Design, Construction and Test of HTS/LTS Hybrid Dipole

R. Gupta, M. Anerella, J. Cozzolino, P. Joshi, W. Sampson, P. Wanderer (BNL)

J. Kolonko, D. Larson, R. Scanlan, R. Weggel and E. Willen (PBL)

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70 YEARS OF DISCOVERY

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U.S. DEPARTMENT OF ENERGY

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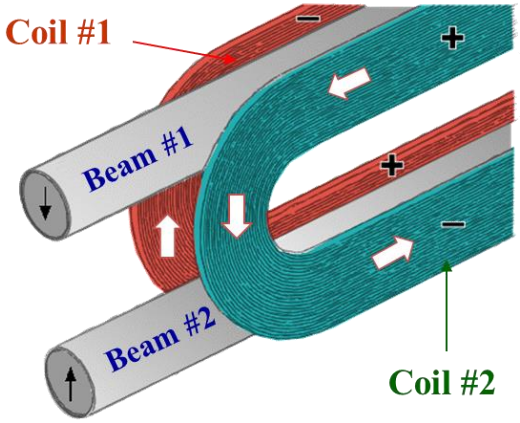
Background

- *To achieve very high operating dipole fields (20T or above), development of HTS/LTS technology is a must*
  - ➢ *Use expensive HTS in regions where field is very high and relatively less expensive LTS (Nb_3Sn and/or NbTi) where field is moderate*
- *Whereas HTS/LTS hybrid solenoids have been built and tested, no significant field hybrid dipoles have been*
- *This presentation shares the initial test experience*

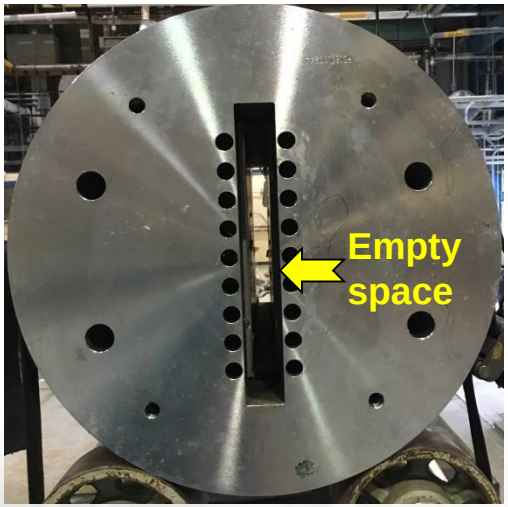
Overview

- *HTS/LTS Hybrid Dipole Design and Construction*
- *Quench Tests*
  - ***Several HTS coil quenches in hybrid dipole***
  - ***<u>NO</u> degradation in performance observed***
- *Magnetization studies of HTS coils*
  - ***By themselves and in hybrid dipole structure***

Unique BNL Common Coil Dipole

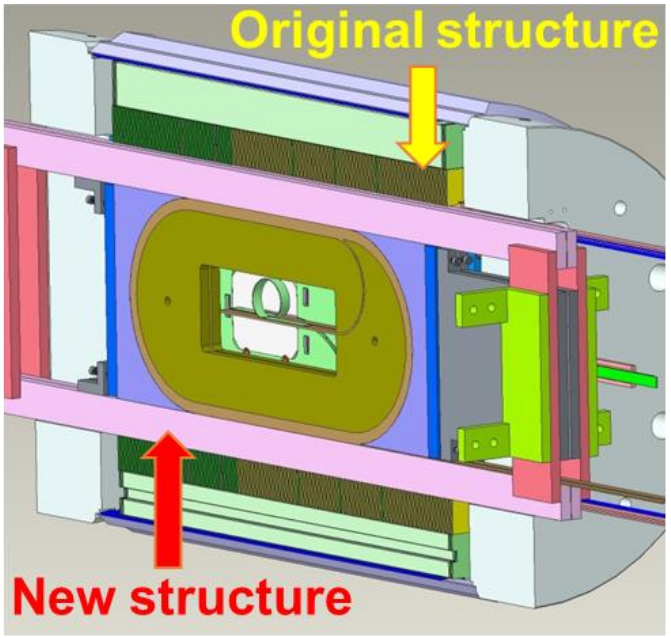


- Common coil 2-in-1 dipole design with simple racetrack coils that are common to both apertures
- Structure specifically designed to provide a large open space (31 mm wide, 338 mm high)
- New racetrack coils can be inserted in the magnet without requiring any disassembly or reassembly
- New insert coils become an integral part of the magnet. Coil tests become magnet tests
- Rapid-turn-around, lower cost approach allowed hybrid dipole in DOE/SBIR program (2 years, 1M$)



HTS/LTS Hybrid Dipole Structure

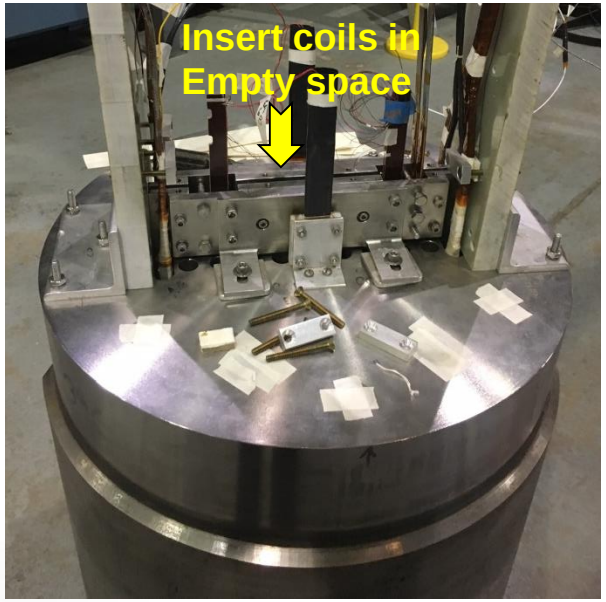
Design



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

Assembly of a pair of insert coils

HTS coils get pushed inside the LTS coils



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HTS Coil Winding (two coils wound)

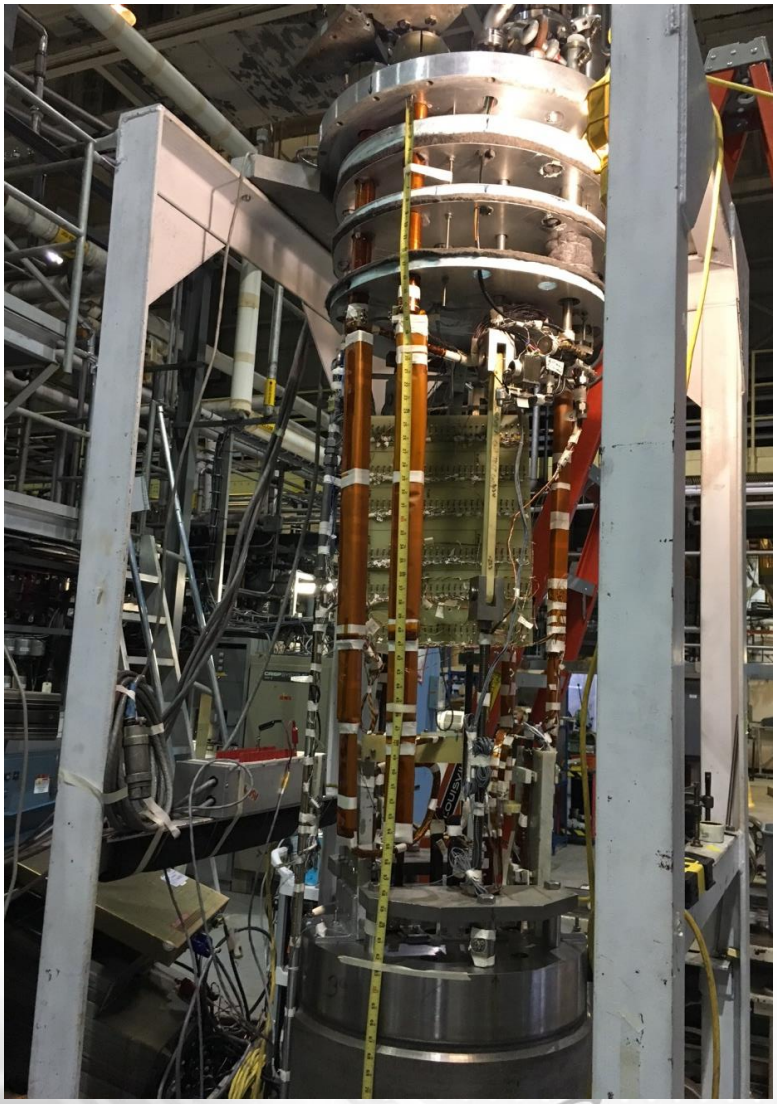
Conductor:
- **12 mm ASC tape**

Insulation:
- **Nomex**

Two coils used ~300 meters of 4 mm equivalent

HTS/LTS Hybrid Dipole Quench Test Results

Challenges with the HTS/LTS Hybrid Dipole



- **Large coupling between HTS/LTS coils**
  - **Maximum current in HTS: ~800 A**
  - **Maximum current in Nb_3Sn: ~10 kA**
- **Protection of the HTS coils at 4 K**
- **Quench protection of HTS coils in HTS/LTS hybrid configuration**

