Design, Construction and Test of the HTS Quad for FRIB

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THE NEXT CENTURY OF SUPERCONDUCTIVITY

FACILITY FOR RARE ISOTOPE BEAMS

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Outline

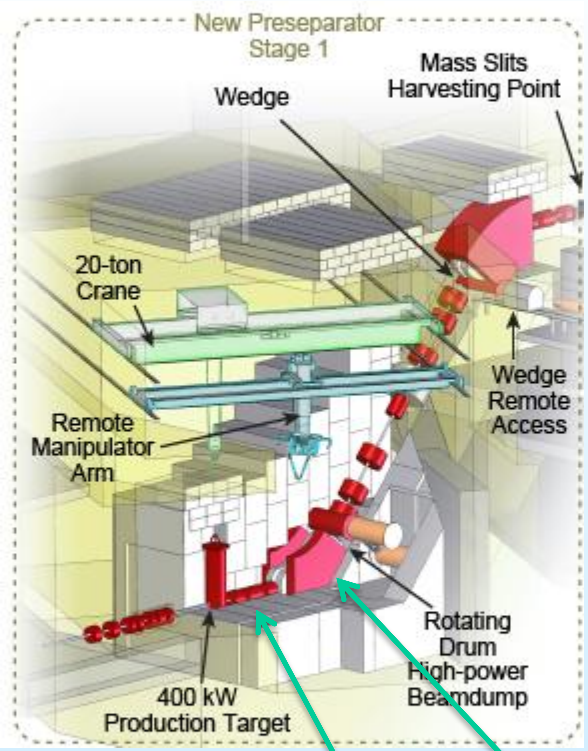
- **Motivation for HTS magnets in FRIB**
  - HTS is now the baseline design for some critical magnets
- **First Generation Design**
  - 30 K operation
- **Second Generation Design**
  - 50 K operation and higher gradient
- **Summary and future outlook**

FRIB

- Facility for Rare Isotope Beams (FRIB) will create rare isotopes for research in intensities not available anywhere today.
- It will be located at MSU in Michigan, USA
- To create intense rare isotopes, 400 kW beam hits the production target.
- Quadrupoles in Fragment Separator will be exposed to unprecedented level of radiation and heat loads
- BNL Magnet Division has designed, developed, built and tested High Temperature Superconducting (HTS) quadrupole for FRIB that provides a unique solution for these magnets

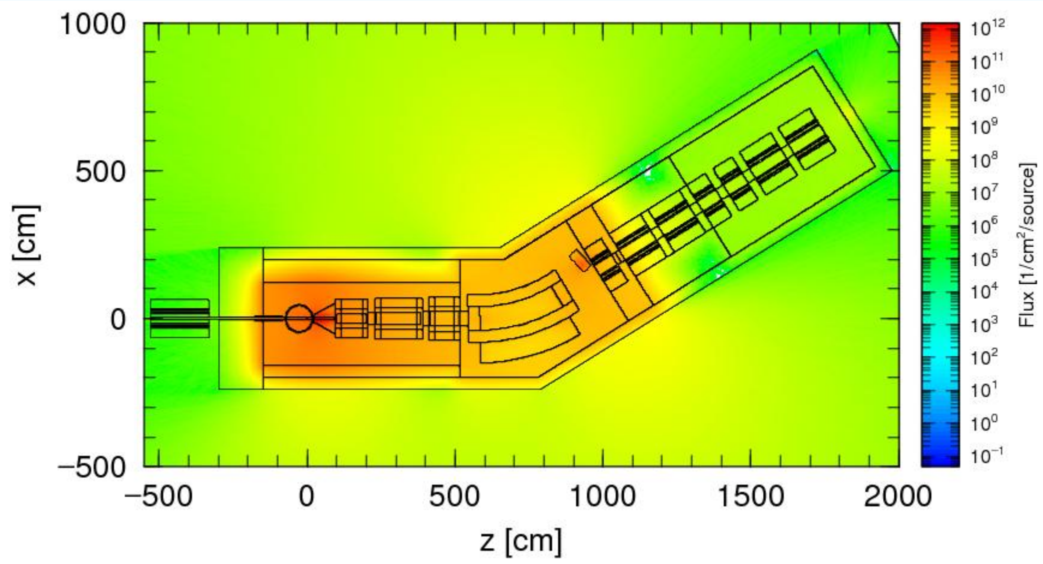
Large Radiation and Heat Loads

Magnets in FRIB Fragment Separator Region



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

Copper or NbTi Magnets don’t satisfy the requirements

Benefits of HTS Magnets

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

Technical Benefits:

➢ HTS provides large temperature margin – HTS can tolerate a large local and global increase in temperature, so are resistant to beam-induced heating

Economic Benefits:

➢ Removing large heat loads at higher temperature (40-50 K) rather than at ~4 K 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.

HTS Quad is now the baseline design in the fragment separator of FRIB

First Generation Design

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

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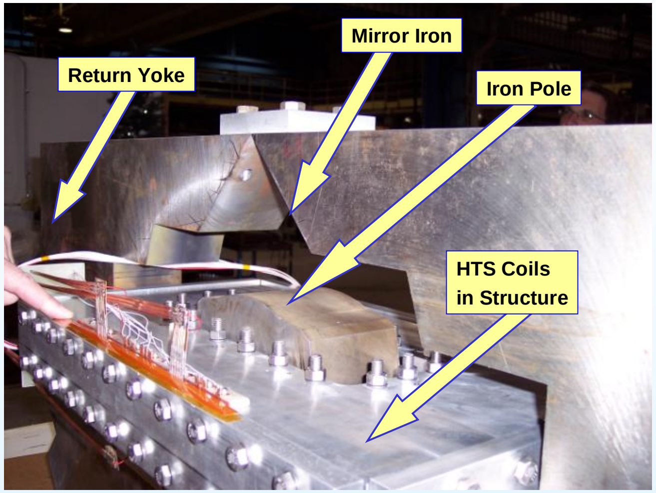
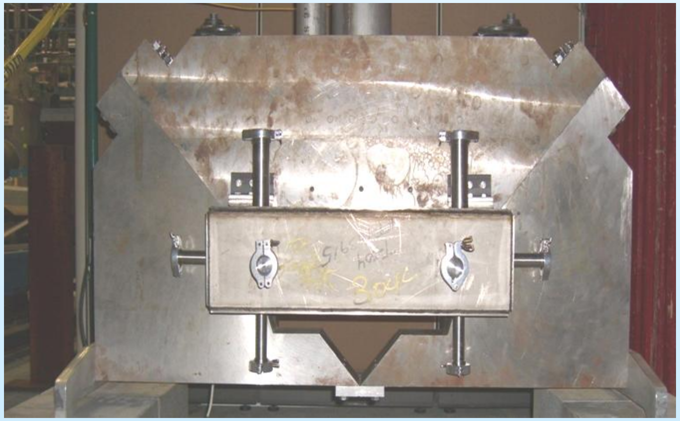
HTS Quad Structures

