HTS Magnets for FRIB (and other applications)

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FACILITY FOR
RARE ISOTOPE BEAMS

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Office of Science
U.S. DEPARTMENT OF ENERGY

Outline (1)

- **Motivation for HTS magnets**
  – Facilitating possibilities that were not available before
- **HTS Magnet R&D for FRIB (and its contributions)**
  – Highlights of a program (3 magnet structures) that in addition to providing a unique solution to FRIB, also made significant contributions to the wider field
- **Significant Test results on FRIB Magnets**
  – Brief summary with emphasis on the recent test results

Outline (2)

- **Future Work on FRIB Magnets**
  - **Higher performance magnets based on the test results**
    - **Larger gradient and/or aperture (~20% to even ~2X)?**
    - **Does that bring a major improvement machine performance/design?**
  - Demonstration of reliability (extended series of tests)
  - Miscellaneous tasks (integration)
- **Other HTS Magnet Programs at BNL**
  - Record high fields and a number of other programs
- **Summary**

Motivation for 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

Application of HTS in Accelerator Magnets

High Field, Low Temperature Application

Example: Muon Accelerator Program and IR Magnets for large luminosity

• At very high fields (>20 T), no superconductor can carry as high current as HTS do.

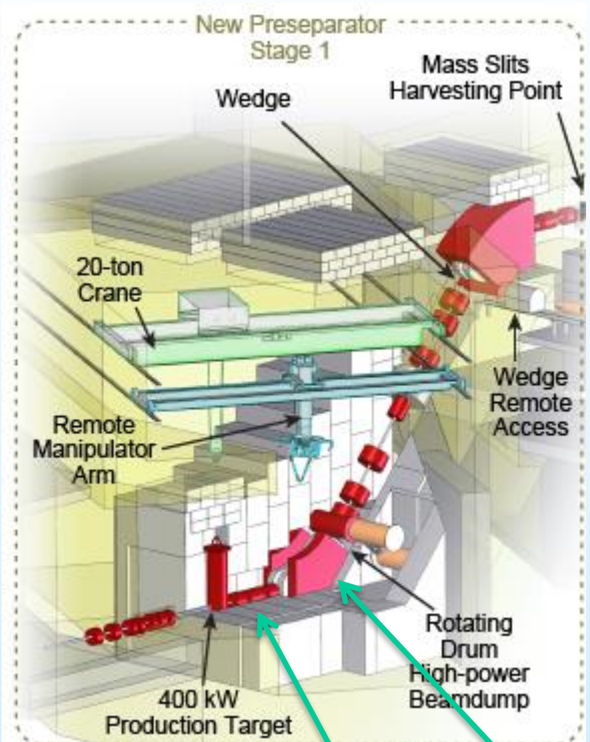
Medium Field, Higher Temperature Application

Example: Quads for Facility for Rare Isotope Beams (FRIB) and cryogen free magnets

• The system design benefits enormously from HTS because HTS offers the possibility of magnets to operate at a significantly higher temperature than 4K; say at 30-60 K.

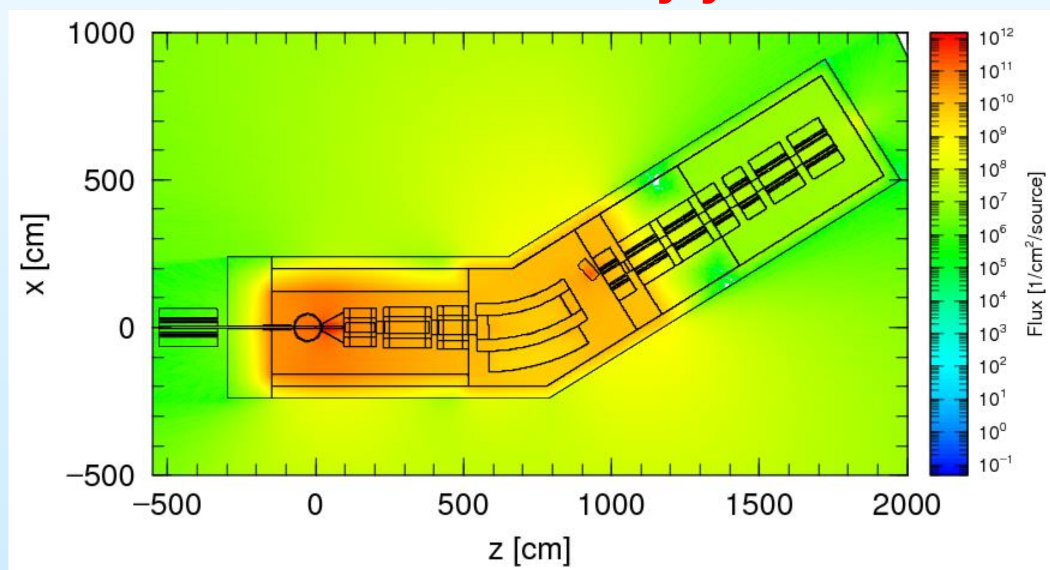
Large Radiation and Heat Loads

Magnets in FRIB Fragment Separator Region



Exposure in the first magnet itself:

- **Head Load : ~10 kW/m, 15 kW**
- **Fluence : 2.5 x10^{15} n/cm^2 per year**
- **Radiation : ~10 MGy/year**



Radiation resistant

Pre-separator quads and dipole

Copper or NbTi Magnets don't satisfy the requirements

Motivation for HTS Magnets in FRIB

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

Technical Benefits:

➢ Provides higher gradient and/or larger aperture than copper magnets (increases acceptance and beam intensity transmitted through the beam line)

➢ Provides large temperature margin than LTS – HTS can tolerate a large local and global increase in temperature (resistant to beam-induced heating)

Economic Benefits:

➢ Removing large heat loads at higher temperature (30-50 K) rather than that at ~4 K (as in LTS) 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.

Appears to be a custom made application of HTS magnets.

Major Achievements/Spin-off of FRIB HTS Magnet R&D

A Story Being Prepared for NP Spin-off

Superconducting Magnetic Energy Storage (SMES)

High Field, High Energy Density HTS SMES for GRIDS

The Science

Like batteries store energy in chemicals, superconducting coils store energy in magnets with low loss. High Temperature Superconductor can store it at elevated temperatures and/or in extremely high densities that was not feasible before.

The Impact

The basic HTS magnet technology developed under a program funded by Nuclear Physics (NP) is being further extended to build SMES. SMES can store energy during day time from sun and can deliver it continuously when sunlight is not available or in remote areas where electrical power can't be delivered.

Summary

A significant development of HTS magnet technology at BNL was funded by DOE/NP to provide a unique solution for the magnets in the fragment separator region of the Facility for Rare Isotope Beams (FRIB). The same coil technology (HTS tape co-wound with stainless steel tape) is used in **high field (~24 T) SMES** that can withstand high stresses that are present in high field magnets. This technology has already been successfully applied in demonstrating **high field magnets for Muon Accelerator Program (MAP)** that created the record 16 T field in an all HTS magnet. High fields significantly reduce the amount of conductor for the same stored energy in SMES. This is because of the fact that, whereas the stored energy increases essentially as the square of the field, the currently carrying capacity of HTS (unlike conventional low temperature superconductor) hardly decreases as a function of field in high field SMES. In addition, HTS SMES can operate at higher temperatures where high efficiency of cryo-coolers provides a practical cryogen free operation.

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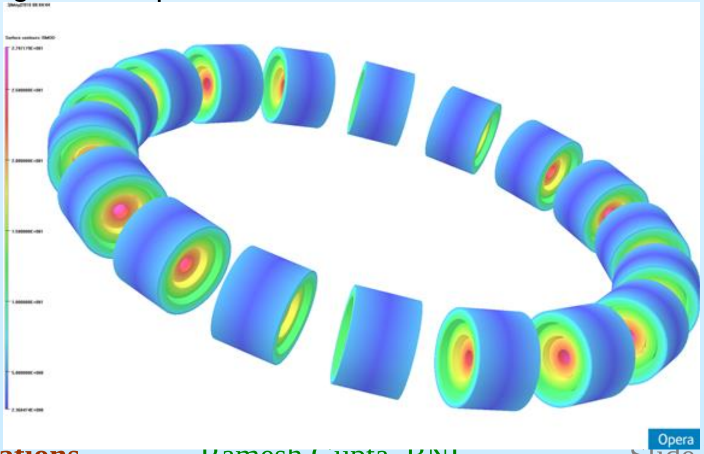


Image courtesy of Brookhaven National Laboratory
A toroid SMES system consisting of a number of high field coils made with the High Temperature Superconductors (HTS)

Patent Application on Novel Quench Protection

- A concept of novel quench detection system has been developed.
- This work was started initially for FRIB (as a result of a request from FRIB following a review).
- A "provisional patent" application was filed last year and "non-provisional patent" application this year

  BSA 12-13 - Joshi, et al. - Non-Provisional Patent Application - "Quench Detection System for Superconducting Magnets" - Request No. 2436 - Our Docket No. 1004305.070US was filed on March 2013.

- The basic concept is described in PAC2011 paper by Joshi, et al., "Novel Quench Detection System for HTS Coils".

Development of a Significantly New Magnet Technology

- The radiation tolerance requirements in FRIB magnets for fragment separation region are unprecedented
- In addition to the conductor, all magnet parts (including insulation, cryogenic and support structure) must withstand large radiation loads (verified by Al Zeller)
- This is the first time that we have made a superconducting magnet that is built with no organic component in it (including insulation)
- In addition to high radiation, the magnet technology developed is able to withstand large energy deposition too

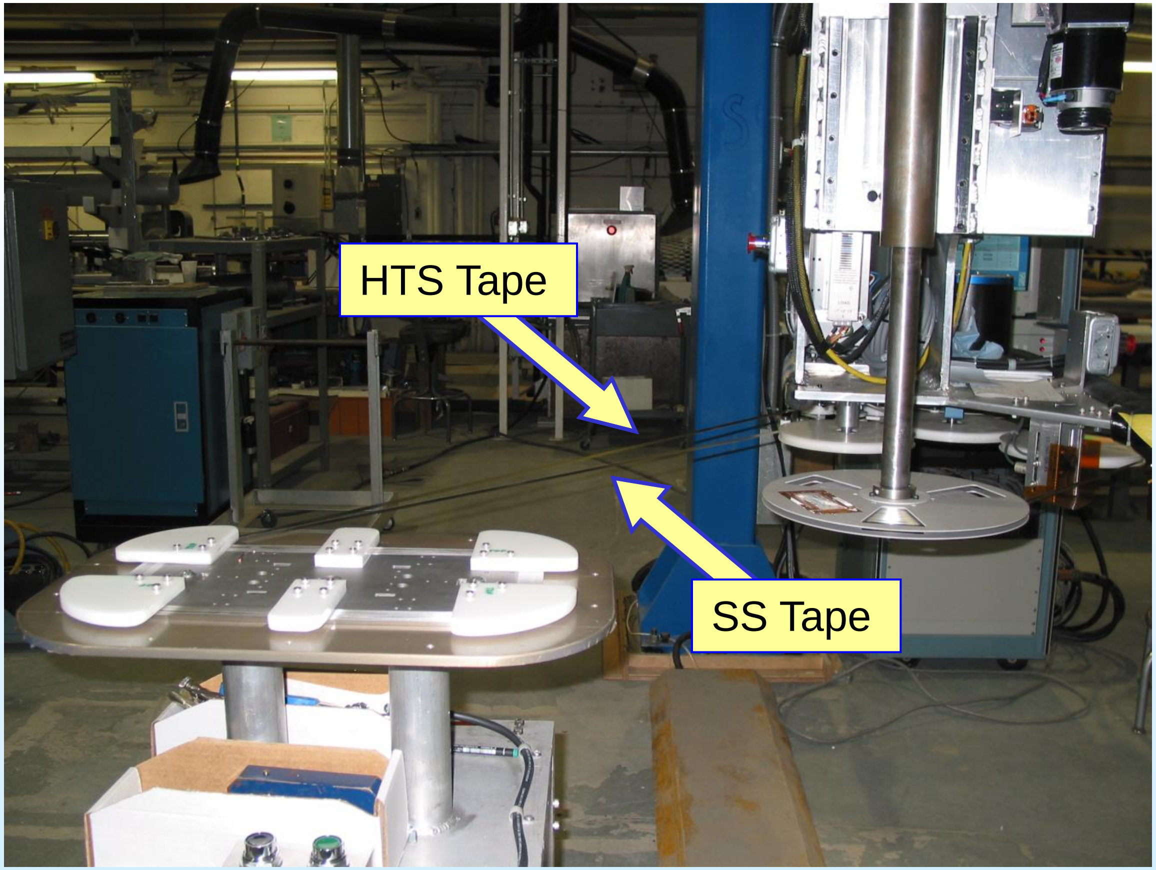
Components of RIA/FRIB Magnet R&D Program (spanning over a decade)

- **First Generation HTS Quad (RIA period)**
  - 10 T/m, 1st Generation HTS (1G - Bi2223), 30 K operation
- **R&D Program during the Transitional Period (RIA to FRIB)**
  - Evaluate prospects of 2nd Generation HTS (2G - YBCO), 40 K operation
  - A simple six-coil magnet based on cryo-coolers
- **Second Generation HTS Quad (FRIB period)**
  - 15 T/m, 2G HTS, up to 50 K operation (higher gradient & higher temperature)
- **R&D to ensure that all FRIB requirements are satisfied**
  - Radiation damage studies, energy deposition studies, quench protection, etc.

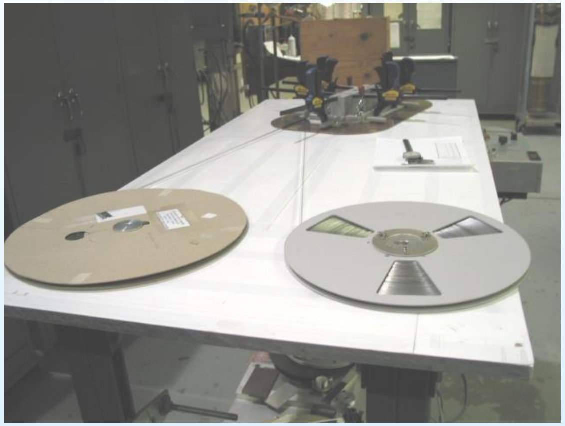
First Generation Design

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

HTS Coil Winding

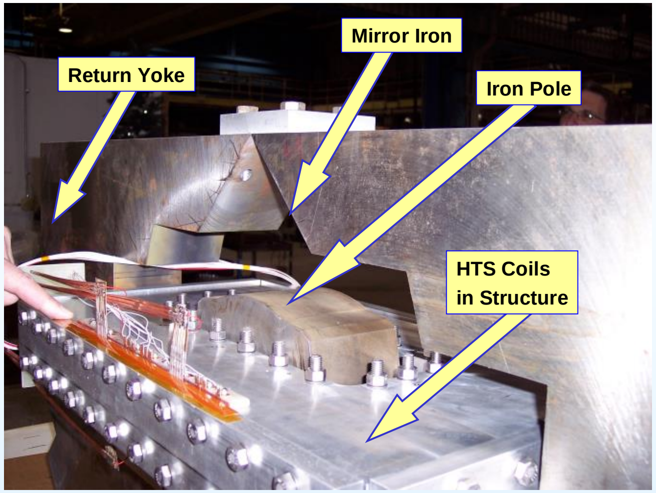


A coil being wound in a computer controlled winding machine.



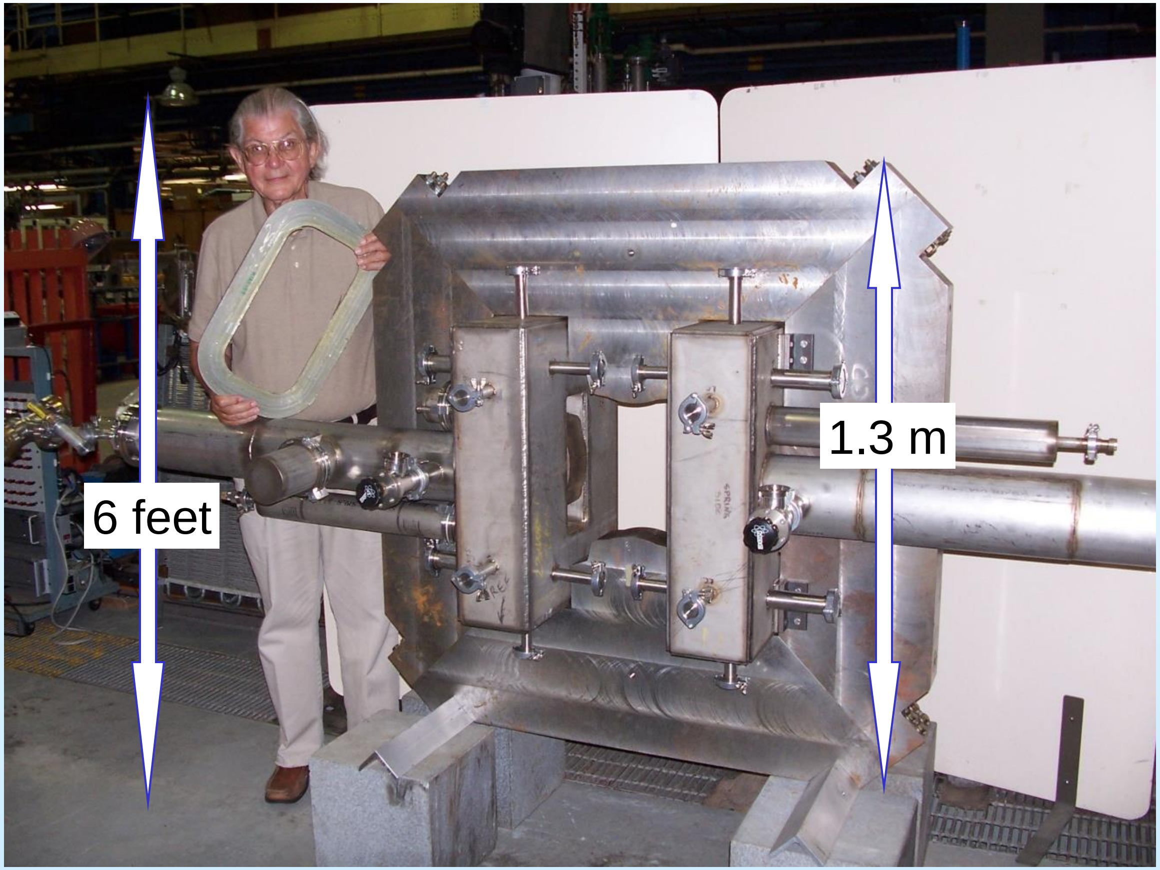
Earlier coils were wound with a machine that has more manual controls.

