XVIII RUPAC Obninsk 2002

Progress on Using High Temperature Materials in New Generation Accelerator Magnets

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Overview of the Presentation

- Why High Temperature Materials in Accelerator Magnets?
- High Temperature Superconductor (HTS) Cable and tape
  - ☐ Status
  - ☐ Testing
- New Magnet Designs and R&D Approach Suitable for HTS
- Construction and Test Results of Short HTS Coil & Technology Magnets
- The Next Step and the Summary

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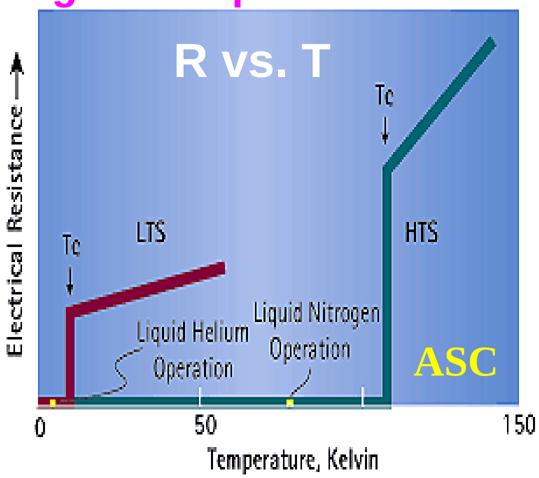
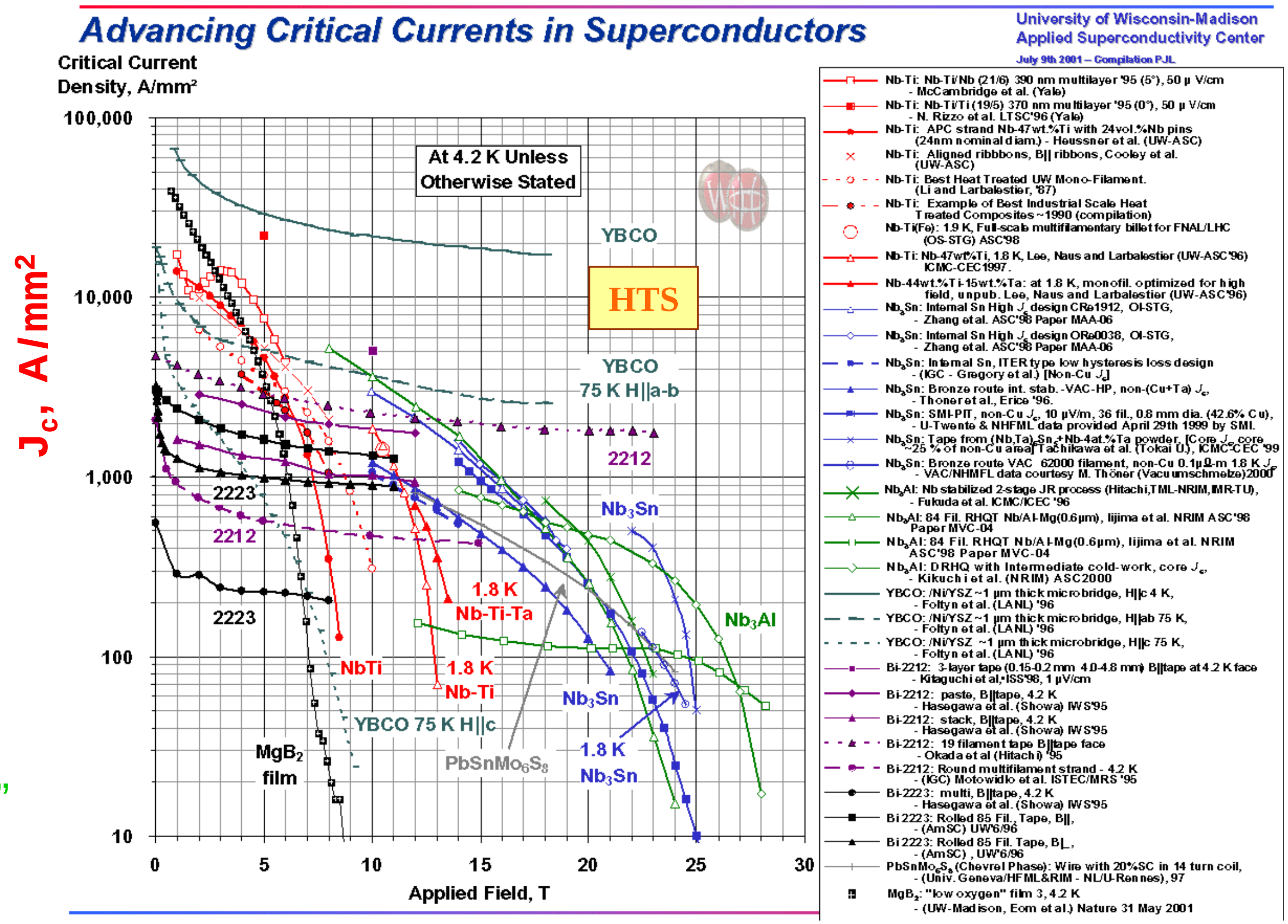
Some Remarkable Properties of HTS (High Temperature Superconductors)

HTS retain superconductivity to higher temperature



Also compare the high field performance of "High Temperature Superconductors (HTS)" as compared to that of "Low Temperature Superconductors (LTS)".



Applied Field, T

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 quantity to make coils of reasonable length (1-10 meter).

Competitive in >17 T magnet today.

We still need a factor of ~3 improvement in current density to make them competitive in 12-14 T magnet.

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 possible improvements over time)

- HTS materials are very brittle

  Work on magnet designs ("conductor friendly designs").

- HTS materials are still very expensive

  Hope the cost comes down in future.

  Also for some applications, the performance and not the material cost is determining factor.

- Large quantities are not available yet

  Situation is improving. Even now we have enough to make test coils.

- Unknown field quality issues

  We are addressing that by measuring field harmonics in HTS magnets (also work on the magnet designs).

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 ~10-15 years from now)

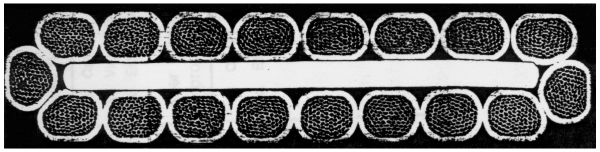
All of above makes HTS a natural choice for next generation IR magnet R&D.

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).

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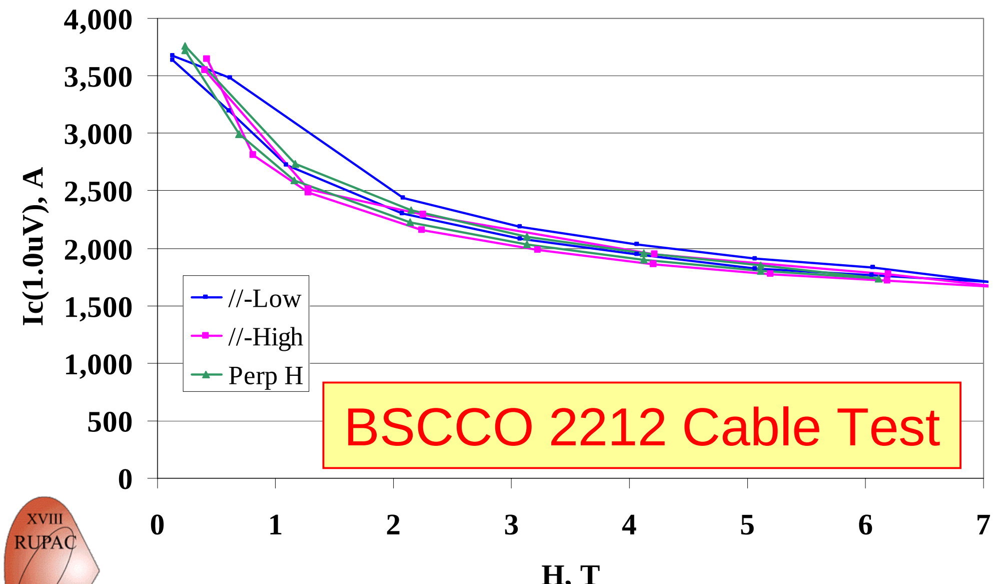
Measured Performance of HTS Cable and Tape As A Function of Field at BNL

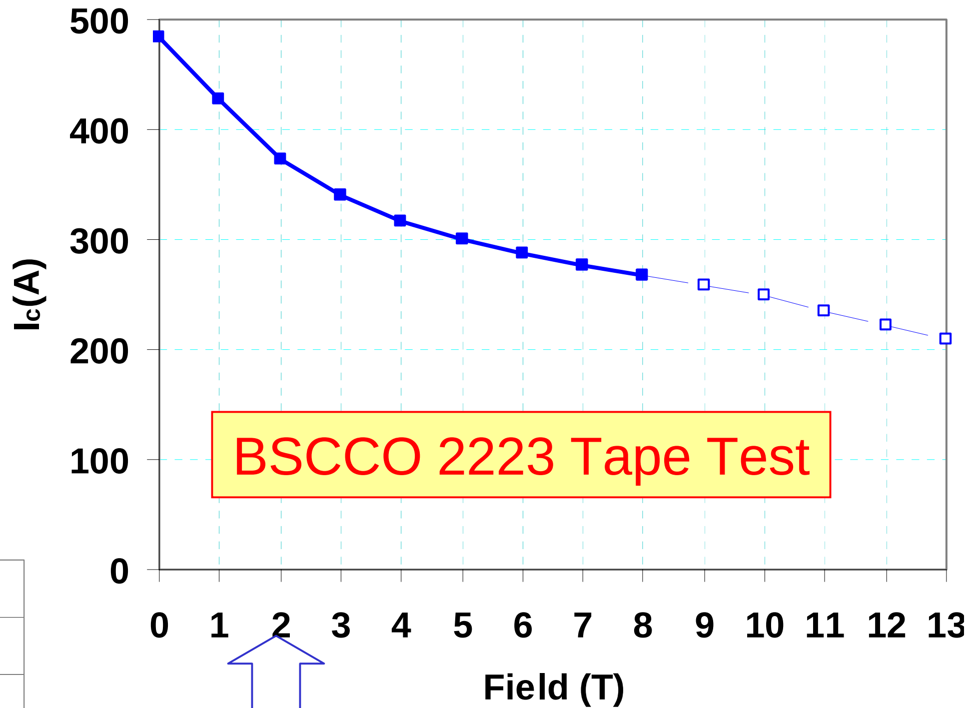
Measurements of "***BSCCO-2212 cable***" (Showa/LBL/BNL) at BNL test facility

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%)

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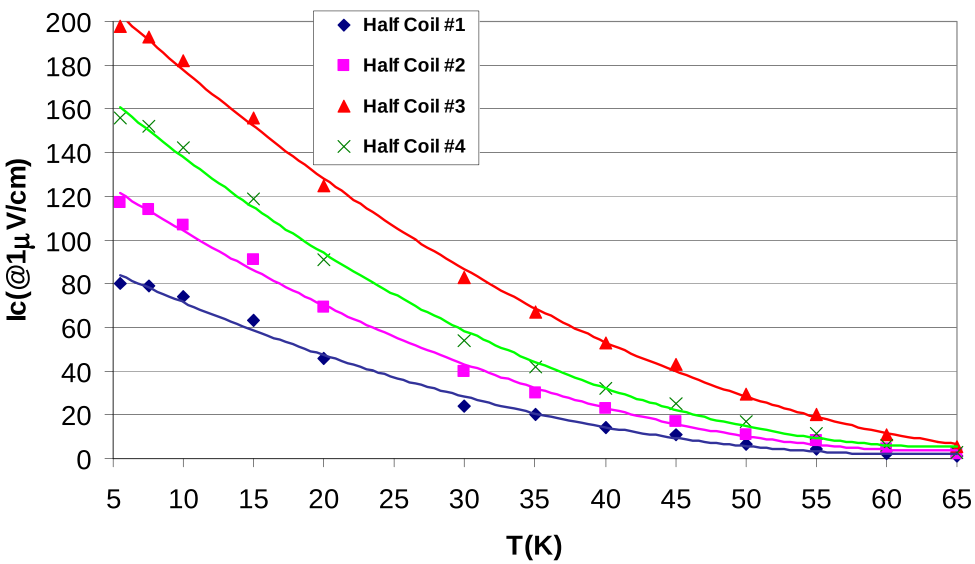
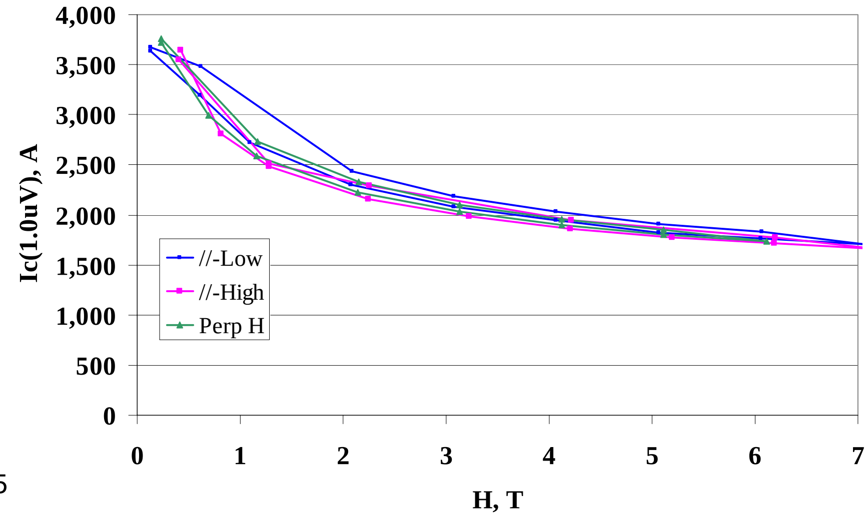
Critical Current as a Function of Temperature & Field





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.

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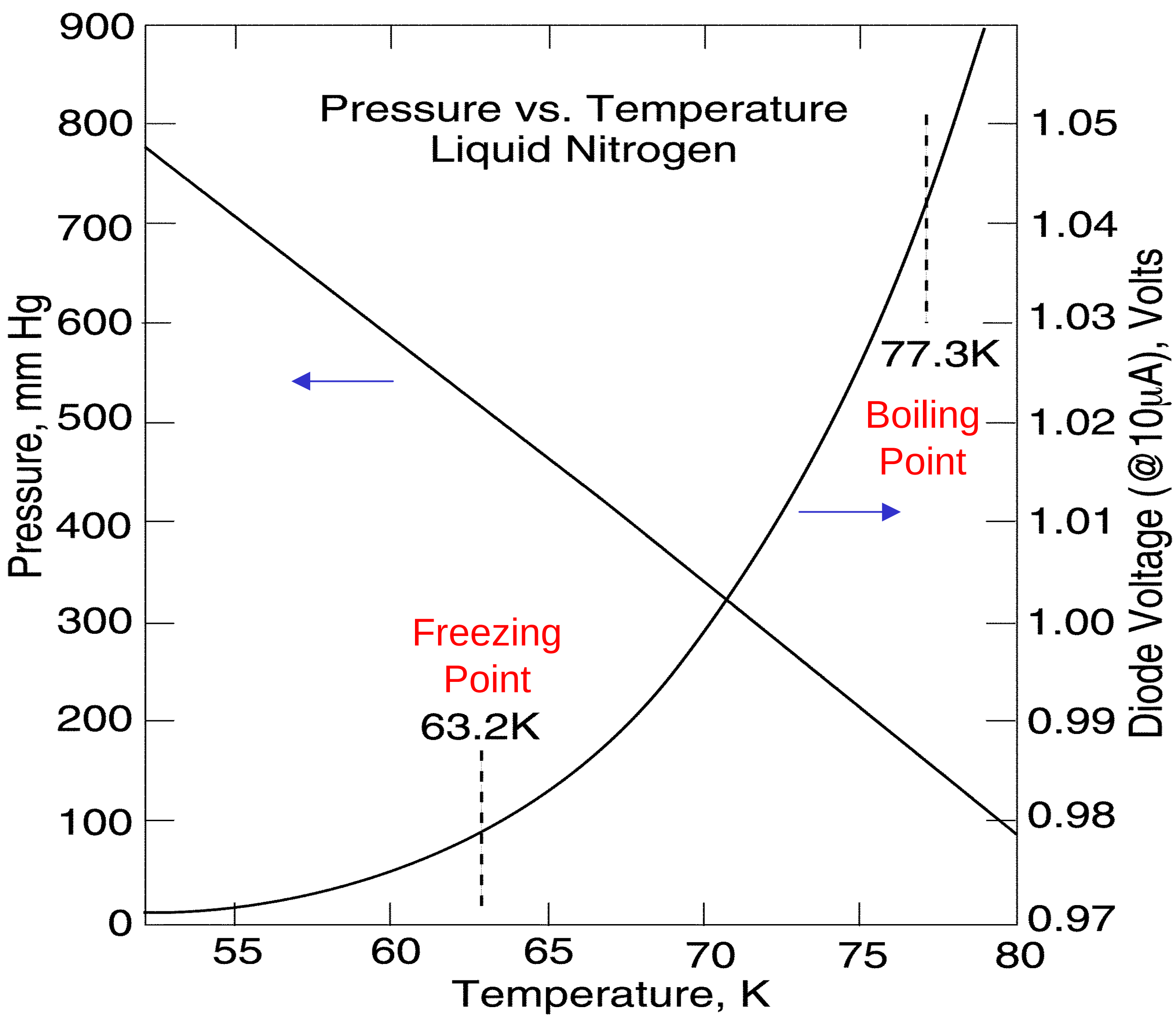
Pressure-Temperature Curve for Liquid Nitrogen

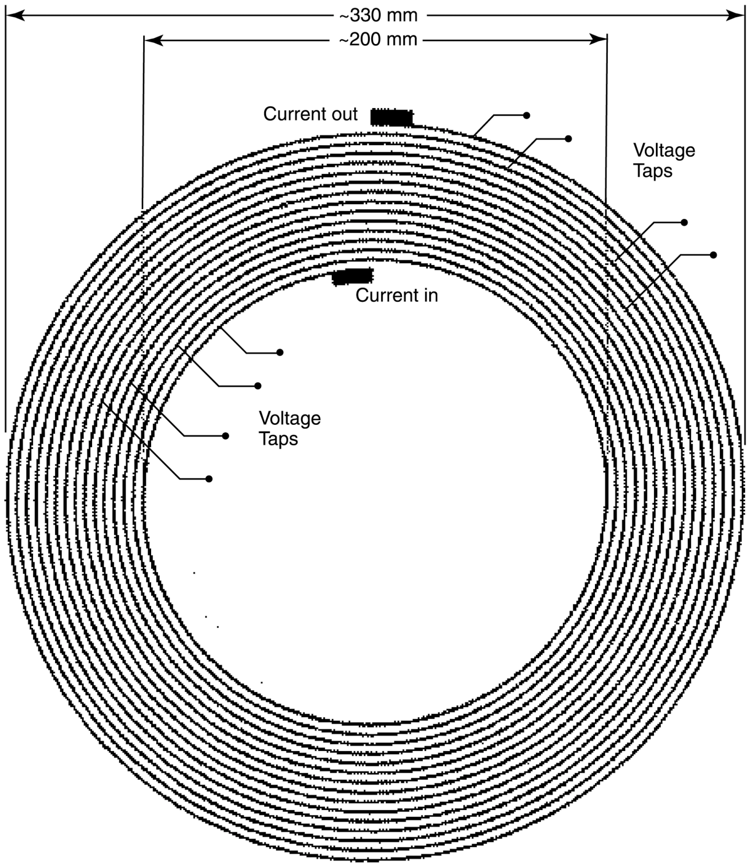


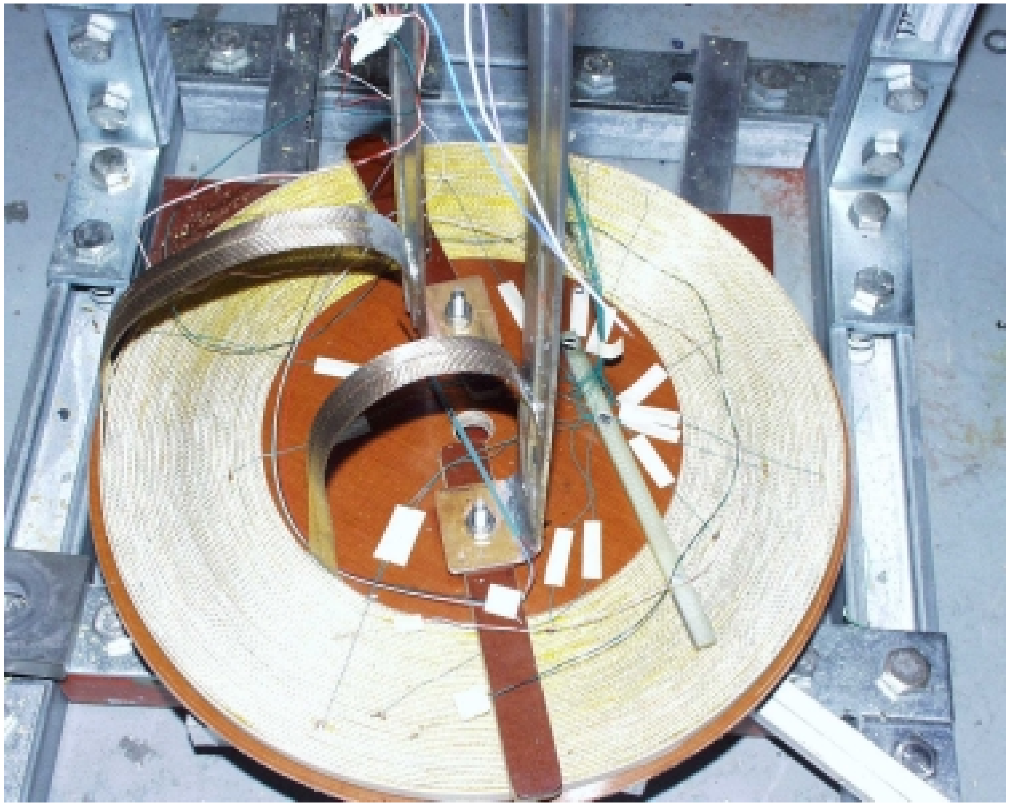
Batch Testing of HTS in LN2

- Batch testing of the much smaller Bi-2223 tape conductors in liquid nitrogen is routinely used for quality control as the transition temperature is well above 77K.
- The transition temperature of Bi-2212 based conductors is usually quite close to the normal boiling point of liquid nitrogen (77.3K). By pumping on the nitrogen bath the temperature can be controlled over a significant range. Testing near the transition temperature ensures that currents are small and the resulting forces and magnetic fields are very low so that the fixture used to hold the cable is simple to assemble and take apart.

