HTS Quadrupole for FRIB

Design, Construction and Test Results

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FACILITY FOR RARE ISOTOPE BEAMS

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Overview

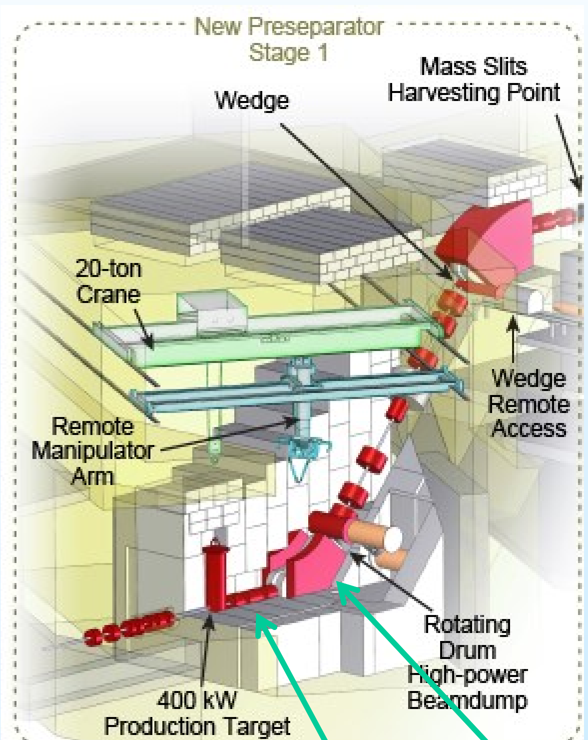
- Why HTS magnets for the Facility for Rare Isotope Beams (FRIB)?
  - FRIB is a major US facility under construction at MSU
- Brief overview of the significant HTS magnet R&D for over last ten years (~4M$)
  - Primary focus: the test results

Radiation Tolerant HTS Quad for the Fragment Separator Region of FRIB

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

Several magnets in the fragment separator region are exposed to unprecedented radiation and heat loads.

Courtesy: Al Zeller, FRIB/MSU

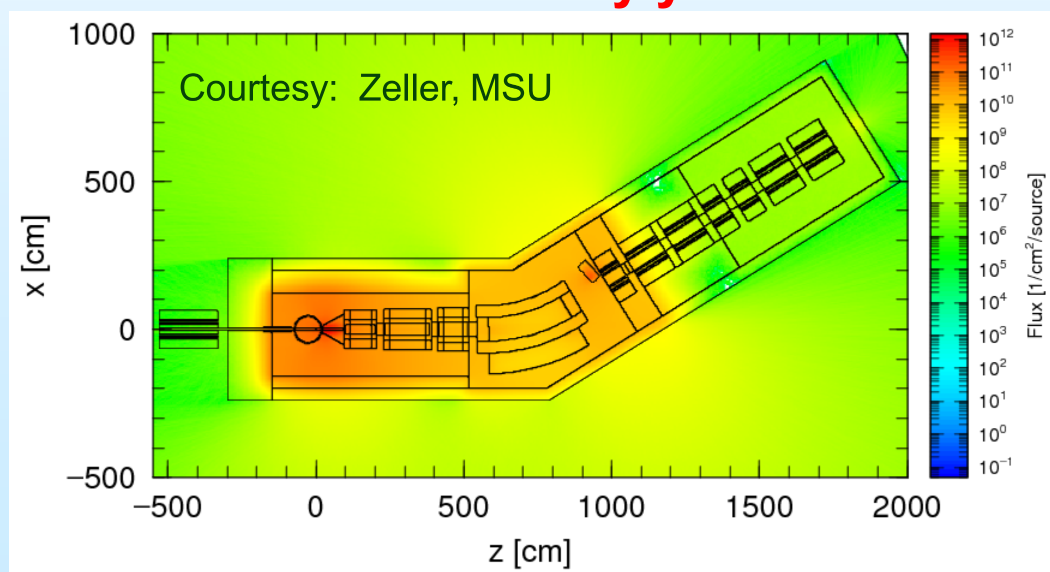


Radiation resistant

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**



Benefits of HTS Magnets Against Large Energy Deposition

Technical Benefits:

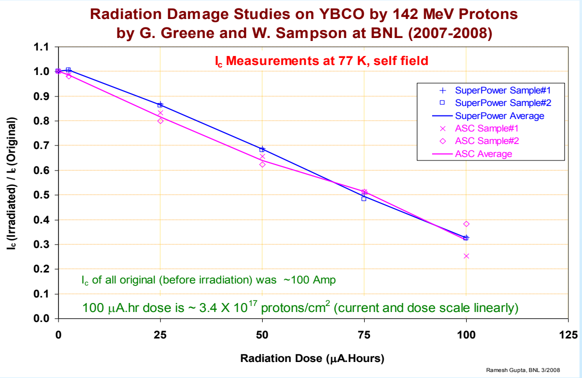
- HTS magnets provide a large temperature margin.
  - ✓ HTS magnets can withstand large (10 K or more) local and global increase in temperature.

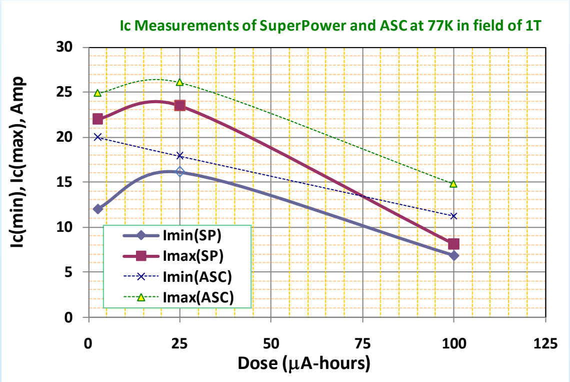
Economic Benefits:

- Removing such large heat loads at 38 K (with HTS) is over an order of magnitude more efficient than at ~4 K (with LTS).

Radiation Tolerant HTS Magnet Design

- All material used in the magnet can withstand large radiation loads (10 MGy/year for > 10 years)
- Most parts used are metallic
  - ➢ Turn-to-turn insulation, often the weak-link in the magnet, is stainless steel
- Experiments performed on 2G HTS at BNL show that it can withstand these doses





➢ **HTS Quad is now the baseline design of FRIB FS**

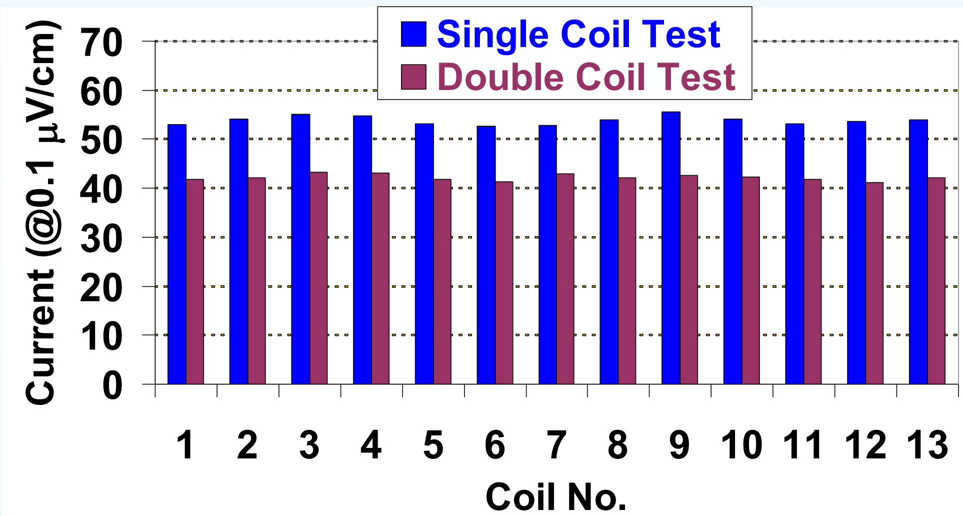
First Generation Design

- Short model built with ~5 km of ~4 mm wide first generation (1G) HTS tape from ASC

