Medium and High Field HTS Magnet R&D at BNL

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Overview

- Variety of HTS Magnet Programs at BNL
- Focus of this Presentation
  - Medium Field HTS Quad for FRIB
    - Significant test results
  - High Field (>30 T) HTS Solenoid for MAP
    - Continuation of PBL/BNL program under MAP funding
- Feedback to Conductor Manufacturer
- Summary

Active HTS Magnet Programs at BNL (1)

- **HTS Solenoid for Energy Recovery Linac (ERL)**
  - **To be inducted in a significant R&D facility at BNL shortly**
- **HTS Magnet for Synchrotron Radiation Source**
  - **To be delivered to an experimental program at BNL shortly**
- **MgB_2 Phase II SBIR (DOE/NP) with HyperTech**
  - **Technology development to upgrade e-lens for RHIC at BNL (high power required by copper solenoids not available locally)**

Active HTS Magnet Programs at BNL (2)

- HTS Quad for FRIB at MSU (funded by DOE/NP)
  - A major HTS program at BNL from last decade
- HTS Dipole Phase II SBIR (DOE/NP) with Muons, Inc.
  - Longer length (>2m) radiation tolerant curved dipole for FRIB
- Development of Quench Protection Technology
  - Partly supported by BNL internal program development funds and partly by individual project funds to fulfill their specific requirements (MAP, FRIB, ARPA-E and SBIR’s)

Active HTS Magnet Programs at BNL (3)

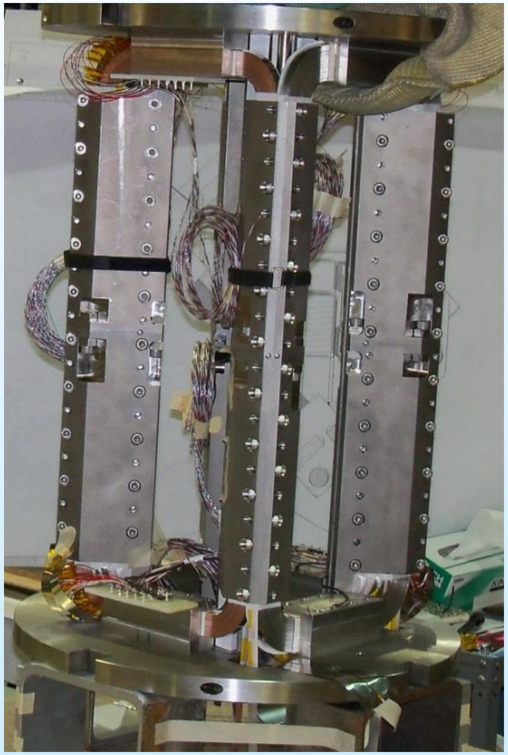
- **High Field (>30 T) Solenoid for MAP**
  - **PBL/BNL solenoid SBIRs (funded by DOE/HEP) created record fields (~16 T peak insert, ~9 T peak half-midsert). The goal is to use these existing coils to develop and demonstrate technology for high field solenoid for MAP**
- **High Field (~24 T) HTS Solenoid for SMES**
  - **A significant HTS R&D program in recent years. Program is funded by DOE/ARPA-E (collaborators: ABB, BNL, SuperPower, UH; BNL/SMD responsible for SMES coil)**

Having acquired over 50 km of HTS (4 mm tape equivalent), made hundreds of HTS coils and tens of HTS magnets, BNL has a unique experience with HTS.

HTS Quad for FRIB

Highlights:

- HTS Magnet built with significant amount of ReBCO (2G HTS) from two vendors
- No observable degradation during winding, cool-down or testing
- Large temperature margin - thanks to HTS
- Magnet survived several events (quenches?) near or above design field



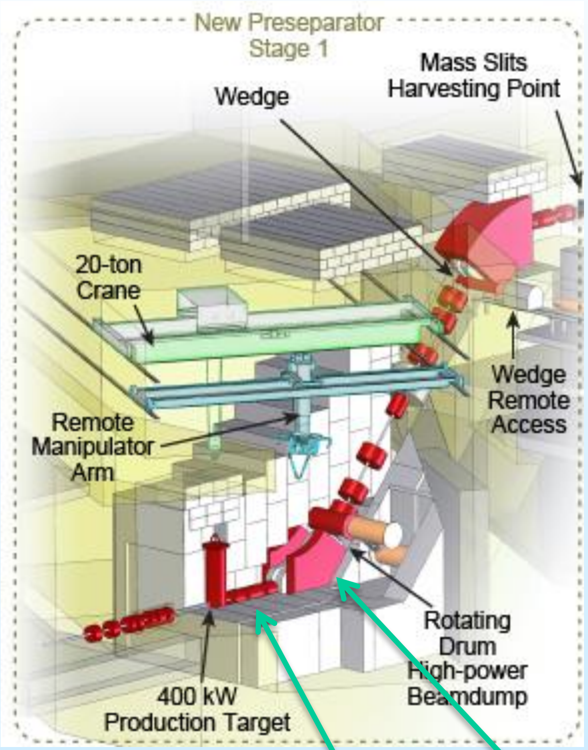
HTS coils in support structure

Radiation Tolerant HTS Quad for the Facility for Rare Isotope Beams (FRIB)

To create intense rare isotopes, 400 kW beam hits the production target.

Several magnets in Fragment separator region (following the target) are exposed to unprecedented level of radiation and heat loads.

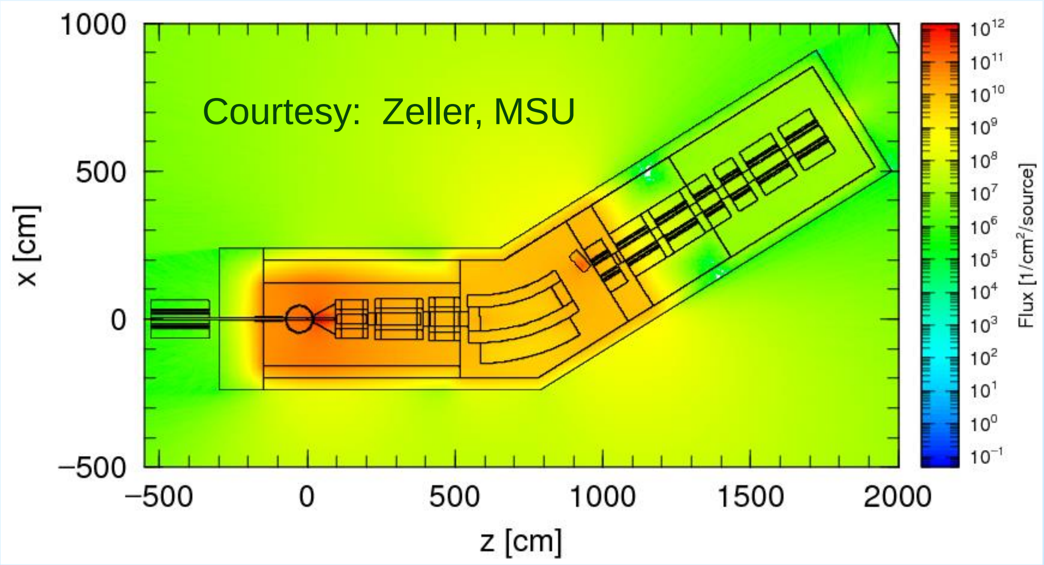
Courtesy: Al Zeller, FRIB/MSU



Radiation resistant
Pre-separator quads and dipole

Exposure in the first magnet itself:

- **Head Load : ~10 kW/m, 15 kW**
- **Fluence : 2.5 x10^{15} n/cm^2 per year**
- **Radiation : ~10 MGy/year**



Second Generation HTS Quad for FRIB (higher gradient and operating temperature)

First generation quad was made with the 1G HTS (Bi2223)

