HTS Magnets for Special Applications

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August 23, 2012

Rare Isotope Science Project

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Outline

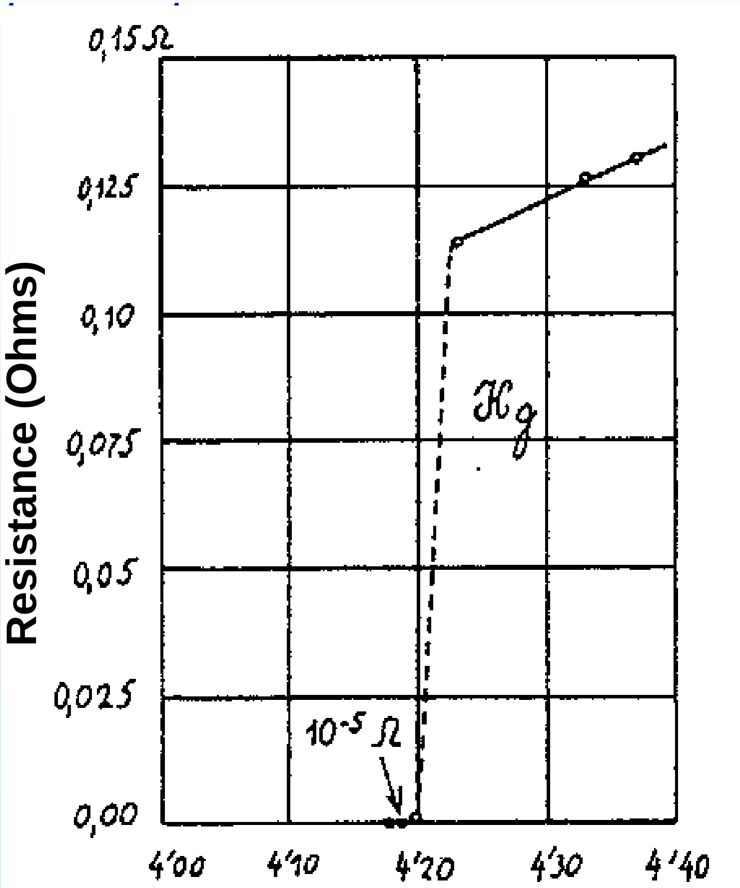
- High Temperature Superconductors (HTS)
- HTS magnet program at BNL
- Benefits of HTS magnets in FRIB (and in RISP)
- HTS Magnet R&D for FRIB
  - Phase I (including Energy deposition studies)
  - Phase II (including Radiation damage studies)
- Other HTS magnets for FRIB (quad, dipole, corrector)
- HTS magnets for other projects (including 40 T for MAP)
- Summary

HTS Magnet Technology

Conventional Low Temperature Superconductors (LTS) and New High Temperature Superconductors (HTS)

Low Temperature Superconductor Onnes (1911)

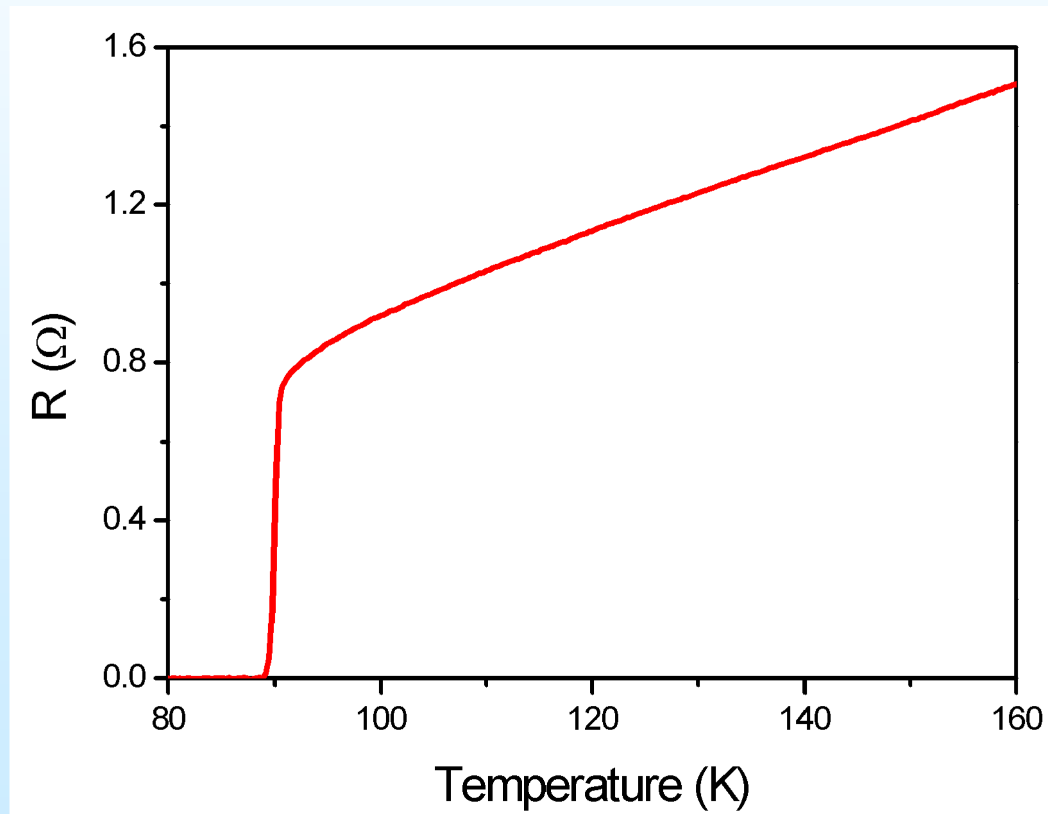
Resistance of Mercury falls suddenly below meas. accuracy at very low (4.2)



Temperature (K)

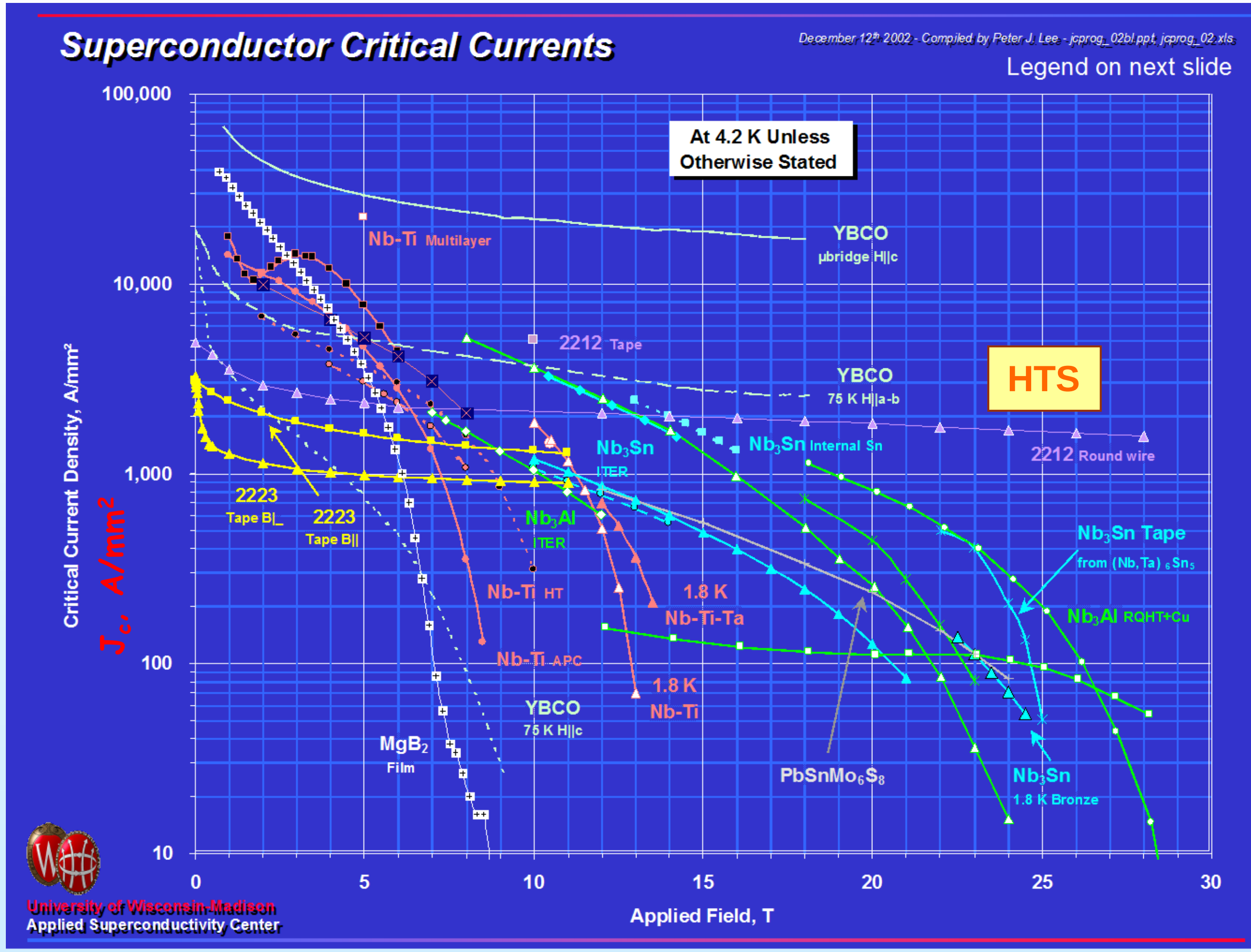
New materials (ceramics) loose their resistance at NOT so low temperatures (Liquid Nitrogen)!

High Temperature Superconductors (1986)



Another Remarkable Property of HTS
The High Field Current Carrying Capacity

Compare J_c Vs. B between conventional Low Temperature Superconductors (LTS) and High Temperature Superconductors (HTS)



Applied Field, T

Advantages of using HTS in Accelerator Magnets

As compared to Low Temperature Superconductors (LTS), the critical current in High Temperature Superconductors falls slowly

- as a function of temperature
- as a function of field

<u>Translate this to magnet design and accelerator operation:</u>

- HTS based magnets can operate at elevated temperatures
  - a rise in temperature from, e.g., decay particles can be tolerated
  - the operating temperature doesn't have to be controlled precisely
- HTS has the potential to produce very high field magnets

Possible Application of HTS in Accelerator Magnets

High Field, Low Temperature Application

Example: Interaction Region (IR) Magnets for large luminosity

• At very high fields (~18 T or more), no superconductor has as high a critical current density as HTS does.

Medium Field, Higher Temperature Application

Example: Quads for Rare Isotope Science Project (RISP)

• These applications don't require very high fields.

• The system design benefits enormously from HTS because HTS offers the possibility of magnets which operate at a temperature higher than 4K, say at 20-40 K.

• In both cases, HTS magnets can tolerate a large increase in coil temperature with only a small decrease in magnet performance.
• Moreover, the operating temperature need not be controlled precisely
➢ One can relax about an order of magnitude in controlling temperature variations

HTS allows a few degrees variation, as compared to a few tenth of a degree in LTS.

HTS Magnet Program at BNL

HTS Magnet Programs at BNL (1)

- BNL has been active in developing HTS technology for well over a decade.
- We have used all types of HTS
  - Bi2212 (tape and Rutherford cable)
  - Bi2223
  - MgB_2
  - YBCO (Second Generation)
- The size of our HTS program is significant. It can be gauged by the amount of HTS coming in. We have received or are in the process of receiving over 50 km of HTS (normalized to the standard 4 mm tape equivalent) for various programs.

HTS Magnet Programs at BNL (2)

- Designed, built and tested a large number of HTS magnets:
  - Number of HTS coils built: >>100
  - Number of magnet structures built and tested: >10
- HTS magnet R&D on a wide range of programs:
  - High T, low B
  - Medium T, medium B
  - Low T, high B
- These varieties of programs help each other in developing a wider understanding while efficiently sharing resources

BNL Role in HTS Magnet Development for FRIB

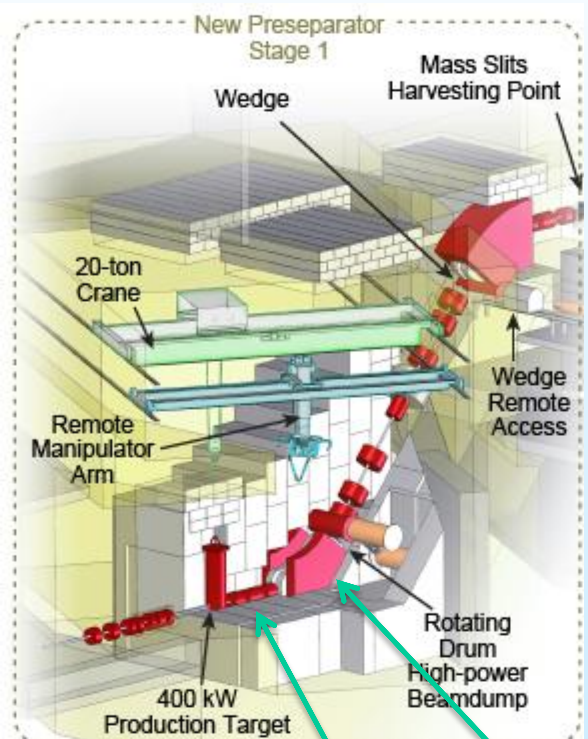
- BNL proposed HTS magnets for FRIB and has been the primary institution for developing HTS magnet technology for FRIB
- BNL has designed, built and tested 1st and 2nd generation HTS quad for FRIB
- BNL has carried out energy deposition experiments
- BNL has carried out radiation damage experiments
-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

Benefits of
HTS Magnets in FRIB
(also in RISP)

Radiation and Heat Loads in Fragment Separator Magnets

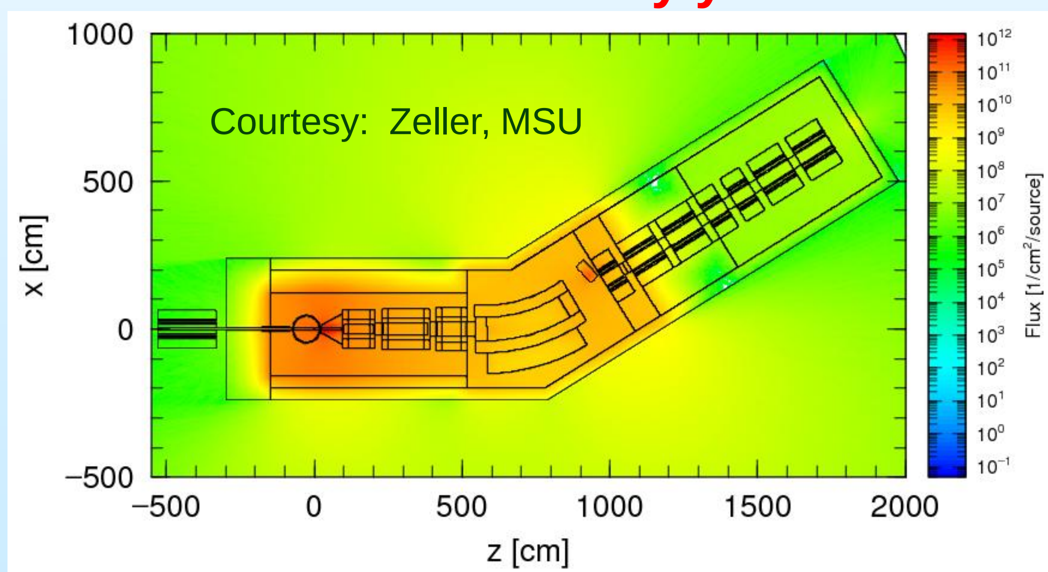
To create intense rare isotopes, 400 kW beam hits the production target.

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



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

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 reduces experimental times
- Robust and resistant to beam-induced quenches

Courtesy: Al Zeller, FRIB/MSU

Possible Technologies for Fragment Separator Magnets

1. Radiation resistant magnets with copper coils with special conductor using ceramic or other similar insulator
2. NbTi conventional superconducting magnets with radiation tolerant epoxy
3. Low temperature superconducting magnets with cable-in-conduit conductor (CICC), either NbTi or Nb3Sn
4. Radiation resistant and magnets with High Temperature Superconductor (HTS) that can operate at elevated temperature and can easily tolerate large energy and radiation deposition

Detailed investigation gave a surprised answer:
Not only HTS provided a technically superior solution, it was also a cheaper solution, when all costs were included

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

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

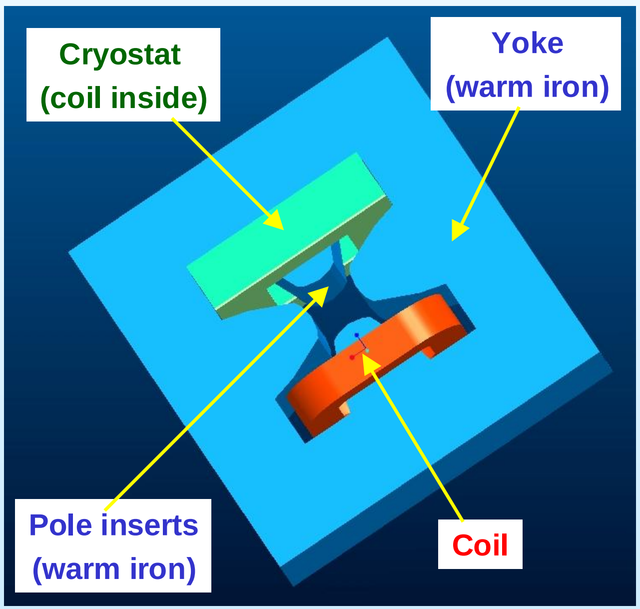
FRIB Quadrupole Design To Minimize Heat Load

The magnet is designed with warm iron and a compact cryostat to significantly reduce the amount of cold-mass on which the heat and radiation are deposited.

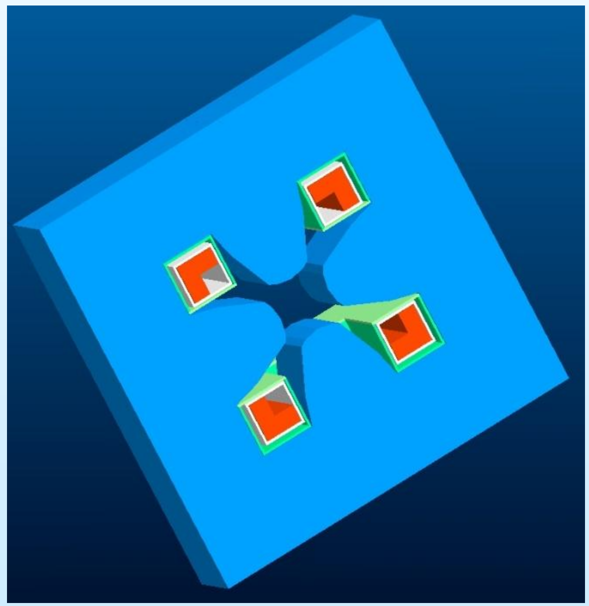
Quad is designed with two coils (NOT four) to reduce radiation load in ends.

Coils are moved further out to reduce radiation dose.

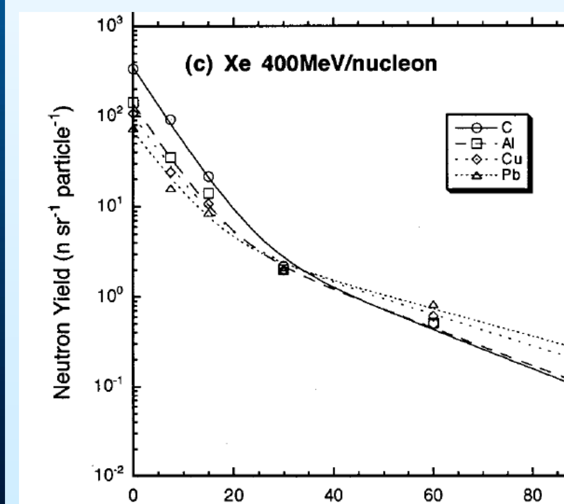
This design reduces the heat load from ~15 kW to ~0.13 kW on cold structure.



