High Temperature Superconductor (HTS) Magnet R&D and Designs

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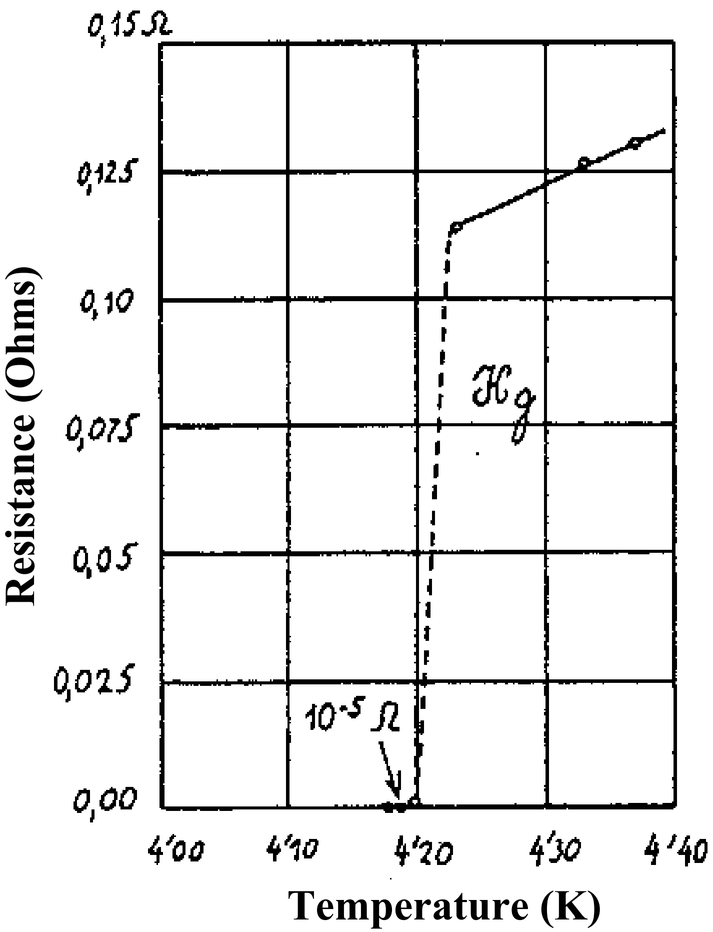
The Conventional Low Temperature Superconductors (LTS) and the New High Temperature Superconductors (HTS)

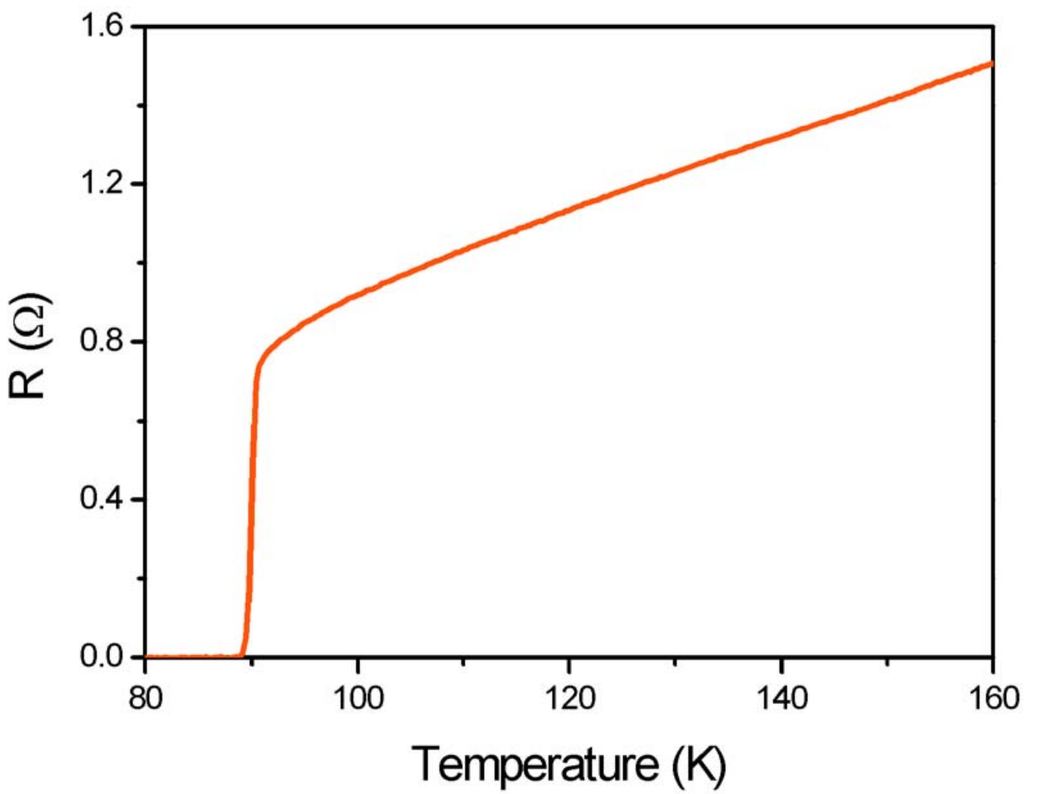
Low Temperature Superconductor Onnes (1911)

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

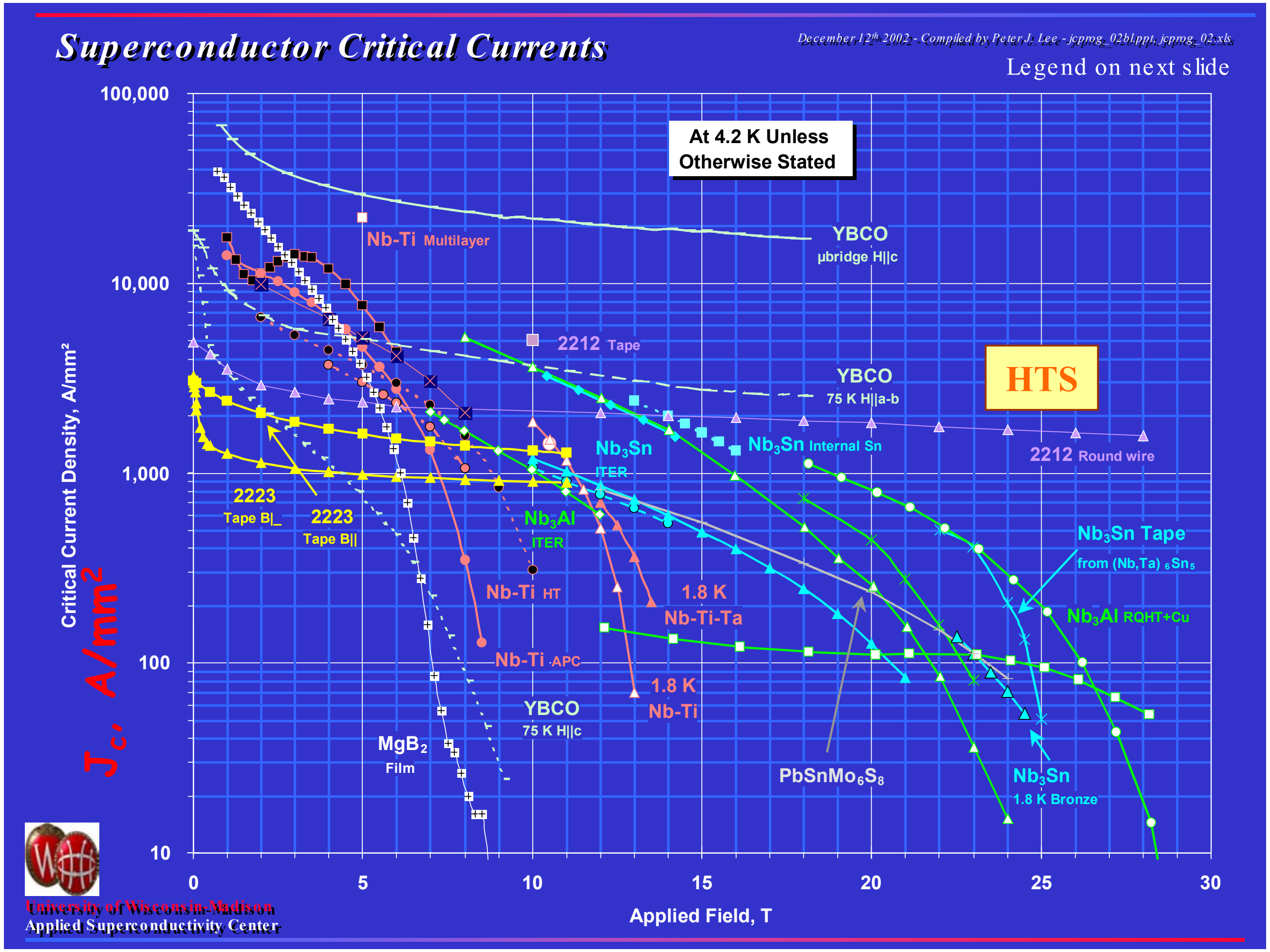
- BSCCO 2223 $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$
- BSCCO 2212
- YBCCO

- 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/mm^2

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 field
- as a function of temperature

Translate this to magnet design and accelerator operation:

- HTS has a potential to produce very high field magnets
- 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 based magnets don't appear to quench in the normal sense
- Weak spots don't limit the magnet performance, instead the local temperature rises a bit (major difference from LTS magnets).

It becomes a question of heat load rather than a weak spot limiting 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^{o}-890^{o}C over the entire reaction volume.

Possible Applications of HTS in 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.

Medium Field, Higher Temperature Application

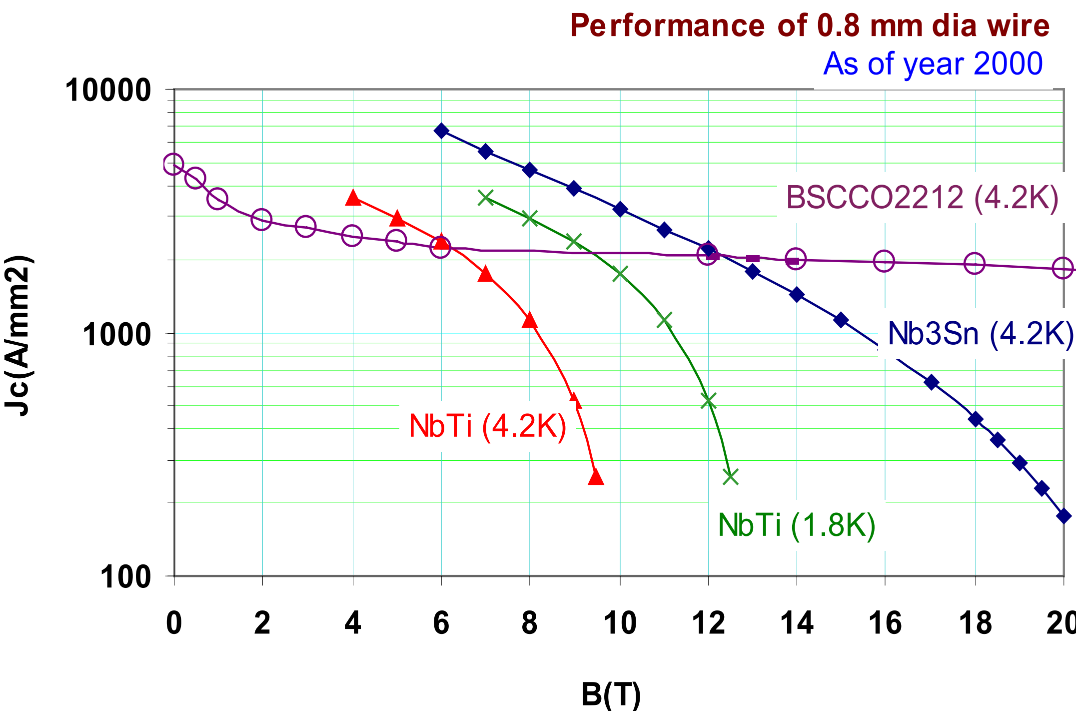
Example: Quads for Rare Isotope Accelerator (RIA)

- The system design benefits enormously because the HTS offers the possibility of magnets to operate at higher than 4K, say at 20-40 K.

Special Benefits of HTS

- 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).

Expected Performance of HTS-based Magnets



(performance in ~100 meter or longer lengths)

Year 2000 data for J_c at 12 T, 4.2 K

Nb_3Sn: 2200 A/mm²

BSCCO-2212: 2000 A/mm²

Near future assumptions for J_c at 12 T, 4.2 K

Nb_3Sn: 3000 A/mm² (DOE Goal)

BSCCO-2212: 4000 A/mm² (2X today)

Expected performance of all Nb_3Sn or all HTS magnets at 4.2 K for the same amount of superconductor:

Year 2000 Data	
All Nb_3Sn	All HTS
12 T	5 T
15 T	13 T
18 T	19 T*

*20 T for Hybrid

Near Future	
All Nb_3Sn	All HTS
12 T	11 T
15 T	16 T
18 T	22 T

Cu(Ag)/SC Ratio

BSCCO: 3:1 (all cases)

Nb_3Sn: 1:1 or J_{cu}=1500 A/mm²

First Likely Application of HTS: Interaction Region (IR) Magnets

Interaction region magnets for the next generation colliders

or luminosity upgrade of existing colliders

(LHC is existing collider for this purpose)

can benefit a lot from:

- Very high fields
- Ability to take large energy deposition without much loss in performance
- Ability to operate at elevated temperatures that need not be uniform

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

→ These magnets can be, and perhaps should be, replaced in a few years.

(for LHC, the first installment may be due ~10 years from now)

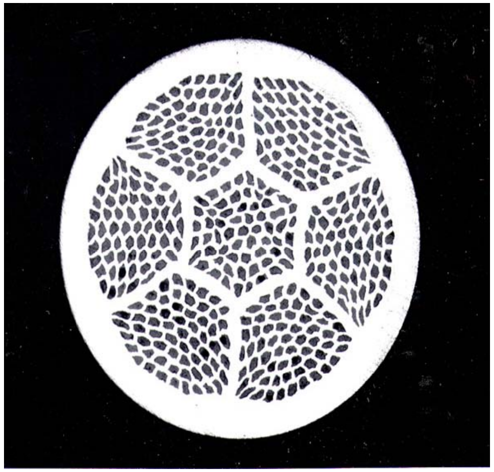
All of above makes HTS a natural choice for next generation IR magnet R&D.

