HTS Quadrupole R&D at BNL for FRIB

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Overview

- Few slides on the results of IBS/BNL collaboration
  - High field HTS solenoid for CAPP with SuNAM conductor
- First Generation Radiation Resistant HTS Quad for FRIB
  - Brief overview
- Second Generation Quad for FRIB (most of this presentation)
  - Design
  - Construction
  - Test
  - Quench protection
- Extra slides
  - Radiation damage studies
  - Energy deposition studies

Motivation of High Field Solenoid for CAPP (slides from Yannis Semertzidis)

What's there to improve over ADMX?

$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L$$

- B^2, energy density
- Q, resonator quality factor
- B-field/resonator volume V
- Ampl. noise/physical temperature, S/N

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B-field possibilities

- Magnetic field B:
  - Develop 25T magnet.
  - 35T magnet based on high T_c.

(CAPP) Axion dark matter plan

- We have started an R&D program with BNL for new magnets: goal 25T; then 35T. Currently all axion experiments are using <10T.
- Based on high T_c cables (including SuNAM, a Korean high T_c cable company). ~5 year program.

To create state of the art facility, Center for Axion and Precision Physics (CAPP), needs large aperture, high field solenoid (B^2V)

High Field, Large Aperture Solenoid for Axion Search Research at CAPP

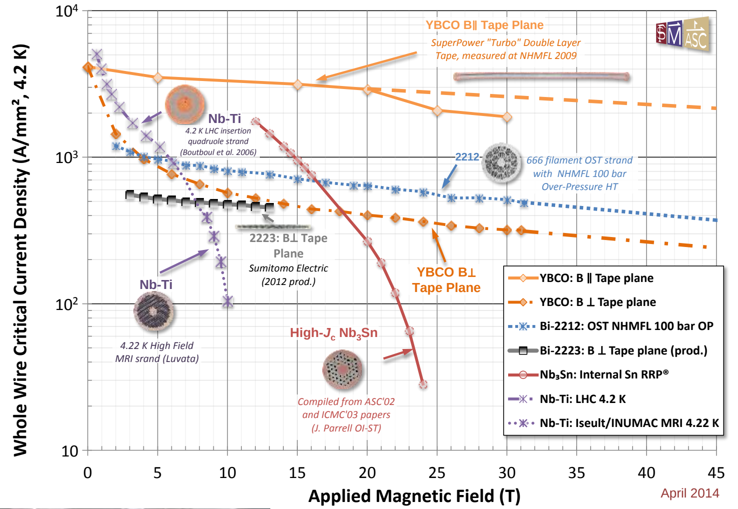
HTS/LTS hybrid design

- 25 T from HTS and 10 T from LTS

HTS used only in high field region

- HTS is expensive

LTS Outer solenoid from commercial vendor but HTS must be developed



HTS magnet pose huge challenges

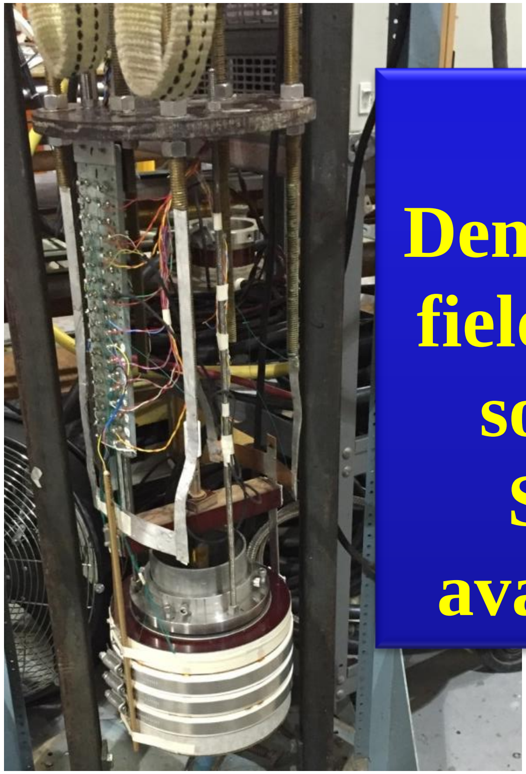
- Large stresses
- Quench protection
- New conductor

- **Field: 25 T@4 K**
- **Bore: 100 mm**
- **Stresses: 400 MPa**

Magnet design and technology developed for HTS SMES can be directly applied to CAPP research

Work Performed at BNL for CAPP/IBS

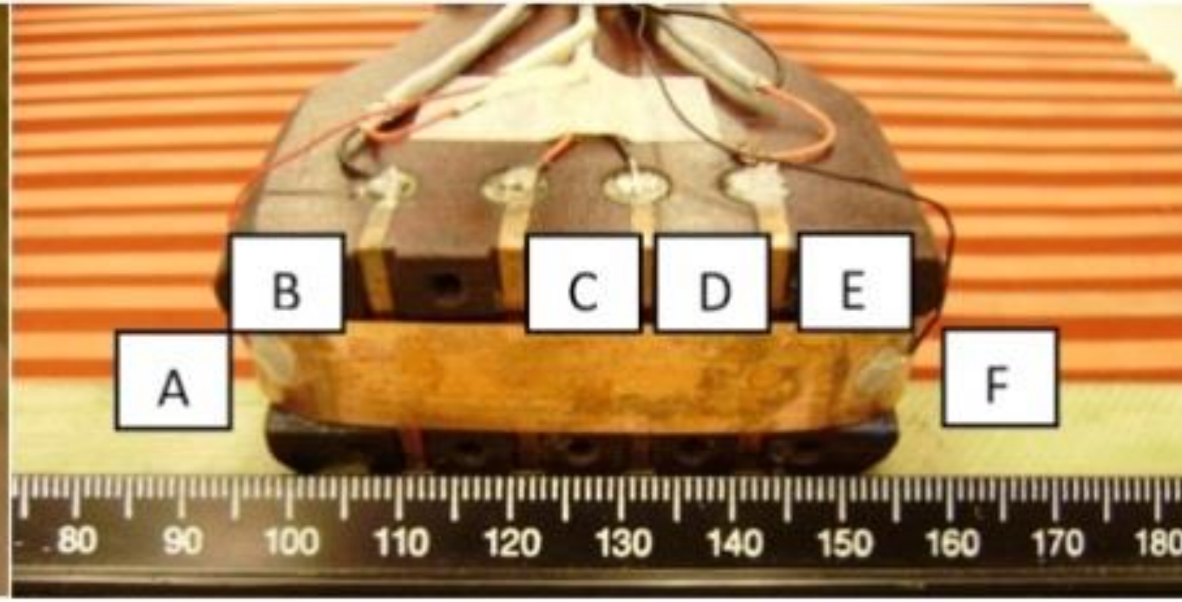
- Conductor Test
- Coil Construction and Test
- Magnet Assembly and Test



Task:

Demonstrate 10 T peak field in a 100 mm bore solenoid built with SuNAM HTS, as available at that time

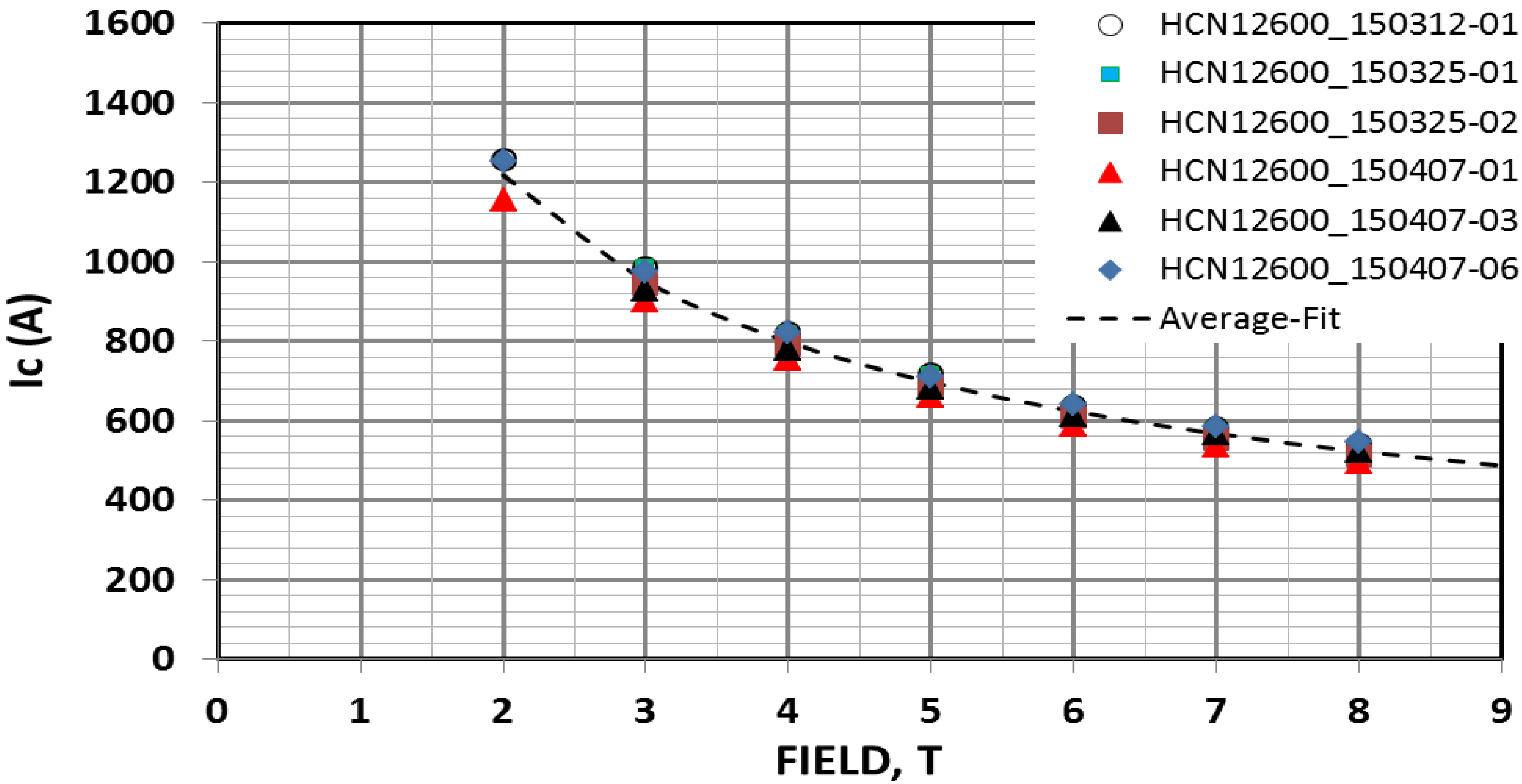
BNL Measurements of SuNAM conductor at 4K, 4-8T



B Sample Holder for in-field I_c Measurements at BNL

A. Ghosh/SMD/BNL

Measurements at BNL (@4K, $B_\perp$ - I_c Vs. Field)



Remarkably uniform performance

(specially for conductor delivered in 3 batches)

Summary of Conductor Measurements

CRITICAL CURRENT OF SHORT SAMPLES TAKEN AT BNL AND AT SUNAM

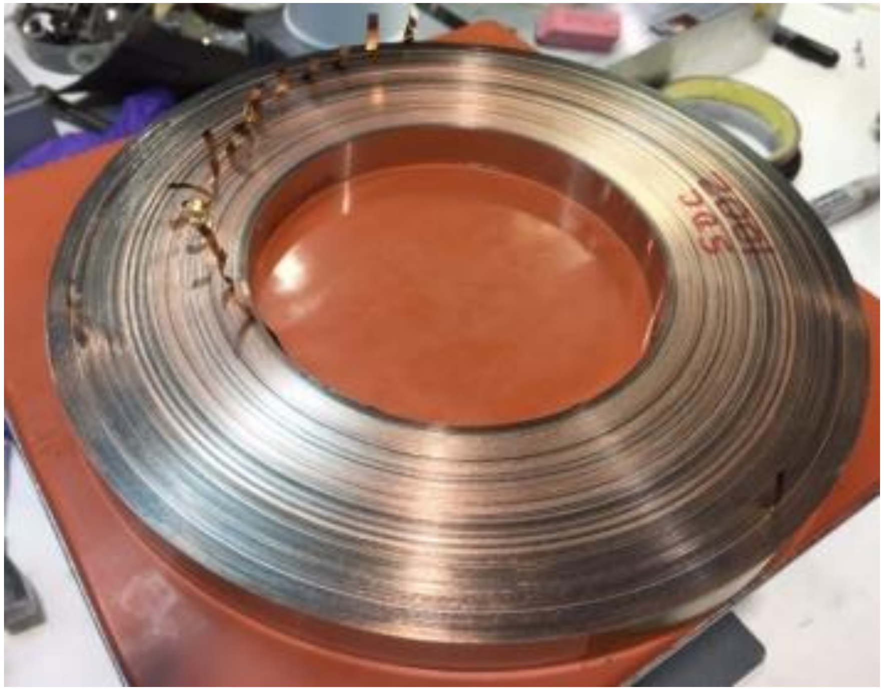
Lab	Temp. [K]	Field [T]	Average [A]	σ [A]	σ/Average
SuNAM	77	0	634	36	5.7%
SuNAM	20	4	423	28	6.7%
BNL	77	0	628	51	8.1%
BNL	4.2	4	793	28	3.5%
BNL	4.2	8	524	20	3.7%

SuNAM: Measurements at SuNAM (77 K and 20 K, 4T)

BNL: Measurements at BNL (77 K and 4 K, 4-8 T)

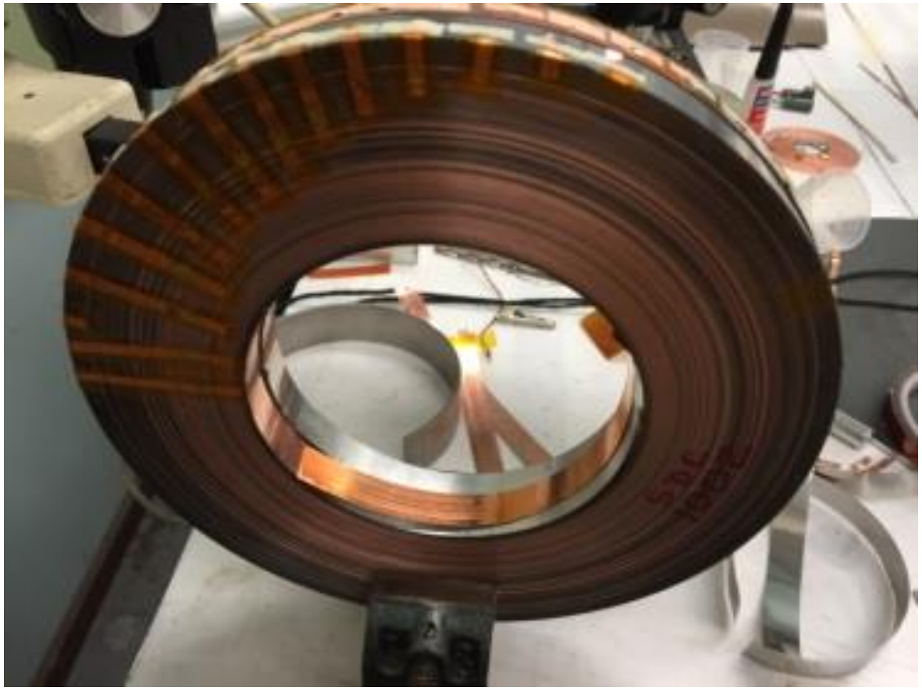
Coil Winding

Pancake coils



V-taps for extensive QA

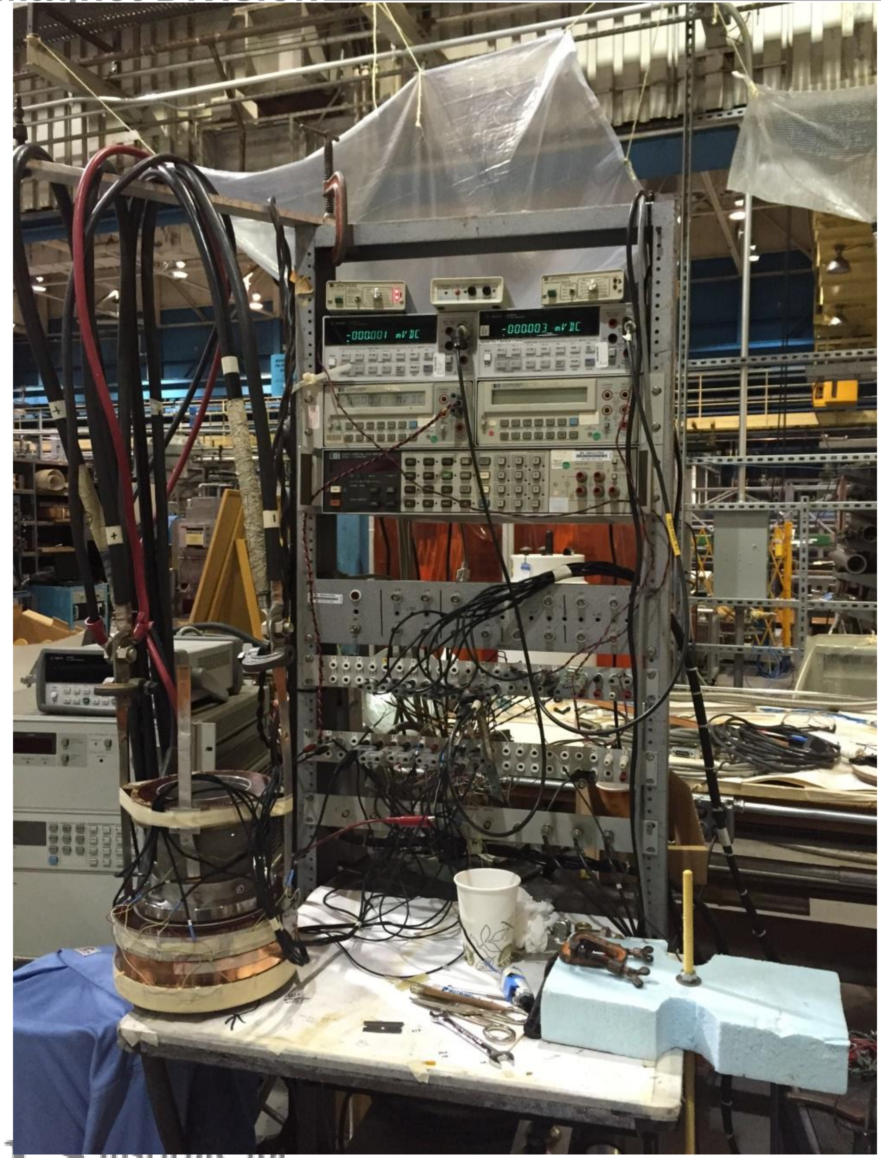
i.d.=101.6 mm, o.d.=192 mm

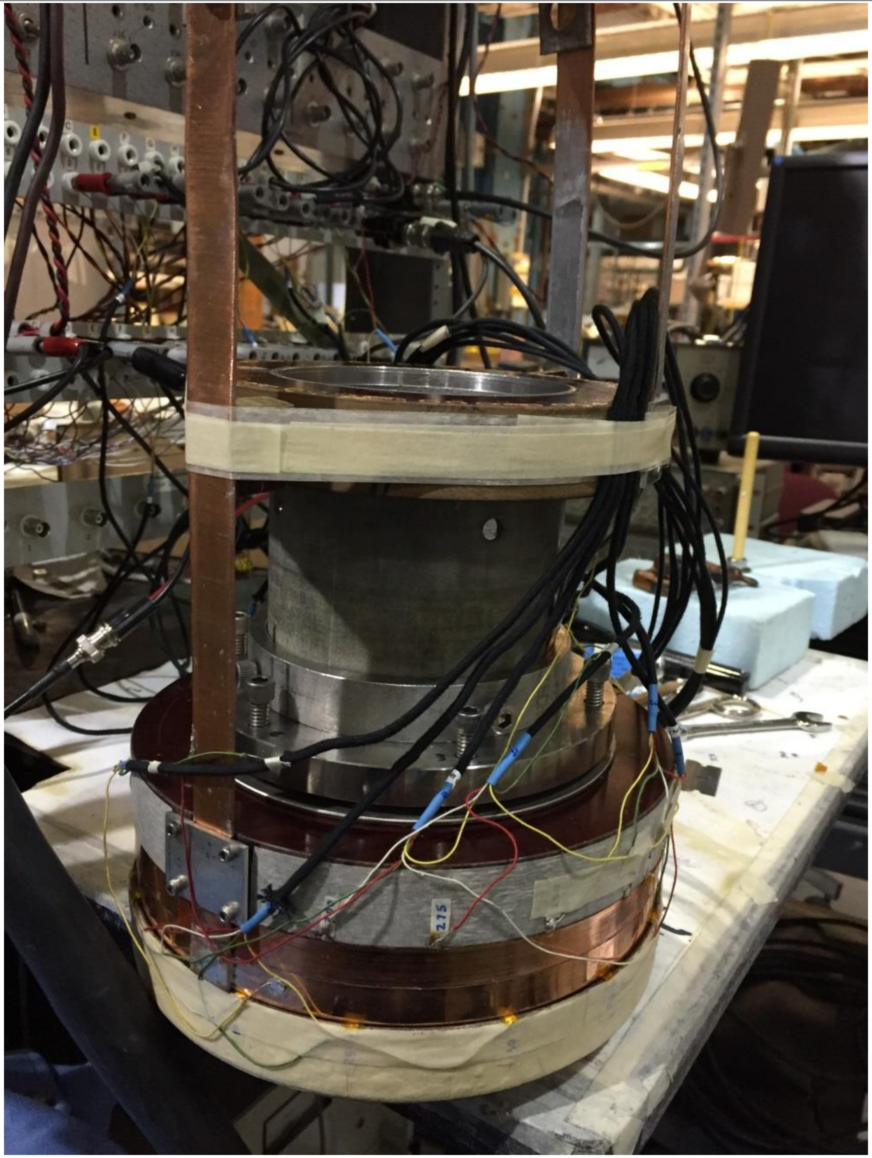


Spiral Splice for making Double Pancakes

(~300 meter, 12 mm tape)

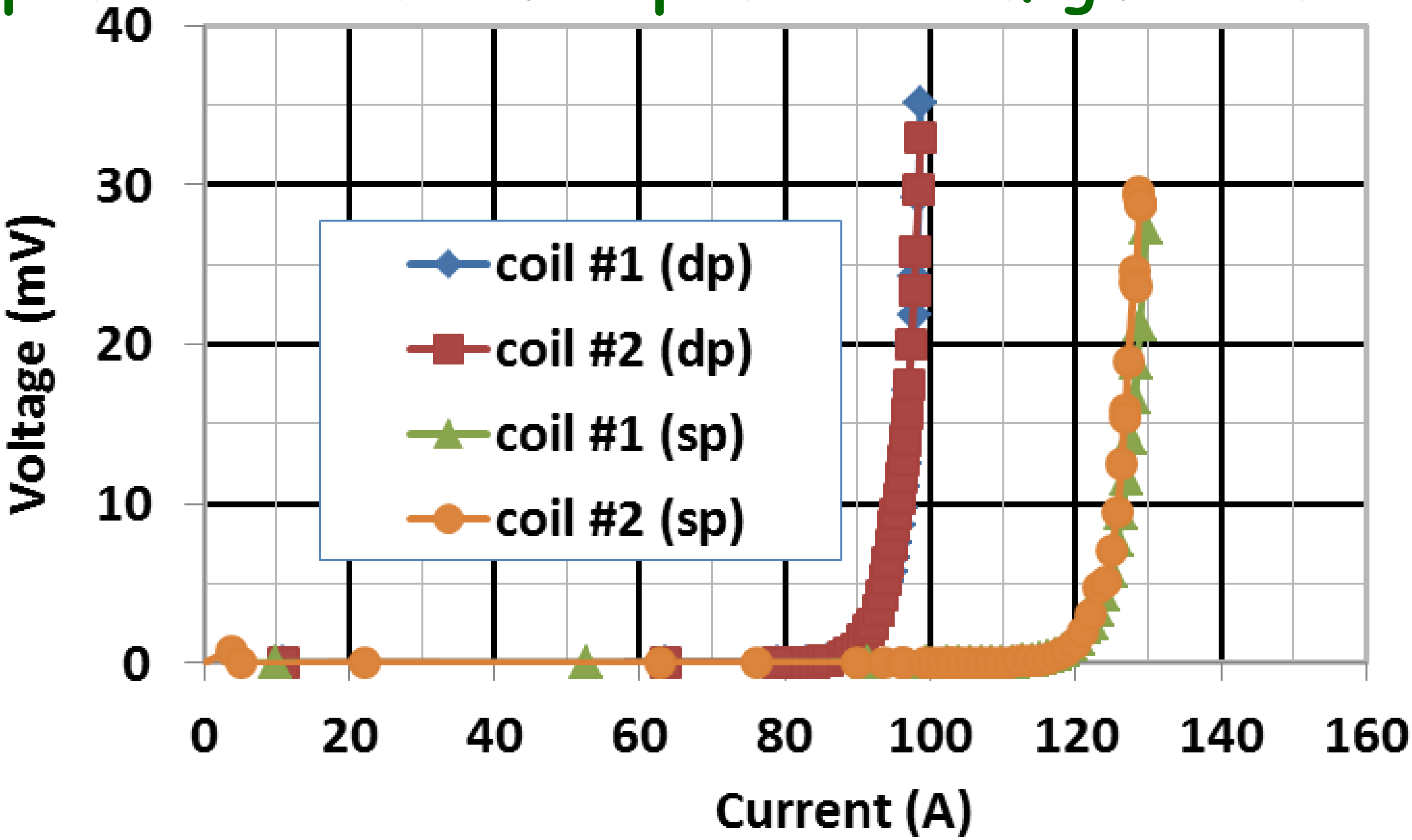
Double Pancake Coil at Test Station





77 K QA Test of Double Pancakes

Three leads to power coils either in single pancake or in double pancake configurations



