Status of the
25 T, 100 mm Bore HTS Solenoid
for an Axion Dark Matter Search Experiment

R. Gupta, M. Anerella, J. Cozzolino, P. Joshi, S. Joshi,

S. Plate, W. Sampson, H. Song and P. Wanderer, BNL

W. Chung, J. Kim, B.R. Ko, S.W. Youn and Y. K. Semertzidis, IBS

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science

U.S. DEPARTMENT OF ENERGY

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SEATTLE, 2018 OCTOBER 28 - NOVEMBER 2

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Overview

- **Overall Design and Design Approach (25 T, 100 mm, No-Insulation)**
  - **Motivation: Plenary talk (5PL1A: Y. Semertzidis) tomorrow @10:30**
- **Focus of this Presentation: 4 K Quench* studies in two sets of coils**
  - **~17 T peak field, 400+ MPa hoop stress**
  - **Many quenches (~10) and many shutdown (~30) in four series of runs**
  - **Superconducting to normal state in only "*a few hundreds milliseconds*"**
    - **Fast propagation within a pancake and pancake to pancake**
- **Summary**

***Strictly speaking, in HTS we don't have quenches; these are runaways!**

Design Requirements and Design Approach

Design Challenges:

- High Field:25 T
  - Must use HTS
- Large Bore:100 mm
  - Huge Stresses
    - (J X B X R)
- User Magnet
  - Healthy Margin
  - Reliable Operation

Special Opportunities:

- Relaxed Field quality:~10% over 200 mm
- Slow Charging Time: up to 1 day

An Ideal Application of No-Insulation Coil*

- Defect Tolerance
  - Because HTS is still an R&D Conductor
- Quench Protection @4K
  - We find early IBS test results positive

*…No-Insulation… Seungyong Hahn, 4LOr3B-01

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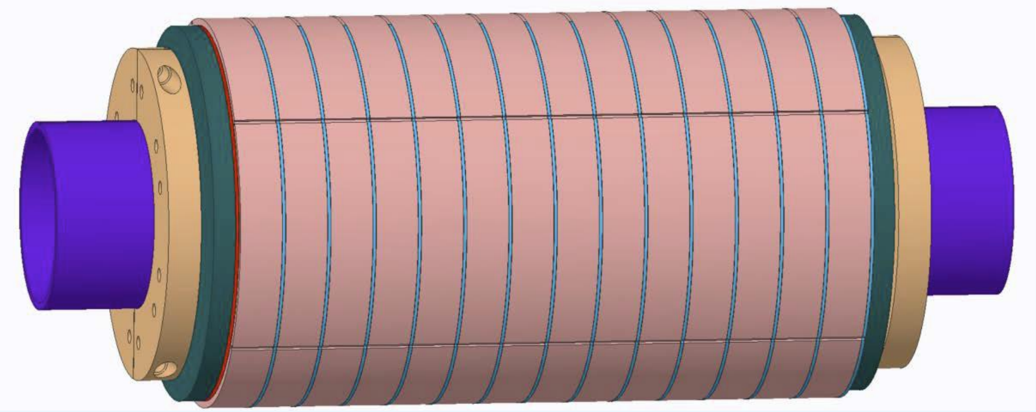
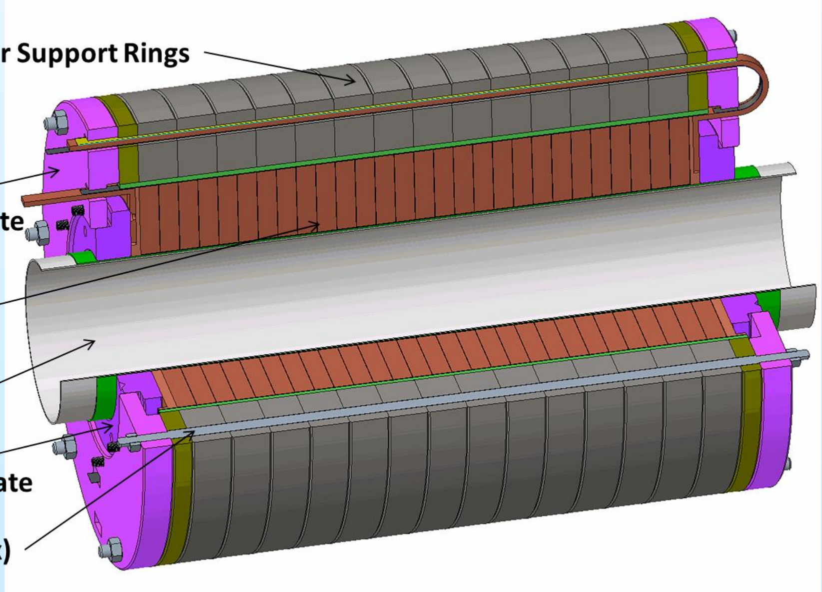
IBS 25 T, 100 mm HTS Solenoid Design Summary



- 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
- Overall Current Density: ~500 A/mm^2 (+ >50% margin)
- Stored Energy: ~1.3 MJ
- Inductance: ~13 Henry
- Maximum Hoop Stress: ~480 MPa (+ >50% margin)
- Maximum Axial Stress: ~180 MPa
- Outer Support Ring: 40 mm High Strength Aluminum

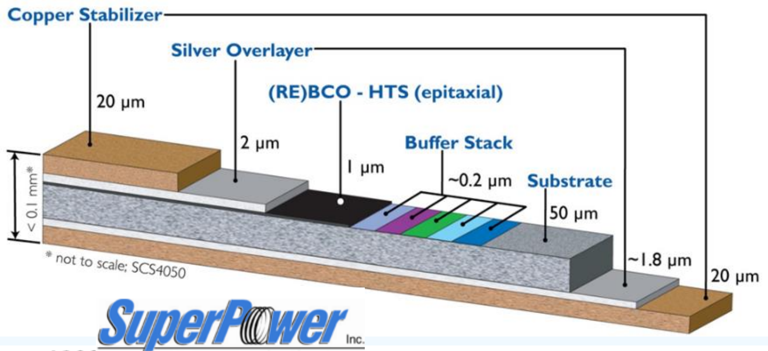


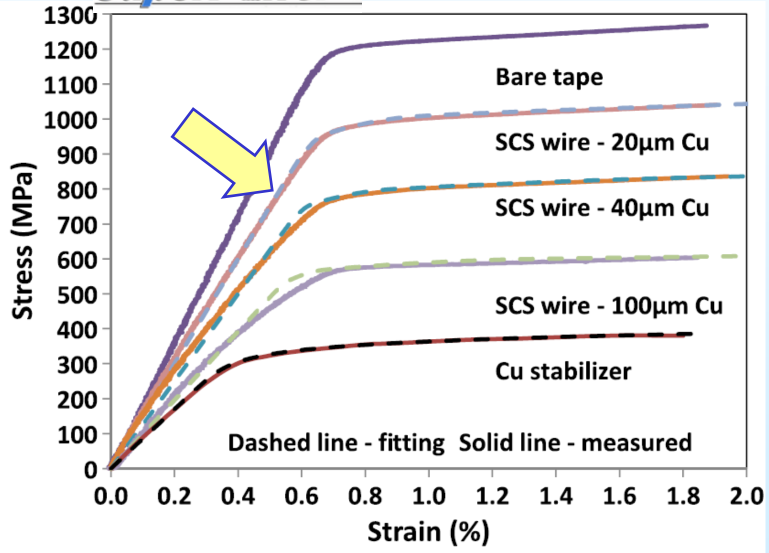
Superconductor

- **12 mm wide 2G HTS tape**
- **Optimized for high field**
  - ➢ **I_c margin @ 25 T : > 50 % (no limit on Max)**
- **High strength: 50 µm Hasetalloy, 20 µm Cu**
  - ➢ **Mechanical margin @ 25 T: > 50%**
- **Amount needed: ~9 km needed**
  - ➢ **4 km already supplied by SuperPower**