Construction and Test Results from HTS Technology Development Program at BNL

Next Few Slides will Show:

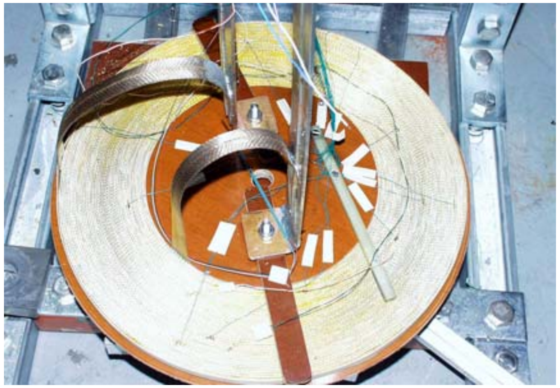
- Results of HTS Tape and Cable Tests
- Construction and Test Results of HTS Coils and R&D Magnets

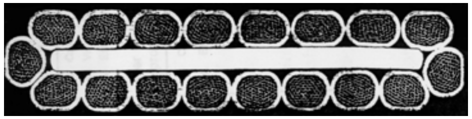
Please see the tape and cable being distributed



HTS Wire

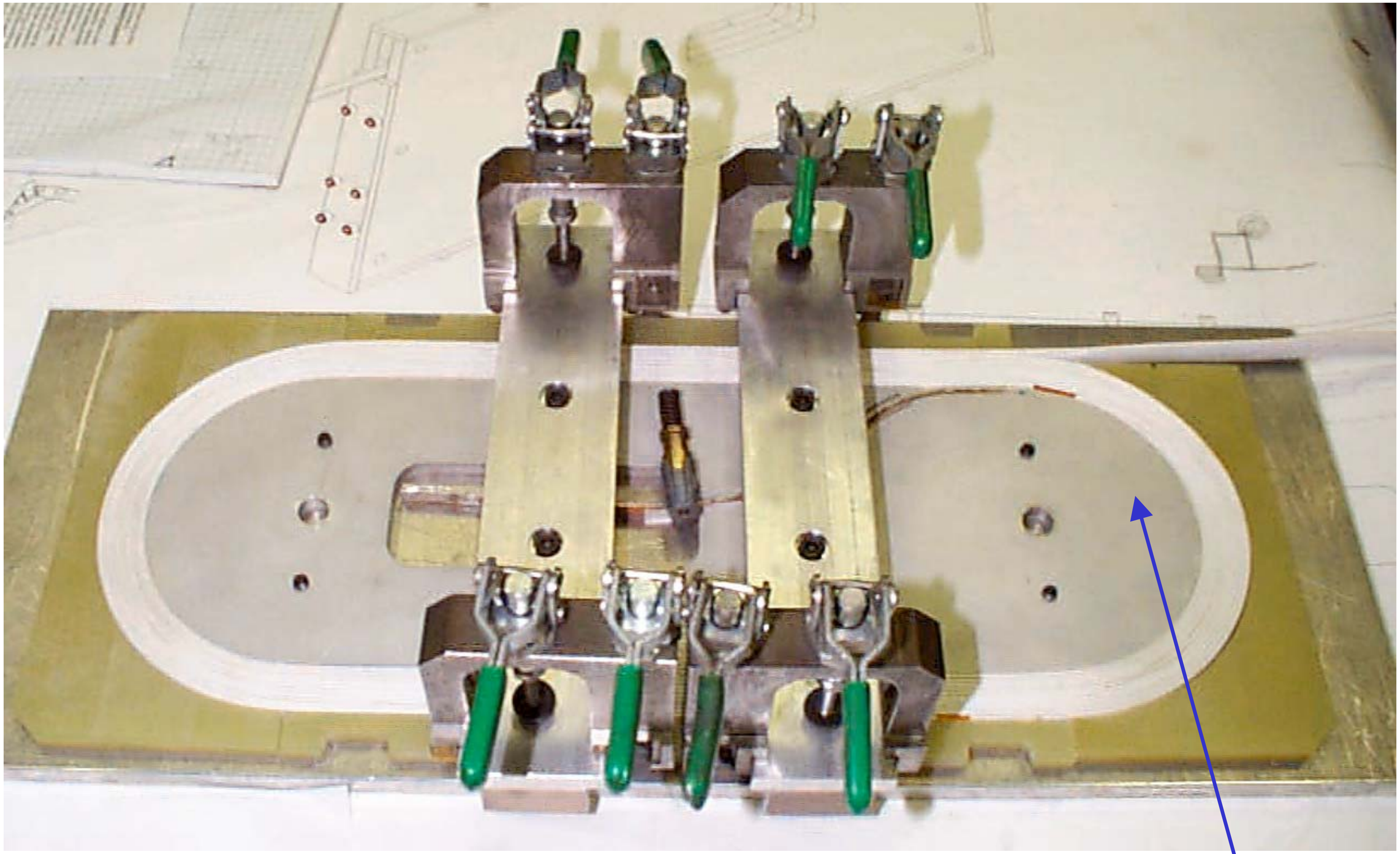
HTS Tape





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

HTS Coil Wound by Hand



Al Bobbin (70 mm radius)

(also used, Fe, SS and brass bobbins)

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Magnet Division

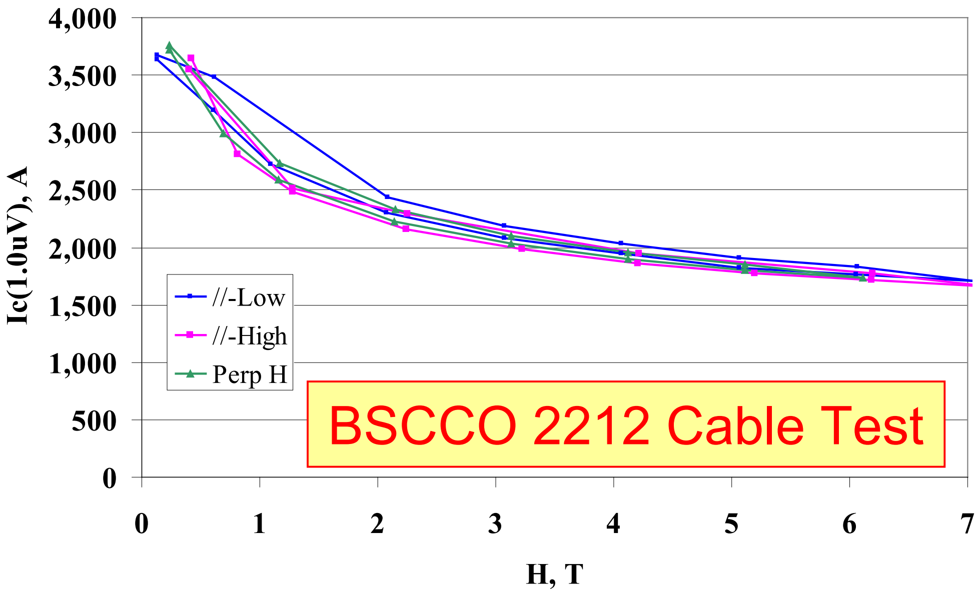
Measured Performance of HTS Cable and Tape As A Function of Field at BNL

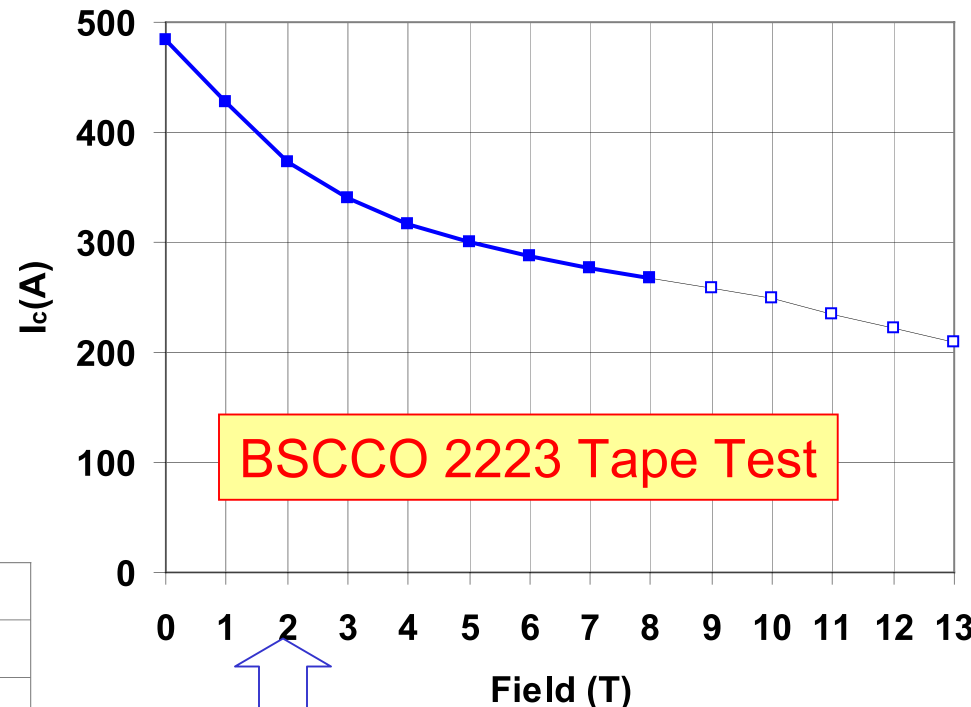
Measurements of "***BSCCO-2212 cable***" (Showa/LBL/BNL) at BNL test facility

Reported Ic in new wires is ~ 3x better than measured in the cable.

This was a narrow (18 strand) cable. Wider cable with new conductor should be able to carry 5-10 kA current at high fields!

(self field correction is applied)

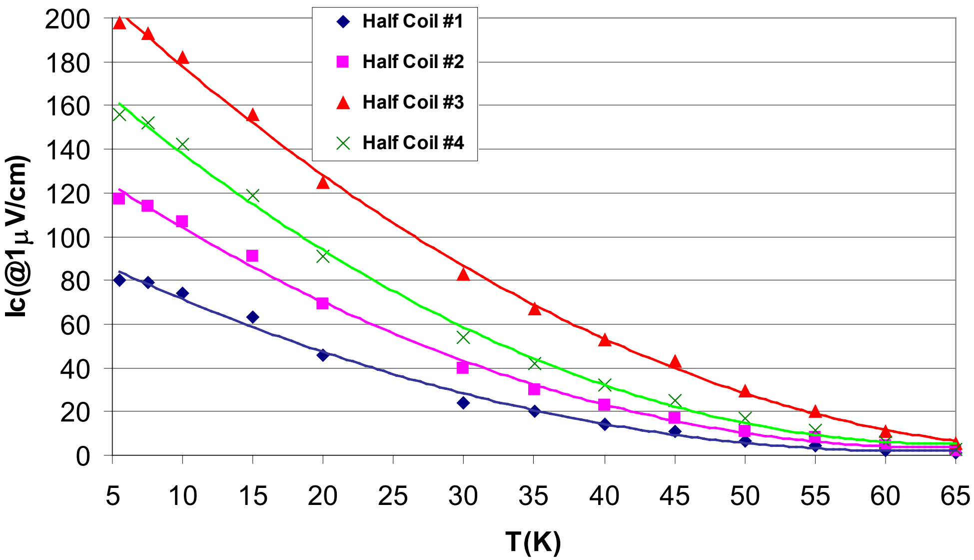


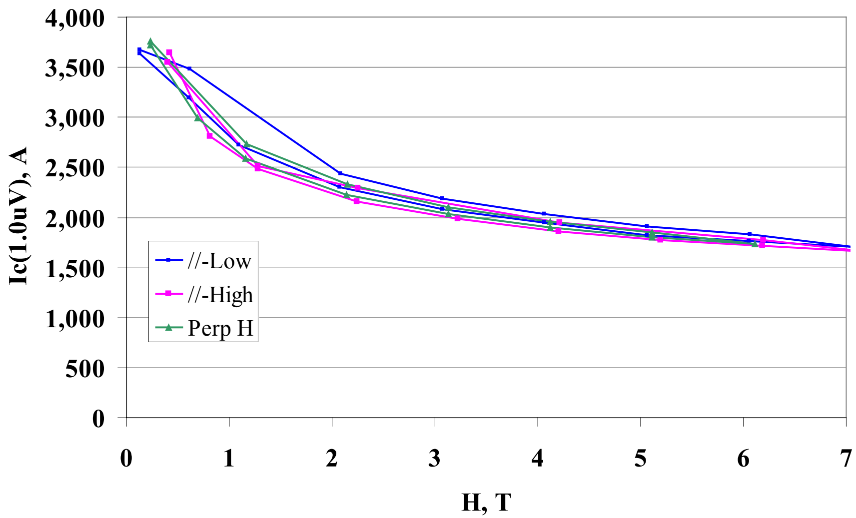


Measurements of "***BSCCO 2223 tape***" wound at 57 mm diameter with applied field parallel (1μV/cm criterion)

(field perpendicular value is ~60%)

Critical Current as a Function of Temperature & Field





For very high field magnet applications, we are interested in low temperature and high field characteristics of high temperature superconductors.

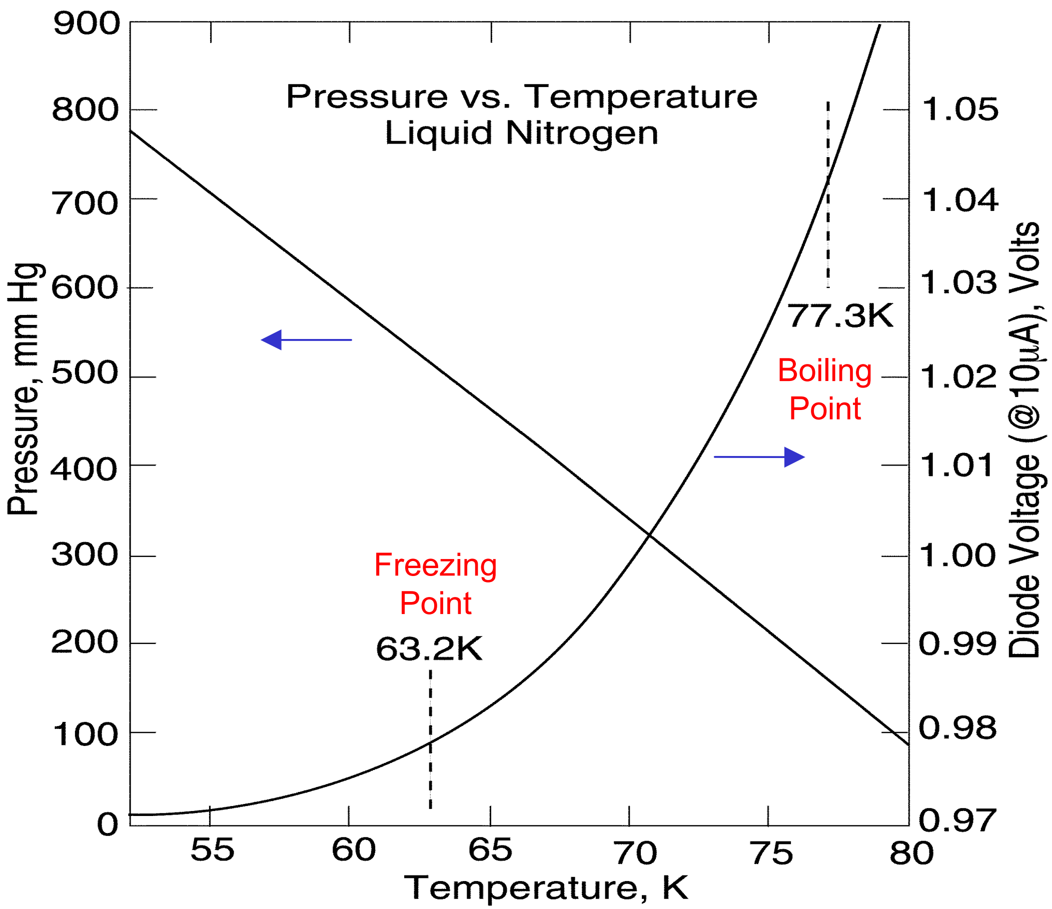
However, these conductors still have significant critical current at higher temperature.

Testing at Liquid Nitrogen (LN_2) temperature is much more easier than testing at Liquid Helium (LHe) temperatures.

BNL has developed and extensively used LN2 testing in HTS cable, coil and magnet R&D.