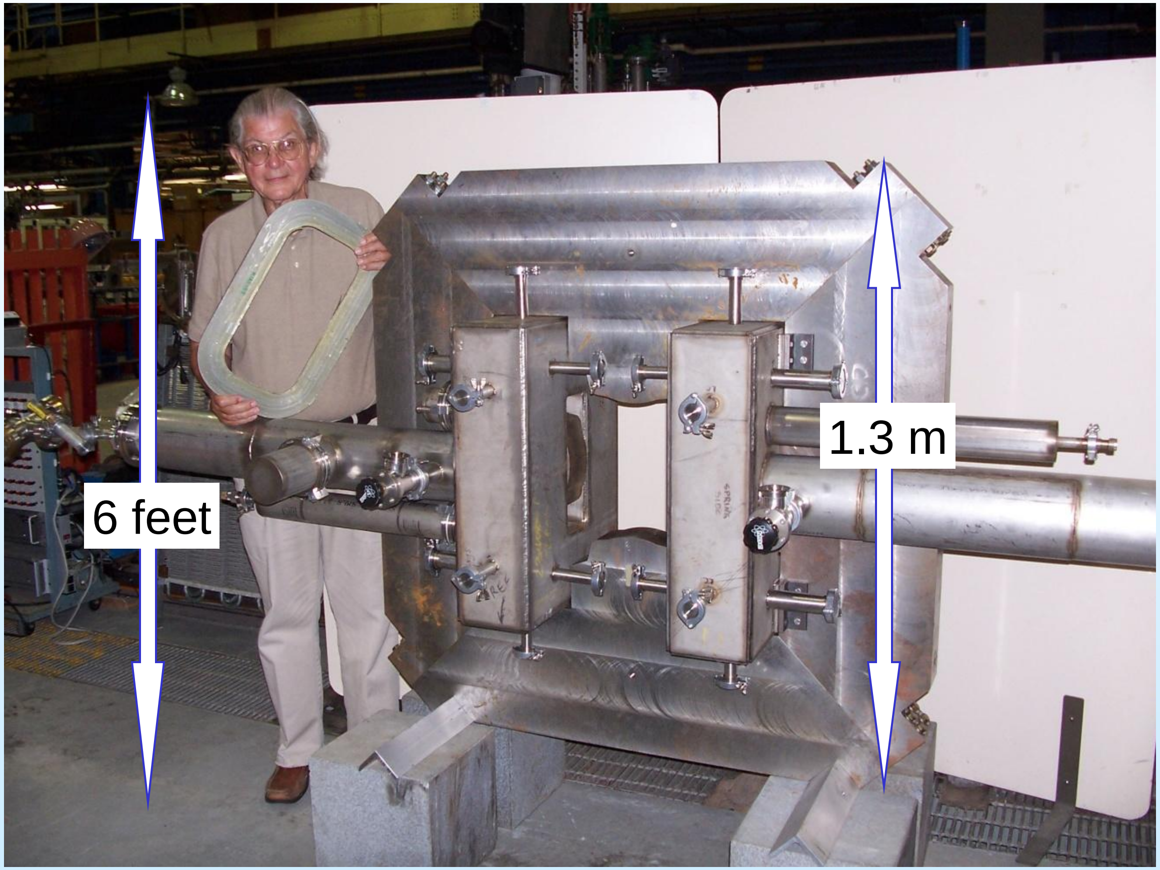


Mirror cold iron

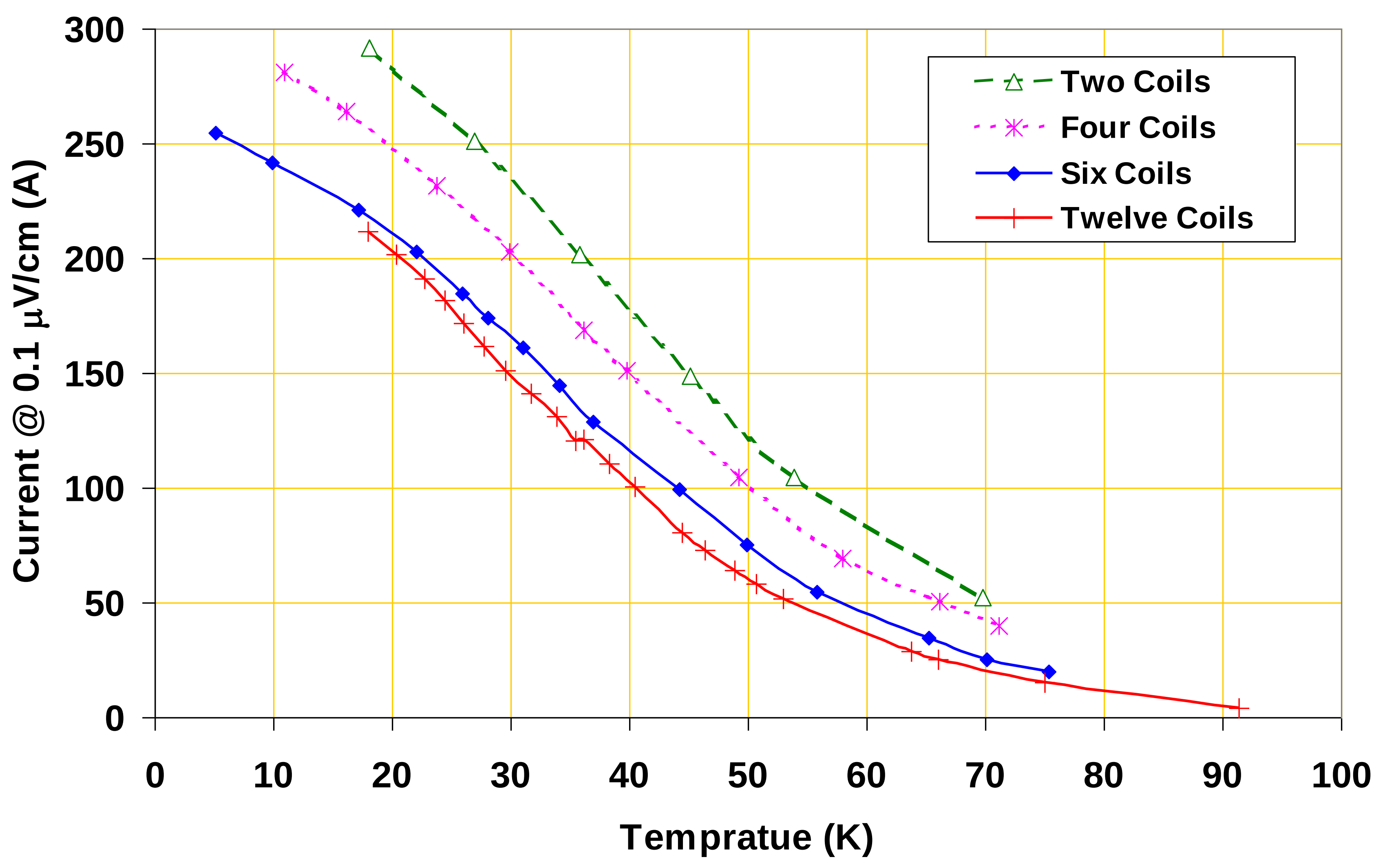


Mirror warm iron

Warm Iron Design to Reduce Heat Load

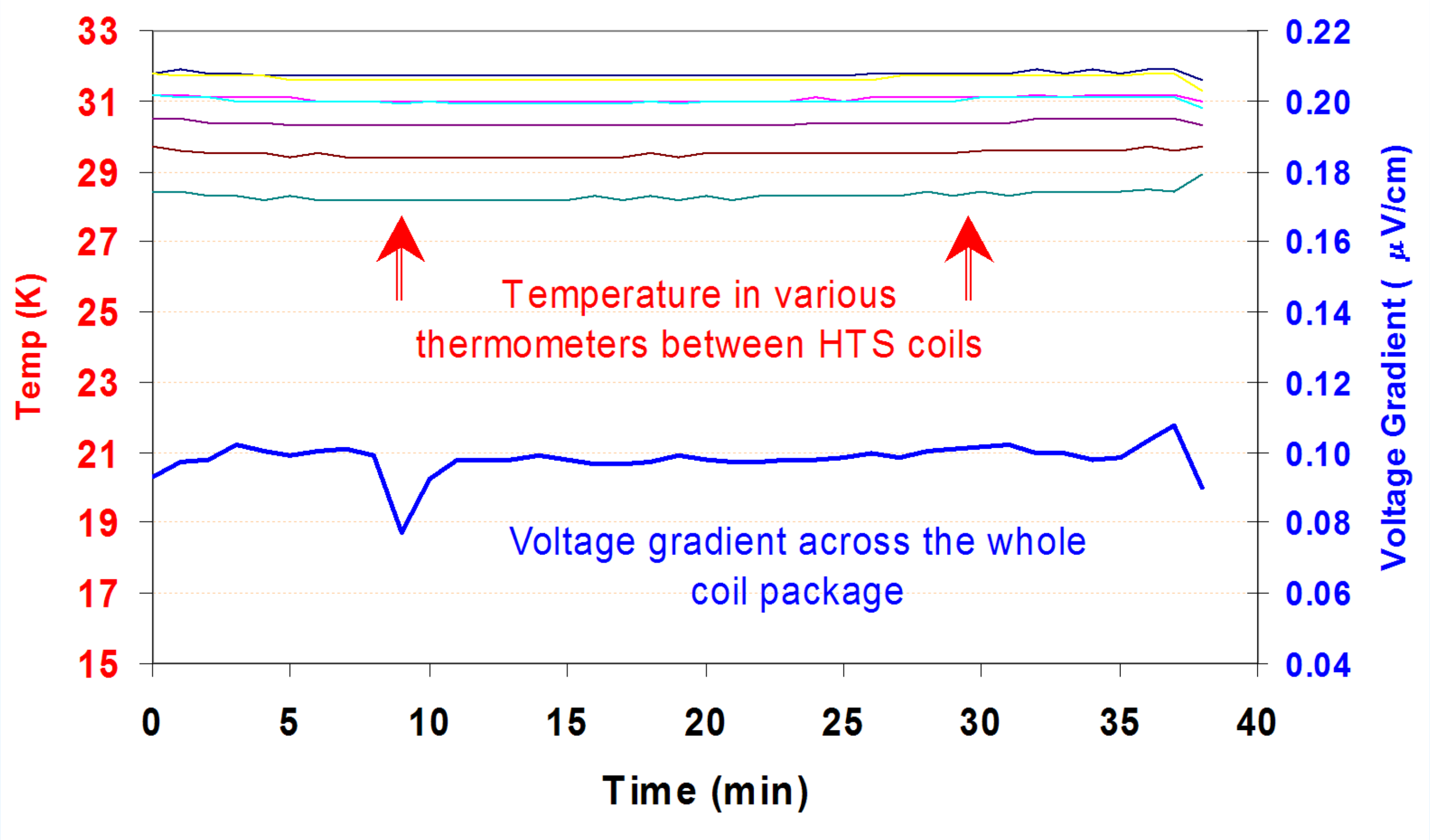


First Generation HTS Quad Test
(operation over a large temperature range)



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

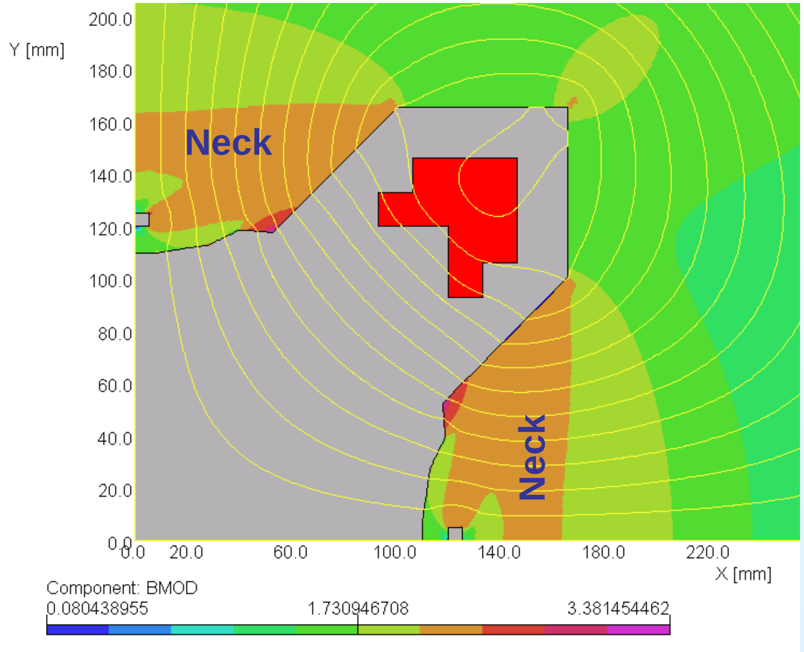
Second Generation Design

- 20 K higher operating temp (50 K instead of 30 K) and 50% higher gradient (15 T/m instead of 10 T/m)

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

  - ~9 km equivalent of 4 mm tape

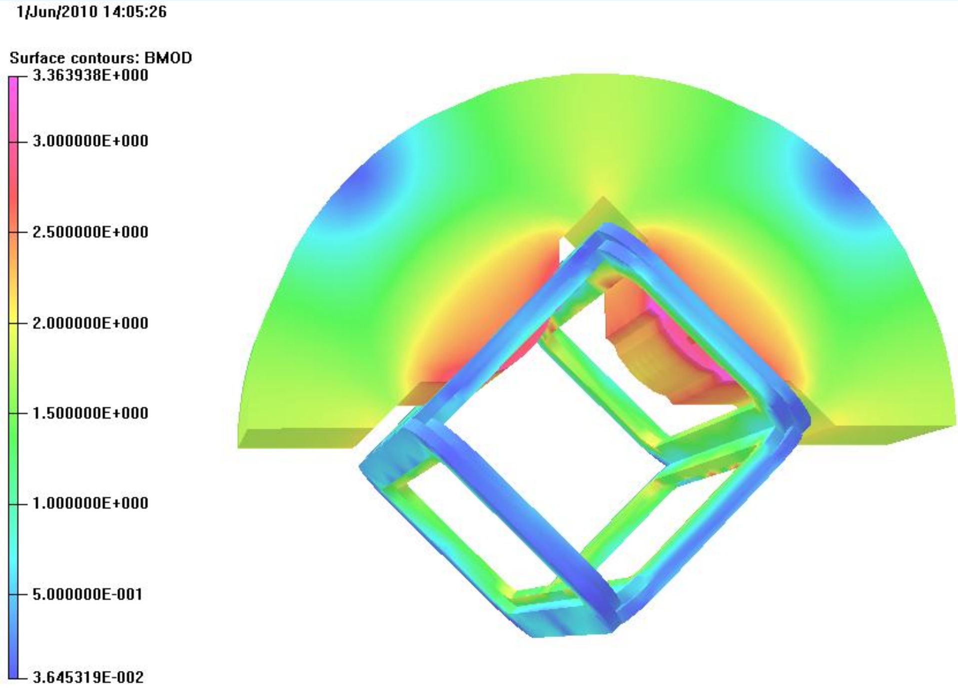
Magnetic Design



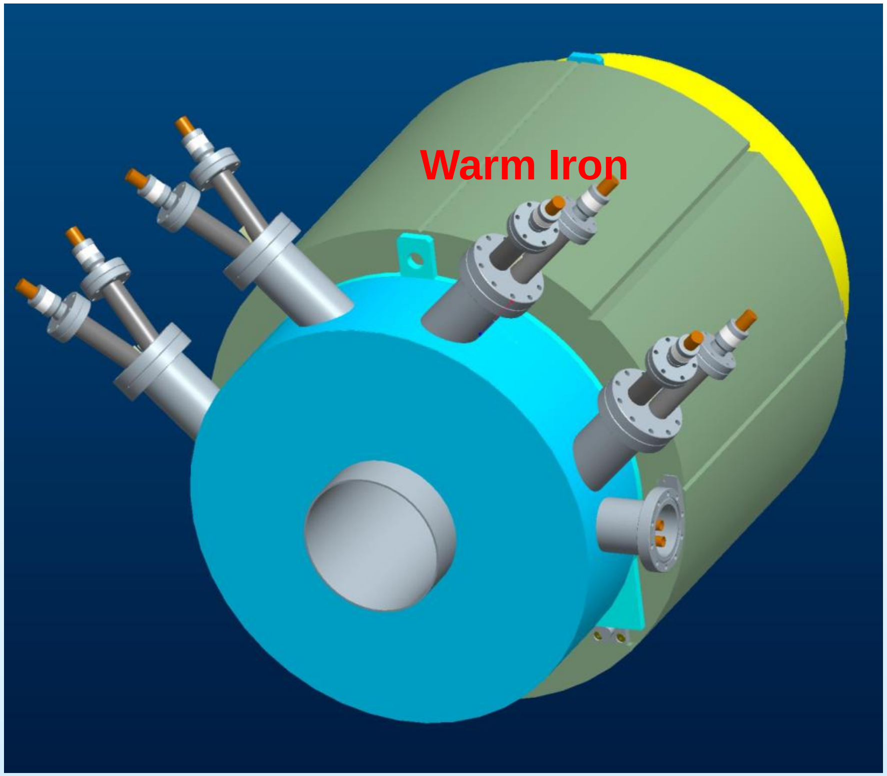
Uses 12 mm tape rather than 4 mm tape

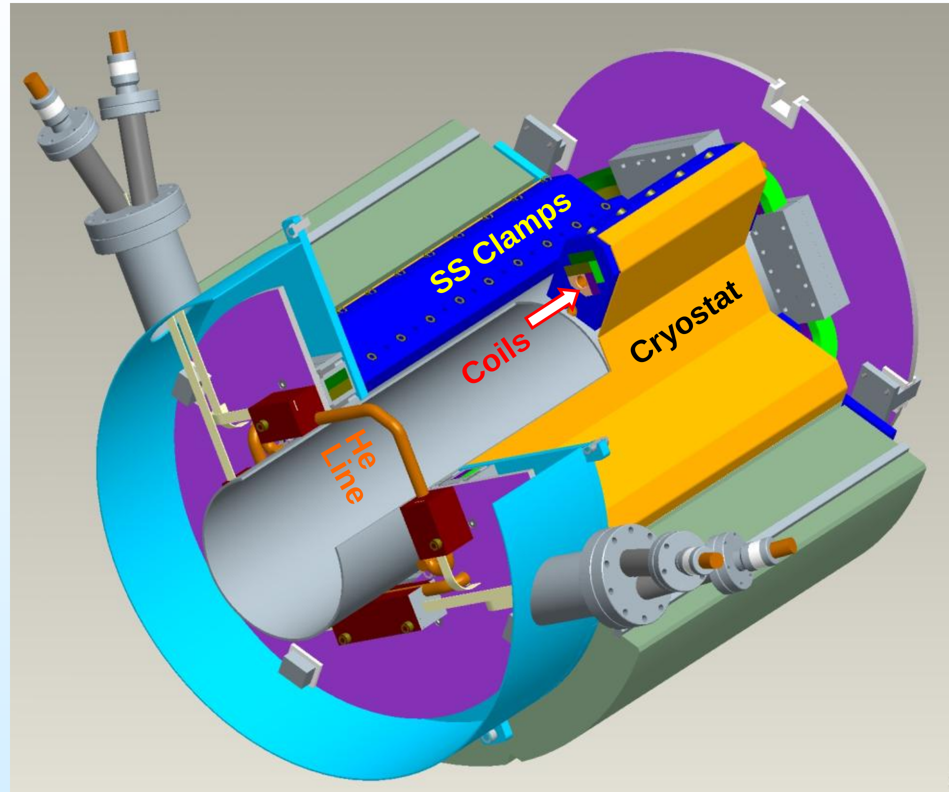
Benefits of 12 mm Tape:

- Minimizes the number of coils and joints
- Current is higher (inductance is lower)
- Relative impact of local weak micro-spot less



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 design allowed larger space for coils and reduction in pole radius)

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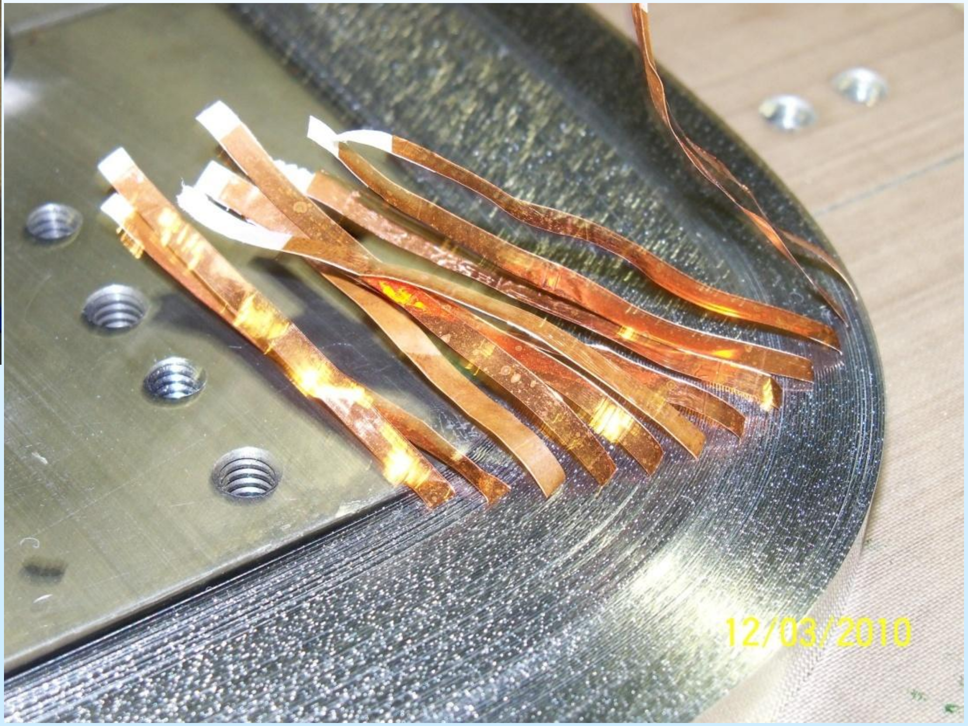
Winding of Second Generation HTS Racetrack Coil for FRIB

Coils Made with ASC HTS

~210 m (~125 turns), 12 mm double HTS tape per coil.



One coil was wound without any splice

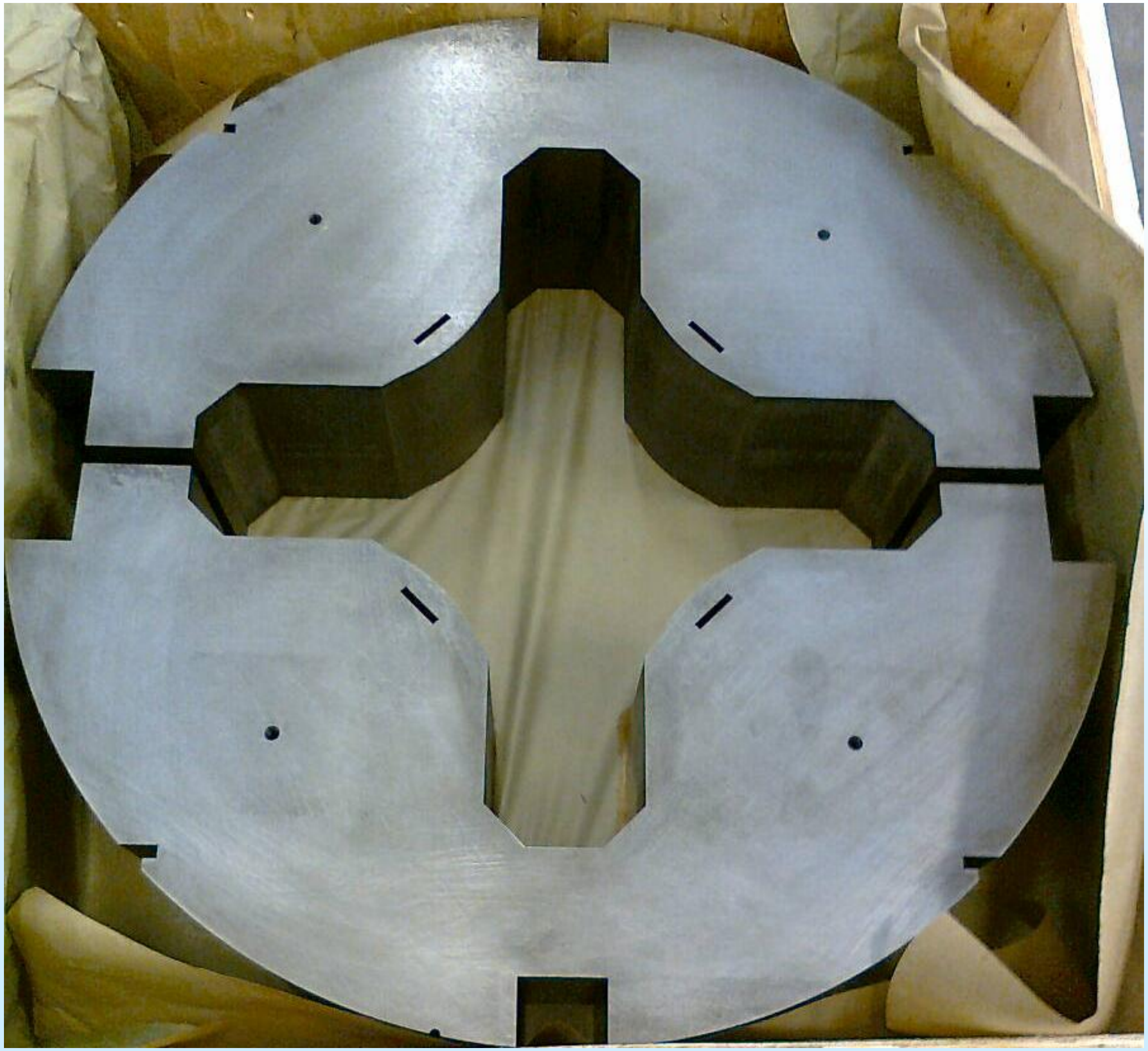
FRIB Coil Made With SuperPower Tape

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

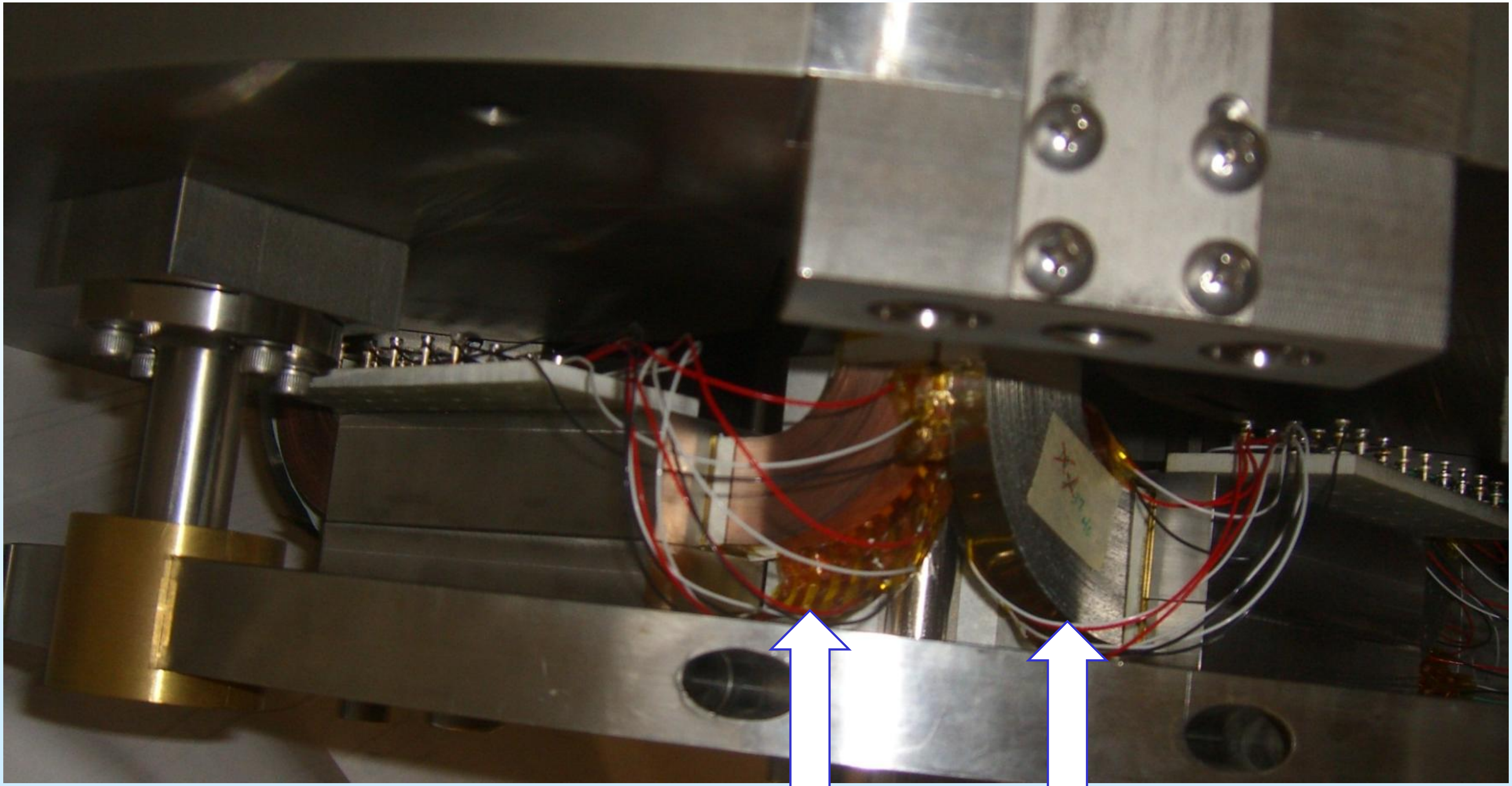
Fully wound coil with SuperPower tape with one splice

Coils Assembled in Quadrupole Support Structure

Yoke Iron for FRIB Quad



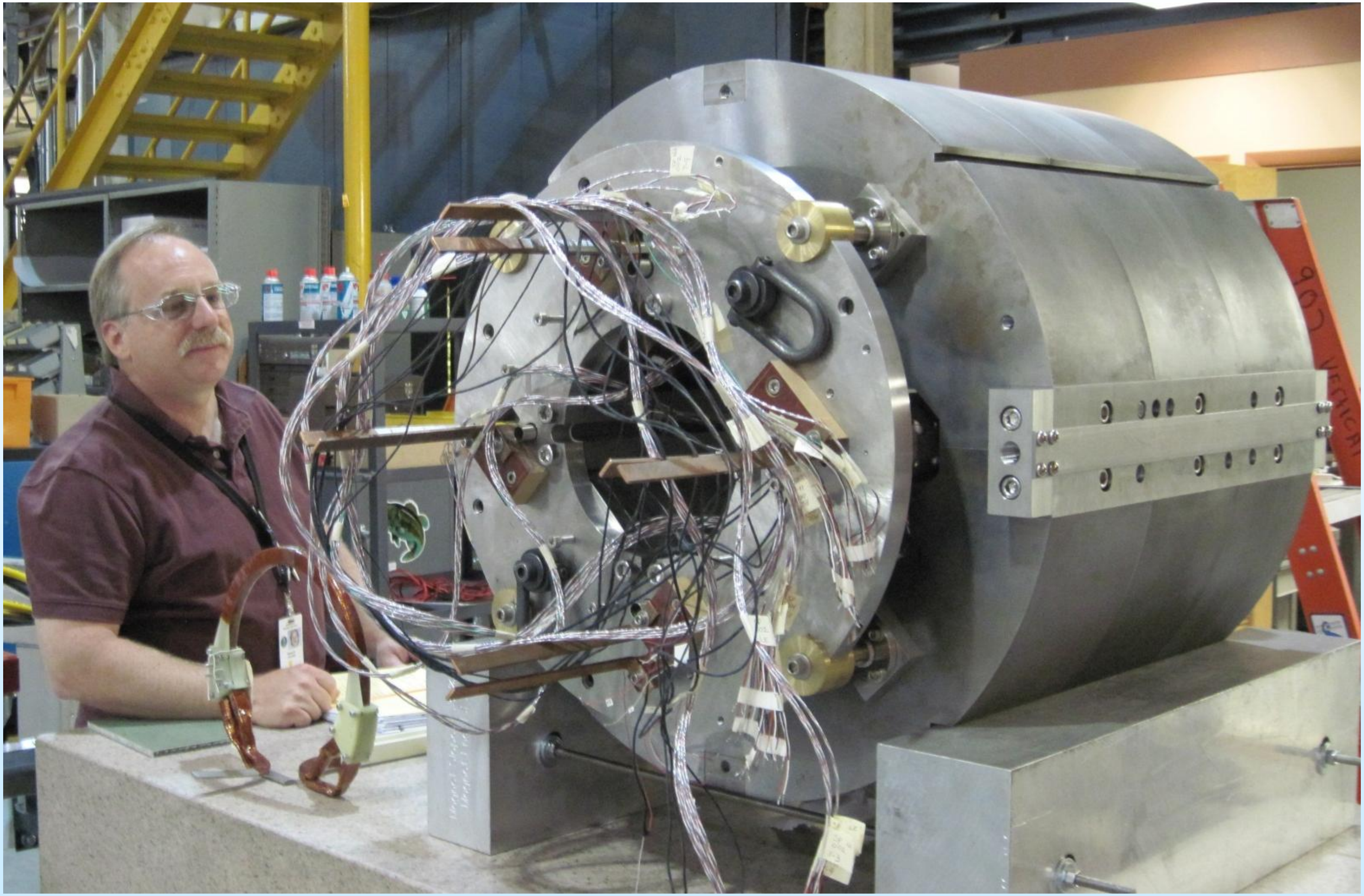
Coils Made with HTS from 2 Vendors (SuperPower and ASC)



