HTS-based Quadrupoles

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Radiation Effects in Superconducting Magnet Materials
RESMM'12, FermiLab, Feb 13-15, 2012

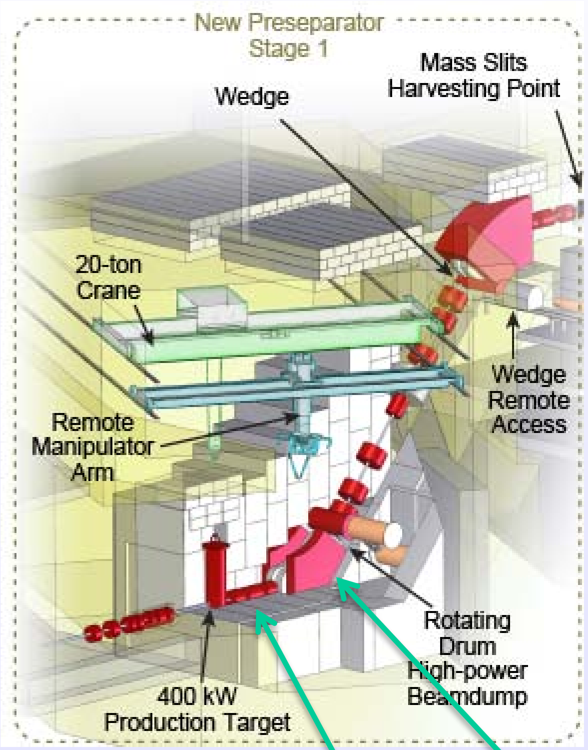
Overview

- **Why HTS Quadrupoles for FRIB ?**
- **1st Generation HTS Quad**
  - **brief overview and large energy deposition experiments**
- **2nd Generation Design, Construction and Test Results**
  - **Also radiation damage experiments at BNL**
    - **Related technology: Recent test results on 16T HTS solenoid**
- **Summary**

Radiation and Heat Loads in Fragment Separator Magnets

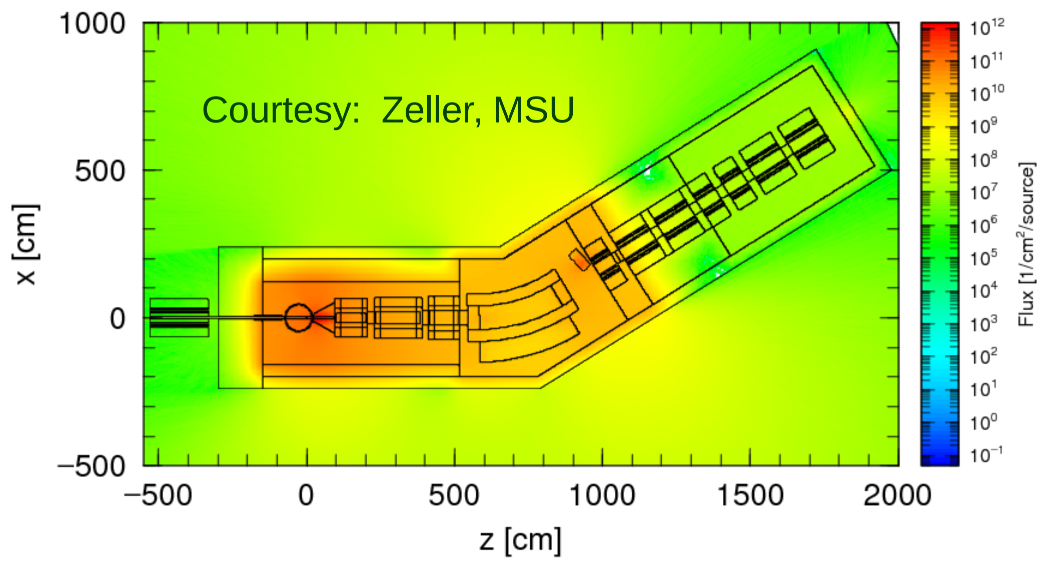
To create intense rare isotopes, 400 kW beam hits the production target.

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



Exposure in the first quad 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

HTS Magnets in Fragment Separator

Use of HTS magnets in Fragment Separator region over conventional Low Temperature Superconducting magnets is appealing because of :

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 (~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.

First Generation Magnet

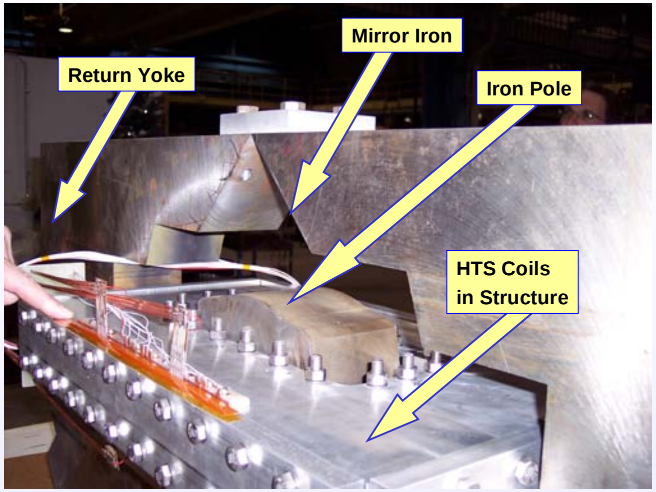
(made with Bi2223 from ASC)

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

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

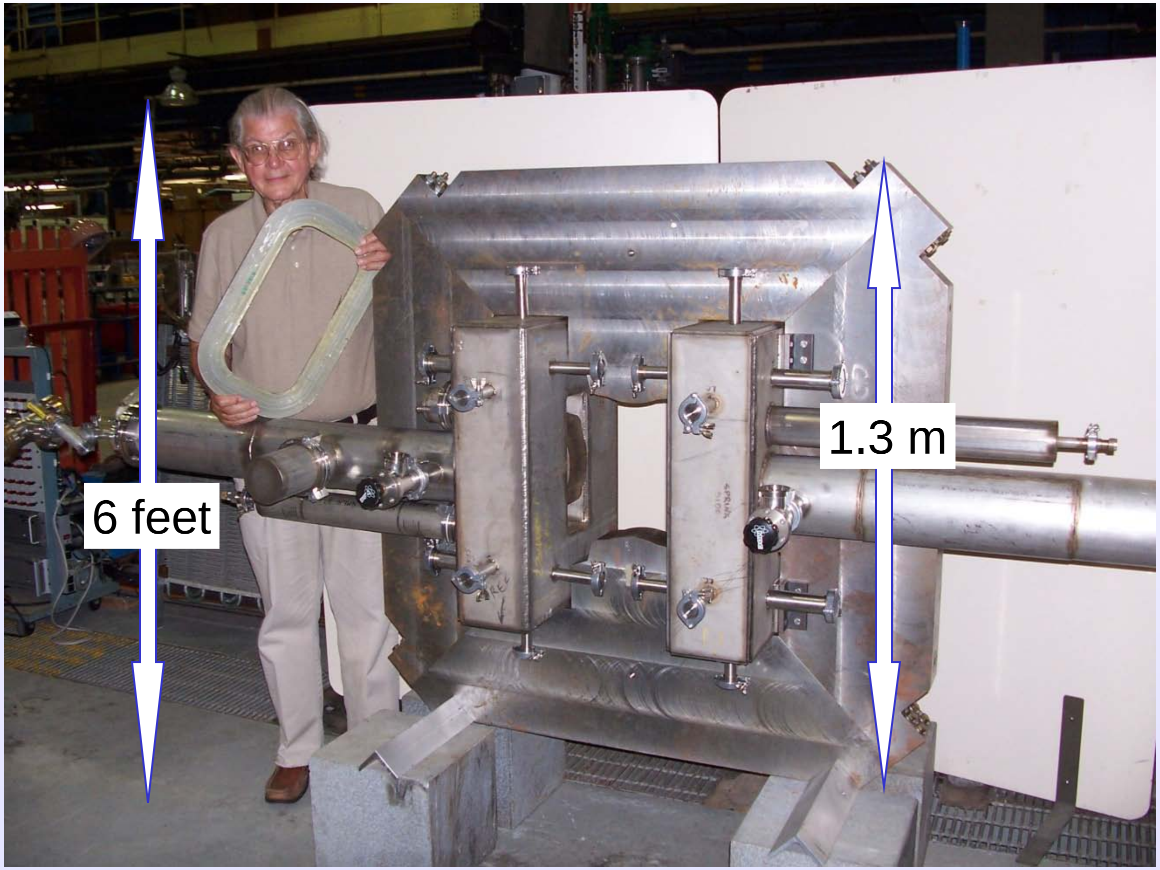
Parameter	Value
Aperture	290 mm
Design Gradient	10 T/m
Magnetic Length	425 mm (1 meter full length)
Coil Width	500 mm
Coil Length	300 mm (1125 mm full length)
Coil Cross-section	62 mm X 62 mm (nominal)
Number of Layers	12 per coil
Number of Turns per Coil	175 (nominal)
Conductor (Bi-2223) Size	4.2 mm 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

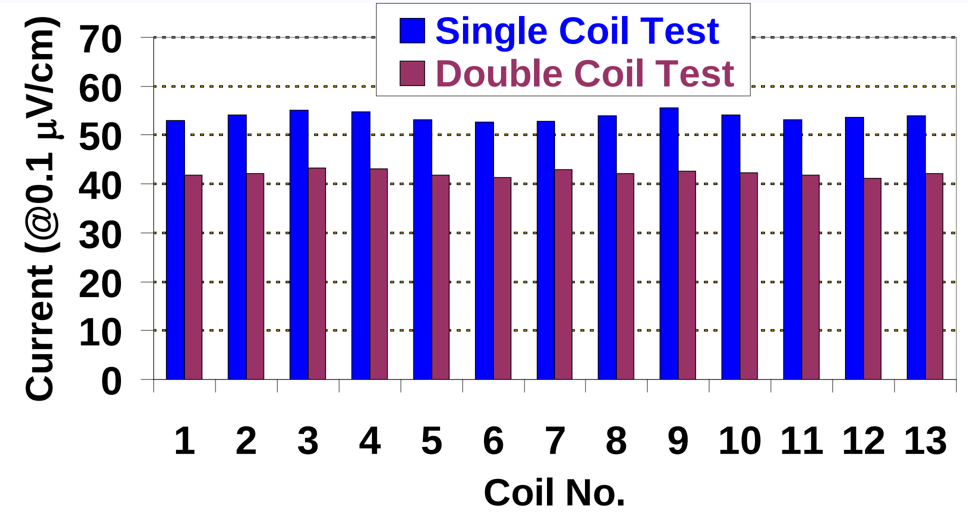
Mirror warm iron



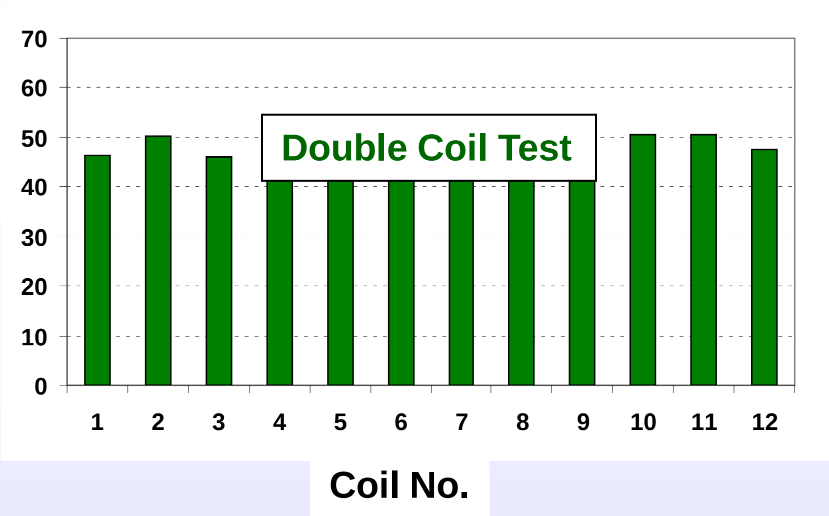
LN_2 (77 K) Test of Coils Made with ASC 1st Generation HTS

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 !