Higher performance 2nd generation quad is made with 2G HTS

Eight coils wound

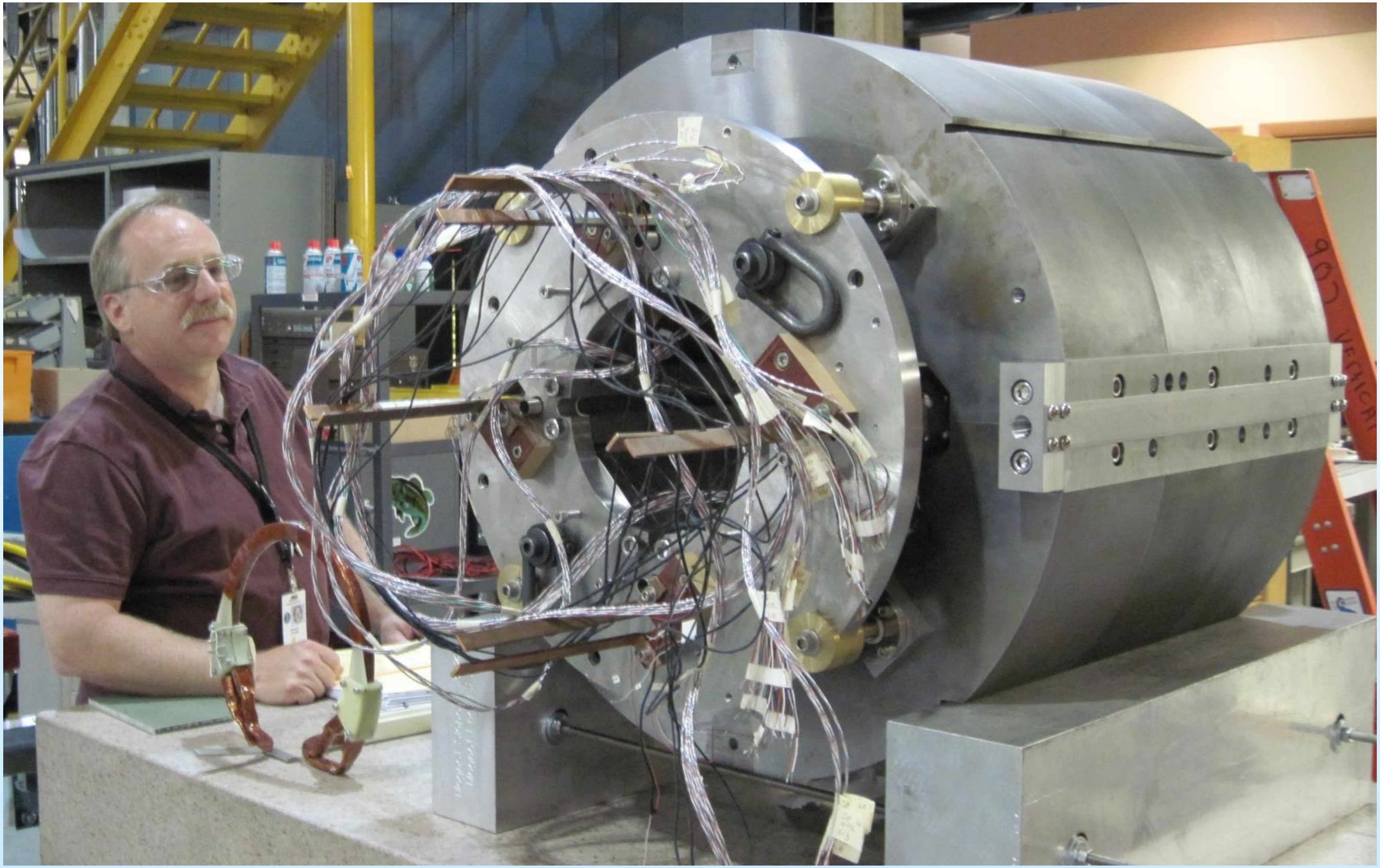
4 coils made with ASC:
- ~210 m double sided
- (420 m HTS per coil)
- ~2x125 turns

4 coils with SuperPower:
- ~330 m per coil
- ~213 turns

Note: This is a 12 mm tape (3X the standard 4 mm)

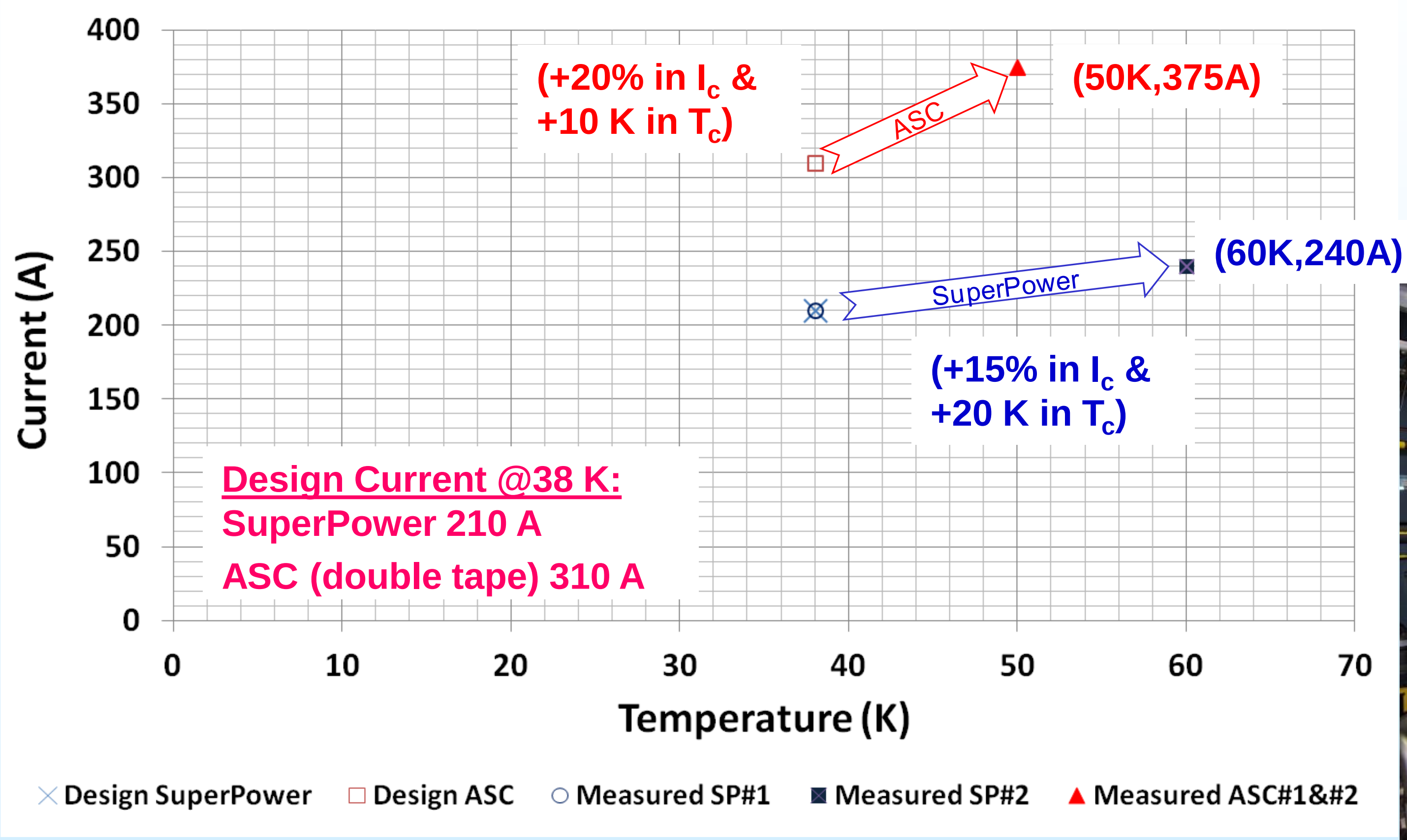
(over 8 km of 4 mm equivalent used)