Coils inside the cryostat at the end of the magnet

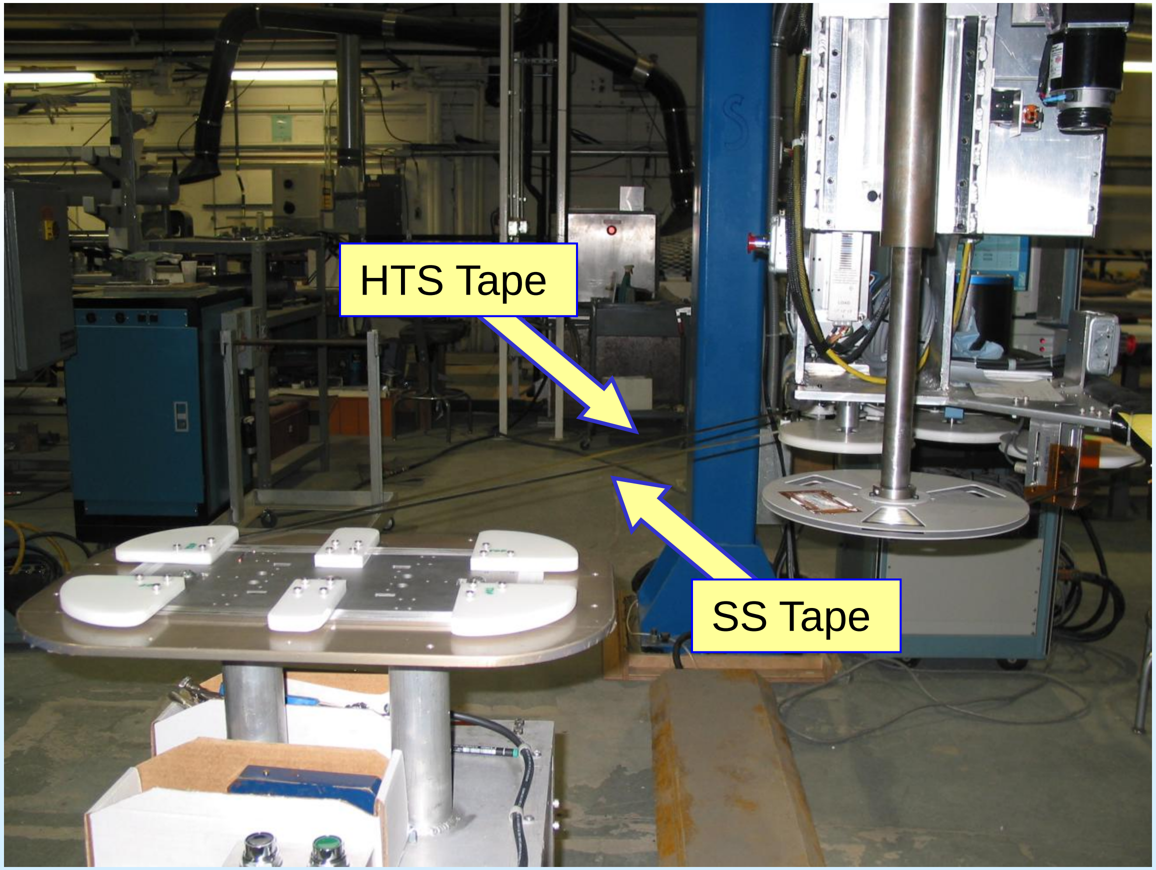


Cutout at the middle of the magnet

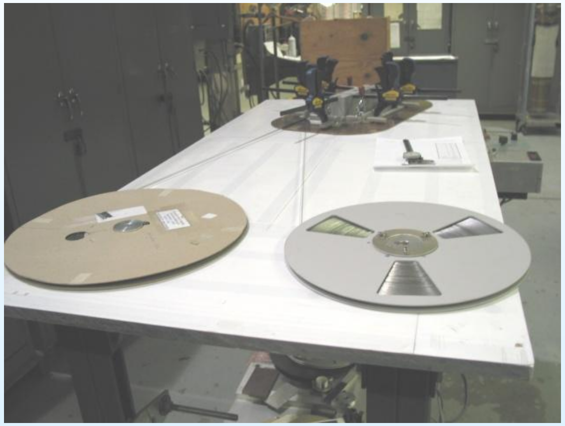


Significantly large neutron yield (radiation load) at small angles

HTS Coil Winding



A coil being wound in a computer controlled winding machine.



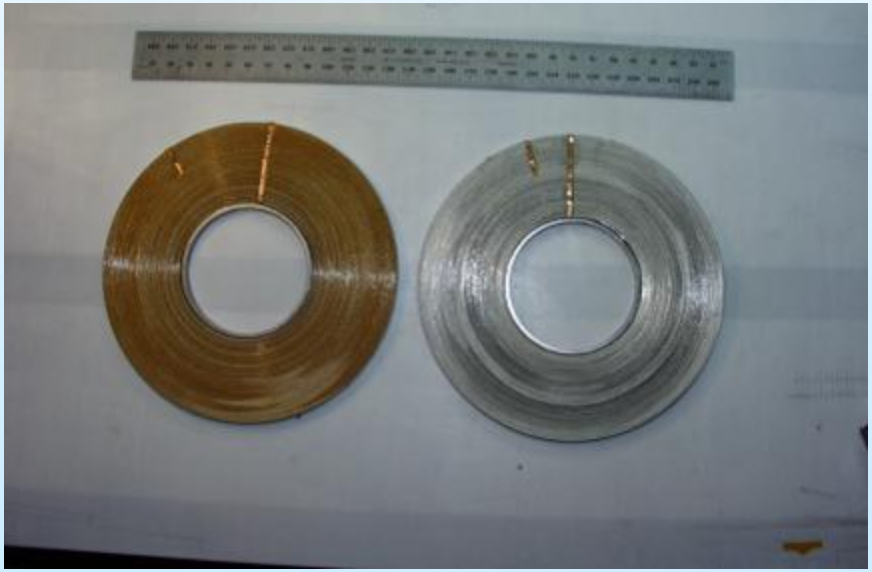
Earlier coils were wound with a machine that has more manual controls.

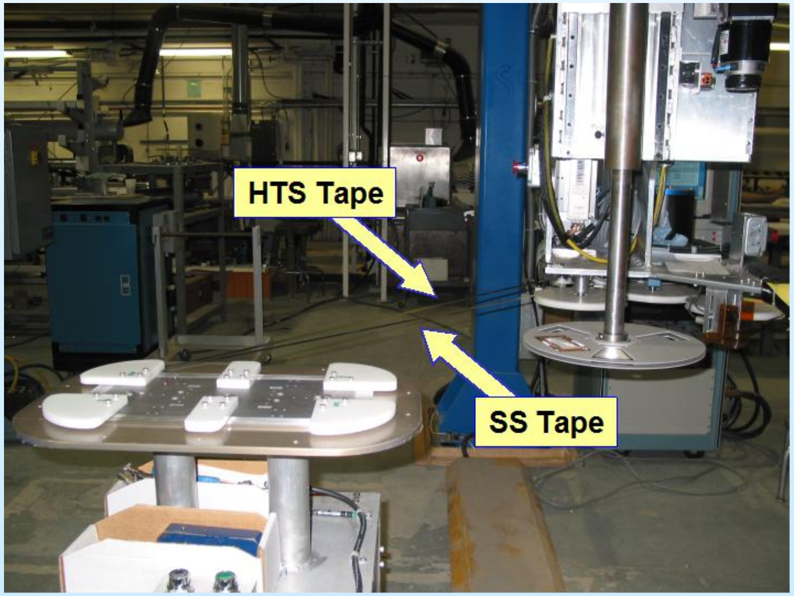
Insulation in HTS Coils in High Radiation Environment

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.

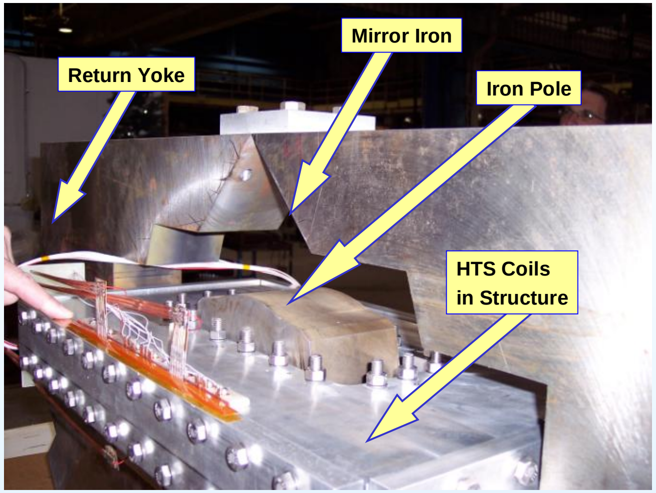




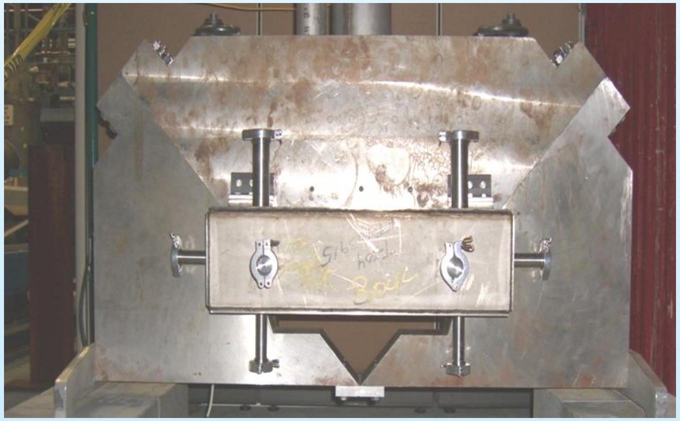
Design Parameters of 1st Generation HTS R&D Quadrupole for FRIB/RIA

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

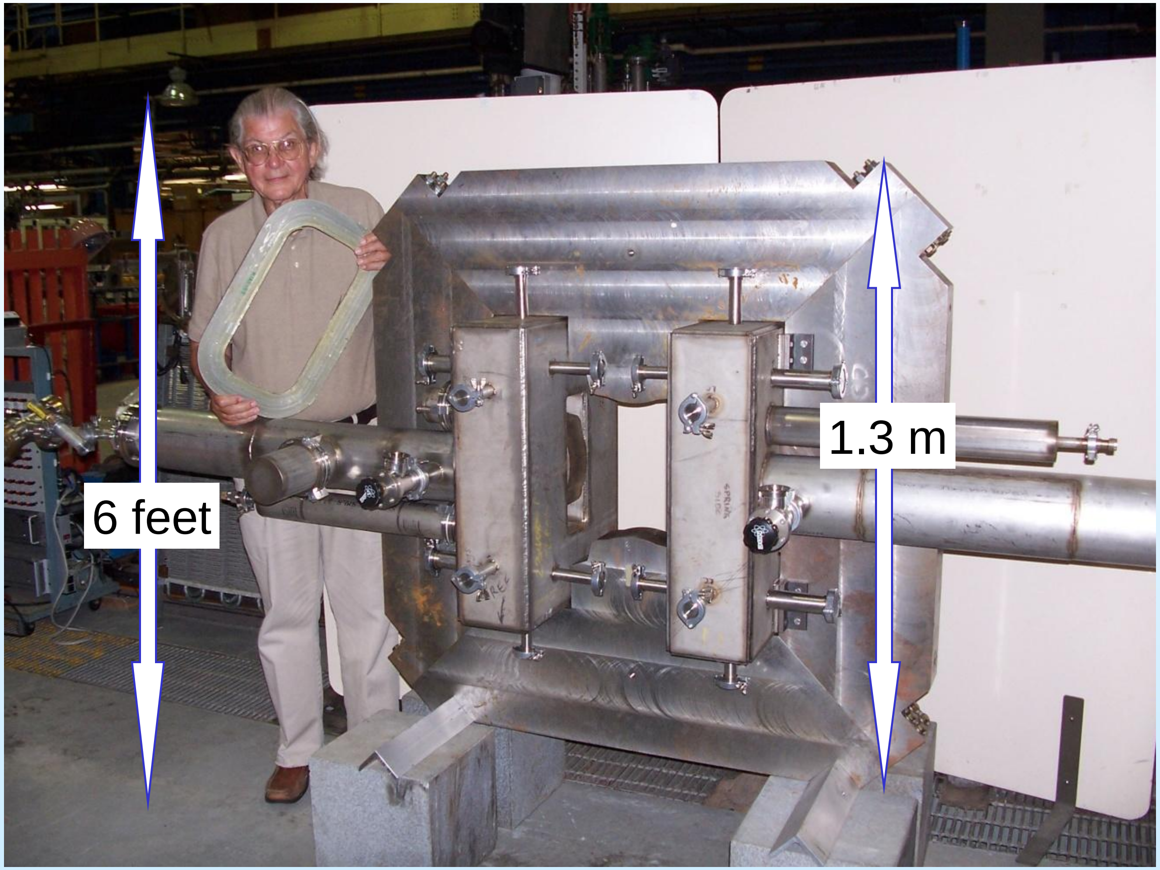
Magnet Structures for FRIB/RIA HTS Quad
(Several R&D structures were built and tested)



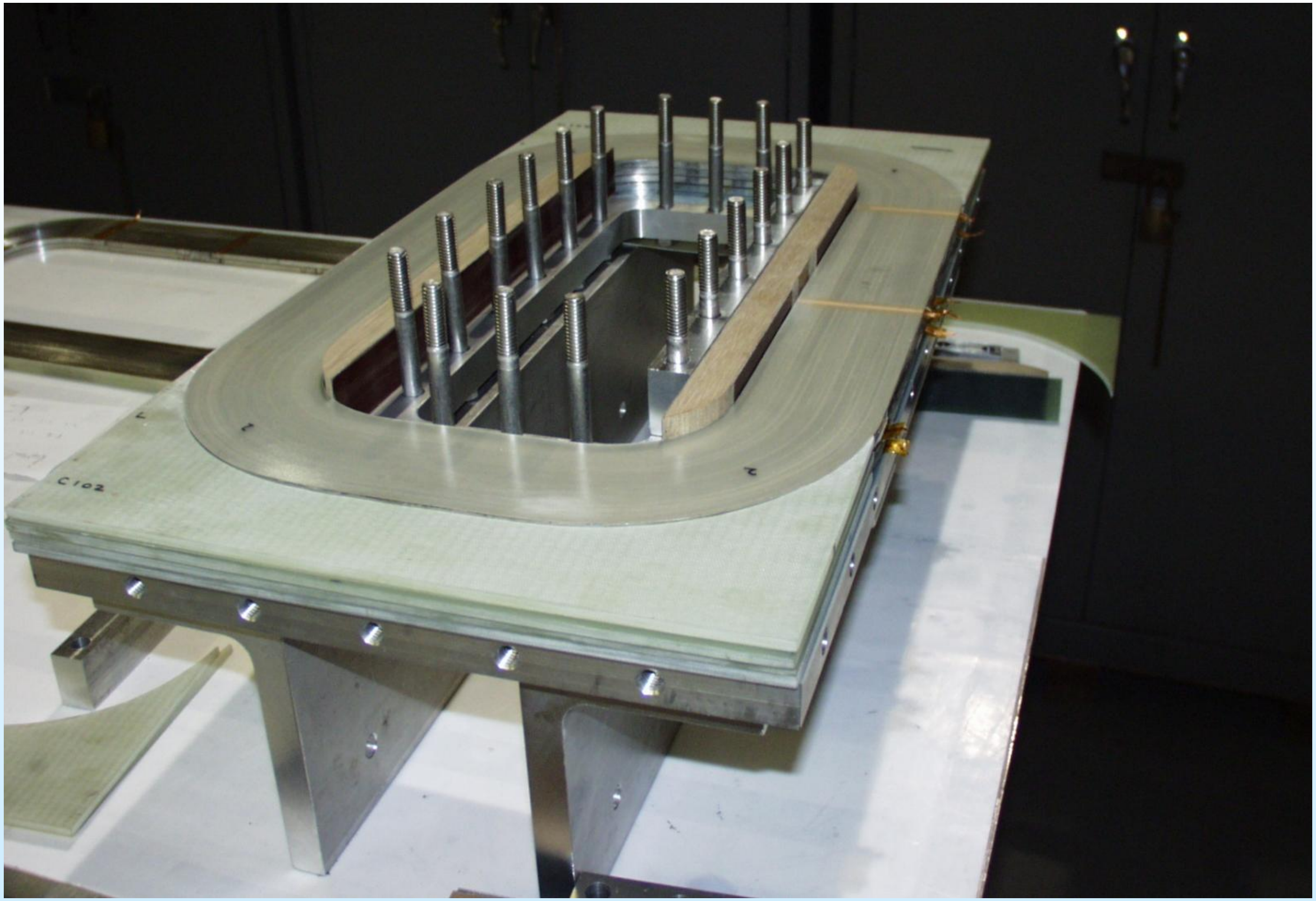
Mirror cold iron



Mirror warm iron



Assembled Coils with Internal Splice

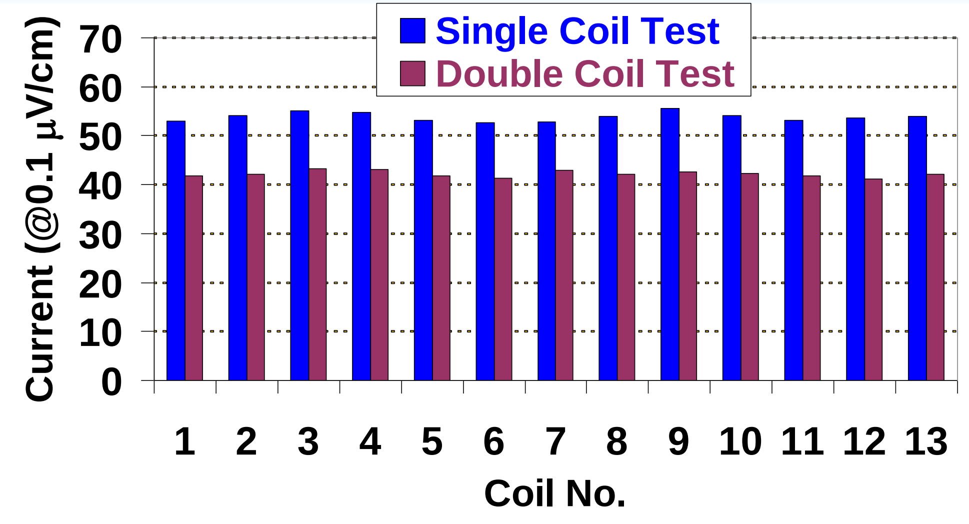


Three pairs of coils during their assembly a support structure.