Higher field means lower current in a double pancake

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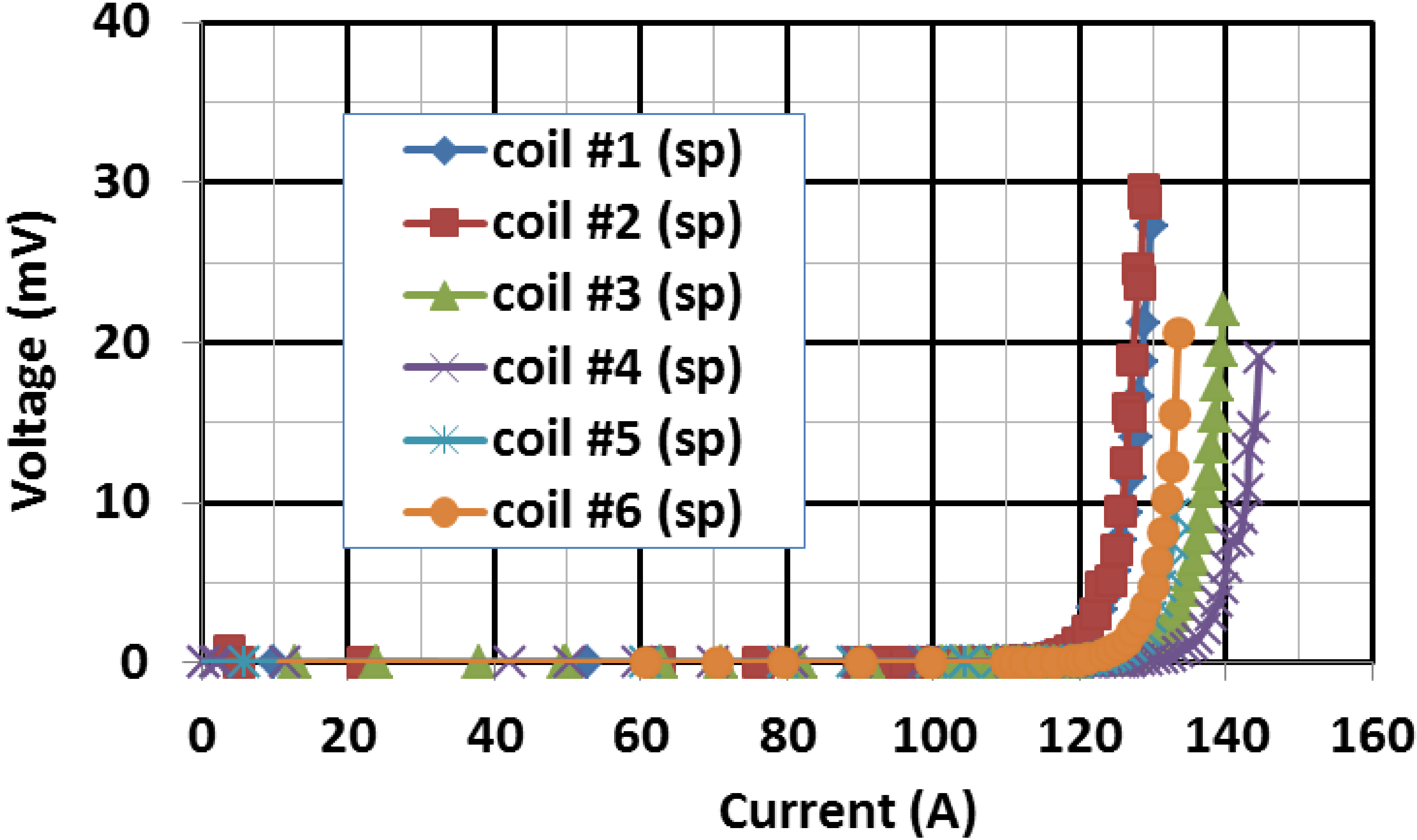
Superconducting Magnet Division

Performance of Six Coils
(Powered Individually as Single Pancakes)



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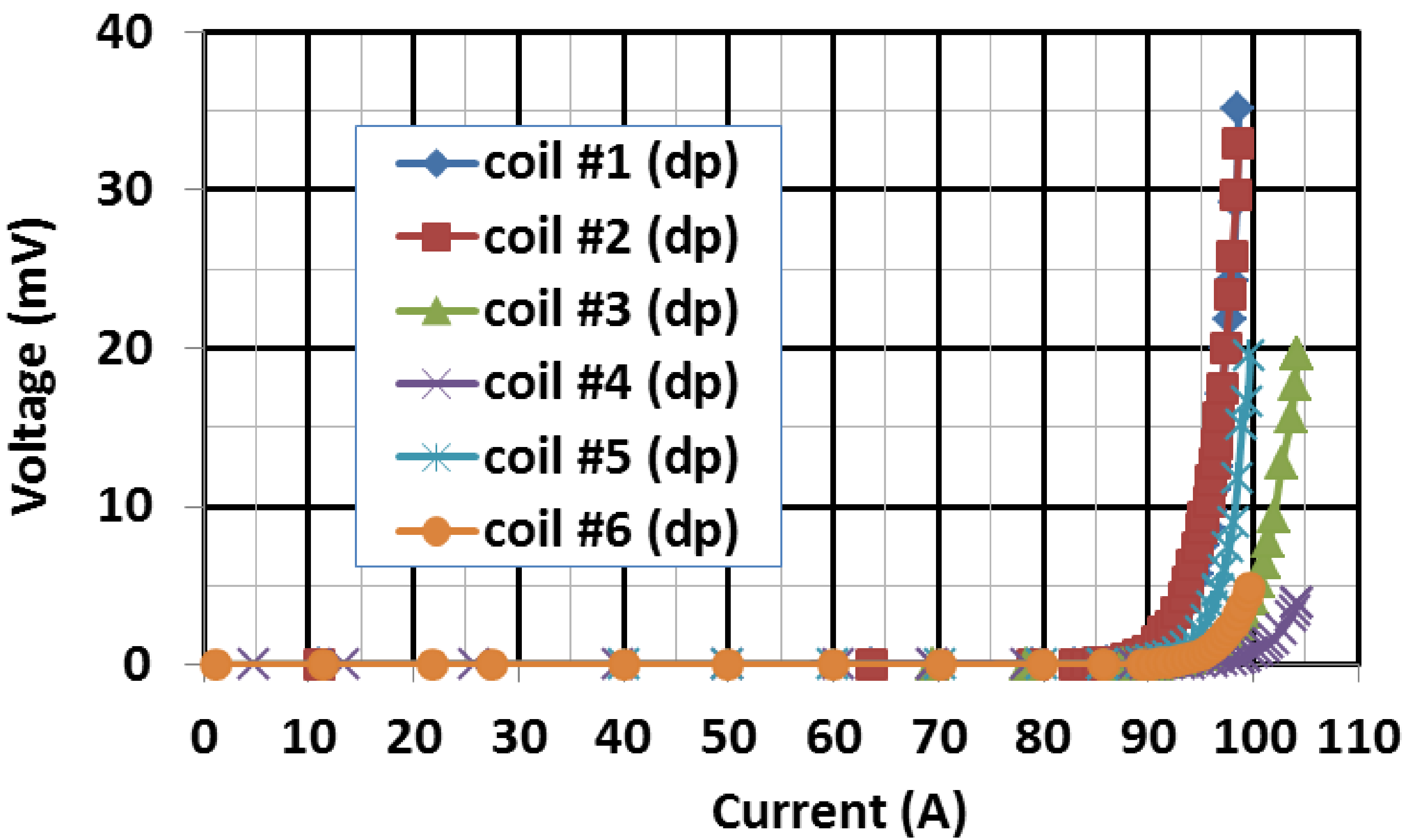
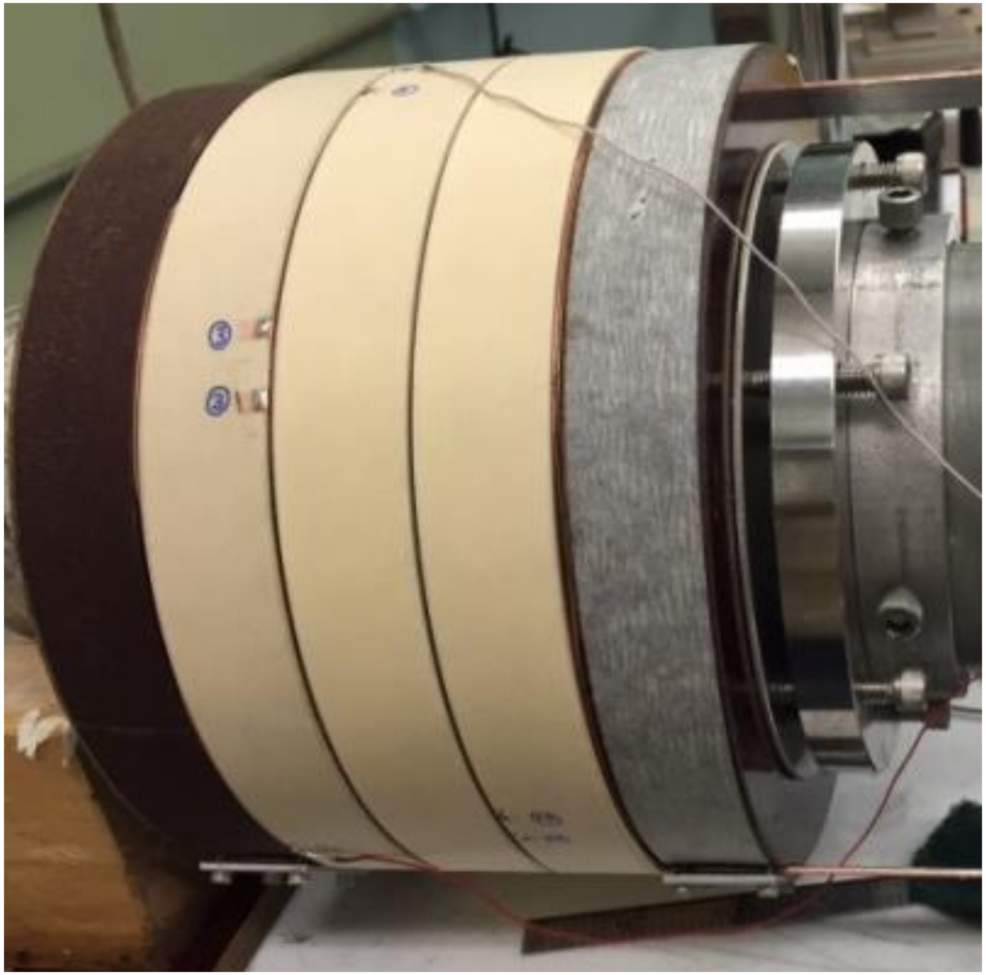
Superconducting Magnet Division

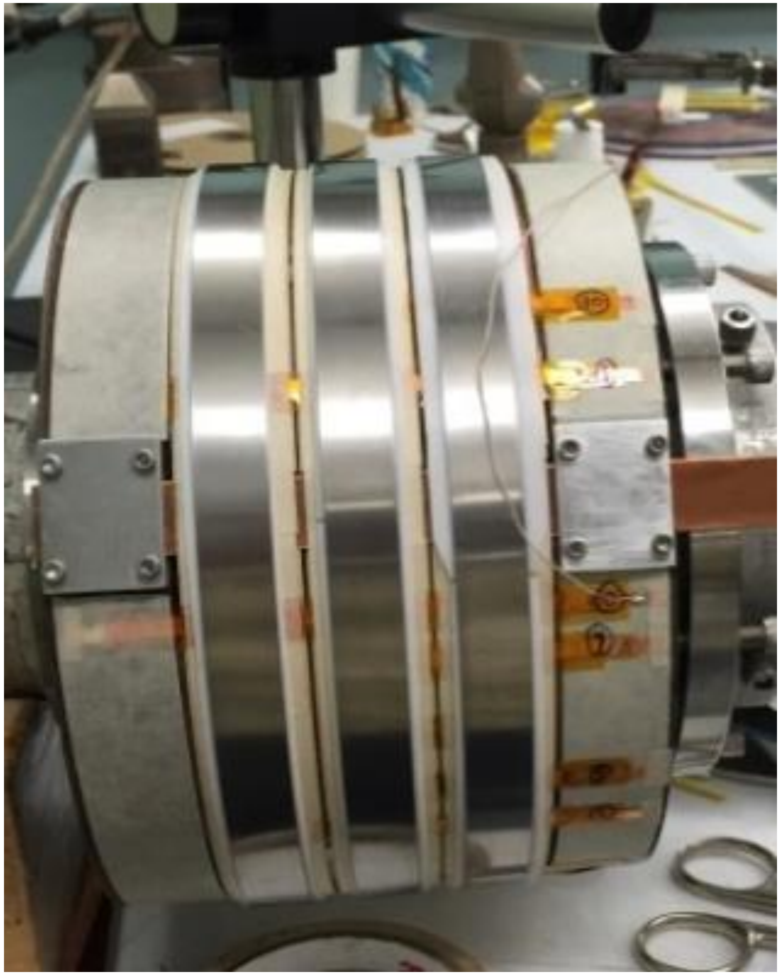
Performance of Six Coils

(Powered two together as Double Pancakes)



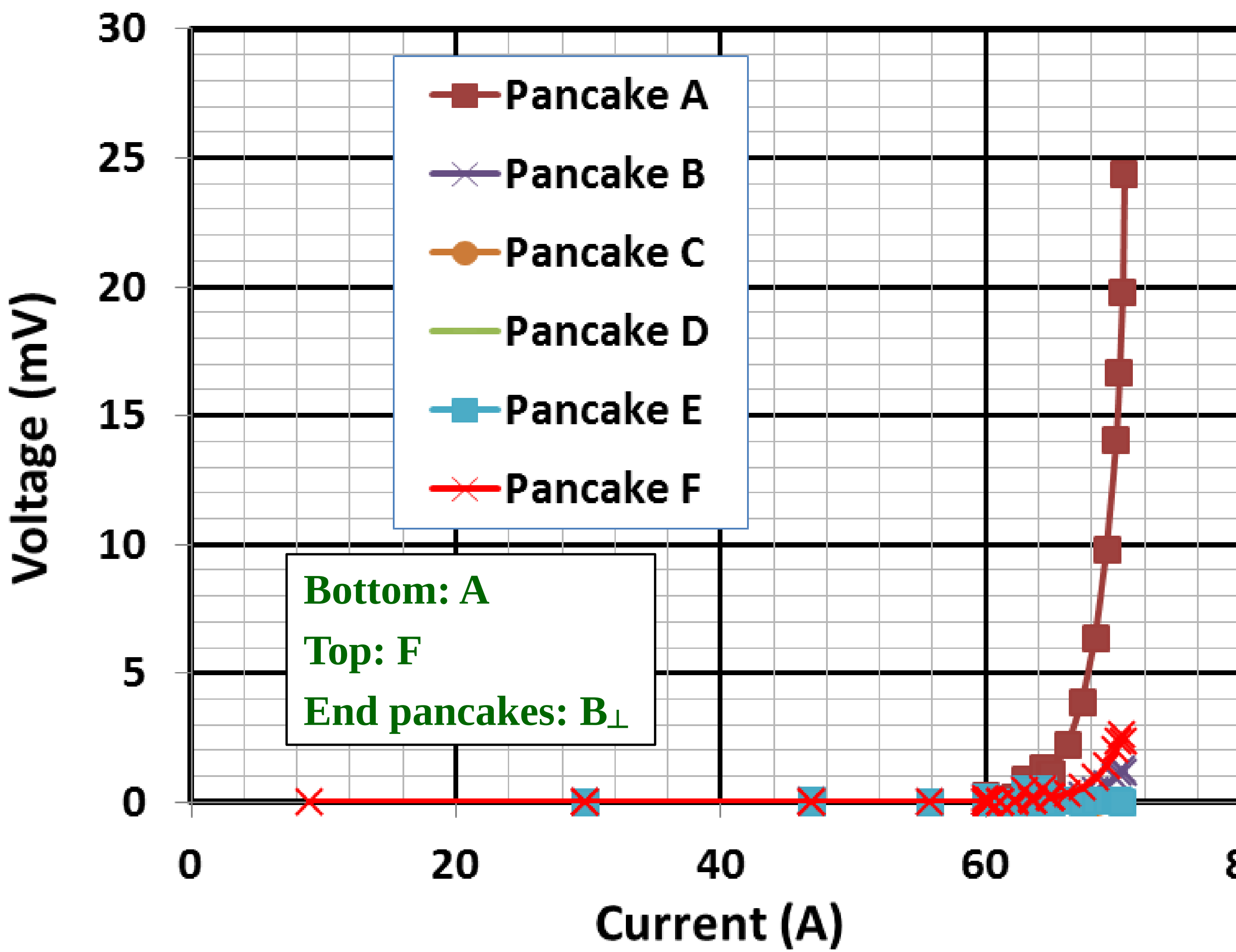
Final Solenoid Construction



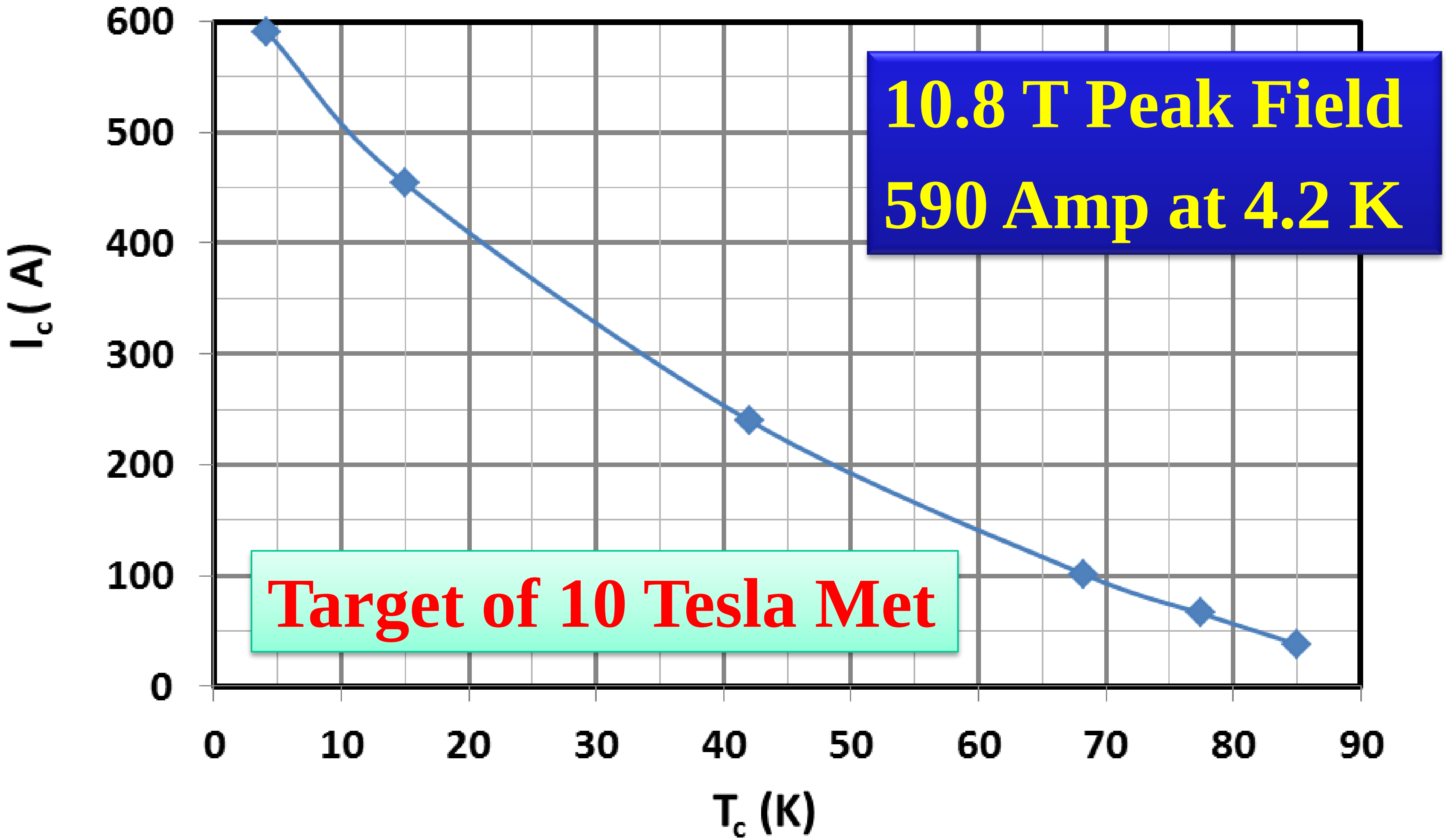


Six Pancake Solenoid @77 K

(V-I curve of each pancake, powered together)



Critical Current Vs. Temperature



First Generation HTS Quad Design for FRIB

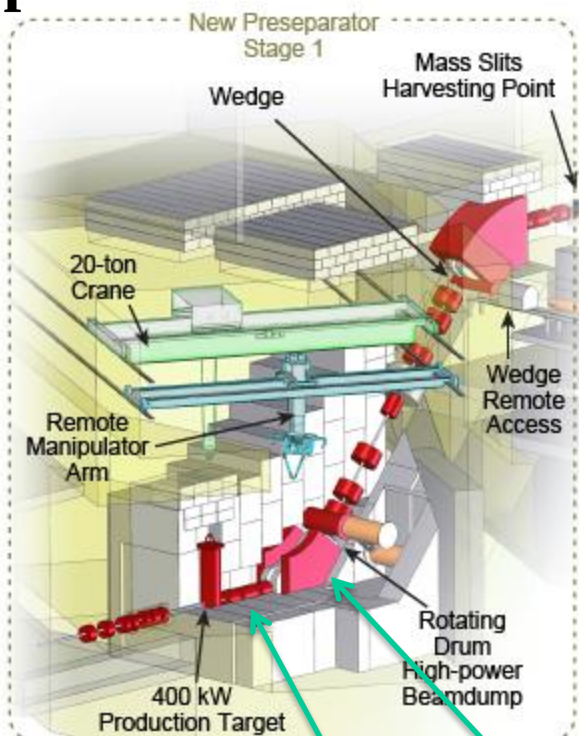
- Short model built with ~5 km of 4 mm wide first generation (1G) HTS tape from American Superconductor Corporation (ASC)
- ~30 K Operation, 10 T/m, 290 mm aperture

Radiation Tolerant HTS Quad for the Fragment Separator Region of FRIB

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

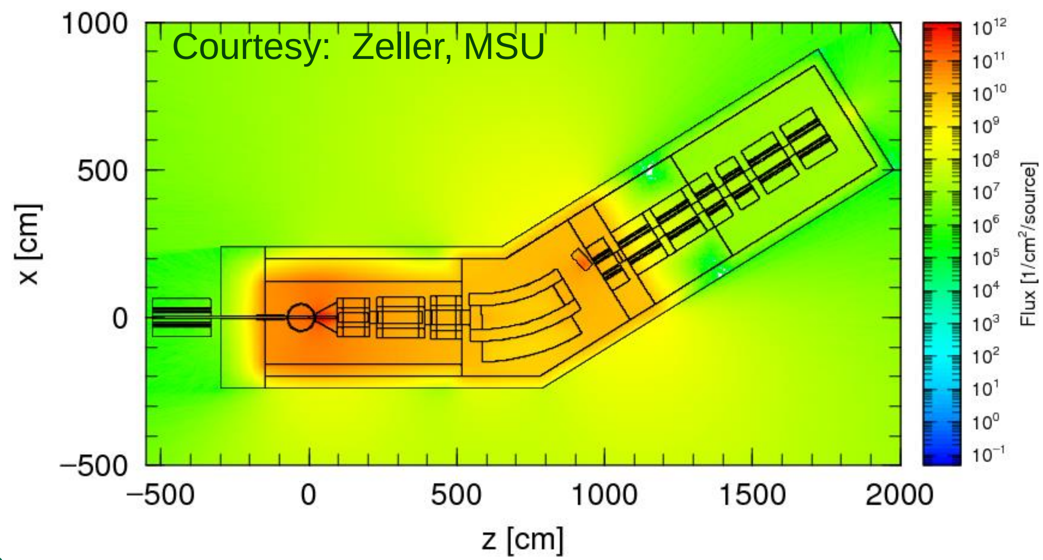
Several magnets in the fragment separator region are exposed to unprecedented radiation and heat loads.

Courtesy: Al Zeller, FRIB/MSU



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**



Radiation resistant

Pre-separator quads and dipole

Motivation for HTS Magnets in FRIB

HTS magnets in Fragment Separator region over Low Temperature NbTi Superconducting magnets provide:

Technical Benefits:

- Provides higher gradient and/or larger aperture than copper magnets (increases acceptance and beam intensity transmitted through the beam line)
- Provides large temperature margin than LTS – HTS can tolerate a large local and global increase in temperature (resistant to beam-induced heating)

Economic Benefits:

- Removing large heat loads at higher temperature (30-50 K) rather than that at ~4 K (as in LTS) is over an order of magnitude more efficient.

Operational Benefits:

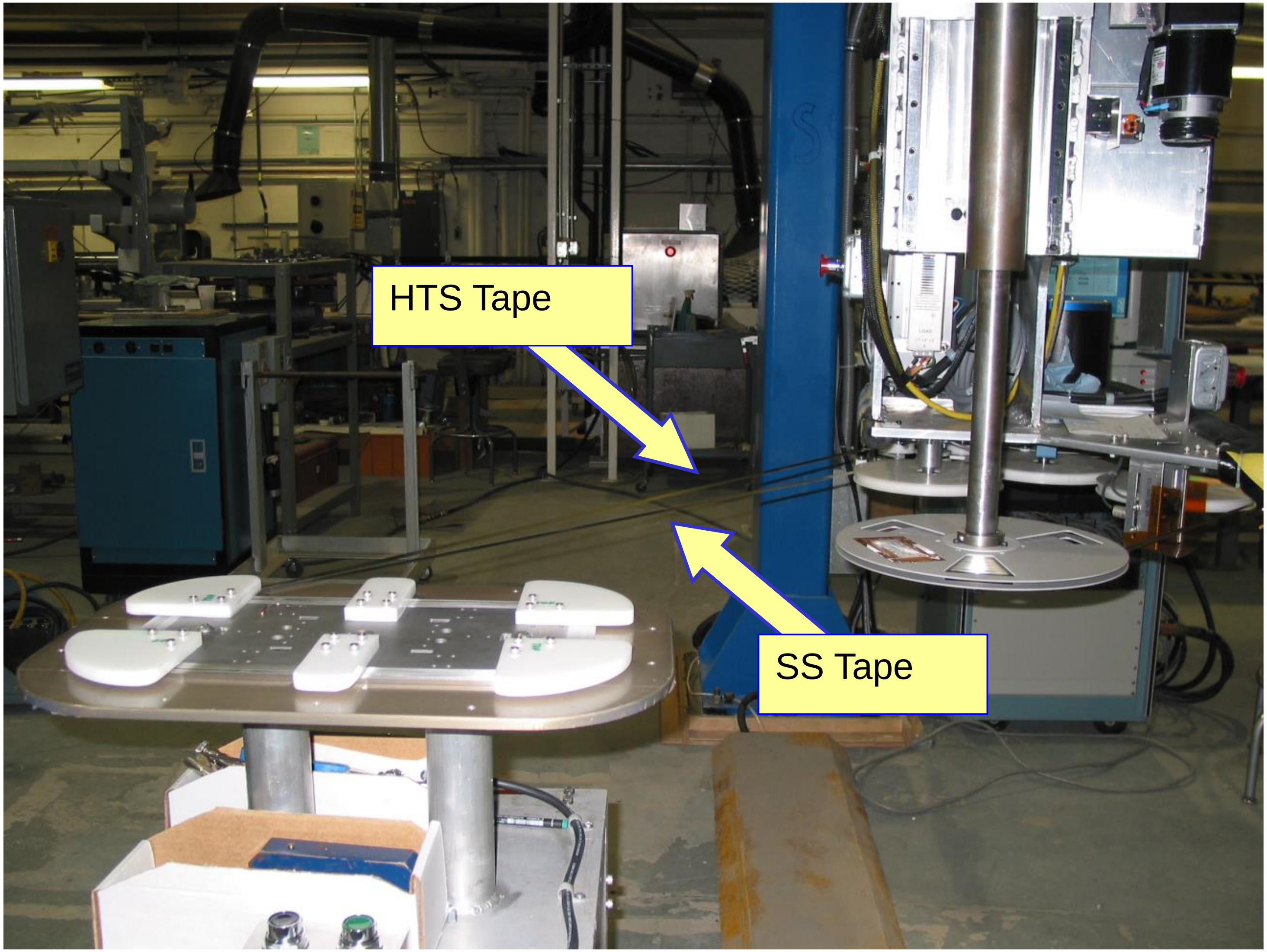
- In HTS magnets, the temperature need not be controlled precisely. This makes magnet operation more robust, particularly in light of large heat loads.

