HTS Magnet Program at BNL

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Outline

- **Magnet R&D at BNL using Bi2212, Bi2223, YBCO and MgB_2**
  - ❑ High field @ low temperature : Muon collider solenoid (PBL SBIR)
  - ❑ Medium field @ high temperature : FRIB/RIA quad
  - ❑ Recent results of MgB_2 solenoid
- **HTS conductor obtained/ordered (~4 mm tape equivalent)**
  - ❑ So far : ~15+ km
  - ❑ Last 12 months: ~ 8 km (for FRIB quad and PBL solenoid)
- **Program needs – *The Magnet Pull***
  - ❑ 2G optimization for (a) high field, low temperature applications and (b) medium field, high temperature applications.
  - ❑ To encourage this development, conductor vendors could be motivated with added support.

Next few slides:

- Quick summary of several (built and tested) HTS programs
- More details on select two

We are and have been optimistic about the viability of HTS in a variety of applications.

It may be because of our longer (over a decade) and successful association with HTS coil and magnet R&D.

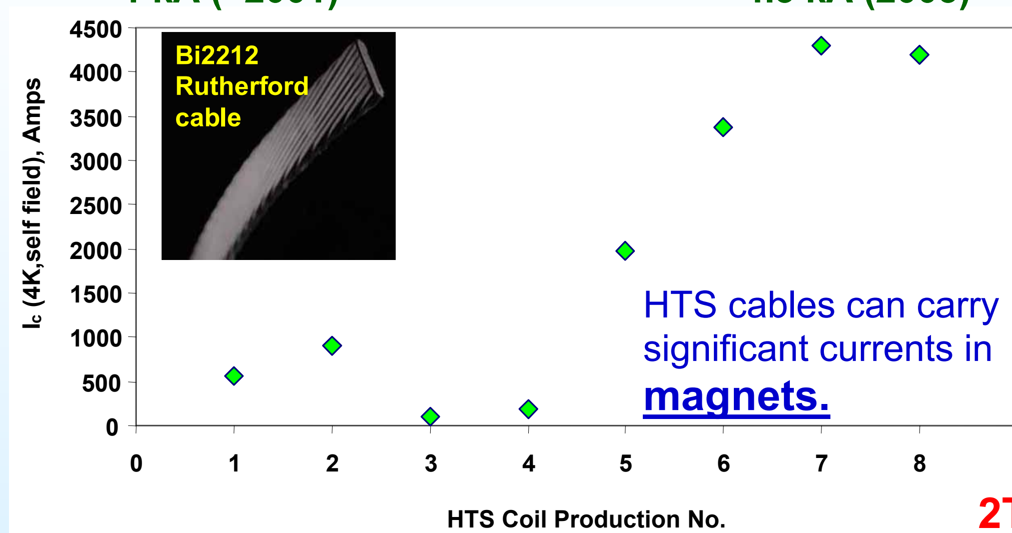
HTS Common Coil Dipole with Bi2212 R&W Rutherford Cable

Coils and Magnets built at BNL with Rutherford Bi2212 Cable

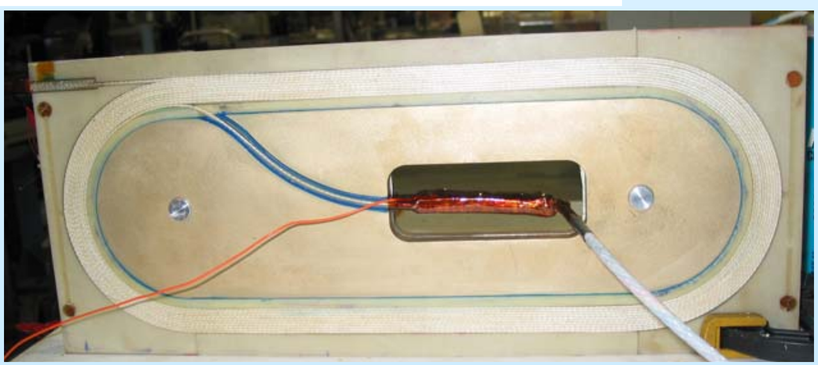
Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands	Common coil configuration	900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	2 HTS coils (mixed strand)	94	91 [41]	0.023
CC011 DCC006	0.81 mm wire, 2 HTS, 16 Ag	74 mm spacing Common coil	182	177 [80]	0.045
CC012 DCC008	0.81 mm wire, 18 strands	Hybrid Design 1 HTS, 2 Nb_3Sn	1970	212 [129]	0.66
CC023 DCC012	1 mm wire, 20 strands	Hybrid Design 1 HTS, 4 Nb_3Sn	3370	215 [143]	0.95
CC026 DCC014	0.81 mm wire, 30 strands	Hybrid Common Coil Design	4300	278 [219]	1.89
CC027 DCC014	0.81 mm wire, 30 strands	2 HTS, 4 Nb_3Sn coils (total 6 coils)	4200	272 [212]	1.84

Earlier coils
<1 kA (~2001)

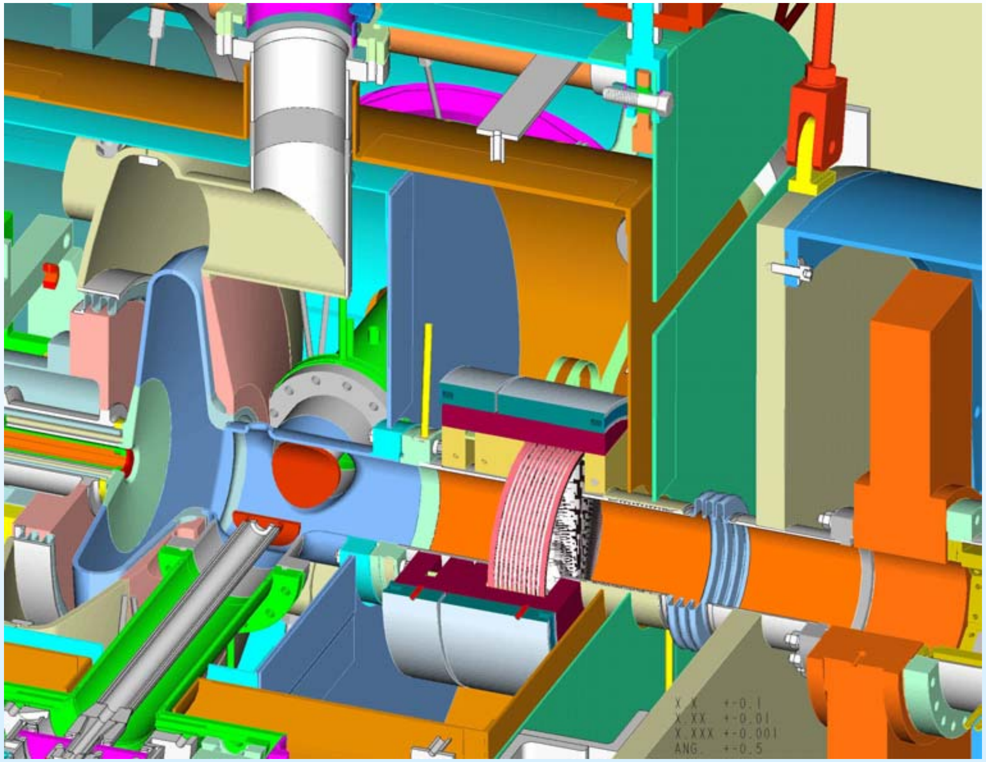
Later coils
4.3 kA (2003)