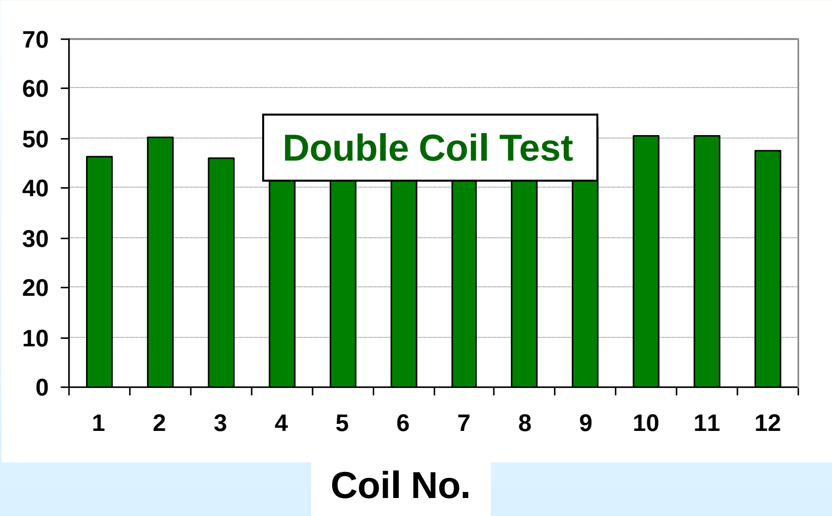
LN_2 (77 K) Test of Coils Made with ASC 1st Generation HTS

Each single coil uses ~200 meter of tape

13 Coils made HTS tape in year #1



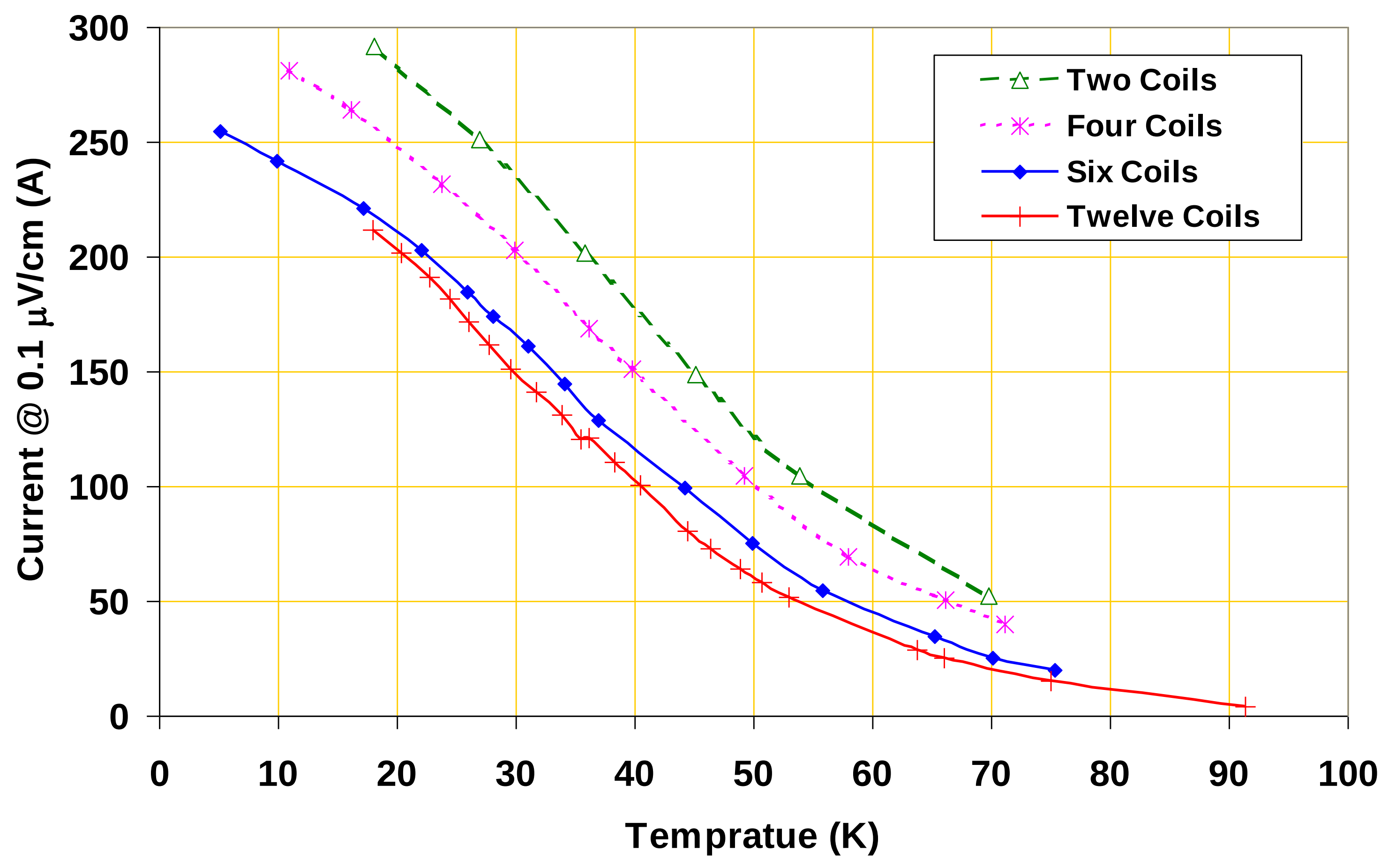
12 coils with HTS tape in year #2



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

It shows that the HTS coil technology has matured !

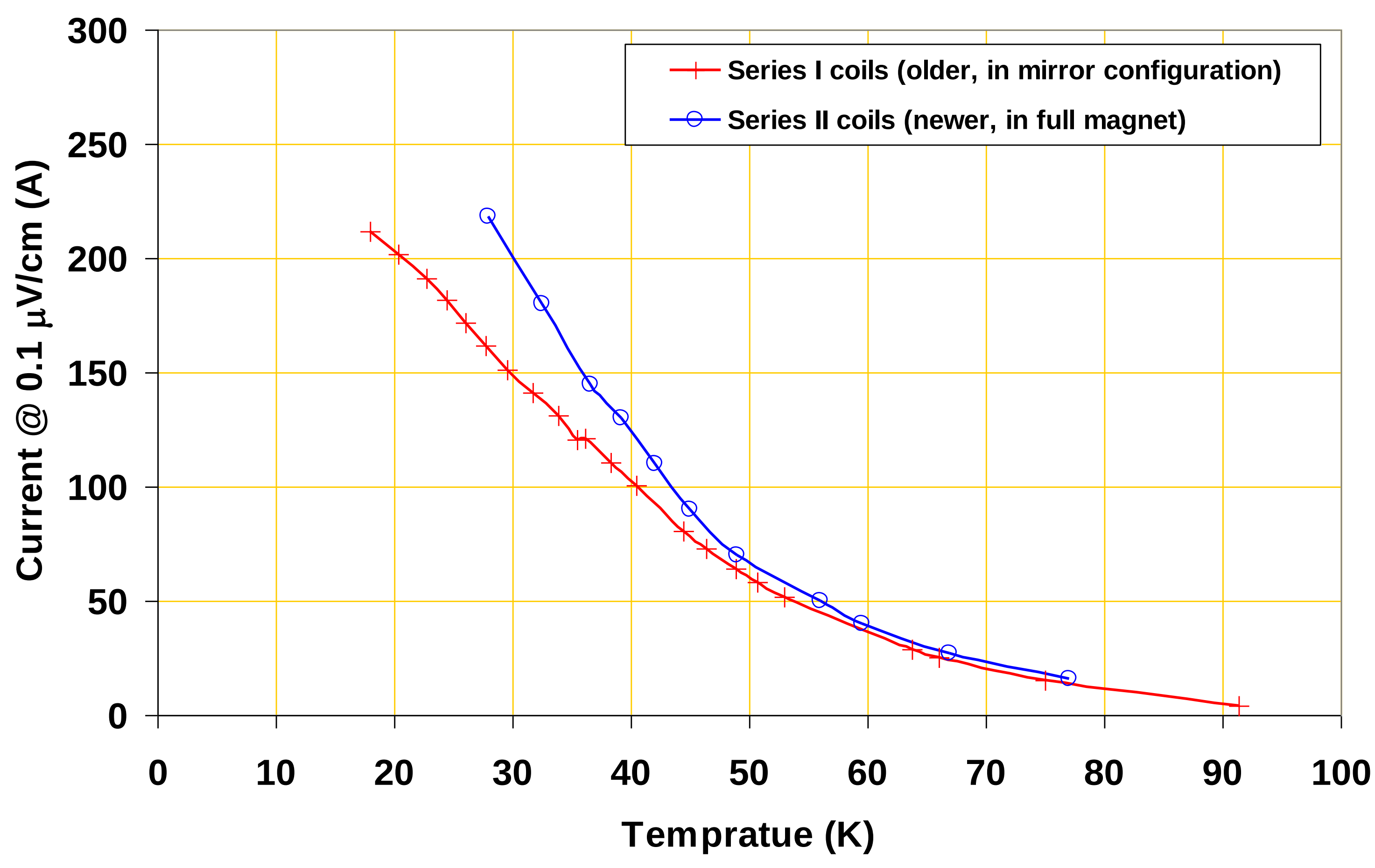
HTS Mirror Model Test Results
(operation over a large temperature range)



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

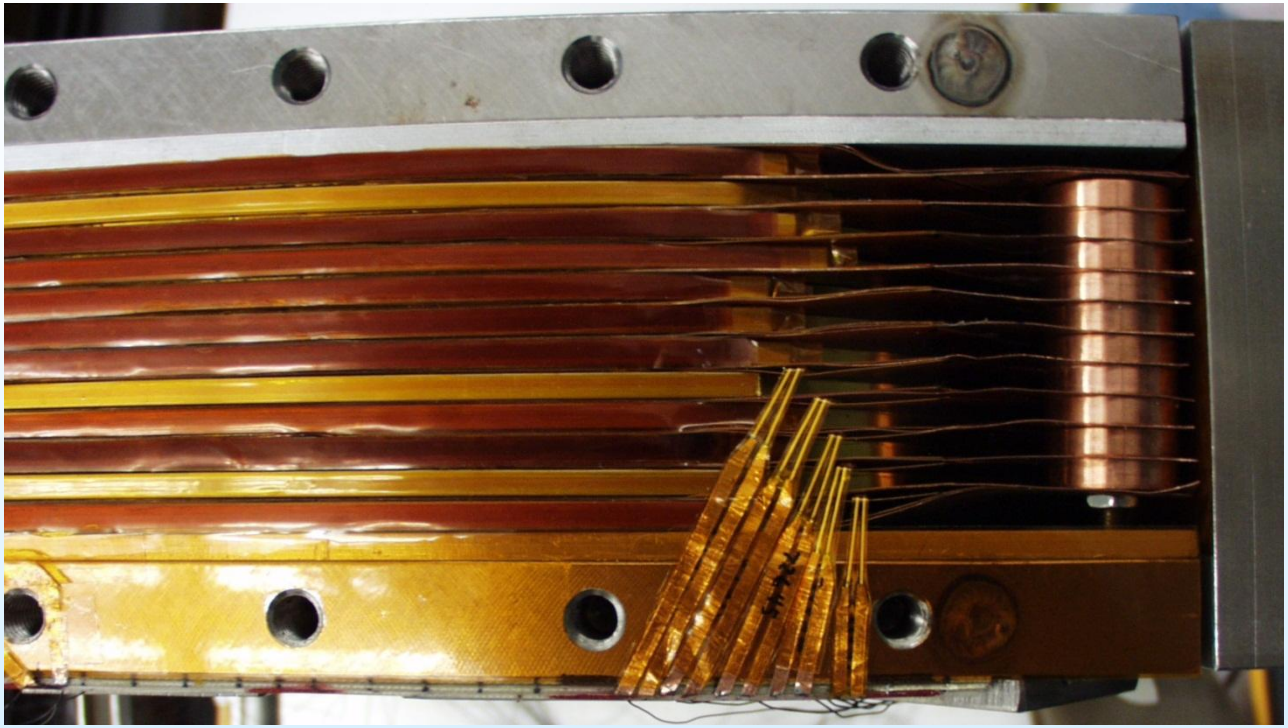
A summary of the temperature dependence of the current in two, four, six and twelve coils in the magnetic mirror model. In each case voltage first appears on the coil that is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for two coils.

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



Newer (series II) conductor was not only better at 77 K but also had relatively better performance at lower temperature.

Energy Deposition Experiments

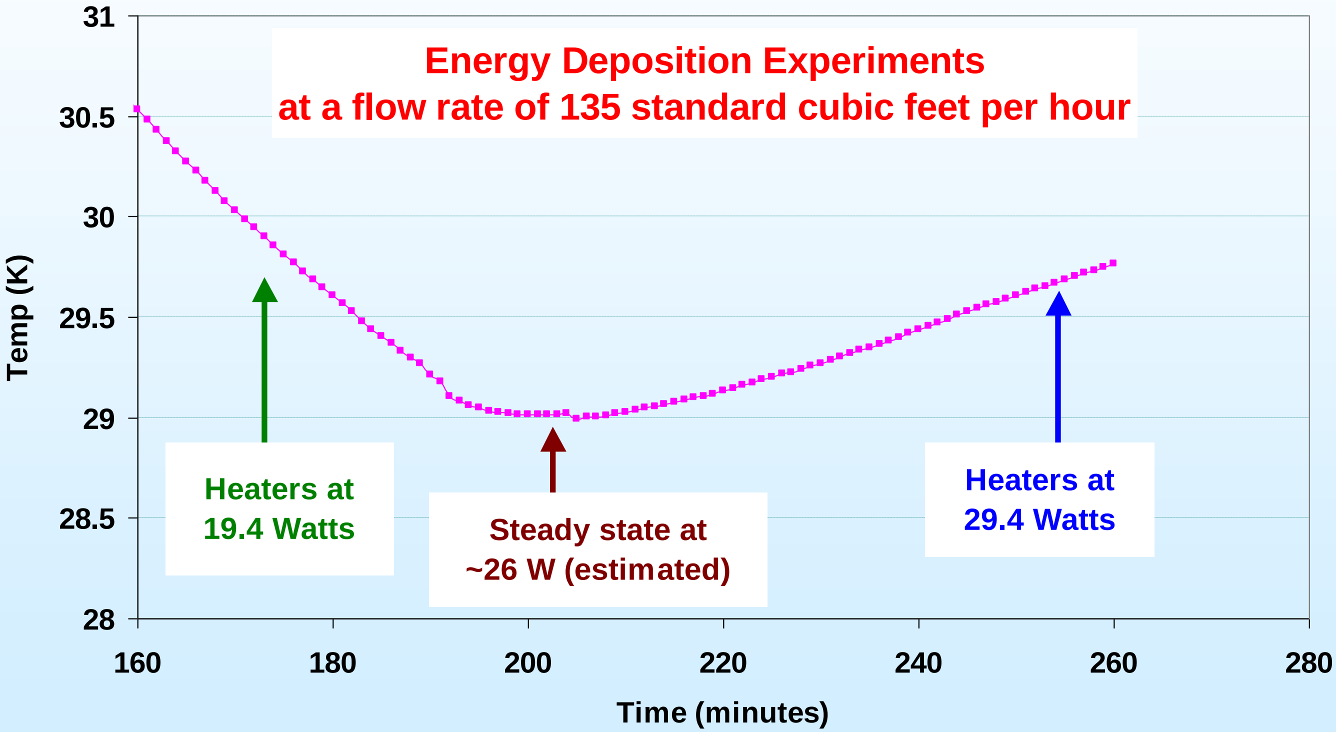


Stainless steel tape heaters for energy deposition experiments

- 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.

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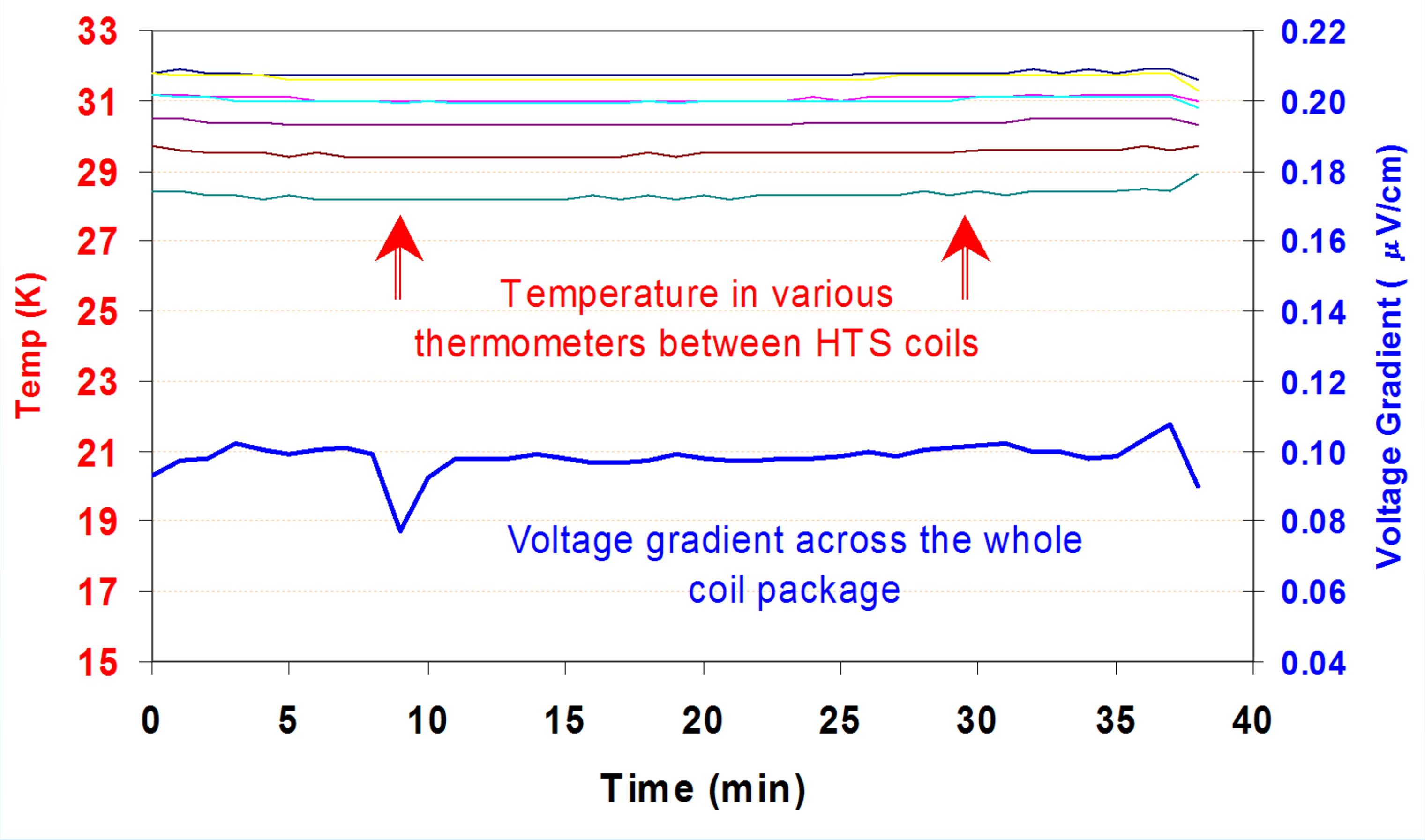
Superconducting Magnet Division