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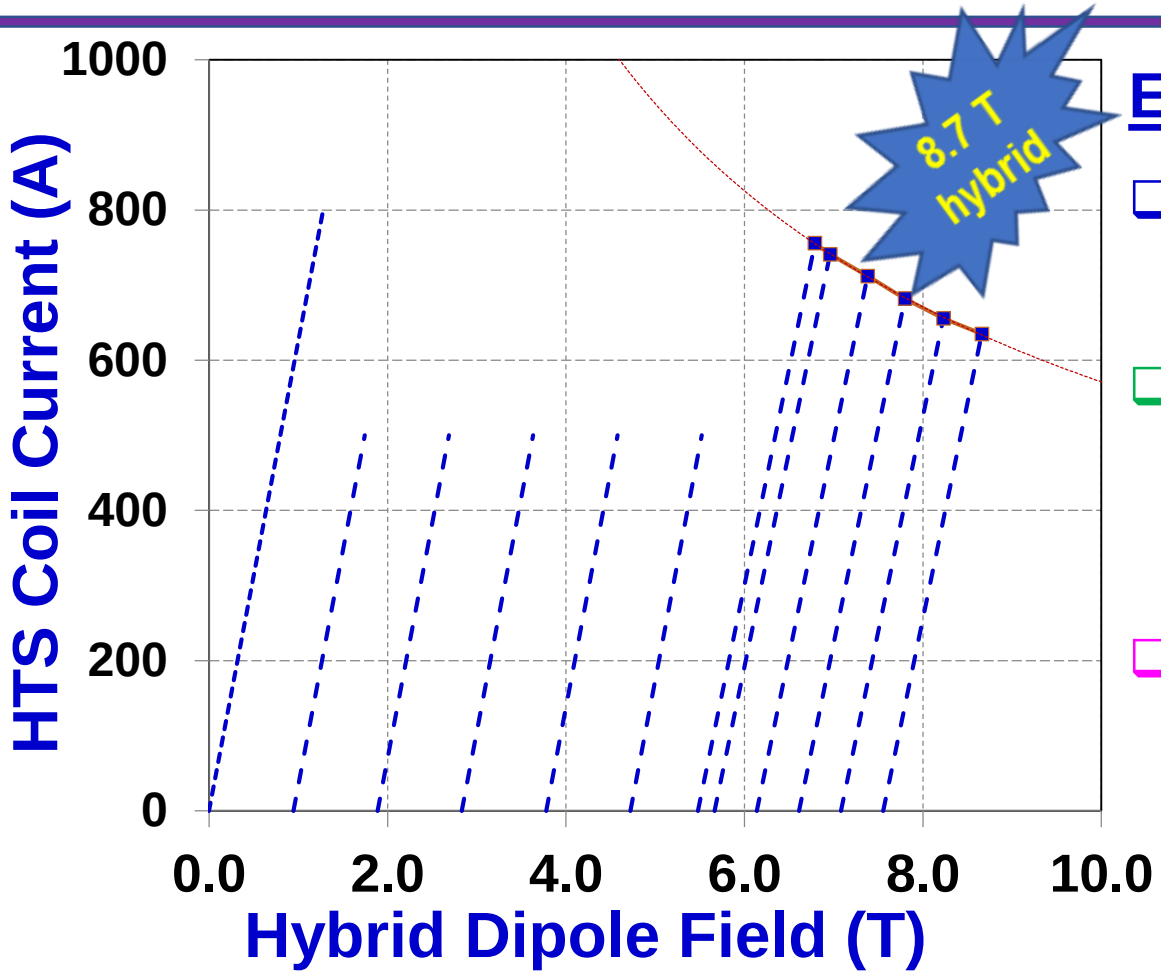
Questions:

- **Can HTS coil survive quenches without significant degradation?**
- **Can HTS coils be operated like LTS**

Operation of HTS/LTS Hybrid Dipole



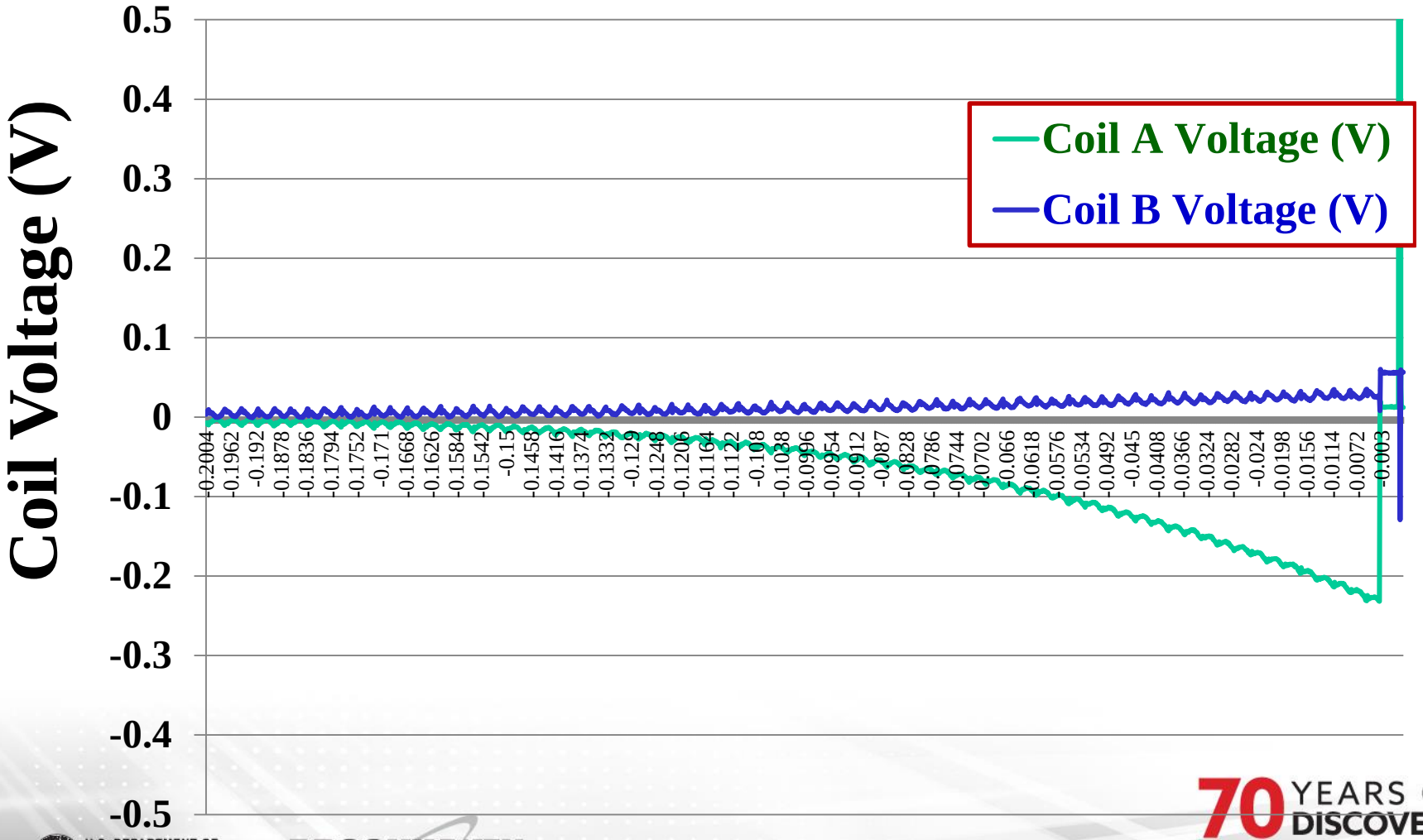
Encouraging Results:

- HTS coils were ramped to quench, just like LTS coils
- No degradation in HTS coils despite a number of quenches
- Significant demonstration. 8.7 T may be the highest field HTS/LTS hybrid dipole magnet

- Performance limited by the leads (not by coils)
- ~14 T possible with new HTS tapes, in favorable direction

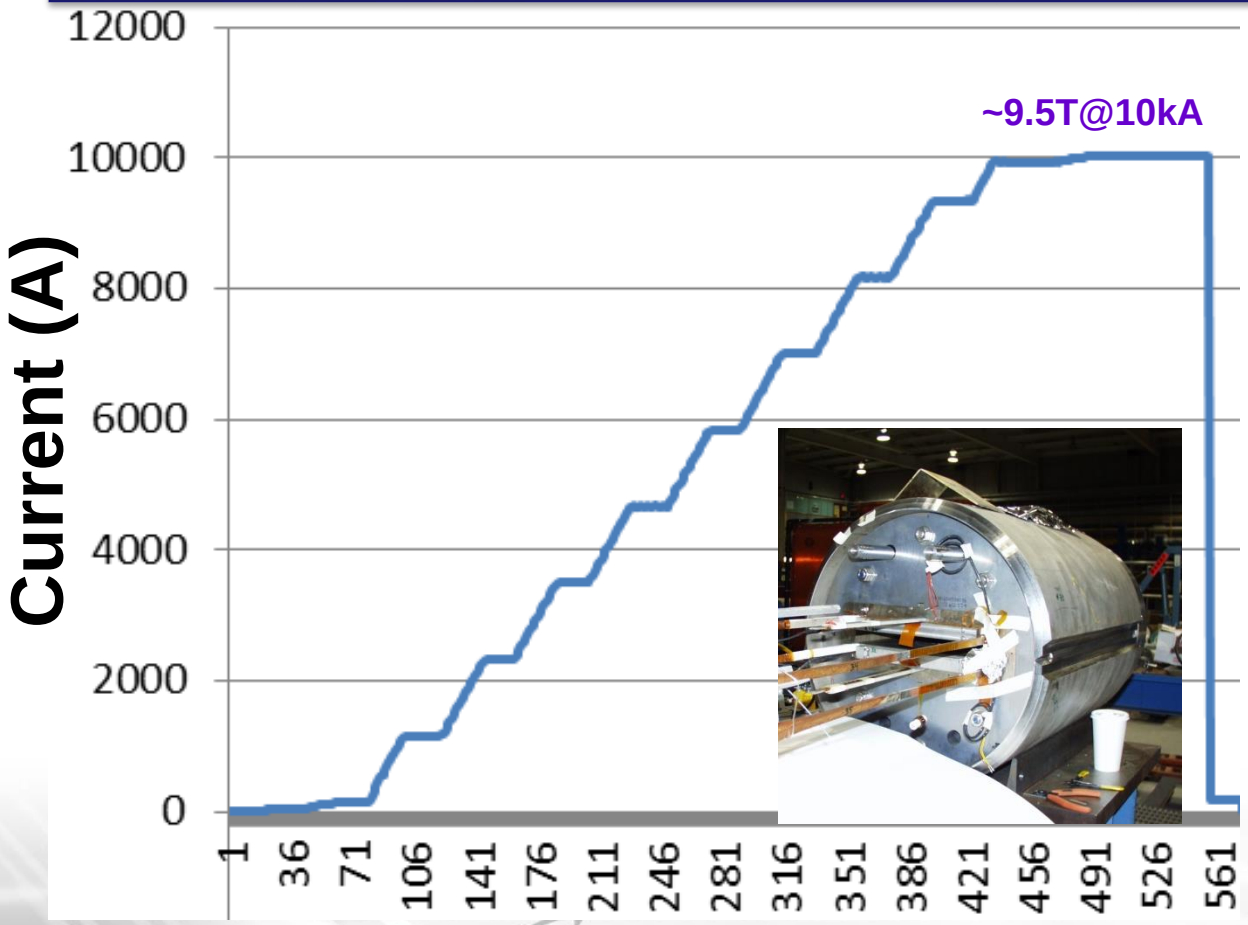
HTS coils operated like LTS coils

- Significant voltage in HTS coils: >0.2 Volts



Retest of Nb_3Sn Common Coil Dipole After a Decade

- **Short Sample: 10.8 kA (reached during 2006 test)**
- **Retest: No quench to 10 kA (>92% of short sample)**



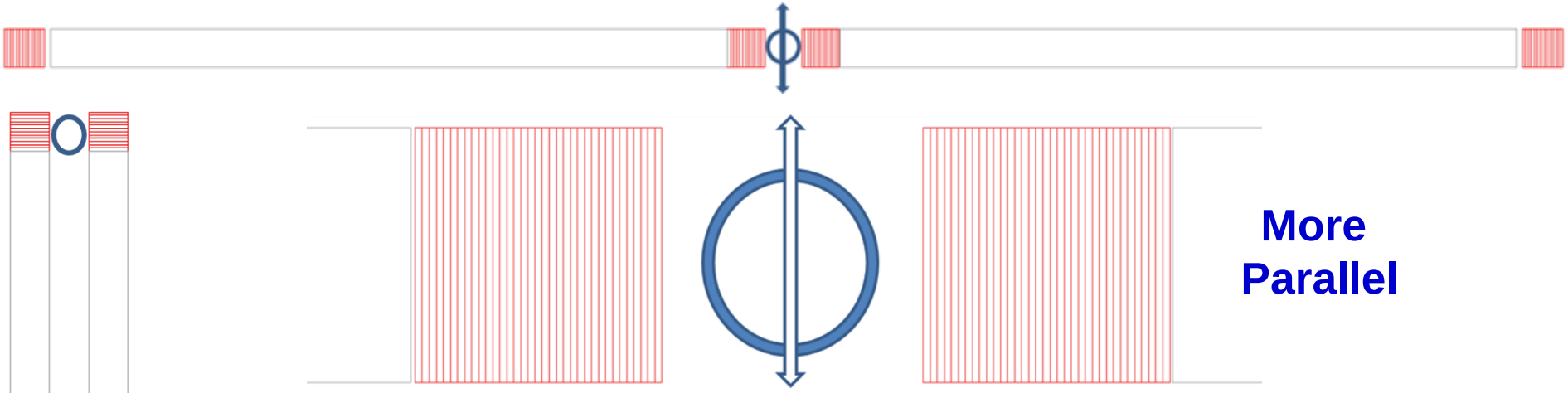
Was a display piece of Nb_3Sn "React & Wind" technology for dipole

Worked well when cold tested after a decade

Magnetization studies in magnets made with the HTS tapes

(Hall probe measurements)

