HTS R&D Activities at BNL

Ramesh Gupta
Superconducting Magnet Division
Brookhaven National Laboratory (BNL)
Upton, NY 11973 USA

HTS R&D at BNL

Test HTS tapes, wires and cables in a temperature range of 4 K to 77 K

- Develop accelerator magnet designs that are suitable for HTS
- Build and test coils made with HTS tapes and HTS cables
- Carry out tape, wire, cable and coil tests with an applied field of up to 7 T

In addition, we have material scientists and conductor specialists to understand and guide us in the material development.

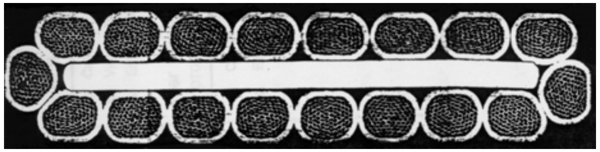
In this talk, I would give a general overview.
More detailed discussions may be continued later.

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



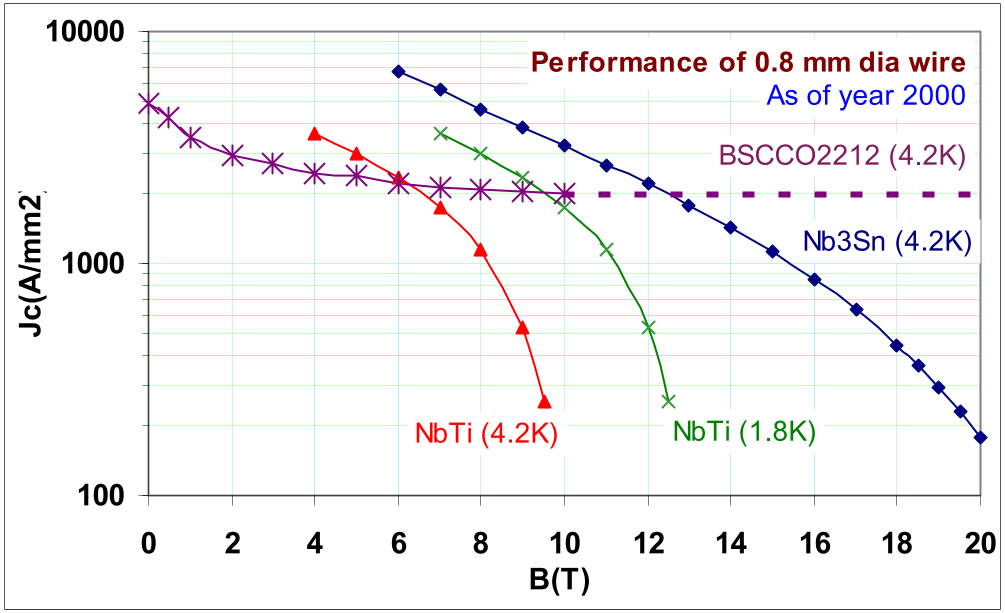
A good and productive international collaboration has been established between labs (BNL, LBL) and industries (Showa), with unique skills and resources with a common goal of advancing the field.

The cable development has been possible because of the support from Chubu Electric to Showa. This development has been used in demonstrating significant progress towards building HTS coils for accelerators.

Latest results indicate that for building/protecting large systems, we still need to carry some more R&D. We believe that that with our experience, we can contribute a lot.

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)**
- **Super-ferric Dipole for RIA operating at 20 K or higher temperature**

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Design Issues for High Field Accelerator Magnets using HTS

- HTS is very brittle

  Conventional designs are not the most suitable

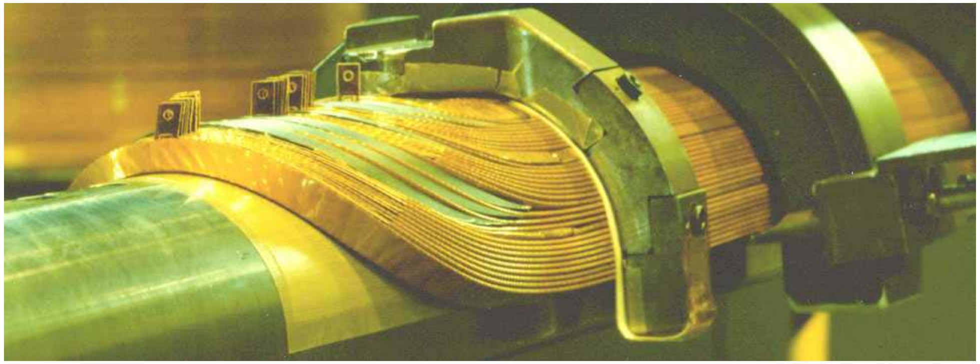
- Large Lorentz forces

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

  ~1/2 degree at ~890° C

React & Wind Approach

Paper at ICMC: relax control to ~5K?



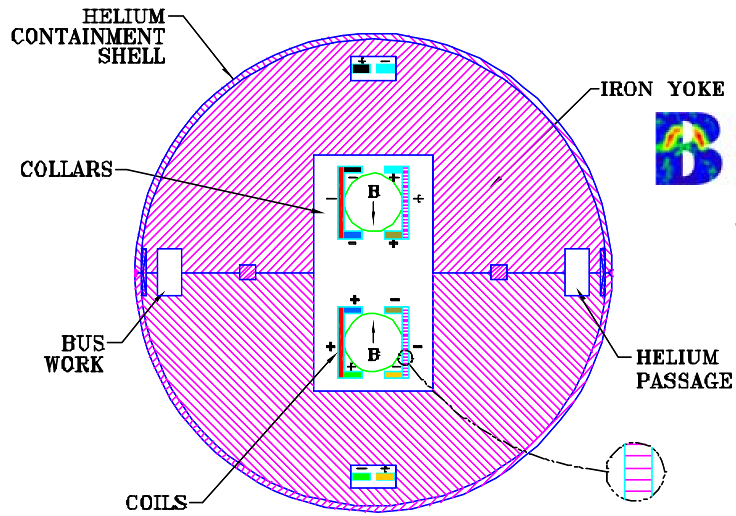
Conventional cosine θ design (e.g., RHIC magnets)

