Special Magnet Needs: HTS Magnets for High Radiation Environment

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νSTORM

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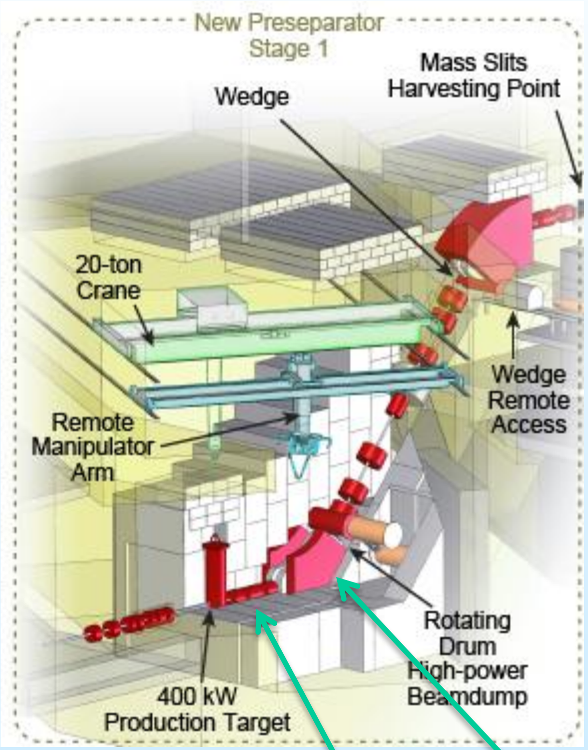
Outline

- **Motivation for HTS magnets in FRIB and nuSTORM**
  - HTS magnets are now part of the baseline design for FRIB in some special magnets with critical needs
- **First Generation Magnets**
  - 30 K operation
- **Second Generation Magnets**
  - 50 K operation and higher gradient
- **Summary and discussion on potential use of this development in nuSTORM**

Radiation and Heat Loads in Fragment Separator Magnets

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

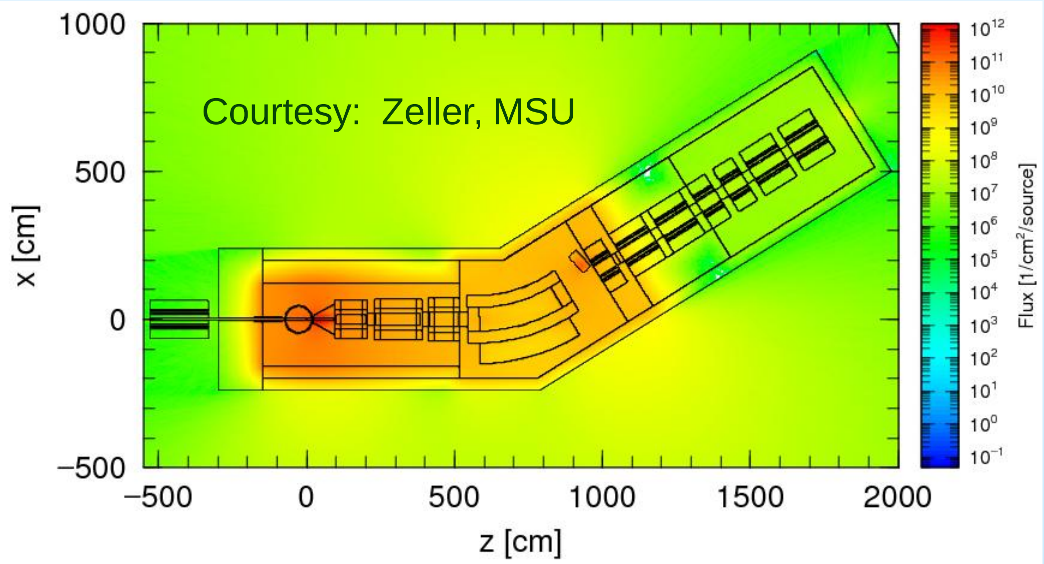
Quadrupoles in Fragment Separator (following that target) are exposed to unprecedented level of radiation and heat loads



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**



Technical Requirements

High fields and large apertures require superconducting magnets!

Magnets in the fragment separator target area that survive the high-radiation environment

- Require that magnets live at least 10 years at full power
- Require refrigeration loads that can be handled by the cryo-plant
- Require magnets that facilitate easy replacement

Reduced operational costs

- No down time for magnet replacement
- Higher acceptance (large aperture) reduces experimental times
- Robust and resistant to beam-induced quenches

Courtesy: Al Zeller, FRIB/MSU

HTS Magnets in Fragment Separator

HTS magnets in Fragment Separator region over Low Temperature 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

HTS Magnets in nuSTORM

A few special magnets in nuSTORM face several challenges that are similar to those faced in FRIB:

- High radiation environment
- Large energy deposition
- Large aperture
- Respectable gradient (need super-ferric magnets)

Therefore, instead of starting from scratch, one can apply design and technology developed for FRIB HTS magnets to nuSTORM

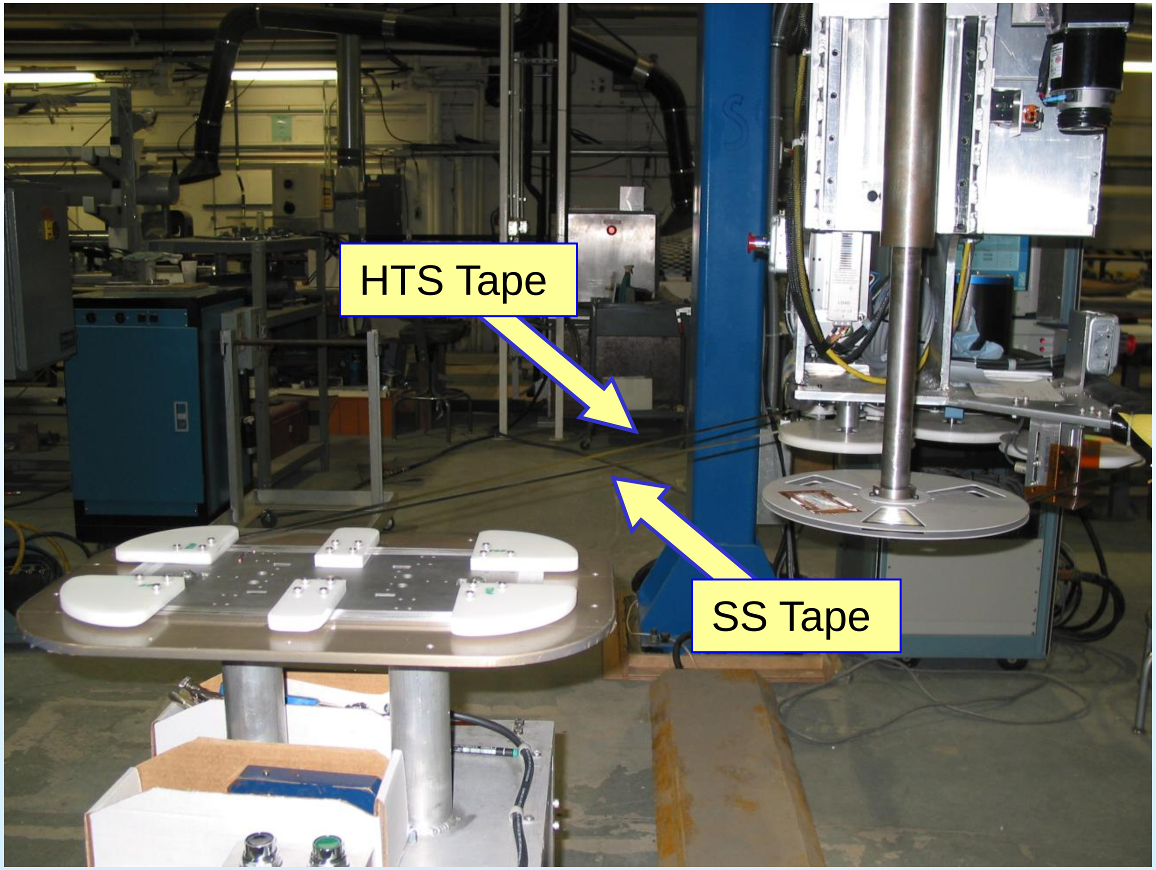
BNL Role in HTS Magnet Development for FRIB

- BNL proposed HTS magnets for FRIB and has been the primary institution for developing HTS magnet technology for FRIB
- BNL has designed, built and tested 1st and 2nd generation HTS quad for FRIB
- BNL has carried out energy deposition experiments
- BNL has carried out radiation damage experiments
- BNL is involved in developing variety of HTS magnets for FRIB (quads, dipoles, correctors)

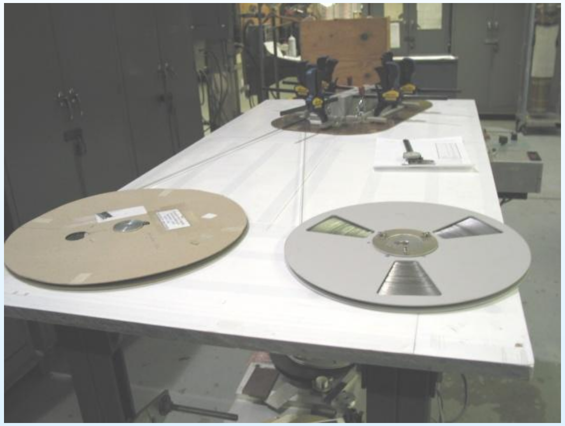
Review of the First Generation HTS Magnet R&D for FRIB

- Demonstration of a HTS magnet built with ~5 km of ~4 mm wide first generation (1G) HTS tape
- Demonstration of stable operation in a large heat load (energy deposition) environment

HTS Coil Winding



A coil being wound in a computer controlled winding machine.



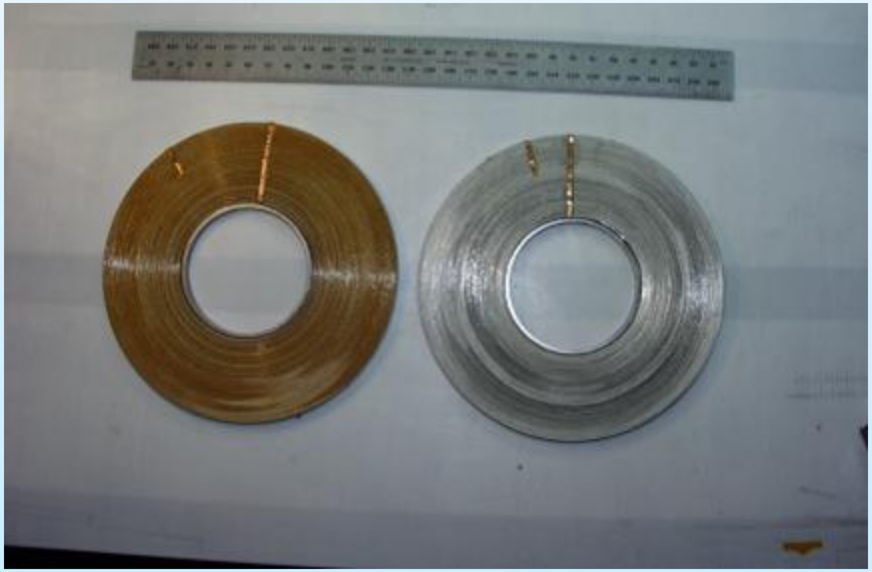
Earlier coils were wound with a machine that has more manual controls.