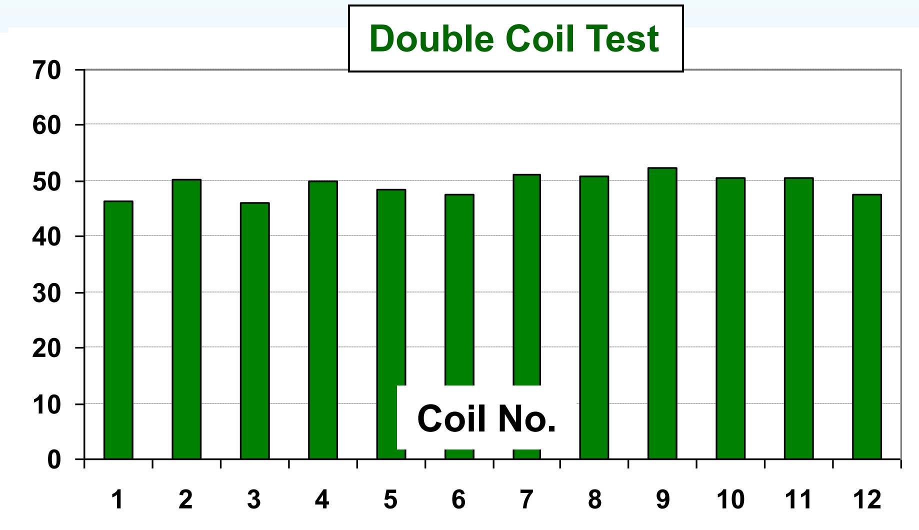
77 K Test of Coils Made with ASC 1st Generation HTS

- Each single coil uses ~200 meter of tape

13 Coils made HTS tape in year #1



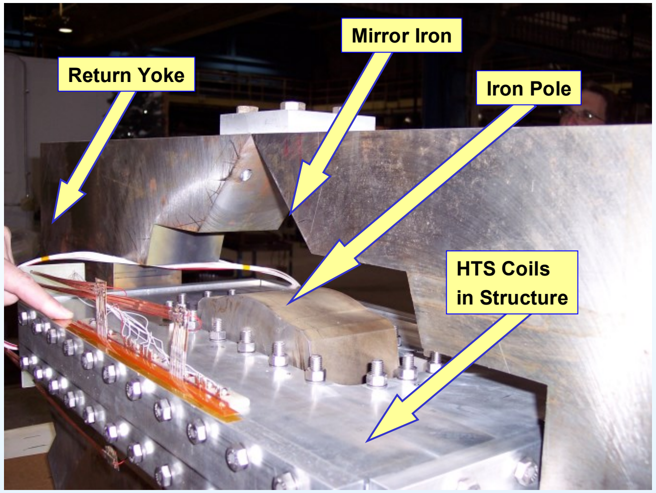
12 coils with HTS tape in year #2



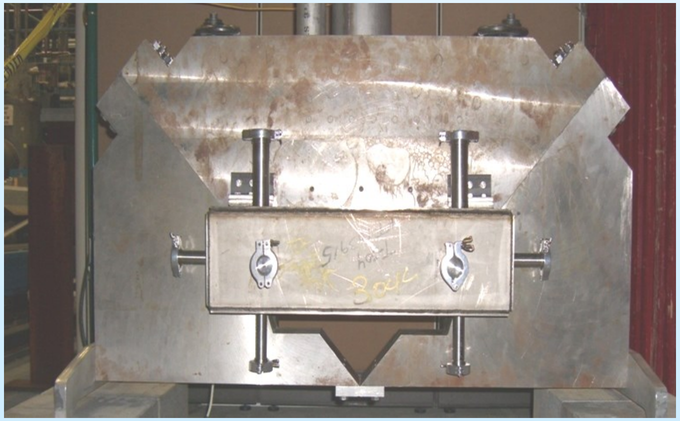
Note: A uniformity in performance of a large number of HTS coils

1st Generation HTS Quad

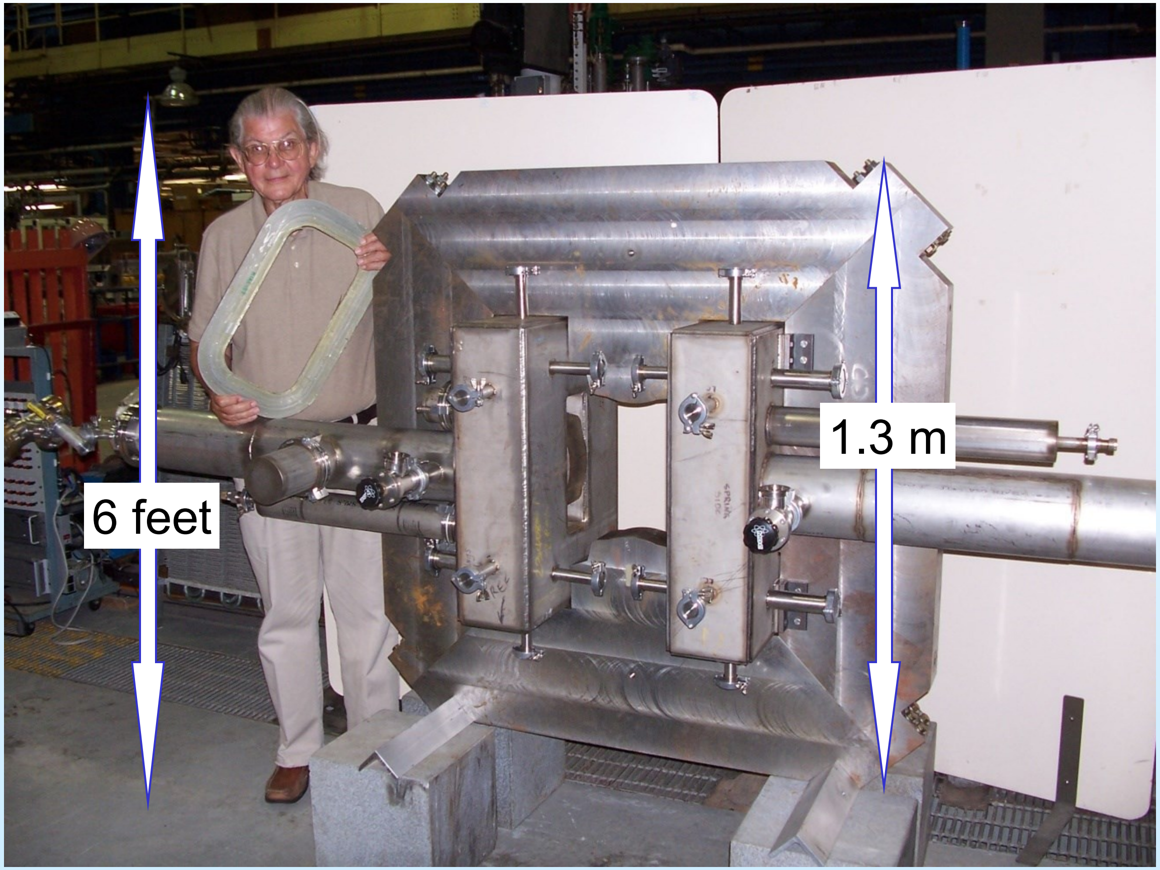
Three magnet structures, built and tested