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

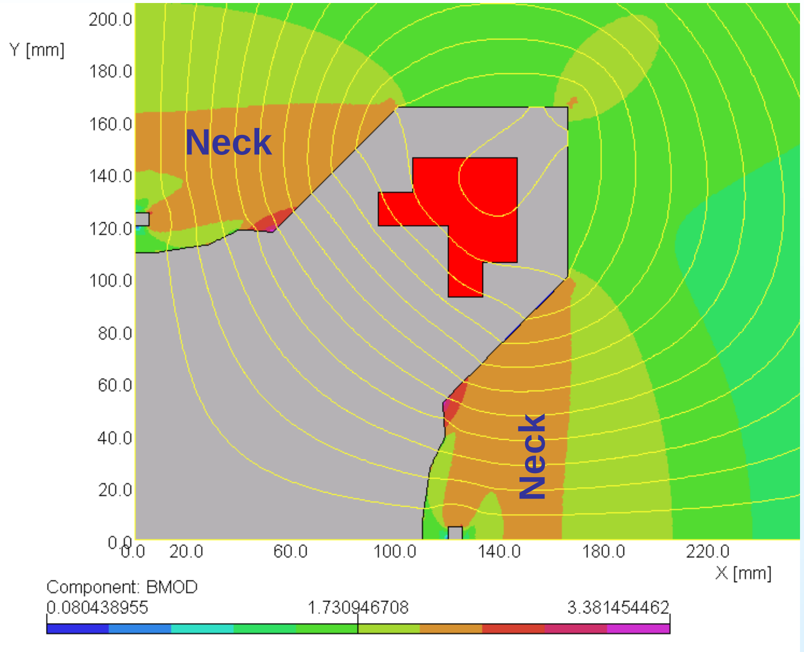
Why 2G HTS

- 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

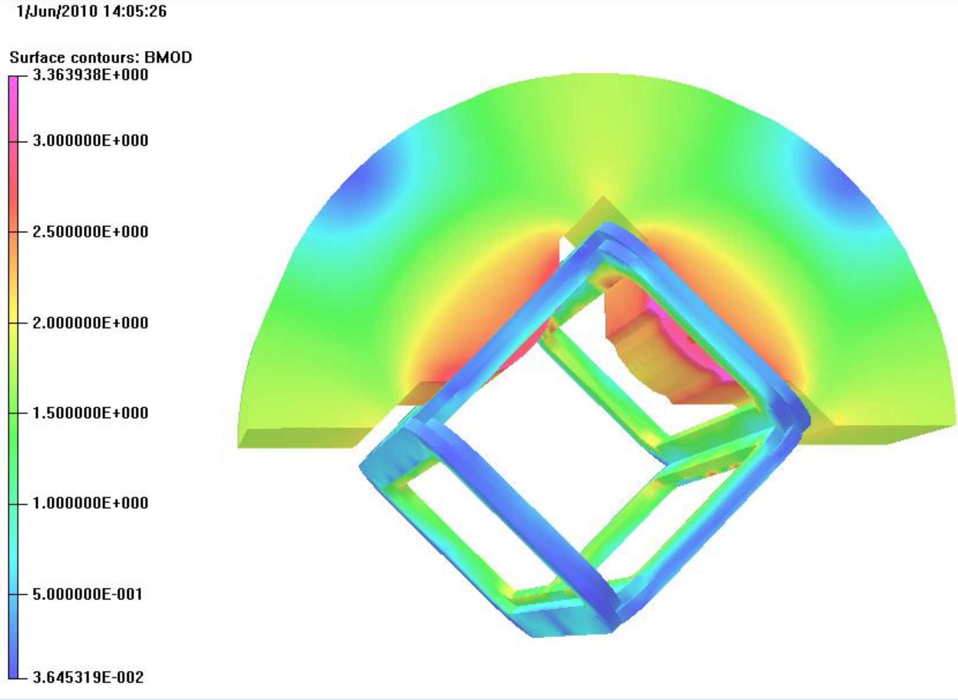
Magnetic Design



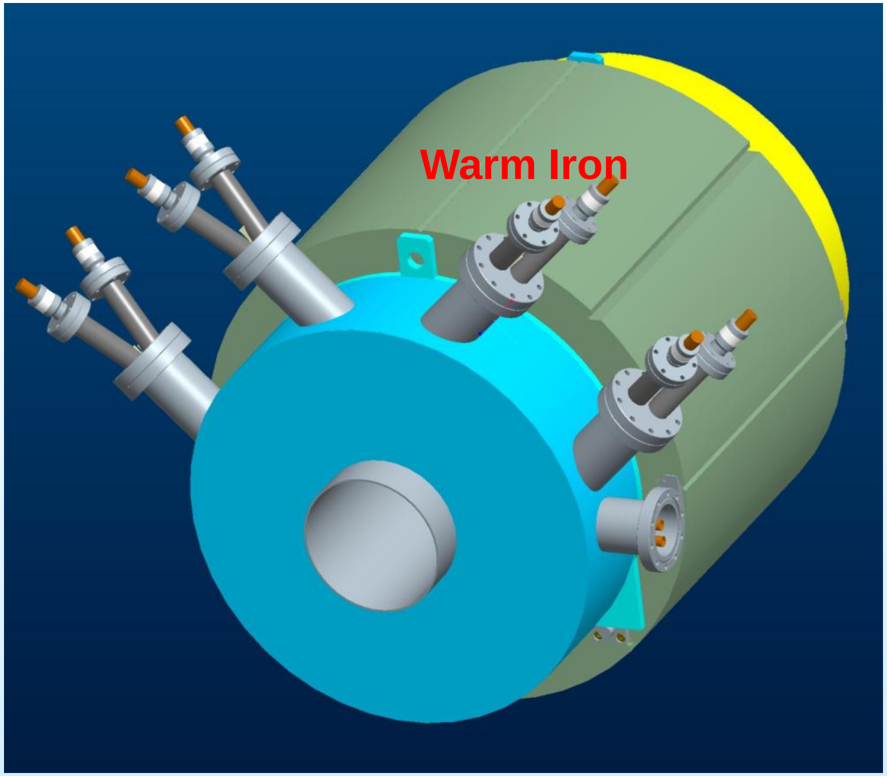
Uses 12 mm tape rather than 4 mm tape

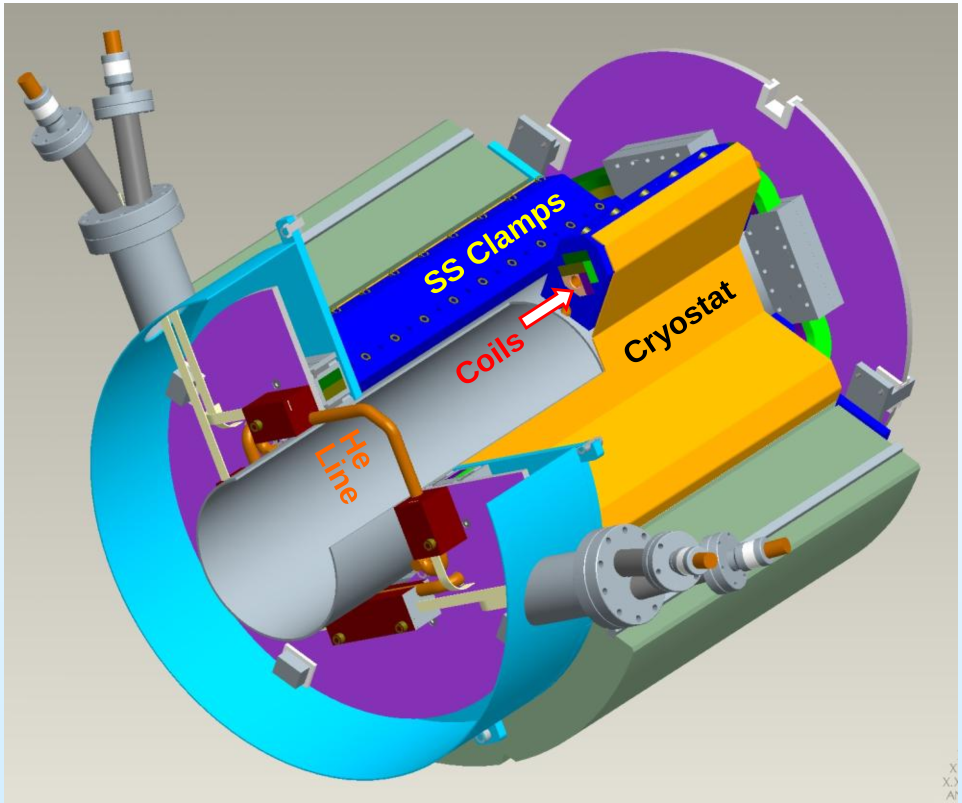
Benefits of 12 mm Tape:

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



Cryo-mechanical Structure





R&D Magnet in cryo-stat

(allows independent testing of four HTS coils)

Cut-away isometric view of the assembled magnet

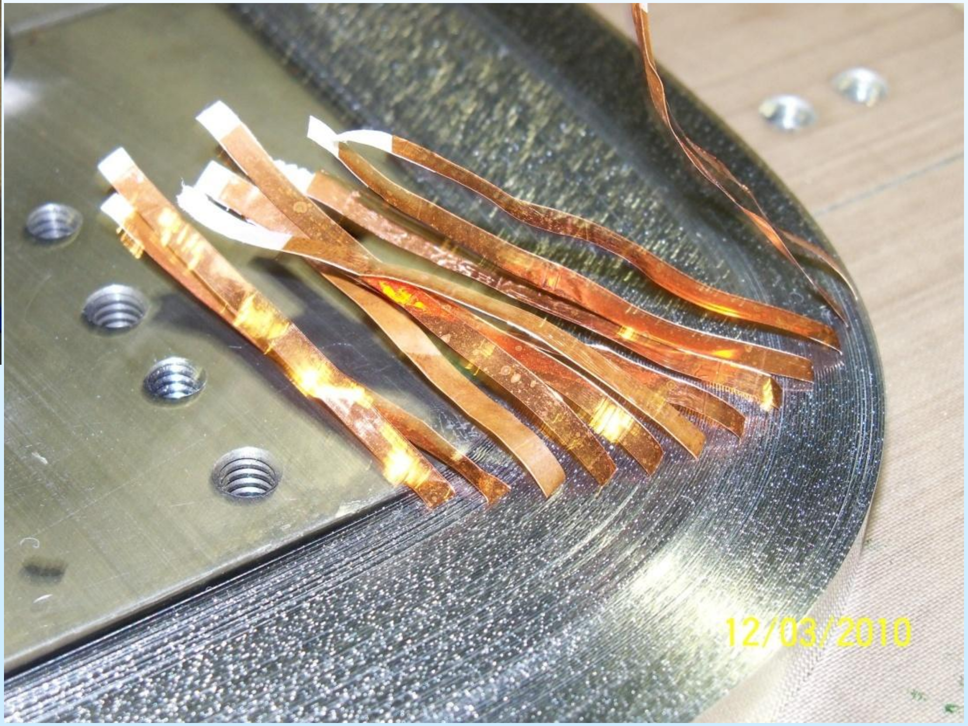
(compact cryo design allowed larger space for coils and reduction in pole radius)

Winding of Second Generation HTS Racetrack Coil for FRIB

Two vendors:
ASC and
SuperPower

Coils Made with ASC HTS

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



One coil was wound without any splice

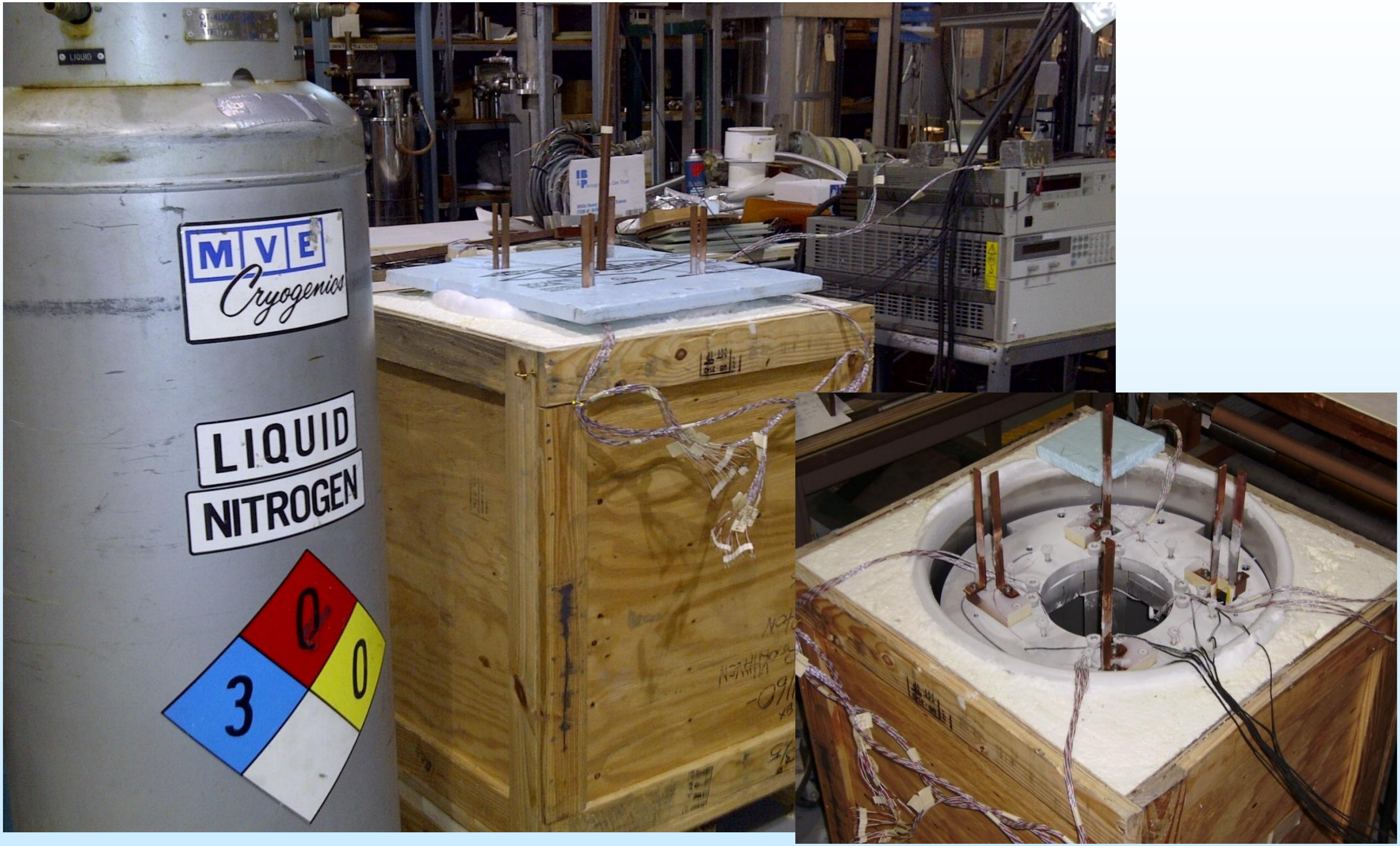
FRIB Coil Made With SuperPower Tape

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

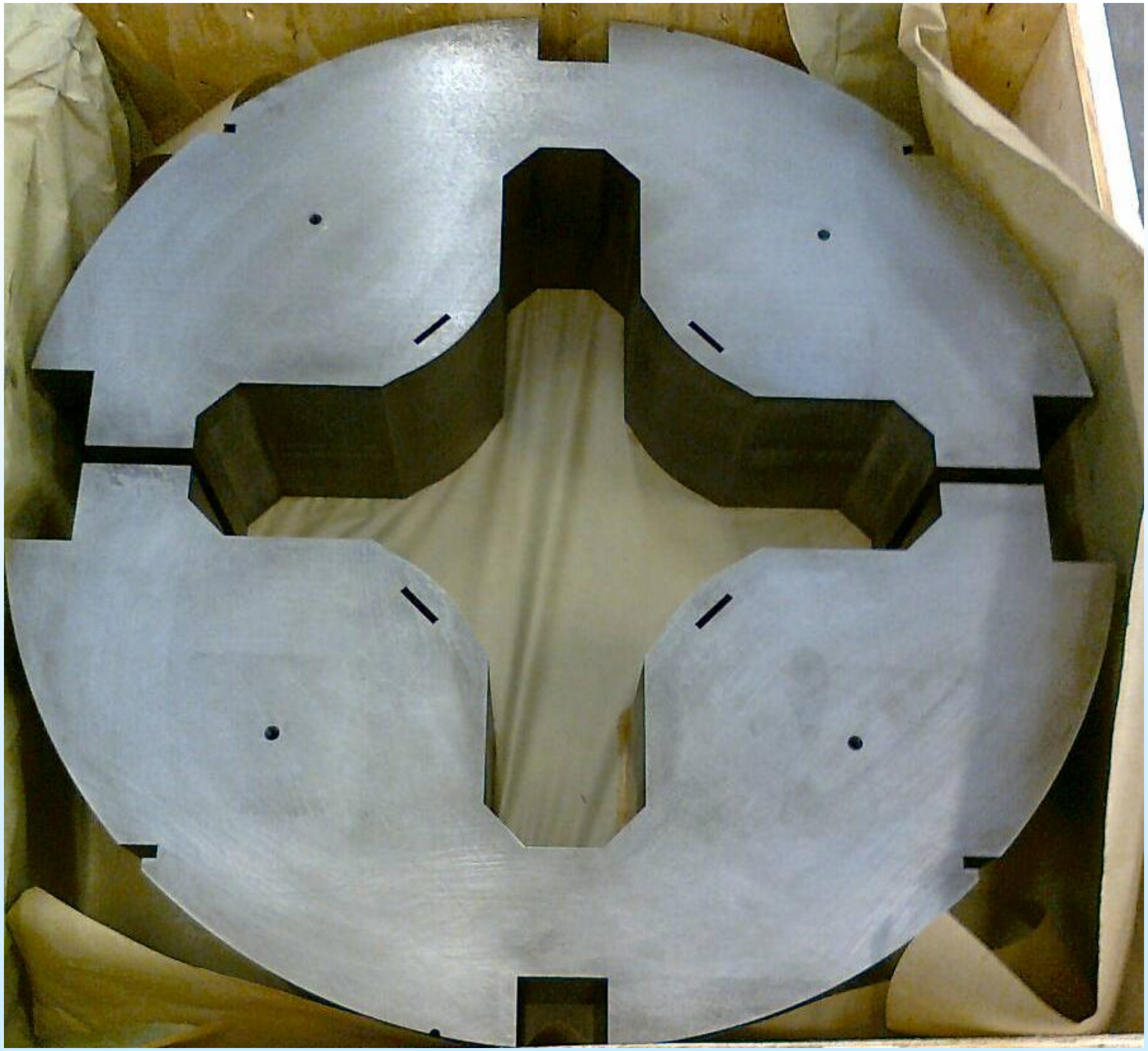
Fully wound coil with SuperPower tape with one splice