Appears to be a custom made application of HTS magnets

Development of a Significantly New Magnet Technology

- The radiation tolerance requirements in FRIB magnets for fragment separation region are unprecedented
- In addition to the conductor, all magnet parts (including insulation, cryogenic & support structure) must withstand large radiation loads (10 MGy/year for > 10 years)
- This is perhaps the first time that we have made a superconducting magnet that is built with no organic component in it (including metallic SS insulation)
- In addition to high radiation, the magnet technology developed is able to withstand large energy deposition too

HTS Coil Winding

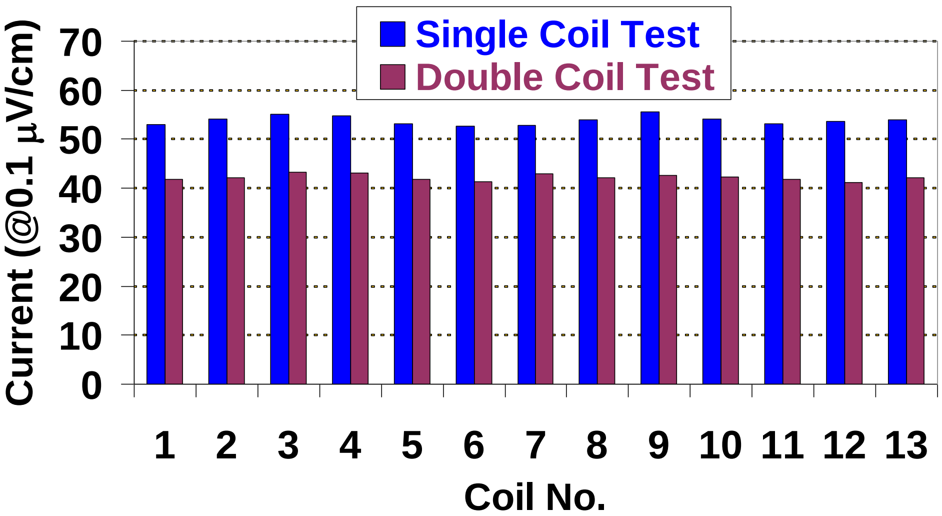


A coil being wound in a computer controlled winding machine

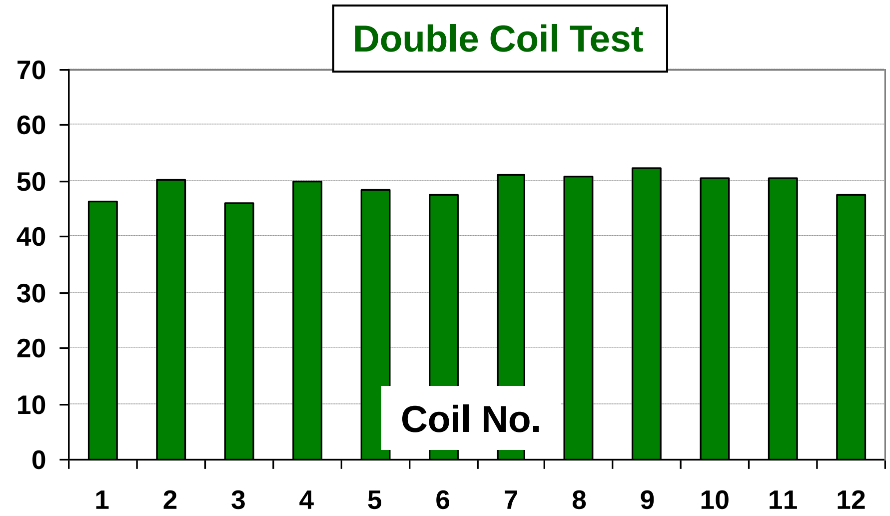
77 K Test of Coils Made with ASC 1st Generation HTS

- Each single coil uses ~200 meter of tape

13 Coils made HTS tape in year #1



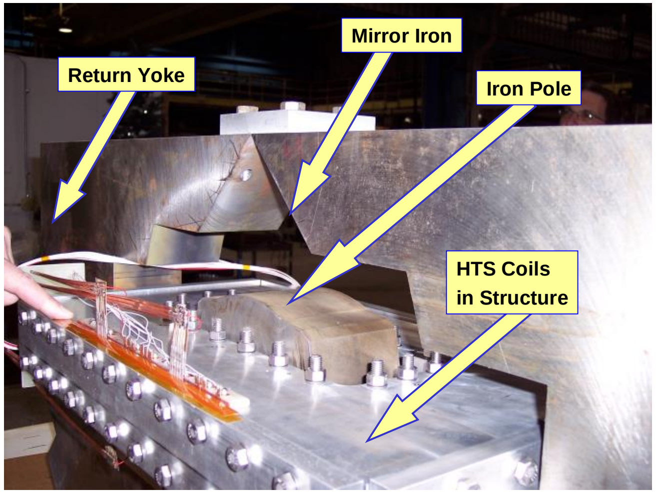
12 coils with HTS tape in year #2



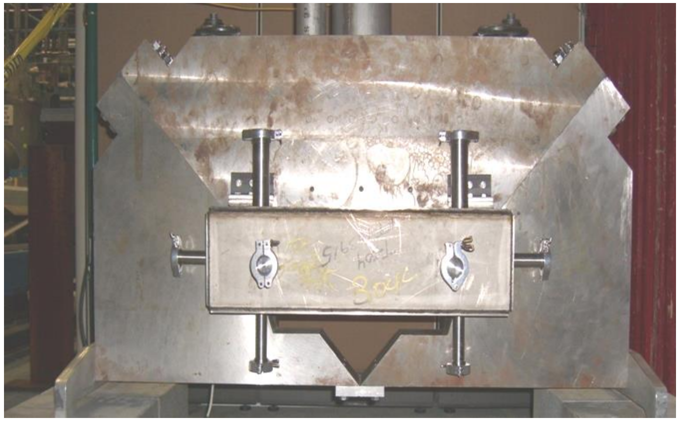
Note: A uniformity in performance of a large number of HTS coils

1st Generation HTS Quad

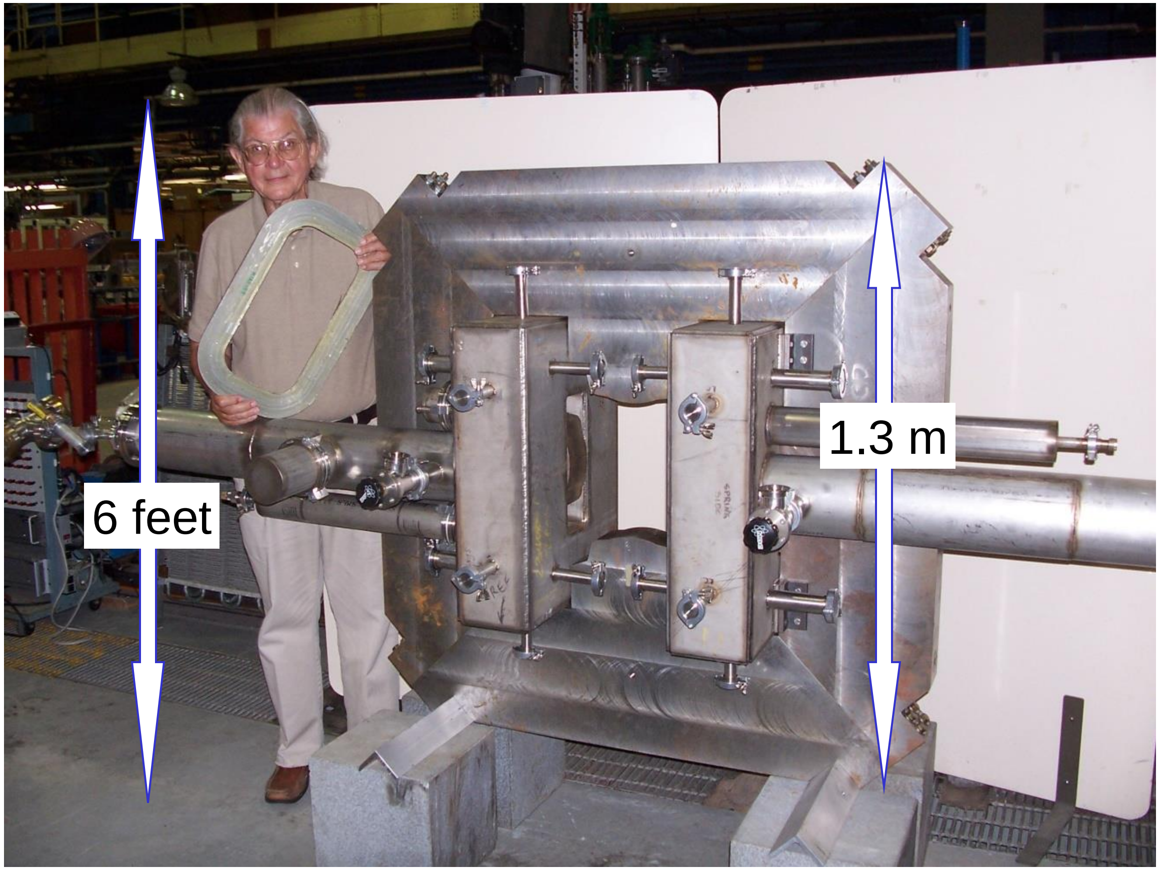
Three magnet structures, built and tested



Mirror cold iron

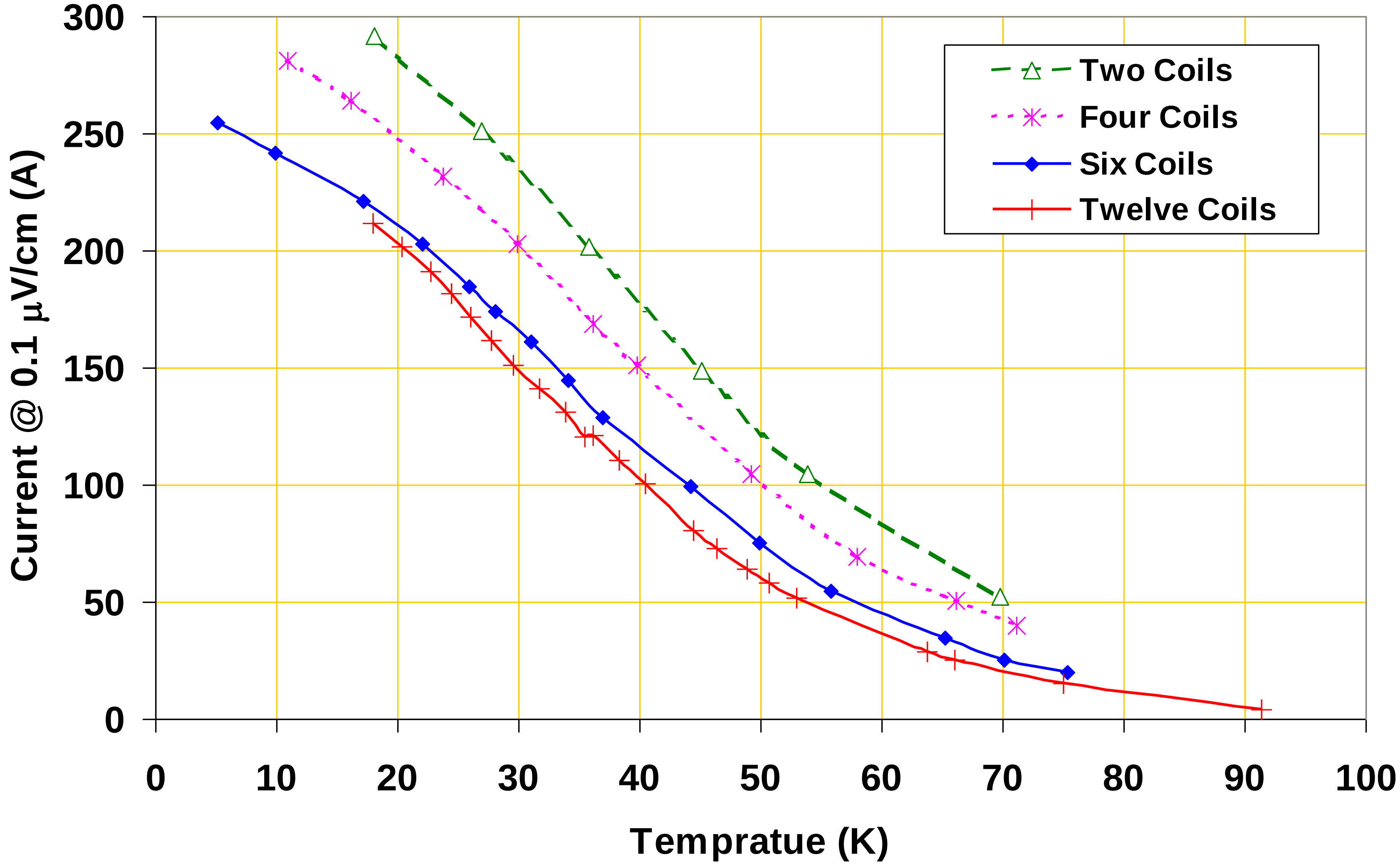


Mirror warm iron



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 HTS Quad for FRIB

- Higher operating temperature (up to 50 K instead of 30 K in the 1st) and higher gradient (15 T/m instead of 10 T/m in the 1st)

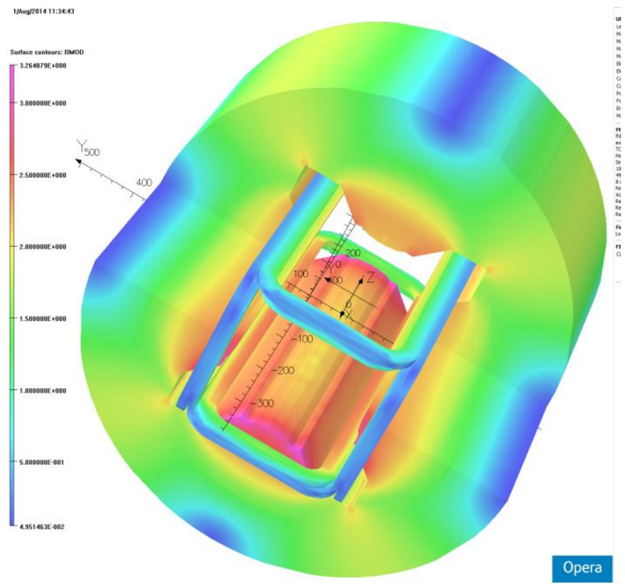
- Full size model built with 12 mm wide 2G HTS tape from two US vendors (SuperPower and ASC)

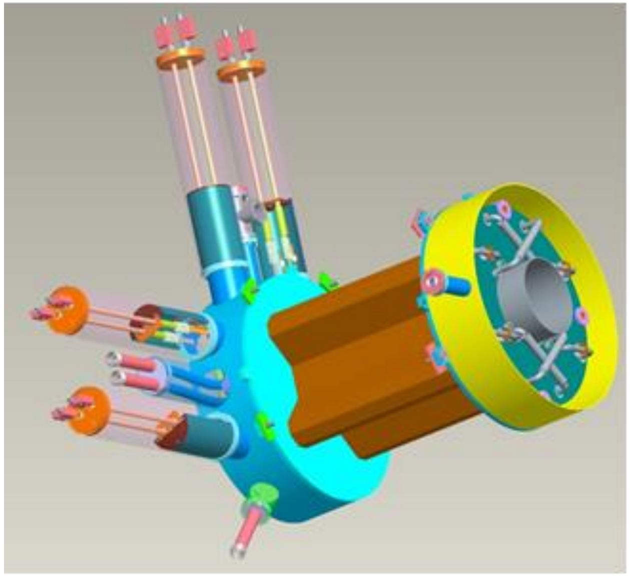
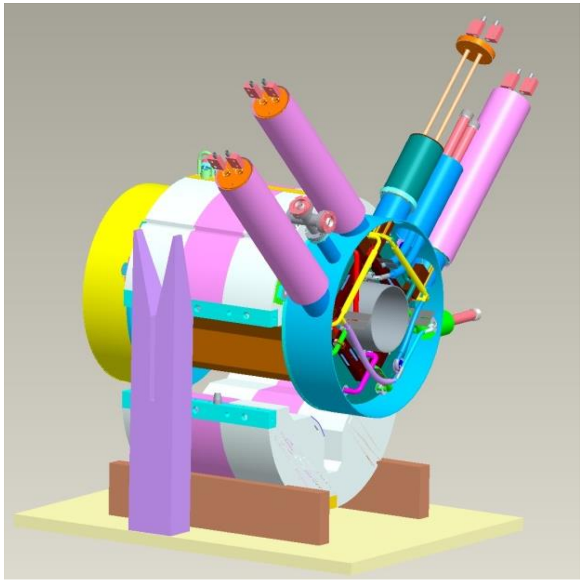
    - ~9 km equivalent of 4 mm tape

Design

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

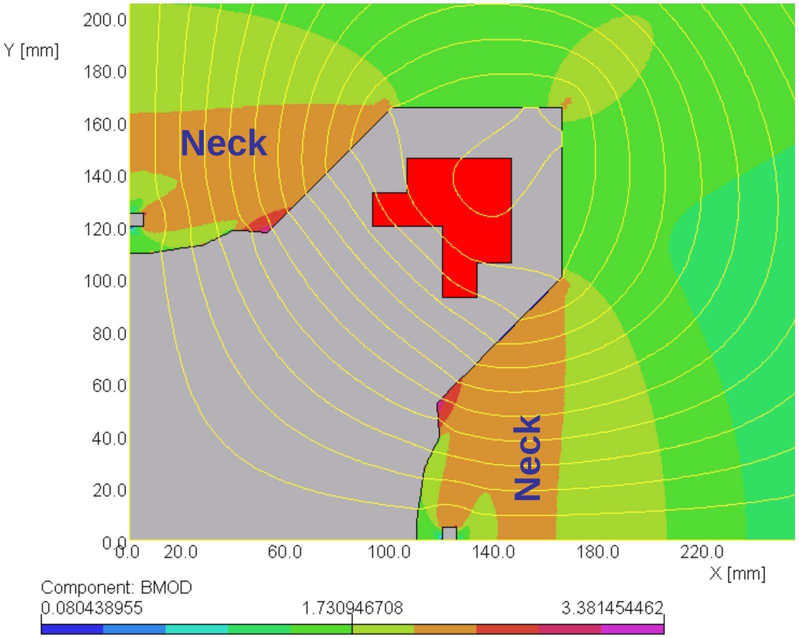
15 T/m

38 K

12 mm 2G SuperPower and ASC

8 HTS coils

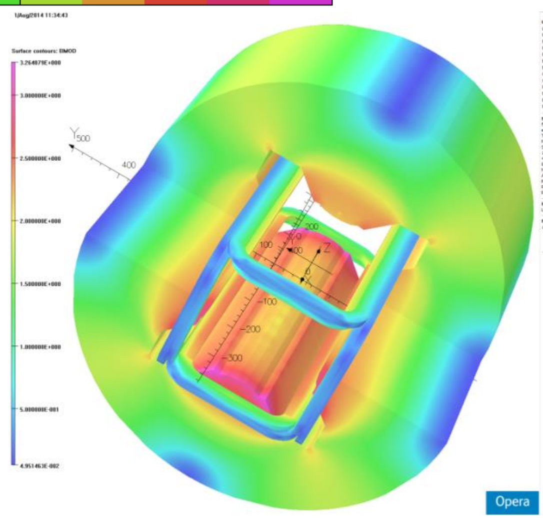
Magnetic Design

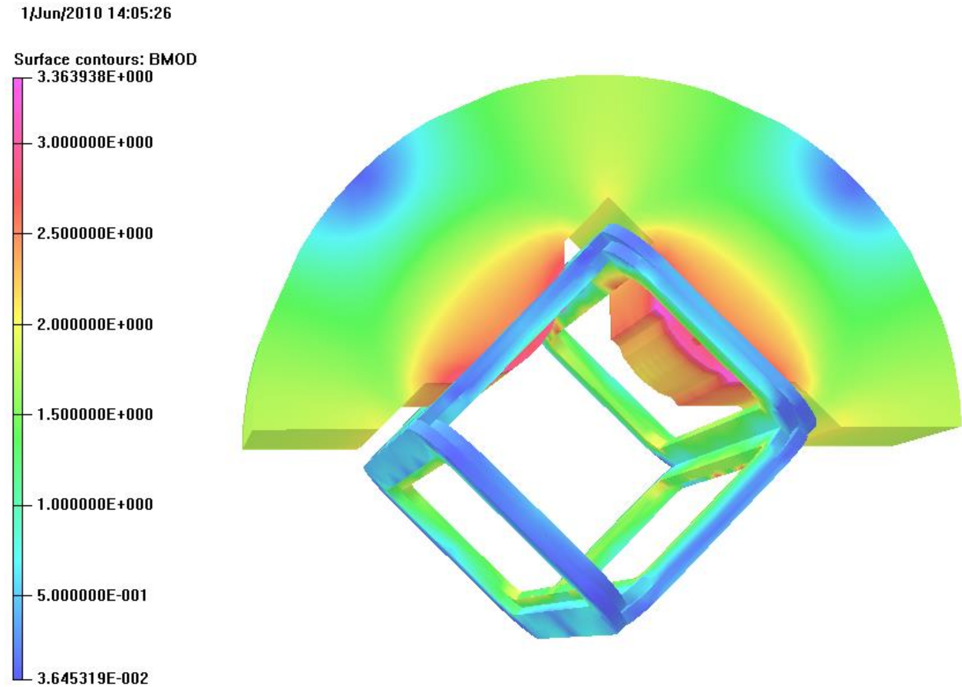


Uses 12 mm tape rather than 4 mm tape

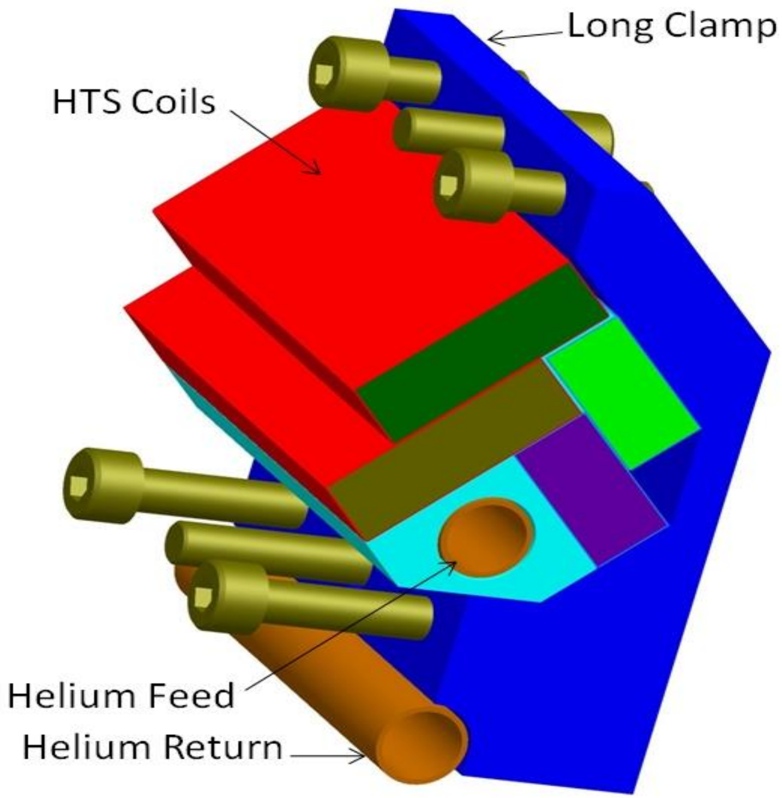
Benefits of 12 mm Tape:

- **Minimizes the number of coils and joints**
- **Current is higher (inductance is lower)**
- **Relative impact of a weak section is less**