A good conductor is critical to the success:

➢ **Electrical (I_c), Mechanical, QA**



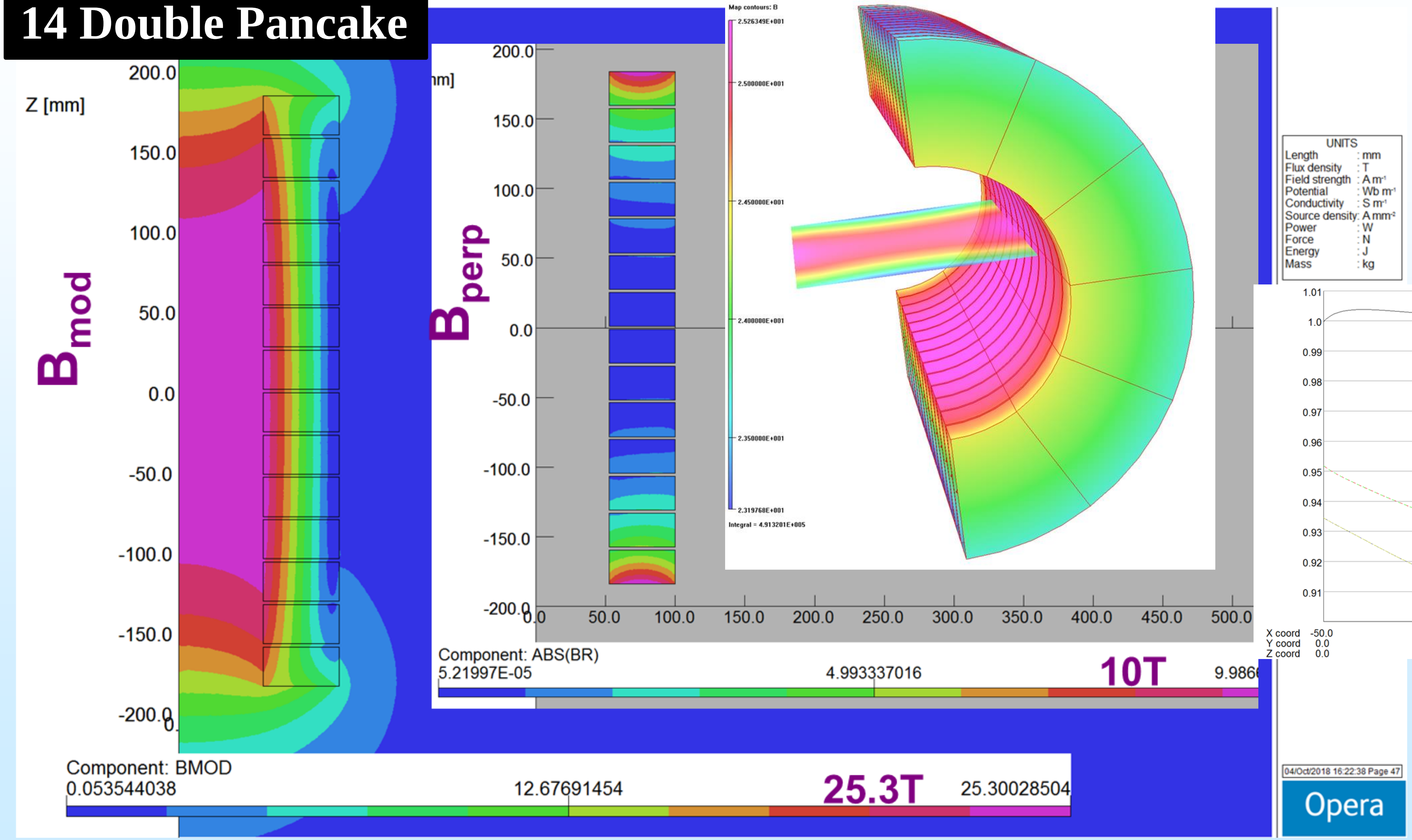


IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 26, NO. 4, JUNE 2016 8400406

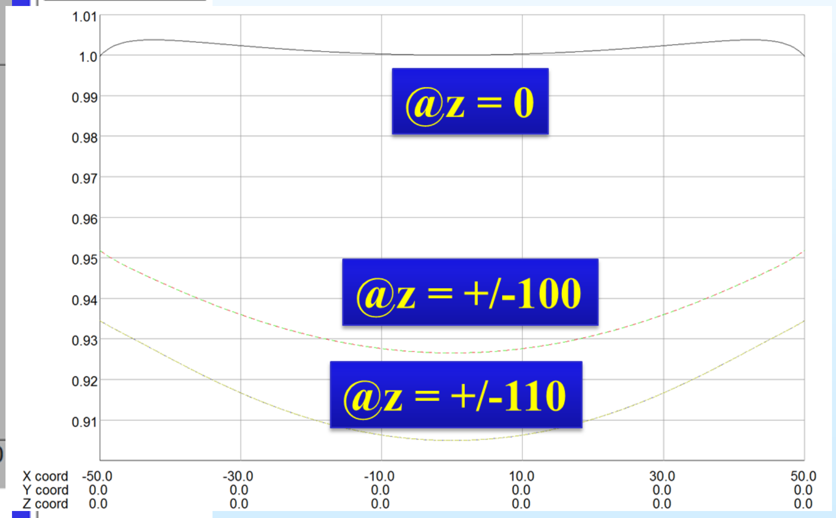
Stress–Strain Relationship, Critical Strain (Stress) and Irreversible Strain (Stress) of IBAD-MOCVD-Based 2G HTS Wires Under Uniaxial Tension