Complex 3-d geometry in the ends

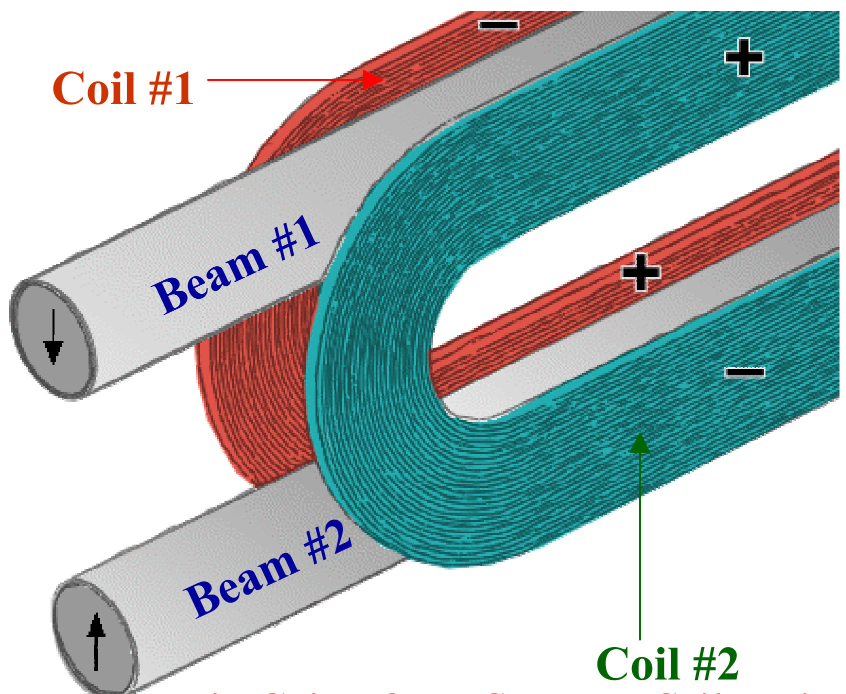
"Conductor friendly" racetrack coil with large bend radius

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 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*

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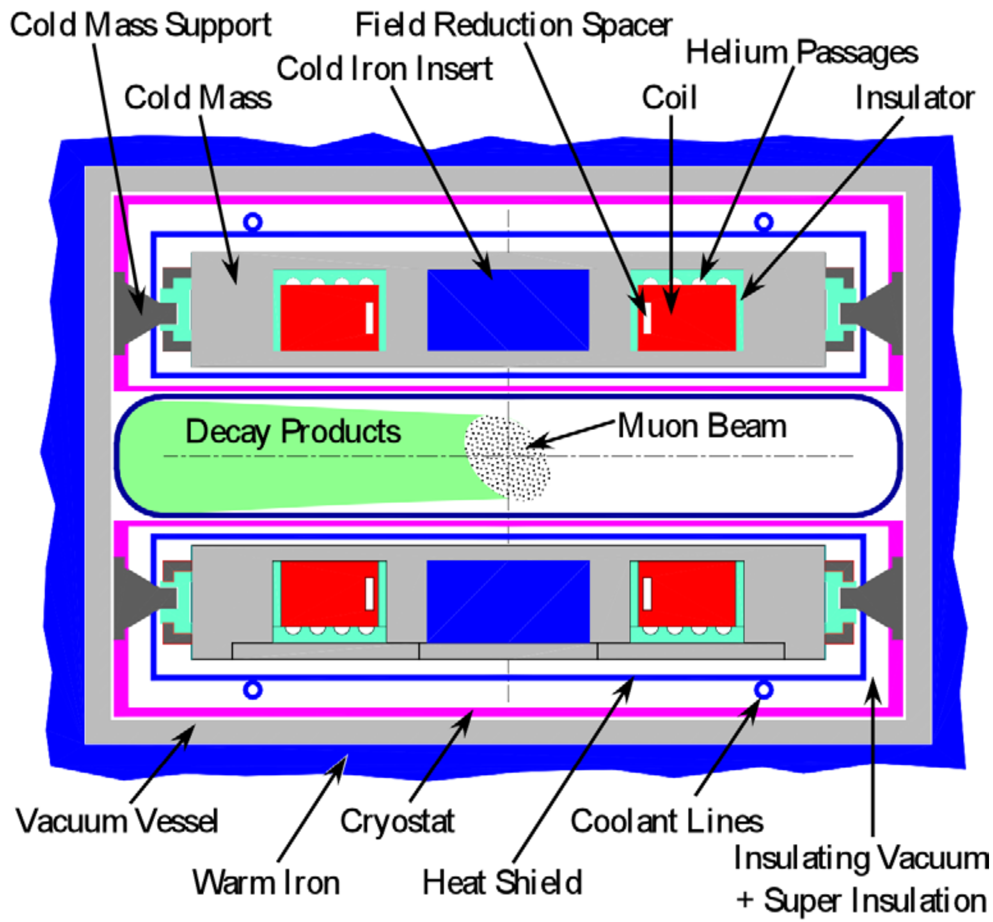
Magnet Design for ν Factory

This application requires medium field magnets (~8T).

However, the coils must deal with a large energy deposition from decay particles.

HTS can tolerate a significant temperature rise.

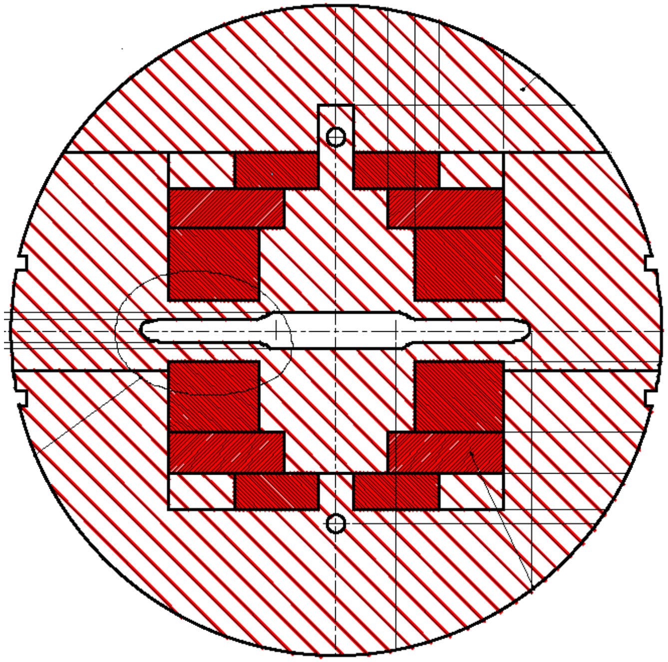


Simple racetrack coils with large bend radii

Interaction Region (IR) Magnets

Interaction region magnets for the next generation colliders, for example, LHC, 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