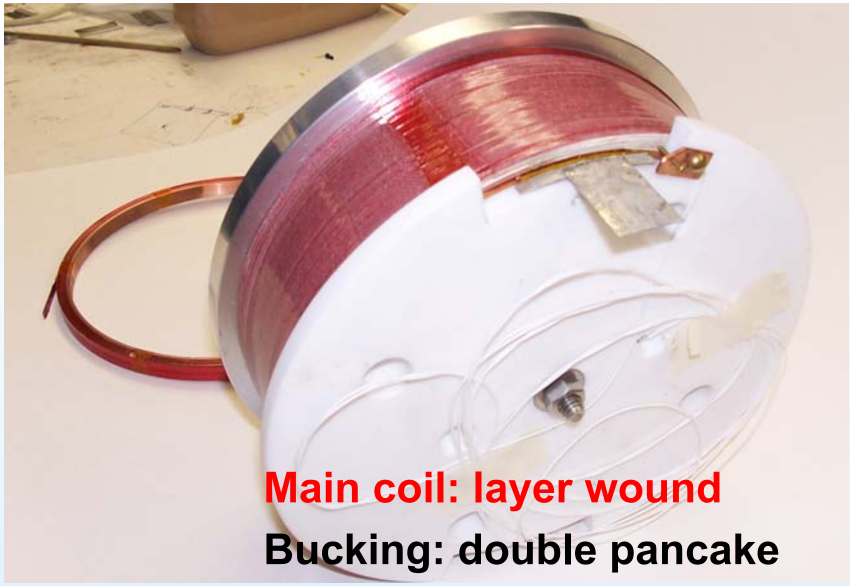


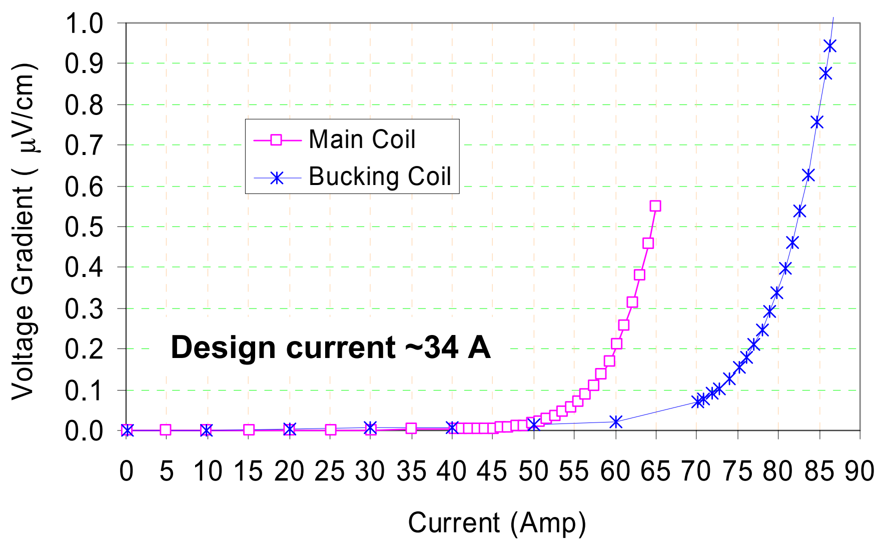
Racetrack HTS coil with Bi2212



HTS Solenoid for the Proposed ERL (Electron Recovery Linac) at BNL







- HTS solenoid provides a unique technical solution.
- HTS solenoid magnet is placed over the bellows before the gate valve in cold to warm transition region (~20 K)

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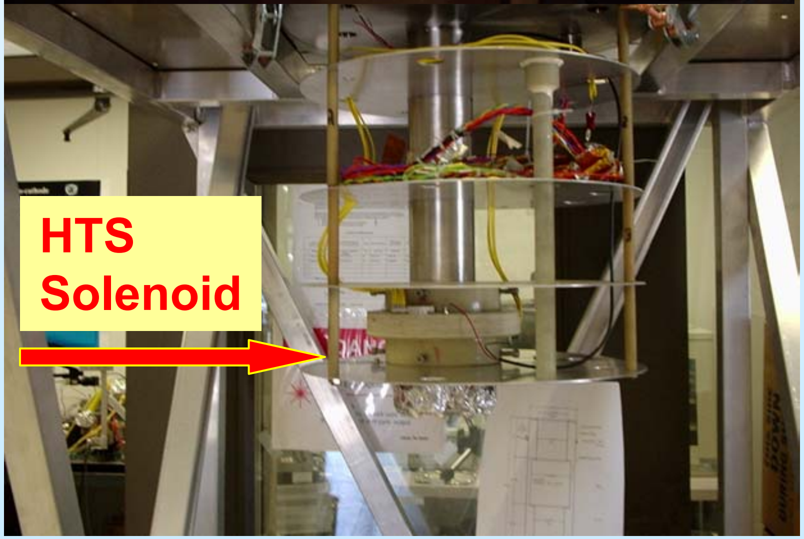
HTS Solenoid for LDRD on SRF Electron Gun



- No room for LTS solenoid in Liquid Helium (LHe)
- Temperature between the first set of baffles is ~20 K
- Copper solenoid would generate ~500 W heat as against the ~5 W heat load of the entire cryostat
- Copper solenoid outside the cryostat will be too far away and will not provide the desired focusing and will result in a large deterioration in performance
- **HTS solenoid provided a technical solution that was not possible with either with copper or with conventional low temperature superconductors.**
- **Design current was achieved at 77 K itself. That made HTS solenoid option to be an overall cheaper solution (design + build + test) as well since testing at ~77 K is much cheaper than testing at ~4 K .**