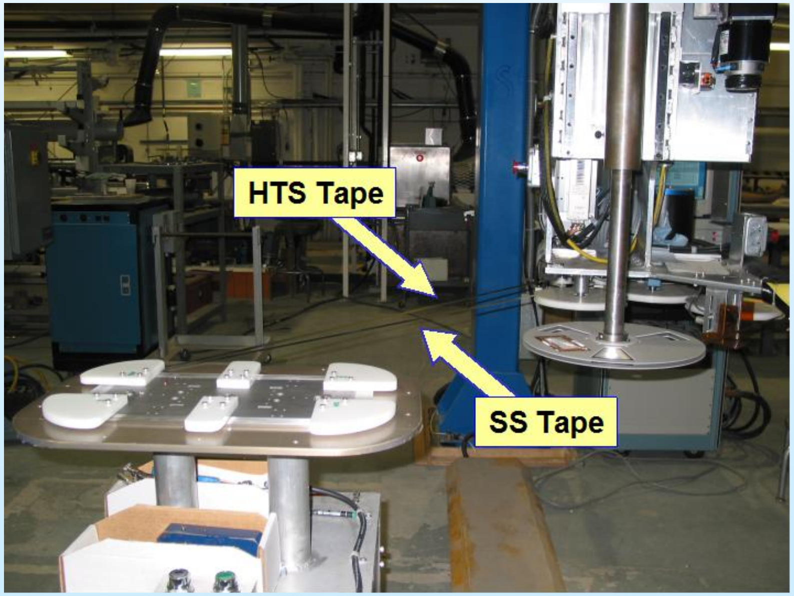
Insulation in HTS Coils in High Radiation Environment

Radiation damage to insulation is a major issue for magnets in high radiation area.

Kapton, epoxy and other organic insulation may not be able to survive the unpredented amount of radiation present in FRIB (or in RISP).

Stainless steel tape (very good insulator as compared to superconductor), being a metal is highly radiation resistant. SS tape serves as a turn-to-turn insulation.

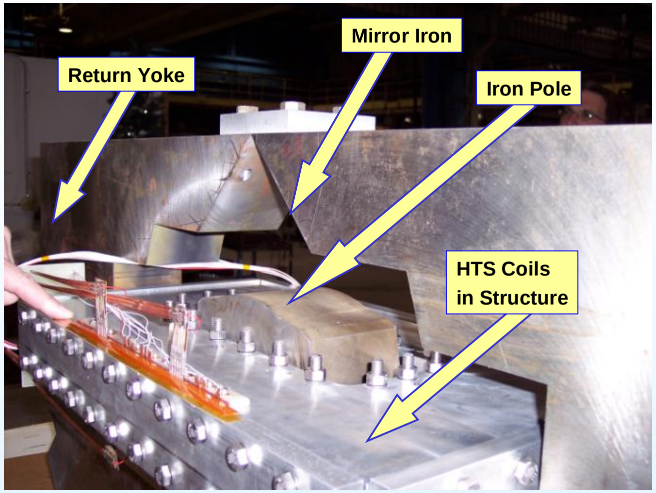




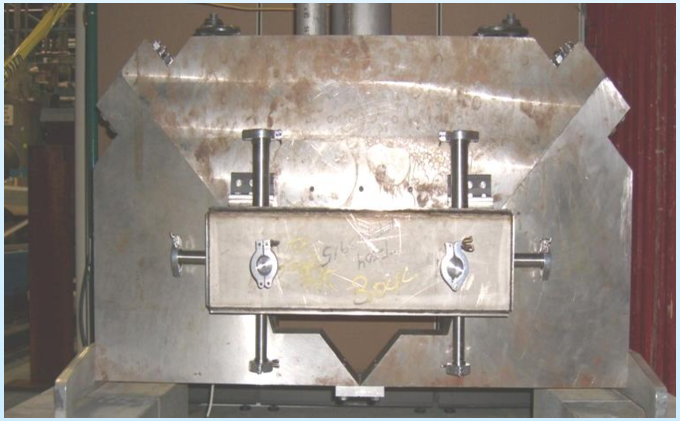
Design Parameters of 1st Generation HTS R&D Quadrupole for FRIB/RIA

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

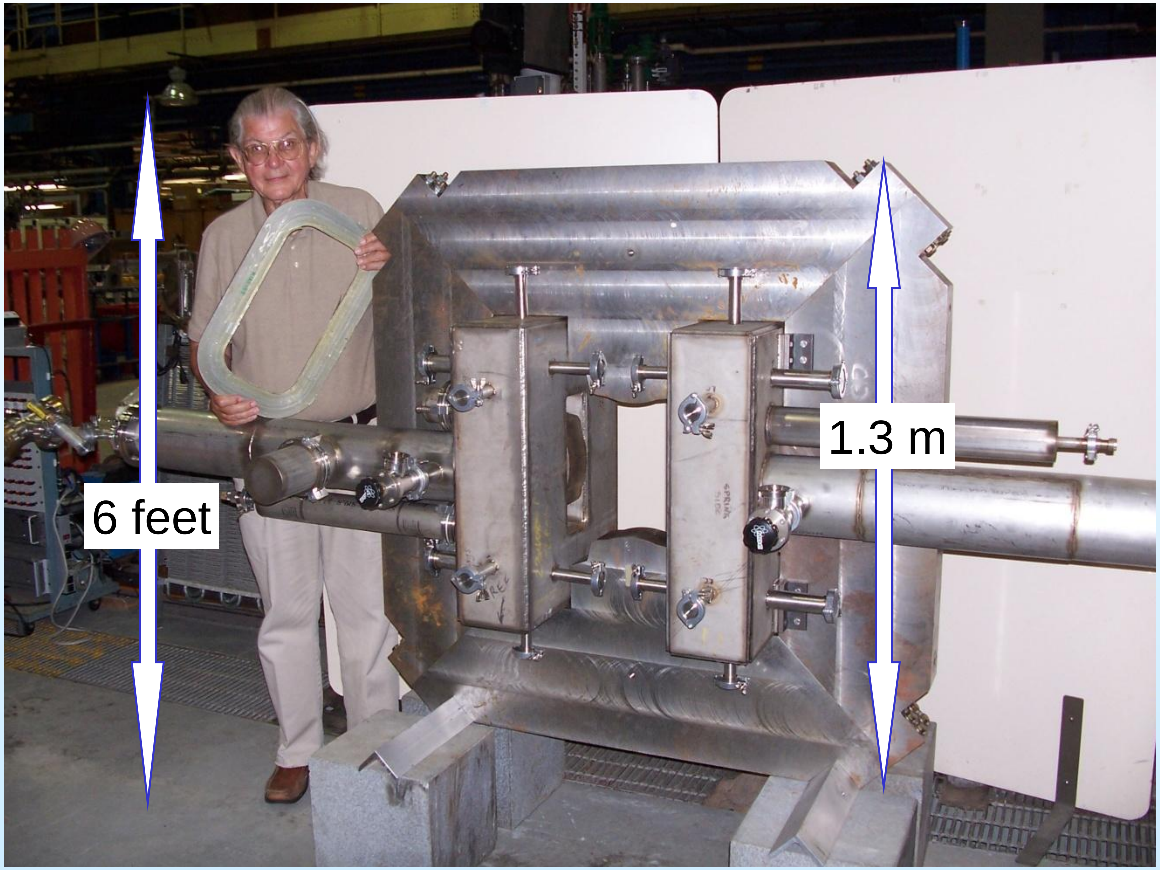
Magnet Structures for FRIB/RIA HTS Quad
(Several R&D structures were built and tested)



Mirror cold iron



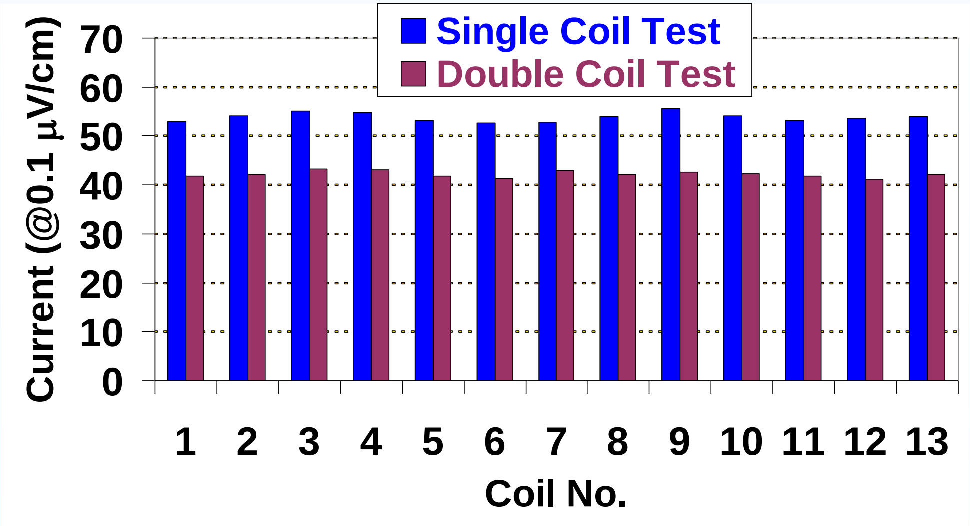
Mirror warm iron



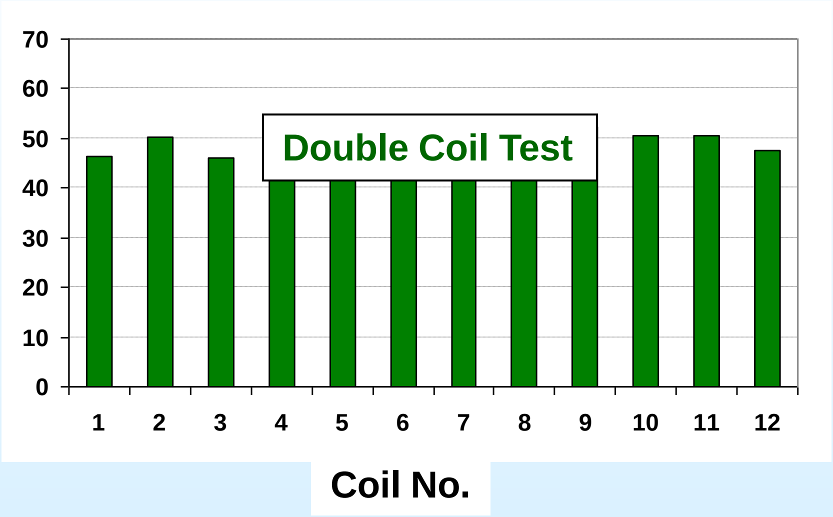
LN_2 (77 K) Test of Coils Made with ASC 1st Generation HTS