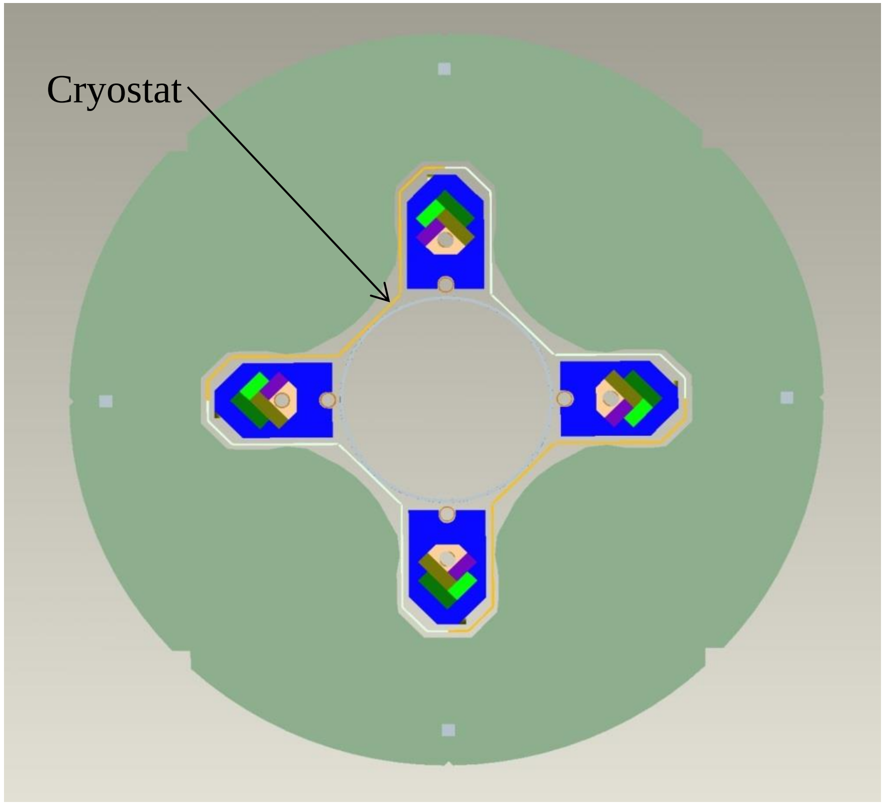




Structure for the Body of the Magnet

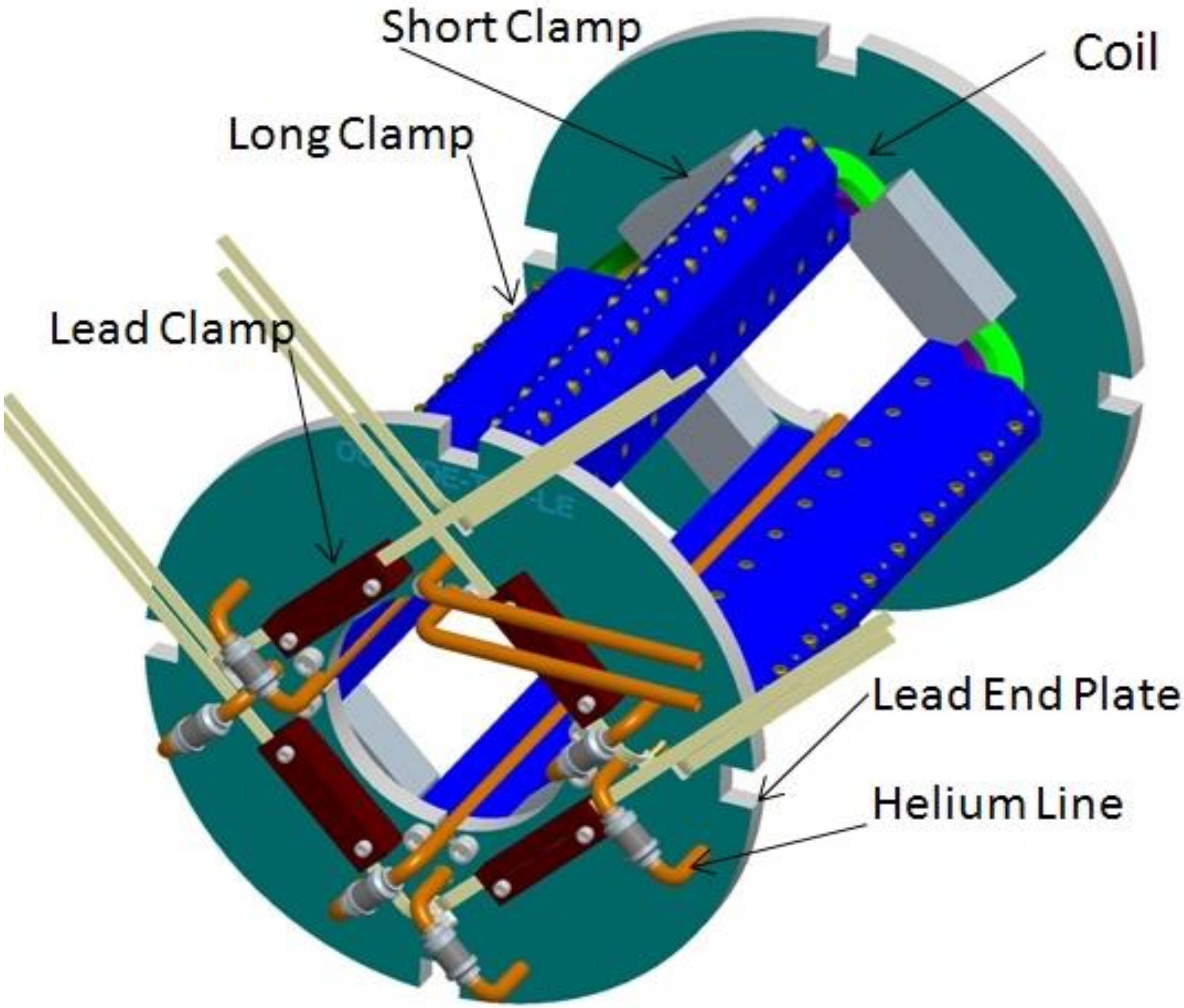


Partial View of Clamped Coil

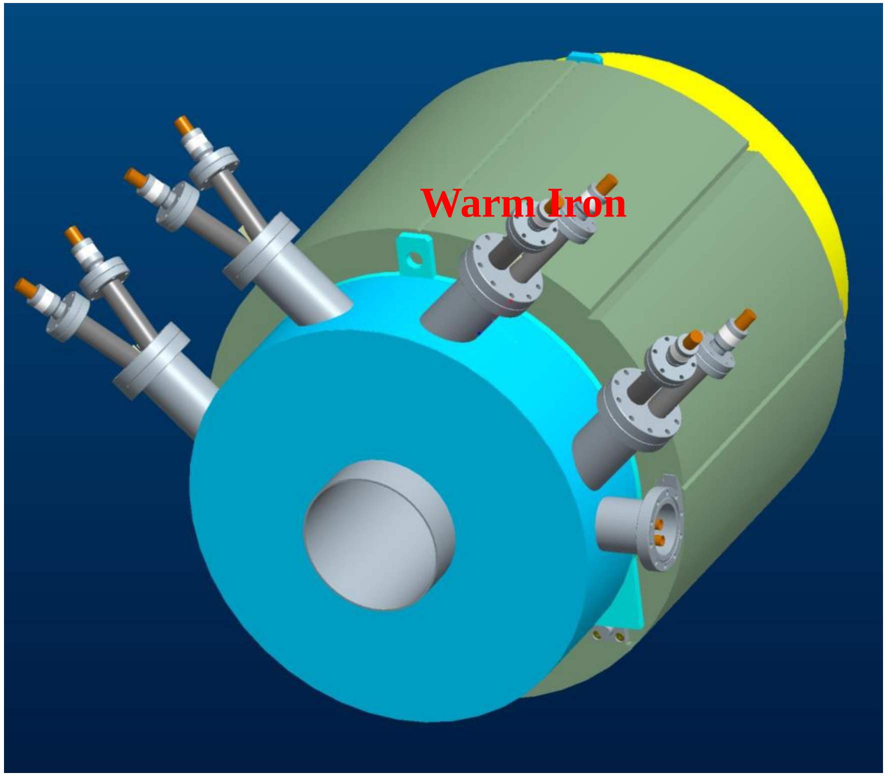


Magnet Cross-Section

Coil Assembly with Clamps and End Plates

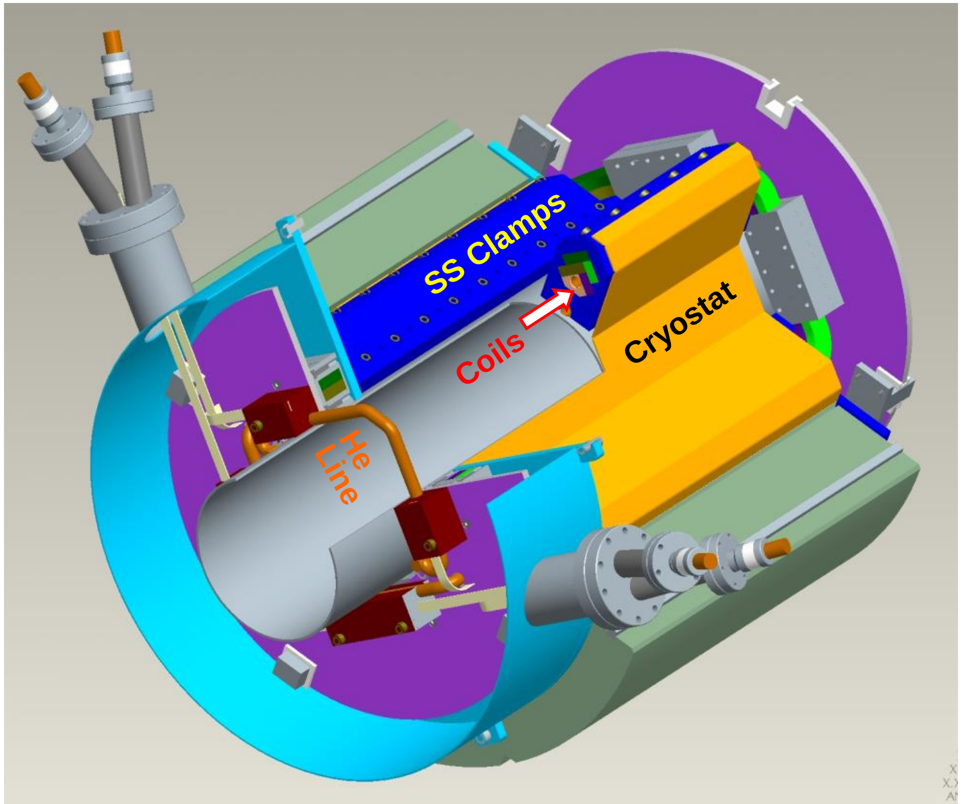


Cryo-mechanical Structure



R&D Magnet in cryo-stat

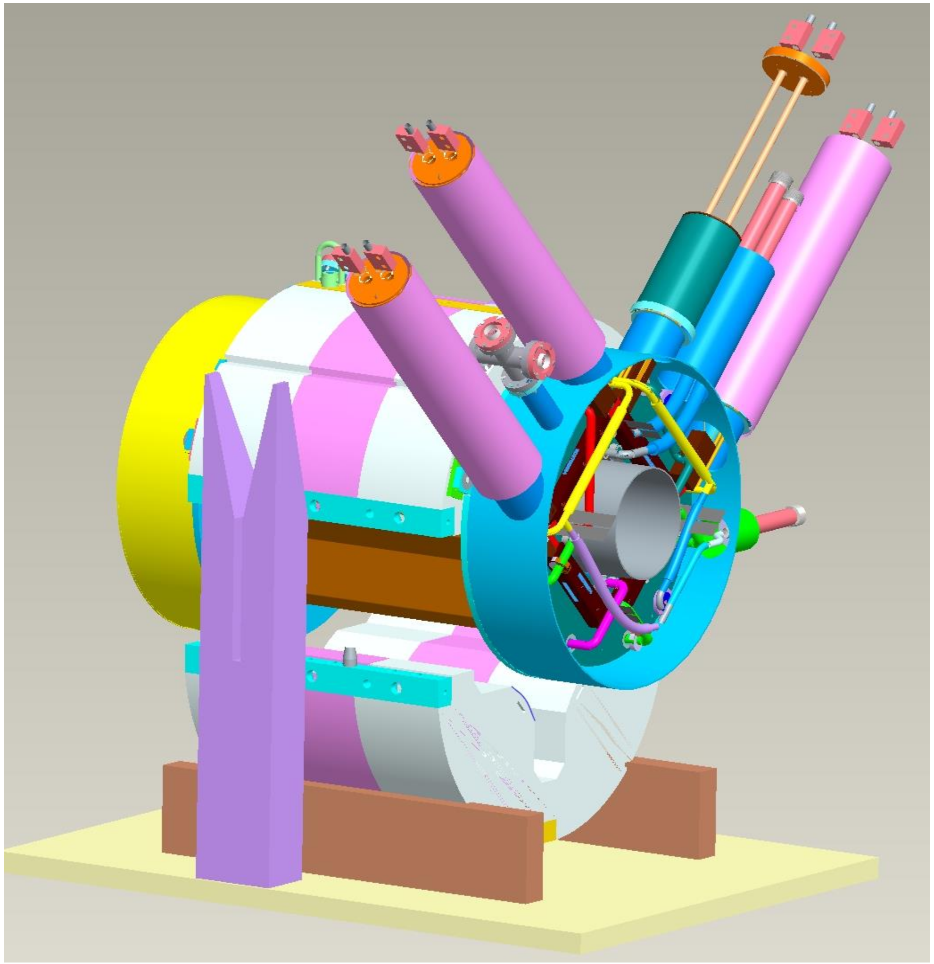
(allows independent testing of four HTS coils)

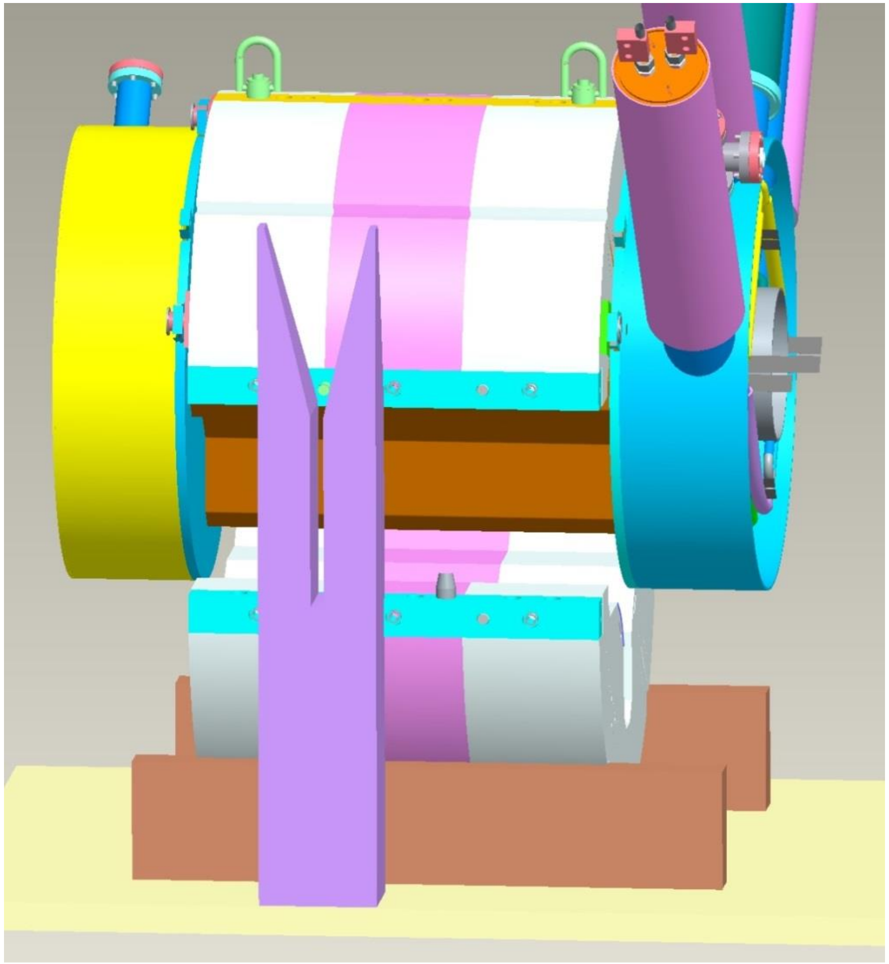


Cut-away isometric view of the assembled magnet

(compact cryo-structure design allowed larger space for coils and reduction in pole radius)

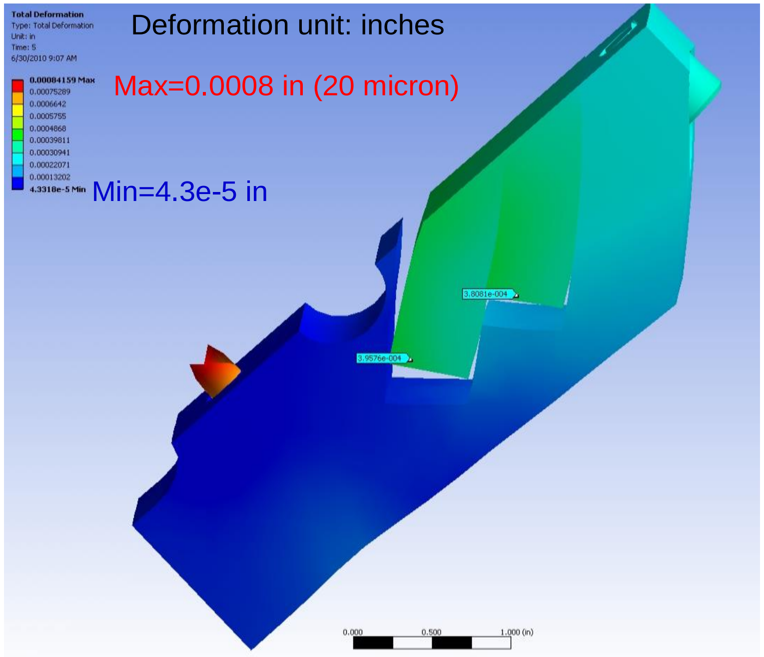
Structure to Facilitate Remote Handling



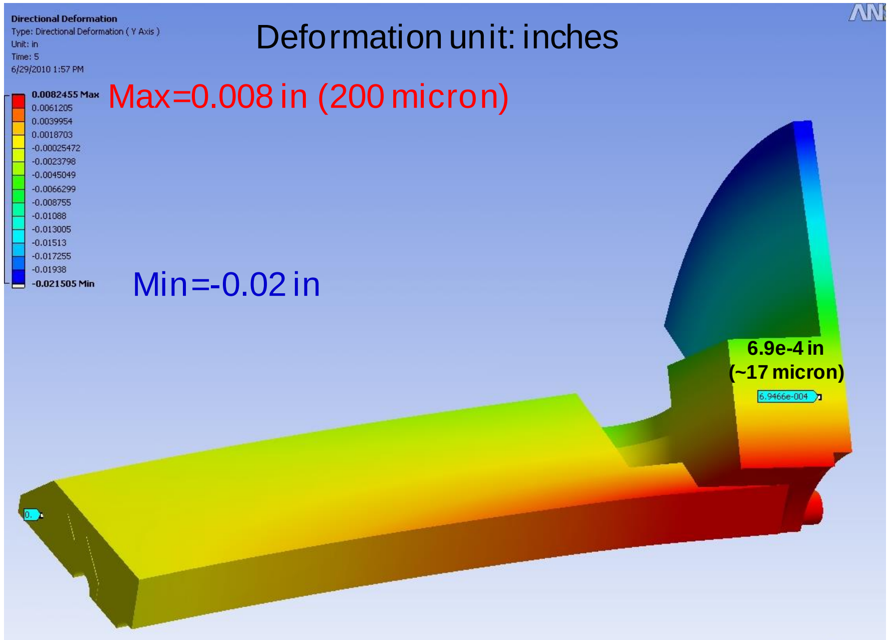


Mechanical Analysis with ANSYS

- The ability of the clamping system to withstand radial and axial Lorentz forces
- All clamp bolts sized and arranged to maintain stress and deflection within acceptable limits
- Analysis results indicate deformation in coils does not exceed 25 microns
- Long clamps made from stainless steel instead of aluminum to reduce deflections



FE Analysis of Long Clamp CS with Coils



FE Analysis of Coil Axial Deflection

Winding of HTS Coils and 77 K Tests in LN_2

- All coils tested individually
- All coils tested together in a structure

Winding of HTS Coil 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

Remember: 12 mm tape
(3X the standard 4 mm)

(~9 km of standard 4 mm equivalent used)

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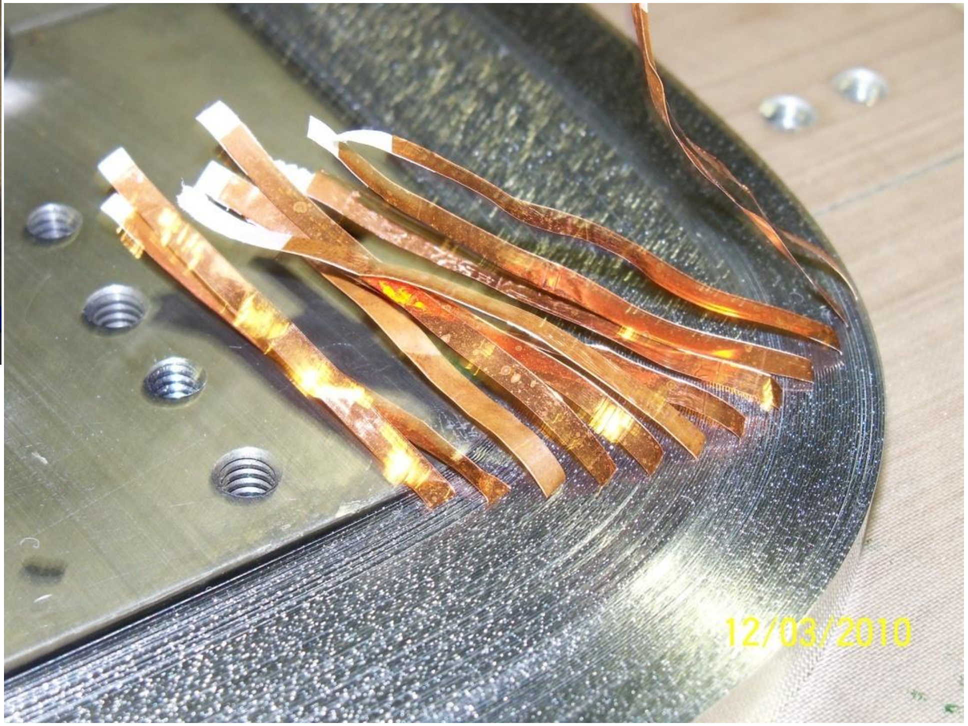
Coils Made with ASC HTS

- ~210 m (~125 turns), 12 mm double HTS tape per coil.
- One coil was wound without any splice in the coil



Voltage taps are placed generally after every 25 turns and also on either side of an internal splice

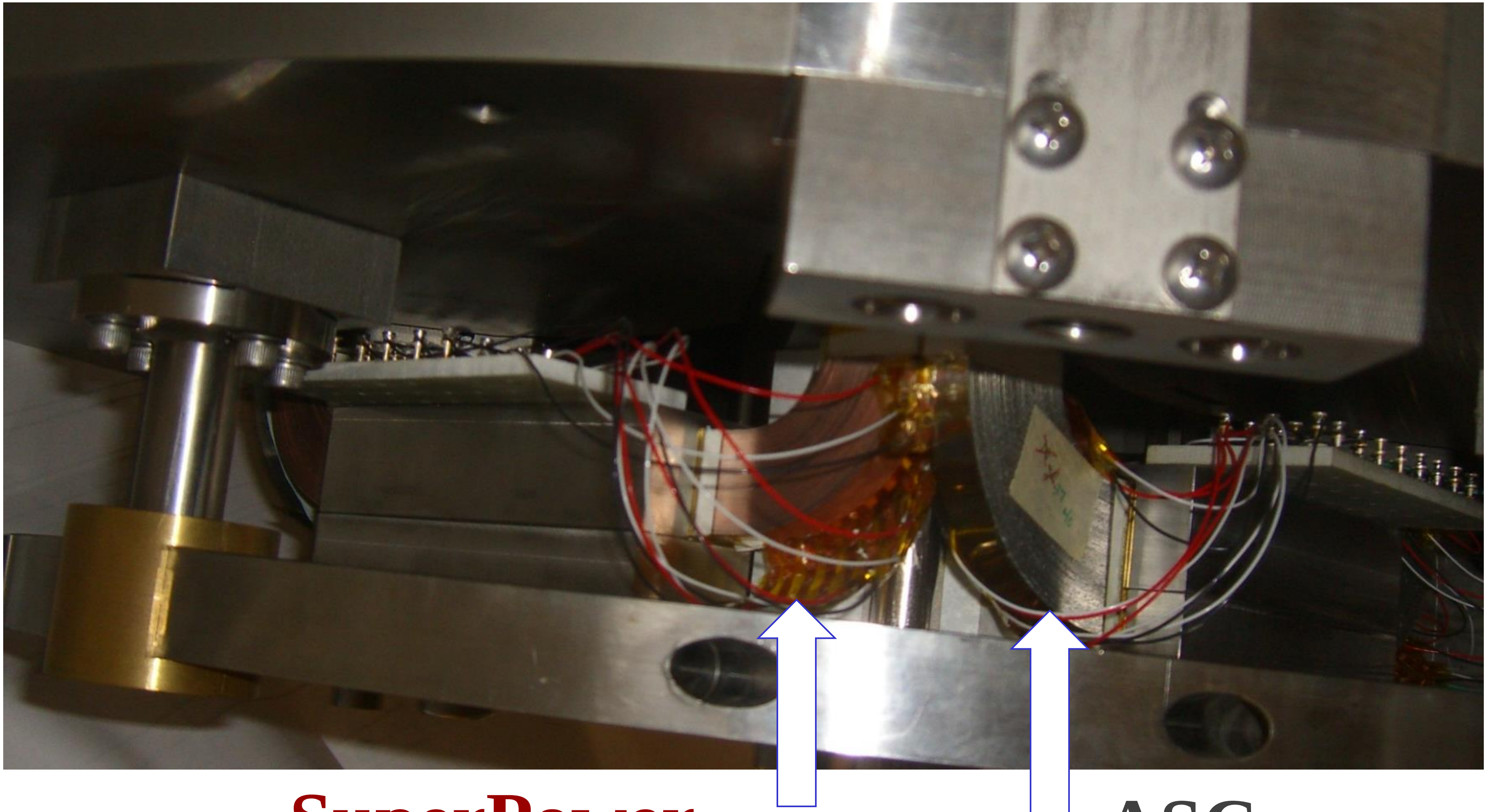
FRIB Coil Made With SuperPower Tape

SuperPower coil uses ~330 m 2G tape (~213 turns) per coil.

Fully wound coil with SuperPower tape with one splice

Coils Assembled in Quadrupole Support Structure

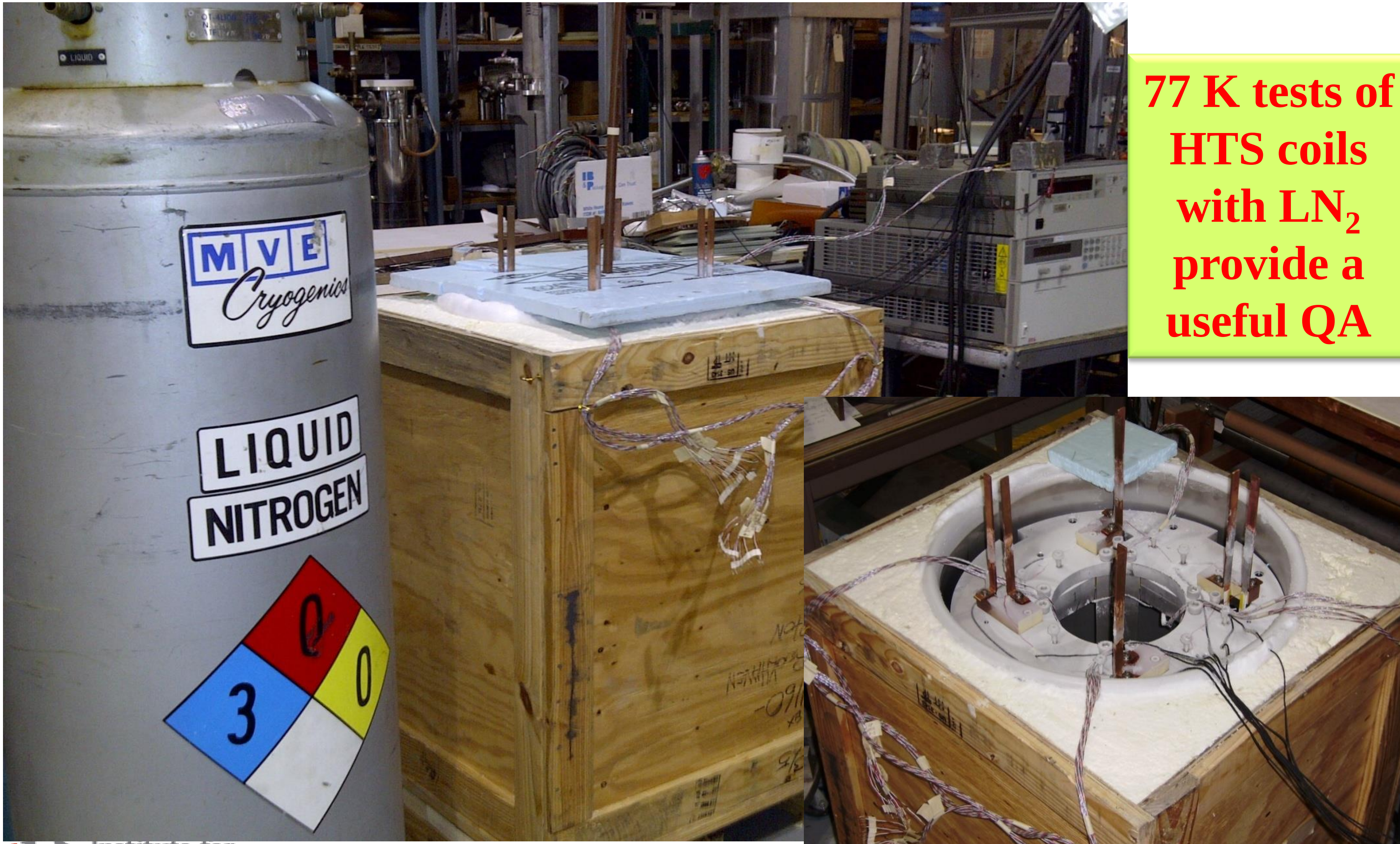
Coils Made with HTS from 2 Vendors (SuperPower and ASC)