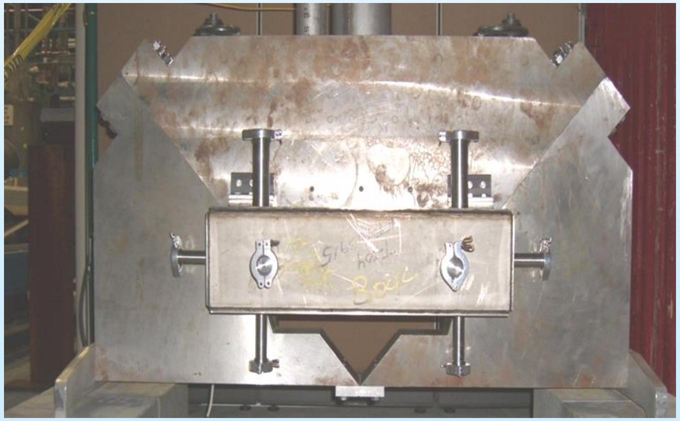
HTS Quad Structures



Mirror cold iron

Warm Iron Design to Reduce Heat Load





Mirror warm iron

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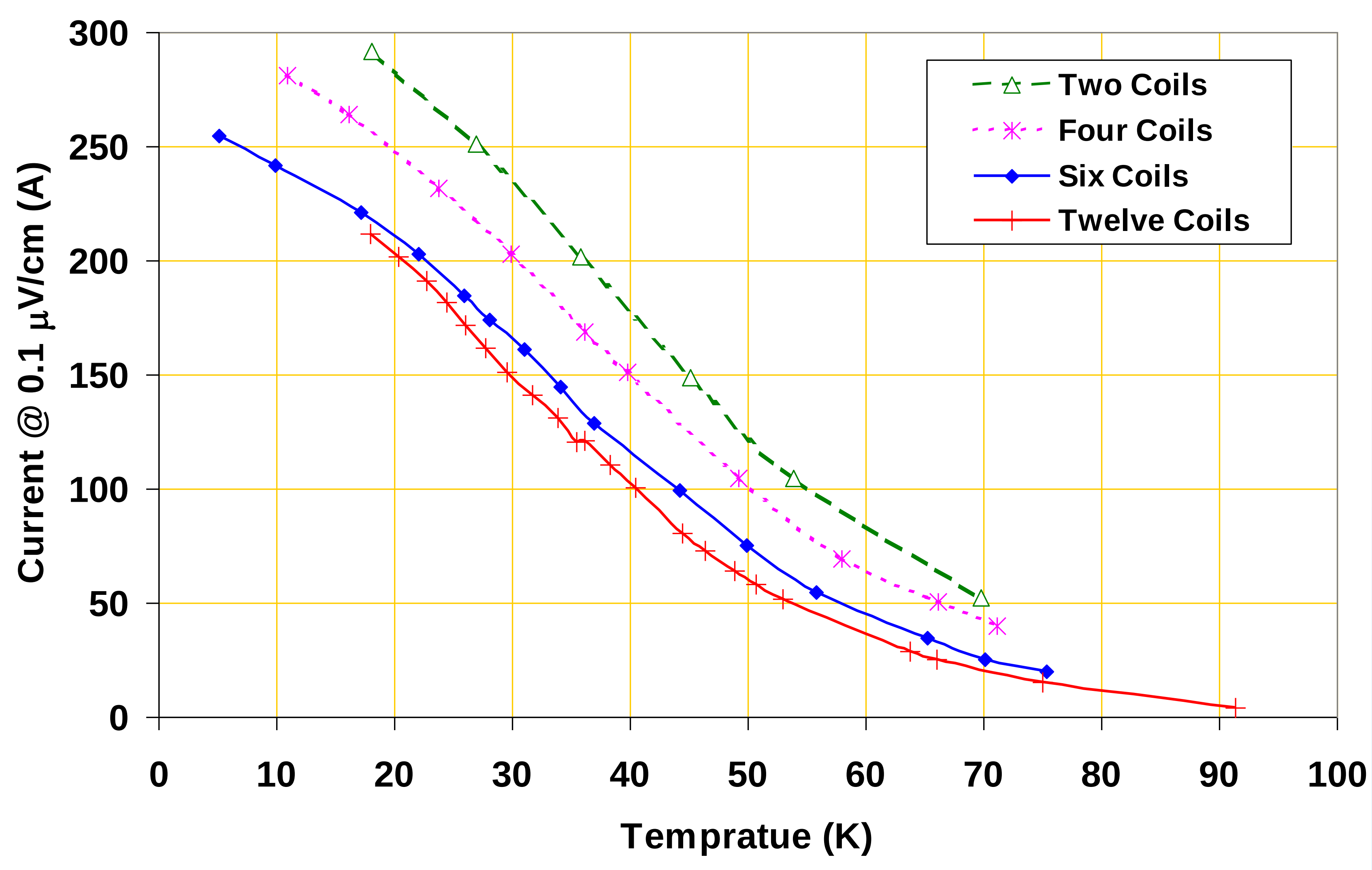
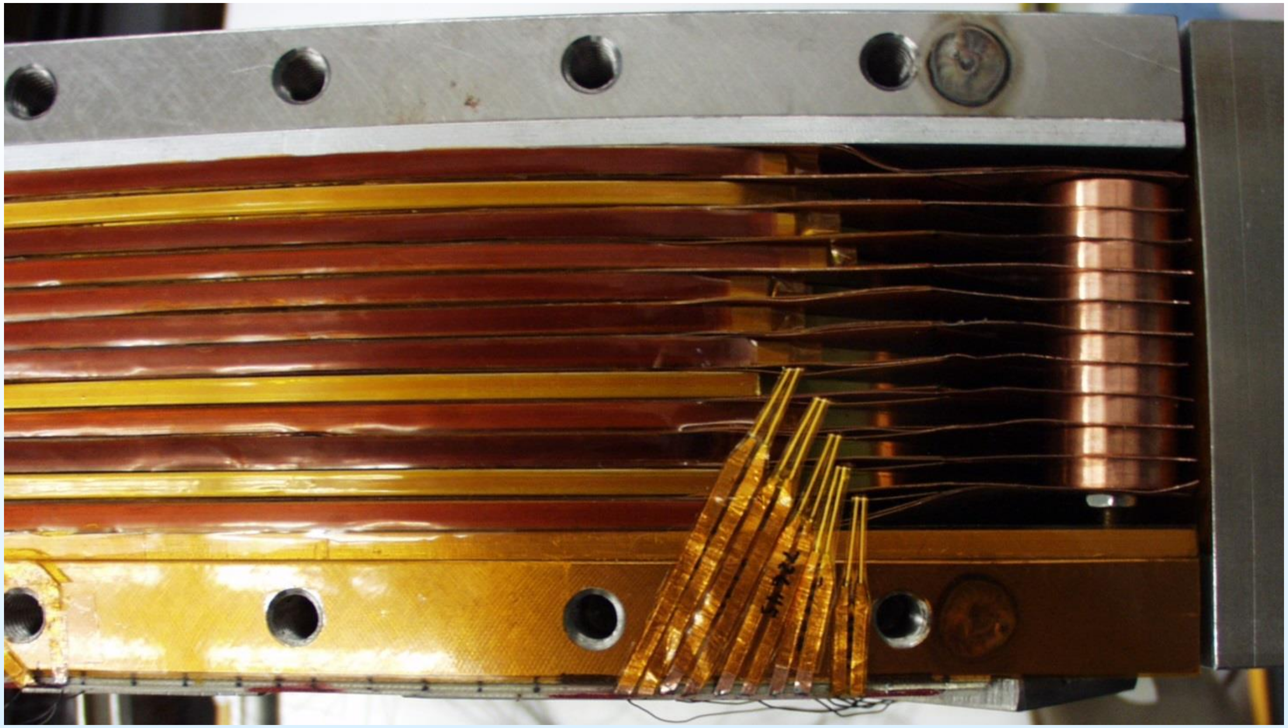
First Generation HTS Quad Test (operation over a large temperature range)



Energy Deposition and Cryogenic Experiments on Conduction Cooling

Stainless steel tape heaters for energy deposition experiments

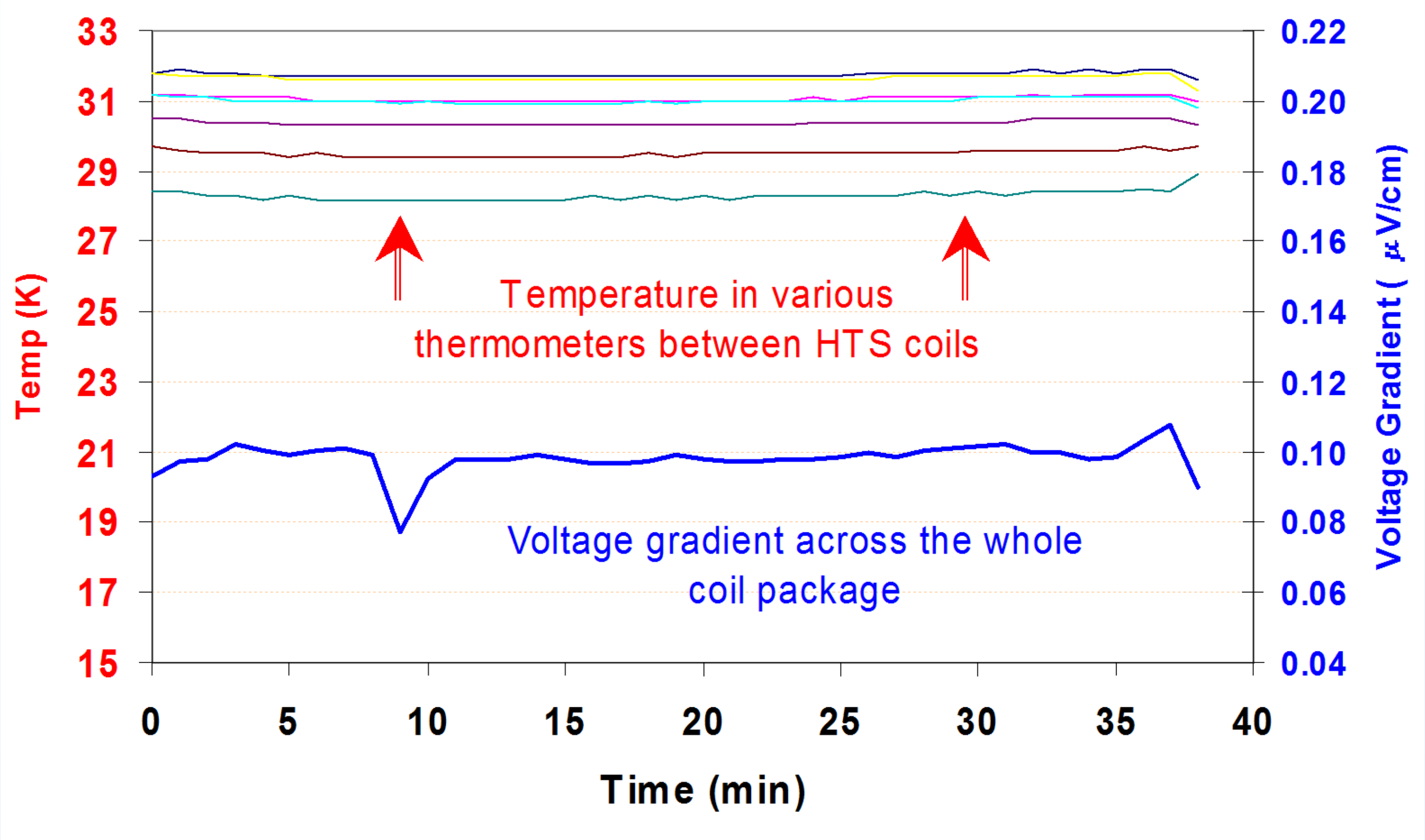


Copper sheets between HTS coils with copper rods and copper washers for conduction cooling

- 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.
- Since the magnet performed well in both cases, one can use either approach.

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).



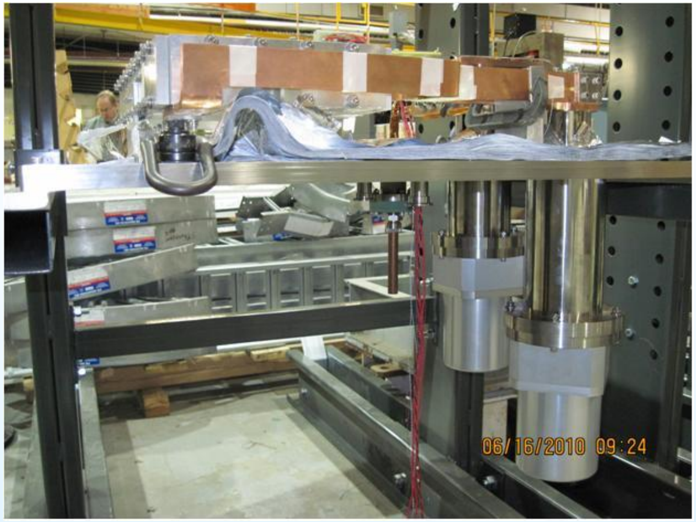
Stable operation for ~40 minutes

Voltage spikes are related to the noise

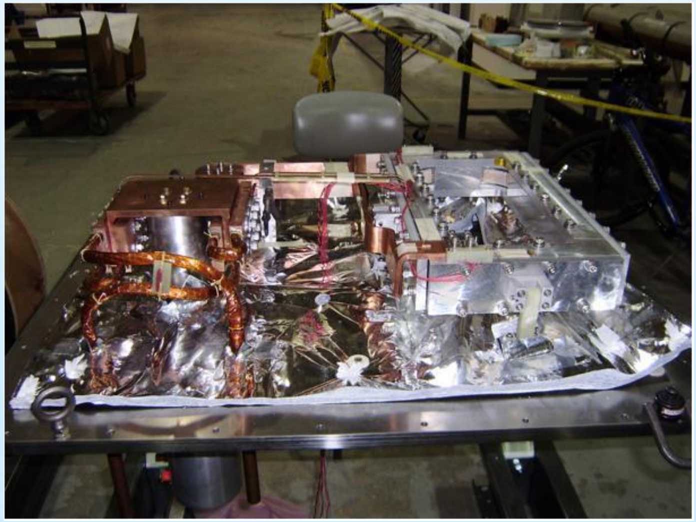
Transition from the First Generation (1G) to the Second Generation (2G) HTS

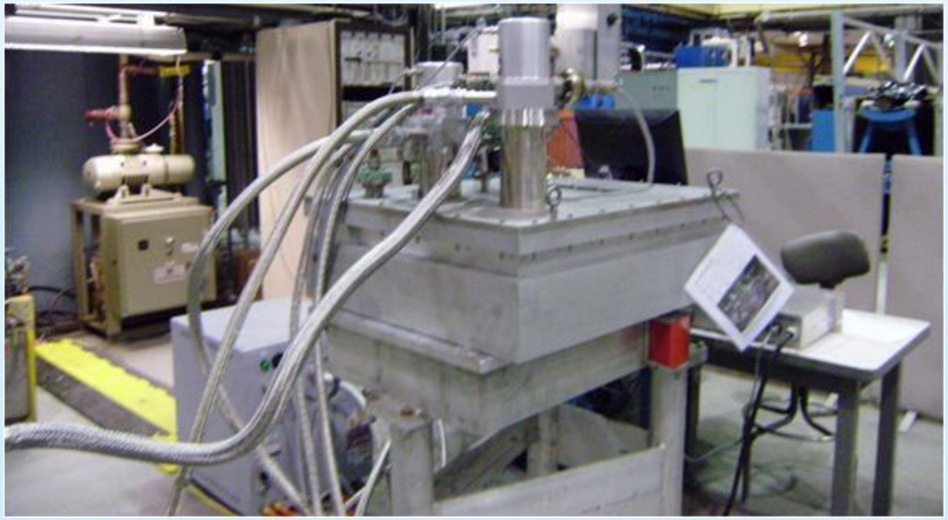
Superconducting
Magnet Division

Cryo-cooler based FRIB HTS Coils (initial R&D to investigate 2G HTS)

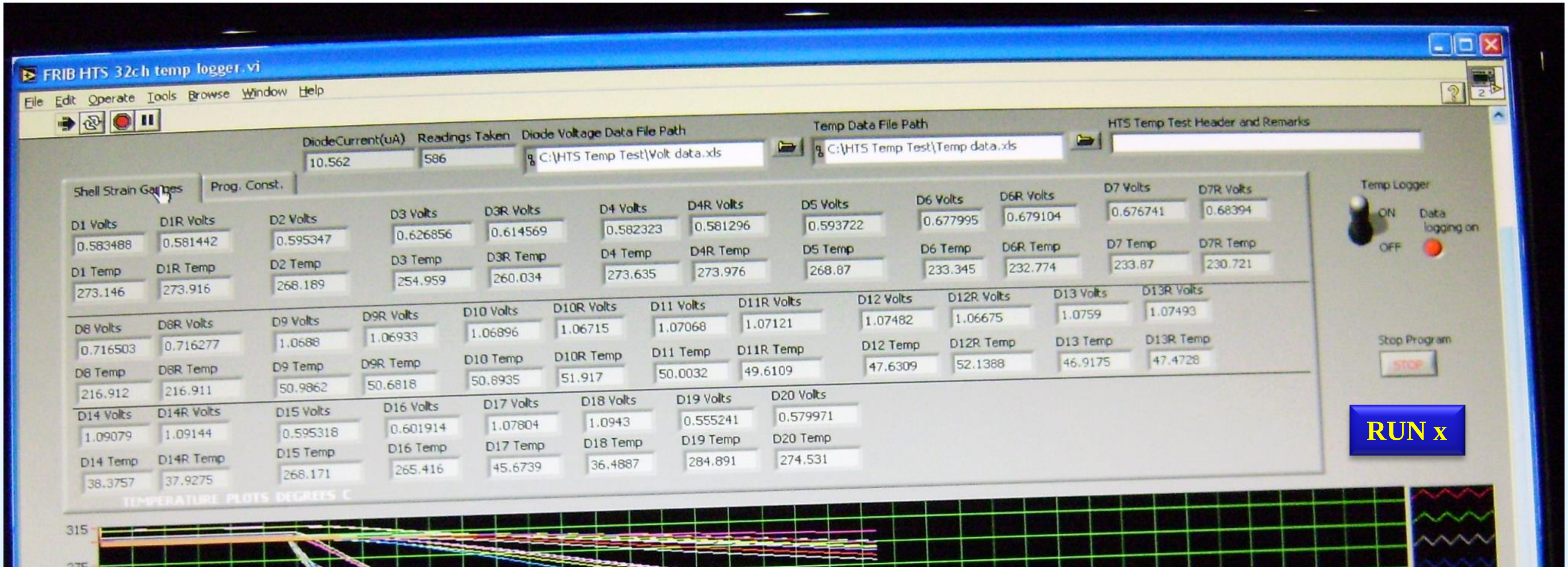


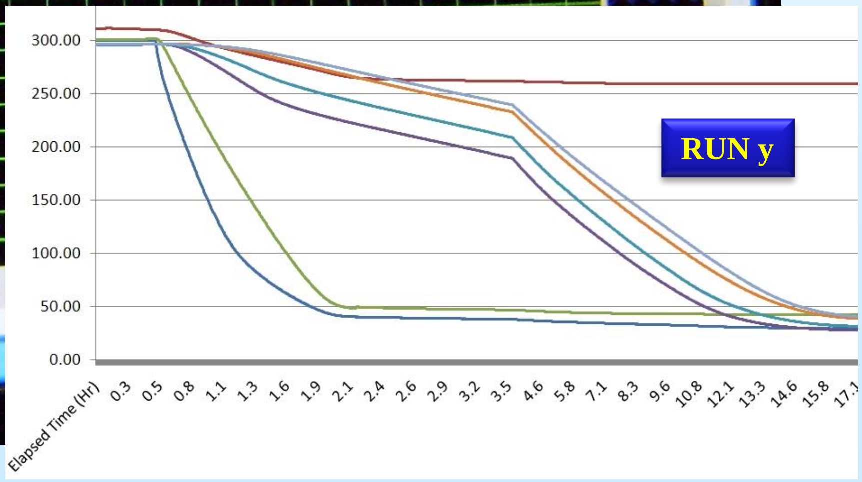
- ASC announced “no more” manufacturing of 1G HTS.
- New coils were made with 2G HTS from ASC and SuperPower (now two US vendors in case of 2G).
- Coils reached <40 K (goal was 40 to 50 K)
- Cryo-coolers were turned on in the evening before and coils were cold in the morning.
- Six coils successfully tested in various configurations.
- Energy deposition experiments performed.
- 25 W at 50 K can be removed with a few cryo-coolers (but questions about the radiation tolerance remain).





Cool-down of FRIB Coils with Cryo-coolers (over-night)





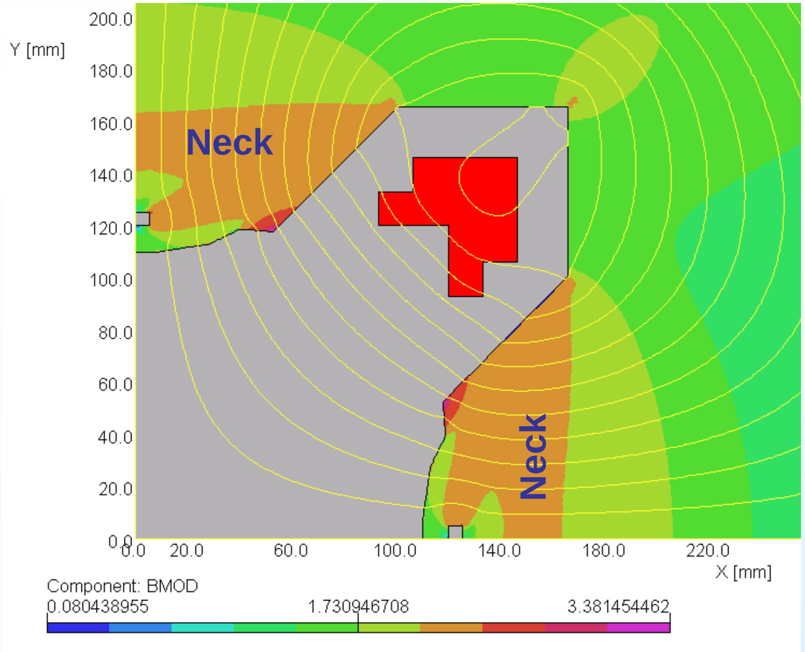
Second Generation Design

- Higher operating temperature (up to 50 K instead of 30 K in the 1st) and higher gradient (15 T/m instead of 10 T/m in the 1st)

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

  - ~9 km equivalent of 4 mm tape

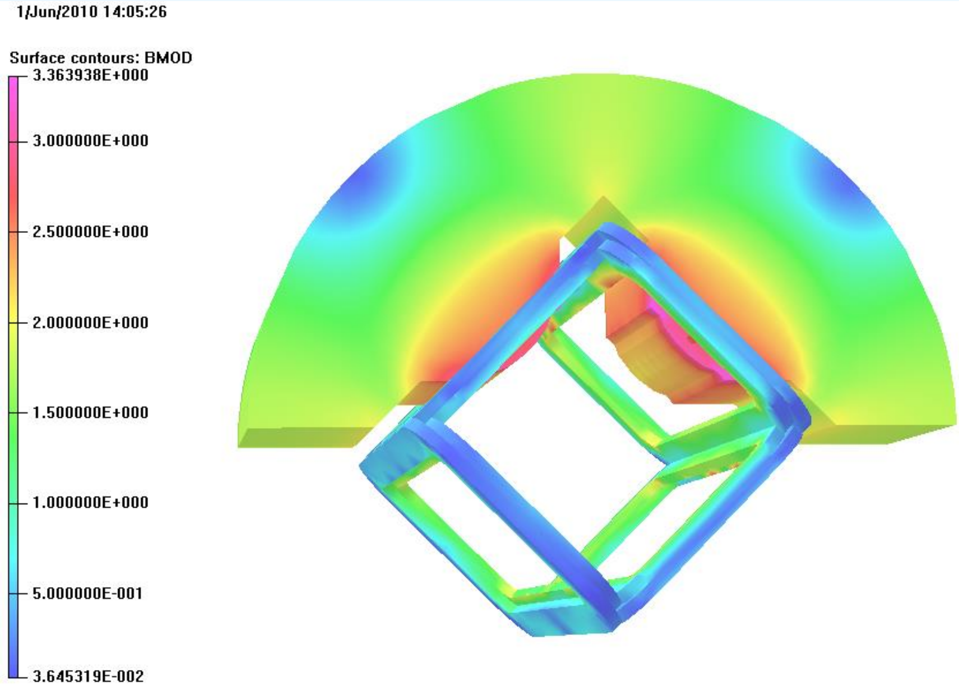
Magnetic Design



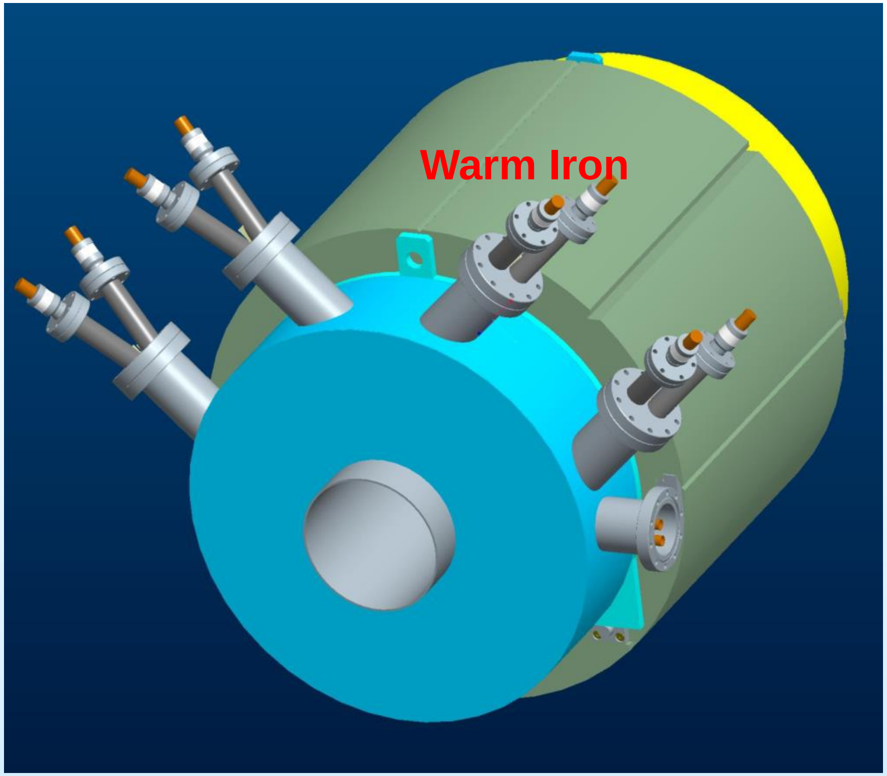
Uses 12 mm tape rather than 4 mm tape

Benefits of 12 mm Tape:

- Minimizes the number of coils and joints
- Current is higher (inductance is lower)
- Relative impact of a weak section along the width is less

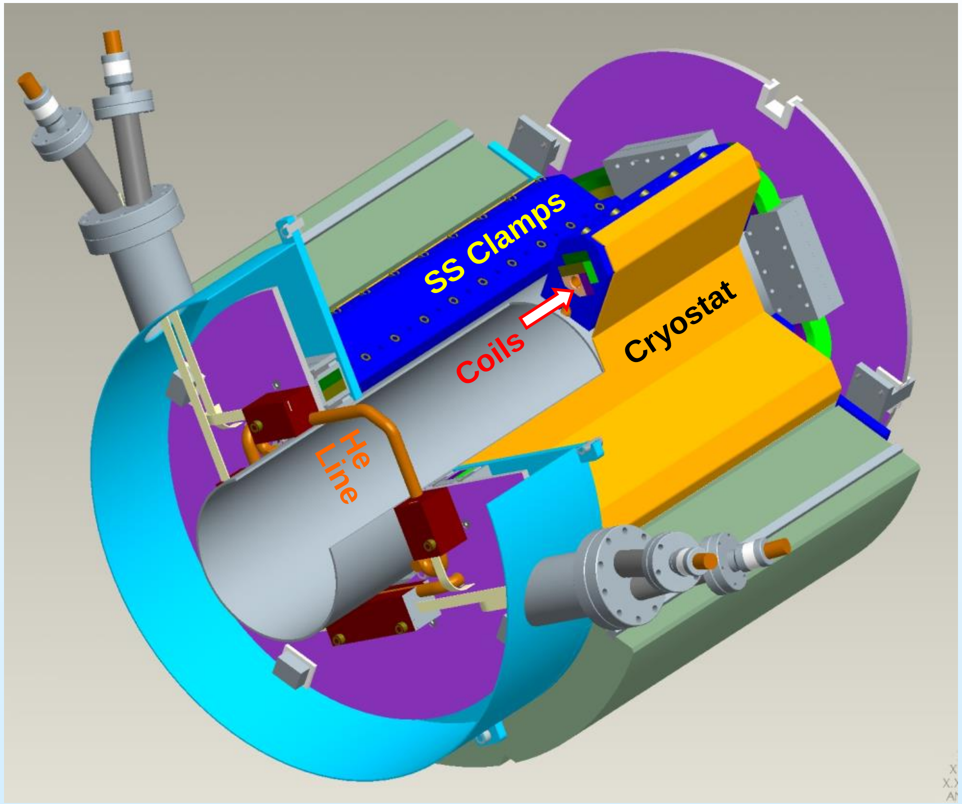


Cryo-mechanical Structure



R&D Magnet in cryo-stat

(allows independent testing of four HTS coils)



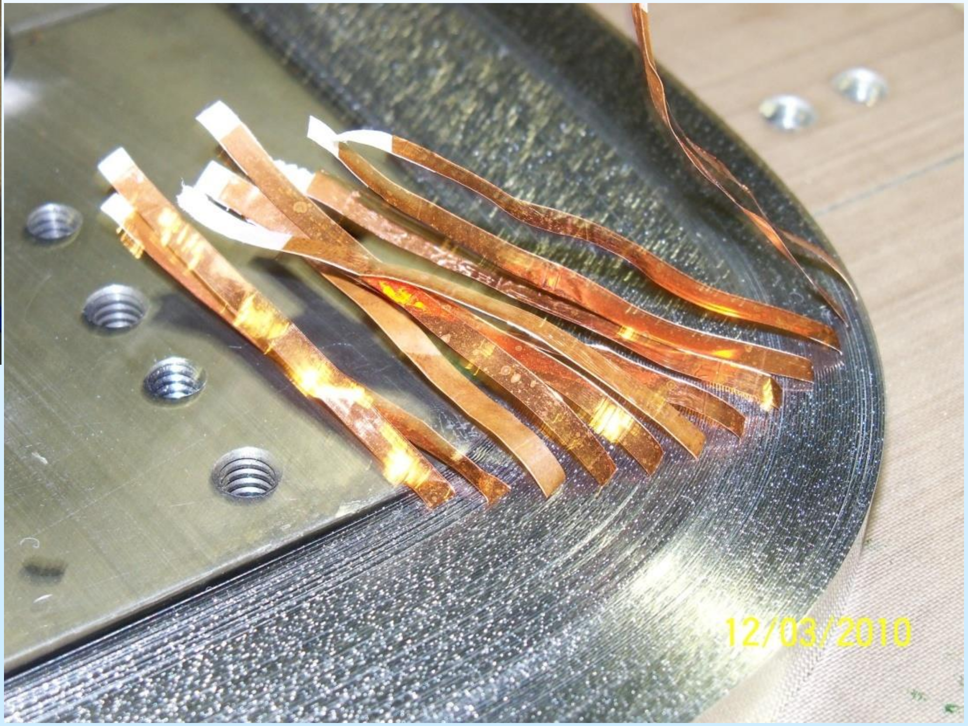
Cut-away isometric view of the assembled magnet

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

Winding of Second Generation HTS Racetrack Coil for FRIB

Coils Made with ASC HTS

- ~210 m (~125 turns), 12 mm double HTS tape per coil.
- One coil was wound without any splice in the coil



Voltage taps are placed generally after every 25 turns and also on either side of an internal splice

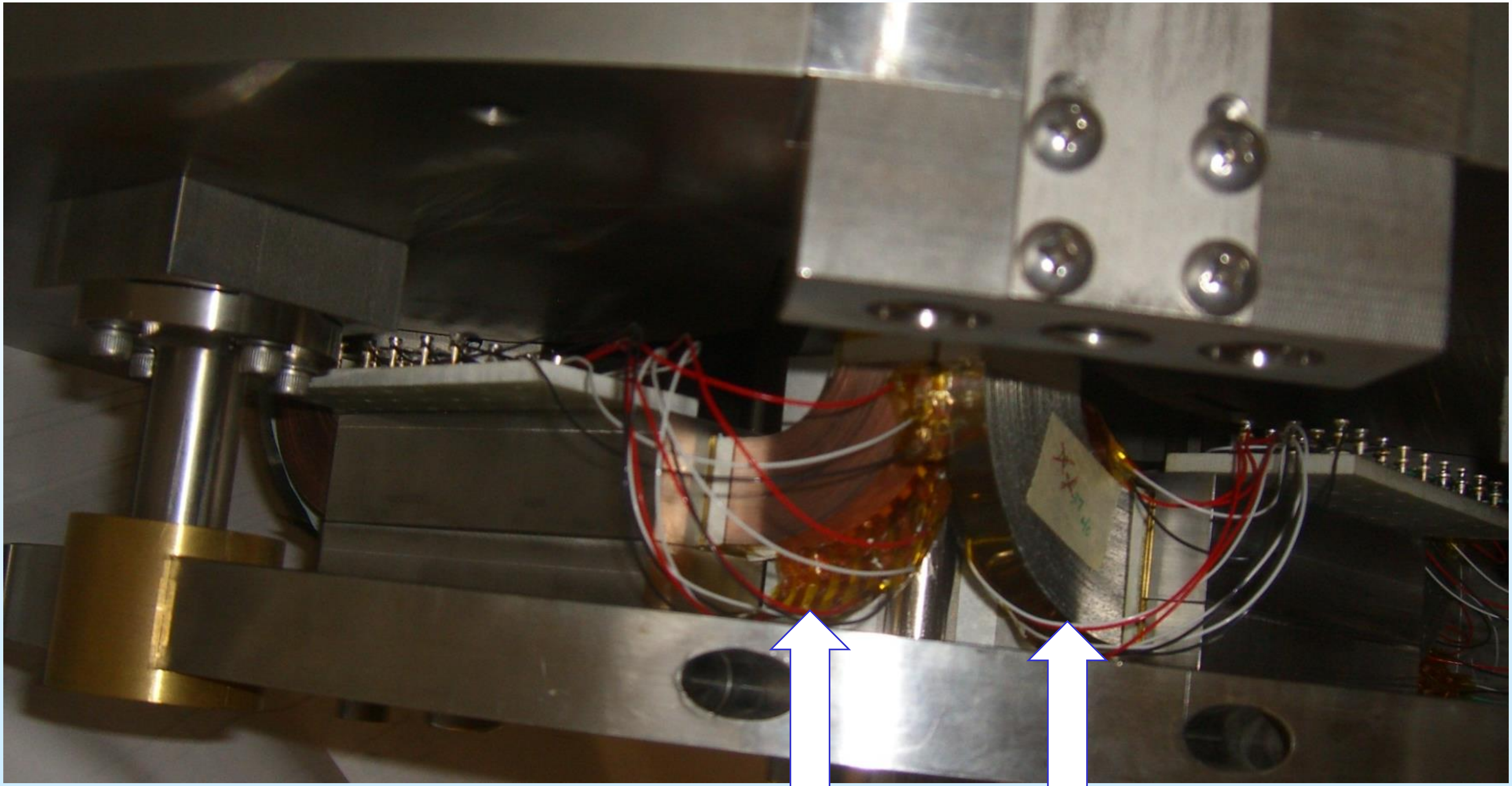
FRIB Coil Made With SuperPower Tape

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

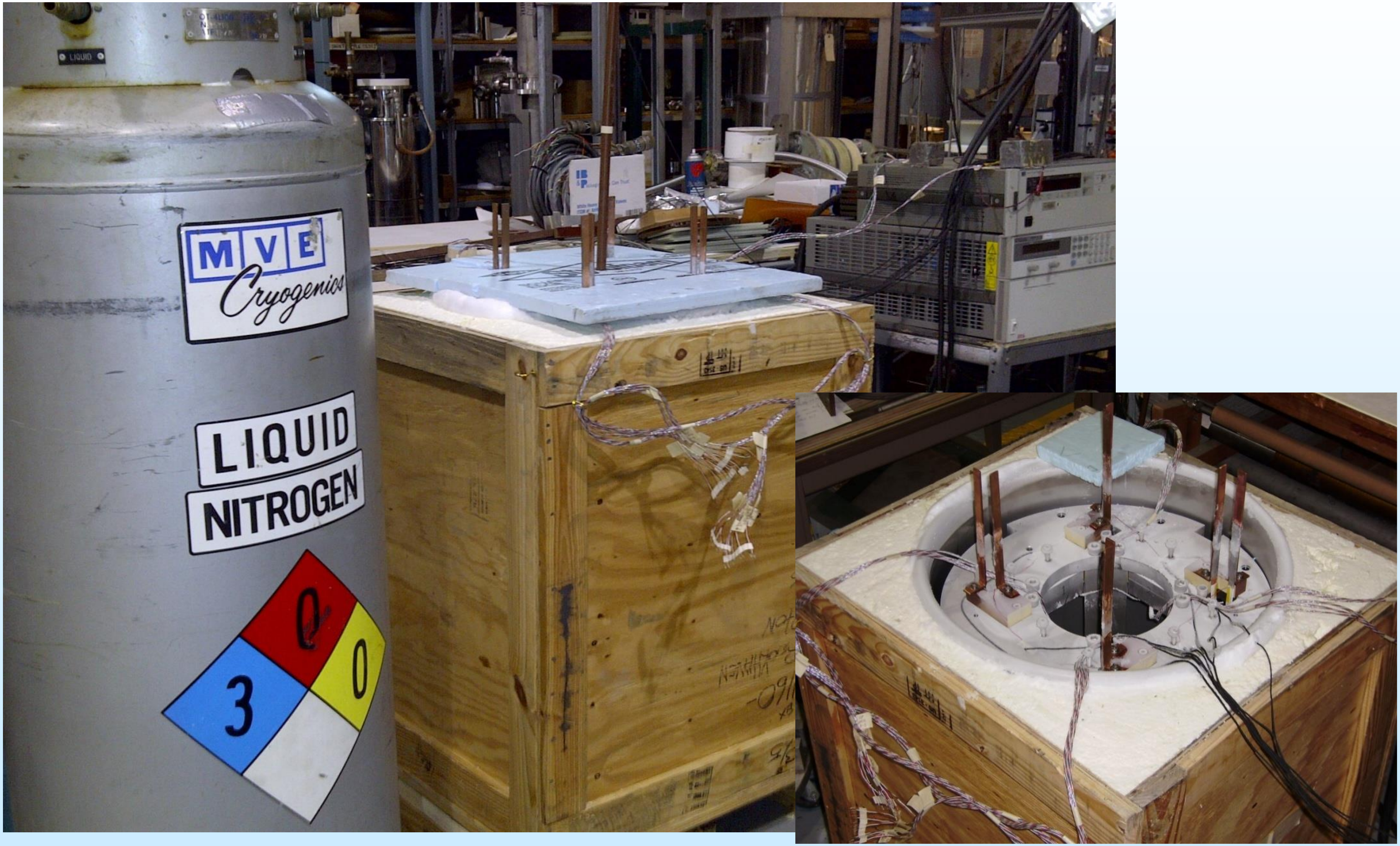
Coils Made with HTS from 2 Vendors (SuperPower and ASC)



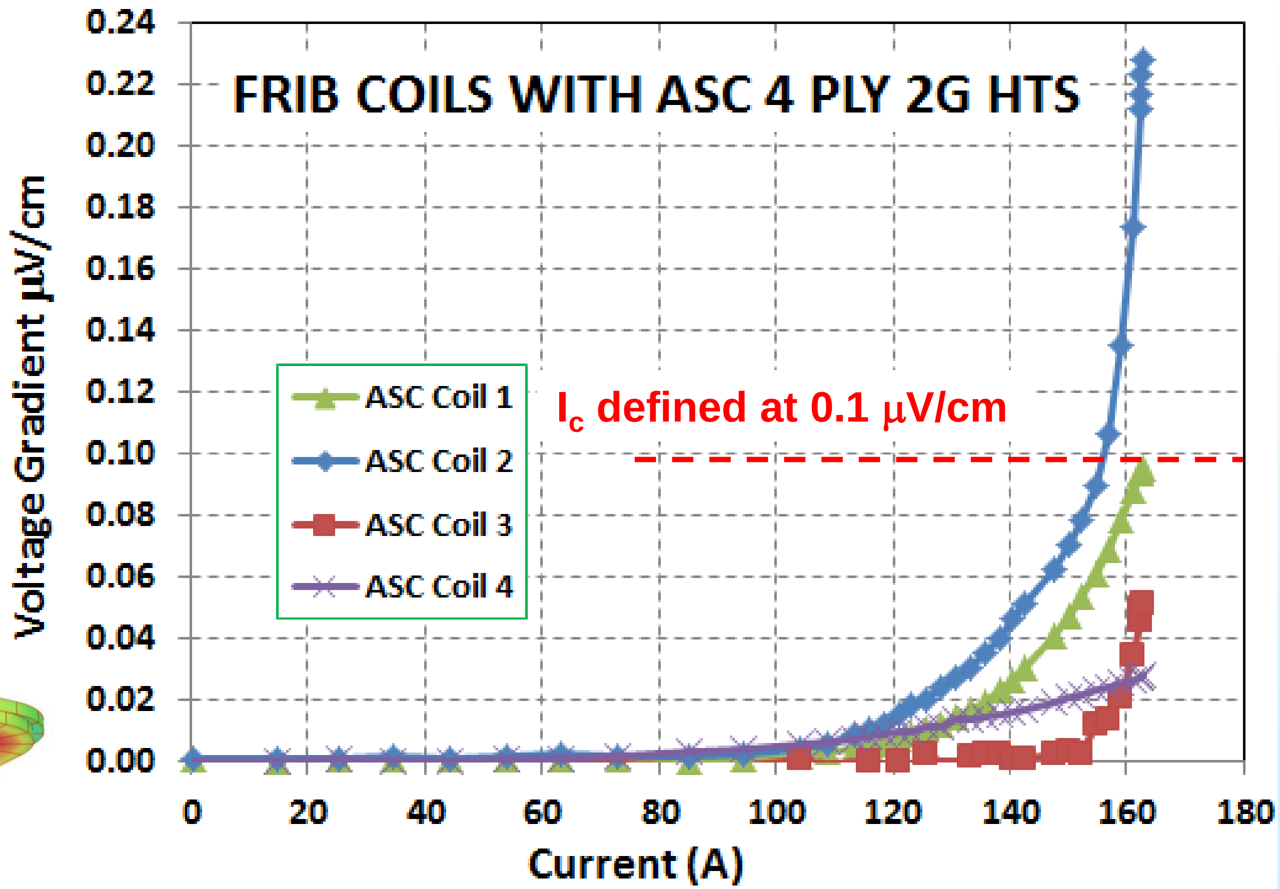
SuperPower

ASC

HTS Quad in a Simple Cryostat

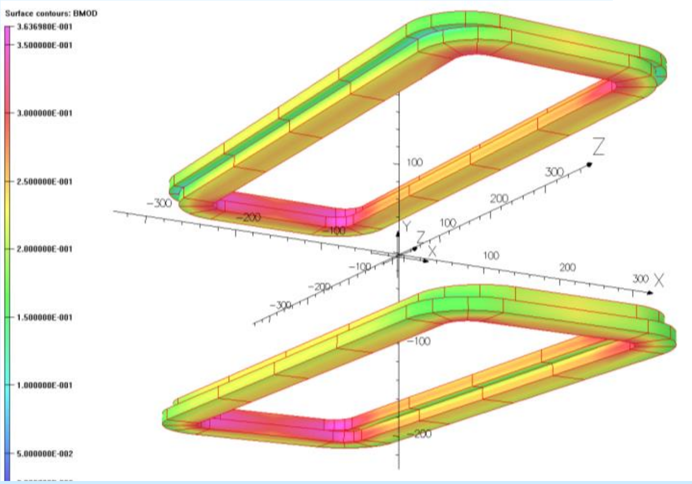


Performance of ASC Coils (four coils of eight powered)



ASC Tape:

2 plies of HTS and 2 plies of Cu

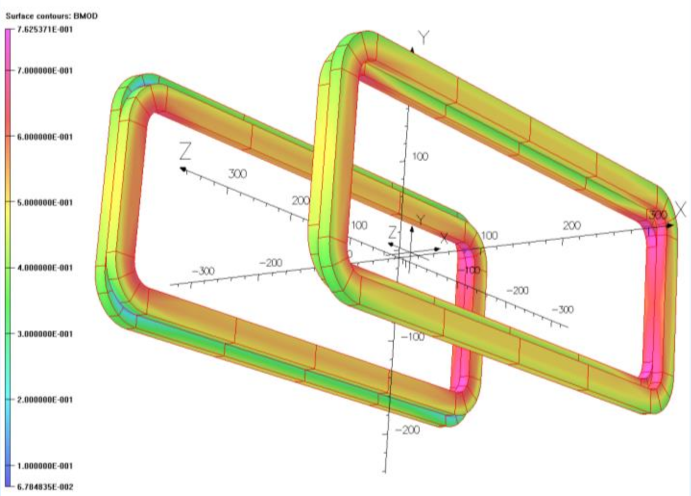


Field on ASC coils at 100 A

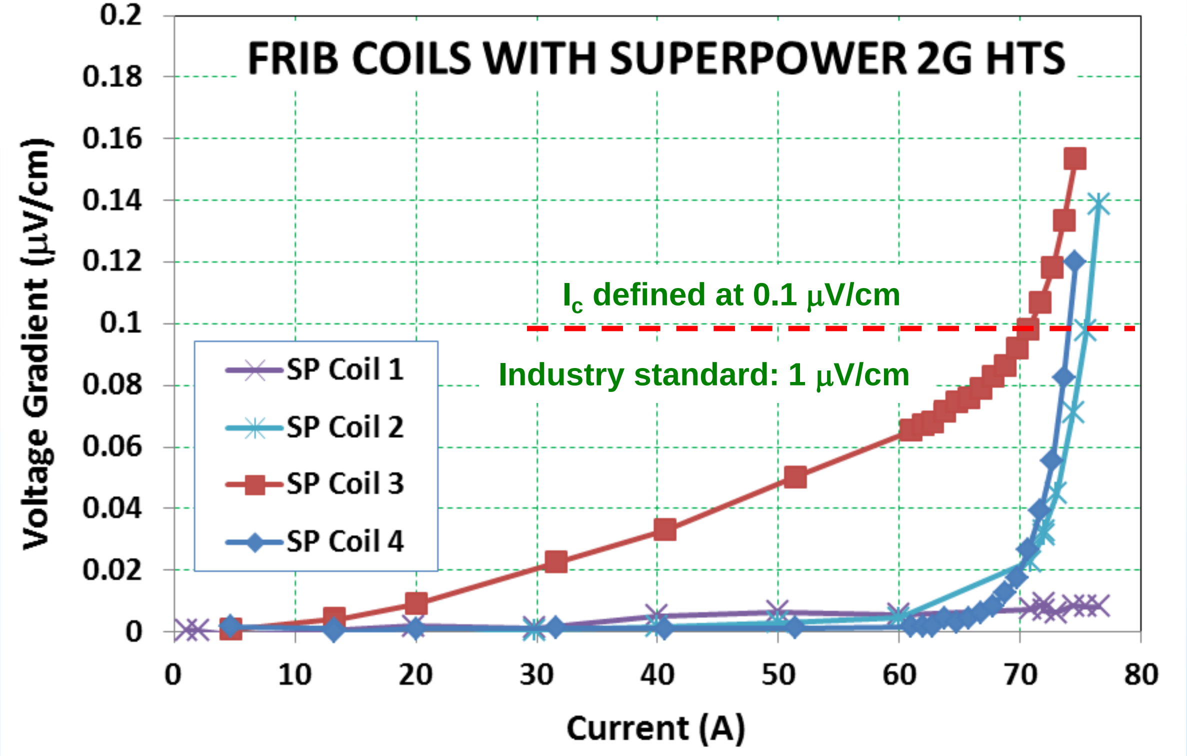
Four SuperPower coils not powered

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 small as compared to the energy deposition.