Coils Assembled in Quadrupole Support Structure

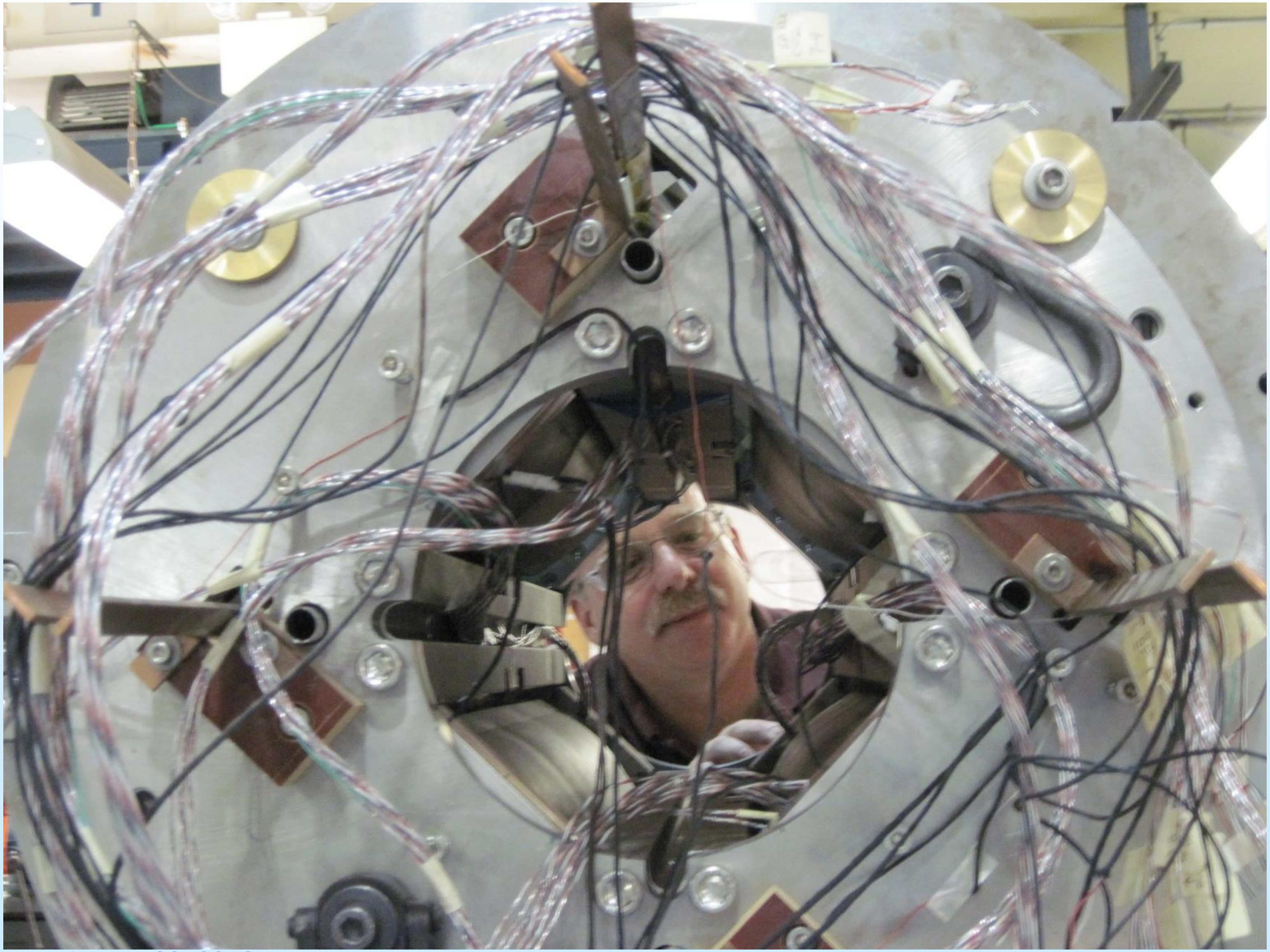
HTS Quad in Unique Cryostat



Yoke Iron for FRIB Quad

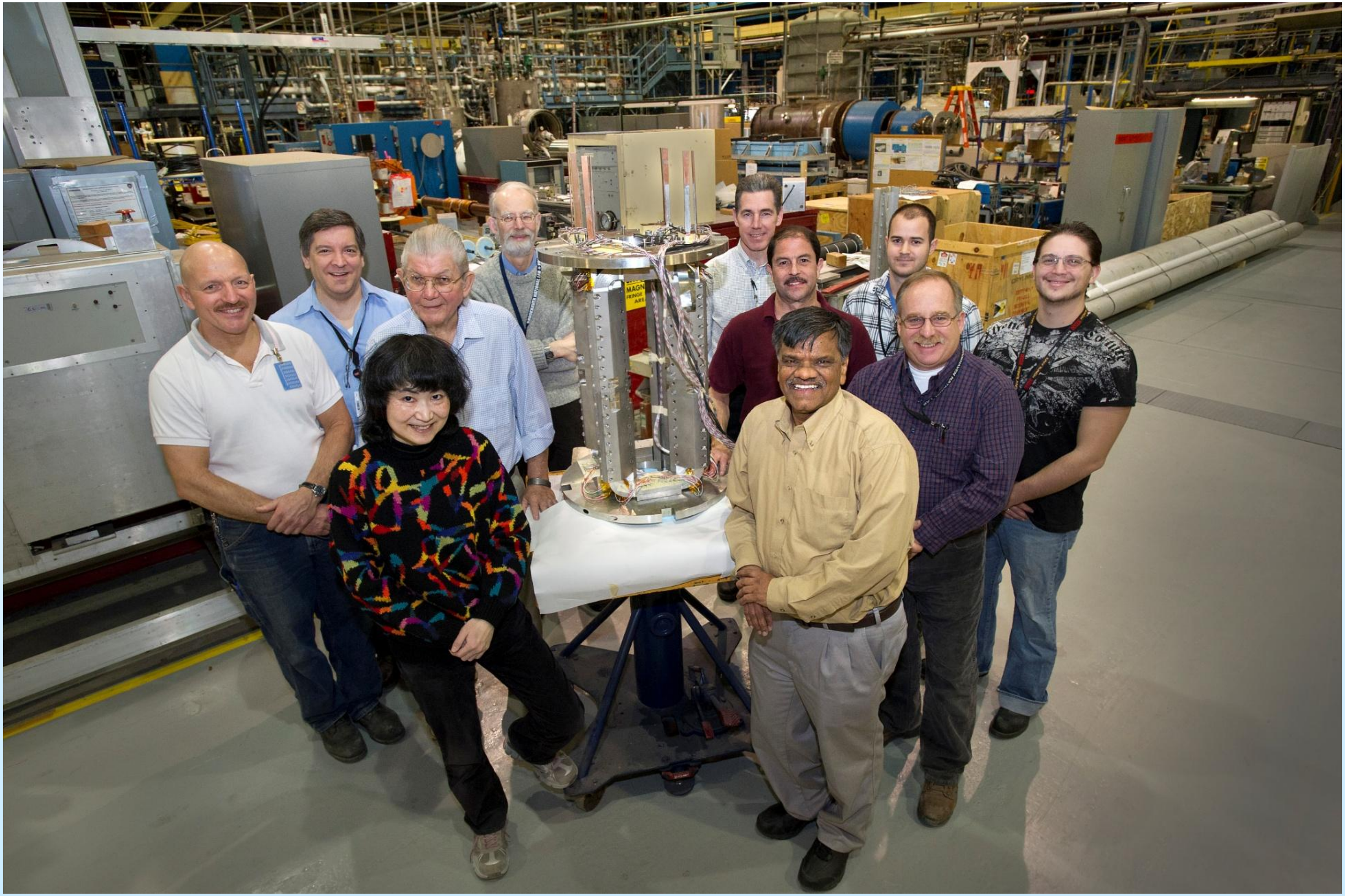


Aperture of 2G HTS Quad for FRIB

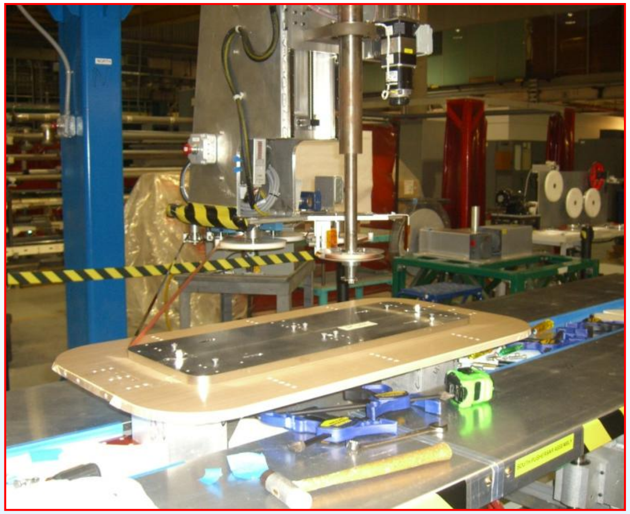


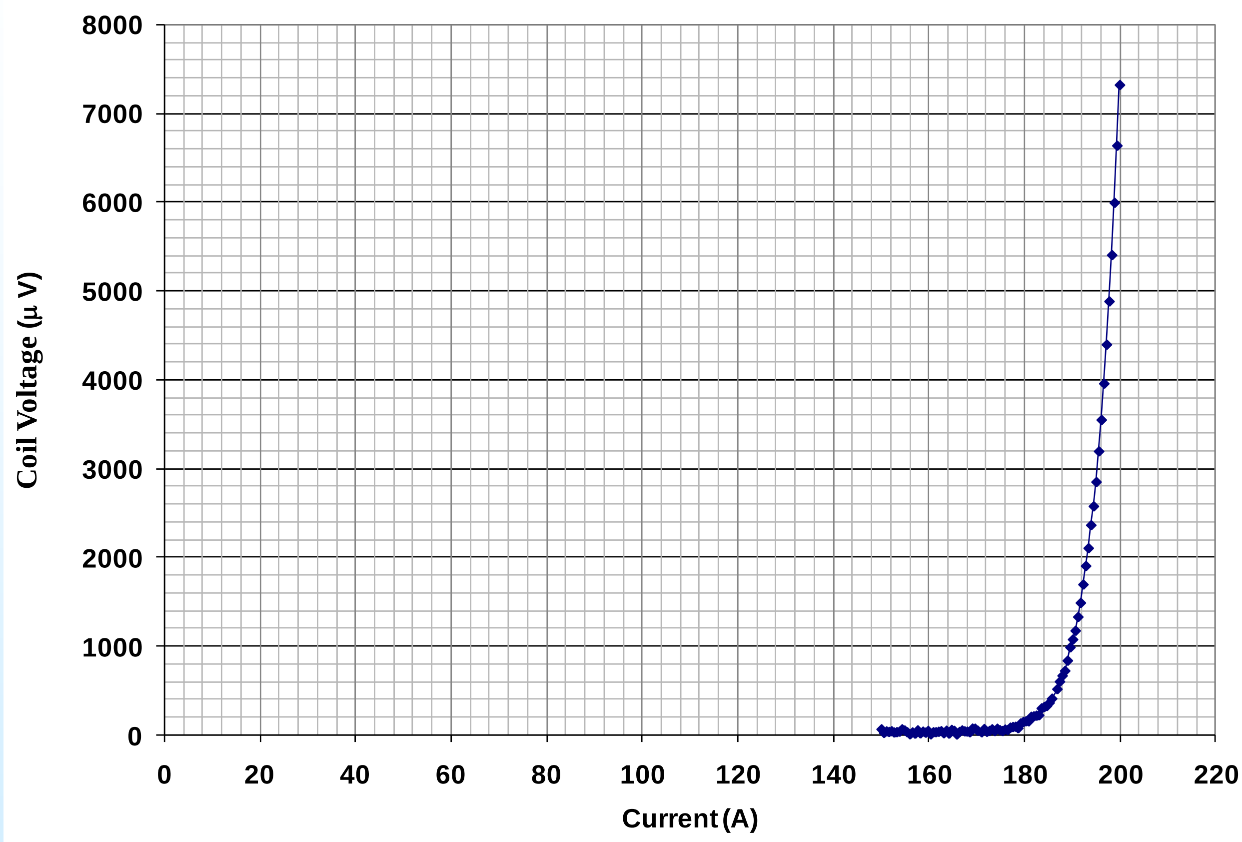
Completed 2G HTS Quad for FRIB

Proud Team Members



77 K Test Results of an Individual Coil

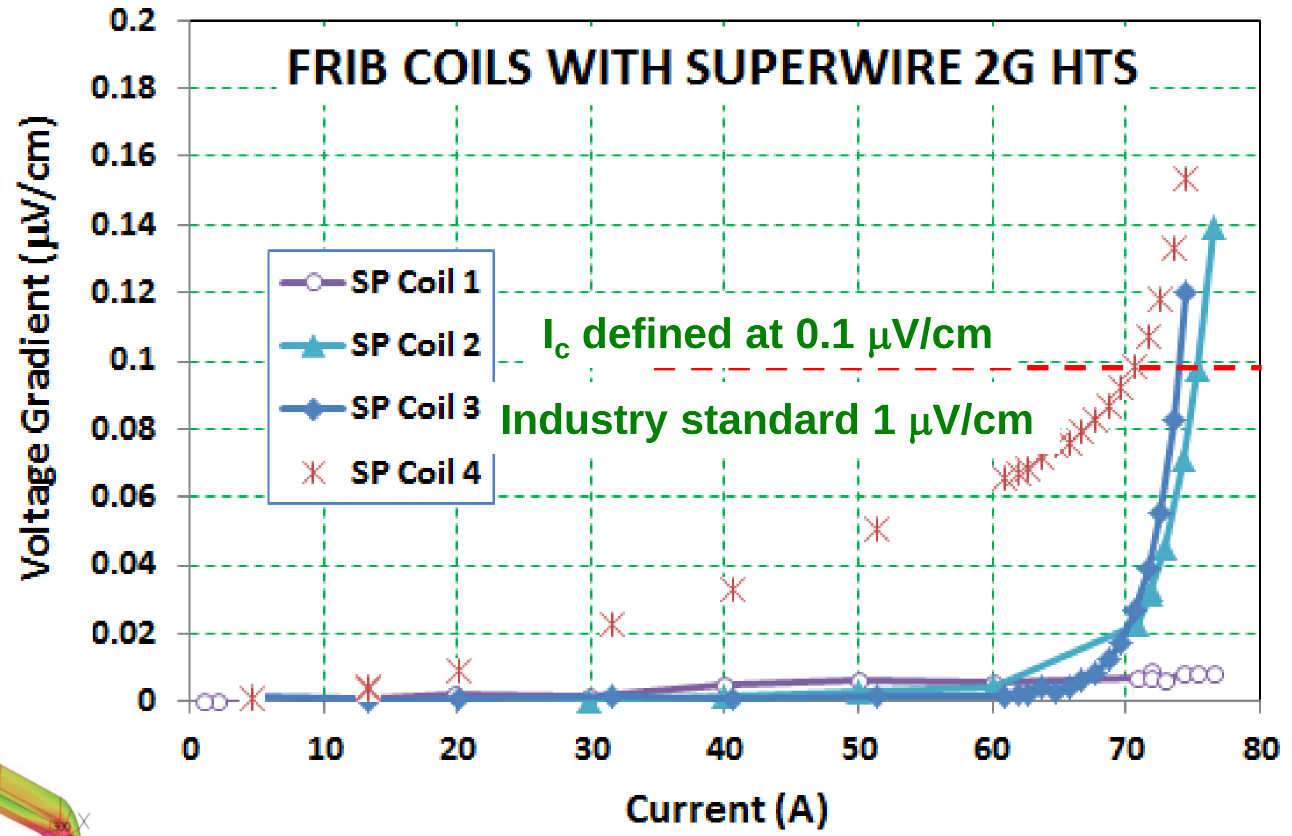




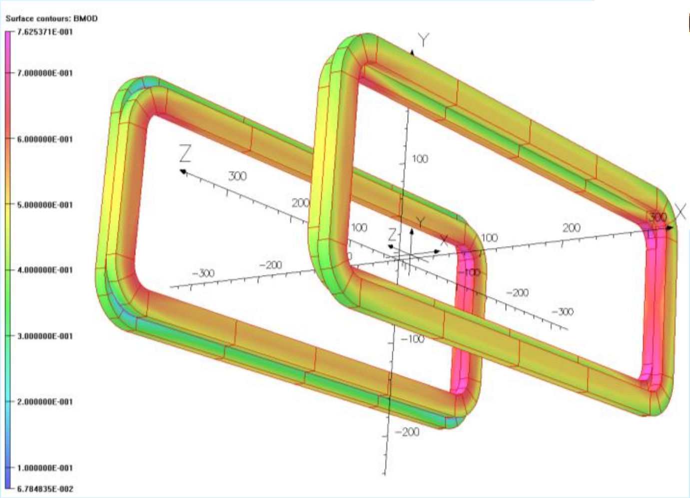
Measurement in liquid nitrogen (~77 K) of critical current in FRIB coil (large, outer, 126 turns made with ~210 meter tape from American Superconductor Corporation). The critical current in coil with 0.1 µV/cm definition (total coil voltage 2100 mV) is 193.4 A.

Performance of SuperPower Coils (four of eight coils powered)

Four ASC coils were not powered

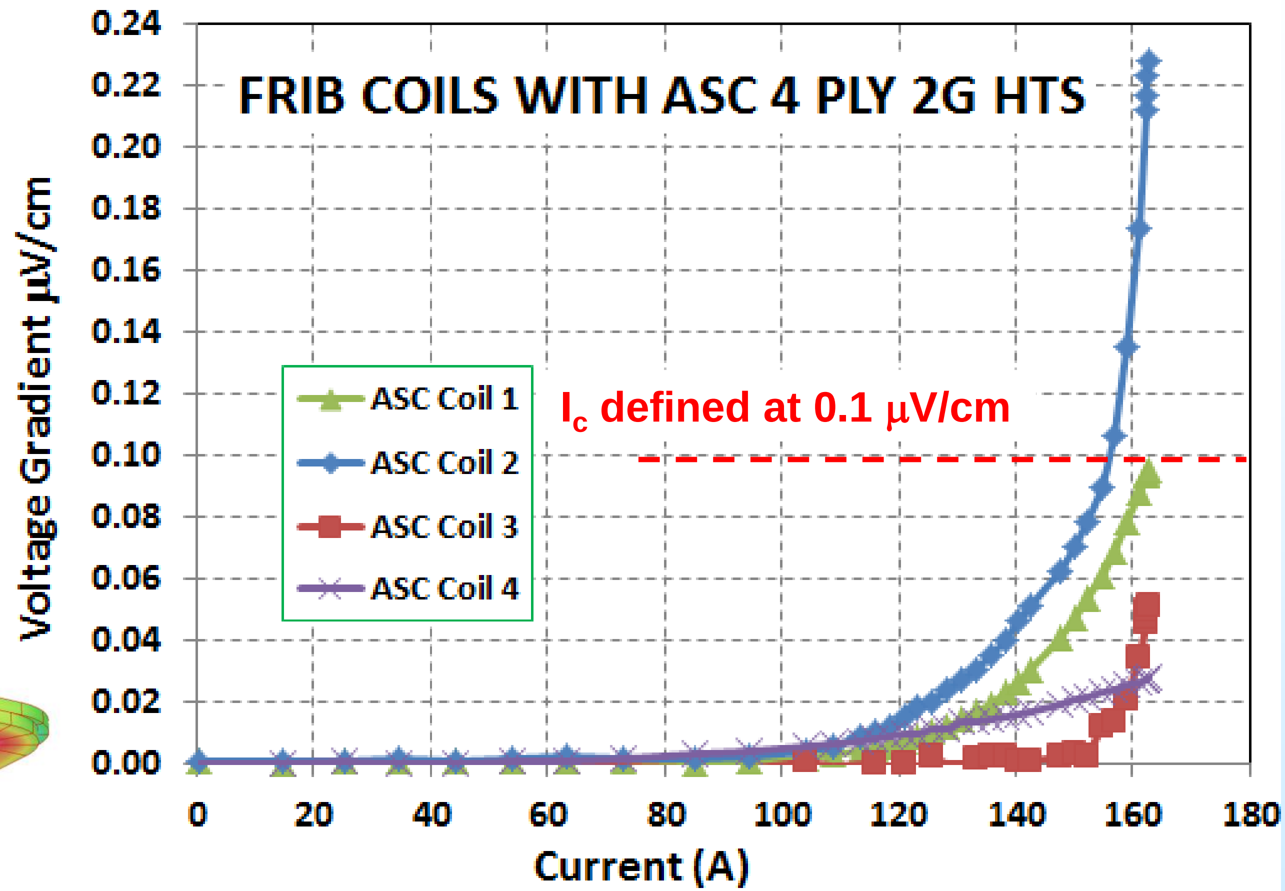


Field on SuperPower coils at 100 A



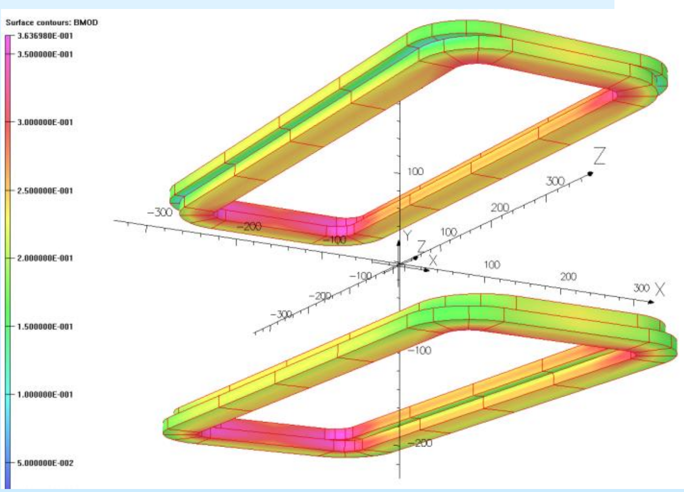
Internal splice on wrong tape side shows higher resistance. This is not an operational issue as the heat generated is negligible as compared to the energy deposition.