Completed Second Generation HTS Quad for FRIB

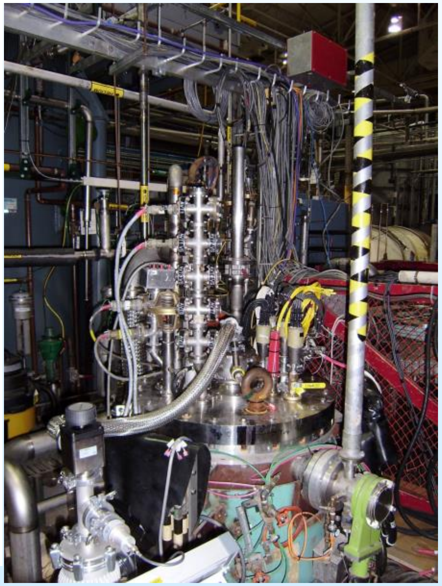


{8 racetrack coils, 4 made with SP tape and four with ASC tape (double)}

Test Results
Large Temperature Margin

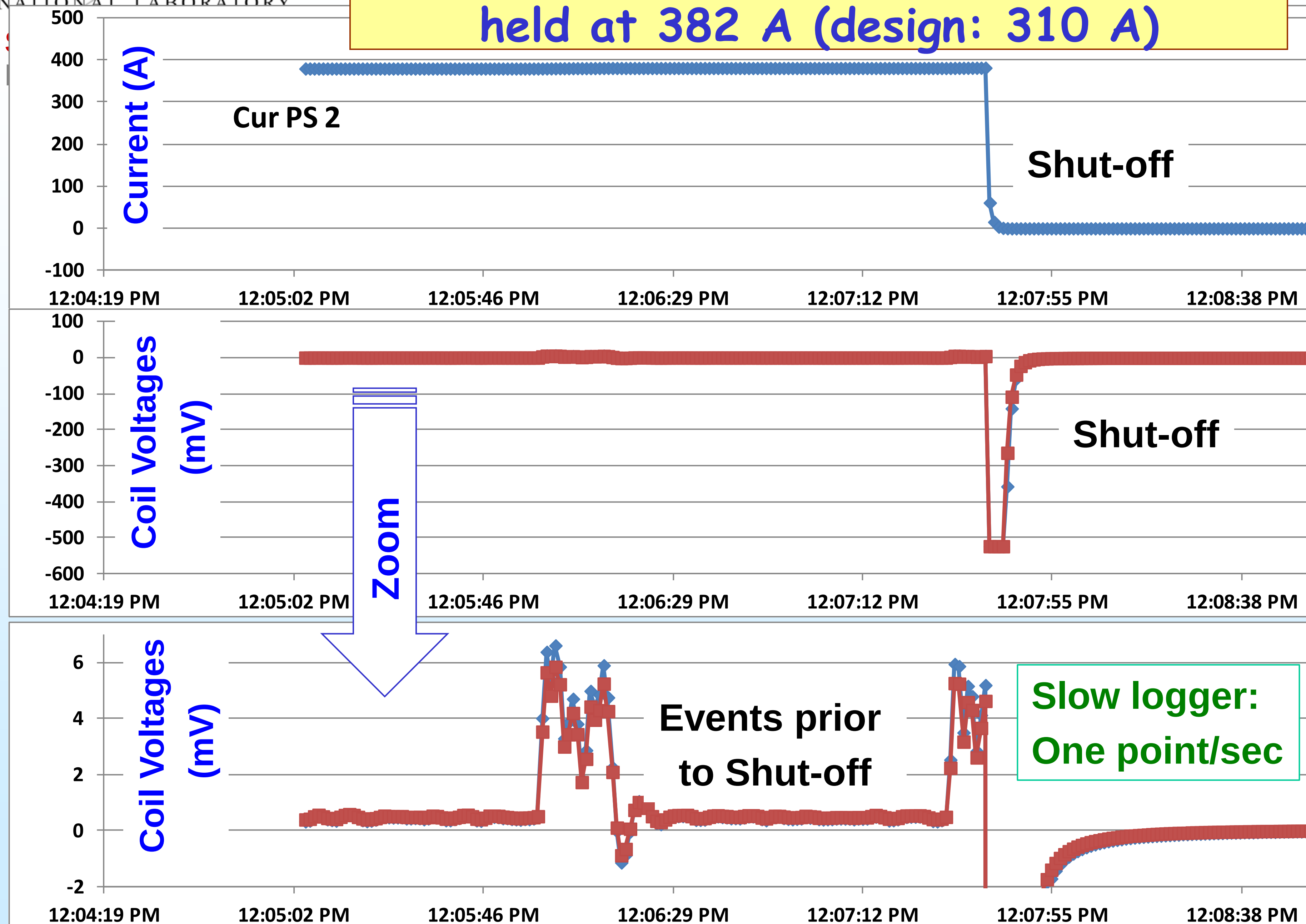


No observable degradation during cool-down or energizing

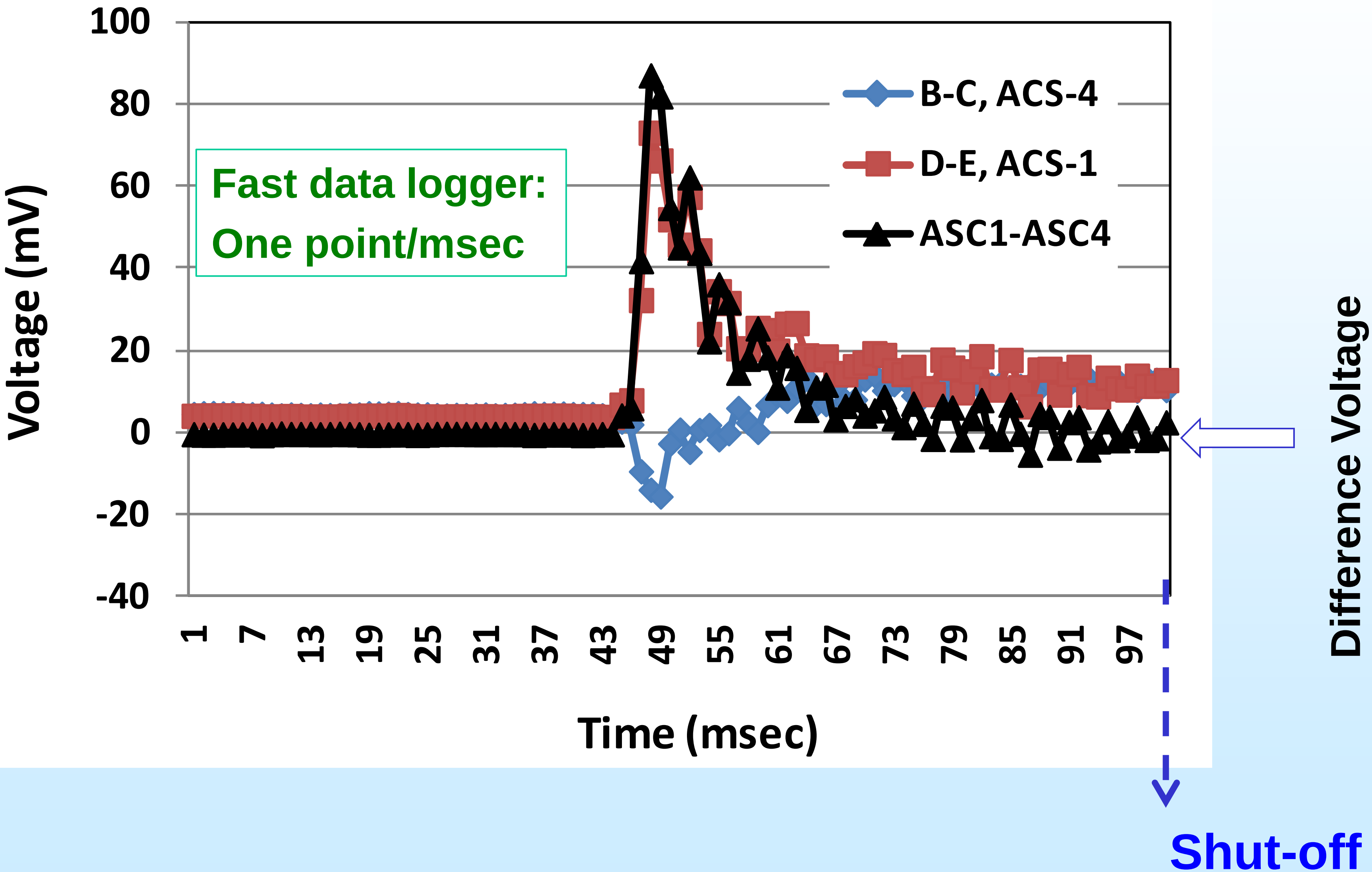


- Magnet with significant amount of HTS performed well
- Unprecedented temperature margin – only possible with HTS

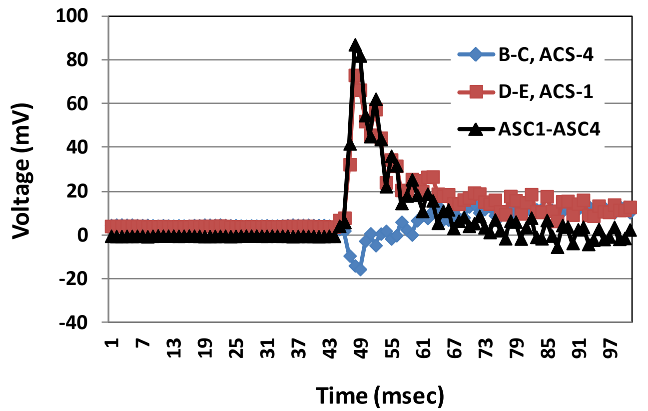
Event (Quench?) while ASC Coils were held at 382 A (design: 310 A)

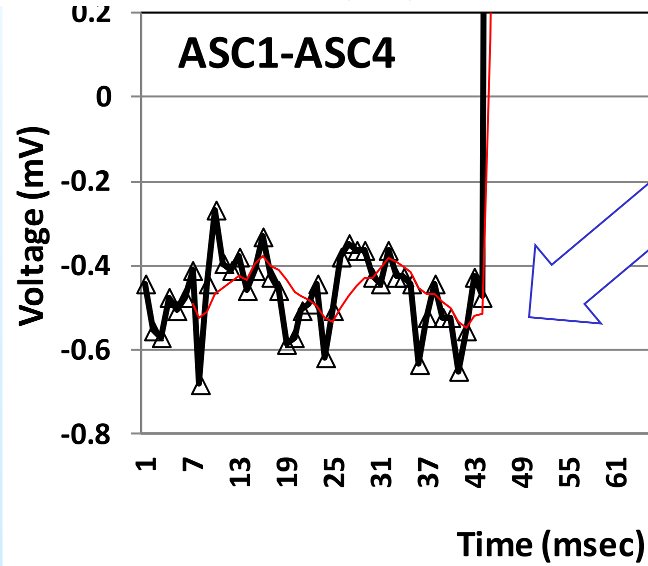


Snap Shot of the Event in ASC Coils (individual and difference voltages)