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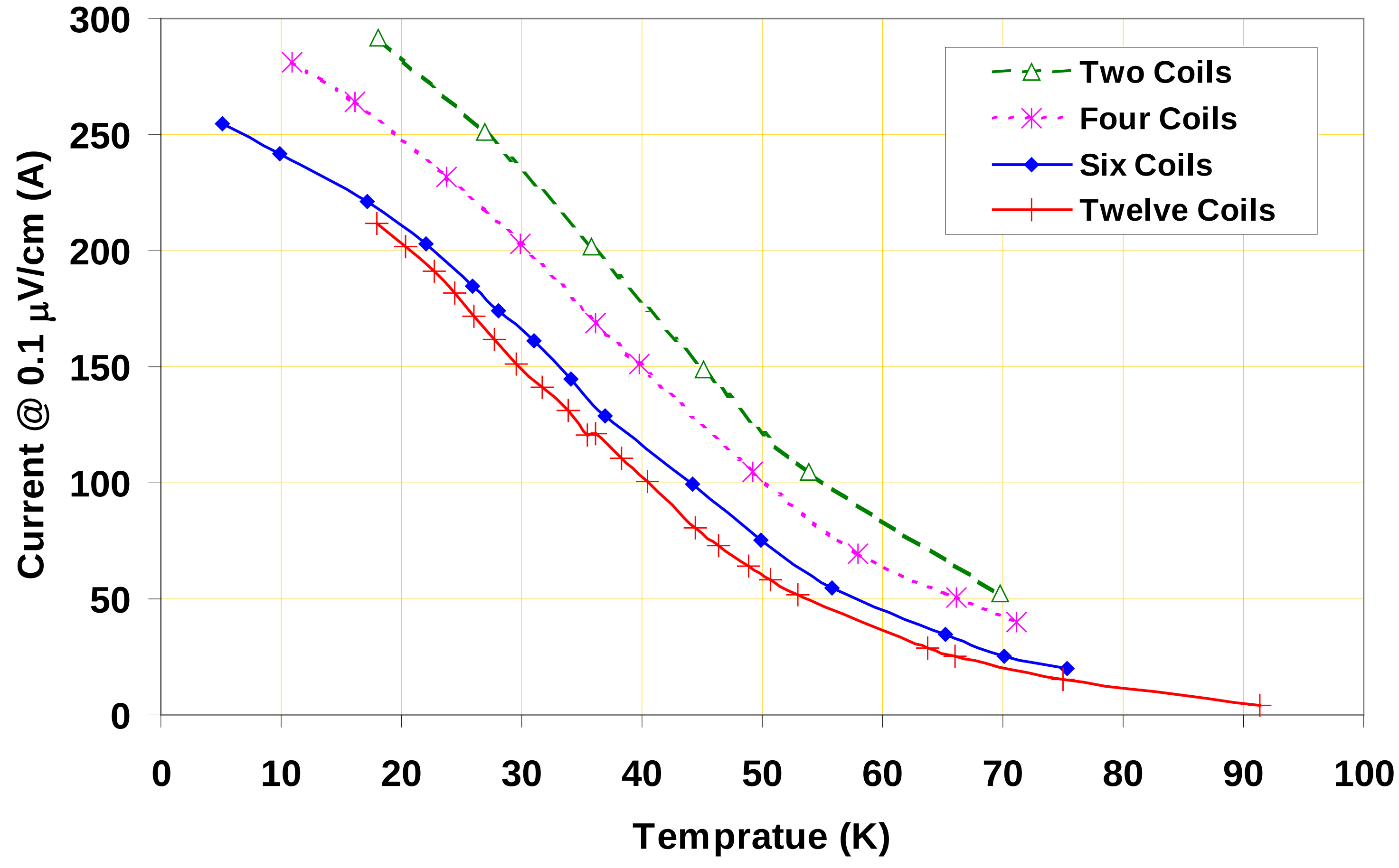
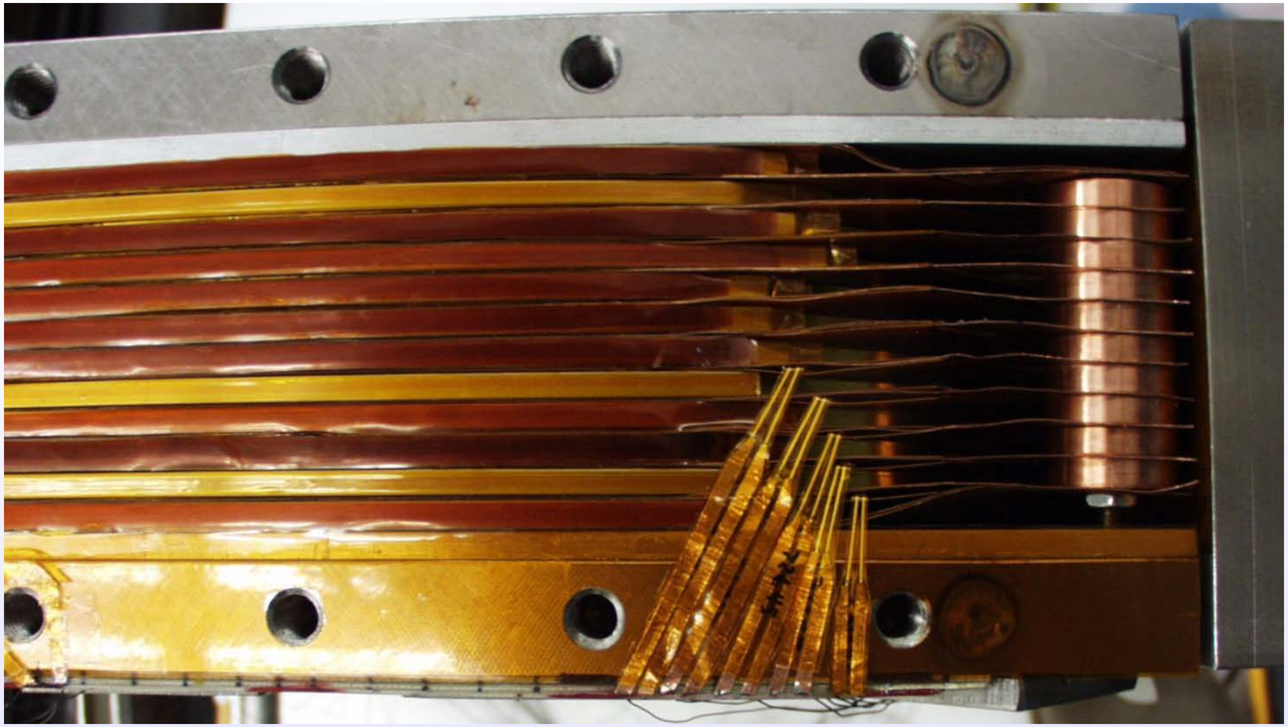
RIA HTS Mirror Model Test Results (operation over a large temperature range)



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 and Cryogenics Experiments



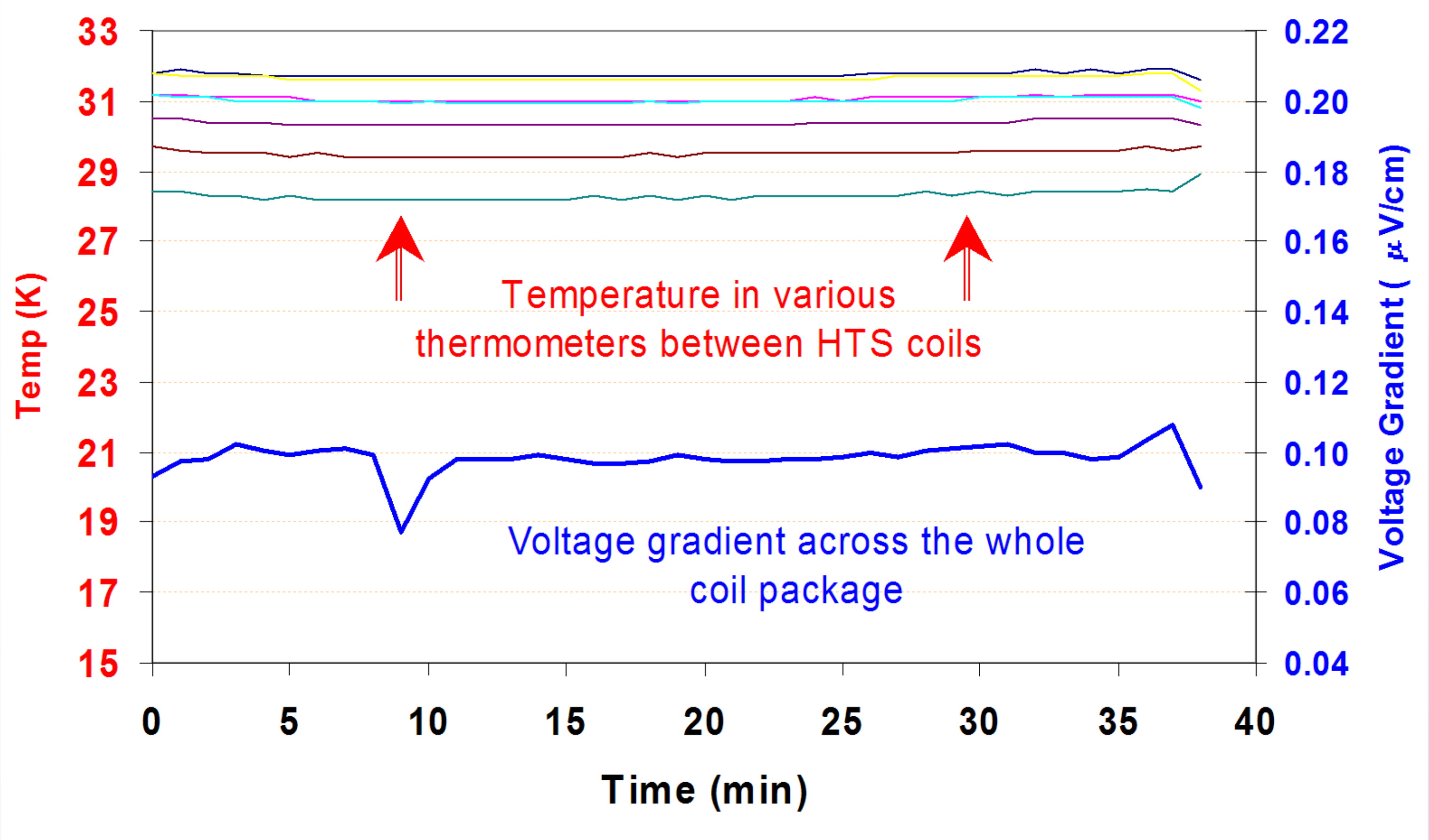
Stainless steel tape heaters for energy deposition experiments

Copper sheets between HTS coils with copper rods and copper washers for conduction cooling

- **In conduction cooling mode, helium flows through top and bottom plates only.**
- **In direct cooling mode, helium goes in all places between the top and bottom plates and comes in direct contact with coils.**
- **Energy deposition in magnet worked well in both cases.**

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

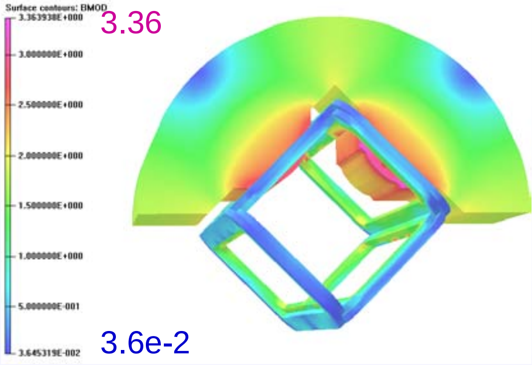
Second Generation Magnet
(made with 12 mm ReBCO/YBCO)

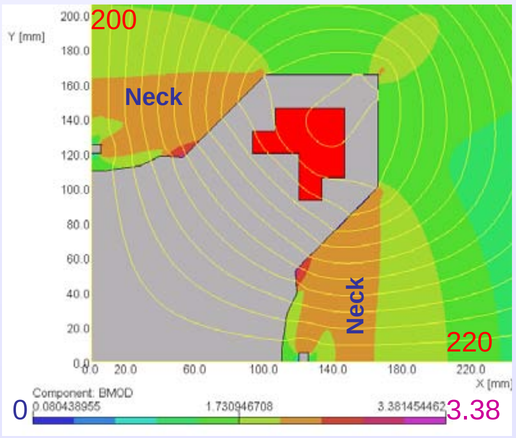
- HTS magnet technology demonstrated with significant quantities from two vendors (SuperPower and ASC)
  - ~9 km equivalent of 4 mm tape
- Radiation damage test in high radiation environment

