

# HTS-based Quadrupoles

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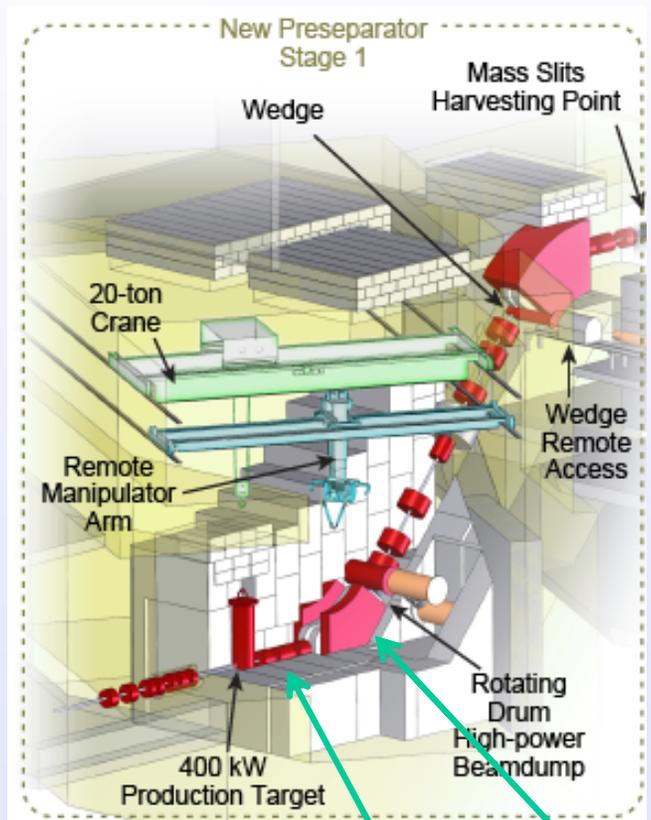
Radiation Effects in Superconducting Magnet Materials  
RESMM'12, FermiLab, Feb 13-15, 2012

# Overview

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

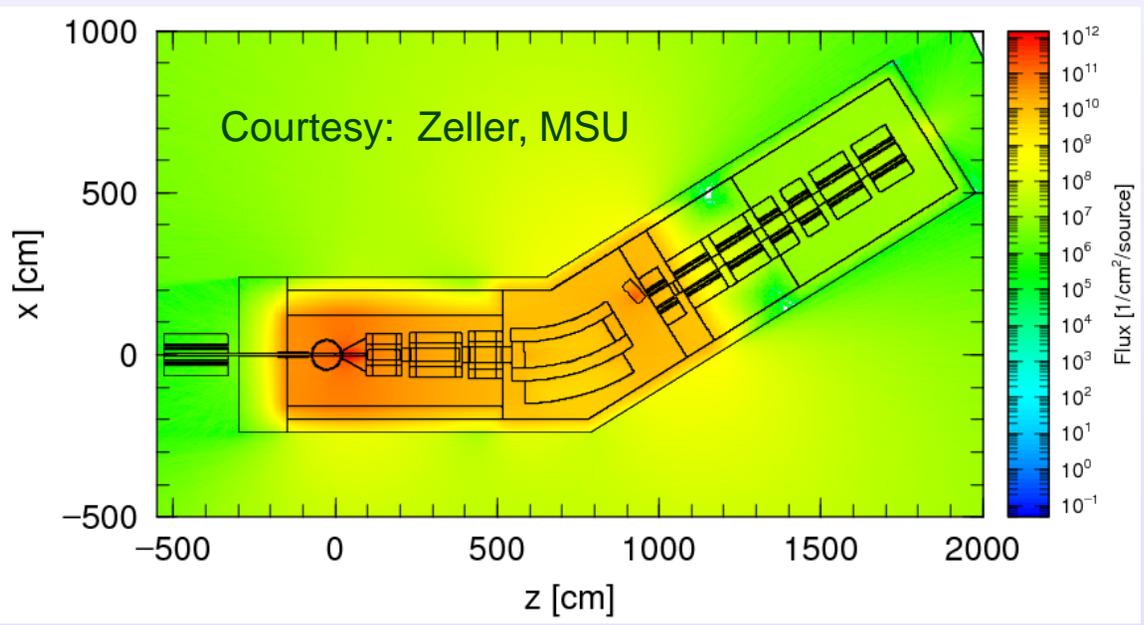
# Radiation and Heat Loads in Fragment Separator Magnets

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 :  $2.5 \times 10^{15}$  n/cm<sup>2</sup> 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

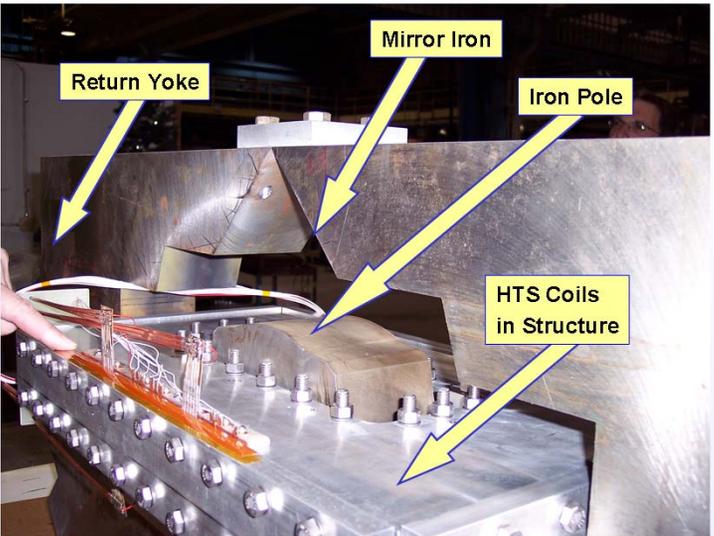
(made with Bi2223 from ASC)

- **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 1<sup>st</sup> Generation HTS R&D Quadrupole for FRIB/RIA

<b>Parameter</b>	<b>Value</b>
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 <sup>3</sup>

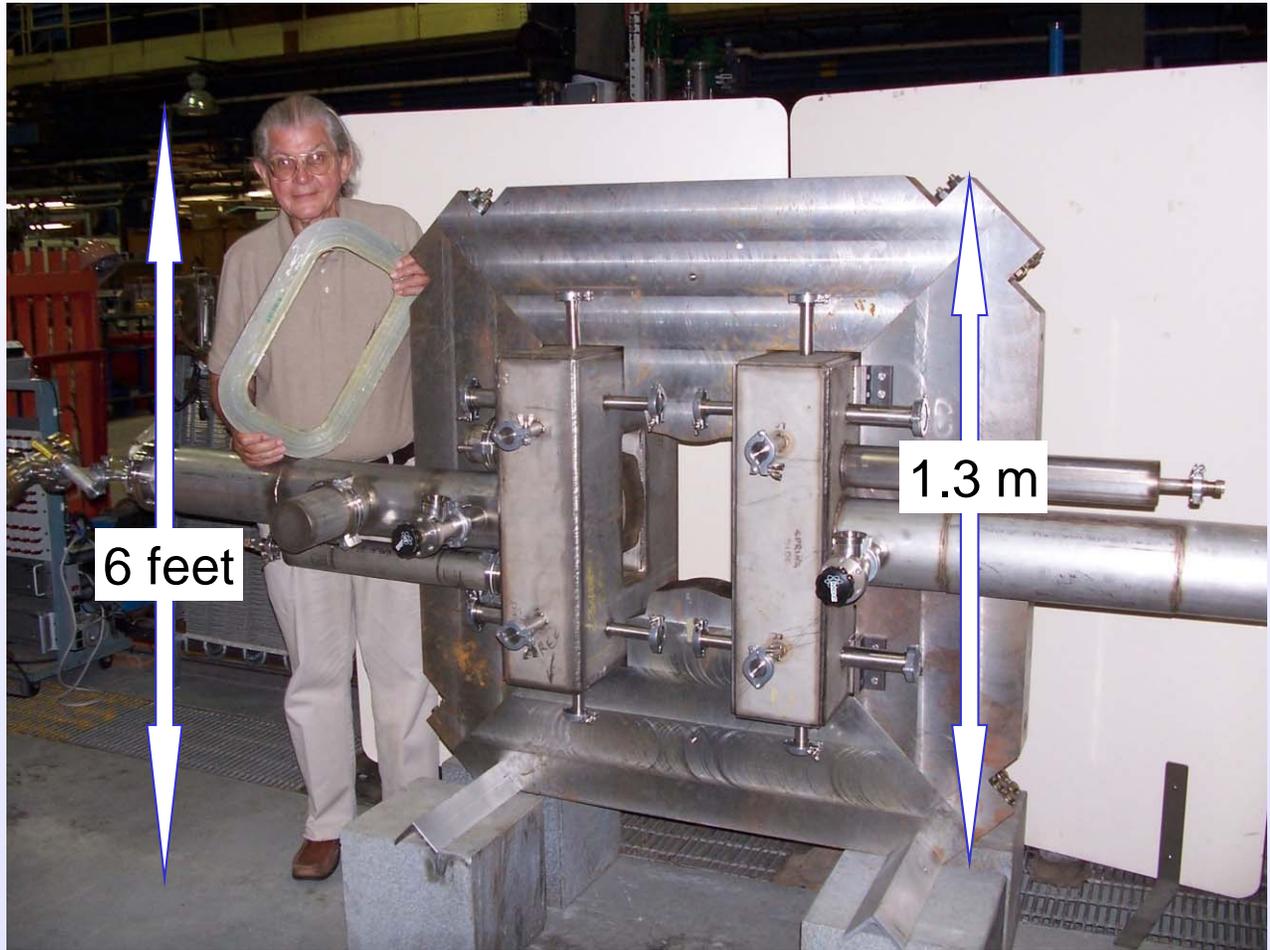
**Magnet Structures for FRIB/RIA HTS Quad**  
(Several R&D structures were built and tested)



Mirror cold iron



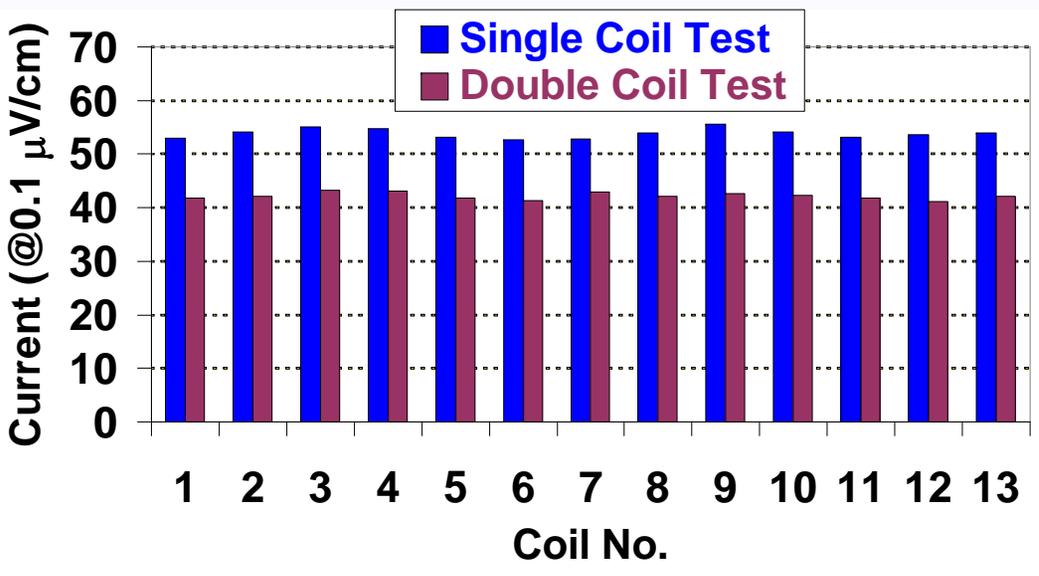
Mirror warm iron



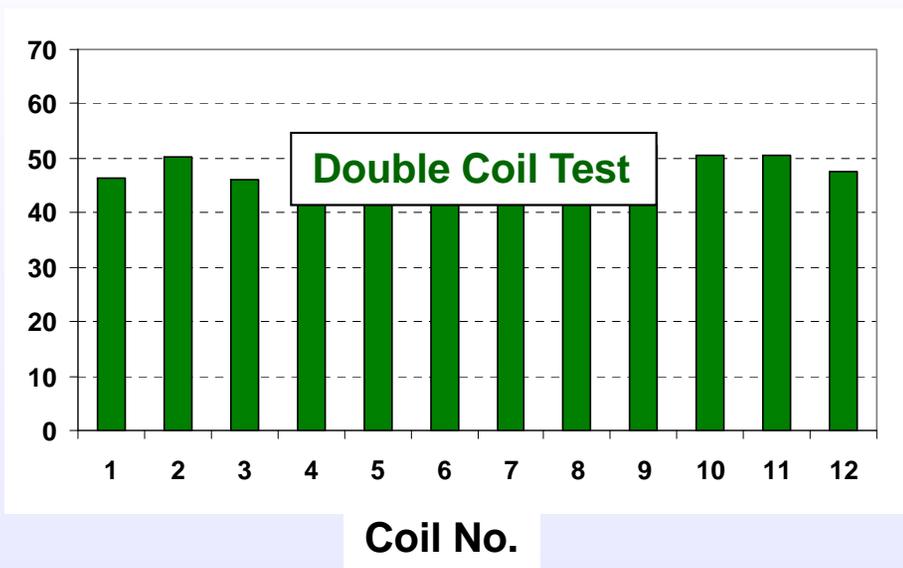
# LN<sub>2</sub> (77 K) Test of Coils Made with ASC 1<sup>st</sup> Generation HTS