Mirror cold iron

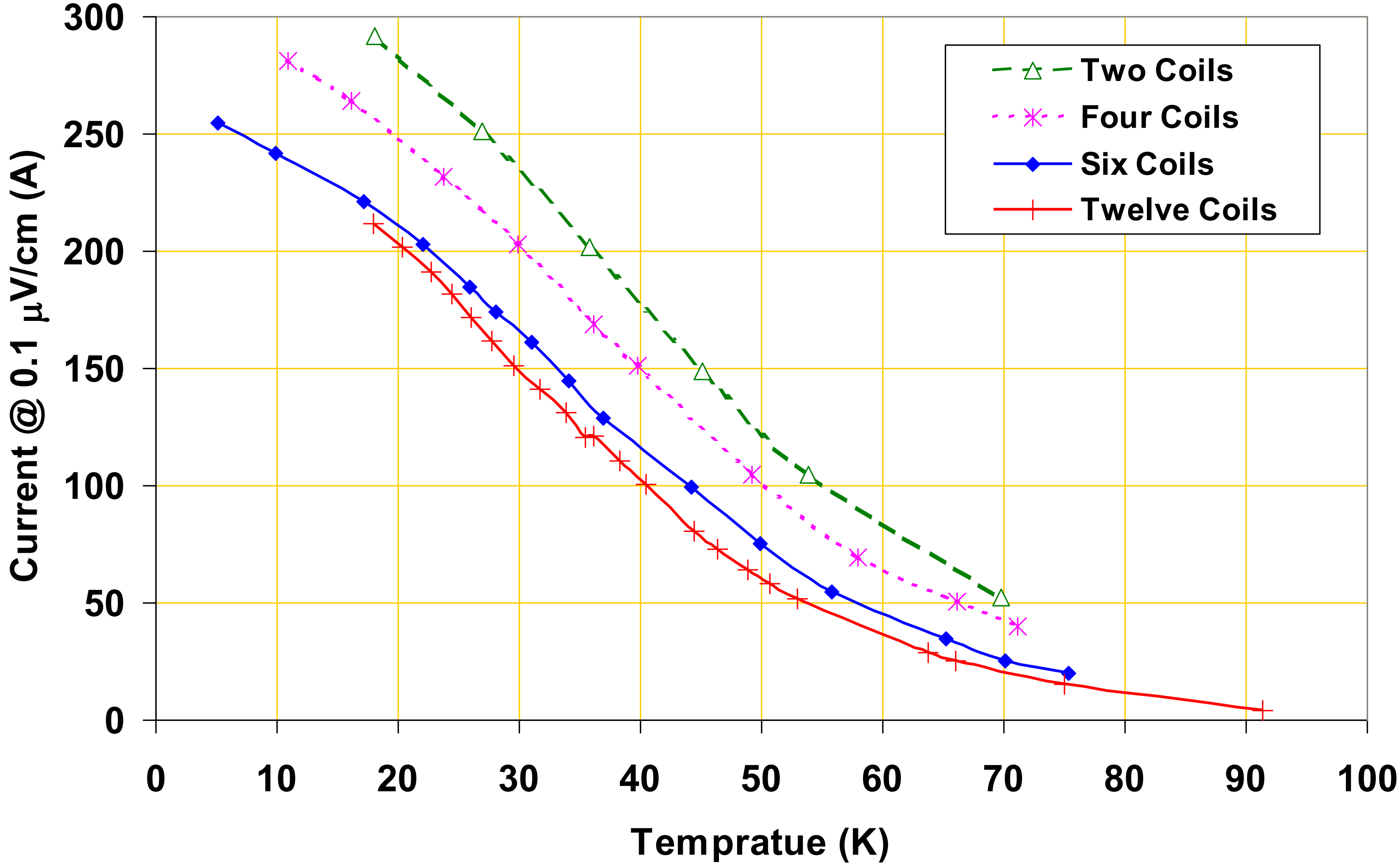


Mirror warm iron



Warm Iron Design to Reduce Heat Load

Summary of First Generation HTS Quad Tests



Operation over a large temperature range- only possible with HTS

Second Generation Design

- Full size model built with 12 mm wide 2G tape from two vendors (SuperPower and ASC)
  - ~9 km equivalent of 4 mm tape

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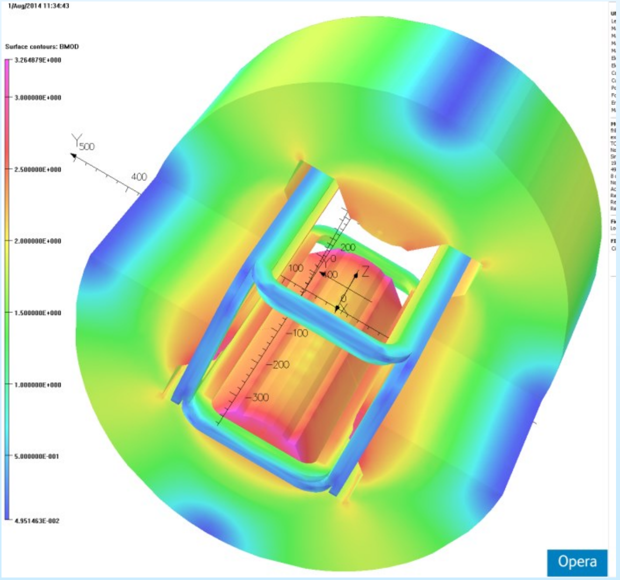
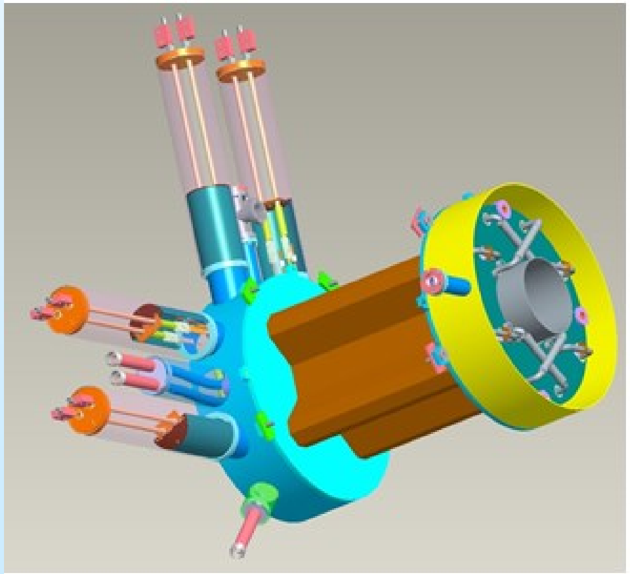
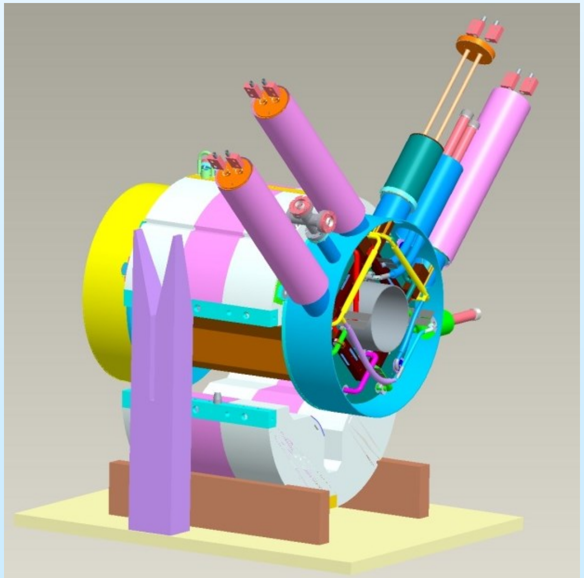
Magnet Design

- Warm iron magnet design to reduce heat loads
- 12 mm ReBCO (2G) HTS Tape from two vendors
- Designed for remote/robotic replacement of coil







Parameter List of the Second Generation Design

Parameter	Value
Pole Radius	110 mm
Design Gradient	15 T/m
Magnetic Length	600 mm
Coil Overall Length	680 mm
Yoke Length	546 mm
Yoke Outer Diameter	720 mm
Overall Magnet Length	~880 mm
HTS Conductor Type	Second Generation (2G)
Conductor Vendors	Two (SuperPower and ASC)
Conductor width, SP	12.1 mm ± 0.1 mm
Conductor thickness, SP	0.1 mm ± 0.015 mm
Cu stabilizer thickness SP	~0.04 mm
Conductor width, ASC	12.1 mm ± 0.2 mm
Conductor thickness, ASC	0.28 mm ± 0.02 mm
Cu stabilizer thickness ASC	~0.1 mm
Stainless Steel Insulation Size	12.4 mm X 0.025 mm
Number of Coils	8 (4 with SP and 4 with ASC)
Coil Width (for each layer)	12.5 mm
Coil Height (small, large)	27 mm (SP), 40 mm (ASC)
Number of Turns (nominal)	220 (SP), 125 (ASC)
Field parallel @design (maximum)	~1.9 T
Field perpendicular @design (max)	~1.6 T
Minimum I_c @2T, 40 K (spec)	400 A (in any direction)
Minimum I_c @2T, 50 K (expected)	280 A (in any direction)
Operating Current (2 power supplies)	~210 A (SP), ~310 (ASC)
Stored Energy	~40 kJ
Inductance	0.45 H (SP), ~1.2 (ASC)
Operating Temperature	~38 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

220 mm

15 T/m

38 K

12 mm 2G SuperPower and ASC

8 HTS coils

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Winding with Computer Controlled Universal Coil Winder

