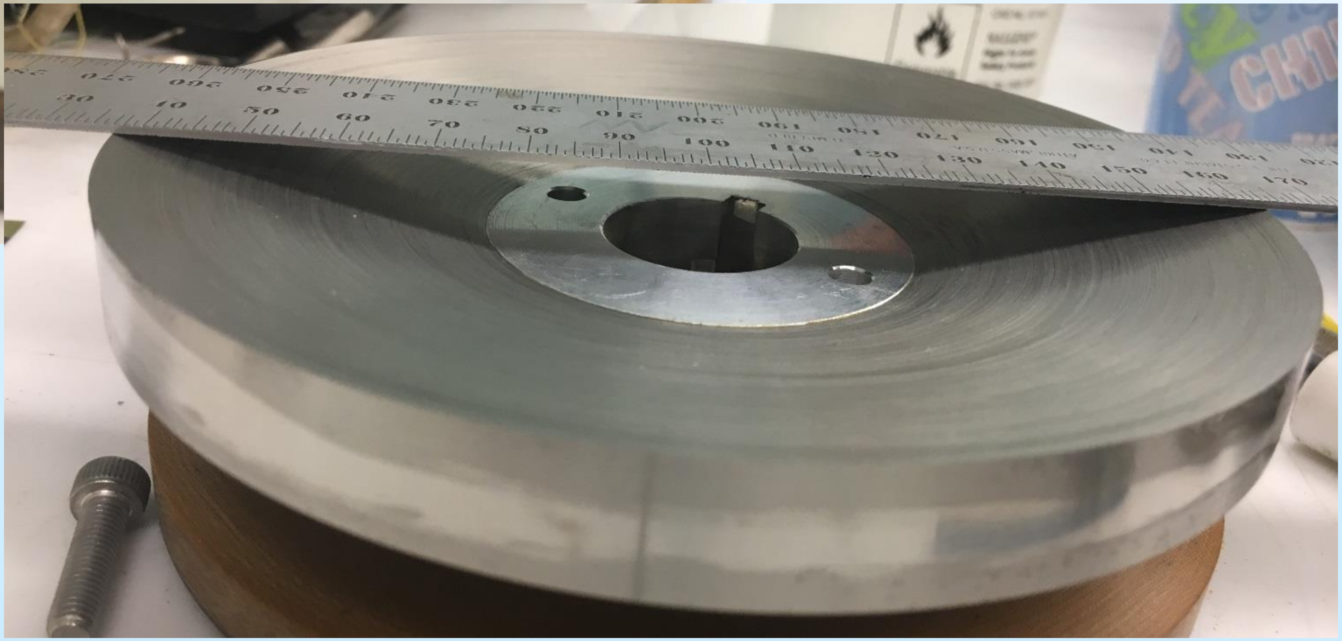
Develop innovative designs and technologies with large opening angles that could revolutionize the capabilities of neutron diffraction

- Specifically exploit the concept of the open-midplane design (developed under HEP for Muon collider and LHC luminosity upgrade)
- Also HTS coils conical angle to maximize the reach of experiment. A NI 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

Practice Winding of Conical Shape Coil (made with Stainless Steel tape)





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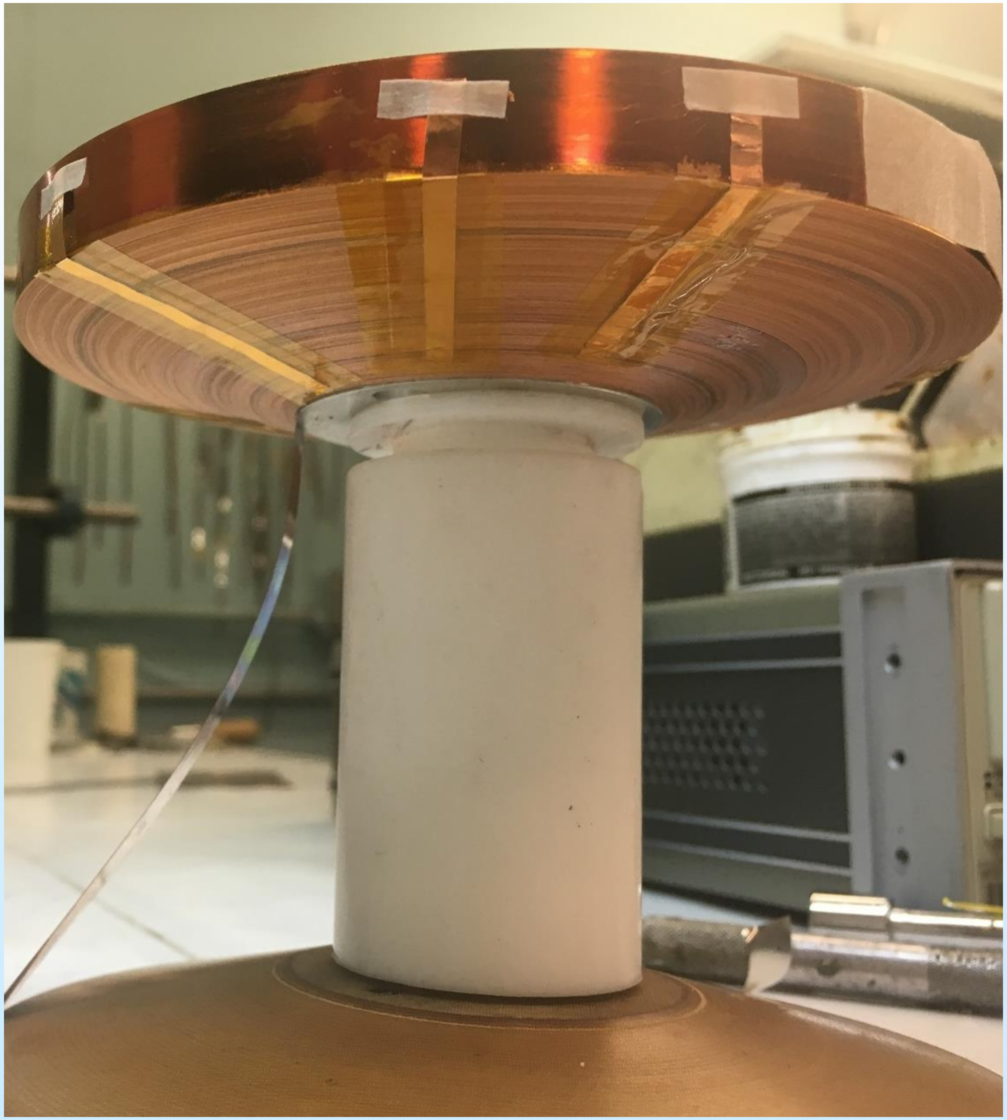
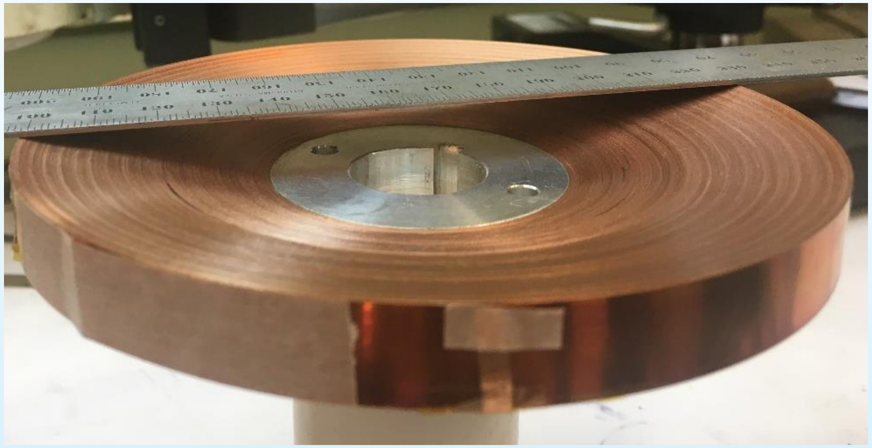
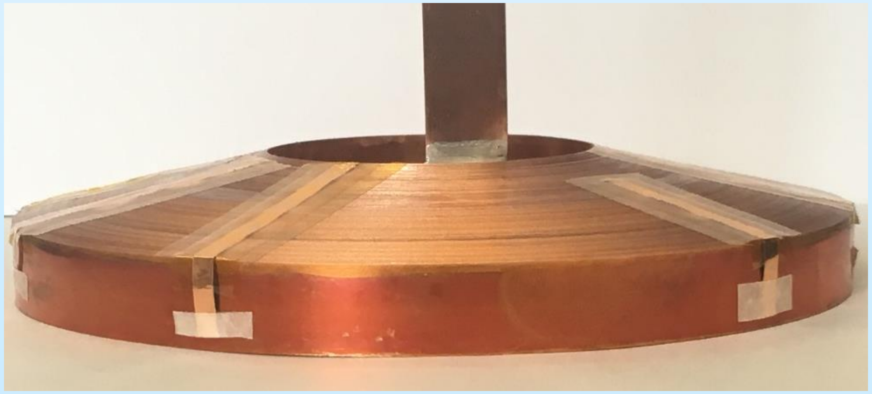
Superconducting Magnet Division