Each single coil uses ~200 meter of tape

13 Coils made HTS tape in year #1



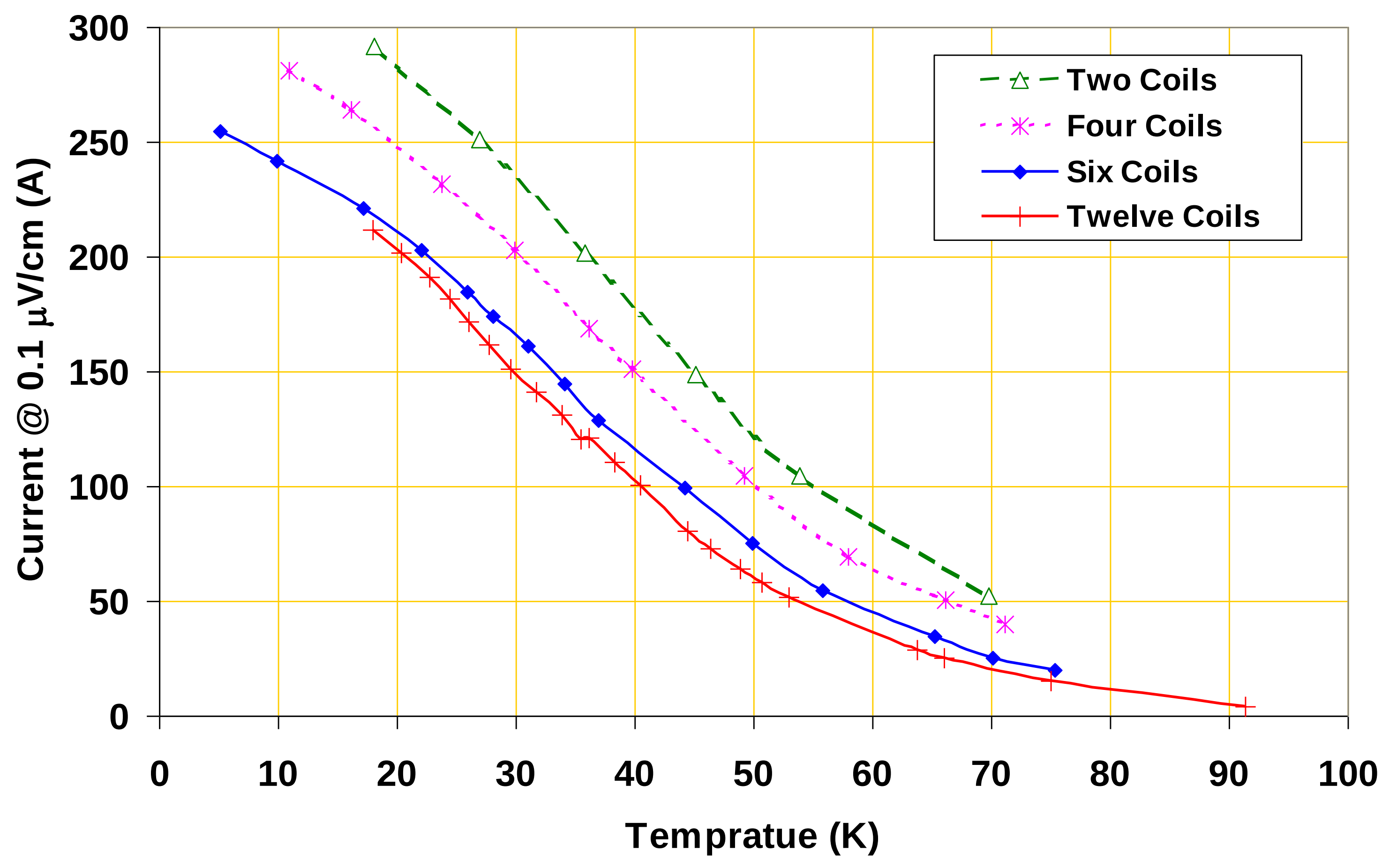
12 coils with HTS tape in year #2



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

It shows that the HTS coil technology has matured !

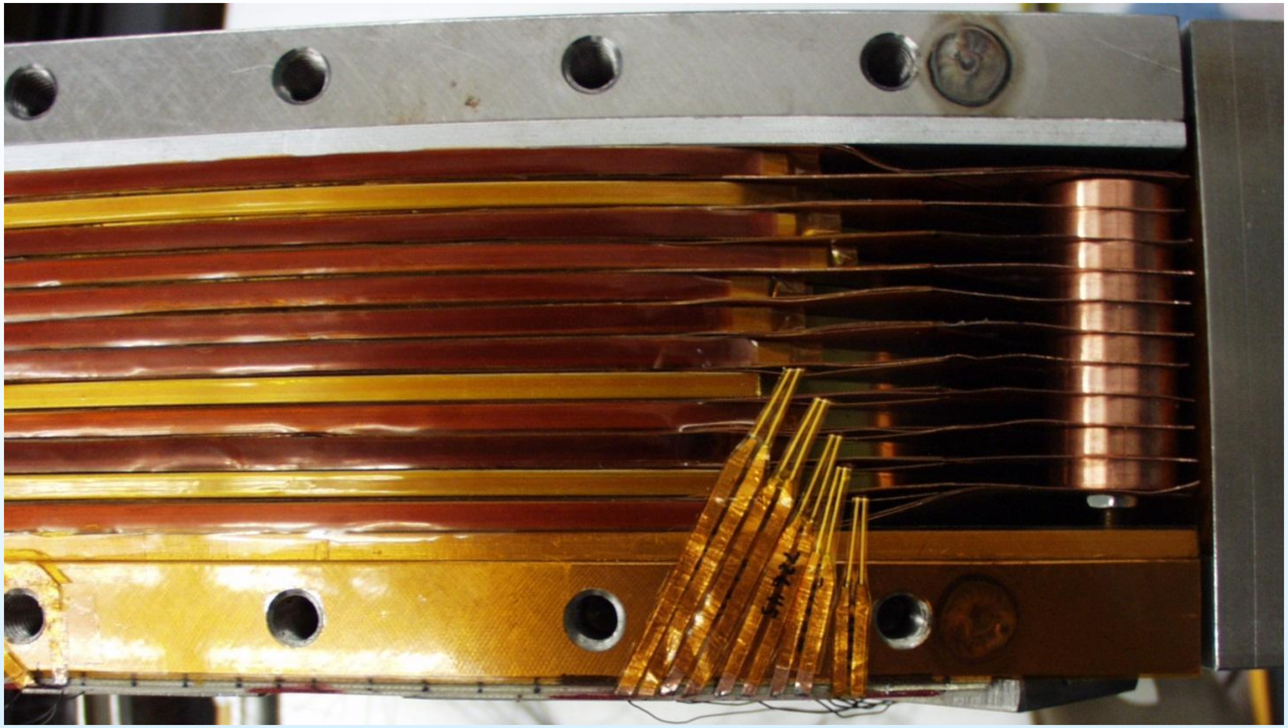
HTS Mirror Model Test Results
(operation over a large temperature range)



More coils create more field and hence would have lower current carrying capacity

A summary of the temperature dependence of the current in two, four, six and twelve coils in the magnetic mirror model. In each case voltage first appears on the coil that is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for two coils.

Energy Deposition Experiments

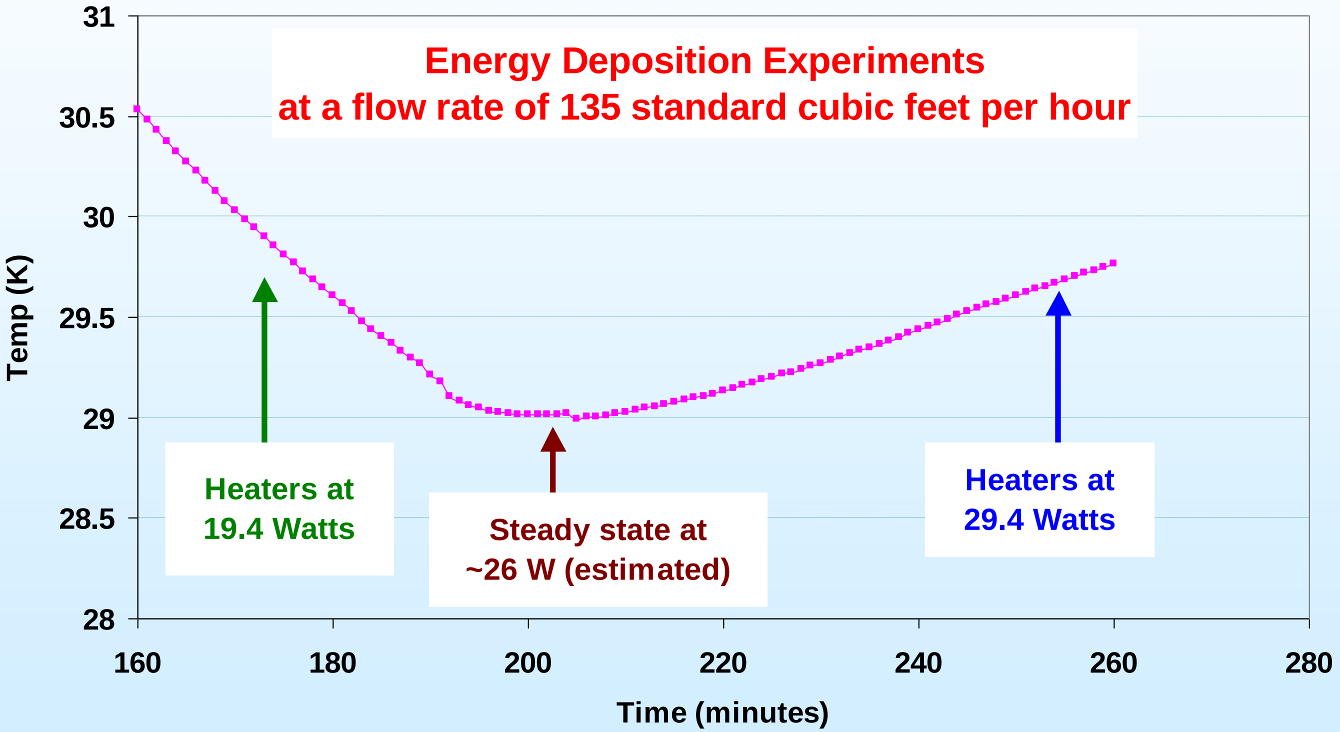


Stainless steel tape heaters for energy deposition experiments

- 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)