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

Magnetic Design and Analysis



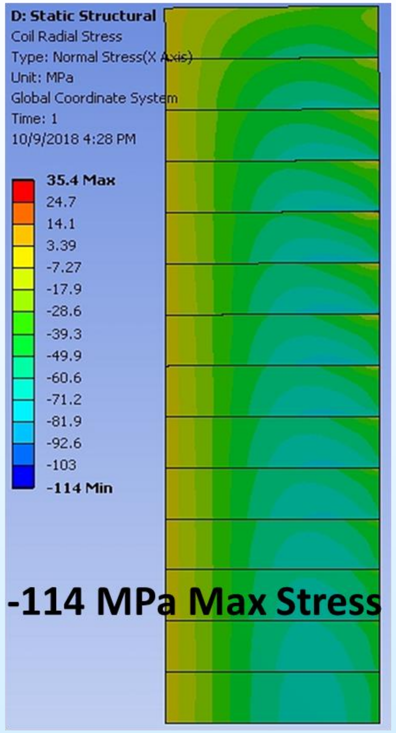
Design Guidance:
> 50% I_c Margin

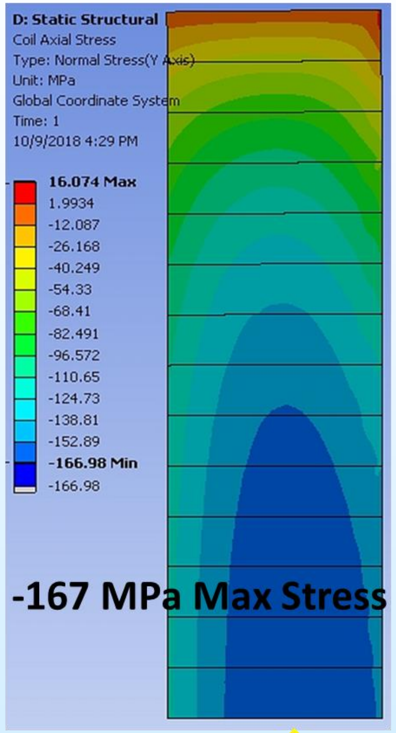


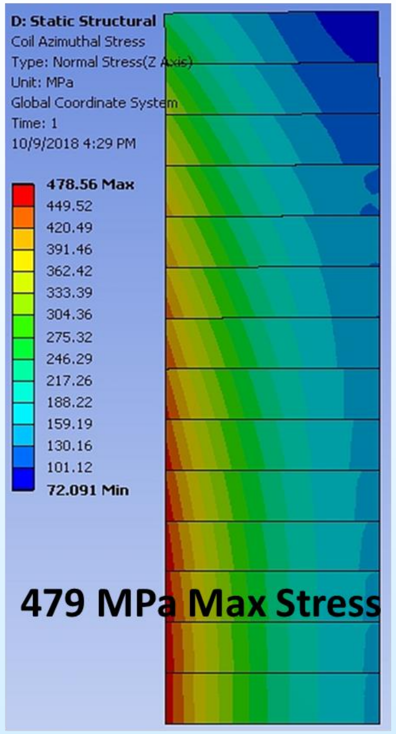
Specifications on relative errors <10% in 200 mm

Mechanical Design and Analysis

Orthogonal Coil Stresses (MPa) @ 4 K, 25 T

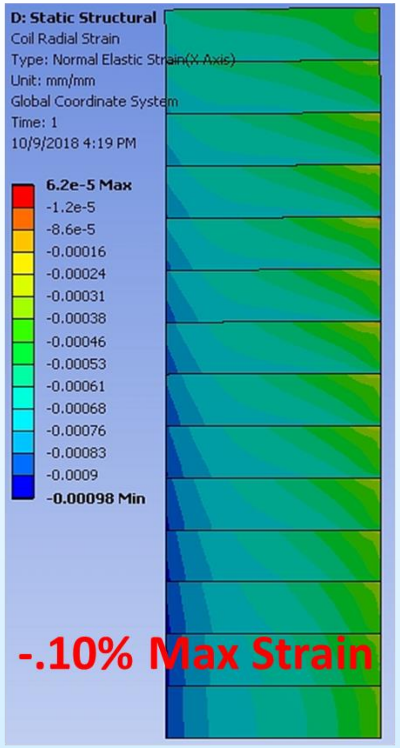


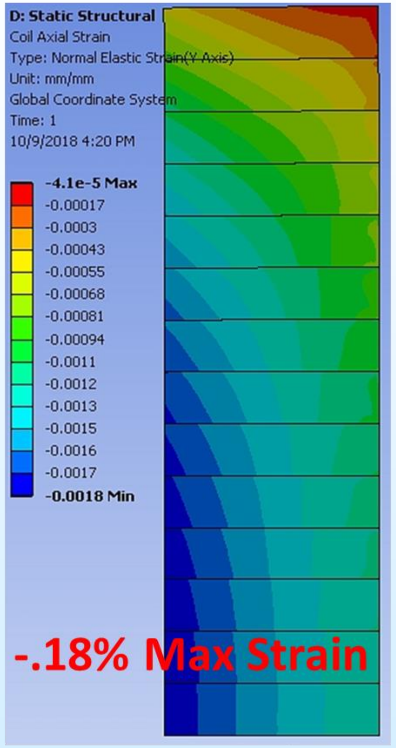


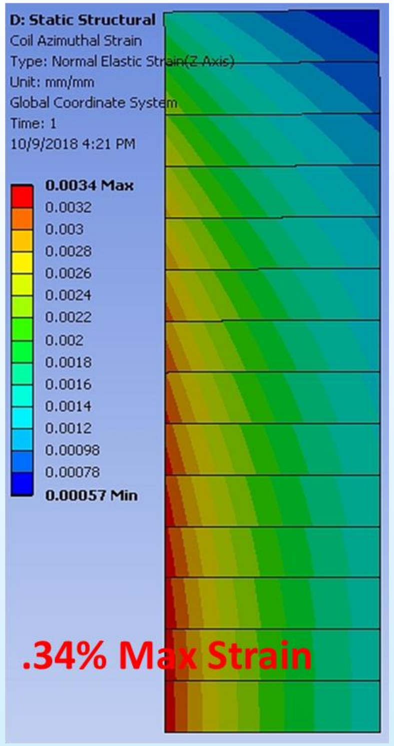


Radial + Axial + Azimuthal

Orthogonal Coil Strains @ 4 K, 25 T





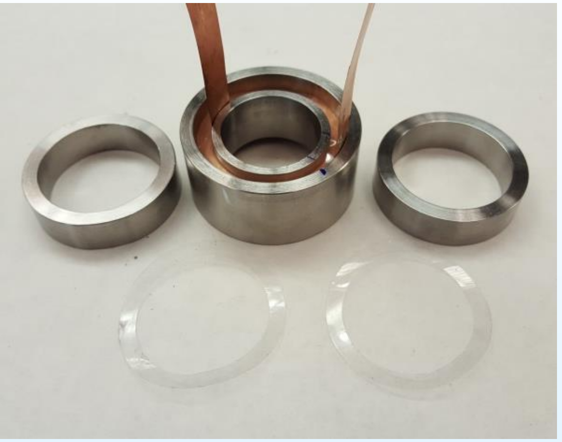
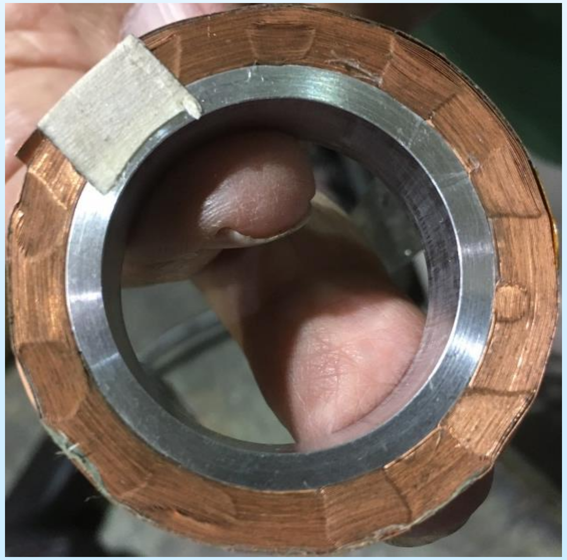