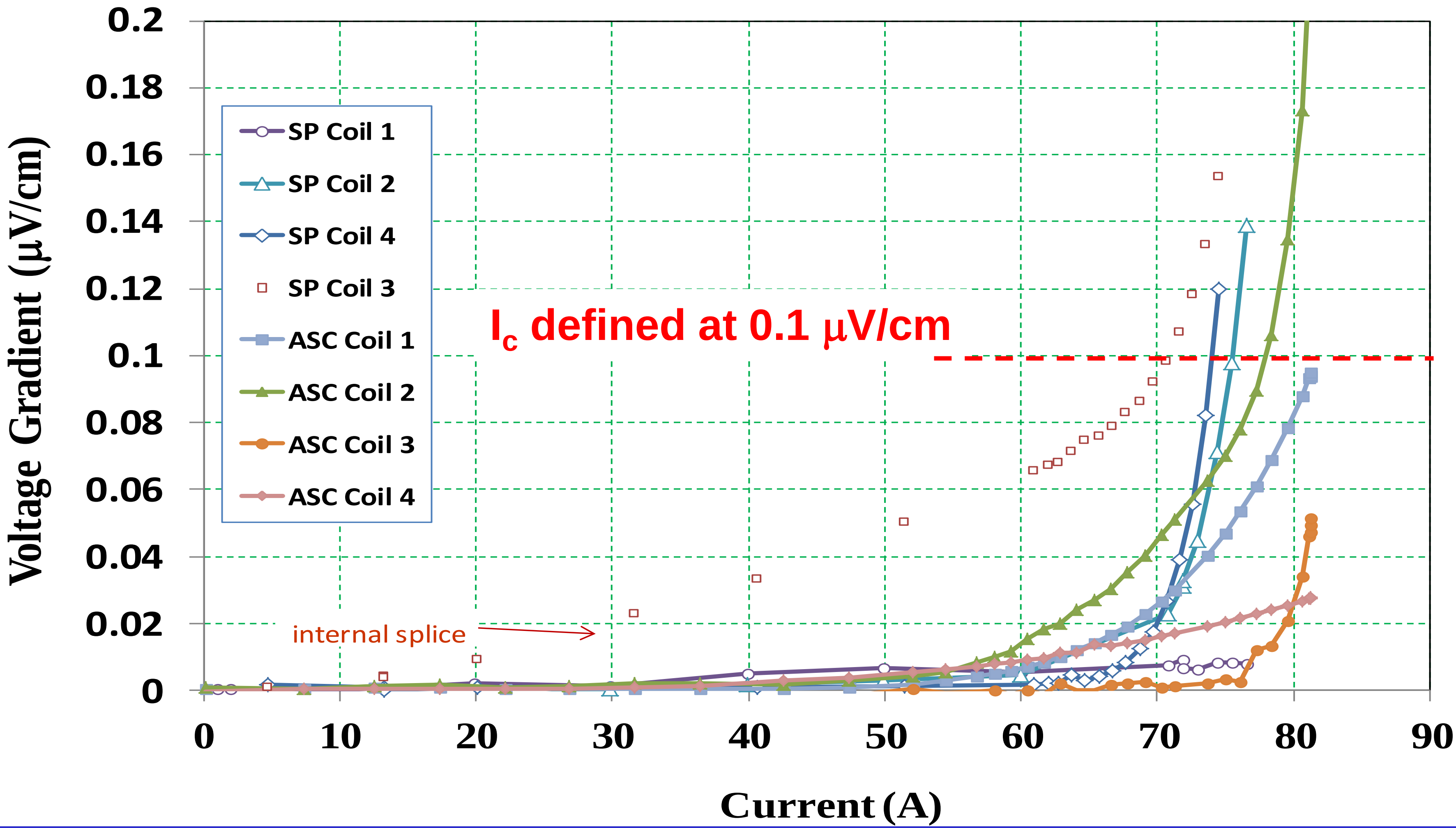
- **Therefore, the expensive coil was not discarded.**

Location confirmed with Voltage taps that are typically placed after every 25 turns and on either side of an internal splice

(slope localized to splice section)

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

Performance normalized to per tape (ASC has double)



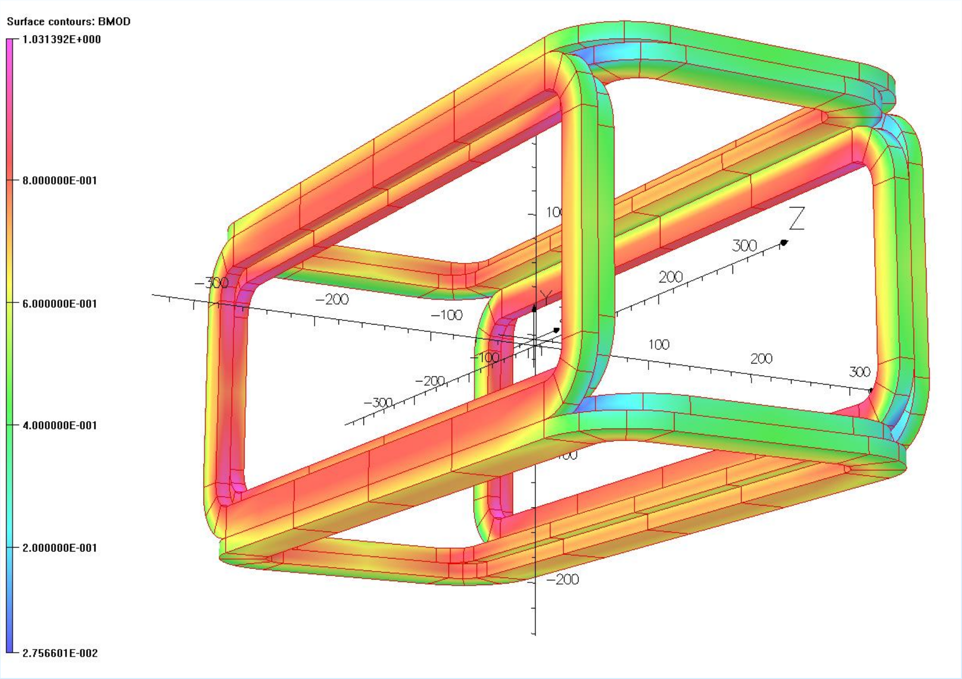
Relative performance between SP and ASC may change @40K, 2T

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

Currents used for quadrupole mode at 77 K (equal Je)

SP	ASC
40	69.3
50	86.7
60	104

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



Design (38 K): SP coils ~210 A & ASC coils ~310 A (equal Amp-turns).

- **Coils reached about 1/3 of the design current at 77 K itself.**
- **Extrapolation to 38 K indicates a significant margin.**

Note: No iron yoke yet in this structure.

Construction and Test of the Second Generation FRIB Quad with Iron at Operating Temperature

Assembly of HTS Coils in Yoke

HTS Coils in Support Structure

Warm Iron Yoke

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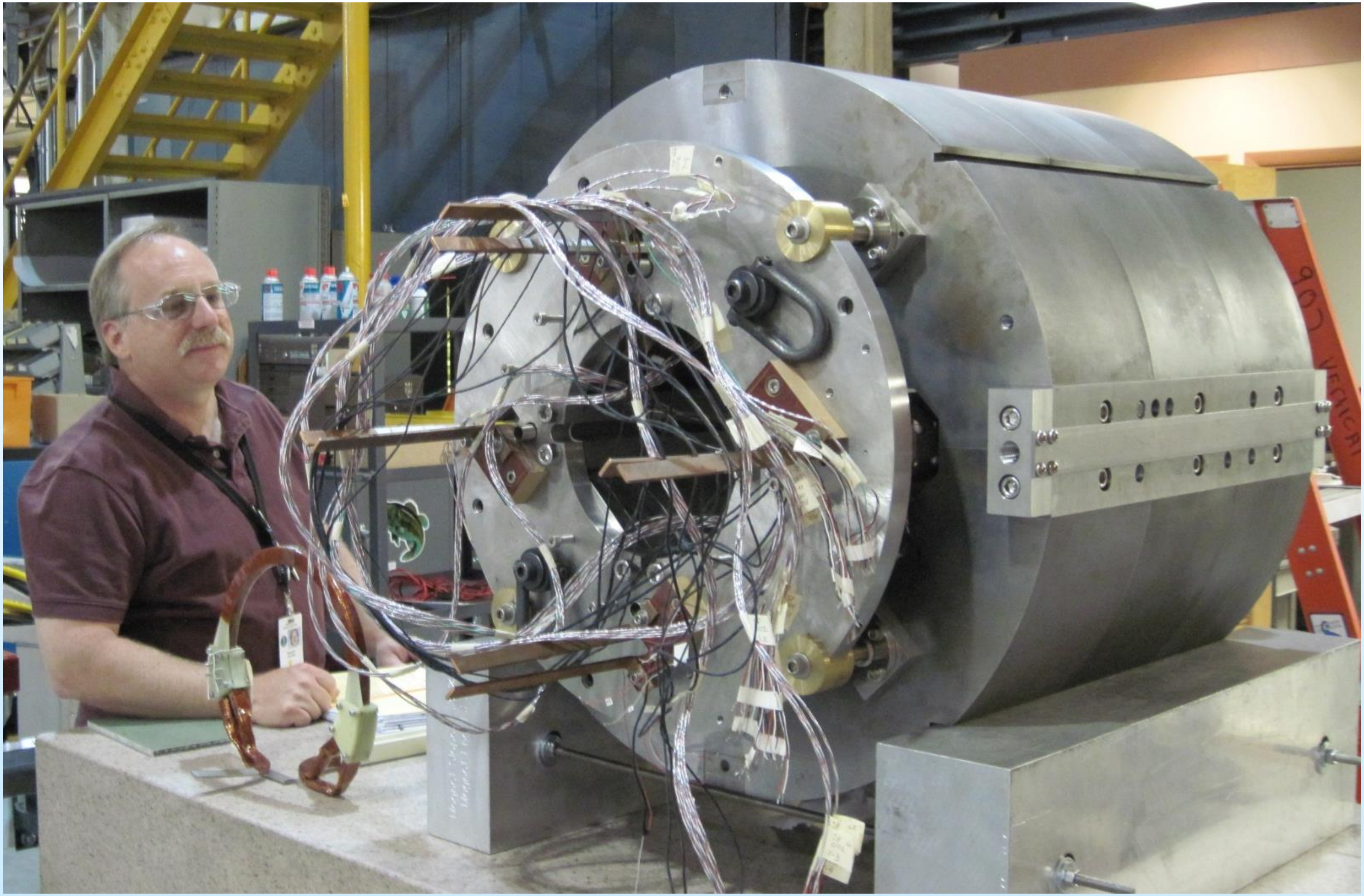
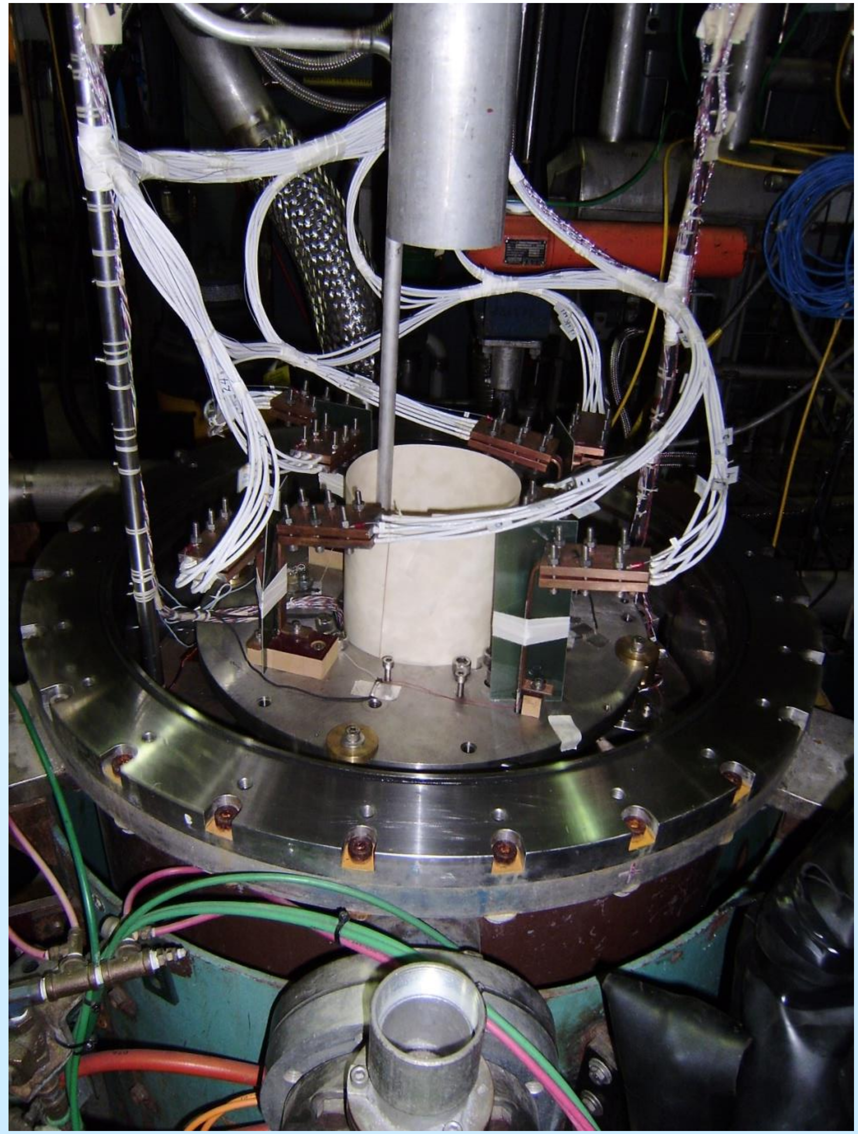
Completed 2G HTS Quad for FRIB

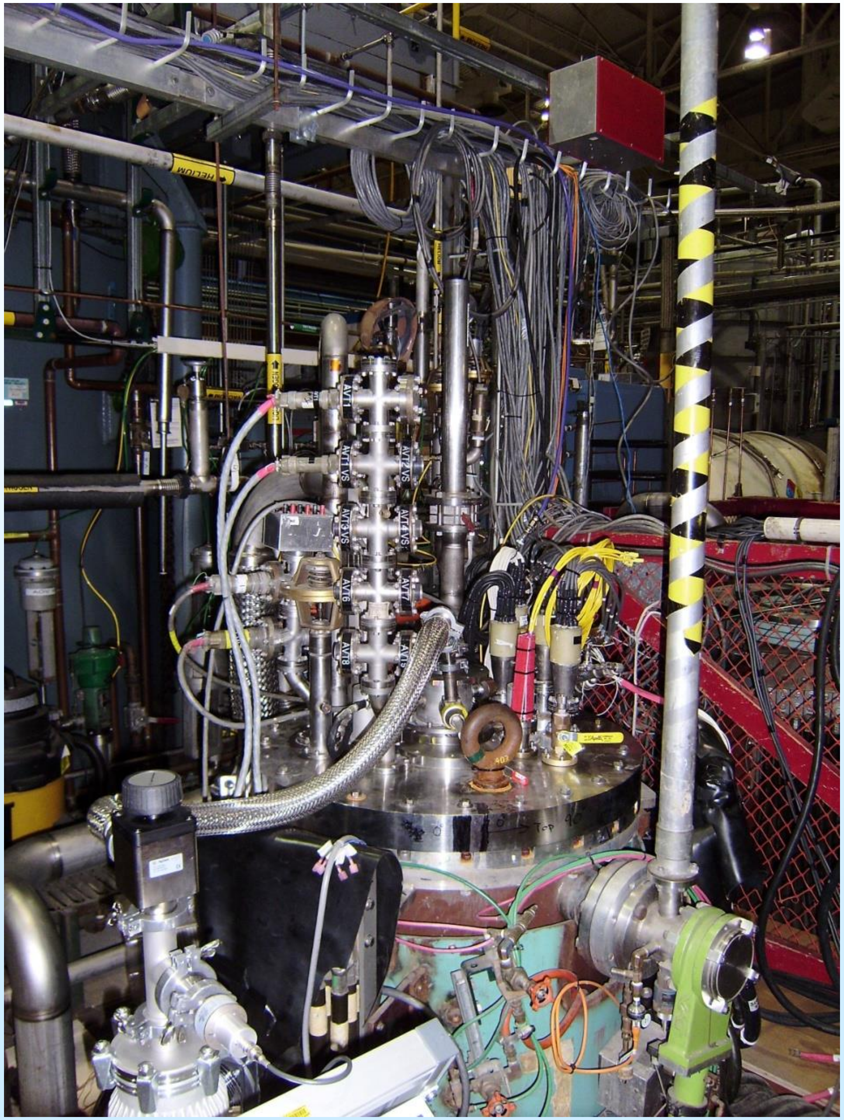


Test Preparation

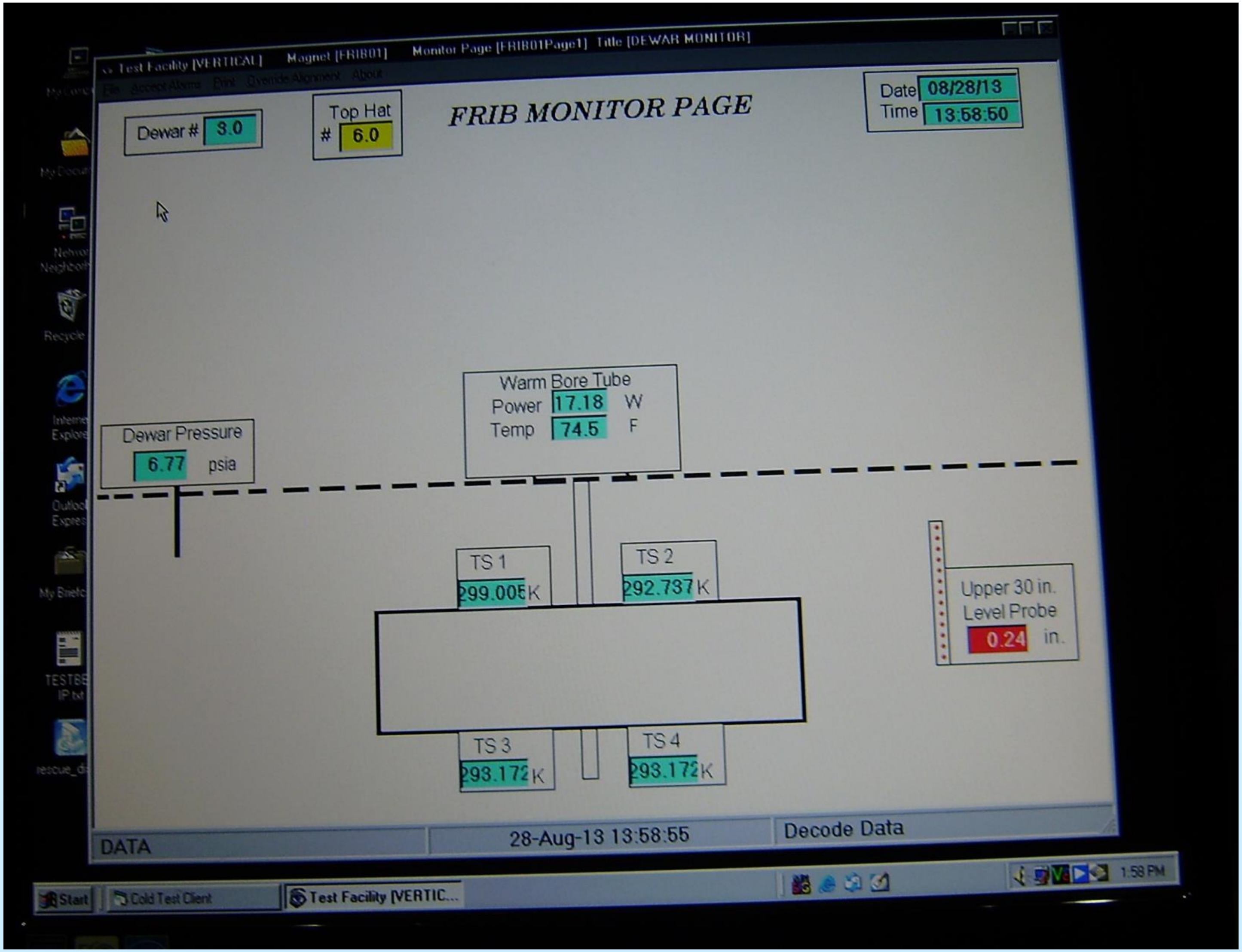


8 leads, each must carry ~400 A (He Gas cooled at the top)

Magnet at the Test Station



FRIB Test Control



Magnet Operation and Quench Protection

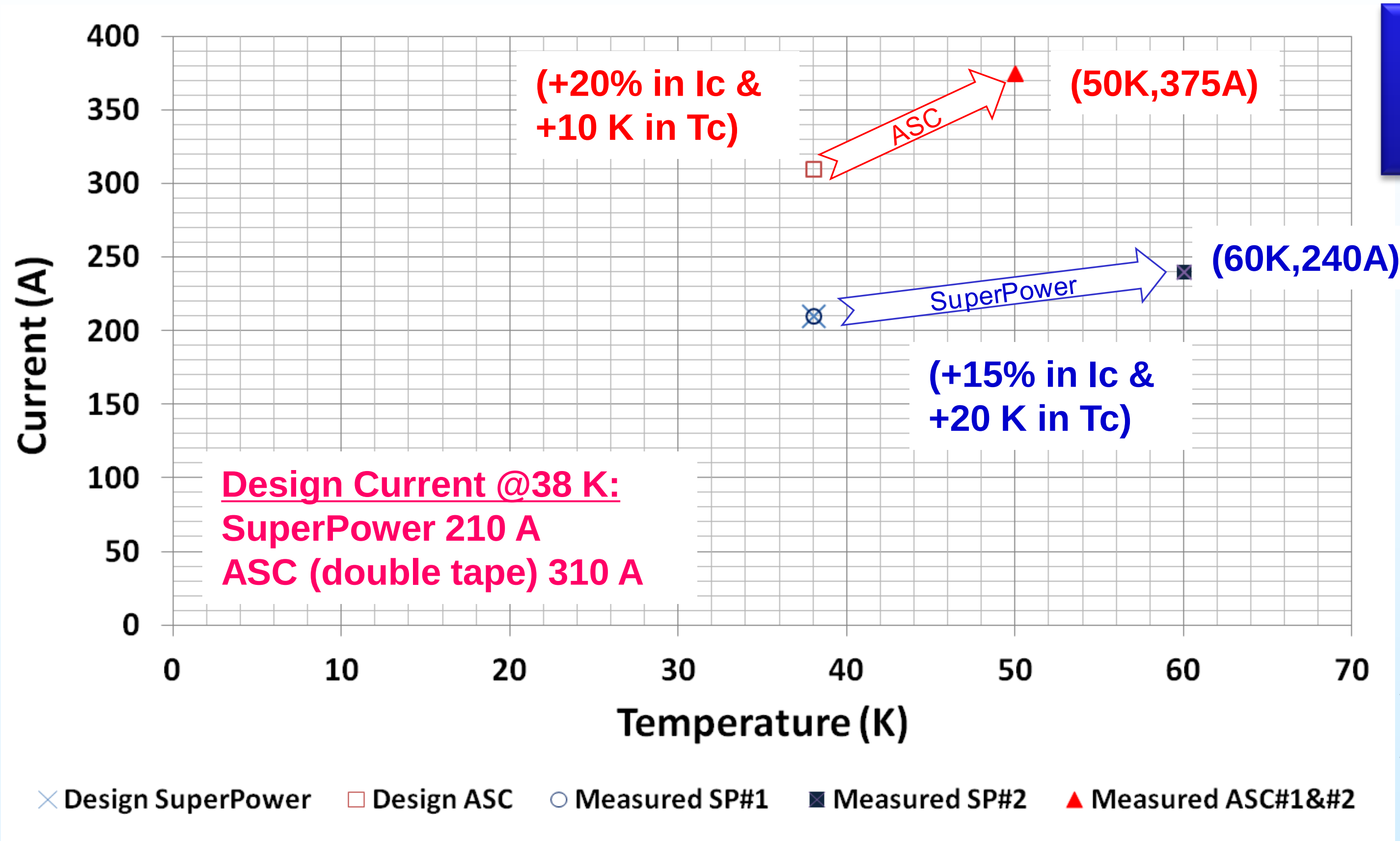
Test Environment

- Overnight cool-down of outer jacket with Nitrogen
- Direct cool-down of Magnet with Helium gas
  - Energize SuperPower and ASC coils in various configurations during this cool-down

Minimum Requirement of the Test:

- **Demonstrate that all coils can reach operating conditions (T=38 K; I_{SP} = 210 A, I_{ASC} = 310 A)**

Design and Tested Performance



Impressive Performance

Note: Above are not the limits of the coils (I_c).

