High Temperature Superconductors in Future Accelerator Magnets

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Overview of the Presentation

- High Temperature Superconductors (HTS)
    - ☐ Introduction and Status
- Advantages of using HTS in Accelerator Magnets
- **HTS for RIA Quads (NSCL/BNL collaboration)**
    - ➢ **High Temperature, Medium Field Application**
        - ☐ A Preliminary Design will be presented.
- Other HTS Applications: Low Temp., Very High Field Magnets
- BNL Experience With HTS
    - ☐ HTS Tape & Cable Testing
    - ☐ Test Coils and Magnet R&D
        - ✓ Yes, HTS hardware has been built & tested !
- Summary

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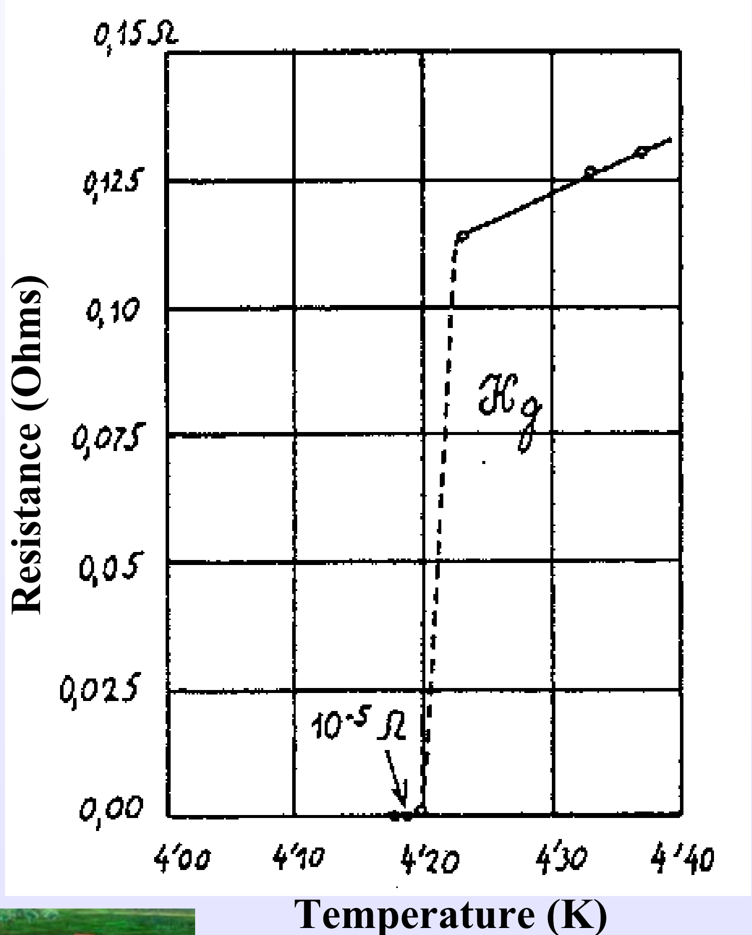
The Conventional Low Temperature Superconductors (LTS) and the New High Temperature Superconductors (HTS)

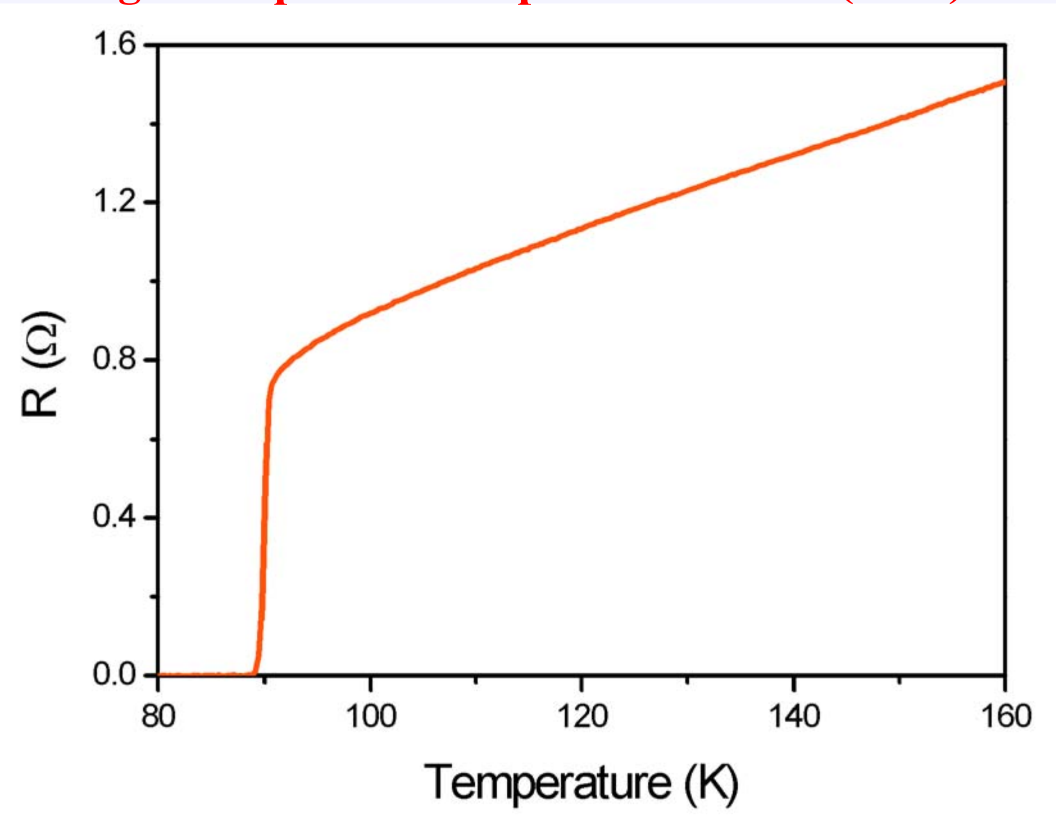
Low Temperature Superconductor Onnes (1911)

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



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

High Temperature Superconductors (1986)



Popular HTS Materials of Today

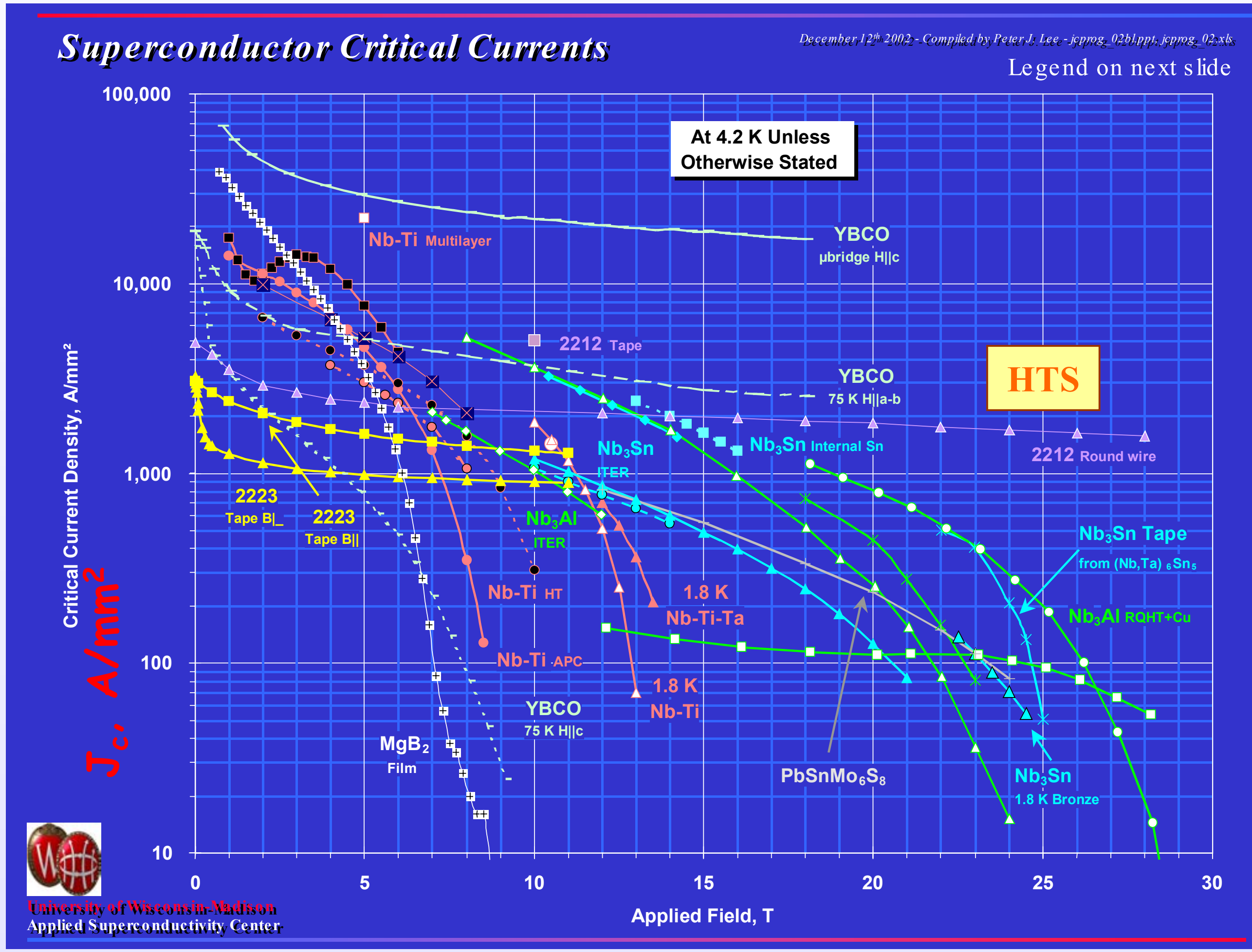
- BSCCO 2223 $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$
- BSCCO 2212
- YBCCO

- MgB_2 is technically a low temperature superconductor (LTS) with critical temperature ~39 K.

Of these only BSCCO2212 and BSCCO2223 are now available in sufficient quantities to make accelerator magnets.

Another Remarkable Property of HTS
The High Field Current Carrying Capacity

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



J_c, A/mm²

Applied Field, T

Advantages of using HTS in Accelerator Magnets

As compared to LTS, the critical current density (J_c) falls slowly

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

Translate this to magnet design and accelerator operation:

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

Operation of HTS Based Accelerator Magnets

• HTS based magnets don’t appear to quench in a normal way.

• One (or even a few) weak spot (s) won’t limit the ultimate performance of the magnet. That would only cause the local temperature to rise a bit but the magnet will continue to operate.

• This becomes more a question of the heat load rather than the weak spot limiting the performance of the whole magnet.

• This is a major difference from the LTS based magnets where a single weak spot limits the performance of the entire magnet.

Challenges with HTS (and the way they are being addressed)

- HTS materials are very brittle

  Work on magnet designs => make “conductor friendly designs”.

- HTS materials are still very expensive

  Cost/Amp is coming down continuously, primarily because of the improvements in performance. Also for some applications, the performance and not the material cost should be the main consideration. One must consider the overall system and operational cost.

- Large quantities are not available

  Situation has significantly improved. We purchased 1.5 km long wire. The tapes are available in similar length. Now we can make coils and magnets having reasonable length.

  The technical question is controlling the temperature of reaction furnace to ~1/2 degree at 880°-890°C over the entire reaction volume.

Possible Applications of HTS in Accelerator Magnets

Medium Field, Higher Temperature Application

Example: Quads for Rare Isotope Accelerator (RIA) --- *To be discussed first*

- These applications don't require very high fields.
- The system design benefits enormously because the HTS offers the possibility of magnets to operate at higher than 4K, say at 20-40 K.
- The HTS can tolerate a large increase in temperature in superconducting coils (caused by the decay particles) with only a small loss in performance.
- Moreover, the temperature need not be controlled precisely (Think about an order of magnitude relaxation in temperature variations, as compared to the LTS used in current accelerator magnets).

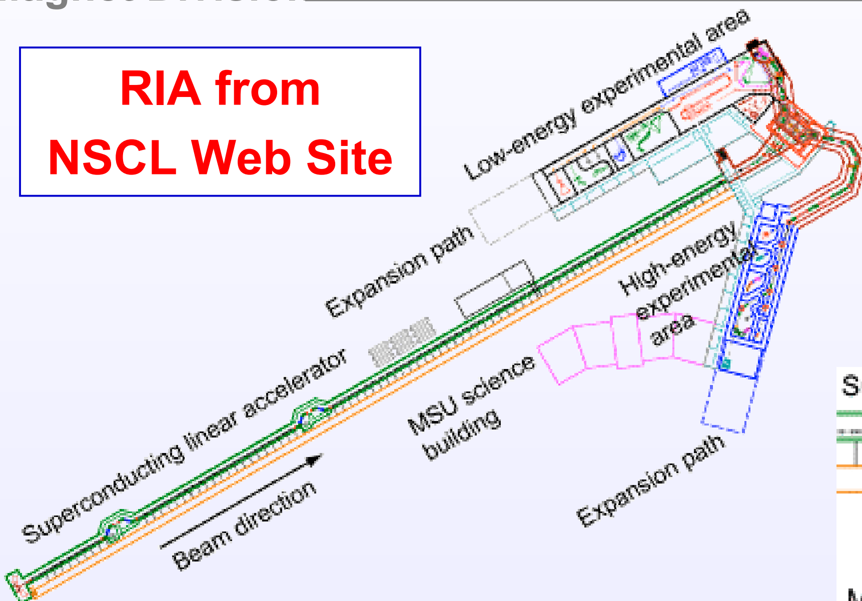
High Field, Low Temperature Application

Example: Interaction Region (IR) Magnets for large luminosity upgrade or very high field main ring dipoles to achieve highest possible energy in existing given tunnel.

- At very high fields (>15 T), no superconductor carries as much critical current density as HTS.

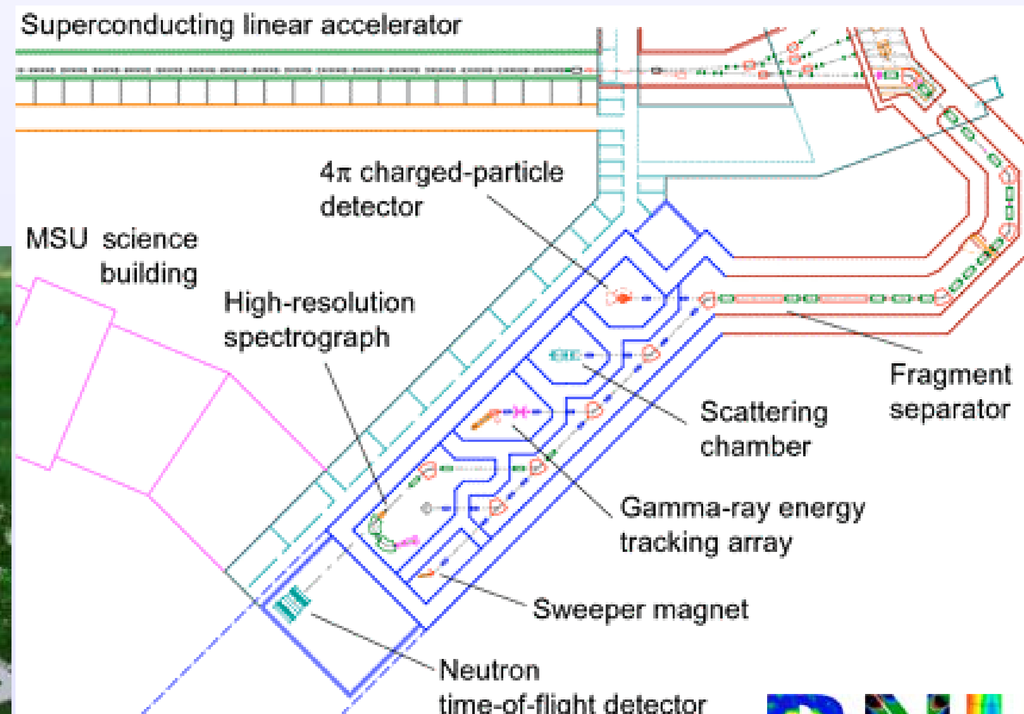
High Temperature Superconductor (HTS) Quads in Fragment Separator Region of RIA

RIA from NSCL Web Site



BNL/NSCL Collaboration:

We propose HTS quadrupoles for the first three magnet elements in the RIA Fragment Separator.



NSCL NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY AT MICHIGAN STATE UNIVERSITY

Basic Requirements of Quadrupoles for Fragment Separator in RIA

They are the first magnetic elements in the fragment separator for RIA

- Required Gradient: 32 T/m in the first quadrupole of the triplet.
- This gradient points to superconducting magnet technology.

- Quads are exposed to high radiation level of fast neutrons (E > 1 MeV)
- Beam looses 10-20% of its energy in production target, producing several kW of neutrons.
- A large fraction of above hit the superconducting quadrupole triplet.
  - This raises several short tem and long term time scale issues.

Room temperature, water cooled copper magnets produce lower gradient and/or lower aperture quads. That will lower acceptance and make inefficient use of beam intensity. Also moving quad back and adding more shielding, requires higher gradient and larger aperture quadrupoles.