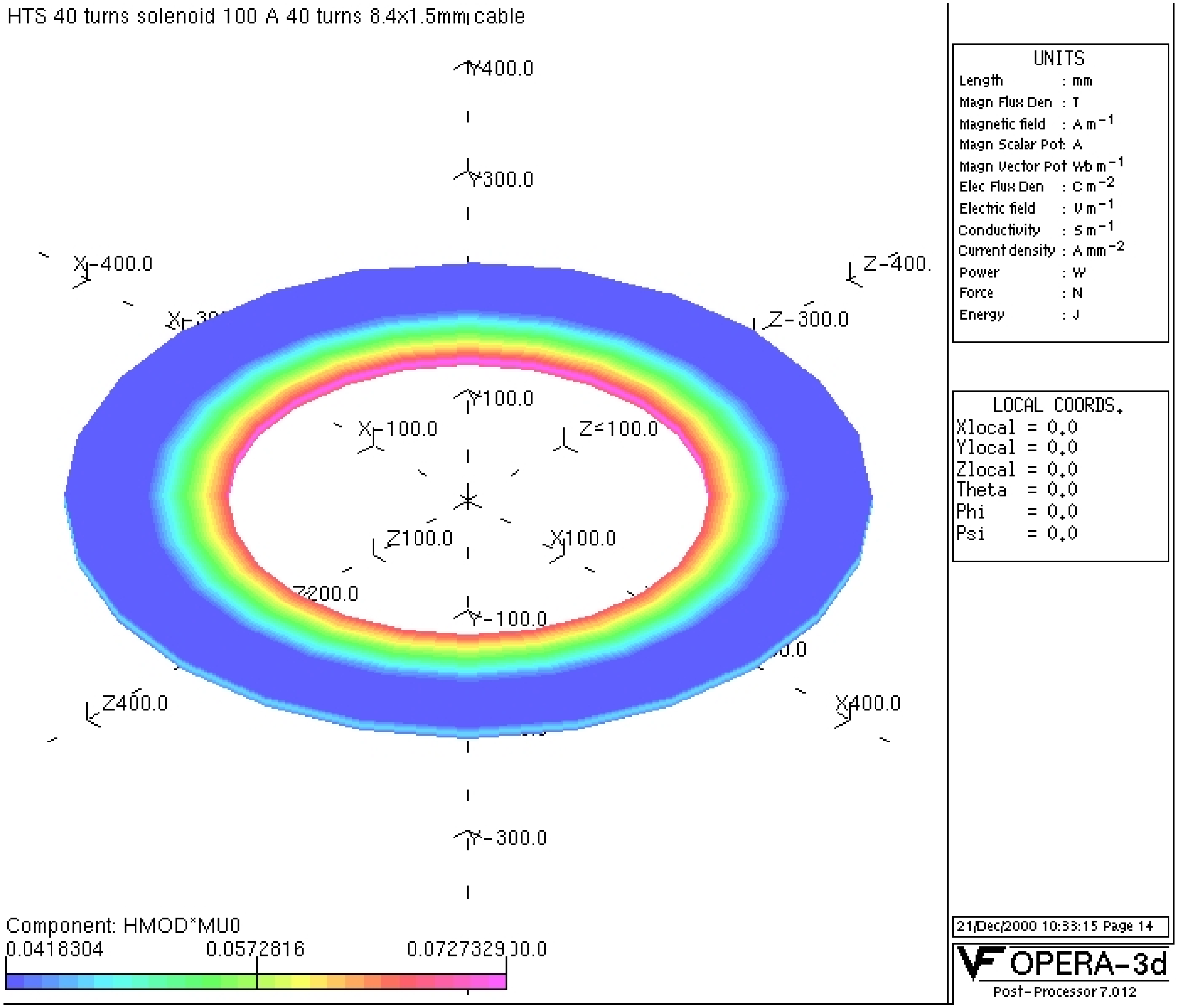
BSCCO-2212 Cable "Pancake Coils"