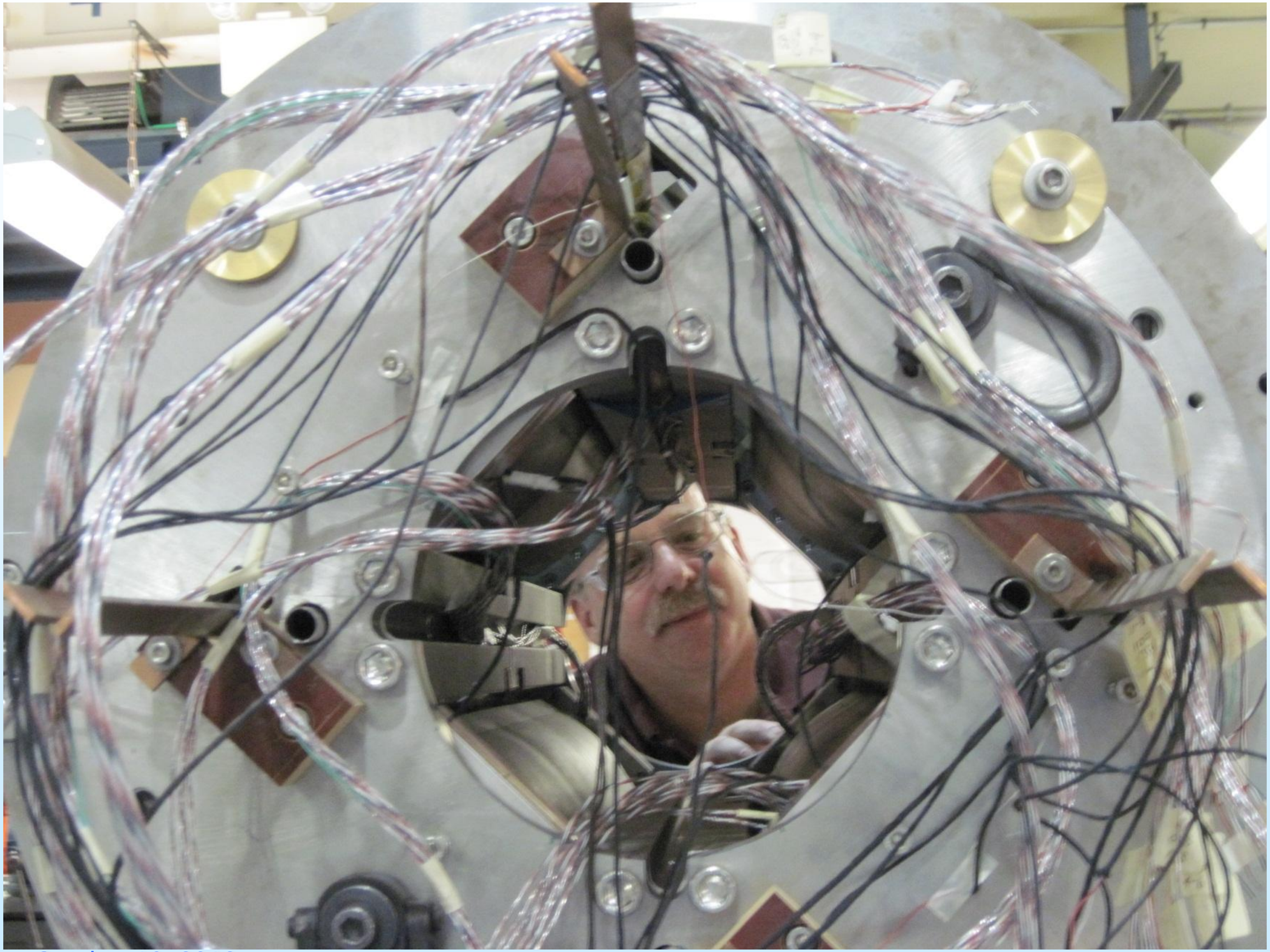
SuperPower

ASC

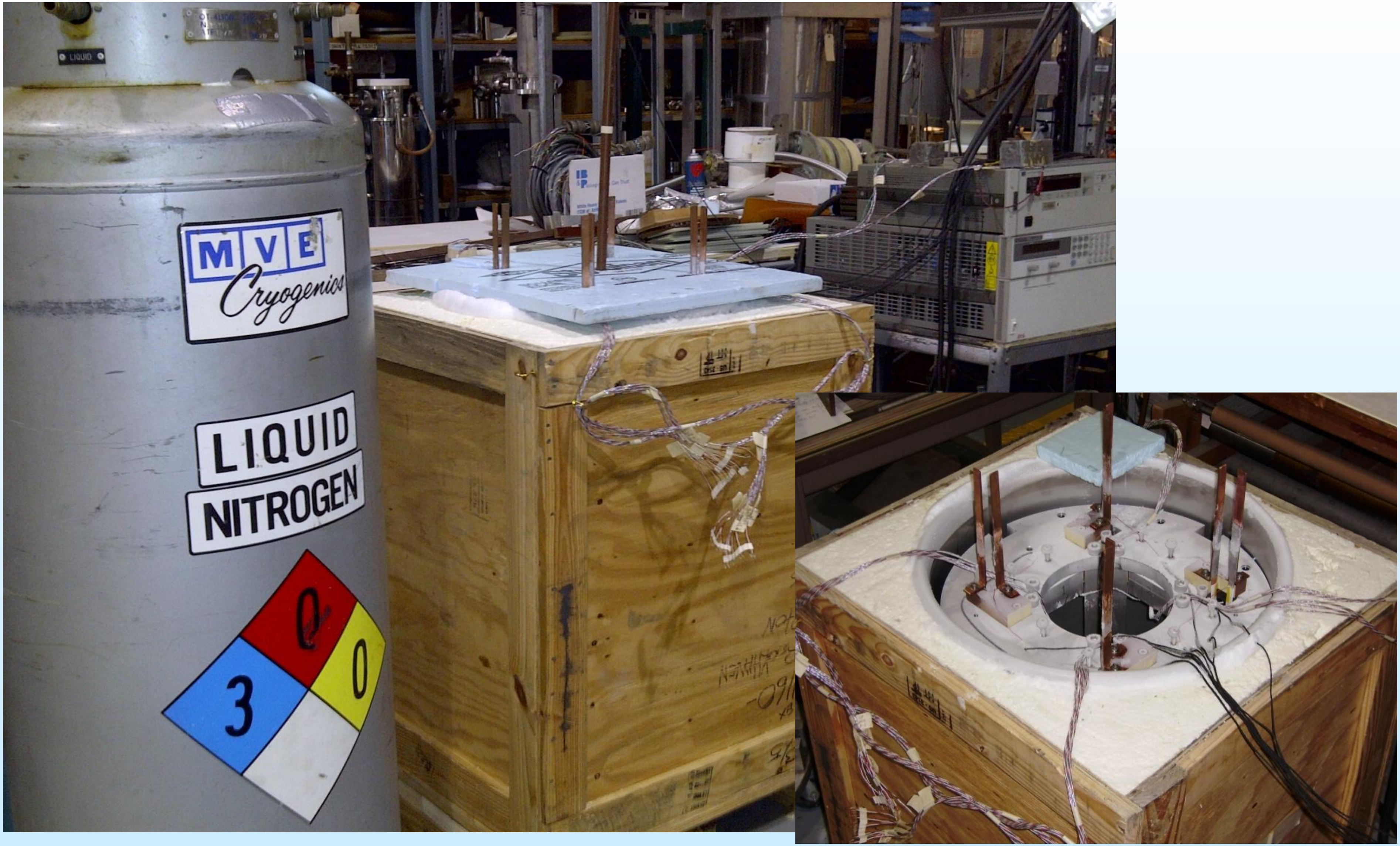
Completed 2G HTS Quad for FRIB



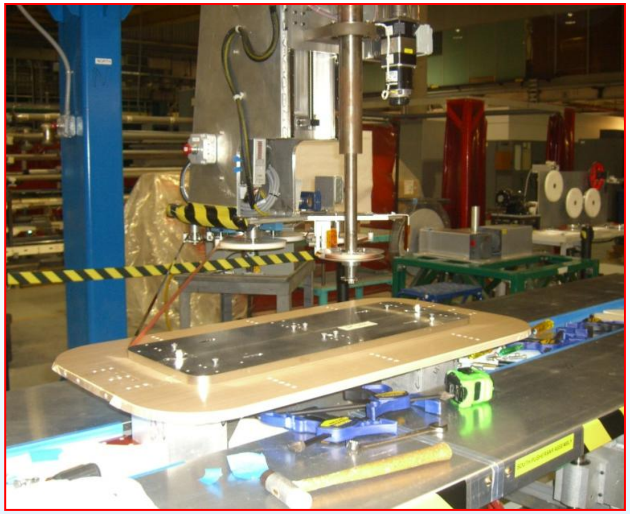
Aperture of 2G HTS Quad for FRIB

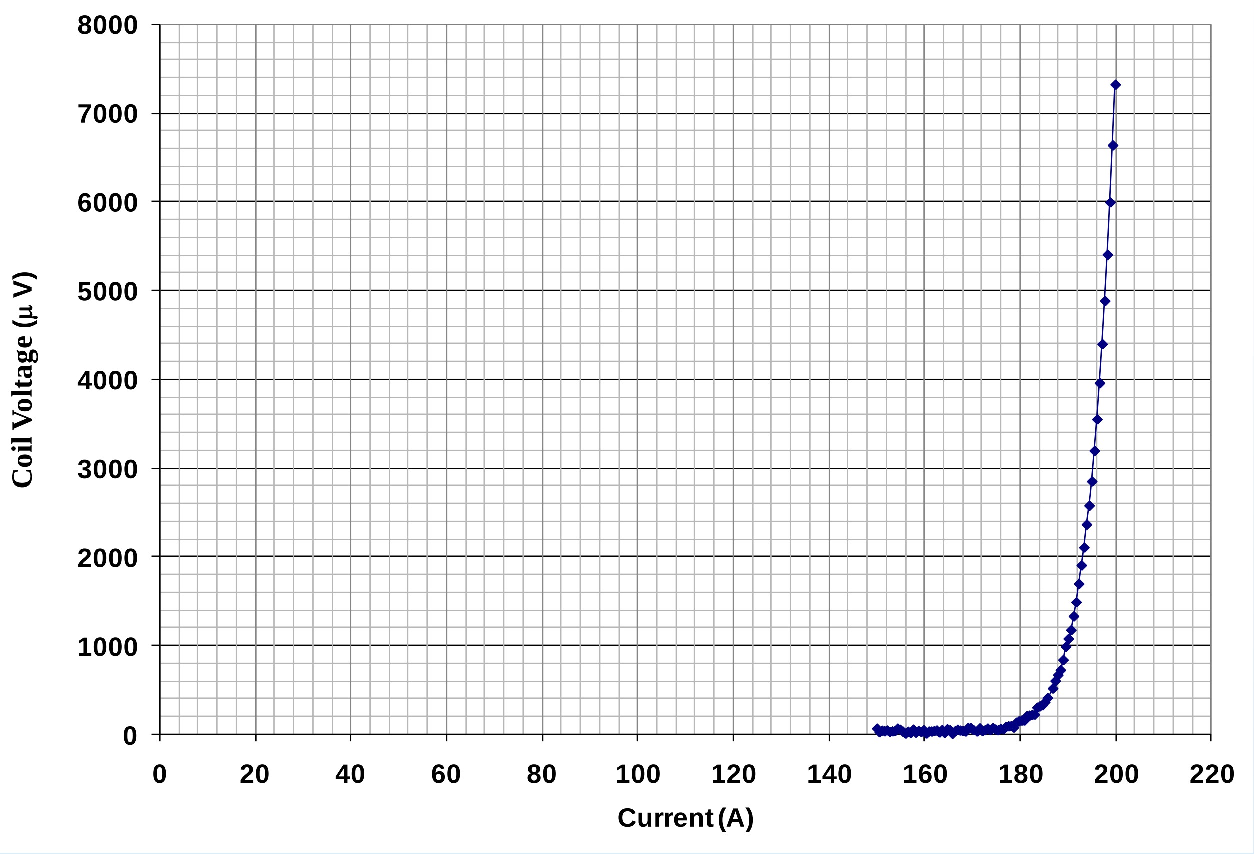


HTS Quad in Unique Cryostat



77 K Test Results of an Individual Coil



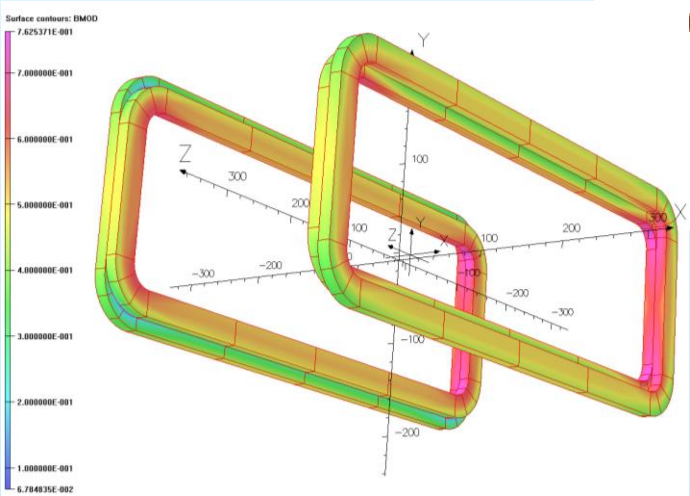


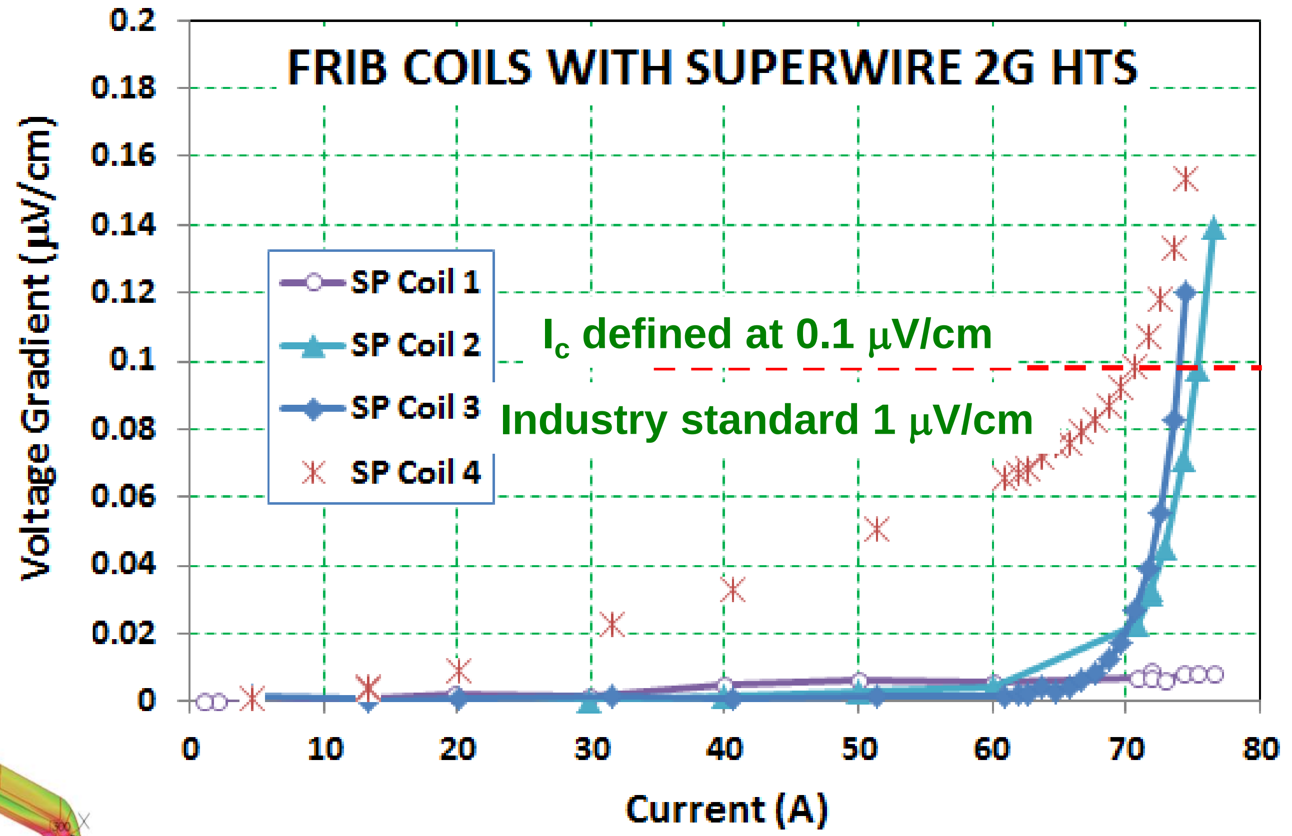
Measurement in liquid nitrogen (~77 K) of critical current in FRIB coil (large, outer, 126 turns made with ~210 meter tape from American Superconductor Corporation). The critical current in coil with 0.1 µV/cm definition (total coil voltage 2100 mV) is 193.4 A.

Performance of SuperPower Coils (four of eight coils powered)

Four ASC coils were not powered

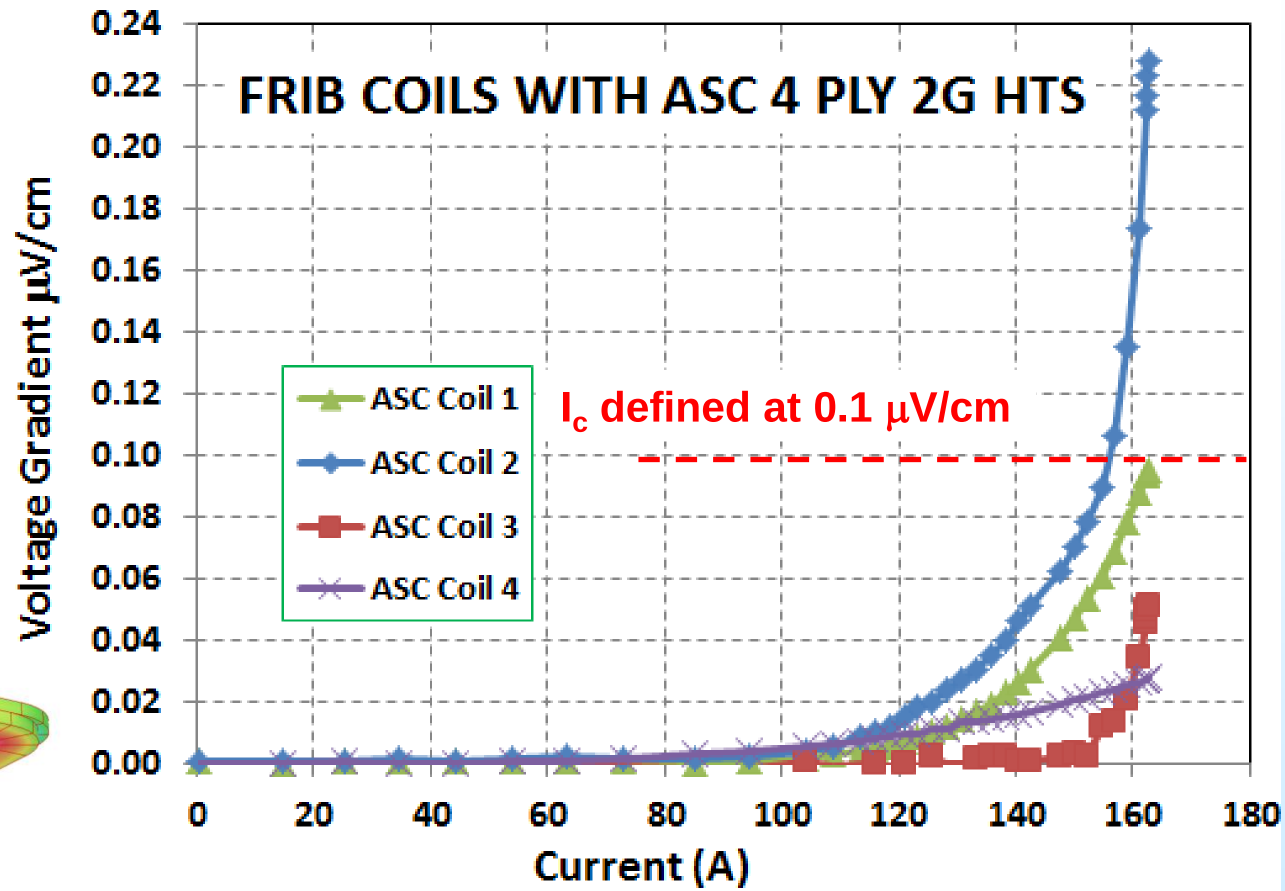