Radial + Axial + Azimuthal

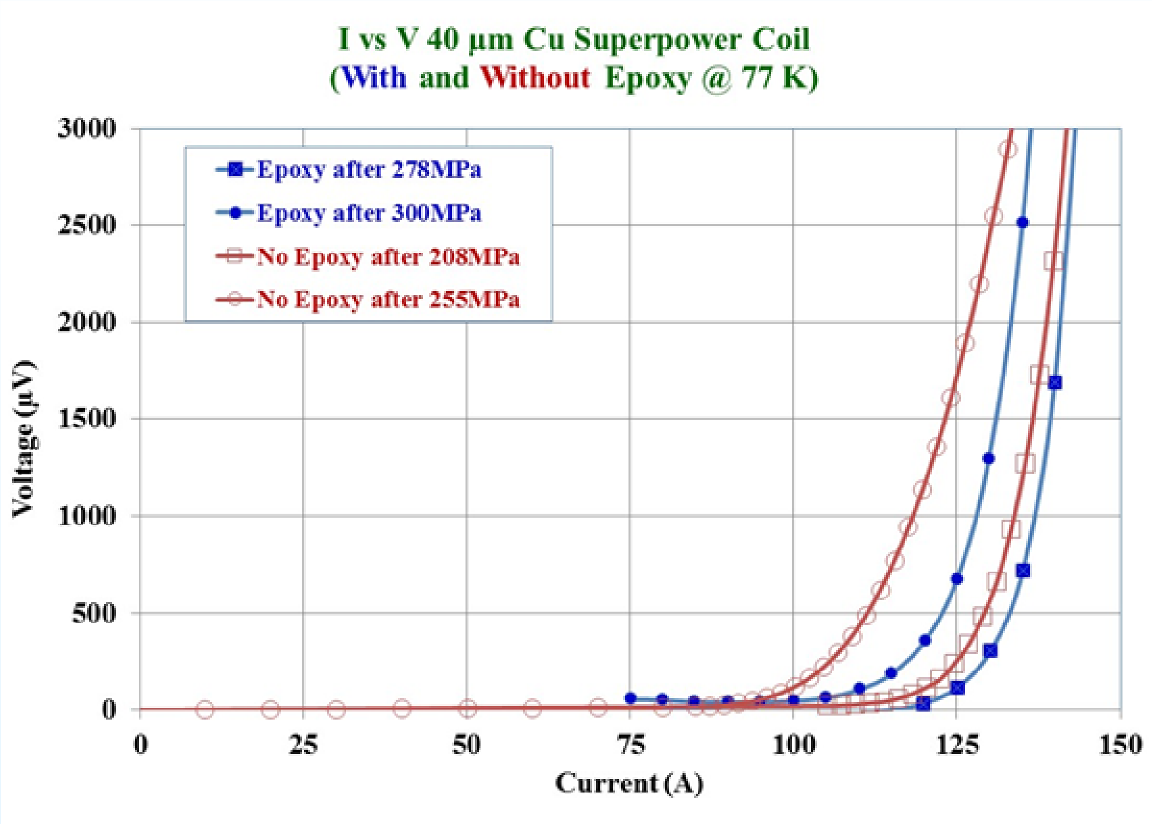
Design Guidance : > 50% Mechanical Margin

Loading on the Narrow Face

Loading test on the narrow face

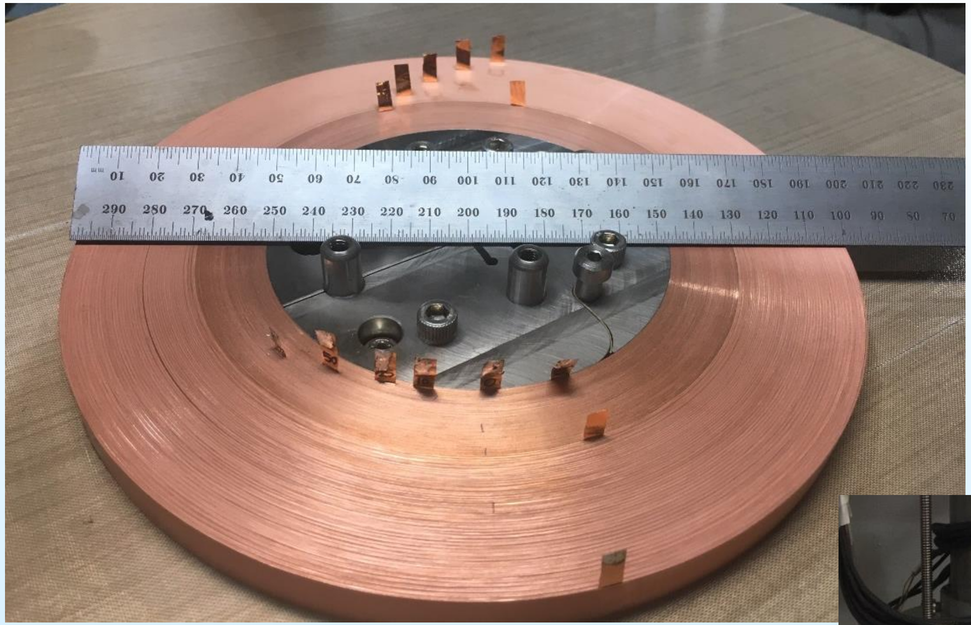
Surface coating with Epoxy helps



Design requirement: 170 MPa
Tested to 300 MPa Load

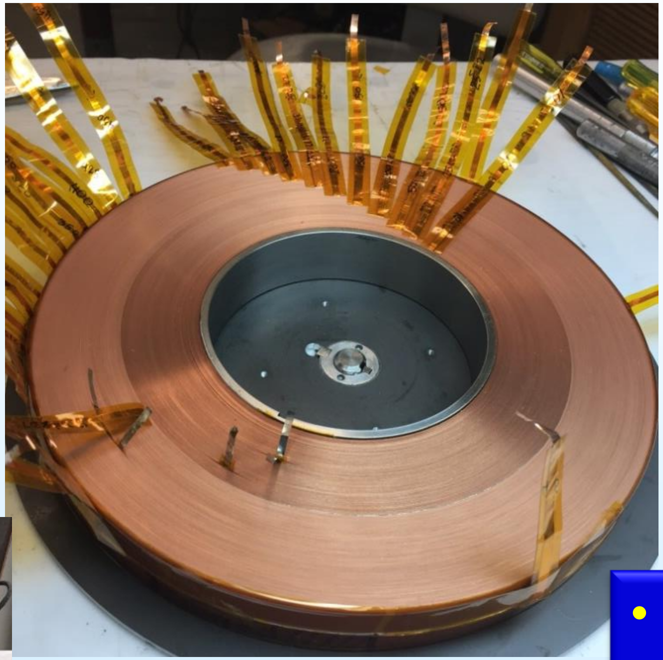
IBS Double Pancake Coils

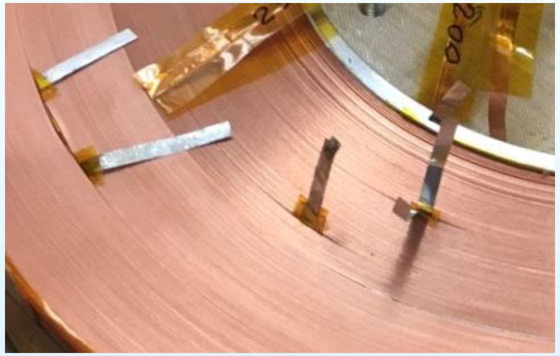
IBS Production Coil



Major parameters:
- i.d. : 105 mm
- o.d. 200 mm
- Turns: ~1250 (DP)
- Conductor: ~600 m, 12 mm wide (20 μm Cu)
- 2 single pancakes spliced to double pancake

IBS R&D Coil





- A significant number of v-taps in both coils.
- Three heaters in R&D coil to simulated local defects.

Major parameters:
- i.d. : 100 mm
- o.d. 220 mm
- Turns: ~971 (DP)
- Conductor: ~550 m, 12 mm wide (65 μm Cu)
- Double pancake; Rewound at 3X tensions

Quench* in HTS Coils : A Shift in Thinking

- Well rooted worry in HTS magnets is with the low quench propagation velocities.
- If energy keeps getting deposited in a small local area for far too long, it may degrade and even potentially damage the conductor or coil there.
- One proven solution: Large fast acting heaters to spread quench => a challenge in HTS because of “the large” and “different thermal margin across the magnet”.
- Plus you limit yourself from using the best conductor available. Why do that?