Conical Shape NI HTS Coil

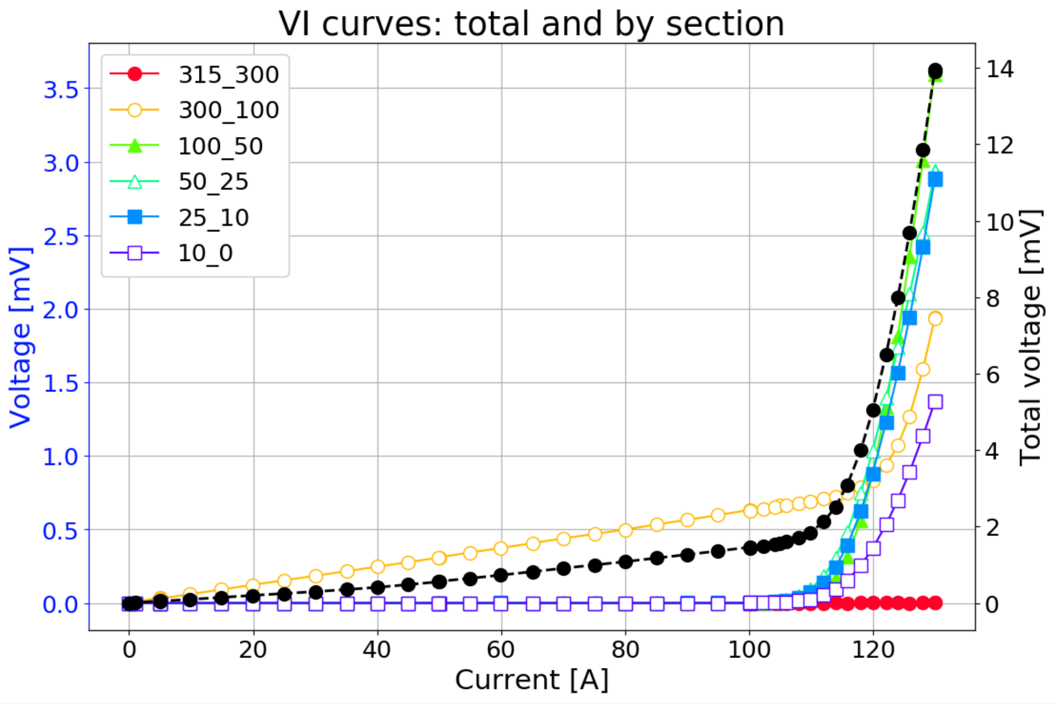


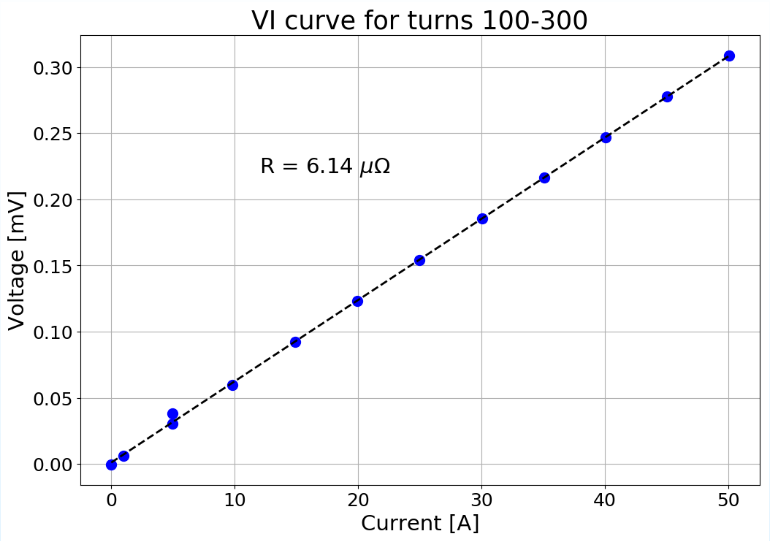
- Cone angle = ±15 degrees
- 315 turns with 12 mm wide tape
- Inner diameter = 2” (50.8 mm)
- Outer dimeter = 5” (127 mm)

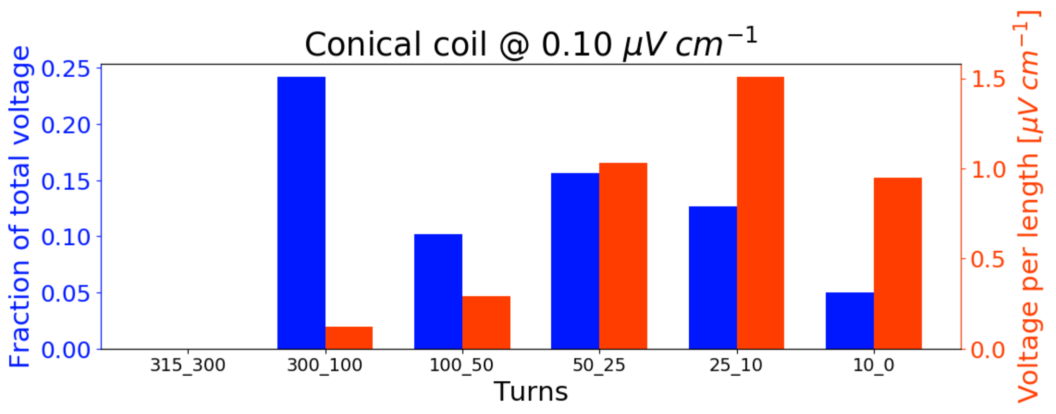




77 K Test Results (just received)







- **Local resistive component**
- **Starts from the beginning, source needs to be examined (is it real?)**
- **Perhaps wind another coil**
- **Apart from this, the winding experience went well**

BNL Participation in USMDP

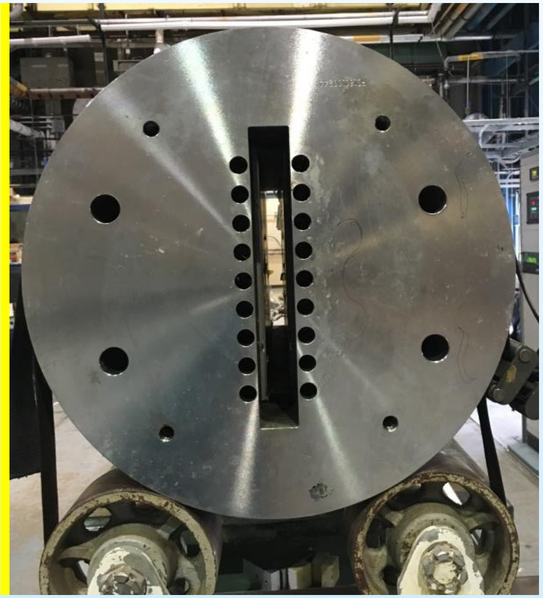
- BNL has recently joined the US Magnet Development Program
- Specific tasks this year uses BNL's common coil dipole to perform R&D for high field accelerator magnets based on HTS

1. Quench studies on CORC cable in dipole field
2. Magnetization studies on HTS tape coils with dipole field primarily parallel to wide face and hybrid field over 10 T

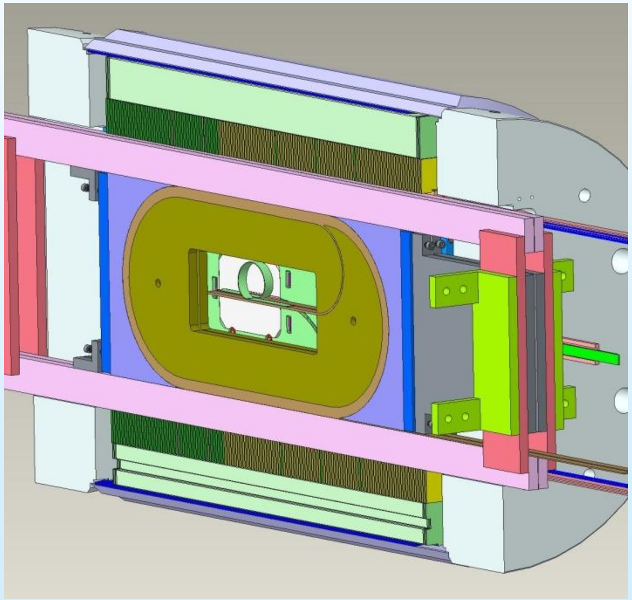
Plans underway to make this magnet available for a wider use. It will operate in an independent test stand providing a background field of 10 T and current for cable/coil up to 30 kA (100 kA option)

A Unique Facility for Magnet R&D

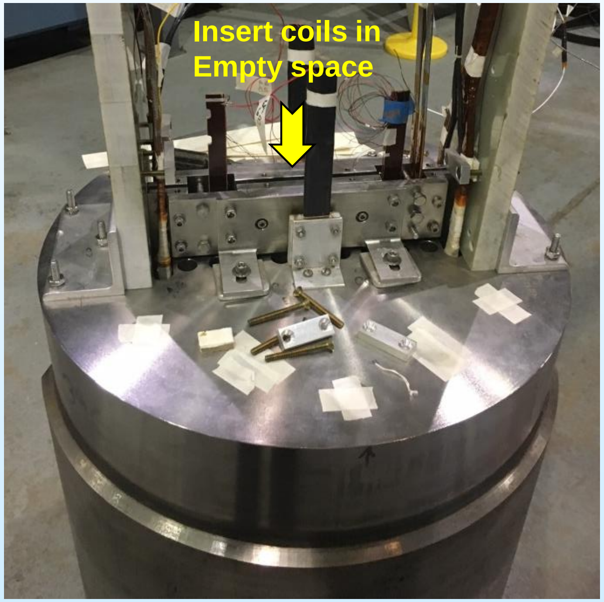
- BNL Common coil dipole offers a large open space for inserting and testing "coils" at high fields without requiring any disassembly
- New racetrack coils come in direct contact with the existing Nb_3Sn coils, just as in any other coils in magnets
- A coil test becomes a magnet test with a rapid around and lower cost