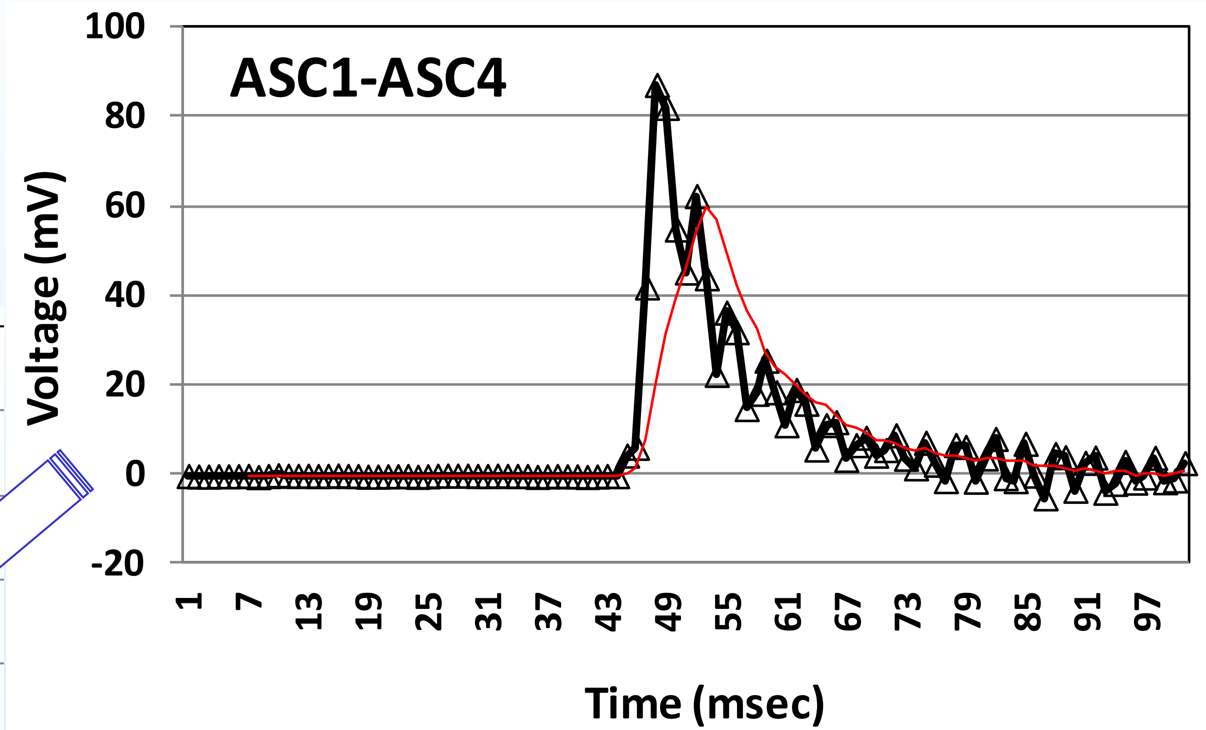


Snap Shot of the Event (Quench?) that Triggered the Shut-off





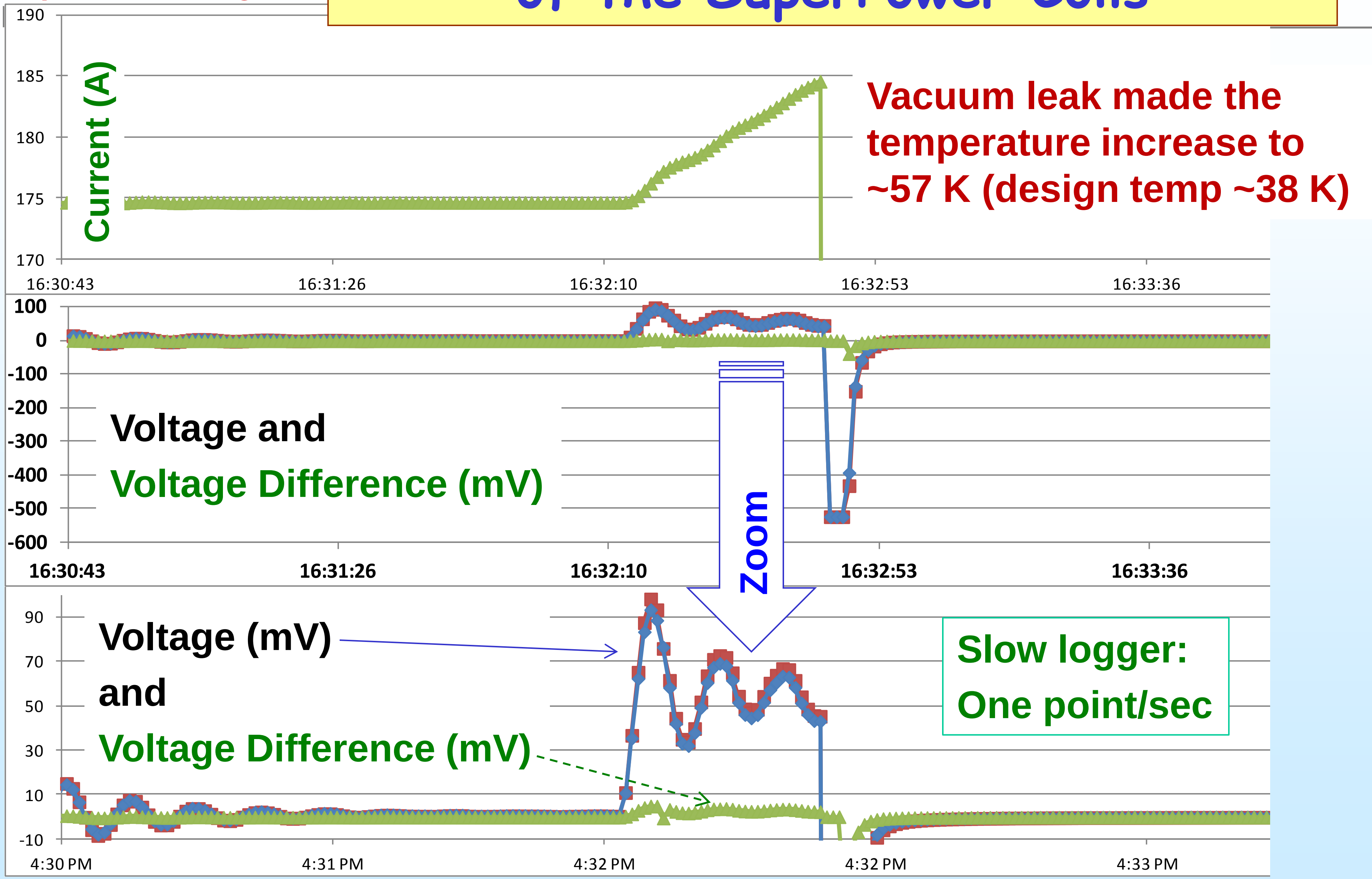
Difference Voltage



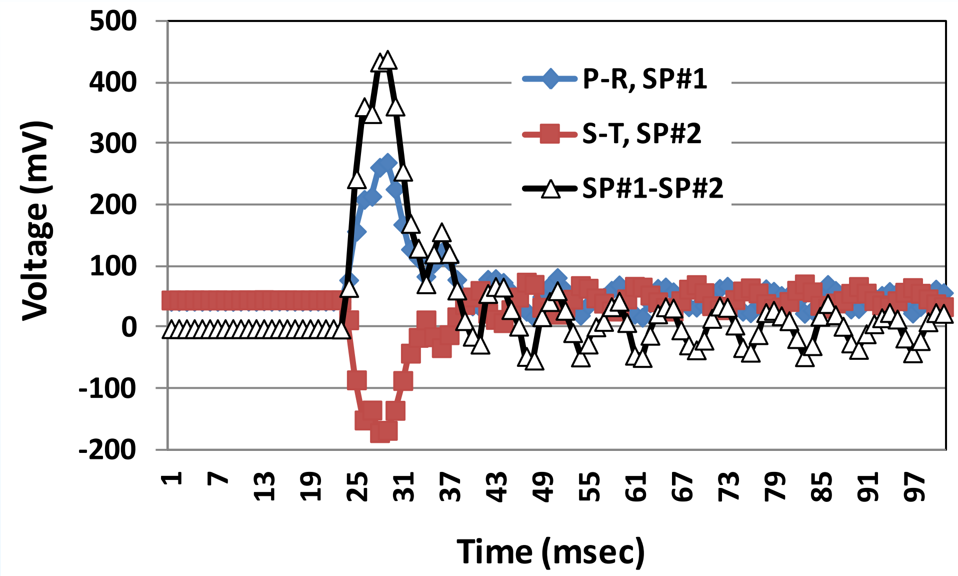
Low threshold (few hundred μV) can be kept due to the advanced quench detection system

No degradation in performance observed after the event