SuperPower

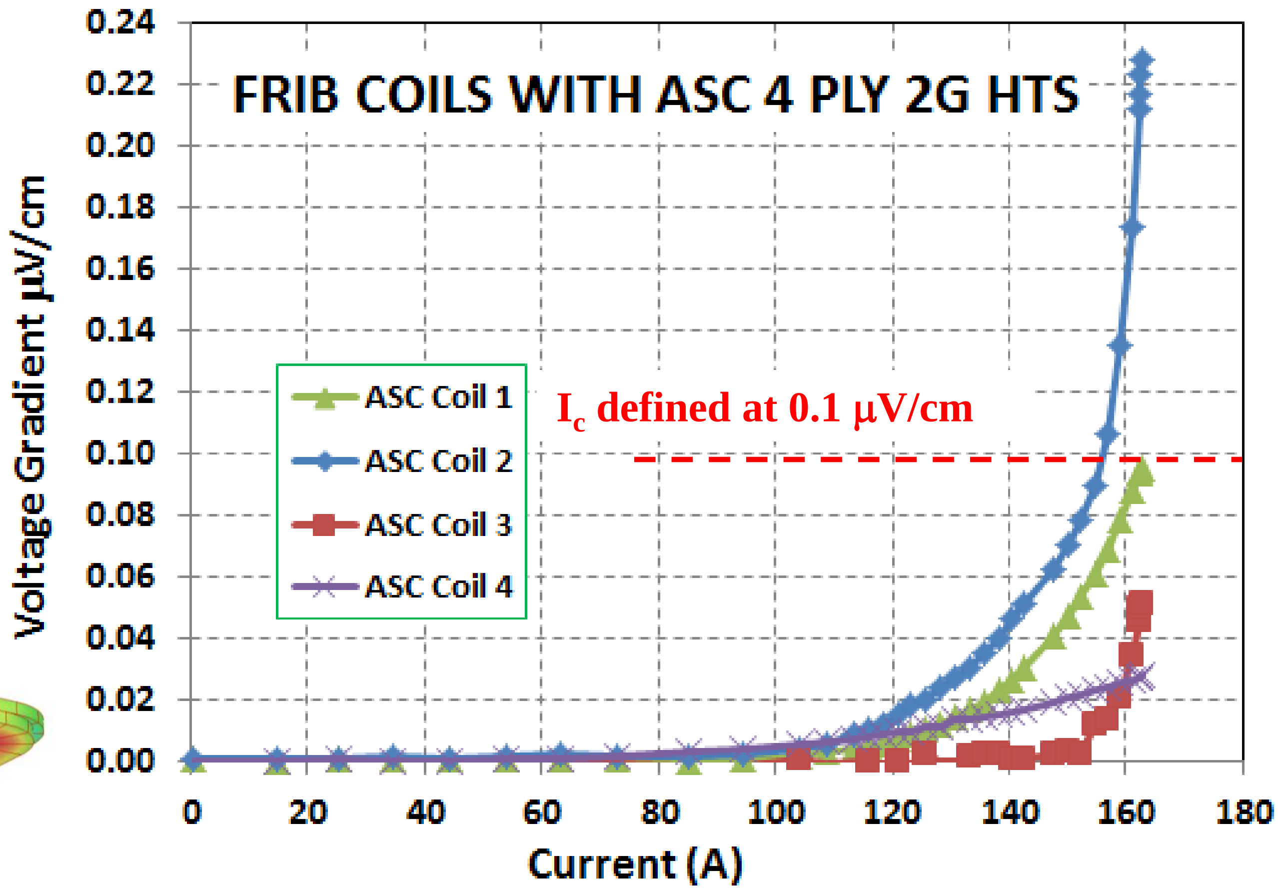
ASC

FRIB HTS Quad in Simple Cryostat



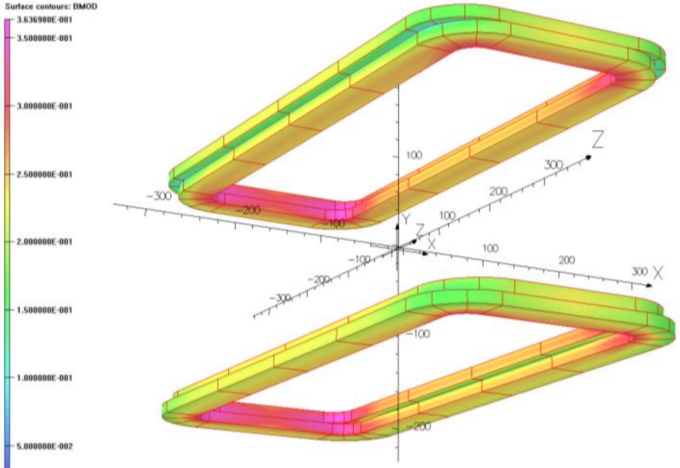
77 K tests of HTS coils with LN_2 provide a useful QA

Performance of ASC Coils (four coils of eight powered)



ASC Tape:

2 plies of HTS and 2 plies of Cu

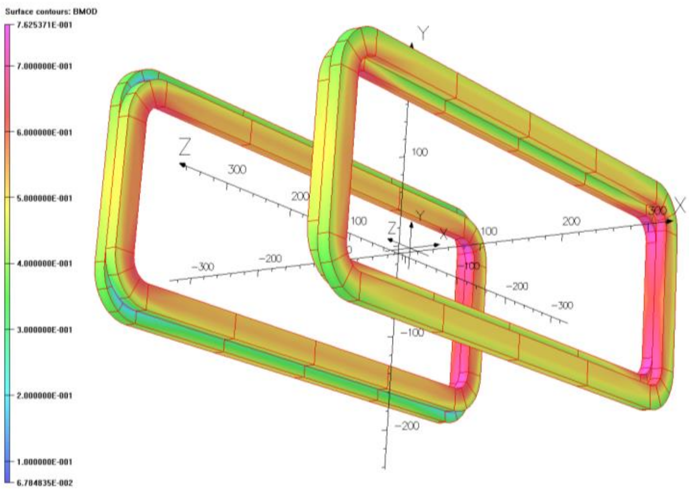


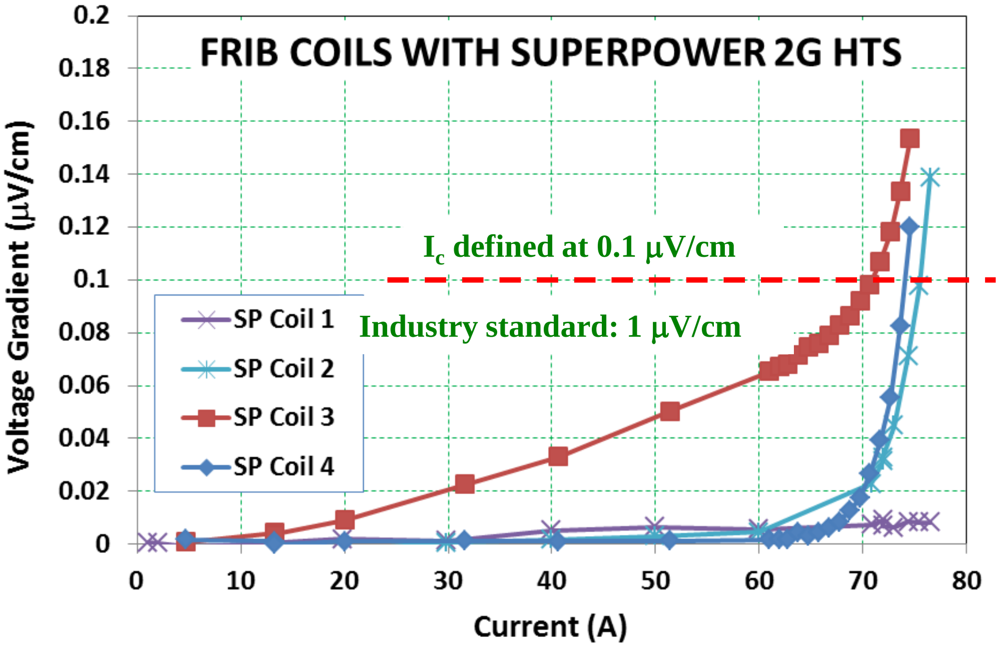
Field on ASC coils at 100 A

Four SuperPower coils not powered

Performance of SuperPower Coils (four of eight coils powered)

Four ASC coils were not powered





Field on SuperPower coils at 100 A

Internal splice on wrong tape side shows higher resistance. This is not an operational issue as the heat generated is small as compared to the energy deposition.

- **Therefore, the expensive coil was not discarded.**

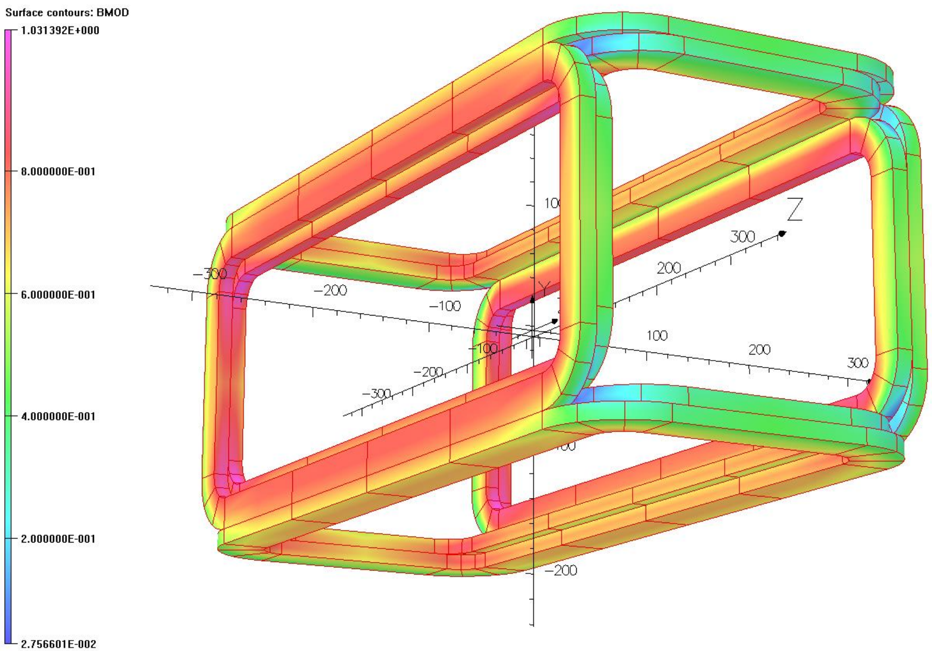
Location confirmed with Voltage taps that are typically placed after every 25 turns and on either side of an internal splice (slope localized to splice section)

77 K Test in Quadrupole Mode (all eight coils powered)

Currents used for quadrupole mode at 77 K (equal Je)

SP	ASC
40	69.3
50	86.7
60	104

Field with ASC coils at 200A and SuperPower coils at 115.5 A

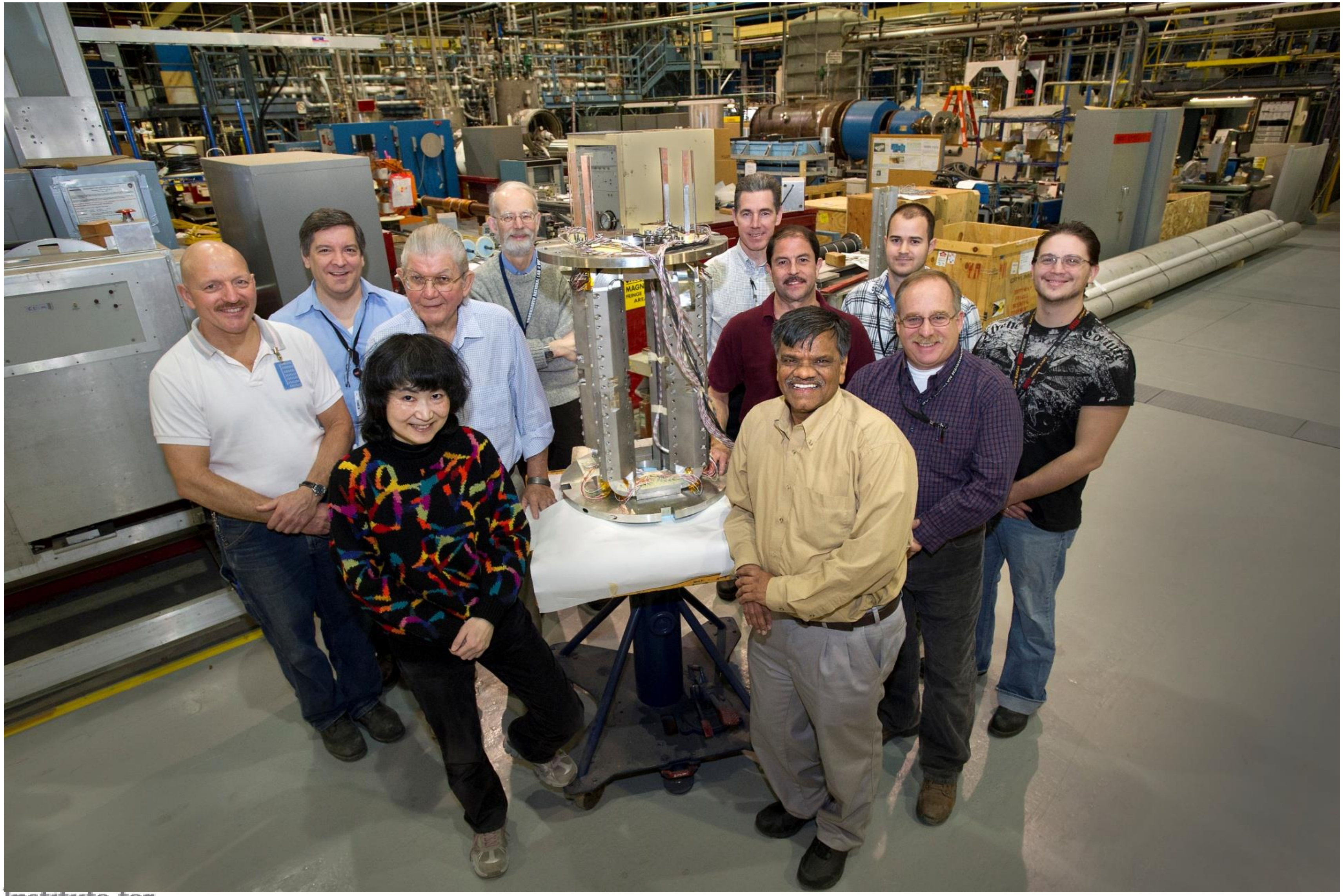


Design (38 K): SP coils ~210 A & ASC coils ~310 A (equal Amp-turns).

- **Coils reached about 1/3 of the design current at 77 K itself.**
- **Extrapolation to 38 K indicates a significant margin.**

Note: No iron yoke yet in this structure.

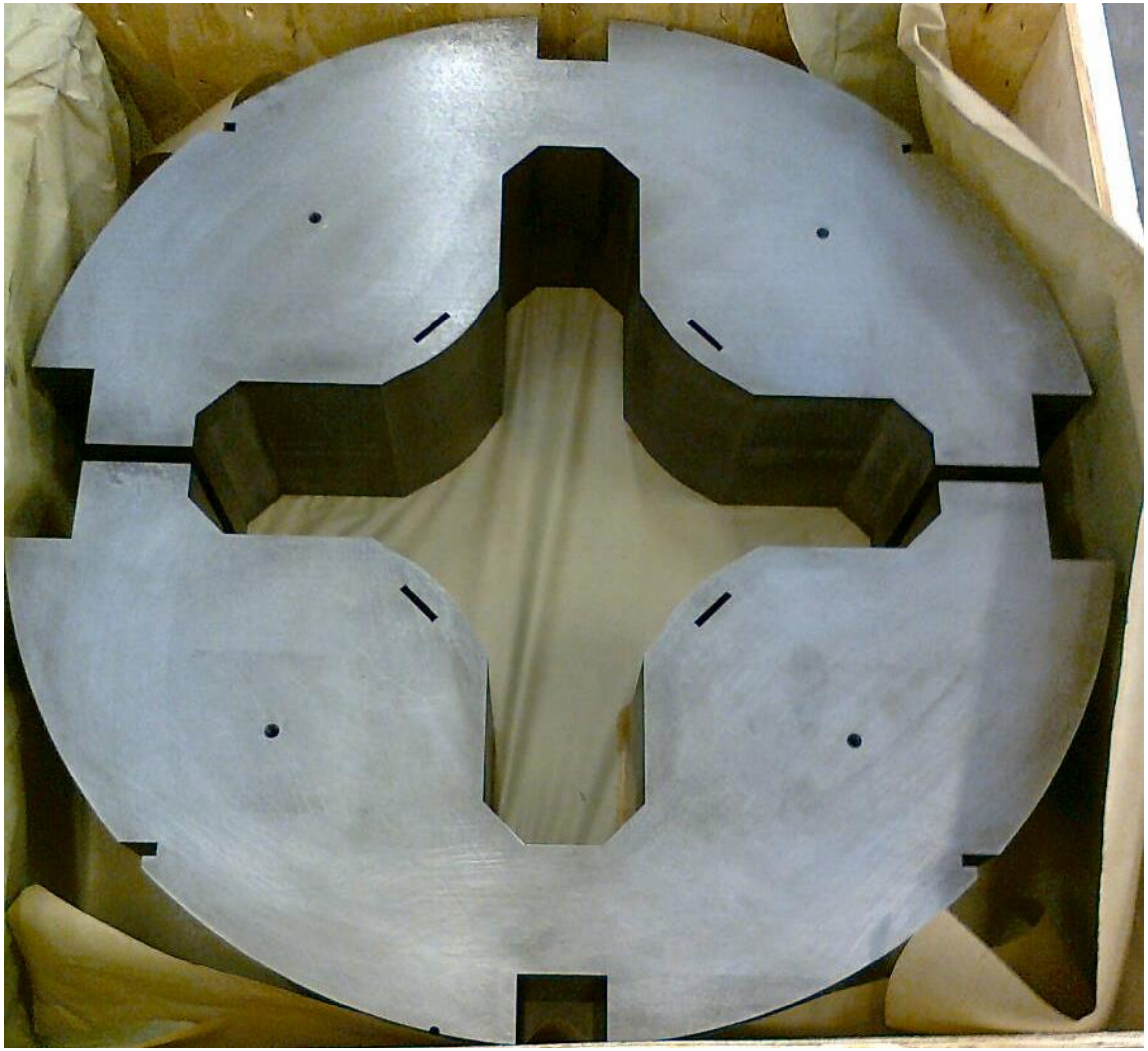
Proud Team Members



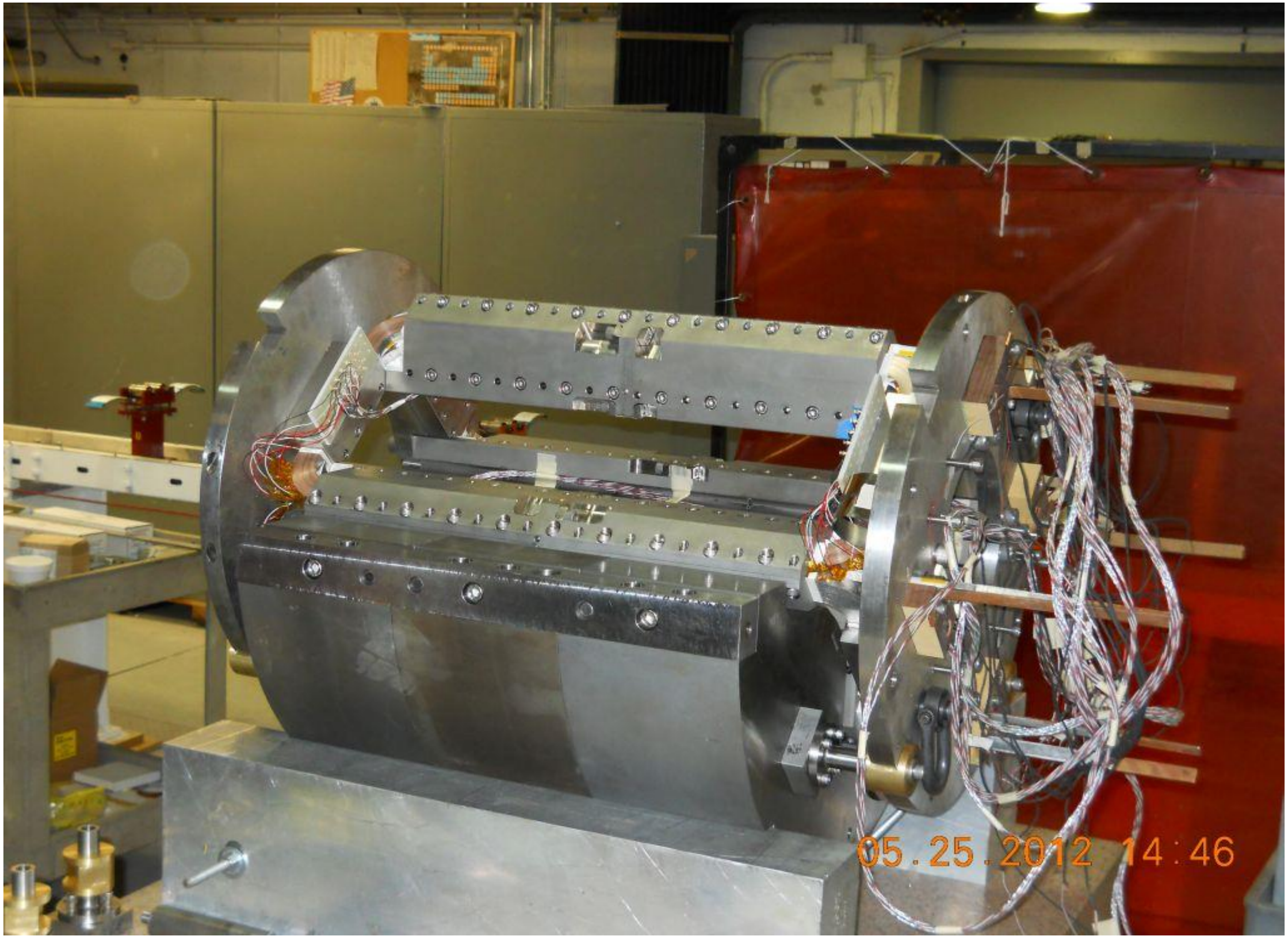
Construction and Test of the FRIB HTS Quad with Iron at the Operating Temperature

FRIB Quad with Clamps (in preparation for installing yoke)