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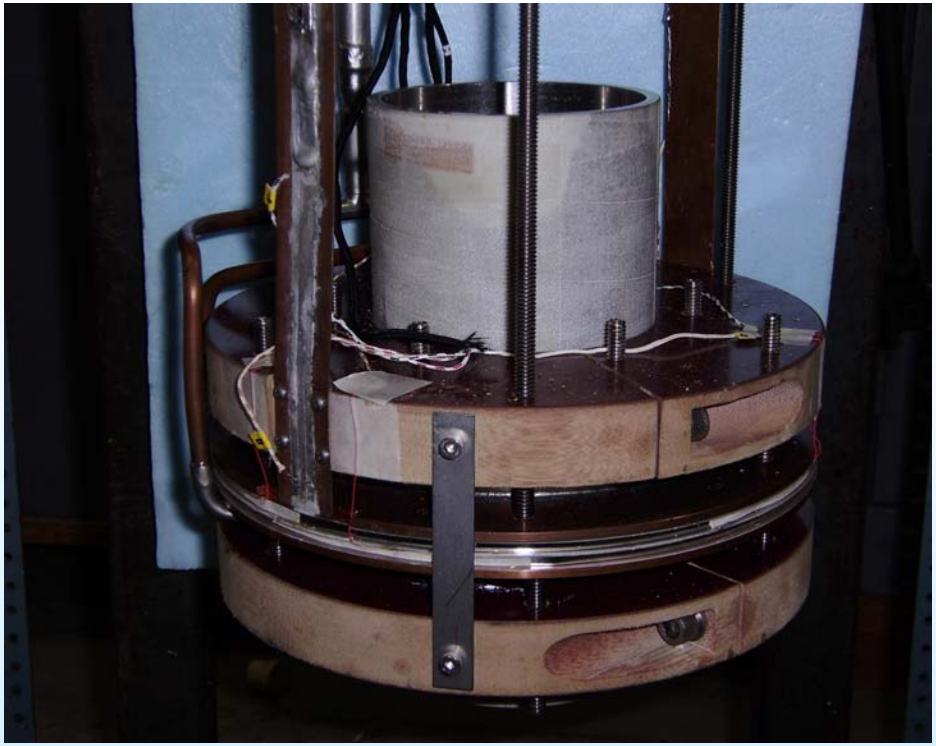
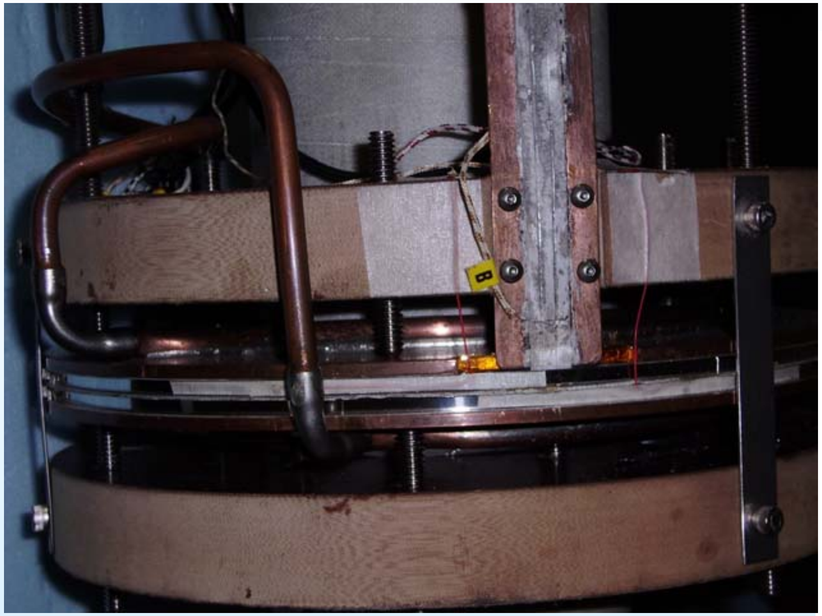
MgB_2 Solenoid made with Conductor from COLUMBUS SUPERCONDUCTORS SpA

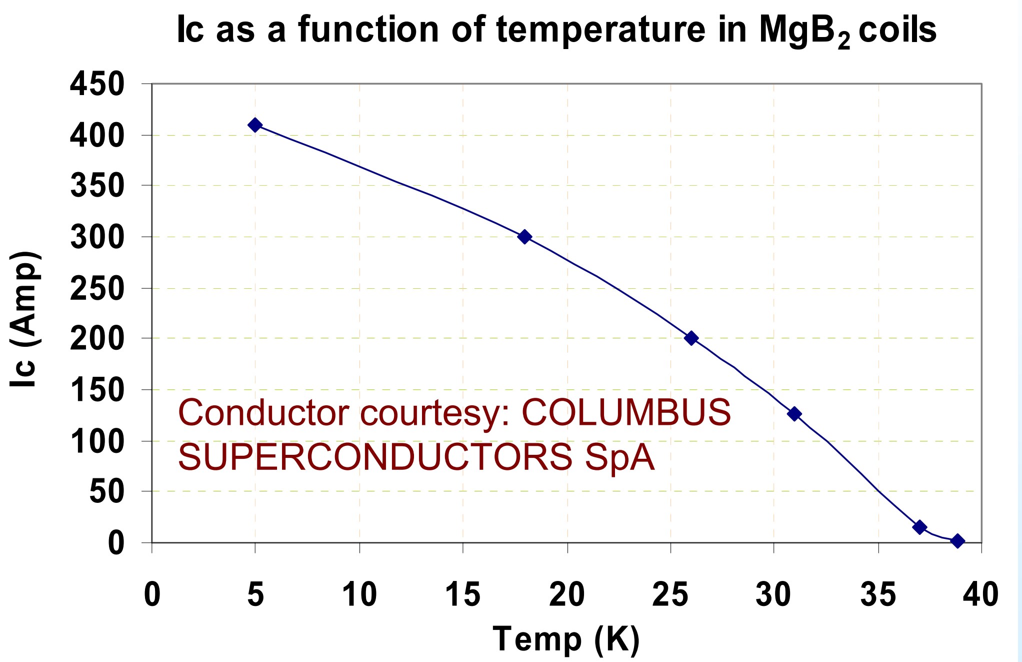


Coil i.d. = 100 mm
Coil o.d. = 200 mm
# of Turns = 80

MgB_2 Solenoid with a double pancake coil

MgB_2 Solenoid
Critical Current as a Function of Temperature





- Top and bottom plates are conduction cooled with the helium gas
- Helium flow is adjusted to vary the temperature.

~1.3 T peak field

100 A => ~0.31 T

More Details on Select Two

(current major HTS programs at BNL)

High Field Muon Collider Solenoid SBIR with PBL (Particle Beam Lasers)

- A forward looking collaborative SBIR program between PBL & BNL.
- PBL brings ideas with highly respected individuals (most working part time)
  - Some of them are: Bob Weggel, Bob Palmer, Ron Scanlan (in magnets) and Al Garren, David Cline, Jim Kolonko (in accelerators)
- BNL contributes its staff, ideas, facilities and past experience with HTS and AP.
- There is not enough funding in one SBIR to build 35-40 T solenoid. So why not attempt to build it with several serial SBIRs. It provides a natural segmentation for Lorentz force purpose and allows lessons learnt from one to transfer to other.
- Currently there are two funded Phase 2 SBIR : (1) ~100-165 mm, ~10 T solenoid and (2) 25-95 mm ~12 T insert solenoid.
- There is also one important upcoming Phase 1 proposal for Nb_3Sn > 165 mm outsert solenoid with hope that with Phase 1 this year and Phase 2 funding next year, all three will attempt to make a short 35-40 T superconducting solenoid.