Why 2G HTS

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

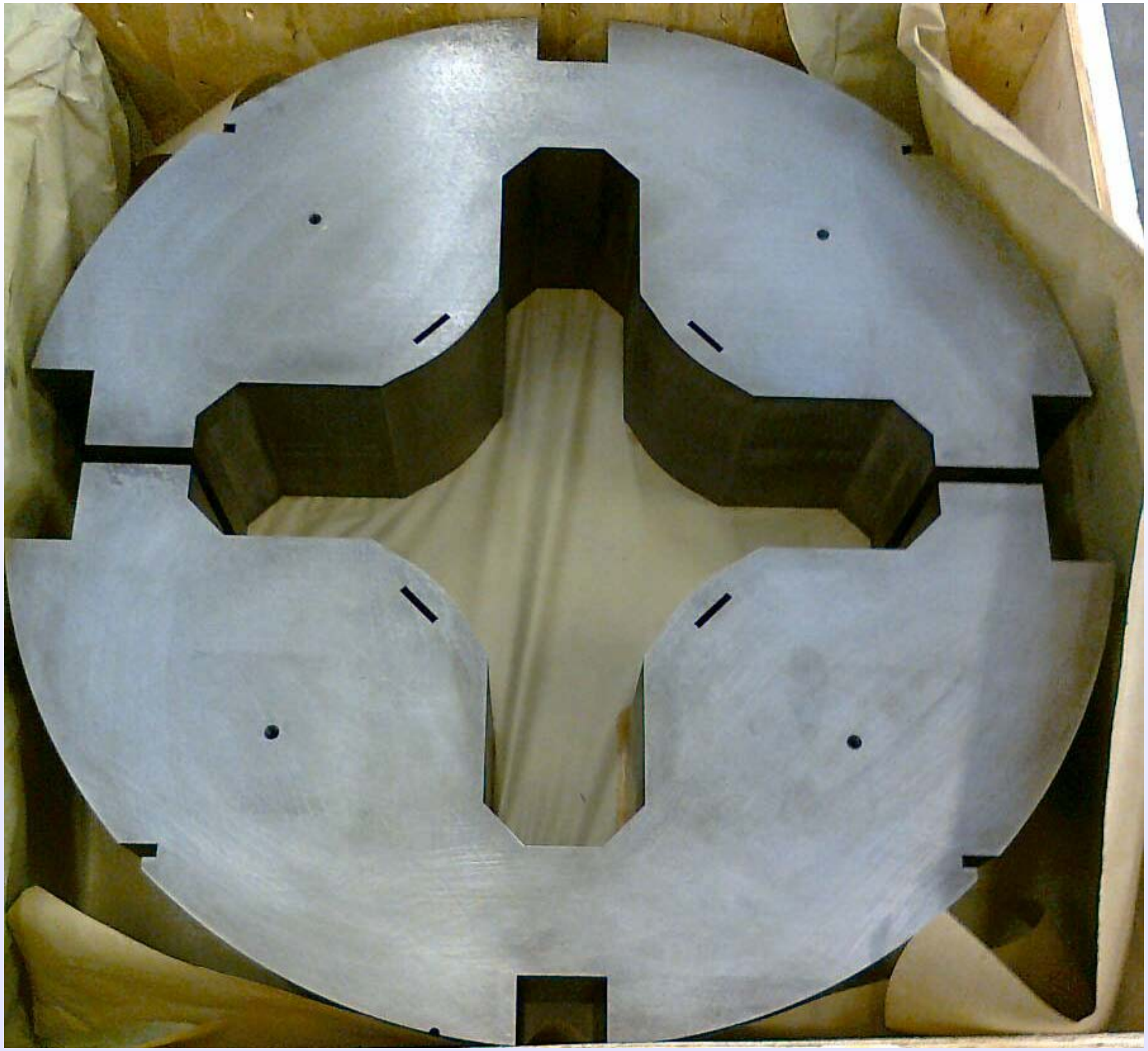
Parameter List (full size Q1)





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(including cryostat)	~880 mm
Number of Layers	2 per coil
Coil Width (for each layer)	12.5 mm
Coil Height (small, large)	27 mm, 40 mm
Number of Turns:	
for coils made with SuperPower conductor	213 turns each for all four coils (for ~27 mm)
for coils made with ASC conductor	121, 125 and 118, 128 turns (for ~40 mm)
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 (2 HTS tapes soldered together)
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	~172 A (SuperPower), ~300 A (ASC)
Stored Energy	37 kJ
Inductance	~1 H
Operating Temperature	**50 K (nominal)** ***higher grad at lower temp***
Design Heat Load on HTS coils	5 kW/m^3

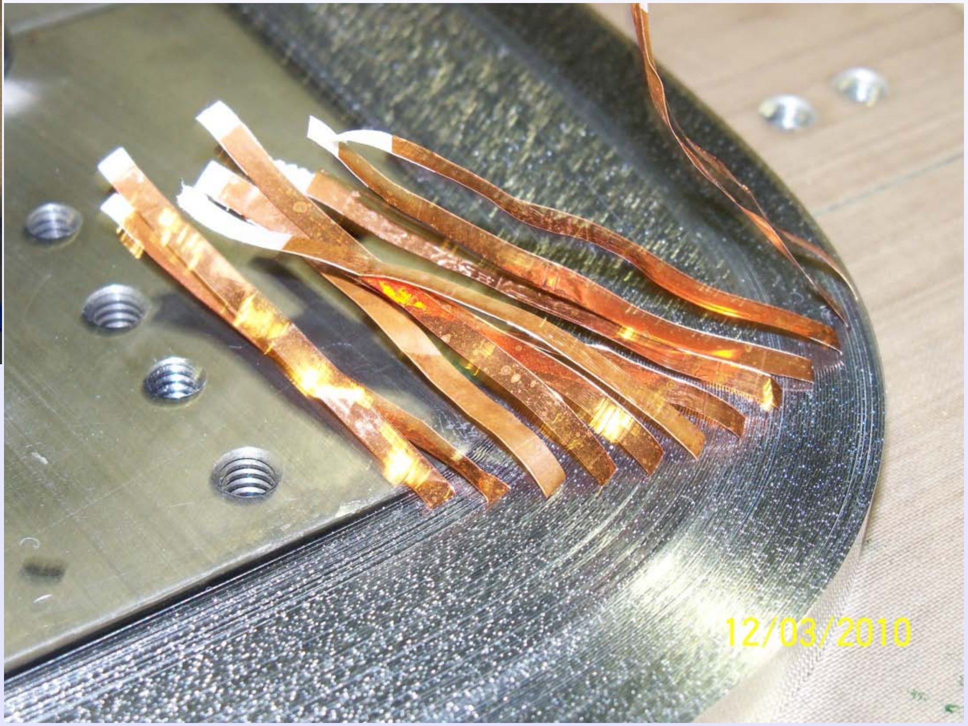
Yoke Iron for FRIB Quad



Coils Made with ASC HTS

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

Coil width = ~40 mm.



One coil was wound without any splice
(one more was possible)

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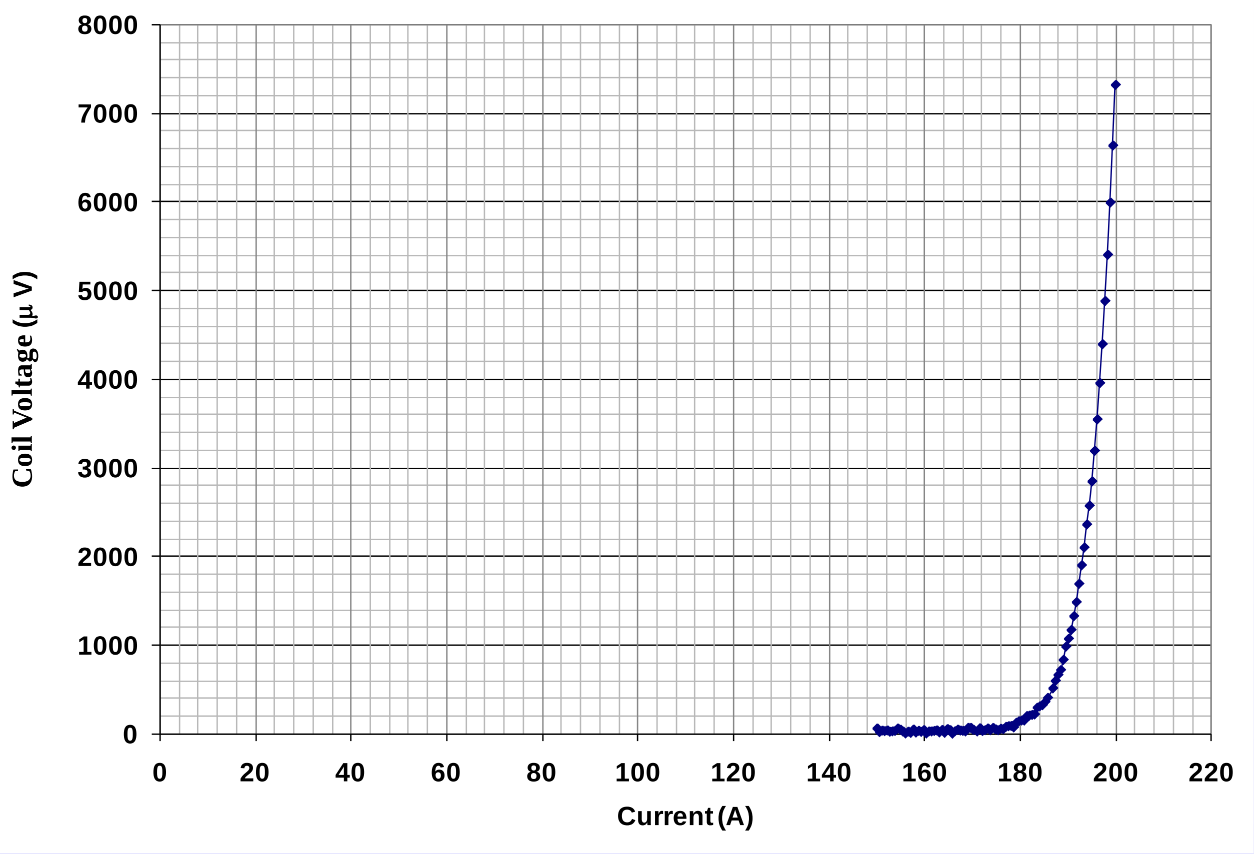
77 K Test Results of ASC Coil



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.

FRIB Coil Made With SuperPower Tape

Partially wound coil with SuperPower tape before the first splice

SuperPower coil uses ~330 meter of tape (~213 turns) per coil.

Coil width = ~27 mm.