These are the currents to which the coils were energized.

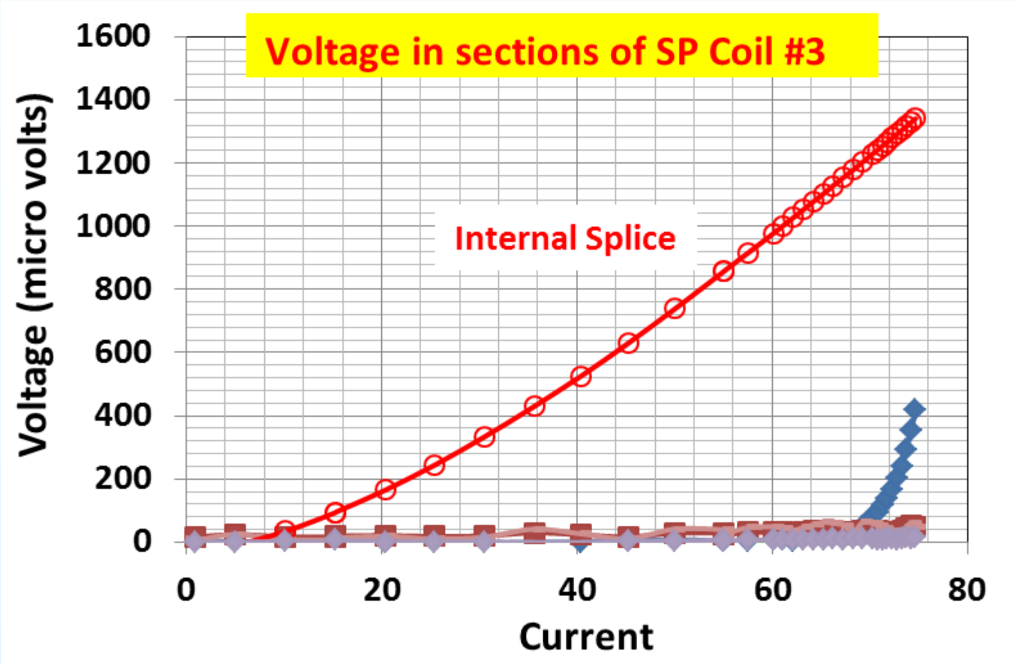
- **Coils from both vendors performed well (easily met the requirements).**
- **This is an unprecedented temperature margin (thanks to HTS).**

Consideration of Splice Resistance During the Test of a Coil

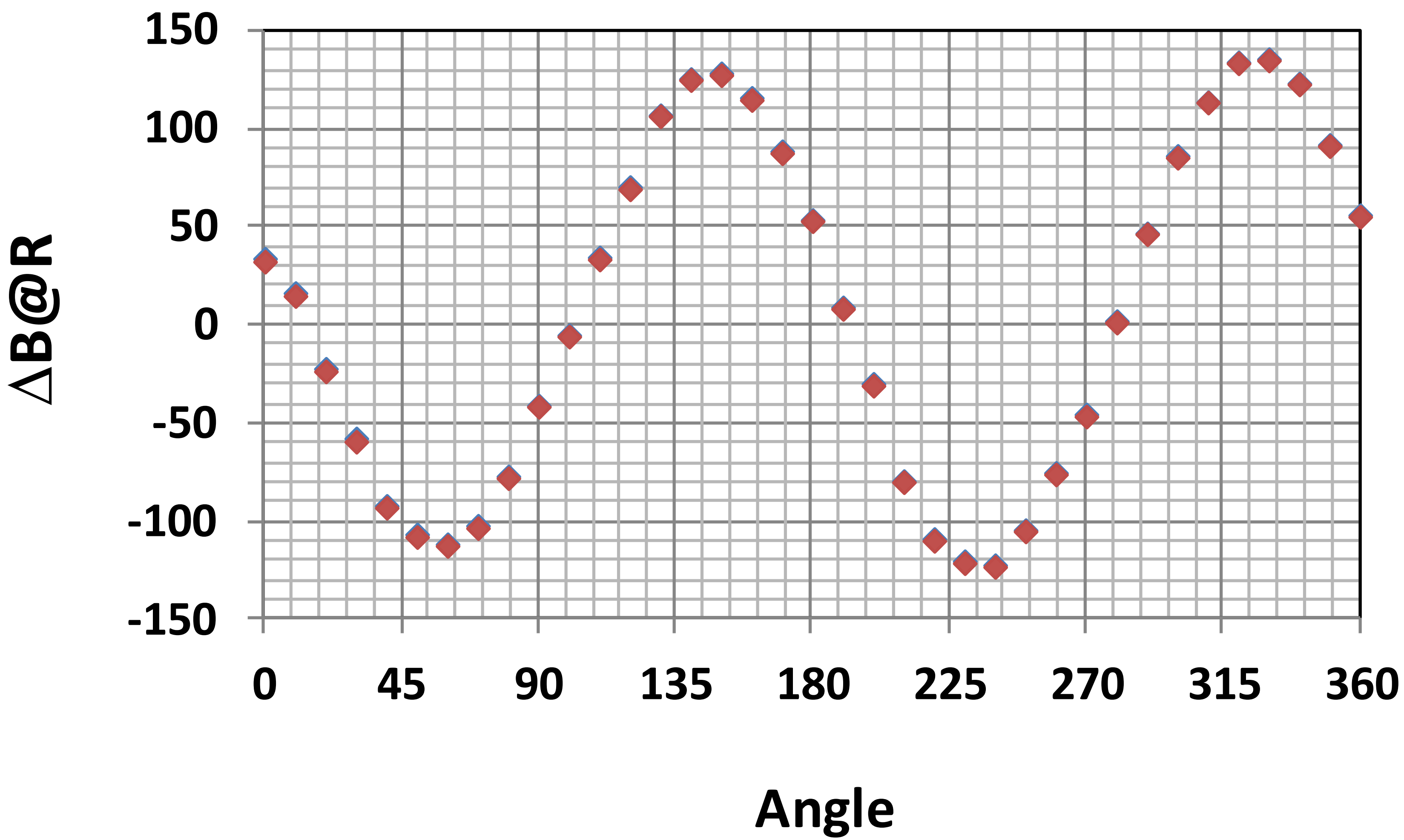
Caveat: During this test, one of the coil was not powered beyond the design current as a precaution since the system could not be tuned in time to minimize the noise.

We didn't want to take a chance in distinguishing splice voltage to the onset of resistive voltage. Since the test time during was limited due to certain practical circumstances and therefore we focused on demonstrating that the all coils meet the requirements.

As such this coil was fully tested at 77 K and performed similar to other coils.



Hall Probe Measurements



Future Work on HTS Quad (1)

- Perform test in conduction cooling mode in vertical Dewar with helium line connected to the cooling line inside the magnet structure

  i.e., HTS coils cooled by support structure which is cooled by Helium gas
- Measure critical current of each double pancake coil as a function of temperature (this is expected to be different for the SuperPower and ASC coils)

  This test can be performed since eight leads are coming out of the vertical Dewar (top-hat)
- Perform energy deposition experiments in both SuperPower and ASC coils
- Perform lifetime cycle tests where the coils are go through a large number of power cycles, thermal cycles, etc.
- Evaluate what happens in the thermal runaway (quench) situation. Verify that the quench protection system will be able to detect and protect the coils.
- Perform studies in small coils of forced quench (or thermal runaway situation). Apply these lessons learned to the full size magnet to ensure that the magnet will remain protected under all circumstances

Future Work on HTS Quad (2)

- Measure field quality in magnet with coils powered in quadrupole configuration
- Do iteration in the magnetic design (for example, end chamfering, etc. to optimize field quality); perform magnetic measurements again to obtain measured field quality in the iterated design
- At present four coils are made with HTS from SuperPower and four with HTS from ASC. The two conductors are very different in size and in performance. Consider making four new coils from the conductor which is more promising on the basis a series of test performed in this magnet.
- The test results show that we can generate significantly higher field than was the target of the current design. Perform initial design of higher performance quad (higher field gradient, larger aperture, etc.) to see if it brings significant improvement in overall machine performance
- Complete detailed engineering design for remote handling (if not completed already) and make whatever modifications needed in the magnet structure
- Modify and/or construct leads as per the requirements of FRIB

Other HTS Magnet Activities at BNL

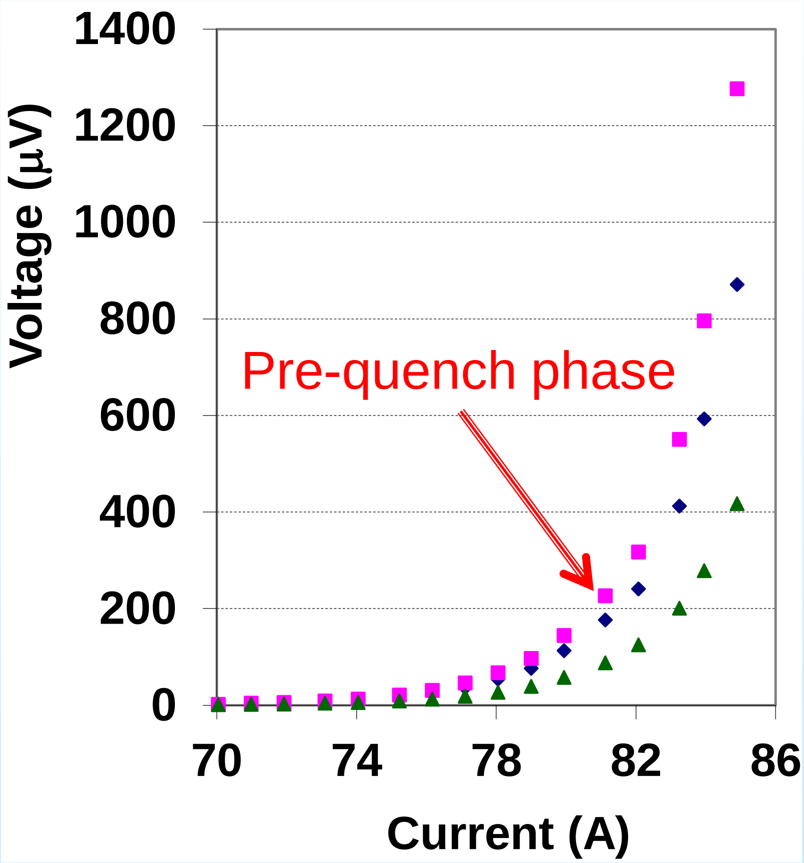
Quench Protection (avoid runaway situation)

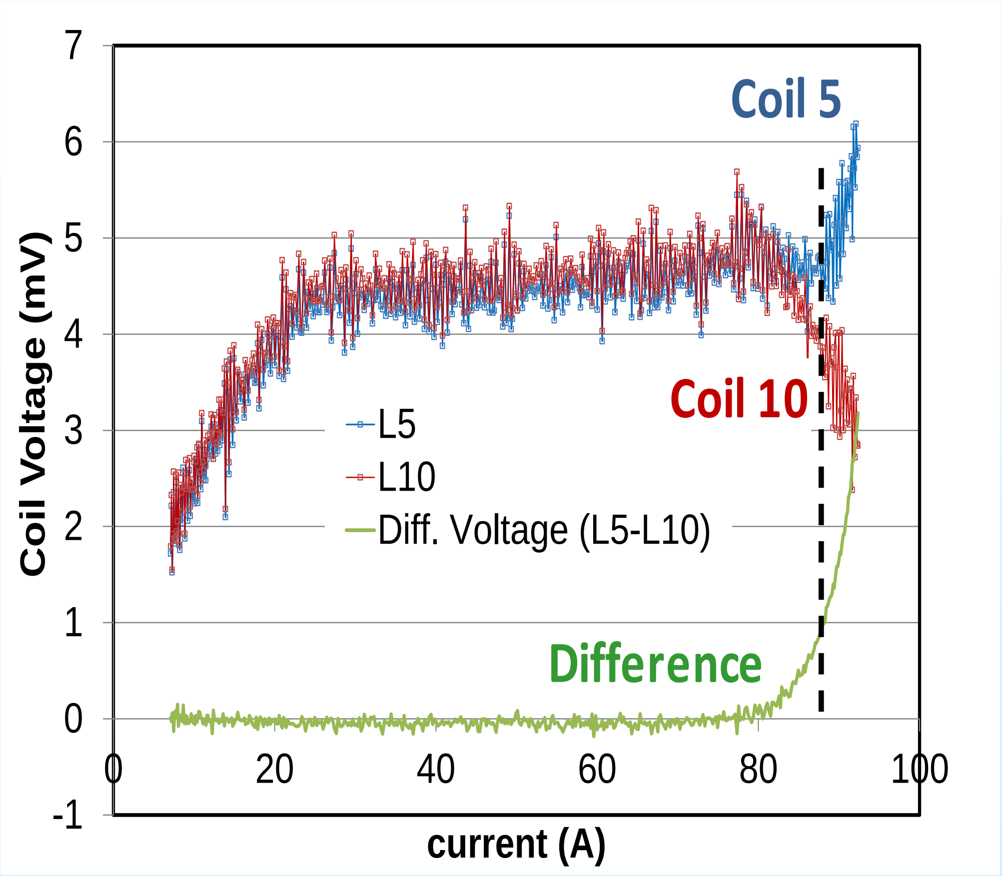
Quench protection of high field HTS magnets is a major challenge!

- **We take a multi-prong approach to overcome this challenge:**
  - **Advanced quench detection system to detect onset of "pre-quench" phase and start action while it is still safe to operate for some time**
  - **Special electronics to tolerate high isolation voltage (> 1 kV) to allow fast energy extraction once the pre-quench phase is detected**
  - **Inductively coupled copper discs to reduce current instantaneously**
  - **Spread heating across the coil faster because of SS tape insulation**
  - **Also possible: quench heaters as used in LTS magnets (NHMFL)**

Advanced Quench Detection System

Advanced quench detection system detects onset of small "pre-quench" voltage (<1 μV/cm) in the presence of large noise and inductive voltage





Detection at ~100 μV level (1 μV/cm in 100 m => 10 mV)

Detection while ramp rate is changing

Advanced Quench Detection System with Fast Energy Extraction

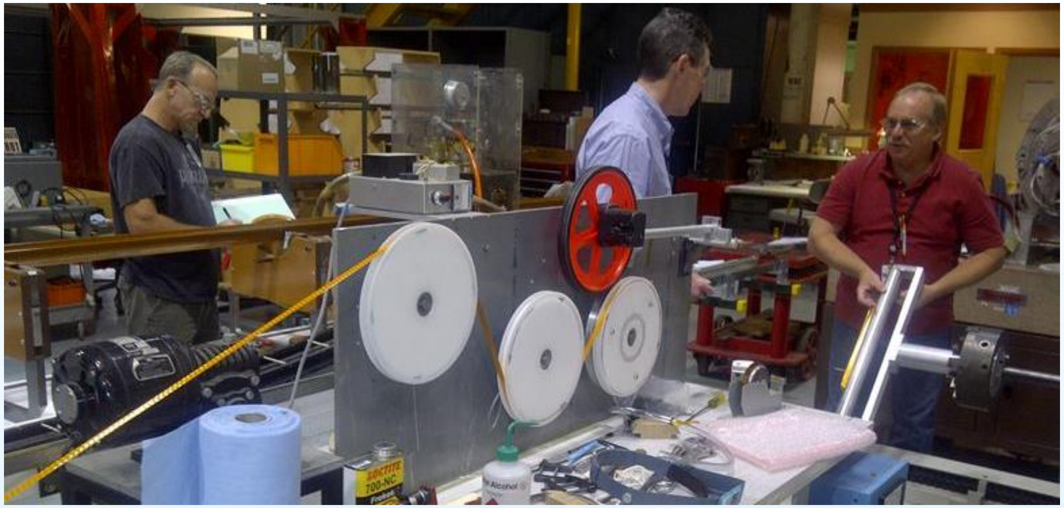
- Fast energy extraction in larger magnets creates high voltages as "L" increases
- Develop electronics that can tolerate high isolation voltage (>1 kV)
- Divide coils in several sections

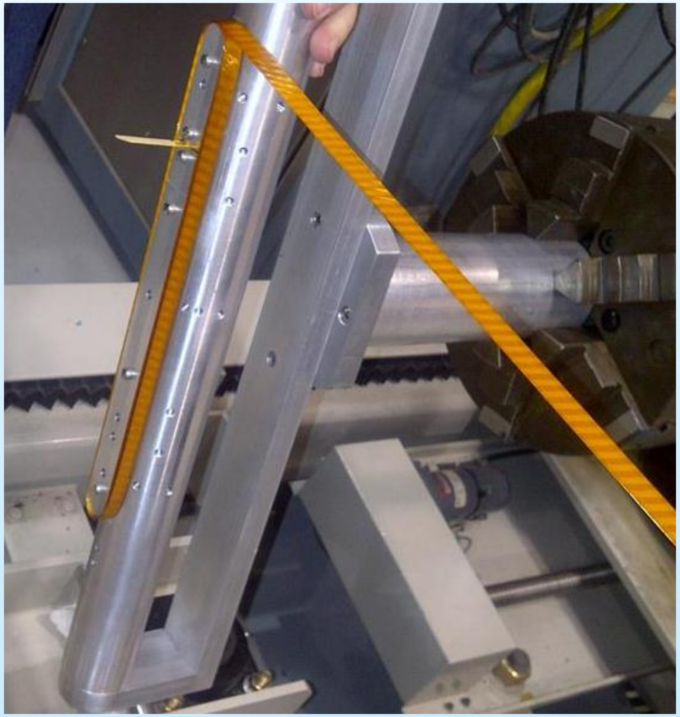
Cabinet #1 (32 channels, 1kV)


Cabinet #2 (32 channels, 1kV) (expandable to 64 and 3kV)

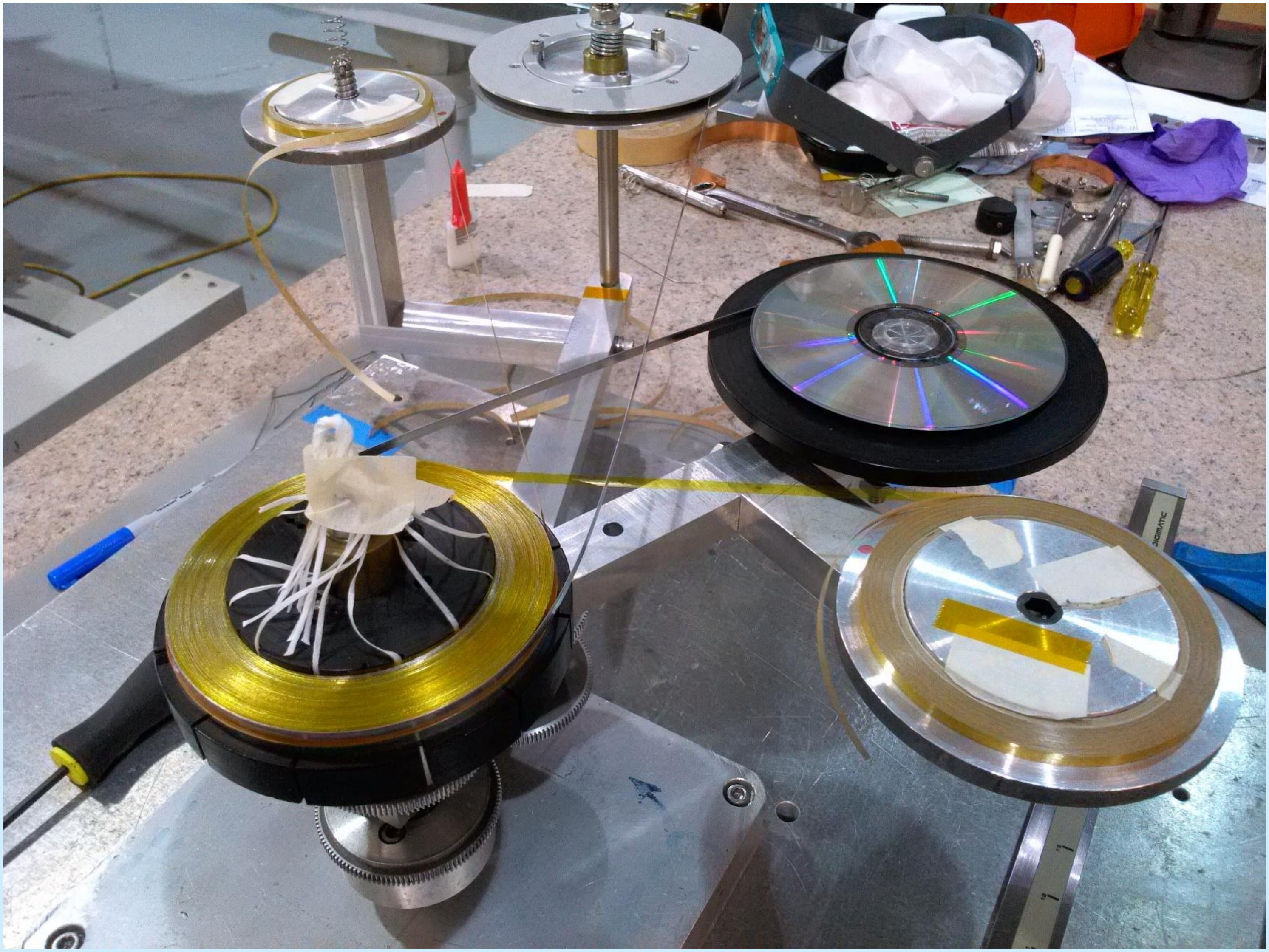

Winding of Cos (θ) Coil Block at BNL

- Kapton-Ci insulation on 2G Tape
- 77 K Test showed coils worked well (no degradation in ends)
- **For FRIB correctors**, modify techniques to replace Kapton