Basically, we need *"radiation resistant"* superconducting quads, working in a "hostile environment", where no known magnet has ever lived so long before!

Short Time Scale Issues

Superconducting magnets will quench if large amount of energy is dumped on superconducting coils (over several mJ/g).

In addition, there is a large constant heat load on the cryogenic system : ~ 1 W/kg to the cold mass.

- The temperature increase must be controlled within the acceptable tolerances of the superconductor used.
- The large amount of heat deposited must be removed economically.

- HTS appear to have a potential of offering a good technical and a good economical solution with the critical current densities that are available today (of course, we can always do better with higher J_c).
- However, we need to develop magnet technology and prove that the above potential can be utilized in a real magnet system.

Long Time Scale Issues

- One must look at the impact on the material properties of such a radiation dose over the life time (estimated 10^{19} neutrons/cm^2 in the region of 0 to 30 degrees in ~12 years).

- Iron and copper are expected to be able to withstand about ~100 times the above dose.

Note: The normal water cooled electromagnet can not generate the required field gradient.

The development of the radiation resistant superconducting magnet designs & technologies is highly desirable for RIA.

BNL/NSCL Collaboration

RIA R&D Proposal:

Development of Radiation Resistant Quadrupoles based on High Temperature Superconductors for the Fragment Separator.

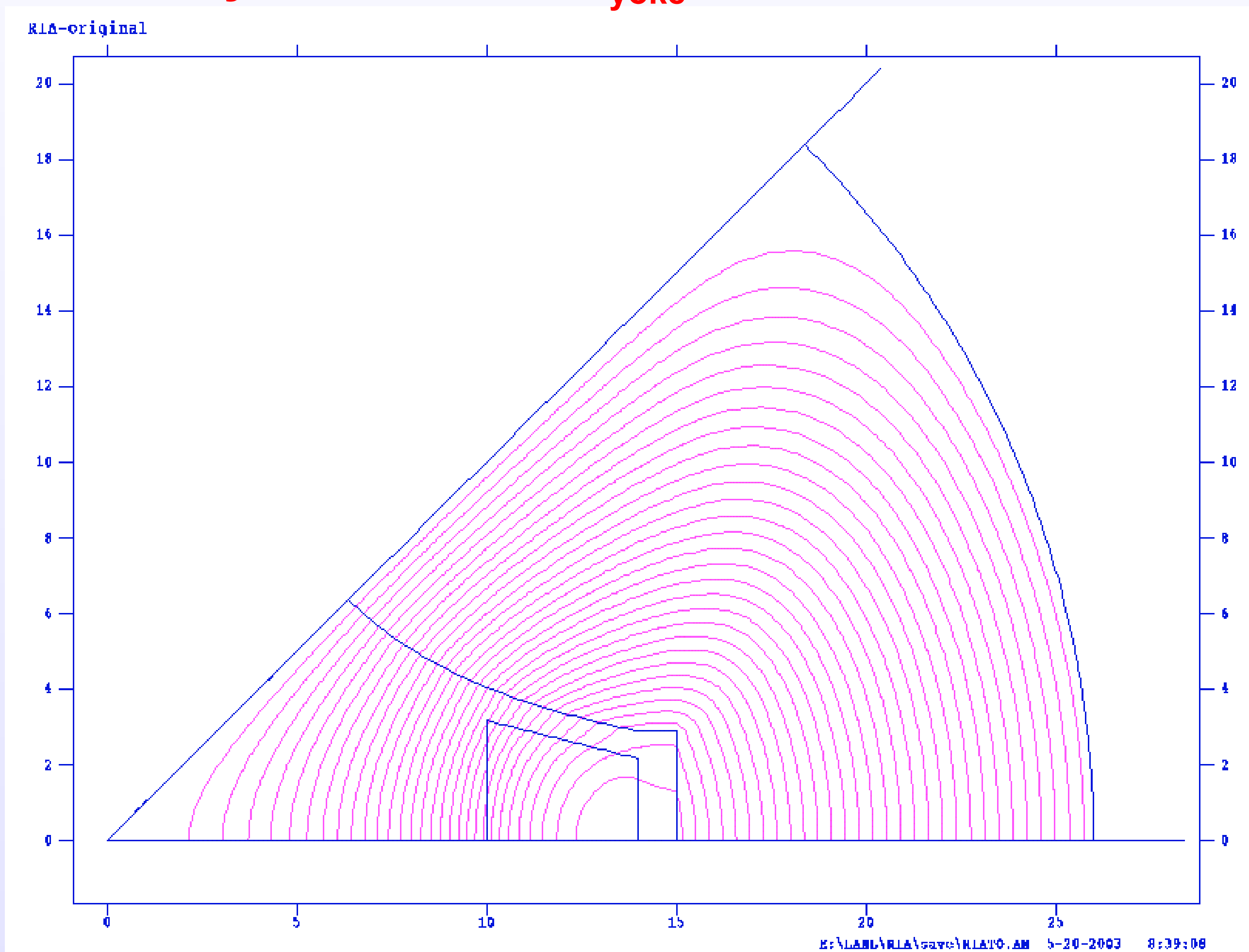
- BNL has a unique experience with HTS technology and expertise in designing and building a variety of superconducting magnets. The primary responsibility of BNL is to develop designs and technologies that can satisfy both short term & long term requirements.
- NSCL has the knowledge of radiation related issues & requirements of RIA and has the expertise on the impact of radiation on various materials. The primary responsibility of NSCL is to carry out necessary model calculations and plan experiments to assure that the magnet can withstand the required dose over the specified period of time.
- In a collaboration, we both benefit with each others experience in magnet designs & material properties. Initial results of this collaboration follows.

Superconducting
Magnet Division

Present Design for the 1st RIA Quad in the Triplet of Fragment Separator

A Super-ferric design with coil making significant contribution to field.
Coil starts at x = 10 cm and yoke starts at R_{yoke} = 9 cm

A Cold Iron Design using NbTi (LTS) Superconductor



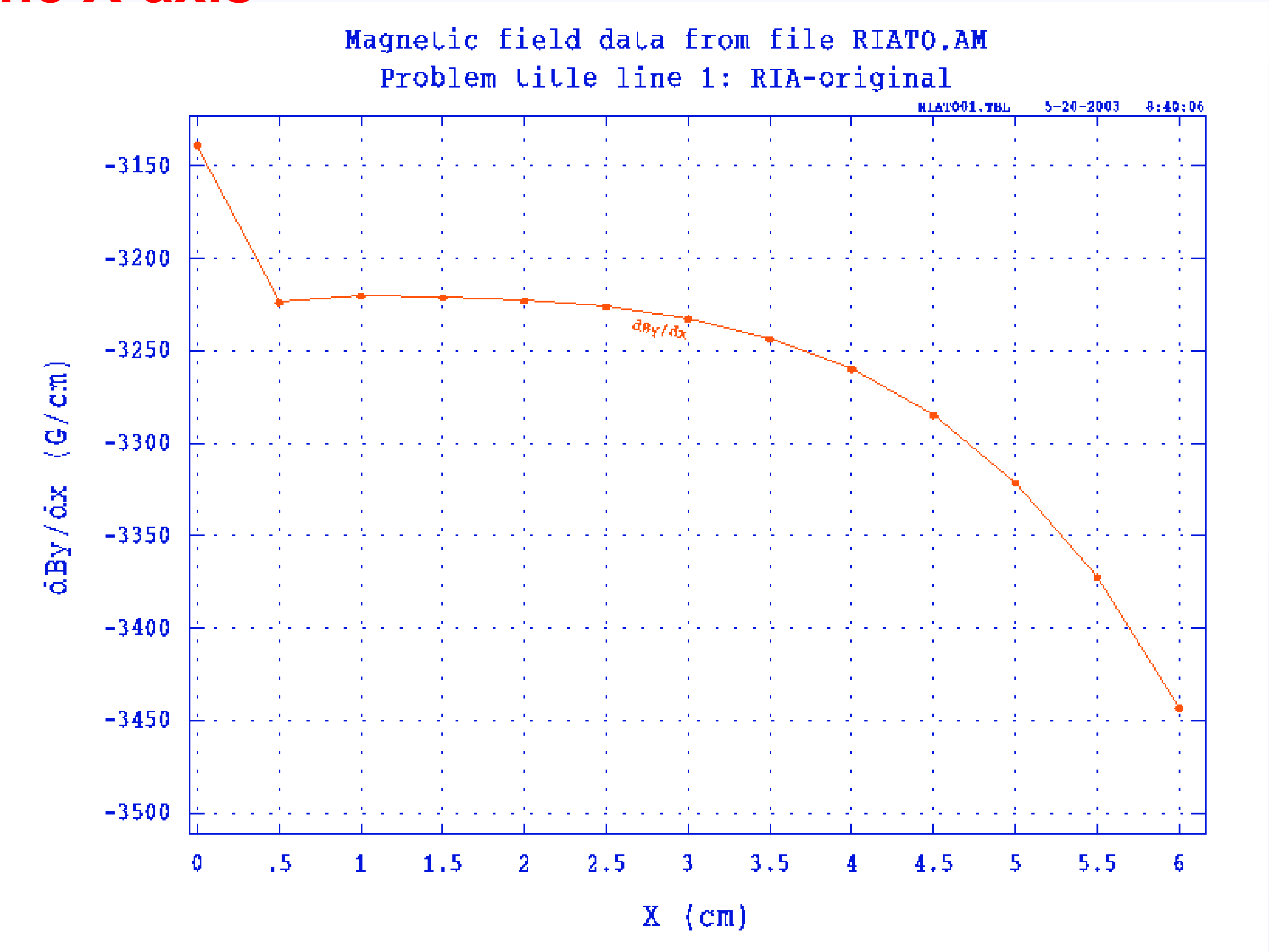
Courtesy:
Al Zeller, NSCL

Field Quality in the present design

Gradient on the X-axis

The required good field aperture is 5 cm

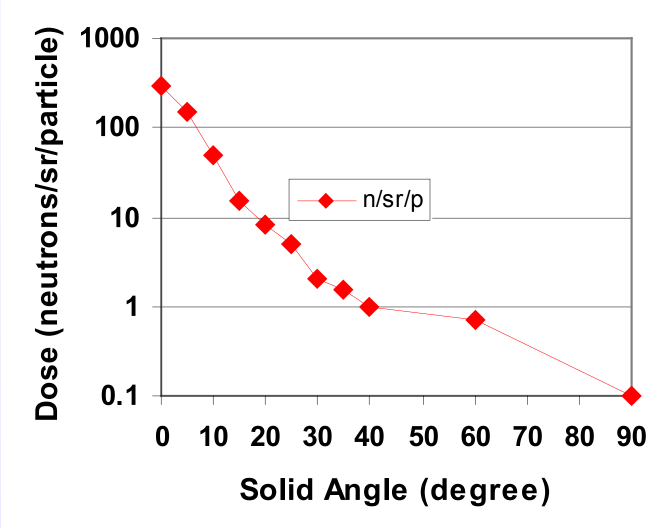
Coil starts at x = 10 cm and yoke at R_{yoke} = 9 cm



Significant Reduction in Neutron Fluence at Larger Angle

Note:

A large (almost exponential) reduction in Neutron Fluence at higher angle.



NOTE: The radiation dose on superconducting coils can be significantly reduced by moving them outward (larger solid angle).

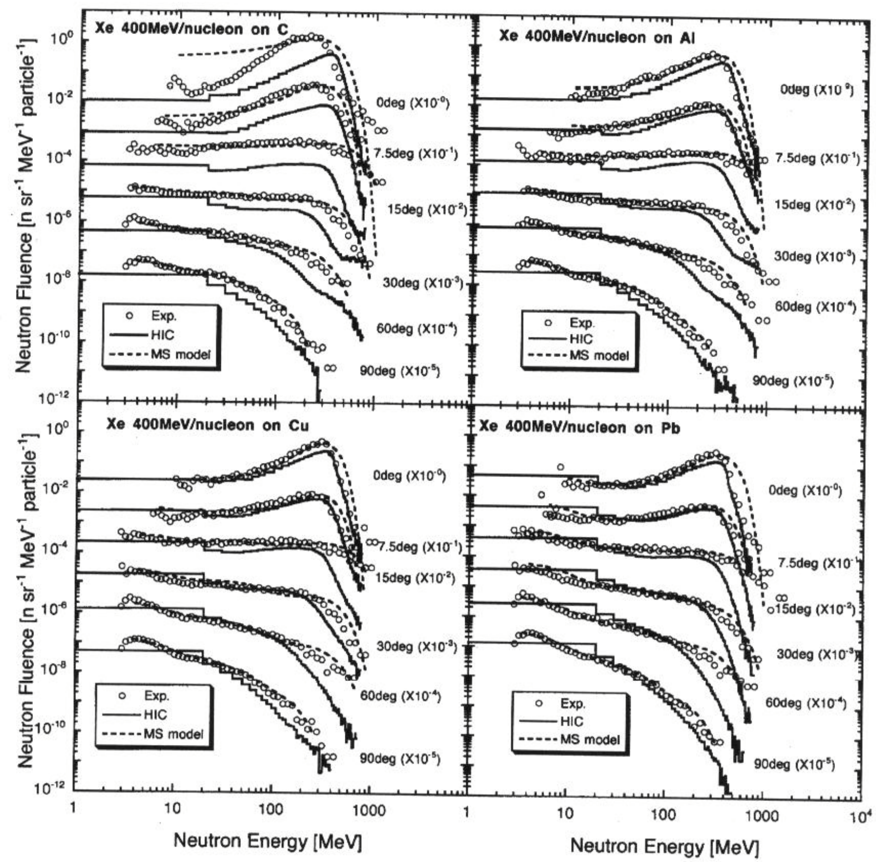


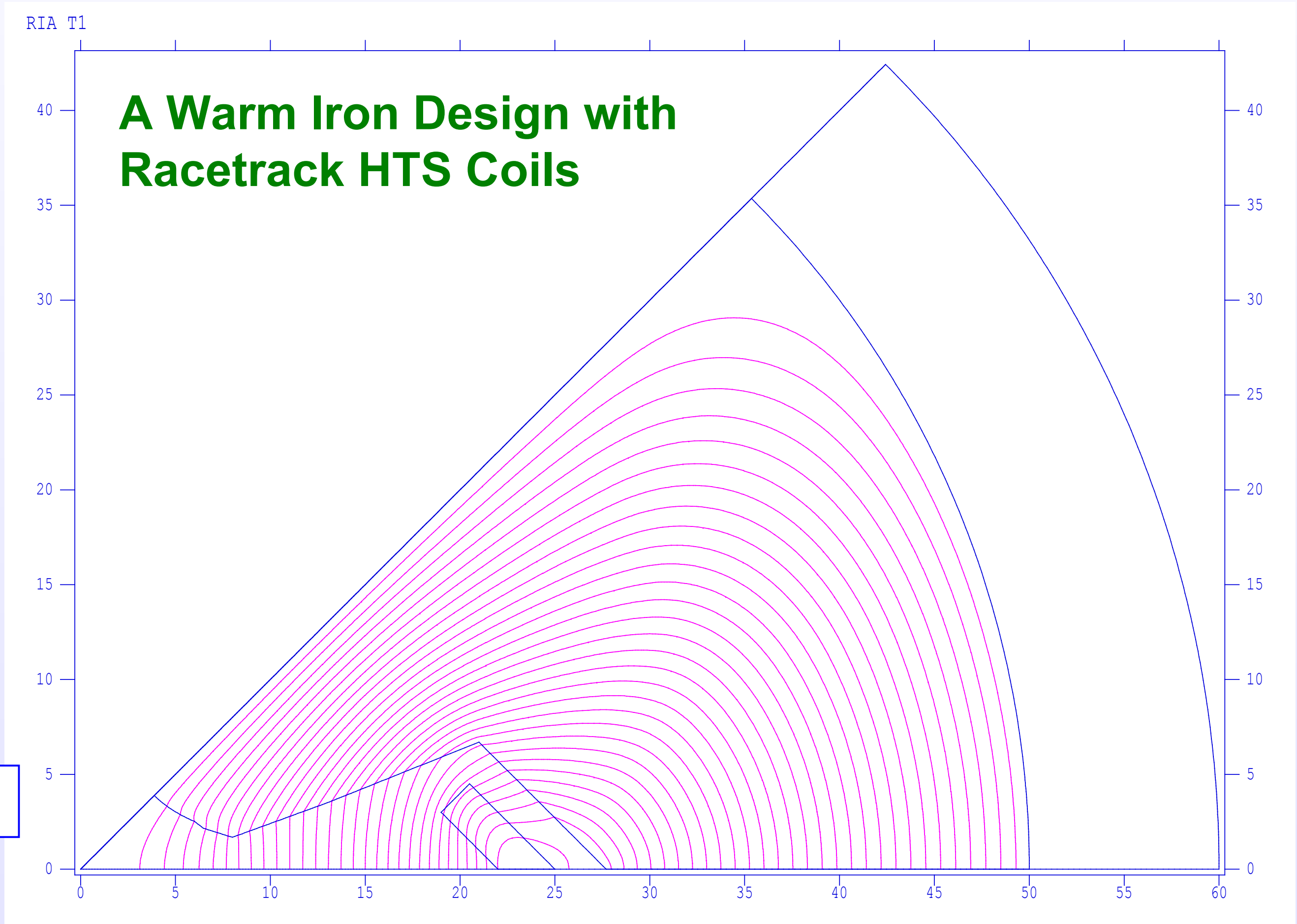
FIG. 3. Neutron-energy spectra from the 400 MeV/nucleon Xe+C, Al, Cu, and Pb system at 0° to 90°. The data are shown by the symbols indicated in the plot. The solid lines are from the calculation by HIC, and the dashed lines come from a fit to the data using Eq. (11).