Fully wound coil with SuperPower tape with one splice

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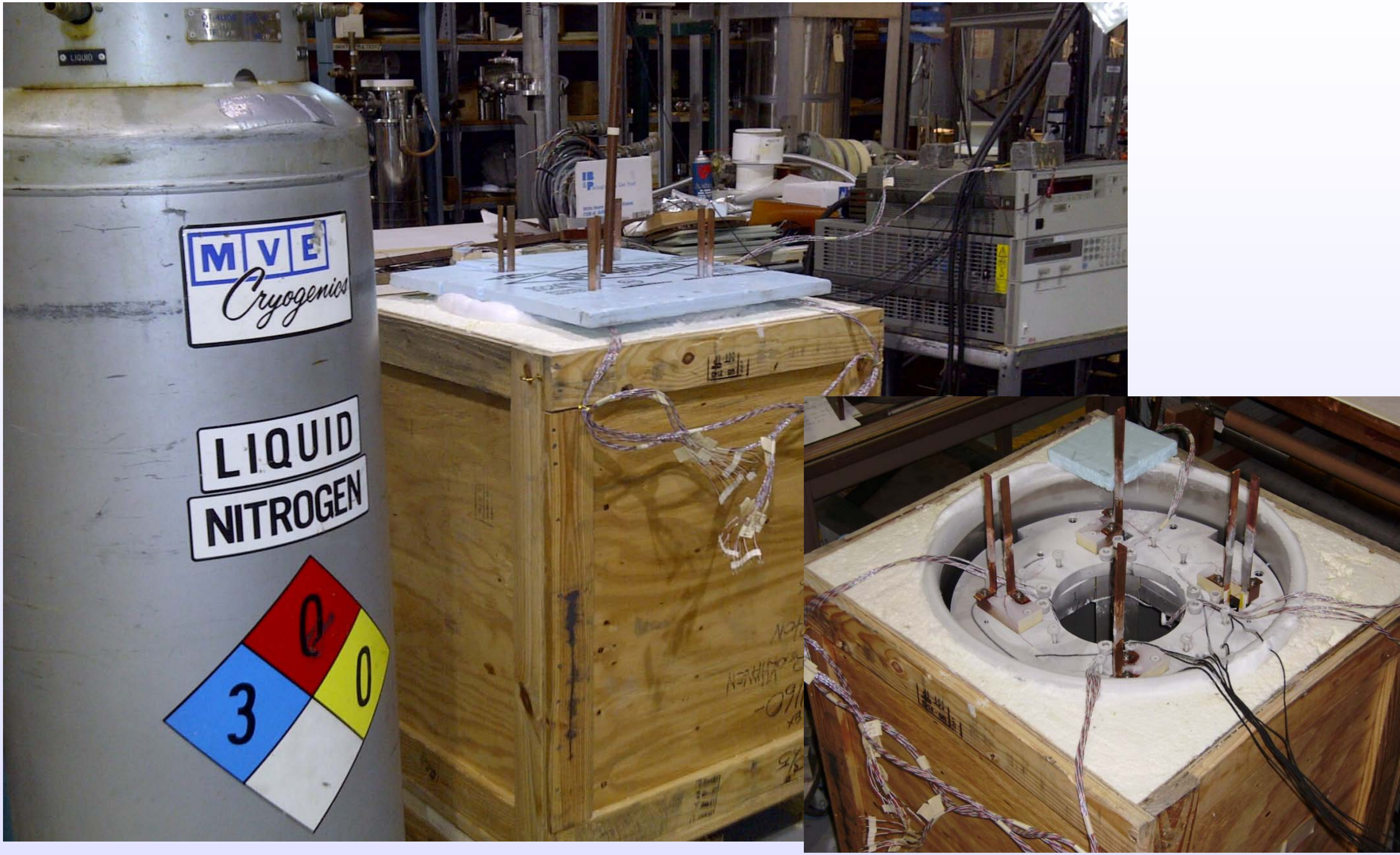
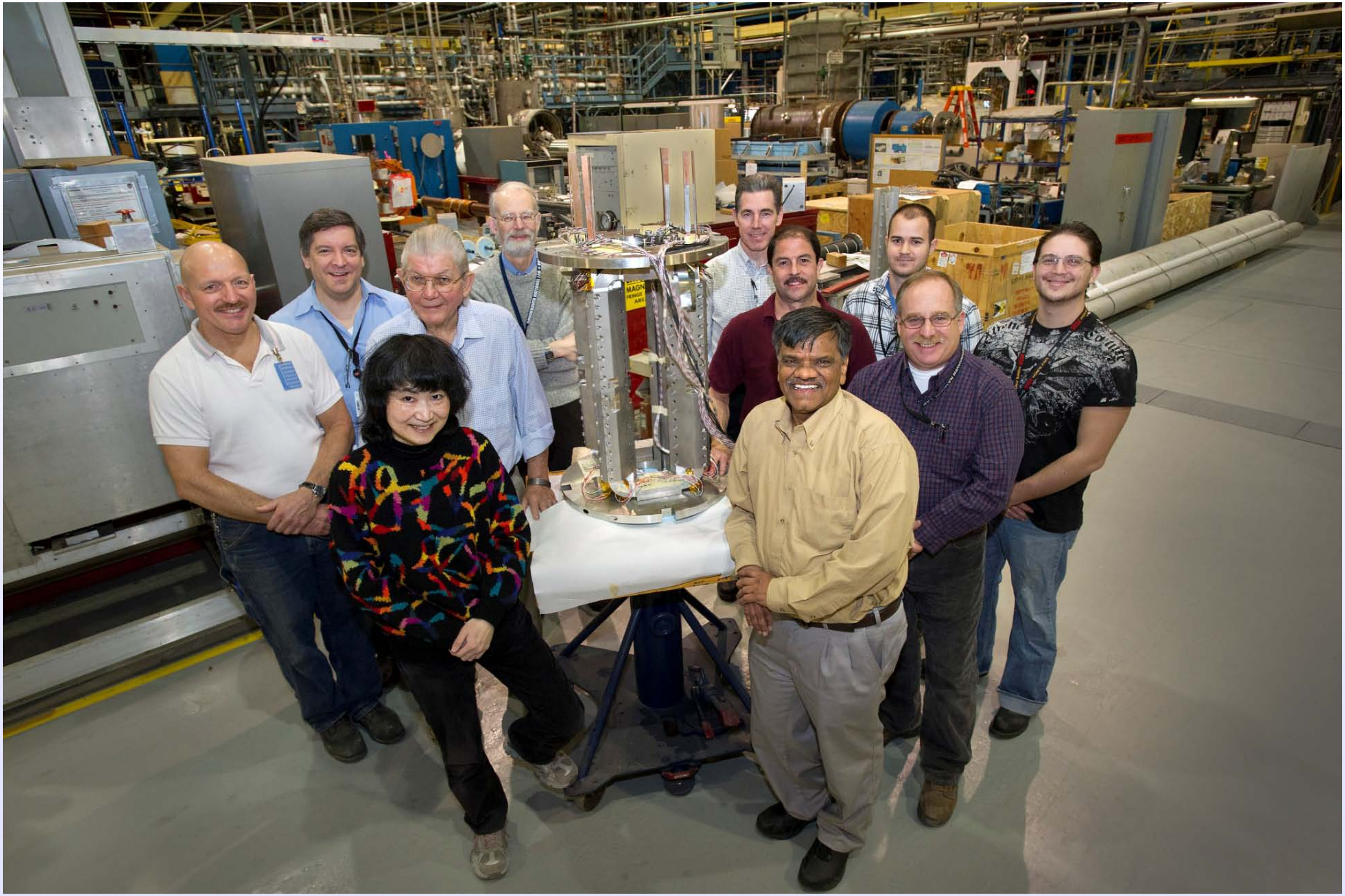
Coils Assembled in Quadrupole Support Structure

HTS Quad in Advanced Cryostat



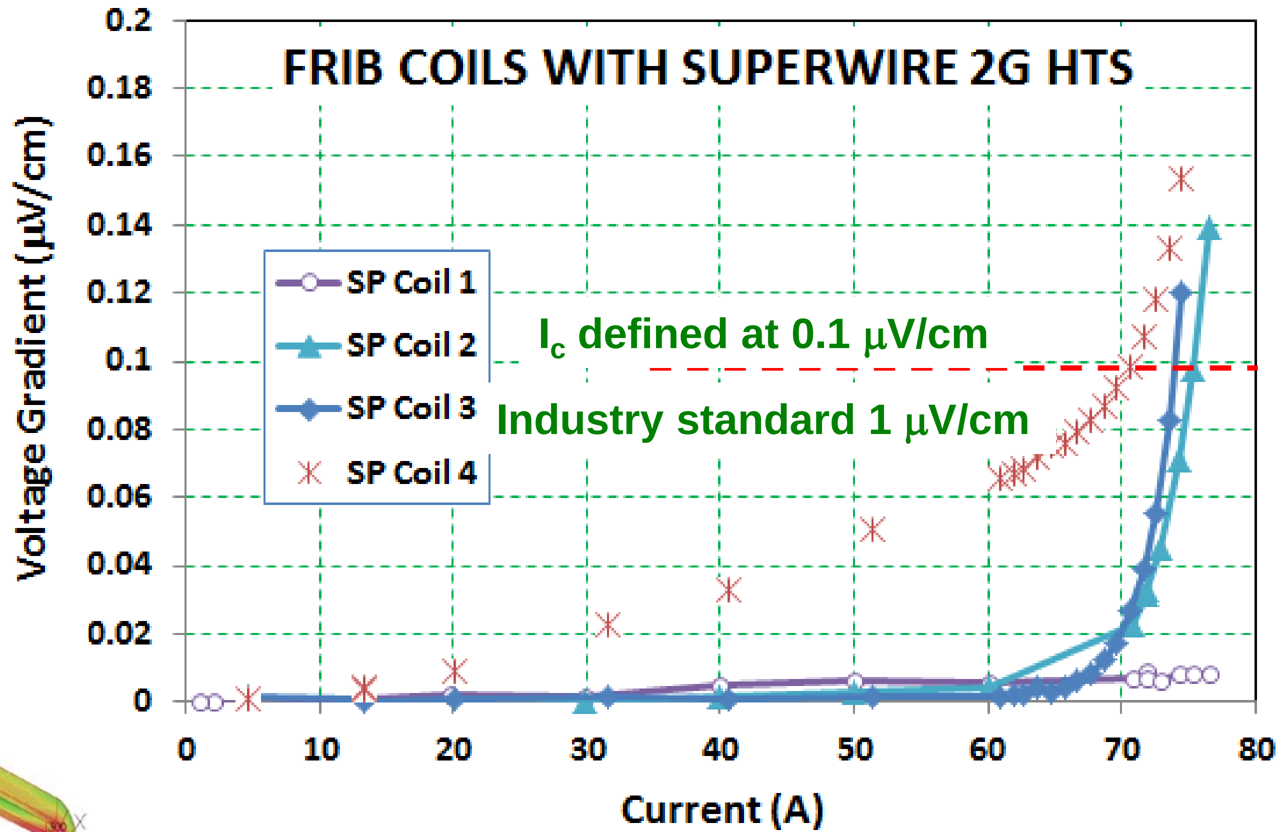
Proud Team Members

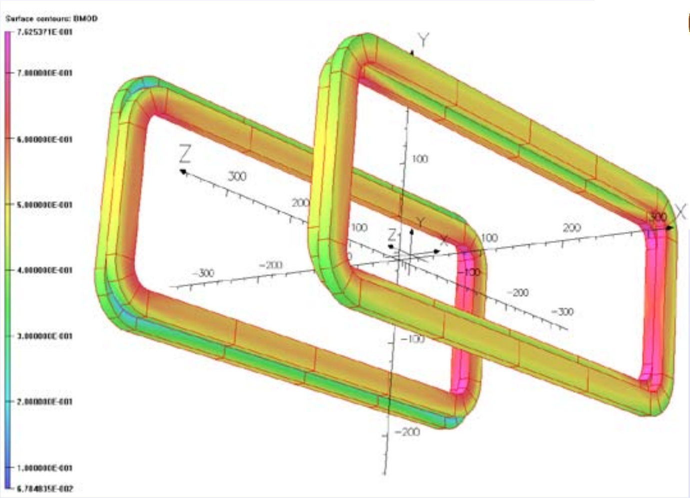


Performance of SuperPower Coils (four of eight coils powered)