Event (Quench?) During the Ramping of the SuperPower Coils

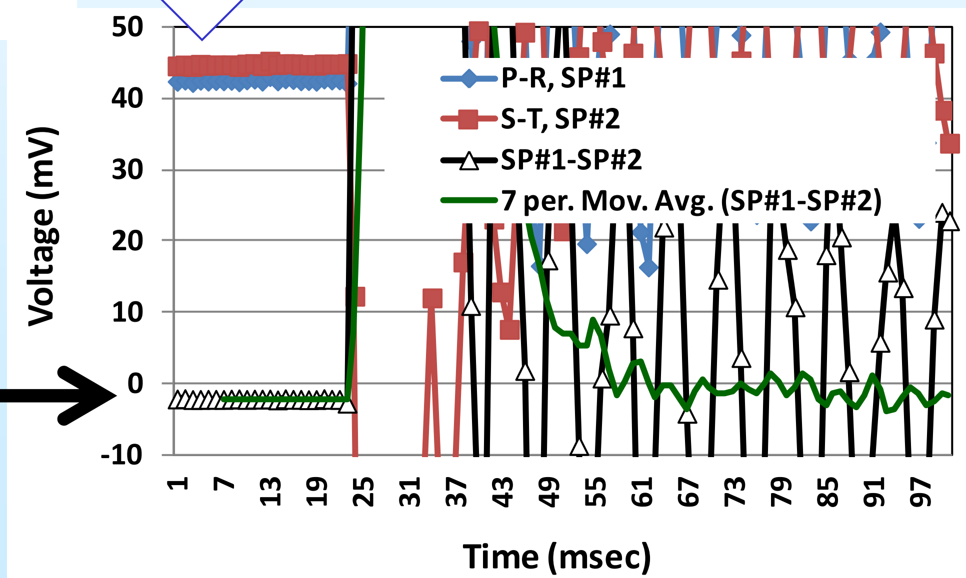


Snap Shot of the Event (Quench?) that Triggered the Shut-off



Fast logger: One point/msec

Large inductive voltage in individual coils (ramp)

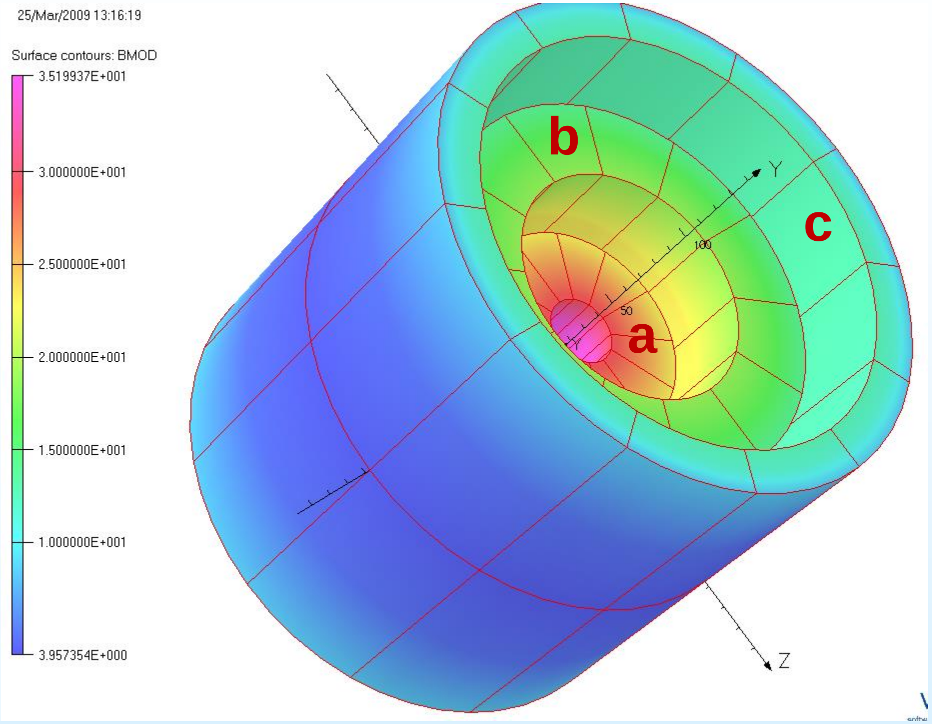


Small quench detection threshold (2 mV) kept during the ramp by monitoring difference voltage