BNL Nb_3Sn common coil dipole DCC017 without insert coils

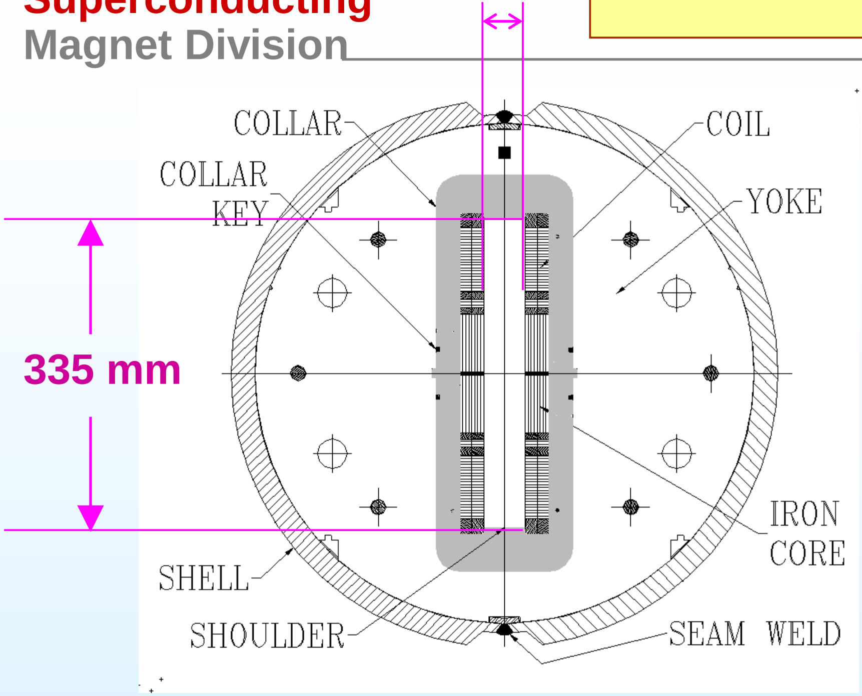


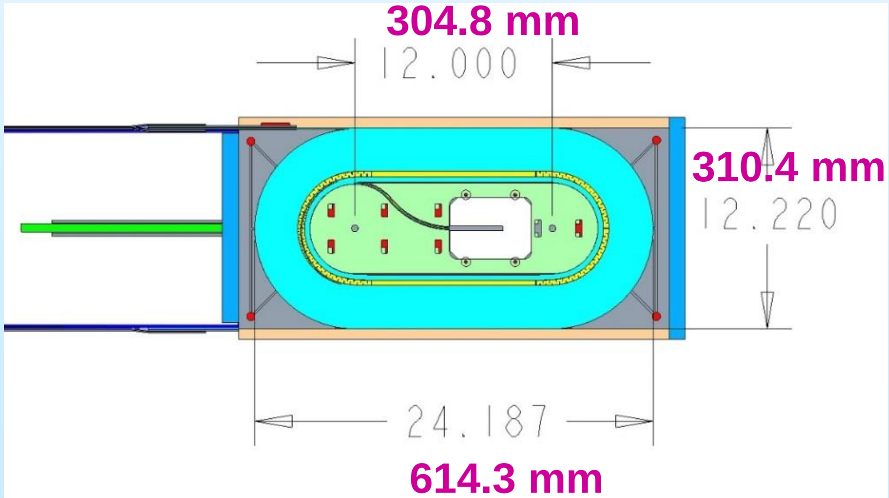
New HTS coils with the existing Nb_3Sn coils and become part of the magnet



HTS coils inside Nb_3Sn dipole - early experience of HTS/LTS hybrid dipole

Parameters of BNL Dipole DCC017





- Two layer, 2-in-1 common coil design
- 10.2 T bore field, 10.7 T peak field at 10.8 kA short sample current
- **31 mm horizontal aperture**
- **335 mm vertical aperture**
  - **A unique feature for insert coil or cable testing**
- 0.8 mm, 30 strand Rutherford cable
- 70 mm minimum bend radius
- 85 mm coil height
- 614 mm coil length
- One spacer in body and one in ends
- Iron over ends
- Iron bobbin
- Stored Energy@Quench ~0.2 MJ

Summary

- Slow ramp rate and relaxed field quality in IBS 25 T, 100 mm bore HTS solenoid allows the use of No-insulation (NI) winding (courtesy S. Hahn)

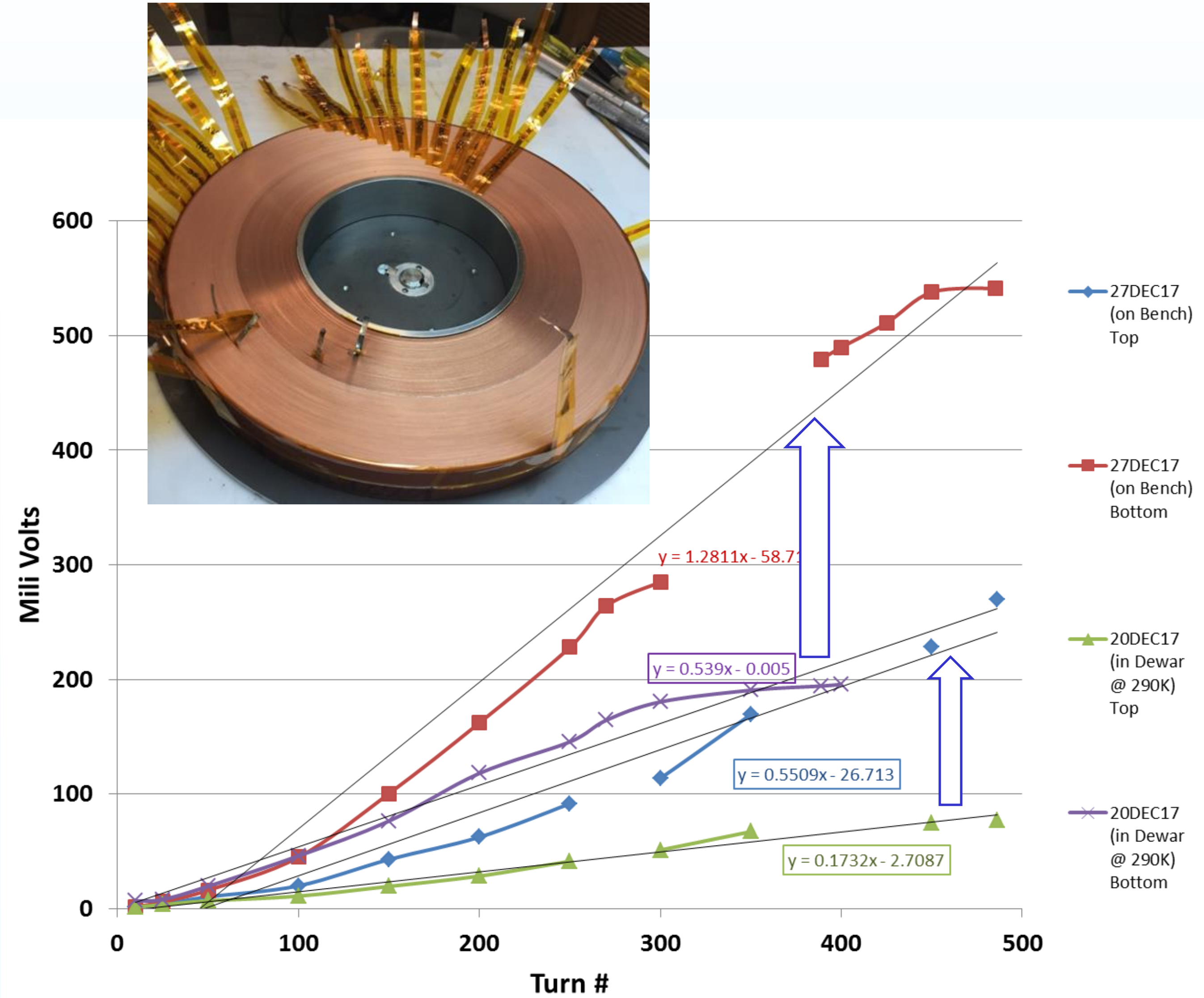
- Four sets of 4 K test runs with many voltage taps in two sets of coils. A large number of v-taps provide useful information for extensive analysis

- IBS double pancake coils were 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, implying 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

Extra Slides

Observed Change in Contact Resistance

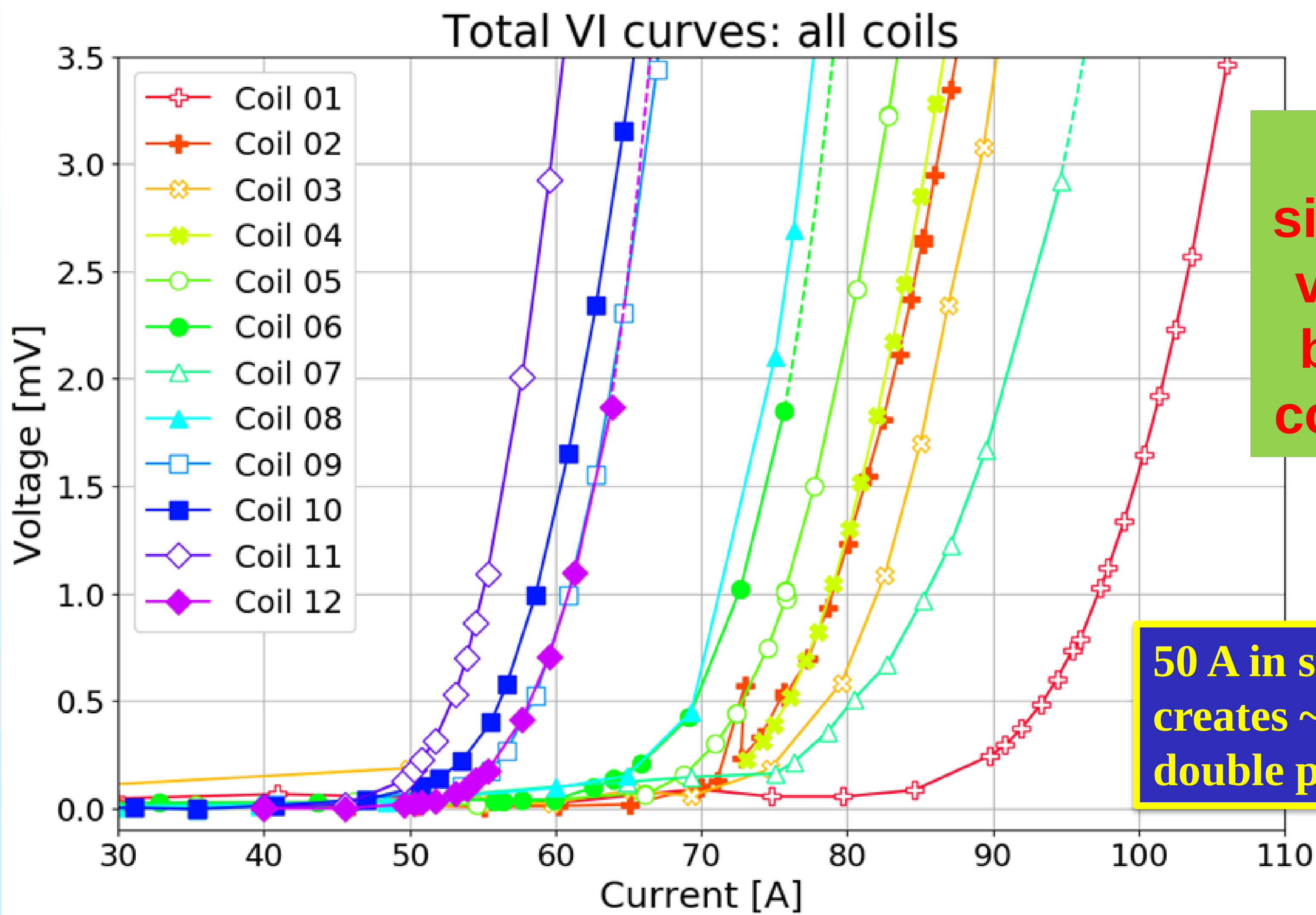


- Large coil (100 mm id, 220 mm od, using >500 m 12 mm tape)
- No epoxy painted on the surface
- Coil was rewound at higher (3X) tension
- Better situation with higher tension.
- Higher tension used in production coils.