T. Kurosawa, et al., Phys Rev C, Vol 62, 044615

Proposed Alternate Design for the 1st RIA Quad in the Triplet of Fragment Separator

A Super-ferric design with yoke making significant contribution to field.
Racetrack Coil is at x = 22 cm and yoke starts at R_{yoke} = 5.5 cm

- Coils are moved further out to reduce radiation dose.
- Field lines are funneled at the pole to create larger gradient.
- Warm iron (cryostat around the coil), to reduce heat load on the system.



BNL/NSCL Collaboration

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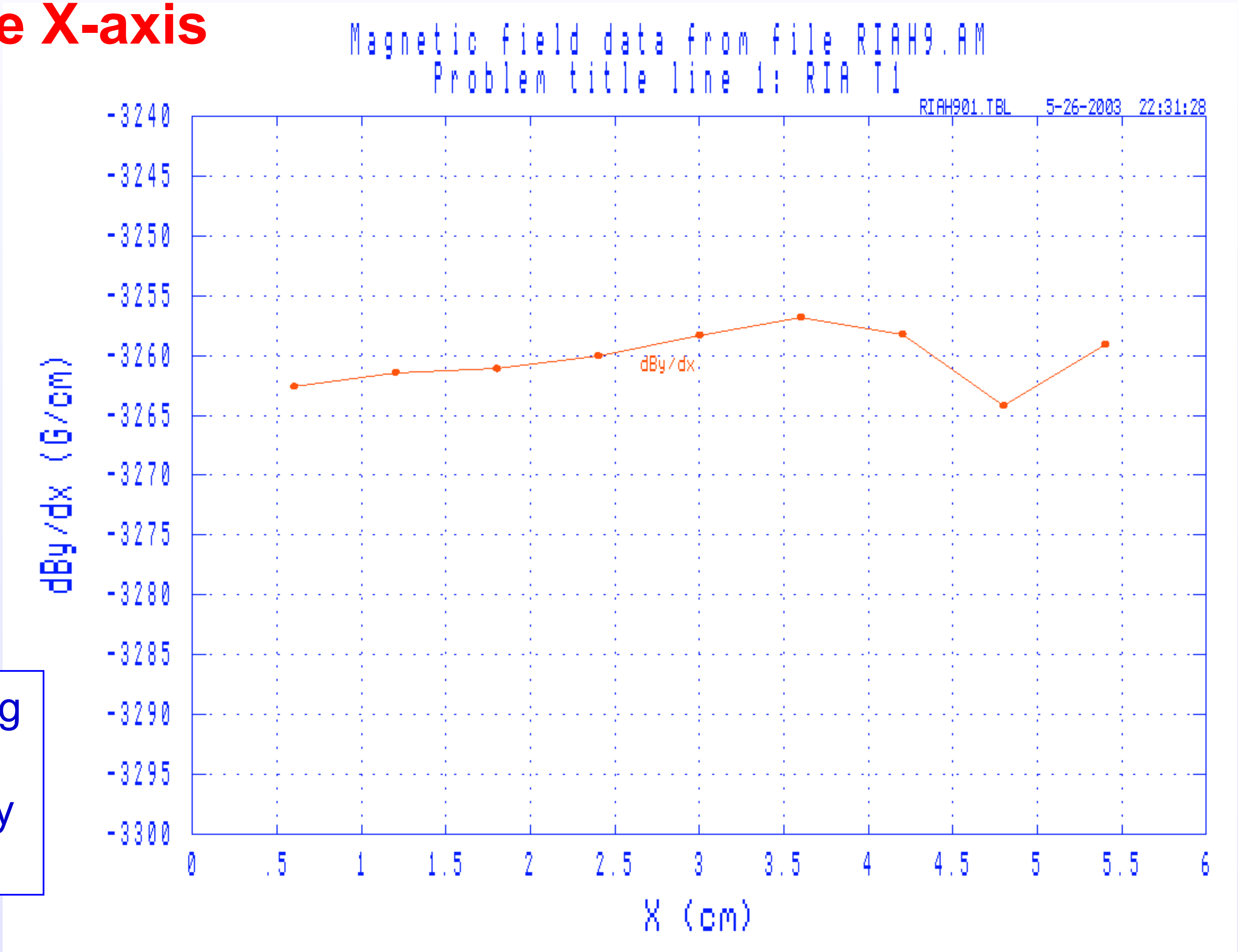
Field Quality in the Proposed Alternate Design

Gradient on the X-axis

The required good field aperture is 5 cm

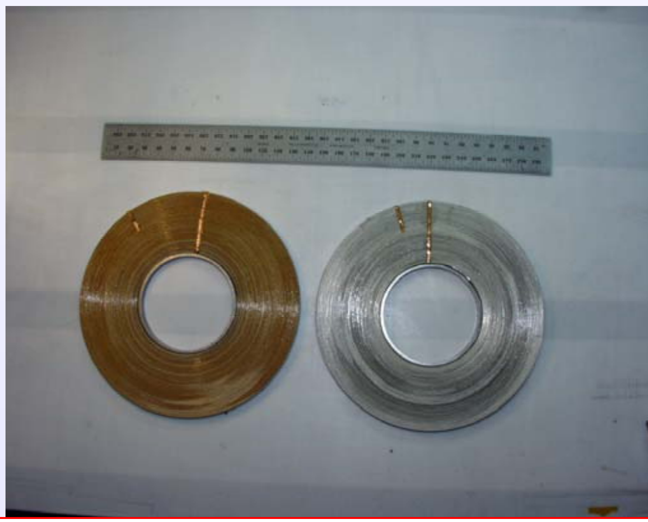
Coil starts at x = 22 cm and yoke at R_{yoke} = 5.5 cm

The design is still being optimized. The field quality in this geometry is already OK.



Insulation in HTS Coils Built at BNL

BNL has successfully tested several HTS R&D magnets and test coils made with BSCCO 2212 and BSCCO 2223 tape. A unique and very pertinent feature of these coils is the successful use of stainless steel as the insulation material between turns. This technique was developed to provide a strong mechanical coil package capable of withstanding the large Lorentz forces in a 25T environment, but will also provide a highly radiation resistant coil.



Two double pancake NMR coils, one with kapton insulation and the other with stainless steel.

S.S. insulation works well with superconductors

HTS Test Coil for an Accelerator Magnet

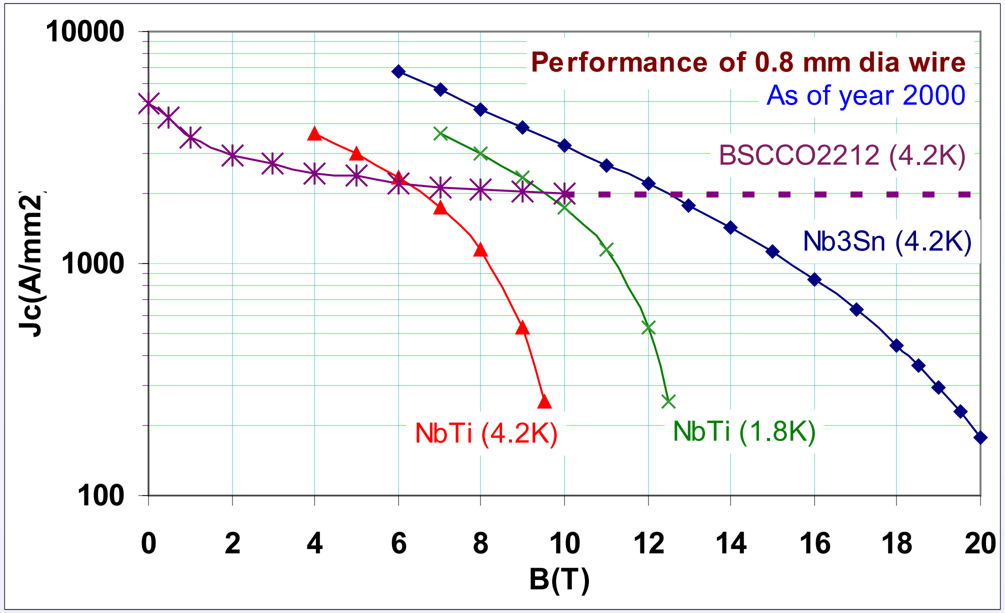
Summary and Status of the Alternate Design of the 1st QUAD in RIA Fragment Separator

Apart from providing a good technical solution, this design should bring a large reduction in the operating costs.

- HTS Quads can operate at much a higher temperature (20-40 K instead of 4K).
- The iron yoke is warm (or at least at ~80 K, which can be cooled by liquid nitrogen). This brings a major reduction in amount of heat to be removed at lower temperature.
- The coils are moved significantly outward to reduce radiation dose by a large amount.
- HTS can tolerate an order of magnitude higher temperature variations during operation.
- The possibility of stainless steel insulation is highly attractive.
- It is shown that the field quality requirements can be met.

High Field Magnet Designs with HTS

NOTE: High Temperature Superconductors (HTS) are uniquely suitable for generating very high fields since, unlike in conventional Low Temperature Superconductors (LTS), the reduction in critical current density as a function of field is much smaller at very high fields.



Applications Under Considerations

- Common Coil 2-in-1 Dipole Design for Hadron Colliders
- Neutrino Factory Storage Ring/Muon Collider Dipole (and Quads) Design
- Interaction Region Magnets (Dipole and Quadrupoles) for High Luminosity Colliders (e.g. for LHC Luminosity Upgrade)

Design Issues for High Field Accelerator Magnets using HTS

- HTS is very brittle

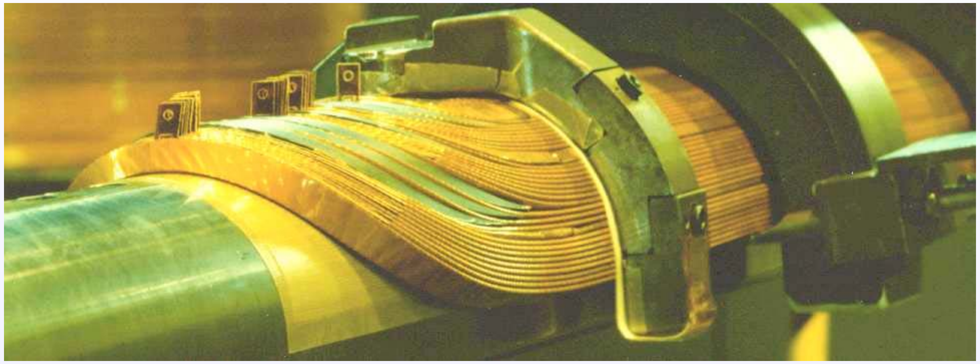
  Conventional designs are not the most suitable

- Large Lorentz forces

- The required temperature uniformity during the heat treatment is high:

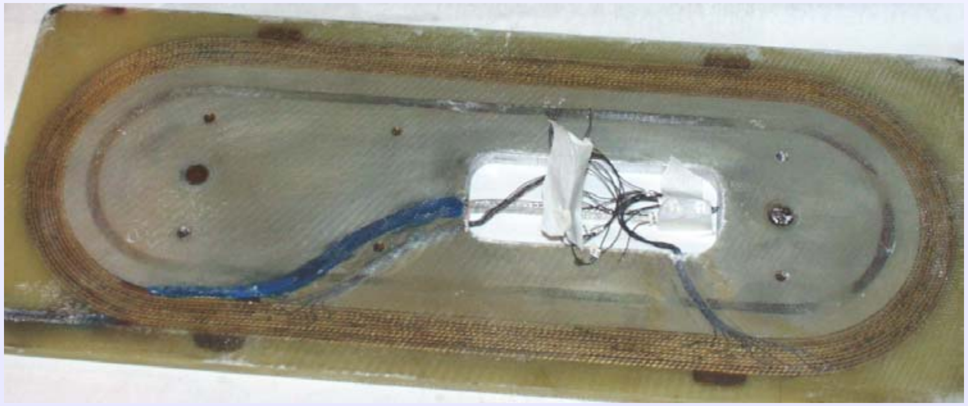
  (~1/2 degree at ~890^o C)

⇒ React & Wind Approach



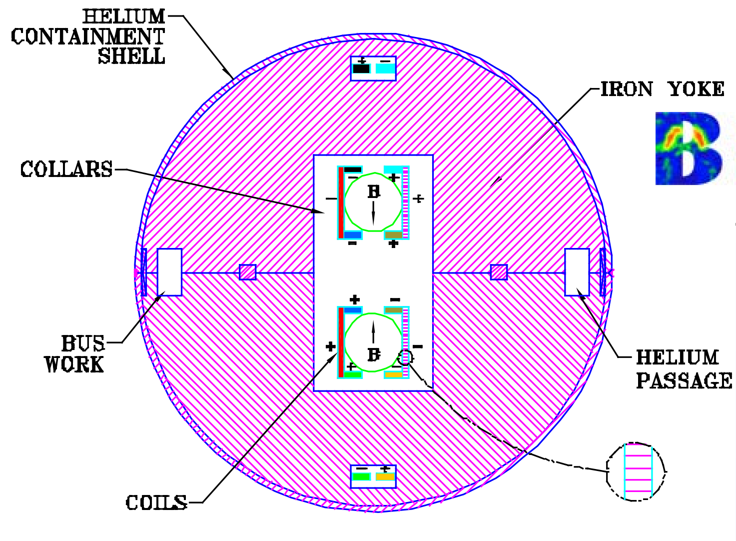
Conventional cosine θ design (e.g., RHIC magnets)

Complex 3-d geometry in the ends



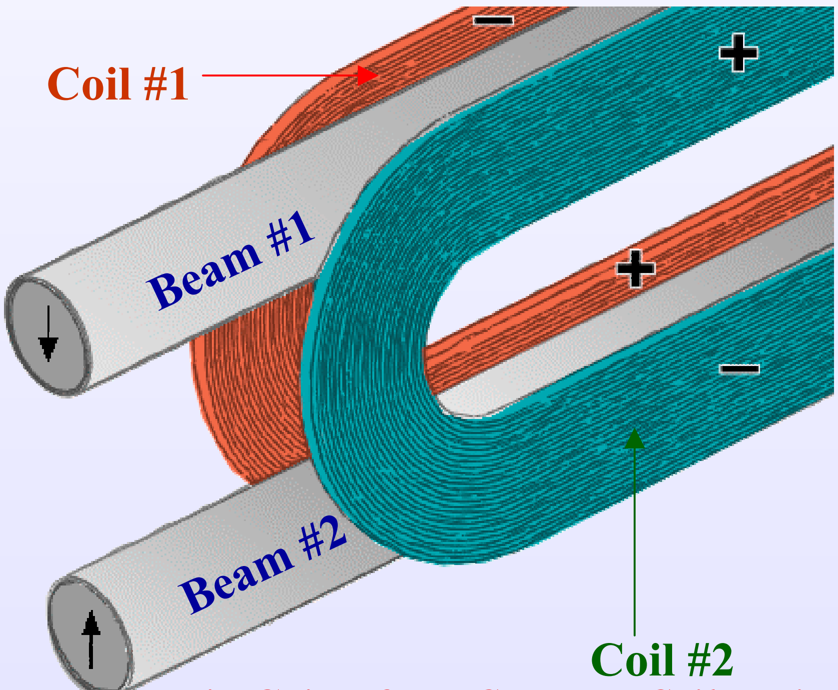
"Conductor friendly" racetrack coil with large bend radius