HTS Cable and Coil Test at Liquid Nitrogen

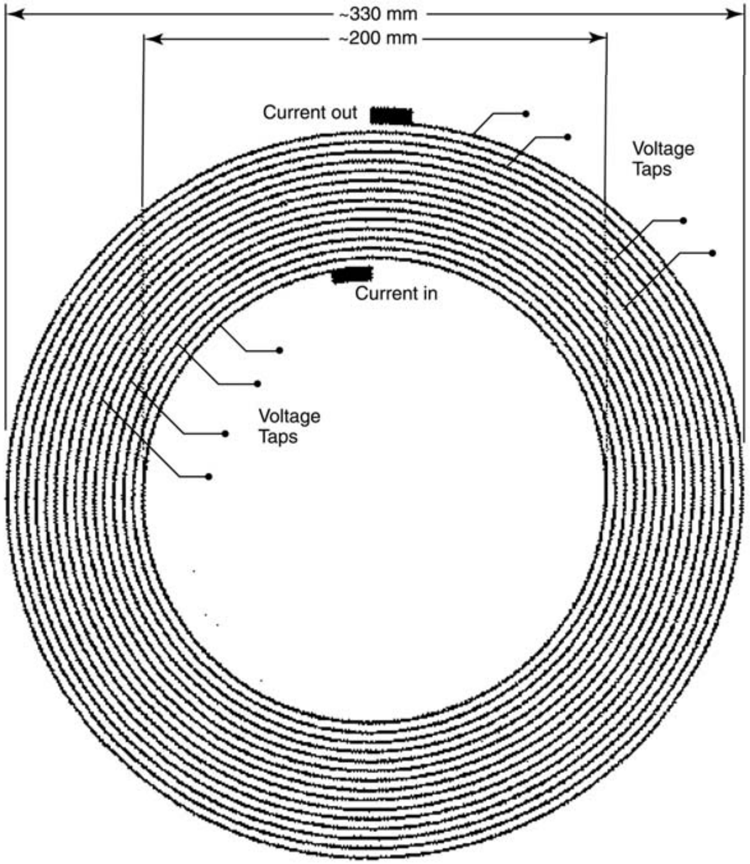
Testing of HTS cables (or tapes) at LN2 is a powerful method even if the cables are to be used in magnets that would operate at LHe temperatures

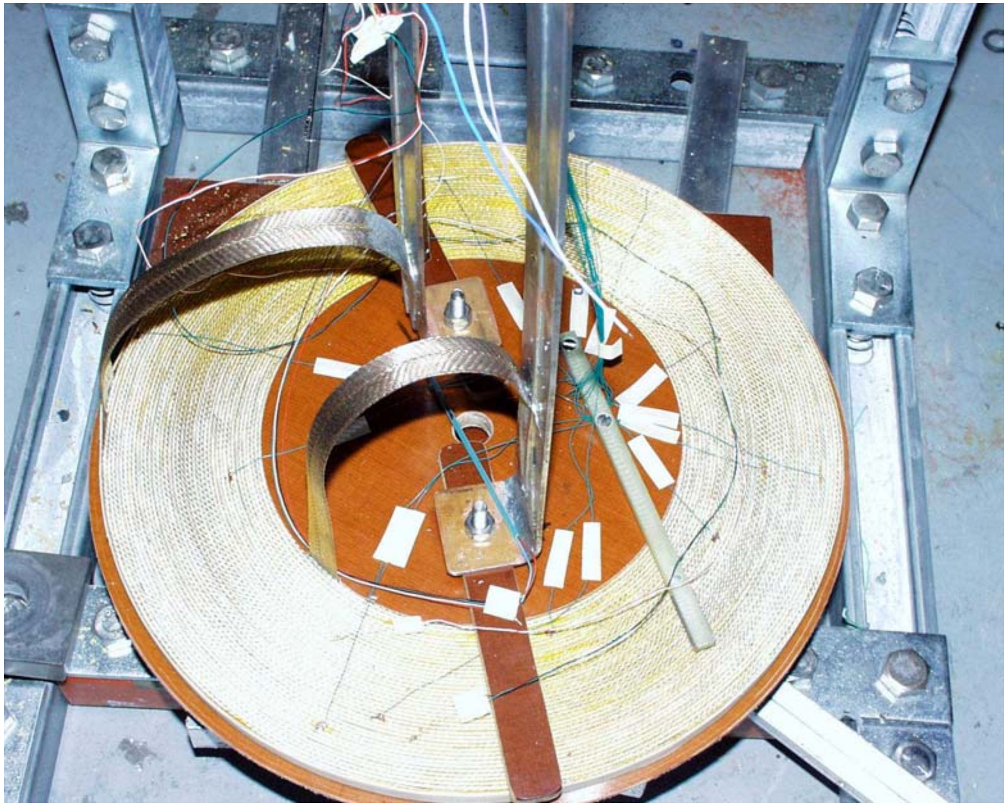


- LN2 testing is much easier than LHe testing
- Yet LN2 testing gives a good indication of the cable behavior in LHe

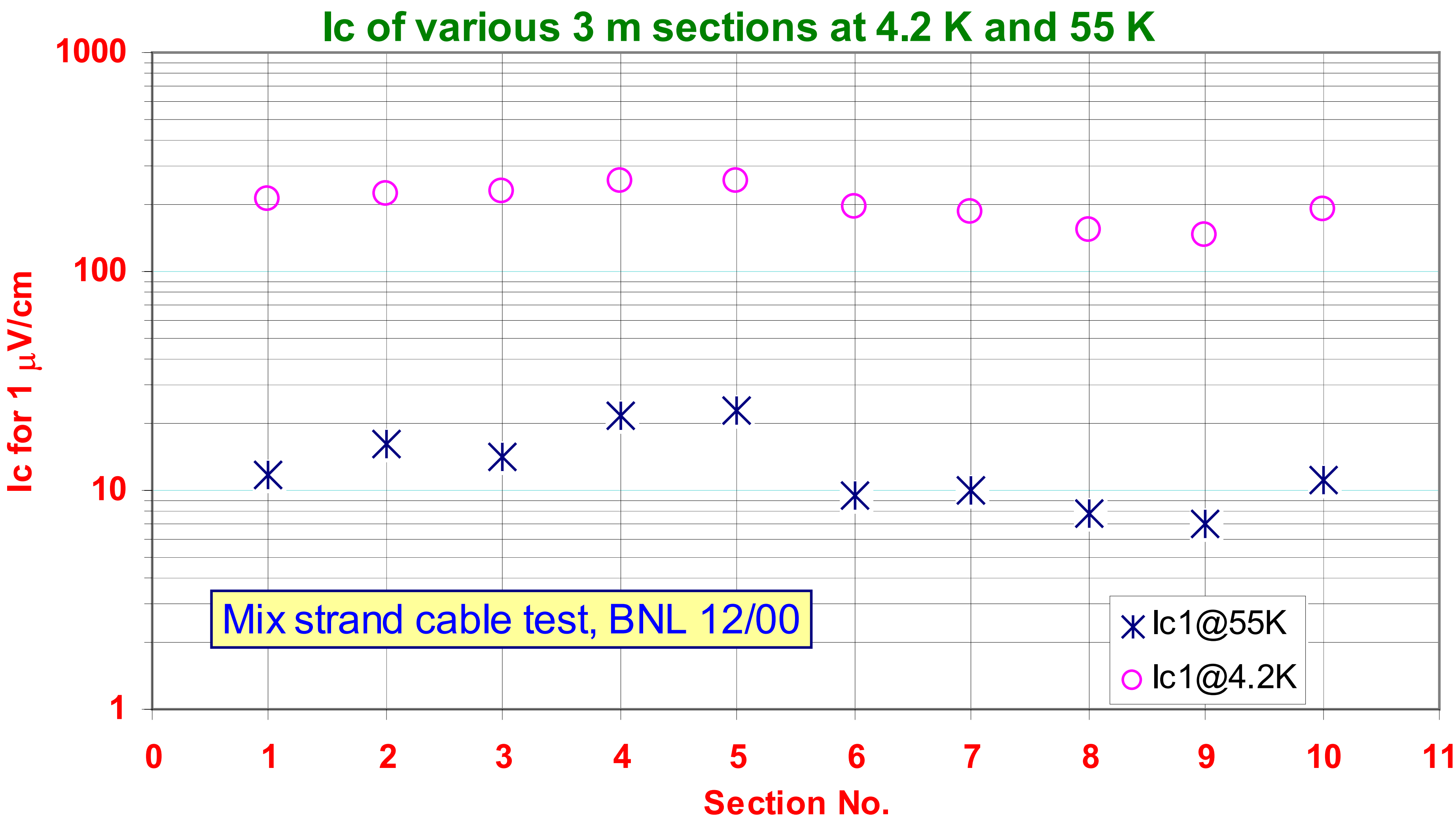
BSCCO-2212 Cable "Pancake Coils"

HTS cable is carefully wound in large radius pancake coil for testing at liquid nitrogen temperatures