Unique Features of Phase 1 Nb_3Sn Solenoid Proposal

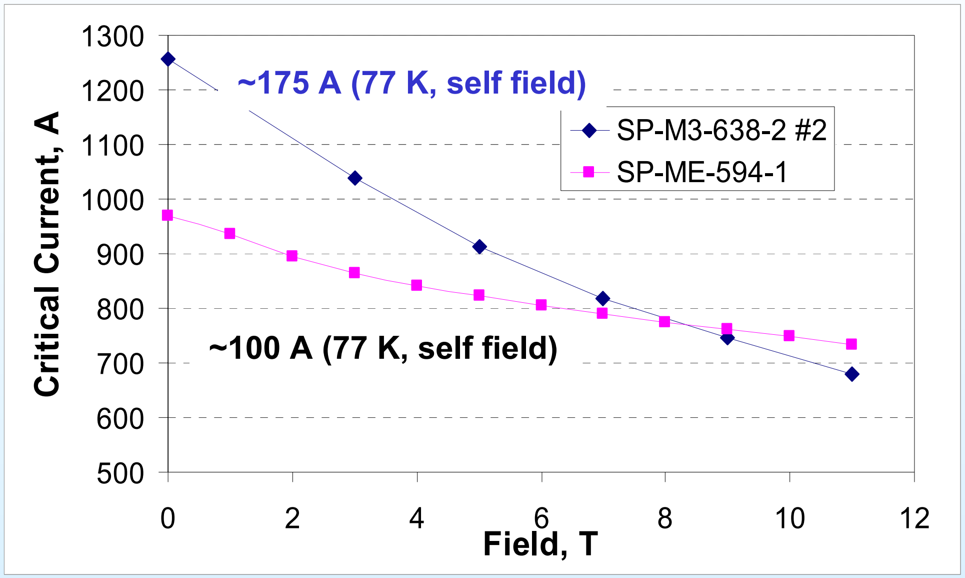
- High field Nb_3Sn solenoid have been primarily built with CICC technology.
- CICC is proven technology. However, it offers a relatively lower J_w as compared to the Rutherford cables, used in accelerator magnets.
- Higher J_w offers many advantages. However, industry is more likely to use this technology after it is proven in solenoids.
- One purpose of this SBIR is to do just that - that will be a significant contribution to high field solenoid technology in itself.
- Another purpose of this SBIR is to build the outsert to build 35-40 T solenoid with other two segments coming from previous two SBIR.

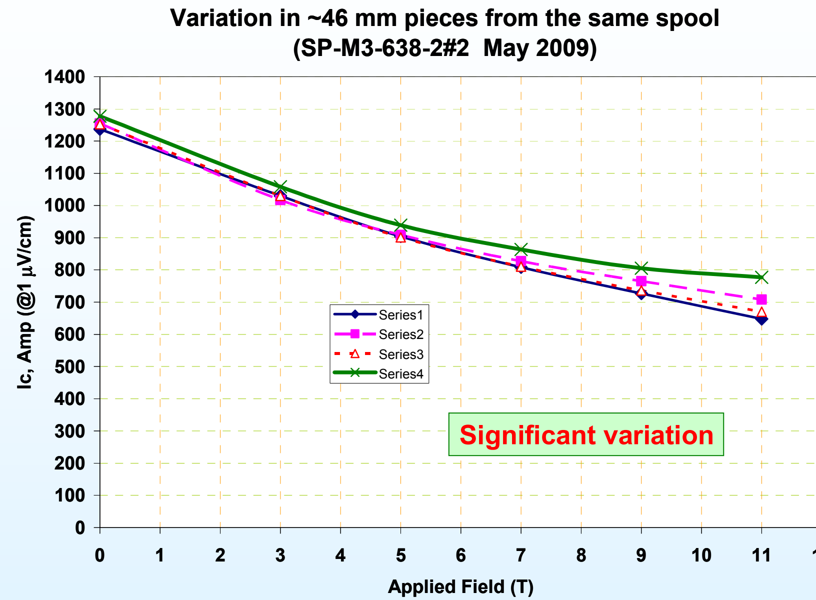
Status of HTS Solenoid

- High Ic conductor (~165 A, 77 K self-field, on average) and high field (advanced pinning) conductor purchased from SuperPower by PBL for the first year. Over 1 km has been delivered, and rest coming soon (making it 1.6 km).
- Test results from the conductors (next slide).
- FRIB/RIA coils and MgB2 solenoid have already been built and tested for several key construction features.
- Solenoid winding with pancake coils to start soon.
- Conductor order (1. 4 km) placed for the second year.
- More conductor order for another Phase 2 started this year is to be placed soon.

Critical Current Measurements at 4K as a Function of B// in SuperPower Wire

Two 2G wires from different time



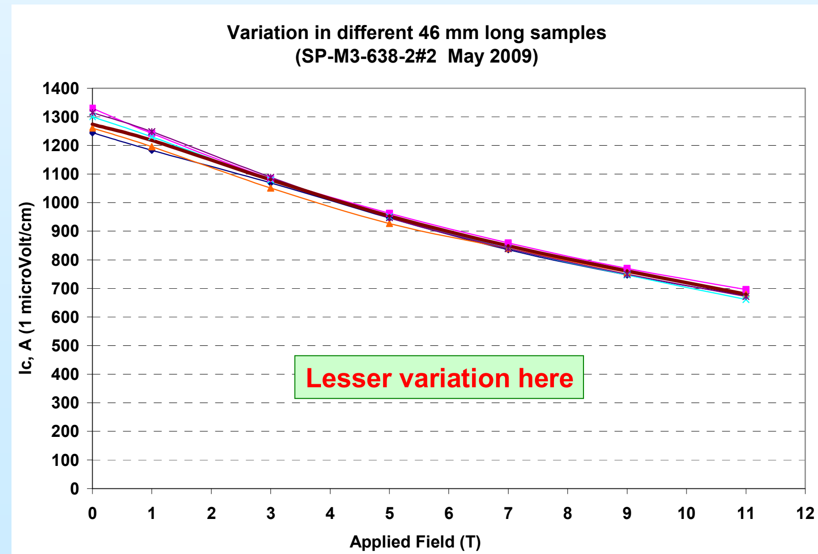


- Wire chemistry influences field dependence.
- At this stage of the production, there could also be a significant variation along the length at higher fields even though there was small at lower fields.

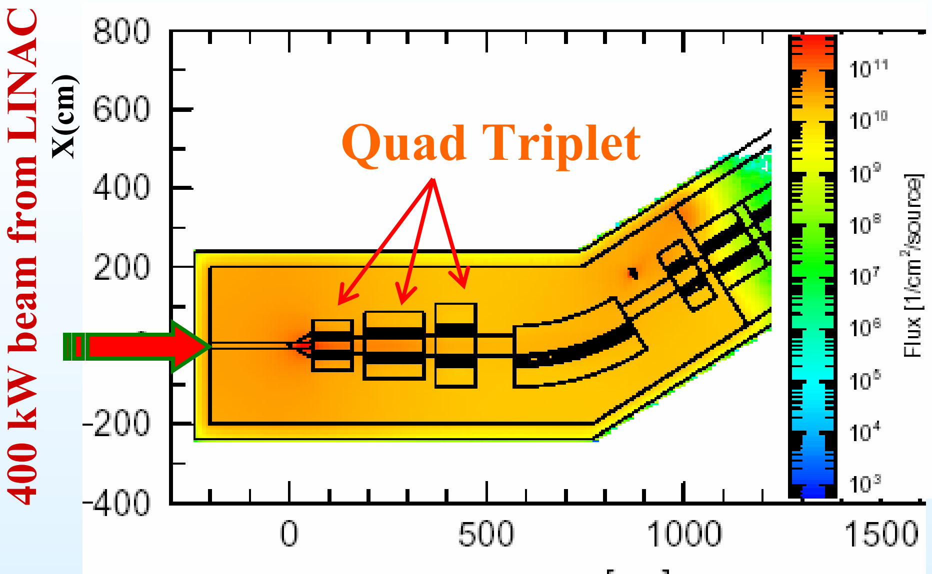
But what happens to the angular dependence?

How much is the difference in the minimum value?

Some tapes got damaged during high field testing.



HTS Quadrupoles for RIA/FRIB



Courtesy: Al Zeller, NSCL

- To create intense beams of rare isotopes, up to 400 kW of beam hits the target before the fragment separator.
- Quadrupole triplet is exposed to very high level of <u>radiation</u> and <u>heat</u> loads (~15 kW in the first quadrupole itself).
- HTS magnets could remove this more efficiently at 30-50 K than LTS at ~4 K.