Suitable for high field magnets with brittle material



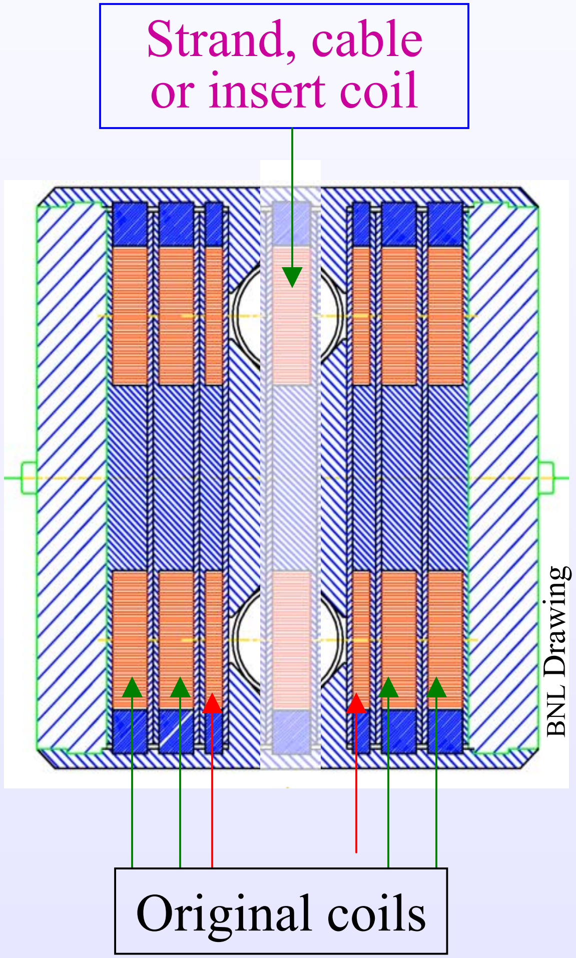
Common Coil Design

- **Simple 2-d geometry with large bend radius** (determined by spacing between two apertures, rather than aperture itself).
- **Conductor friendly (no complex 3-d ends, suitable for brittle materials - most for H.F. are - Nb_3Sn and HTS).**
- **Compact (quadrupole type cross-section, field falls more rapidly).**
- **Block design (for handling large Lorentz forces at high fields).**
- **Combined function magnets possible.**
- **Efficient and methodical R&D due to simple & modular design.**
- **Minimum requirements on big expensive tooling and labor.**
- **Lower cost magnets expected.**



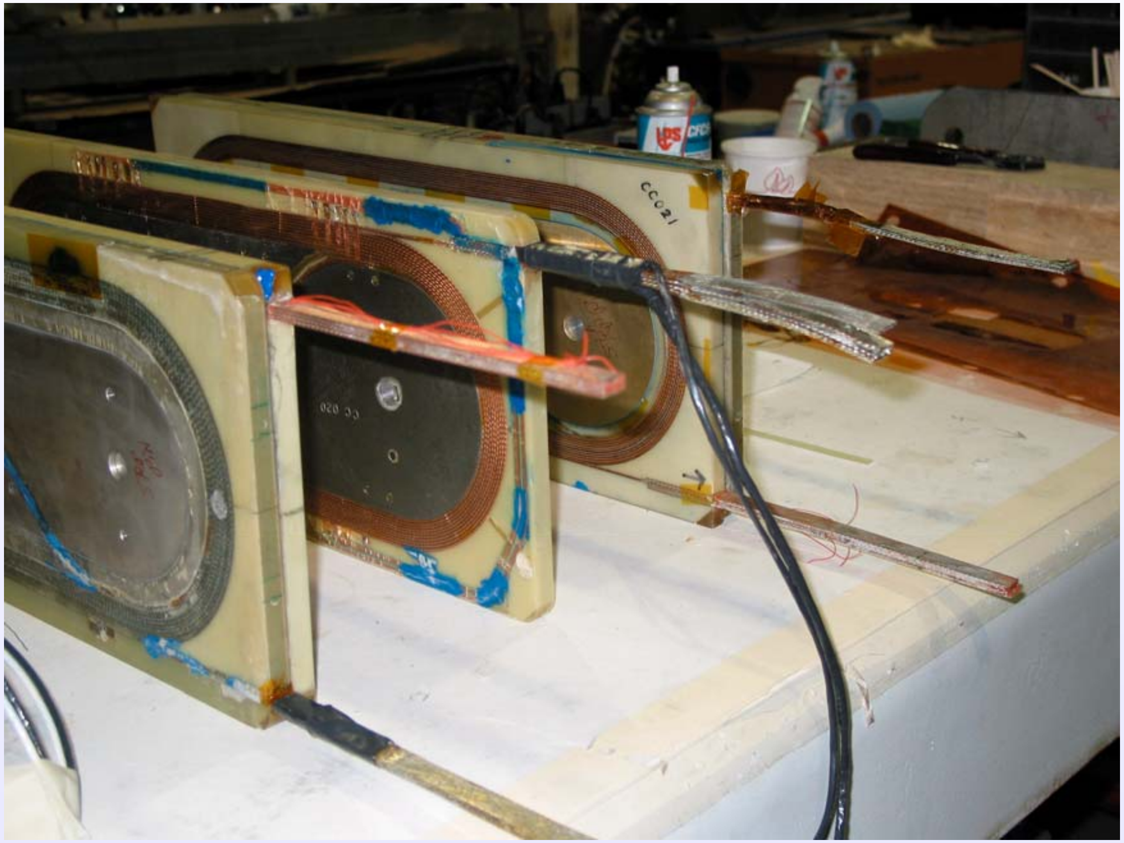
Main Coils of the *Common Coil Design*

Common Coil Magnet As A Test Facility



- **A Modular Design with a significant flexibility.**
- **Coil geometry is vertical and flat. That means a new coil module having even a different cable width can be accommodated by changing only few parts in the internal support structure.**
- **The central field can be increased by reducing the separation between the coils.**
- **The geometry is suitable for testing strands, cables, mini-coils and insert coils.**
- **Since the insert coil module has a relatively small price tag, this approach allows both *"systematic"* and *"high risk"* R&D in a time and cost-effective way. This might change the way we do magnet R&D.**
- **Can use the successful results in the next magnet.**

Racetrack Coil Cassettes for Rapid Turn Around Magnet R&D Facility



5 cassettes for a 2/3 layer magnet test

BNL makes racetrack coils in modular structure. These modules (cassettes) can be mixed and matched for a variety of experiments in a rapid turn around fashion.

For example, one can easily change aperture, number of layers, type of magnet, etc.

Try such things in a cosine theta magnet!!!

Magnet Scientists dream of systematic, cost–effective and rapid turn around magnet R&D. The way science used to be, I am told!

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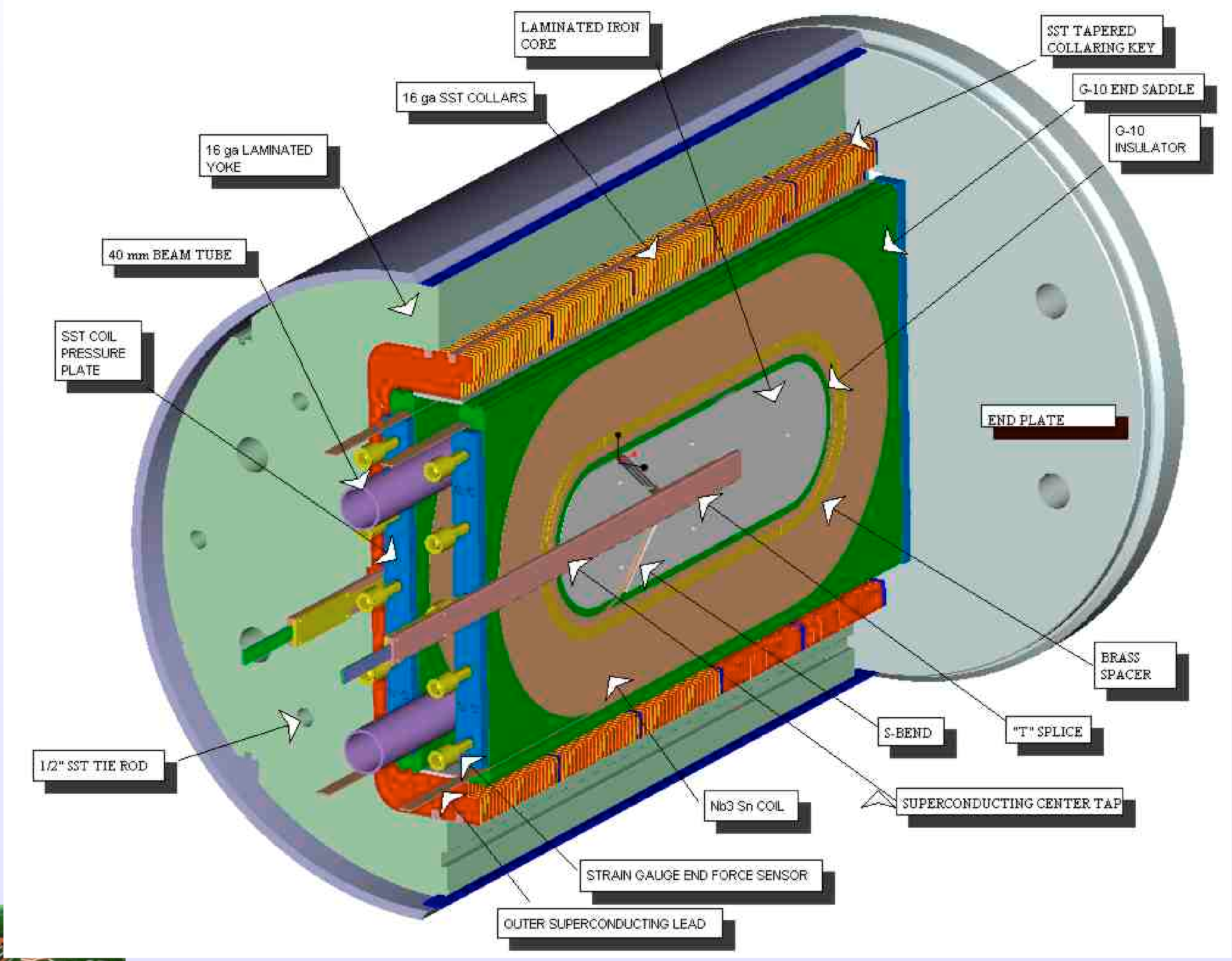
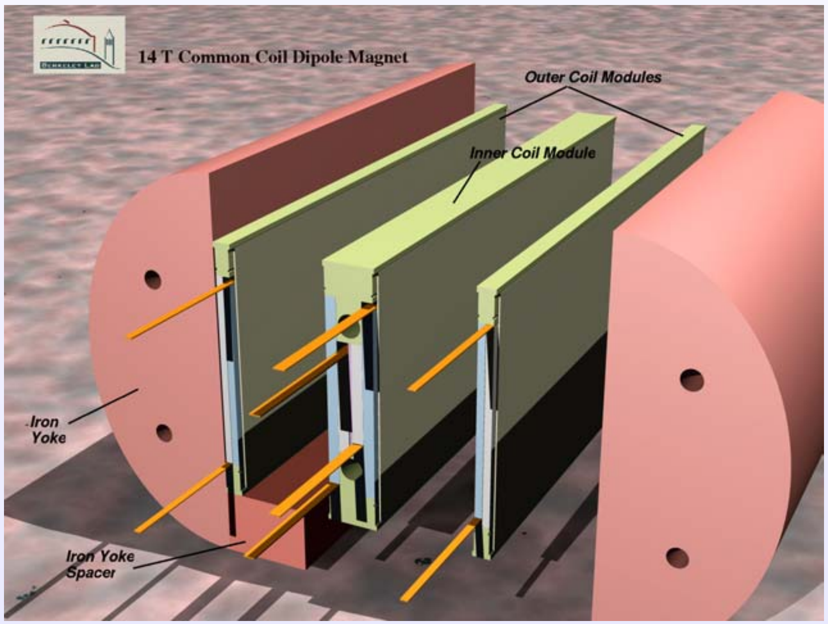
BNL 12 T Nb_3Sn Common Coil Background Field Dipole

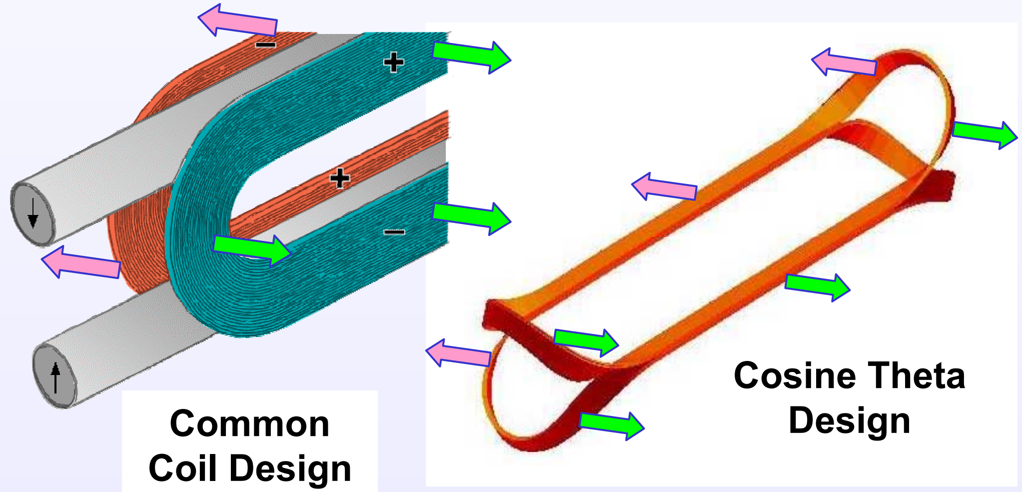


Nb_3Sn conductor for both inner and outer layers is provided by OST

R&D on Common Coil Dipole at Other Labs

Lawrence Berkeley National Laboratory (LBNL) made a new world record (14.7 T) for accelerator R&D dipole using common coil design.





In common coil design, Large Horizontal forces don't create high strain on cable

Fermi National Accelerator Laboratory (FNAL) is working on a 11 T common coil dipole .

Magnet Design for ν Factory

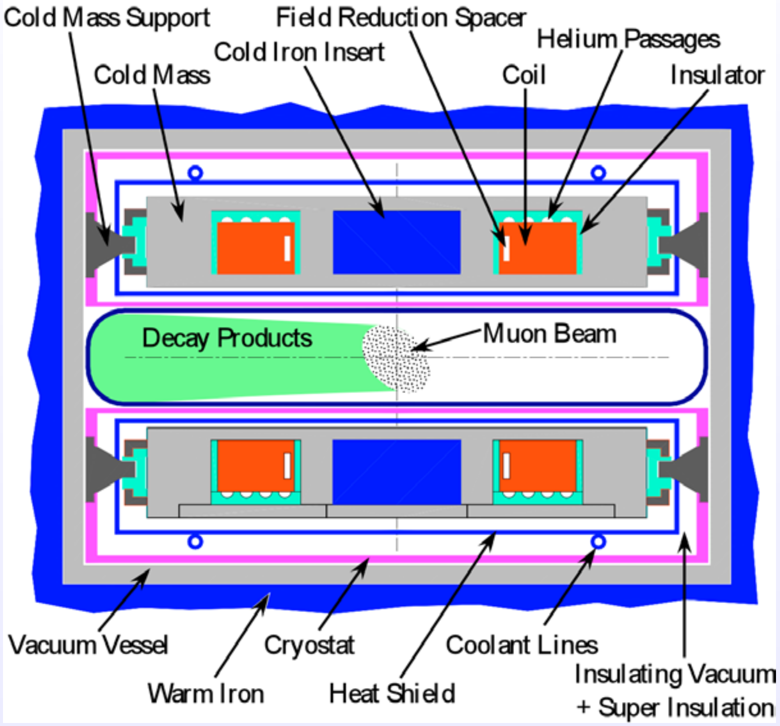
Decay products clear s.c. coils

- **Flat coils with open midplane gap**

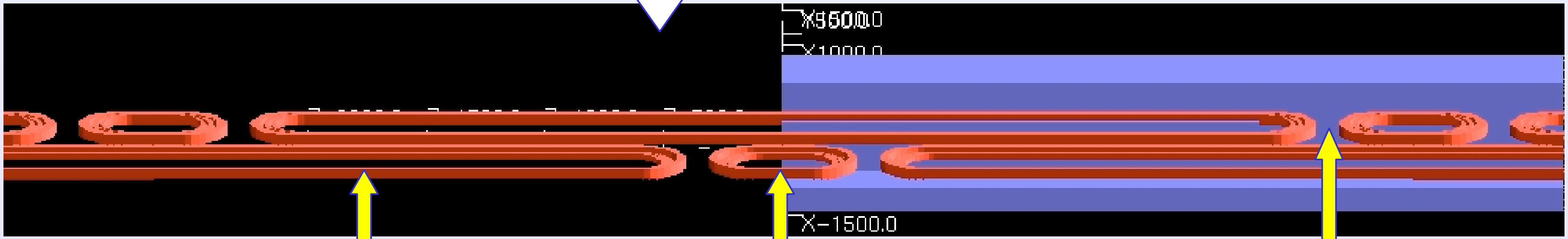
Minimize environmental impact

- High field magnets, efficient design

Simple racetrack coils
with large bend radii



Bx, By errors in the ends
get automatically cancelled



Normal Coils
Dipole

Reverse Coils
Skew Quad

One Coil
1/2 & 1/2

Interaction Region (IR) Magnets

Interaction region magnets for the next generation colliders can benefit a lot from:

- the ability to produce very high fields
- the ability to deal with large energy deposition
- the ability to operate at elevated temperatures that need not be uniform

→ For these IR magnets, the performance, not the material cost is the issue.