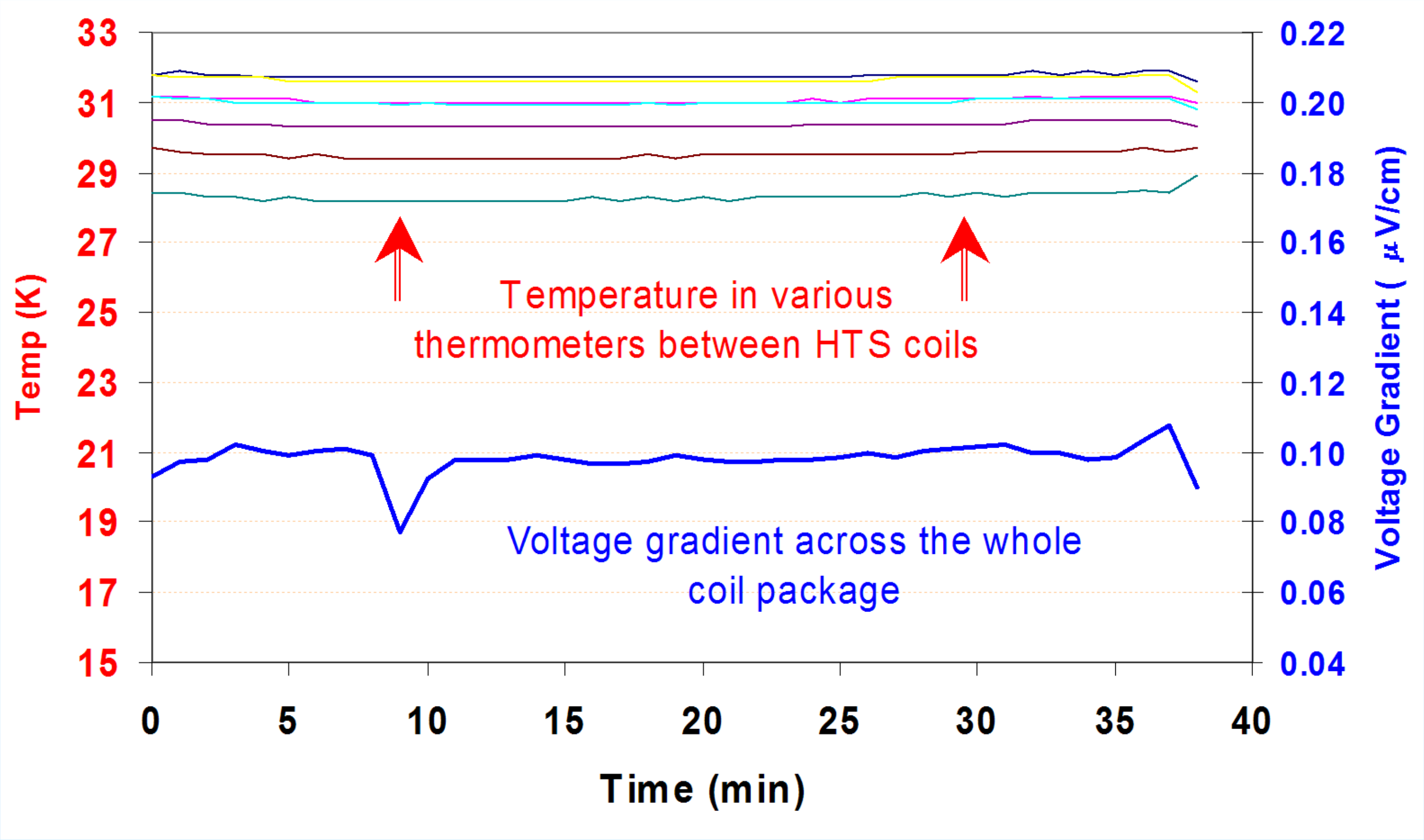


Temperature decreased at 19.4 W
Temperature increased at 29.4 W
Heat load for steady state ~26 Watts

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

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

Review of the Second Generation HTS Magnet R&D for FRIB

- HTS magnets with significant quantities of 12 mm wide 2G tape from two vendors (SuperPower and ASC)
  - ~9 km equivalent of 4 mm tape
- Radiation damage test in high radiation environment

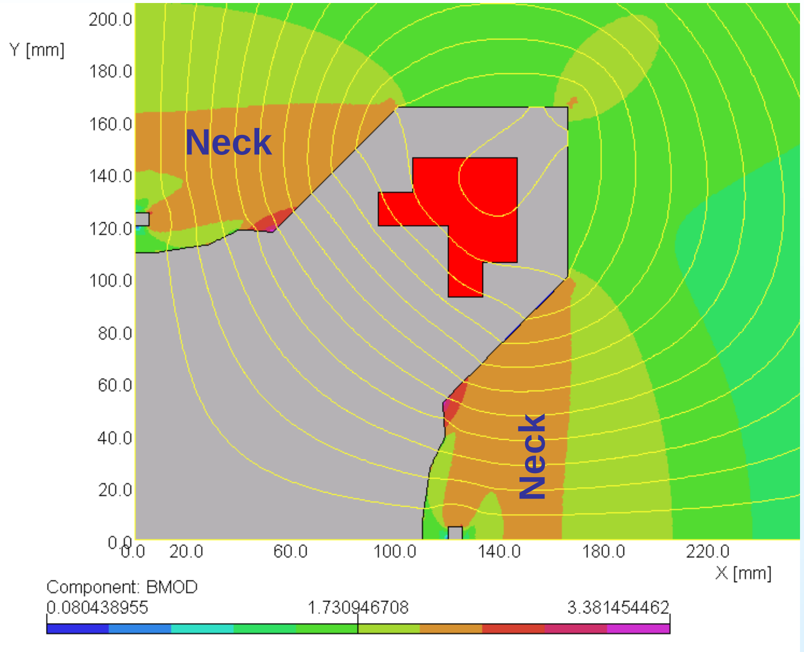
Why 2G HTS

- Allows higher gradient at higher operating temperature
  - 15 T/m instead of 10 T/m
  - 40-50 K operation rather than ~30 K
- Conductor of the future
  - Projected to be less expensive (uses much less silver) and have better performance

Parameter List

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

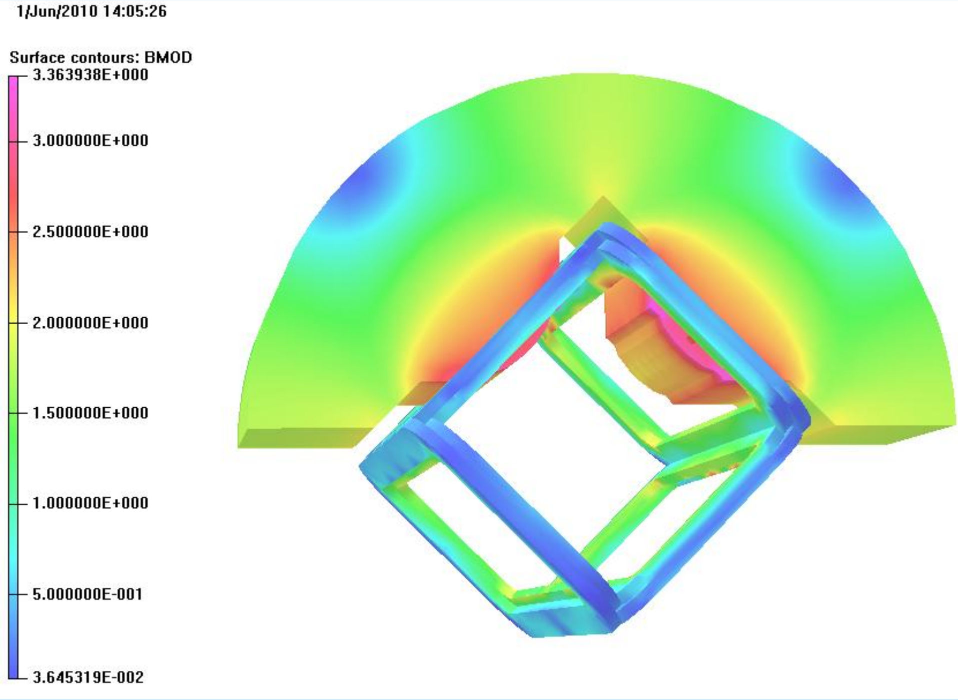
Magnetic Design



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**



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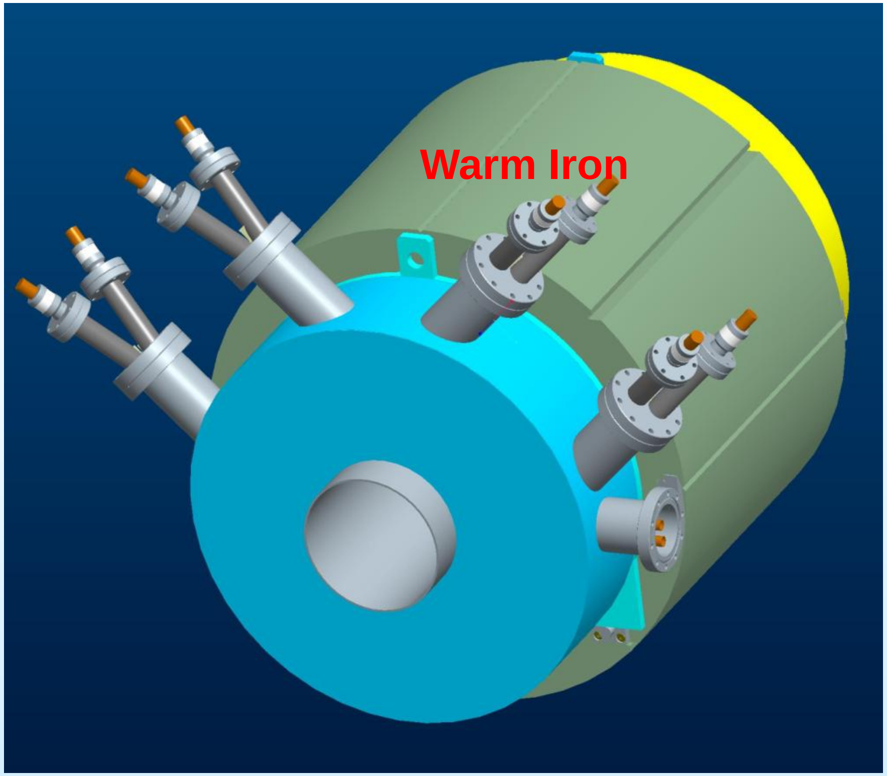
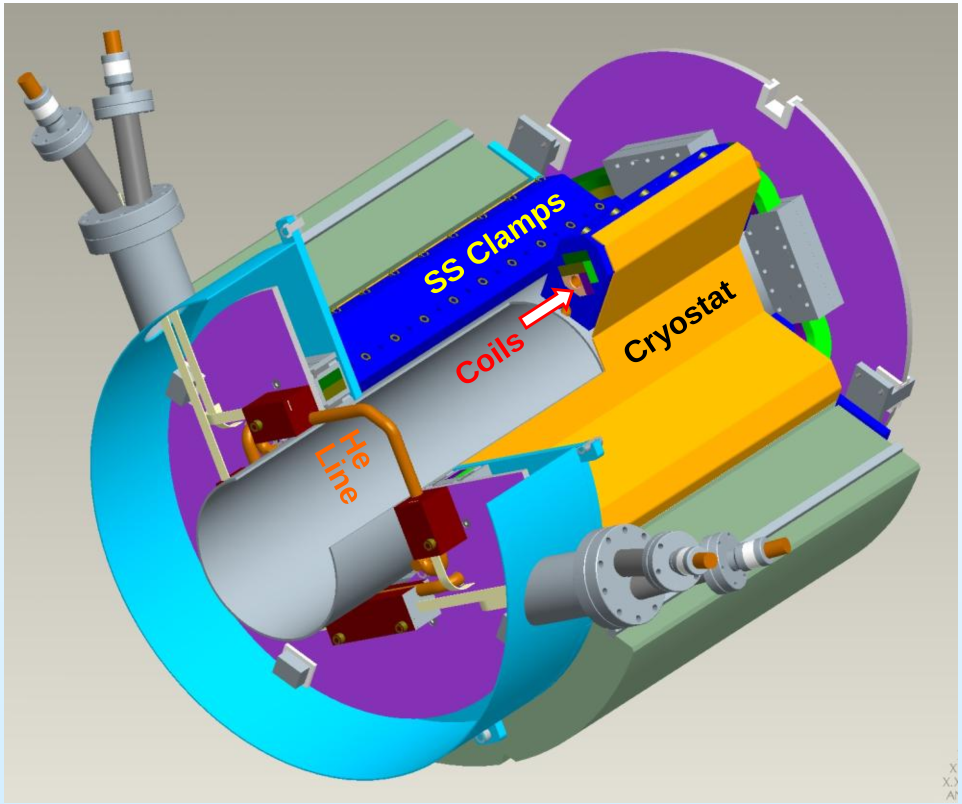
Cryo-mechanical Structure





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)

Winding of Second Generation HTS Racetrack Coil for FRIB

Goal: Demonstrate that HTS from two vendors is suitable.