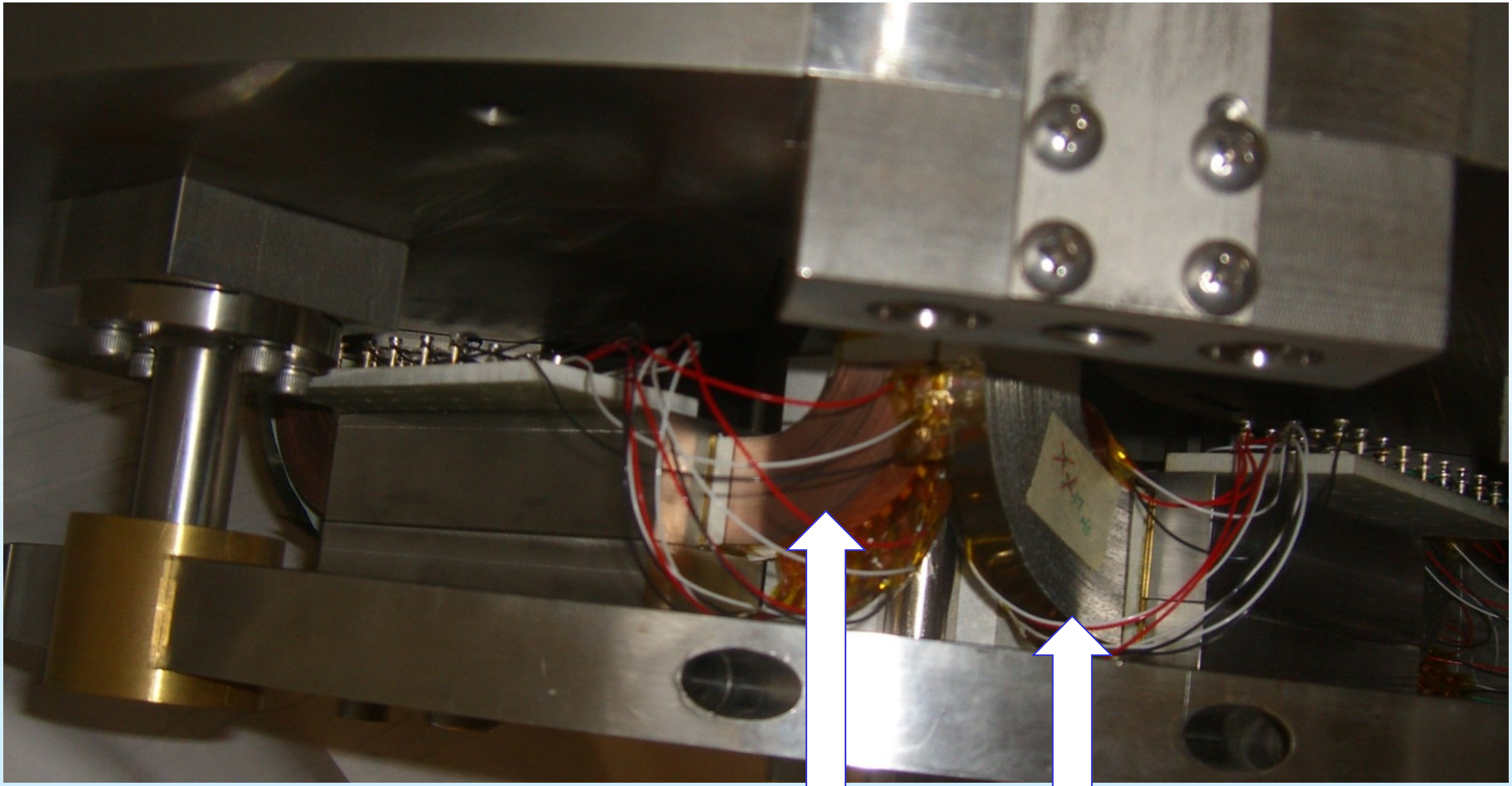
4 coils made with ASC:
- ~210 m double sided
- (420 m HTS per coil)
- ~2x125 turns

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

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

(~9 km of standard 4 mm equivalent used)

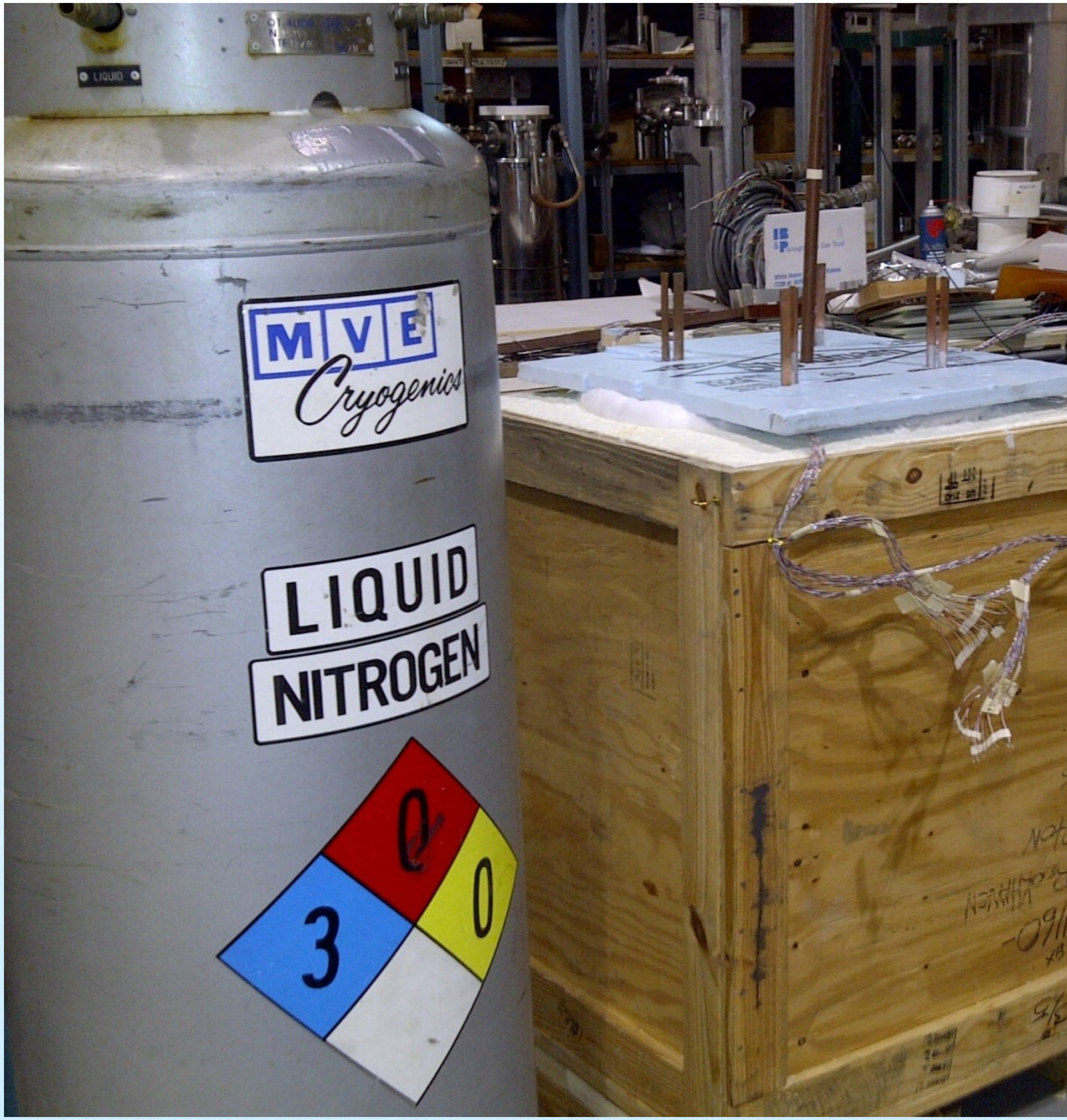
Coils Made with HTS from 2 Vendors (SuperPower and ASC)



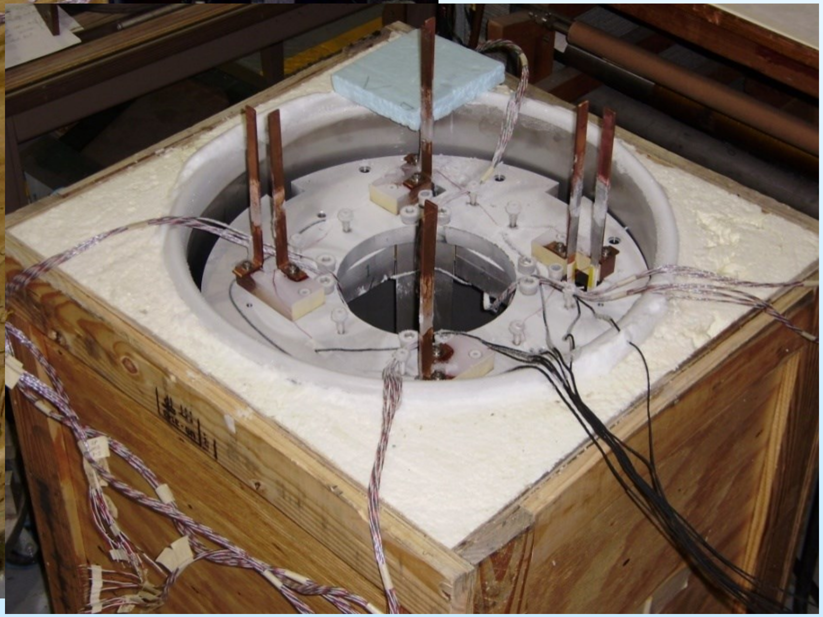
SuperPower
(4 pancakes)