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



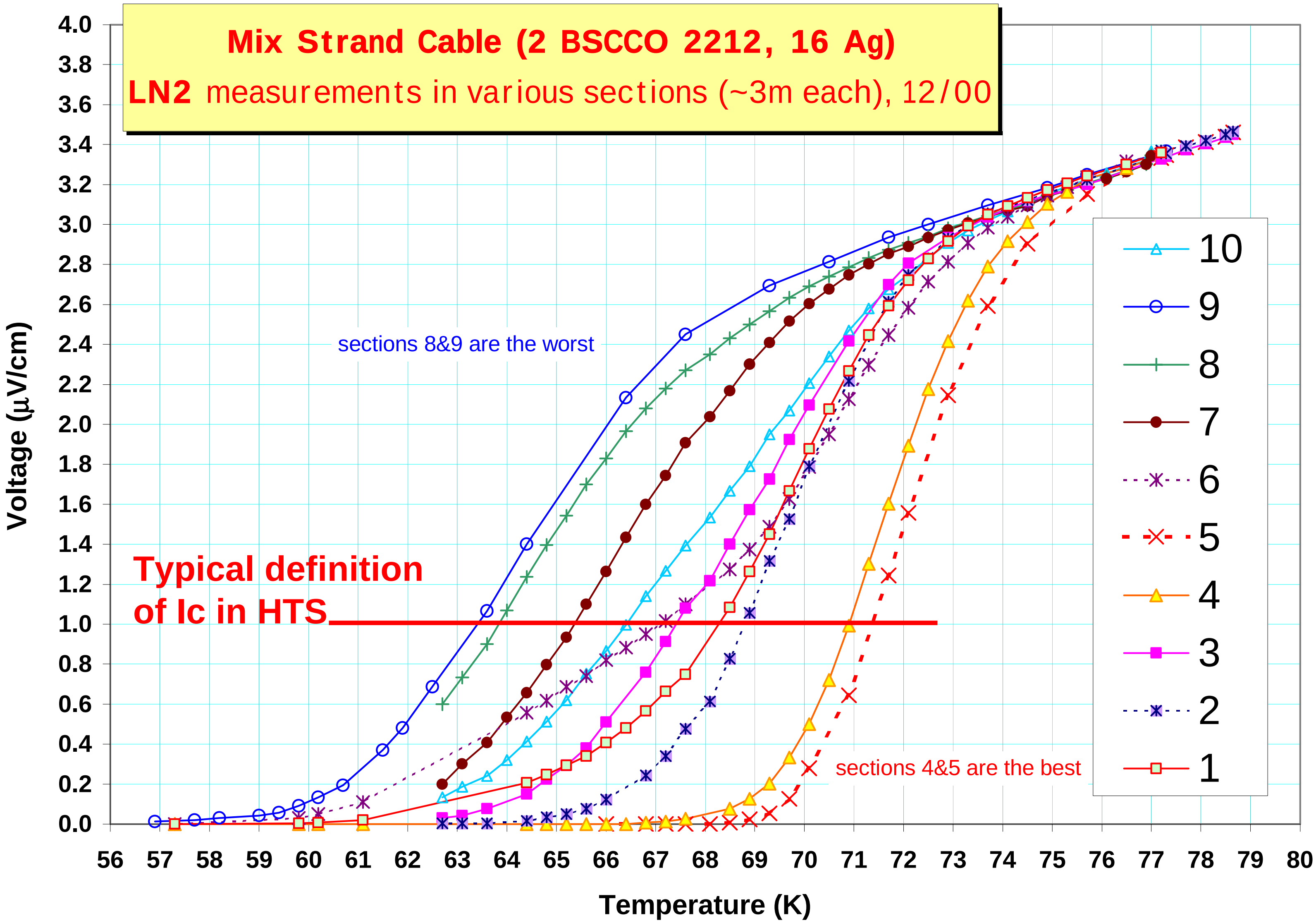


Computed Field at the Surface of Solenoid at 100 A

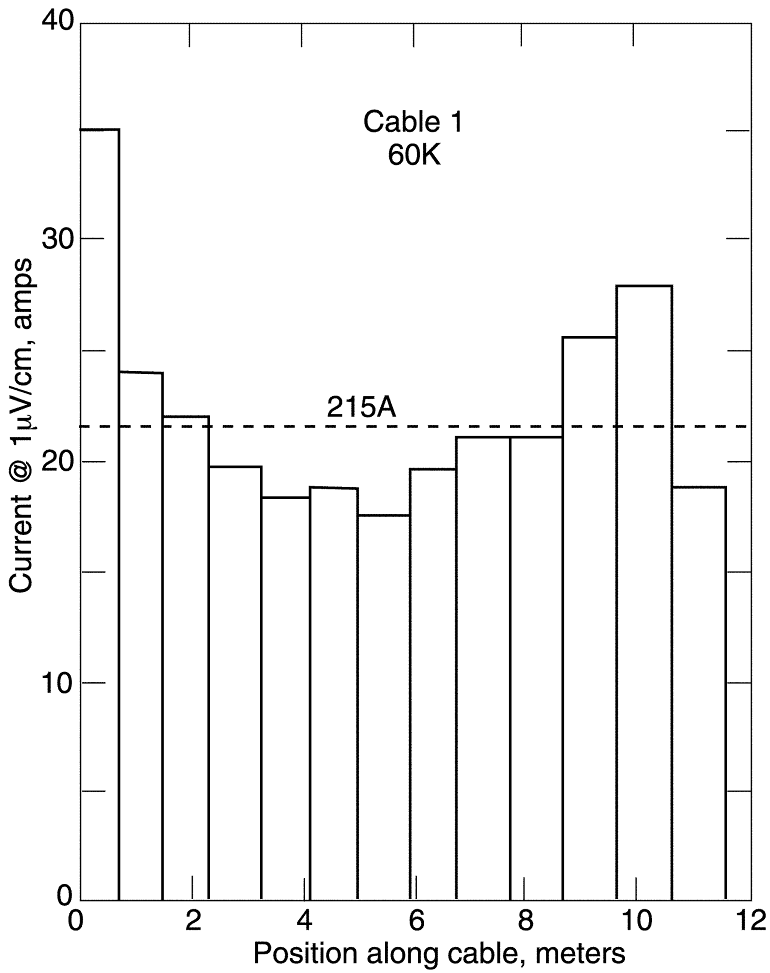


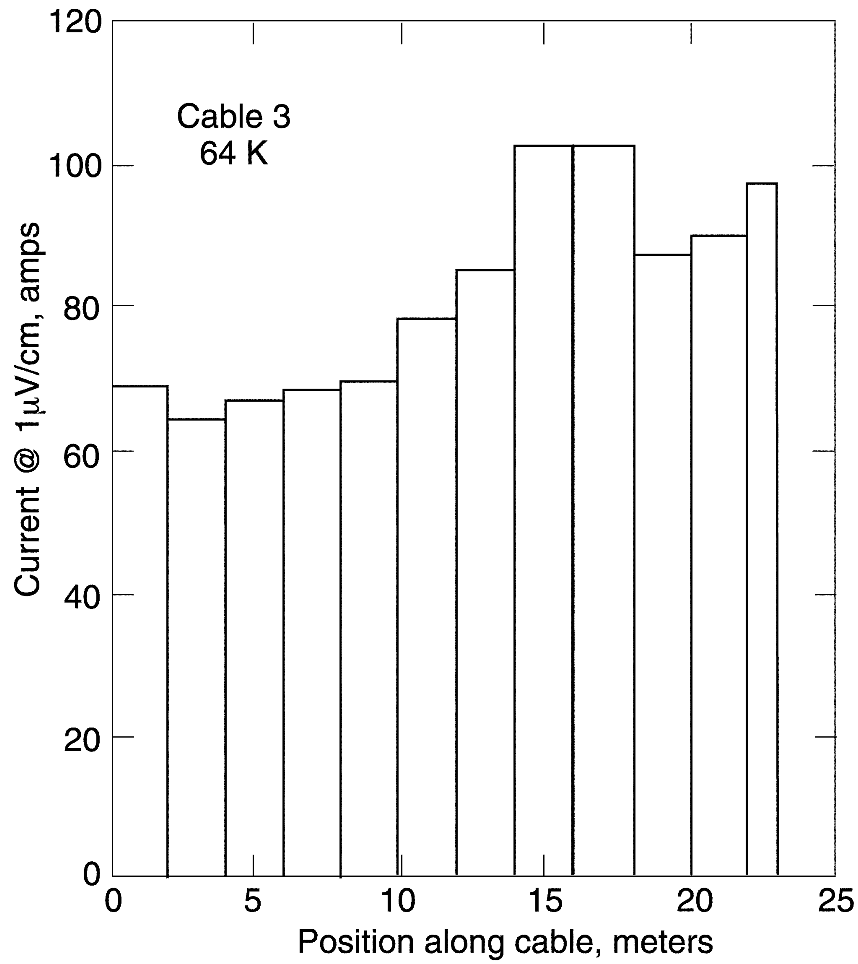
Maximum Field at 260 A is ~0.19 T

T_c Measurements in Liquid Nitrogen

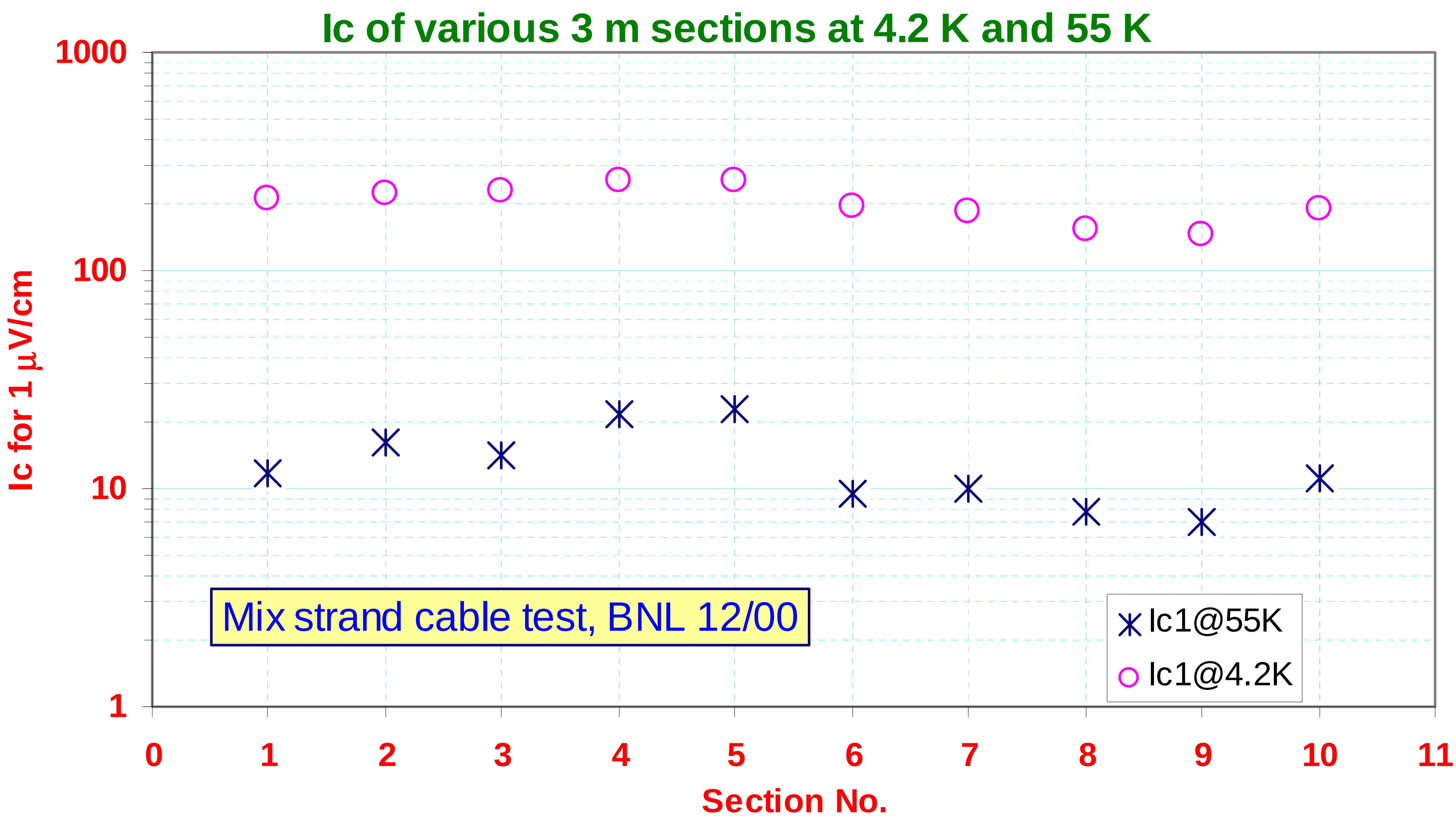


Critical Current variation along the length of the cable

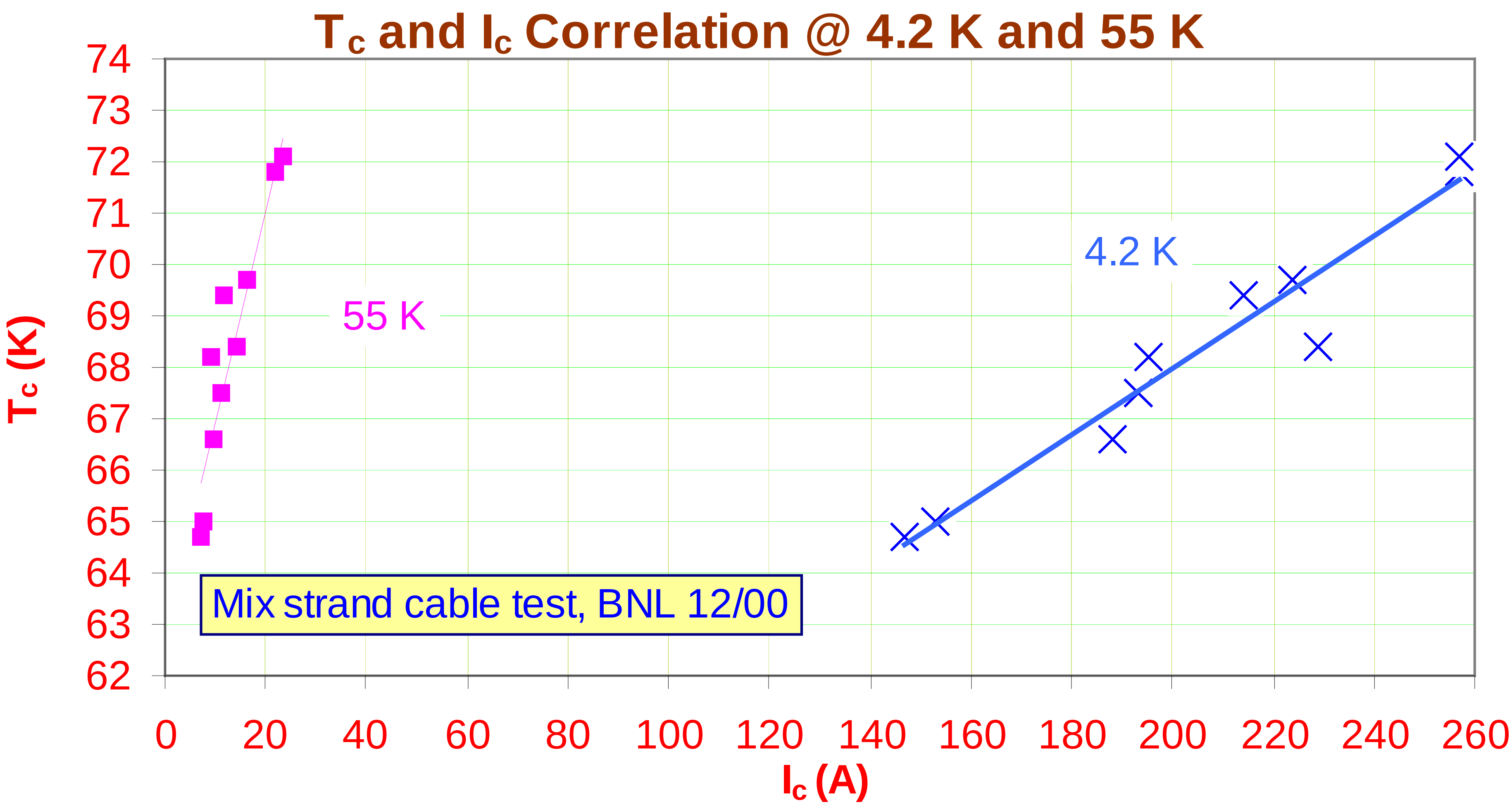




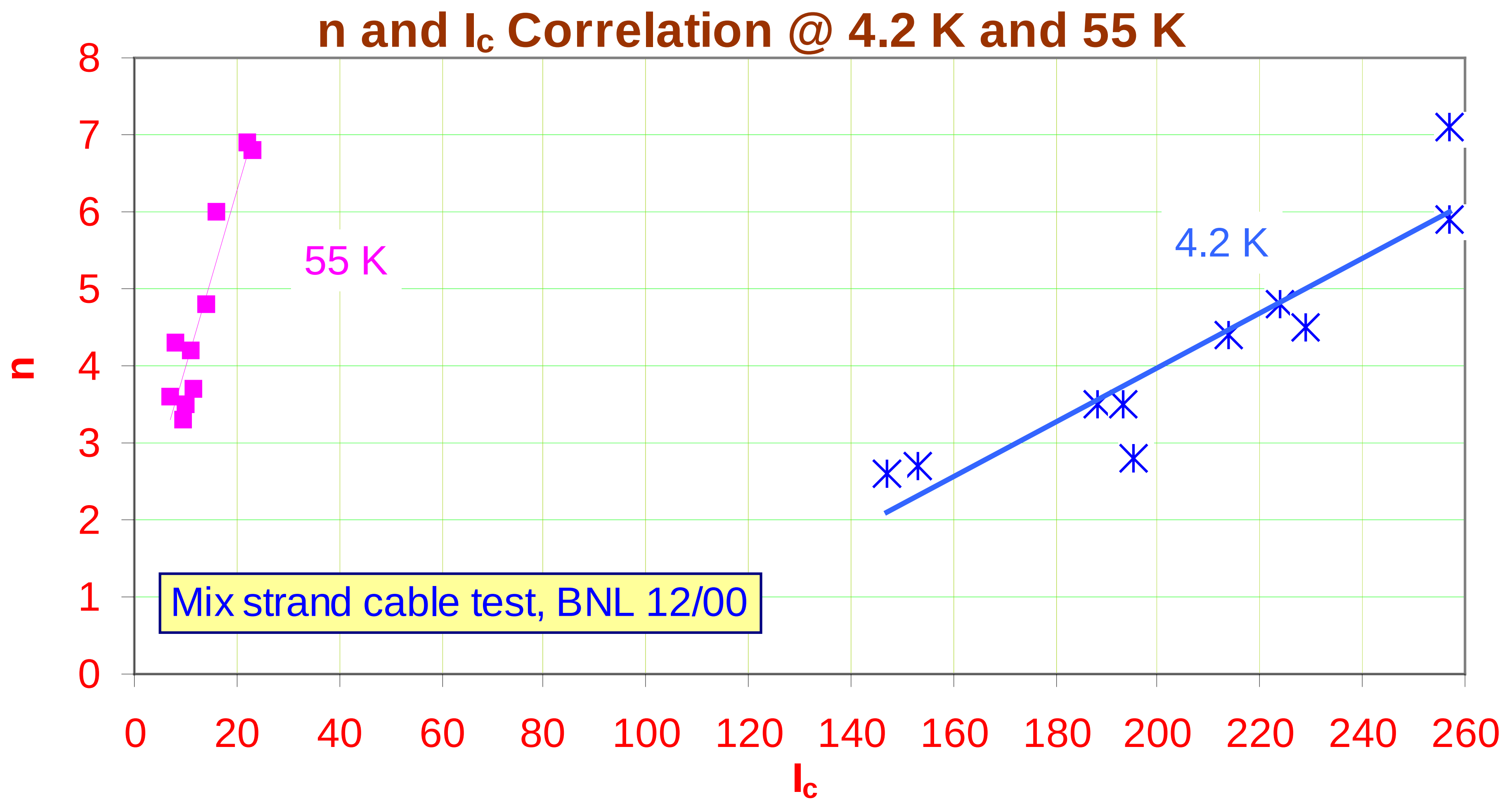
Ic Tracking Between 4.2 K and 55 K



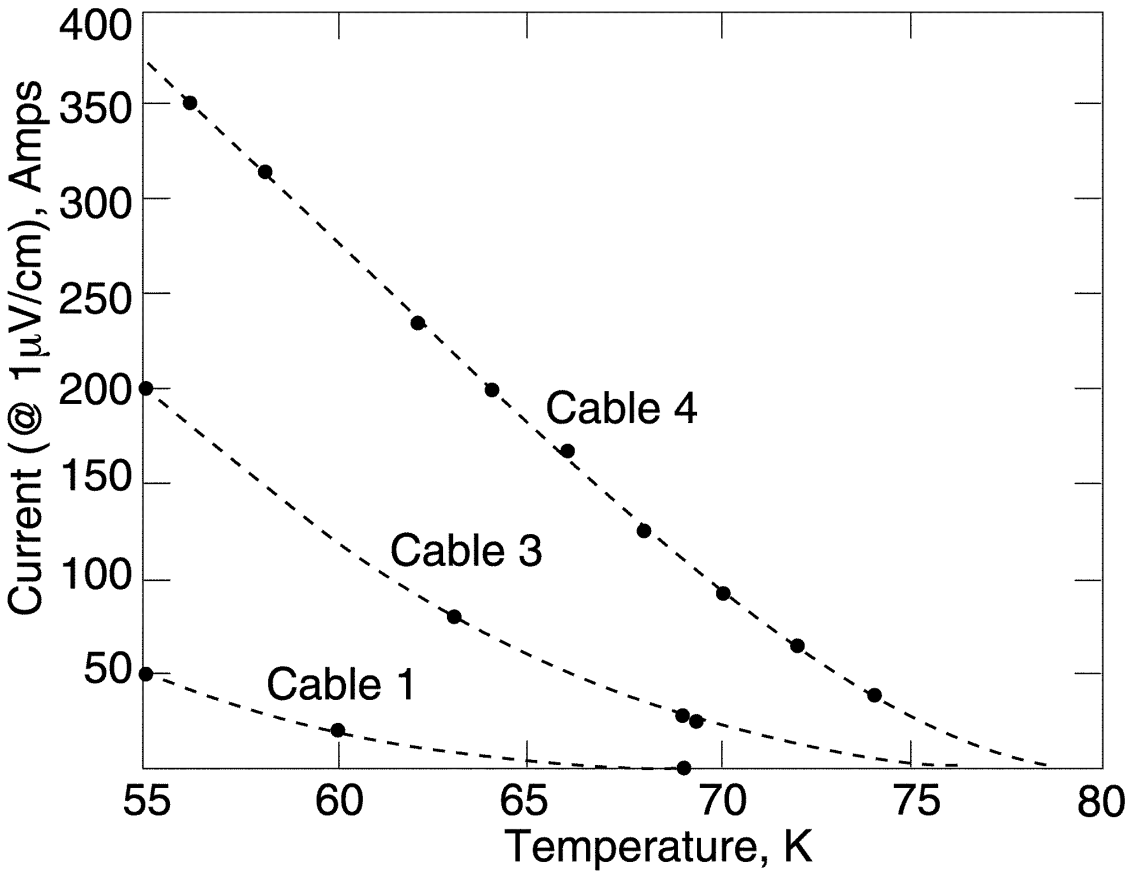
Correlation between T_c and I_c



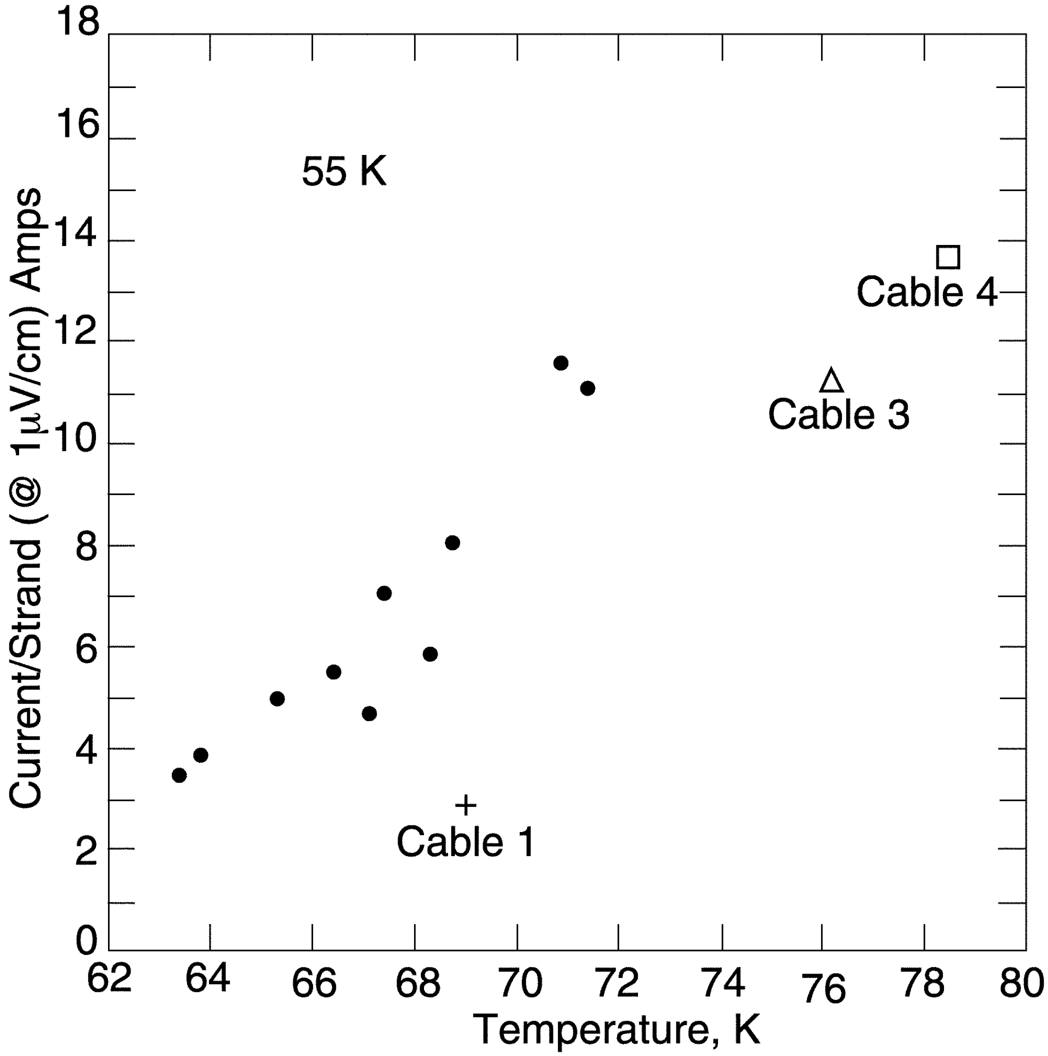
Correlation between T_c and n-value



Ic as a function of Temperature



Correlation between T_c and I_c



Better cables (with higher I_c) also have better T_c

Summary from HTS Cable Test

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

HTS cable still has large potential for improvements

- Large variation in Ic across the length
- Low "n-values"

Design Issues for High Field Accelerator Magnets using HTS

• HTS is very brittle

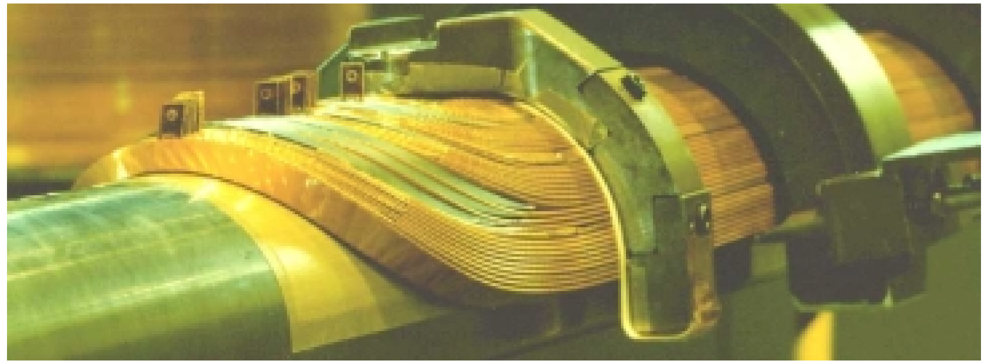
Conventional designs are not the most suitable

• Large Lorentz forces

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

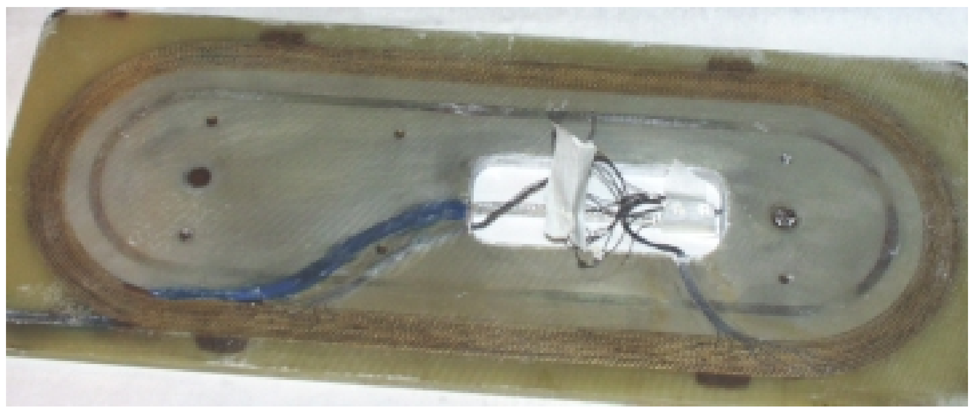
(~1/2 degree at ~890° C)

React & Wind Approach



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

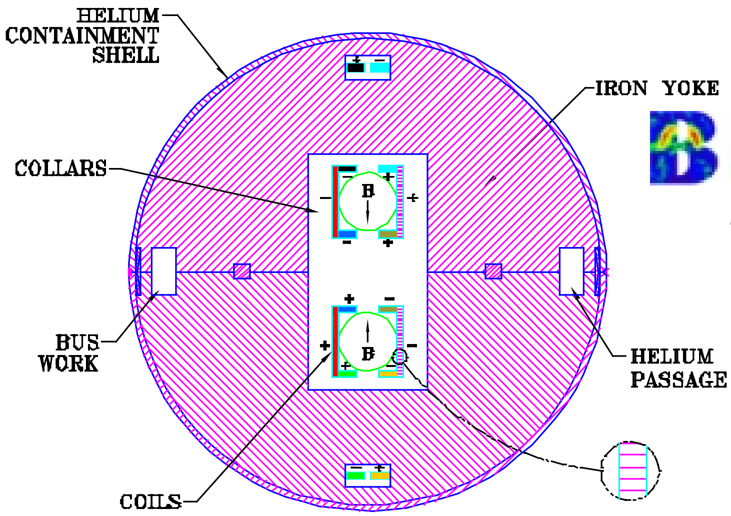
Complex 3-d geometry in the ends



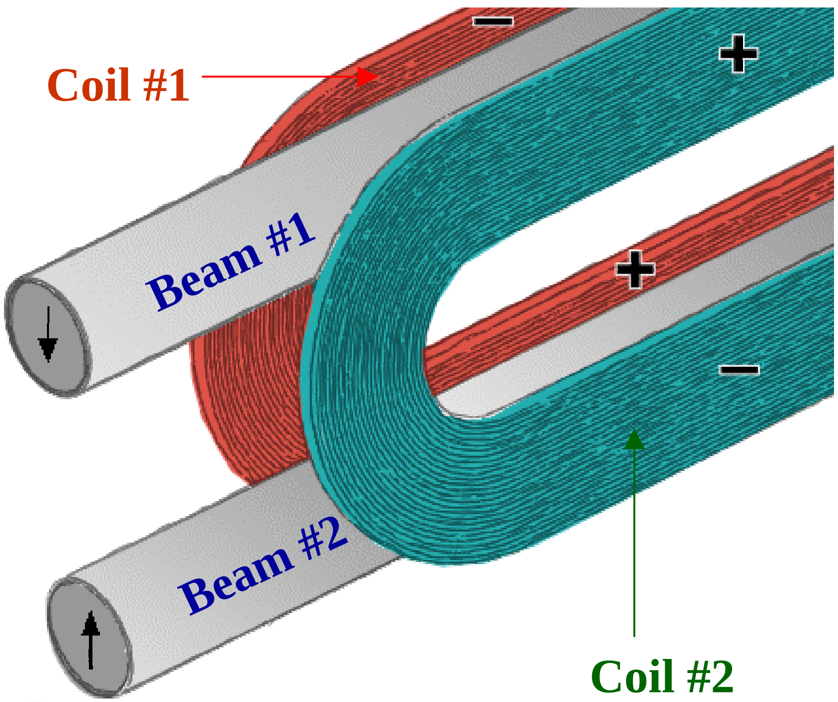
"Conductor friendly" racetrack coil with large bend radius