- **Critical material (didn't want to rely only on one vendor)**

Eight coil wound with significant amount of HTS:

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 a12 mm tape
(3X than standard 4 mm)

Coils Assembled in Quadrupole Support Structure

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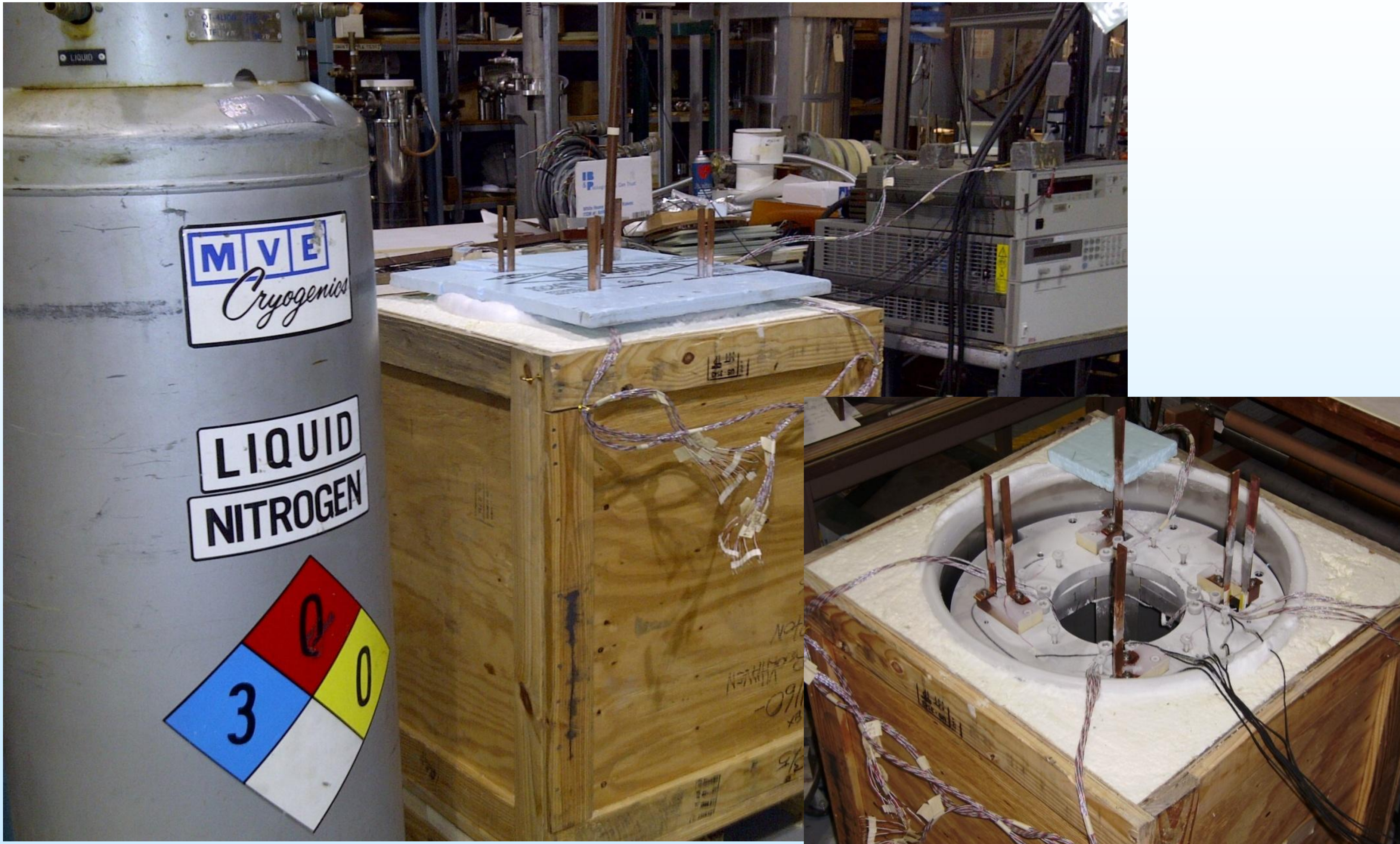
HTS Quad in Unique Cryostat



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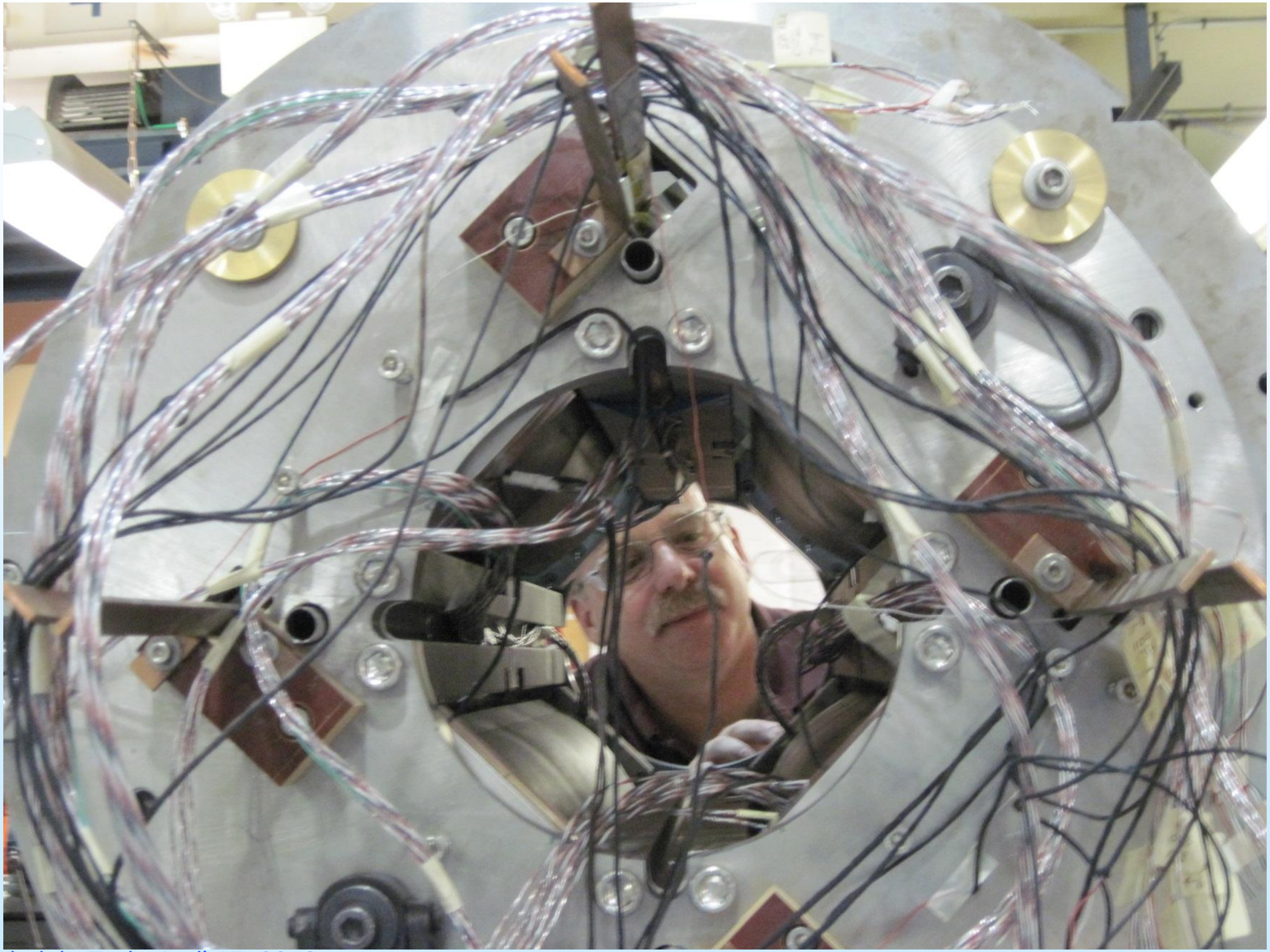
Aperture of 2G HTS Quad for FRIB



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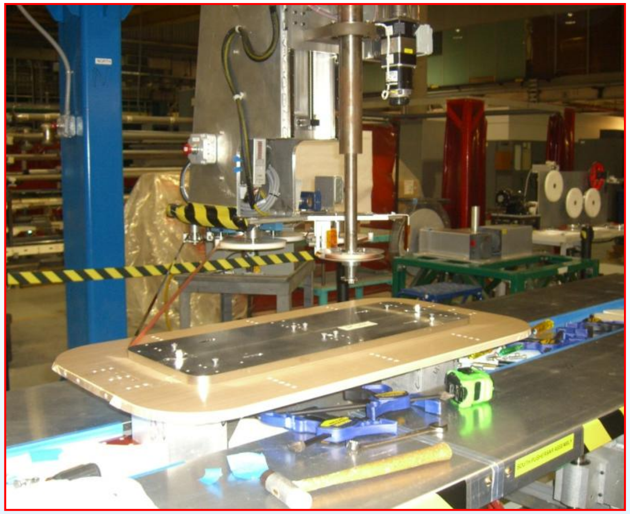
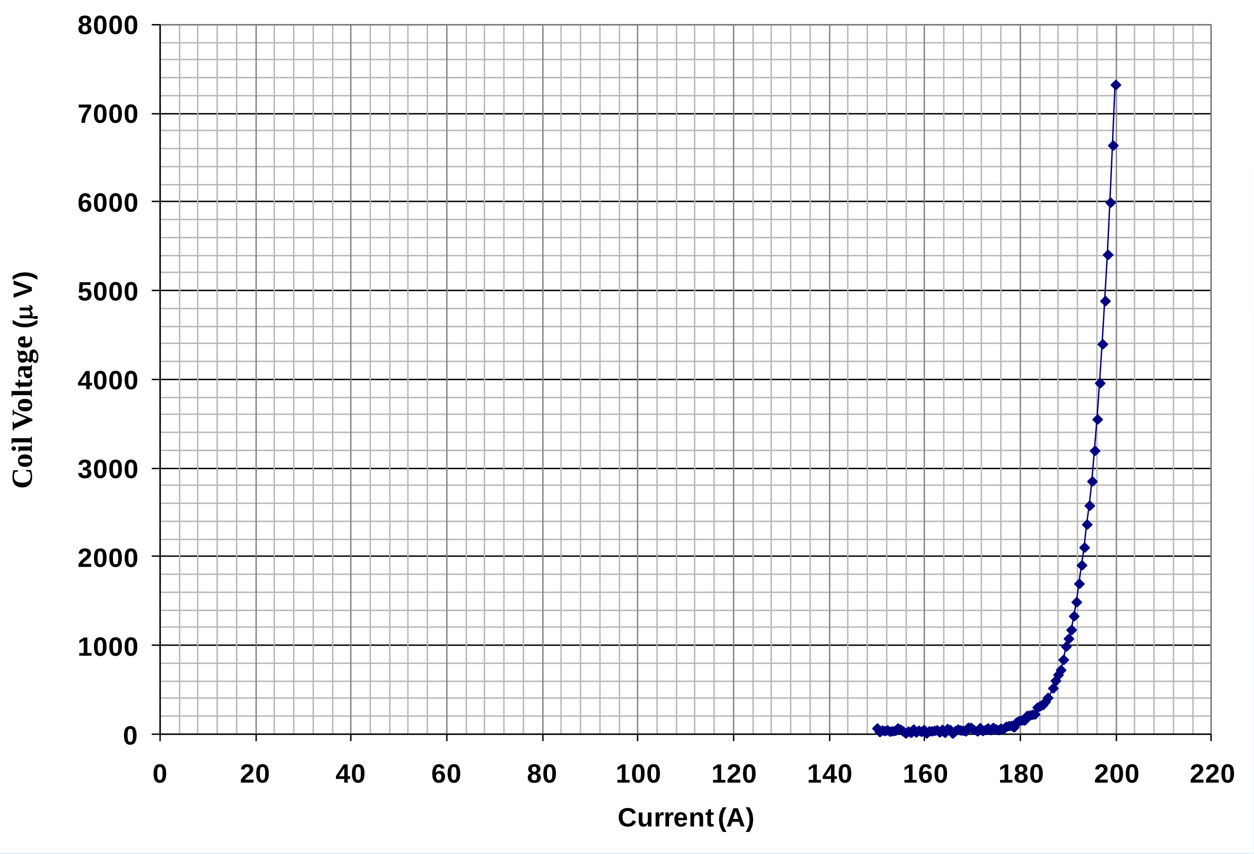
Completed 2G HTS Quad for FRIB