ASC

FRIB HTS Quad in Simple Cryostat



77 K tests of HTS coils with LN_2 provide a useful QA



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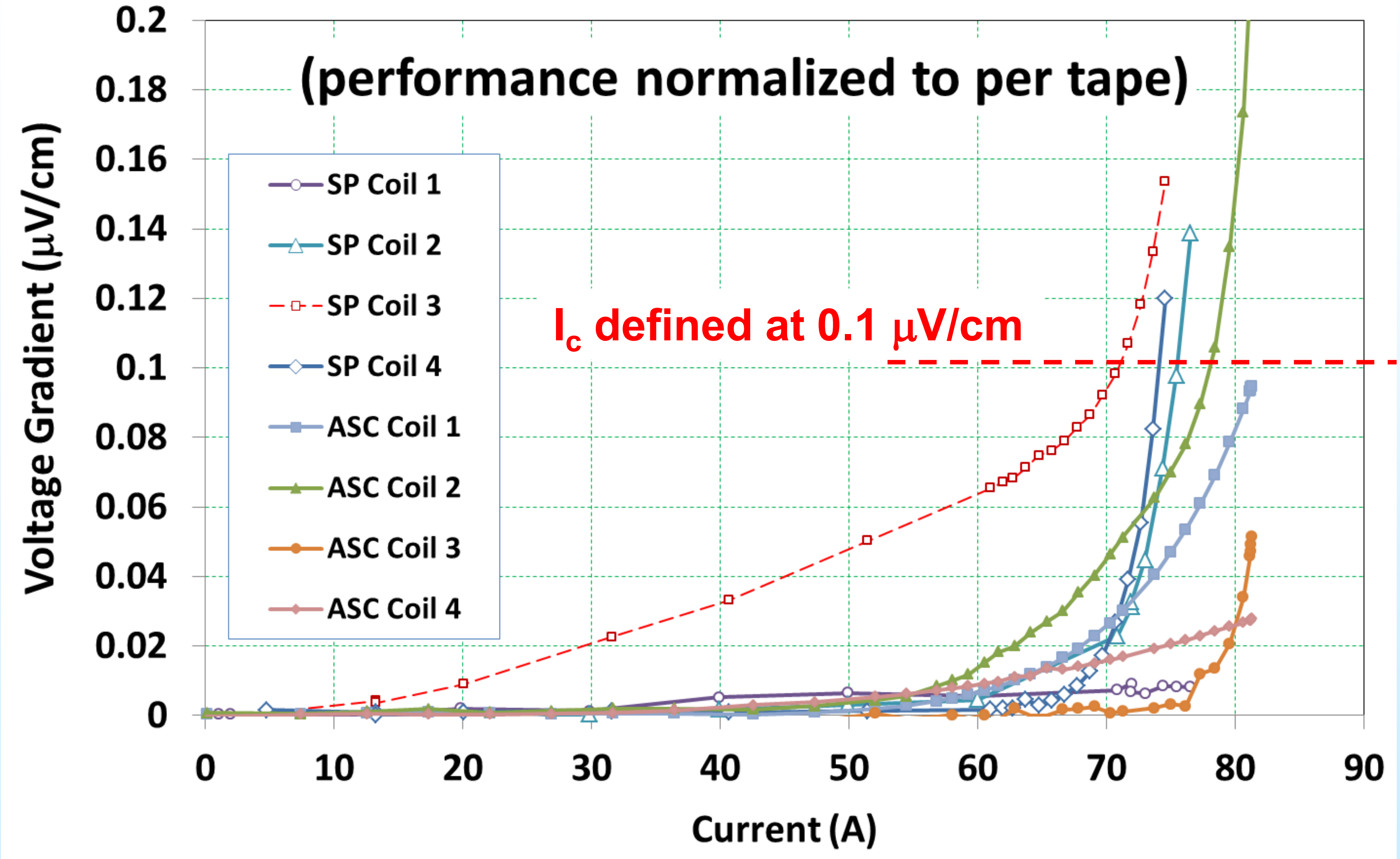
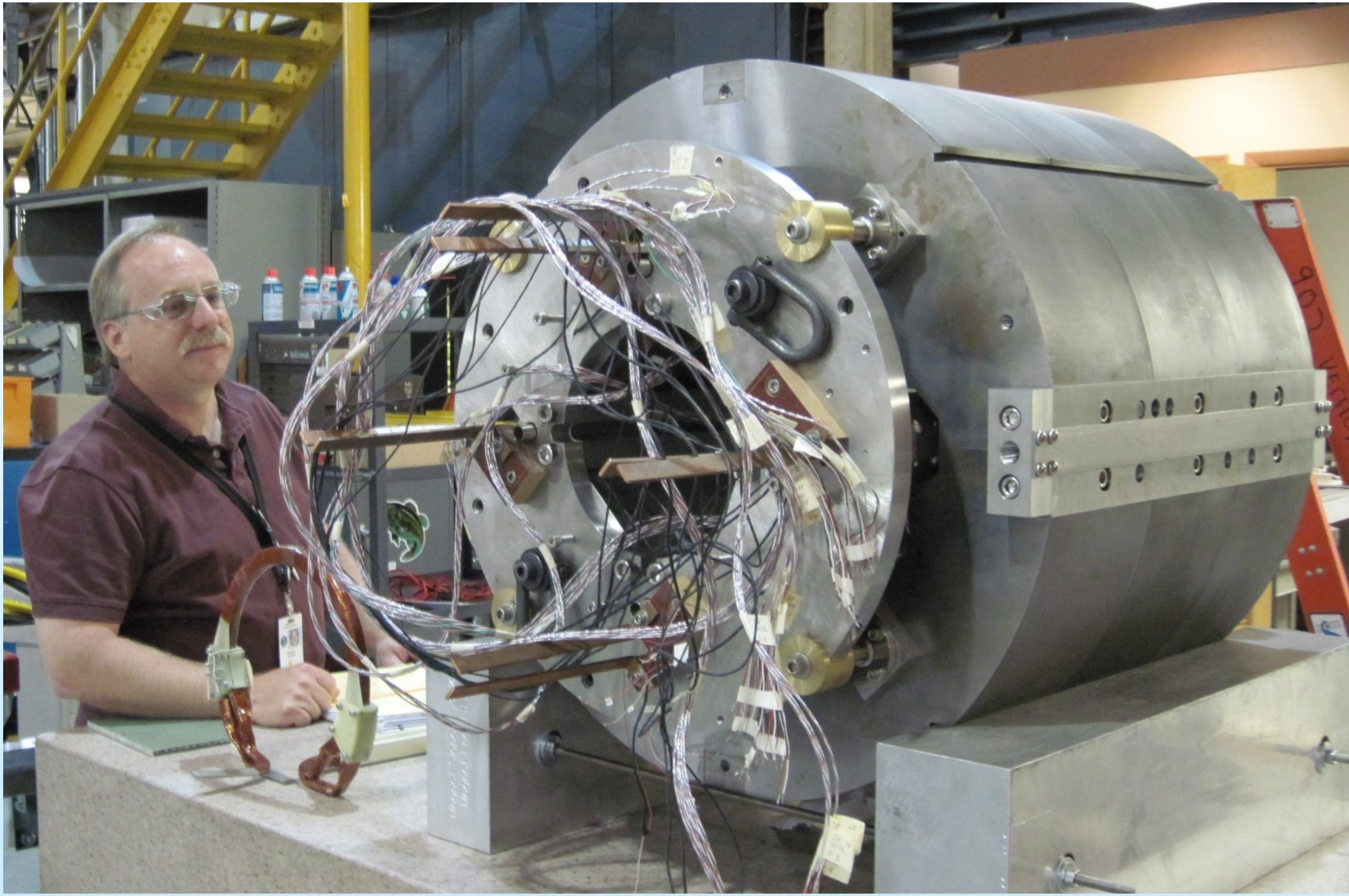
Performance of FRIB Coils @77 K
(4 made with SuperPower and 4 with ASC)