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

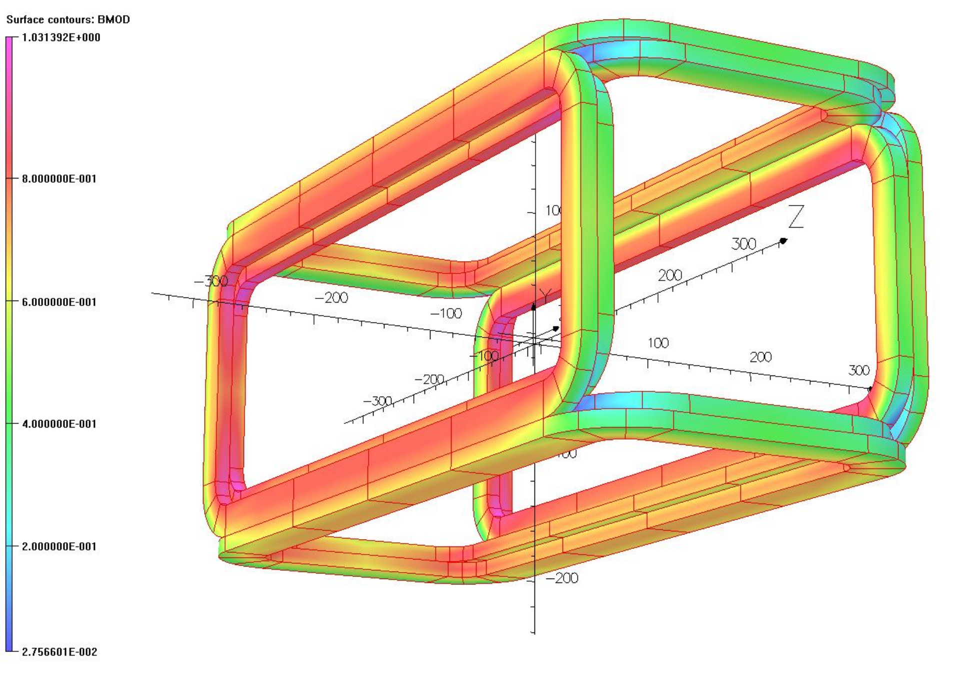
Four SuperPower coils not powered

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



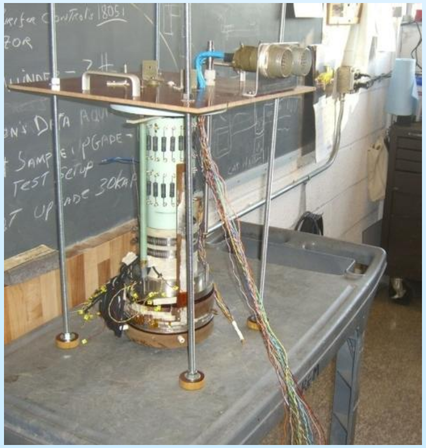
Design: SuperPower coils ~172 A and ASC coils ~300 A (at 40-50 K).

- **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.

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.
- A number of v-taps are installed in the coil to detect quench in small sections.
- 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.



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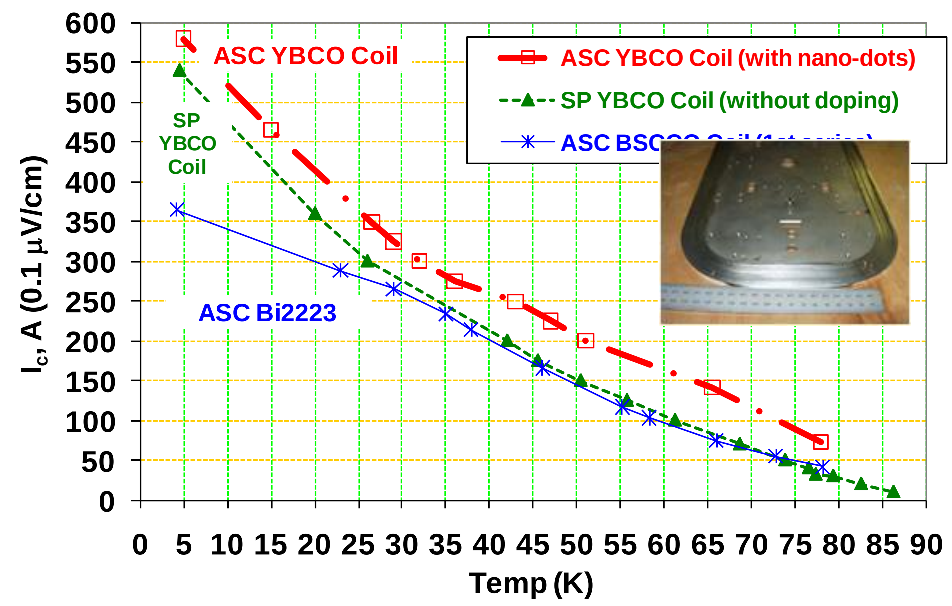
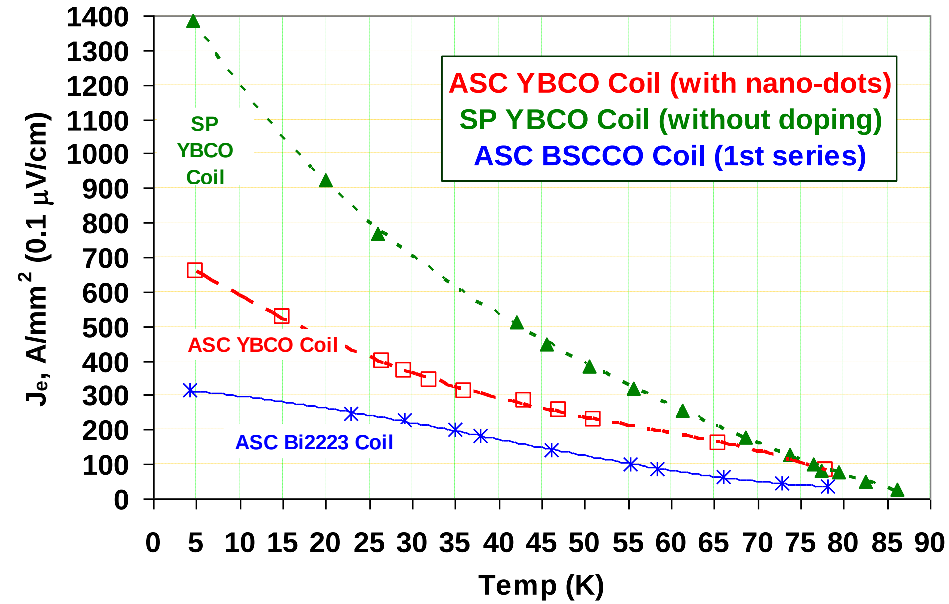
Quench Protection Studies in FRIB 2G HTS Coils





- 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)

Radiation Damage Experiments

Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

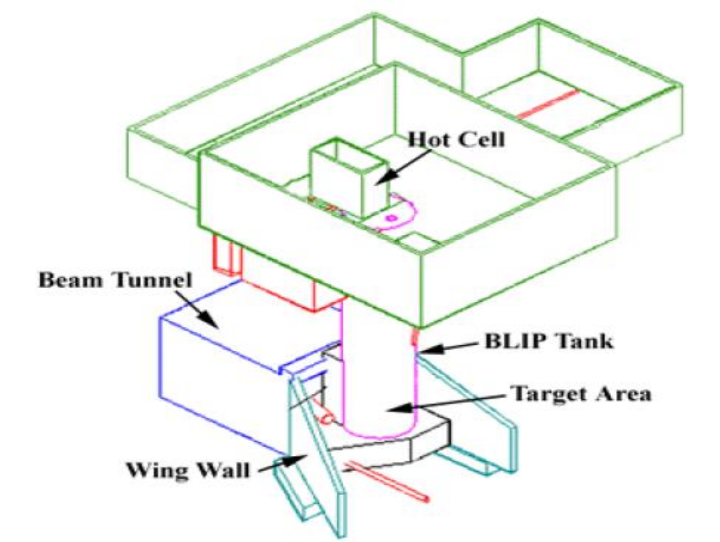
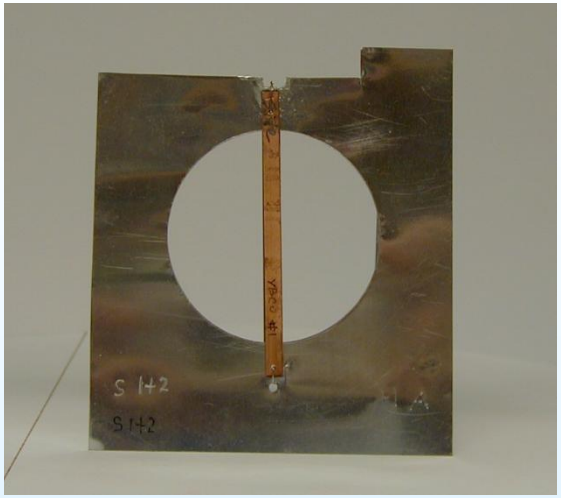


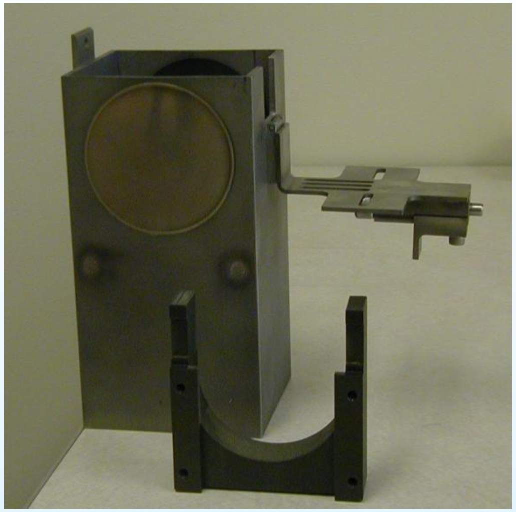
Figure 3. BLIP Beam Tunnel and Target Schematic

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.

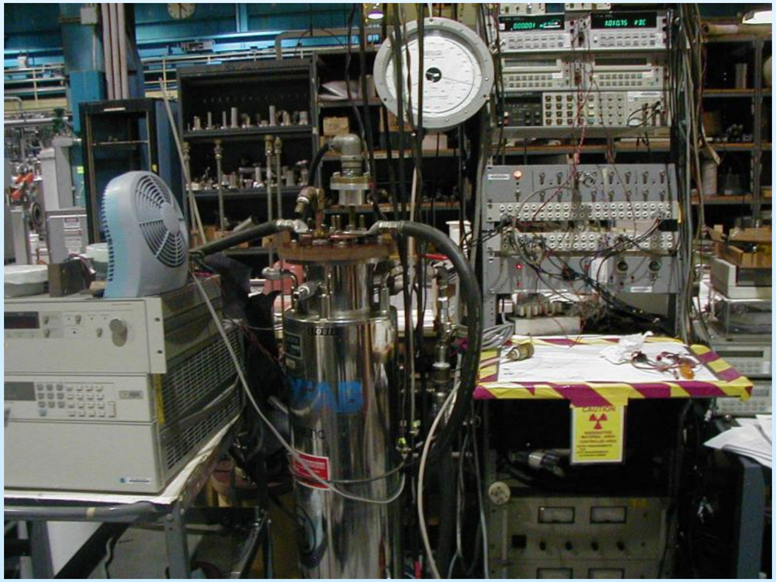
Key Steps in Radiation Damage Experiment





142 MeV,

100 μA protons



HTS Samples Examined

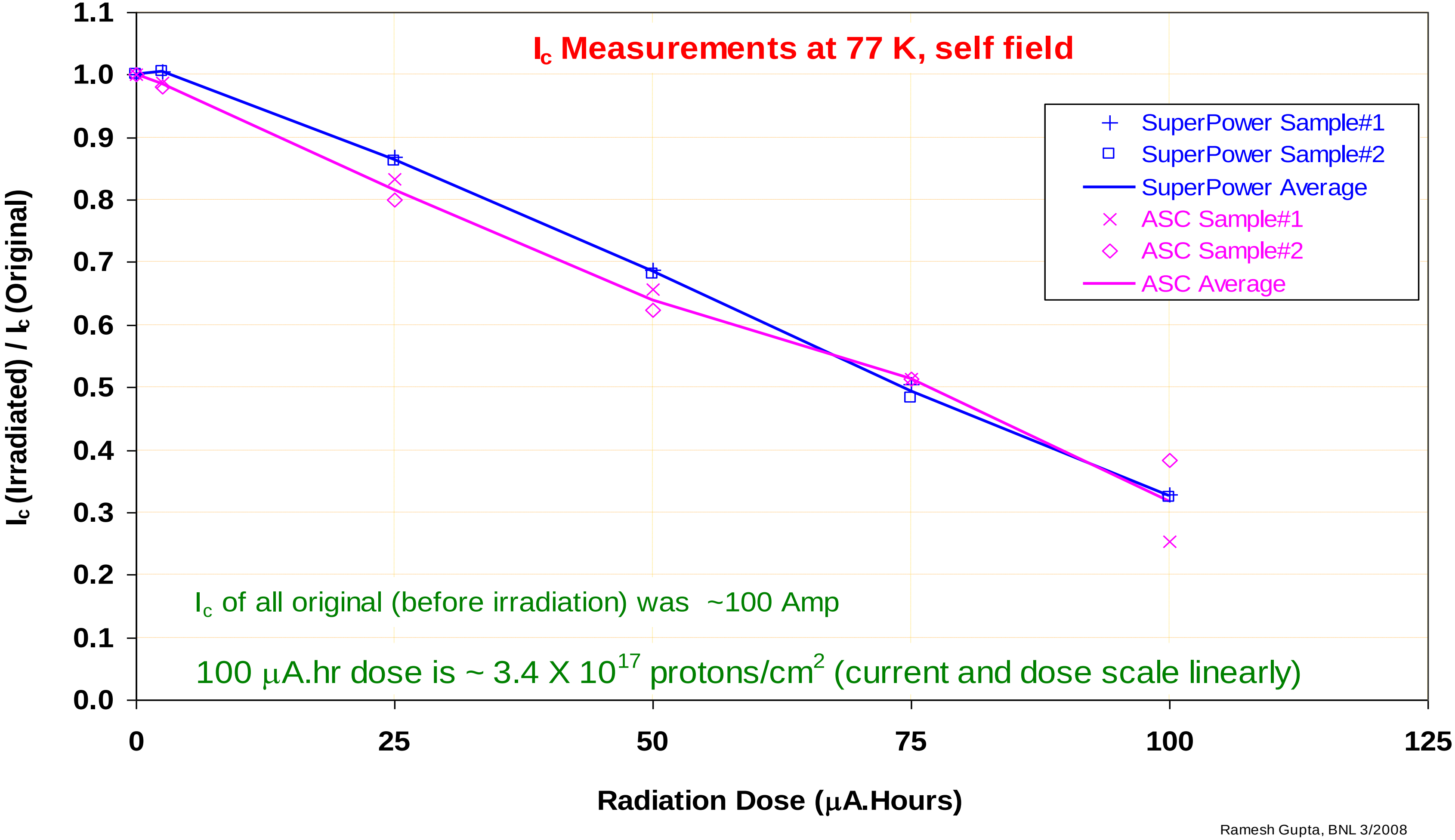
- Samples of YBCO (from SuperPower and ASC), Bi2223 (from ASC and Sumitomo) and Bi 2212 (from Oxford) were irradiated.

- **This presentation will discuss the test results of YBCO only.**
- Twenty samples were irradiated – 2 each at five doses (10^{16}, 10^{17}, 2 x 10^{17}, 3 x 10^{17} and 4 x 10^{17} protons/cm^2) from both vendors.

- 10^{17} protons/cm^2 (25 μA-hrs integrated dose) is equivalent to over 15 years of FRIB operation (the goal is 10 years).

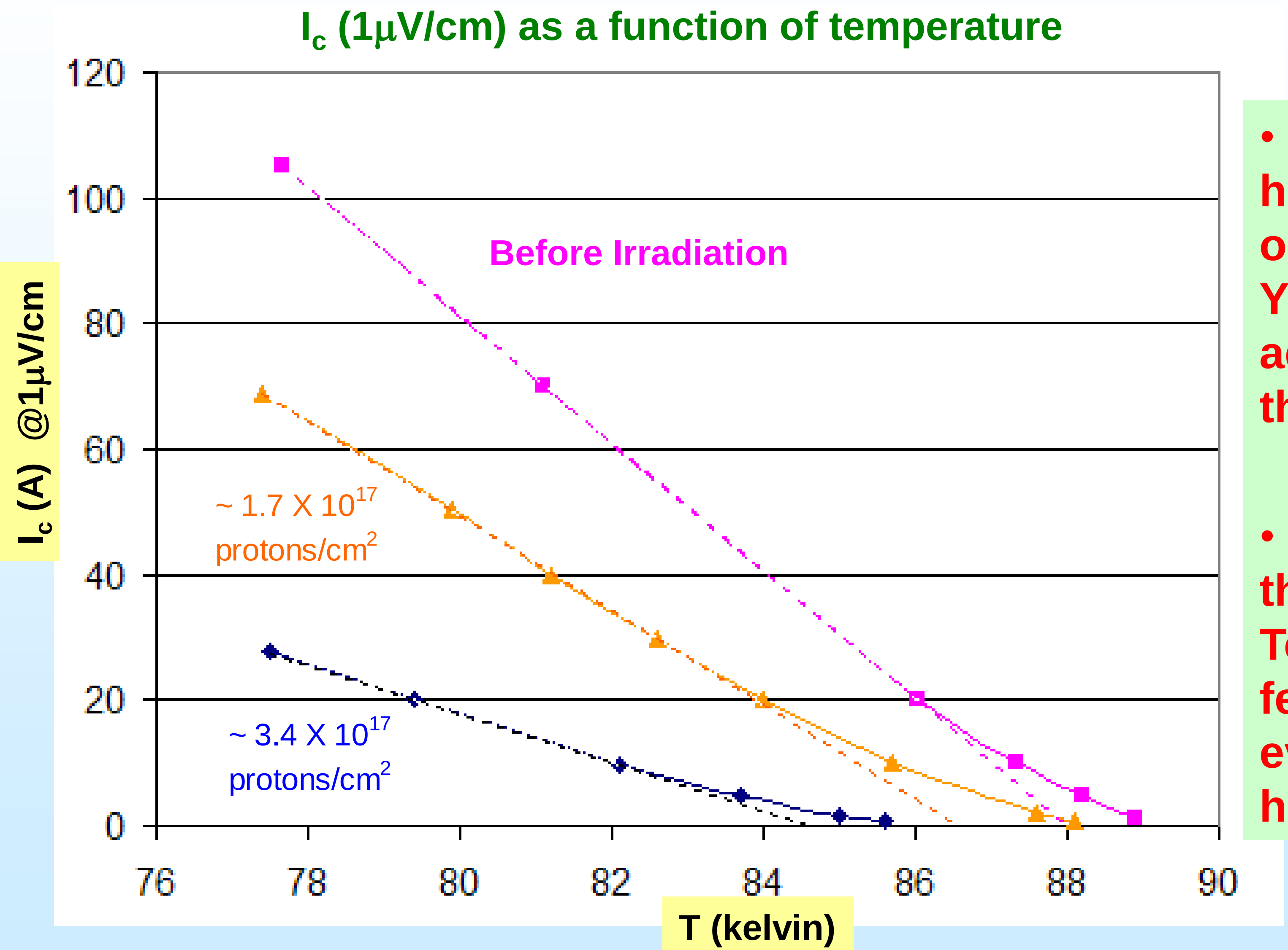
Relative Change in Ic due to Irradiation of SuperPower and ASC Samples

Radiation Damage Studies on YBCO by 142 MeV Protons by G. Greene and W. Sampson at BNL (2007-2008)