77 K Test Results of an Individual Coil

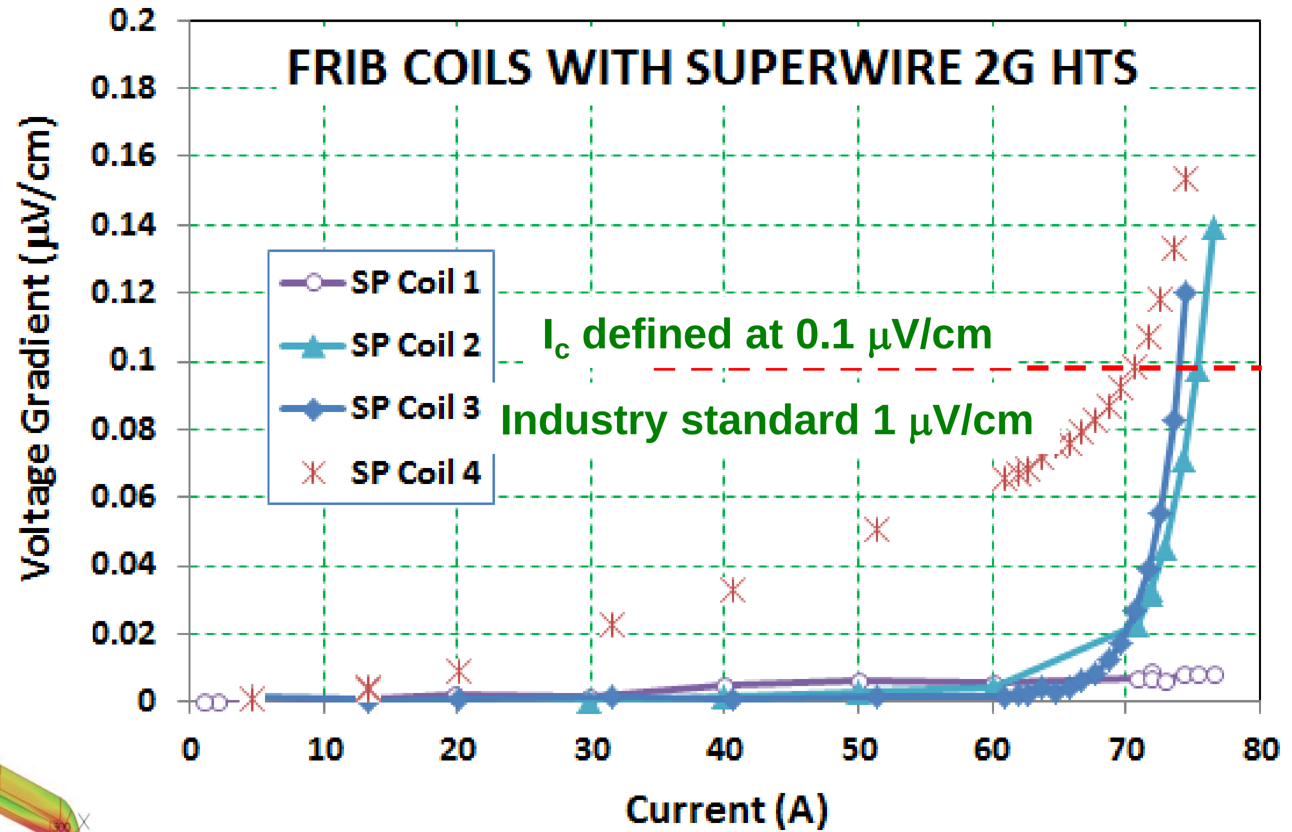




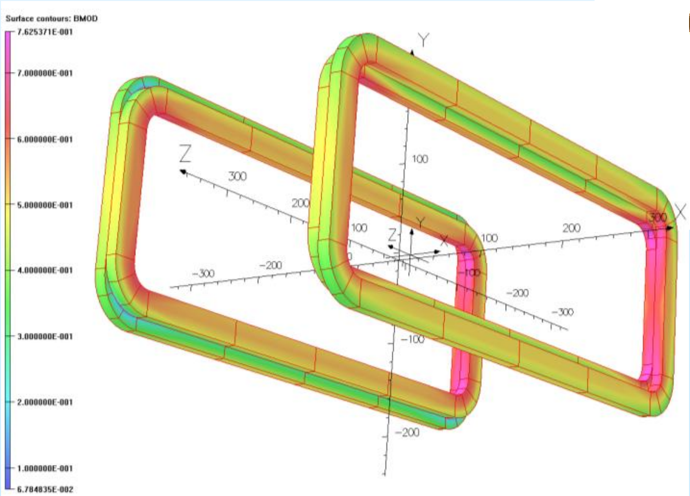
Measurement in liquid nitrogen (~77 K) of critical current in FRIB coil (large, outer, 126 turns made with ~210 meter tape from American Superconductor Corporation). The critical current in coil with 0.1 µV/cm definition (total coil voltage 2.1 mV) is 193.4 A.

Performance of SuperPower Coils (four of eight coils powered)

Four ASC coils were not powered

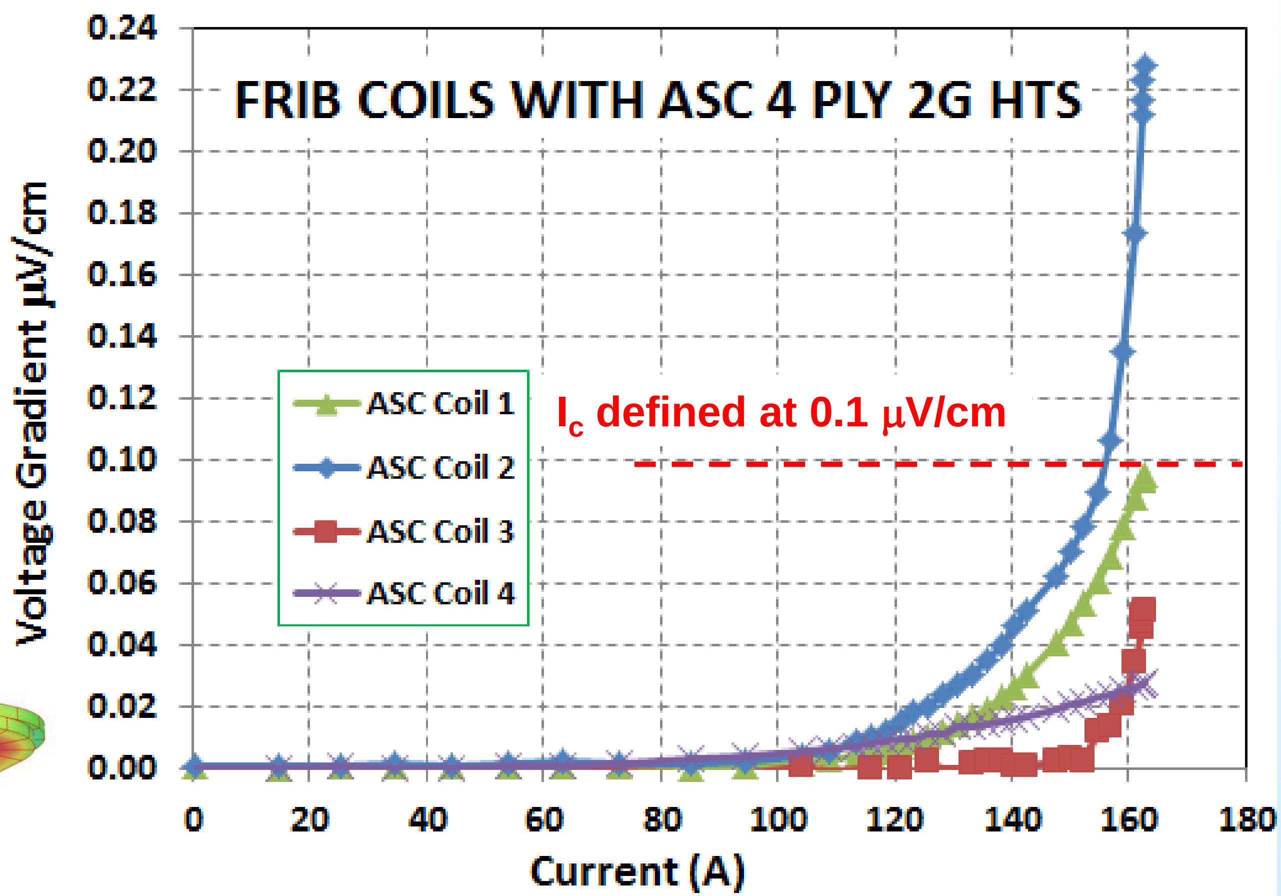


Field on SuperPower coils at 100 A



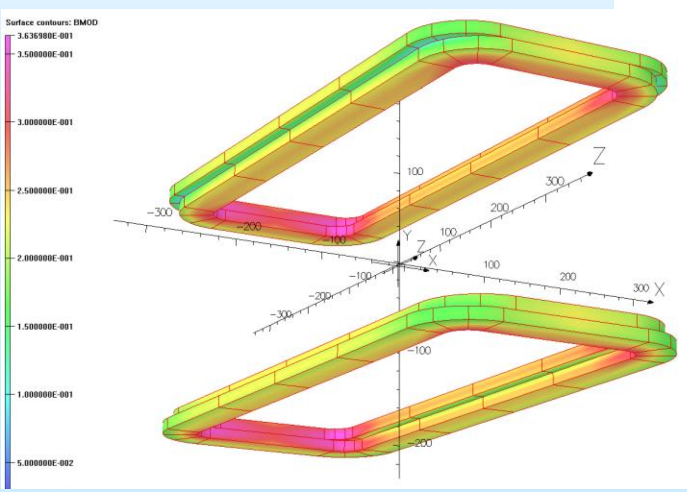
Internal splice on wrong tape side shows higher resistance. This is not an operational issue as the heat generated is negligible as compared to the energy deposition.