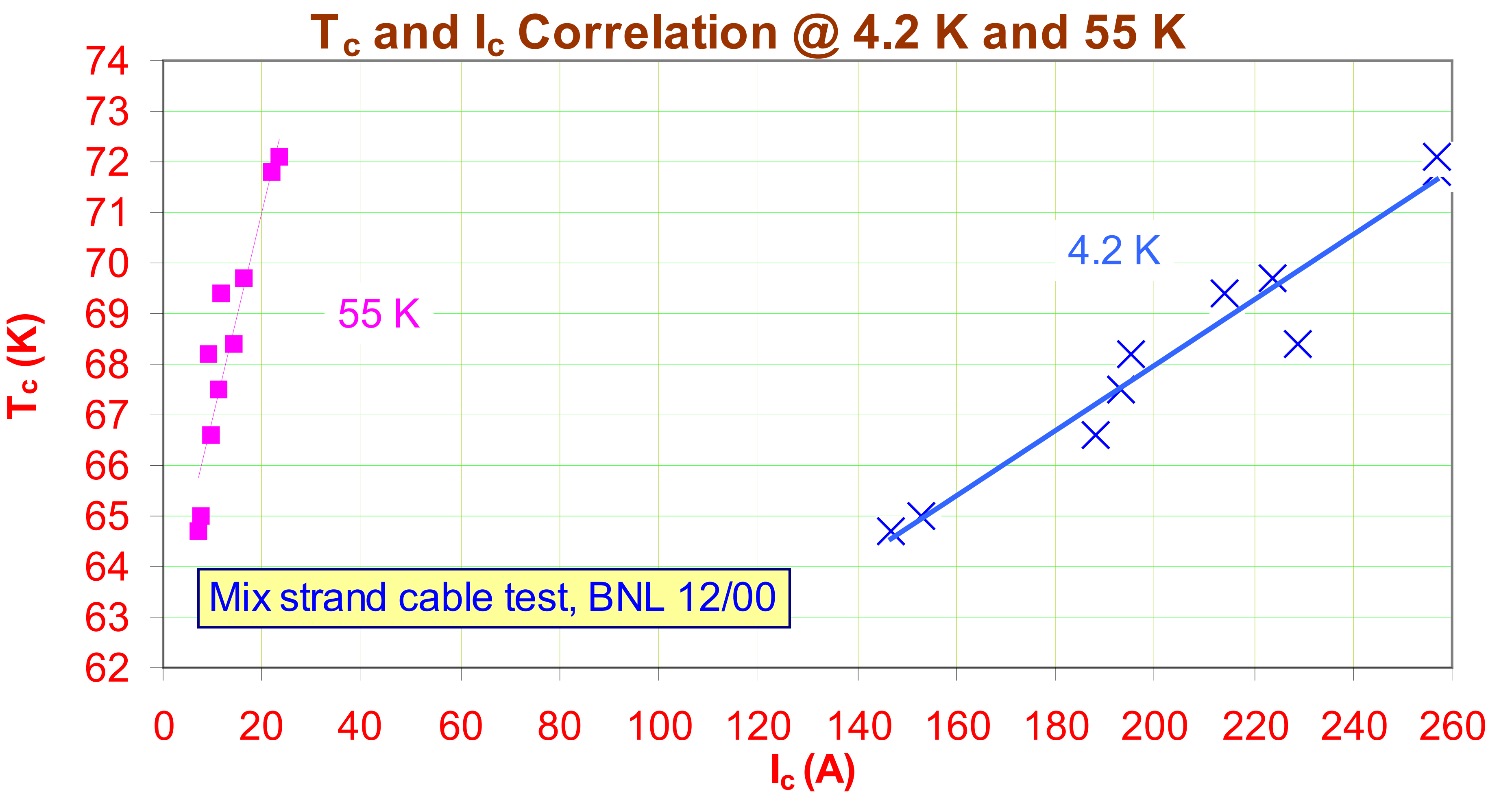




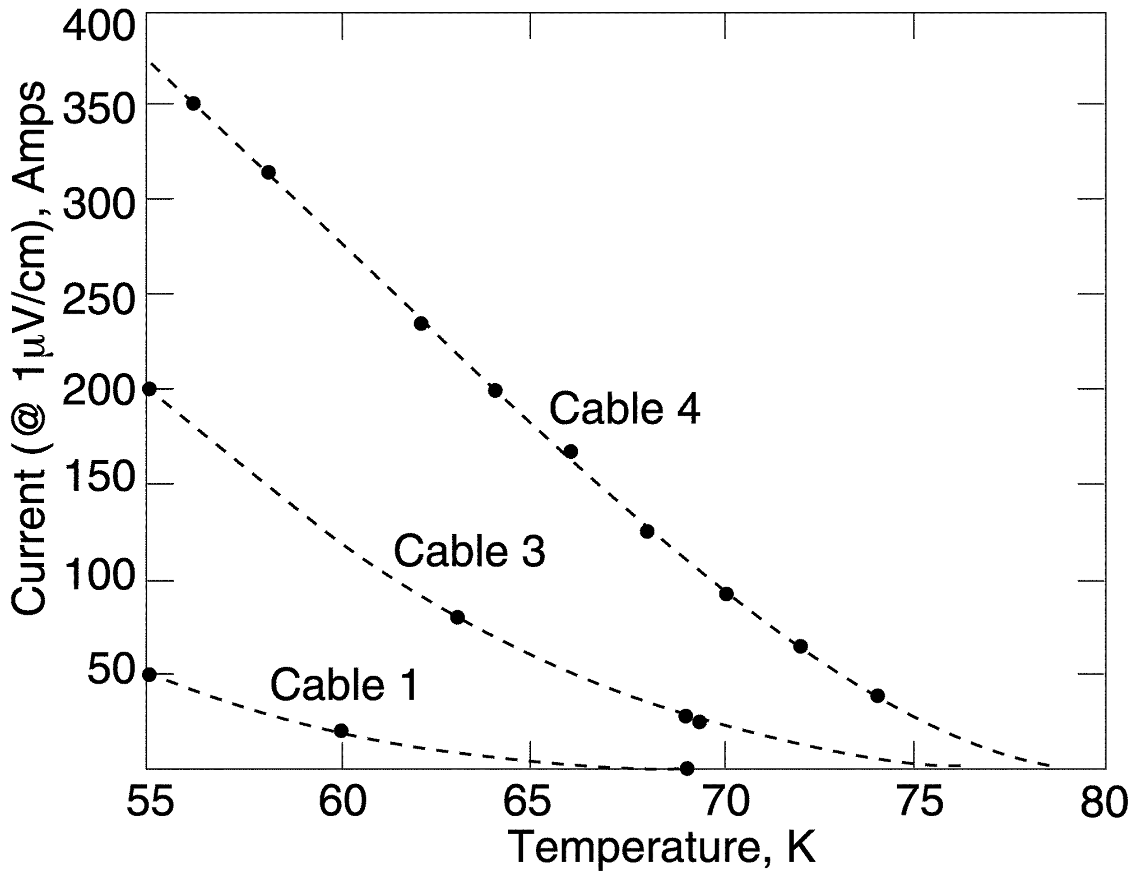
Ic Tracking Between 4.2 K and 55 K



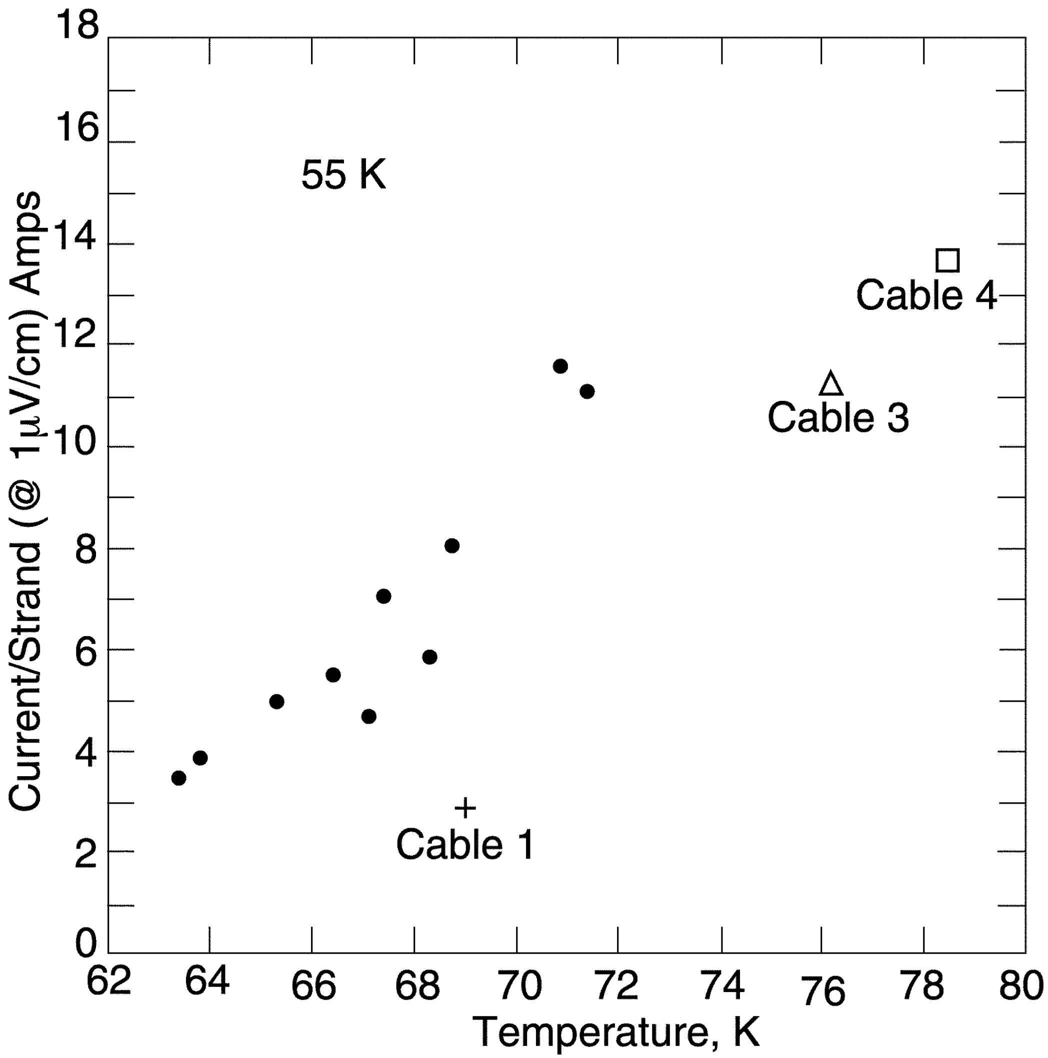
Correlation between T_c and I_c



Ic as a function of Temperature



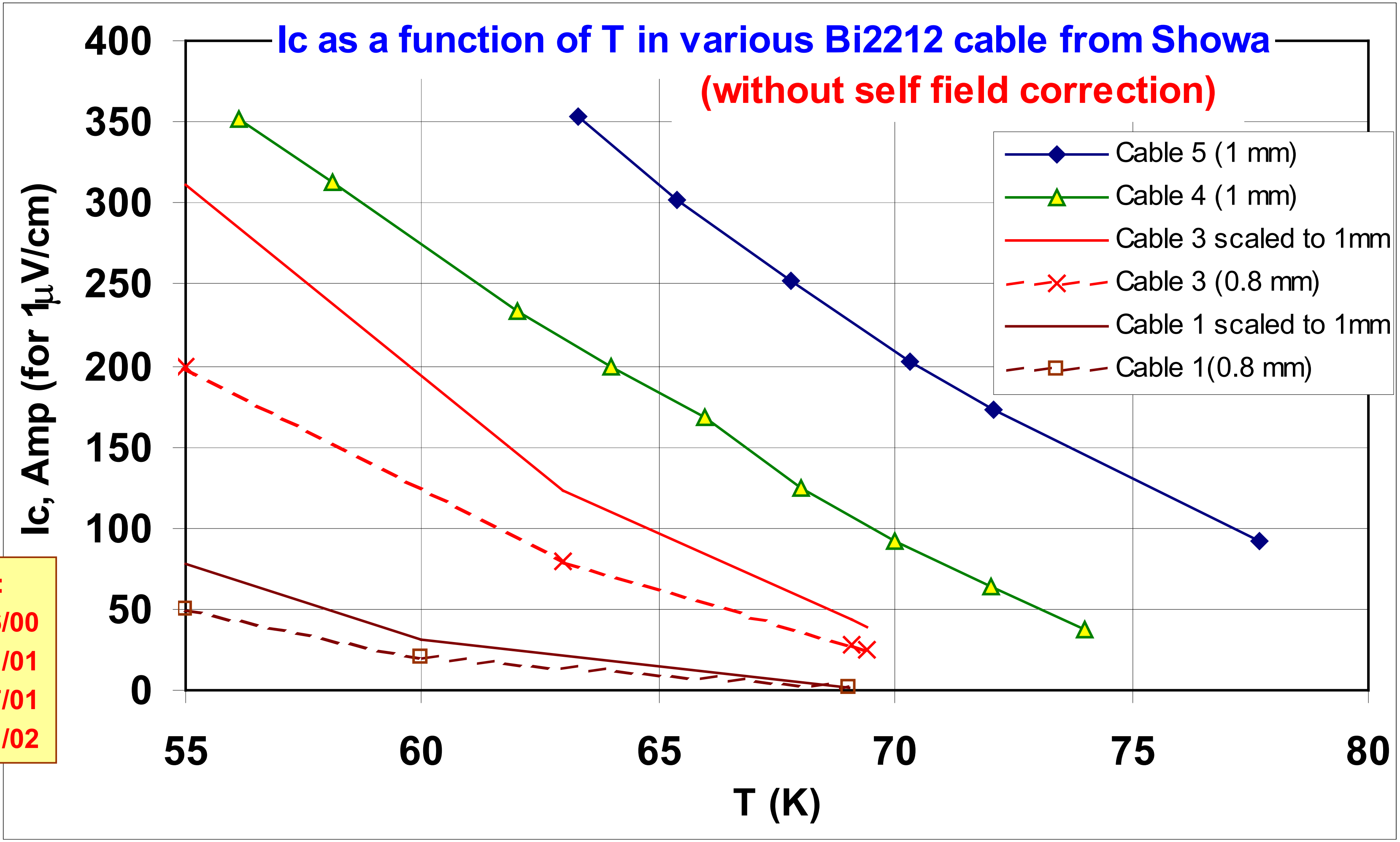
Correlation between T_c and I_c



Better cables (with higher I_c) also have better T_c

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

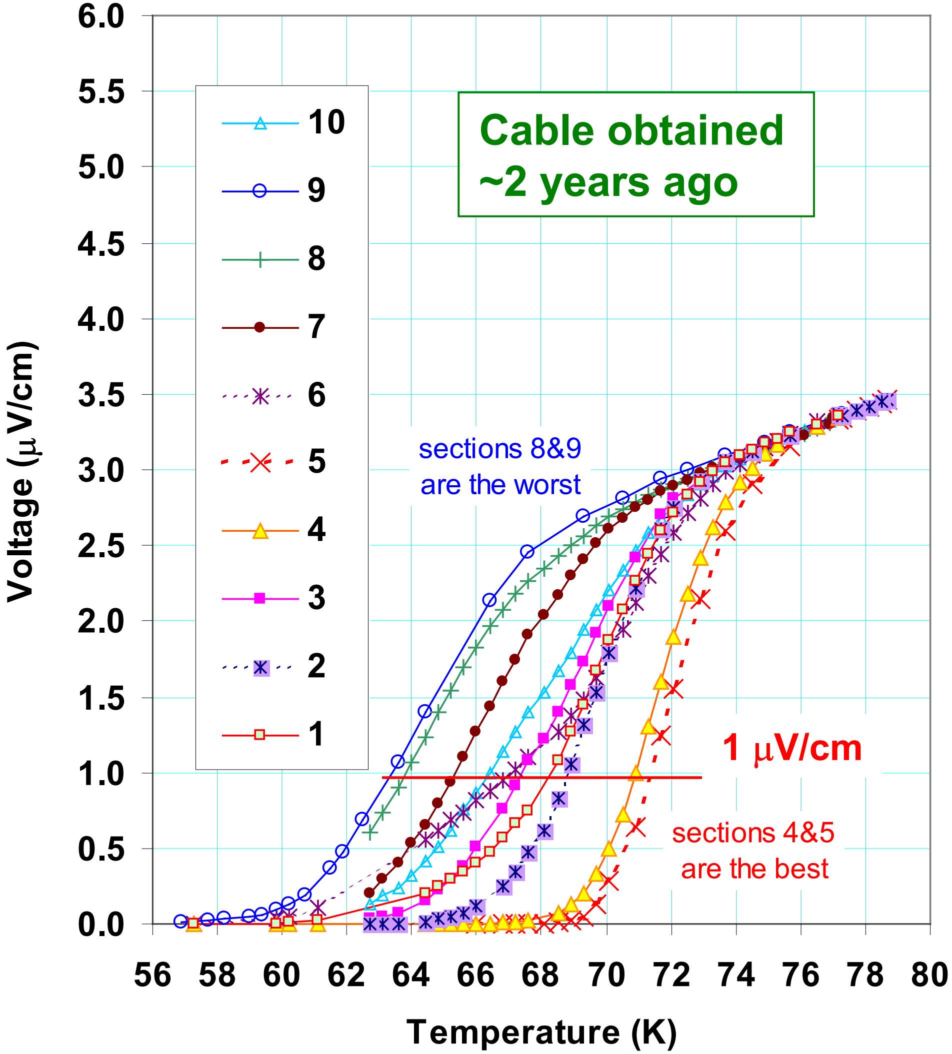
Extrapolated 4 K performance of 20 strand cable (#5) (wire dia = 1 mm) : ~5 kA at high fields and ~9 kA at zero field

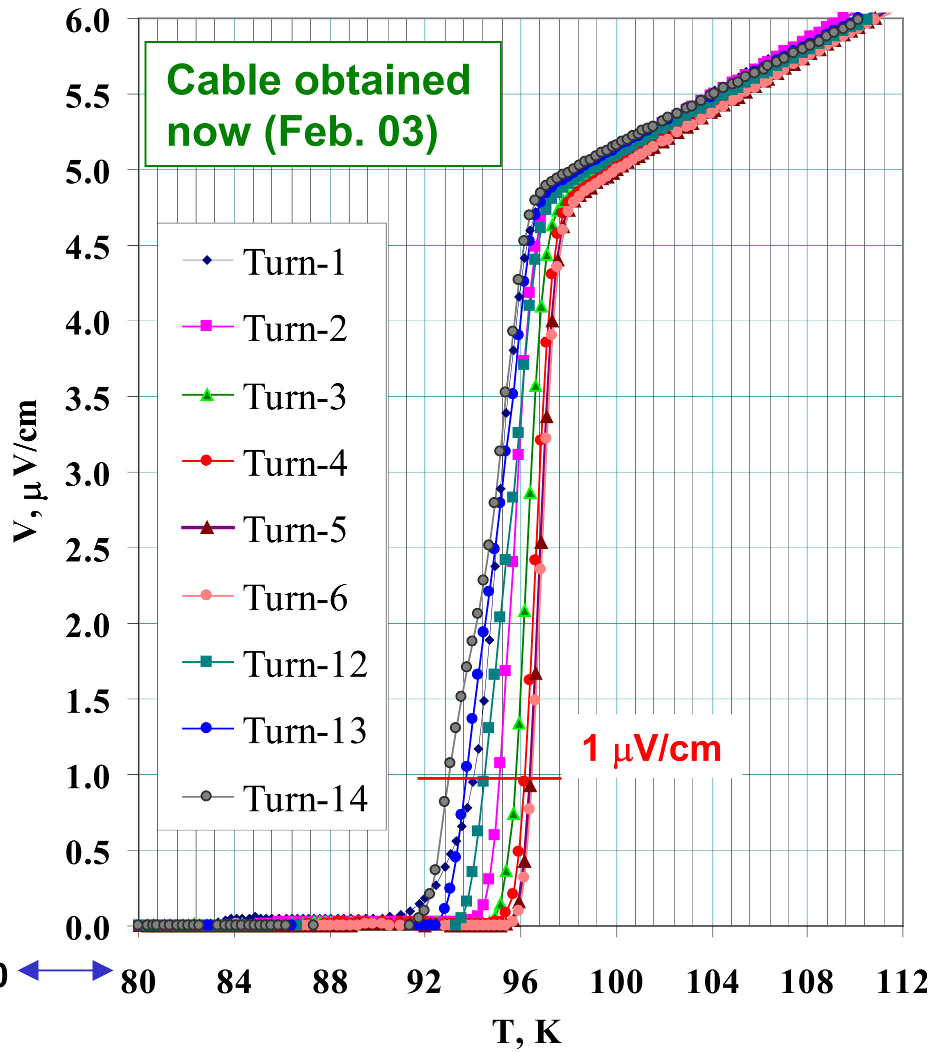


Test Dates:
Cable 1: 06/00
Cable 3: 01/01
Cable 4: 07/01
Cable 5: 11/02

Improvement in Tc of BSCCO-2212 Cable from Showa

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





HTS Magnet R&D and Test Program at BNL

HTS Tape Coil Program:

- Started ~ 4 years ago
- Six 1-meter long coils built and tested

10-turn HTS Cable R&D Program with rapid turn around

- Cost effective with rapid turn around
  - encourages systematic and innovative magnet R&D
  - allows many ideas to be tried in parallel
- Started ~2 year ago