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

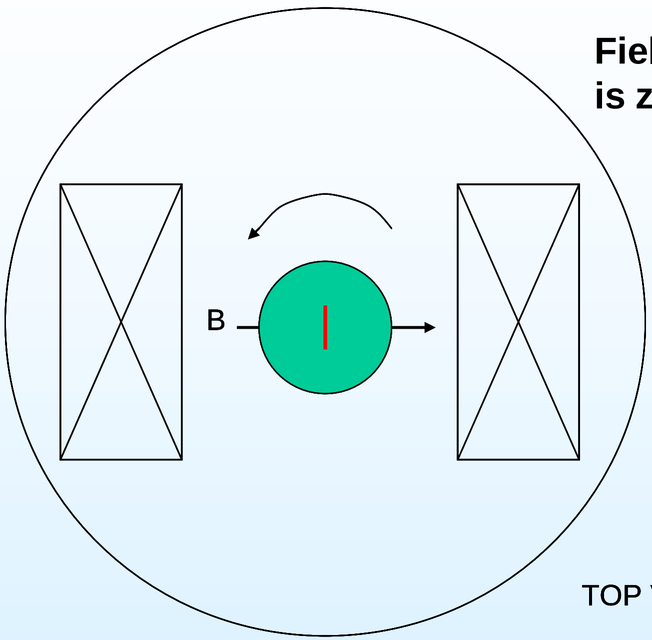
Change in Critical Temperature (T_c) of YBCO Due to Large Irradiation



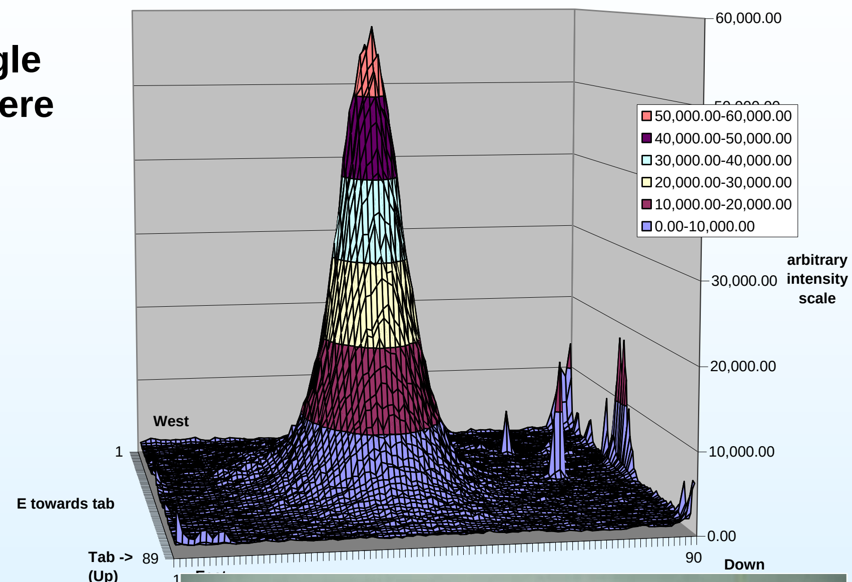
- **Radiation has an impact on the T_c of YBCO, in addition to that on the I_c.**
- **However, the change in Tc is only a few degrees, even at very high doses.**

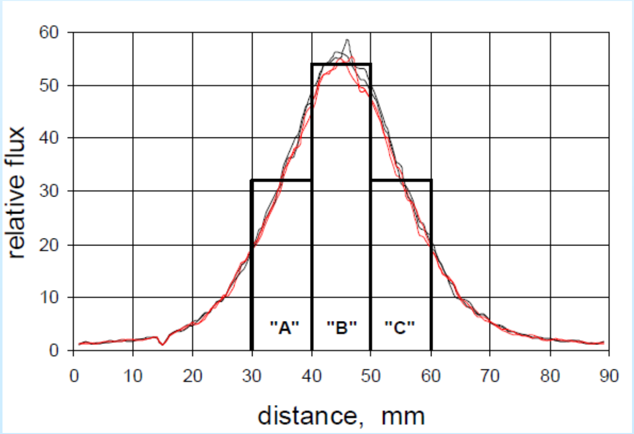
Measurements of Radiation Damage in Presence of Field

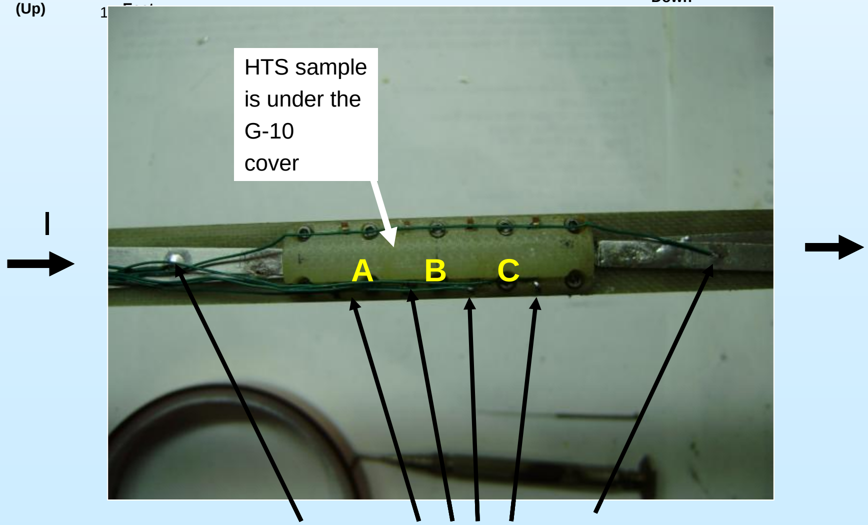
Field angle is zero here



TOP VIEW







Voltage taps

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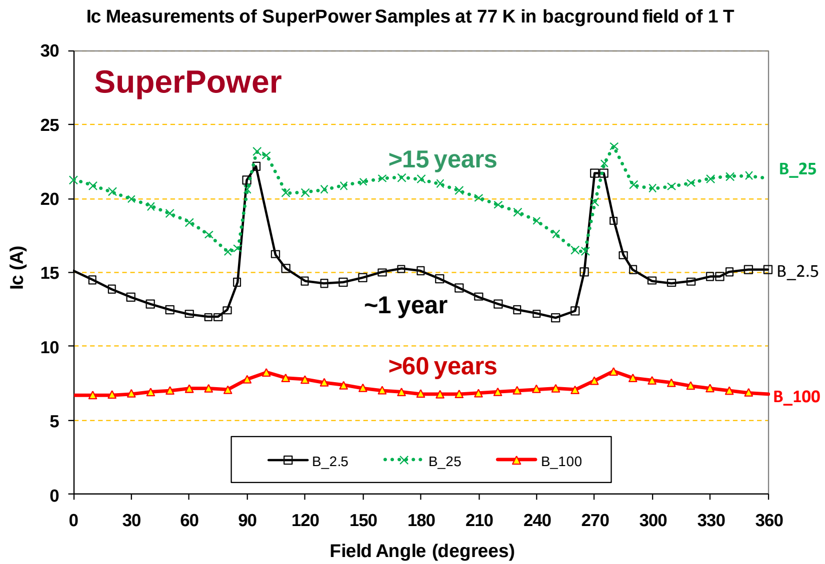
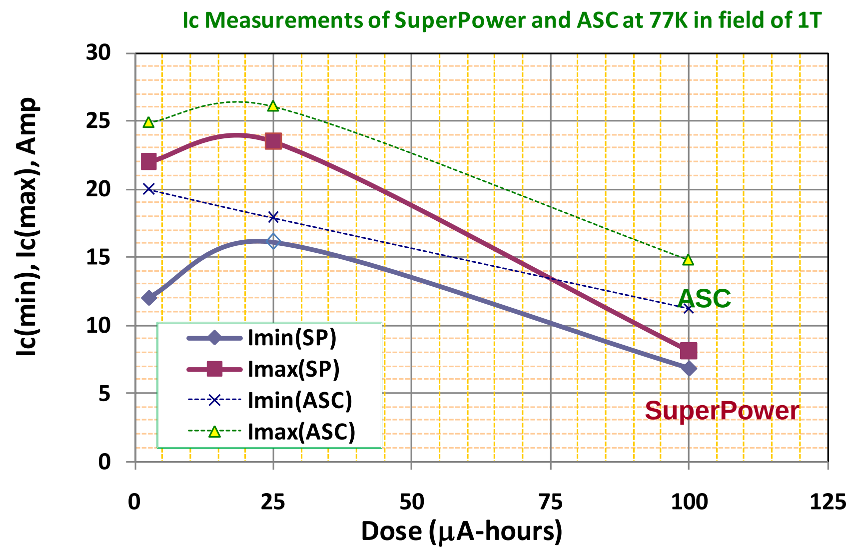
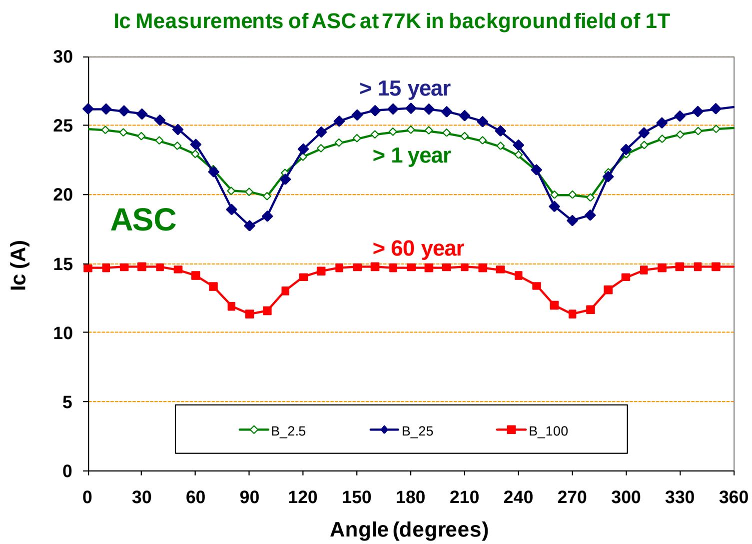
Radiation Damage from 142 MeV protons in SP & ASC Samples (measurements at @77K in 1 T Applied Field)





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)!!!

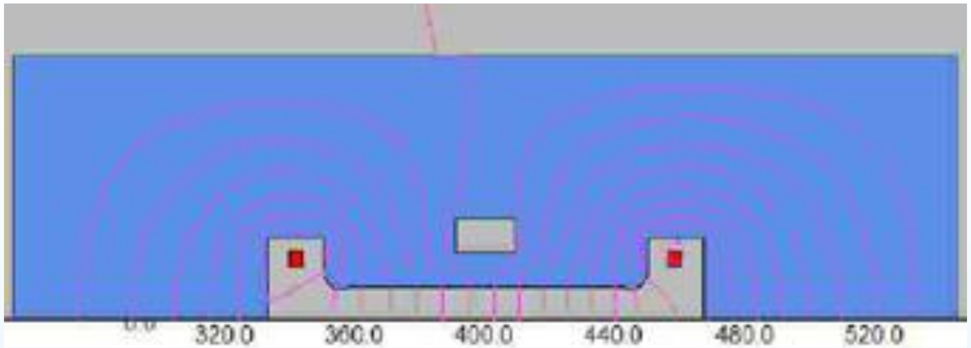
Other HTS Magnets in FRIB/RISP

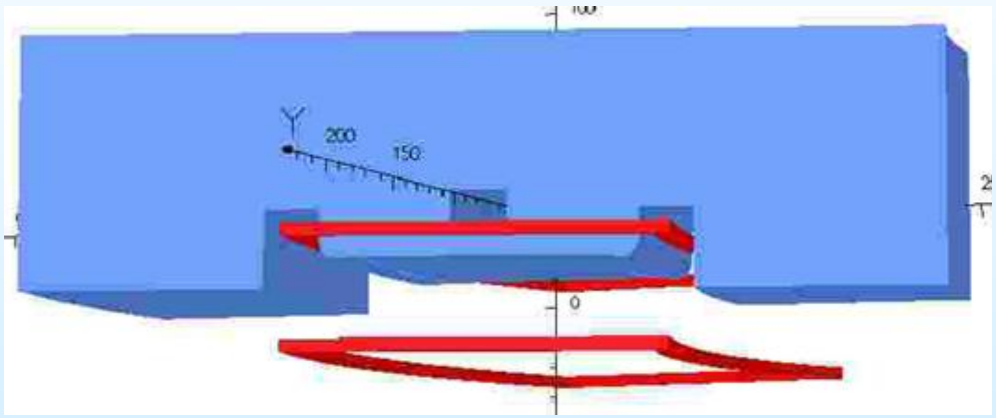
HTS Magnets in FRIB/RISP

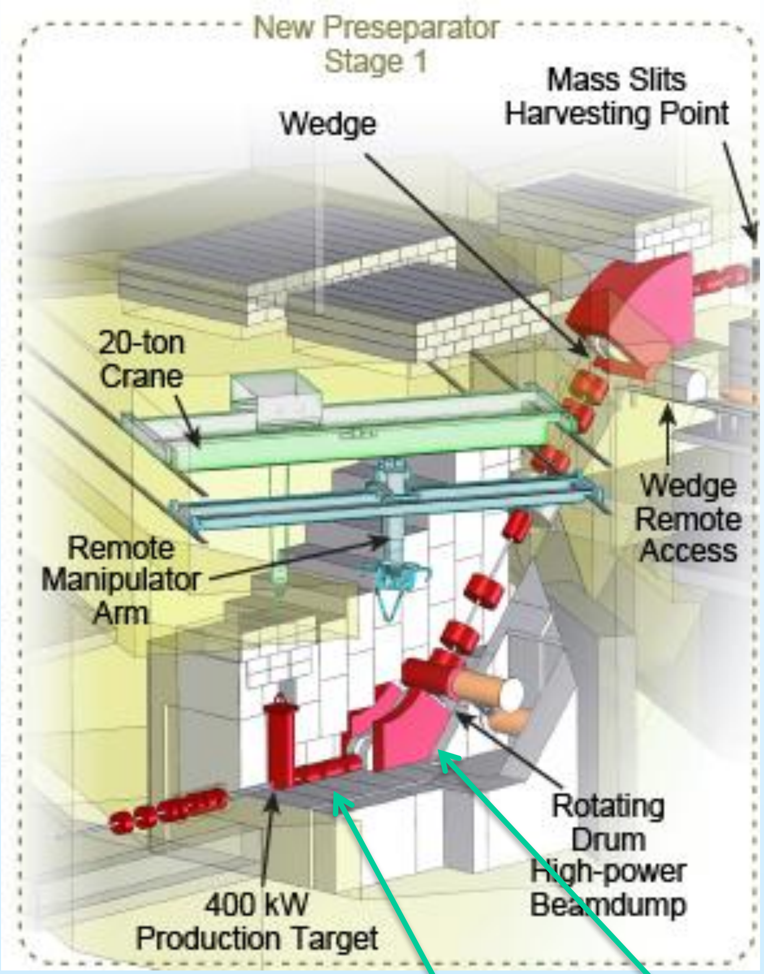
- HTS offers a unique magnet solution for challenging fragment separator environment of FRIB.
- HTS is the baseline design for fragment separator quad Q1.
- HTS is also being seriously considered for fragment separator dipole and corrector magnets.
- BNL has already working on aspects of these magnets with funding from FRIB and from other governmental agencies.

➢ HTS magnets can be also be used in a large number of other magnets in FRIB or RISP.

HTS Dipole for Fragment Separator







From IPAC2012 Paper

Muons, Inc.

High Radiation Environment Nuclear Fragmentation Separator Dipole Magnet

Stephen A. Kahn[1] and Ramesh C. Gupta[2]

[1]Muons, Inc., Batavia, IL 60510, [2]Brookhaven National Laboratory, Upton, NY 11973

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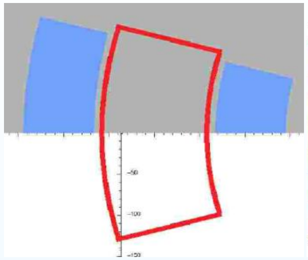
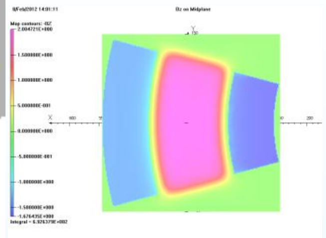
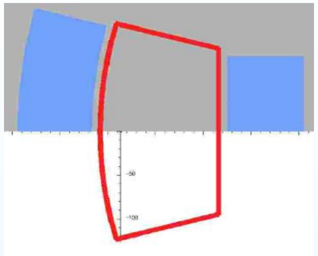
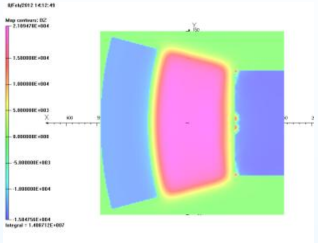
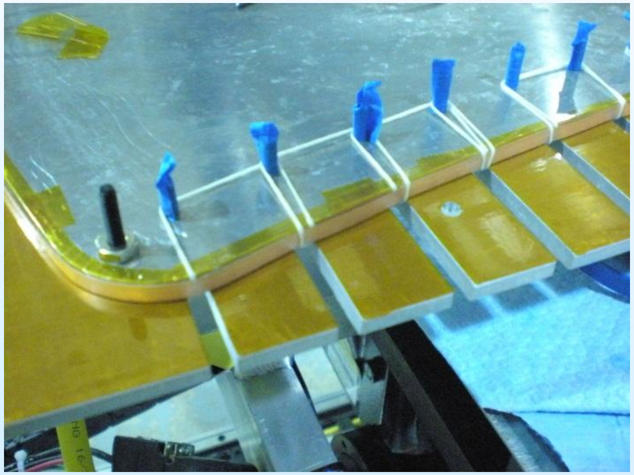
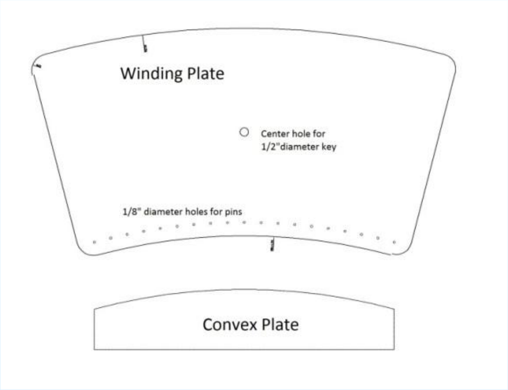
Pre-separator quads and dipole

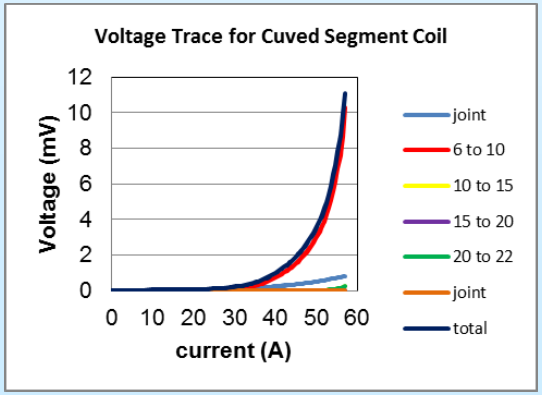
Superconducting Magnet Division

HTS Dipole for FRIB with Curved Coil





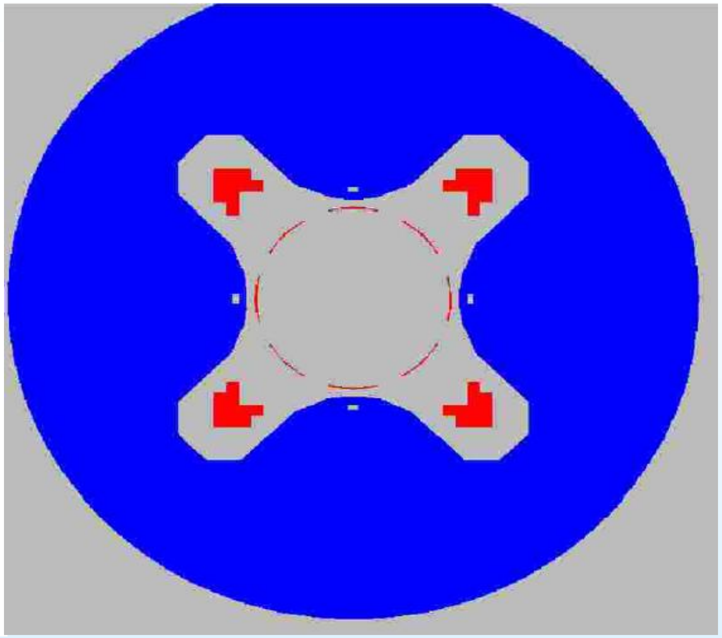
Muons, Inc.