Four ASC coils were not powered

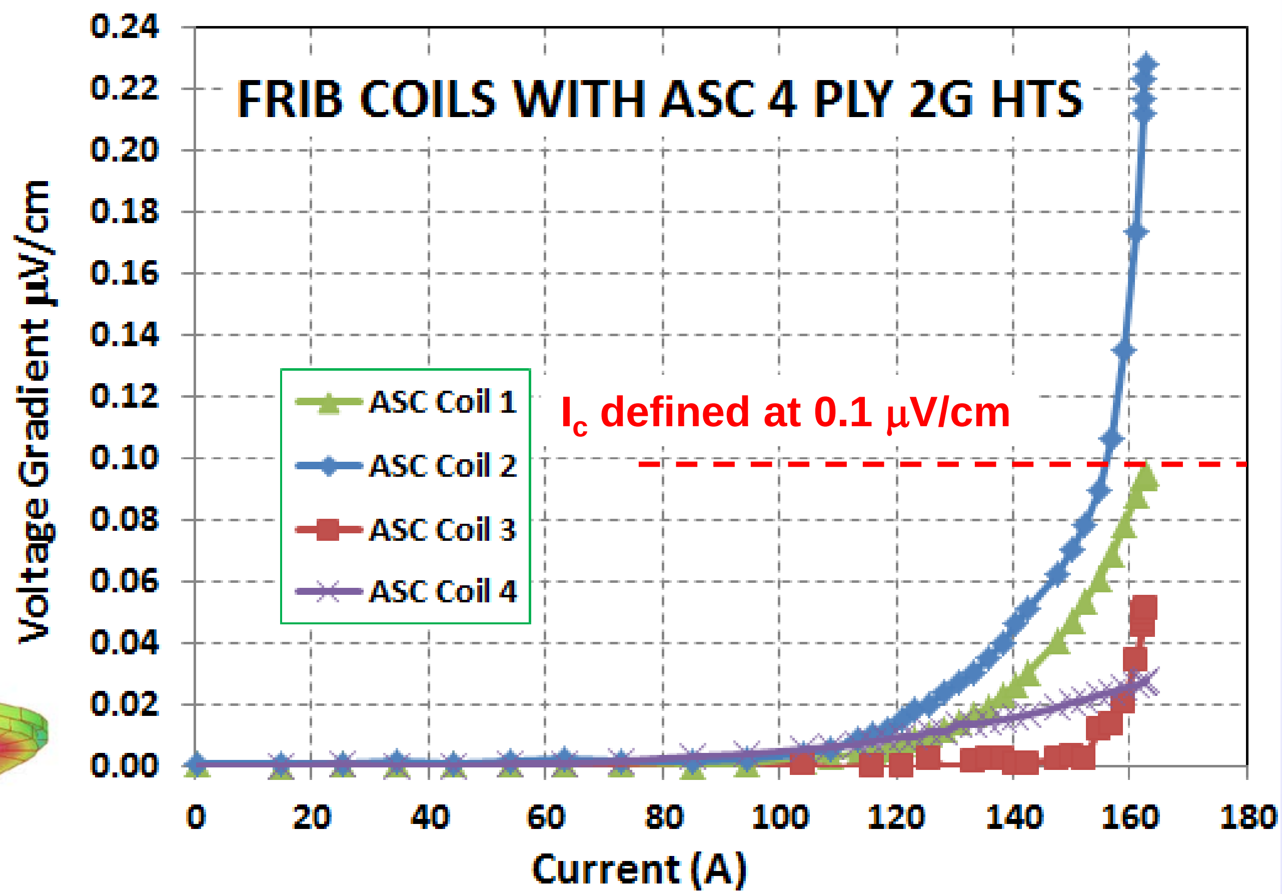
Field on SuperPower coils at 100 A





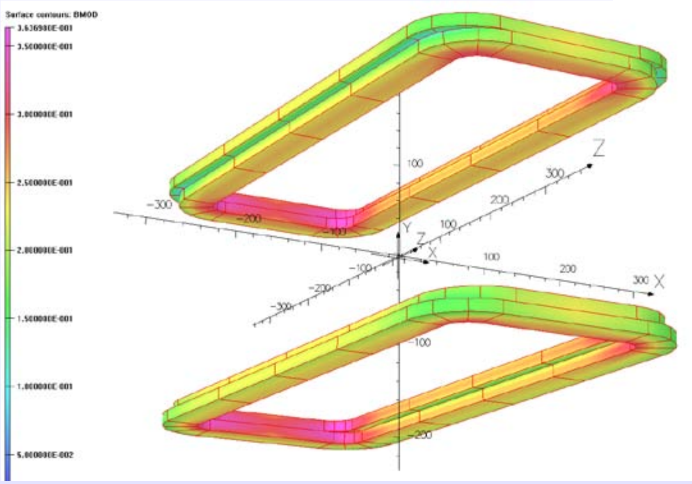
Internal splice on wrong tape side shows higher resistance. This is not an operational issue as the heat generated is negligible as compared to the energy deposition.

Performance of ASC Coils (four coils of eight powered)



ASC Tape:

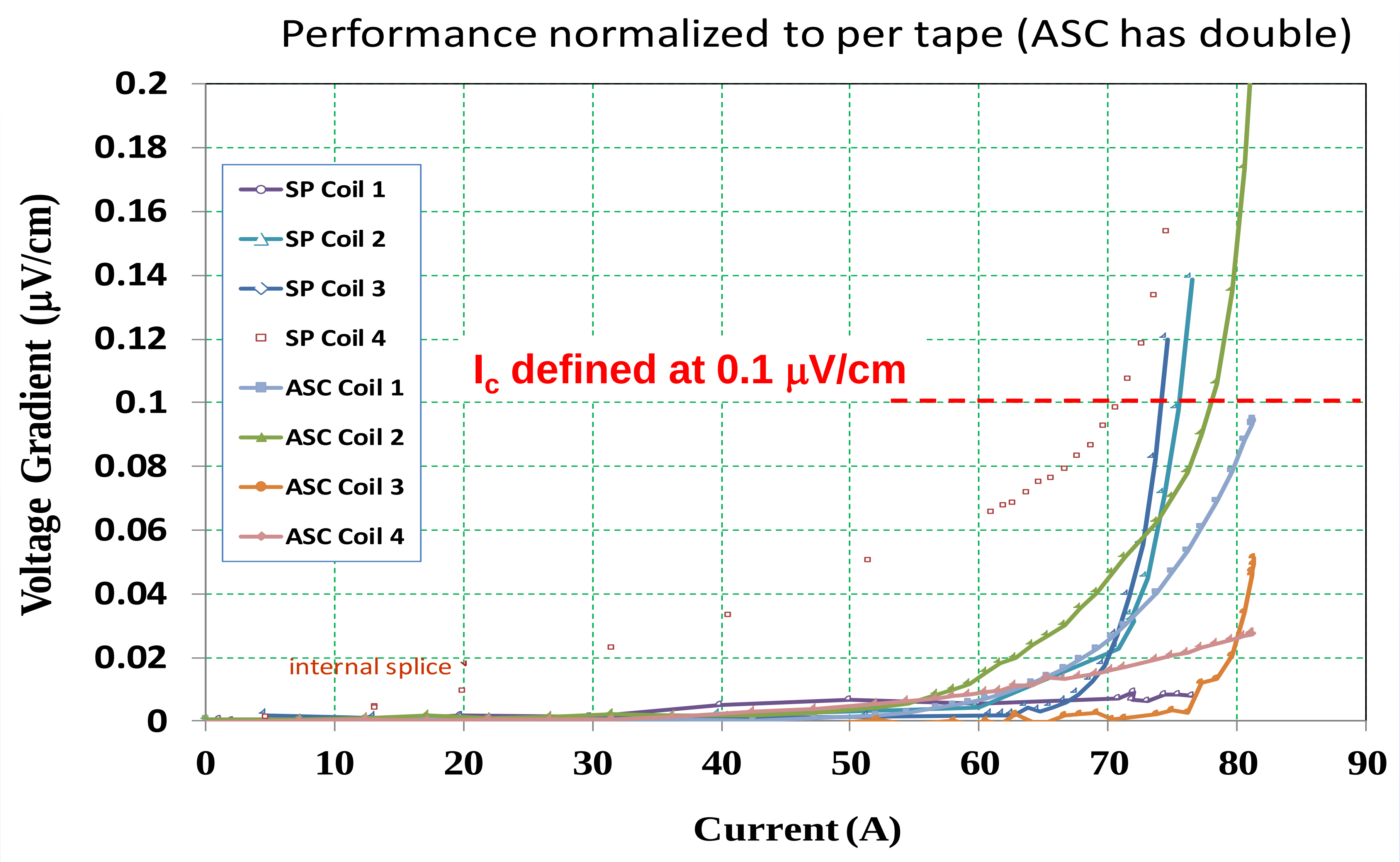
2 plies of HTS and 2 plies of Cu



Field on ASC coils at 100 A

Four SuperPower coils not powered

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

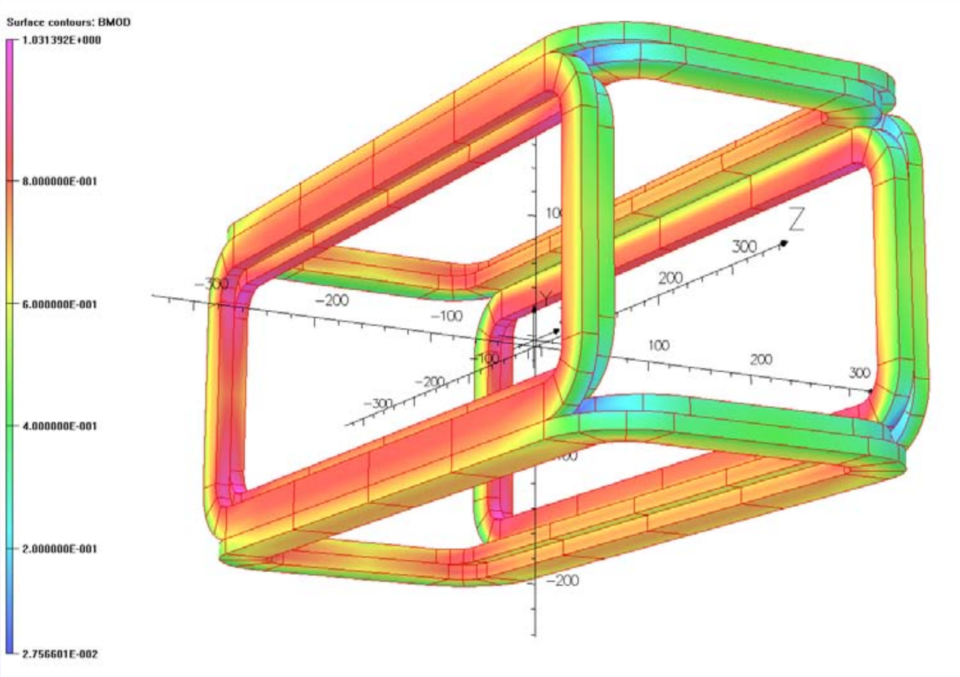


77 K Test in Quadrupole Mode (all eight coils powered)

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



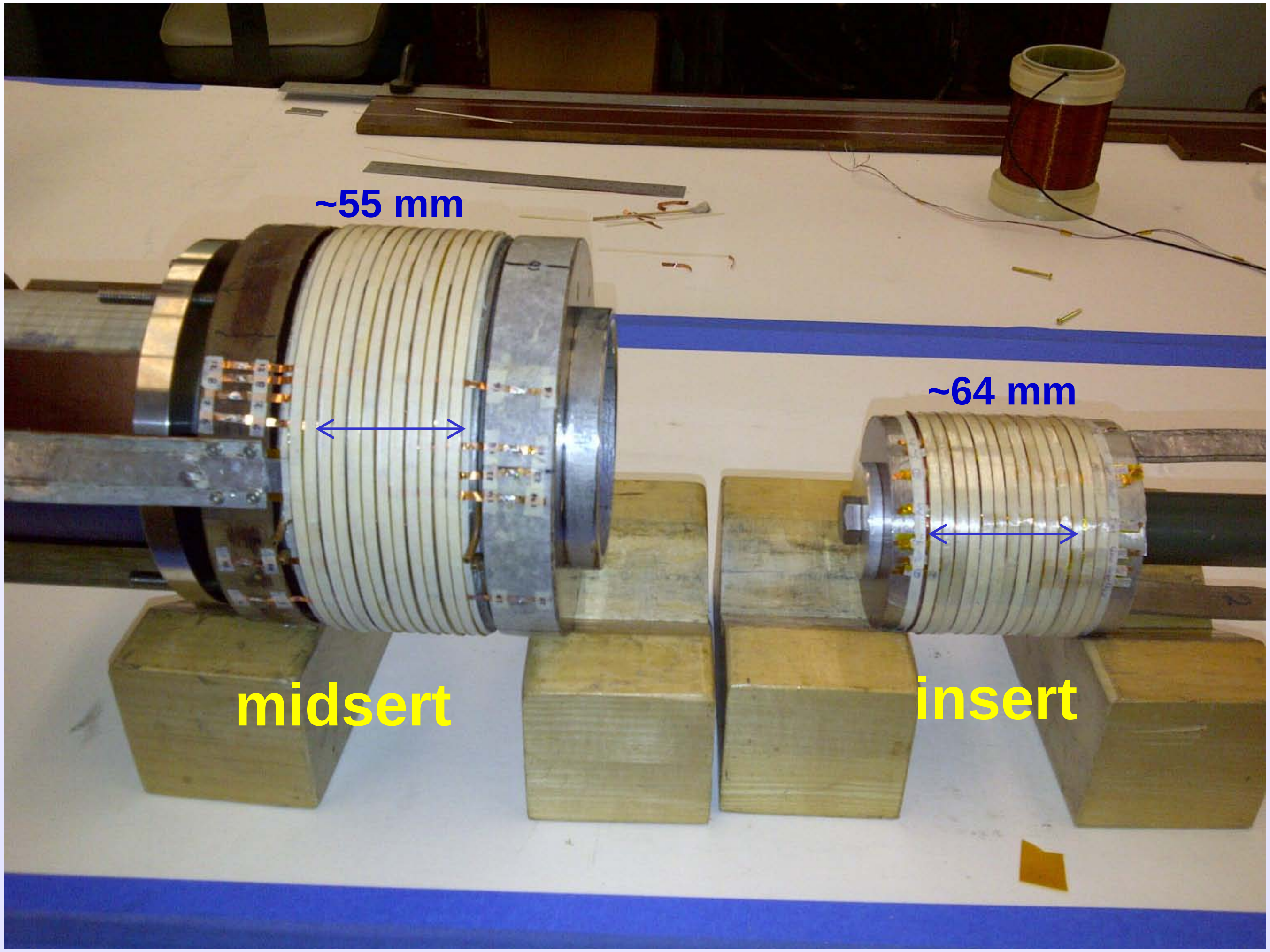
Design: SuperPower coils ~172 A and ASC coils ~300 A (at 40-50 K).