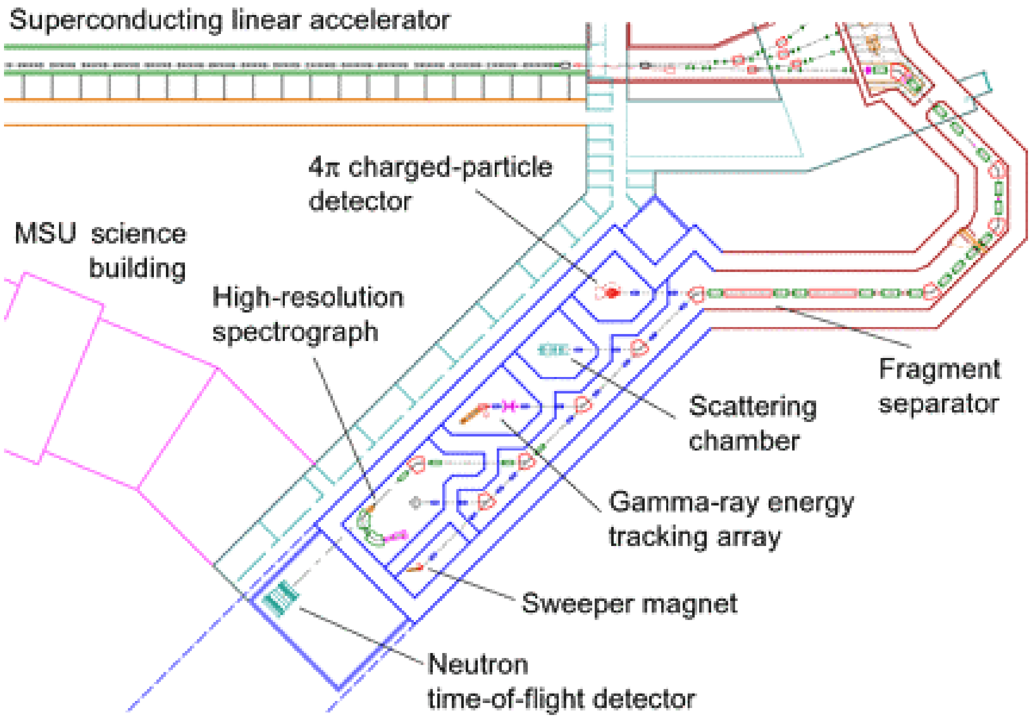


For these IR magnets, the performance, not the material cost is the issue.

Fragment Separator Region of RIA

(a medium field, high operating temperature application of HTS)

Magnetic elements (quads) in fragment separator region will live in a very hostile environment with a level of radiation and energy deposition never experienced by any magnet system before.

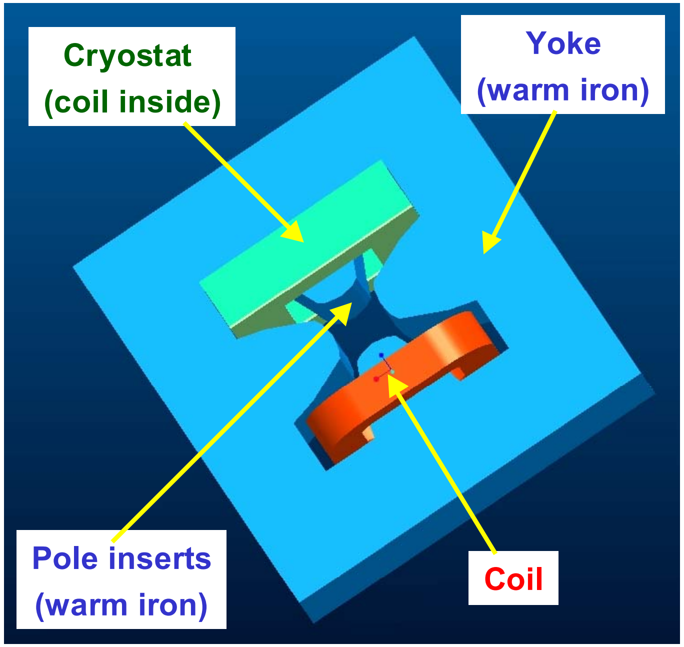


- Beam loses 10-20% of its energy in production target, producing several kW of neutrons.
- Quads are exposed to high radiation level of fast neutrons.

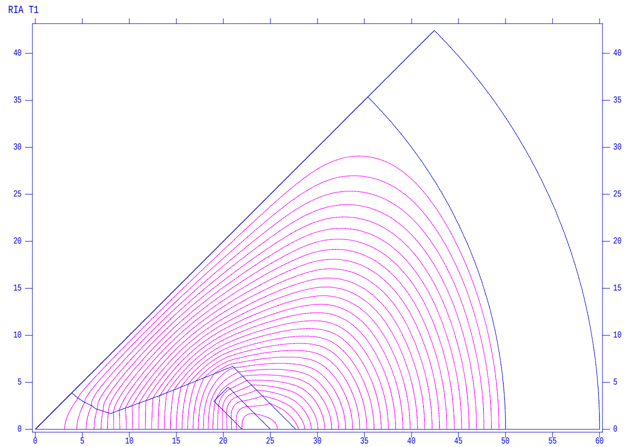
Room temperature, water cooled copper magnets produce lower gradient and/or lower aperture, reducing acceptance and making inefficient use of beam intensity.

Basically, we need *"radiation resistant"* superconducting quads, that can withstand large heat loads. There are many short and long time scale issues!