Detailed test and analysis at BNL on the IBS no-insulation coils:

FAST PROPAGATION – “within a pancake” and “pancake to pancake”

*Runaway

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Summary of the 3rd (of 4) 4 K Test Campaign

- Three quenches at ~850 A, B_{peak} ~17 T, ~450 MPa (similar hoop stress and stored energy/pancake as in full 25 T solenoid)
- Many shut-offs at different currents
- Survivability against unusual events : Out of Helium, sudden jump in current, sudden loss of power, runaway

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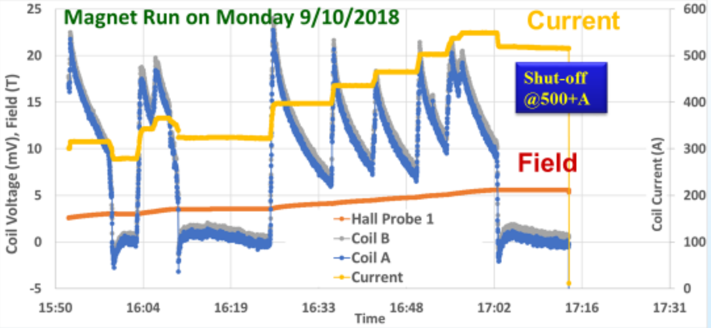
Monday Run Summary



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

- As a part of the study a large number of shut-off (30-50) performed. This gives an early indication, depending on whether coil runs away or not, that we are close to the limit (more discussion in the next slide).

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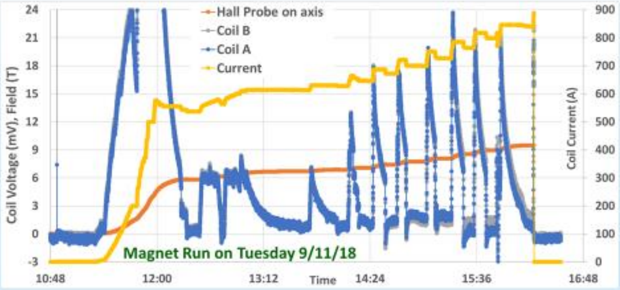
Tuesday Run Summary

- Continue increasing current to the maximum it could go
- Quenched in going from 850 A to 900 A (design: ~450 A)
- It reached maximum field in bore ~9 T and in coil ~17 T



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

- Quench discussed in more details in the next slide

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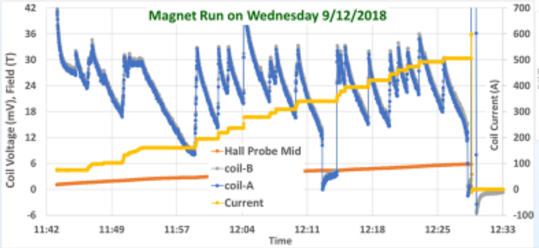
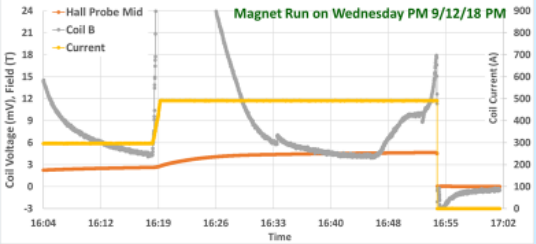
Wednesday Run Summary
(unusual events – not expected during normal operation)





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

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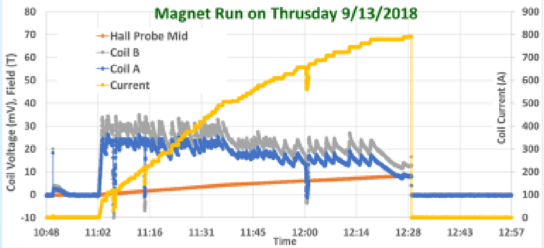
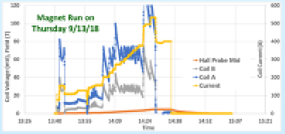
Thursday Run Summary

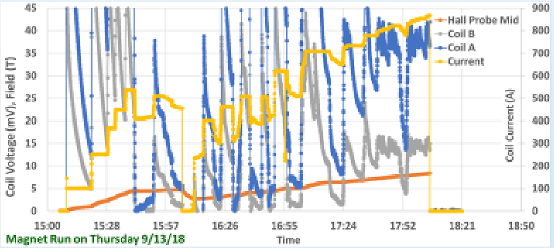


Second quench at ~800 A (design: ~450 A)

Third quench at ~850 A (design: ~450 A)



Shut-off near design current



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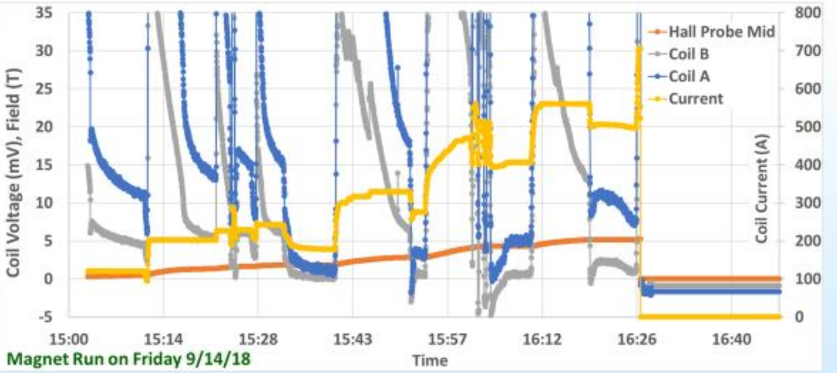
Friday Run Summary