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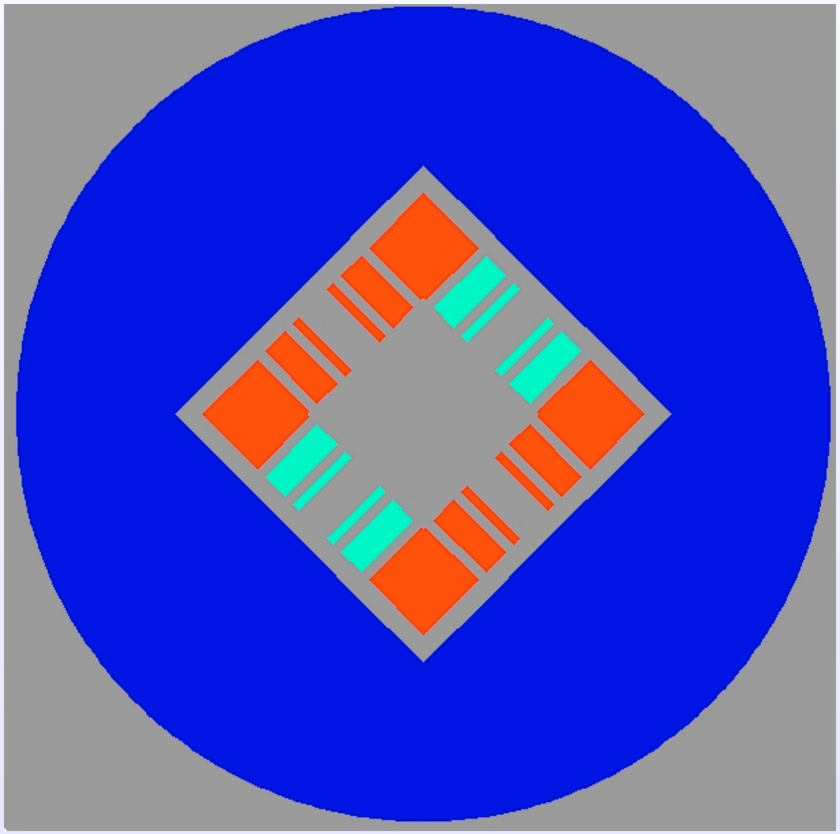
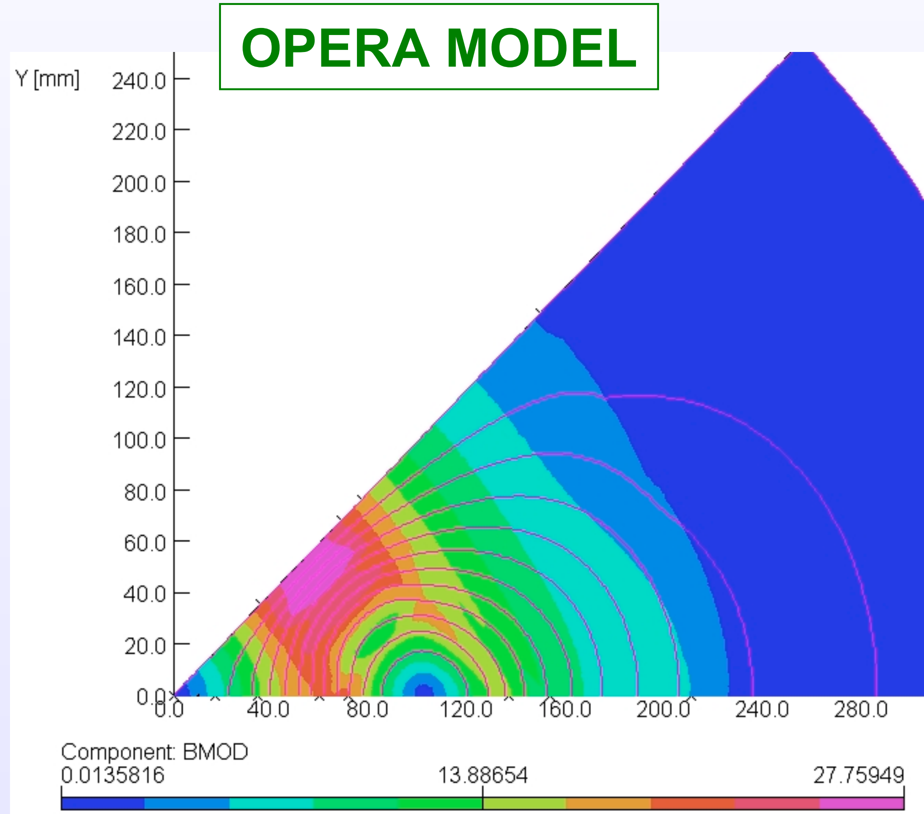
HTS Quad Design for LHC IR Upgrade (Racetrack Coil Geometry)

Gradient: 400 T/m; Jo = 1 KA/mm^2, Jc ~ 4-5 kA/mm^2

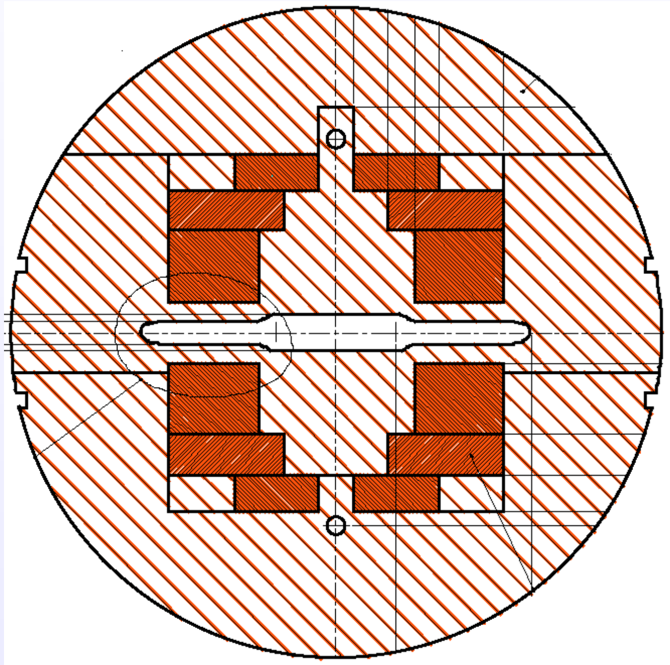


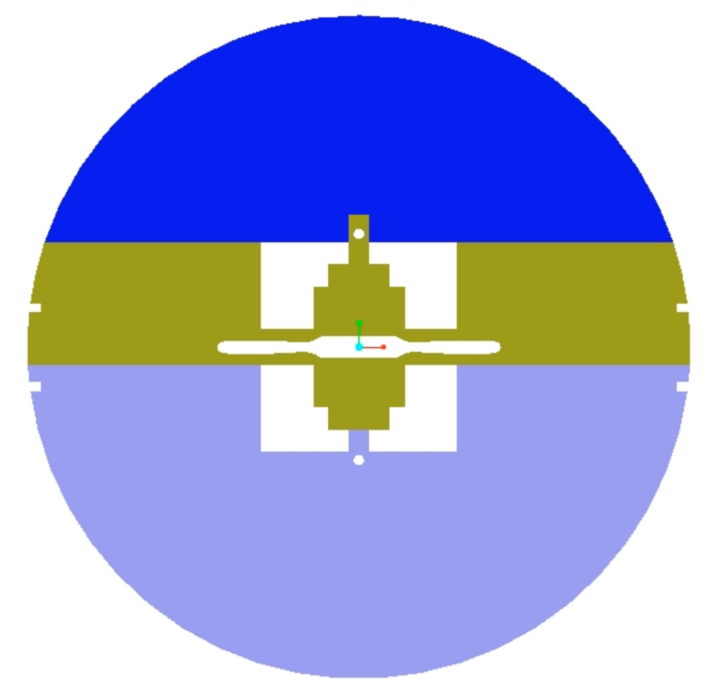


<u>Note:</u> Peak field is not a major concern in HTS quadrupole designs.

LHC IR Dipole: Collared Coil Support Structure (Preliminary)

Open midplane for decay products to pass through without hitting the coils.





Open midplane means no coil or support structure; otherwise showers are created which hit the coil.

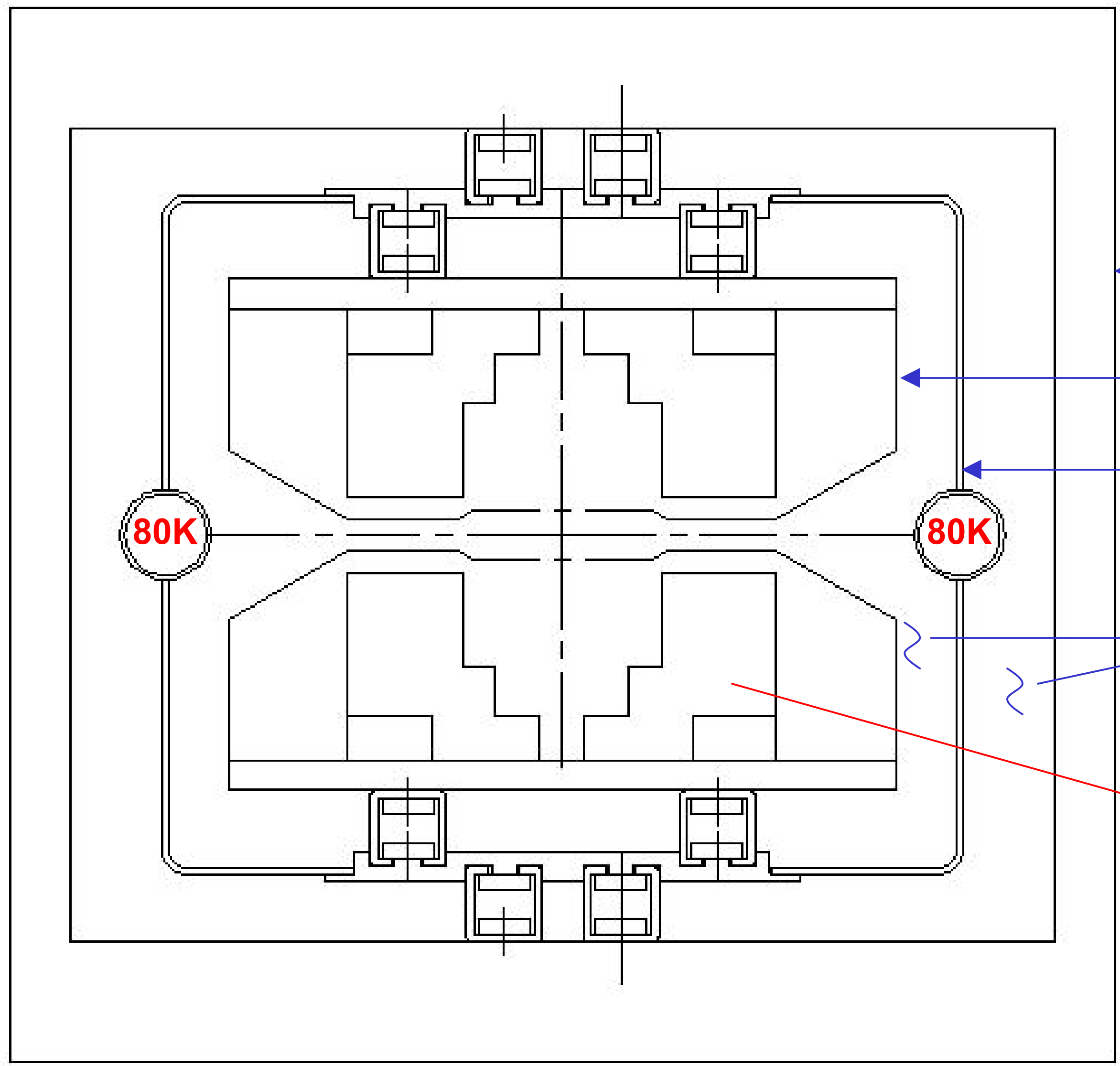
Bss: ~15T
Aperture:
H: ~90 mm
V: 20 mm

Decay products hit the external structure at 4K.

The magnetic and mechanical designs will be optimized more after the initial energy deposition calculations (NEWS FLASH: just completed).

Field quality is poor and the coils should be brought closer to midplane.

LHC IR Dipole: Another Concept for Support Structure



Dump IP shower in a relatively warmer structure

(more efficient heat removal)

Warm Iron Design

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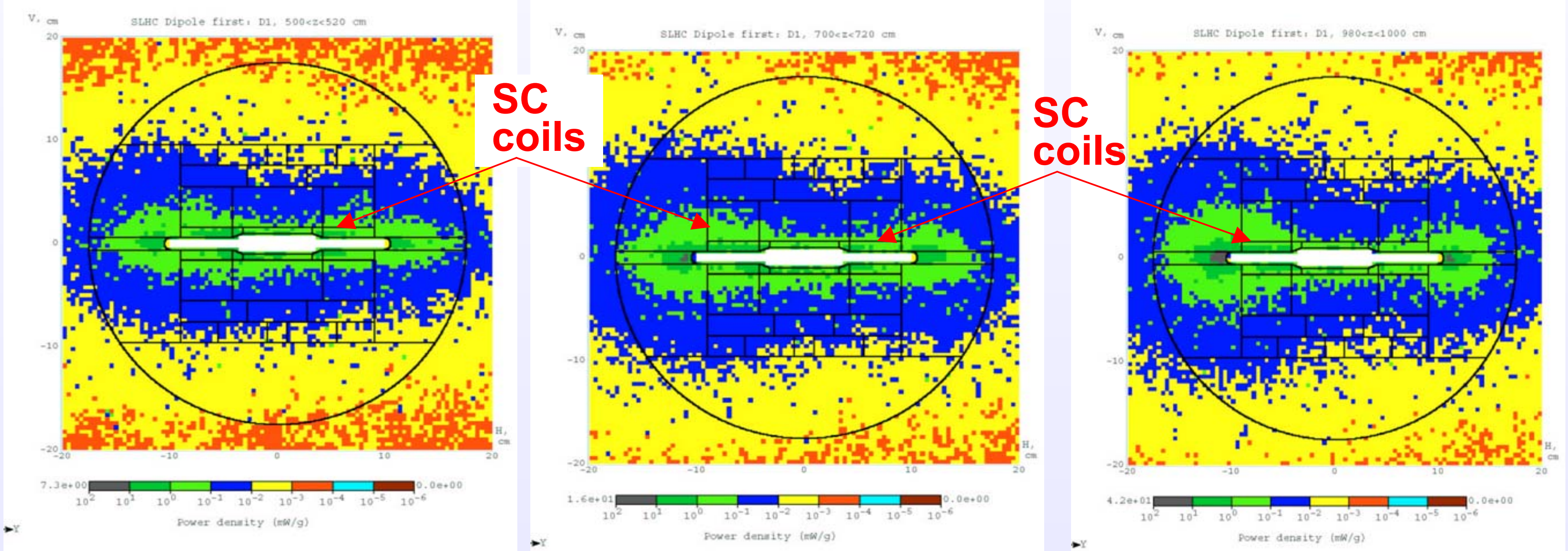
Energy Deposition Calculations

Energy deposition at various axial position along the axis

Computed by Nikolai for a Luminosity of 10^{35} (10X over present design)



@Middle (z=>5m-5.2m) | @70% (z=>7m-7.2m) | @End (z=>9.8m-10m)

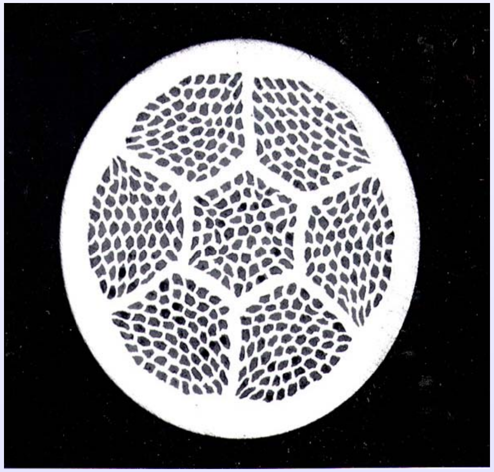
Peak power density in the superconducting coils is only 1-1.3 mW/g, i.e., below our current quench limit of 1.6 mW/g even at 10^{35} luminosity!!!