HTS QUAD for RIA Fragment Separator



Coils inside the cryostat at the end of the magnet



Requirement: ~3 T field in the coils, operating at >20 K

- HTS Quads can operate at a higher temperature (20-40 K instead of 4K) and allow a large variation in temperature.
- A warm iron yoke brings a major reduction in amount of heat to be removed at lower temperature.
- The coils are moved outward to significantly reduce the radiation dose.
- We plan to use stainless steel as the radiation resistant insulation.
- It is shown that the gradient and field quality requirements can be met.

HTS Cable Test Results

Bill Sampson and Arup Ghosh play a major role in this testing

HTS Cable from Showa Tested at BNL Cable Test Facility

TABLE I
DESCRIPTION AND PERFORMANCE OF VARIOUS CABLES MEASURED AT BNL CABLE TEST FACILITY.

Cable Designation	No. of Strands	Strand Diameter	I_c(5T,4.2K) (1μV/cm)	Date Tested
I-00076-1	18	0.81 mm	1827 A	2-Mar-01
S-00825-1a	18	0.81 mm	890 A	3-Jun-01
S-00825-1b	18	0.81 mm	990 A	3-Jun-01
S-00836-3	20	1.0 mm	4750 A	20-Nov-02
S-00836-4	20	1.0 mm	3252 A	20-Nov-02
S-B139-T-1	20	1.0 mm	3452 A	1-Apr-03
S-B139-L-1	20	1.0 mm	3100 A	1-Apr-03
S-R007B147-1	30	0.81 mm	6748 A	10-Apr-03
S-R013B147-1	30	0.81 mm	4861 A	10-Apr-03
S- R013B153-1	30	0.81 mm	4033 A	26-Aug-03
S- R016B155-1	30	0.81 mm	4784 A	26-Aug-03

Note: This list is not complete.

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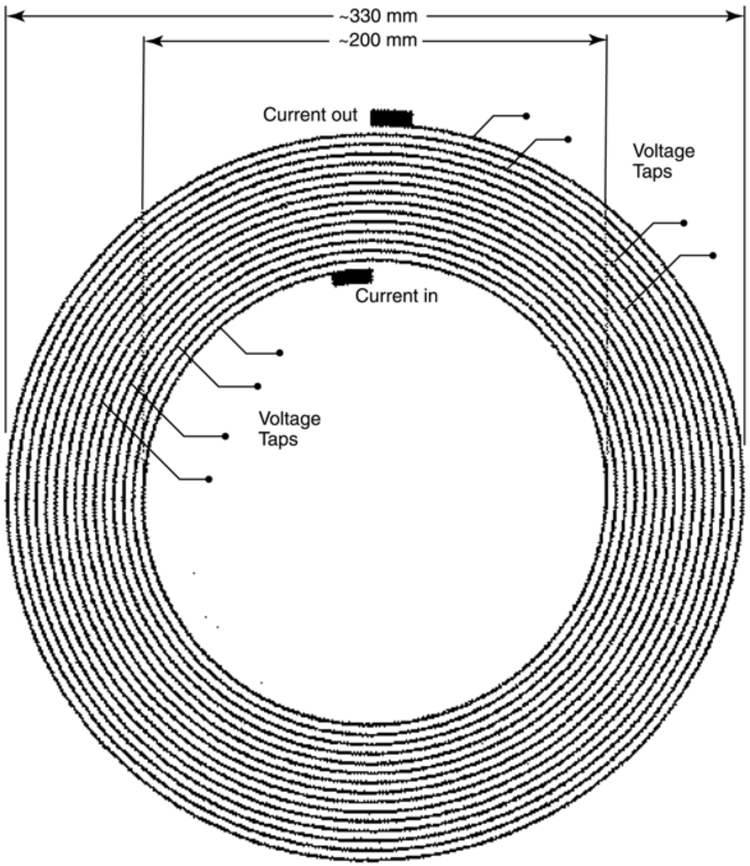
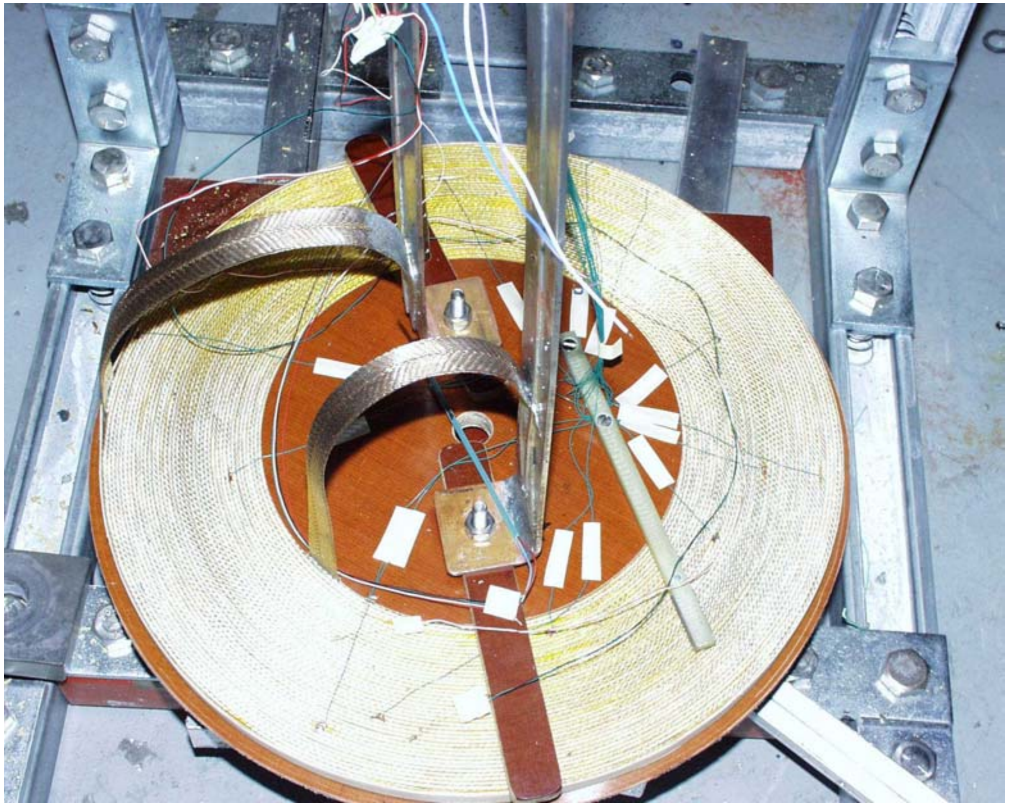
BSCCO-2212 Cable "Pancake Coils" (being prepared for test in LN2)