**Each single coil uses ~200 meter of tape**

13 Coils made HTS tape in year #1

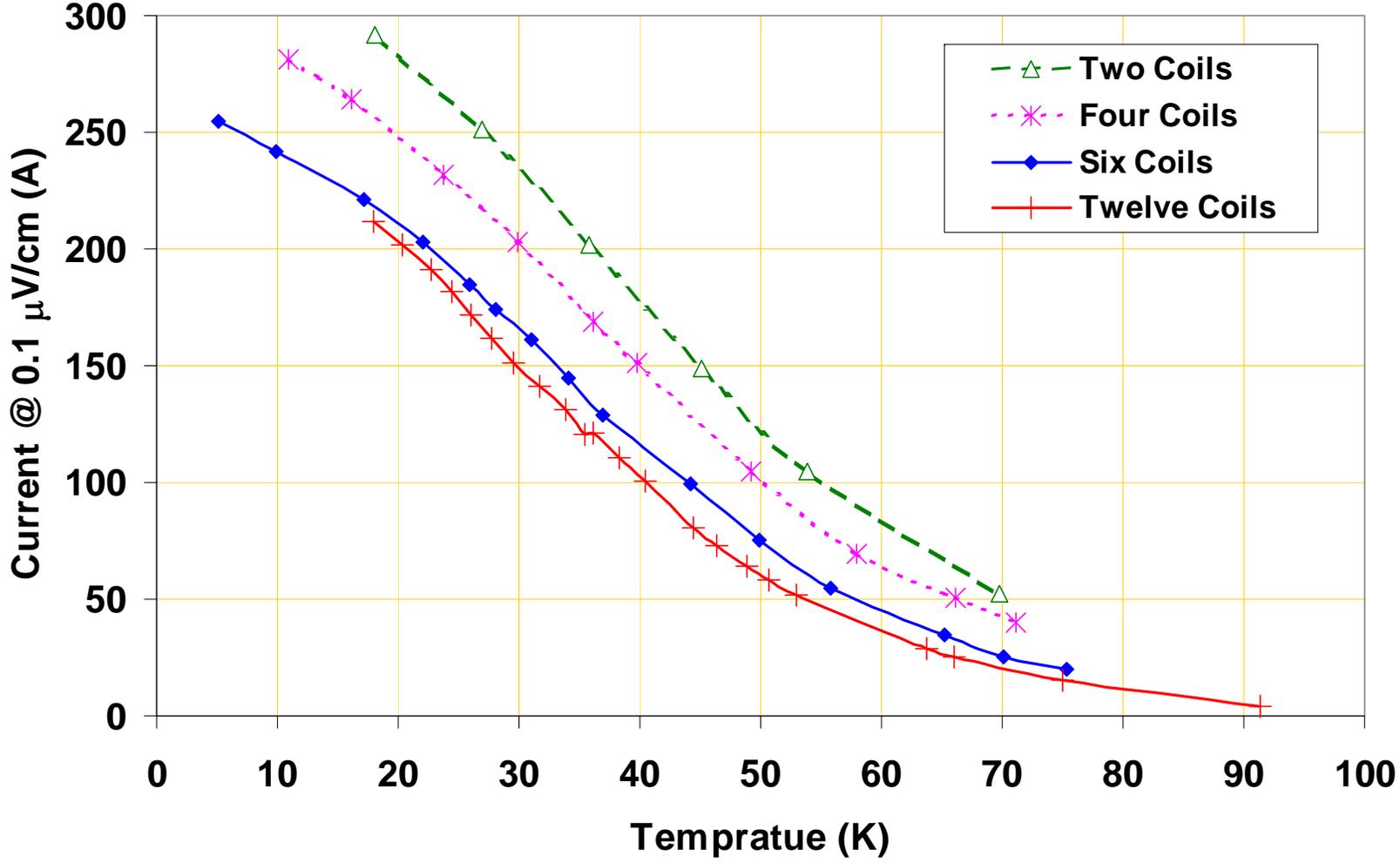


12 coils with HTS tape in year #2



**Note: A uniformity in performance of a large number of HTS coils.  
It shows that the HTS coil technology has matured !**

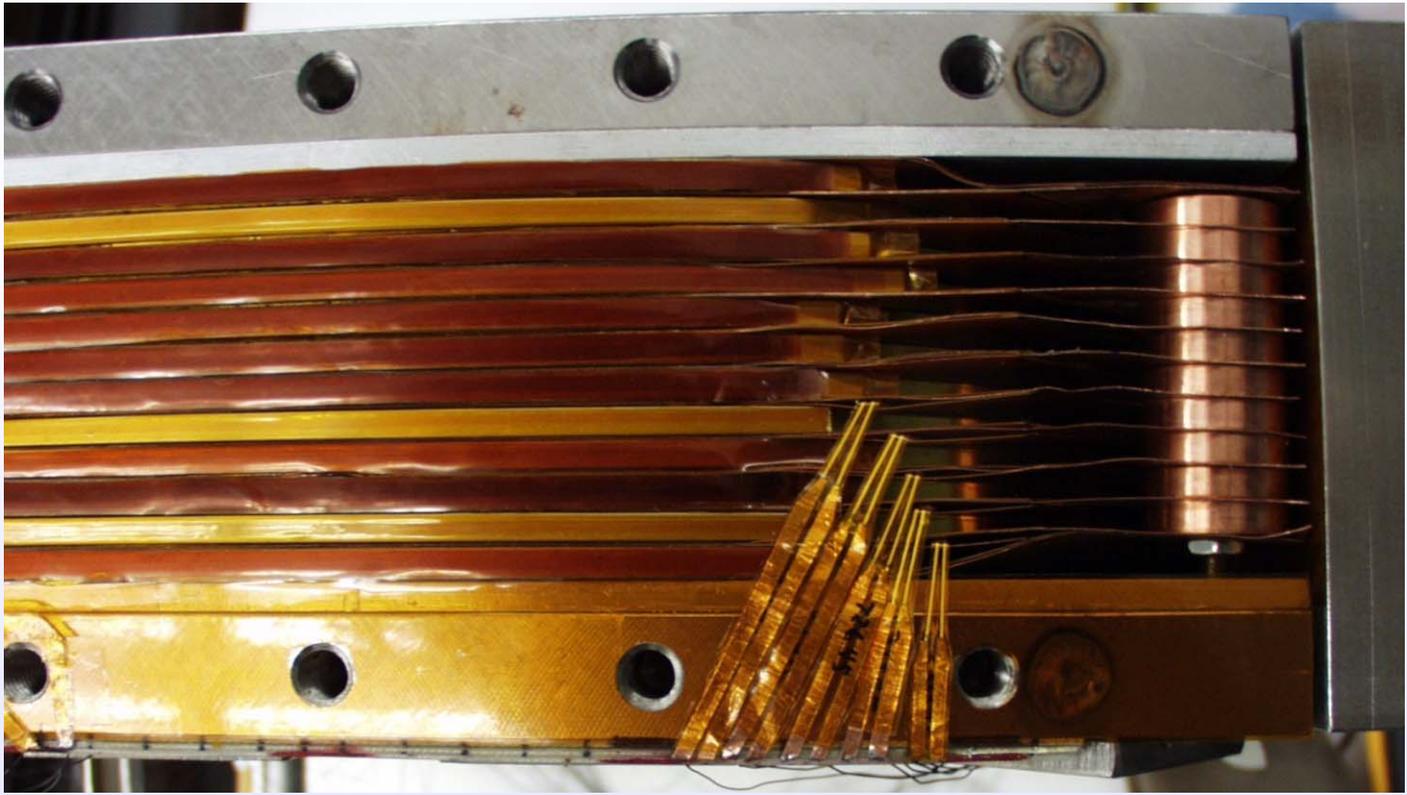
# RIA HTS Mirror Model Test Results (operation over a large temperature range)



**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



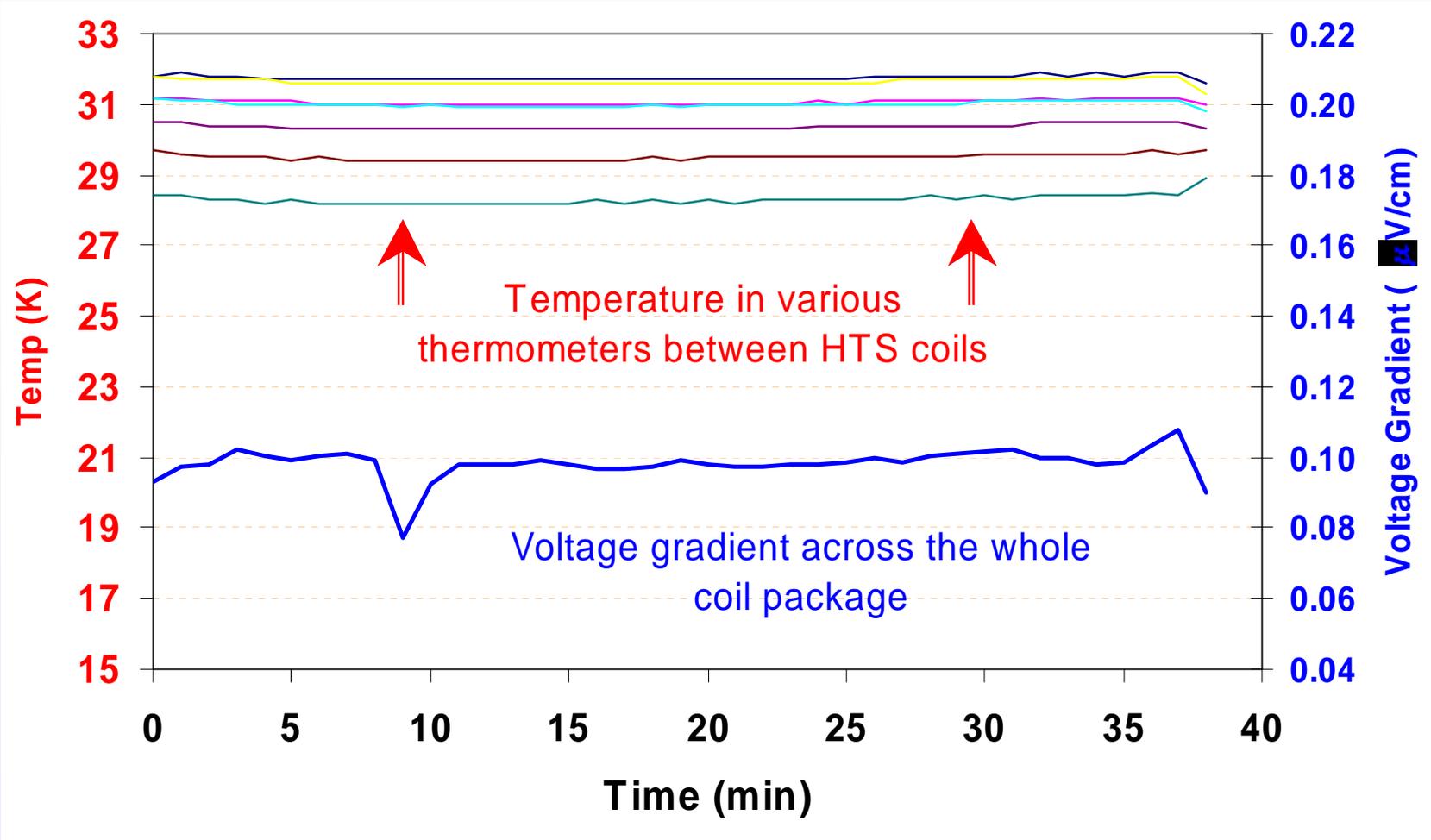
**Stainless steel tape heaters for energy deposition experiments**

## **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<sup>3</sup>) 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