  20 coils with brittle materials (5 HTS, 15 Nb_3Sn) built and tested

12T high background field R&D Program

- Will address issues related to high field, high stress performance of HTS

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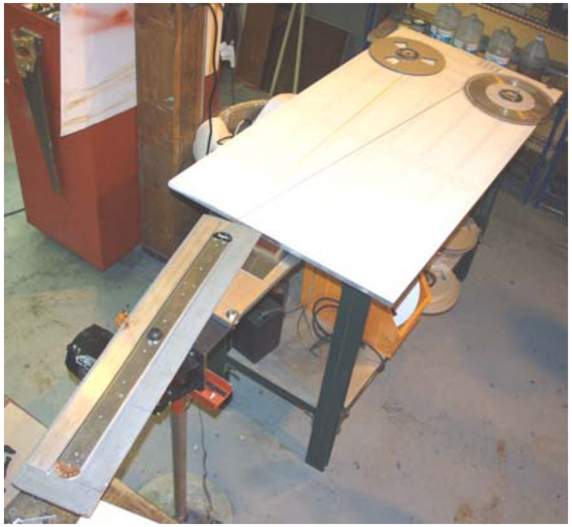
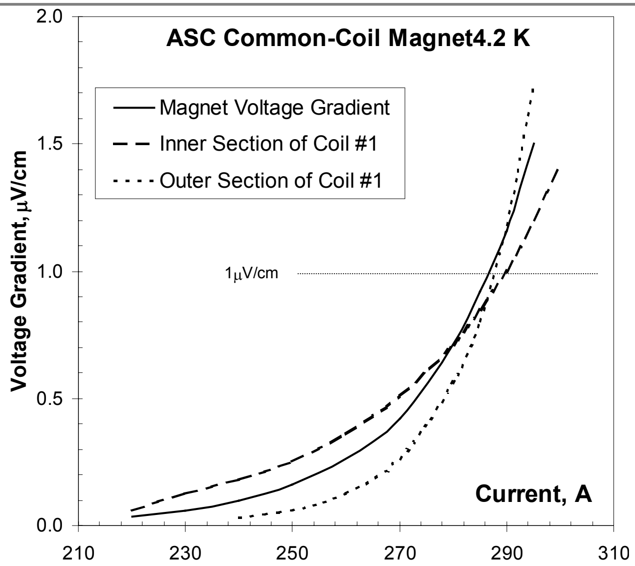
Common Coil Magnets With HTS Tape

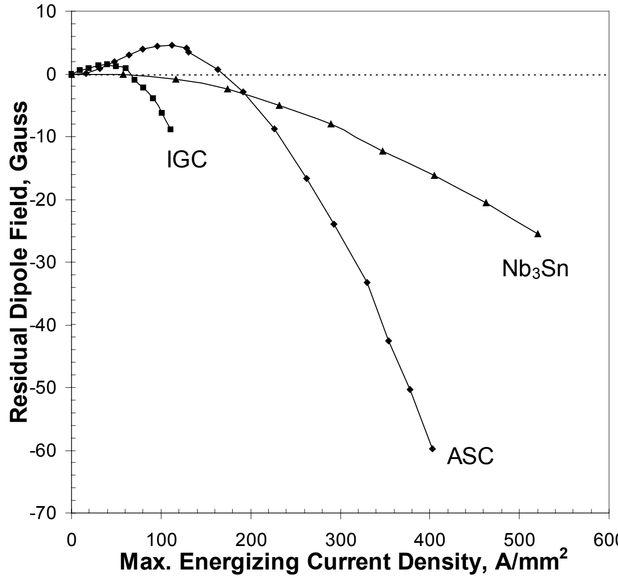
(Field quality in 74 mm aperture to be measured soon)



A coil being wound with HTS tape and insulation.

Two HTS tape coils in common coil configuration





Status of HTS tape coils at BNL

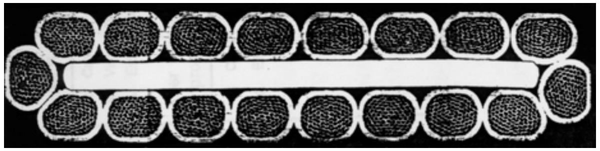
	Size, mm	Turns	Status
Nb_3Sn	0.2 x 3.2	168	Tested
IGC	0.25 x 3.3	147	Tested
ASC	0.18 x 3.1	221	Tested
NST	0.20 x 3.2	220	Under construction
VAC	0.23 x 3.4	170	Under construction

HTS Cable Magnet Program

BSCCO 2212 cable appears to be the most promising high temperature superconductor option for accelerator magnets

- Higher current for operating accelerator magnets
- Plus all standard reasons for using cable

HTS Cable

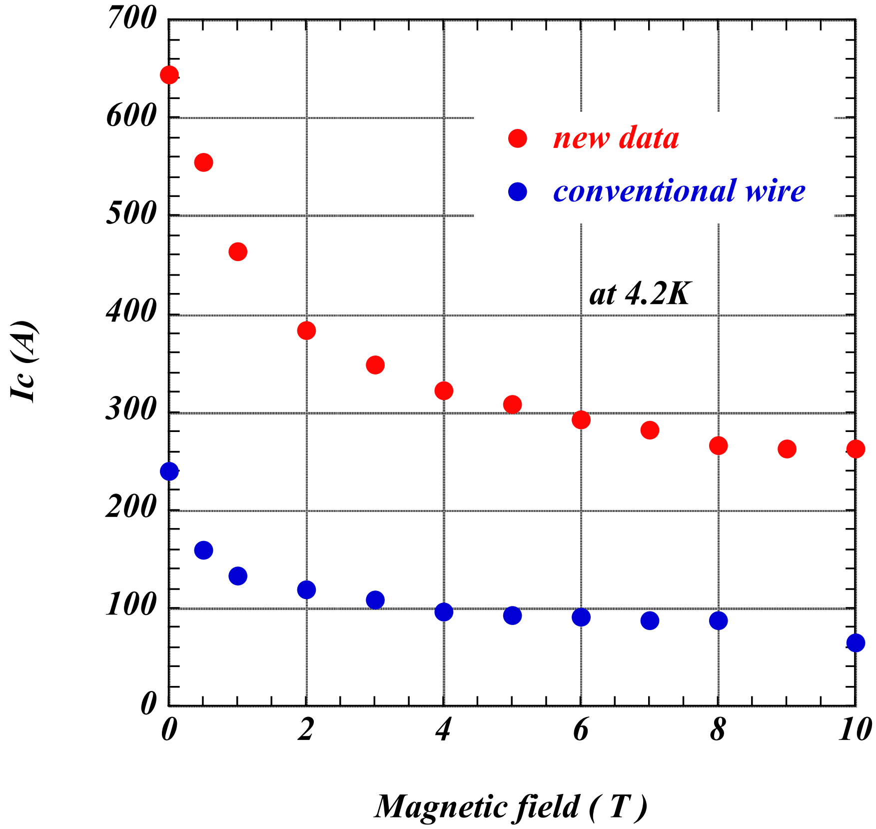


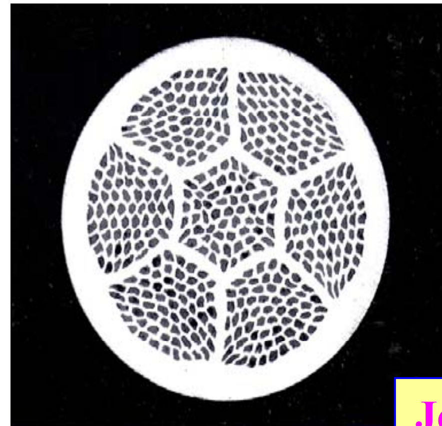
A good and productive collaboration has been established between labs (BNL, LBL) and industries (IGC, Showa).

BSCCO Wire (Year 2000)

Ic-B characteristics of new wire

Showa Electric





Jc(12T,4.2K)
~2000 A/mm^2

I_c (4.2K 0T) : 640A
J_c (4.2K 0T) : 490kA/cm^2
Size : 0.81mm^d
Number of filament : 427
Material of outer sheath
: Ag alloy
Material of inner sheath : Ag
Ag/SC ratio : 3.0
Tensile strength (R.T.)
: 120MPa

T. Hasegawa, "HTS Conductor for Magnets", MT-17, Geneva.

20/05/00

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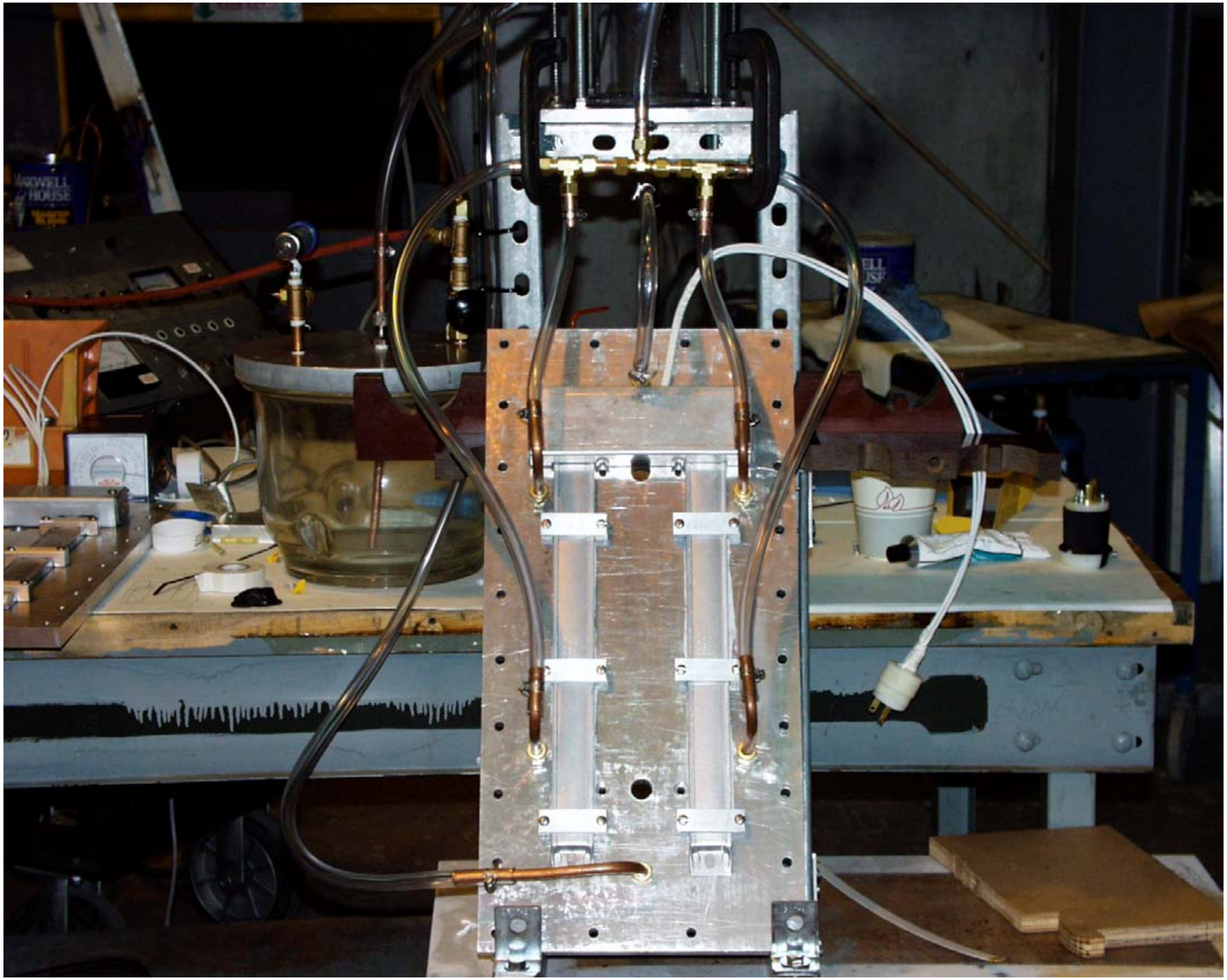
Vacuum Impregnation Setup



HTS Coils in Support Structure

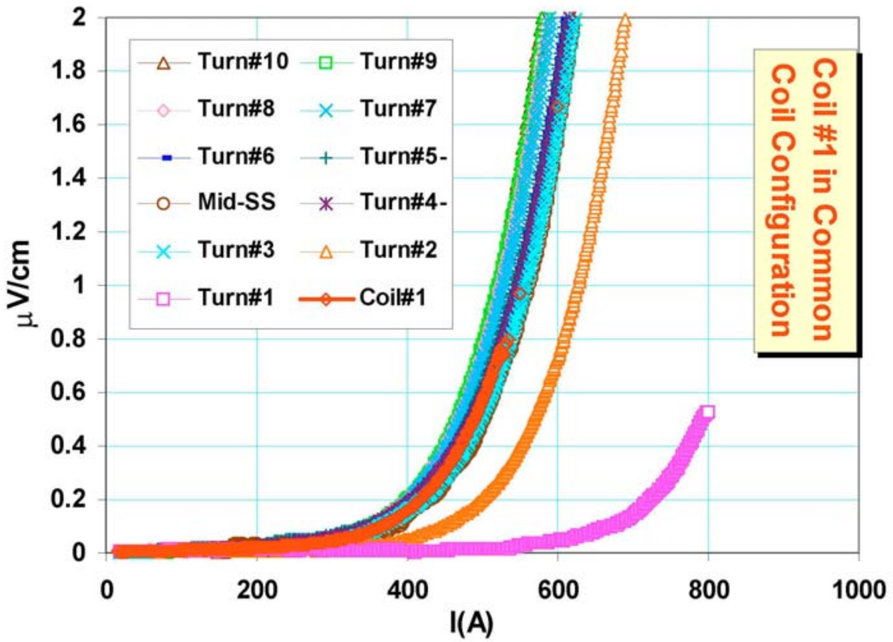
Coils are heavily instrumented. There is a voltage tap after each turn. Data were recorded from all 26 voltage taps.

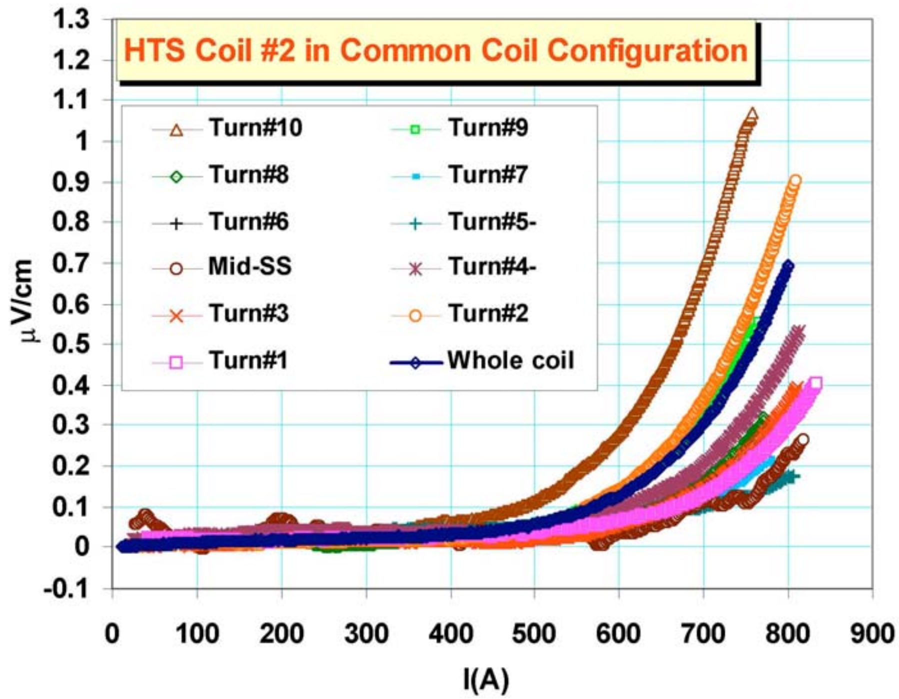
Coils are assembled for the most flexible and extensive testing. Four leads are taken out of the cryostat. During the test the coils were powered separately and together in “common coil” and “split-pair solenoid mode”.