Detailed Analysis of 77 K Test Results

77 K (LN2) Test of 10 Pancake coils

(coils 1-6 tested as single pancakes and 7-12 as double pancakes)

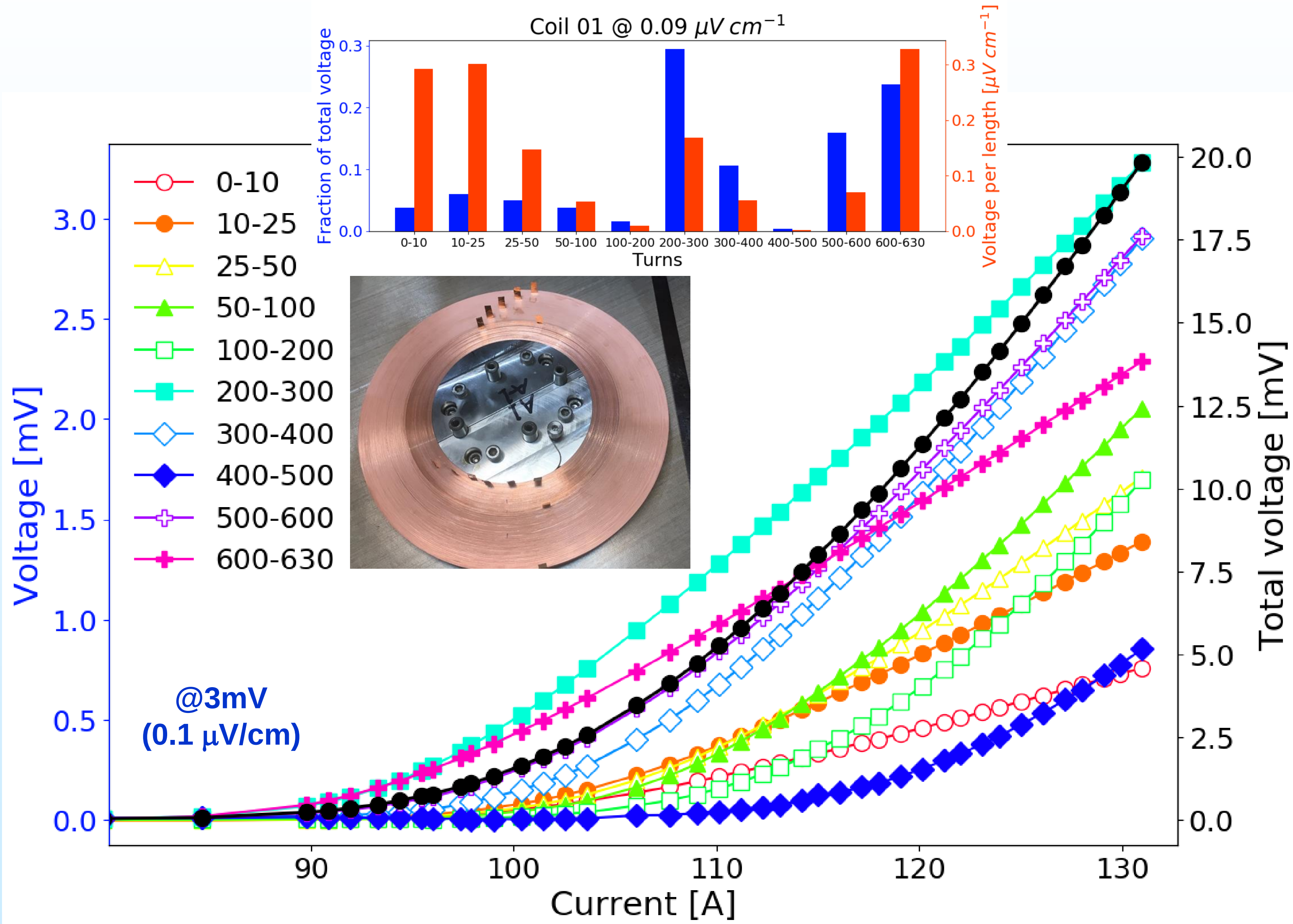


A significant variation between coil to coil

50 A in single pancake creates ~0.5 T and in double pancake ~1 T

@3mV (0.1 μV/cm)

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



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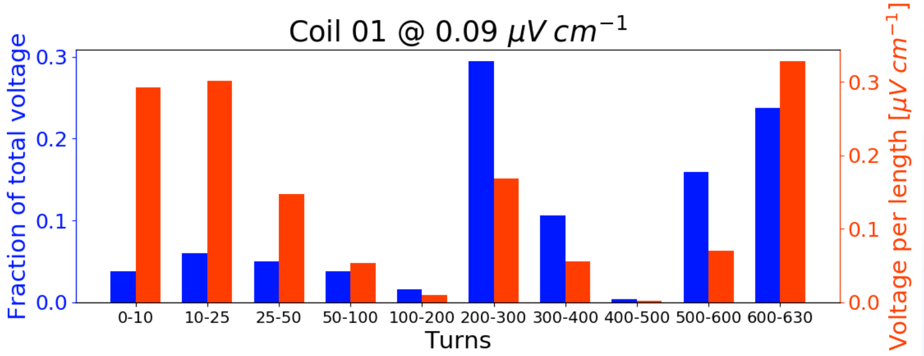
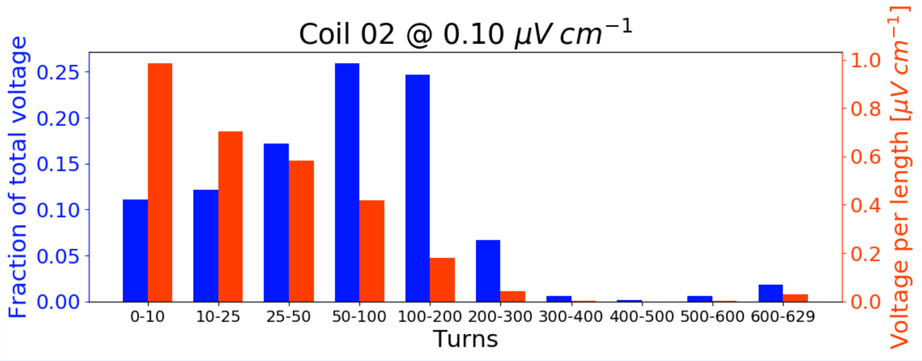
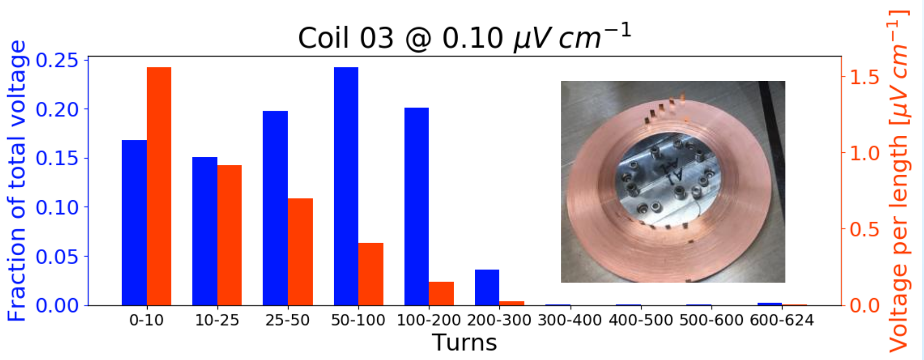
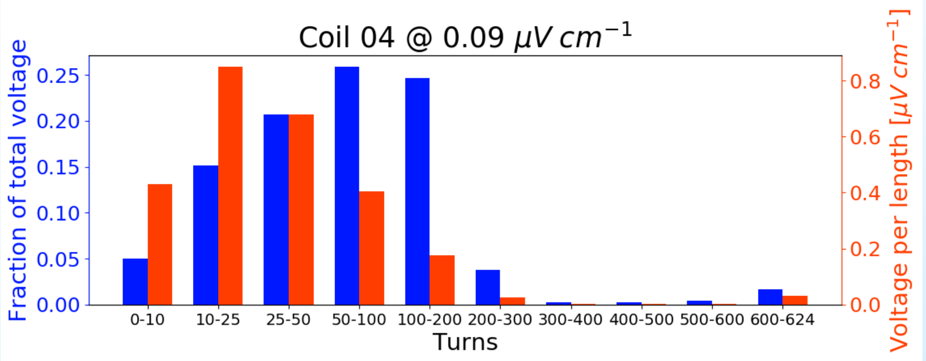
Distribution of Voltage @77K within Pancakes
Coils #1 to Coil #6 (tested as single pancakes)