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**



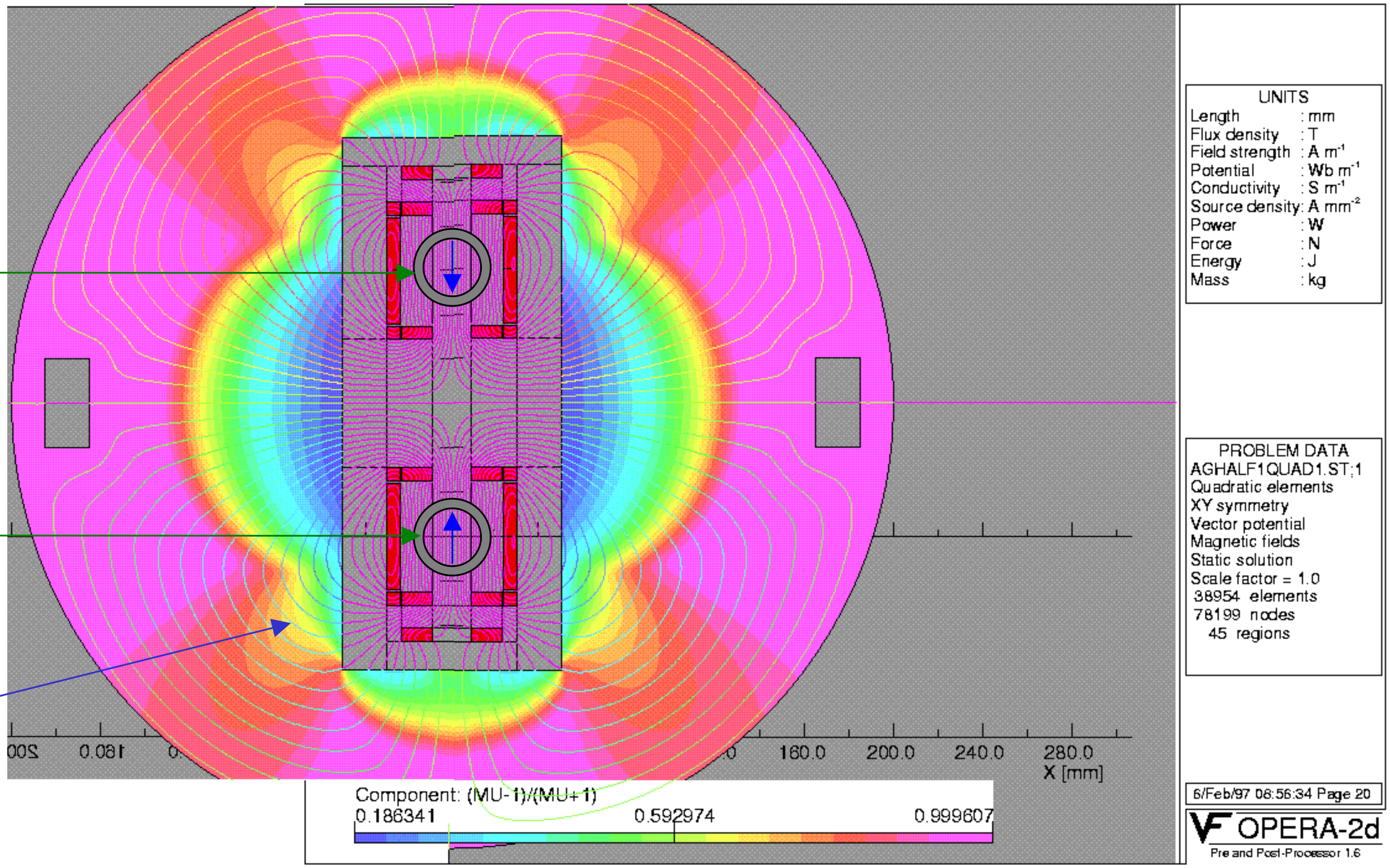
Main Coils of the *Common Coil Design*

Field Lines at 15 T in a Common Coil Magnet Design

Aperture #1

Aperture #2

Place of maximum iron saturation



Common Coil Design to Handle Large Lorentz Forces in High Field Magnets

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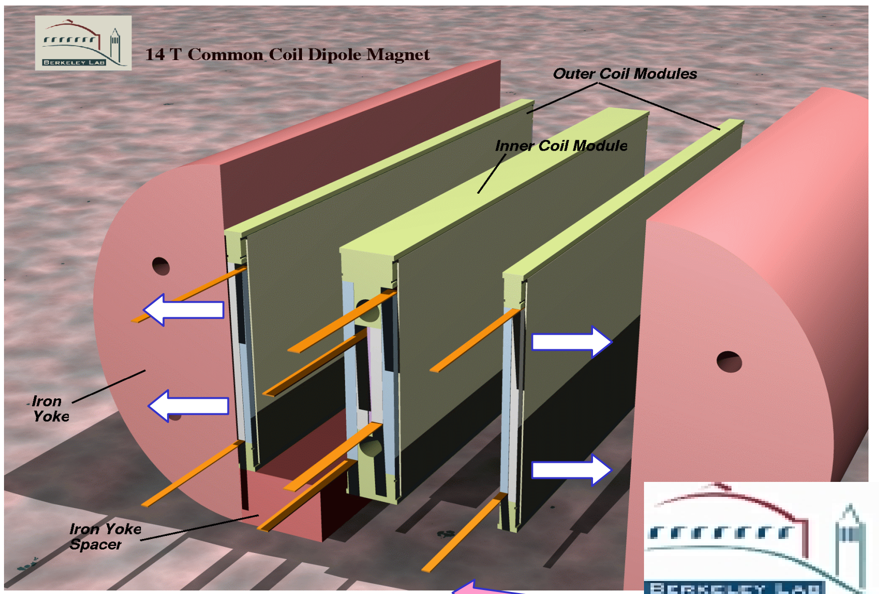
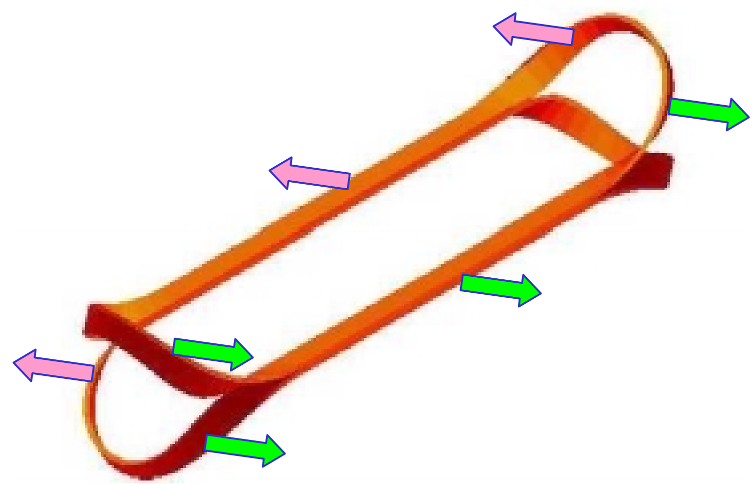
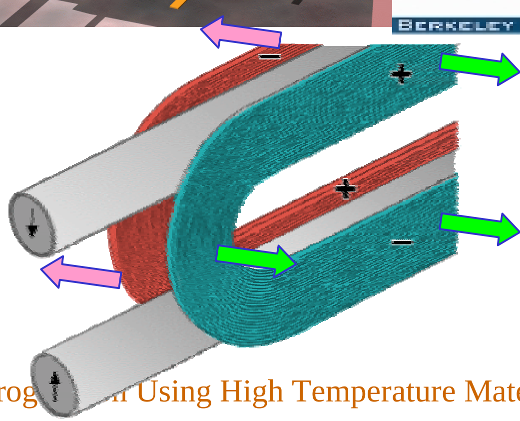
In common coil design, geometry and forces are such that the impregnated solid volume can move as a block without causing quench or damage (over 1 mm motion in LBL RT1 common coil test configuration).



In cosine theta designs, the geometry is such that coil module cannot move as a block. These forces put strain on the conductor at the ends and may cause premature quench. The situation is somewhat better in single aperture block design, as the conductors don't go through complex bends.



Horizontal forces are larger



We must check how far we can go in allowing such motions in the body and ends of the magnet. This may significantly reduce the cost of expensive support structure. Field quality optimization should include it (as was done in SSC and RHIC magnet designs).

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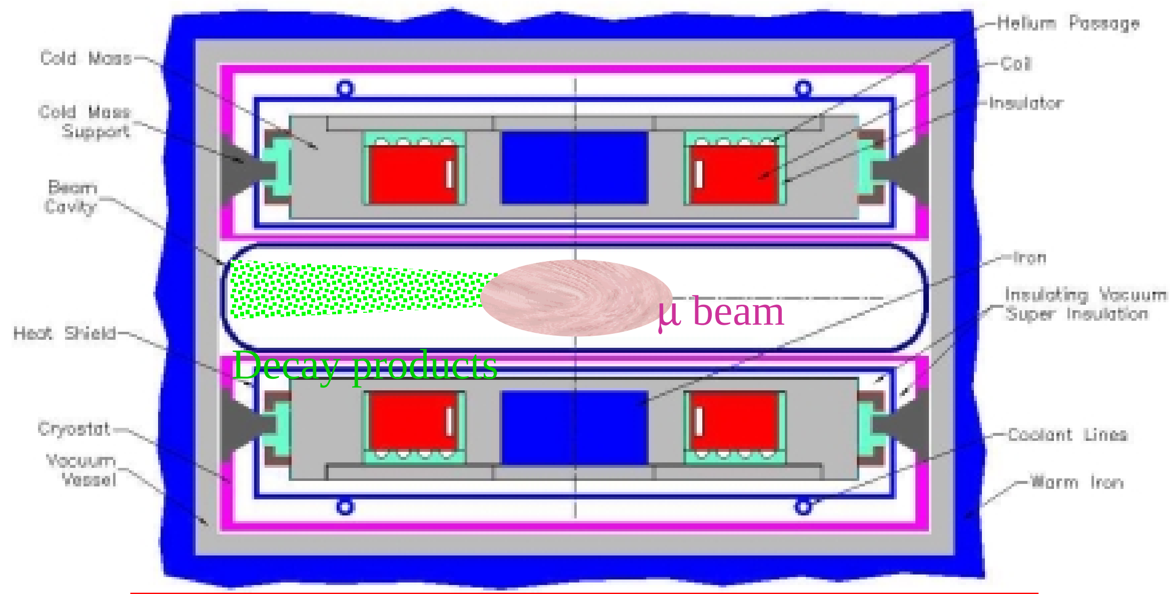
Magnet Design for ν Factory

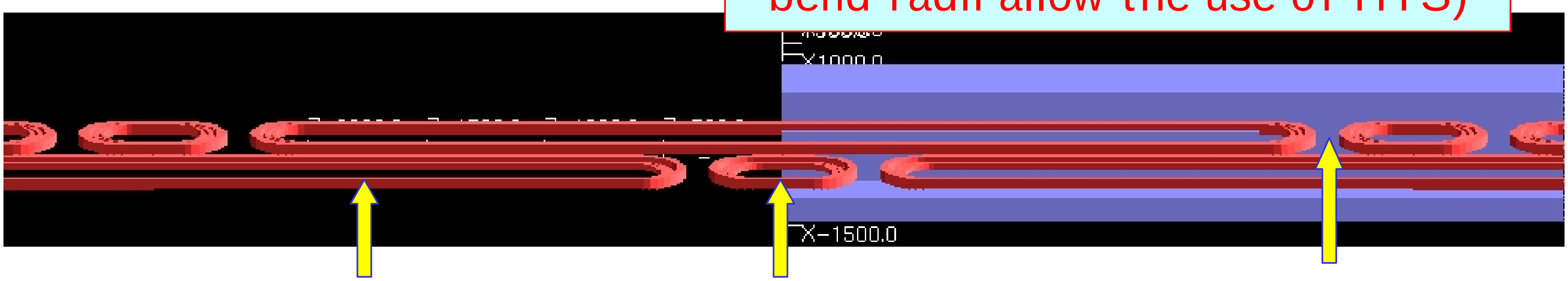
Decay products clear superconducting coils

Compact ring to minimize the environmental impact
(the machine is tilted)

Need high field magnets & efficient machine design



(simple racetrack coils with large bend radii allow the use of HTS)

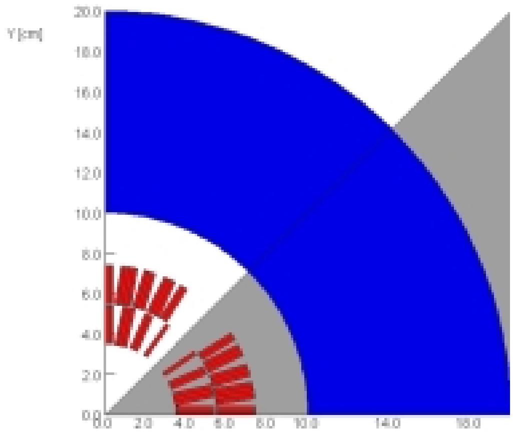


Normal Coils Dipole

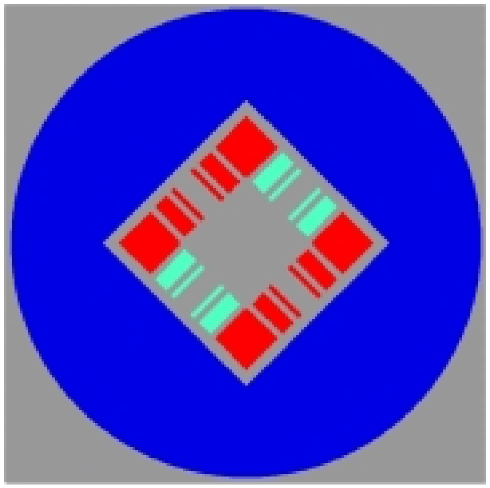
Reverse Coils Skew Quad

One Coil 1/2 & 1/2

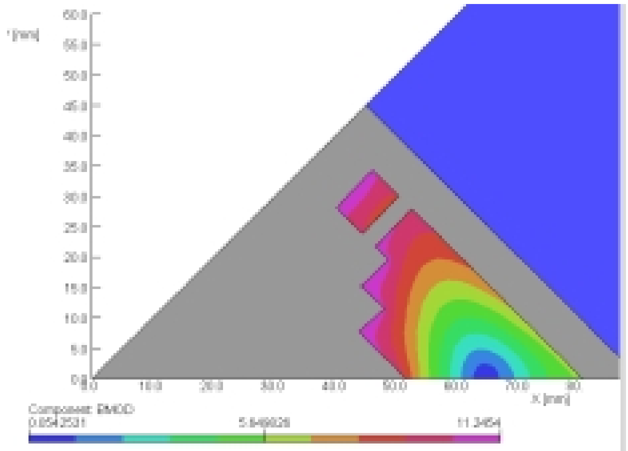
Cross sections for LHC Upgrade Quad



Cosine theta X-section (with improved technology for ends)



Simple Racetrack New End Designs

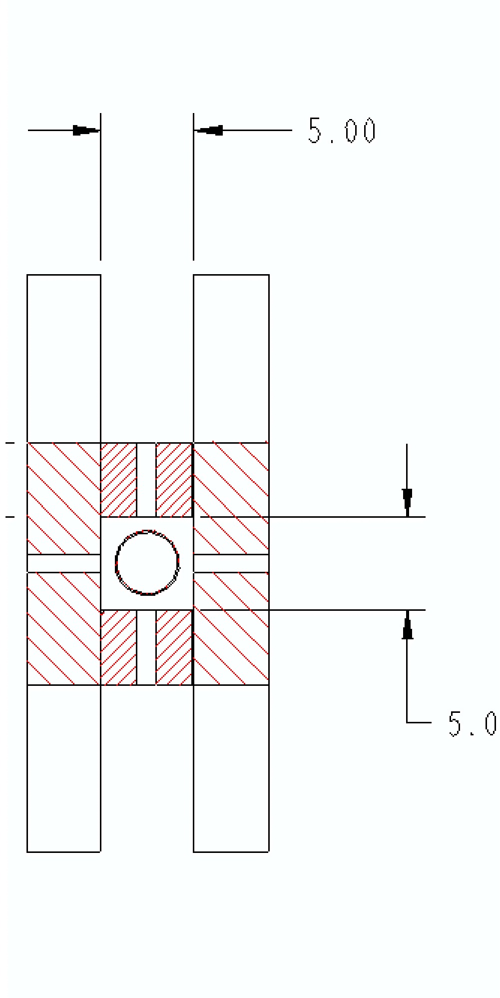


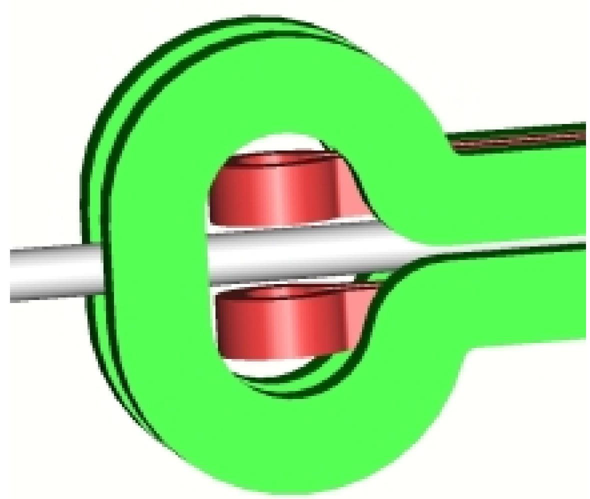
High Performance Racetrack Quads

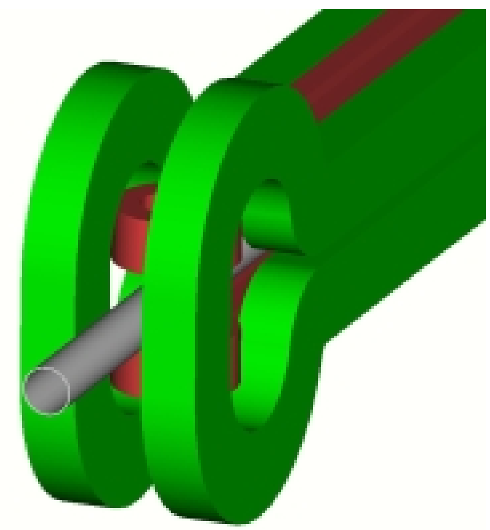
Ends drive the conceptual design of "React & Wind Magnets"

New End Design Concepts

Flat Coil Ends: Nested Coils

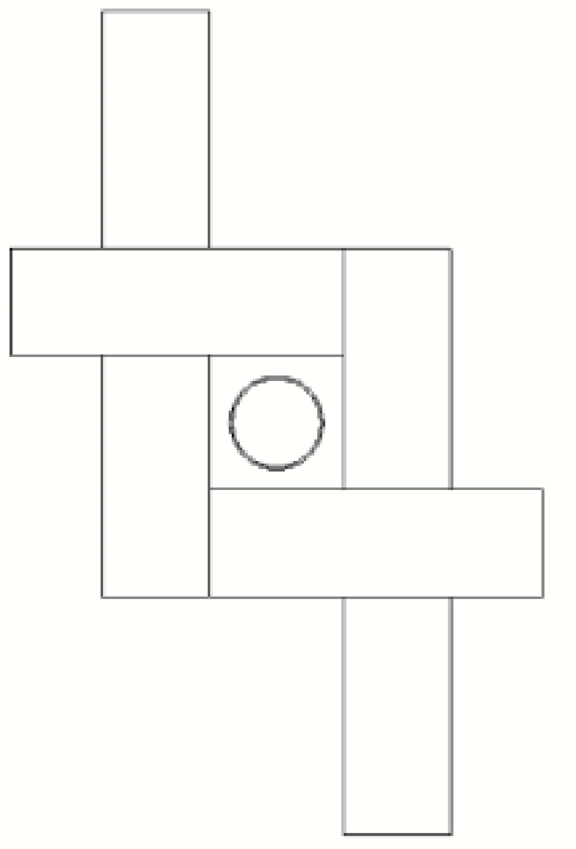


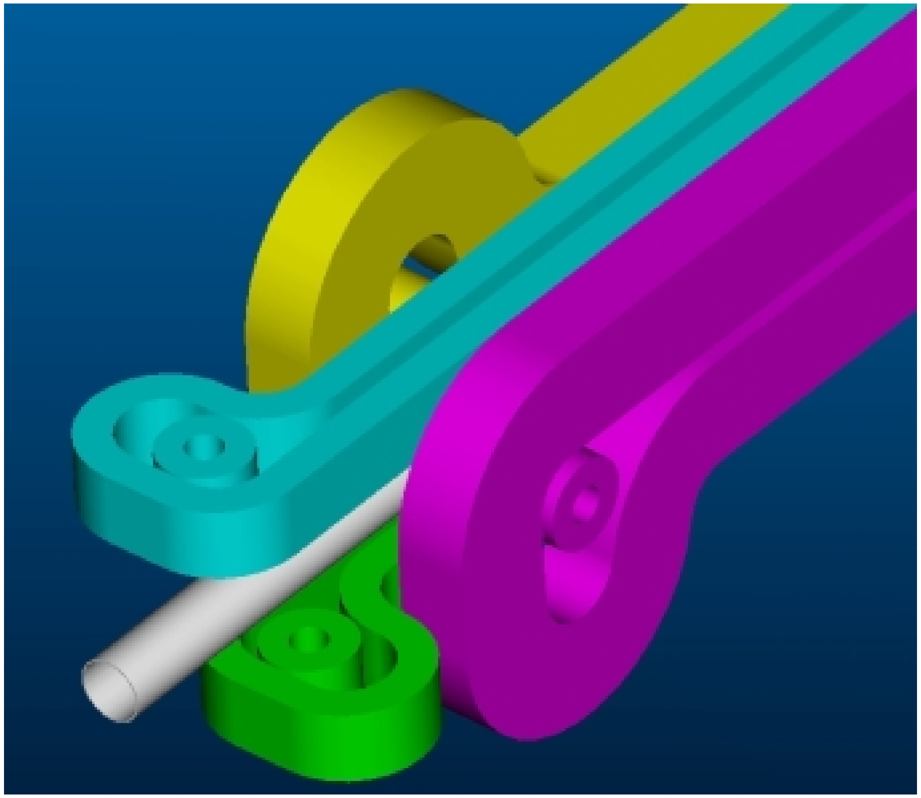




New End Design Concepts (contd.)