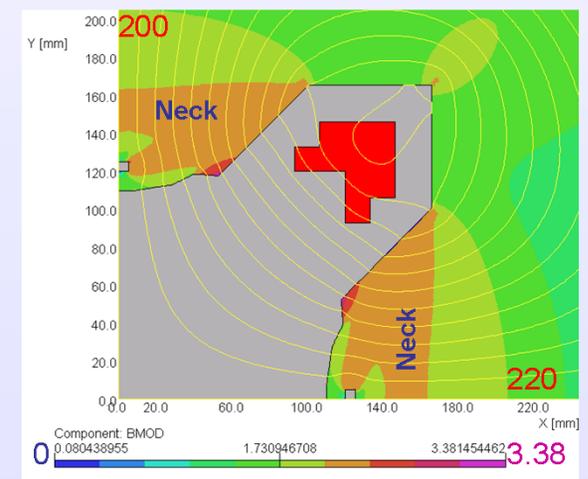
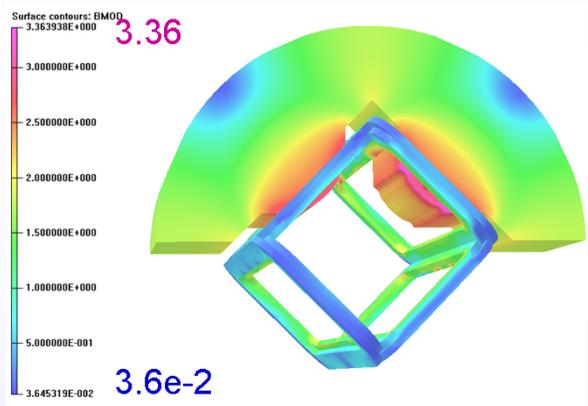
# Second Generation Magnet (made with 12 mm ReBCO/YBCO)

- 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
<b>Design Gradient</b>	<b>15 T/m</b>
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)
<b>Conductor (2G) width, SuperPower</b>	<b>12.1 mm ± 0.1 mm</b>
Conductor thickness, SuperPower	0.1 mm ± 0.015 mm
Cu stabilizer thickness SuperPower	~0.04 mm
<b>Conductor (2G) width, ASC</b>	<b>12.1 mm ± 0.2 mm</b>
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 <sub>c</sub> @2T, 40 K (spec)	400 A (in any direction)
Minimum I <sub>c</sub> @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
<b>Operating Temperature</b>	<b>50 K (nominal) ***higher grad at lower temp***</b>
Design Heat Load on HTS coils	5 kW/m <sup>3</sup>

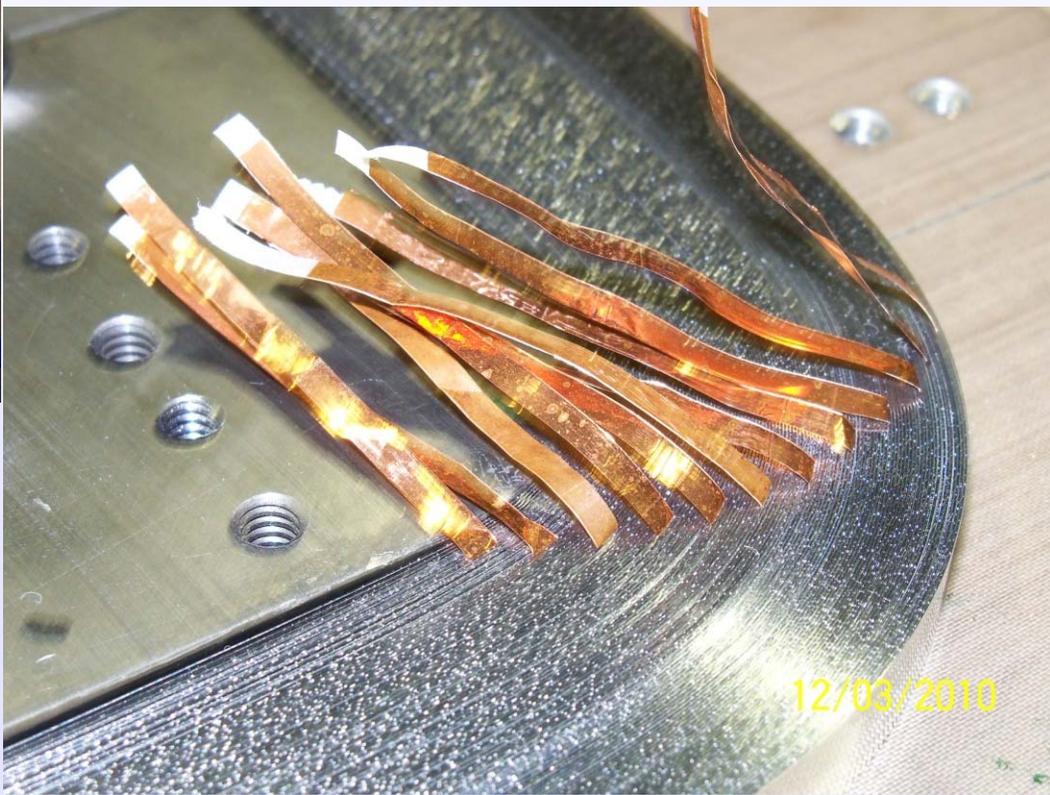
# Yoke Iron for FRIB Quad



# Coils Made with ASC HTS

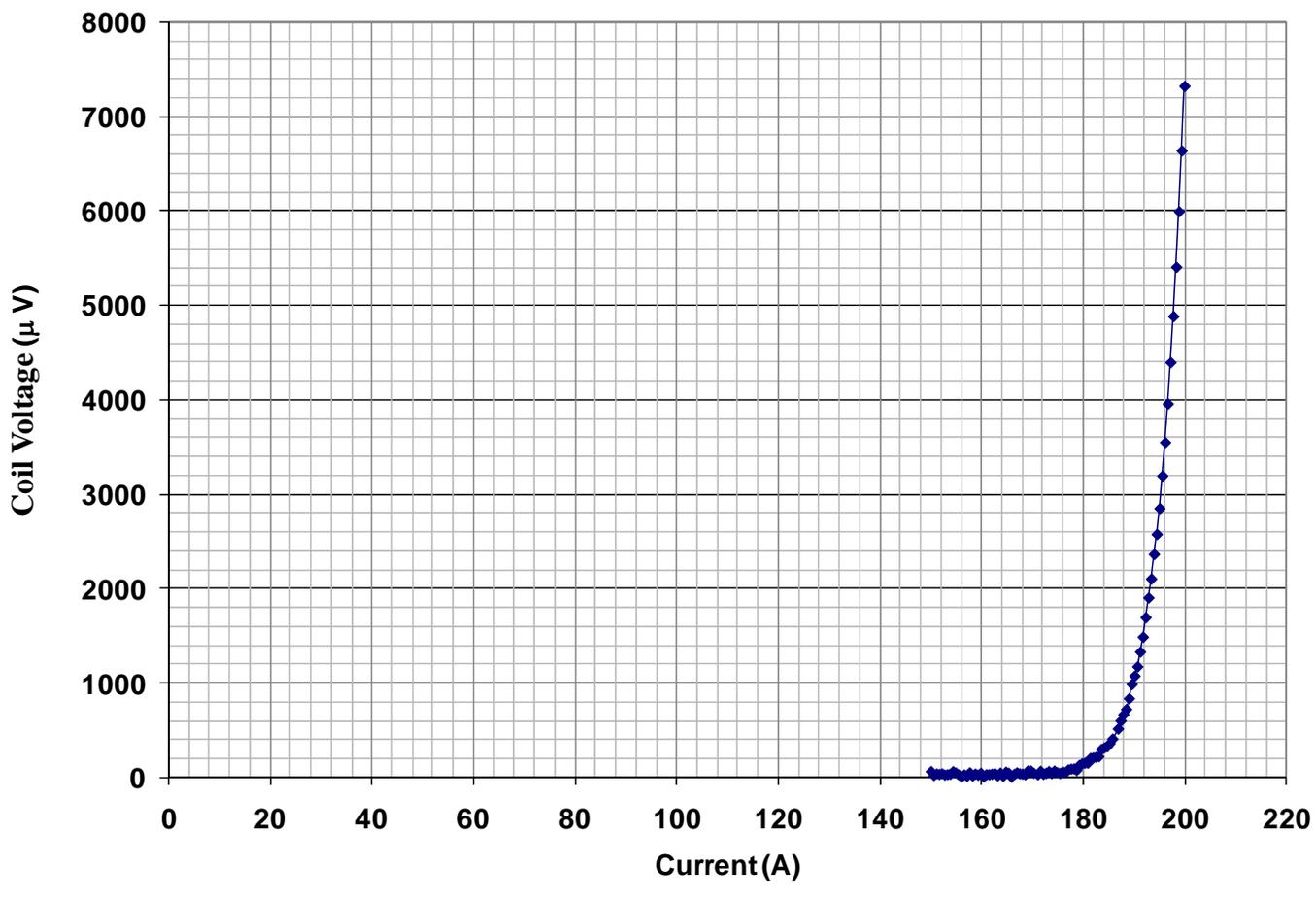


**~210 m (~125 turns), 12 mm double HTS tape per coil.  
Coil width = ~40 mm.**



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

# 77 K Test Results of ASC Coil



Measurement in liquid nitrogen ( $\sim 77$  K) of critical current in FRIB coil (large, outer, 126 turns made with  $\sim 210$  meter tape from American Superconductor Corporation). The critical current in coil with  $0.1 \mu V/cm$  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.**

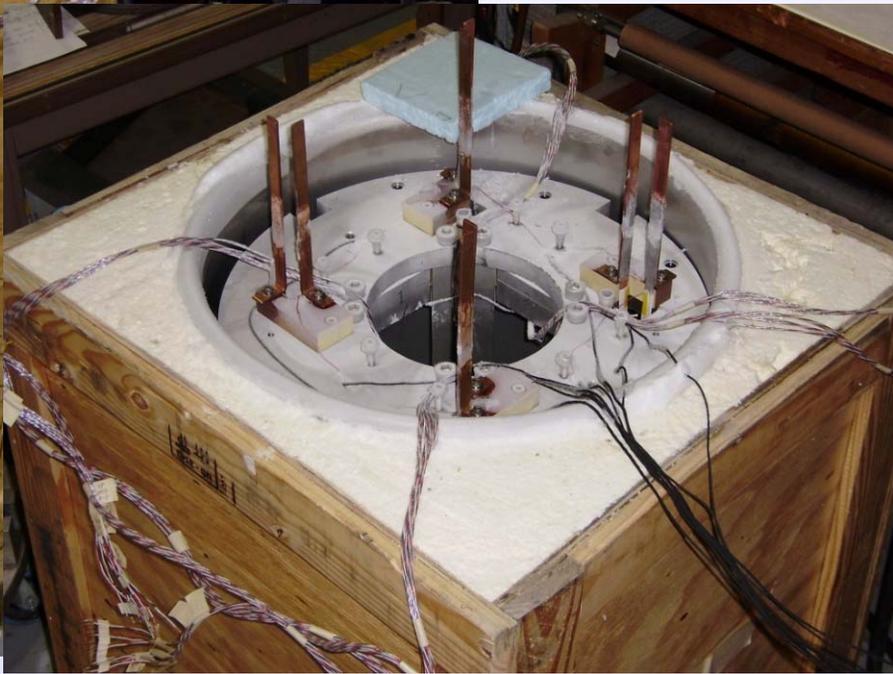
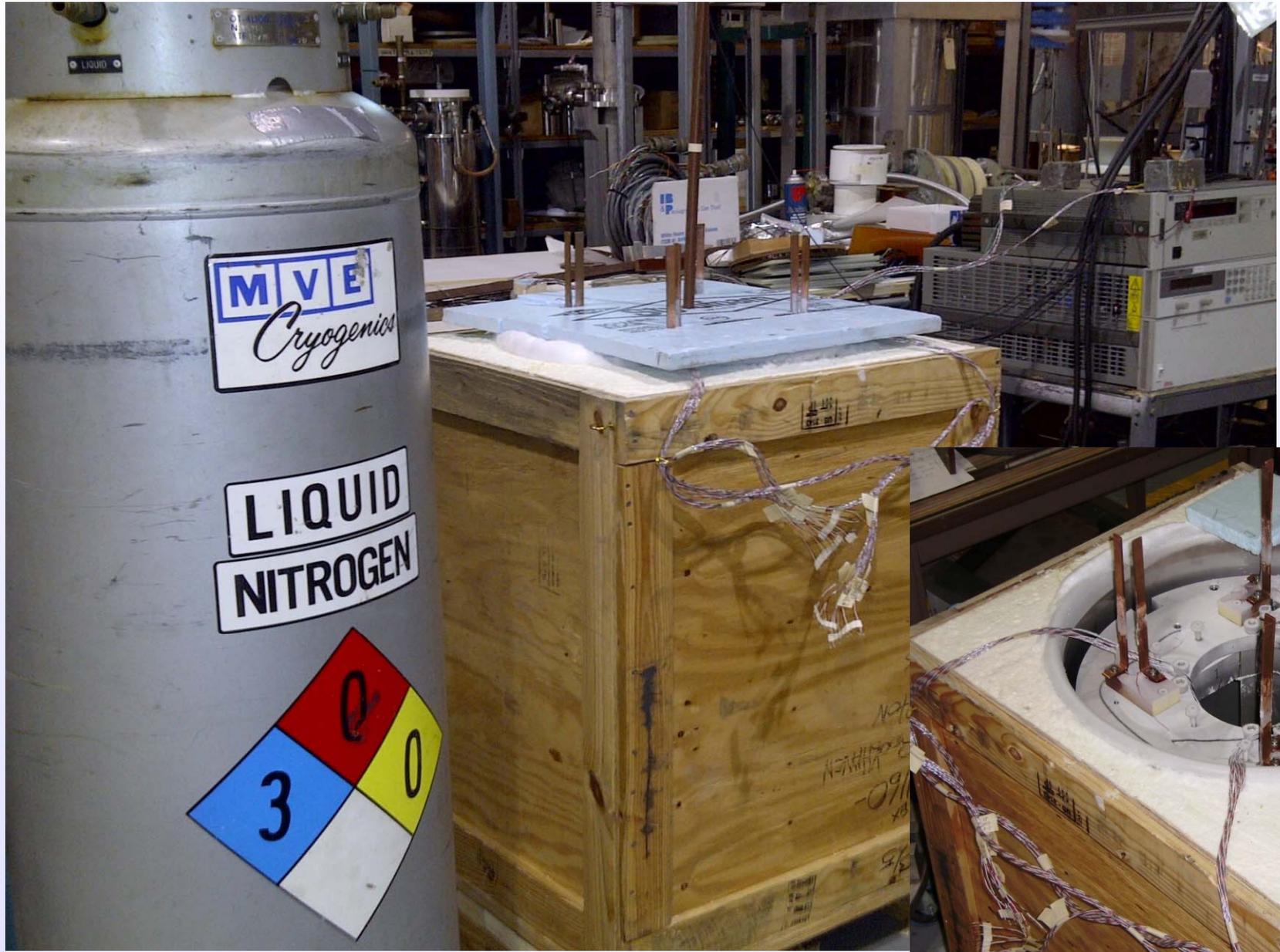