- **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.

High Field HTS Magnet Test Results

Two High Field HTS Solenoids



Part of PBL/BNL SBIRs for developing

20+ T HTS (YBCO) solenoid and 35+ T superconducting solenoid

Conductor from SuperPower with ~45 micron Cu

Test of ~100 mm HTS Solenoid

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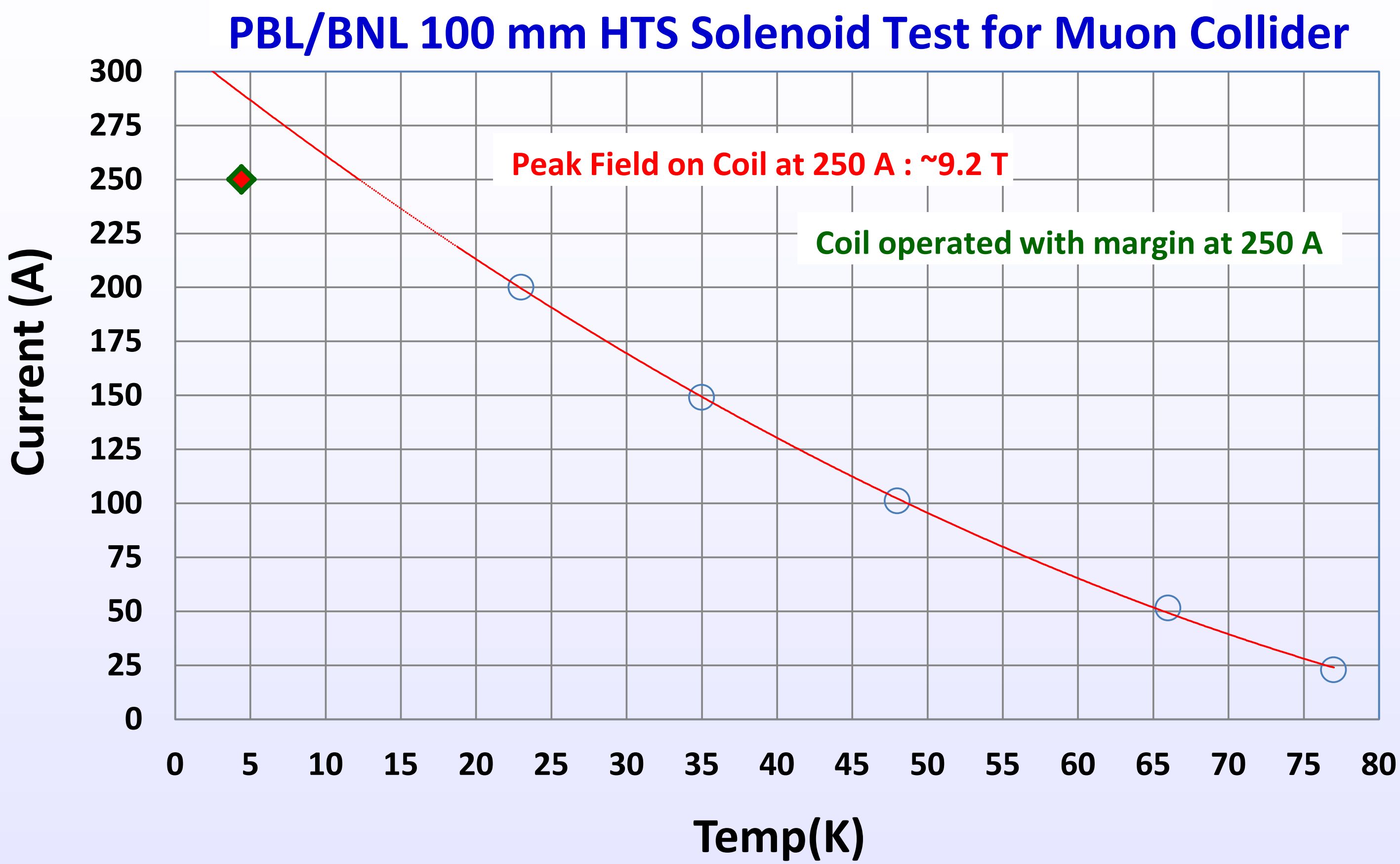


250 A ==>

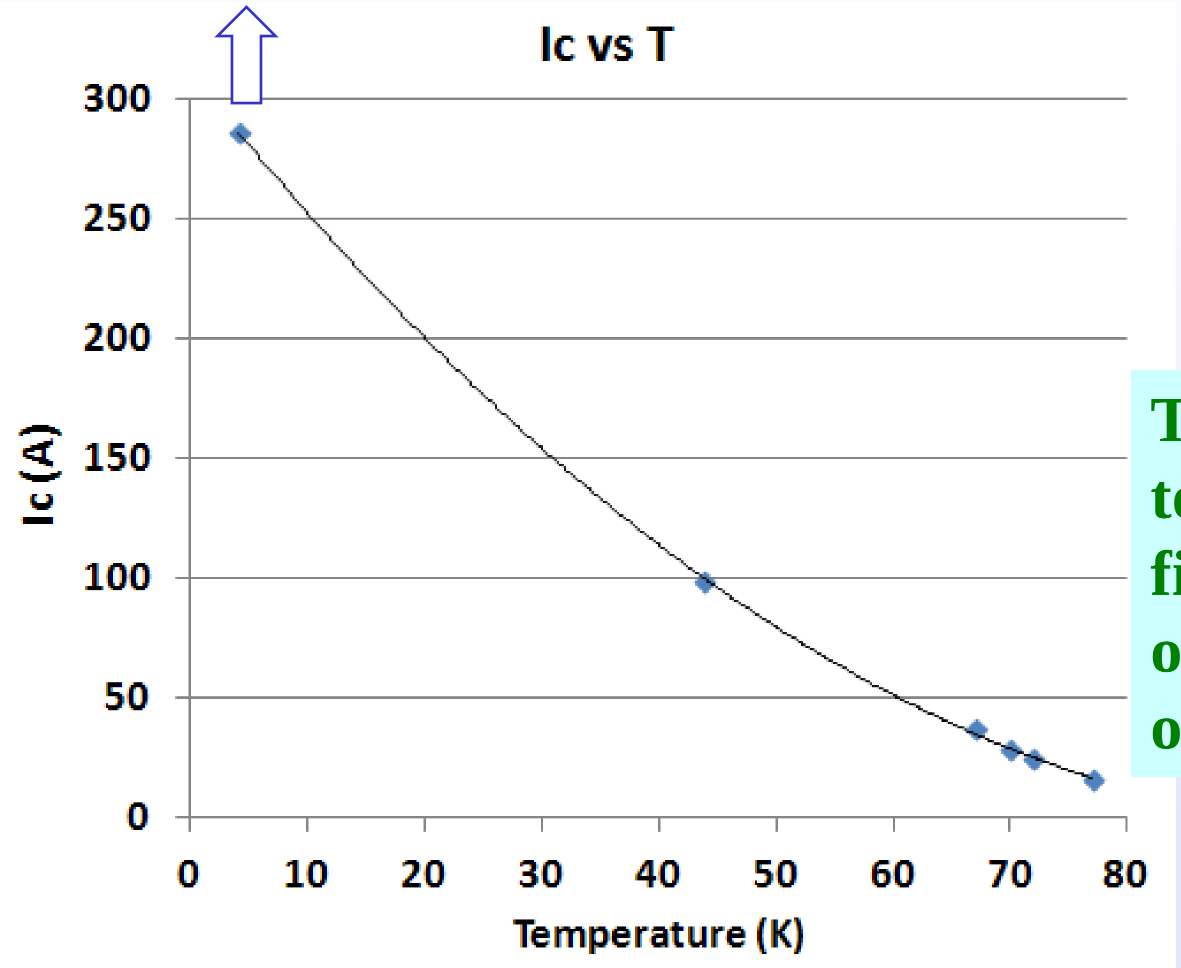
9.2 T on coil

Solenoid could have reached above 10 T, but we decided to hold back to protect our electronics

As per Superpower and search of literature, this is the first test of large aperture high field 2G magnet and also one that uses over 1 km (1.2 km) wire

Test of ~25 mm HTS Solenoid

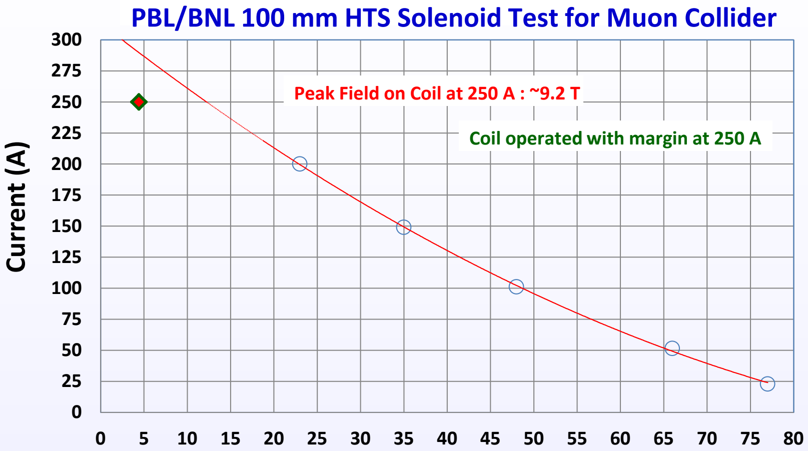
Field at 285 A: over 15 T on axis and over 16 T on coil

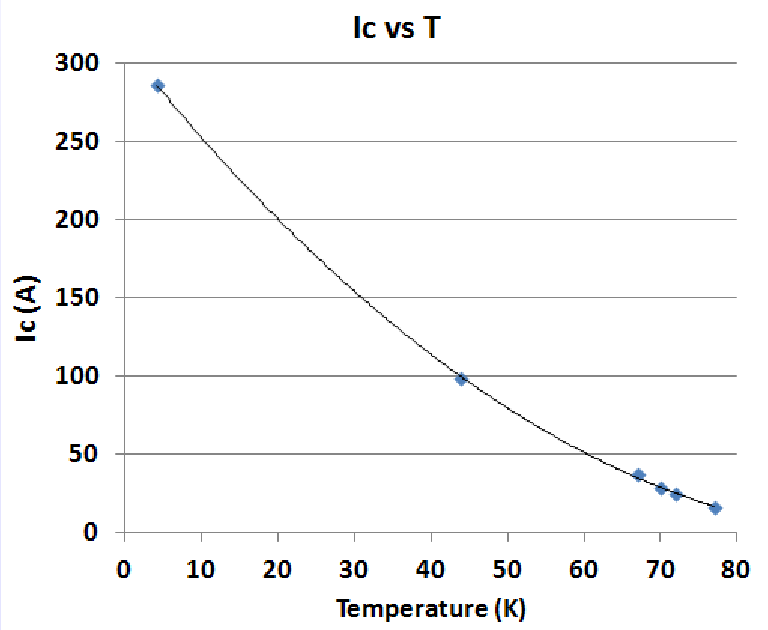


Highest field HTS magnet ever

The magnet has potential to go to even higher fields, as there was no onset of resistive voltage on the coil yet at 285 A.