Construction and Test Results from HTS Technology Development Program at BNL

Next Few Slides will Show:

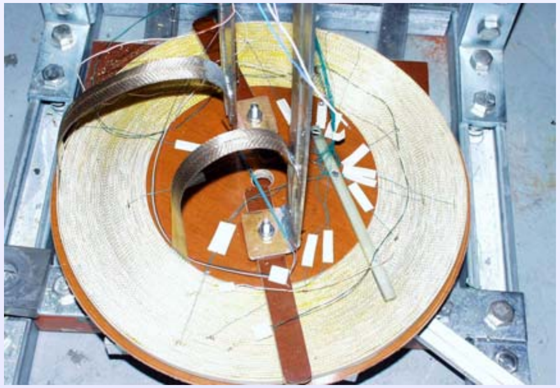
- Results of HTS Tape and Cable Tests
- Construction and Test Results of HTS Coils and R&D Magnets

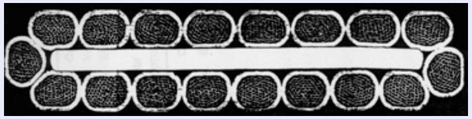
Please see the tape and cable being distributed



HTS Wire

HTS Tape





10+ kA HTS Rutherford Cable
BNL/LBL/Industry collaboration

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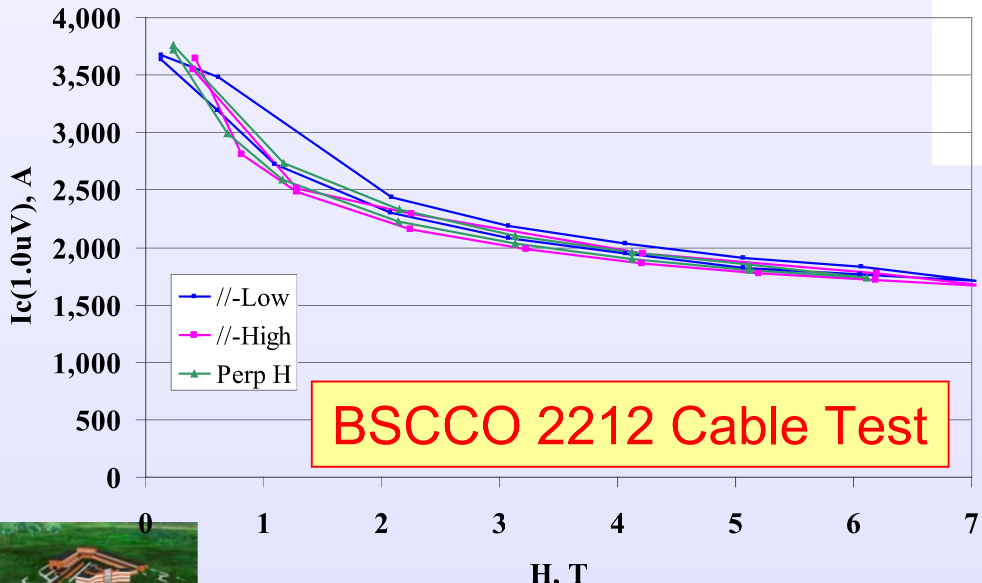
Measured Performance of HTS Cable and Tape As A Function of Field at BNL

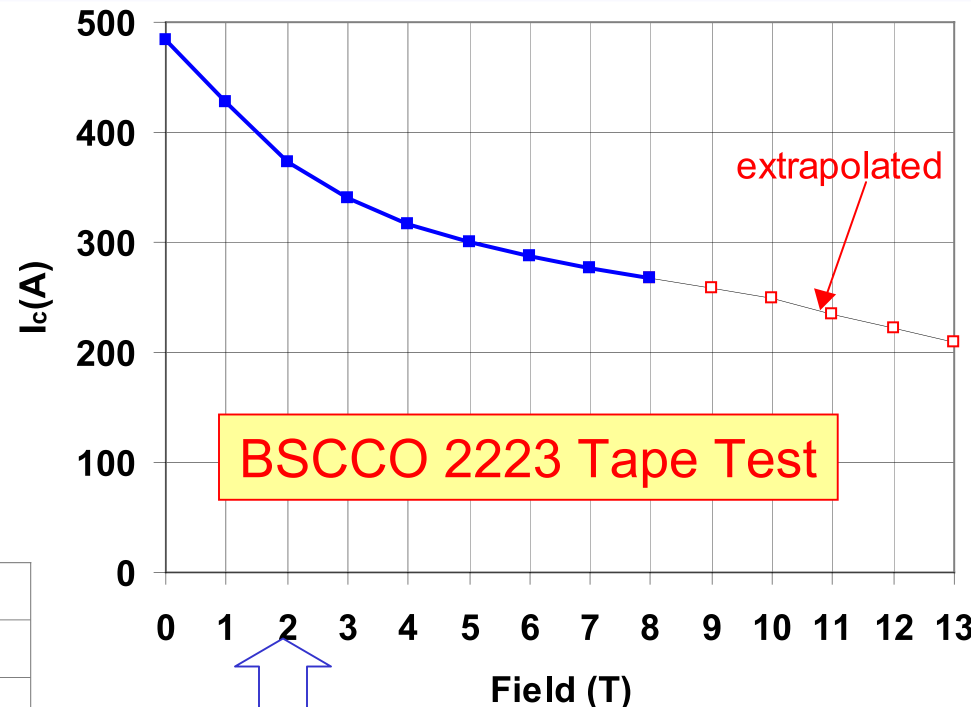
Measurements of "***BSCCO-2212 cable***" (Showa/LBL/BNL) at BNL test facility

The latest cables are ~ 3x better than the one shown below.

These new cables can carry 5-10 kA current at high fields!

(self field correction is applied)



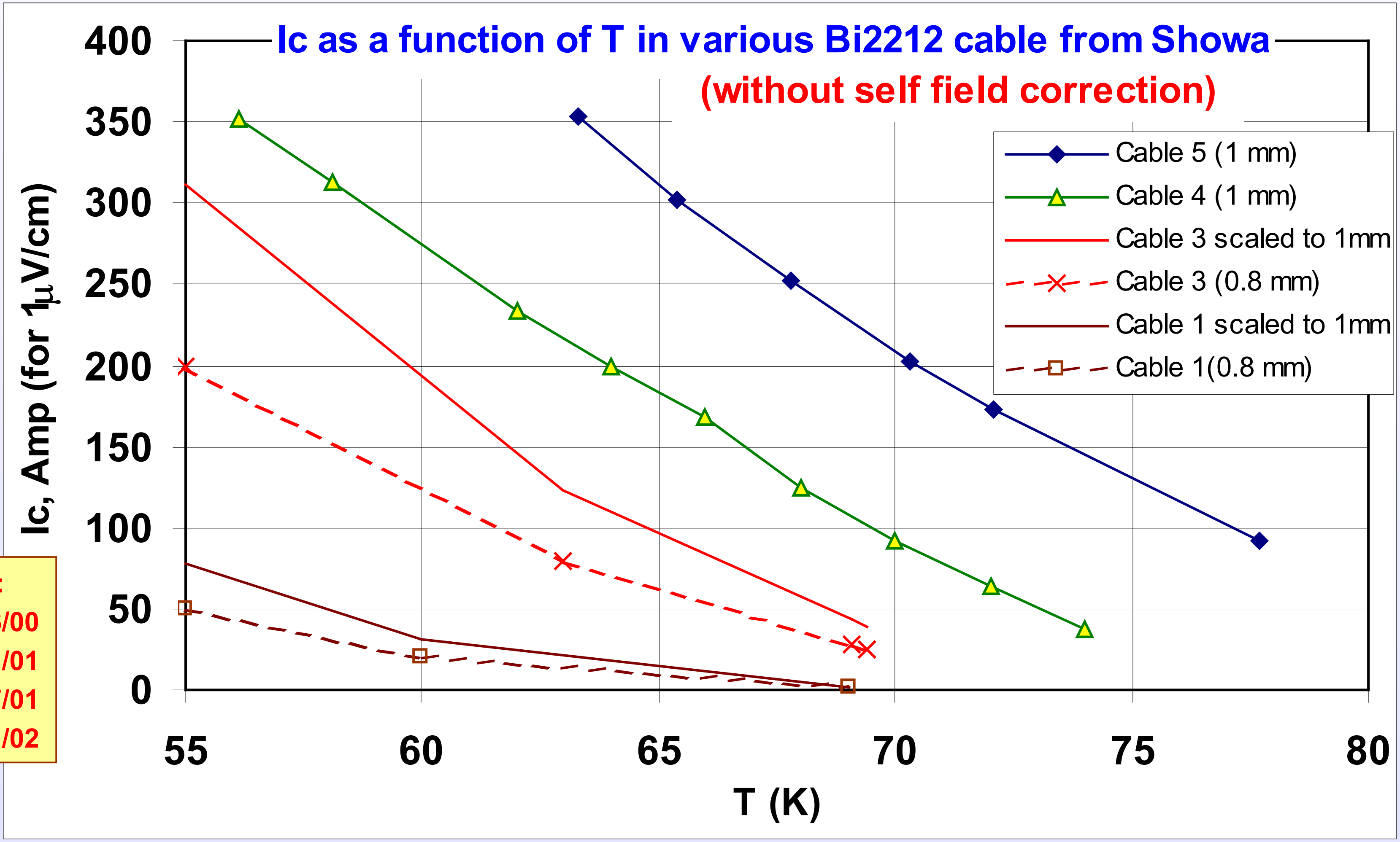


Measurements of "***BSCCO 2223 tape***" wound at 57 mm diameter with applied field parallel (1μV/cm criterion)

(field perpendicular value is ~60%)

BNL Measurements of Various Cables from Showa (Note: Continuous progress in cable performance)

Extrapolated 4 K performance of 20 strand cable (#5) (wire dia = 1 mm) : ~5 kA at high fields and ~9 kA at zero field



Test Dates:
Cable 1: 06/00
Cable 3: 01/01
Cable 4: 07/01
Cable 5: 11/02

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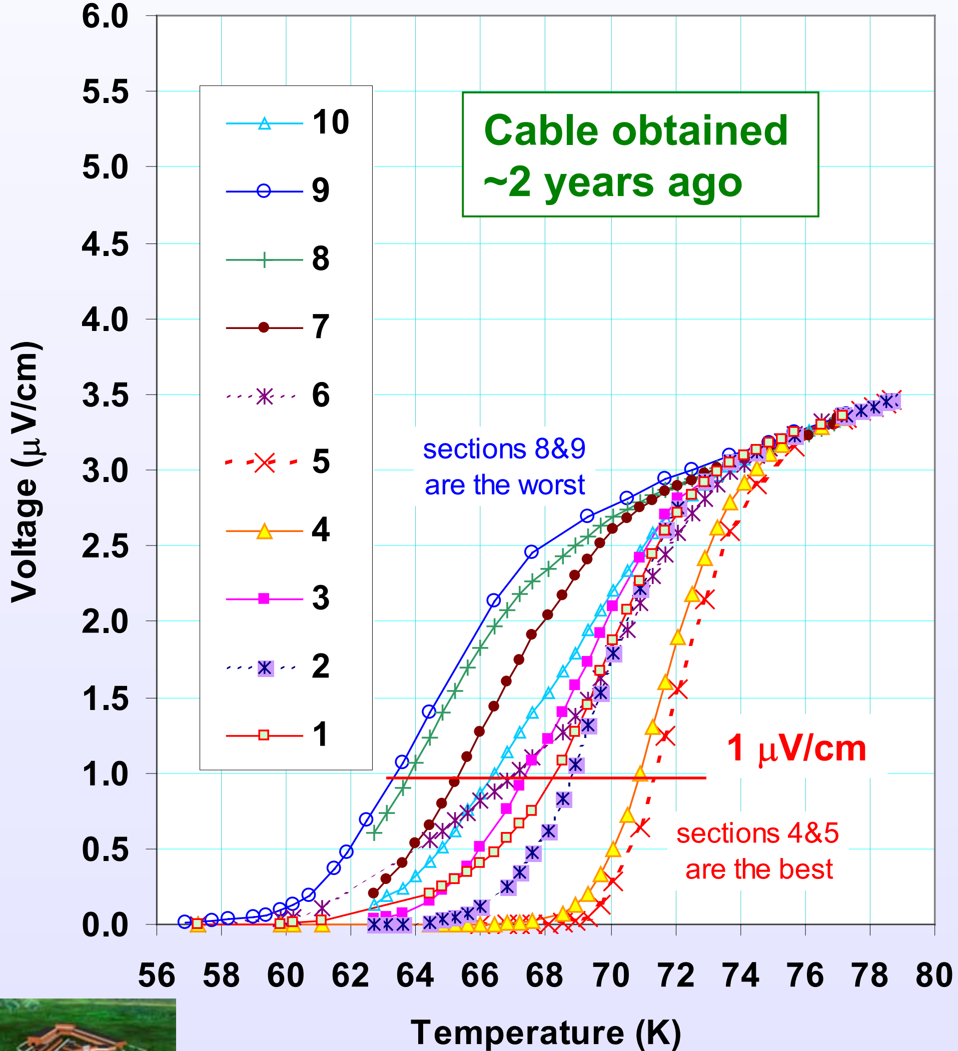
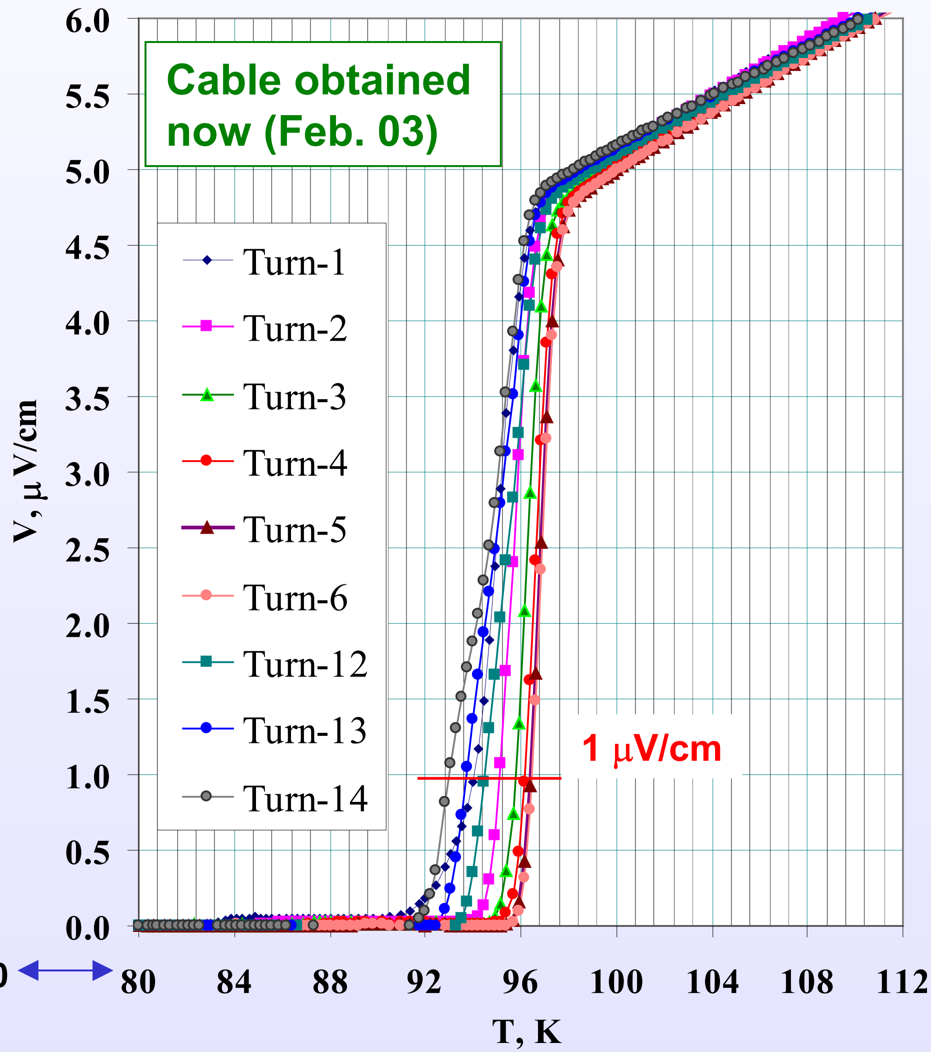
Improvement in Tc of BSCCO-2212 Cable from Showa

Note the improvements both, in the absolute value and in the spread.





Common Coil Magnets With HTS Tape

NOTE:

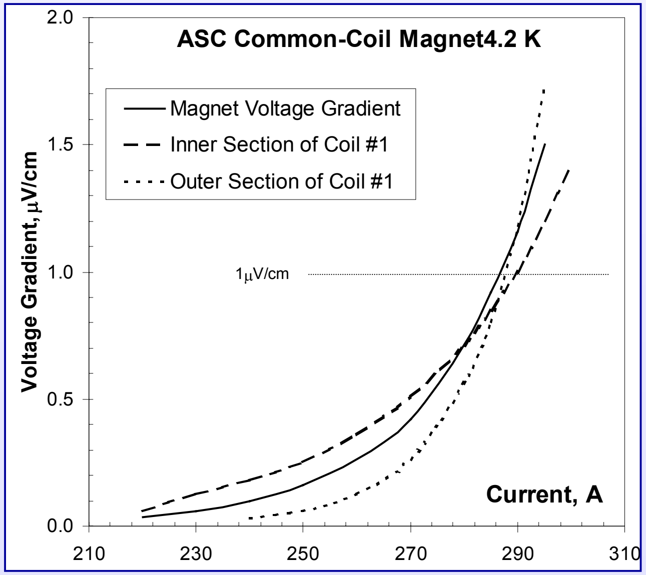
This coil package is very similar to the one that is required for the RIA Quads.