**Fully wound coil with SuperPower tape with one splice**

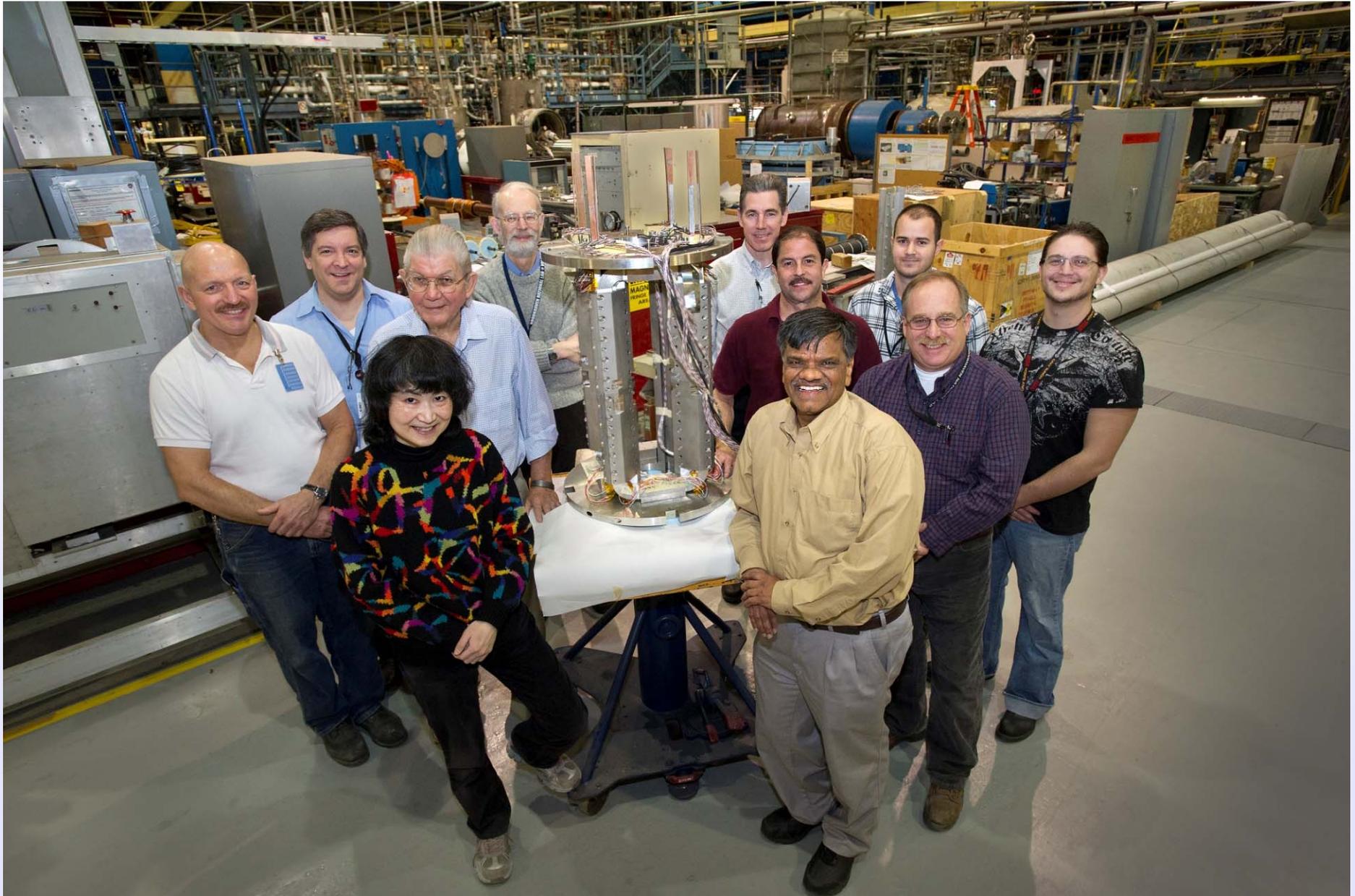
# Coils Assembled in Quadrupole Support Structure



# HTS Quad in Advanced Cryostat



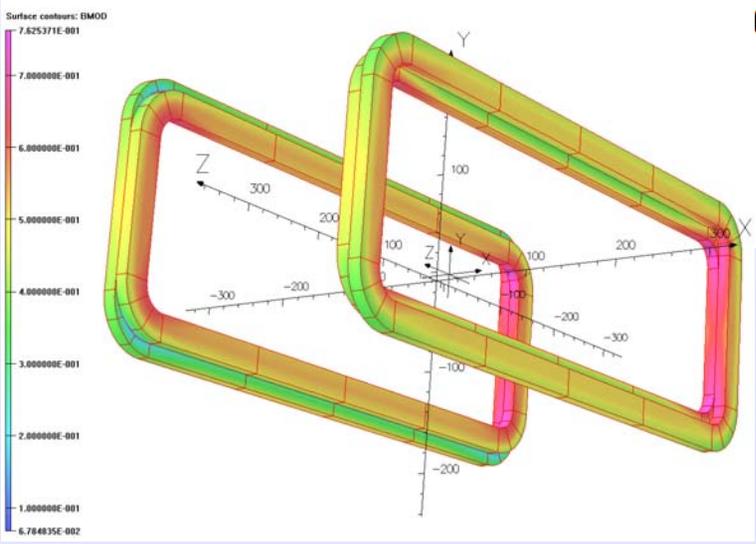
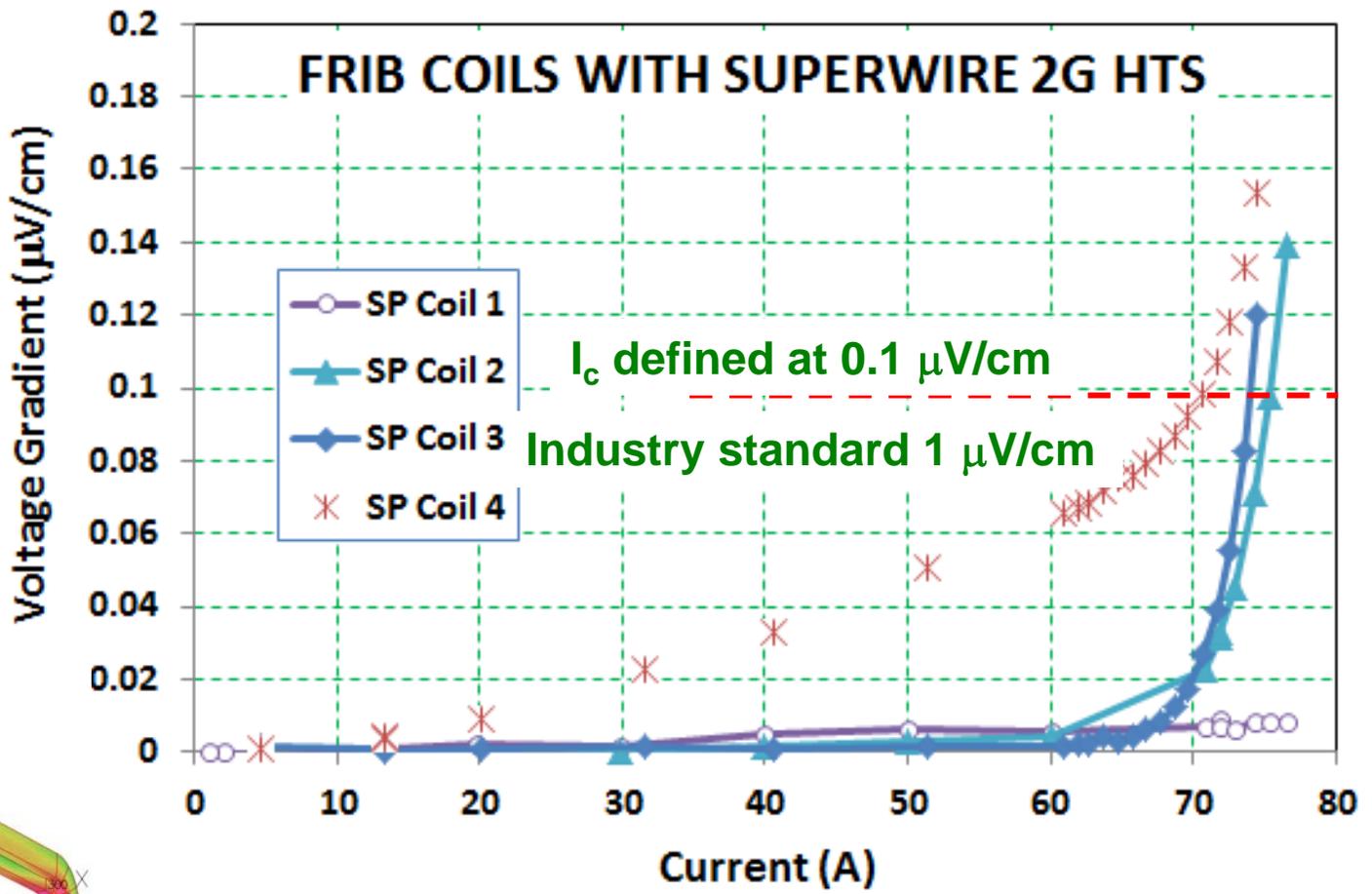
# Proud Team Members