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 (DCC002)

Voltage difference between each consecutive turn and on each coil



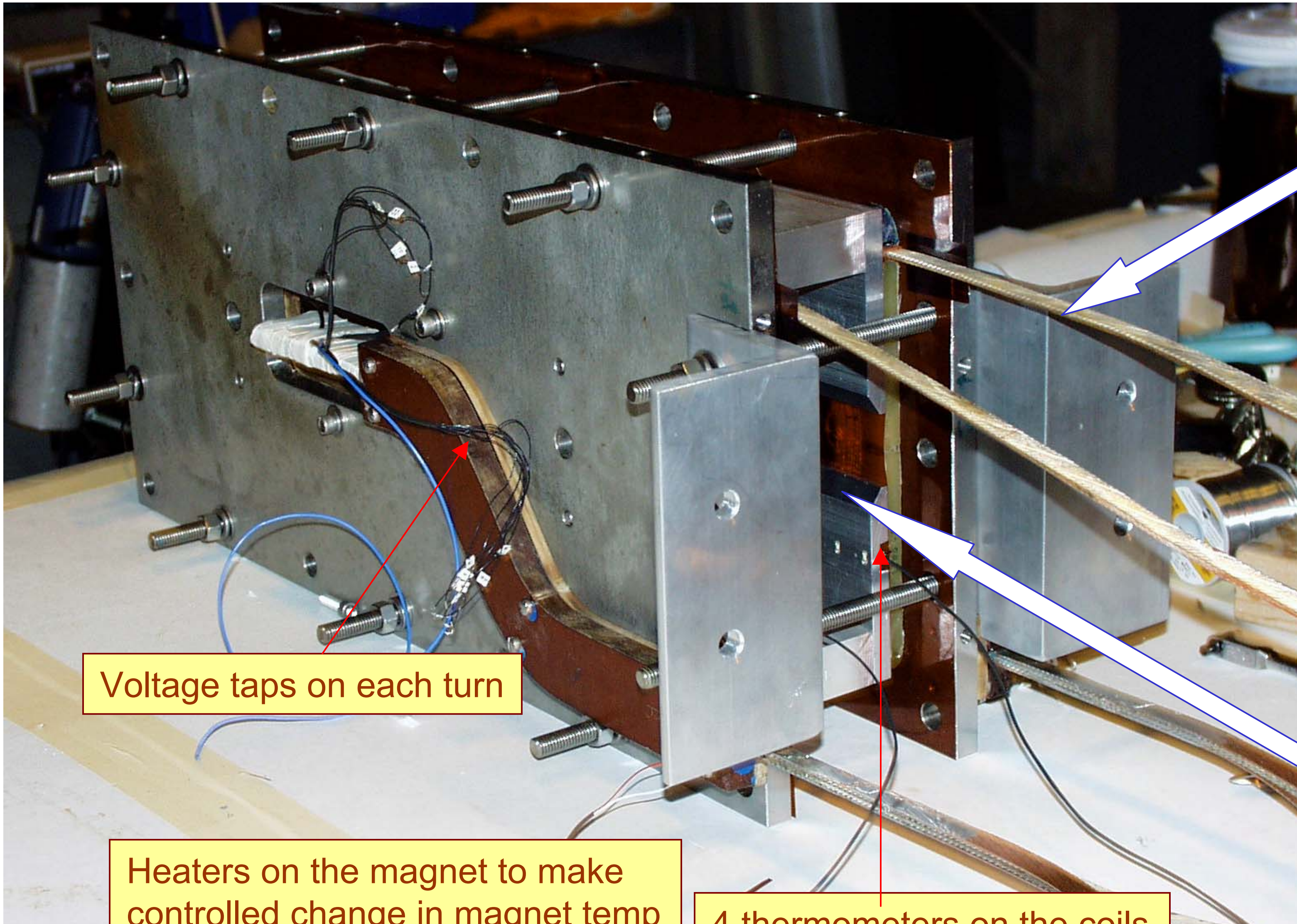


Measurements in HTS Magnet DCC004 at 4.2 K

Magnet DCC006: 2nd HTS Dipole

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

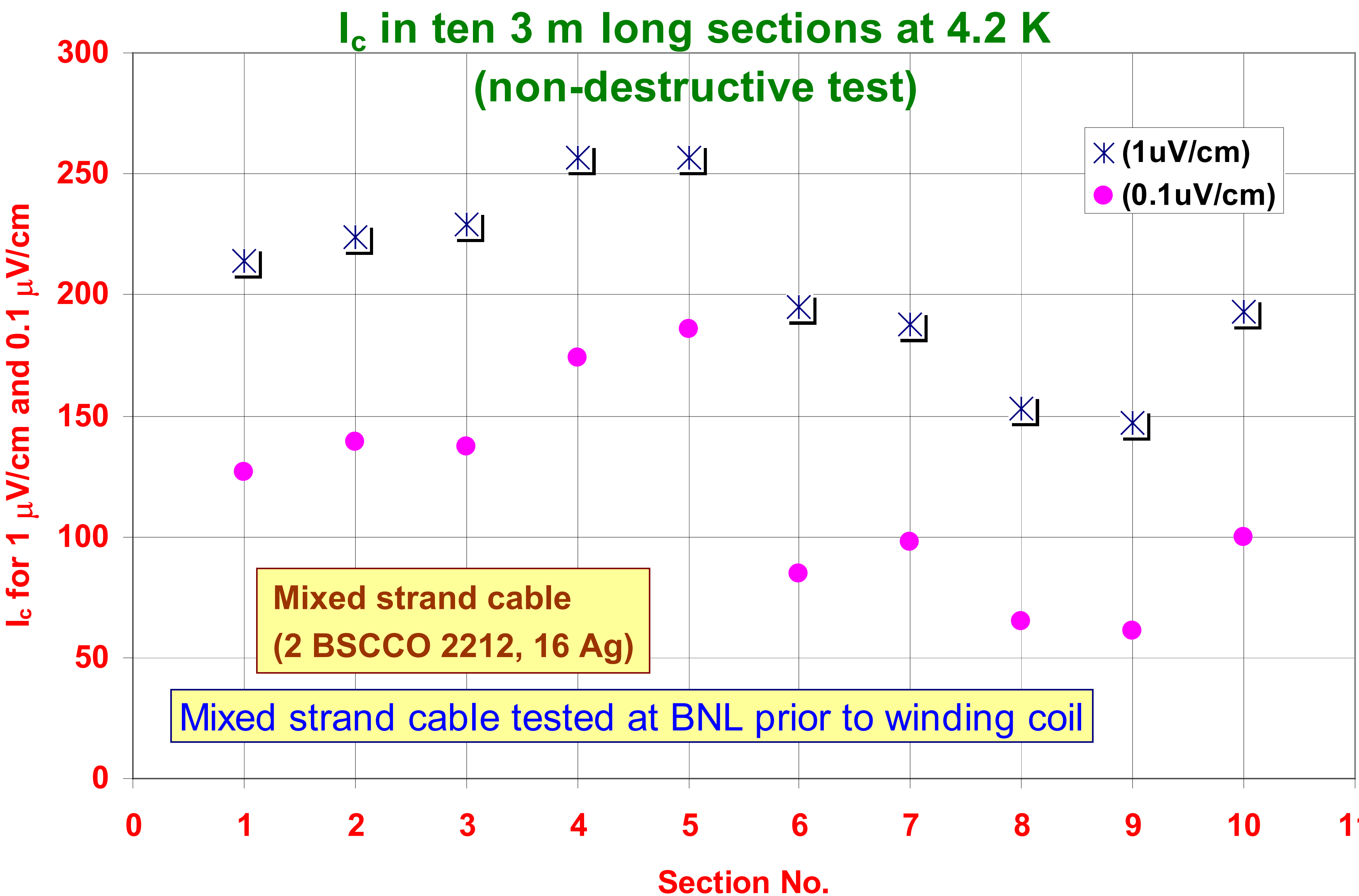
A versatile structure to test single or double coils in various configurations



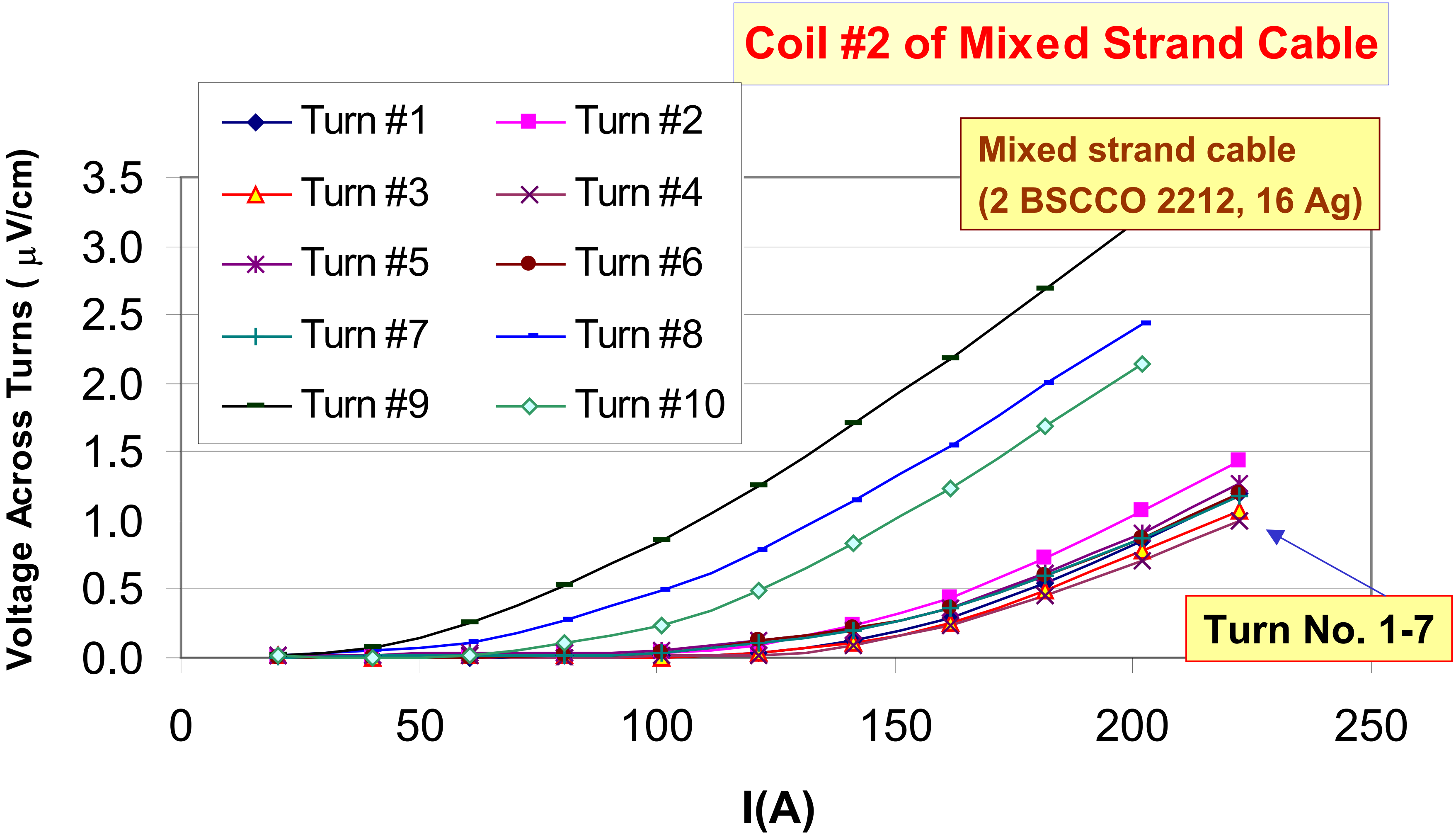
HTS Cable Leads to make high temp measurements

74 mm aperture to measure field quality

Critical Current in Mixed Strand Cable

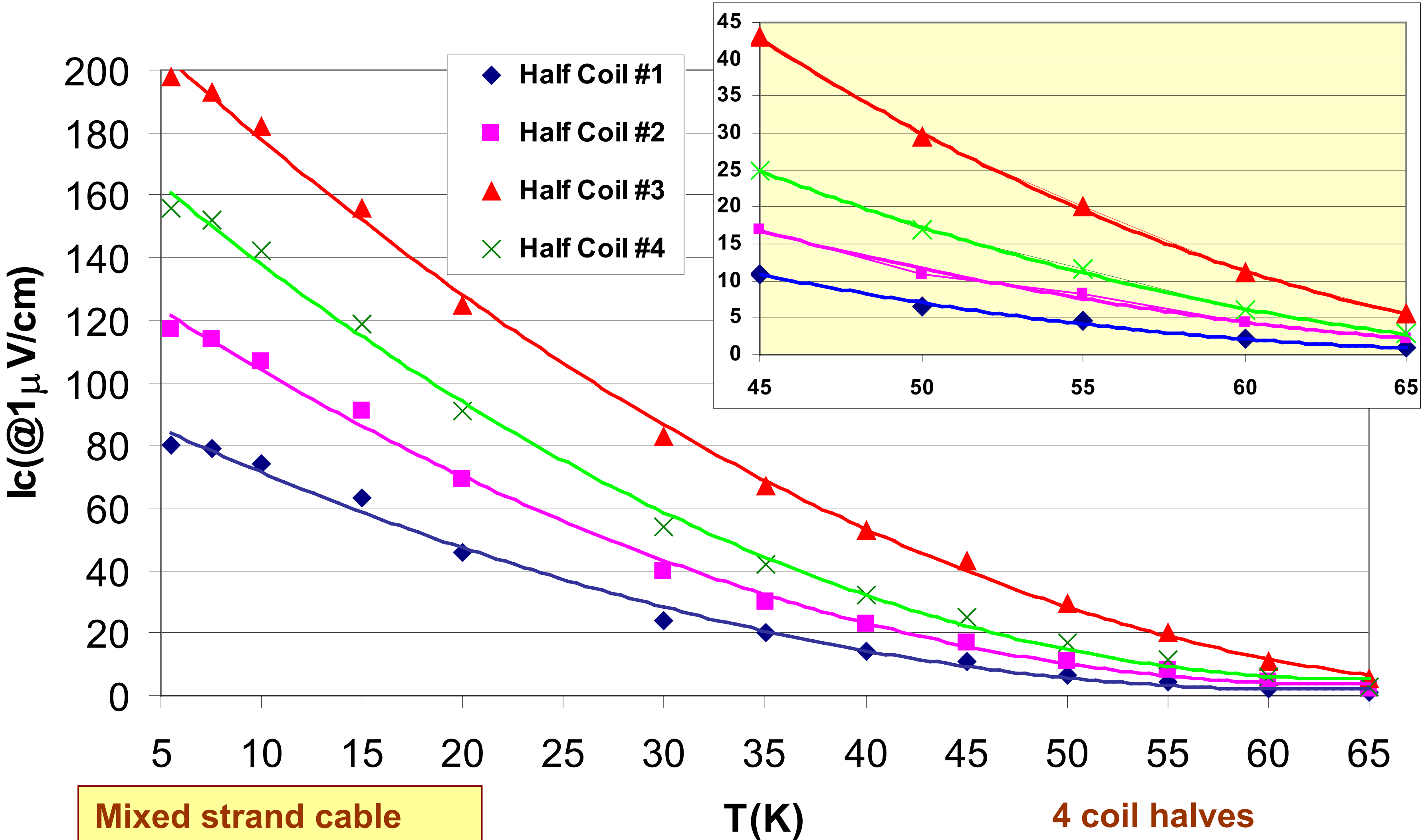


Measured Ic of Various Turns



Turns No. 1-7 show an I_c close to the best measured in cable prior to winding. This suggest a low level of degradation.