Coil and Magnet Cross-section for Measurements



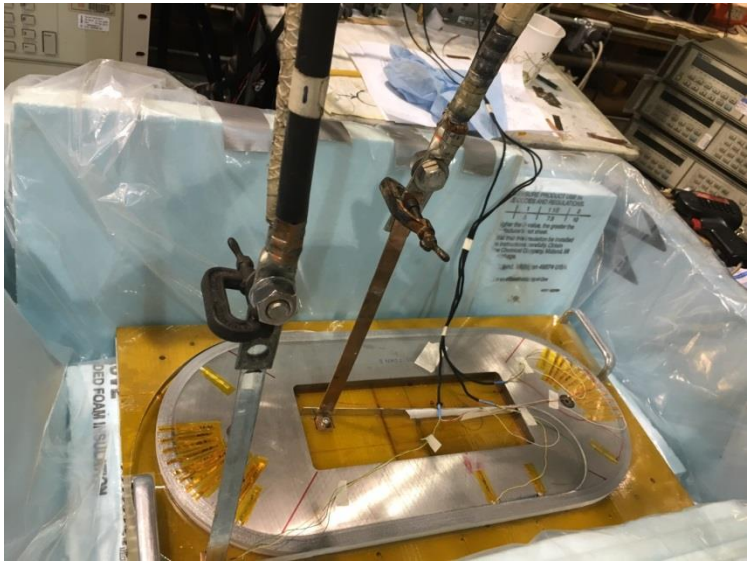
More Parallel

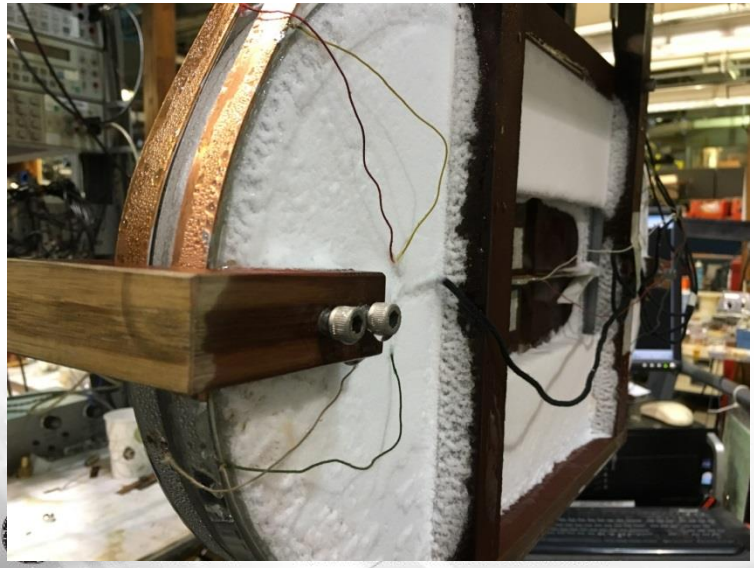
Square cross-section was chosen so that two coils can be placed in two configurations (a) with field more parallel or

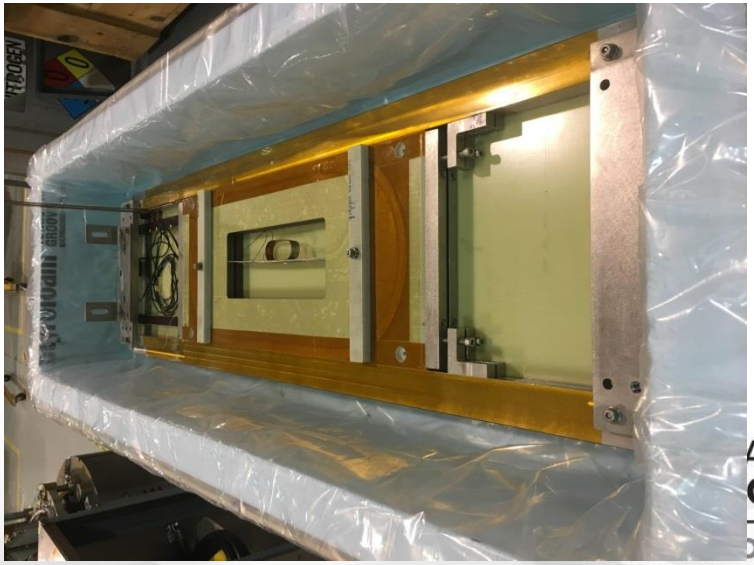
(b) more perpendicular to the wide face of the HTS tape