# Performance of SuperPower Coils (four of eight coils powered)

Four ASC coils were not powered

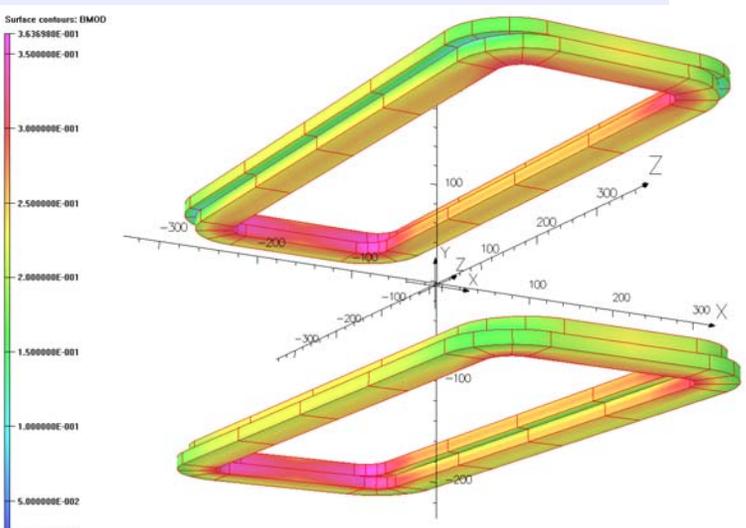
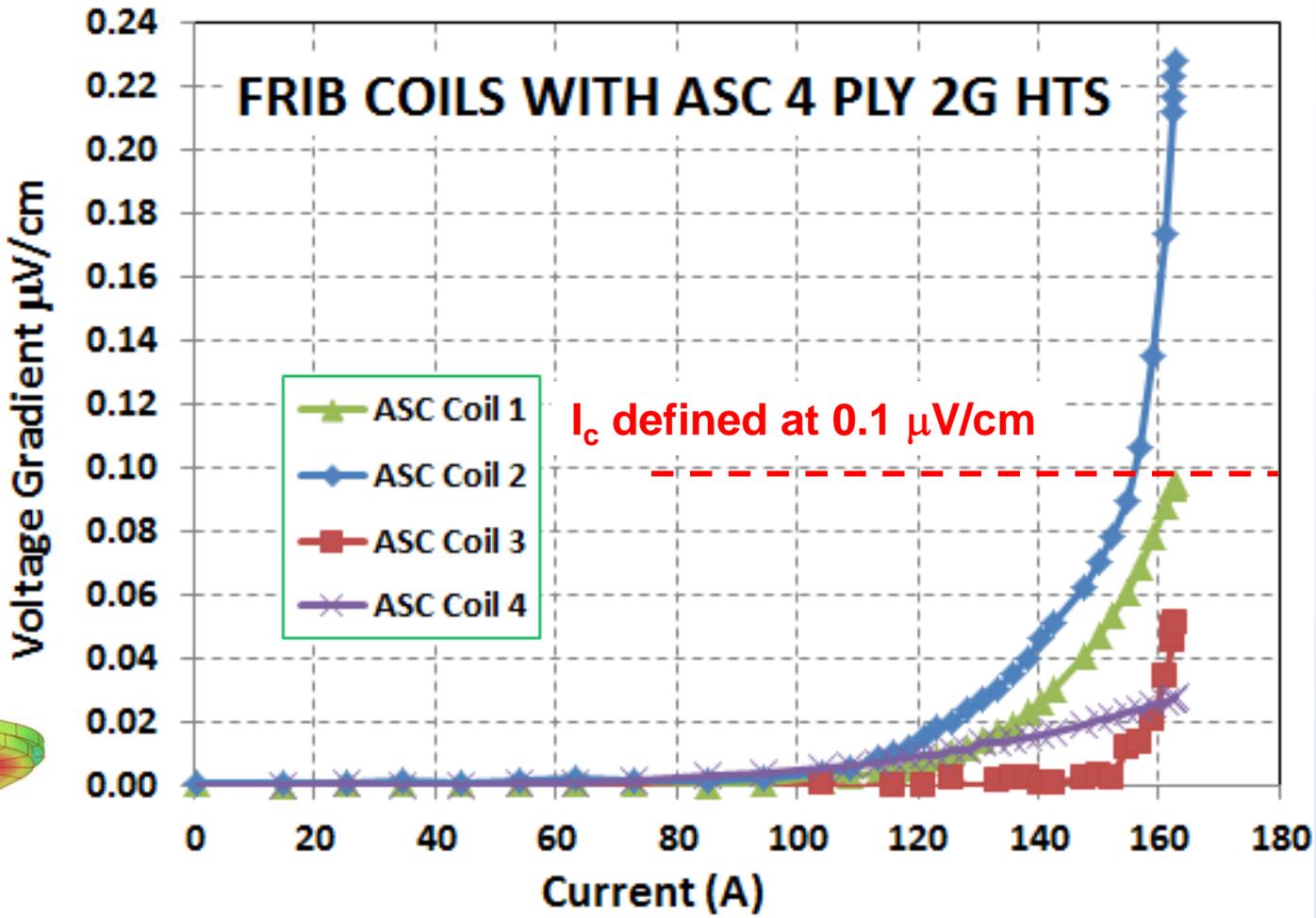
**Field on SuperPower coils at 100 A**



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

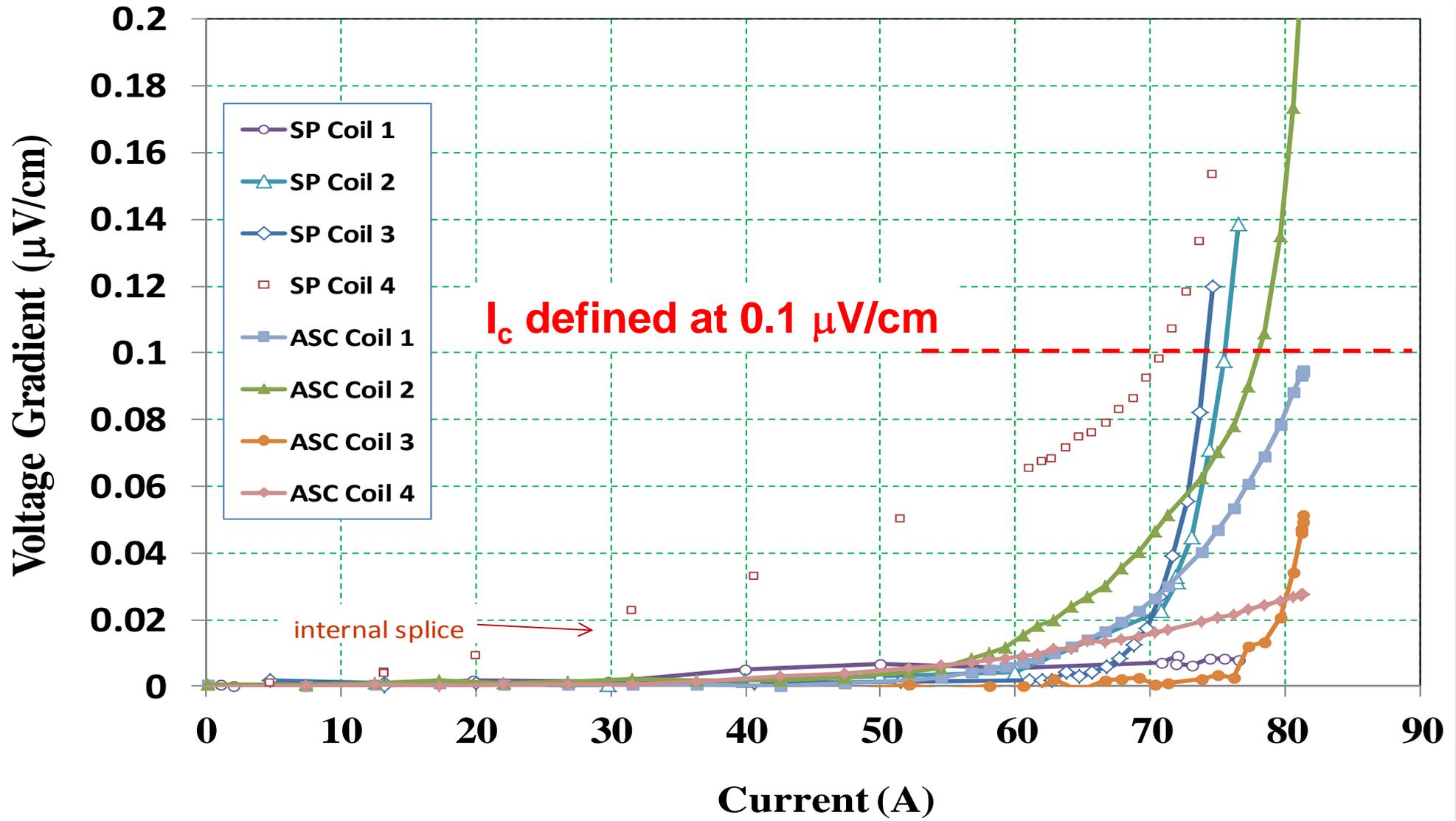


**Field on ASC coils at 100 A**

**Four SuperPower coils not powered**

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

Performance normalized to per tape (ASC has double)

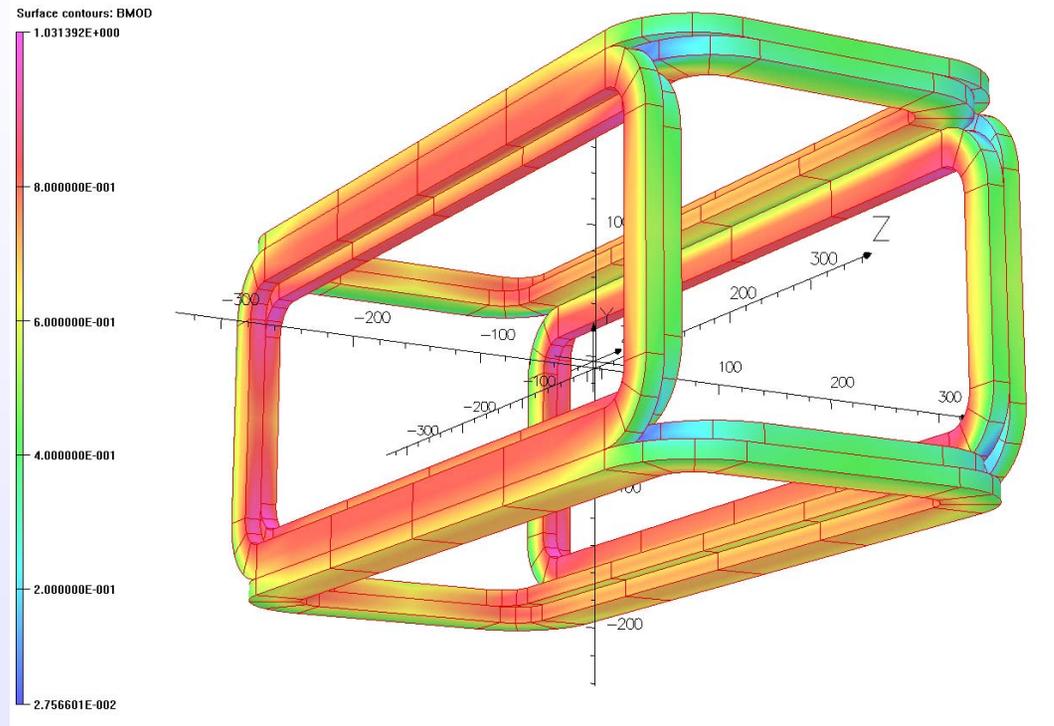


# 77 K Test in Quadrupole Mode (all eight coils powered)

## 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



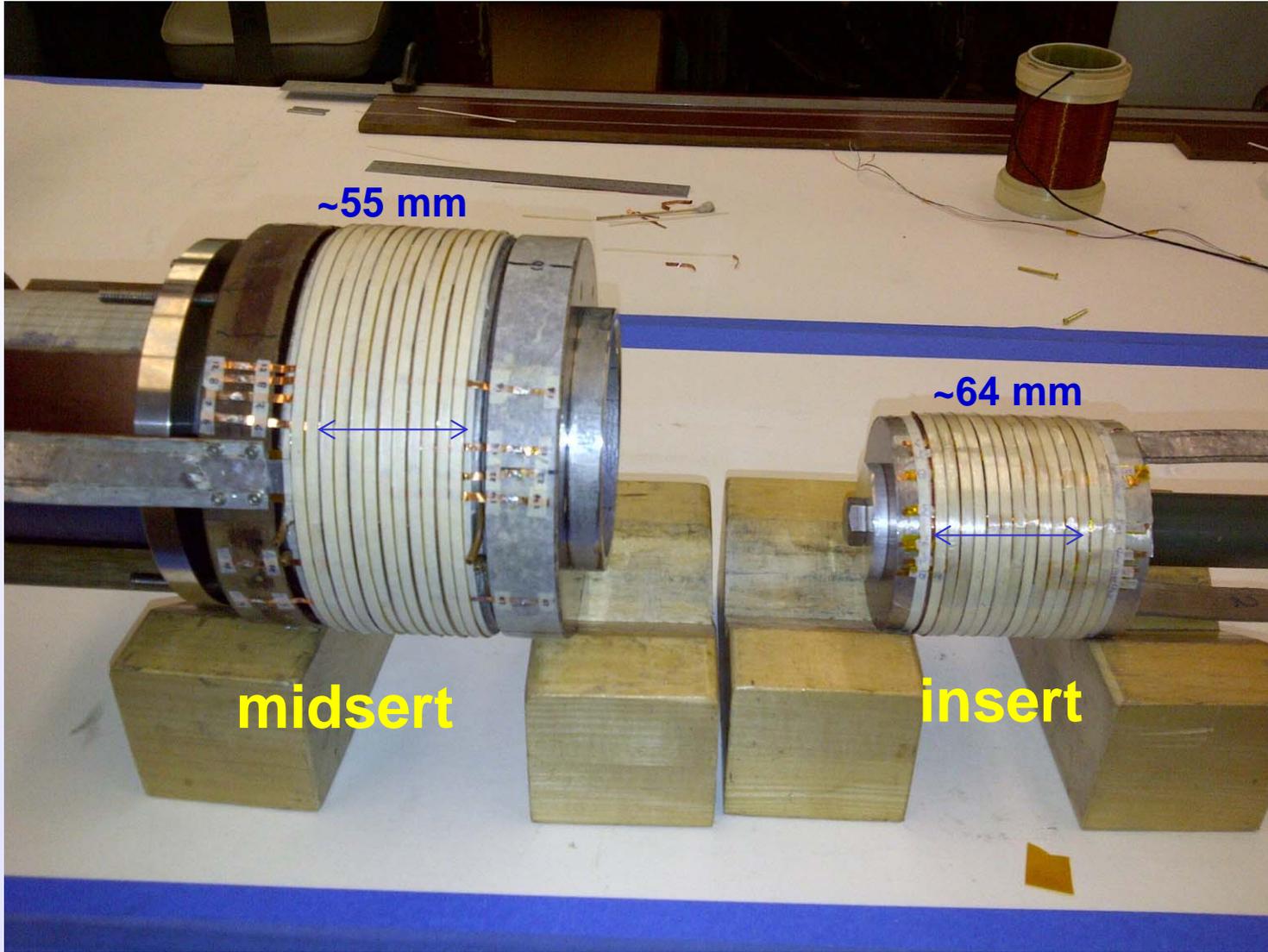
**Design: SuperPower coils ~172 A and ASC coils ~300 A (at 40-50 K).**