Analysis of the Events

- Quench detection system determined the event a quench as the voltage threshold was exceeded
- Quench protection system extracted the energy rapidly
- All coils were re-tested a few times after the event
- No degradation in performance was found in coils made with either SuperPower or ASC conductor
- This shows that the quench protection system can protect the HTS coils against the events like this

High Field (>30T) Solenoid for MAP



a) >12 T HTS solenoid (insert)

b) >10 T HTS (midsert)

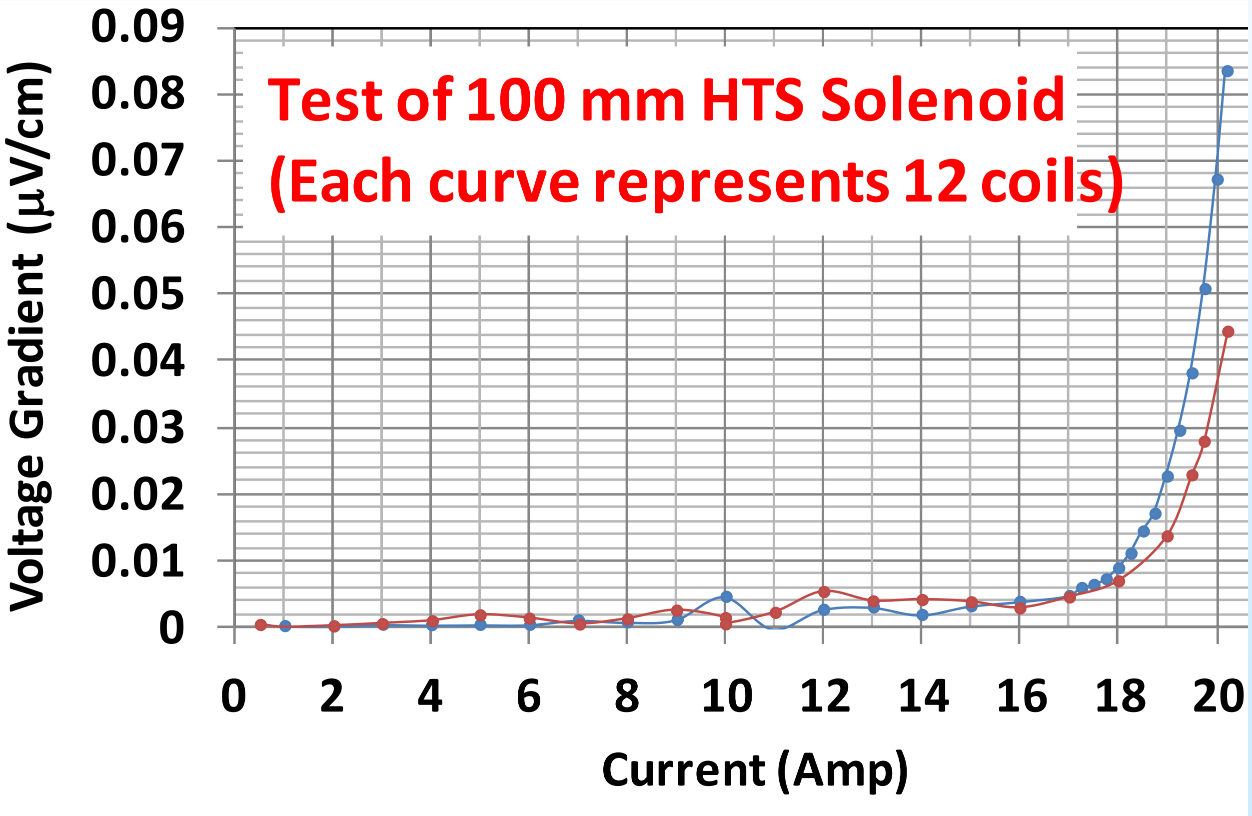
c) >10 T LTS (outsert)

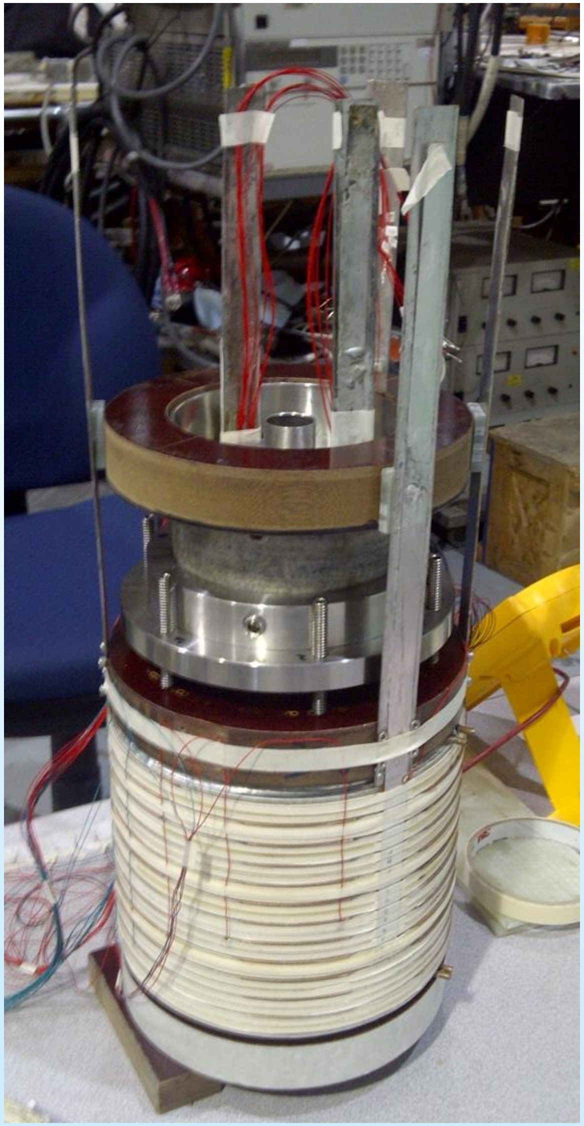
- Promising demos with a series PBL/BNL SBIR (DOE/HEP)
- Work continues under Muon Accelerator Program (MAP)

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Initial Test of HTS Insert and Midsert and Preparation for High Field (>22 T) Test