More Perpendicular

77 K Measurements of the HTS Coils in Various Configurations

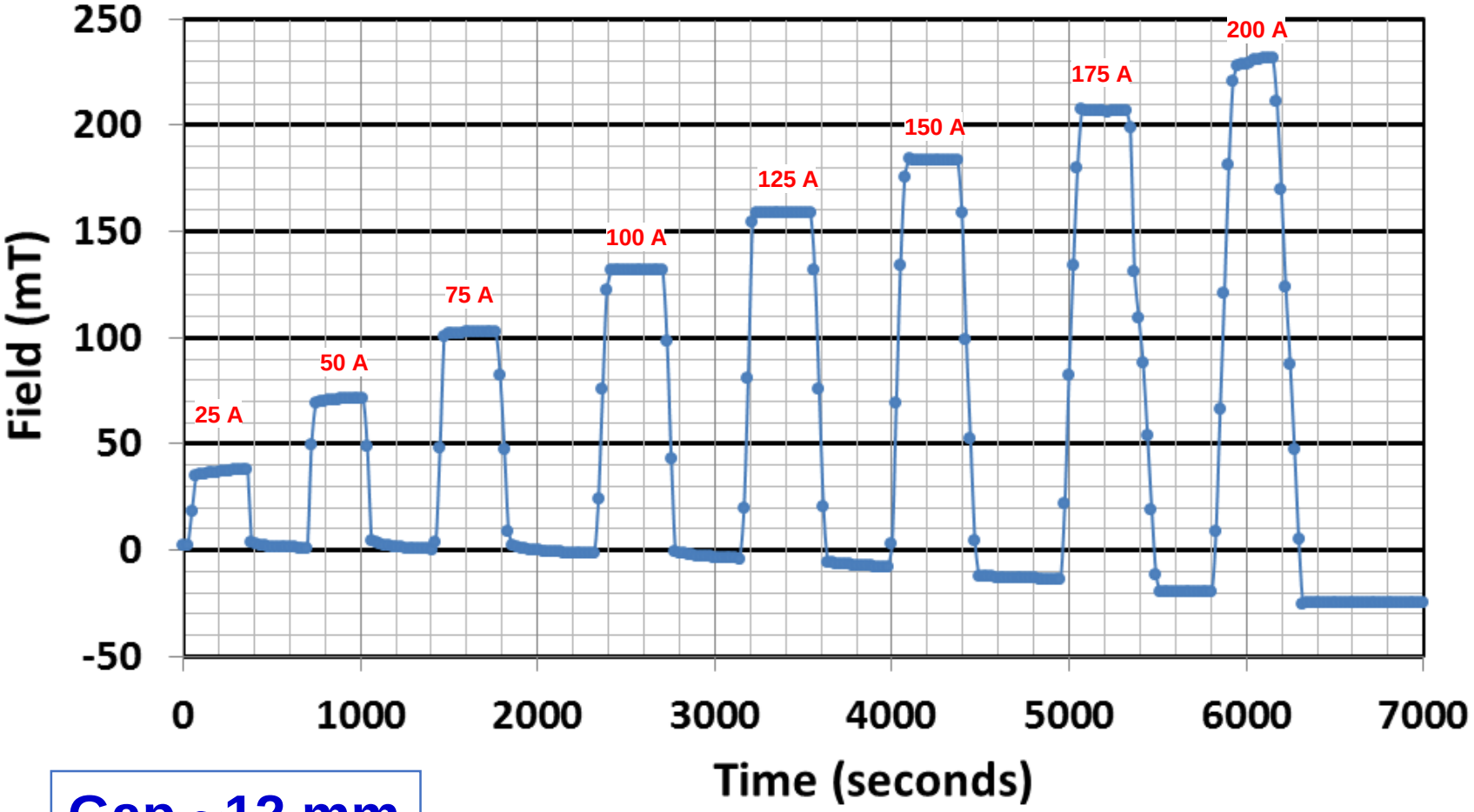






Test Sequence of HTS Coils at 77 K

0 → 25 → 0 → 50 → 0 → 75 → 0, …



Gap ~12 mm

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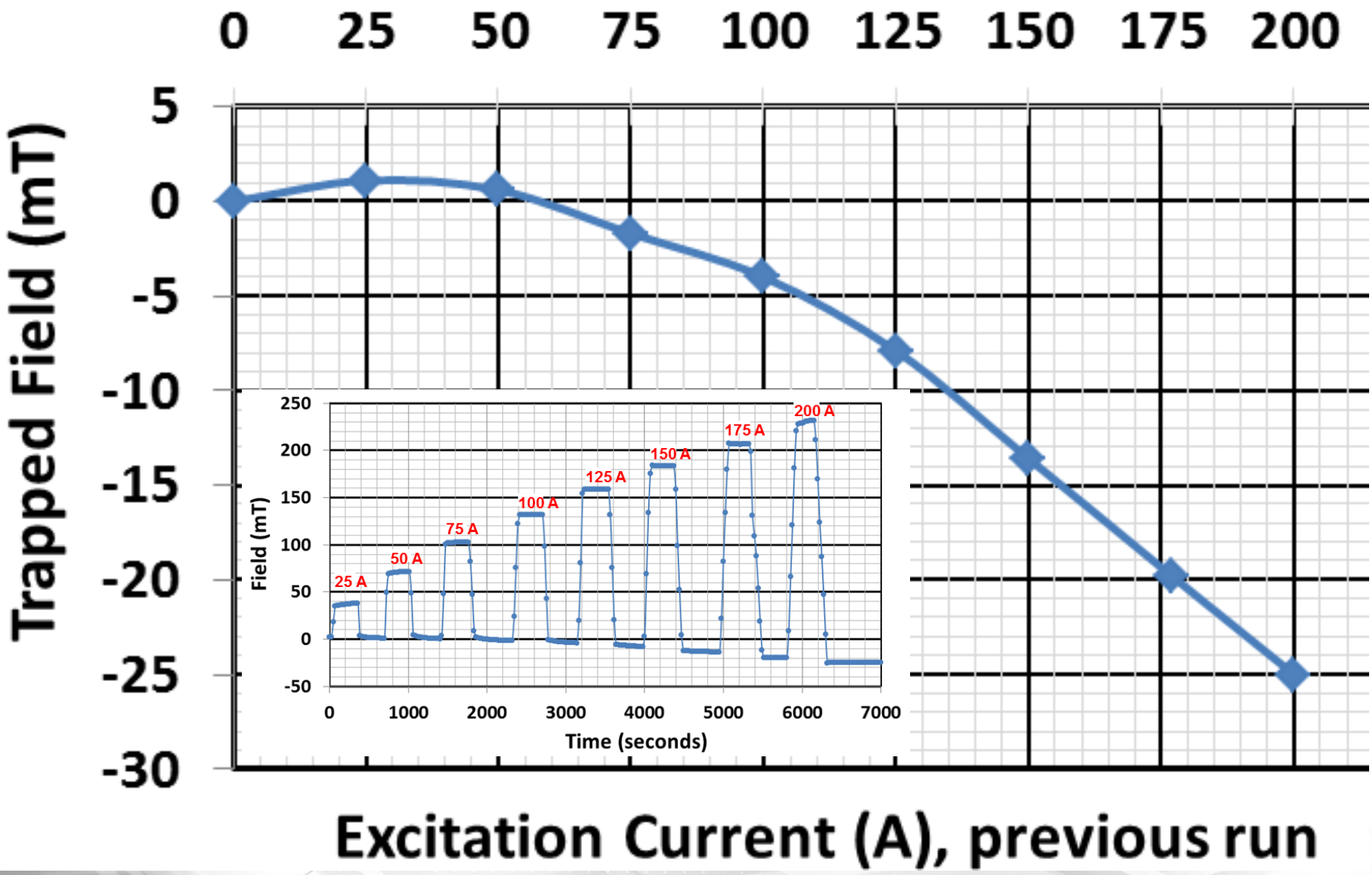
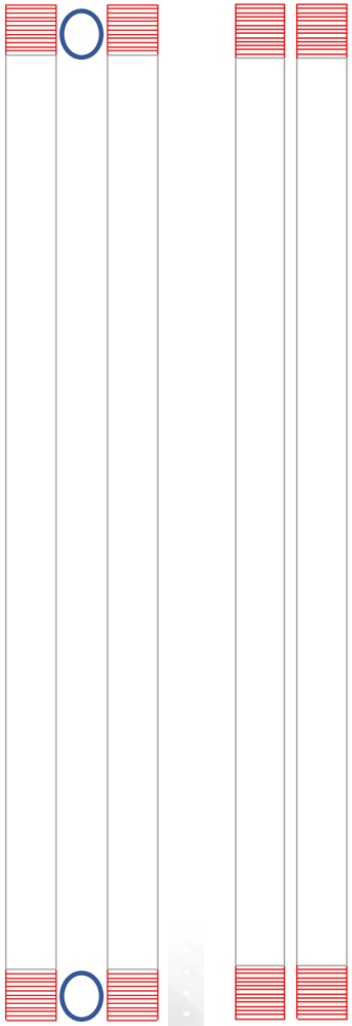
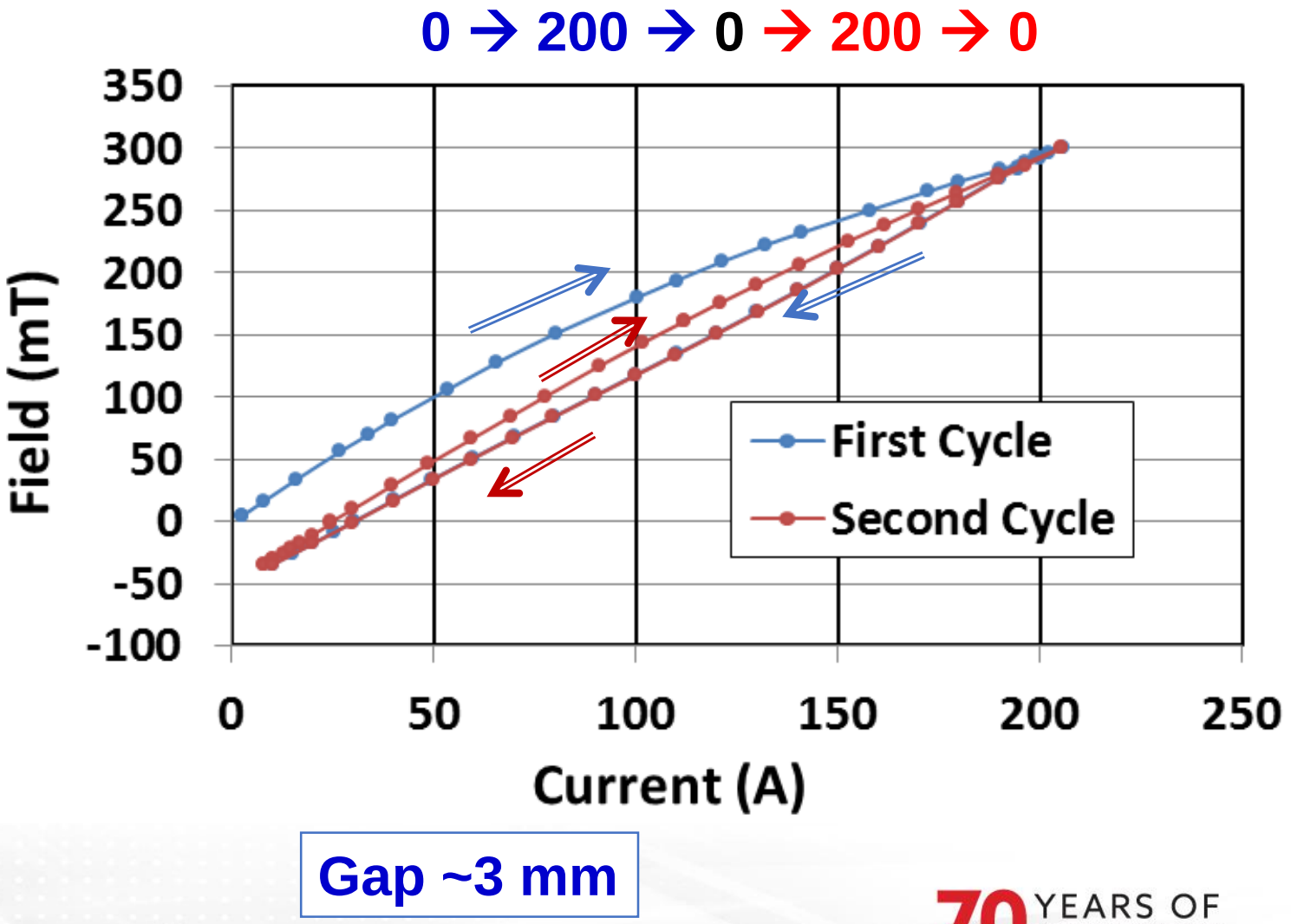
Trapped Field in HTS Coil after Previous Excitation