FABRICATION AND TESTING OF CURVED TEST COIL FOR FRIB FRAGMENT SEPARATOR DIPOLE*

S.A. Kahn, Muons, Inc., Batavia, IL 60510, U.S.A.
J. Escallier, R.C. Gupta†, G. Jochen and Y. Shiroyanagi, BNL, Upton, NY 11973, U.S.A.

From IPAC2012 Paper

HTS Corrector for FRIB



Funding from FRIB for initial R&D and request for funding from other sources

RADIATION TOLERANT MULTIPOLE CORRECTION COILS FOR FRIB QUADRUPOLES*

S.A. Kahn#, Muons, Inc., Batavia, IL 60510, U.S.A.
R.C. Gupta, BNL, Upton, NY 11973, U.S.A.

Muons, Inc.

From IPAC2012 Paper

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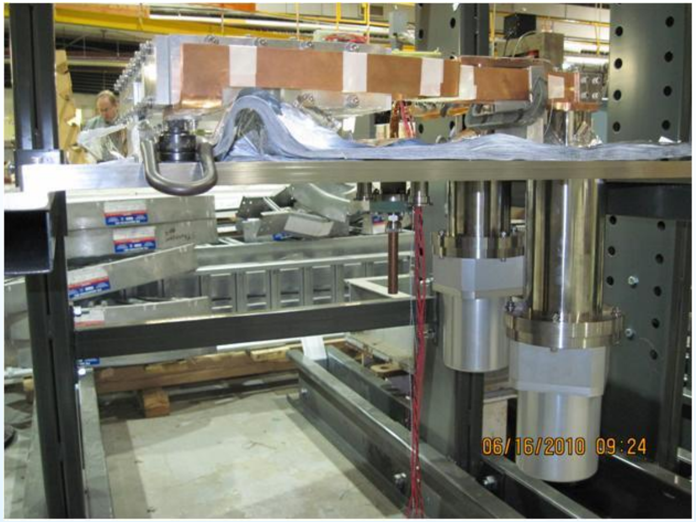
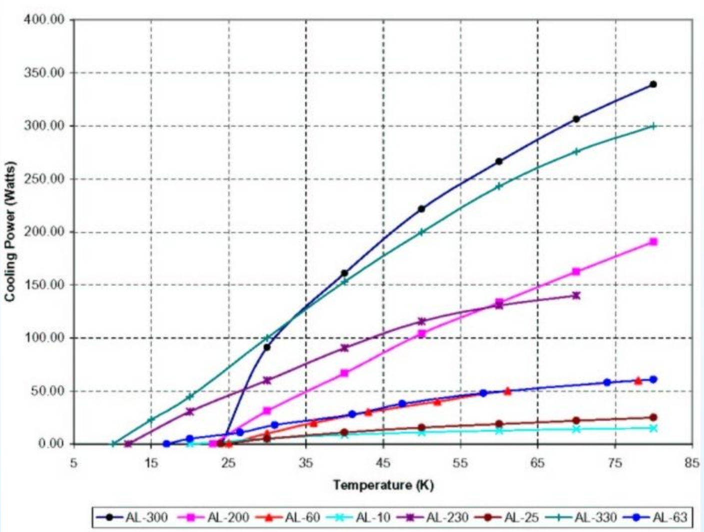
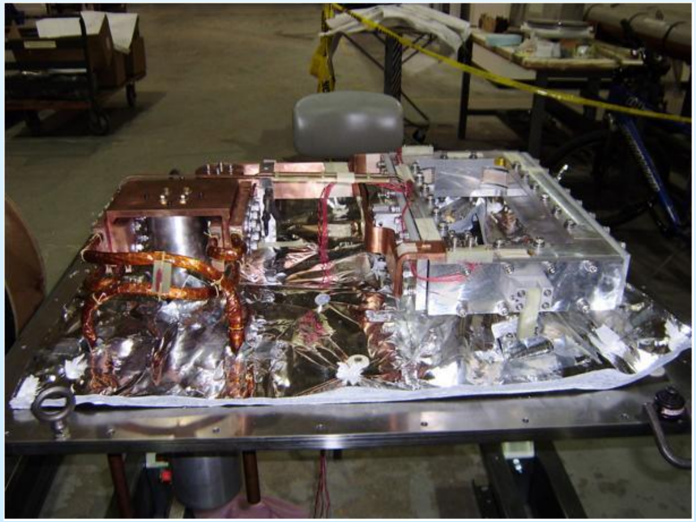
Cryo-cooler based HTS Magnets
(an alternate option for FRIB and elsewhere)

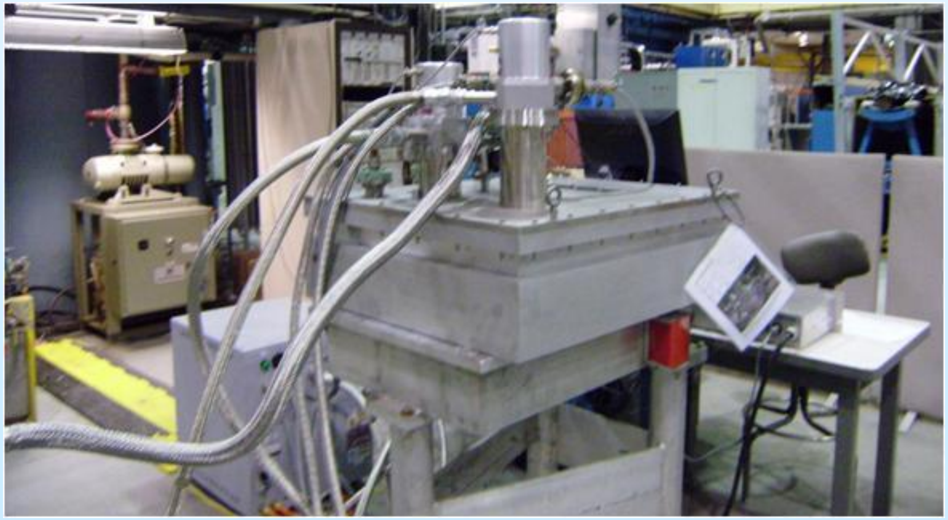


Cryo-cooler based HTS magnet option offers an alternative to Helium based cryo-system.

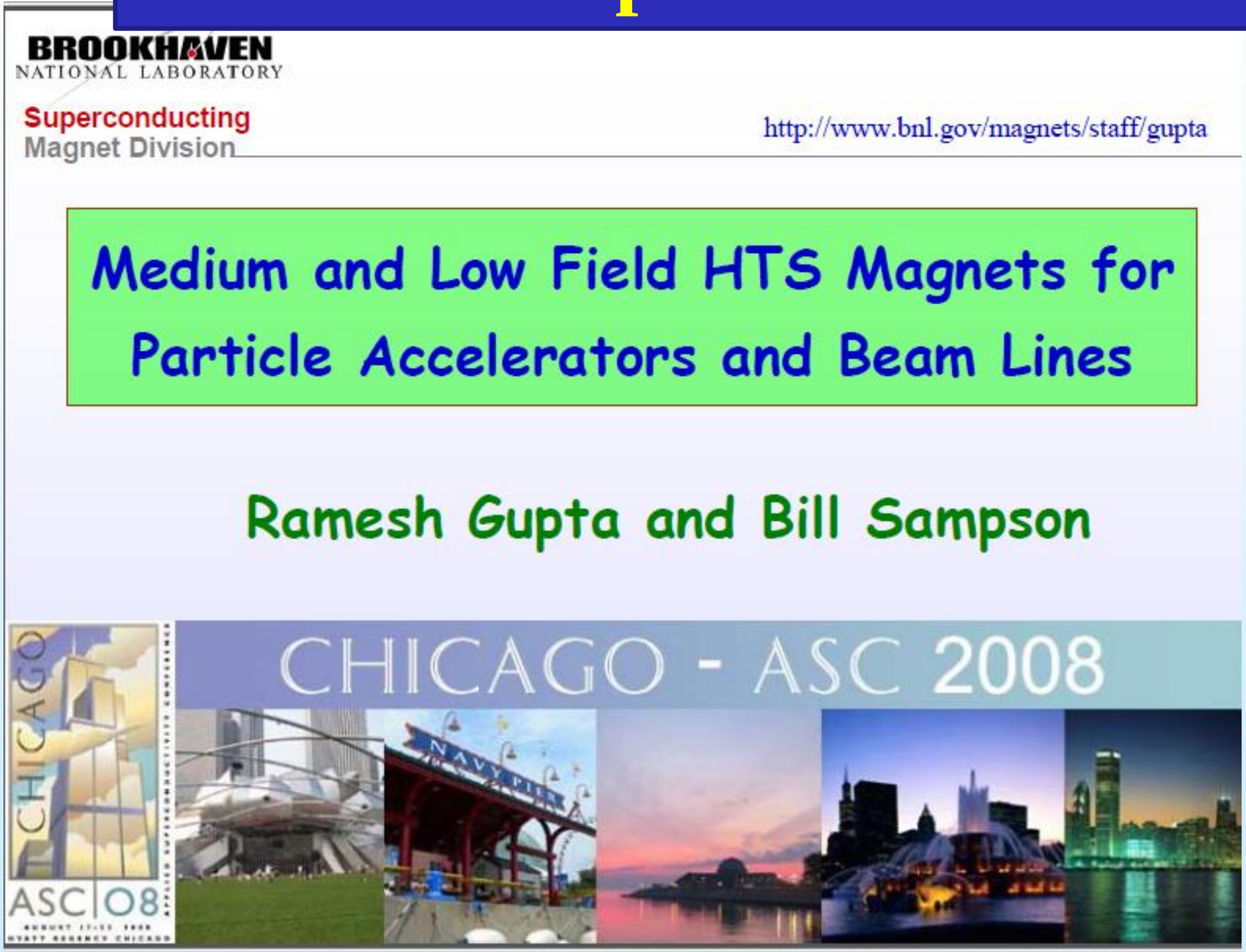
- Coils reached <40 K overnight with cryo-coolers
- 25 W heat load at 50 K can be removed by a number of cryo-coolers







HTS Magnets can be used at several other places in FRIB/RISP



High Field HTS Magnet Test Results

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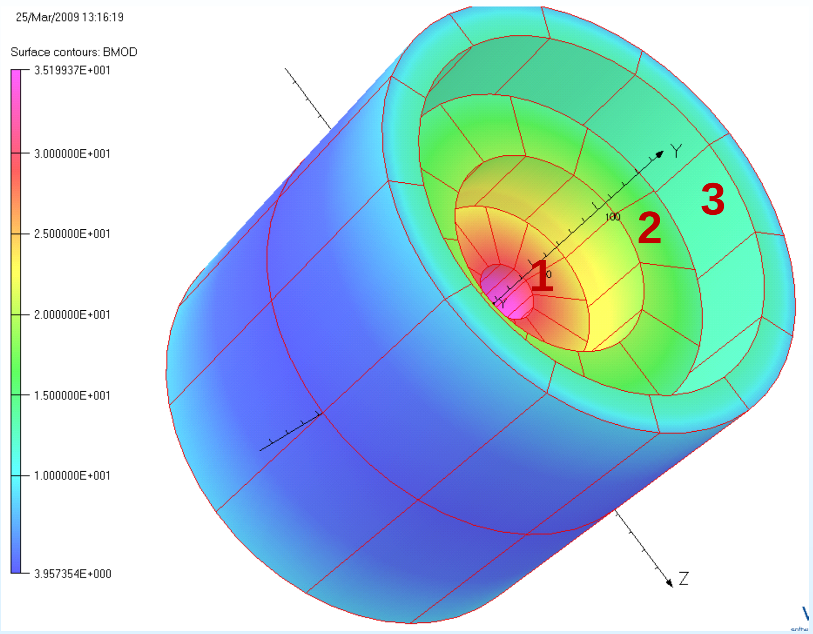
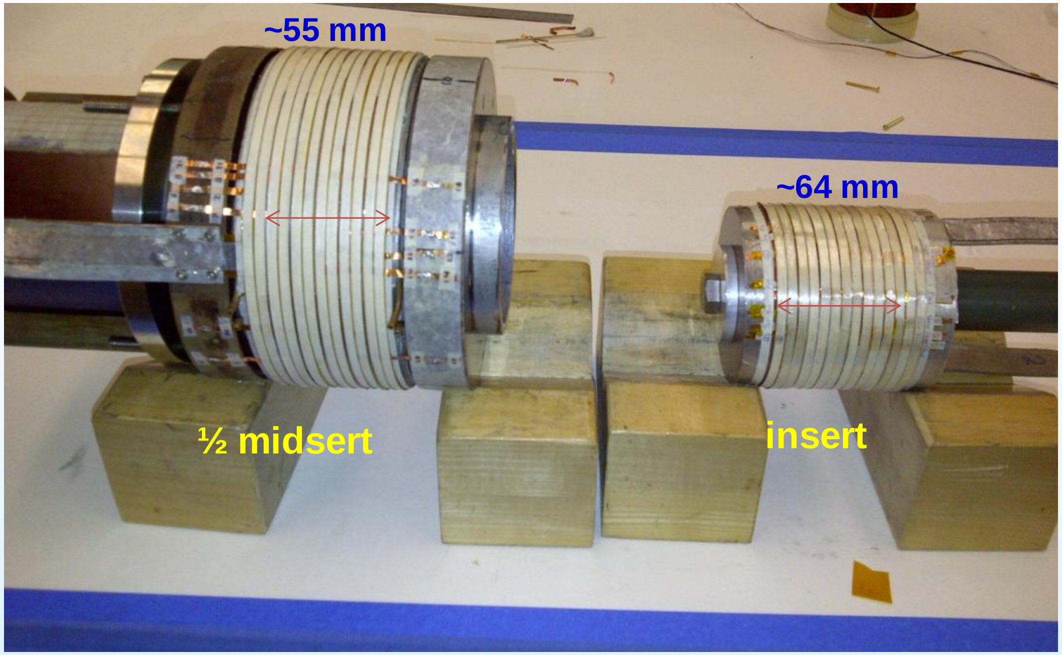
Superconducting Magnet Division

High Field Solenoid (~35 T) R&D for Muon Accelerator Program (with PBL)





- A hybrid design with HTS inserts and LTS outsert(s) to generate ~35 T field
- 38 HTS pancake coils have been built and individually tested at 77 K
- Record field (>15 T) achieved in HTS insert#1
- Record conductor (1.2 km) used in high field 4 K application in ½ HTS insert #2
- Full insert#1 + Full insert#2 to be tested soon with a target field of over 20 T
- Major challenges: Large stresses, quench protection, new material.

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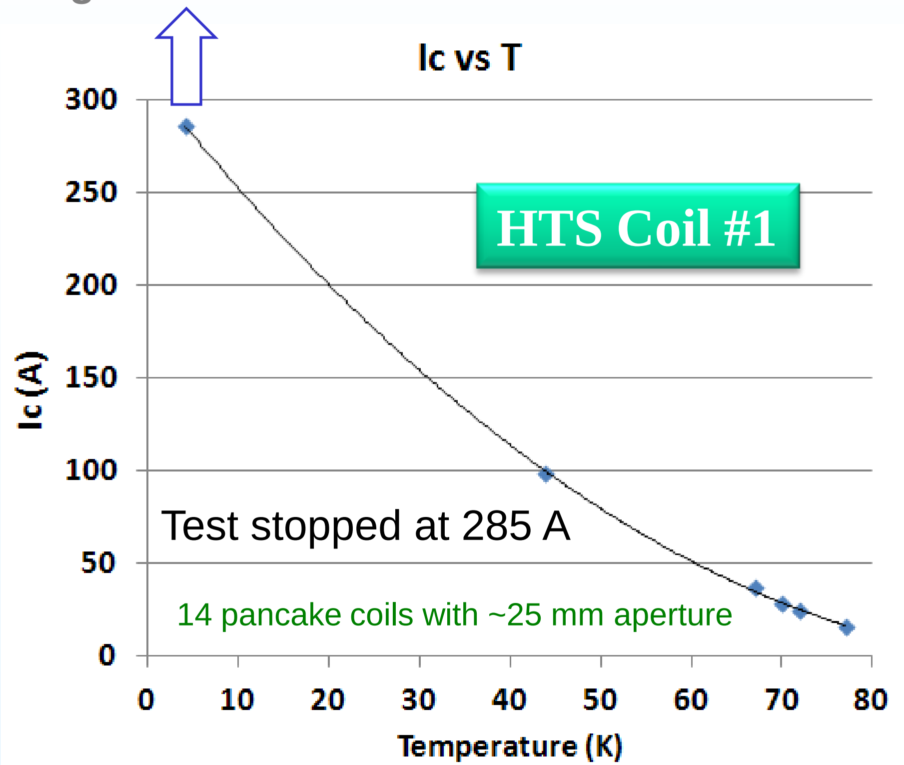
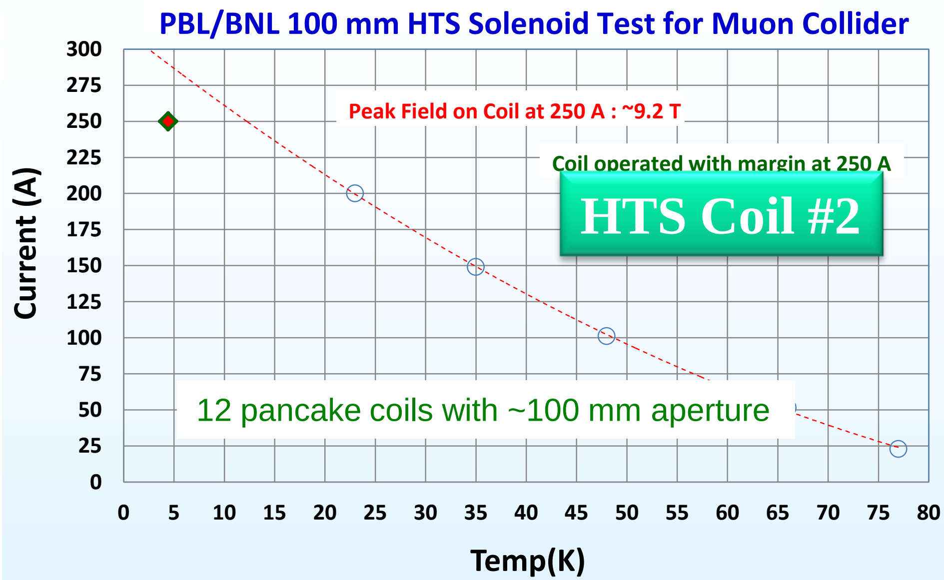
High Field HTS Solenoid Test Results





- **Field on axis: over 15 T**
- **Field on coil: over 16 T**
- Highest field in an all HTS solenoid (previous best SP/NHMFL ~10.4 T)
- **Overall J_o in coil: >500 A/mm^2 at 16 T**

- **Field on axis: 6.4 T**
- **Field on coil: 9.2 T**
- Test stopped at 250 A to protect electronics
- Largest use of HTS (1.2 km) in a high field HTS magnet operating at 4K
- Full magnet will generate over 10 T and use 2.4 km conductor in 24 pancakes

Summary

- HTS offers a unique magnet solution for challenging fragment separator environment of FRIB and RISP.
- In addition to fragment separator, HTS magnets could be beneficial in several other regions.
- R&D for FRIB 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.
- FRIB or RISP could be the 1st major accelerator with HTS magnets playing a crucial role.