HTS cable is carefully wound in large radius pancake coil for testing at liquid nitrogen temperatures (63-77K)

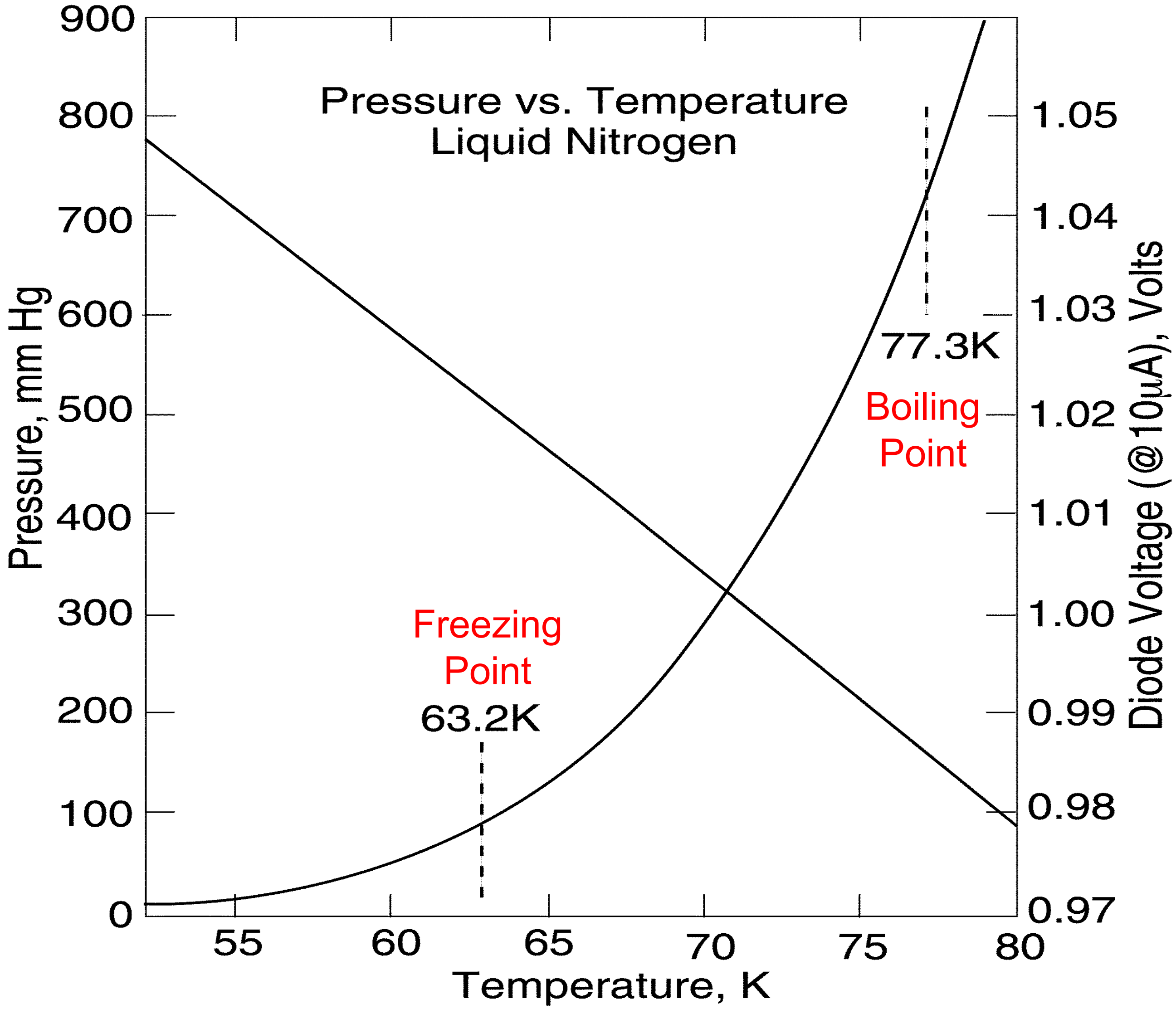




Superconducting
Magnet Division

Pressure-Temperature Curve for Liquid Nitrogen

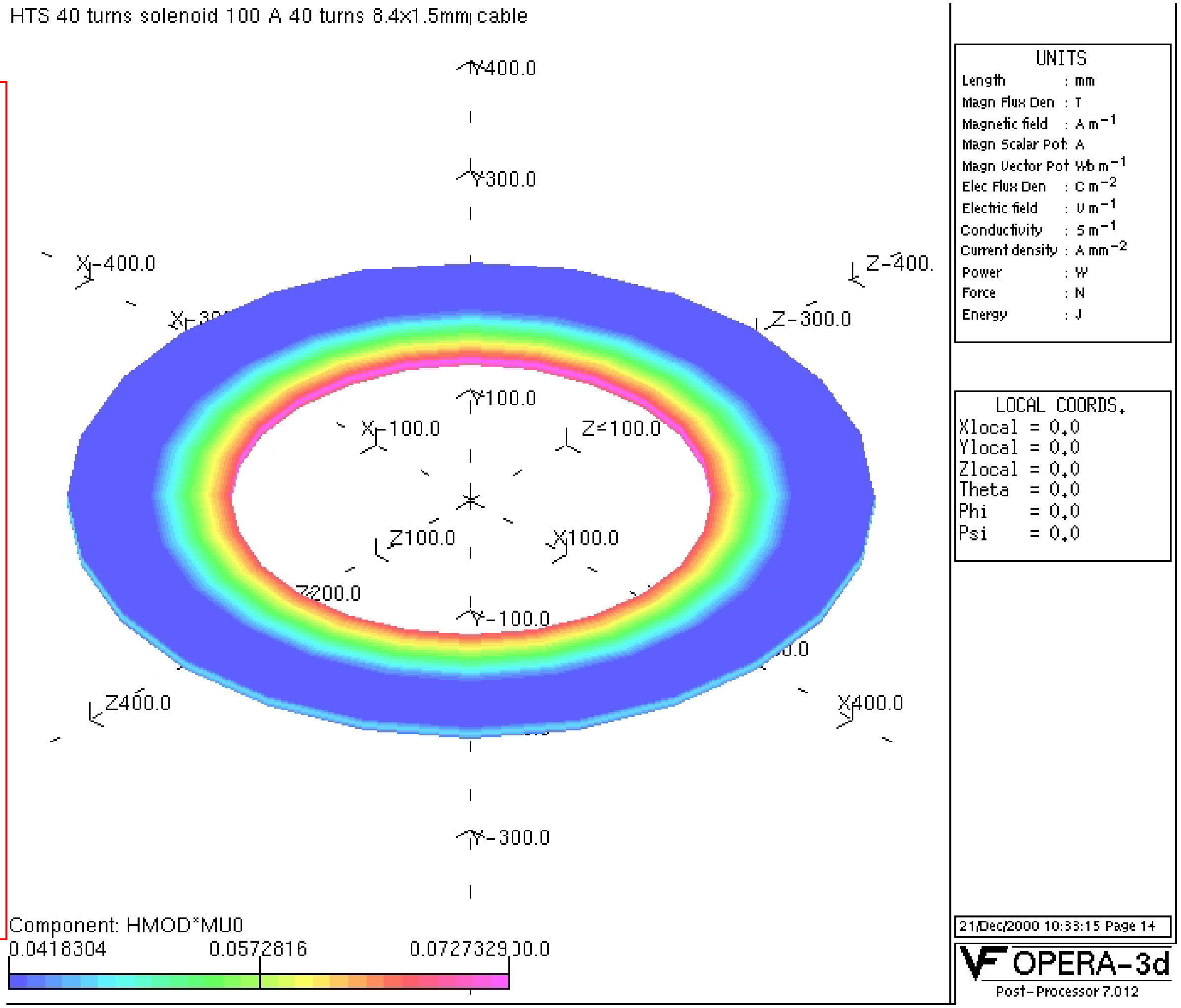
We use LN_2 testing as a QA method, before testing wires, tapes, cables and also coils at 4K (LHe).