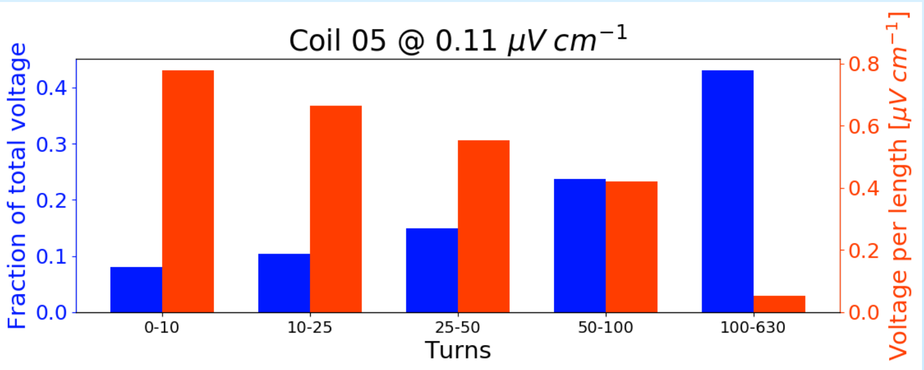


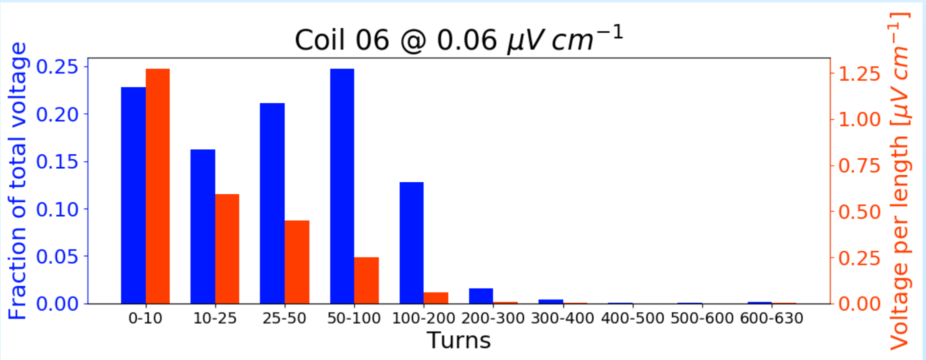






*** Note: A significant coil to coil variation ***





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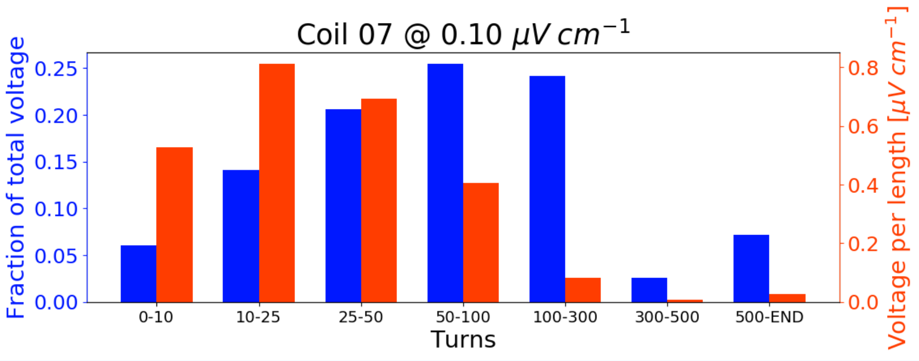
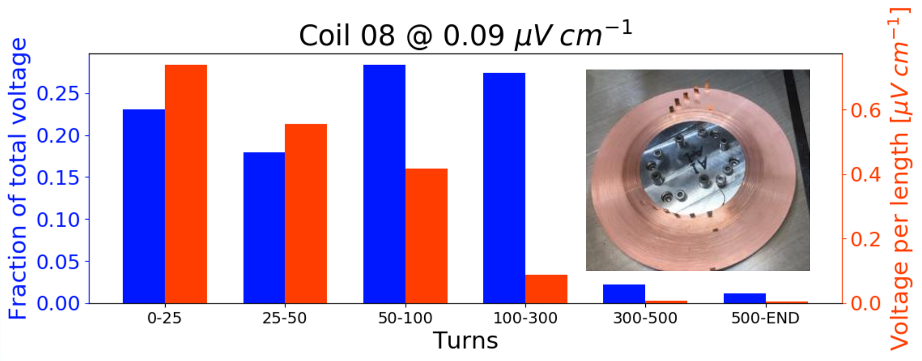
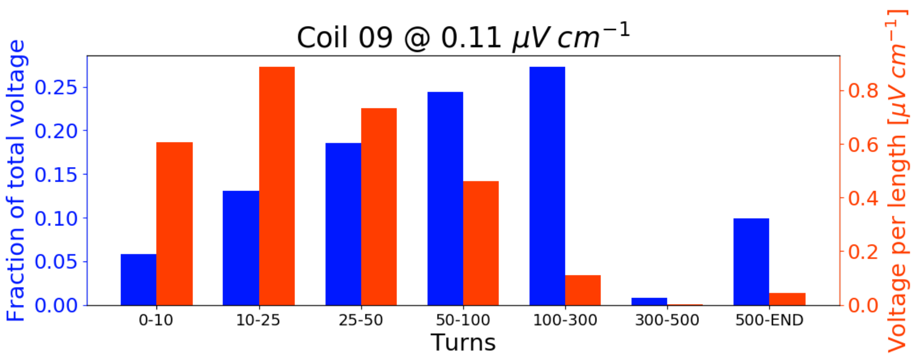
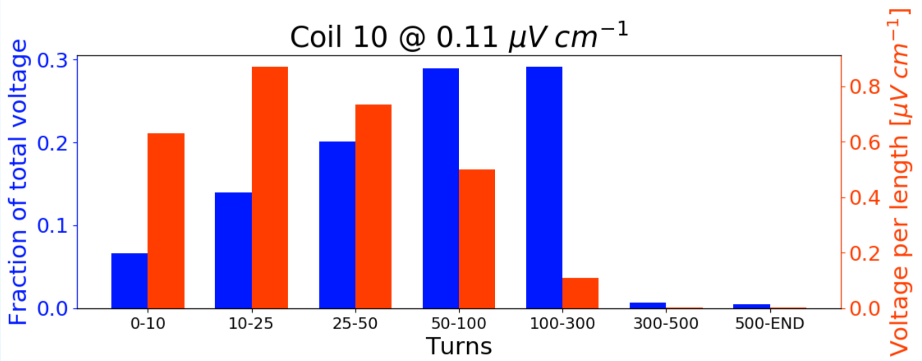
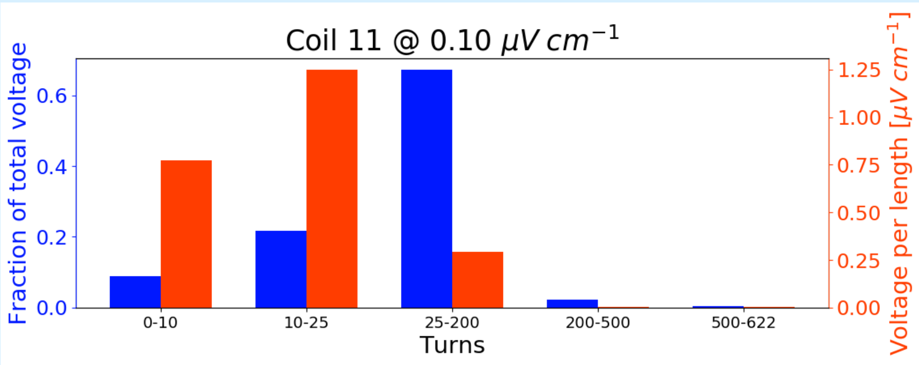
Distribution of Voltage @77K within Pancakes
Coils #7 to Coil #12 (tested as double pancakes)