- **These quads were identified as one of the most critical components of the machine.**
- **We have successfully built and tested a large number of coils and magnets and have performed radiation damage and energy deposition experiments.**

RIA: Rare Isotope Accelerator
FRIB: Facility for Rare Isotope Beams

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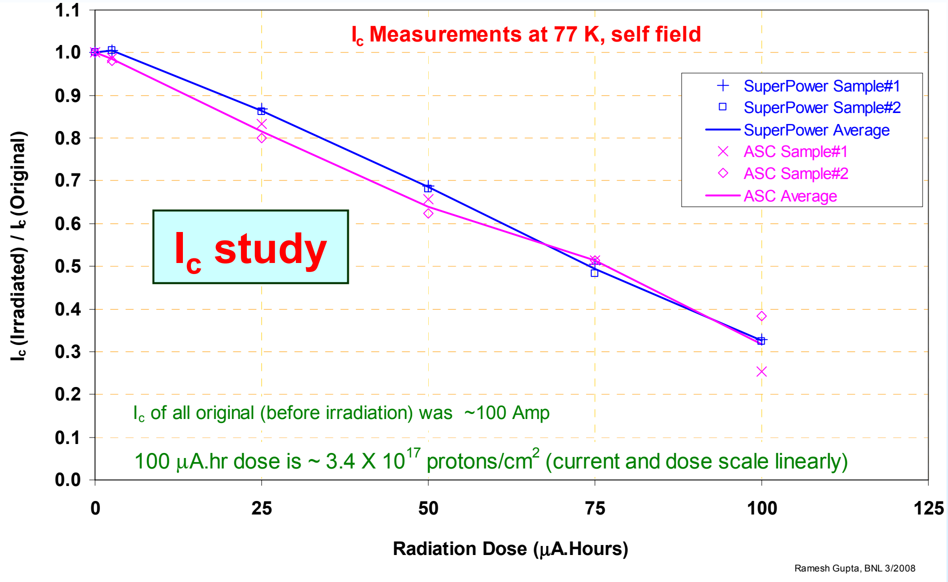
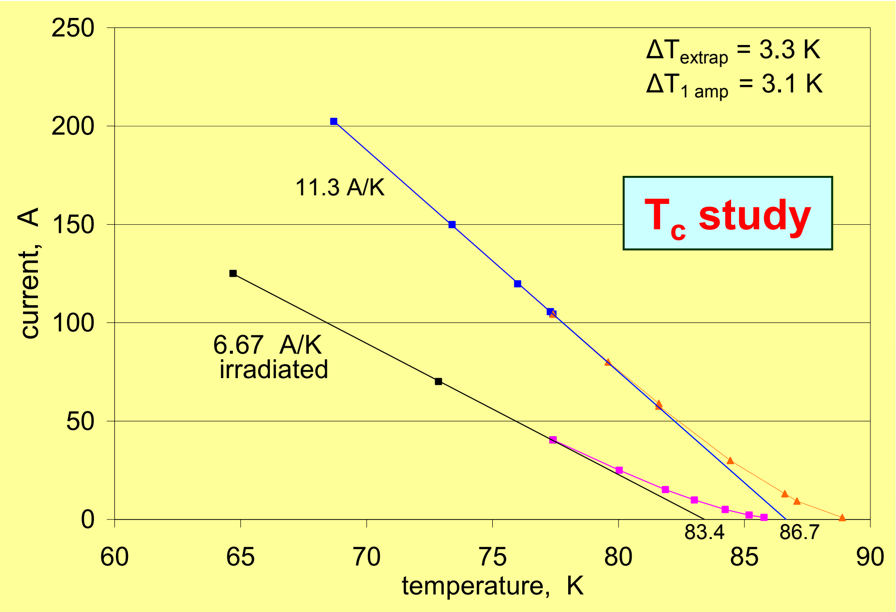
Impact of Large Irradiation on YBCO

PRESENTED AT ASC2008
(Greene, Sampson & Gupta, BNL)

Caveat: 77 K, self field. Lower temp., in field next





Note: The following doses are <u>order of magnitude more than what would be in FRIB</u>

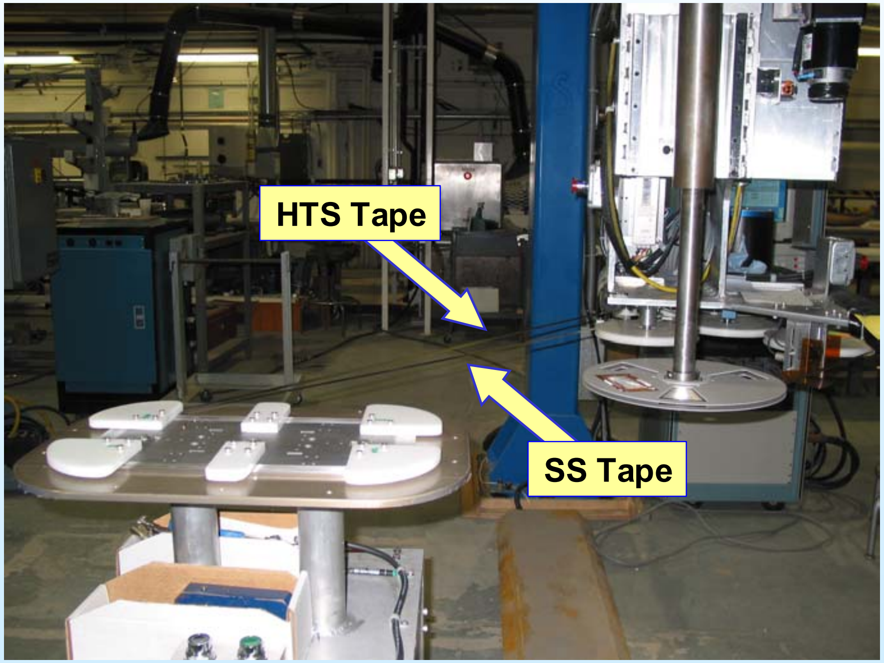
- These doses (~400 kW beam, ~15 kW in first <0.1 m long magnet) are significantly more than those in accelerator magnets, including muon colliders and LHC upgrade.

<u>Bottom line – YBCO is robust against radiation damage</u>:

- **Negligible impact on FRIB performance even after 10 years (Al Zeller, MSU).**

HTS Coils for RIA/FRIB Magnets

- RIA quad is made with 24 coils, each using ~200 meter of HTS. We have purchased over 5 km of 1G wire for this project (FRIB purchase of 2G wire is separate).
- This gives a good opportunity to examine the reproducibility in coil performance.
- Stainless steel tape serves as an insulator which is highly radiation resistant.