- **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

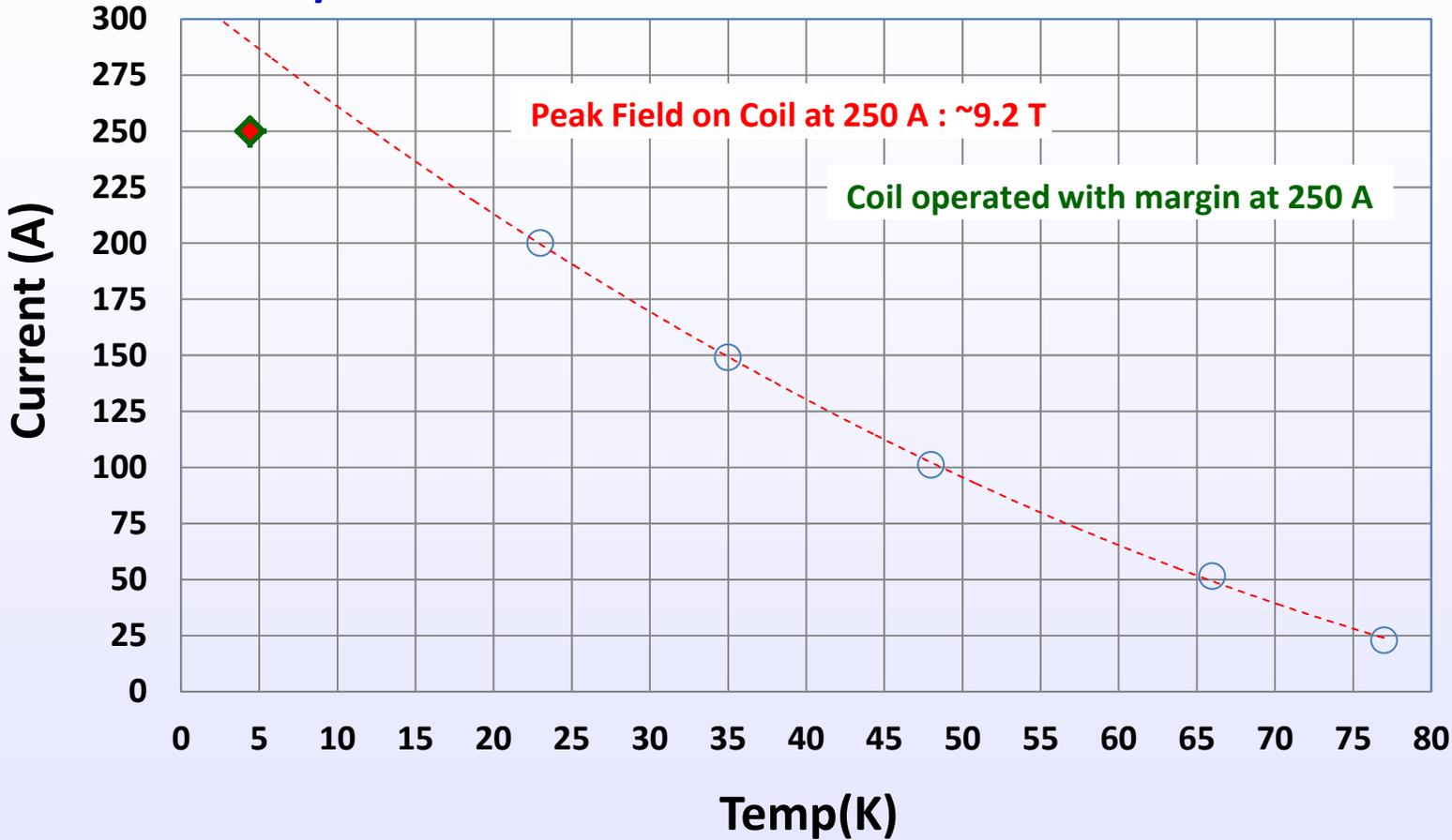


Part of PBL/BNL SBIRs for developing 20+ T HTS (YBCO) solenoid and 35+ T superconducting solenoid

Conductor from SuperPower with ~45 micron Cu

# Test of ~100 mm HTS Solenoid

PBL/BNL 100 mm HTS Solenoid Test for Muon Collider



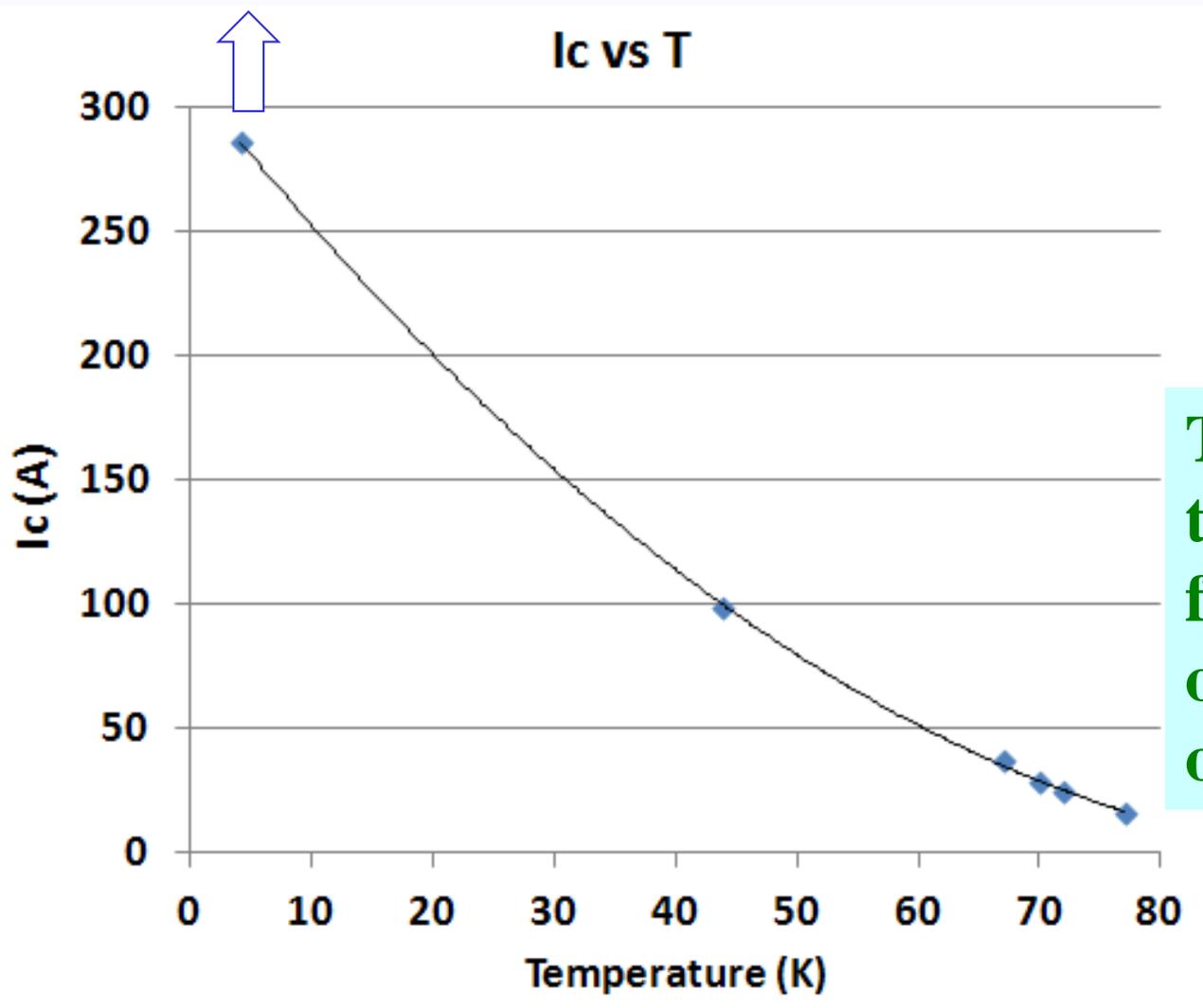
**250 A ==>**  
**9.2 T on coil**

*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

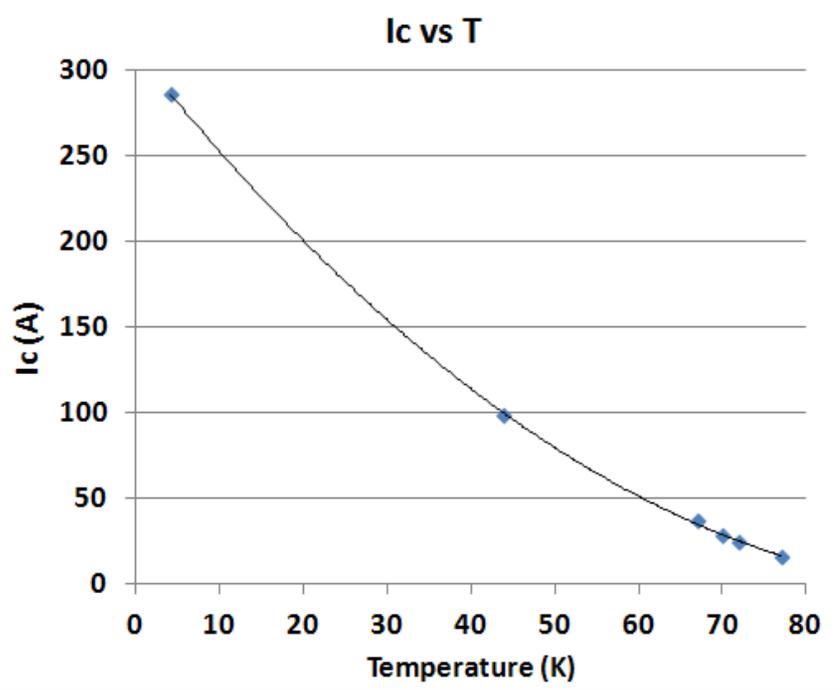
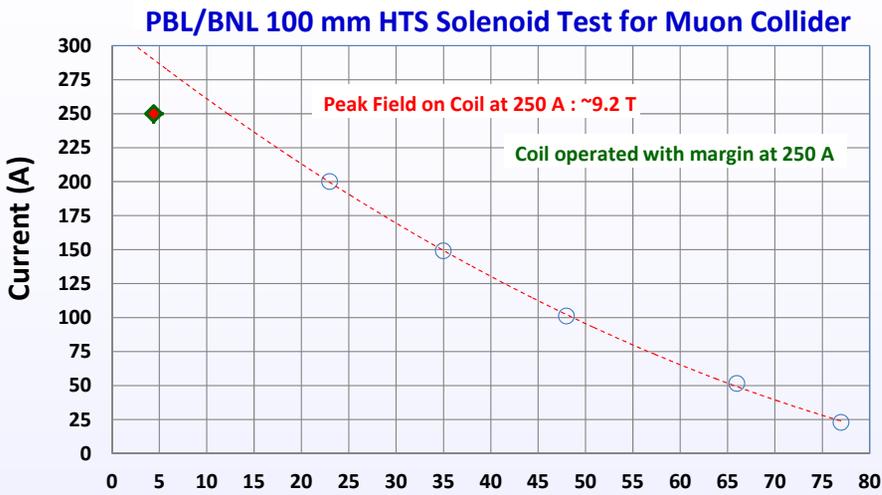
**Field at 285 A: over 15 T on axis and over 16 T on coil**