- Higher temperature operation mostly in Helium gas environment

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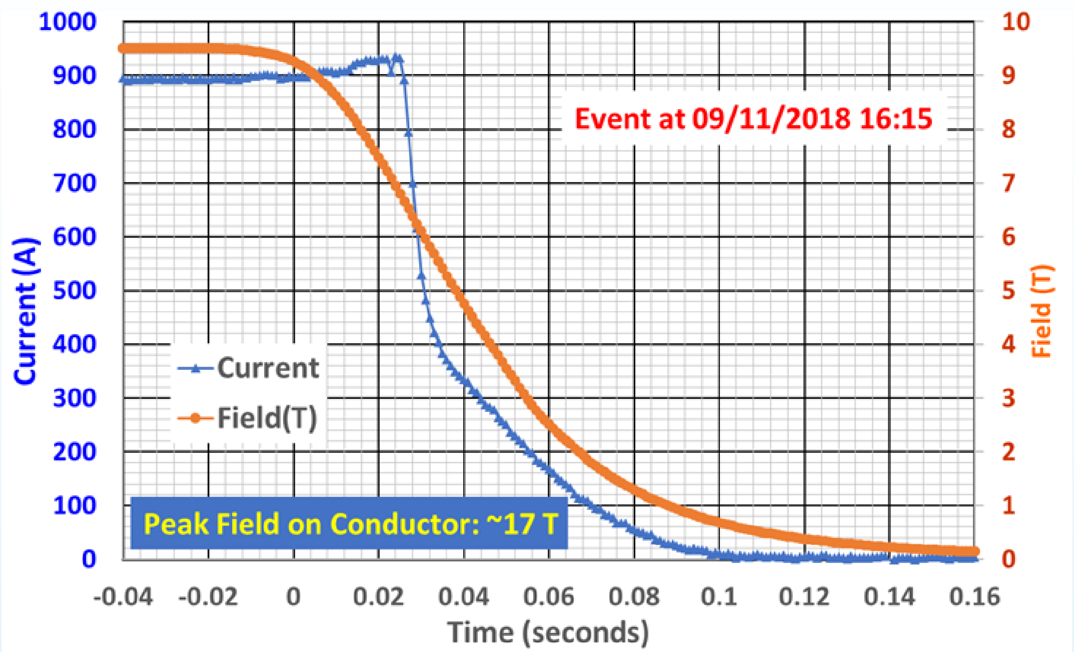
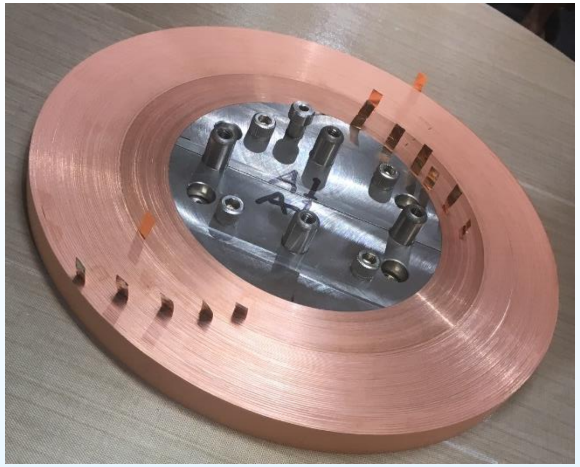
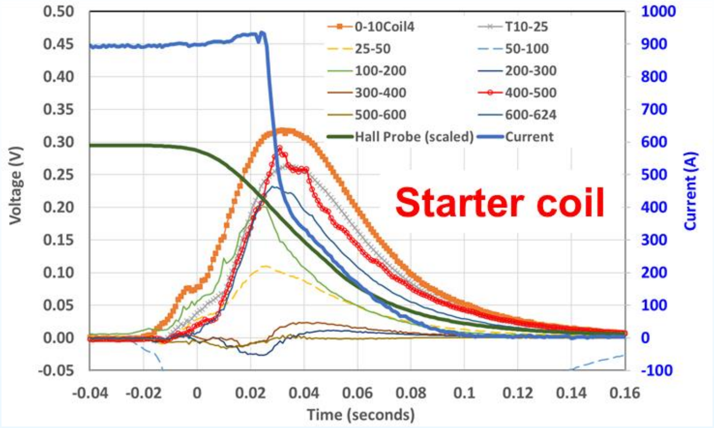
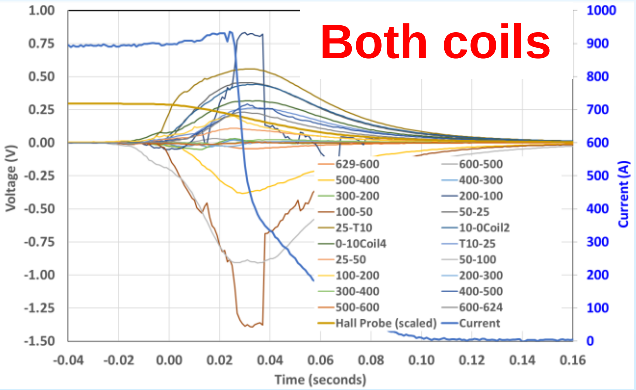
A Typical Quench Propagation in IBS Double Pancake at 4K (a significant number of v-taps provides a good insight)

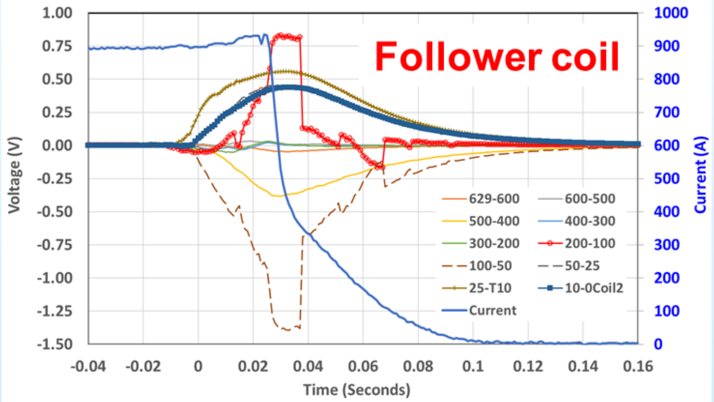


Many v-taps for detailed study





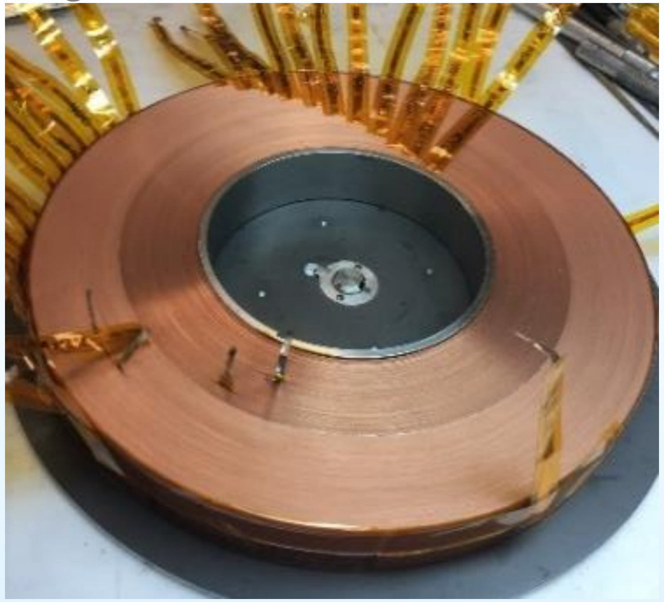




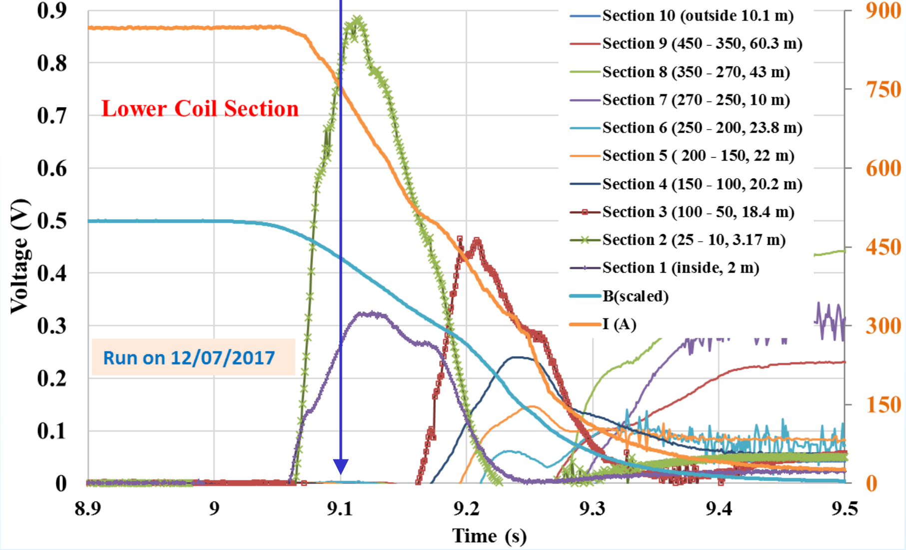
IBS coil became normal in < 200 msec (even faster than in many LTS magnets)

- **Within a pancake: fast propagation due to resistive heating through contact resistance between turns in a "No-insulation" coil when the current goes across (not circulating)**
- **Pancake to pancake: fast propagation due to inductive coupling - local change in field**