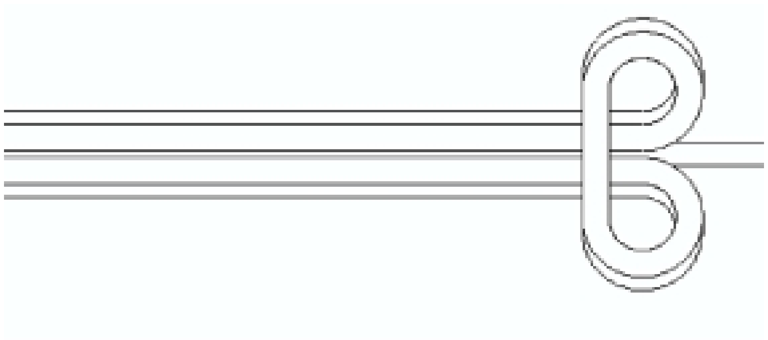
Flat Coil Ends: Sideway Overlap

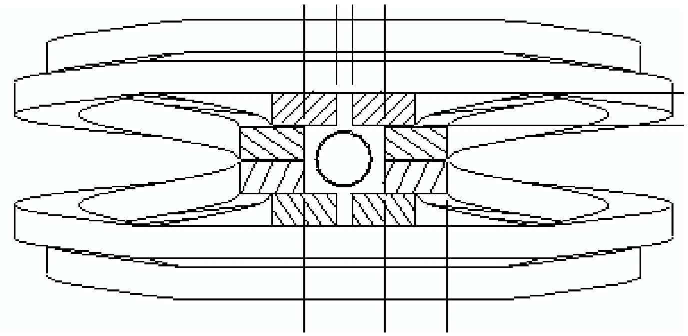


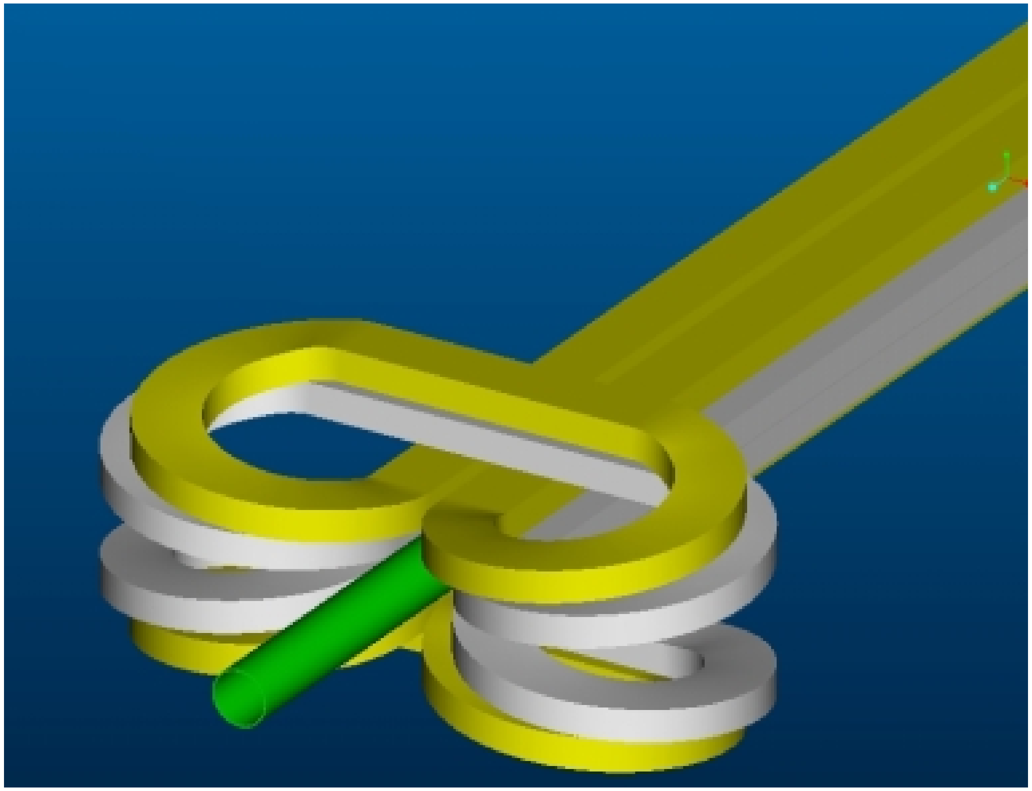


New End Design Concepts (contd.)

Overpass/Underpass (Clover Leaf) Ends: NO Reverse bend needed







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

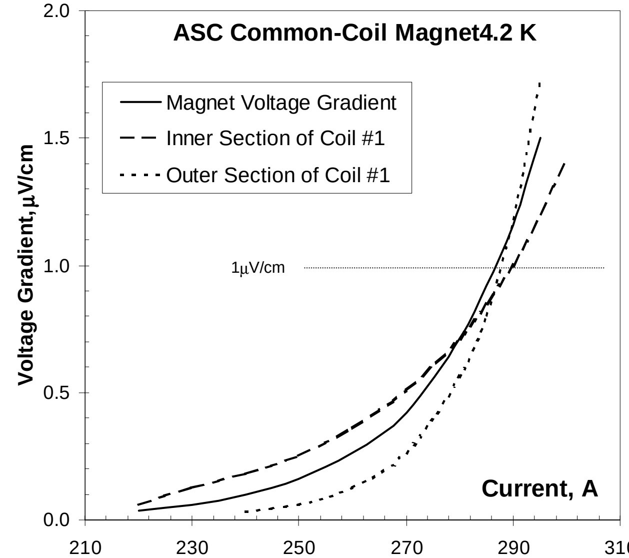
(Field quality in 74 mm aperture to be measured soon)

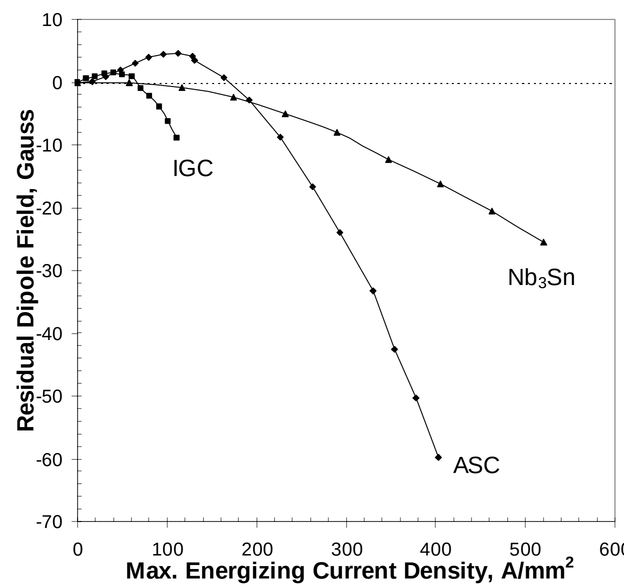
A coil being wound with HTS tape and insulation.

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





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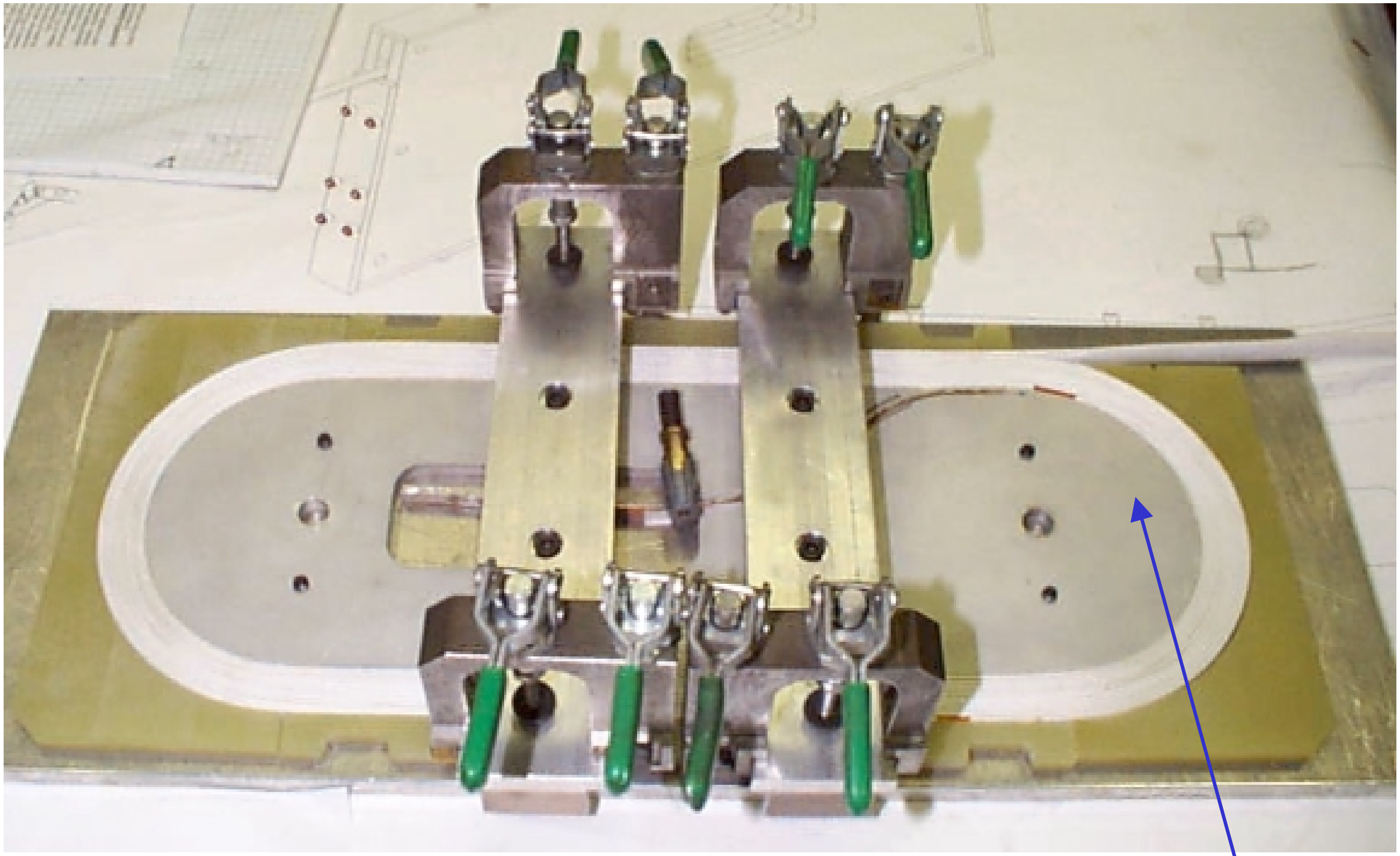
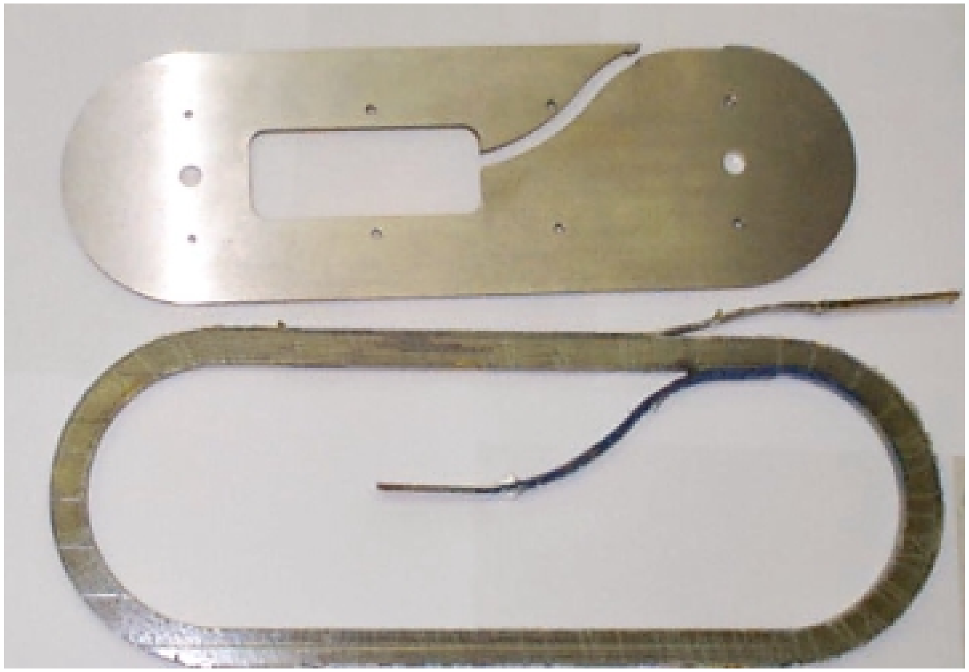
HTS Coil Wound by Hand



Al Bobbin (70 mm radius)

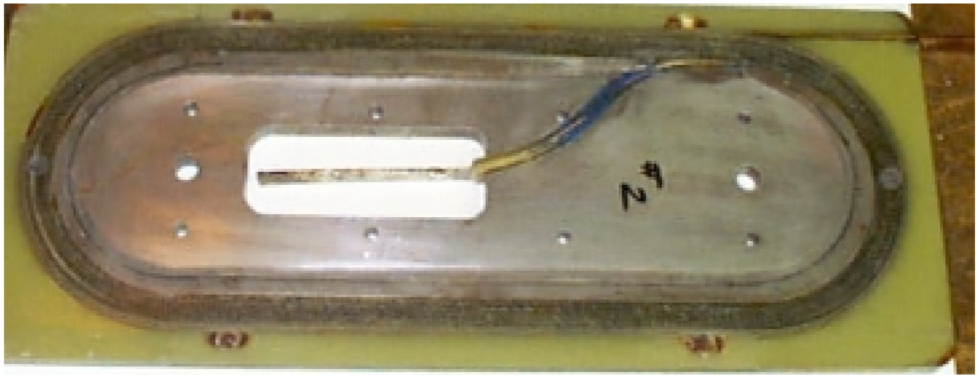
(also used, Fe, SS and brass bobbins)

The Bobbin and the 10-turn Coil



The bobbin
(the coil is wound on it)

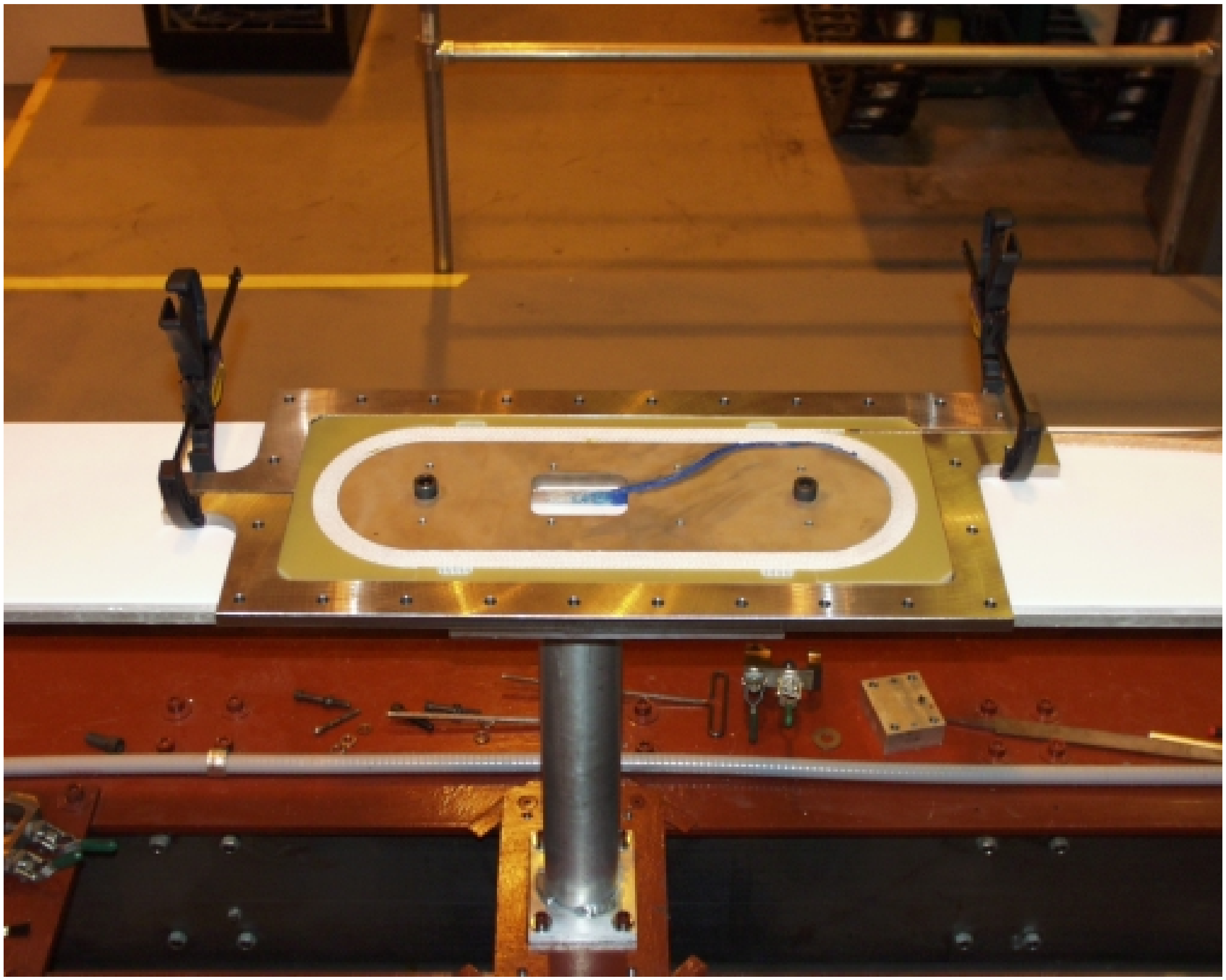
The first 10-turn practice coil
(removed from bobbin after impregnation)