Self field Corrections are Important (even more so at 77 K)

Since self-field measurements do not reflect the actual improvements, and also do not reflect the situation faced in real application,

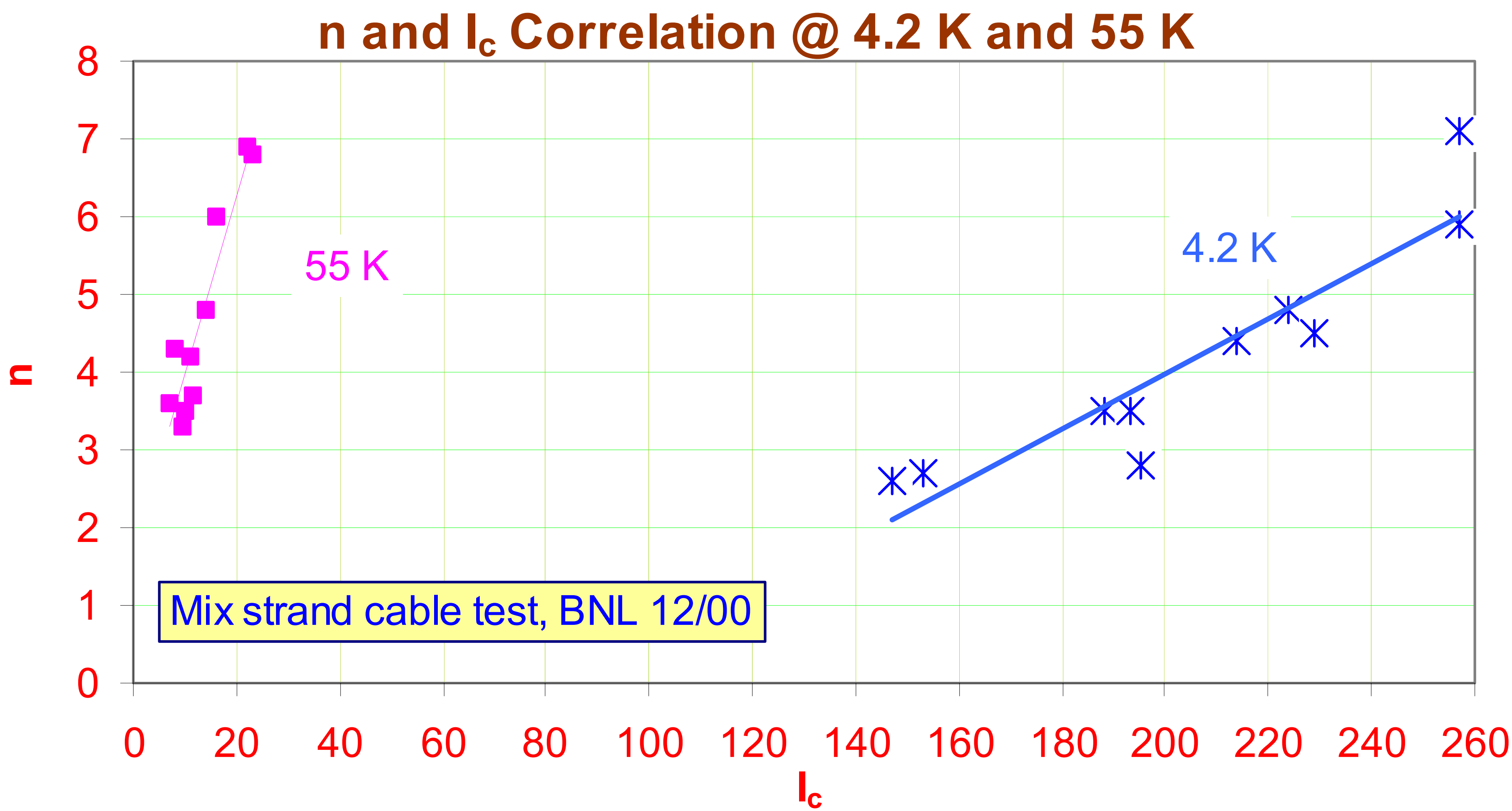
we suggest consider quoting critical currents at (4K, 5T)