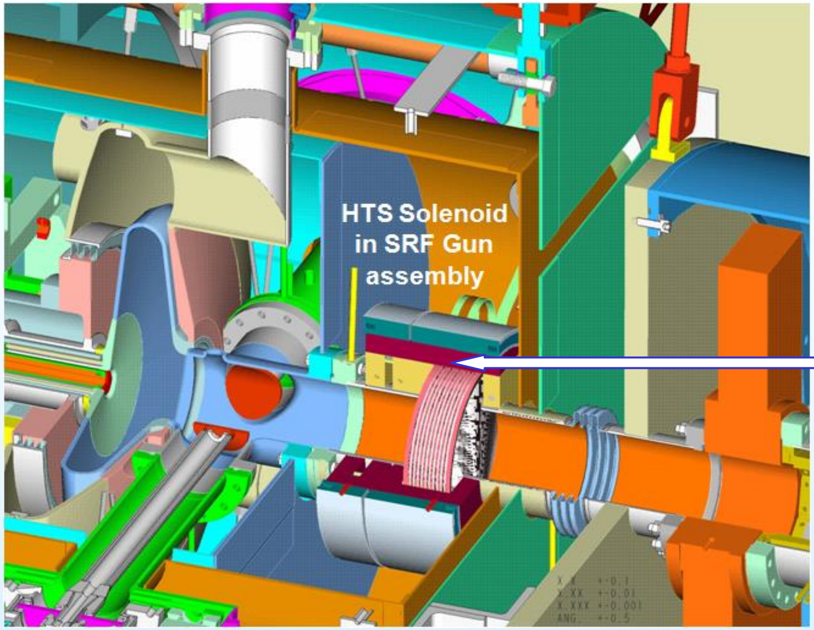


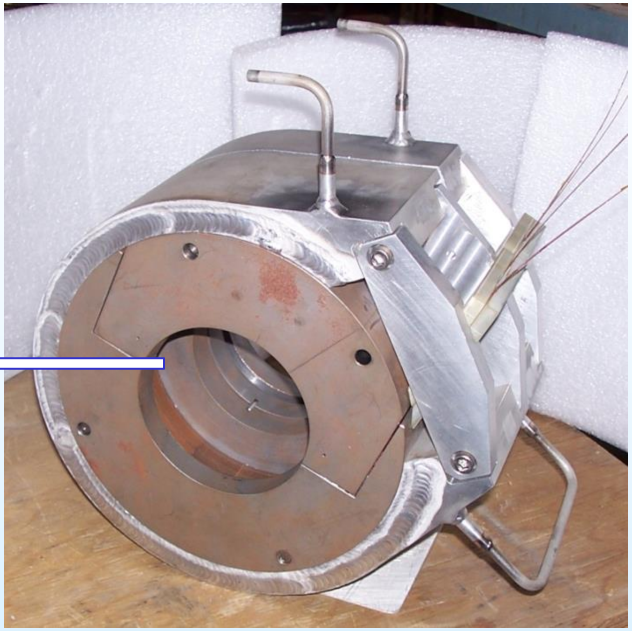


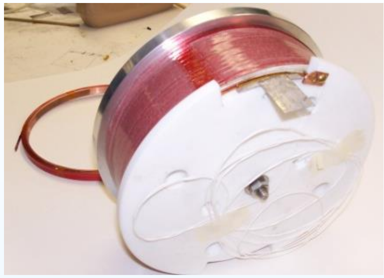
Double Pancake Coil For Light Source at BNL

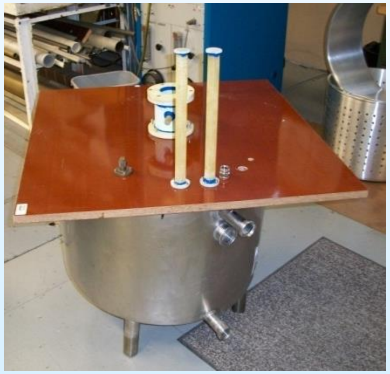


Low Magnetic Field Application
HTS Solenoid with Superconducting Cavity for the Energy Recovery Linac (ERL) at BNL









HTS solenoid is placed in cold to warm transition region after the superconducting cavity where neither LTS or copper solenoid would work

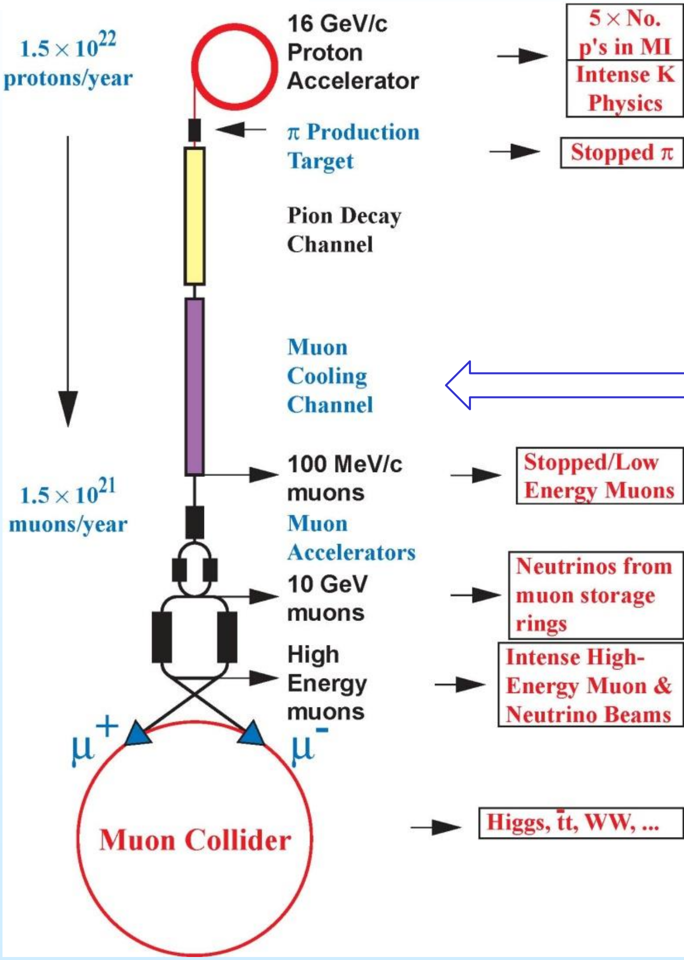
Early focusing provides a unique and better technical solution

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

High Field Solenoids for the Proposed Muon Collider

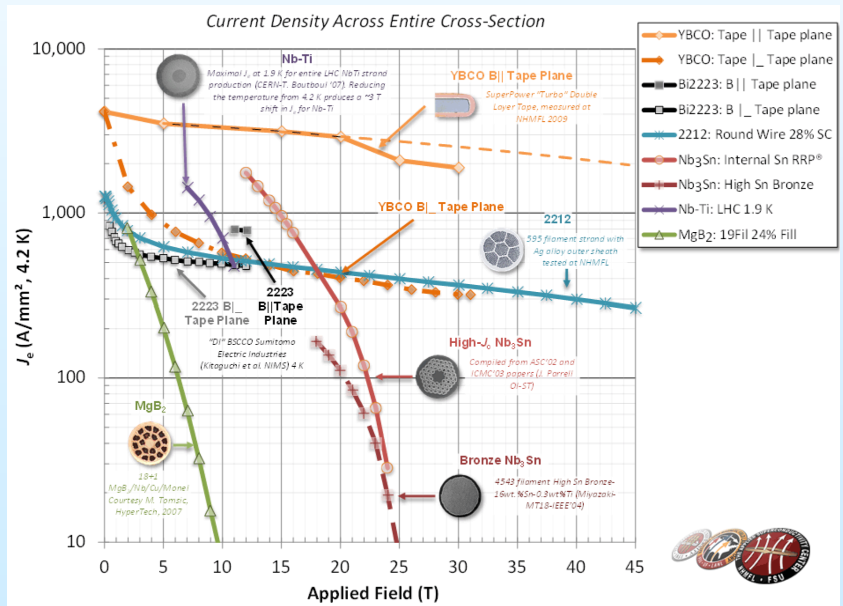
Courtesy: Bob Palmer



One key challenge:

Very High field solenoids (30-50 T)

- Resistive magnets would consume enormous power (**hundreds of MW**)
- **HTS (4K) offers a superconducting solution**



Courtesy: P. Lee, NHMFL

Other Applications of High Fields: NMR, SMES, User Facilities

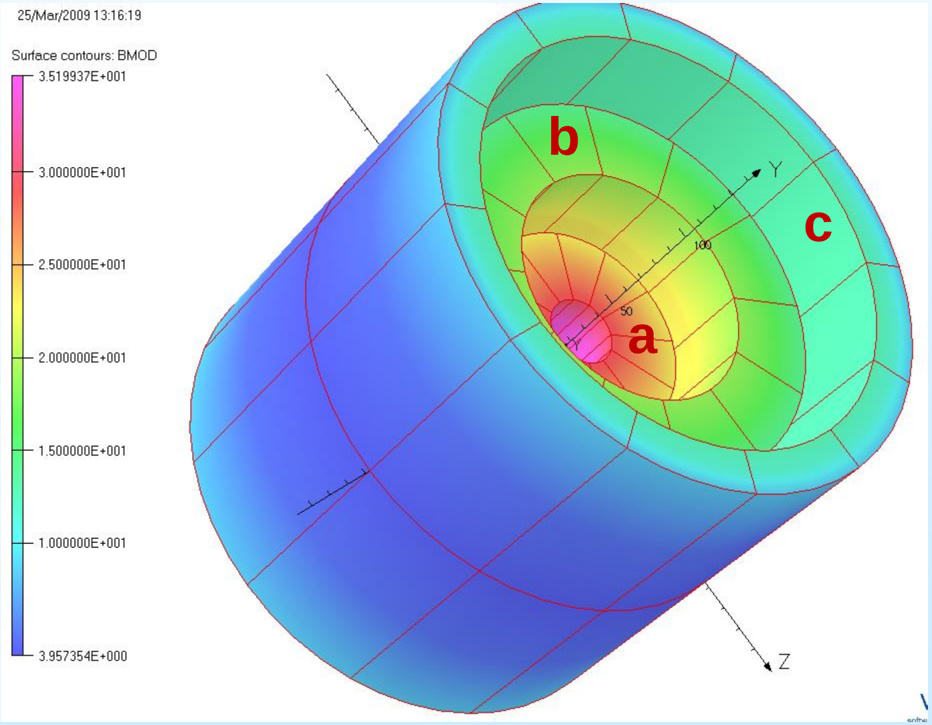
Chosen Path to a 30⁺ T Solenoid

Several significant coils (build and test in their own structure):

a) >12 T HTS solenoid (insert): 25 mm, 14 pancakes, 4 mm tape

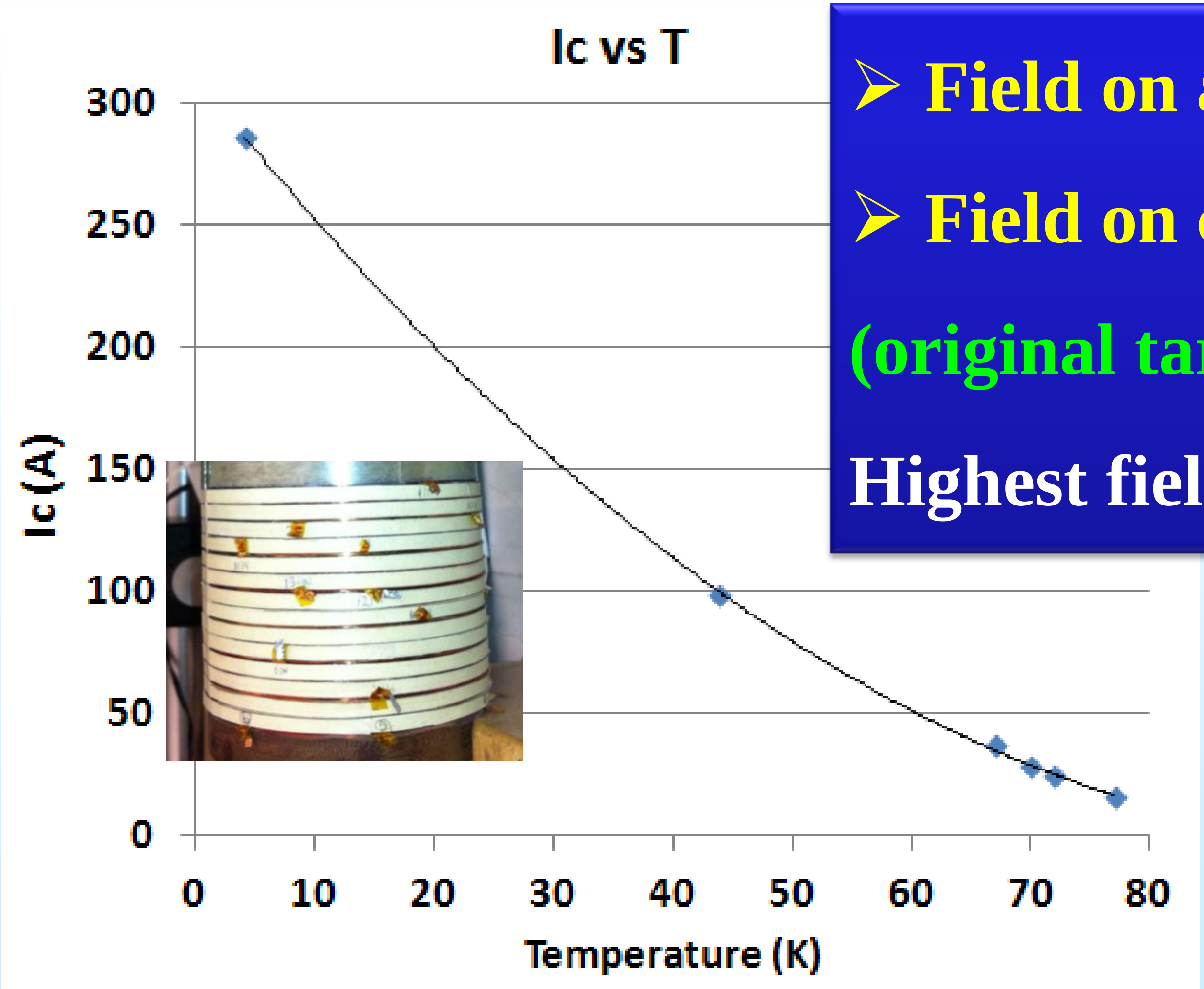
b) >10 T HTS (midsert): 100 mm, 24 pancakes, 4 mm tape

c) >10 T LTS (outsert): NbTi and/or Nb_3Sn, cable (design phase)



- Work initially started with a series of Small Business Innovation Research (SBIR)
- Currently supported by Muon Accelerator Program (MAP)

High Field (16T) Demo of HTS Magnet



- **Field on axis: 15.7 T**
- **Field on coil : 16.2 T**

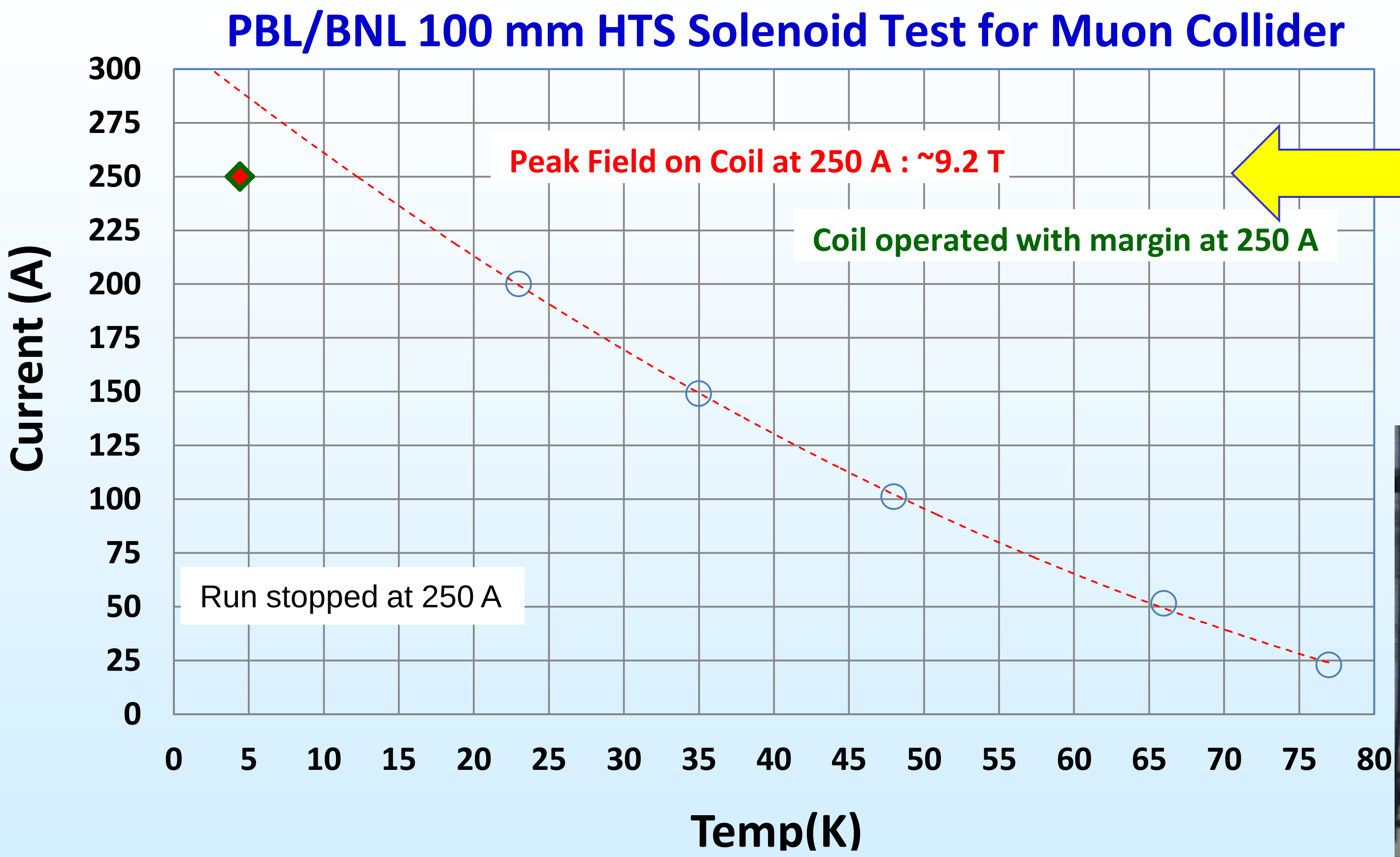
(original target: 10-12T)

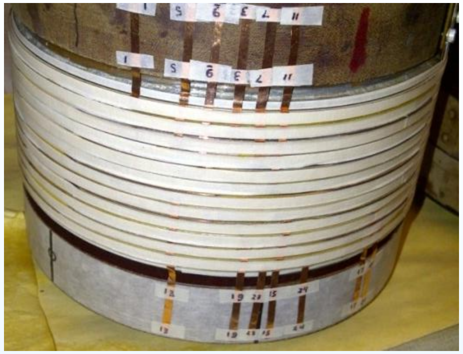
Highest field all HTS solenoid

Overall J_o in coil: >500 A/mm^2 @16 T

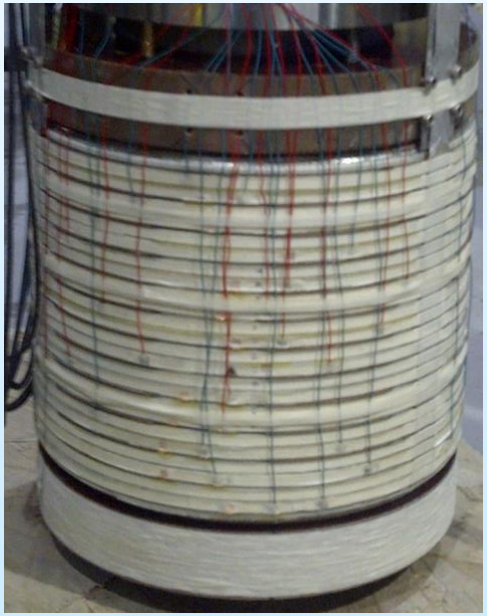
Insert solenoid: 14 pancakes, 25 mm aperture

Large Aperture High Field HTS Magnet





Half midsert (12 pancakes)



Full midsert (24 pancakes)

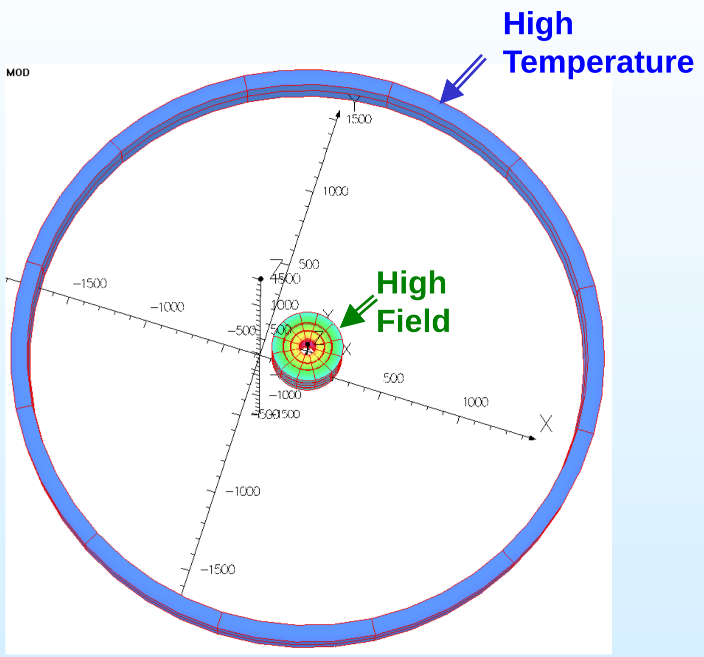
- **Half midsert operated at 250 A @4 K (6.4 T field on axis, 9.2 T peak field on coil**
- **Design value for full midsert: 220 A for 10 T**

HTS Superconducting Magnetic Energy Storage

- ARPA-E invited proposals on energy storage system under stimulus package
- It required demonstration of certain parameters within the funding limitations

Two options examined for HTS:

1. **High Temperature (>55 K) Option:**
   Saves on cryogenics (Field ~2.5 T)
2. **High Field (>20 T) Option:**
   Saves on Conductor (Temp. ~4 K)



Our analysis of HTS option:

Conductor cost dominates the cryogenic cost by an order of magnitude (both in demo device and in large application

Our proposal:

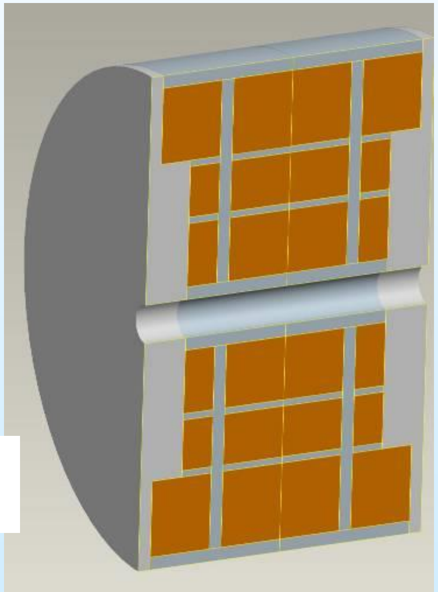
- ➢ **Aggressive design to reduce the amount of conductor needed**
- ➢ **Ultra high fields (24 – 30 T): Energy α B^2 ; B α conductor amount**
- ➢ **For HTS, ultra high field reduces the system size and *cost***

Superconducting Magnetic Energy Storage (SMES)

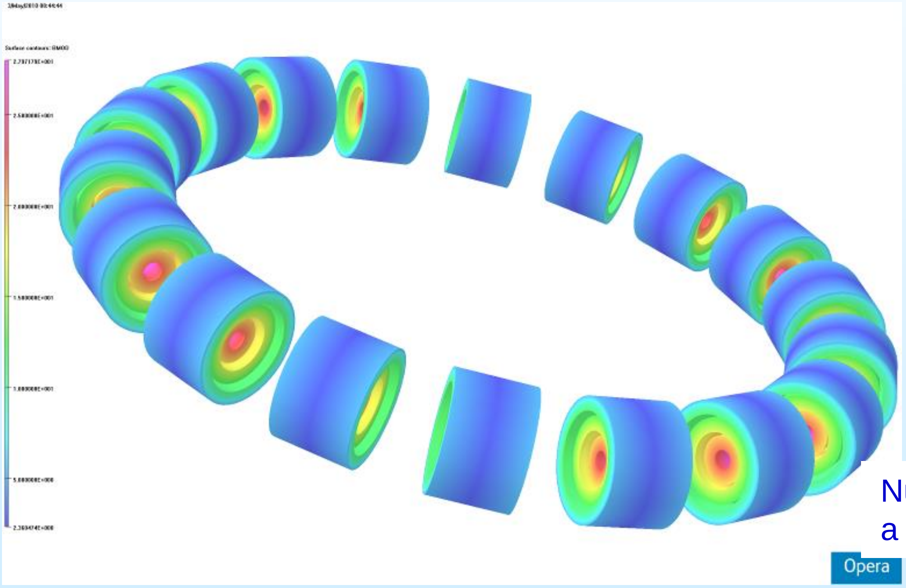
High field, large aperture, HTS solenoid is a highly ambitious goal:

arpa-e specifically asked for "high risk high reward" proposals!