Feedback from High Field HTS Solenoid Magnet Tests





- It has been demonstrated that 77 K measurements can be used as an important QA test.
- A scaling of 4 or more is expected at ~50 K (needed only 3 over measured coil performance at 77 K).
- Expect even higher gradient at ~40 K.
- It is shown that 2G HTS can be used in demanding conditions of high field and high forces (large stress/strain).
- HTS magnets can be protected (quench protection system was developed in part with funding from FRIB).

Radiation Damage Experiments

Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

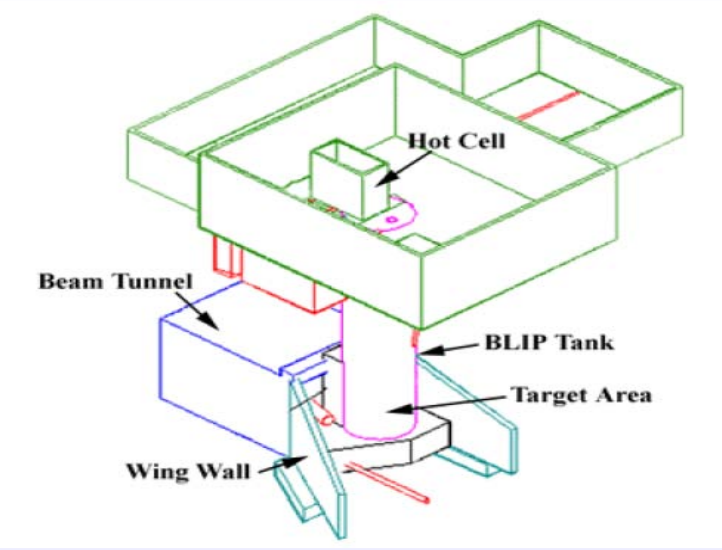
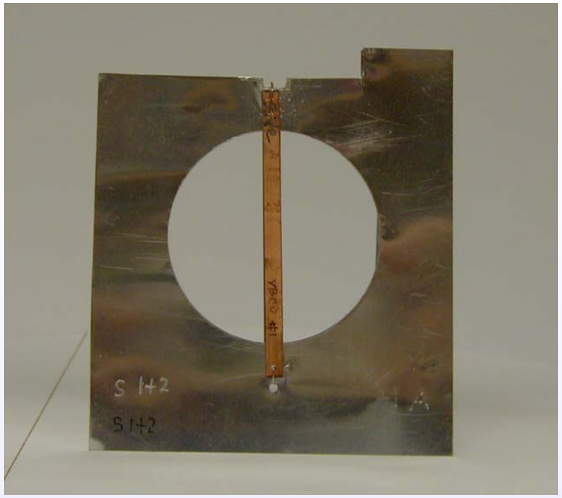


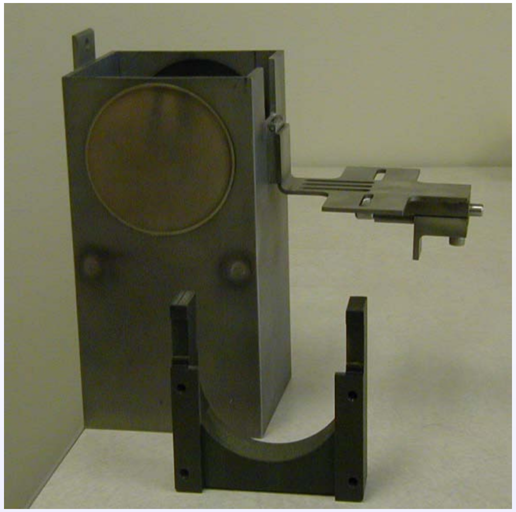
Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

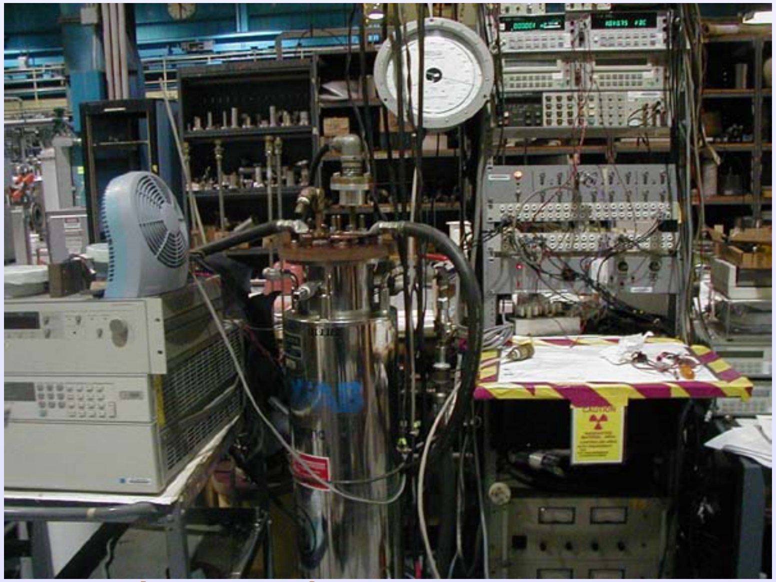
The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 μA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

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).

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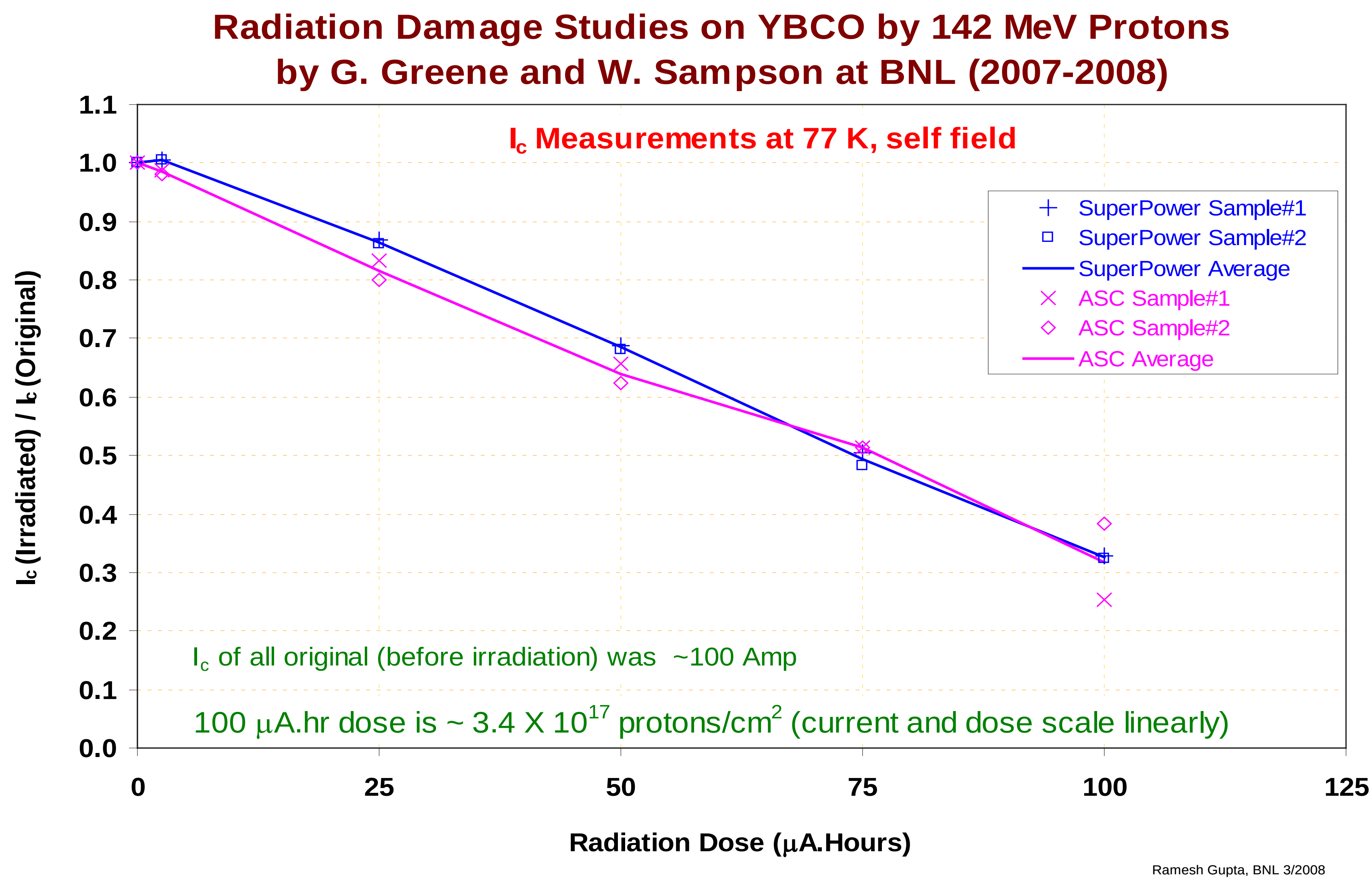
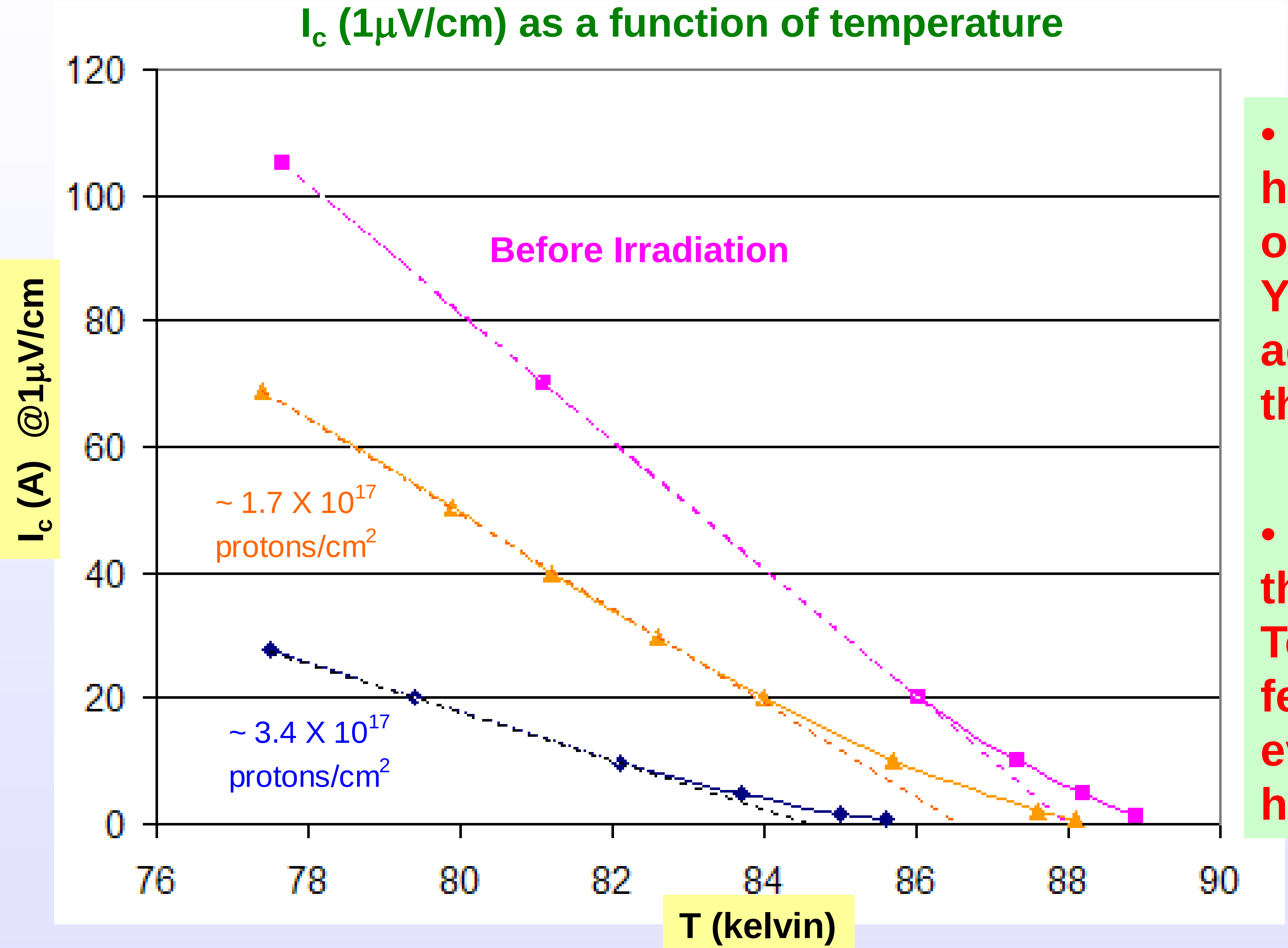
Relative Change in Ic due to Irradiation of SuperPower and ASC Samples