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

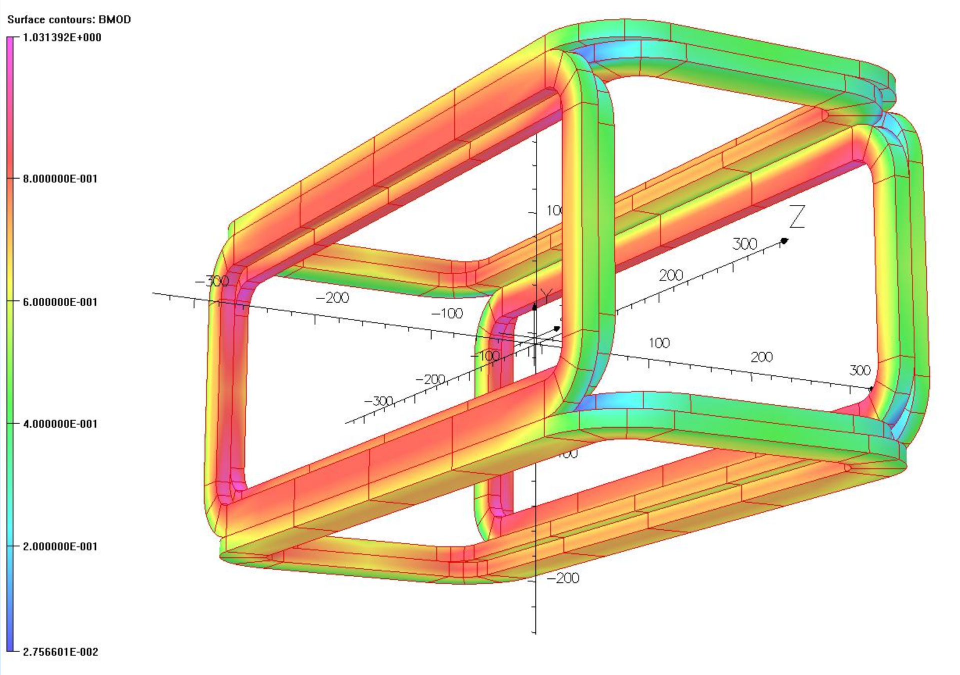
Four SuperPower coils not powered

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.

Radiation Damage Experiments

Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

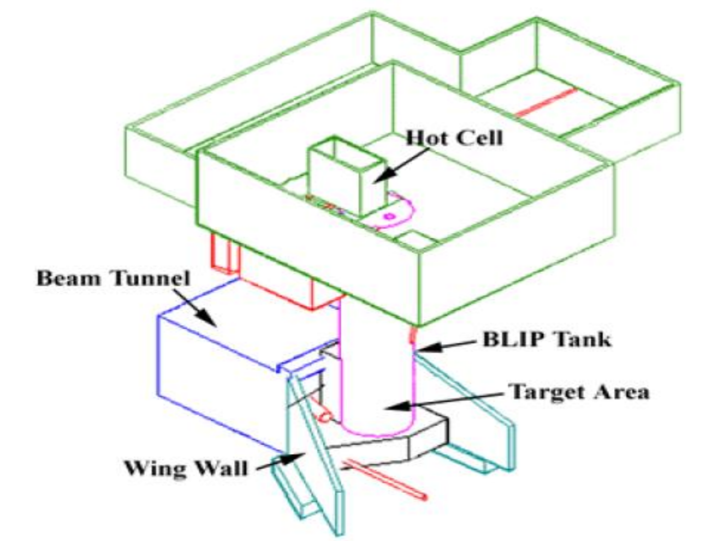
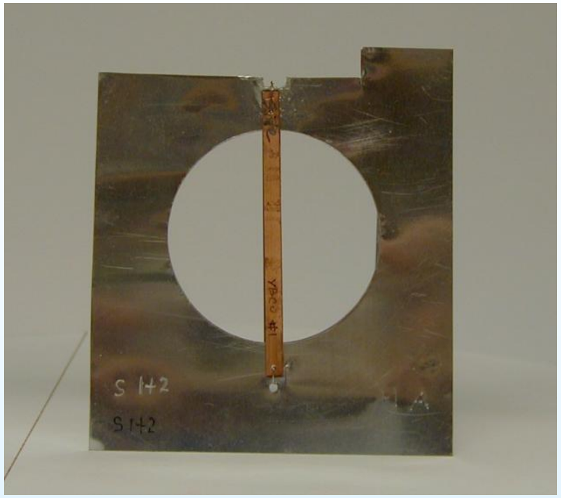


Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

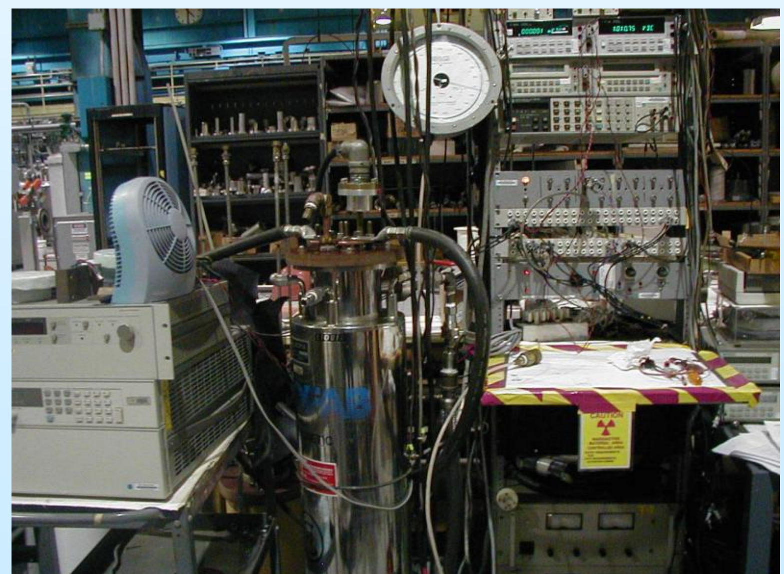
The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 µA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

Key Steps in Radiation Damage Experiment



142 MeV,

100 μA protons



HTS Samples Examined

- YBCO samples from both vendors (SuperPower and ASC).
- Twenty samples irradiated – 2 each from both at five doses (10^{16}, 10^{17}, 2×10^{17}, 3×10^{17} and 4×10^{17} protons/cm^2).
- 10^{17} protons/cm^2 (25 μA-hrs integrated dose) is equivalent to over 15 years of FRIB operation (the goal is 10 years).

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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)

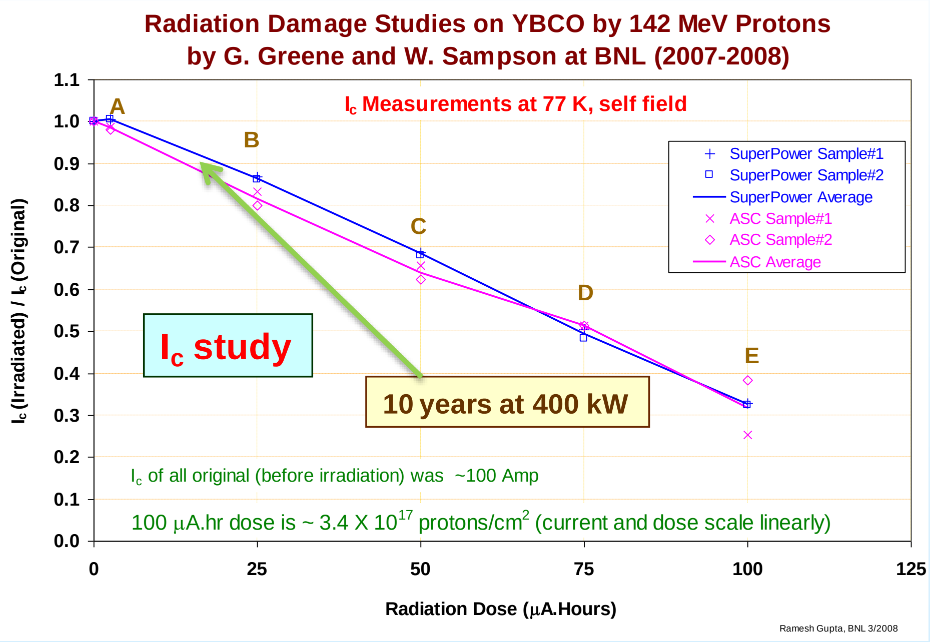
• **This gives ~0.033 dpa at 100 μA.hr for the maximum dose.**

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.**

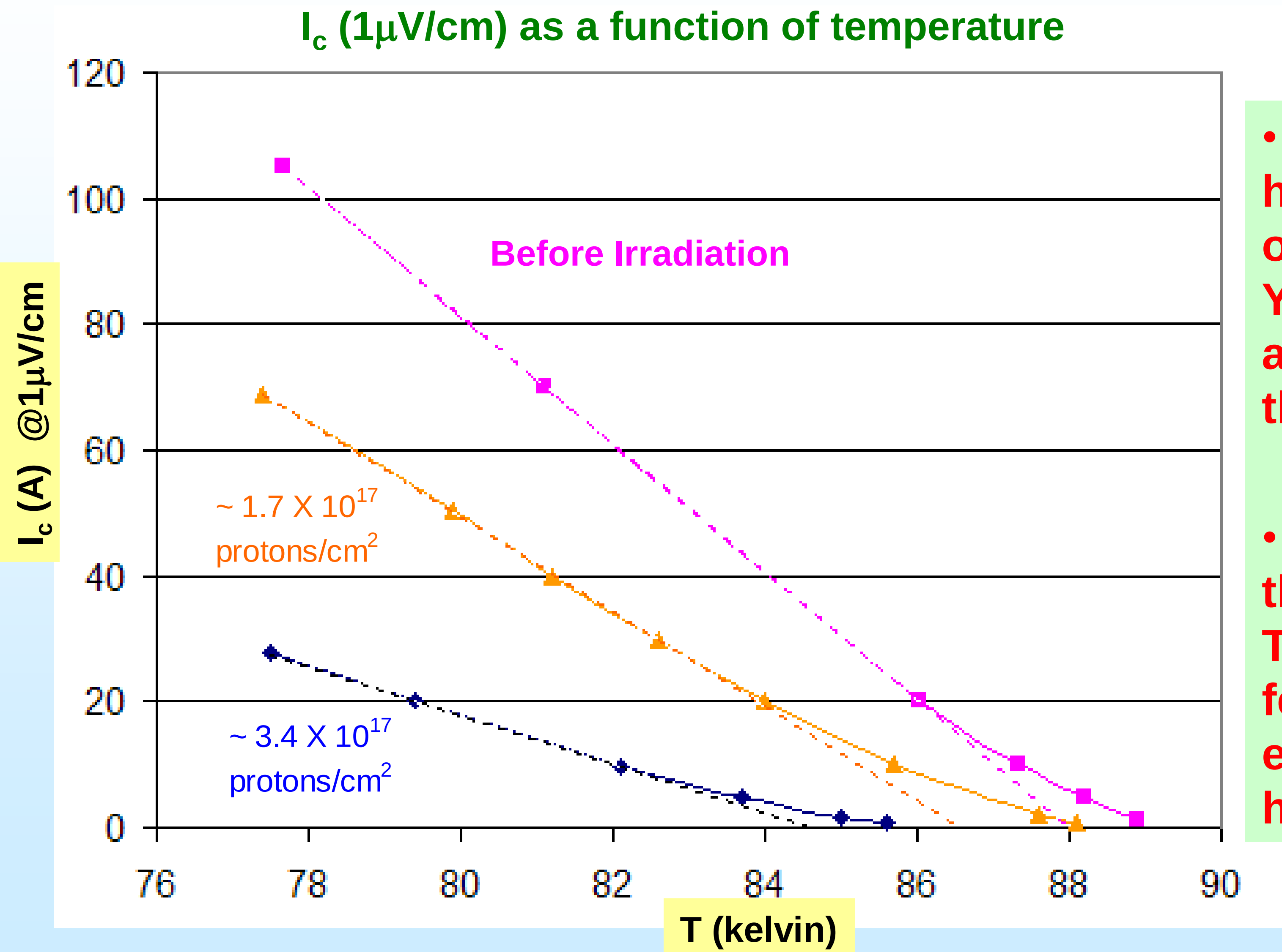
• **Drop in I_c at maximum dose (of theoretical interest) is ~70%.**