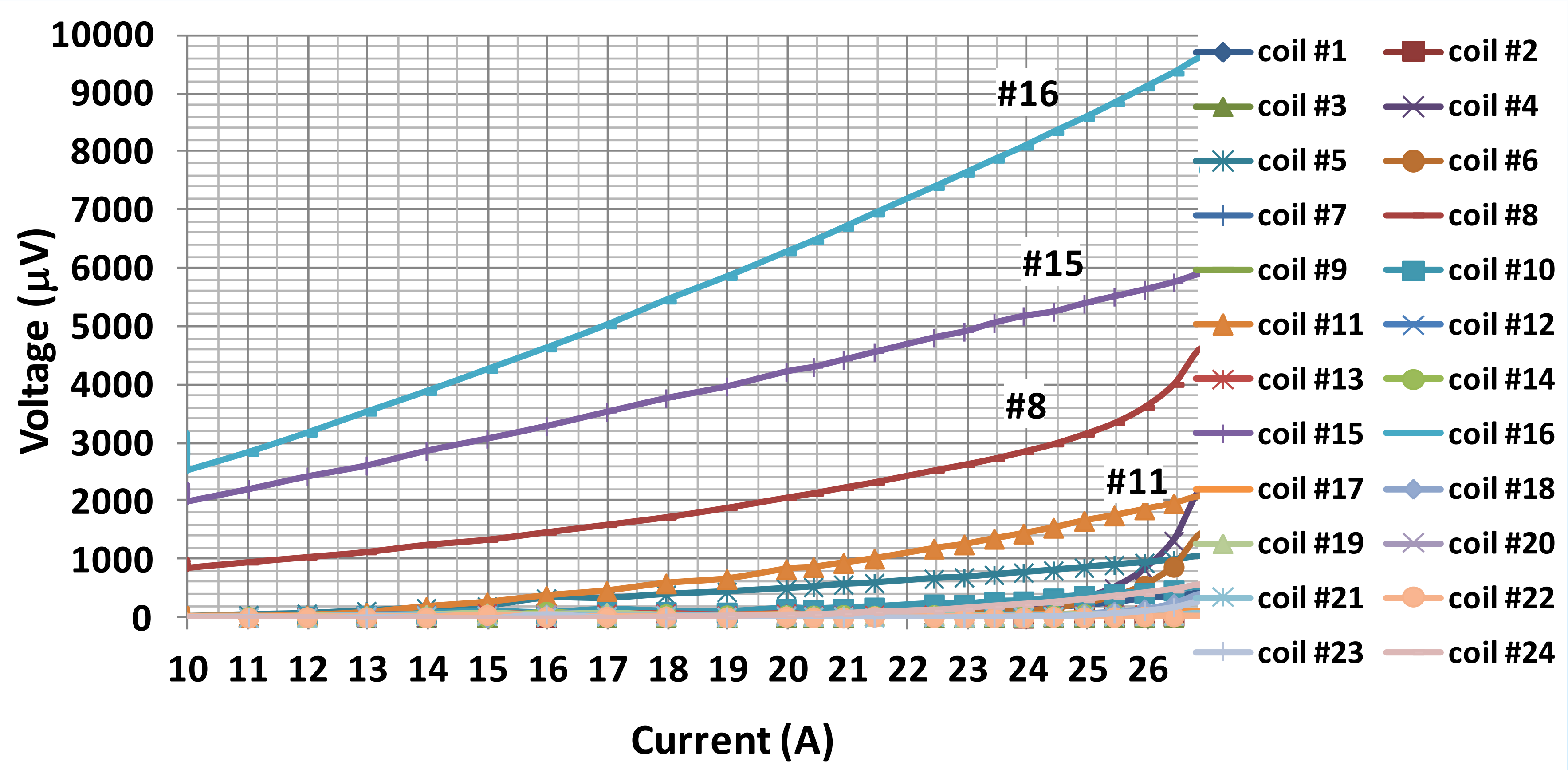
- HTS Insert (14 pancakes, ran at 16 T peak field) and Midsert (24 pancakes, 12 ran at 9 T peak)
- Expected on axis field at 4 K: > 22 T (design)
- All worked well during 77 K Pre-test





Test Results of Combined Structure (HTS Insert and HTS Midsert)

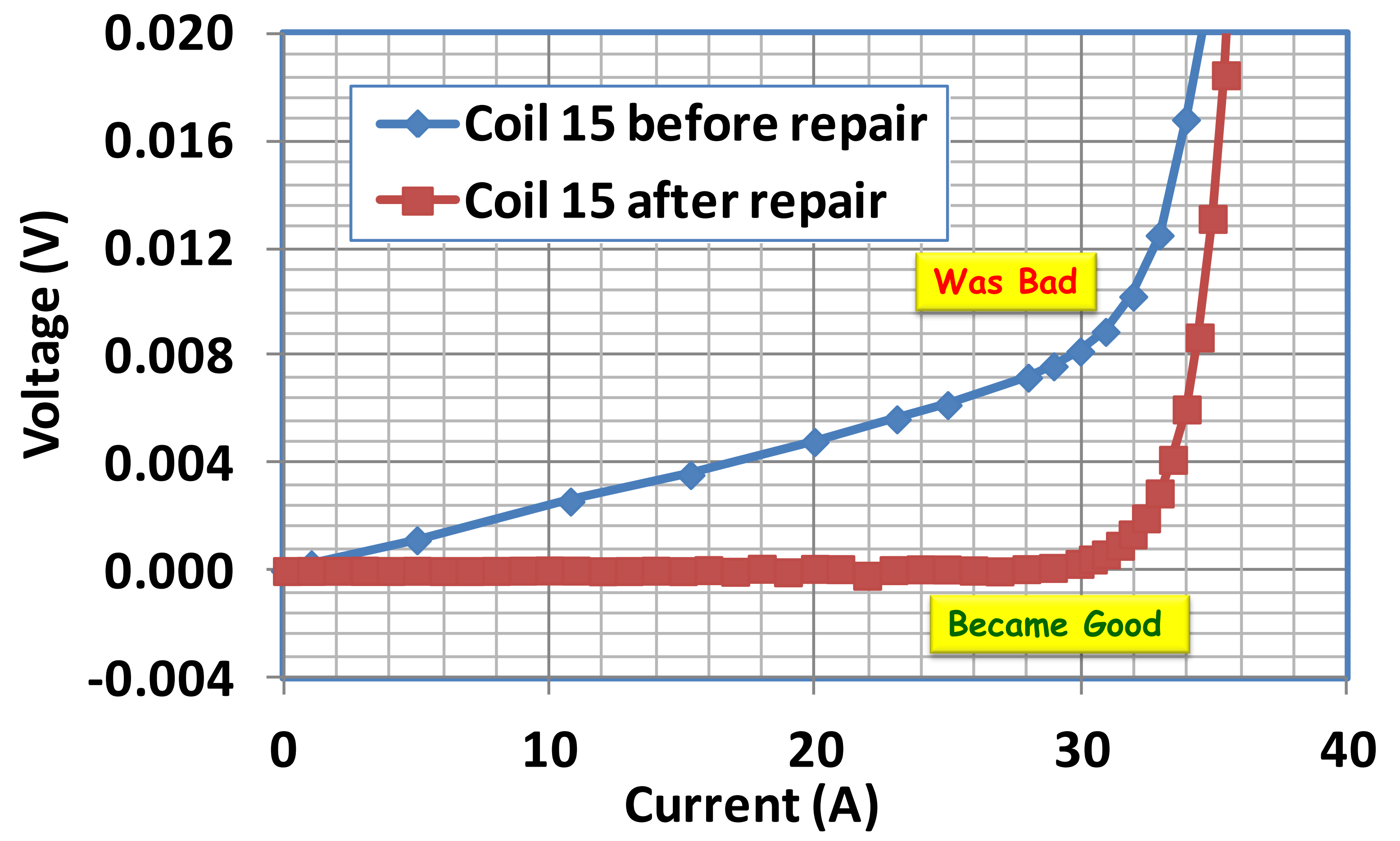
- Several pancakes got degraded during one @77 K test with LN_2



- No further degradation seen after repeated test after this event
- Assumed cause: excessive thermo-mechanical strain during system testing

Repairing the Pancakes

Several (but not all) pancakes have been repaired by removing inner-most turn and by making a new splice between the two single pancakes