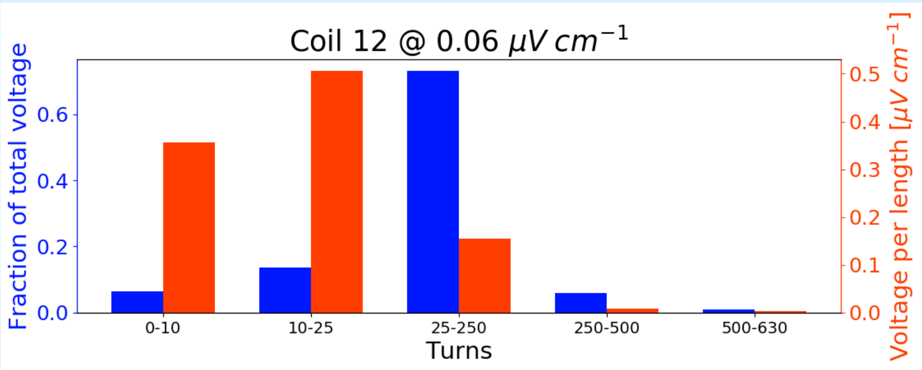








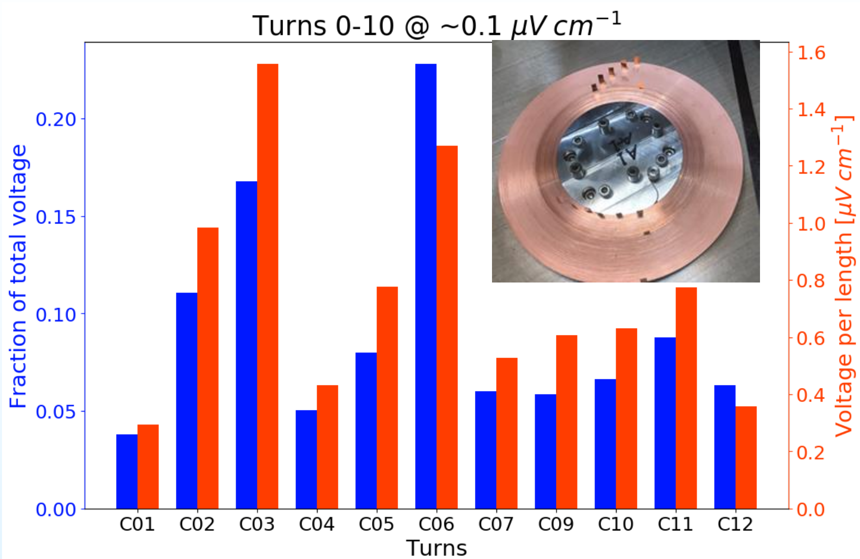


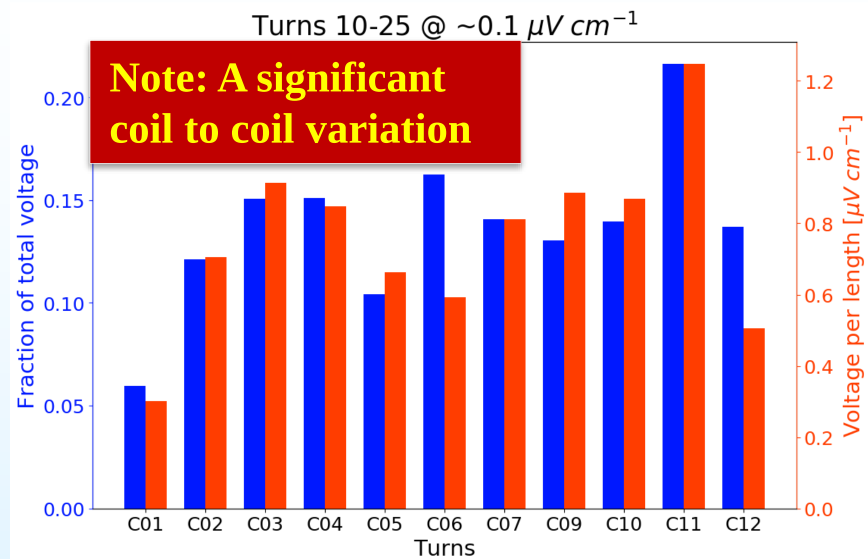


*** Note: A significant coil to coil variation ***

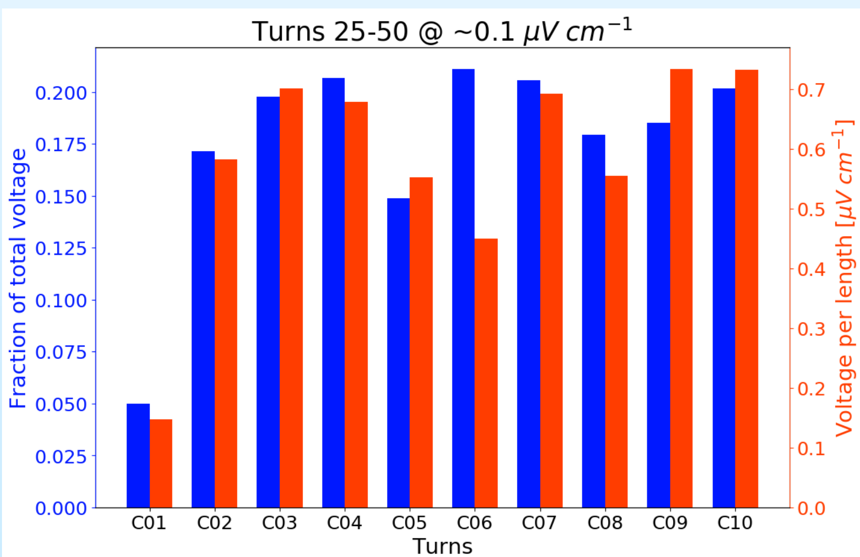
Variation in the Voltage @77K within a set of turns of different Coils (1)

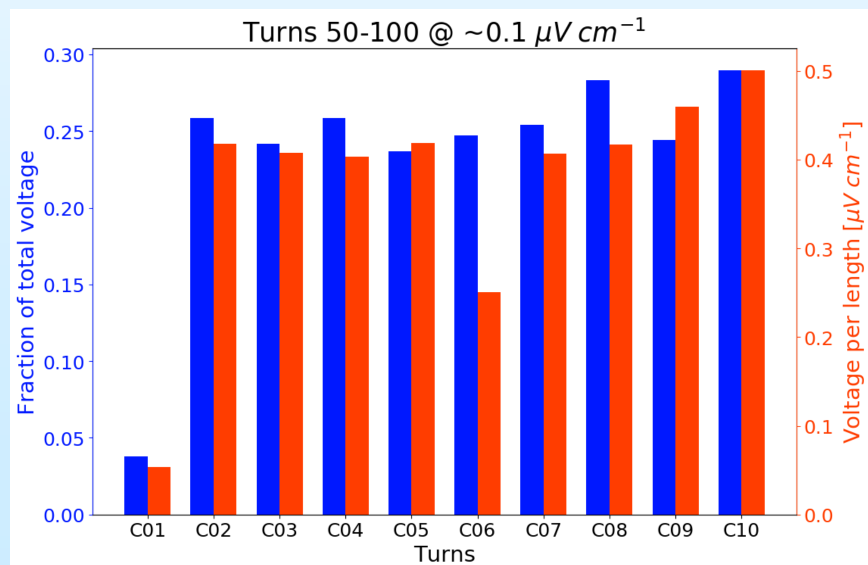
Turns: 0-10, 10-25, 25-50 & 50-100



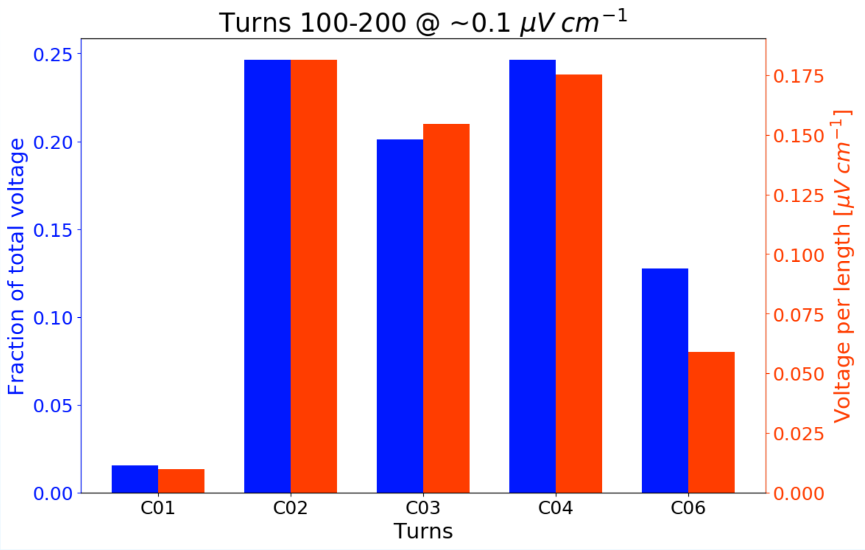


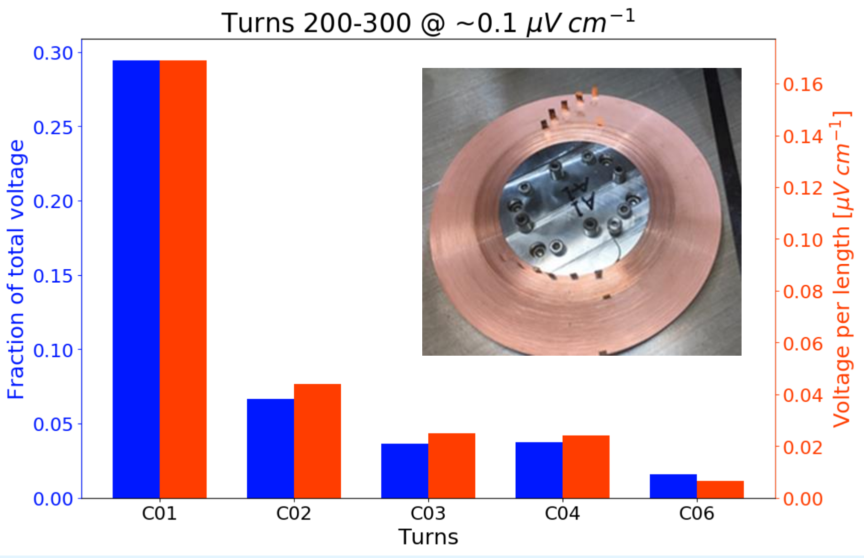
Note: A significant coil to coil variation



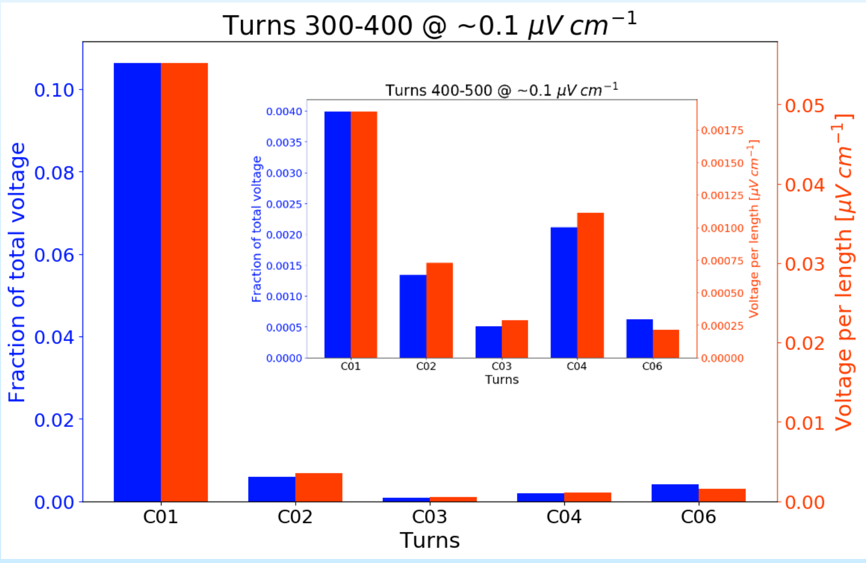


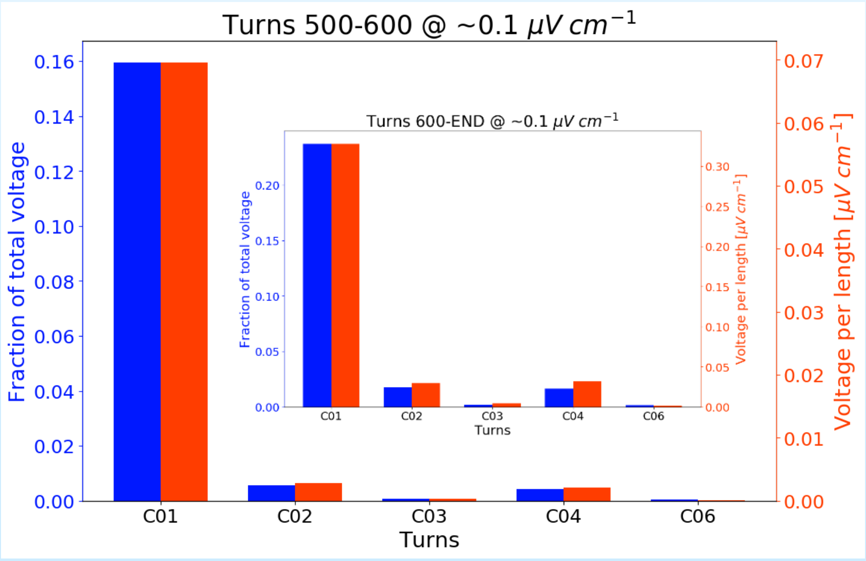
Variation in the Voltage @77K within a set of turns of different Coils (2)