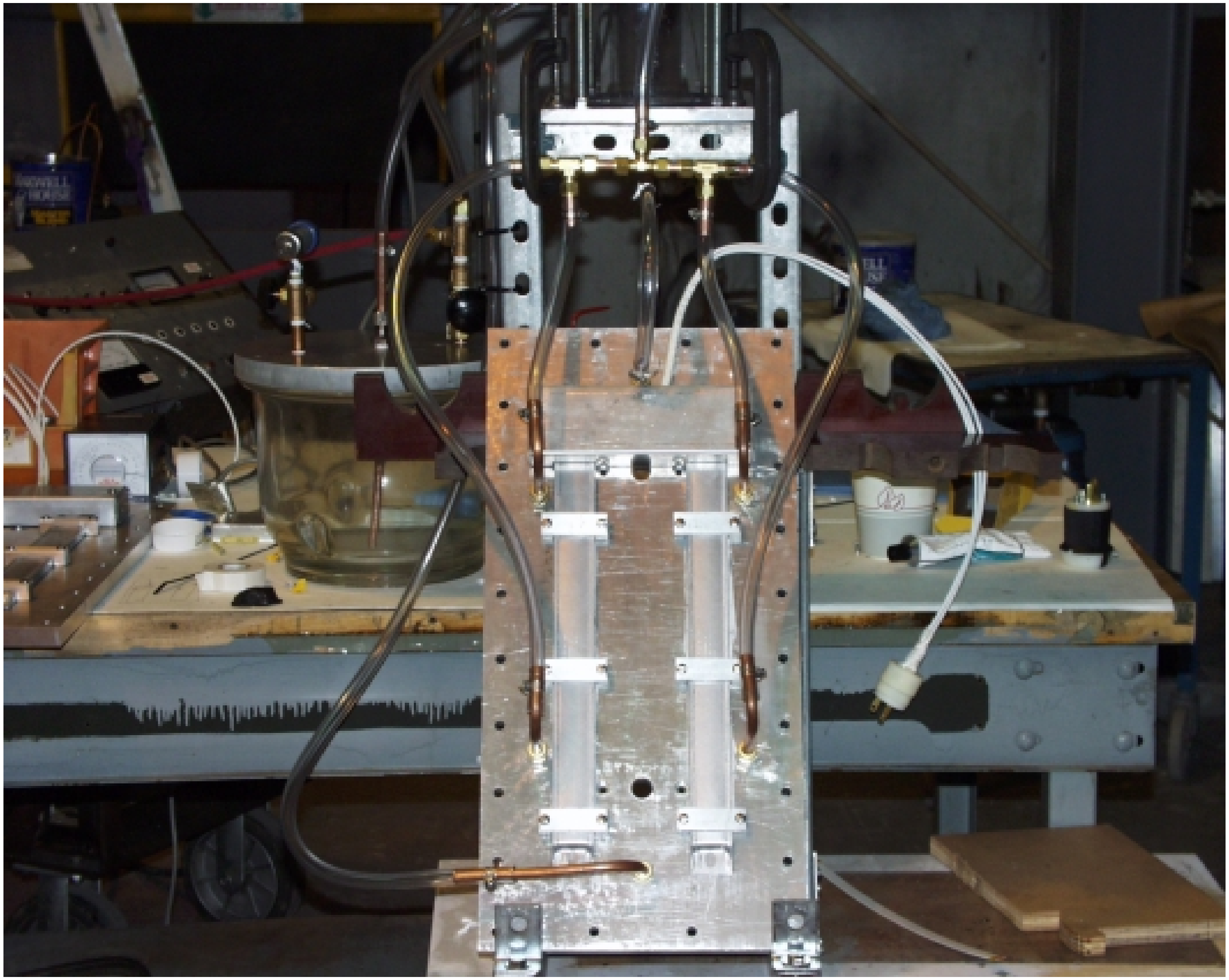
The complete cassette module
(vacuum impregnated coil in bobbin)

In the next generation package, the bobbin will not be part of the final product.

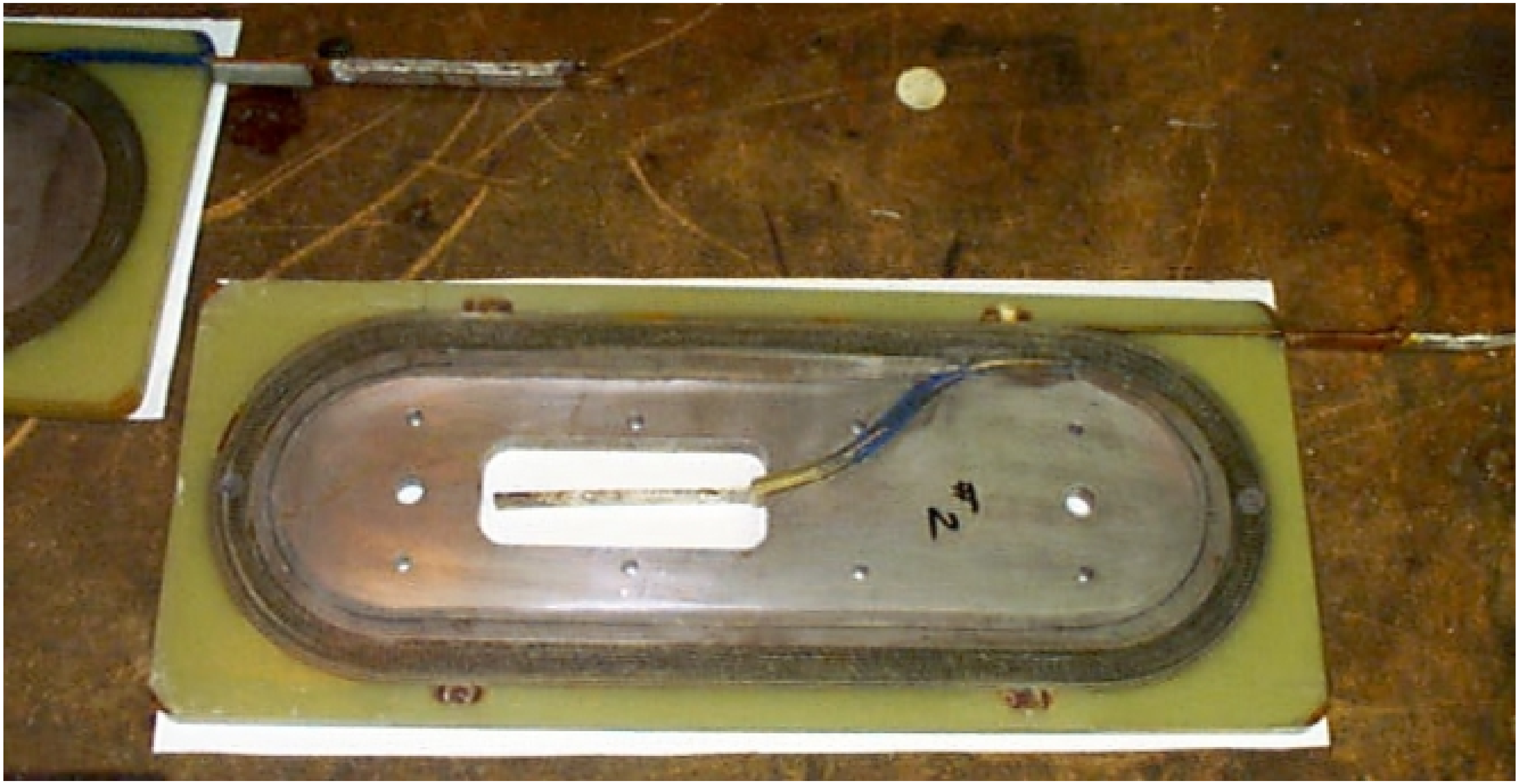
10-turn Coil Being Prepared for Vacuum Impregnation



Vacuum Impregnation Setup



Vacuum Impregnated Coils



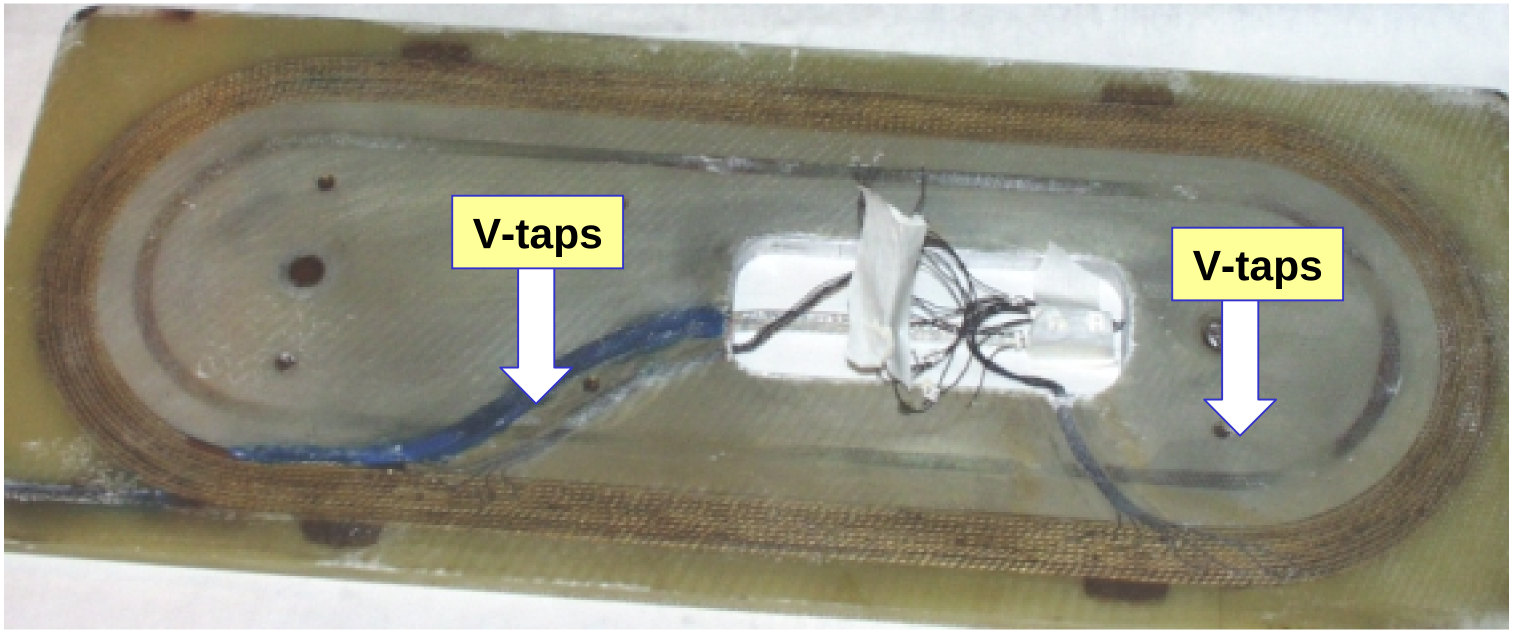
Vacuum impregnated coils made with the “react and wind” technique.

This picture was taken after the coils were tested and removed from the support structure.

Voltage Taps, etc.

We put at least one voltage tap on each turn for detailed study

- Given the aggressive R&D nature of the program we instrument as much as we can to locate the weak spot(s)
  - Remember we are pursuing/pushing the new technology
    - It's OK to follow "learn and burn" approach, as long as we learn from it experimentally in a scientific and systematic way



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.

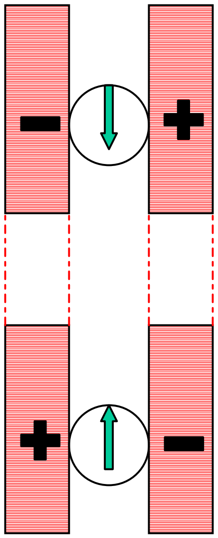
Coils are assembled for the most flexible and extensive testing. Four leads are taken out of the cryostat. During the test the coils were powered separately and together in “common coil” and “split-pair solenoid mode”.

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

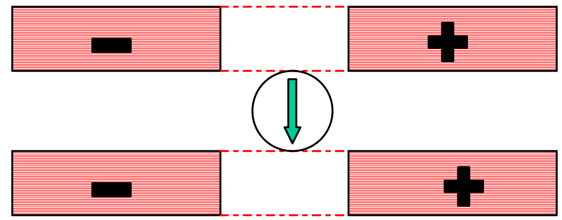
Superconducting
Magnet Division

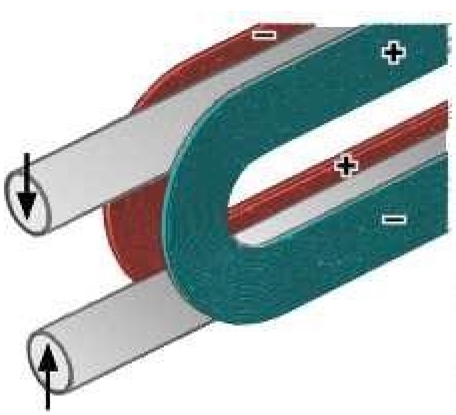
Common Coil and Muon Collider Test Configurations

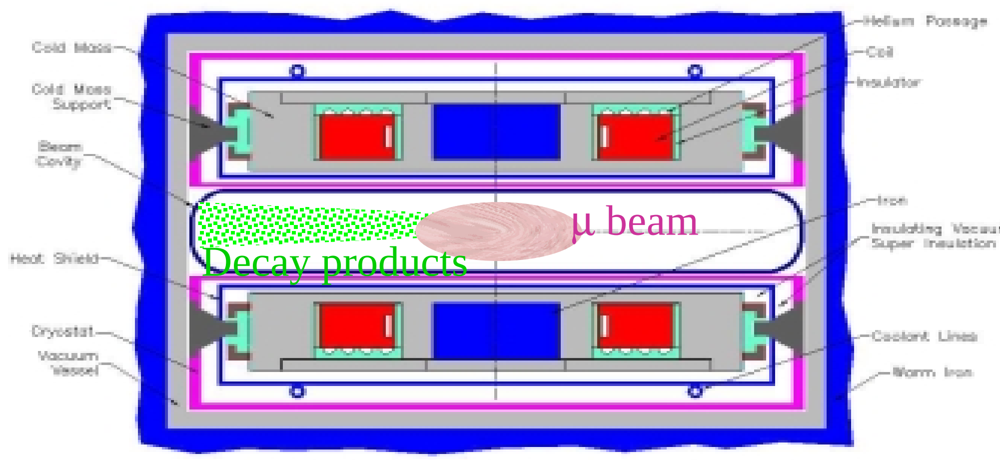
Common Coil configuration | **muon collider configuration**



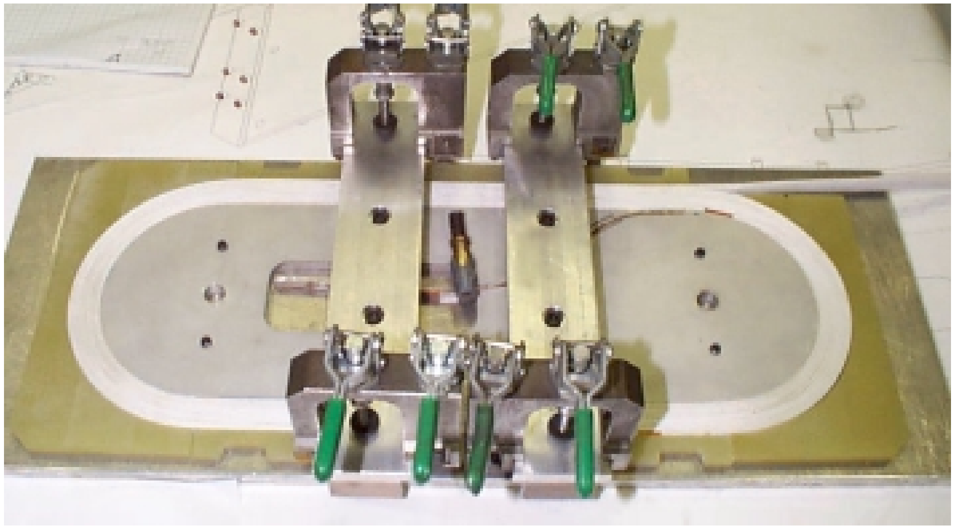
Powering differently changes a common coil design test to a muon collider design test





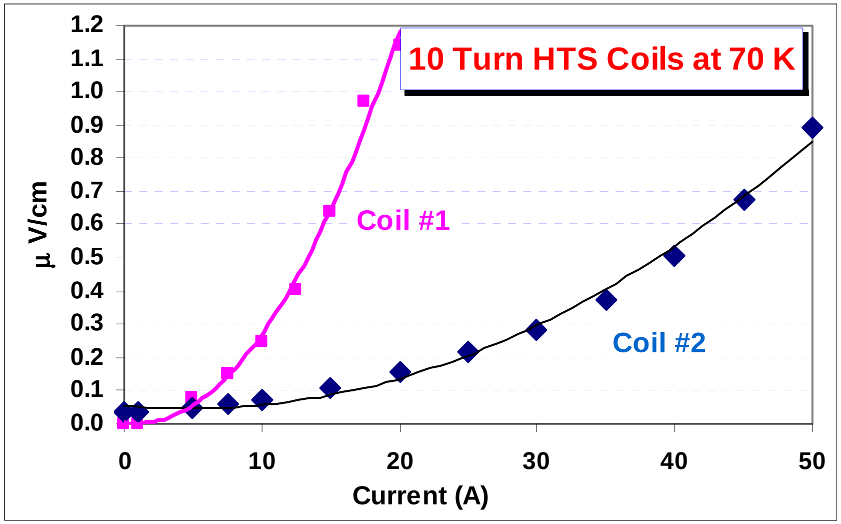


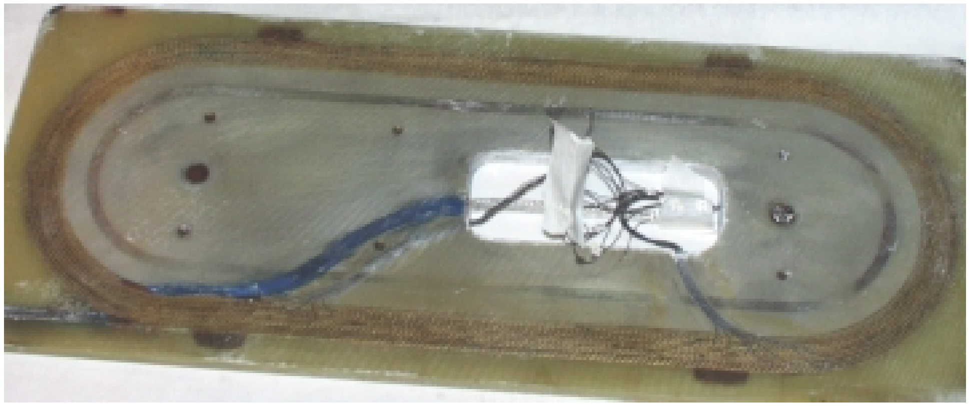
1st Common Coil Magnet (DCC004) With HTS Cable



HTS cable coil prior to vacuum impregnation

Two coils were tested in Liquid Nitrogen





A coil cassette made with HTS cable after vacuum impregnation and instrumentation

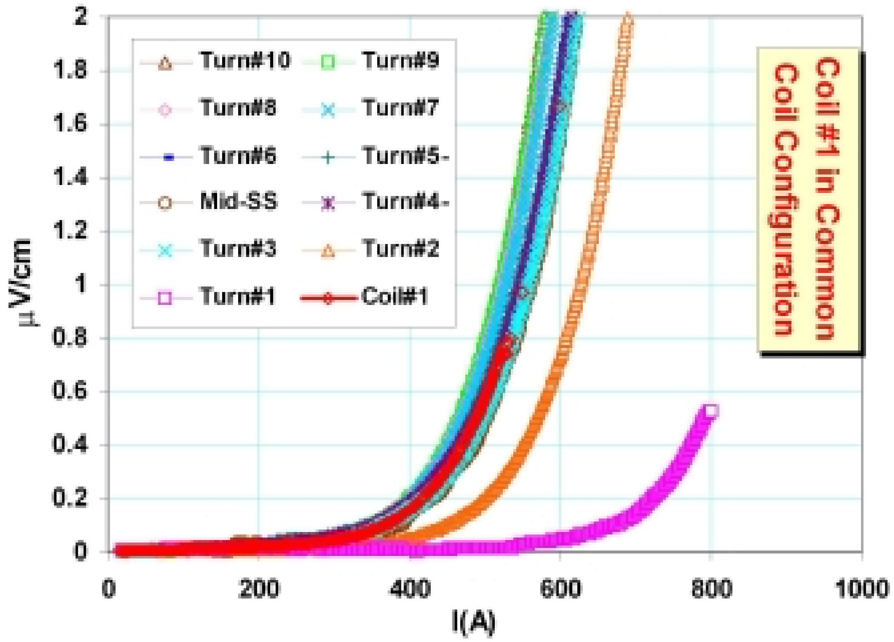
The HTS cables were from two different batches. They behaved differently:

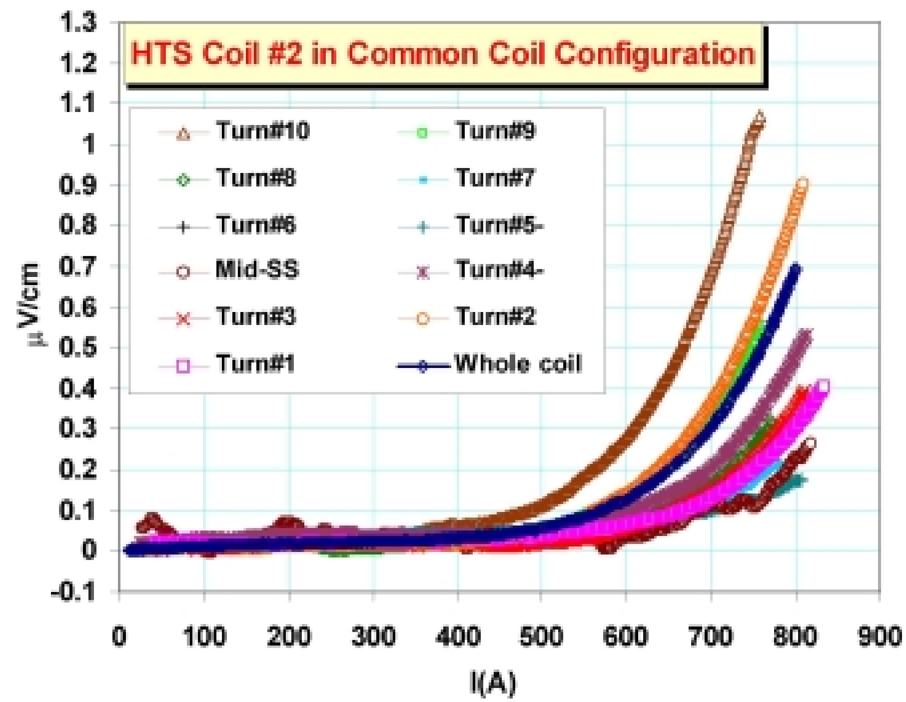
- Different Ic
- Different Tc

Based on preliminary analysis, no large degradation is observed.