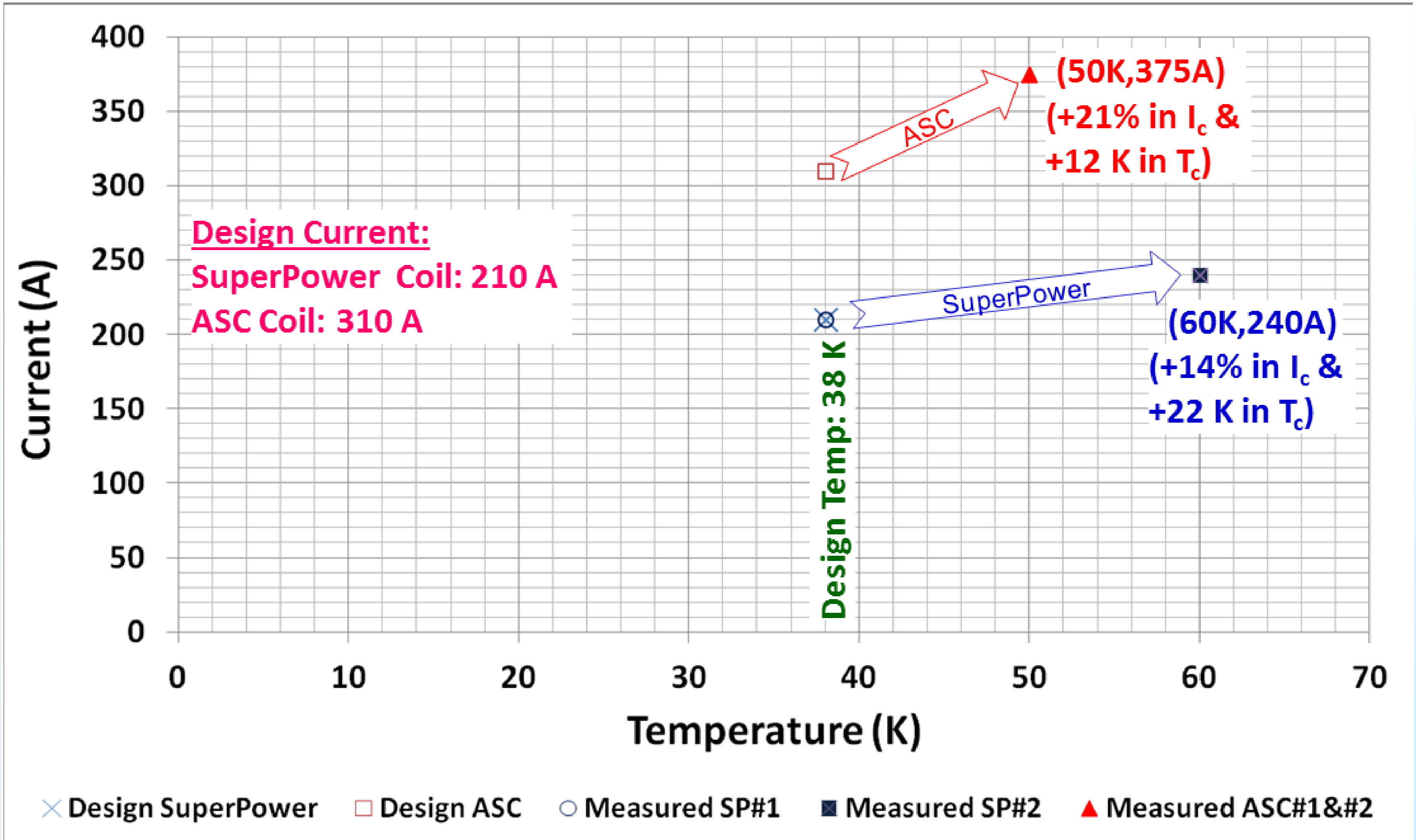
Actual current is coils made with double HTS from ASC HTS was twice

Completed 2G HTS Quad for FRIB



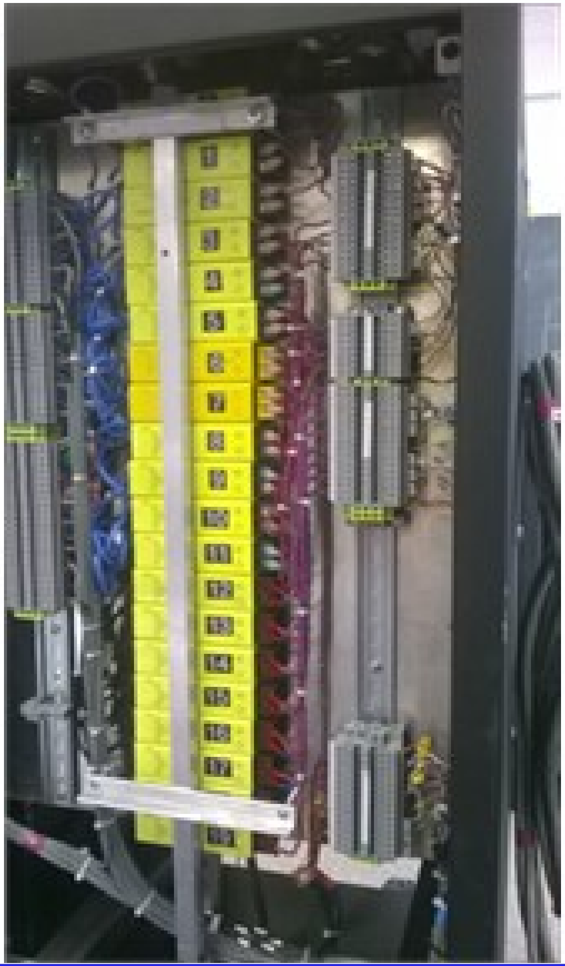
Lower Temperature Tests with Helium

Large Temperature Margins (only possible with HTS)



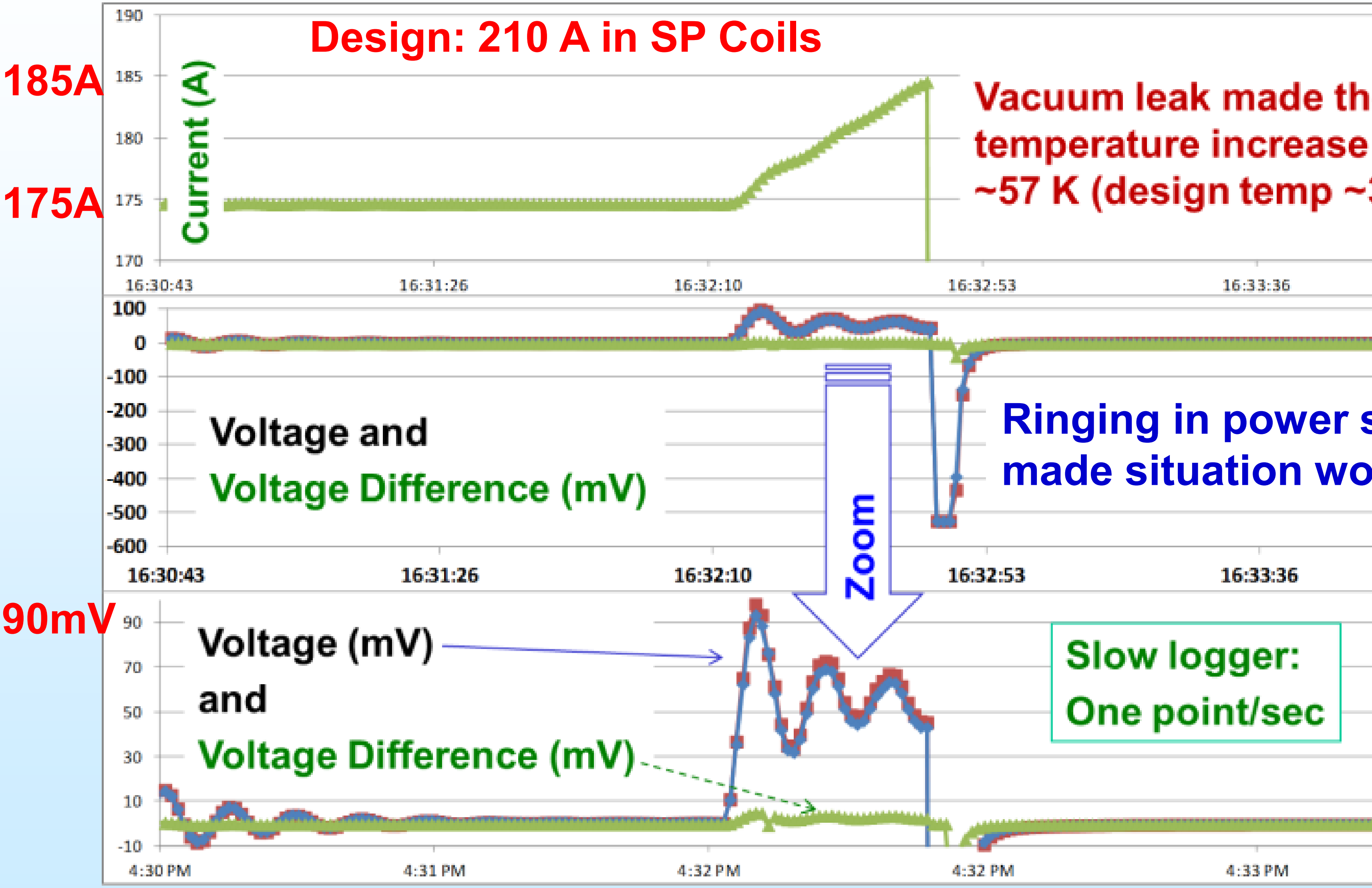
Provides robust operation against local and global heat loads