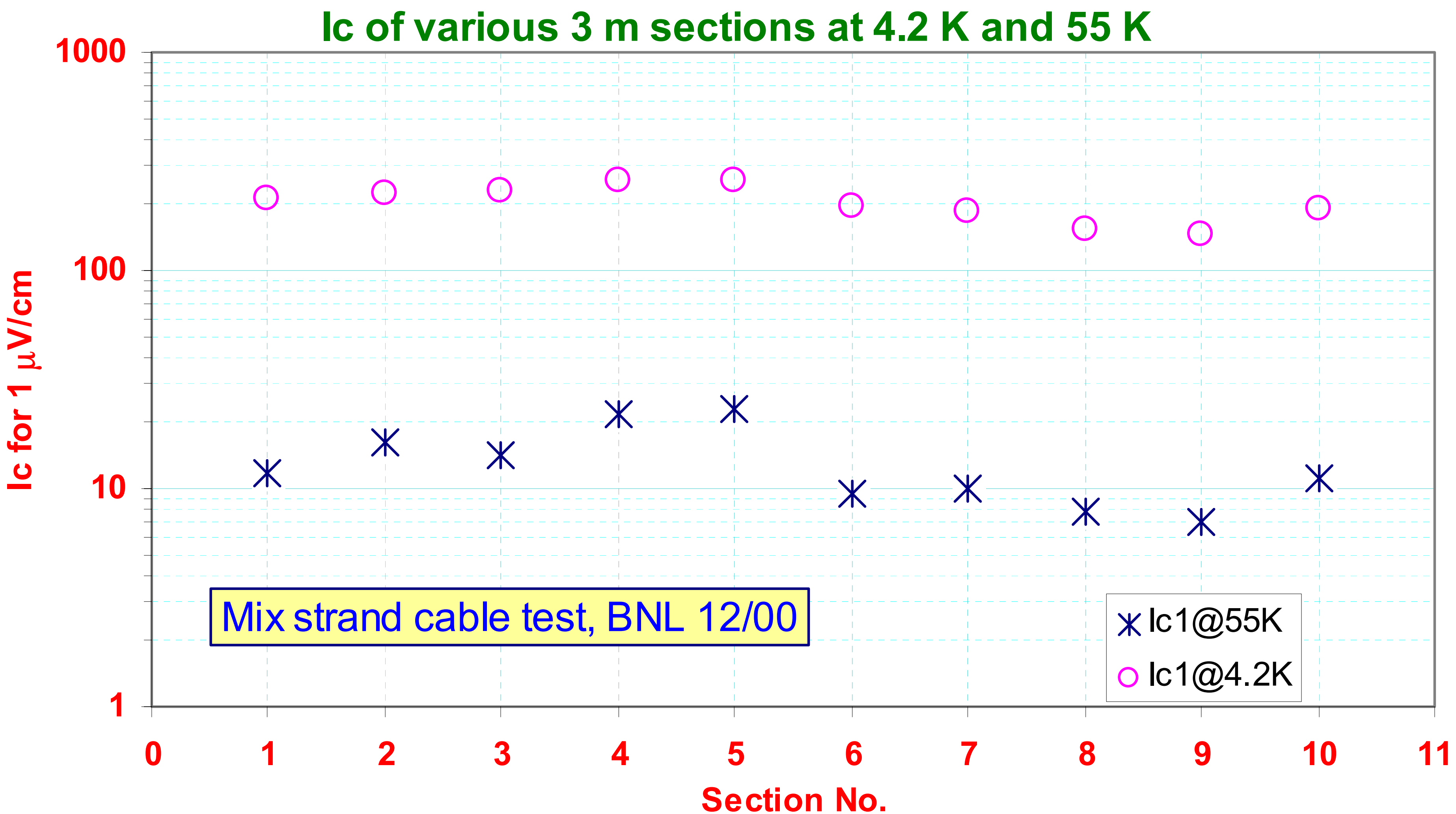
Maximum Field at 260 A is ~0.19 T

Computed Field at the Surface of Solenoid at 100 A

Correlation between I_c and n-value



Ic Tracking Between 4.2 K and 55 K