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

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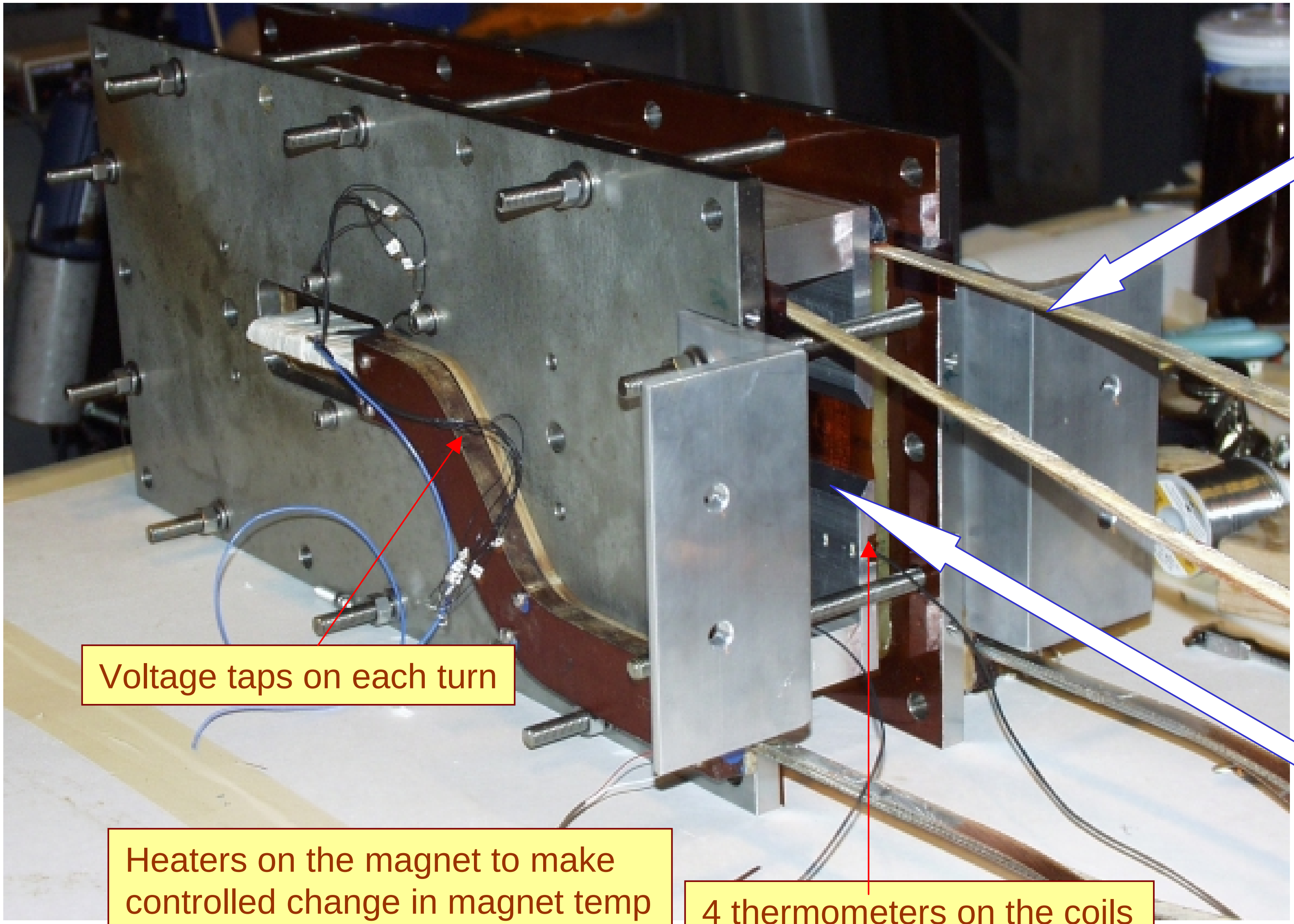
Magnet DCC006: 2nd HTS Dipole

(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

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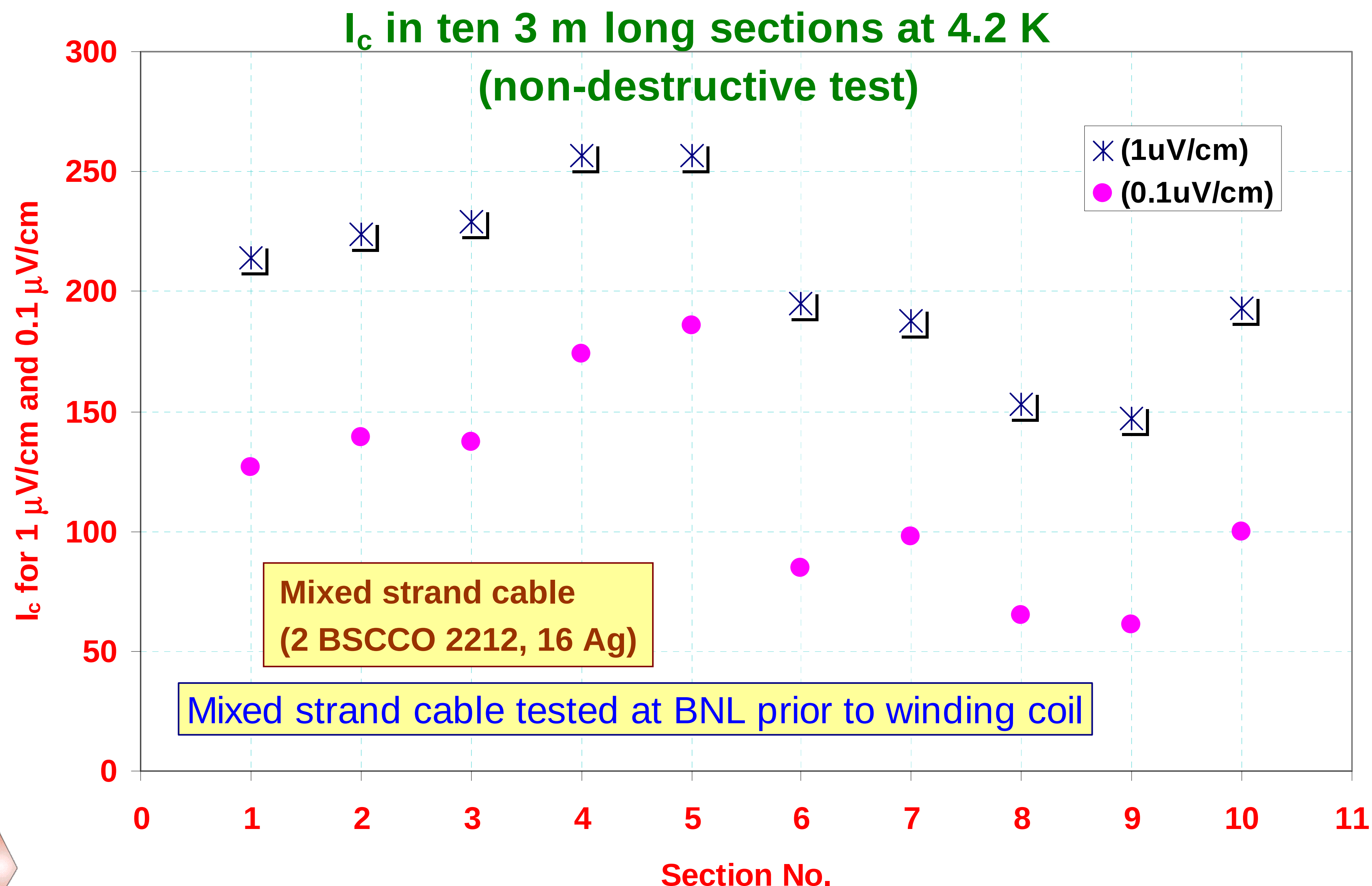
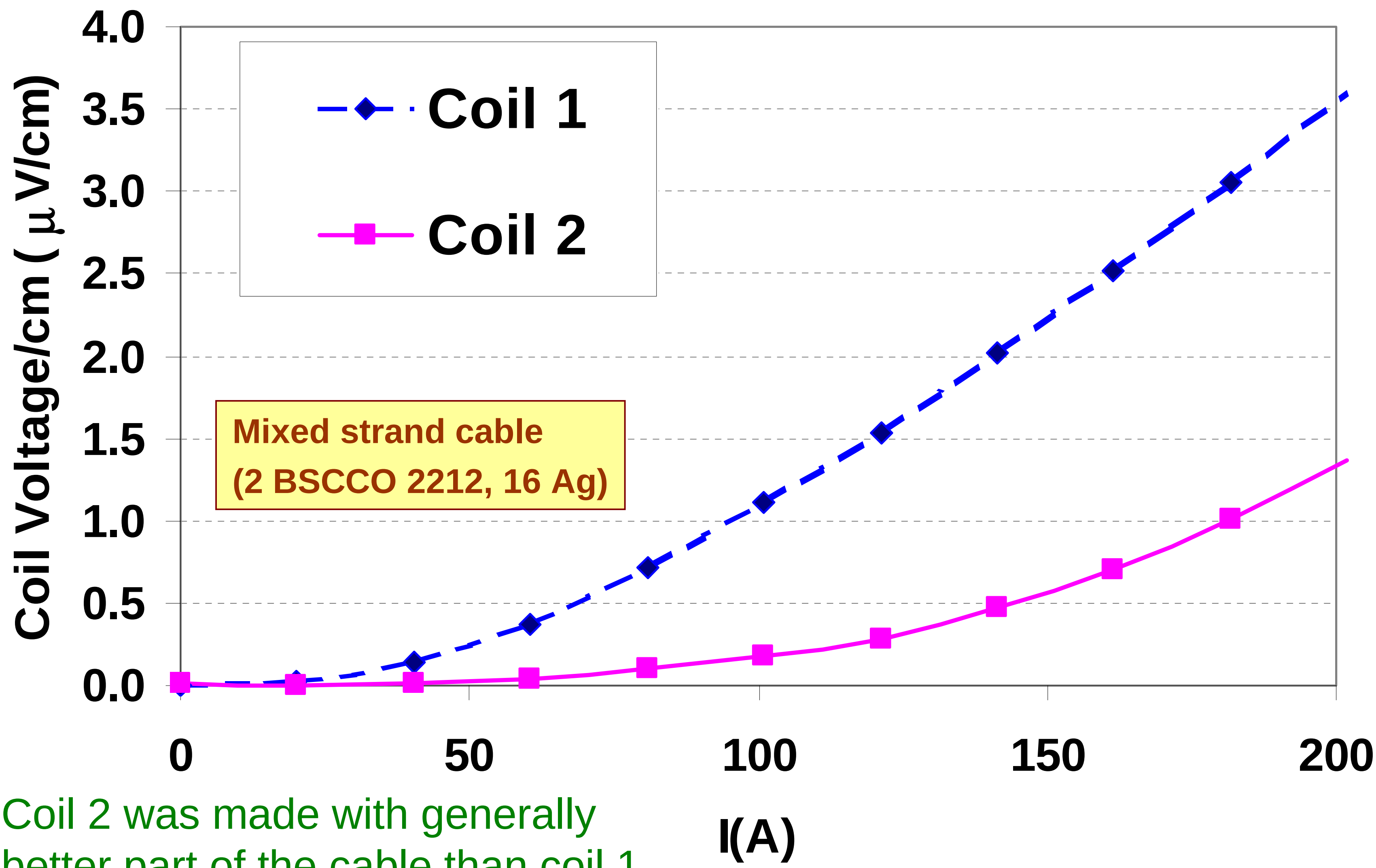
Critical Current in Mixed Strand Cable



Performance of 2 Coils in Muon Collider Dipole Configuration



Coil 2 was made with generally better part of the cable than coil 1

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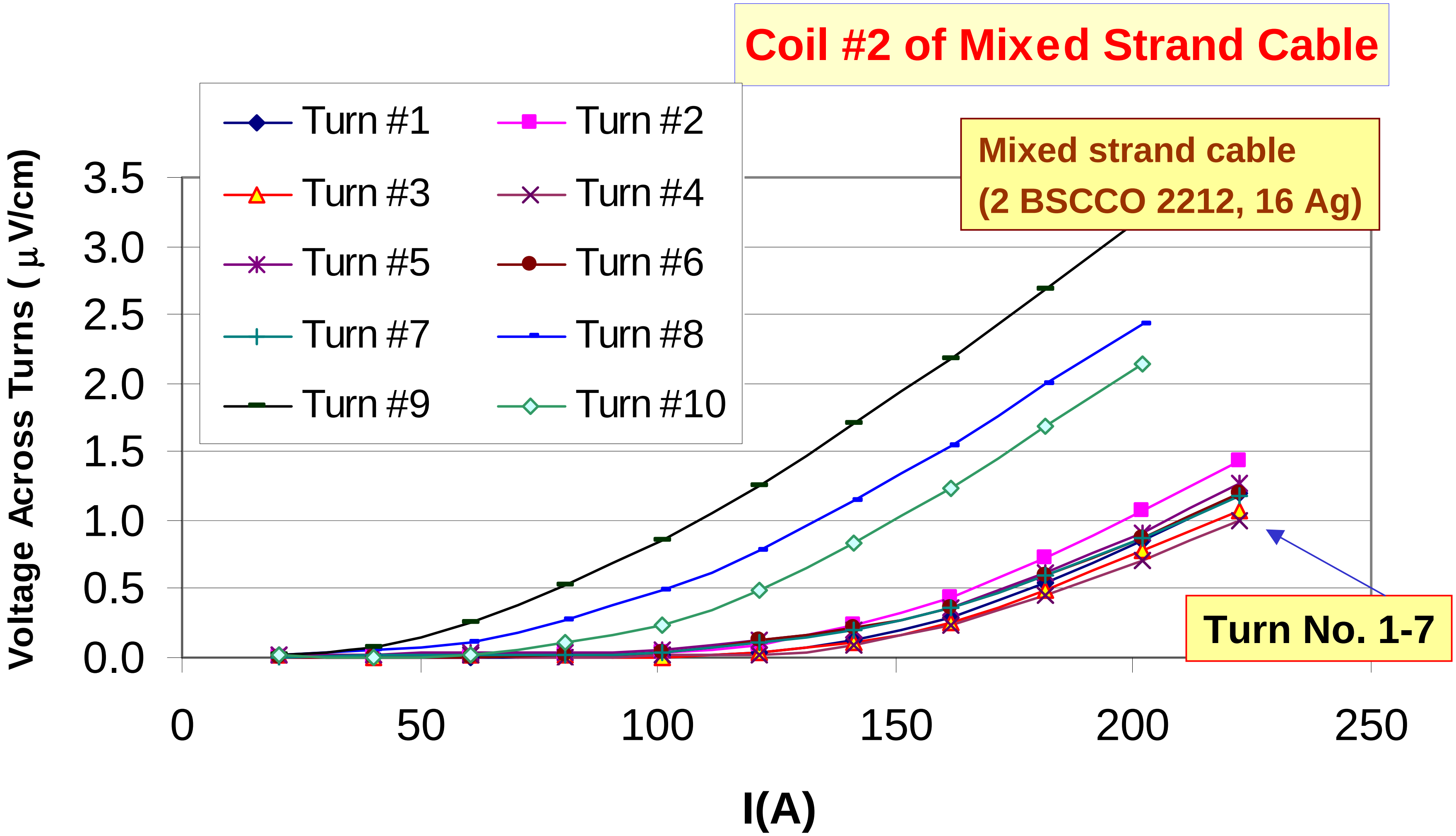
Measured Ic of Various Turns



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.