**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.

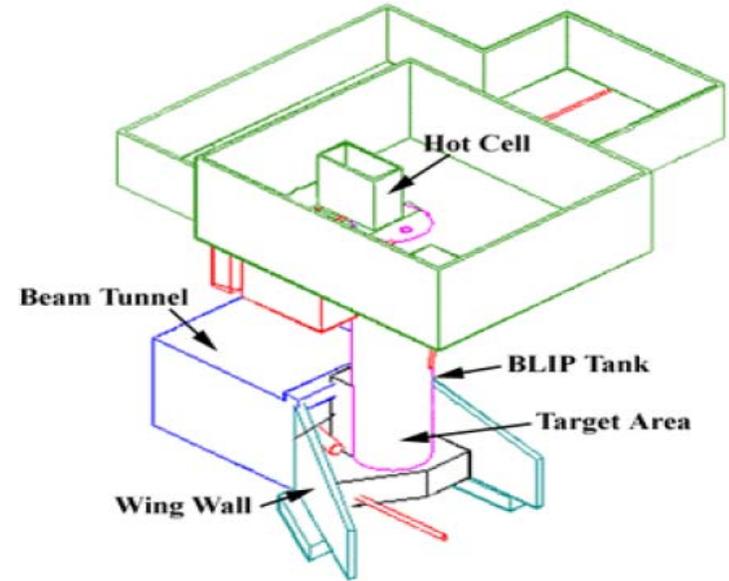
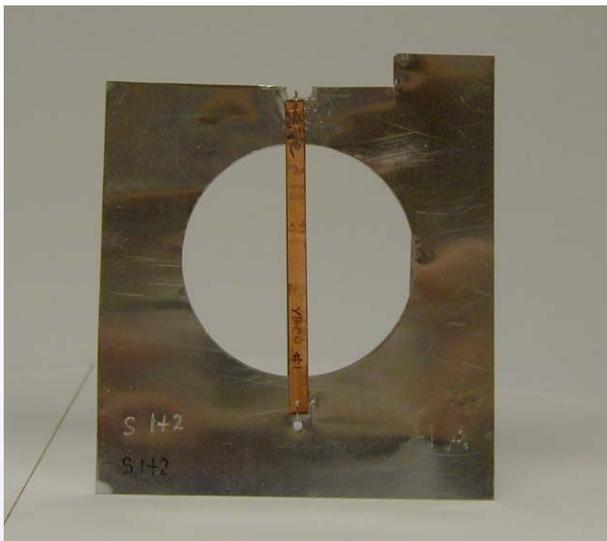


Figure 3. BLIP Beam Tunnel and Target Schematic

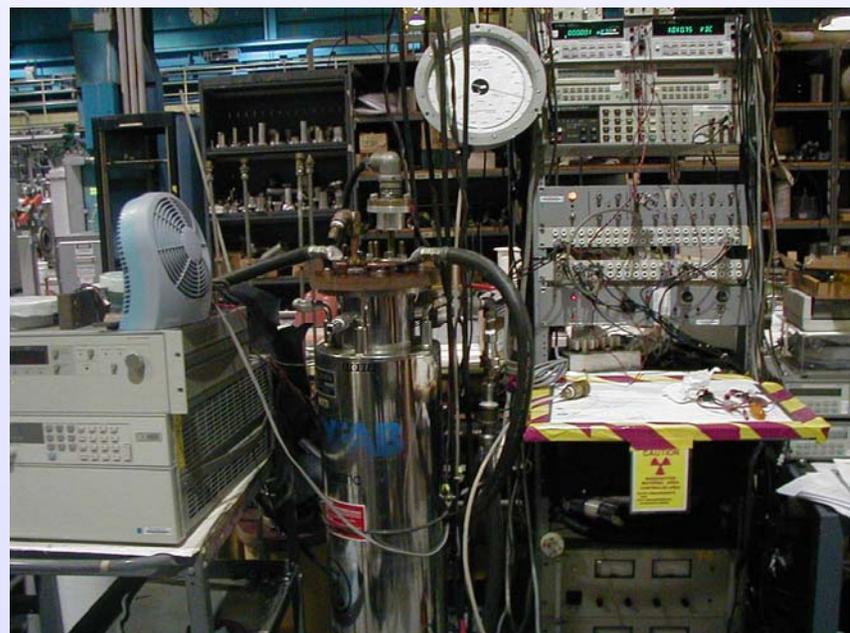
From a BNL Report (11/14/01)

**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  $\mu$ A 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  $\mu$ A protons**

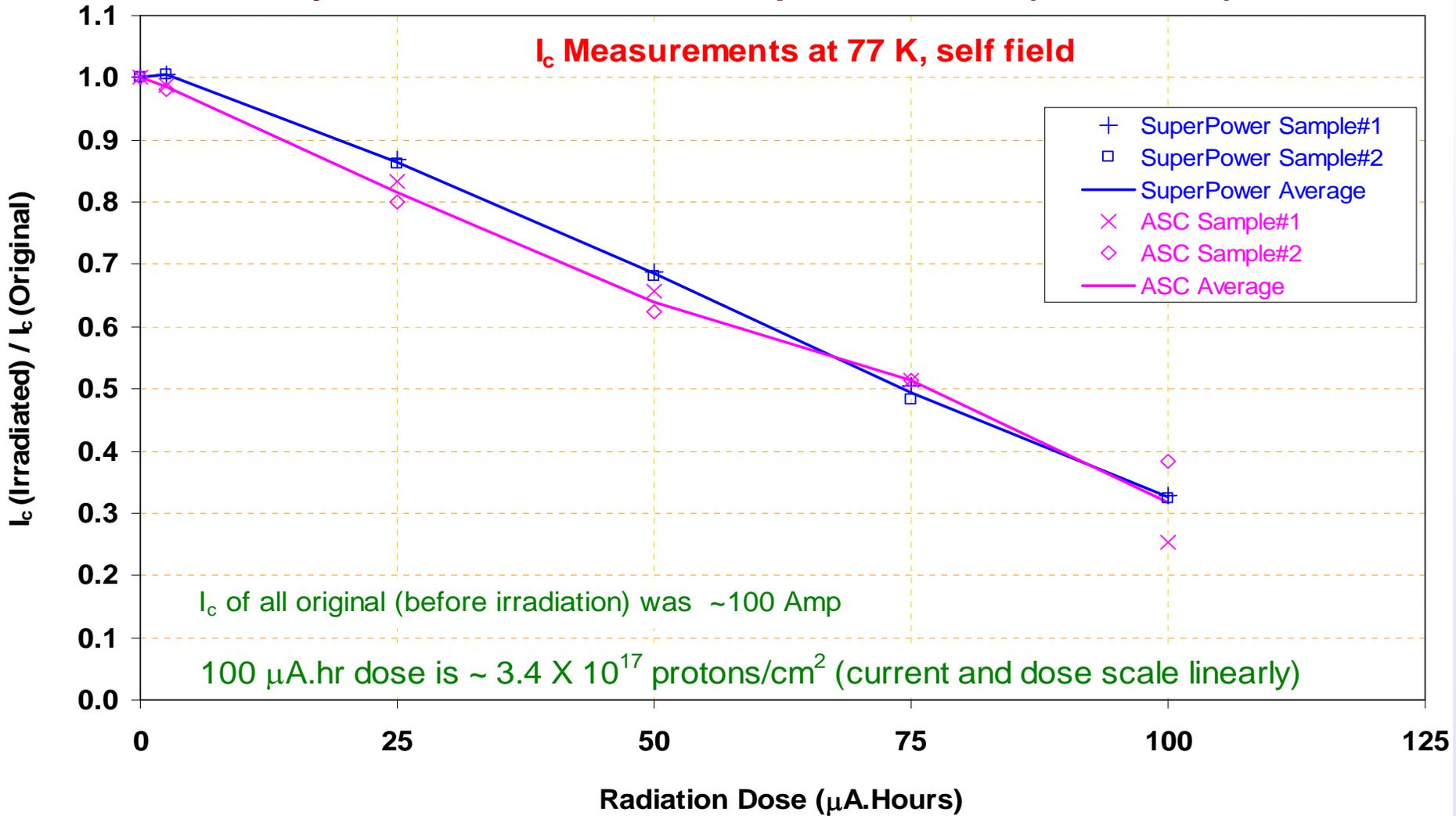


# HTS Samples Examined

- 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 ( $10^{16}$ ,  $10^{17}$ ,  $2 \times 10^{17}$ ,  $3 \times 10^{17}$  and  $4 \times 10^{17}$  protons/cm<sup>2</sup>) from both vendors.
- $10^{17}$  protons/cm<sup>2</sup> (25  $\mu$ A-hrs integrated dose) is equivalent to over 15 years of FRIB operation (the goal is 10 years).