Participants: ABB, USA (Lead), SuperPower (Schenectady and Houston), and BNL (Material Science and Magnet Division)



Basic structure of a single Unit



Number of units in a SMES system

Key Parameters: ~24 T, 100 mm, 2.5 MJ, 12 mm YBCO

Impact of Irradiation on 2G HTS

• The maximum radiation dose was 3.4 X 10^{17} protons/sec (100 μA.hr) with an energy of 142 MeV. Displacement per atom (dpa) per proton is ~9.6 X 10^{-20}. (Al Zeller)

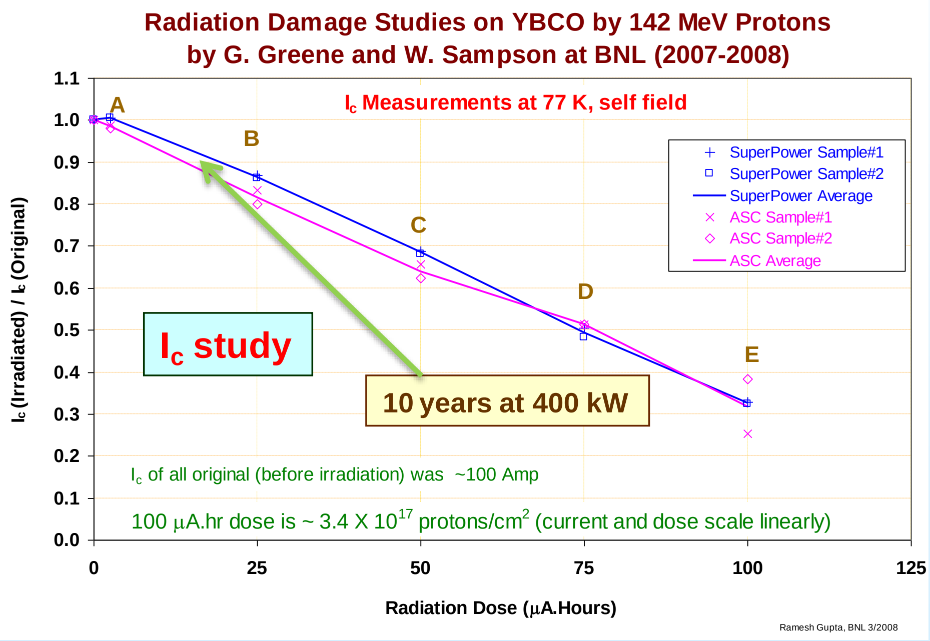
• **This gives ~0.033 dpa at 100 μA.hr for the maximum dose.**

Based on 77 K self field studies:

• **Reduction in I_c performance of YBCO (from both vendors) is <10% after 10 years of FRIB operation (as per Al Zeller, MSU).**

• **This is pretty acceptable.**

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

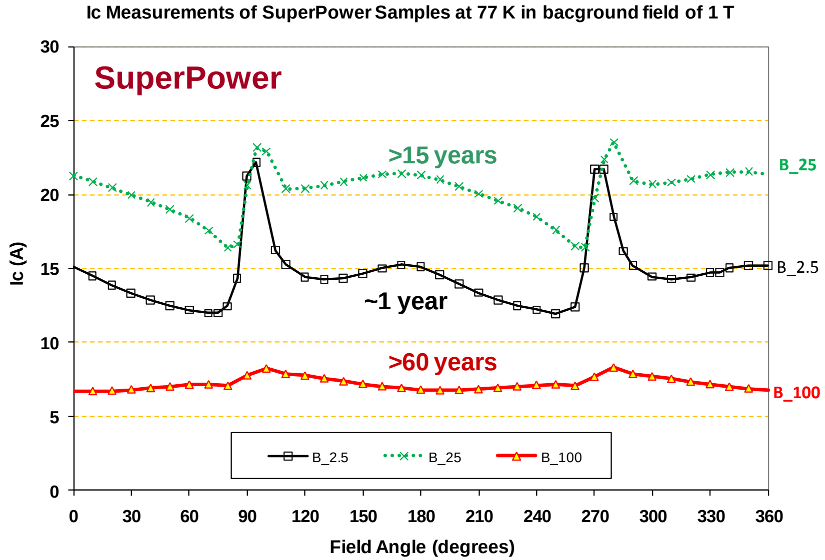


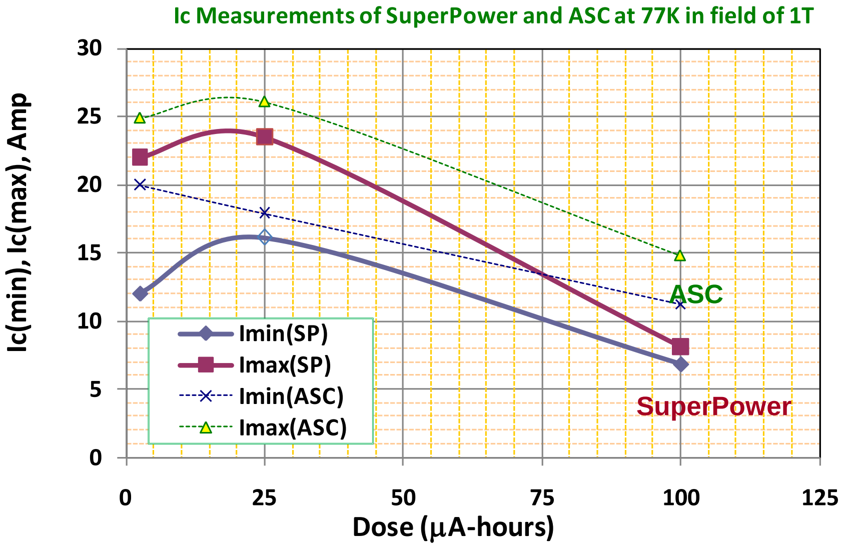
It appears that YBCO is at least as much radiation tolerant as Nb_3Sn is (Al Zeller, MSU).

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

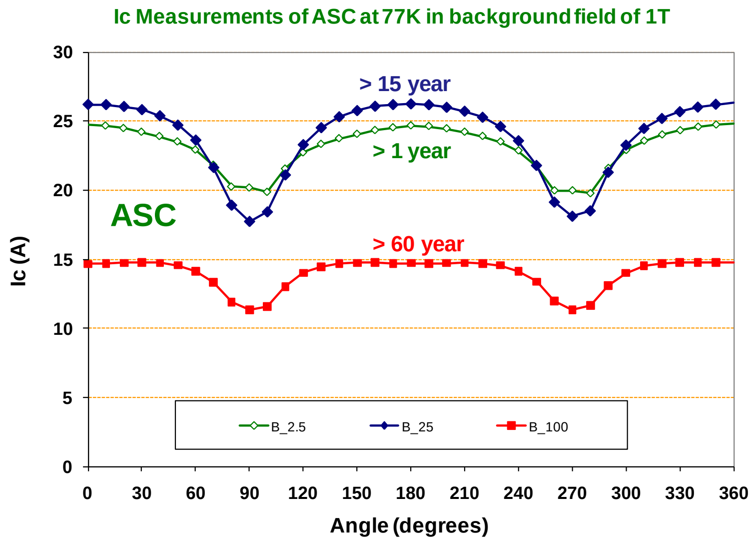
Superconducting Magnet Division

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

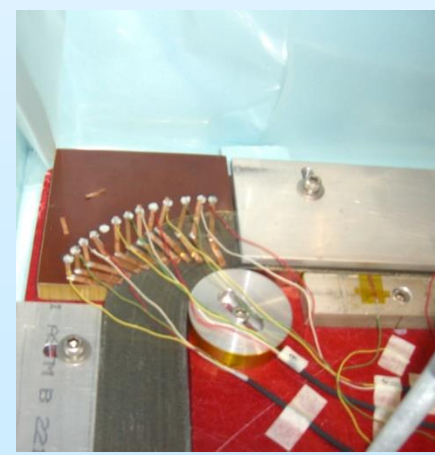
- HTS offers a unique magnet solution for challenging fragment separator environment of FRIB.
- In addition to fragment separator, HTS magnets could be beneficial in several other regions.
- R&D for FRIB has demonstrated that HTS magnets can be successfully built using a large amount of HTS.
- Test results of both first generation and second generation HTS quads for FRIB have been impressive.
- 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 could be the 1st major accelerator with HTS magnets playing a crucial role.

Backup Slides

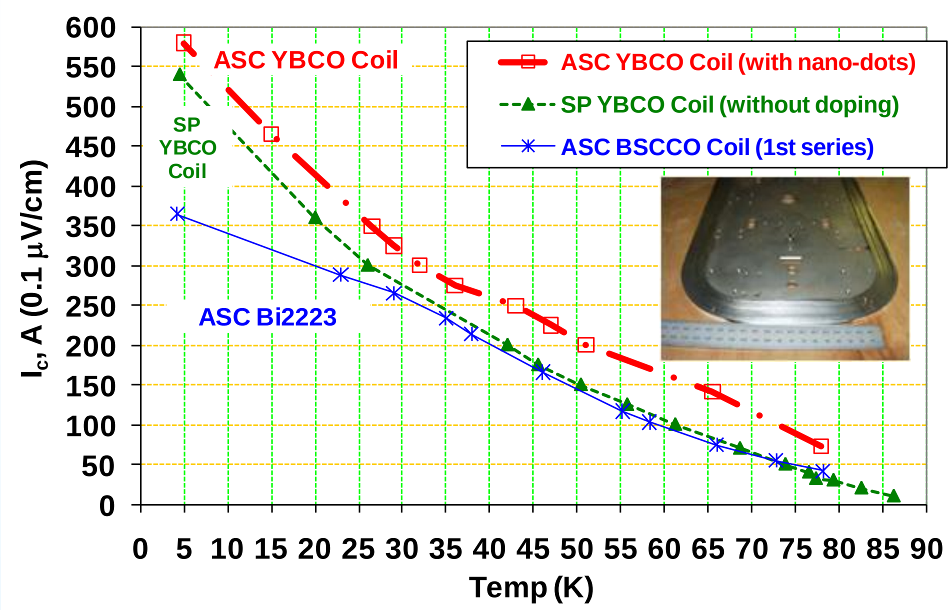
Quench Protection in FRIB HTS Quad

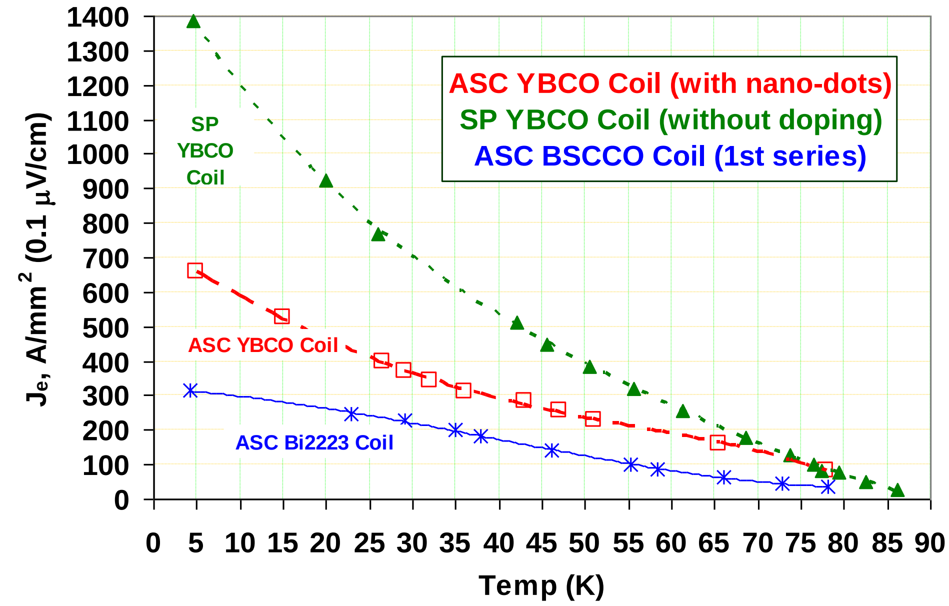
- Quench protection of HTS coils (particularly at 4 K where current densities are high) is considered a major challenge in light of low quench velocities
- To overcome these challenge, an advanced quench protection system with fast electronics and low noise has been developed.
- Modern data acquisition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



Quench Protection Studies in FRIB 2G HTS Coils





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

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

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

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

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

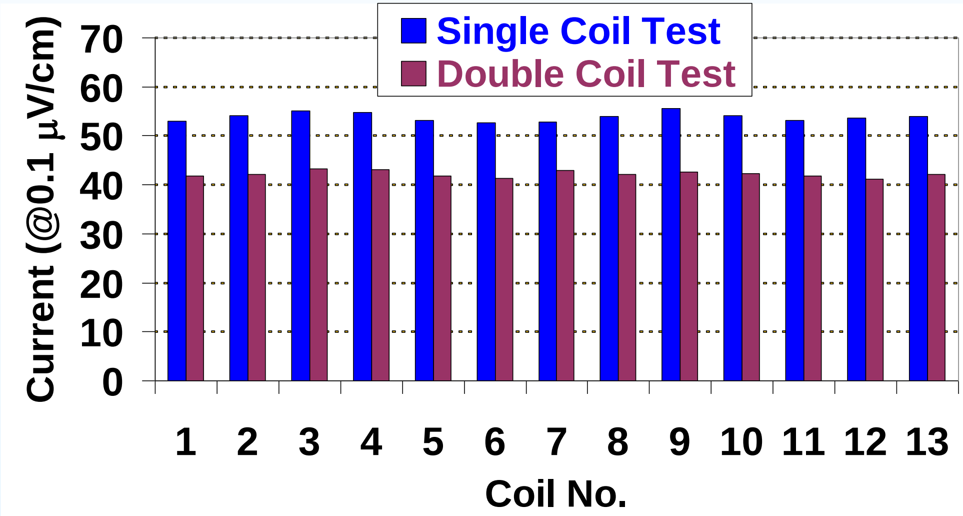
Parameter List of the Second Generation Design

Parameter	Value
Pole Radius	110 mm
Design Gradient	15 T/m
Magnetic Length	600 mm
Coil Overall Length	680 mm
Yoke Length	~550 mm
Yoke Outer Diameter	720 mm
Overall Magnet Length(incl. cryo)	~880 mm
Number of Layers	2 per coil
Coil Width (for each layer)	12.5 mm
Coil Height (small, large)	26 mm, 39 mm
Number of Turns (nominal)	110, 165
Conductor (2G) width, SuperPower	12.1 mm ± 0.1 mm
Conductor thickness, SuperPower	0.1 mm ± 0.015 mm
Cu stabilizer thickness SuperPower	~0.04 mm
Conductor (2G) width, ASC	12.1 mm ± 0.2 mm
Conductor (2G) thickness, ASC	0.28 mm ± 0.02 mm
Cu stabilizer thickness ASC	~0.1 mm
Stainless Steel Insulation Size	12.4 mm X 0.025 mm
Field parallel @design (maximum)	~1.9 T
Field perpendicular @design (max)	~1.6 T
Minimum I_c @2T, 40 K (spec)	400 A (in any direction)
Minimum I_c @2T, 50 K (expected)	280 A (in any direction)
Nominal Operating Current	~280 A
Stored Energy	37 kJ
Inductance	~1 Henry
Operating Temperature	50 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

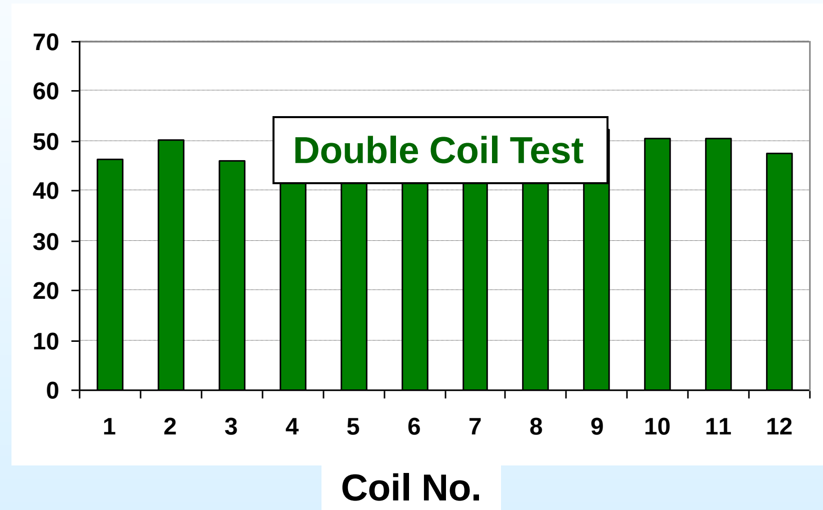
LN_2 (77 K) Test of Coils Made with ASC 1st Generation HTS

Each single coil uses ~200 meter of tape

13 Coils made HTS tape in year #1



12 coils with HTS tape in year #2



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

It shows that the HTS coil technology has matured !