Advanced Quench Protection Electronics

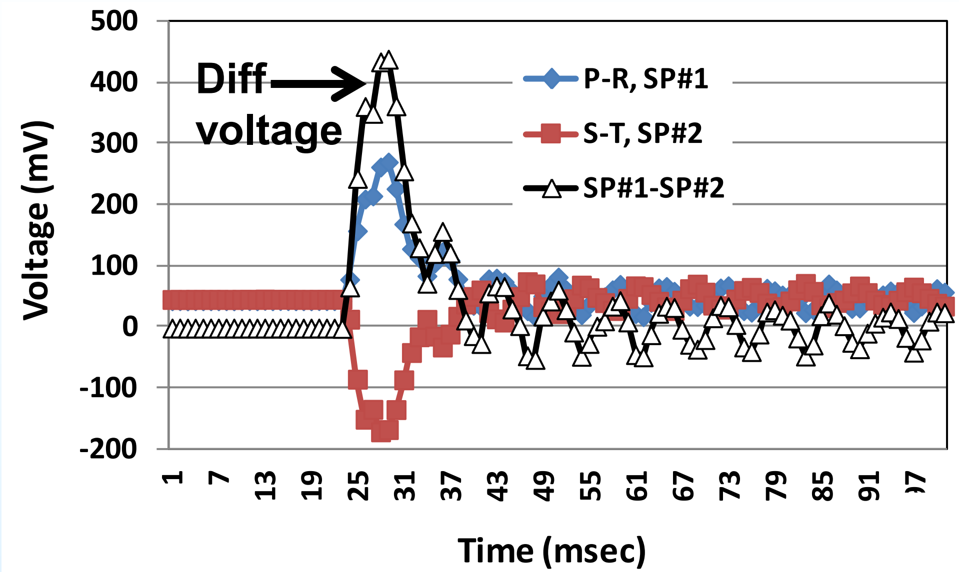




Detects onset of pre-quench voltage at < 1mV and with isolation voltage > 1kV allows fast energy extraction

Protection of HTS Magnet During an Operational Accident Near Design Current



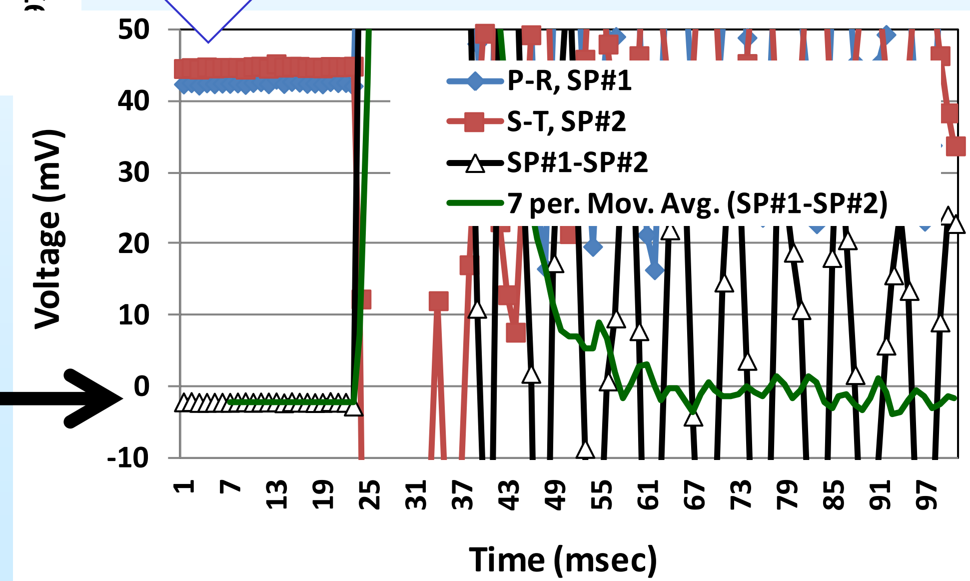
Snap Shot of the Event (Quench?) that Triggered the Shut-off



Fast data logger: One point/msec

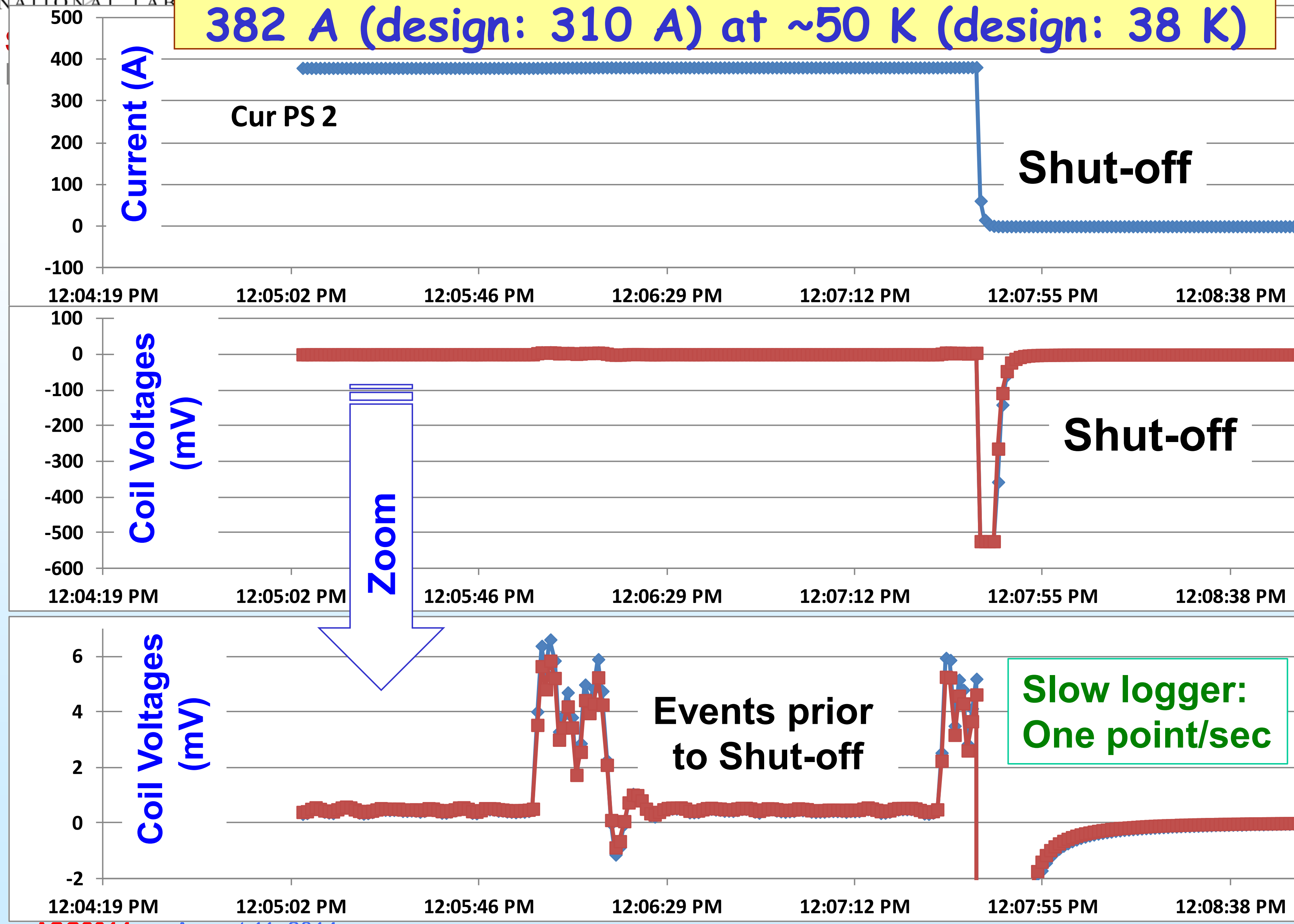
Large inductive voltage in individual coils (ramp)