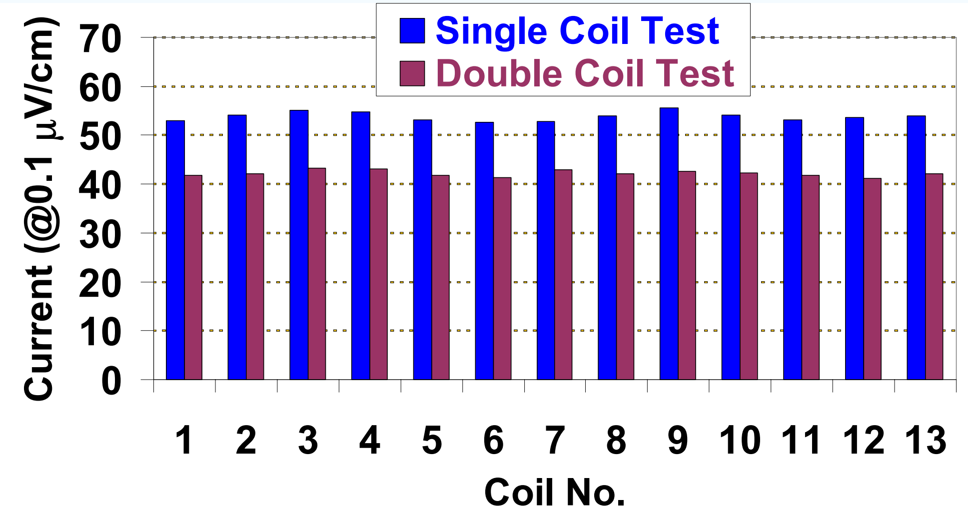
RIA: Rare Isotope Accelerator

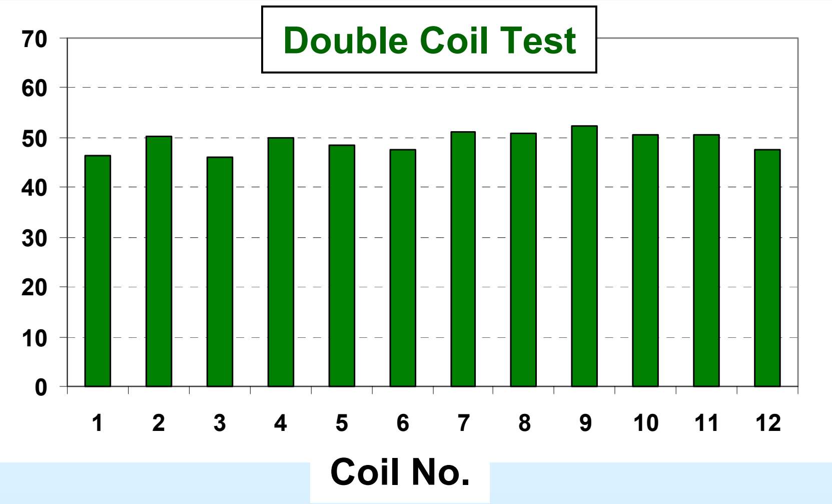
FRIB: Facility for Rare Isotope Beams

LN_2 (77 K) Test of 25 BSCCO 2223 Coils

13 Coils made earlier tape
(Nominal 175 turns with 220 meters)

12 Coils made with newer tape
(150 turns with 180 meters)





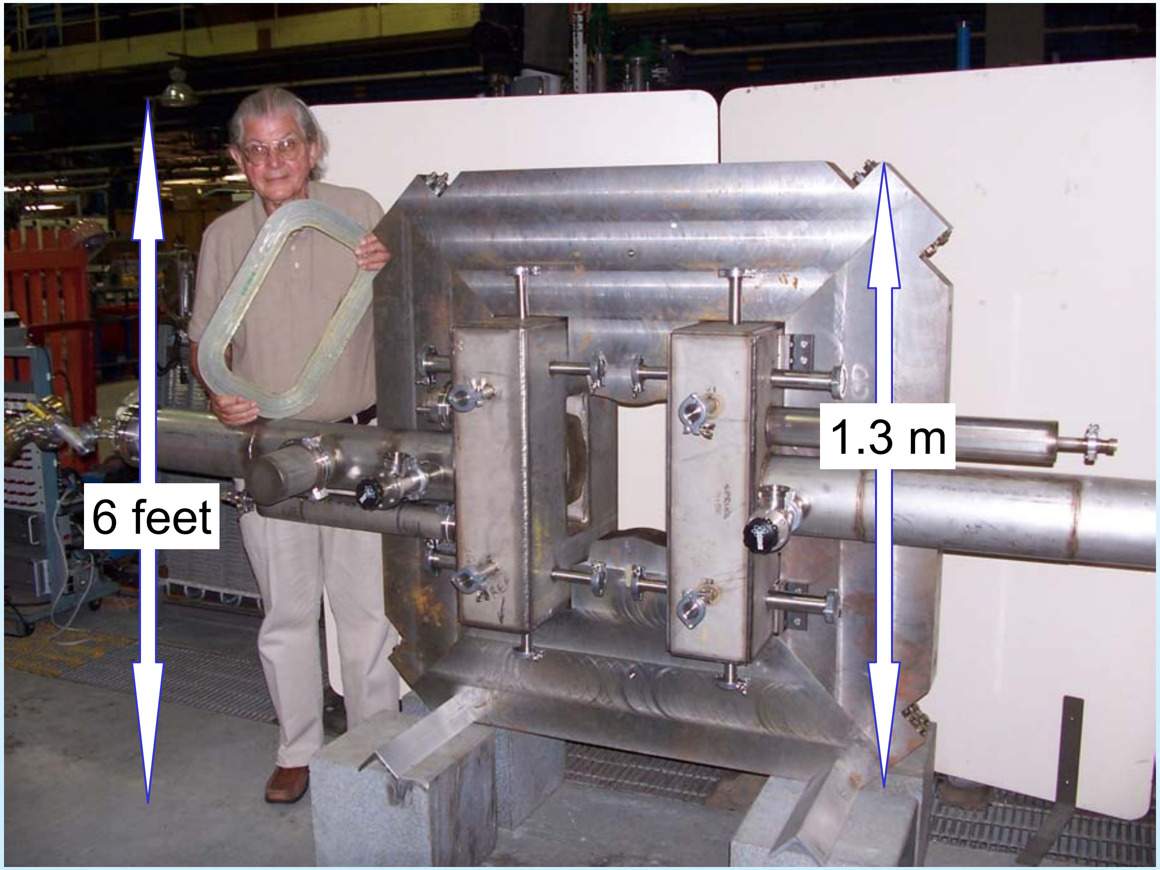
Coil performance generally tracked the conductor performance very well.

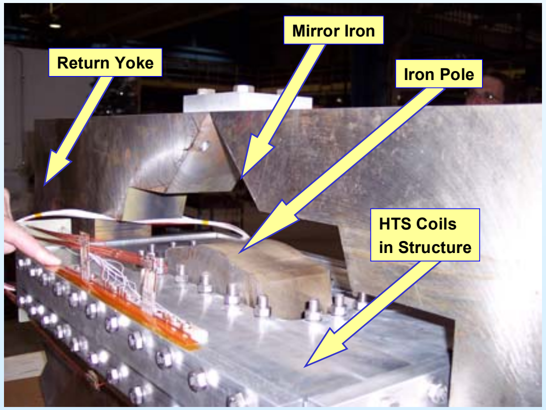
Note: A uniformity in performance of a large number of HTS coils.
It shows that the HTS coil technology is now maturing !