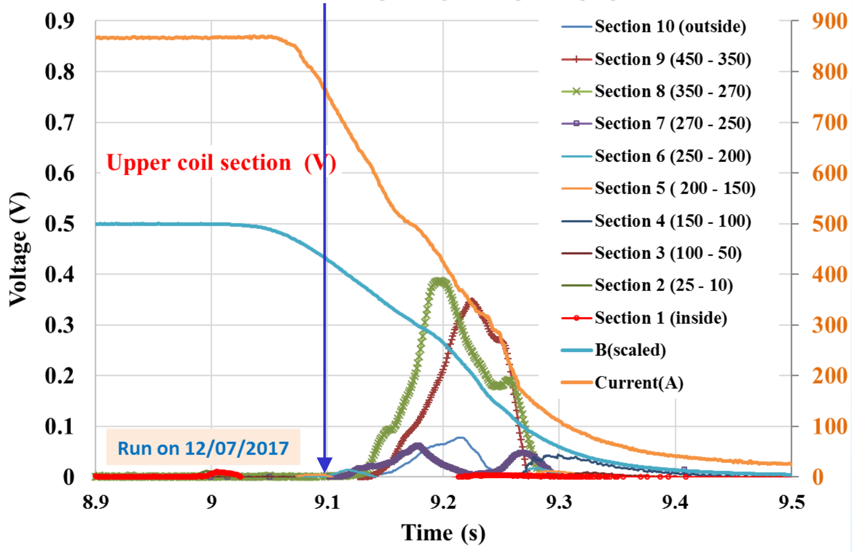
4 K Test of IBS R&D Coil (fast propagation)