Field on SuperPower coils at 100 A





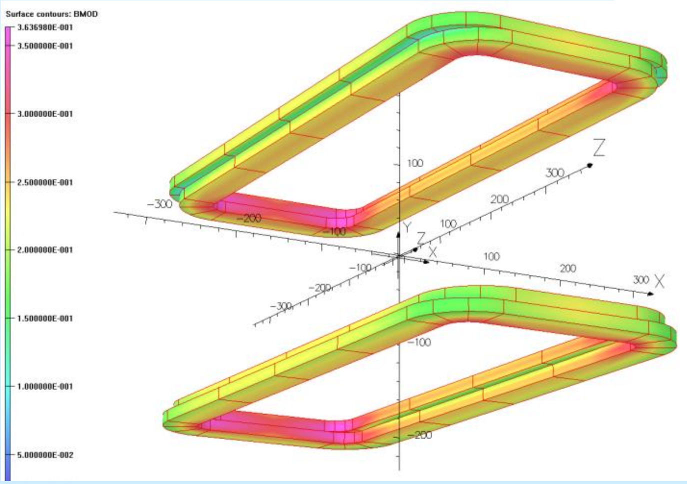
Internal splice on wrong tape side shows higher resistance. This is not an operational issue as the heat generated is negligible as compared to the energy deposition.

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

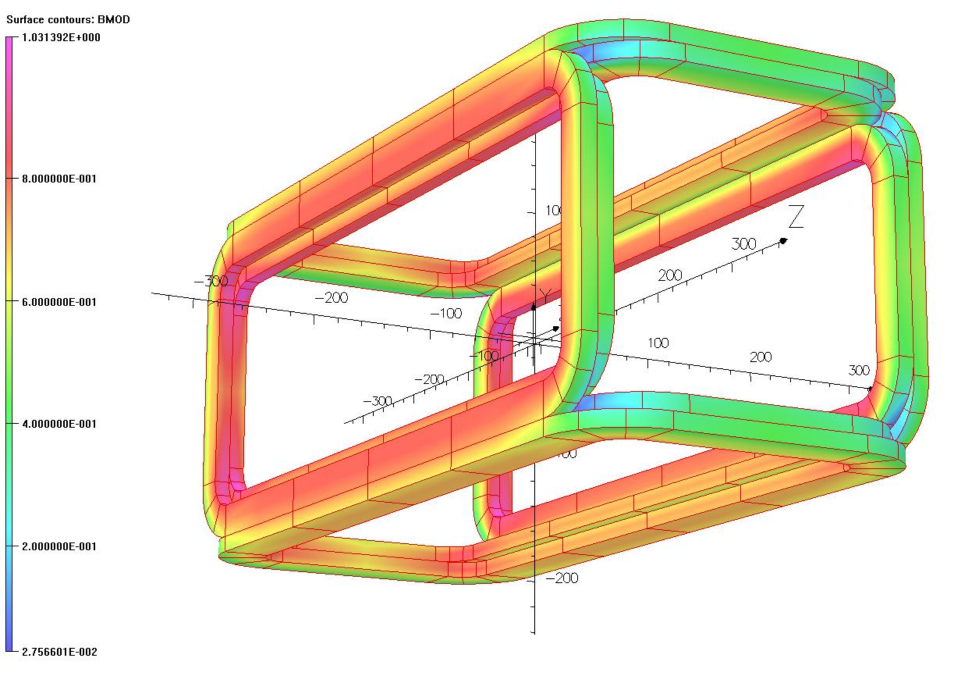
Four SuperPower coils not powered

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

Currents used in quadrupole mode test at 77 K

SP	ASC
40	69.3
50	86.7
60	104

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



Design: SuperPower coils ~172 A and ASC coils ~300 A (at 40-50 K).

- **Coils reached over 1/3 of the design current at 77 K itself.**
- **Extrapolation to 40-50 K indicates a significant margin (next slides).**

Actual 40 K test is expected in a few months.