(measured field at zero current in HTS coil, 77 K)



Two Successive Runs to 200 Amp (77 K)



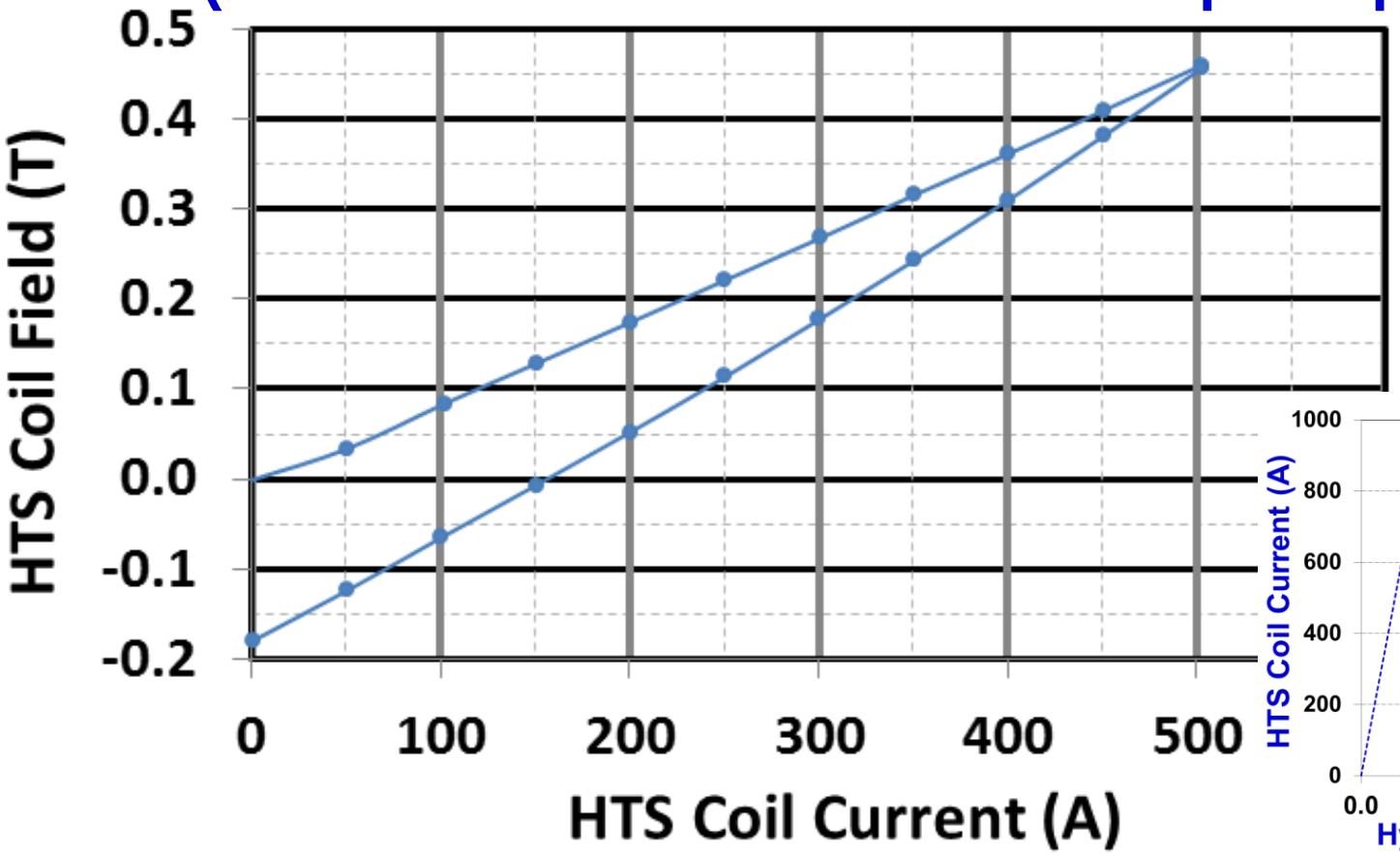


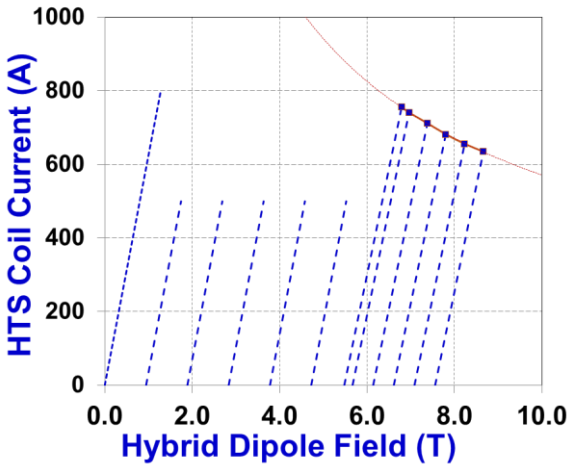
Gap ~3 mm

4 K Measurements

Test Run at 4 K (in 2 T background field from Nb_3Sn coils)

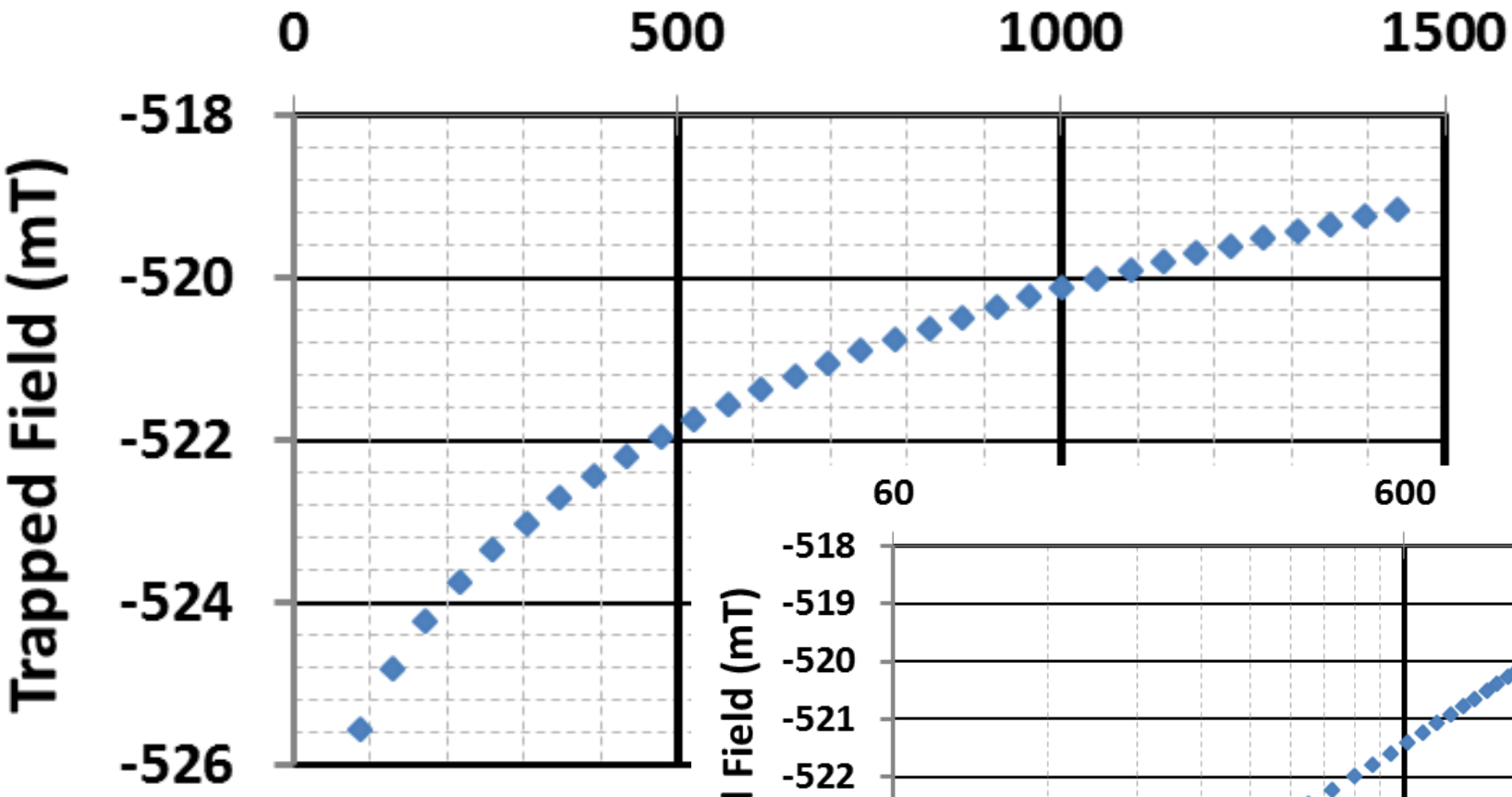
Additional field from the HTS coils in up and down ramp (offset to start from zero to start up-ramp)