Various Magnet Structures of RIA Quad (a part of step by step R&D program)

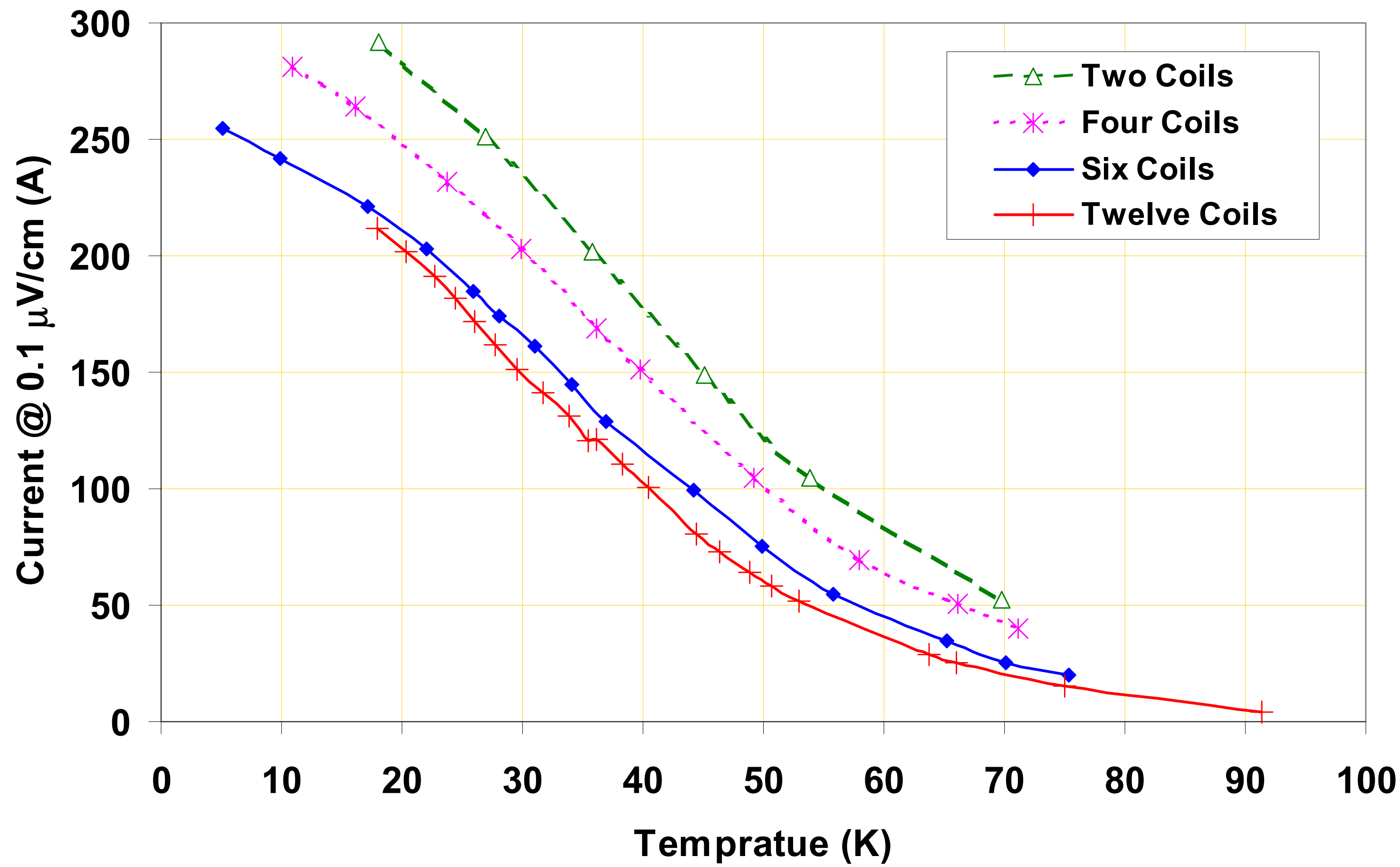
Unique Features of RIA HTS Quad :

- Large Aperture, Radiation Resistant





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

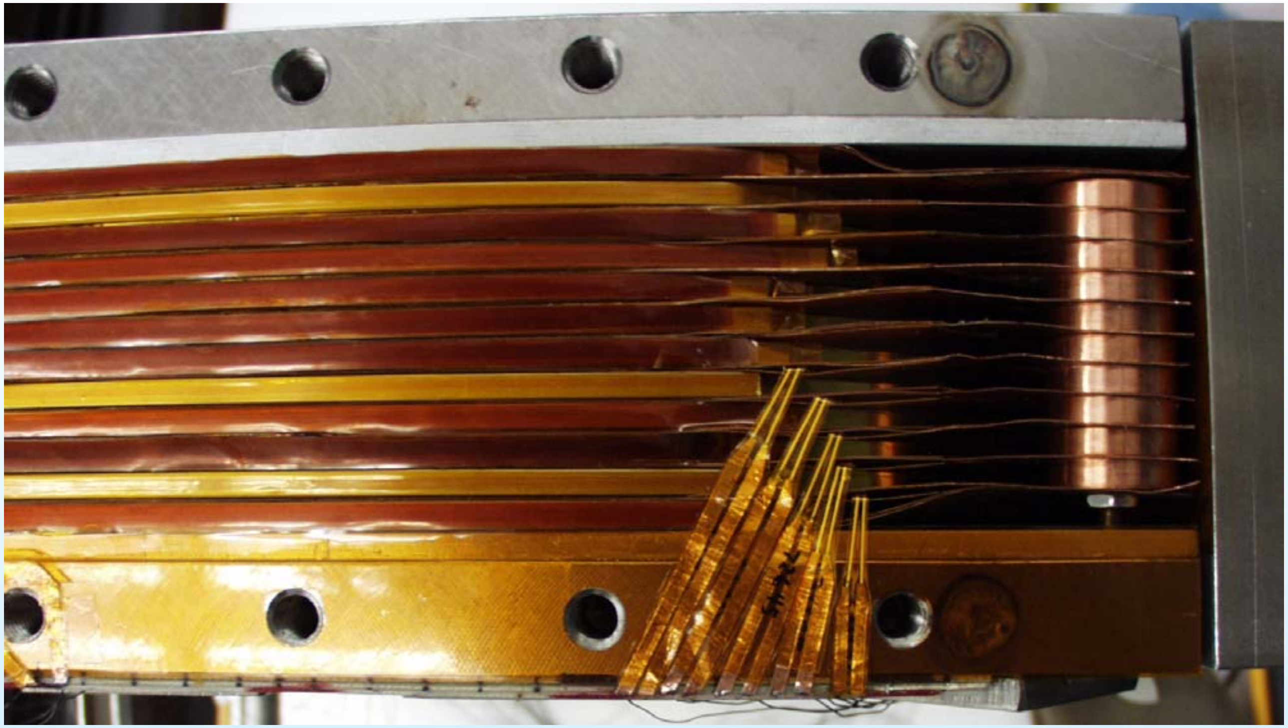


More coils create more field and hence would have lower current carrying capacity