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)

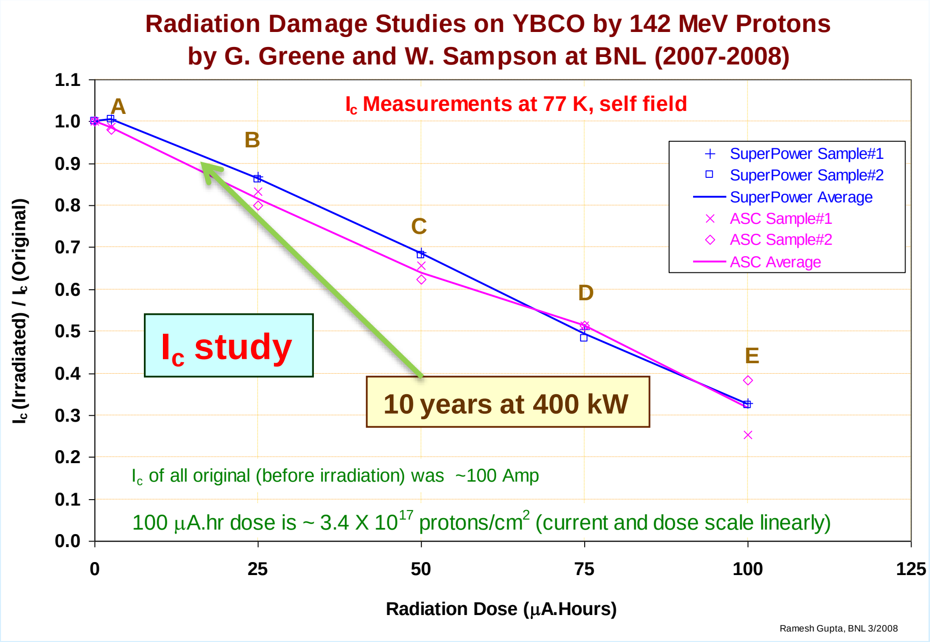
• **This gives ~0.033 dpa at 100 μA.hr for the maximum dose.**

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

Future Plans

- We plan to start the test of second generation HTS quadrupole at lower temperature (38 K – 50 K) during this calendar year
- We are also developing dipole and corrector magnets for the fragment separator region using HTS technology
- Some of the HTS development work for other magnets is also being carried out and/or proposed to be carried out through independent funding sources (e.g., SBIR with Muons, Inc.)

Summary

- HTS offers a unique magnet solution for challenging fragment separator environment of FRIB.
- It will face unprecedented level of energy and radiation loads.
- Test results for both first generation design and second generation design meet or exceed the expectations so far.
- HTS quad is now the baseline design for the quadrupoles in the fragment separator region.
- FRIB could be the 1st major accelerator with HTS magnets playing a crucial role.

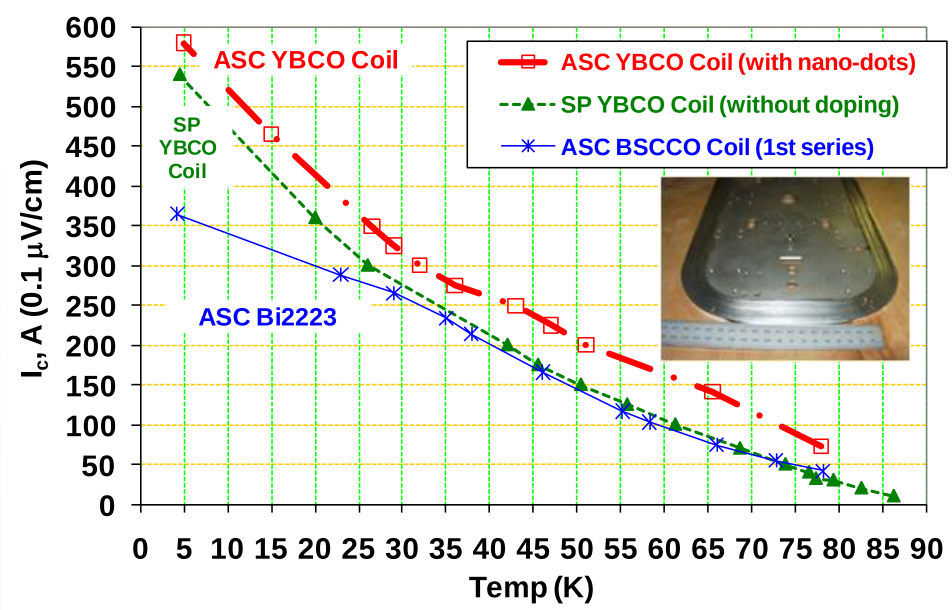
Backup Slides

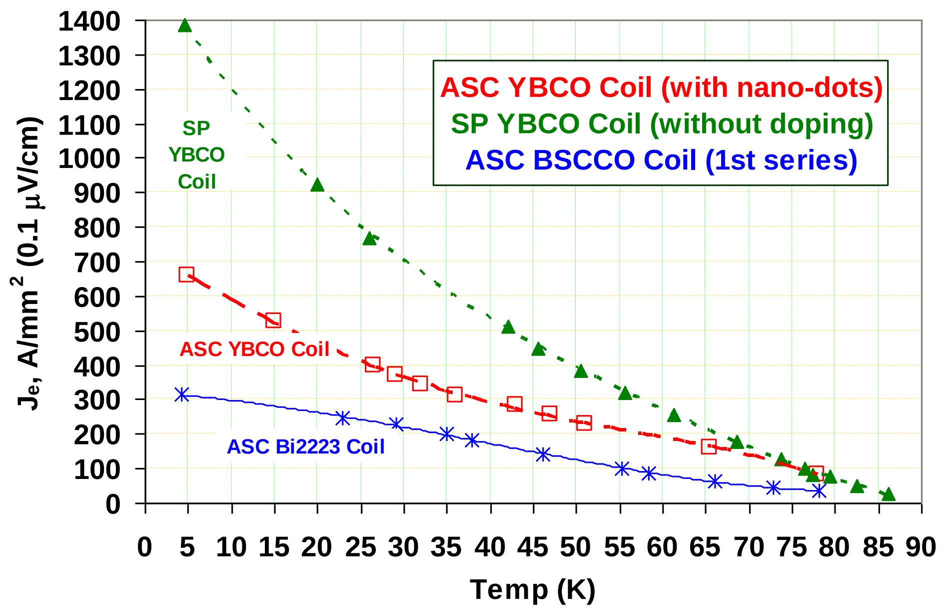
Quench Protection in FRIB HTS Quad

- Quench protection of HTS coils (particularly at 4 K where current densities are high) is considered a major challenge in light of low quench velocities
- To overcome these challenge, an advanced quench protection system with fast electronics and low noise has been developed.
- Modern data acquisition and processing system is also developed.
- This system has been successfully tested for a number of HTS coils.
- As such quench protection in HTS magnets for FRIB is much less of an issue as compared to that in other HTS magnets. This is because of the fact that operating current is much lower at 40-50 K (instead of 4 K), and therefore, the current densities in copper (hence temperature rise) is much lower.




Quench Protection Studies in FRIB 2G HTS Coils





- Experimental studies were performed as a function of temperature to see what happens when coil go normal (due to quench, thermal runaway, etc).

Coils with very high current density in copper at quench survived:
~1500 A/mm^2(ASC); ~3000 A/mm^2(SuperPower)

FRIB design is more conservative (low risk, large margin for real machine):
Current density in Cu is much lower: ~300 A/mm^2 (ASC) or ~700 A/mm^2 (SP)

Design Parameters of 1st Generation HTS R&D Quadrupole for FRIB/RIA

Parameter	Value
Aperture	290 mm
Design Gradient	10 T/m
Magnetic Length	425 mm (1 meter full length)
Coil Width	500 mm
Coil Length	300 mm (1125 mm full length)
Coil Cross-section	62 mm X 62 mm (nominal)
Number of Layers	12 per coil
Number of Turns per Coil	175 (nominal)
Conductor (Bi-2223) Size	4.2 mm X 0.3 mm
Stainless Steel Insulation Size	4.4 mm X 0.038 mm
Yoke Cross-section	1.3 meter X 1.3 meter
Minimum Bend Radius for HTS	50. 8 mm
Design Current	160 A (125 A full length)
Operating Temperature	30 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

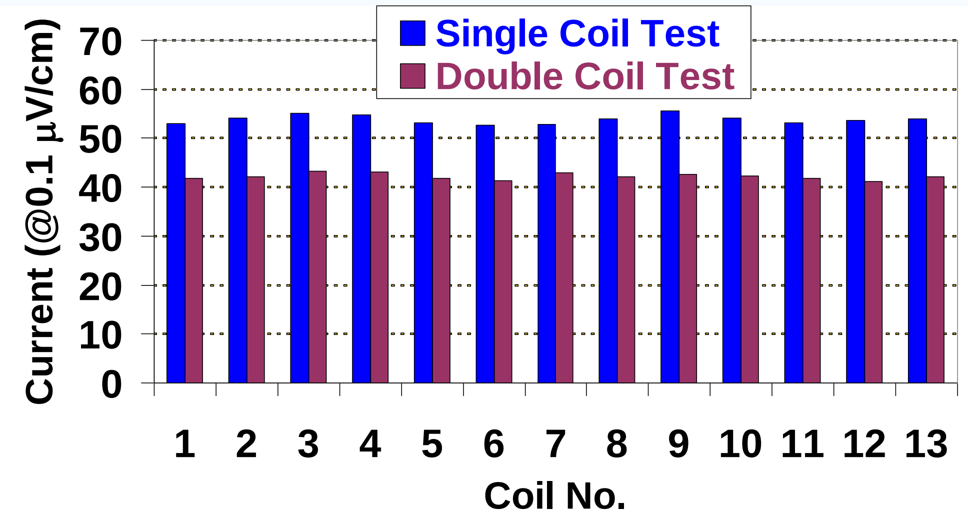
Parameter List of the Second Generation Design

Parameter	Value
Pole Radius	110 mm
Design Gradient	15 T/m
Magnetic Length	600 mm
Coil Overall Length	680 mm
Yoke Length	~550 mm
Yoke Outer Diameter	720 mm
Overall Magnet Length(incl. cryo)	~880 mm
Number of Layers	2 per coil
Coil Width (for each layer)	12.5 mm
Coil Height (small, large)	26 mm, 39 mm
Number of Turns (nominal)	110, 165
Conductor (2G) width, SuperPower	12.1 mm ± 0.1 mm
Conductor thickness, SuperPower	0.1 mm ± 0.015 mm
Cu stabilizer thickness SuperPower	~0.04 mm
Conductor (2G) width, ASC	12.1 mm ± 0.2 mm
Conductor (2G) 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
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)
Nominal Operating Current	~280 A
Stored Energy	37 kJ
Inductance	~1 Henry
Operating Temperature	50 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

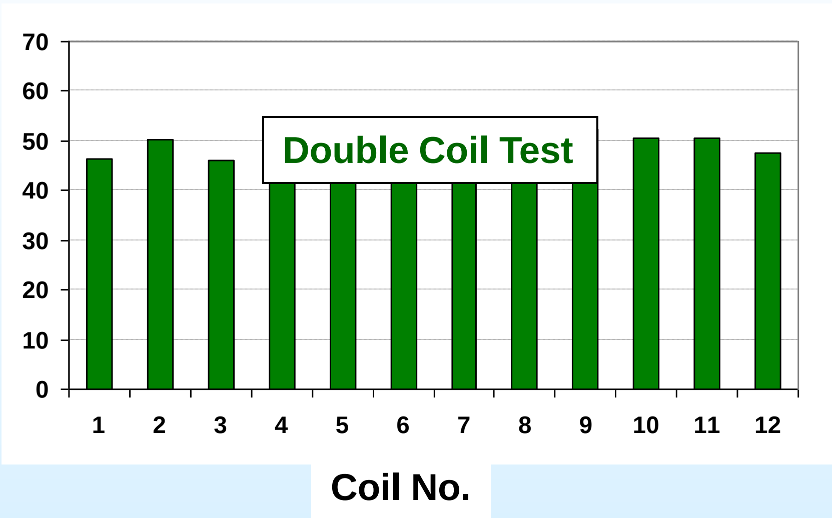
LN_2 (77 K) Test of Coils Made with ASC 1st Generation HTS

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.

It shows that the HTS coil technology has matured !

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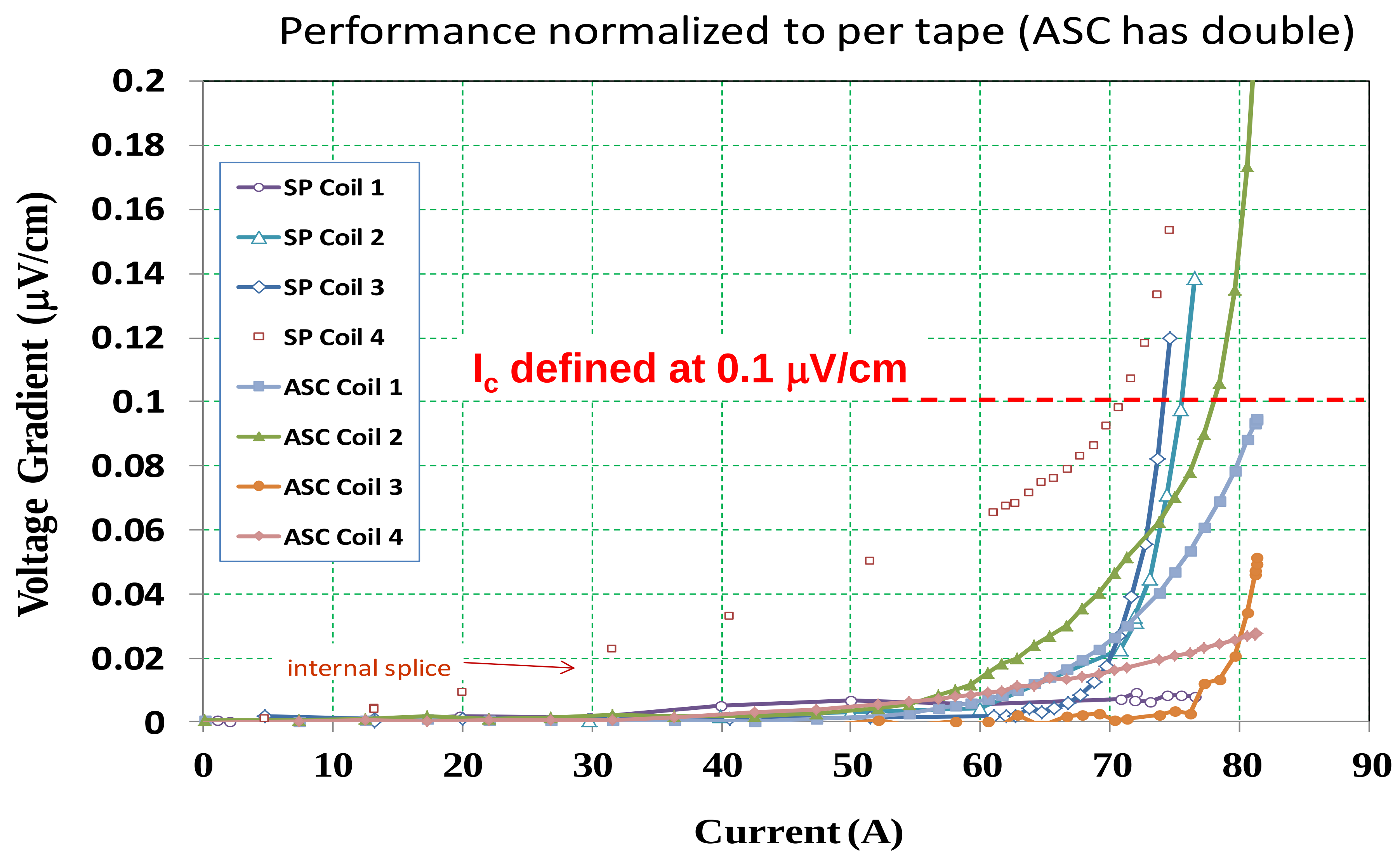
Coils in FRIB Quad Structure @77 K (made with 2G HTS from SuperPower and ASC)



Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

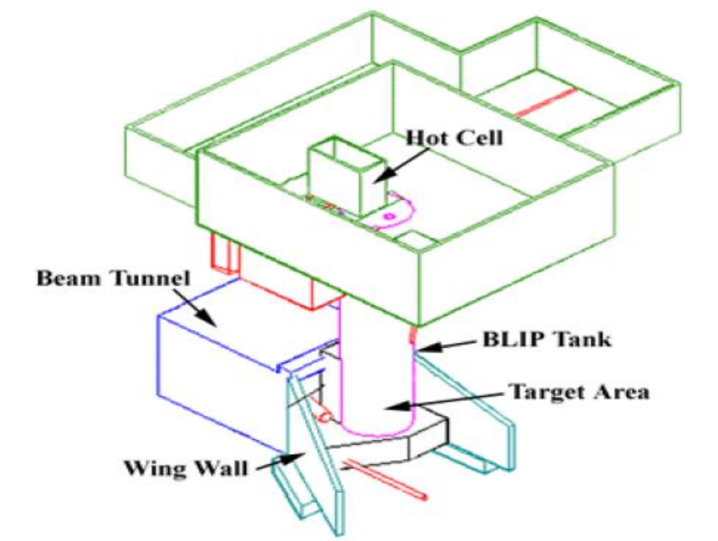
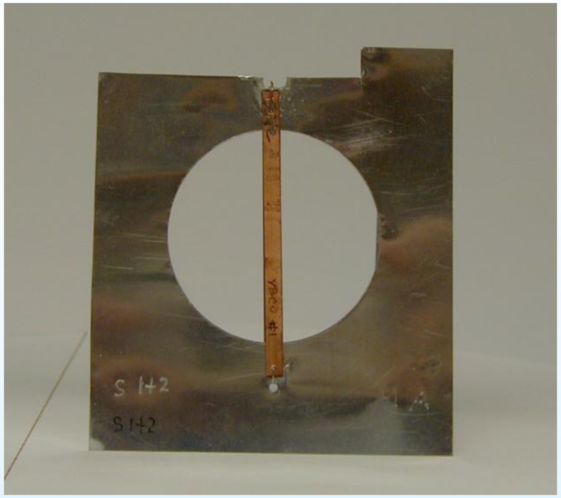


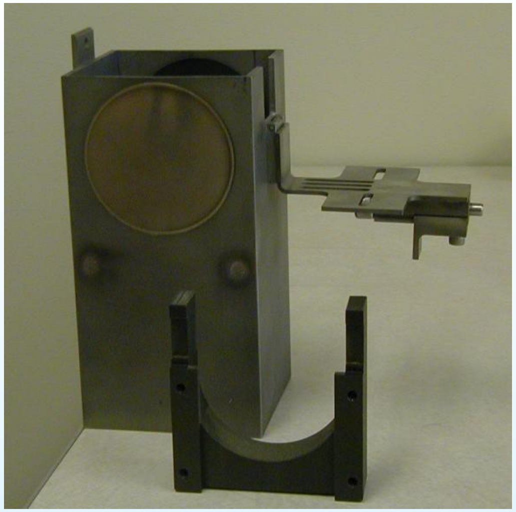
Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

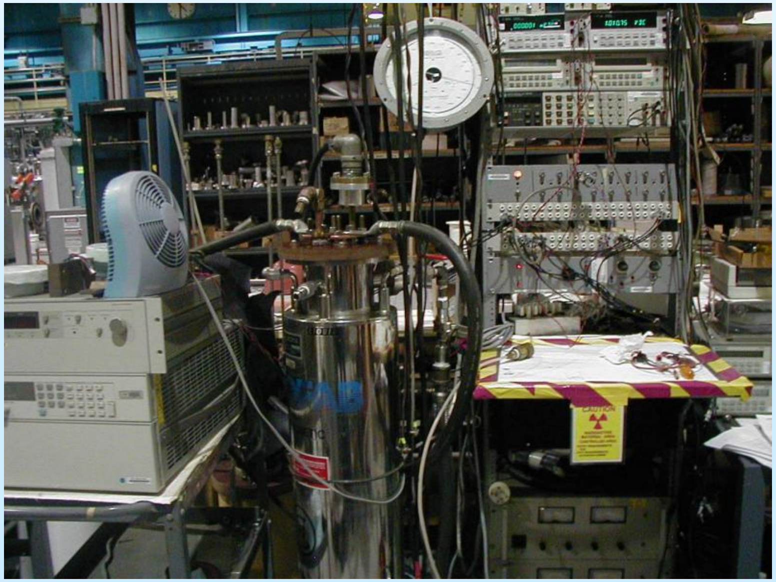
The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 µA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