Measured Critical Current as a Function of Temperature

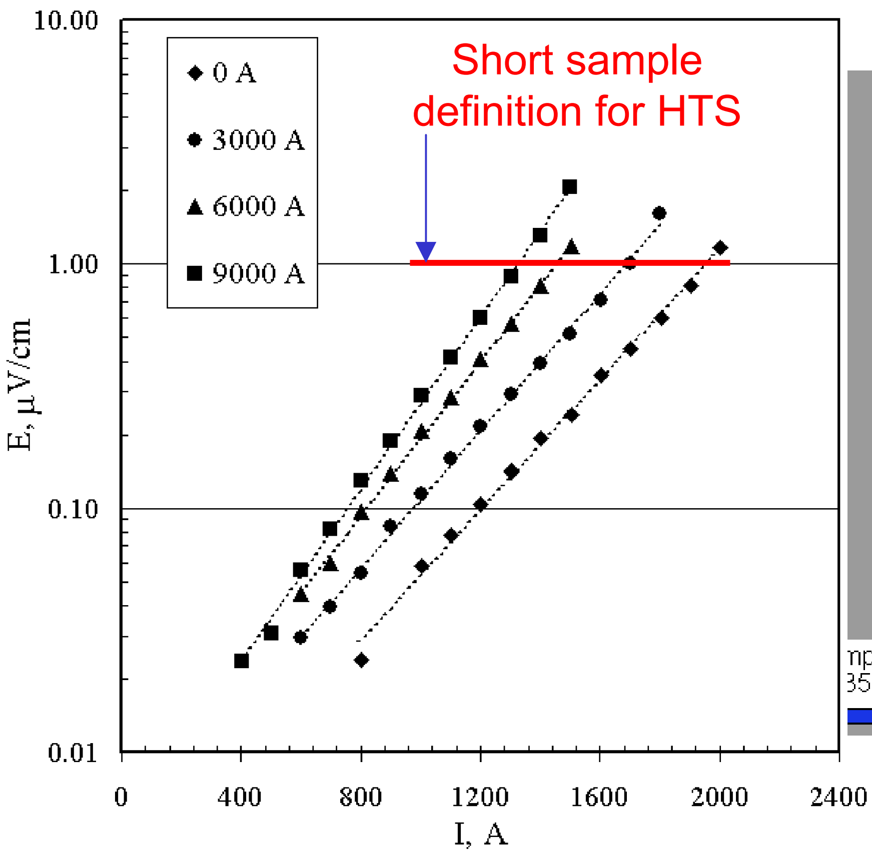


Mixed strand cable
(2 BSCCO 2212, 16 Ag)

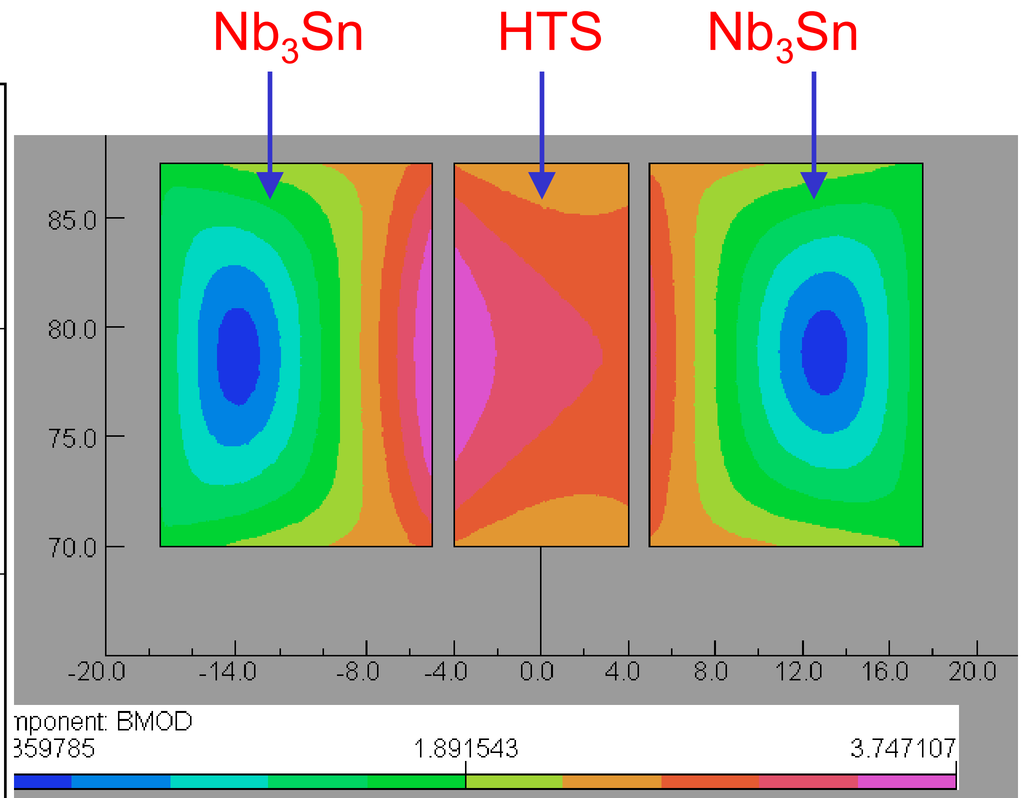
4 coil halves
(2 each of two coils)

Performance of HTS Coil in the Background Field of Nb_3SN Coils

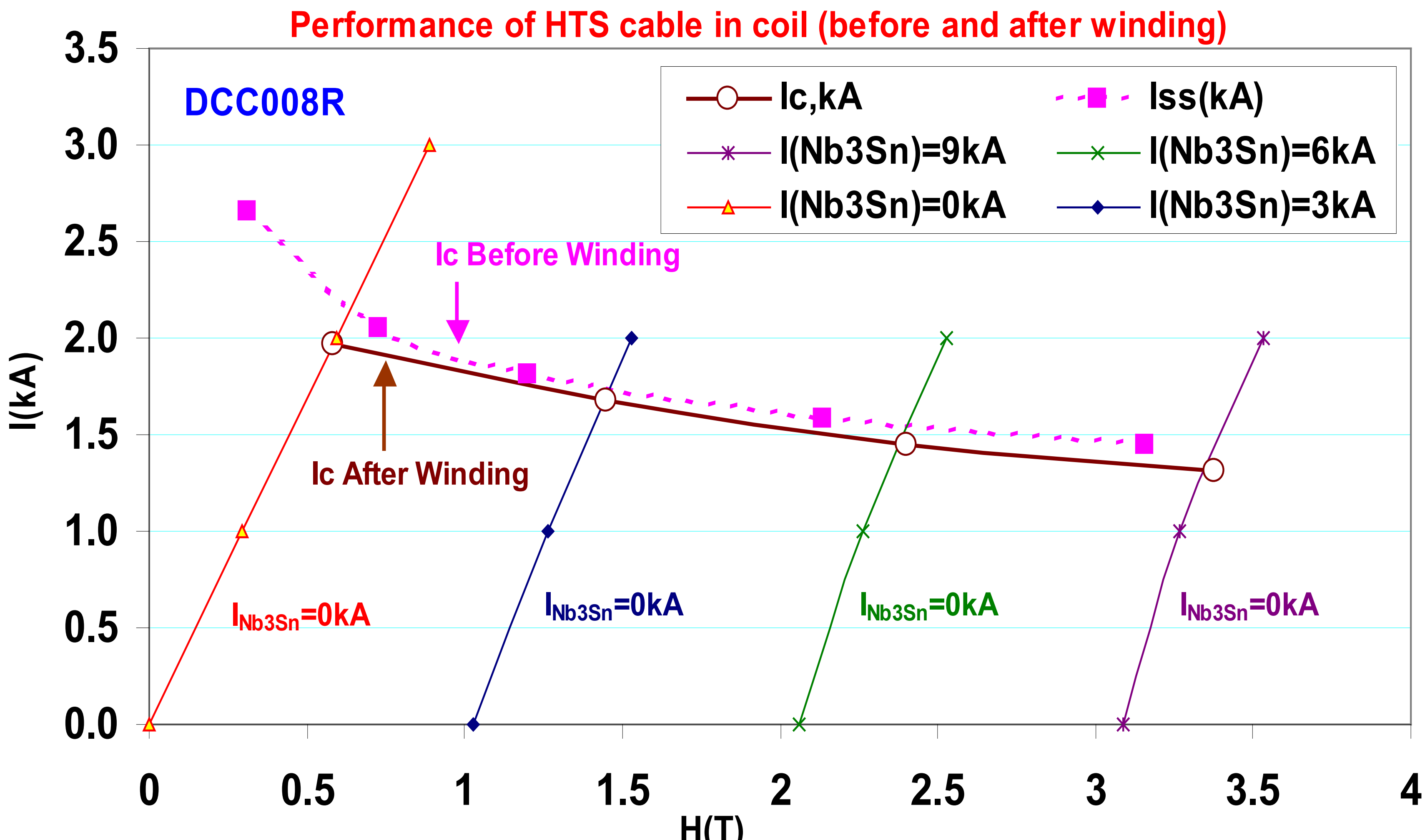
Measured electrical Resistance of HTS coil in the background field provided by various Nb3Sn coils in the magnet DCC008R



Field in various coils



Performance of HTS Coil in the Background Field of Nb_3SN Coils



HTS coil was subjected to various background field by changing current in "React & Wind" Nb_3Sn coils (HTS coil in the middle and Nb_3Sn on either side)

Low Field Magnet Applications of HTS in Accelerators

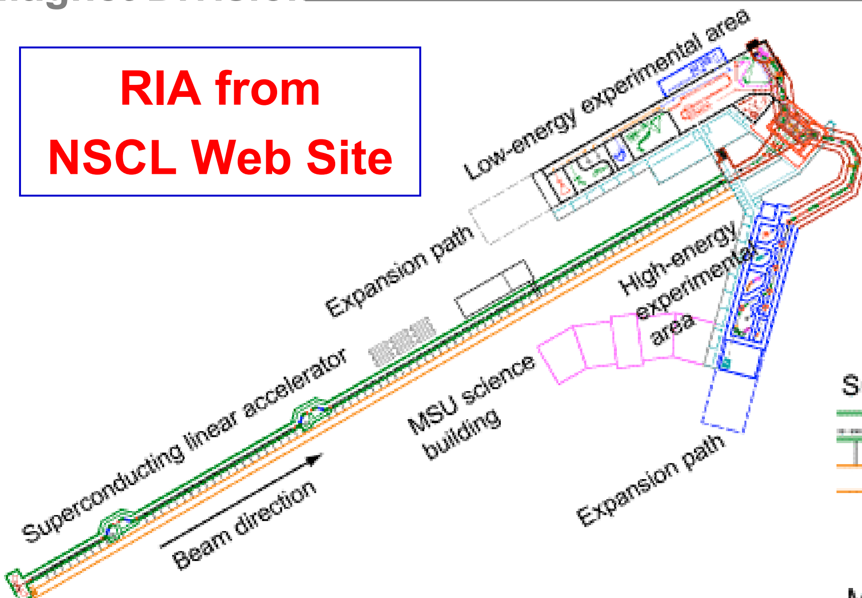
Medium Field, Higher Temperature Application

Example: Quads for Rare Isotope Accelerator (RIA)

- 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 based accelerator magnets).

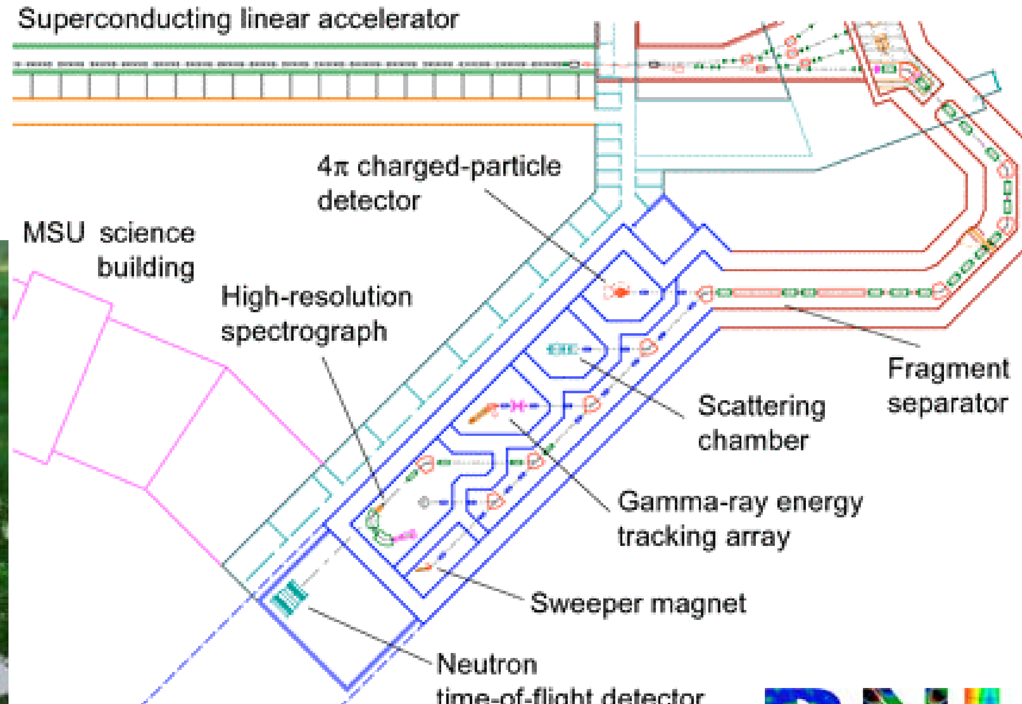
High Temperature Superconductor (HTS) Quads in Fragment Separator Region of RIA

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.

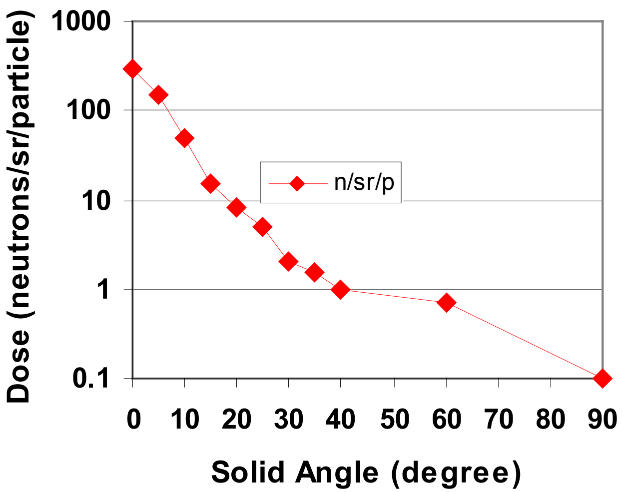
Note: The normal water cooled electromagnet can not generate the required field gradient.

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

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).