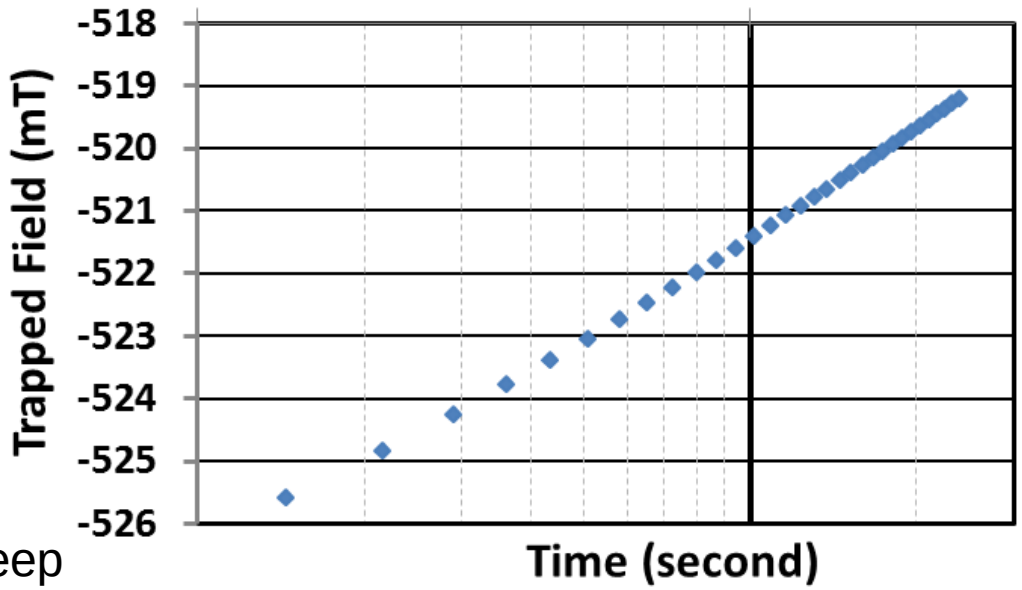




Decay of Trapped Field

(after the final run to ~8.7 T hybrid field @ 4 K)





Flux creep

Summary

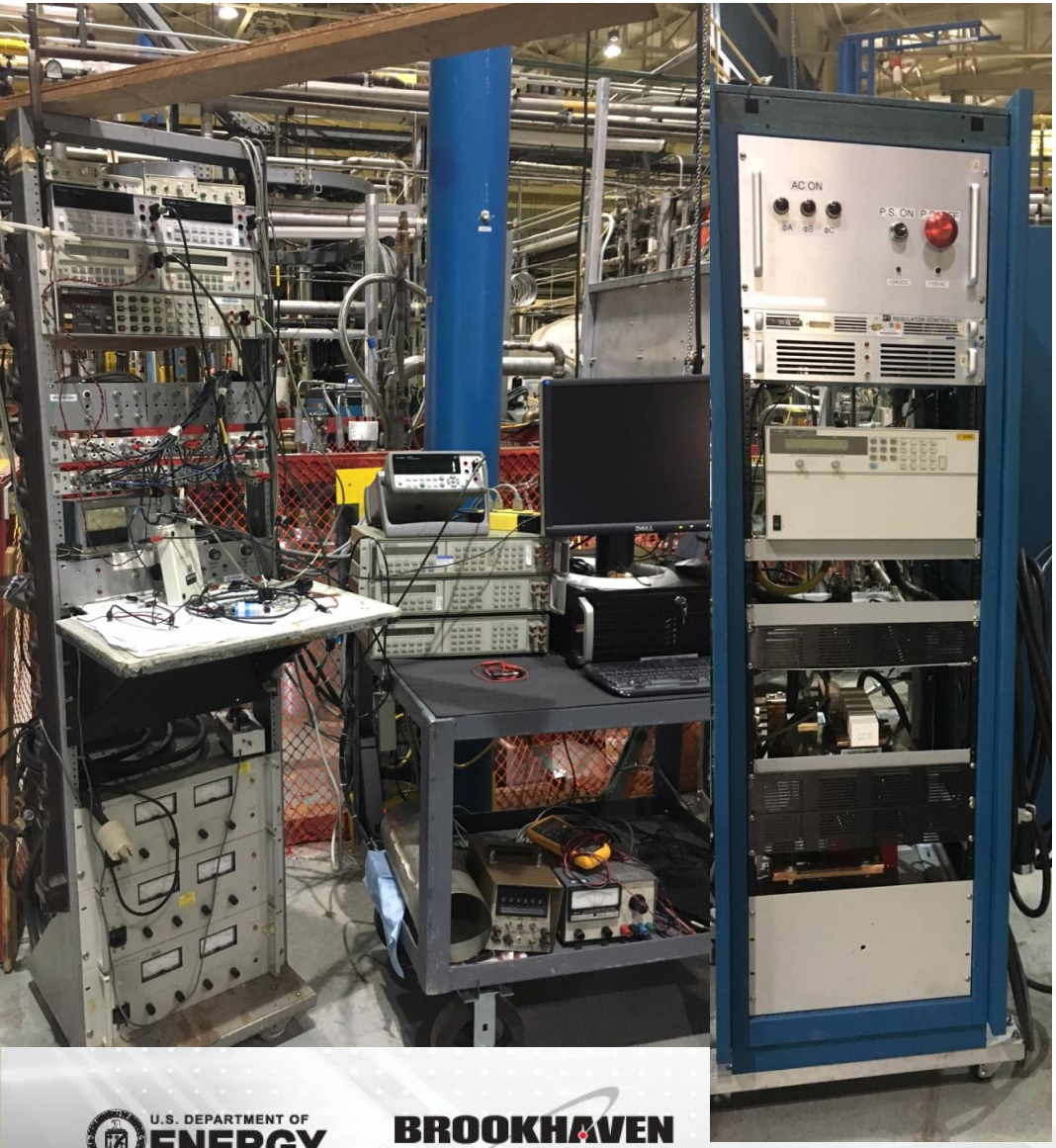
- ❖ Encouraging Test Results of HTS/LTS Hybrid Dipole
- ❖ Many LTS type quenches in HTS coils with no degradation

- A robust rapid-turn-around, low-cost test facility
  - ➢ Insert coils become an integral part of the magnet

- A variety of magnetization studies in HTS tape dipole
  a) at 77 K
  b) at 4 K, including in HTS/LTS hybrid dipole structure

Extra Slides

HTS/LTS Hybrid Operation and Quench Protection



- HTS & LTS powered separately
- Common quench platform; fast energy extraction from both coils
- Quench detection response time: < 5 msec
- Coil current interruption: < 10 micro-second after detection
- HTS coil shut-off: a few msec
- High power IGBT switches
- Electronic threshold for quench detection: ~100 micro-volts
- HTS Quench threshold : 5 mV
- Actual test conditions (more brutal): ~200 mV (like LTS)