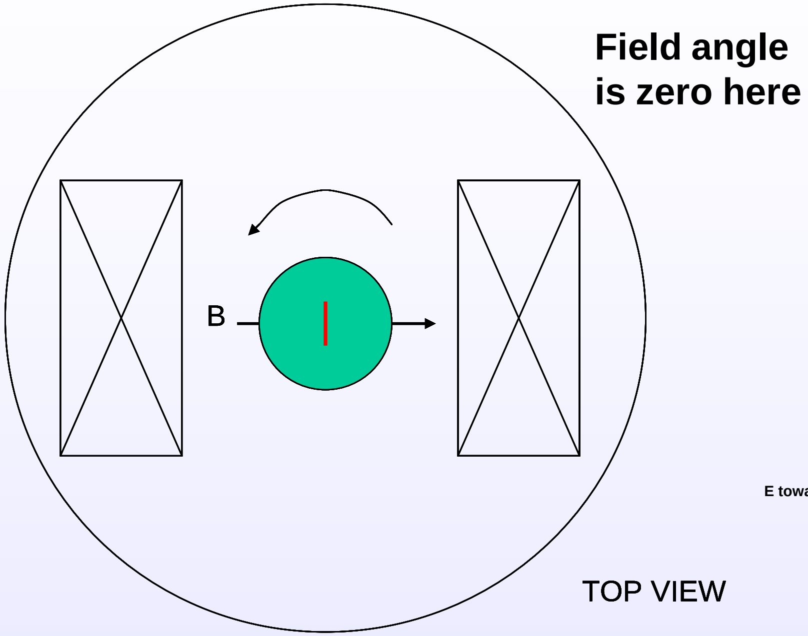
SuperPower and ASC samples show very similar radiation damage at 77 K, self field

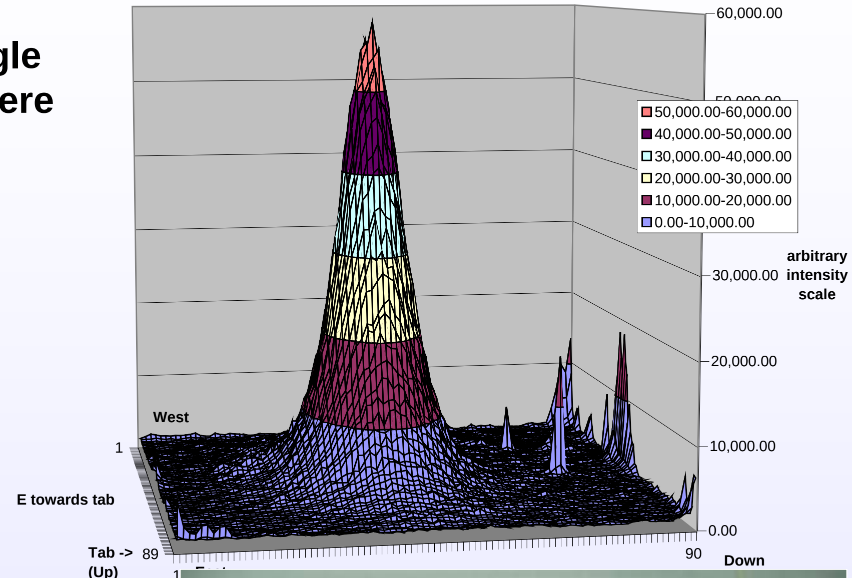
Change in Critical Temperature (T_c) of YBCO Due to Large Irradiation

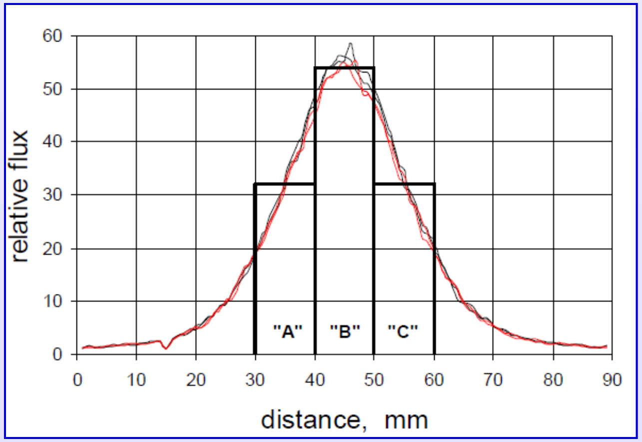


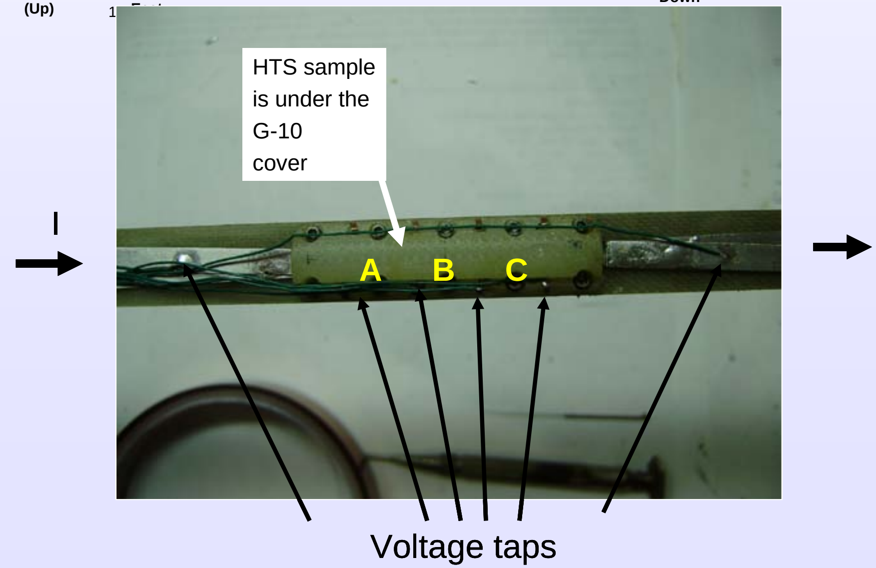
- Radiation has an impact on the T_c of YBCO, in addition to that on the I_c.
- However, the change in Tc is only a few degrees, even at very high doses.

Measurements of Radiation Damage in Presence of Field









- Since critical current of 2G HTS tape is anisotropic with respect to angle, the radiation damage measurements were performed as a function of field angle at 77 K in presence of various applied fields
- Next slide will show a summary of radiation damage for both ASC and SuperPower samples at 1 T
- For more details, please see:
  - G. Greene, R. Gupta and W. Sampson, "The Effect of Proton Irradiation on the Critical Current of Commercially Produced YBCO Conductors", Presented at Applied Superconductivity Conference, August 2008, Chicago.
  - R. Gupta, et al, "HTS for Magnets in High Radiation Environments", 5^{th} Forum on New Material, CIMTEC 2010, Italy, June 18, 2010.
  - Y. Shiroyanangi, et al., "Influence of Proton Irradiation on Second Generation HTS in Presence of Magnetic Field", 2011 Particle Accelerator Conference, New York

Next step: Measurements at 40-50 K, 0-3 T.

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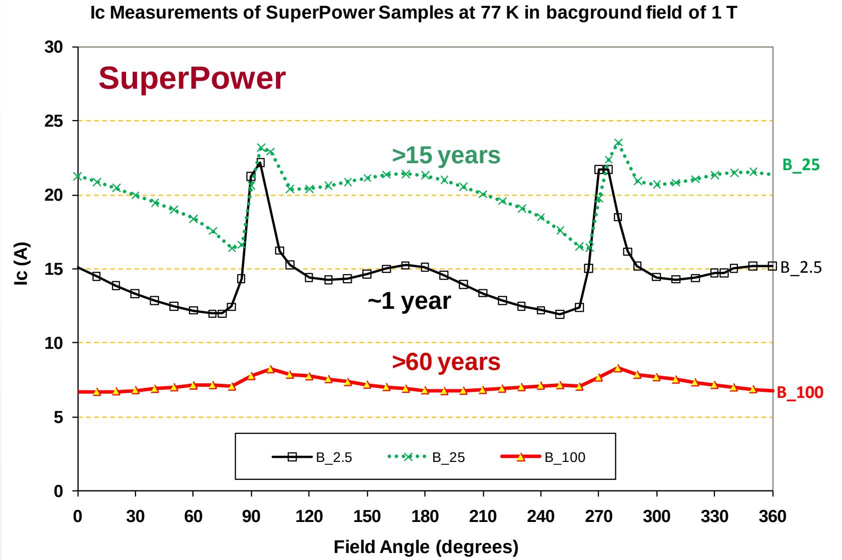
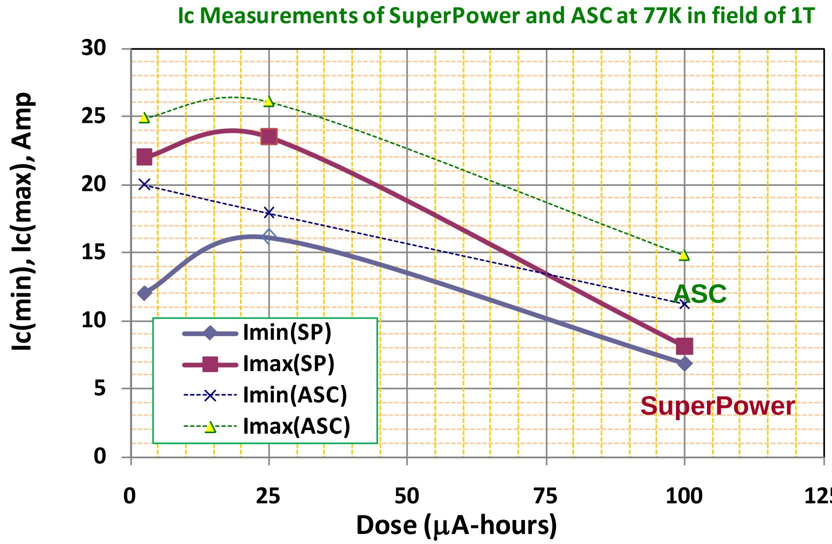
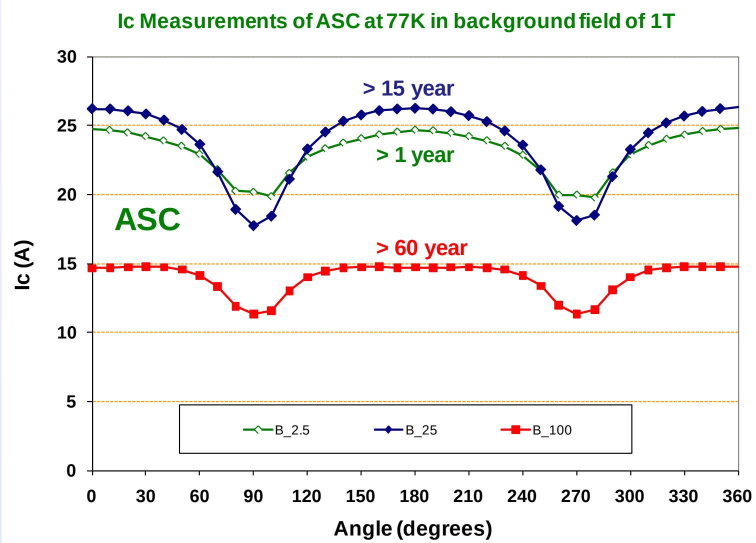
Radiation Damage from 142 MeV protons in SP & ASC Samples (measurements at @77K in 1 T Applied Field)





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)!!!**

We appreciate a close working relationship with NSCL/MSU.

Work supported by U.S Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.

Summary

- HTS offers a unique magnet solution for challenging fragment separator environment of FRIB.
- R&D for FRIB has demonstrated that HTS magnets can be successfully built using a large amount of HTS (~5 km in 1st generation and ~9 km equivalent in 2nd generation
- 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.
- Record high field magnet test show that HTS can be used and magnets can be protected in demanding conditions.
- FRIB could be the 1st major accelerator with HTS magnets.