# Relative Change in $I_c$ 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)**

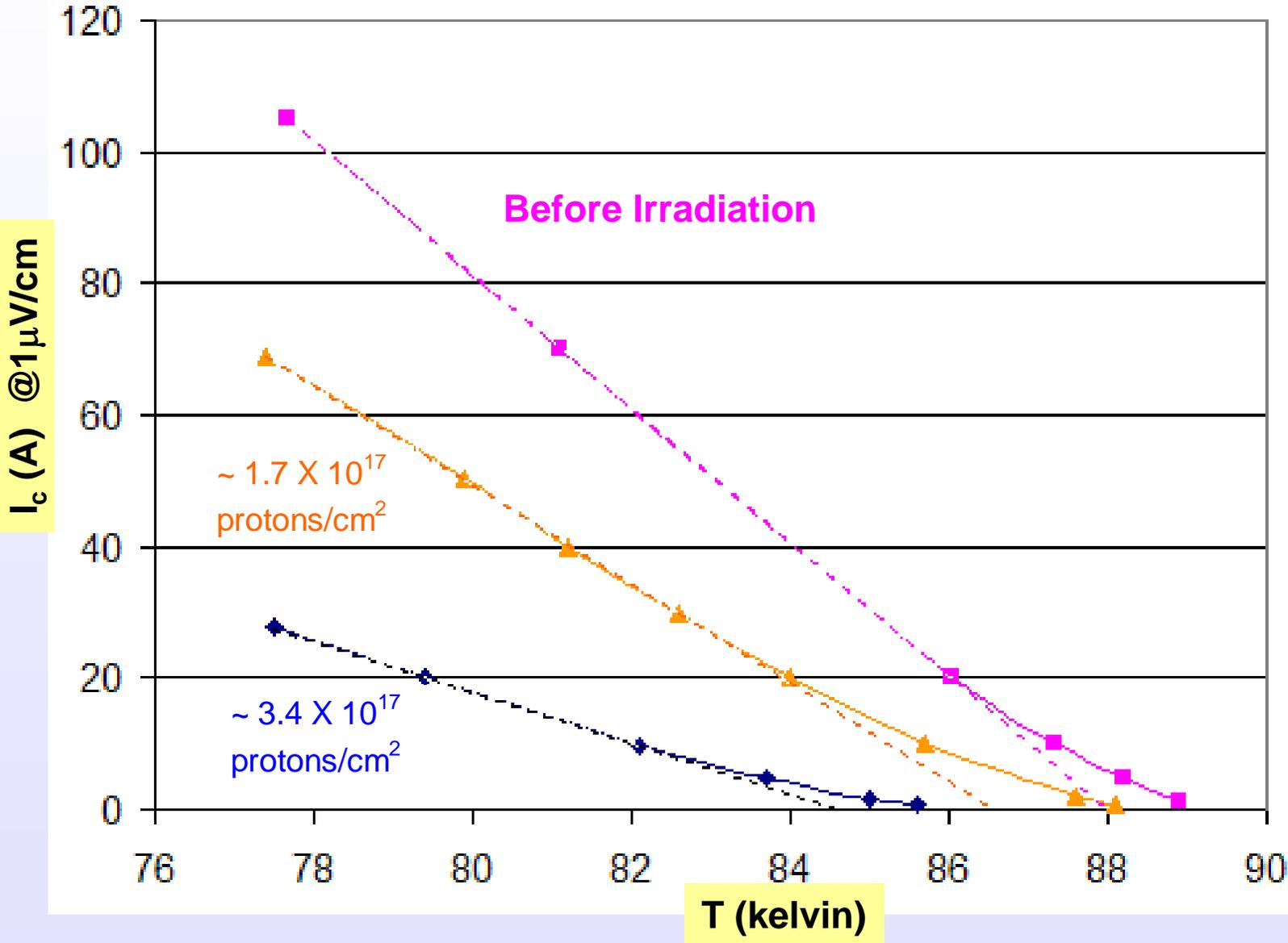


Ramesh Gupta, BNL 3/2008

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

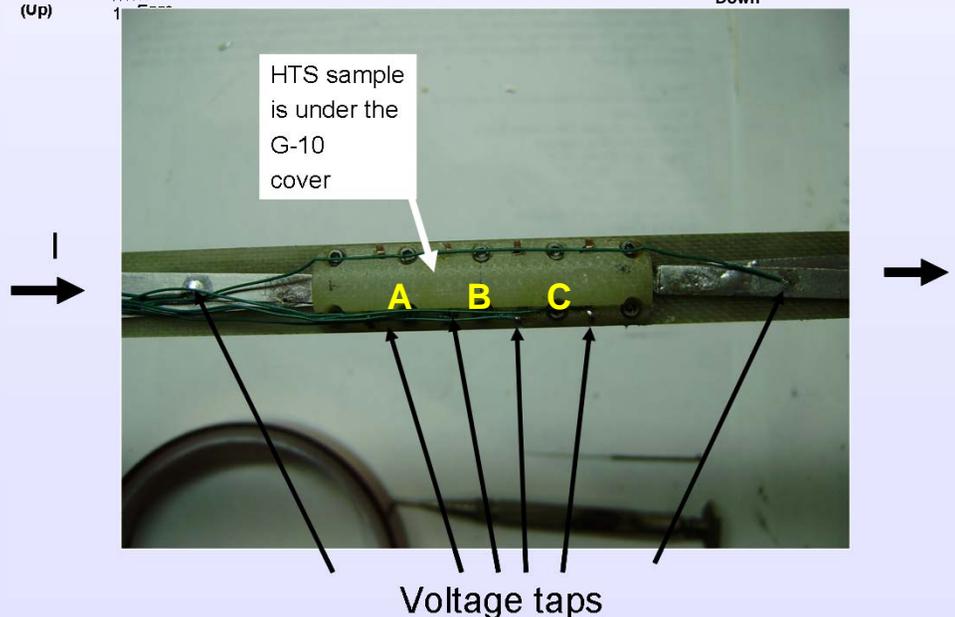
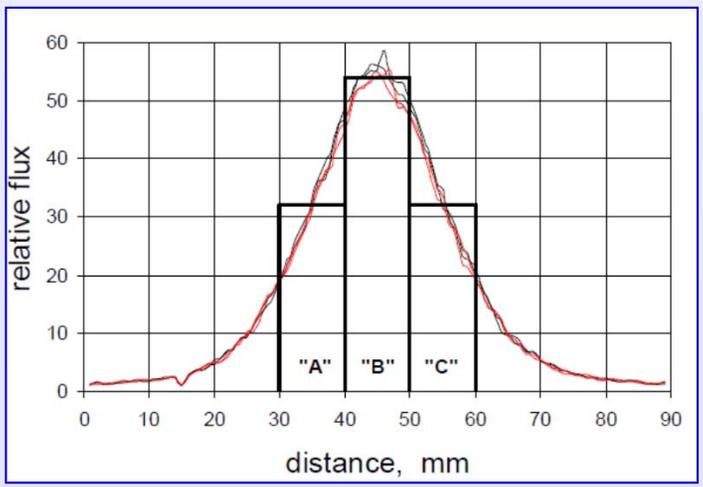
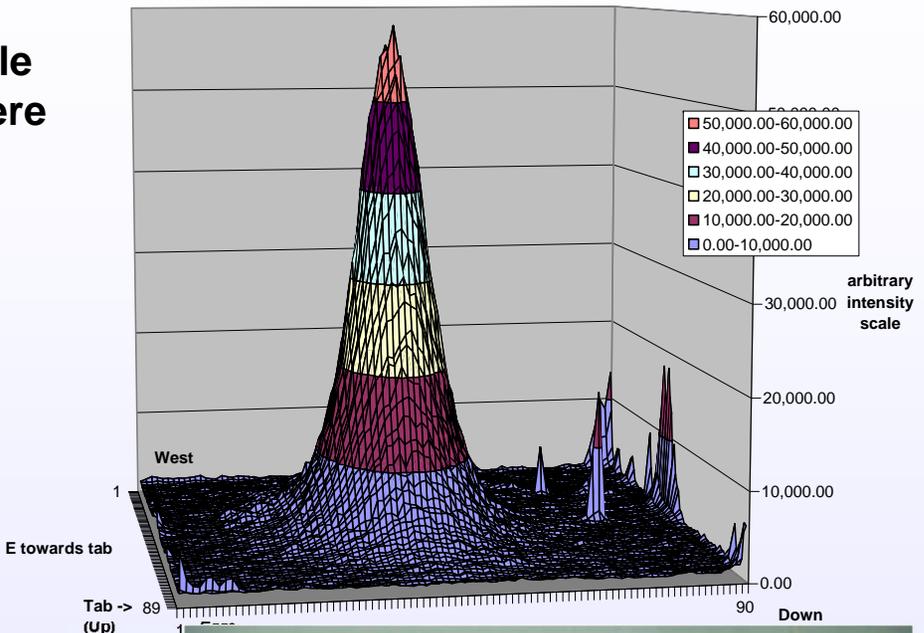
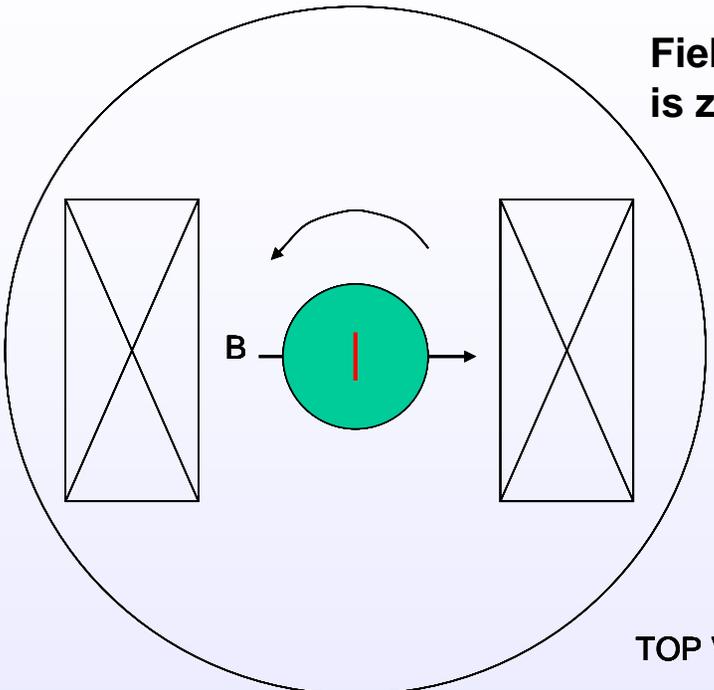
# Change in Critical Temperature ( $T_c$ ) of YBCO Due to Large Irradiation

$I_c$  ( $1\mu\text{V}/\text{cm}$ ) as a function of temperature



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

# Measurements of Radiation Damage in Presence of Field

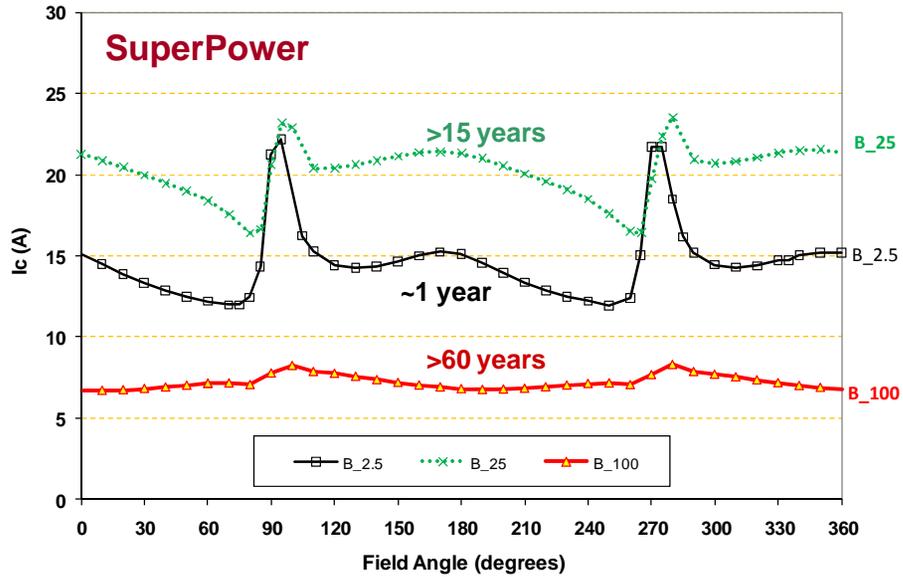


- Since critical current of 2G HTS tape is anisotropic with respect to angle, the radiation damage measurements were performed as a function of field angle at 77 K in presence of various applied fields
- Next slide will show a summary of radiation damage for both ASC and SuperPower samples at 1 T
- For 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<sup>th</sup> 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

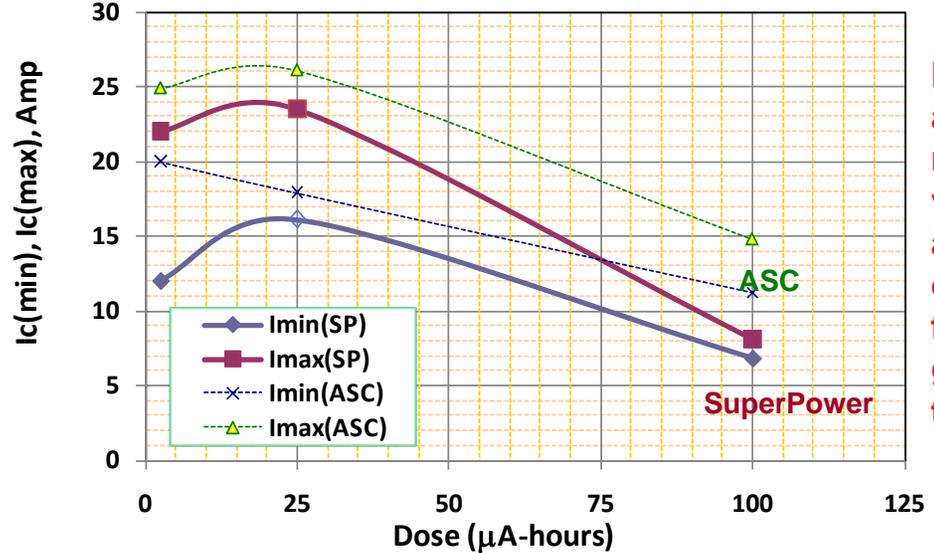
**Next step: Measurements at 40-50 K, 0-3 T.**

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

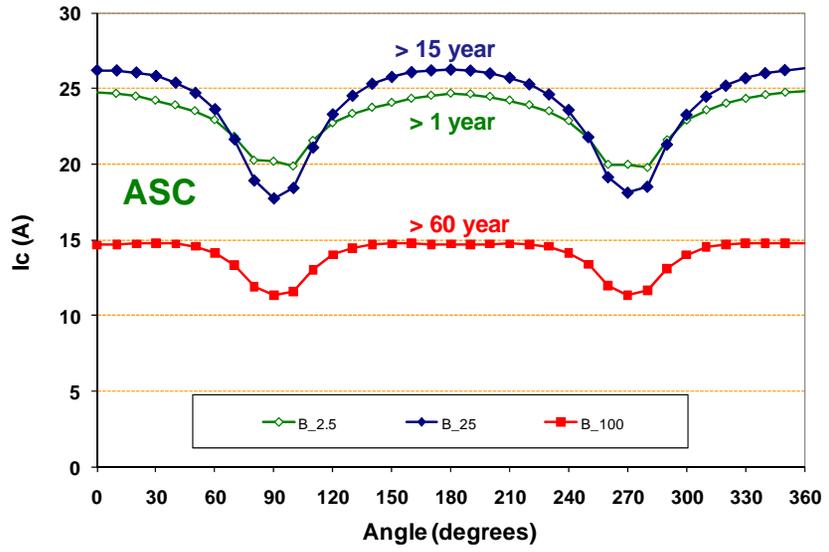
Ic Measurements of SuperPower Samples at 77 K in background field of 1 T



Ic Measurements of SuperPower and ASC at 77K in field of 1T



Ic Measurements of ASC at 77K in background field of 1T



- 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 1<sup>st</sup> generation and ~9 km equivalent in 2<sup>nd</sup> 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 1<sup>st</sup> major accelerator with HTS magnets.**