Courtesy/Contributions
Sampson

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



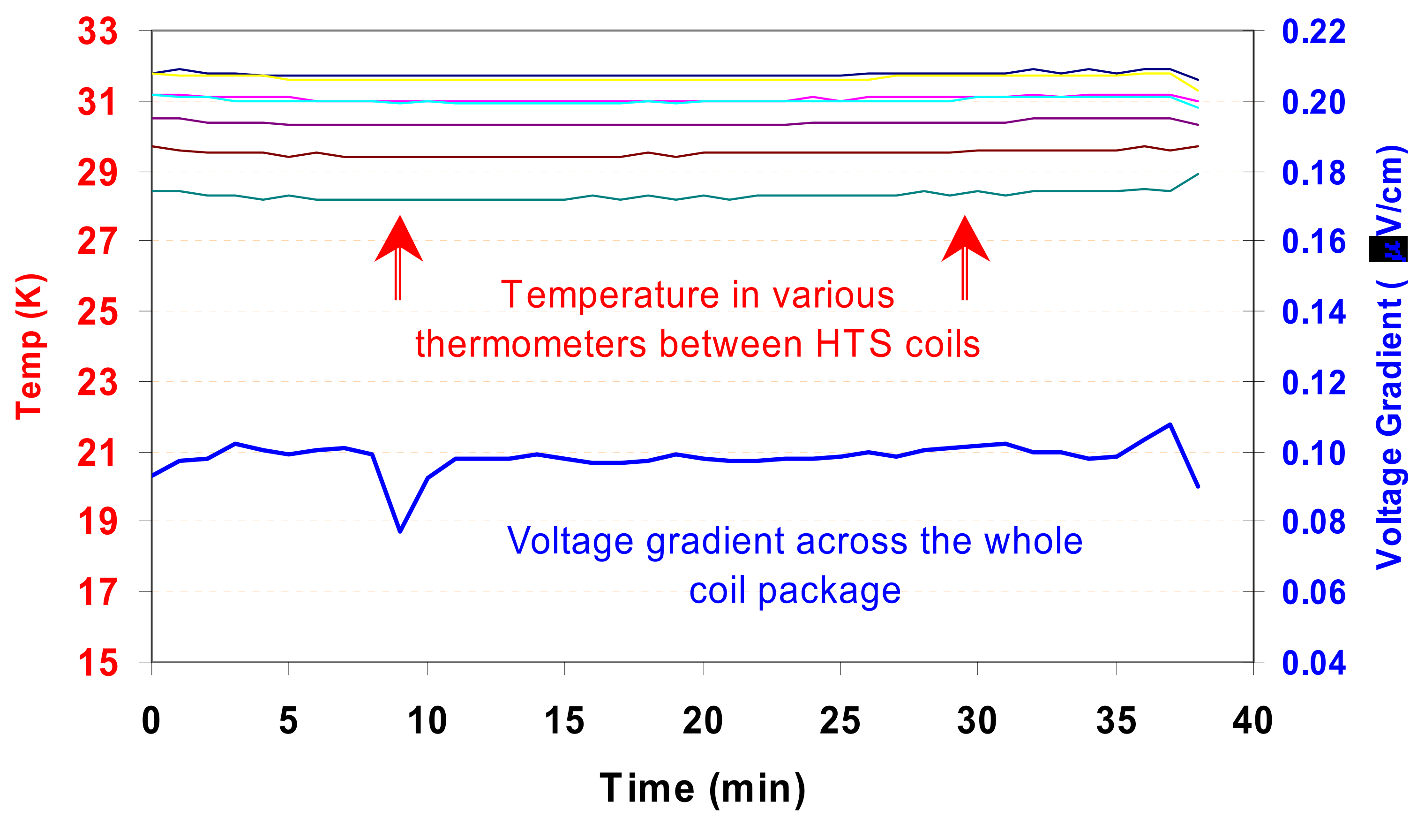
Stainless steel tape heaters for energy deposition experiments

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

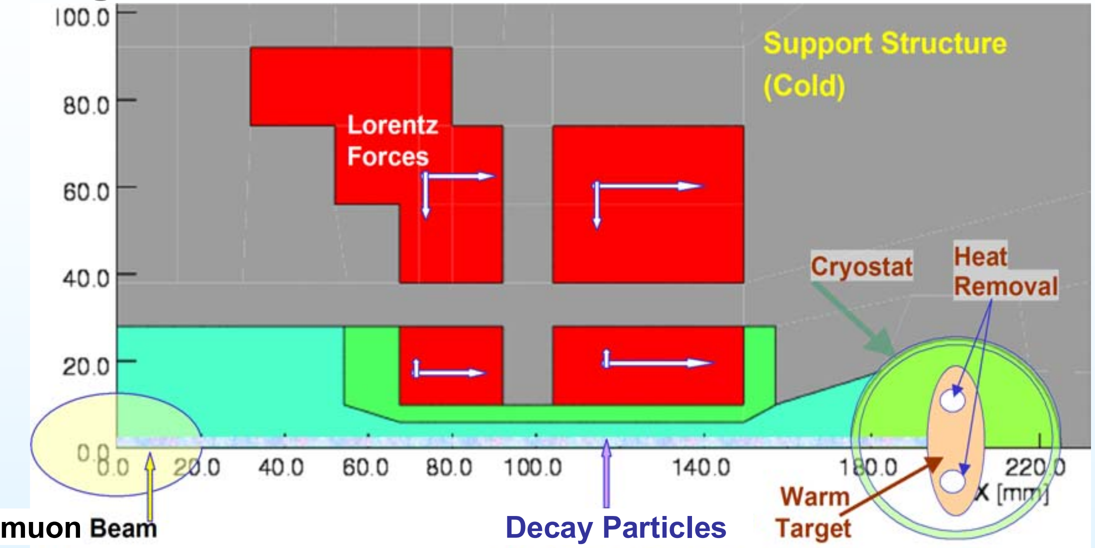
Status of FRIB HTS Quad Program

- Design field gradient increased by 50%
- Desired operating temperature increased from ~30 K to ~50 K
- Moved from 1G to 2G
- Moved from ~4 mm wide tape to ~12 mm wide tape (more current, less number of coils)
- Conductor order placed for 2 km of 12 mm 2G
- Radiation damage experiments move from 77 K self field to lower temperature in applied field

Progress through Conductor PO

- Generally speaking, industry is more willing to talk if they see a purchase order coming. We try to use this as an incentive for them to listen to our needs.
- We just placed purchased orders from two vendors (better to have two).
- This is for ~12 mm wide tape, 1 km from each vendor.
- This encouraged ASC to now deliver ~12 mm wide tape as an standard product.
- SuperPower is responding well to the needs of magnet program (enhancing in-field performance and willing to sell that as standard product)
- This is the first time that there is a specification for in-field, lower temperature performance. This is more meaningful for magnet applications then past 77 K, self-field specification.
- We together (us and conductor vendors) worked hard to develop these specifications and view it is a significant progress. It should be seen as the commitment from the conductor vendor to the magnet application.

HTS Open Midplane Dipole SBIR (Another BNL/PBL collaboration)



- An ideal open midplane design will have no structure on the midplane.
- Use of HTS (a) will allow very high magnetic fields (20 T or above) and (b) can tolerate high heat loads).
- Higher field will allow higher energy and/or higher luminosity.

- Significant progress was made during LARP funding
- A conceptual engineering design was developed which showed how to deal with Lorentz forces, assemble coils and magnet, remove large heat loads and obtain good field quality.
- This has been recognized as a topic of interest by muon collider collaboration and has been placed in DOE SBIR solicitation list.
- Phase 1 is to study this for muon collider and Phase 2 to test key issues.

SUMMARY

• There are a variety of magnet applications where HTS offers unique advantages. Conductor continues to make progress that is relevant to magnet applications.

• A more positive picture is emerging through the development of concepts and through actual demonstration of usefulness of HTS in R&D magnets.

• There are still many issues to be solved. As in past, they generally get solved when the best mind works on them and that happens when there is reasonable funding.