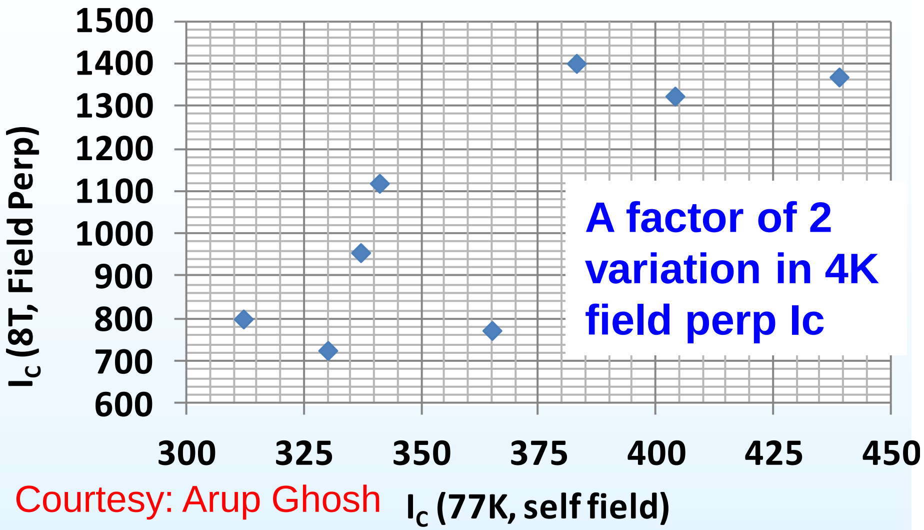
Status and Moving Forward

- Repair as many HTS pancake coils as possible. Then rebuild the magnet structure with either fewer pancakes (lower field) or with replacement pancakes, depending on the funding (SuperPower has kindly offered to contribute some conductor).
- Reduce the thermal strain on HTS coils with improved design (better cooling with copper disks, etc.) and with slow controlled cooling.
- Retest the magnet to high fields to verify the analysis and the design.

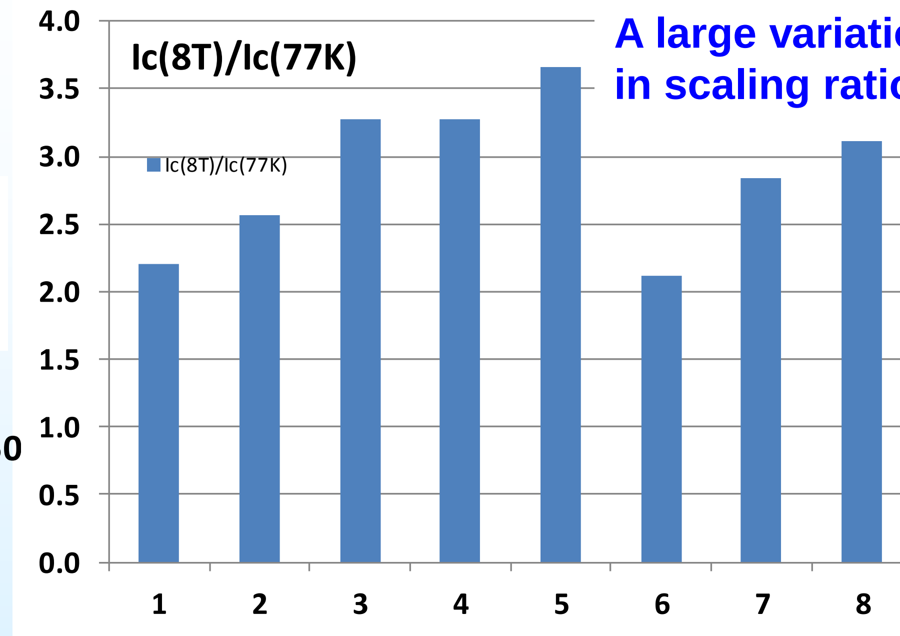
- **Future high field solenoid R&D at BNL relies on MAP (with all SMES coils built and no similar high field program on the radar).**
- **We want to build upon the positives and lessons learnt and use the existing coils, hardware and experience to complete the task.**
- **Modest support may produce significant results (remember: 16 T HTS insert and 9 T half-midsert have already been tested once).**

Feedback to Conductor Manufacturer

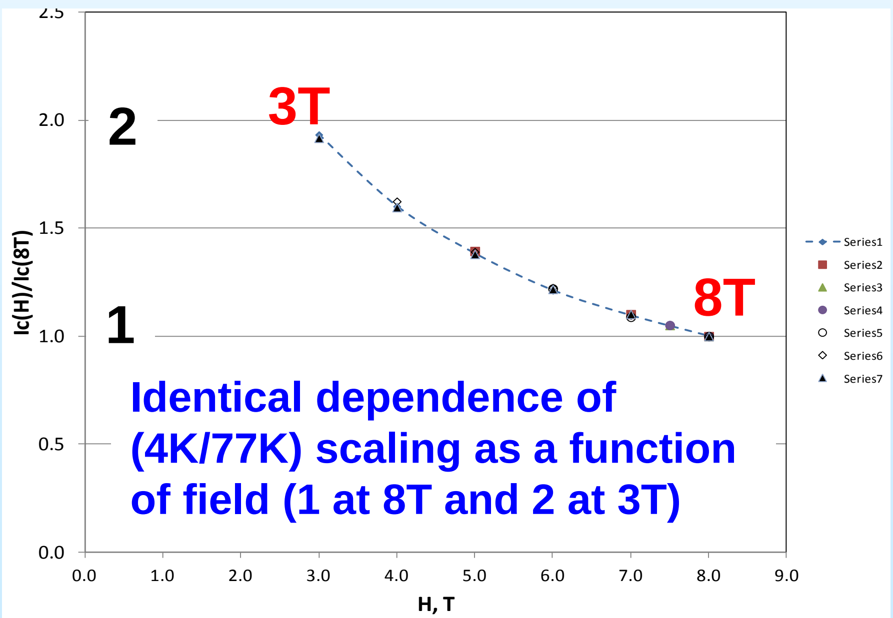
I_c (77K, self field) and (4K, in-field)



Courtesy: Arup Ghosh



See poster by Arup Ghosh



- **An opportunity to understand and improve Ic significantly (2X or more)**
- No variation in 4K scaling Vs Bperp.
- Means low field measurements are OK.
- Add curves at different temperatures.
- Make Ic Vs. T curves at different fields.
- Cheaper measurements improves stat.

More Wish-list on 2G Conductor

- One of the major strength of 2G HTS is its mechanical strength (high modulus to deal with large Lorentz forces). However, current electro-plating may be a weal link. Improve on it and add measurements of various mechanical properties (including peel strength of copper), as needed.
- Wider and/or multi-tape designs (for example like ASC supplied tape for FRIB). It reduces inductances (good for quench protection) and also the impact of weak-spots (a bit more forgiving).
- 2G cables – variety of types may be possible, each with its own advantage for a given application.

Summary

- HTS magnets offer unique solutions. There is no option but to use HTS to build superconducting magnets operating either at very high fields or at very high temperatures (cryo-free) or with large energy deposition (as in FRIB).
- We may be near the exciting period of “1968 Summer Study” in LTS
  http://www.bnl.gov/magnets/staff/gupta/Summer1968/.
- We have several impressive results to indicate what HTS magnets can offer. However, significant work remains to take advantage of their full potential.
- Initial test results of FRIB quad show that HTS may be able to handle quench type events. However, more clear demonstrations are needed.
- Initial results of PBL/BNL high field HTS solenoid have been impressive (particularly demonstration of 16 T insert and 9 T half midsert HTS solenoids under the limited budget of SBIR).
- There is a potential to create ~25 T in HTS solenoid with modest funding, by continuing the above program and coils. This would be a significant contribution to the field with applications in many areas. With conventional LTS outsert, we should be able to address a critical technology area for MAP.