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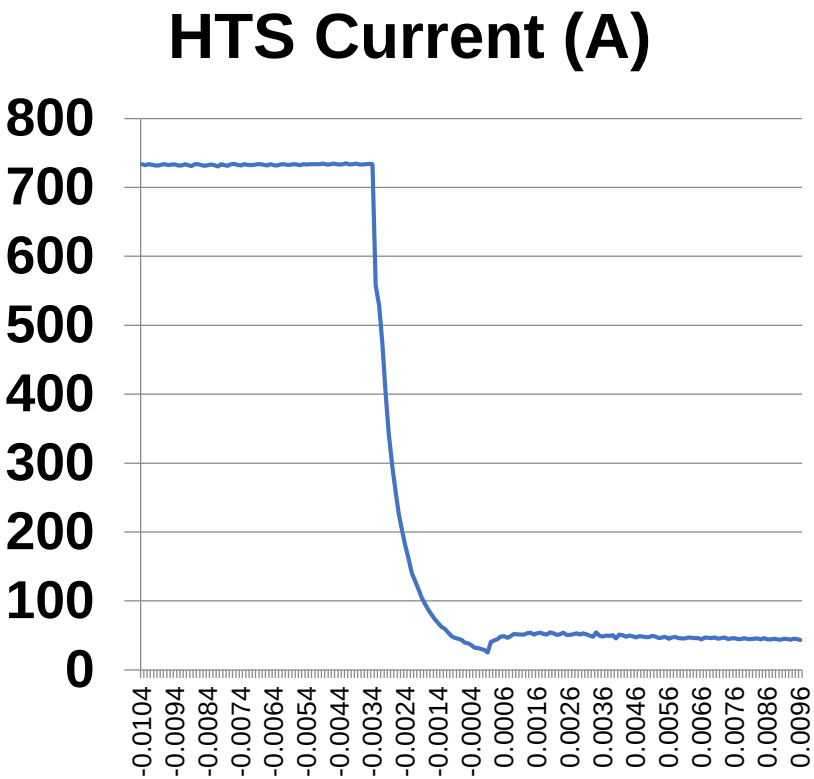
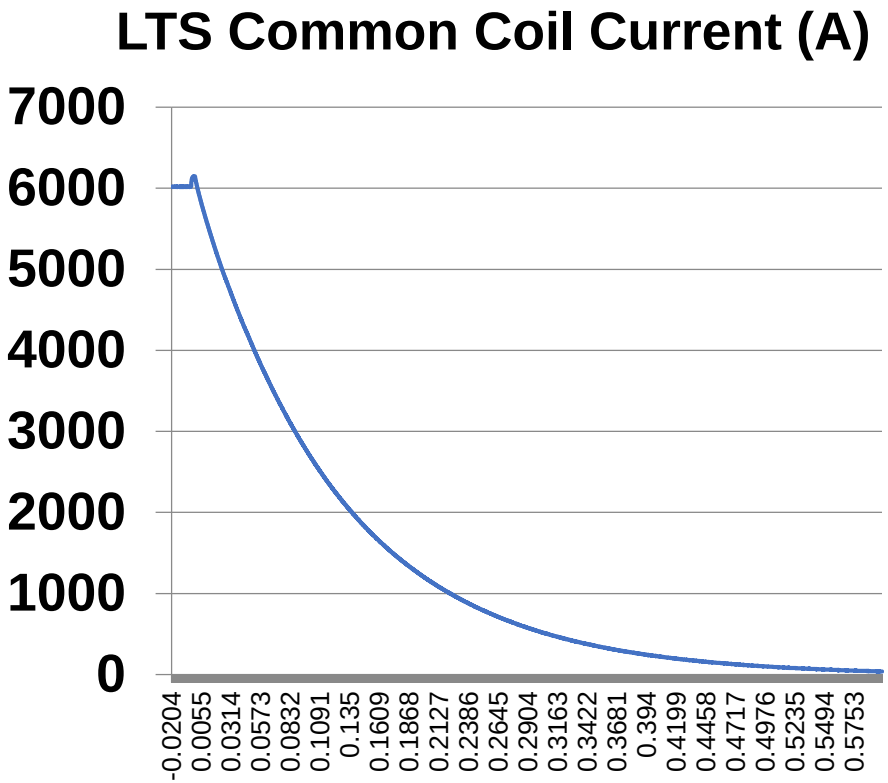
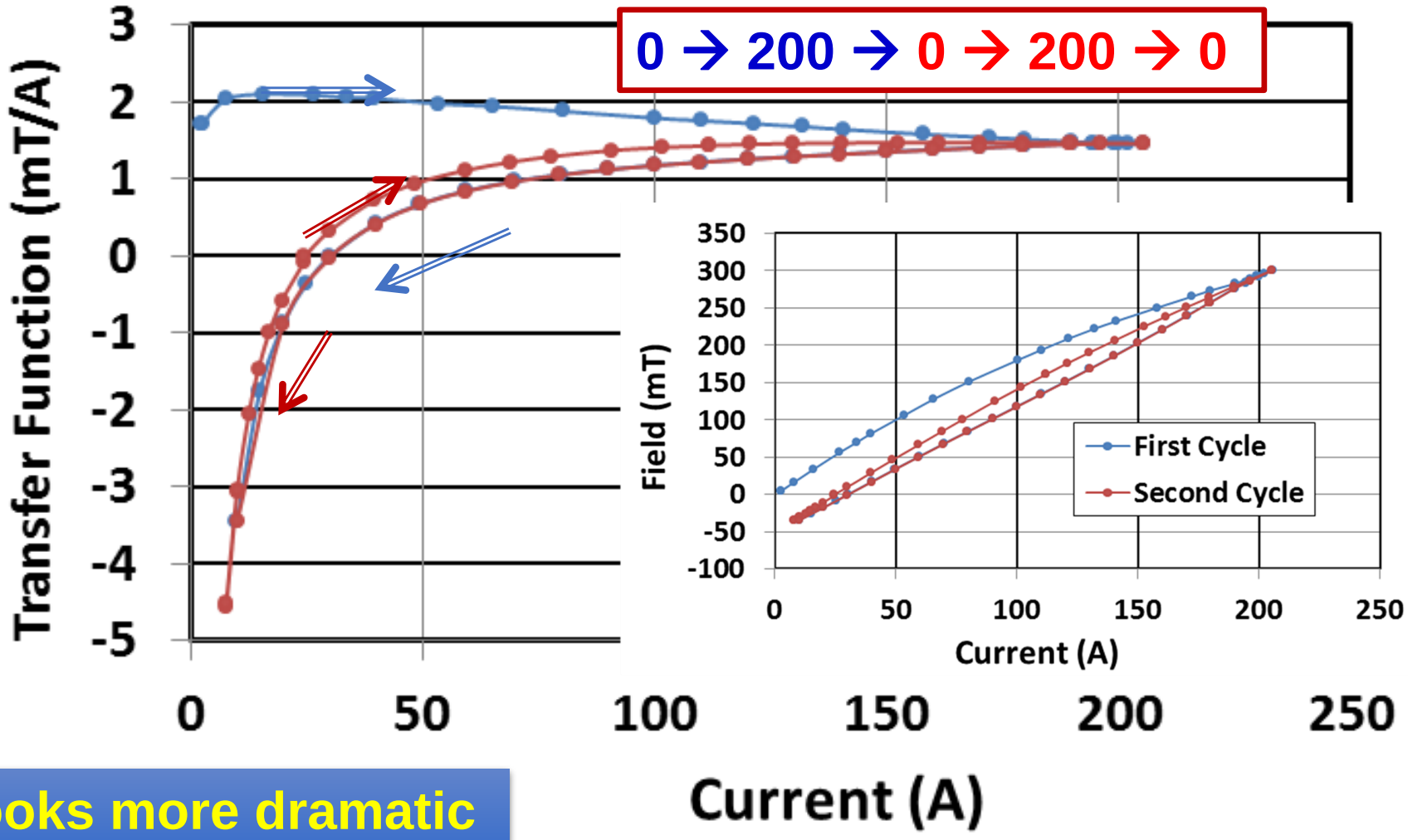
HTS and LTS Currents (just before and after the quench)





Separate power supplies and separate energy extraction for HTS and LTS coils
HTS and LTS coils have different inductances and different characteristics

Two Successive Runs to 200 Amp (77 K)



Looks more dramatic on Transfer Function

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