Two HTS tape coils in common coil configuration

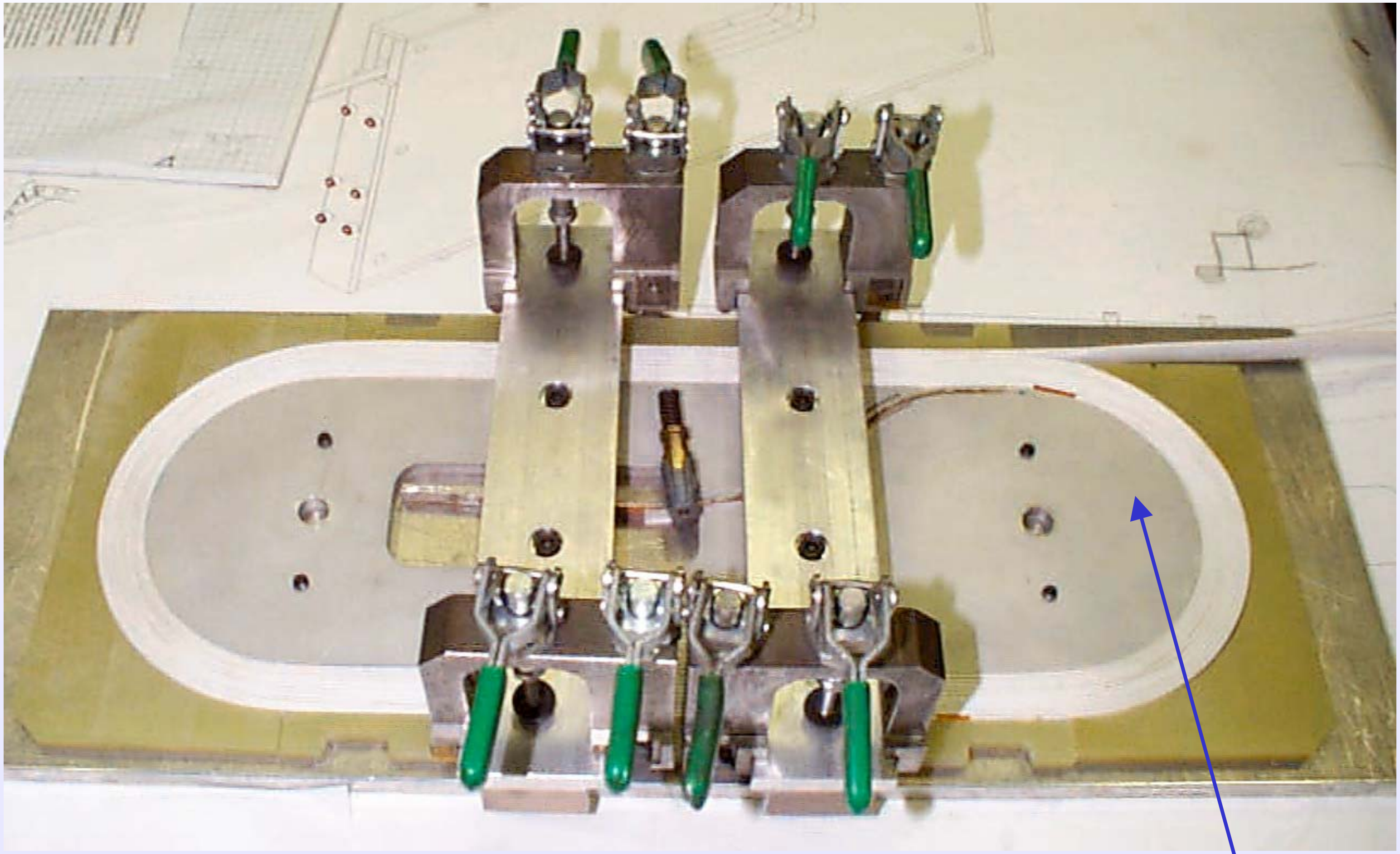
A coil being wound with HTS tape and insulation.

HTS tape coils at BNL

	Size, mm	Turns
Nb_3Sn	0.2 x 3.2	168
IGC	0.25 x 3.3	147
ASC	0.18 x 3.1	221
NST	0.20 x 3.2	220
VAC	0.23 x 3.4	170



First HTS Coil Wound by Hand



Al Bobbin (70 mm radius)
(also used, Fe, SS and brass bobbins)

The first HTS Common Coil Test Magnets (Two HTS Coils in Support Structure)

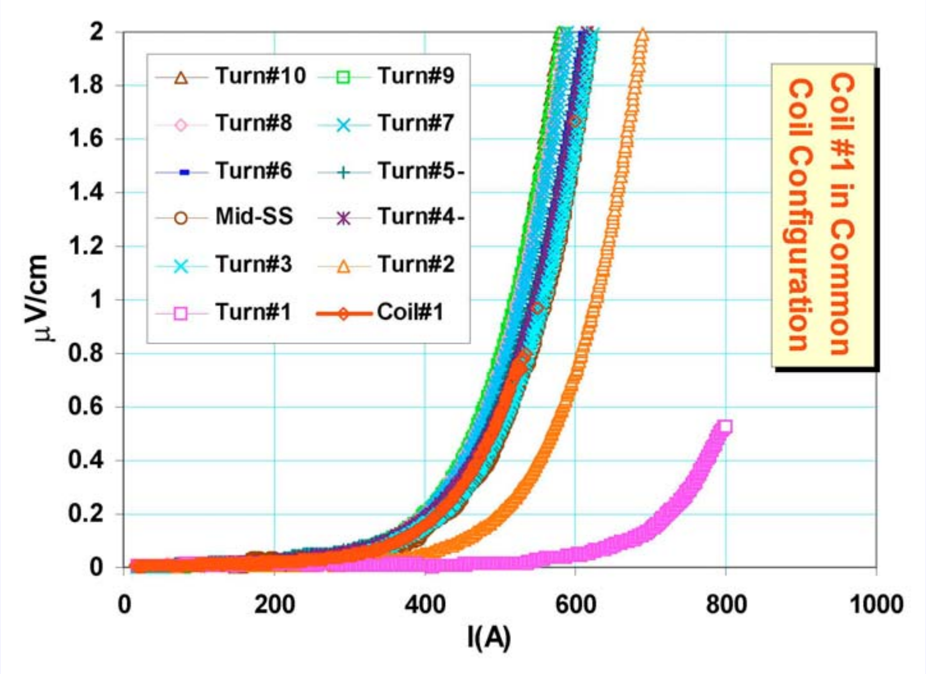
Coils are heavily instrumented. There is a voltage tap after each turn. Data were recorded from all 26 voltage taps.

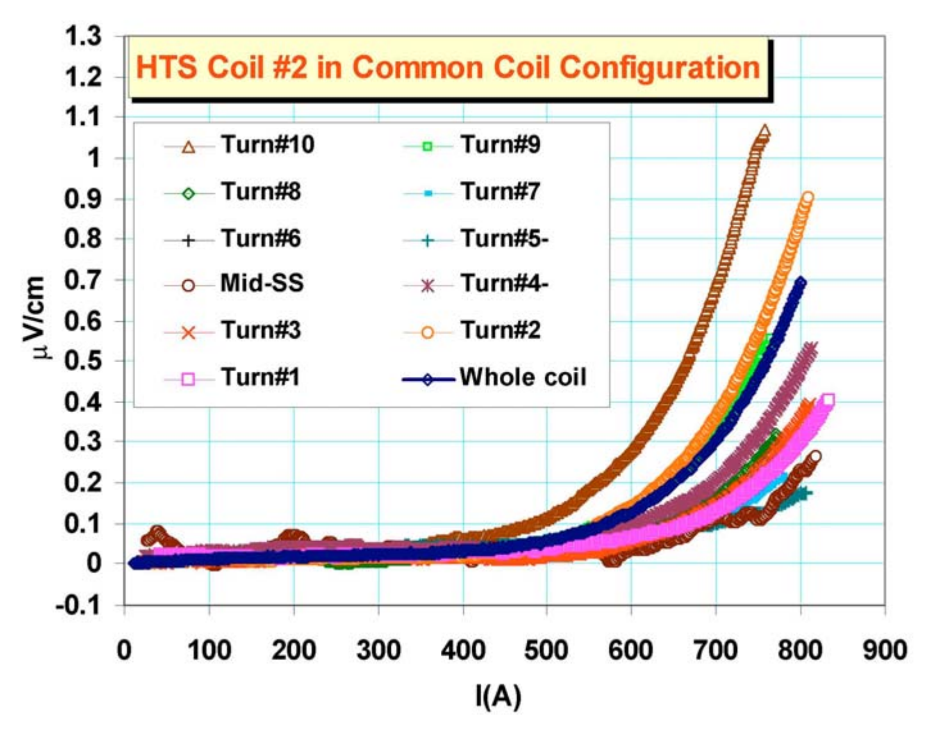
Coils are assembled for the most flexible and extensive testing. Four leads are taken out of the cryostat. During the test the coils were powered separately and together in “common coil” and “split-pair solenoid mode”.

Two Hall probes (between the two coils and at the center of two coils) also recorded the central field.

Performance of Coil #1 and Coil #2 in Common Coil Test Configuration in Magnet (DCC004)

Voltage difference between each consecutive turn and on each coil





Measurements in HTS Magnet DCC004 at 4.2 K

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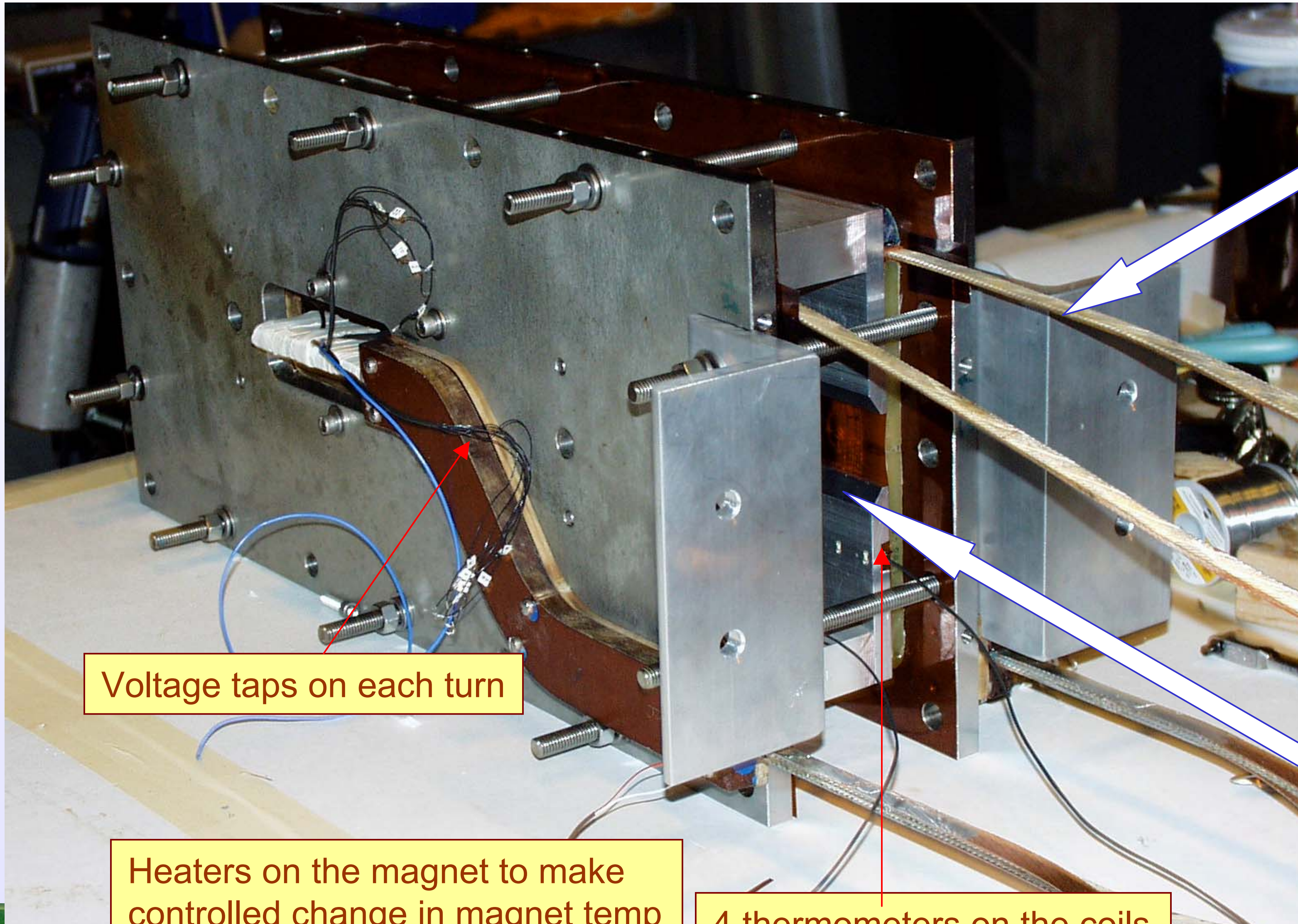
Magnet DCC006: The 2nd HTS Dipole

(Magnet No. 6 in the common coil cable magnet series)

A versatile structure to test single or double coils in various configurations



HTS Cable Leads to make high temp measurements

74 mm aperture to measure field quality

Heaters on the magnet to make controlled change in magnet temp

4 thermometers on the coils

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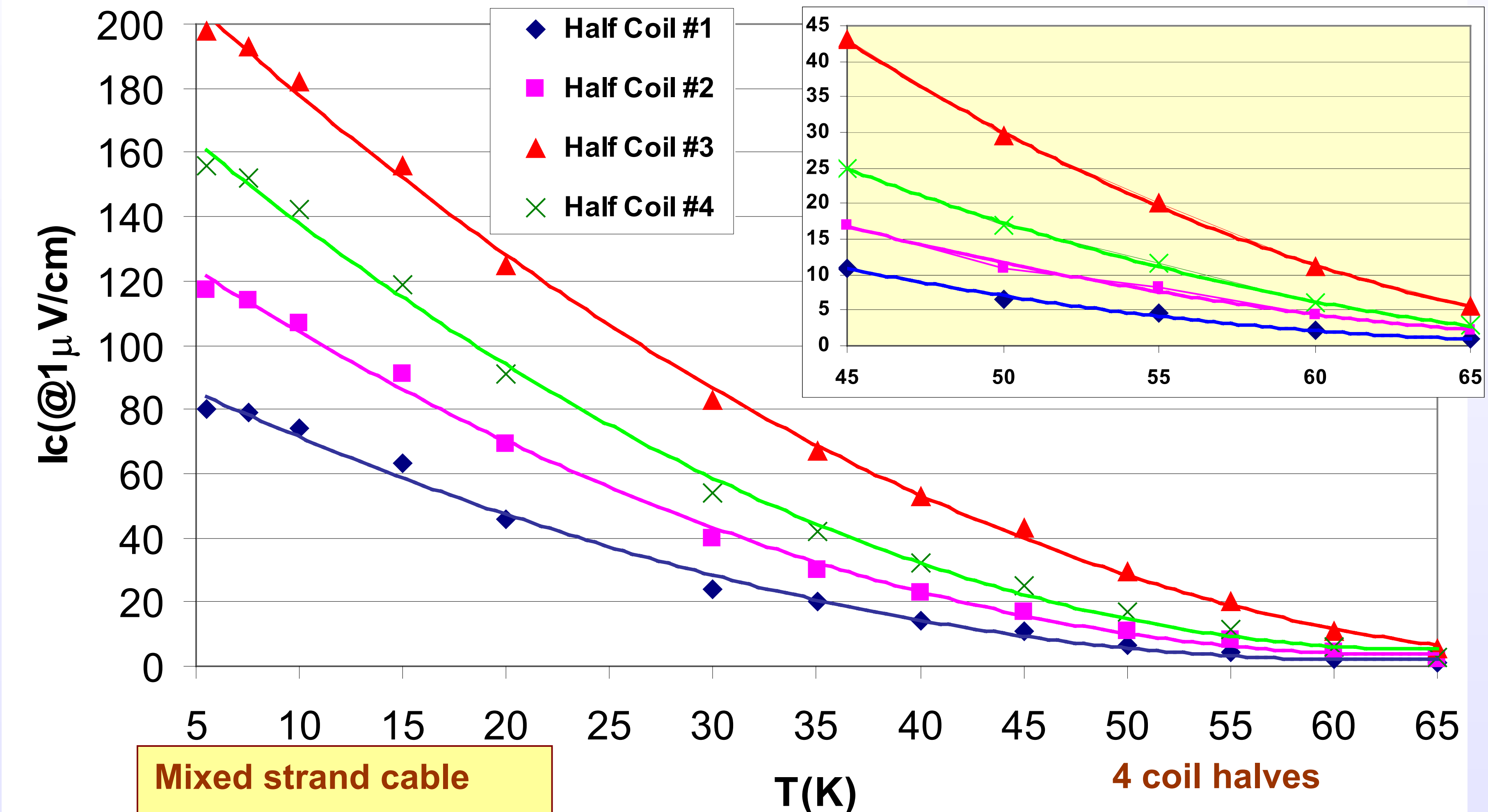
Measured Critical Current as a Function of Temperature