Yoke Iron for FRIB Quad

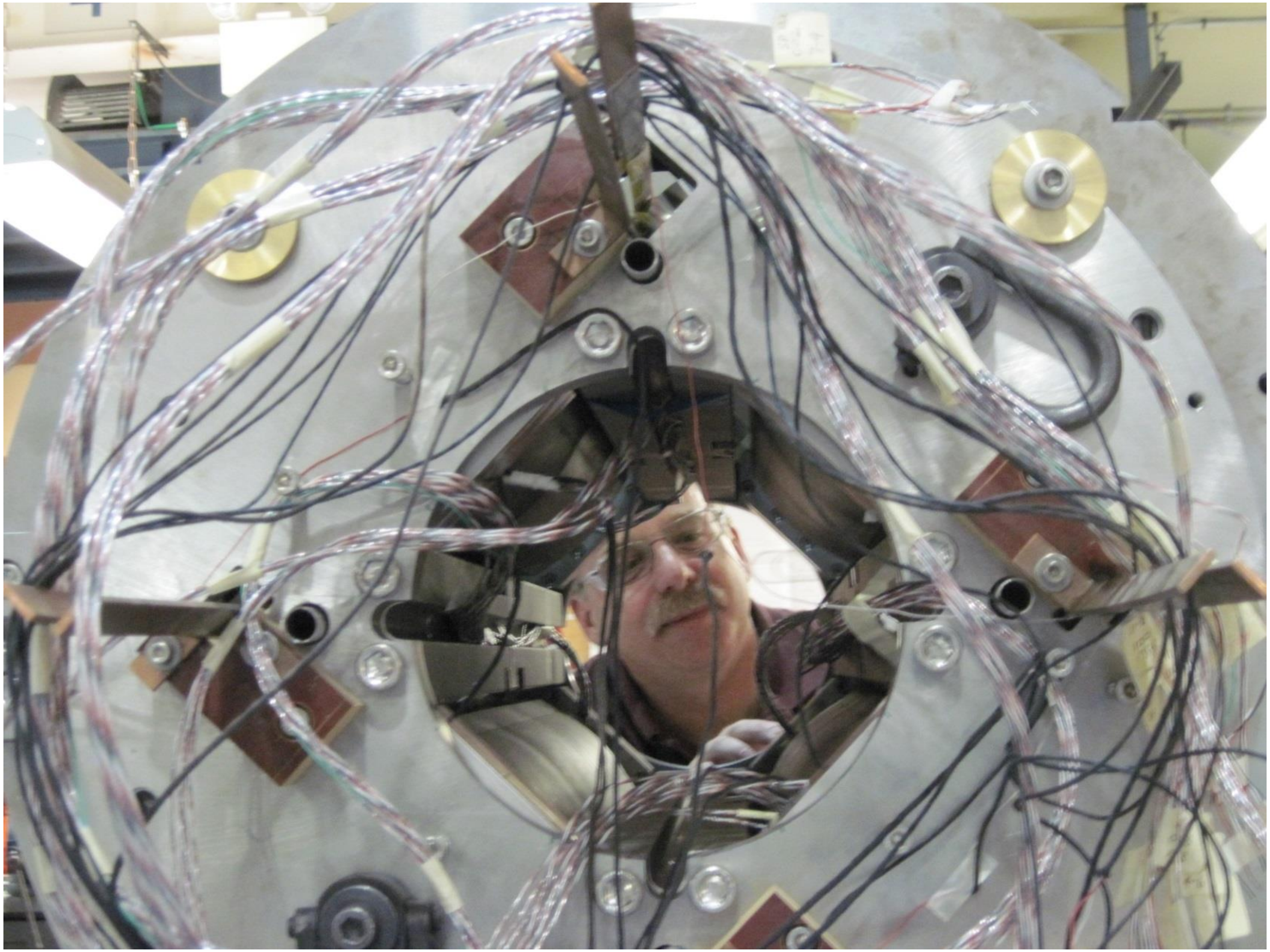


Coil and Support Structure Partially Assembled inside the Yoke

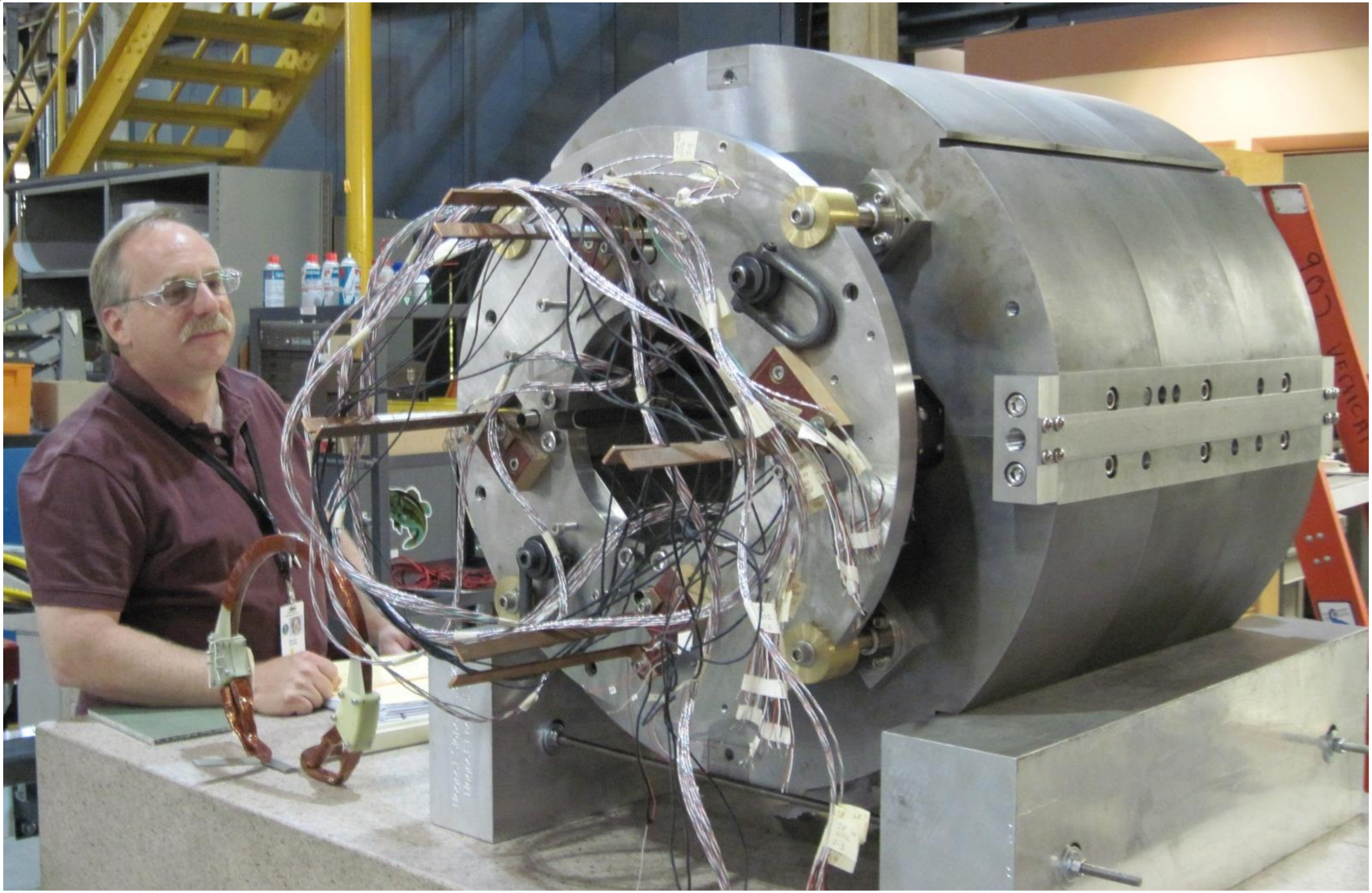


Coil and Support Structure Fully Assembled inside the Yoke

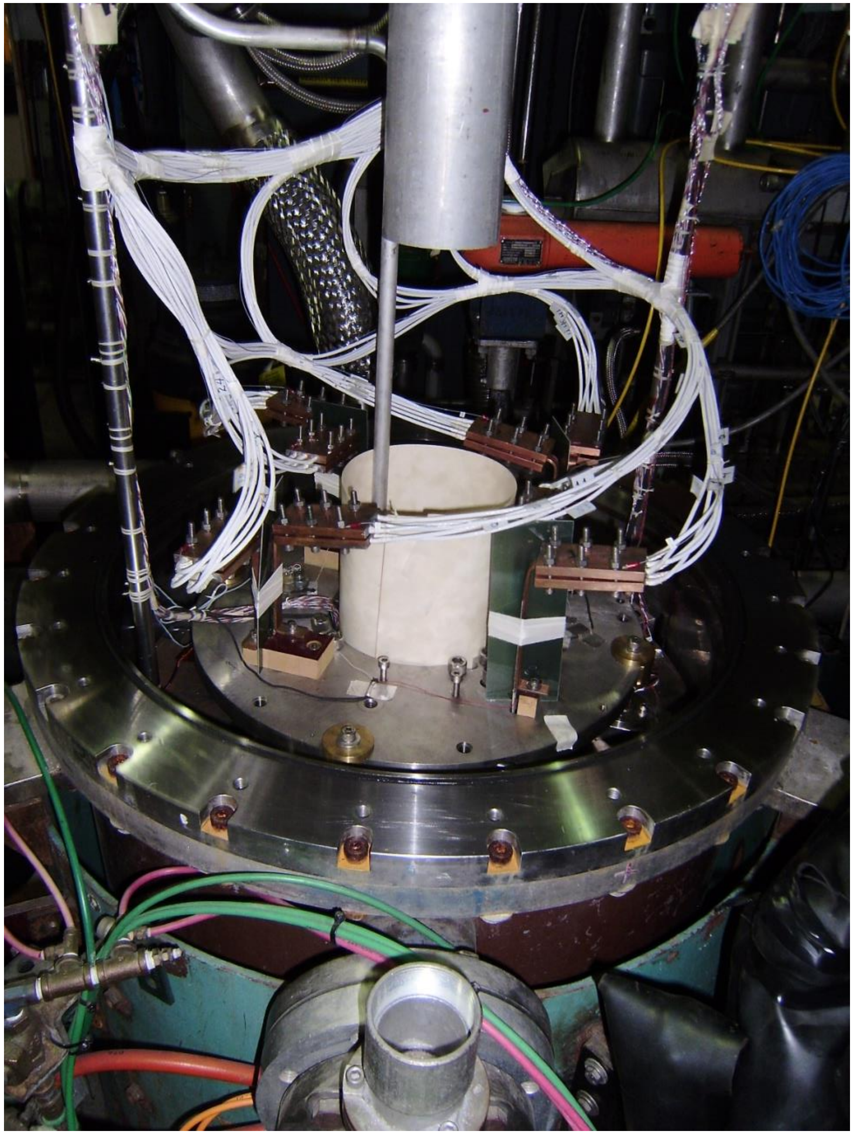
Aperture of 2G HTS Quad for FRIB



Completed 2G HTS Quad for FRIB

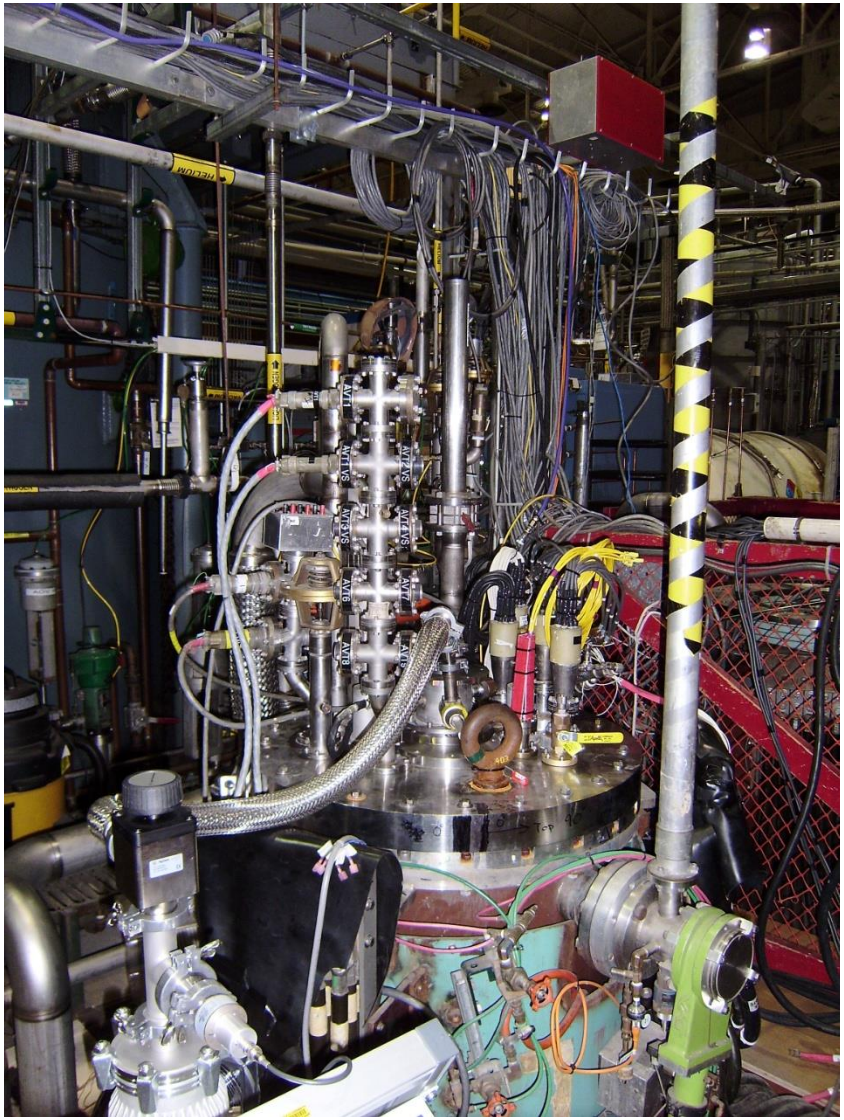


Preparation for Low Temperature Test

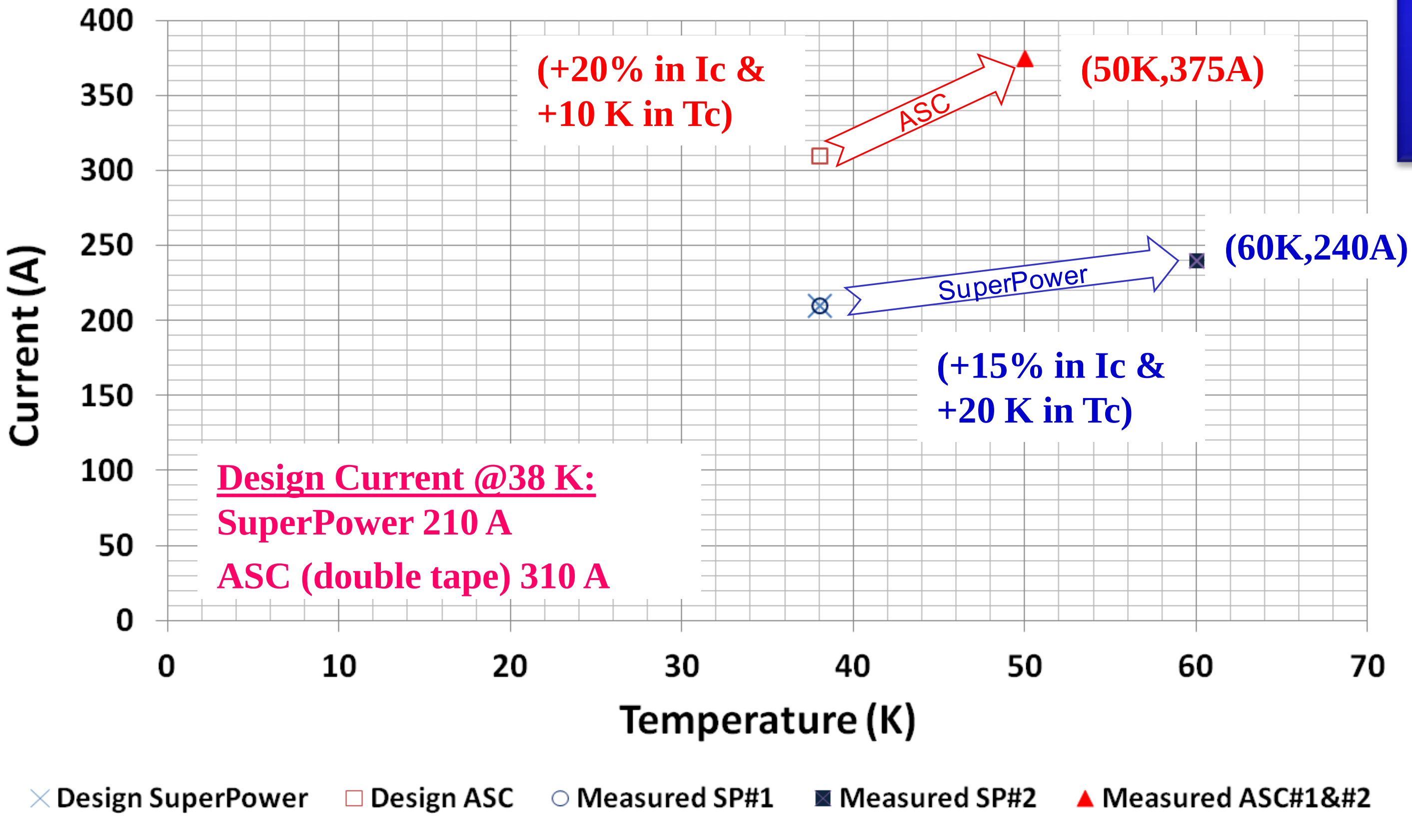


8 leads (Helium Gas cooled at the top)

Magnet at the Test Station



Final Test: Large Temperature Margins (only possible with HTS)



Impressive Performance

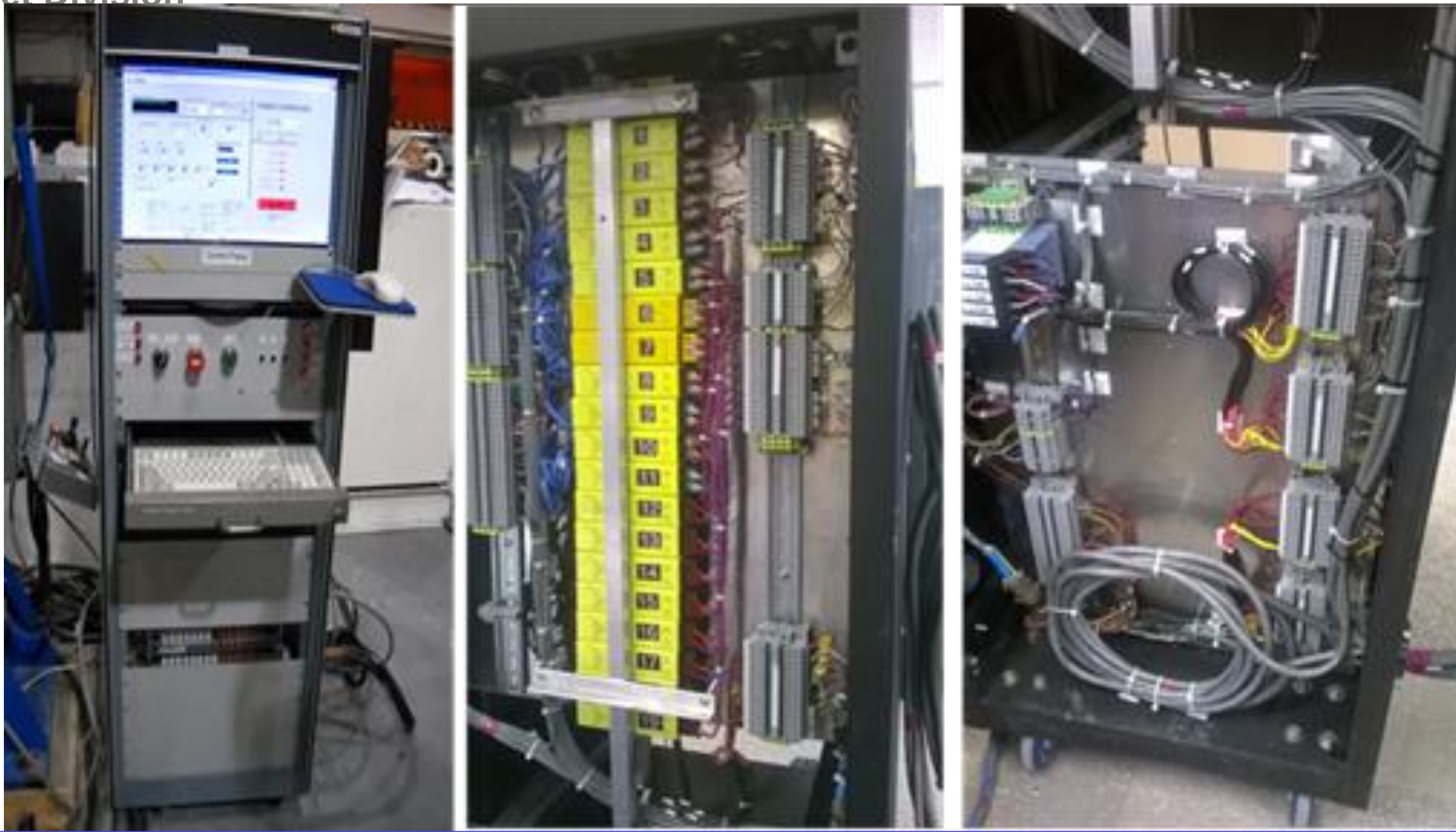
Note: Above are not the limits of the coils (I_c).

These are the currents to which the coils were energized.

- **Coils from both vendors performed well (easily met the requirements).**
- **This is an unprecedented temperature margin (thanks to HTS).**
- **Provides robust operation against local and global heat loads.**

Advanced Quench Protection System

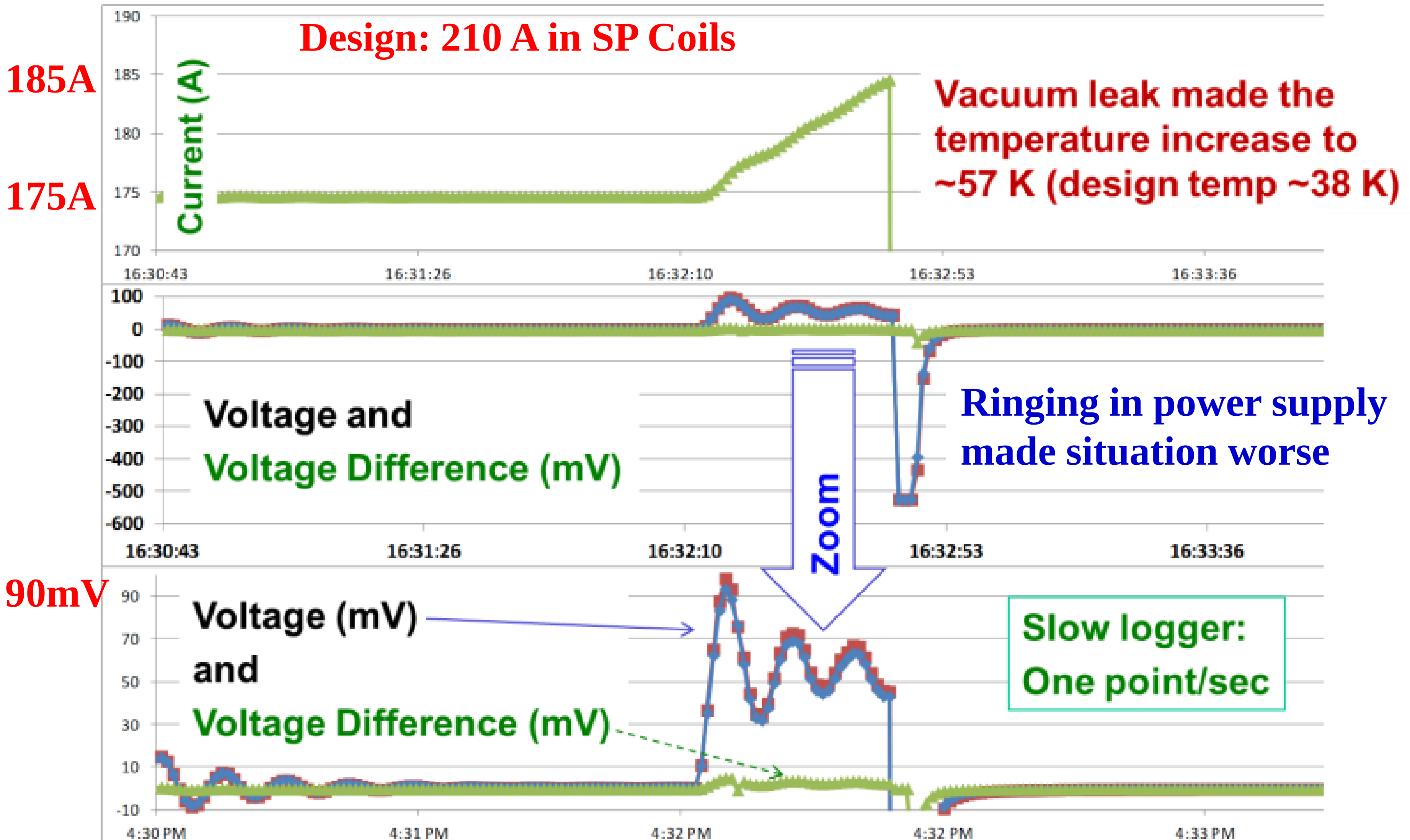
Advanced Quench Protection Electronics



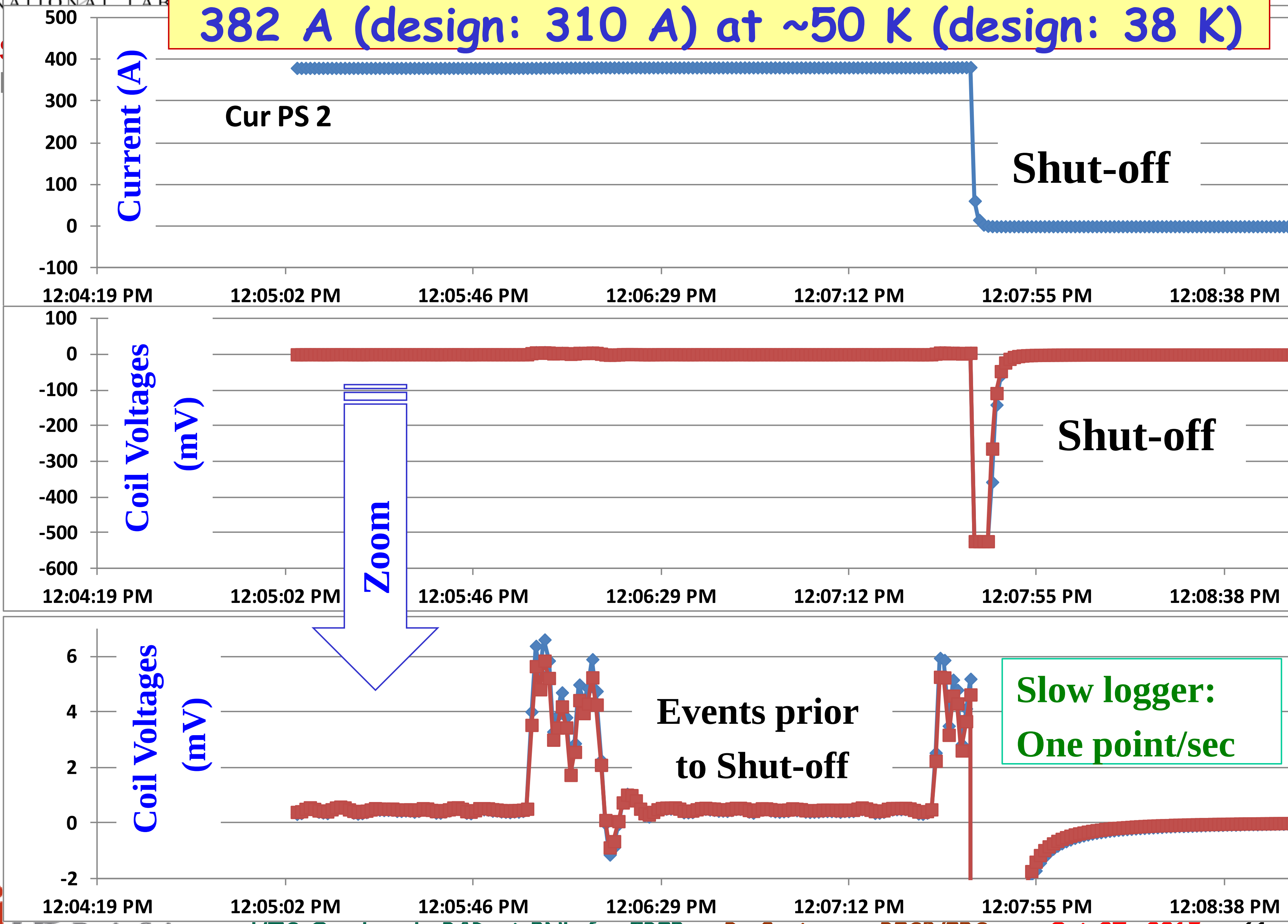
Detects onset of pre-quench voltage at < 1mV and with isolation voltage > 1kV allows fast energy extraction

Magnet Operation and Quench Protection

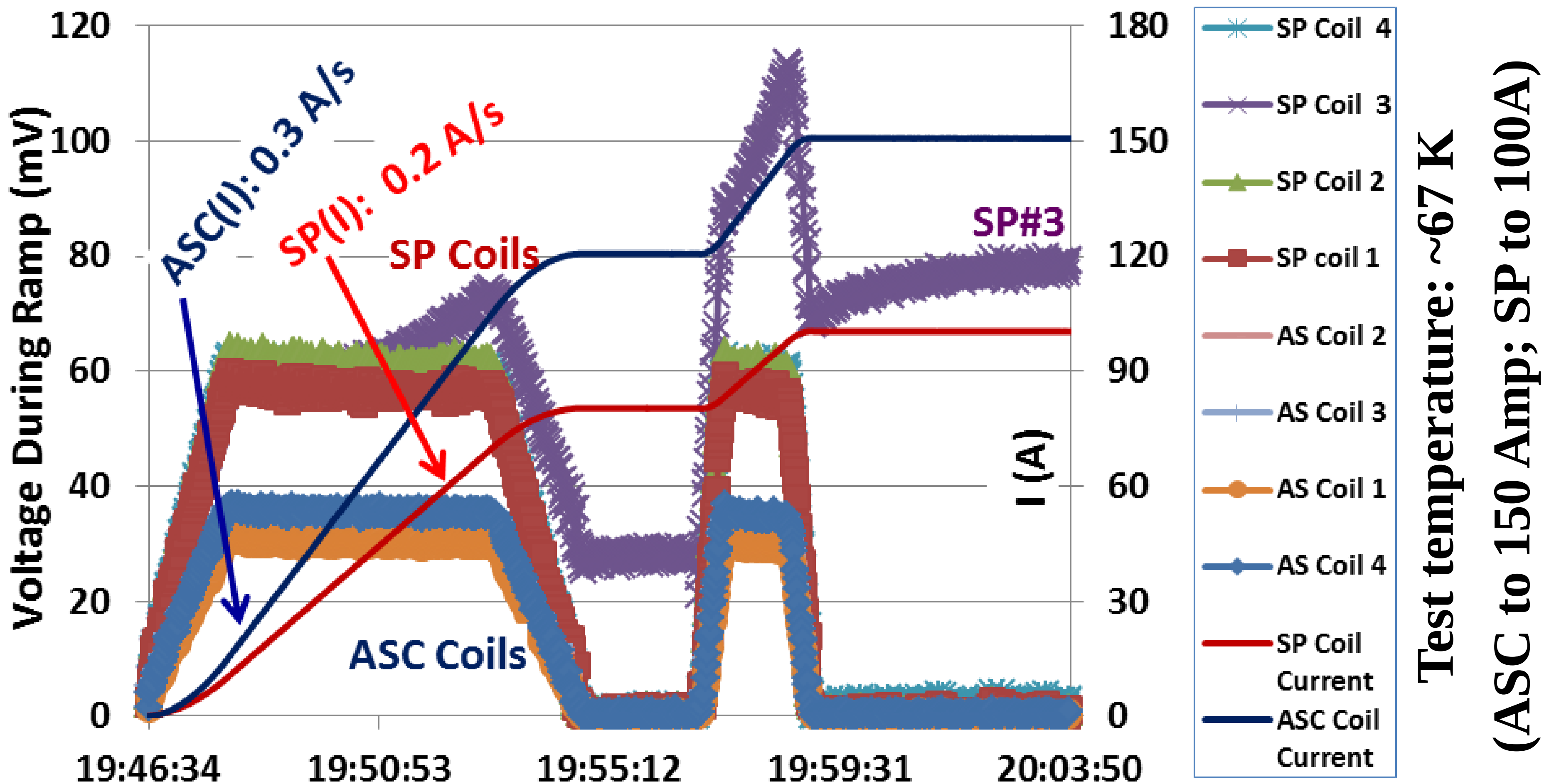
Protection of HTS Magnet During an Operational Accident Near Design Current



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



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.