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

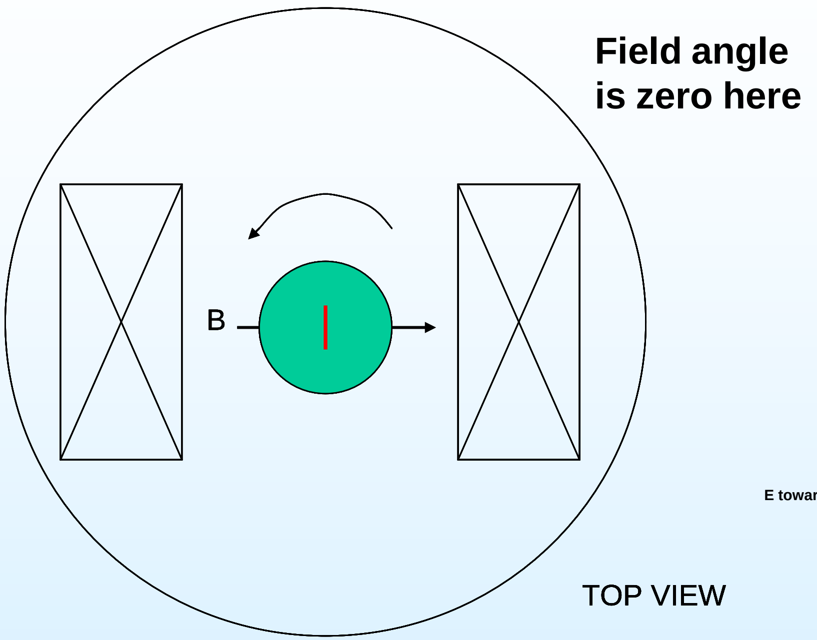
SuperPower and ASC show very similar radiation tolerance at 77 K, self field

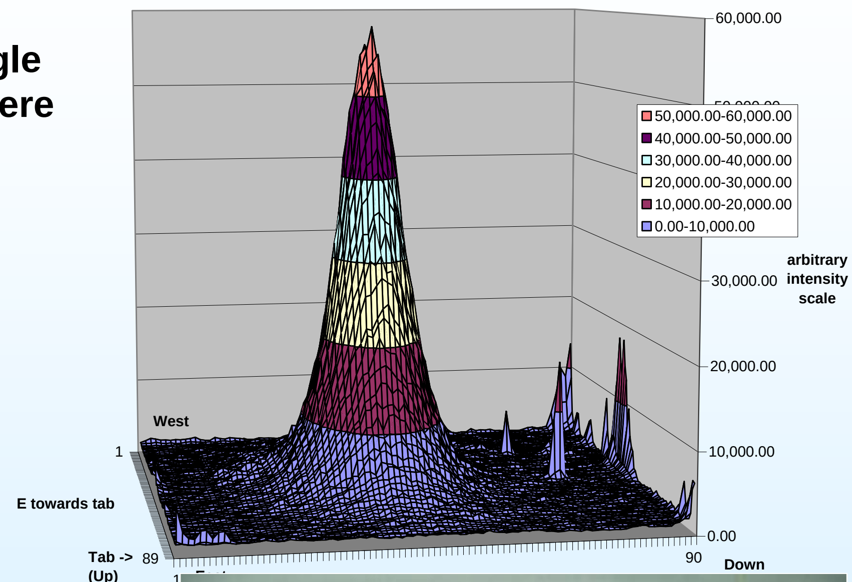
Change in Critical Temperature (T_c) of YBCO Due to Large Irradiation

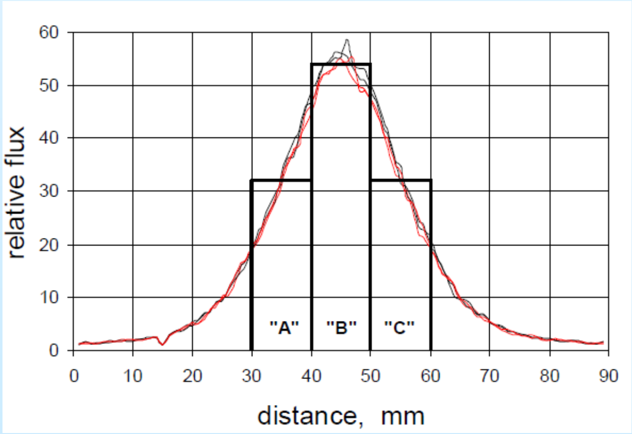


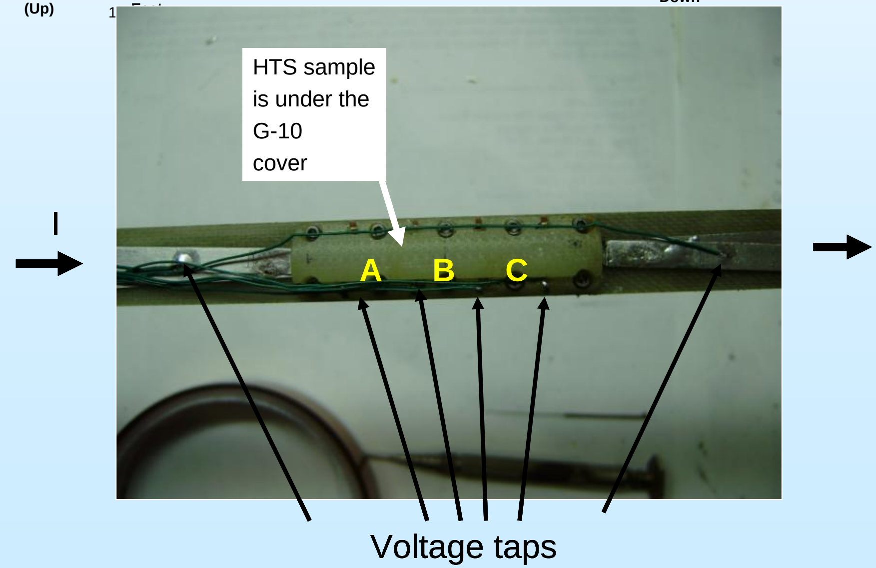
- Radiation has an impact on the T_c of YBCO, in addition to that on the I_c.
- However, the change in Tc is only a few degrees, even at very high doses.

Measurements of Radiation Damage in Presence of Field

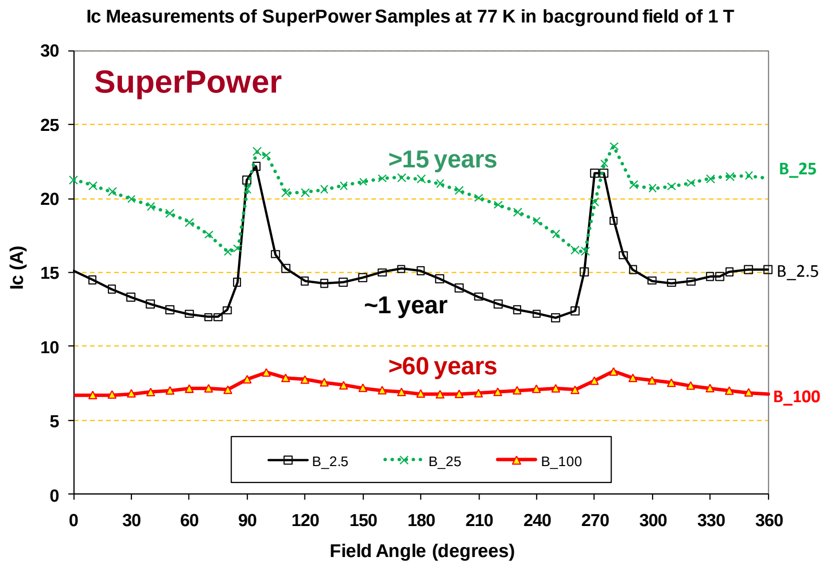


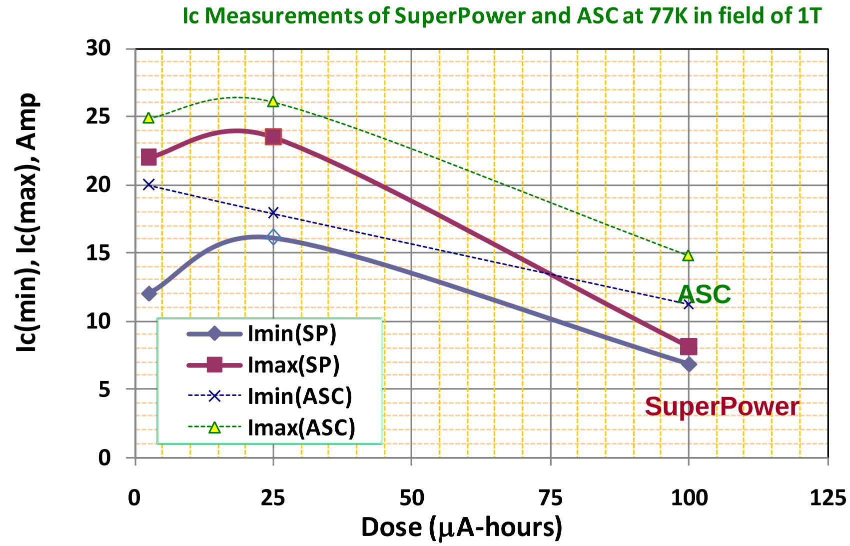




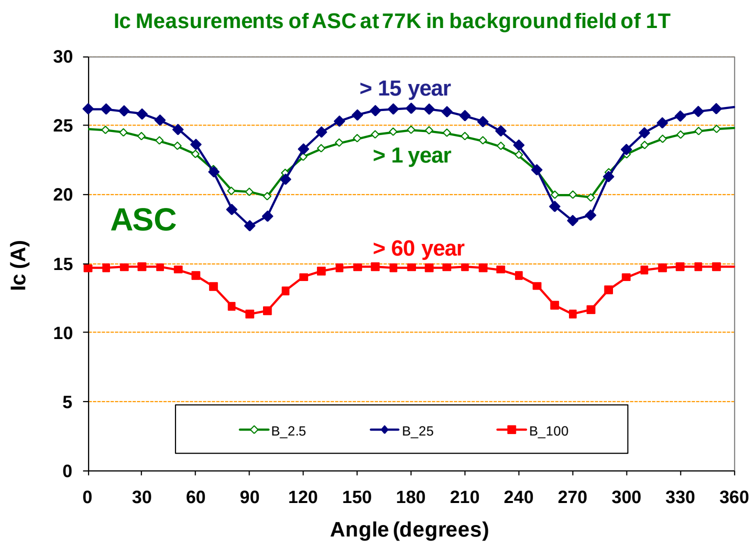


Radiation Damage from 142 MeV protons in SP & ASC Samples (measurements at @77K in 1 T Applied Field)





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)!!!

Summary

- HTS offers a unique magnet solution to some critical magnets of FRIB and nuSTORM.
- Recent experience at BNL has demonstrated that HTS magnets can be successfully built using a large amount of HTS
- It has been demonstrated that HTS can be reliably operated at elevated temperatures in presence of large heat loads.
- Experiments show that HTS is robust against radiation damage.
- HTS quad is now part of the baseline design of FRIB.
- FRIB could be the 1st major accelerator with HTS magnets playing a crucial role and perhaps nuSTORM second.
- HTS magnet design and technology which is currently being developed for FRIB can be applied to nuSTORM too.