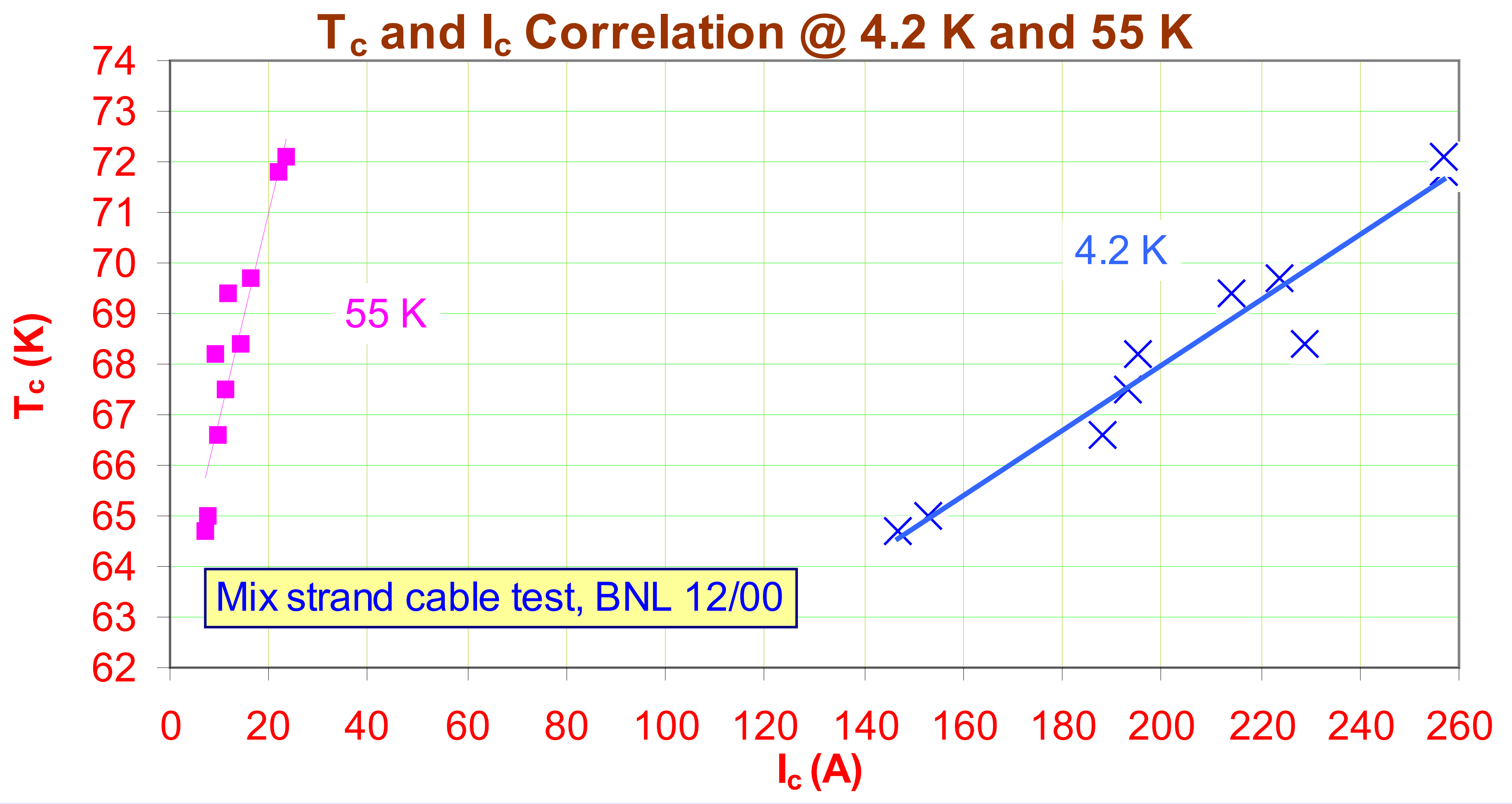
This temperature dependence characteristic is very relevant to RIA Application.



Mixed strand cable (2 BSCCO 2212, 16 Ag)

4 coil halves (2 each of two coils)

Correlation between T_c and I_c



The cable with better T_c also had better I_c

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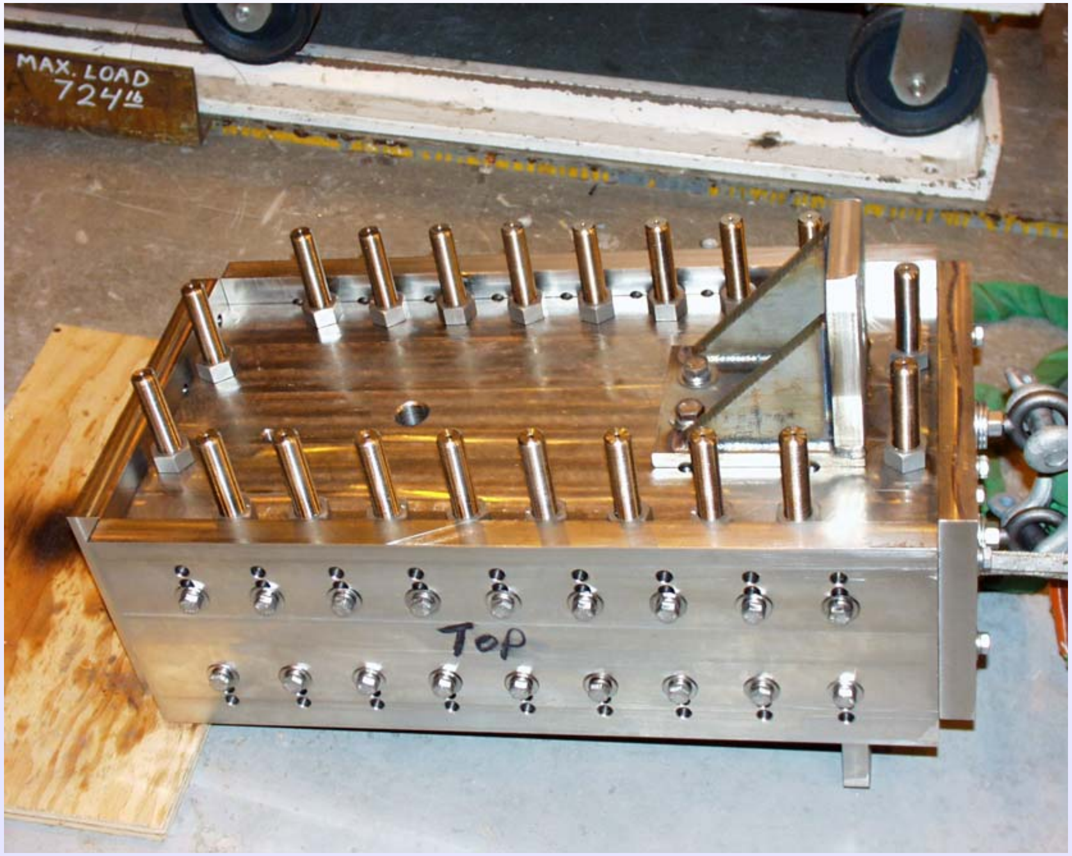
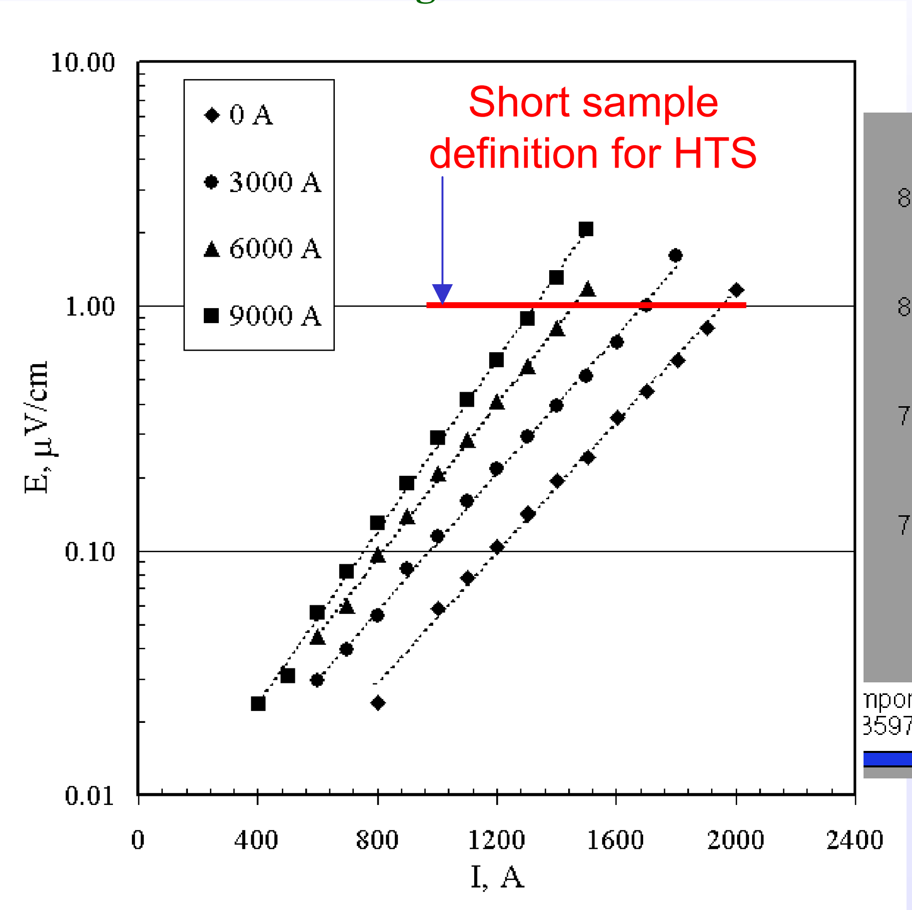
HTS Coil Test Magnet #3



- The HTS coil is made with all HTS strand cable
- A hybrid magnet made with three coils (one HTS and 2 Nb_3Sn); Nb_3Sn coils provide background field on HTS Coil.
- Vary current in Nb3Sn coils (producing background field) to study HTS coil performance at different field level.

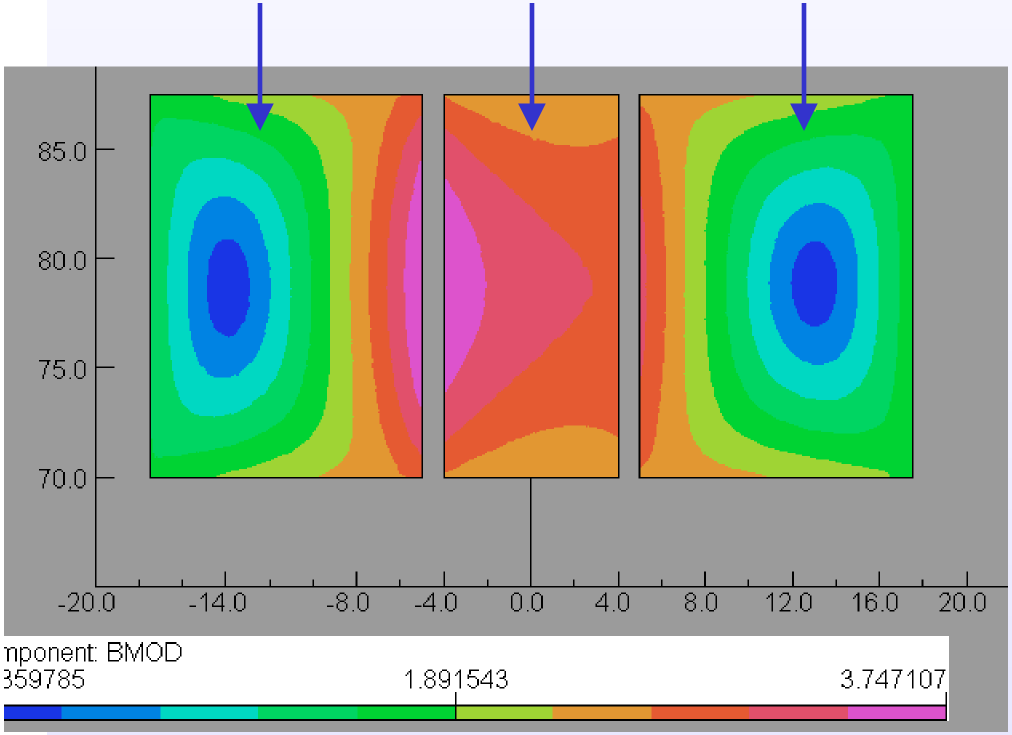
Performance of HTS Coil in the Background Field of Nb_3SN Coils

Measured electrical Resistance of HTS coil in the background field provided by various Nb3Sn coils in the magnet DCC008R



Field in various coils

Nb_3Sn HTS Nb_3Sn



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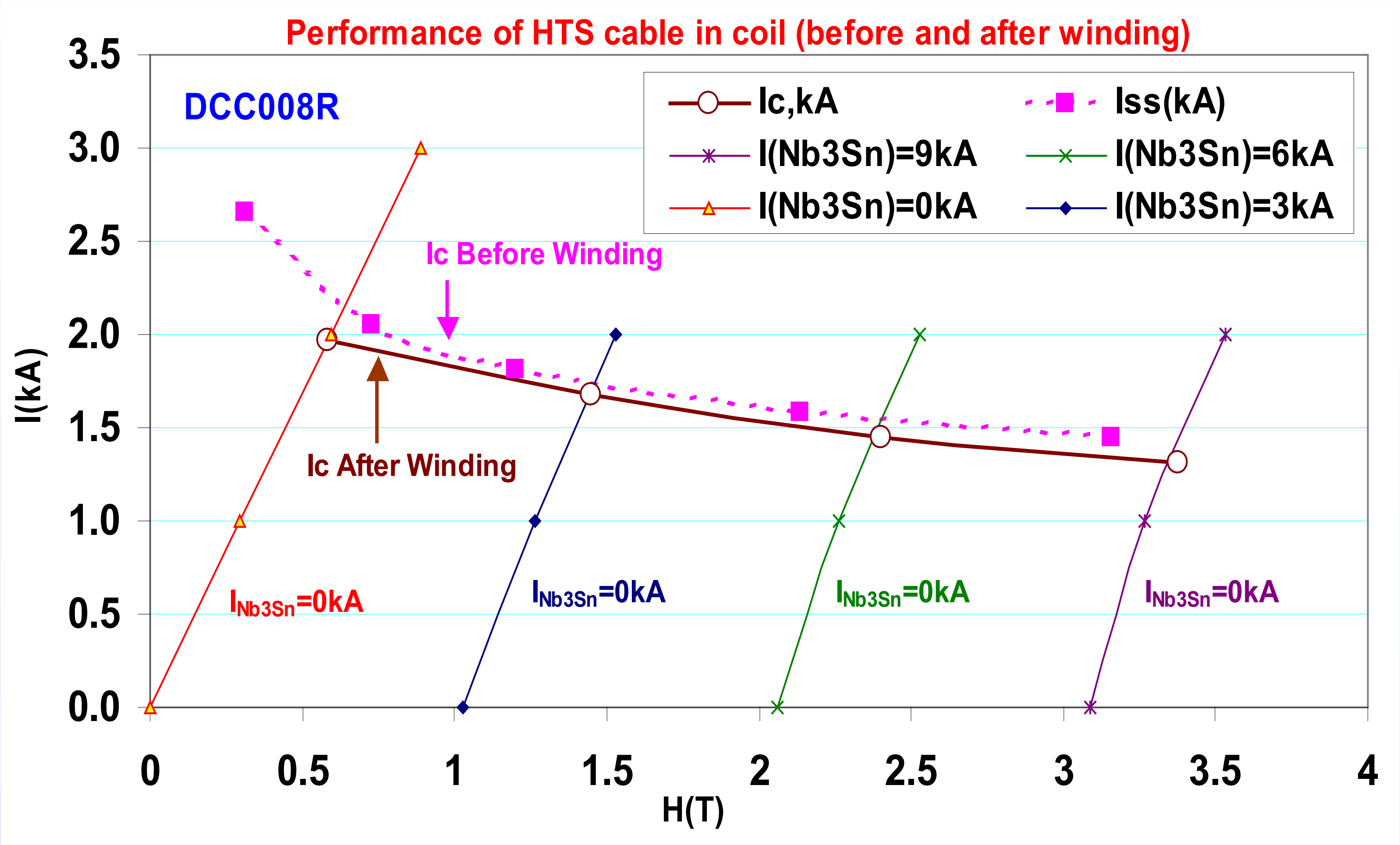
Performance of HTS Coil in the Background Field of Nb_3SN Coils



The background field on HTS coil was varied by changing the current in "React & Wind" Nb_3Sn coils (HTS coil in the middle and Nb_3Sn on either side).

HTS Magnet #4

- HTS Magnet #4 is being tested right now.
- The HTS cable is expected to carry several thousand Amps.

SUMMARY

- **HTS can make a significant impact in certain applications**
  - HTS magnets can operate at elevated temperature which need not be controlled precisely.
  - HTS magnets can generate very high fields.
- **HTS have reached a level that one can do meaning magnet R&D to address various technical issues**
  - The recent test results from Brookhaven are encouraging.
  - HTS offer a potential of good technical and economic operational solution for RIA fragment separator quadrupole triplet.
- **The next step**
  - Examine the impact of large dose of radiation on superconductor and insulation material.
  - Prove HTS magnet design & technology by building a test magnet.