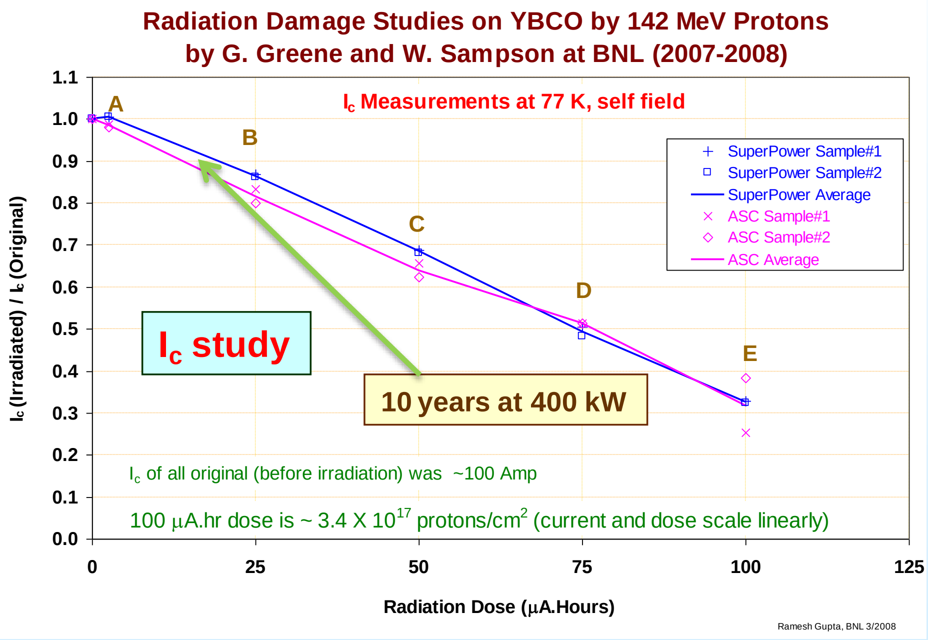
Impact of Irradiation on 2G HTS

• The maximum radiation dose was 3.4 X 10^{17} protons/sec (100 μA.hr) with an energy of 142 MeV. Displacement per atom (dpa) per proton is ~9.6 X 10^{-20}. (Al Zeller)

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

Based on 77 K self field studies:

- **Reduction in I_c performance of YBCO (from both vendors) is <10% after 10 years of FRIB operation (as per Al Zeller, MSU).**
- **This is pretty acceptable.**
- **Drop in I_c at maximum dose (of theoretical interest) is ~70%.**



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

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

Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

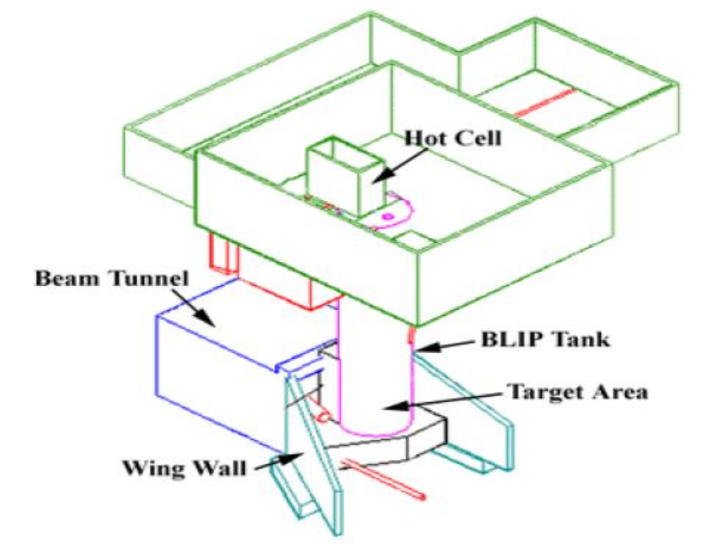
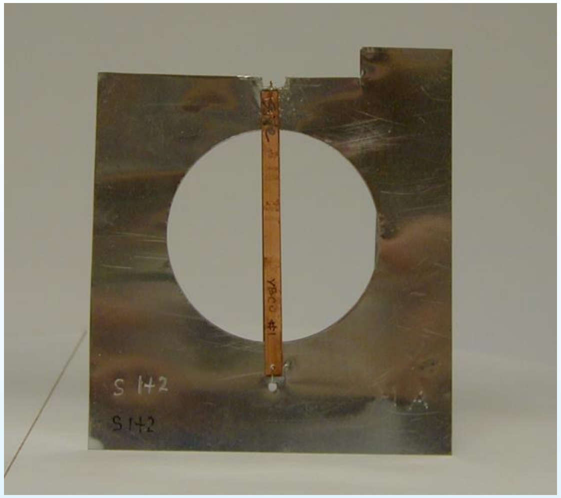


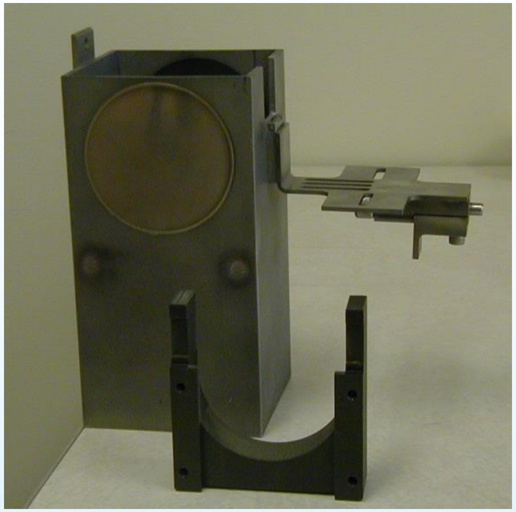
Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

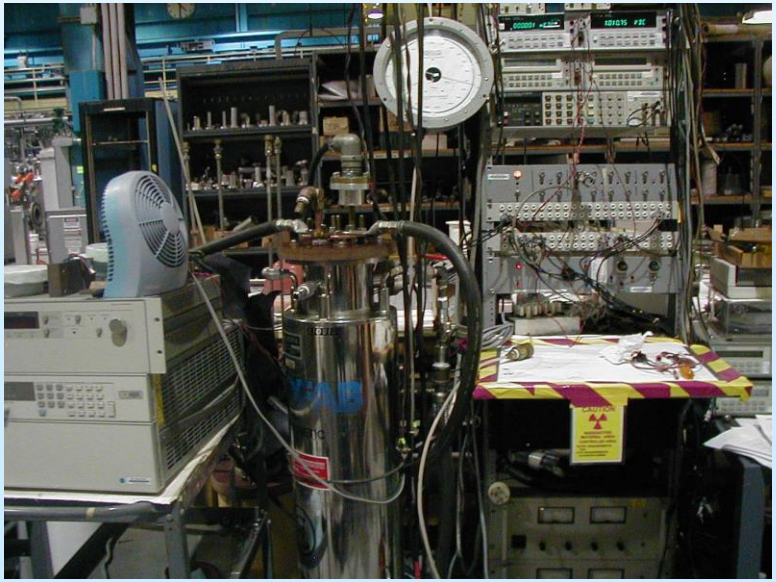
The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 μA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

Key Steps in Radiation Damage Experiment

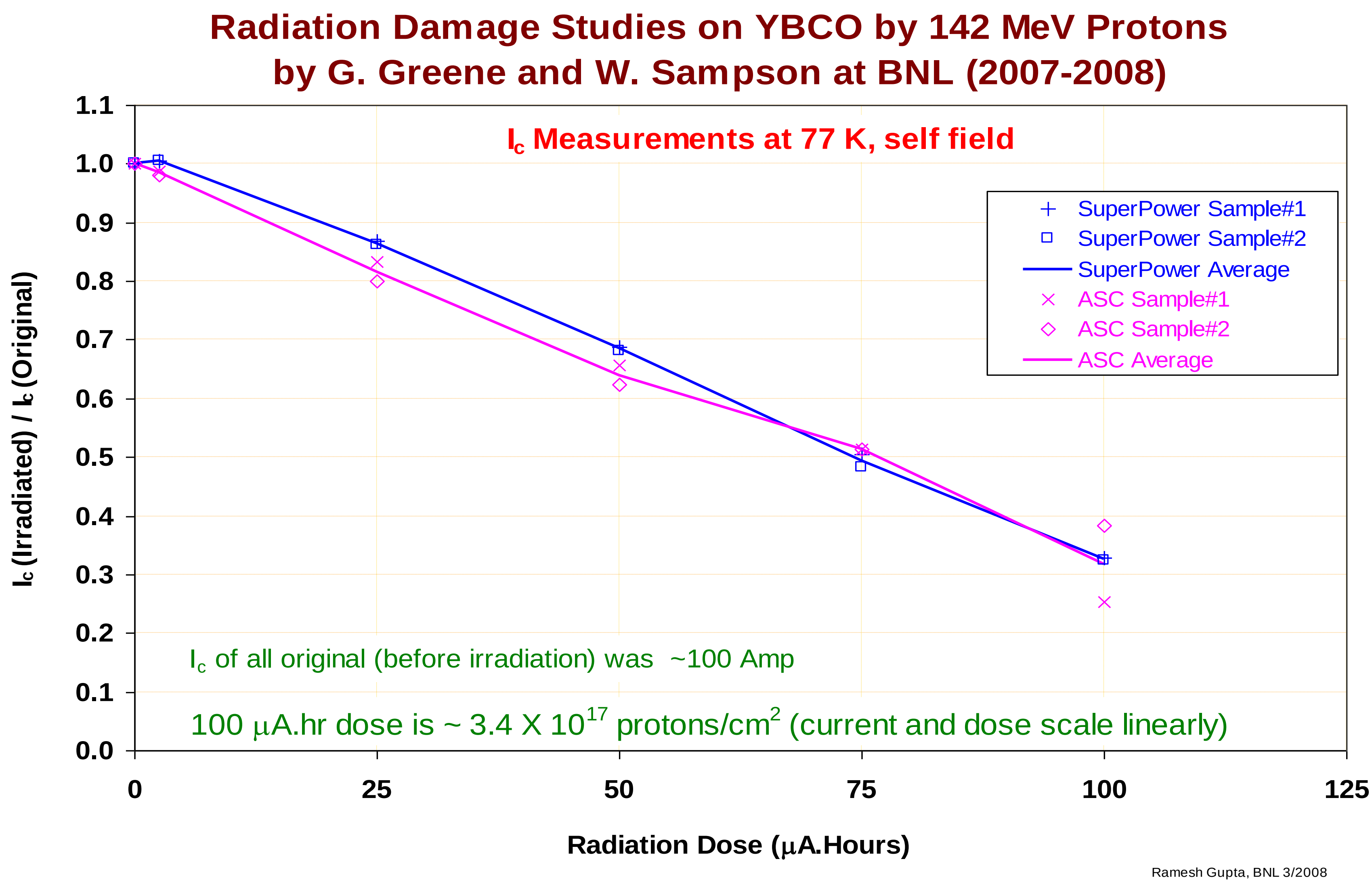




142 MeV,
100 μA protons

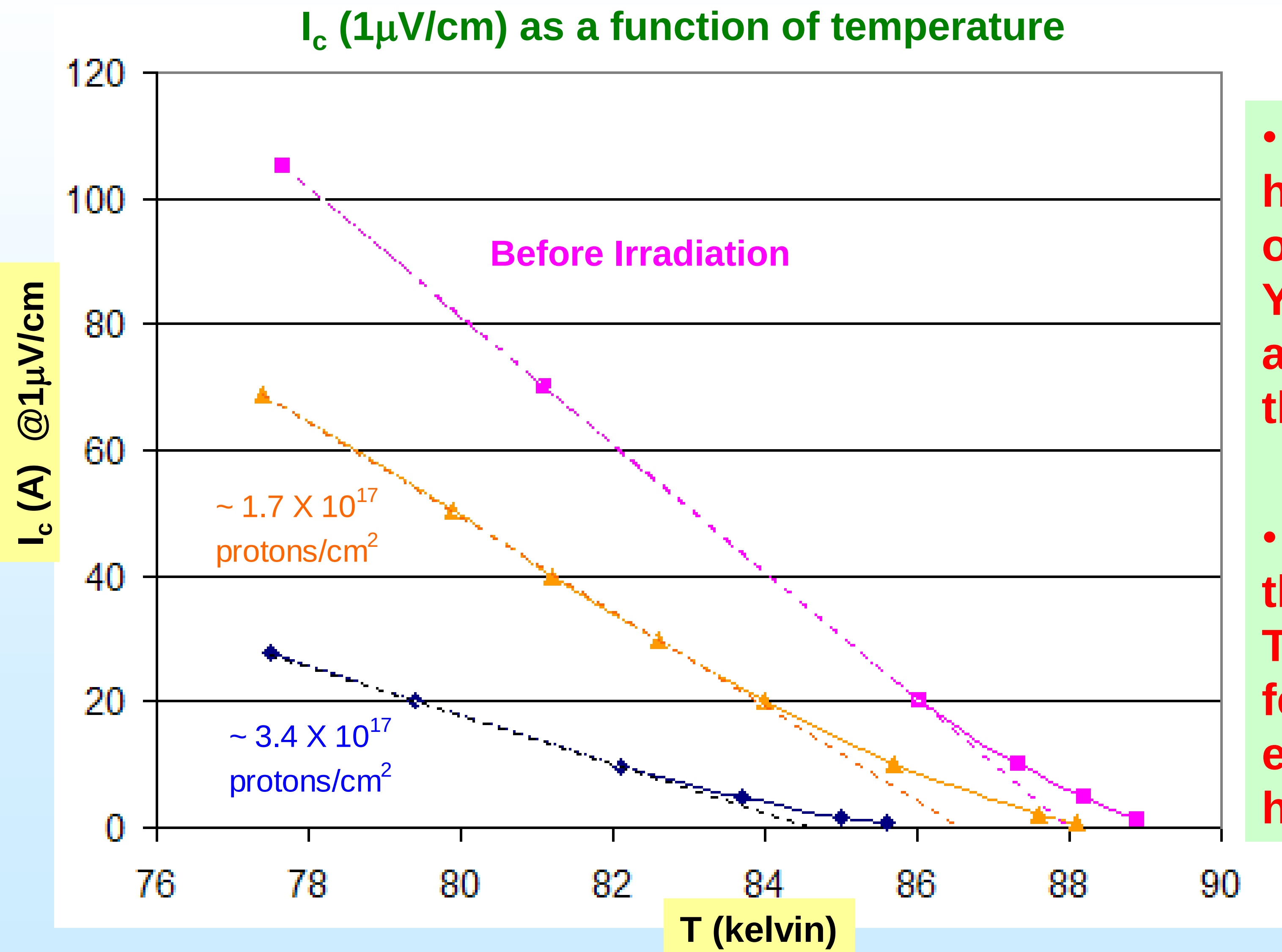


Relative Change in Ic due to Irradiation of SuperPower and ASC Samples



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

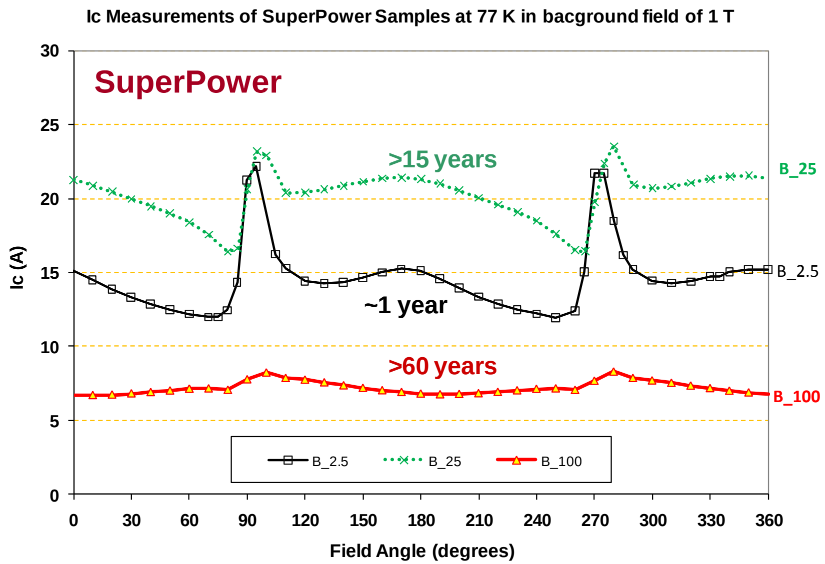
Change in Critical Temperature (T_c) of YBCO Due to Large Irradiation

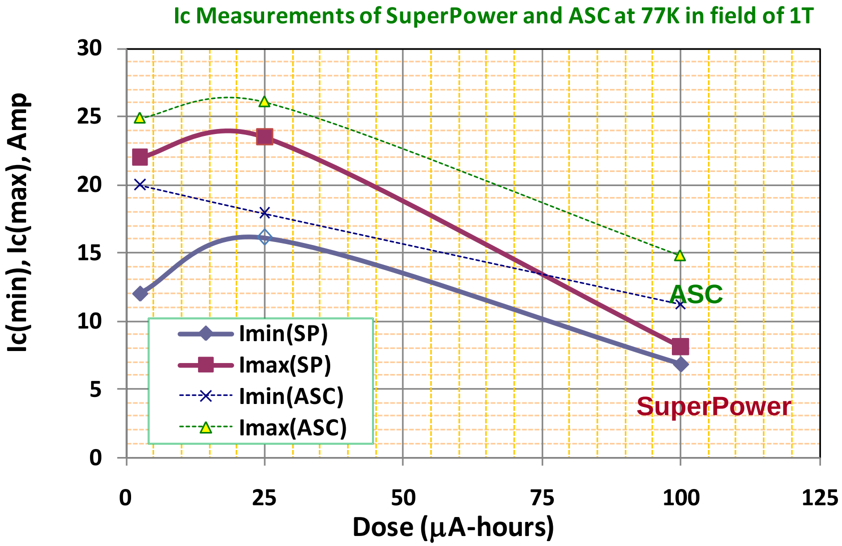


- Radiation has an impact on the T_c of YBCO, in addition to that on the I_c.
- However, the change in Tc is only a few degrees, even at very high doses.

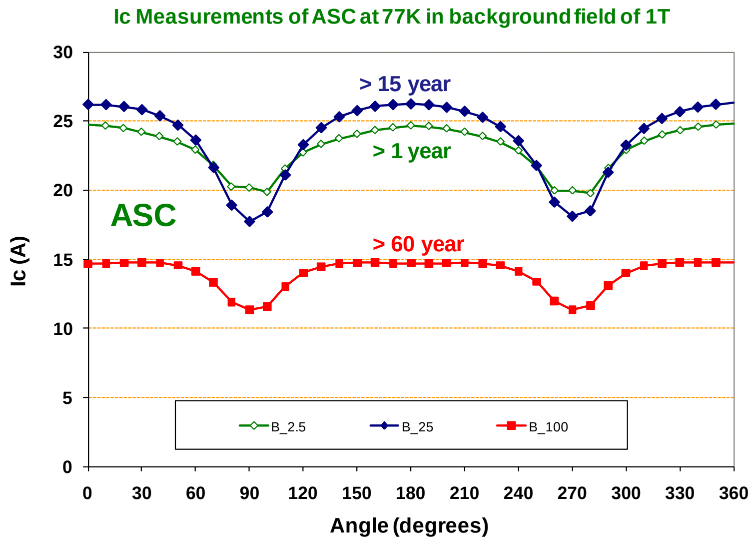
Radiation Damage from 142 MeV protons in SP & ASC Samples (measurements at @77K in 1 T Applied Field)

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division





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



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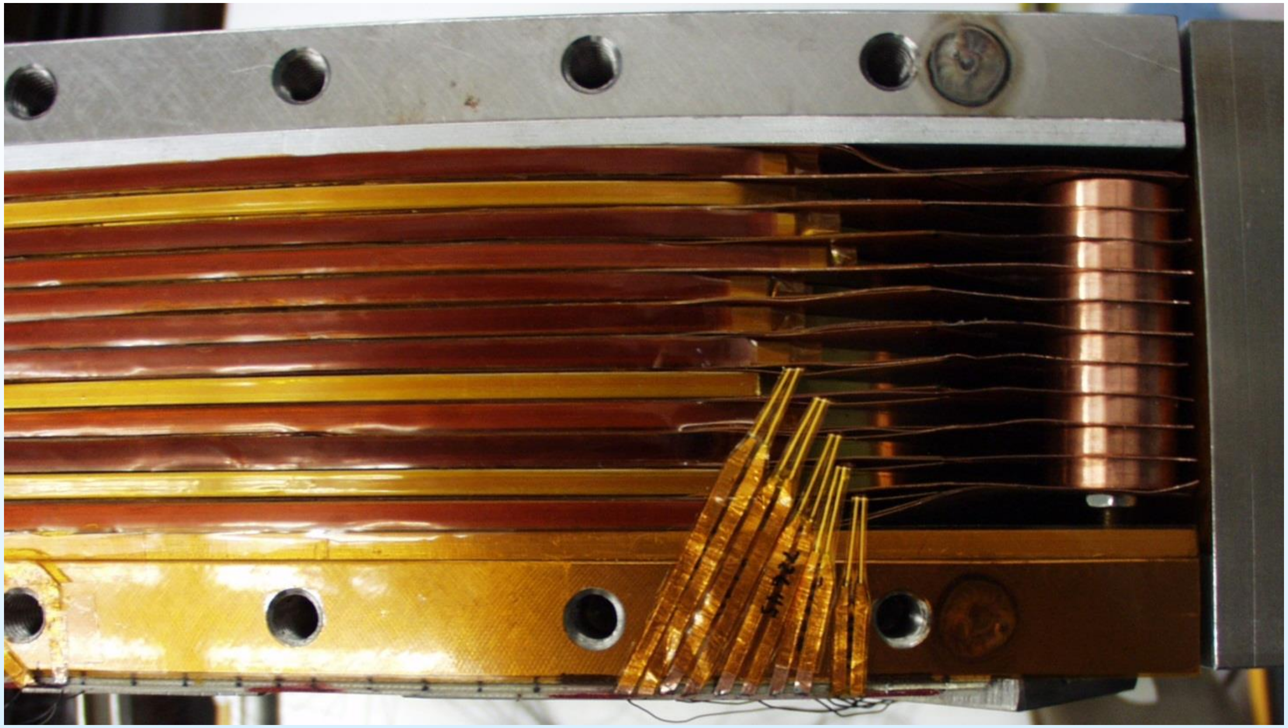
- HTS from both vendors, however, show enhancement to limited damage during the first 10 years of FRIB operation (good news)!!!

Energy Deposition Experiments

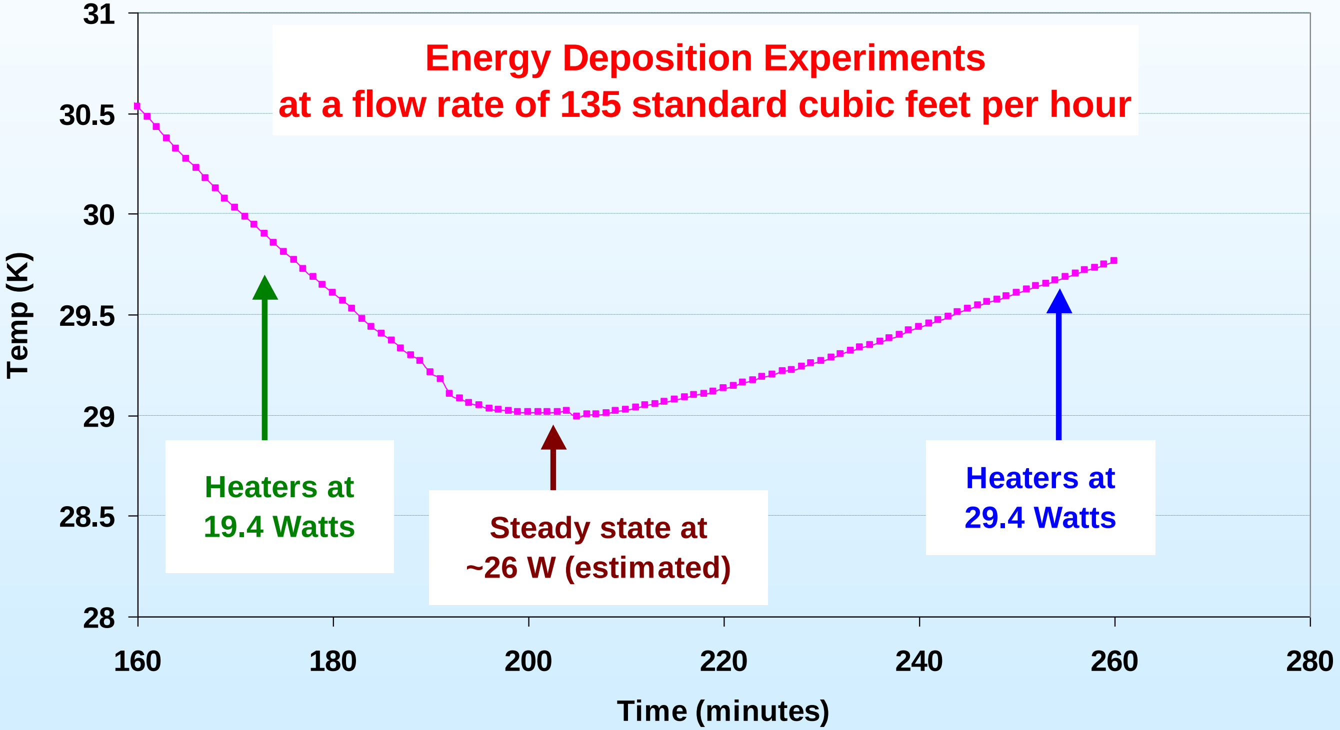


Stainless steel tape heaters for energy deposition experiments

- Energy deposition experiments were carried out at different operating temperature.
- The amount of energy deposited on the HTS coils is controlled by the current in heaters placed between the two coils.

Energy Deposition Experiment During Cool-down at a Constant Helium Flow-rate

Heaters between HTS coils were turned on while the magnet was cooling with a constant helium flow rate of 135 standard cubic feet (SCF)



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

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