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



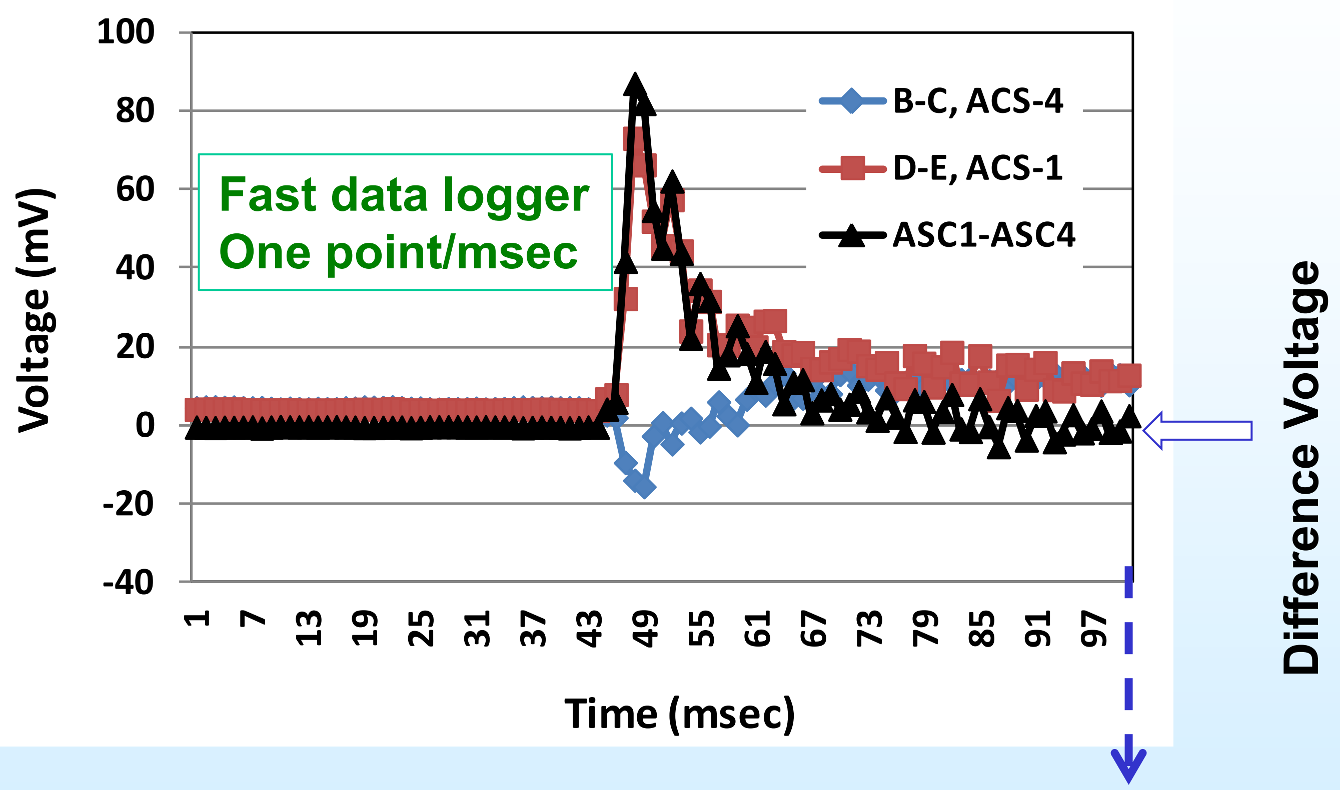
No degradation in coil performance after the event

Event (Quench?) while ASC Coils were held at 382 A (design: 310 A) at ~50 K (design: 38 K)



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

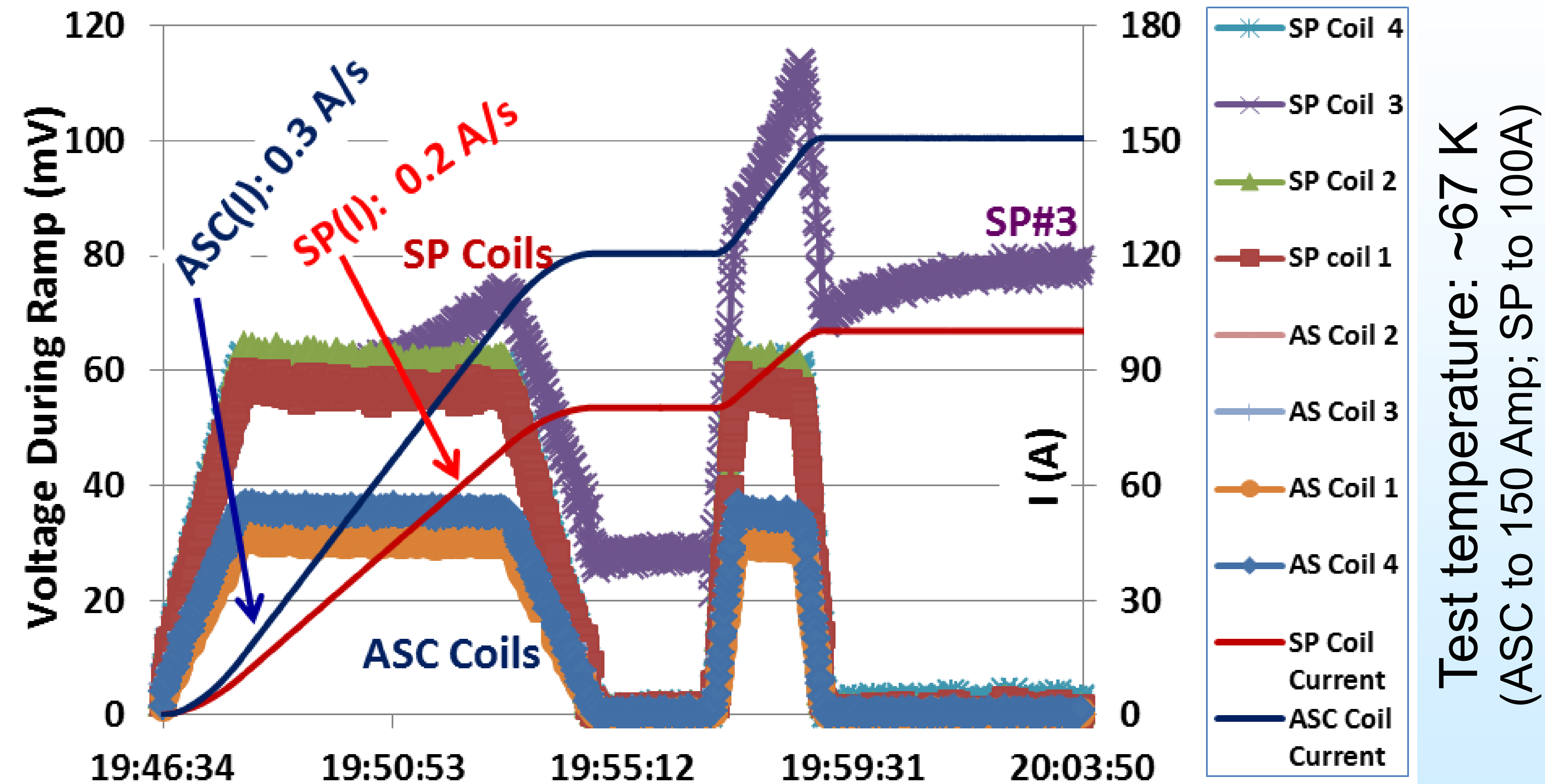
Event at (a)12 K above the design temperature and (b) at 24% above design current



- This and previous event appear to be the sign of flux jump
- This exceeded quench threshold, triggered shutoff & energy extraction

No degradation in coil performance observed

Operation Well Beyond the Quench Detection Threshold Voltage (~ mV)



Operated at about two order of magnitude beyond the quench detection threshold. No degradation in coil performance observed.

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Spinoff of FRIB HTS Magnet Technology

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August 2013

Massive Energy Storage in Superconductors (SMES)

Novel high temperature superconductor magnet technology charts new territory.

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Summary

Significant development of HTS magnet technology at BNL was funded by DOE/NP to provide a unique solution for the magnets in the fragment separator region of the Facility for Rare Isotope Beams (FRIB), which is currently under construction at Michigan State University in East Lansing, Michigan. The same coil technology (HTS tape co-wound with stainless steel tape) is used in high field (~24 Tesla) superconducting magnetic energy storage (SMES) solution that can withstand the high stresses that are present in high field magnets. This technology has already been successfully applied in creating the record 16 T field in an all HTS magnet. High fields significantly reduce the amount of conductor for the same stored energy in SMES. This is mainly because the stored energy increases essentially as the square of the field. In addition, because HTS SMES can operate at high temperatures, the high efficiency cryo-coolers can now replace the more expensive and precious liquid Helium cryogen.

Enlarge Photo

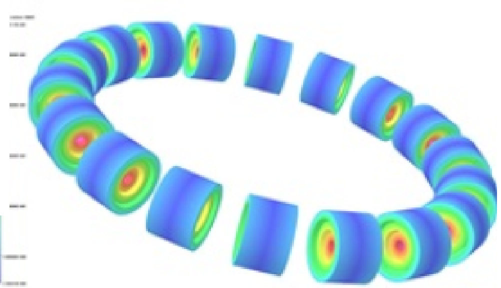

Image courtesy of Brookhaven National Laboratory

A toroid SMES system consisting of a number of high field coils made with the High Temperature

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News

SMES magnet was also tested at about the FRIB design operating temperature

Summary

- A decade of R&D has developed medium field HTS magnet technology to a level that it can be considered in a real machine.
- FRIB could be the 1st major accelerator with HTS magnets playing a crucial role - a unique solution to unprecedented energy deposition and radiation loads.
- A variety of tests have shown that the technology (including quench protection) can withstand several failure mode scansions well beyond the normal operating conditions.
- This demonstration is a major development in magnet technology. This provides a good base for other applications of HTS magnets.

Extra Slides

Major Topics NOT Covered due to Lack of Time

- Details of magnet design
- Details of magnet constructions
- Several other magnet tests
- Quench protection
- Energy deposition experiments
- Radiation damage experiments