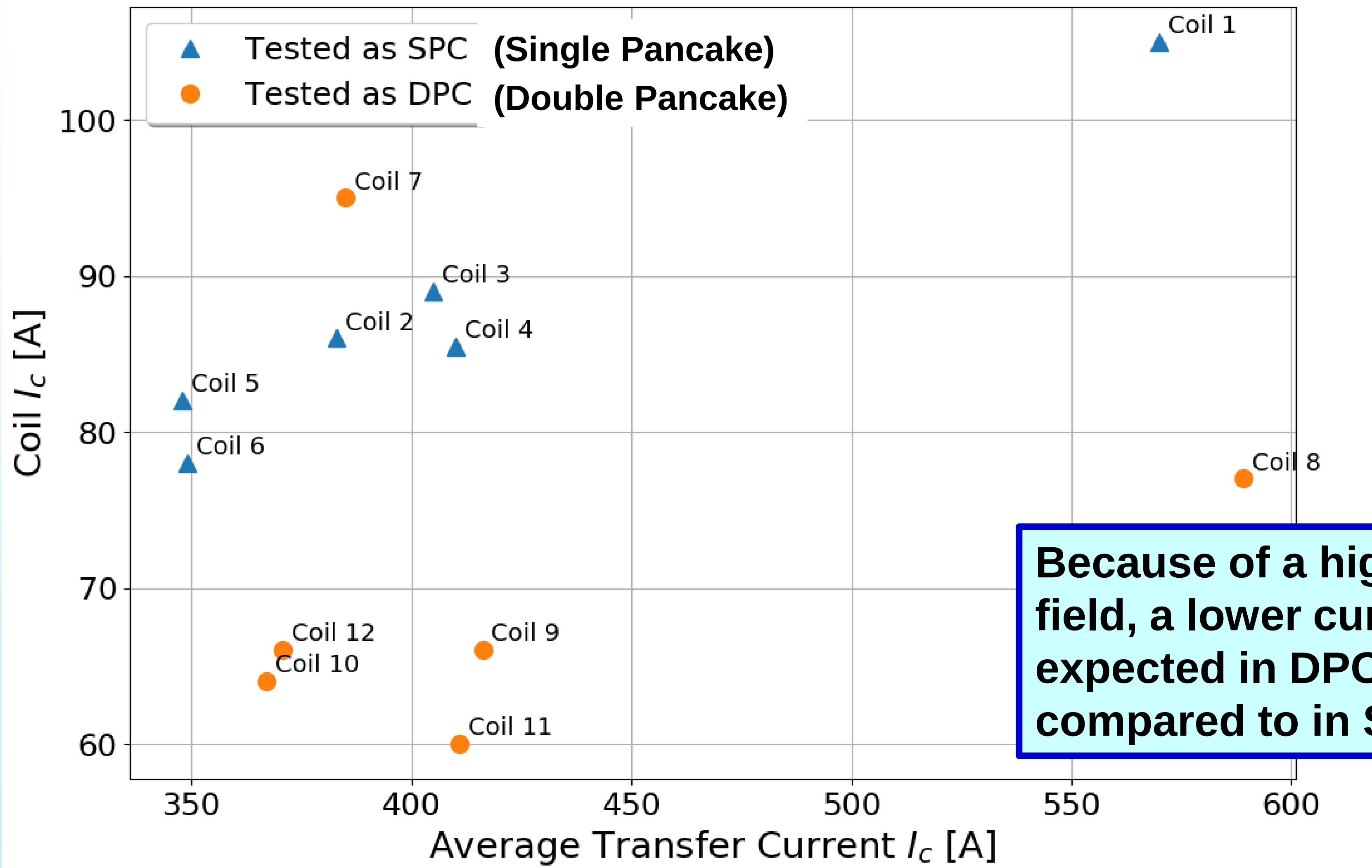


Note: A significant coil to coil variation



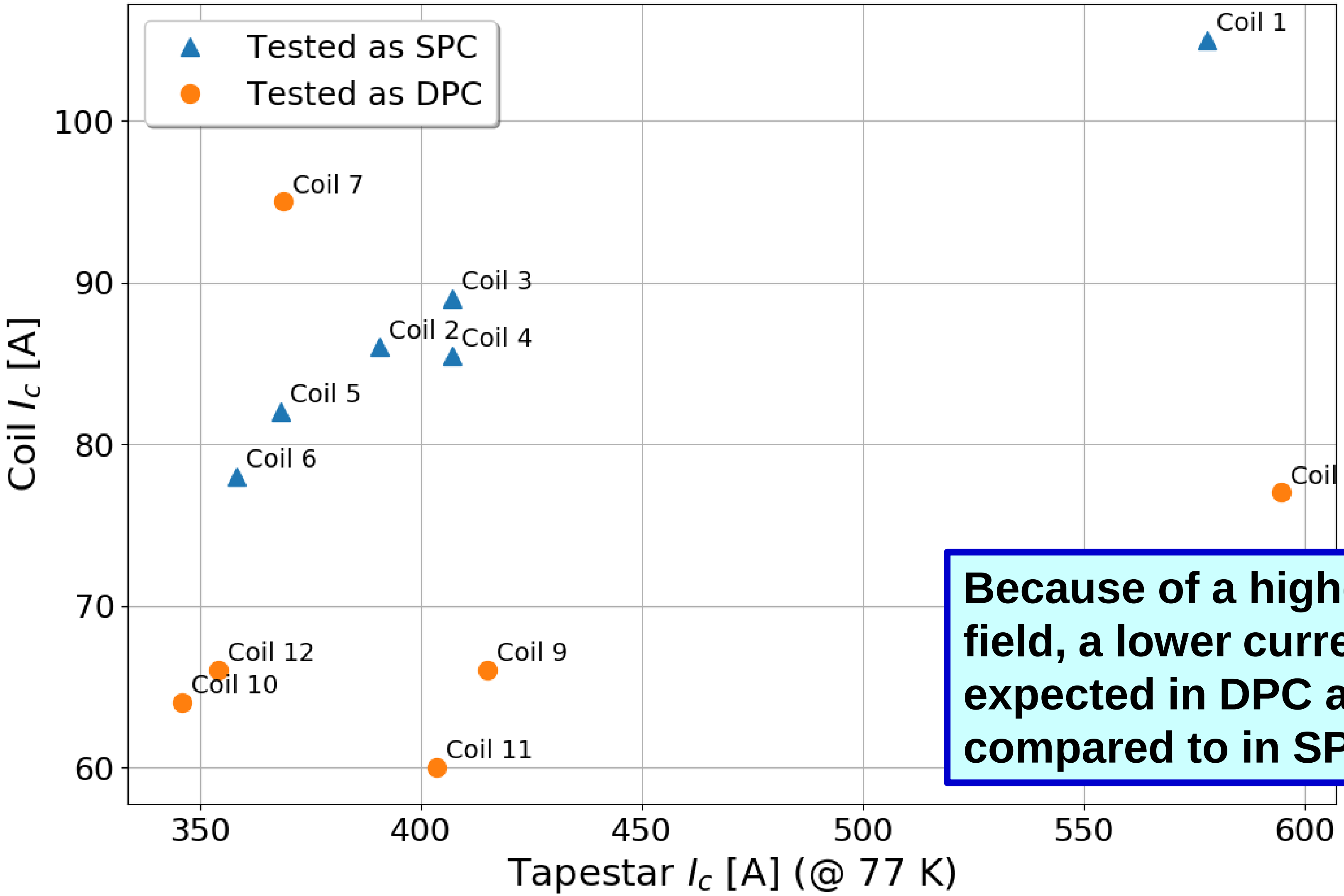


Correlation between Coil I_c (@77K) and Wire Transport I_c (77K, self-field, averaged)



Because of a higher field, a lower current expected in DPC as compared to in SPC

Correlation between Coil I_c (@77K) and Wire Tapestar I_c (77K, self-field, averaged)



Because of a higher field, a lower current expected in DPC as compared to in SPC

Correlation between Coil I_c (@77K) and Wire I_c (30 K, 2 T, ends only)

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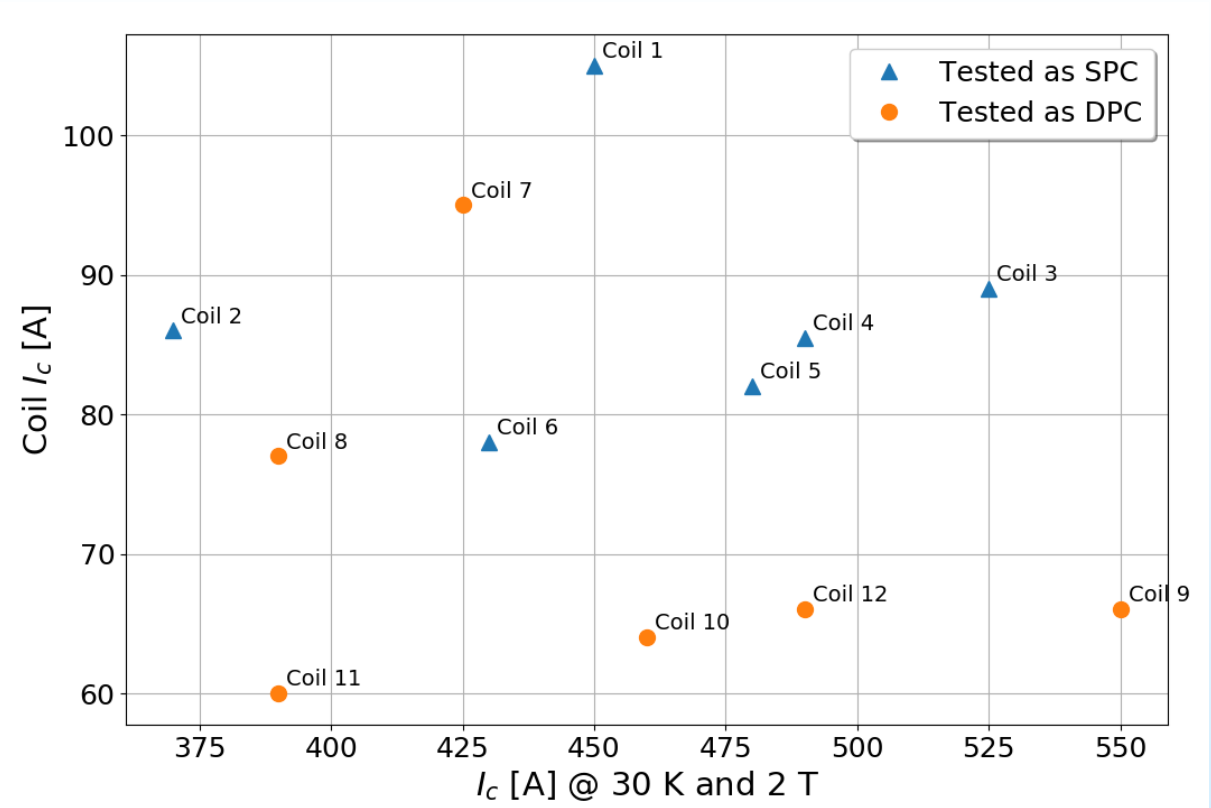
- As a part of contract, SuperPower also measured and provided Ic (30K, 2T) measurements from the samples cut at the two ends.
- Ic (30K, 2T) has been found to have a good correlation with Ic(high field 4K).
- However, often a significant variation was found when comparing the enhancement at the two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