NEUTRON YIELDS FROM THICK C, Al, Cu, AND Pb . . . PHYSICAL REVIEW C **62** 044615

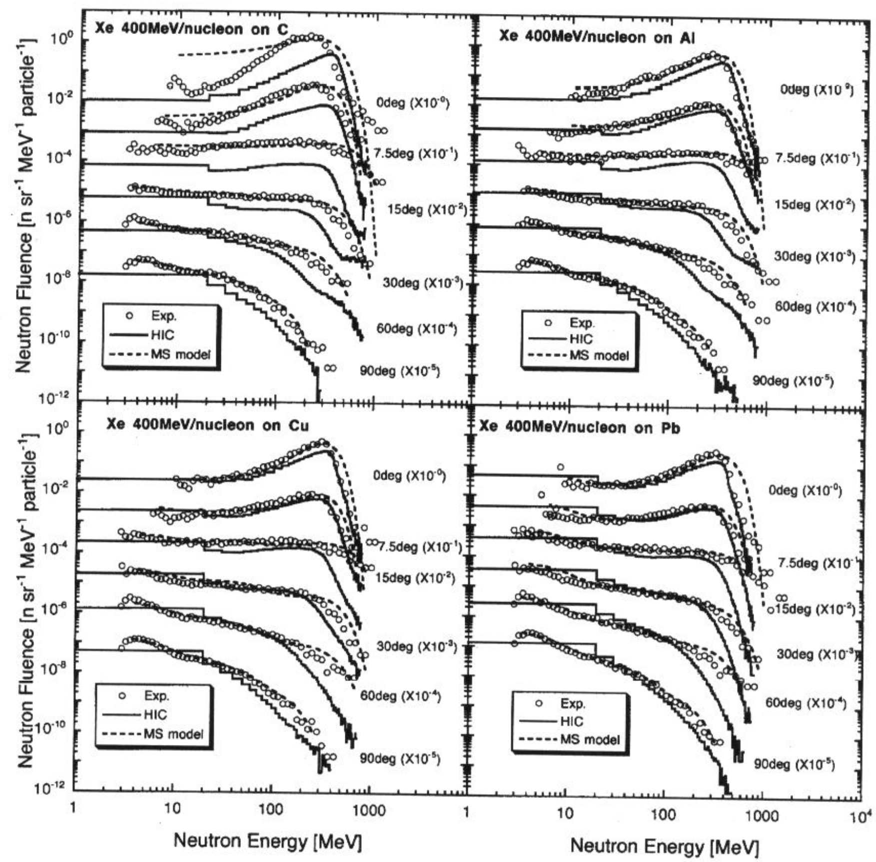


FIG. 3. Neutron-energy spectra from the 400 MeV/nucleon Xe+C, Al, Cu, and Pb system at 0° to 90°. The data are shown by the symbols indicated in the plot. The solid lines are from the calculation by HIC, and the dashed lines come from a fit to the data using Eq. (11).

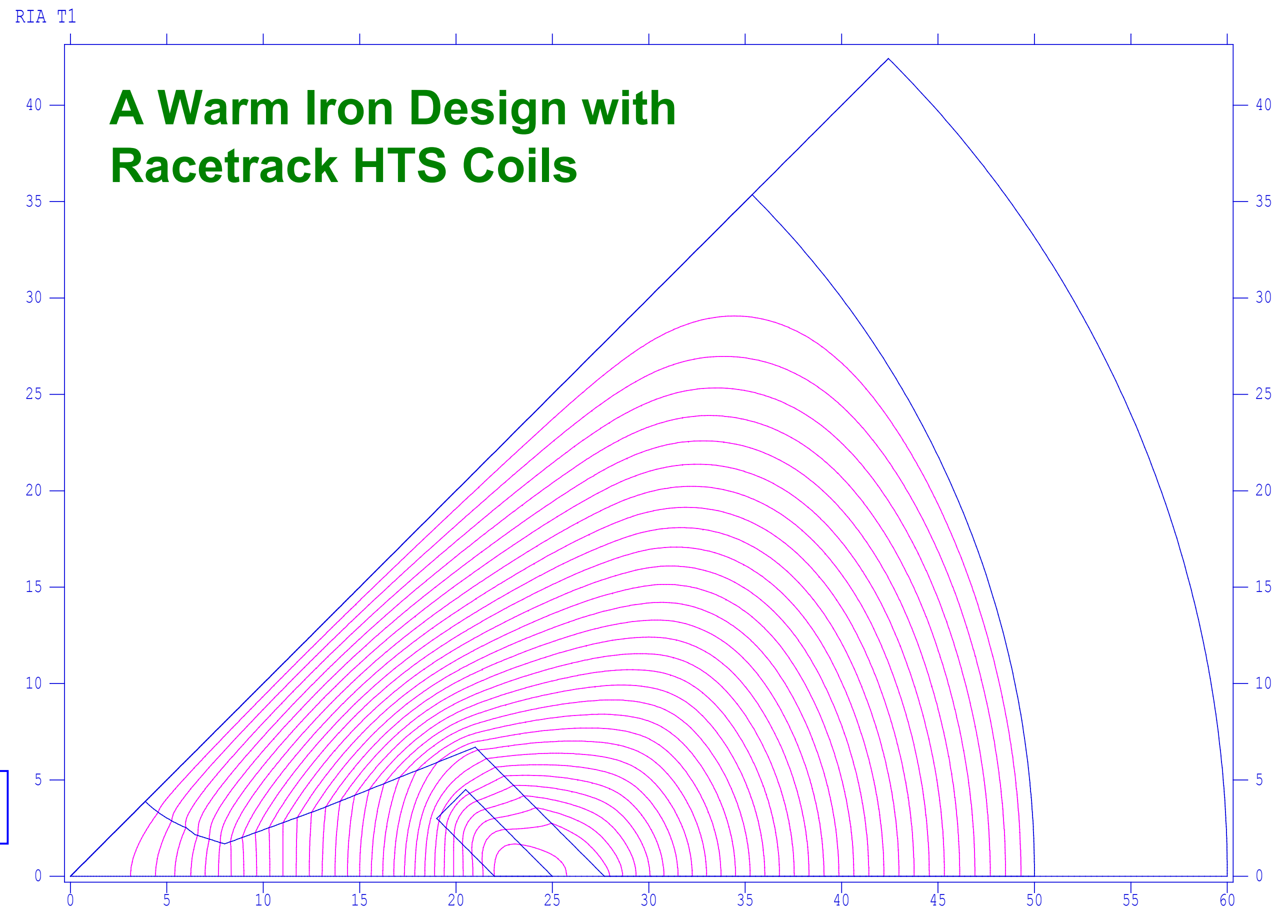
T. Kurosawa, et al., Phys Rev C, Vol 62, 044615

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



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.

Near Term R&D Program at BNL

• Build a series of 10 turn coils with better HTS cable

• Build ~40 turn coils after the technology is reasonably developed

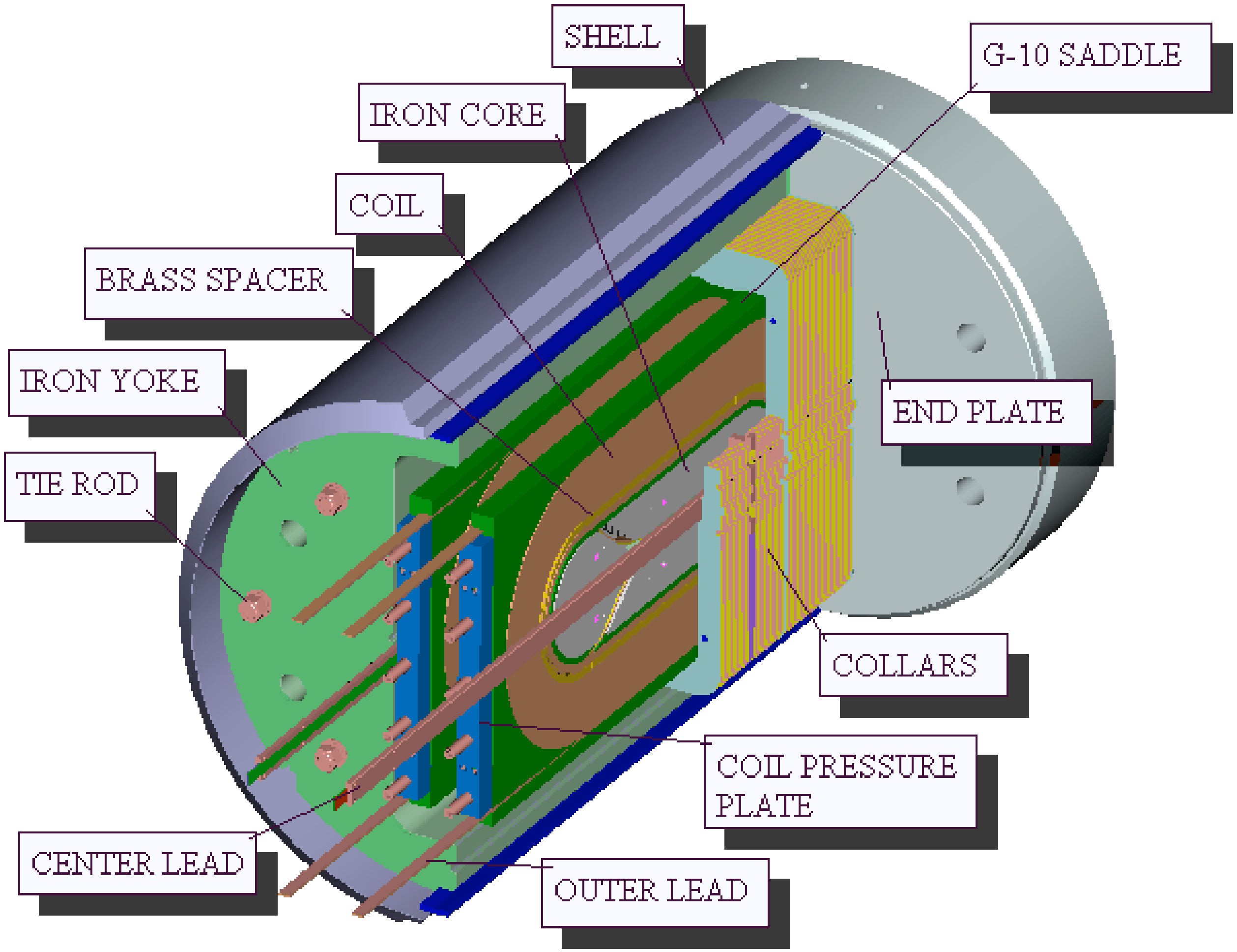
• In parallel build ~12 T magnet with Nb_3Sn to provide background field

• Assemble hybrid magnet to study issues related to the performance of HTS coils in high field environment

•Study field quality issues related to HTS magnets

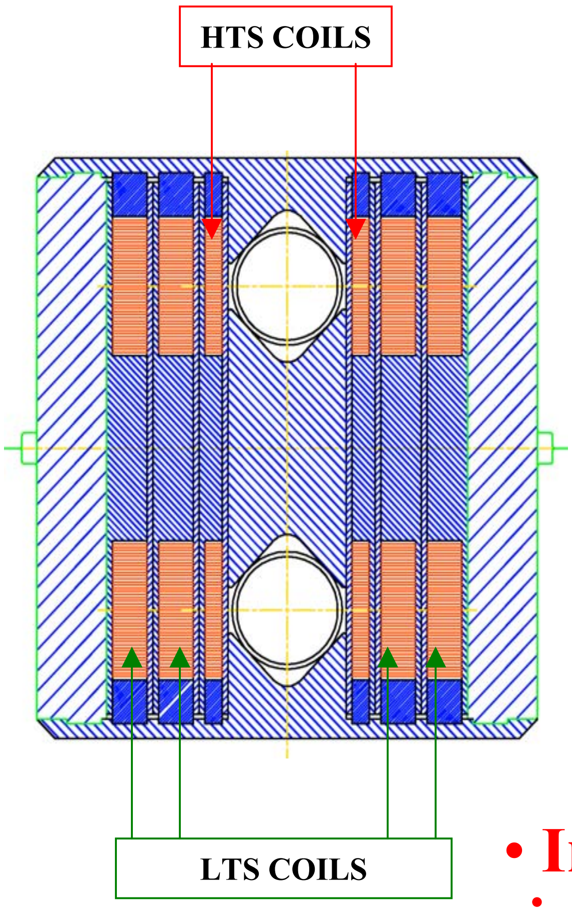
Present the results to accelerator community so it can make an informed decision about the viability of HTS in accelerators to take advantage of exciting benefits it offers.

Cut-away View of the 12 T Magnet



Cut-away view of the 12T Magnet

12 T Magnet: The Important Next Step in HTS R&D Program

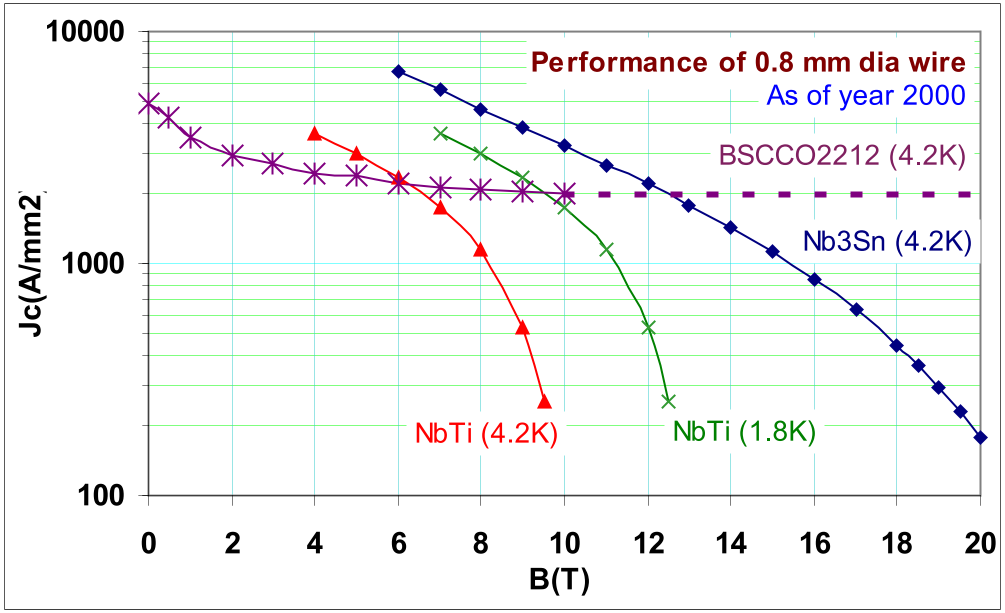


- At present, HTS alone can not generate the fields we are interested in.
- Nb_3Sn coils provides high background fields. The HTS coils will be subjected to high field and high stresses that would be present in an all HTS magnet. Therefore, several technical issues will be addressed.
- Since 12 T Nb_3Sn magnet uses similar technology (building high field magnet with brittle material), it also provides a valuable learning experience in building an all HTS high field magnet.

• Important design consideration: Allow a simple mechanism for testing HTS insert coils.

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)

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.

SUMMARY

- **HTS has potential to make a significant impact on the design and operation of future accelerators**
  - HTS can generate high fields
  - HTS can work at elevated temperature
- **HTS cable and coil testing at Liquid Nitrogen (LN2) temperatures has been found reliable and productive**
  - Good correlation between higher temperature (LN2) and lower temperature testing
  - LN2 tests are much easier, faster and cost effective
- **New "conductor friendly designs" allow HTS "React & Wind" technology to be incorporated in accelerator magnets**