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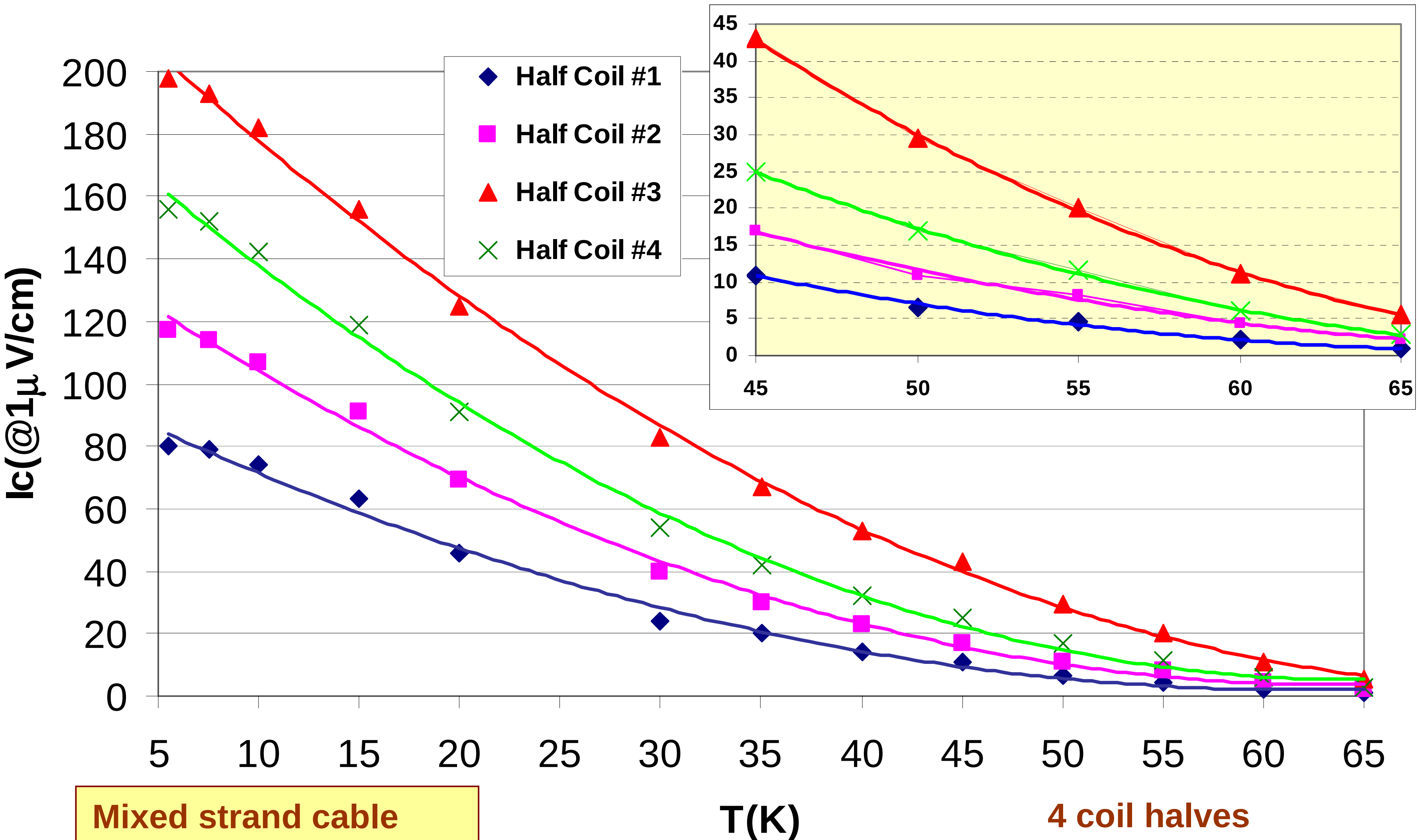
Measured Critical Current as a Function of Temperature



Mixed strand cable
(2 BSCCO 2212, 16 Ag)

4 coil halves
(2 each of two coils)

HTS Coil Test Magnet #3

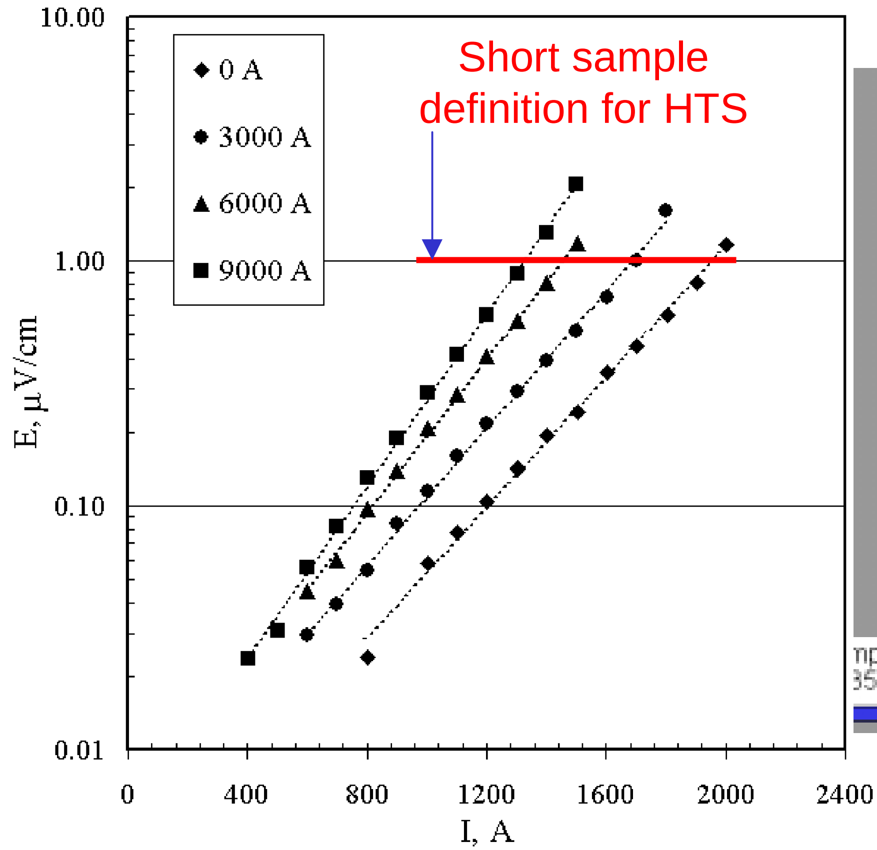
The HTS coil is made with all HTS strand cable

A hybrid magnet made with three coils (one HTS and 2 Nb_3Sn); Nb_3Sn coils provide background field on HTS Coil

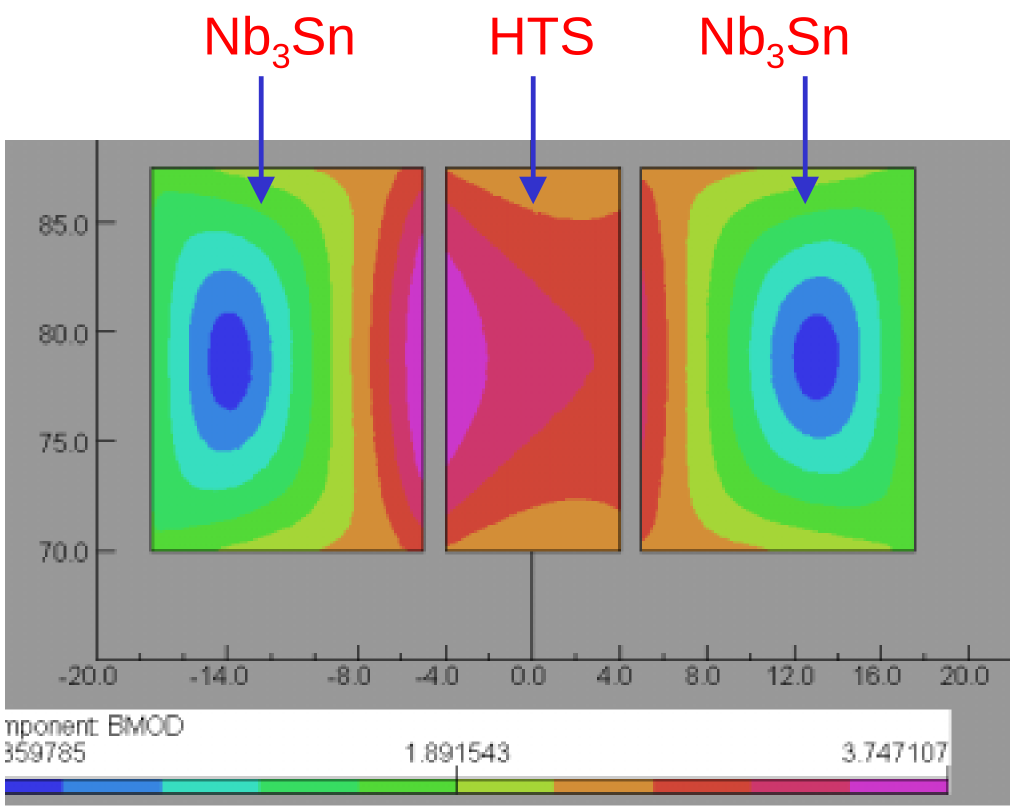
Vary current in Nb3Sn coils (producing background field) to study HTS coil performance at different field level

Performance of HTS Coil in the Background Field of Nb_3SN Coils

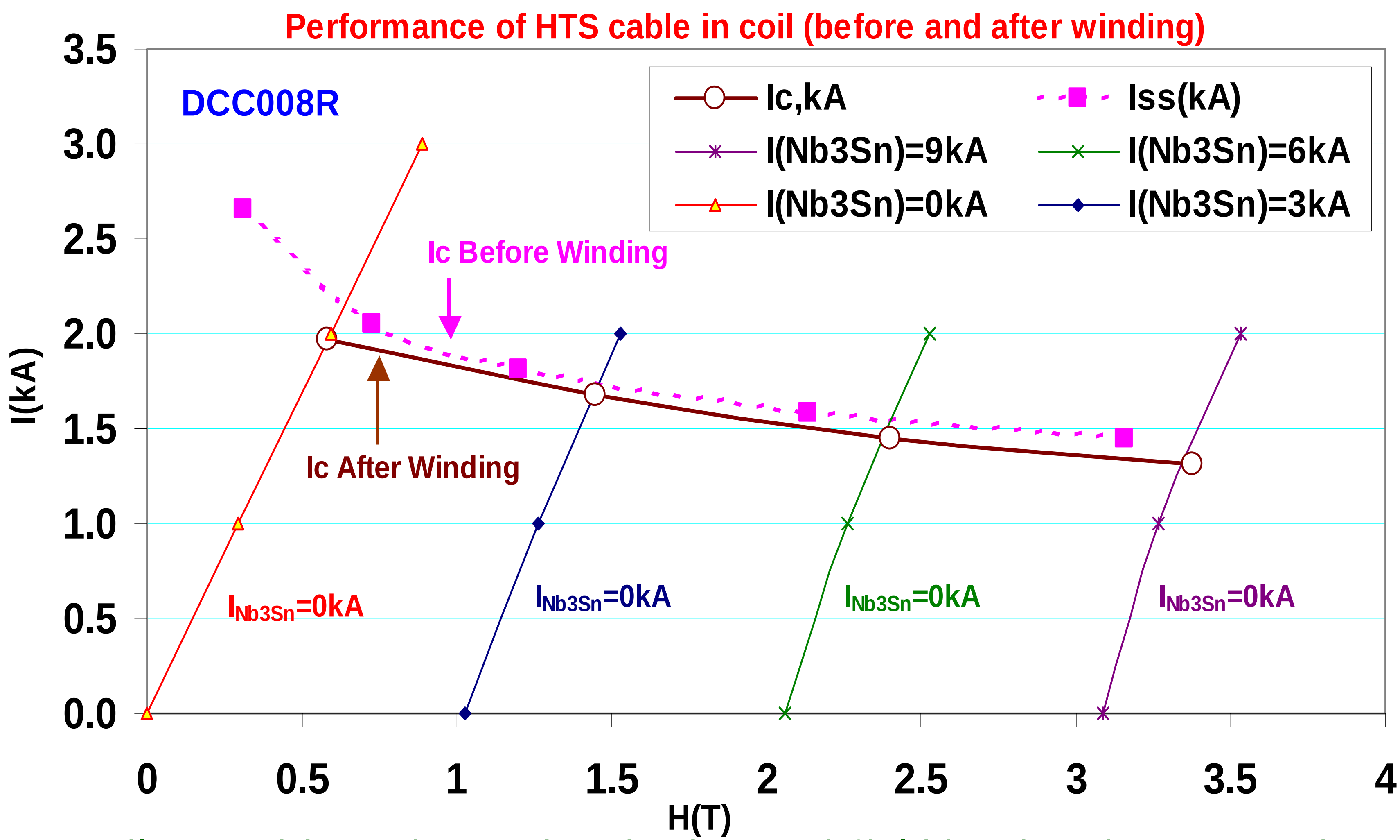
Measured electrical Resistance of HTS coil in the background field provided by various Nb3Sn coils in the magnet DCC008R



Field in various coils



Performance of HTS Coil in the Background Field of Nb_3SN Coils



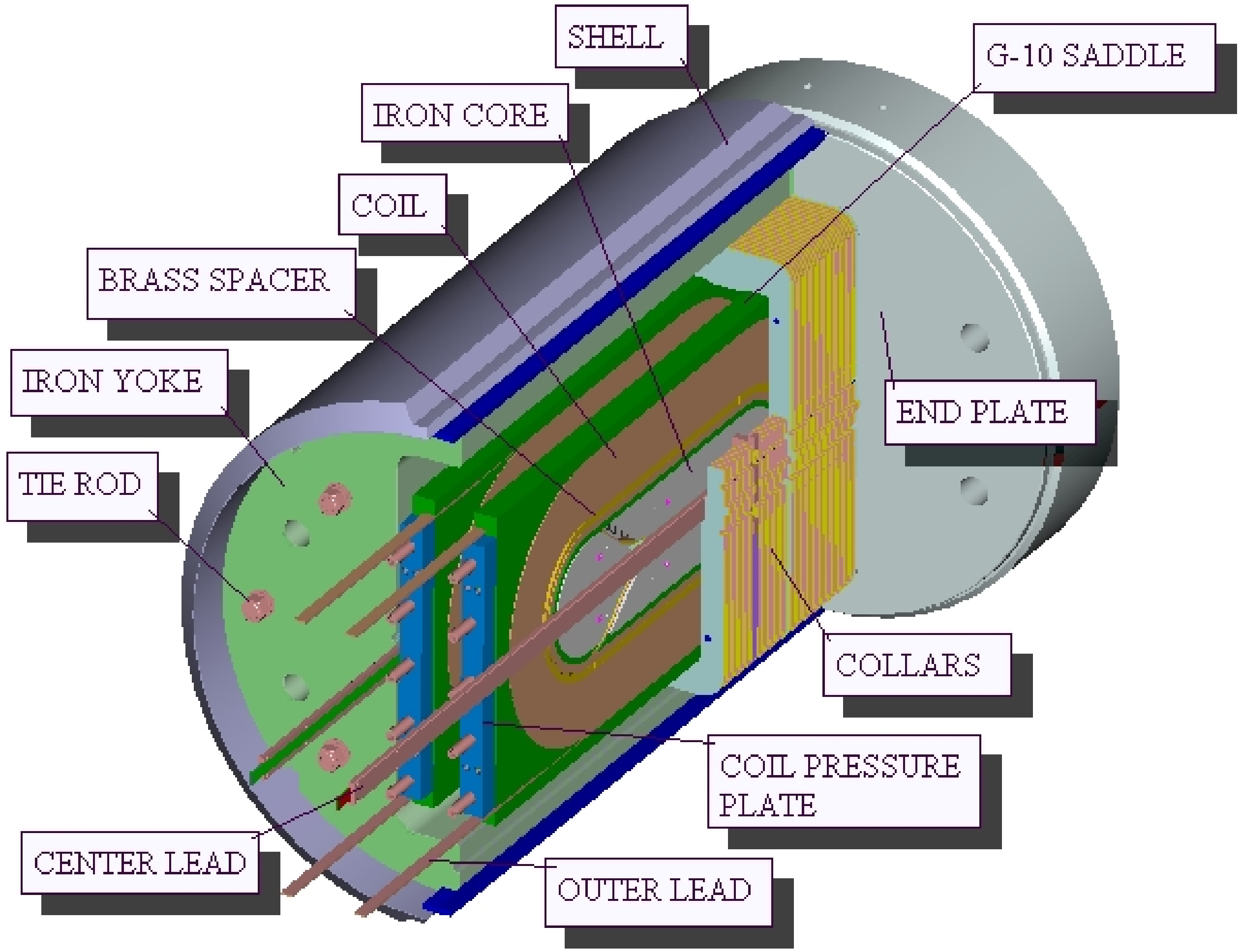
HTS coil was subjected to various background field by changing current in "React & Wind" Nb_3Sn coils (HTS coil in the middle and Nb_3Sn on either side)

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

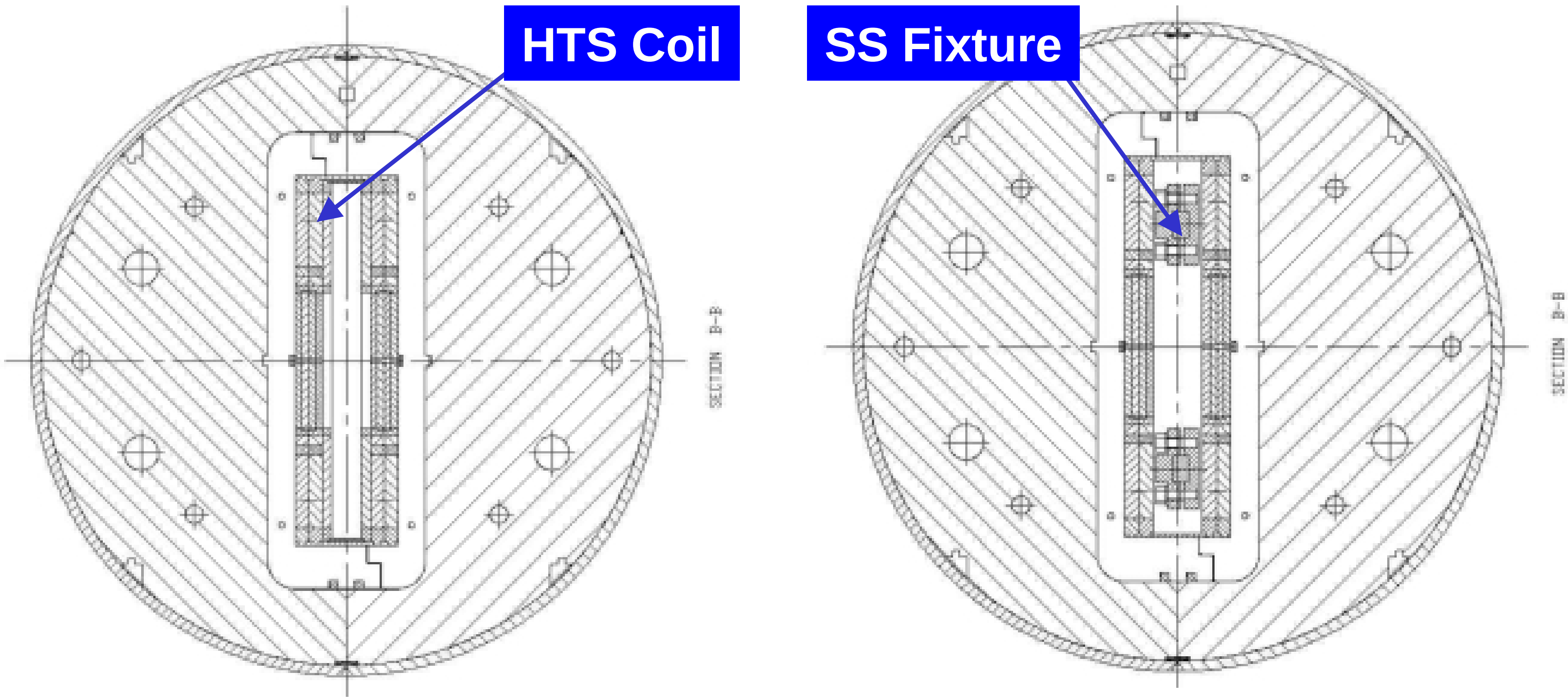
Present the results to accelerator community so it can make an informed decision about the viability of HTS in accelerators to take advantage of exciting benefits it offers.

Cut-away View of the 12 T Magnet



Insert Coil and Sample Test Scenarios

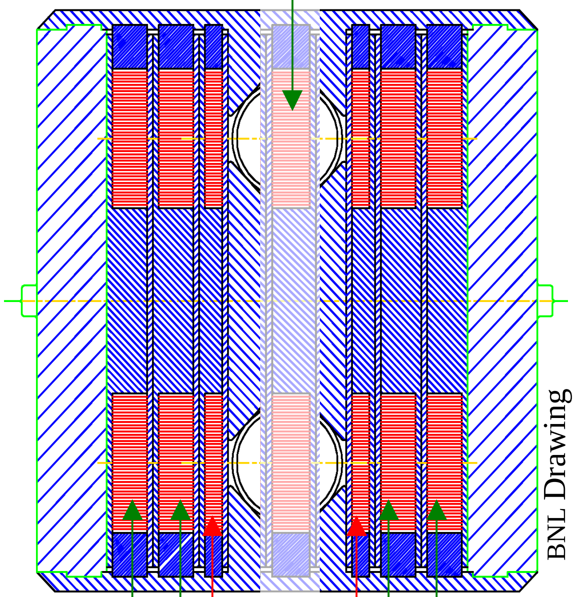
An interesting feature of the design, which will make it a truly facility magnet, is the ability to test short sample and HTS insert coils without disassembling it.



HTS insert coil test configuration

Short sample test configuration

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.**

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**

SUMMARY (continued)

- **Initial test results at the Brookhaven National Laboratory (BNL) have been quiet encouraging**
  - No large degradation of HTS in coil has been observed

- **Expect HTS to play a significant role in future accelerators assuming that about a factor of three improvement in conductor critical current is realized**
  - First likely application of HTS could be the specialty magnets where the performance and not the cost are critical

Example: interaction region magnets for achieving very high luminosity