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

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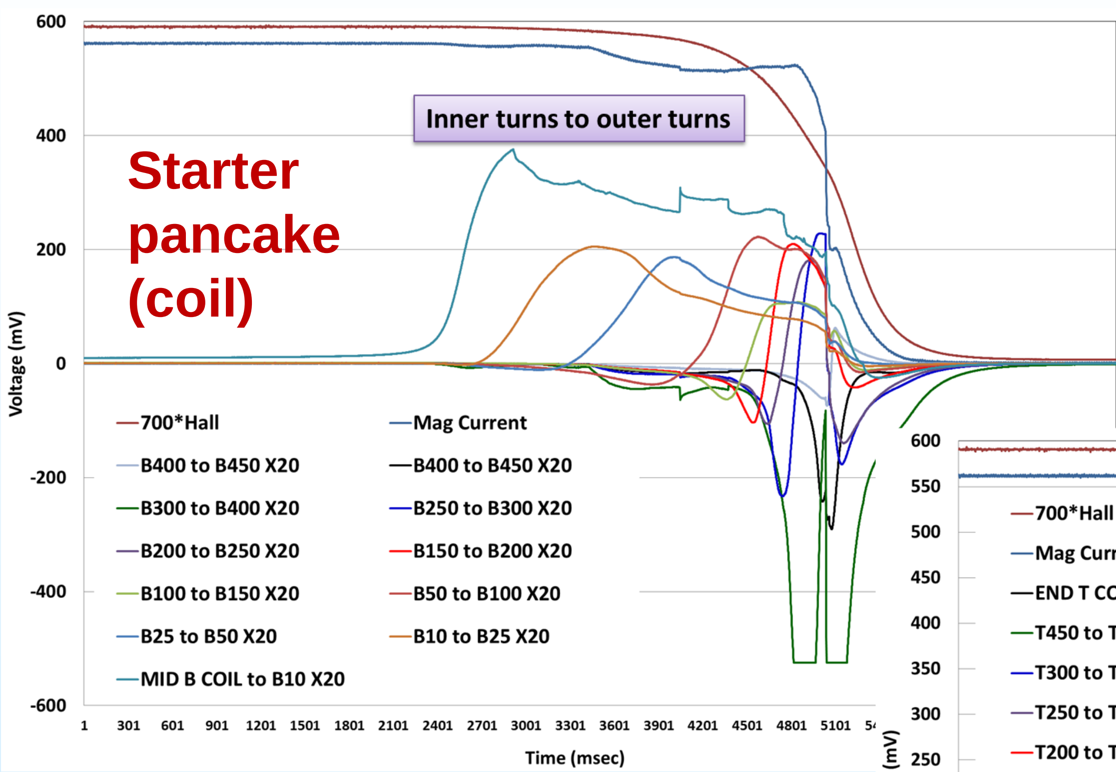
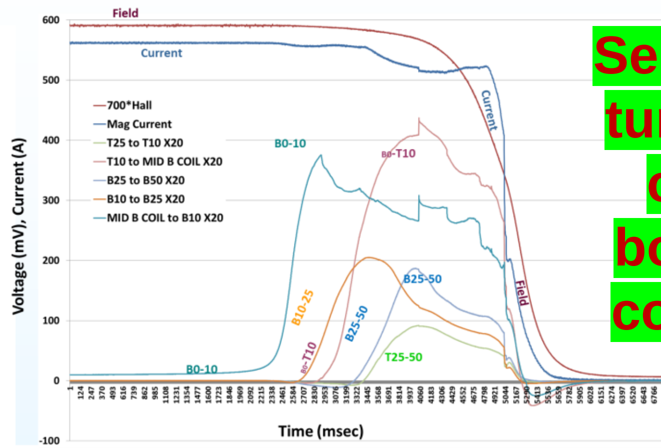
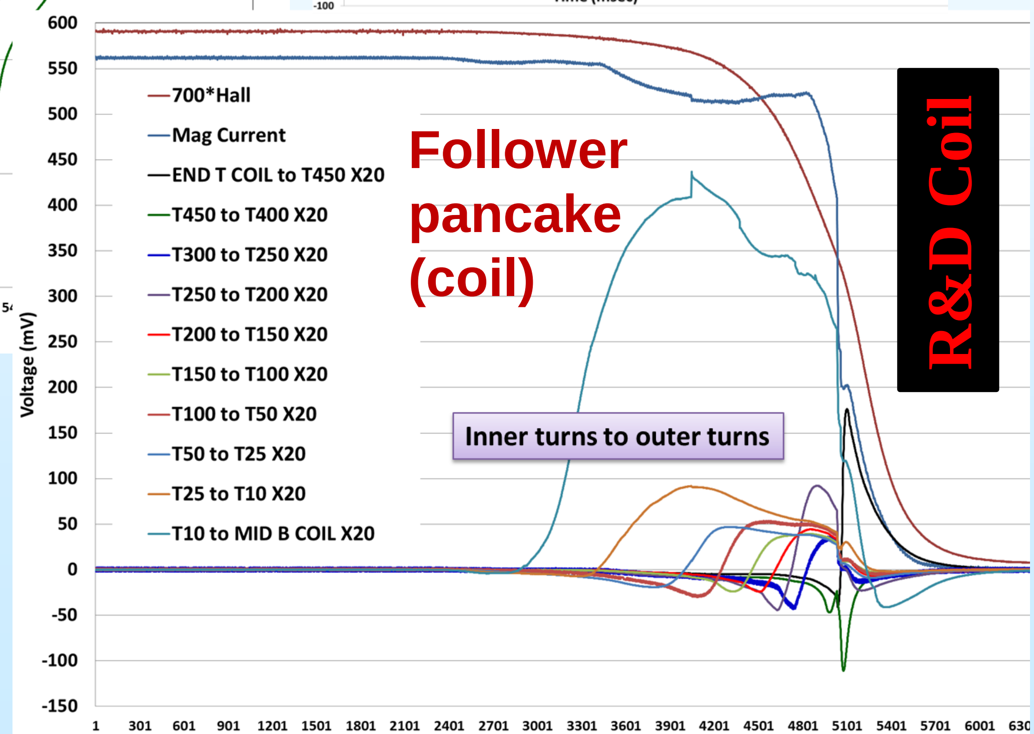
Quench Propagation in the Second Series of Double Pancake Tests





Select turns of both coils



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

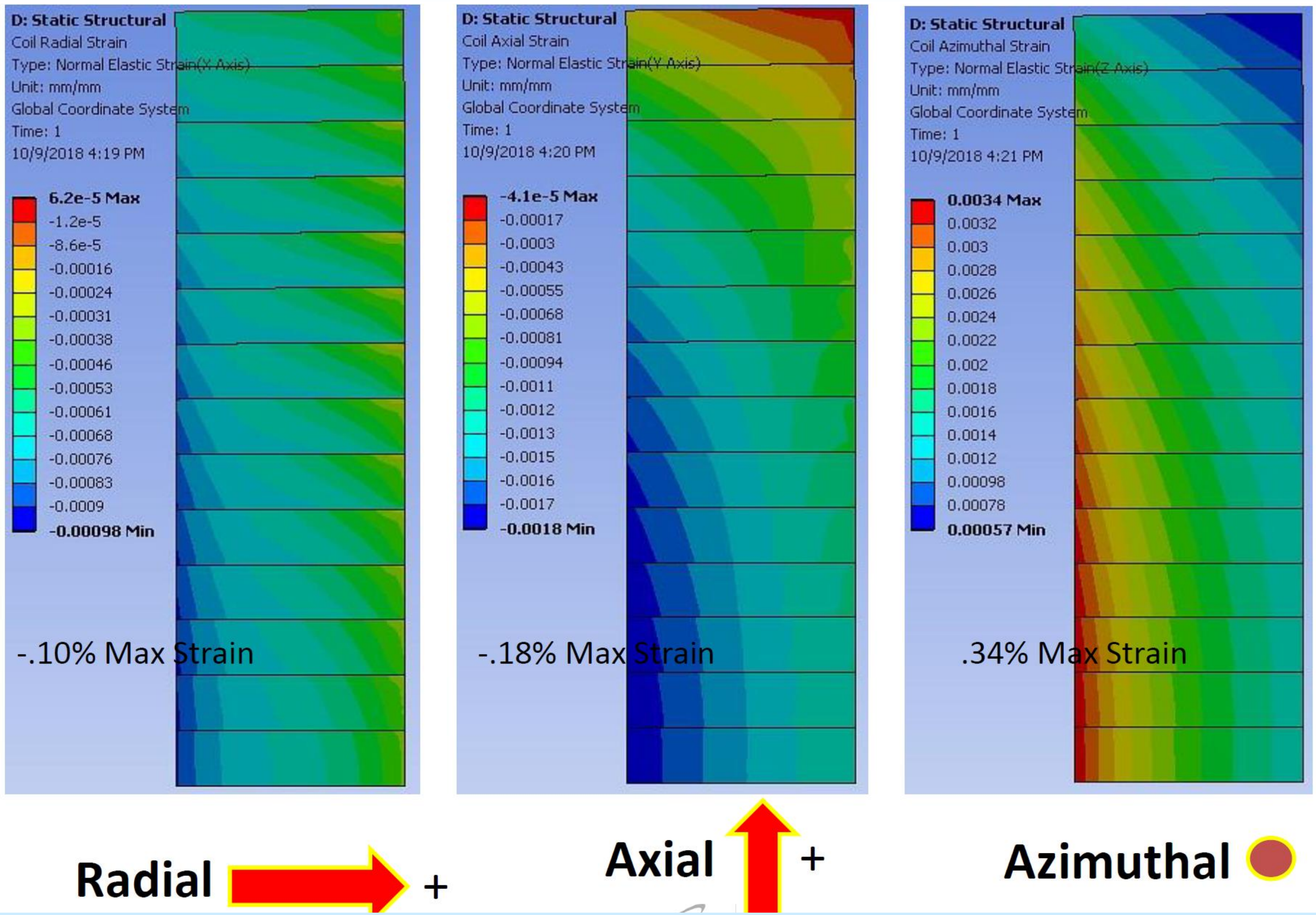
Conductor Requirements

- 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)

Orthogonal Coil Strains @4K, 25 T



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2-d Magnetic Model of DCC017