Spinoff of FRIB HTS Magnet Technology

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http://science.energy.gov/np/highlights/2013/np-2013-08-a/

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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

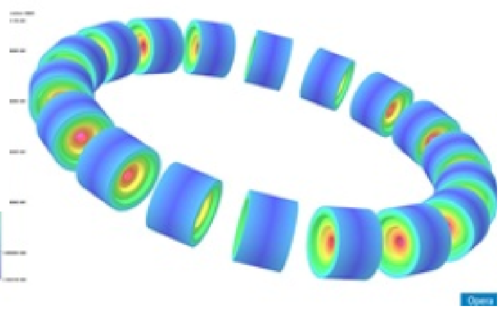


Image courtesy of Brookhaven National Laboratory

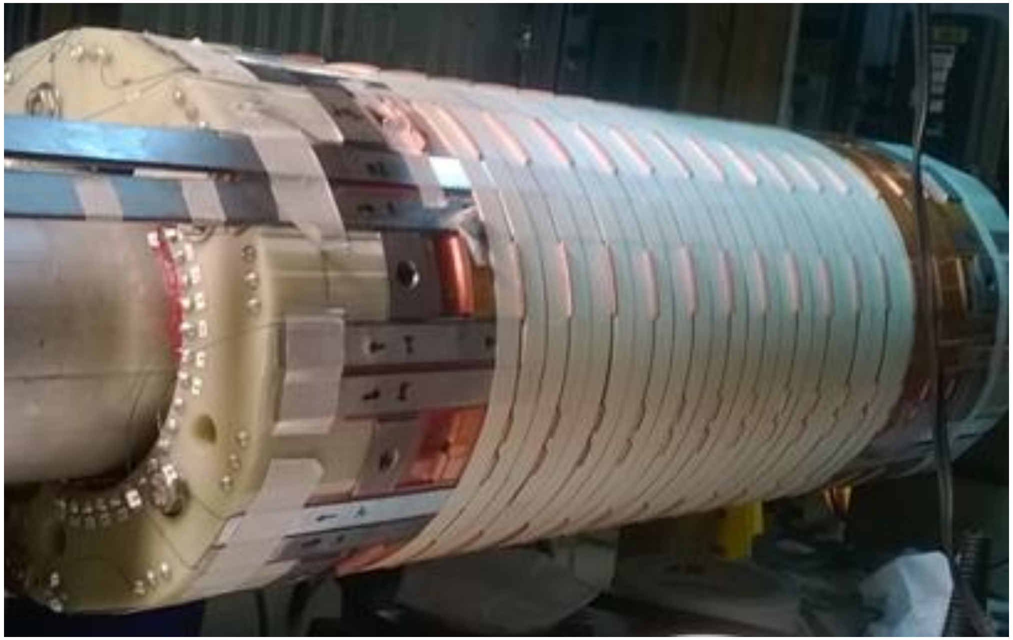
A toroid SMES system consisting of a number of high field coils made with the High Temperature

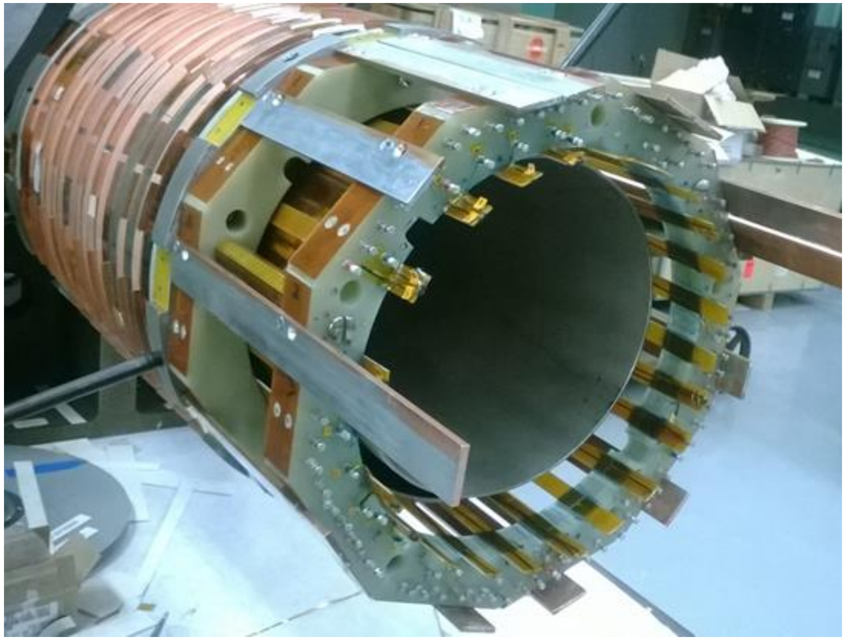
Nucle... Comm...

News

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

Inner and Outer Coils Assembled with Bypass Leads





Inner Coil

(102 mm id, 194 mm od)

28 pancakes

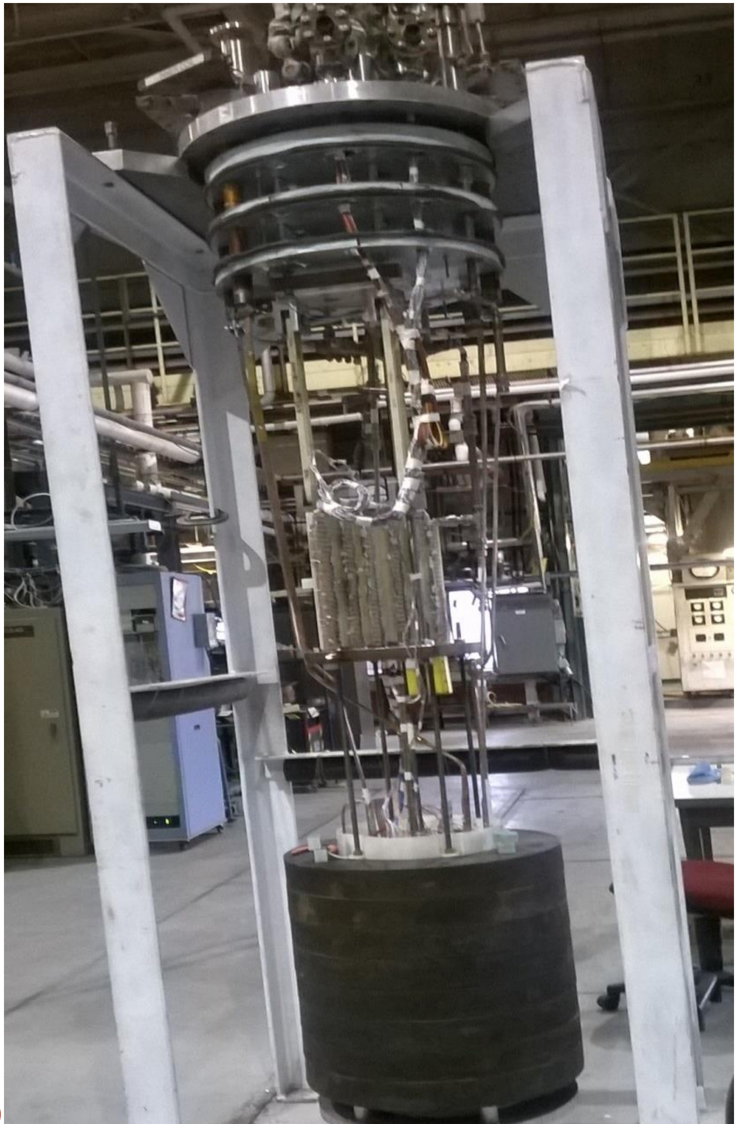
Outer Coil

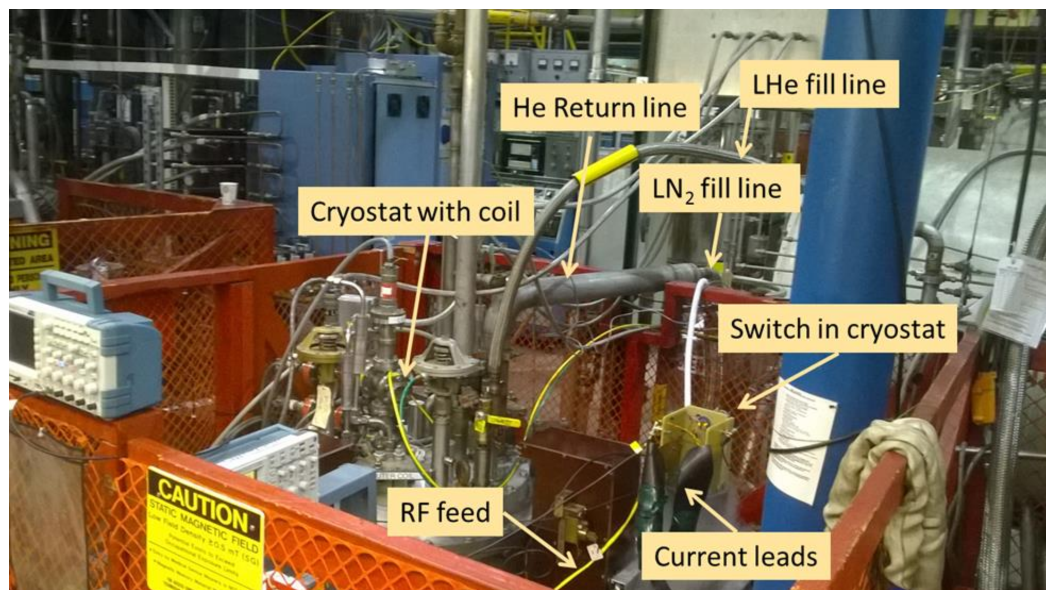
(223 mm id, 303 mm od)

18 pancakes

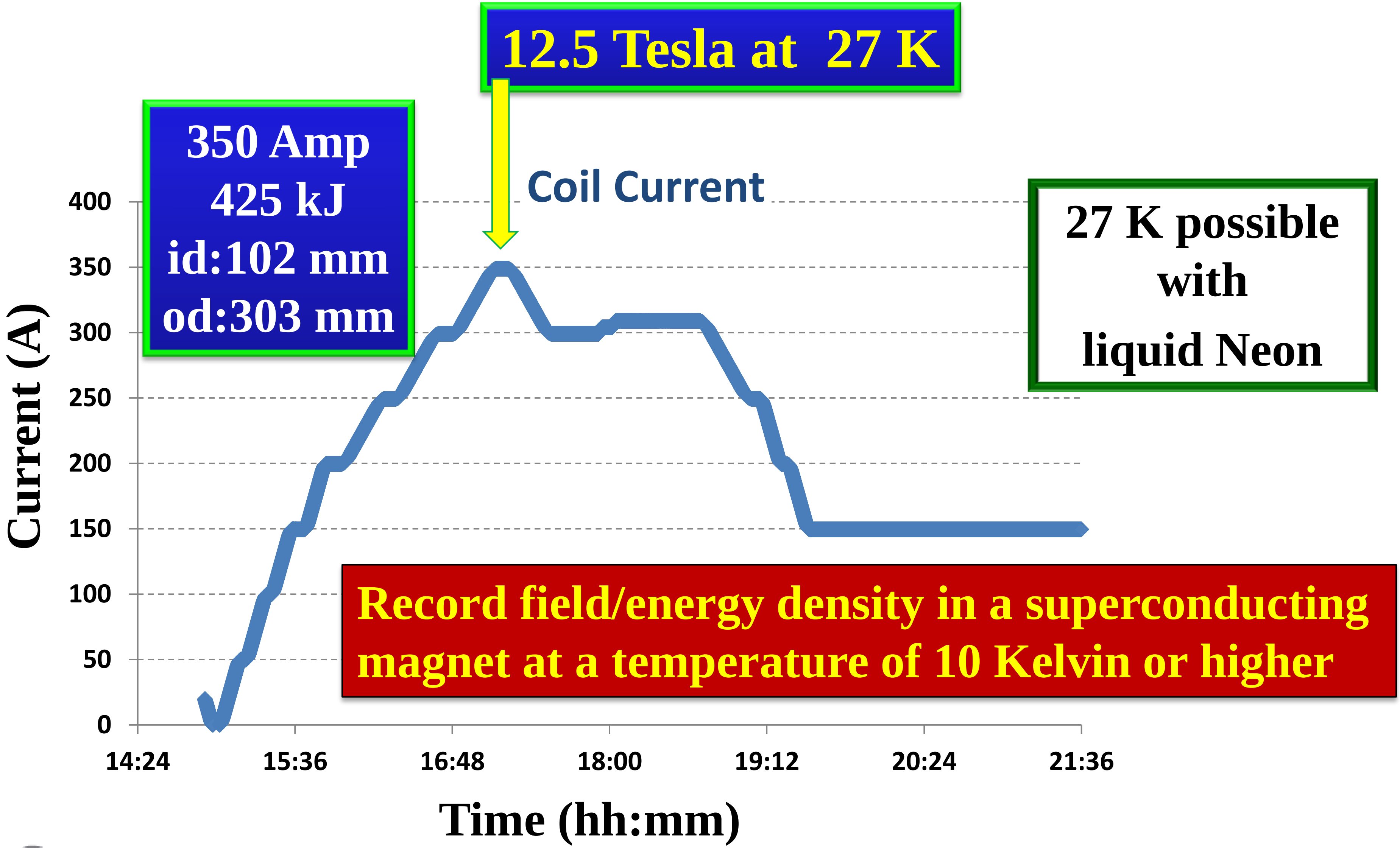
Total: 46 pancakes

Preparation for the Final Test





SMES Coil Test @50%
Critical Current Reached at 27 K



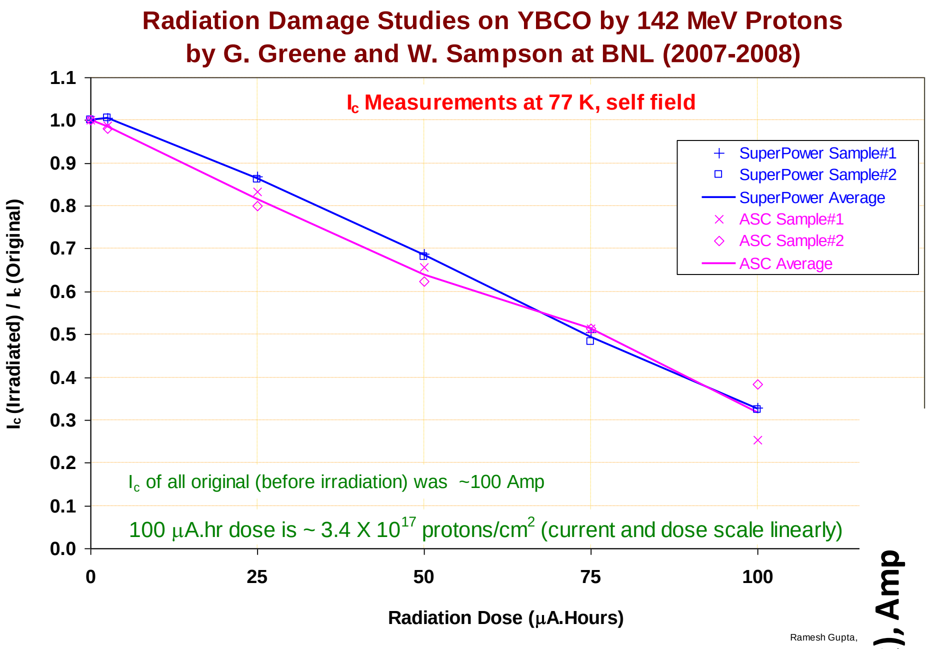
Summary

- A decade of R&D has developed medium field radiation tolerant HTS magnet technology to a level that it can now be considered for use in a real machine.
- HTS magnets could play a crucial role - a unique solution to large energy deposition and high radiation loads (extra slides).
- A variety of tests have shown that the technology (including quench protection) can withstand operational failure (vacuum leak) and can work 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.
- BNL is glad to collaborate with IBS – CAPP already, RISP next?

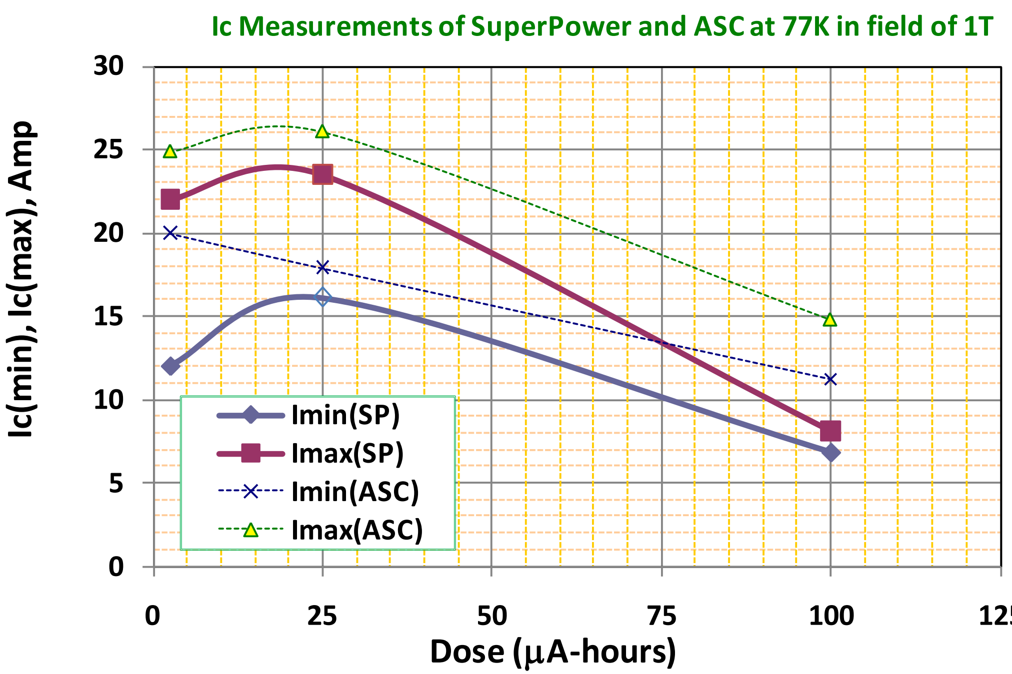
Extra Slides

Radiation Damage

Radiation Damage Measurements @BNL



More detail in the following slides



Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

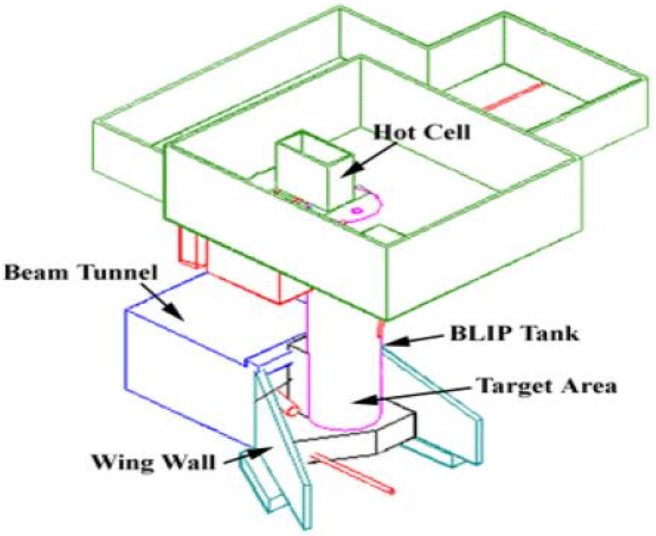
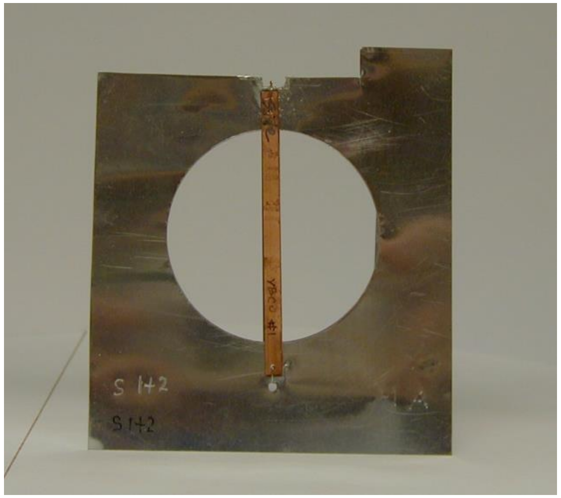


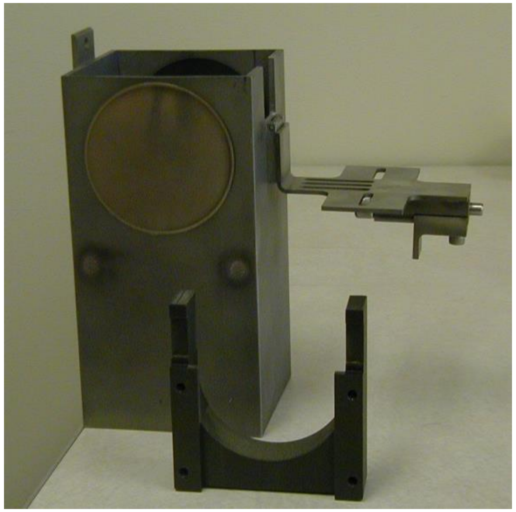
Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

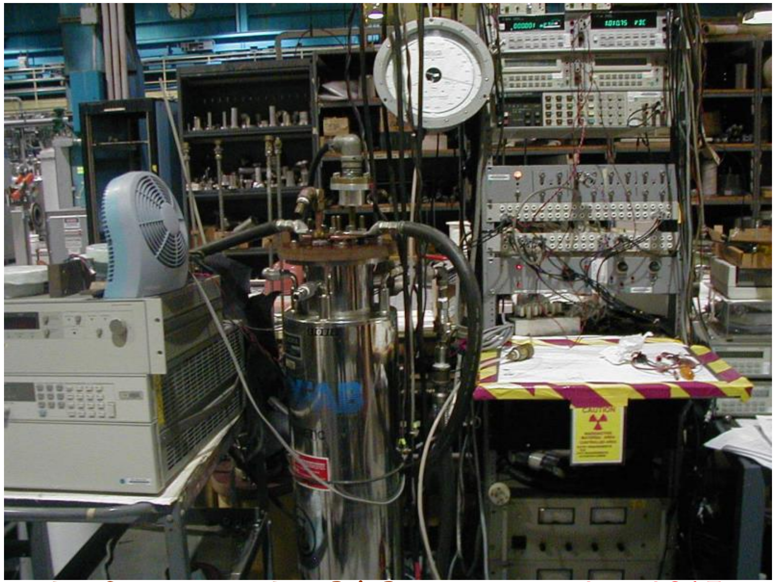
The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 μA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

Key Steps in Radiation Damage Experiment



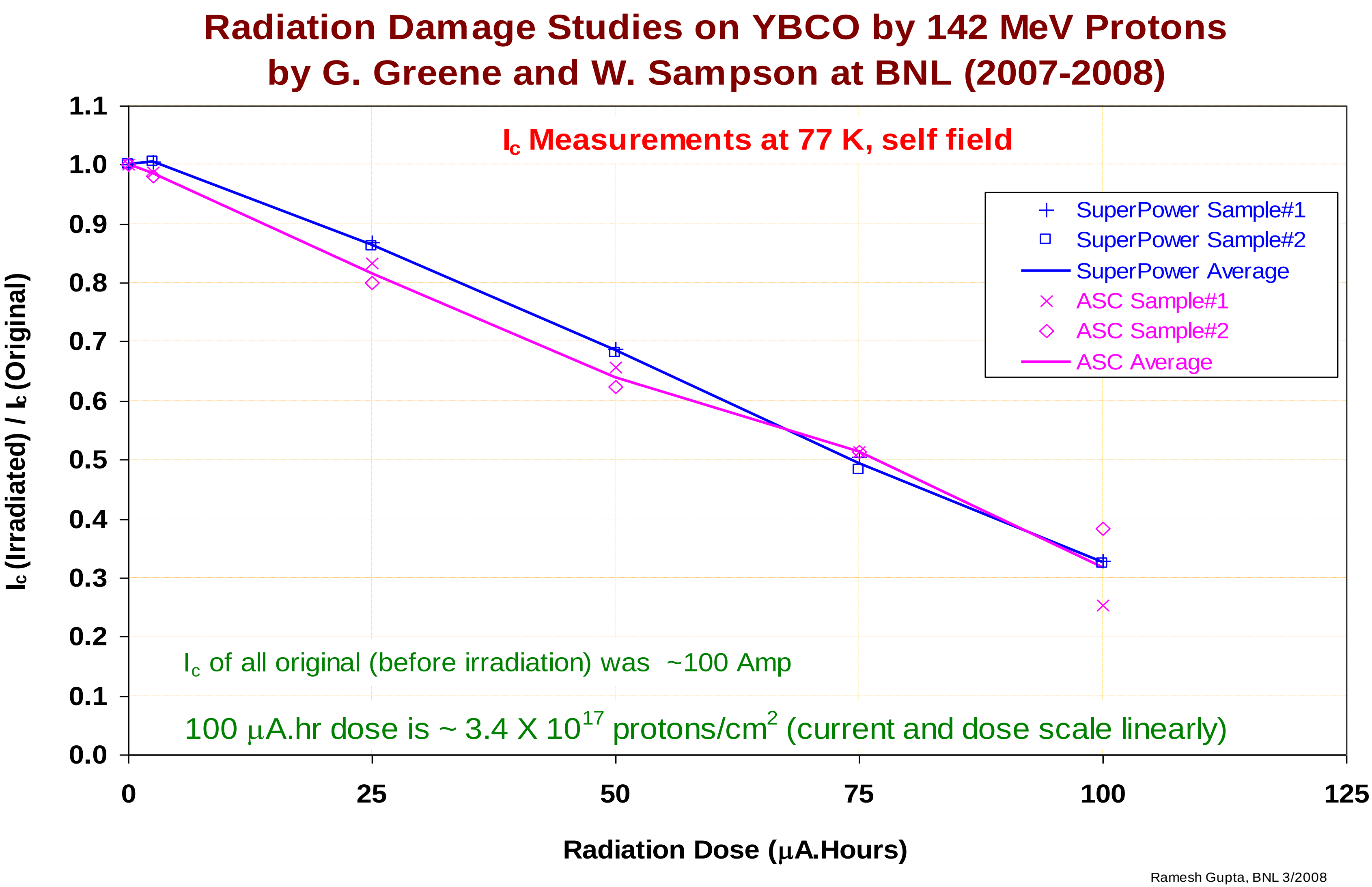


142 MeV,
100 μA protons



Relative Change in Ic due to Irradiation of SuperPower and ASC Samples

Superconducting Magnet Division



SuperPower and ASC samples show very similar radiation damage at 77 K, self field

Impact of Irradiation on 2G HTS

• The maximum radiation dose was 3.4 X 10^{17} protons/sec (100 μA.hr) with an energy of 142 MeV. Displacement per atom (dpa) per proton is ~9.6 X 10^{-20}. (Al Zeller)

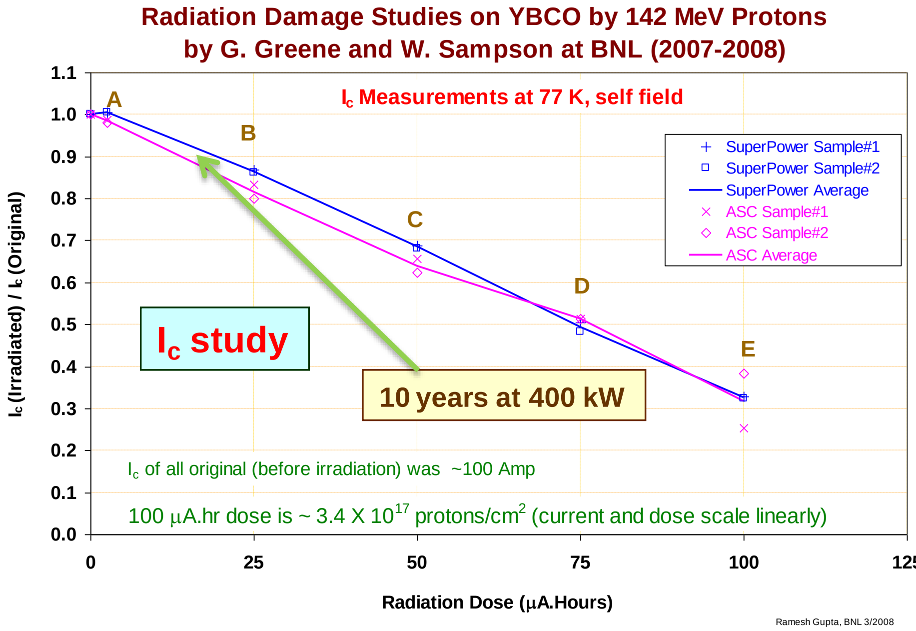
• **This gives ~0.033 dpa at 100 μA.hr for the maximum dose.**