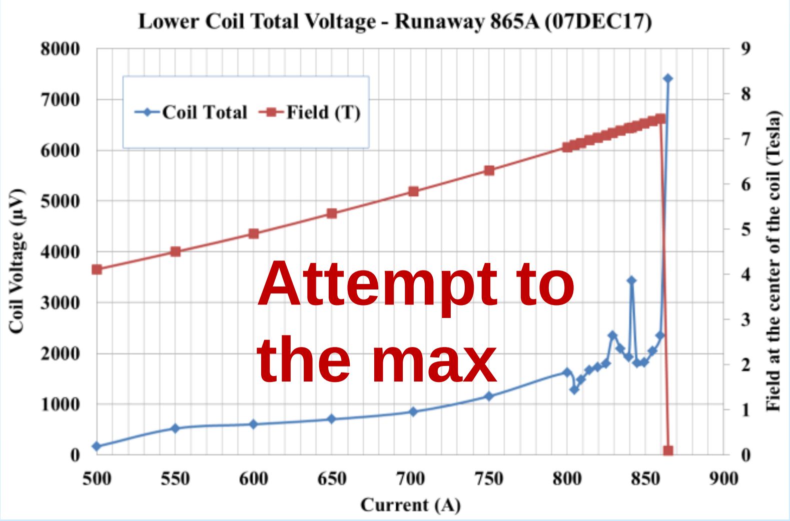


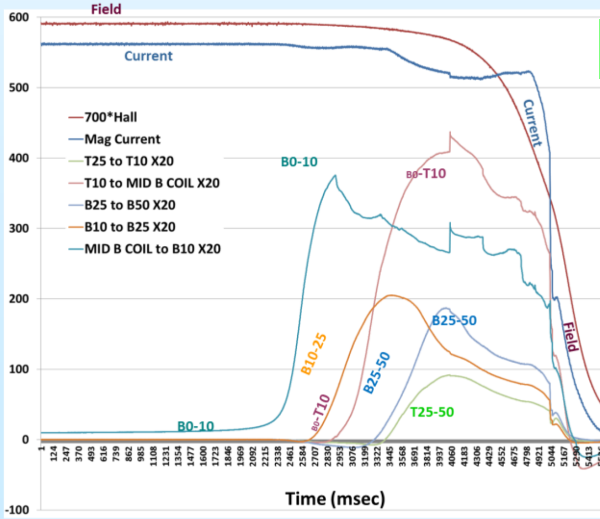
Starter coil



Follower coil



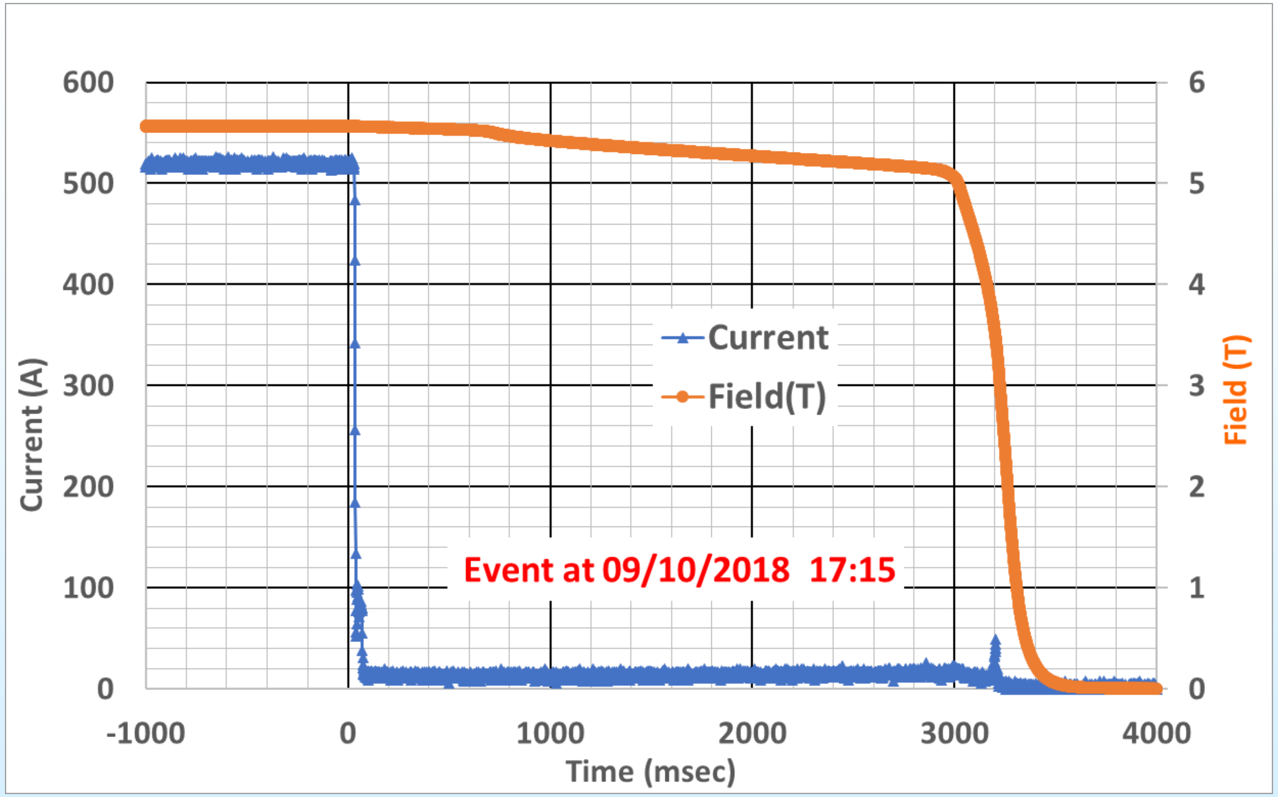




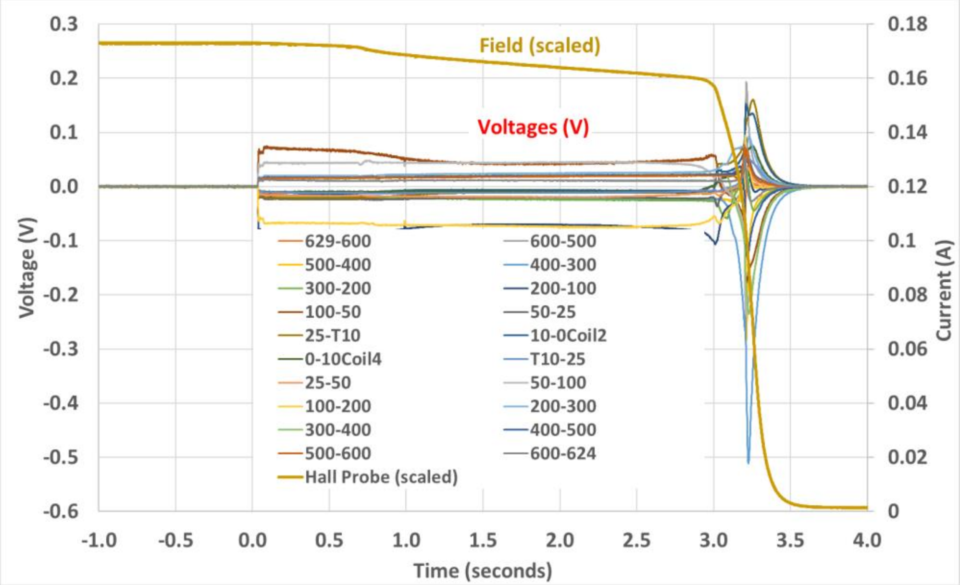
Select turns of both coils

- ➢ Quench propagation from the inner turns to the outer
- ➢ Quench propagation from one pancake to another pancake in < ~1/2 sec

Shut-off Tests in No-insulation Coils (an example @550 A, operating current 450 A)



- No significant energy is extracted during shut-offs or quenches in the no-insulation coils
- Energy is dumped/distributed inside the whole coil with contact resistance between the turns
- Whether coil recovers or runs away depends on how far away it is from critical surface
- Crucial test of inter-connect when it runs-away

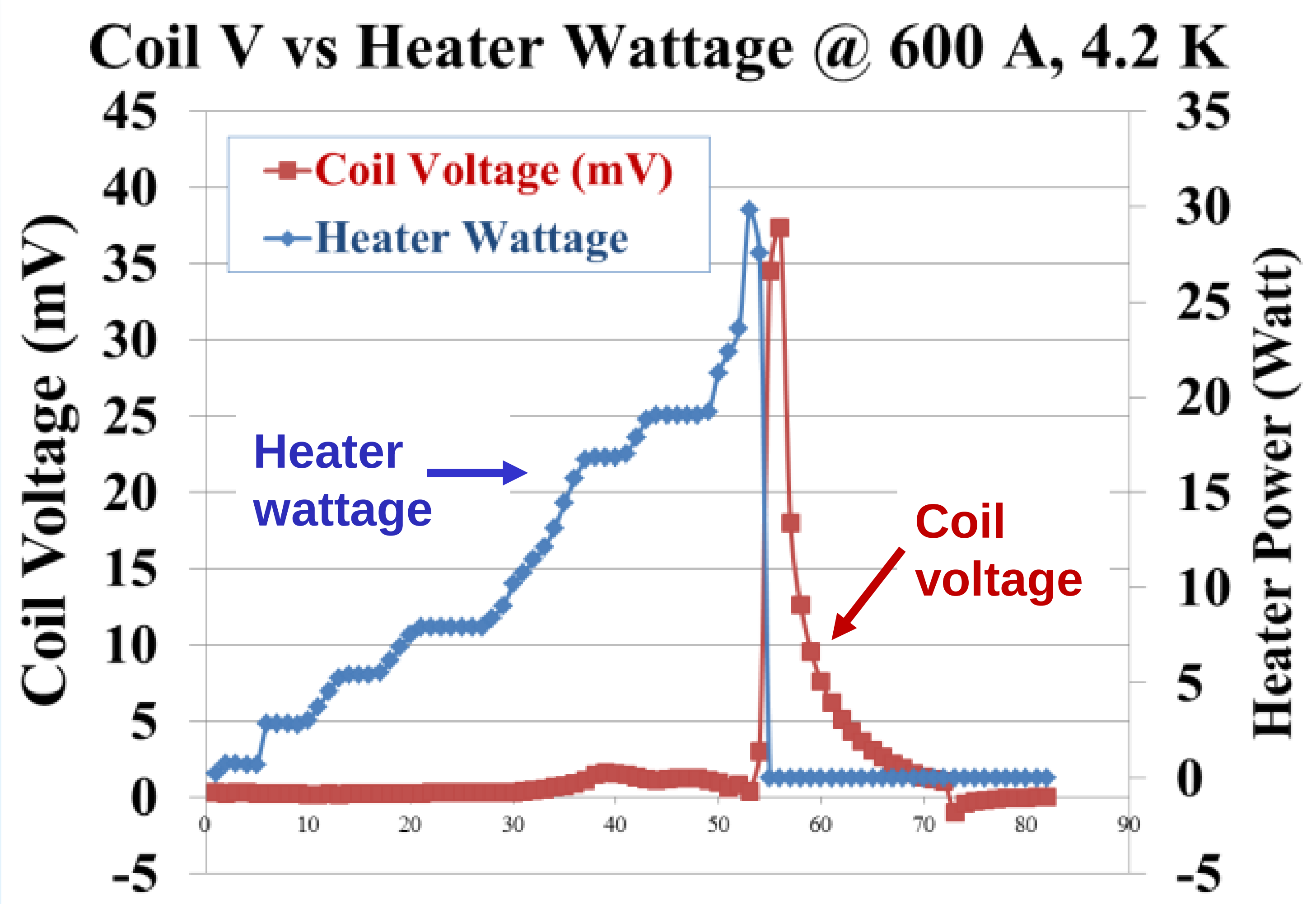


550 A example (operating current 450 A):

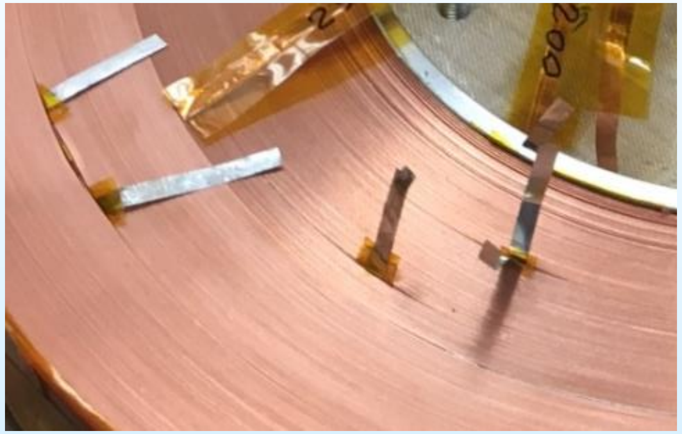
- Slow internal deposition of energy (3 sec)
- Fast run-away (<0.5 sec), once triggered

This coil recovered (no runaway) up to 400 A

Simulation of Large Local Defects @4.2 K



Local defects simulated with three stainless steel heaters



Defect up to 30 W

No measurable degradation in the coil performance observed after the test

Test Plan and Possible Collaboration

- **All single pancake and double pancake coils will be tested at 77 K**
- **The project will proceed with 4 K tests in a step-by-step manner**
  - ➢ **1 Double Pancake (DP) => 3 DP => 7 DP => 14 DP.**
  - ➢ **This will give us a chance to review and adjust, as necessary.**

All feedback and collaboration welcome during this time. We may not be able to provide a financial support. However, we will offer a chance to learn and contribute. Let's work together and get a positive outcome. It's in long term interest of the HTS community.

Summary

- Final design and program is in place for IBS high field, large bore (25 T, 100 mm) HTS solenoid with large stresses
- This is a challenging magnet and is a good application of the No-insulation winding
- Step-by-step program allows opportunity for some adjustments, if needed, before the final magnet is built
- 4 K test results are encouraging so far