Key Steps in Radiation Damage Experiment

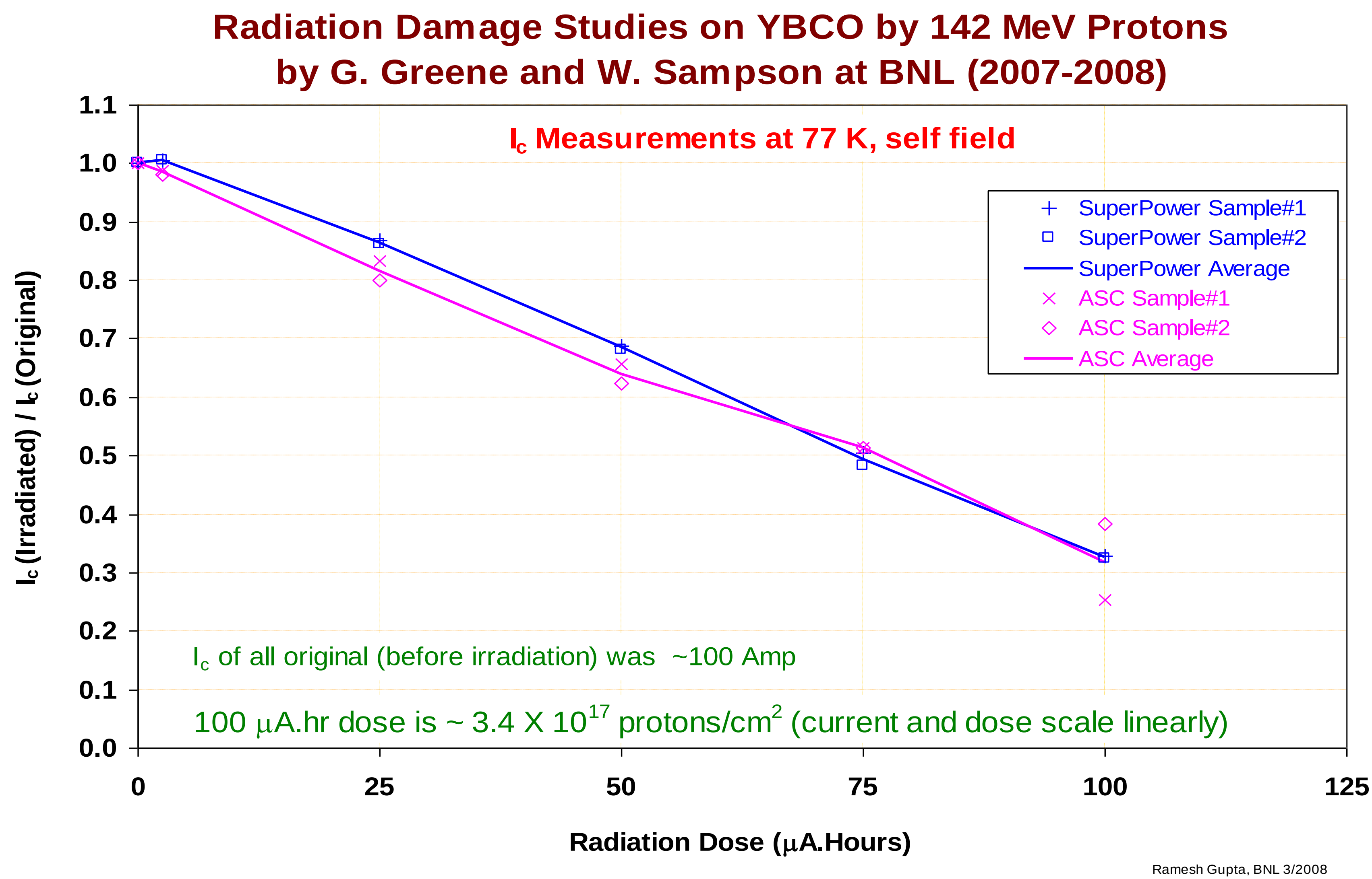




142 MeV,
100 μA protons

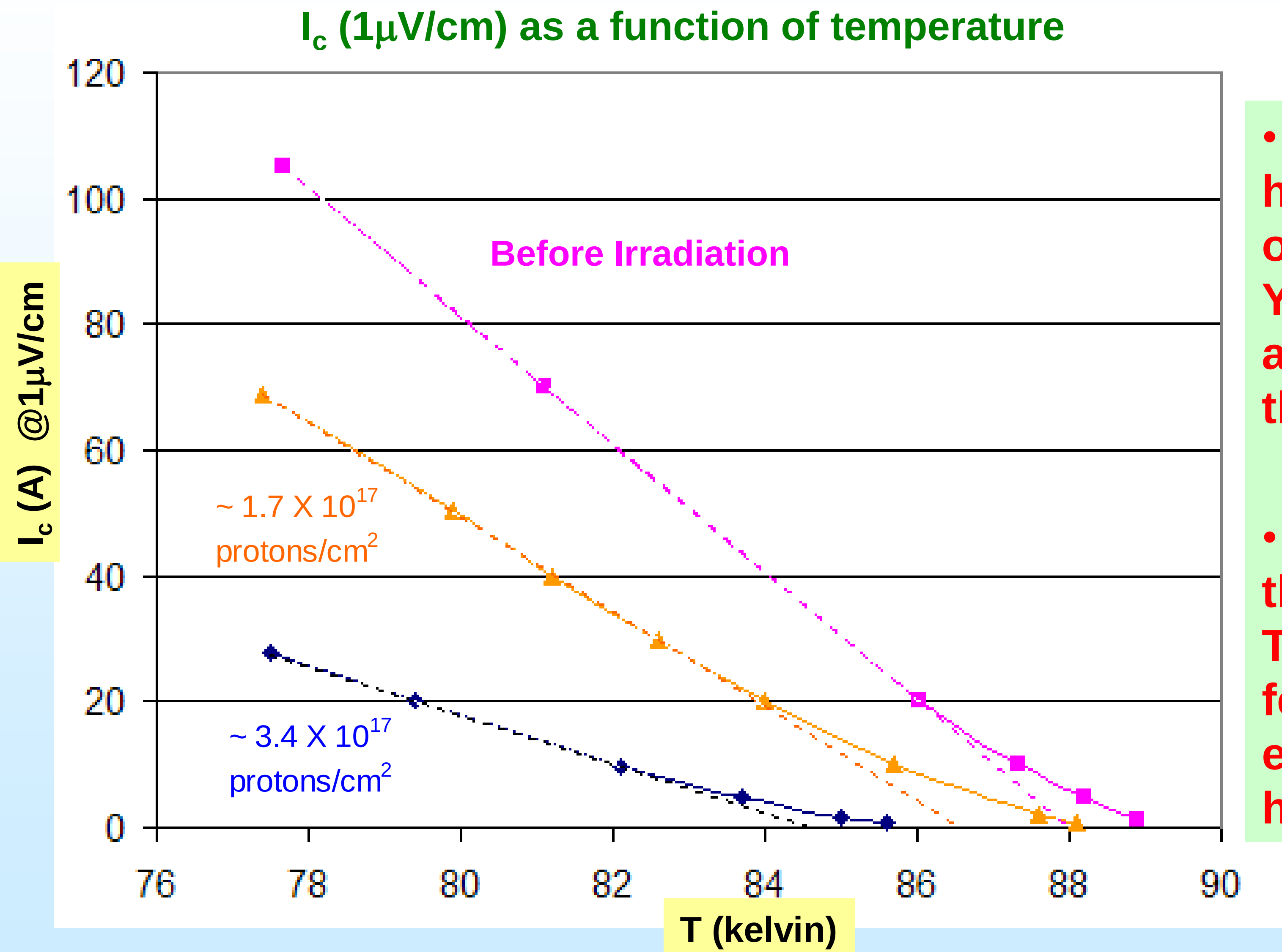


Relative Change in Ic due to Irradiation of SuperPower and ASC Samples



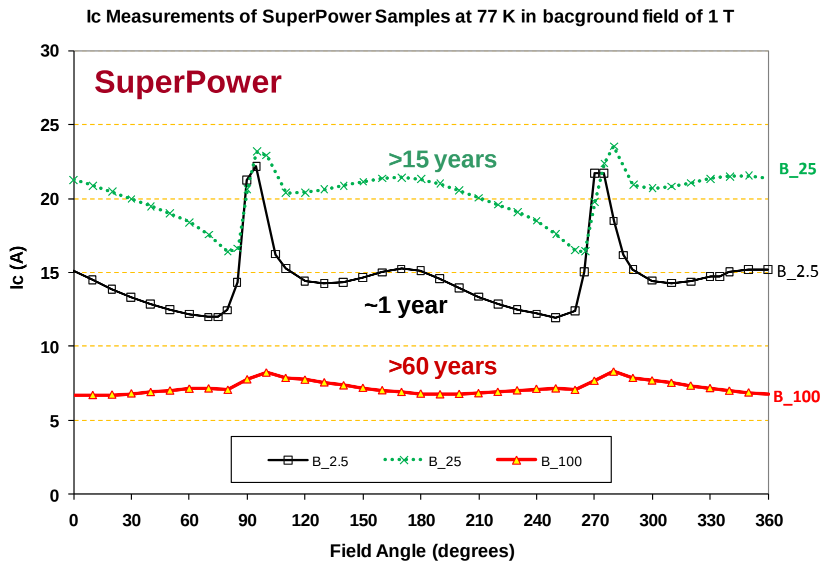
SuperPower and ASC samples show very similar radiation damage at 77 K, self field

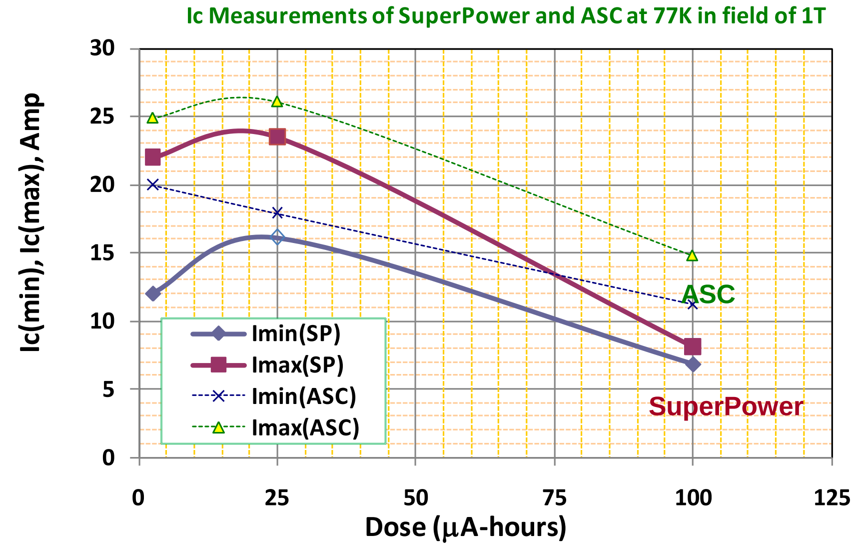
Change in Critical Temperature (T_c) of YBCO Due to Large Irradiation



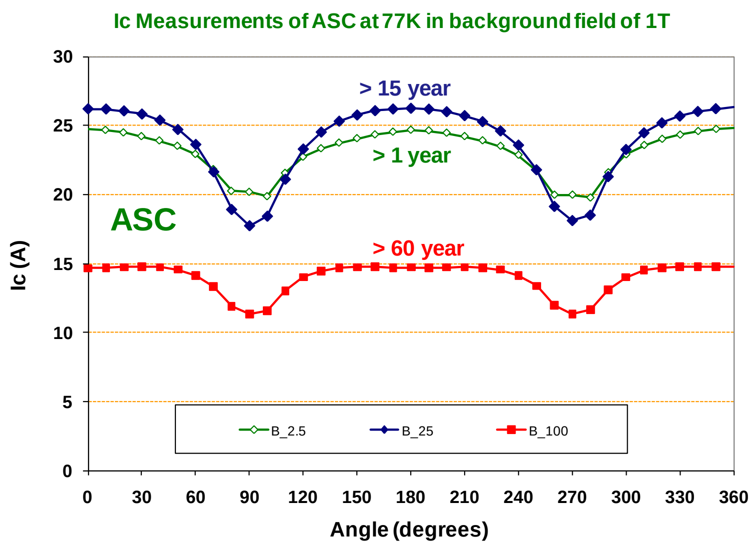
- **Radiation has an impact on the T_c of YBCO, in addition to that on the I_c.**
- **However, the change in Tc is only a few degrees, even at very high doses.**

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



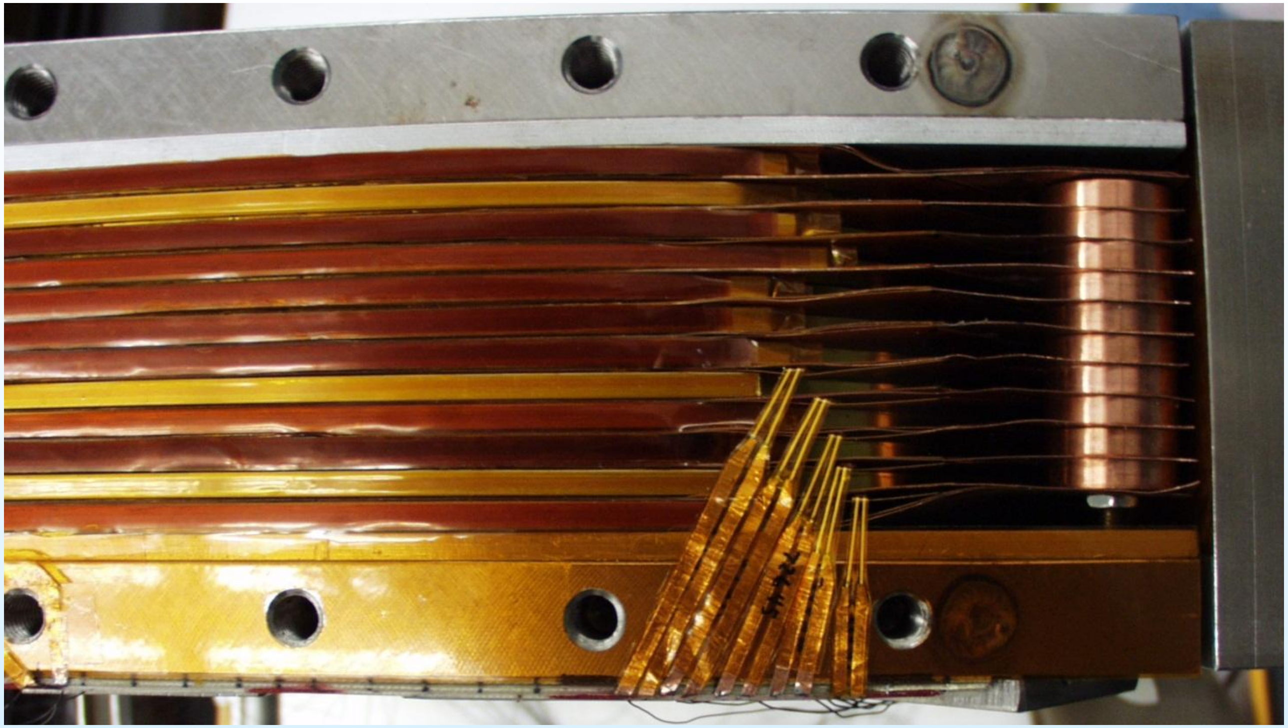


Minimum and maximum values of I_c are obtained from the graphs on the right



- 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 Experiments

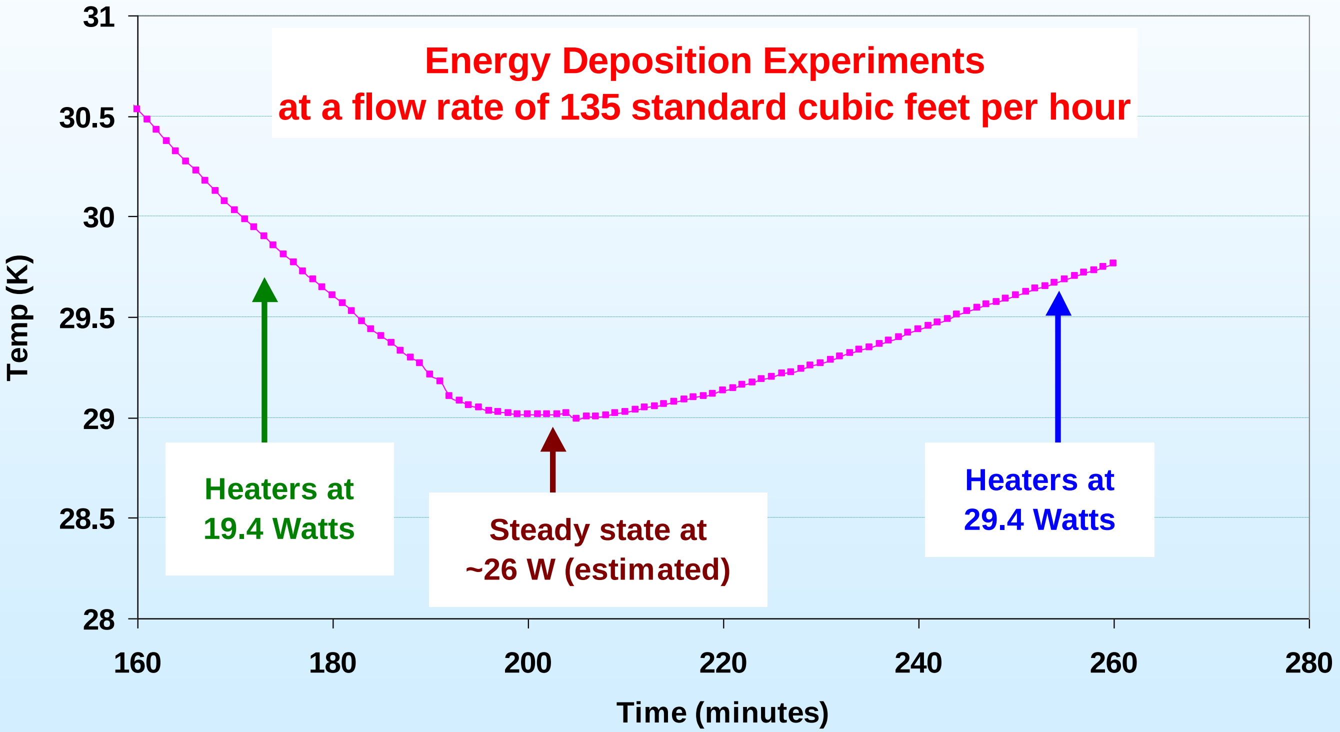


Stainless steel tape heaters for energy deposition experiments

- 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 constant helium flow rate of 135 standard cubic feet (SCF)



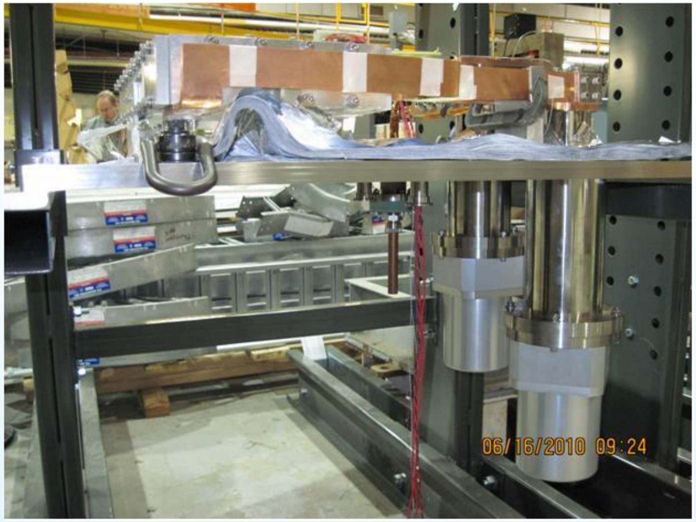
Temperature decreased at 19.4 W

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.

Cryo-cooler based HTS Magnets (an alternate option for FRIB and elsewhere)



Cryo-cooler based HTS magnet option offers an alternative to Helium based cryo-system.

- Coils reached <40 K overnight with cryo-coolers
- 25 W heat load at 50 K can be removed by a number of cryo-coolers