Based on 77 K self field studies:

• **Reduction in I_c performance of YBCO (from both vendors) is <10% after 10 years of FRIB operation (as per Al Zeller, MSU).**

• **This is pretty acceptable.**

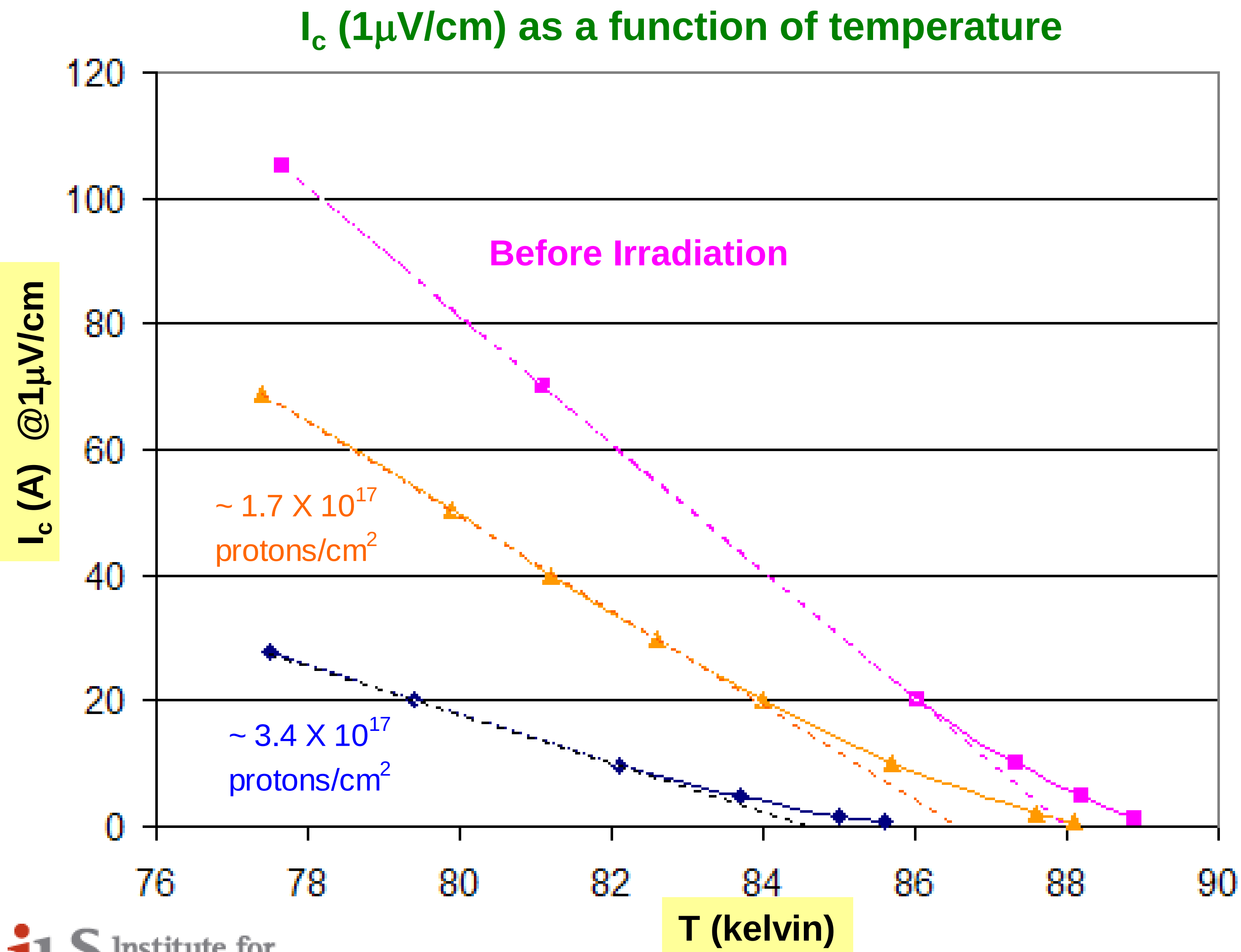
• **Drop in I_c at maximum dose (of theoretical interest) is ~70%.**



It appears that YBCO is at least as much radiation tolerant as Nb_3Sn is (Al Zeller, MSU).

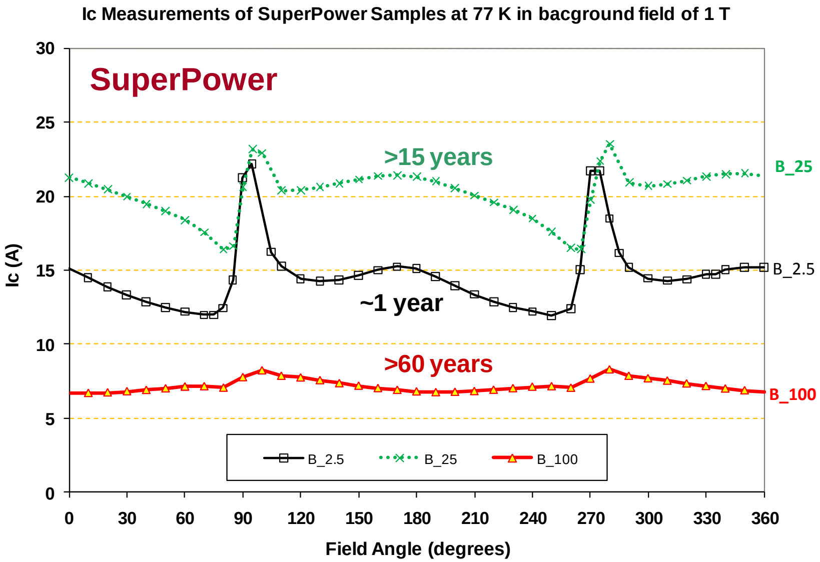
SuperPower and ASC samples show very similar radiation damage at 77 K, self field

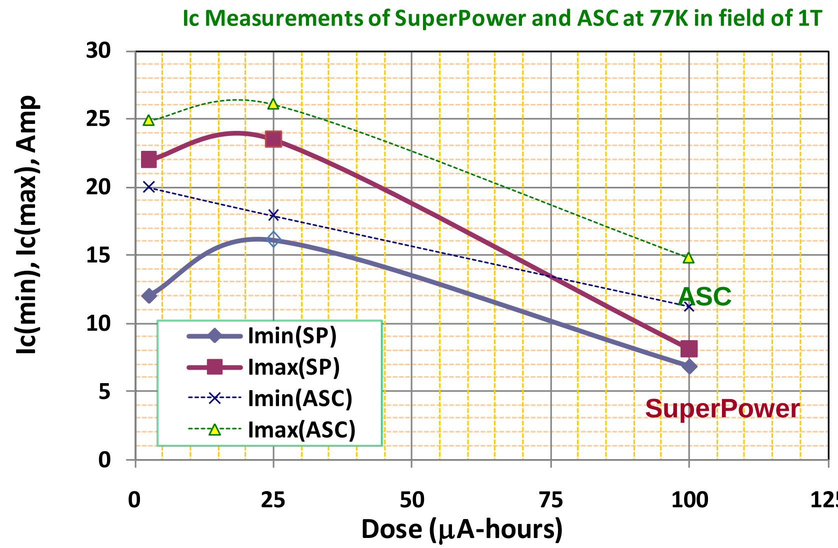
Change in Critical Temperature (T_c) of YBCO Due to Large Irradiation



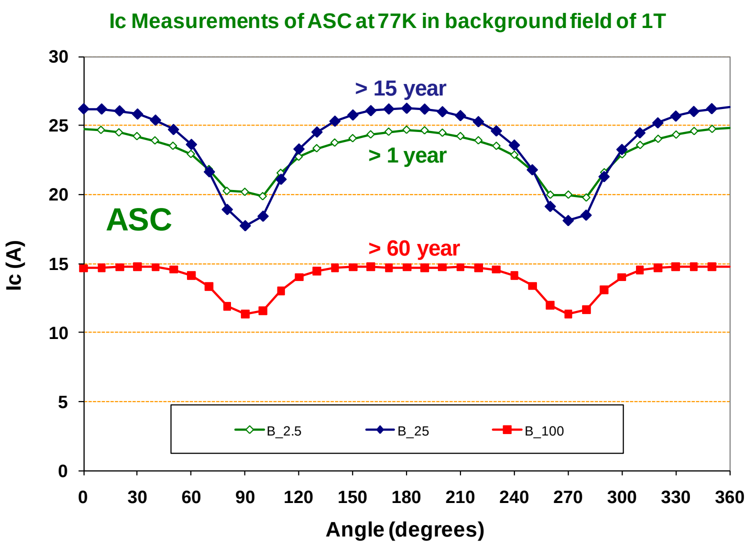
- Radiation has an impact on the T_c of YBCO, in addition to that on the I_c.
- However, the change in Tc is only a few degrees, even at very high doses.

Radiation Damage from 142 MeV protons in SP & ASC Samples (measurements at @77K in 1 T Applied Field)





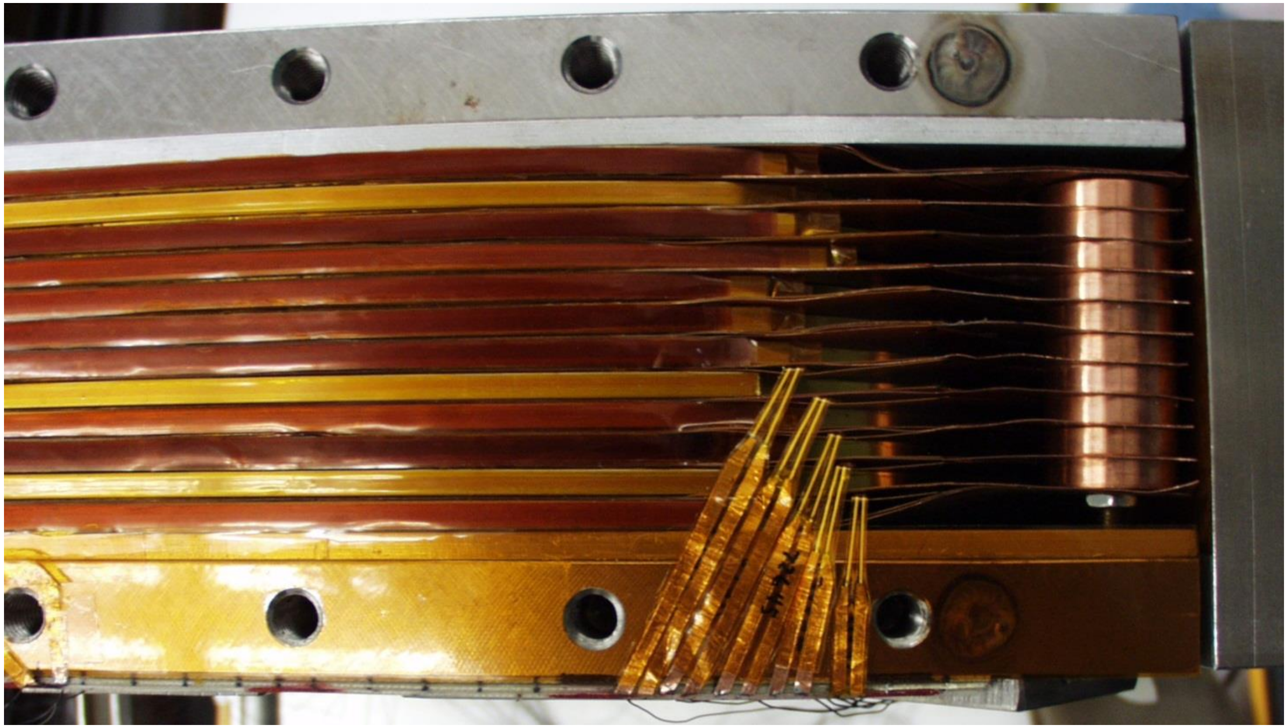
Minimum and maximum values of I_c are obtained from the graphs on the right



- While the SuperPower and ASC samples showed a similar radiation damage pattern in the absence of field, there is a significant difference in the presence of field (particularly with respect to the field angle).
- HTS from both vendors, however, show enhancement to limited damage during the first 10 years of FRIB operation (good news)!!!

Energy Deposition

Energy Deposition Experiments

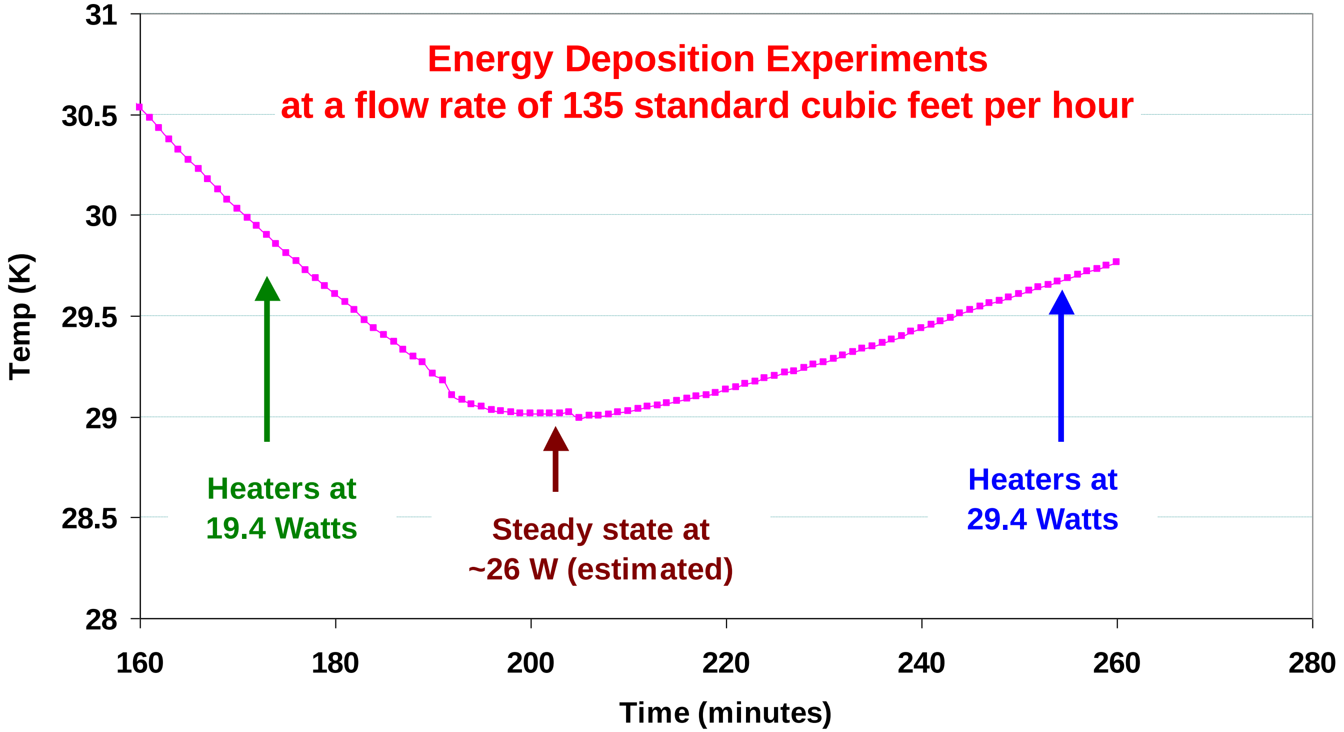


Stainless steel tape heaters for energy deposition experiments

- Energy deposition experiments were carried out at different operating temperature.
- The amount of energy deposited on the HTS coils is controlled by the current in heaters placed between the two coils.

Energy Deposition Experiment During Cool-down at a Constant Helium Flow-rate

Heaters between HTS coils were turned on while the magnet was cooling with a helium flow rate of 135 standard cubic feet (SCF)



Temperature decreased at 19.4 W

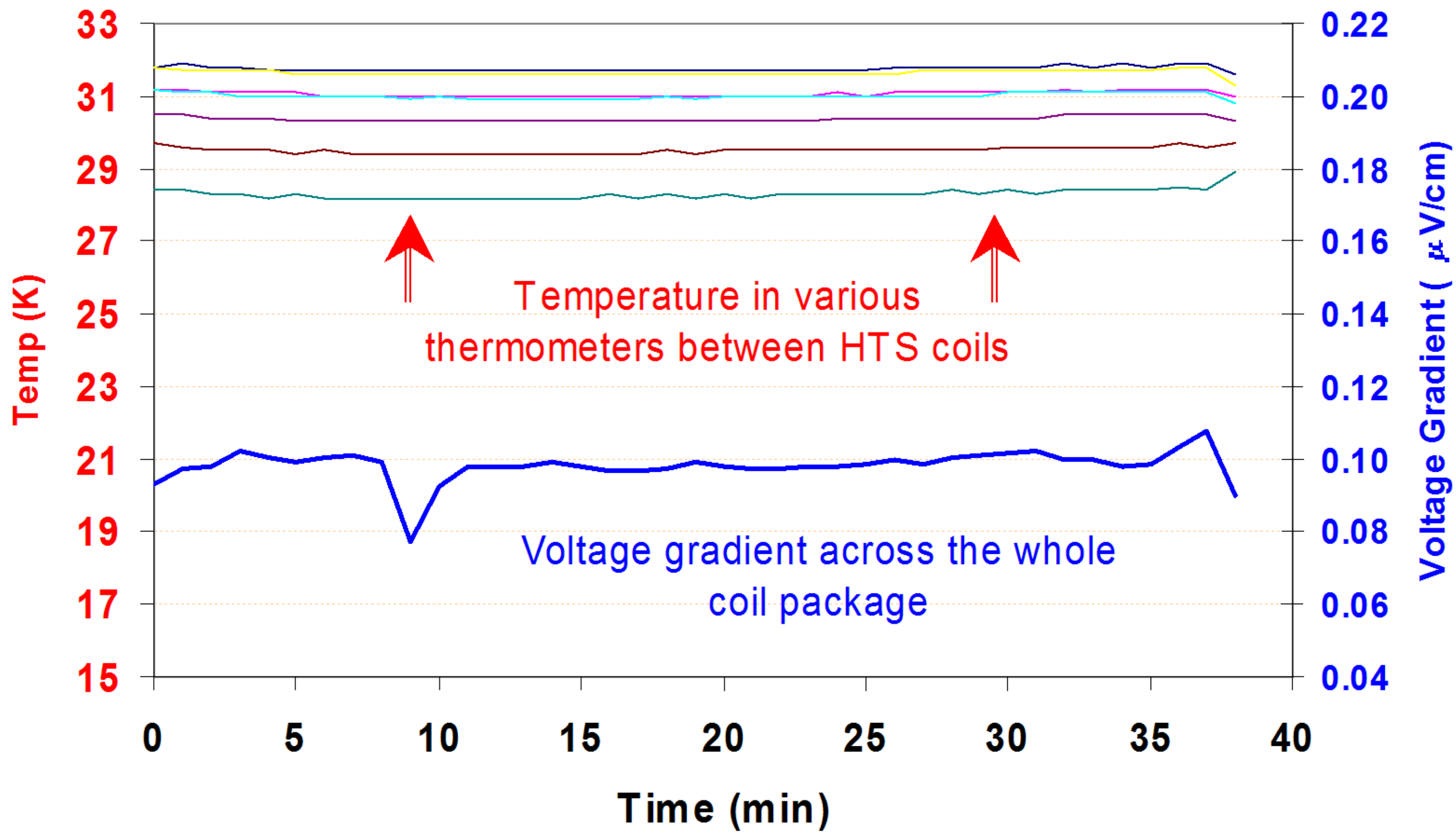
Temperature increased at 29.4 W

Heat load for steady state ~26 Watts

Note: HTS coil remained superconducting during these tests when operated somewhat below the critical surface.

Large Energy Deposition Experiment

Magnet operated in a stable fashion with large heat loads (25 W, 5kW/m^3) at the design temperature (~30 K) at 140 A (design current is 125 A).

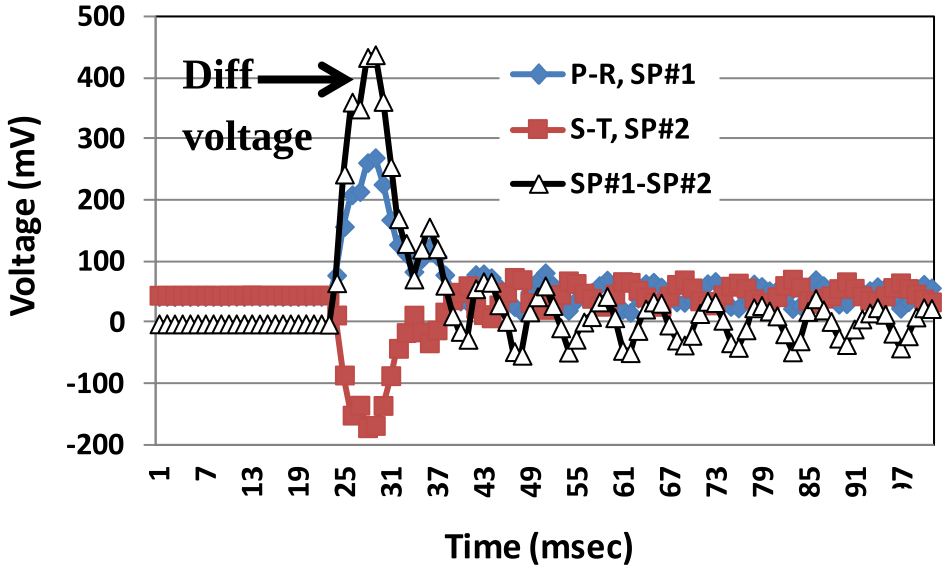


Stable operation for ~40 minutes

Voltage spikes are related to the noise

Quench Protection

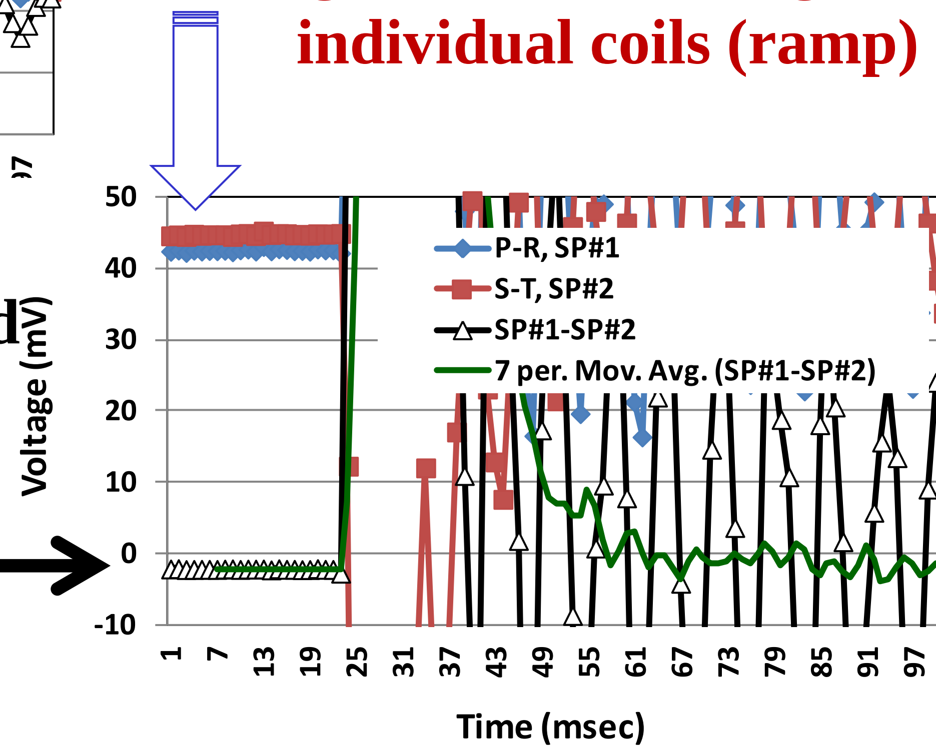
Snap Shot of the Event (Quench?) that Triggered the Shut-off



Fast data logger:
One point/msec

Large inductive voltage in individual coils (ramp)

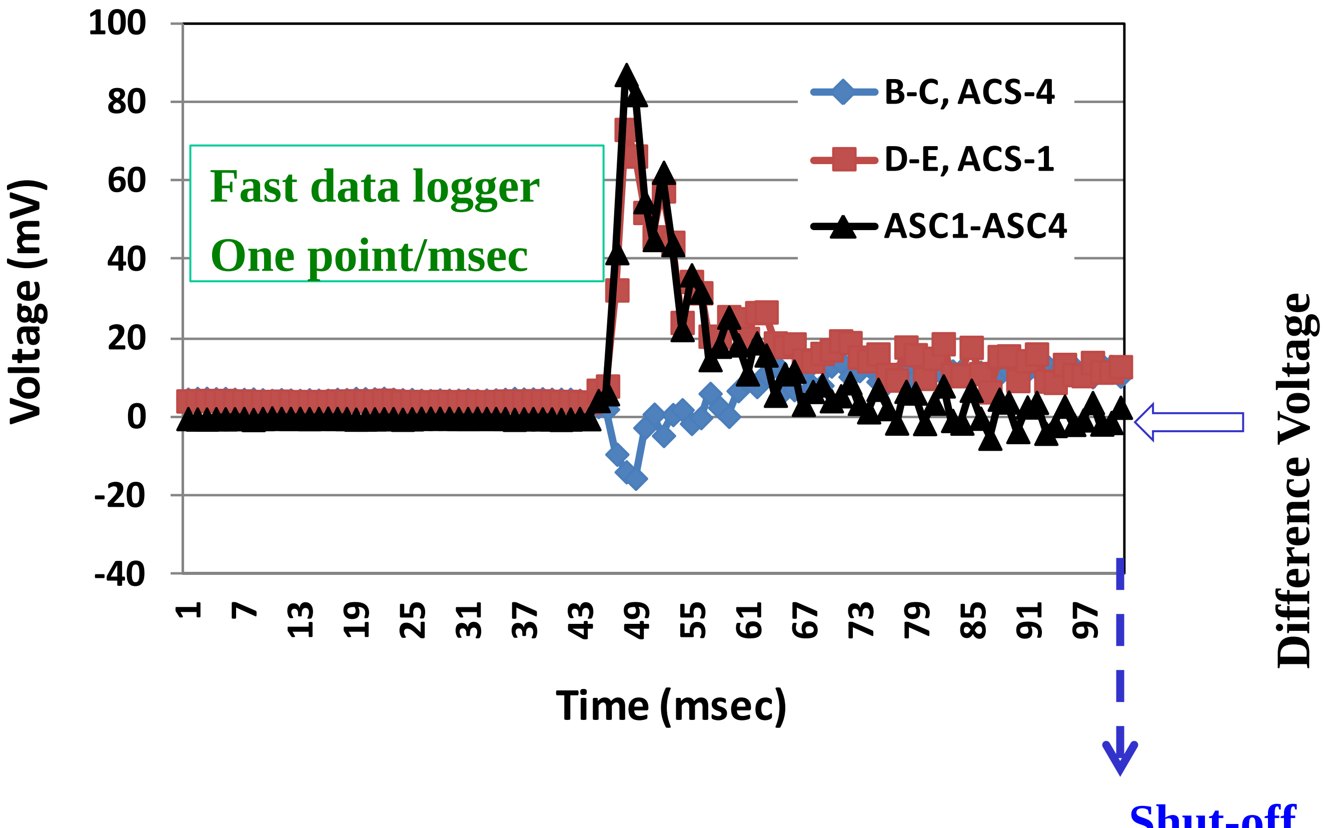
Small quench detection threshold (2 mV) kept during the ramp by monitoring difference voltage



No degradation in coil performance after the event

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