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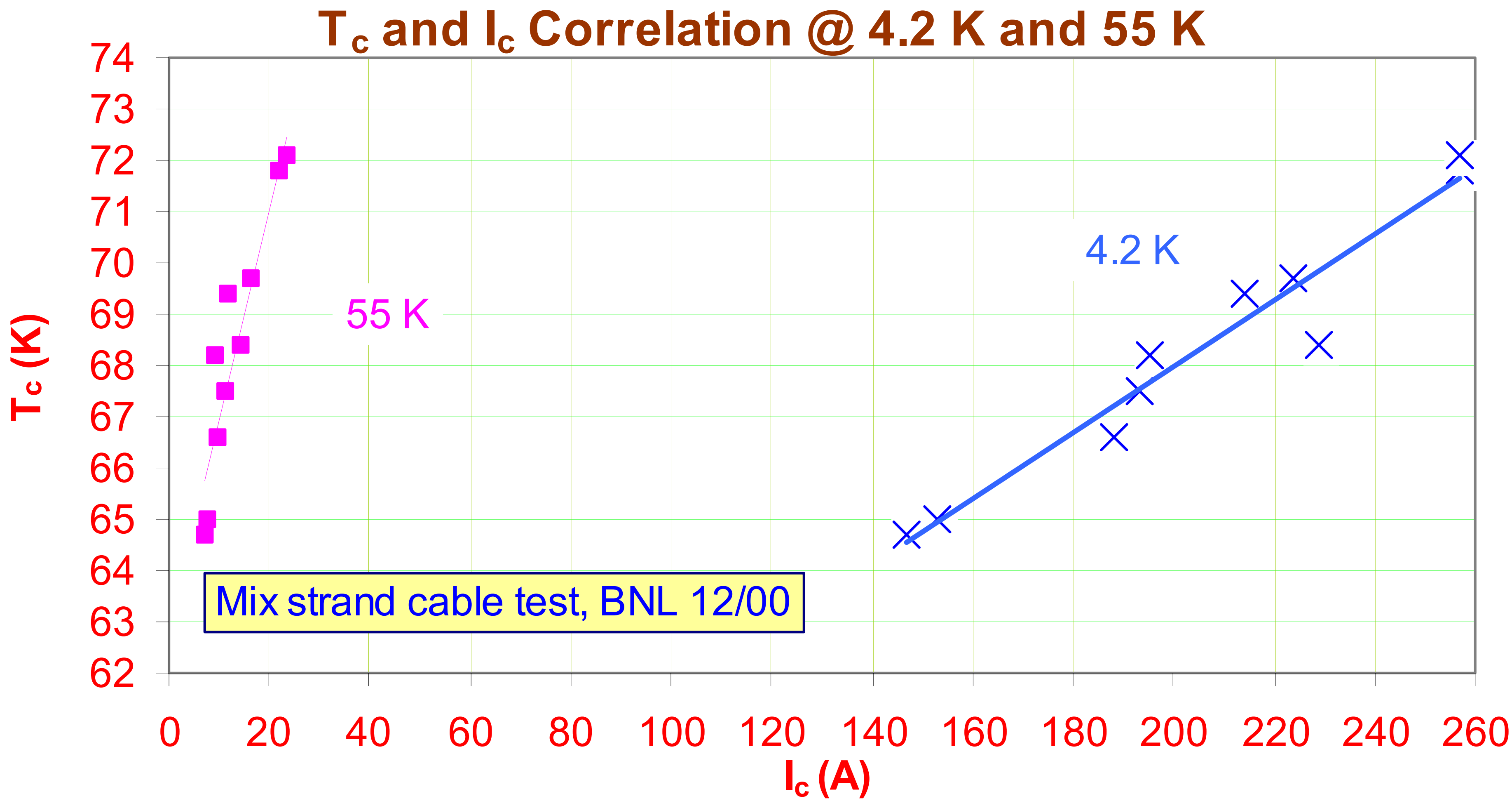
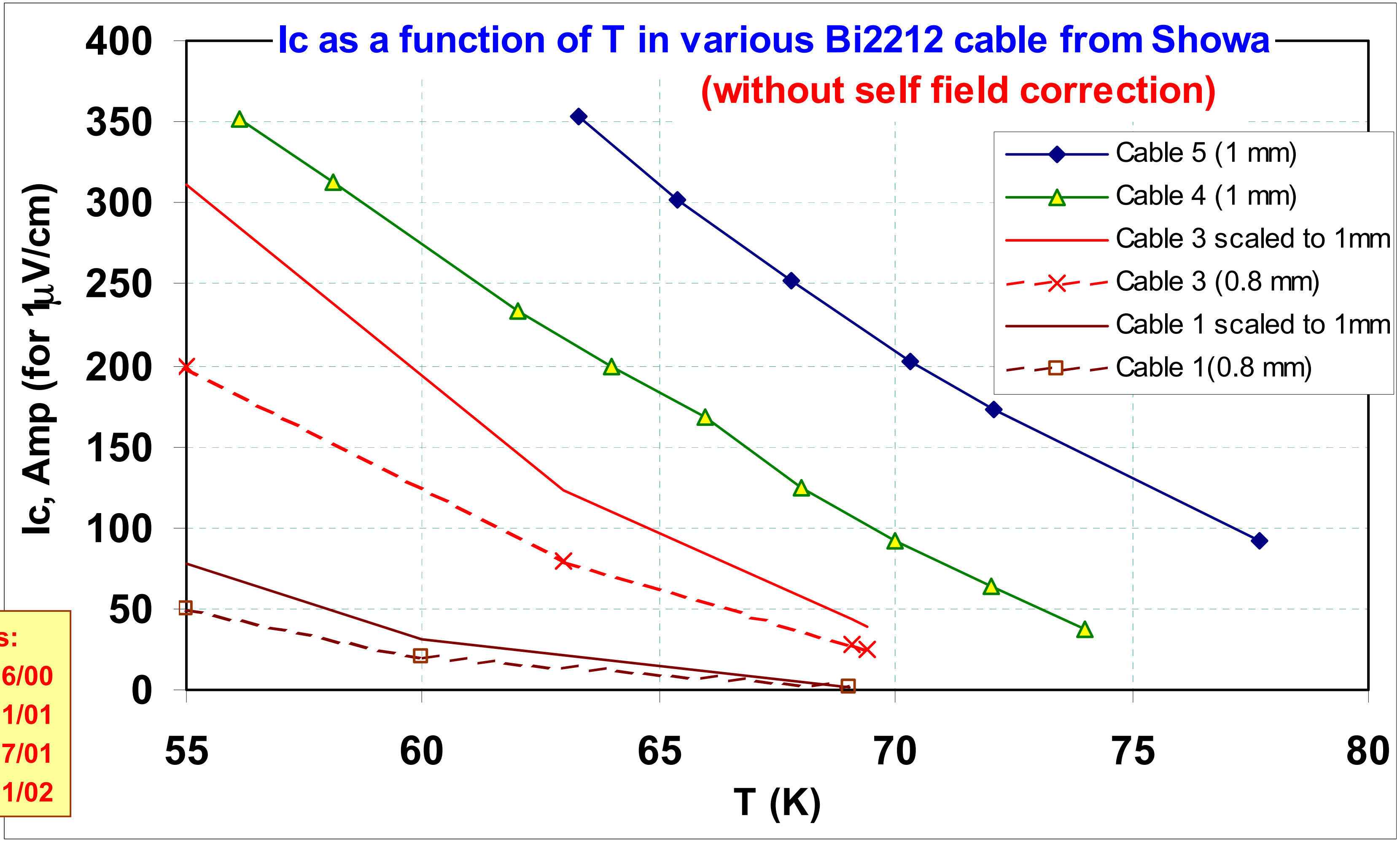
Correlation between T_c and I_c

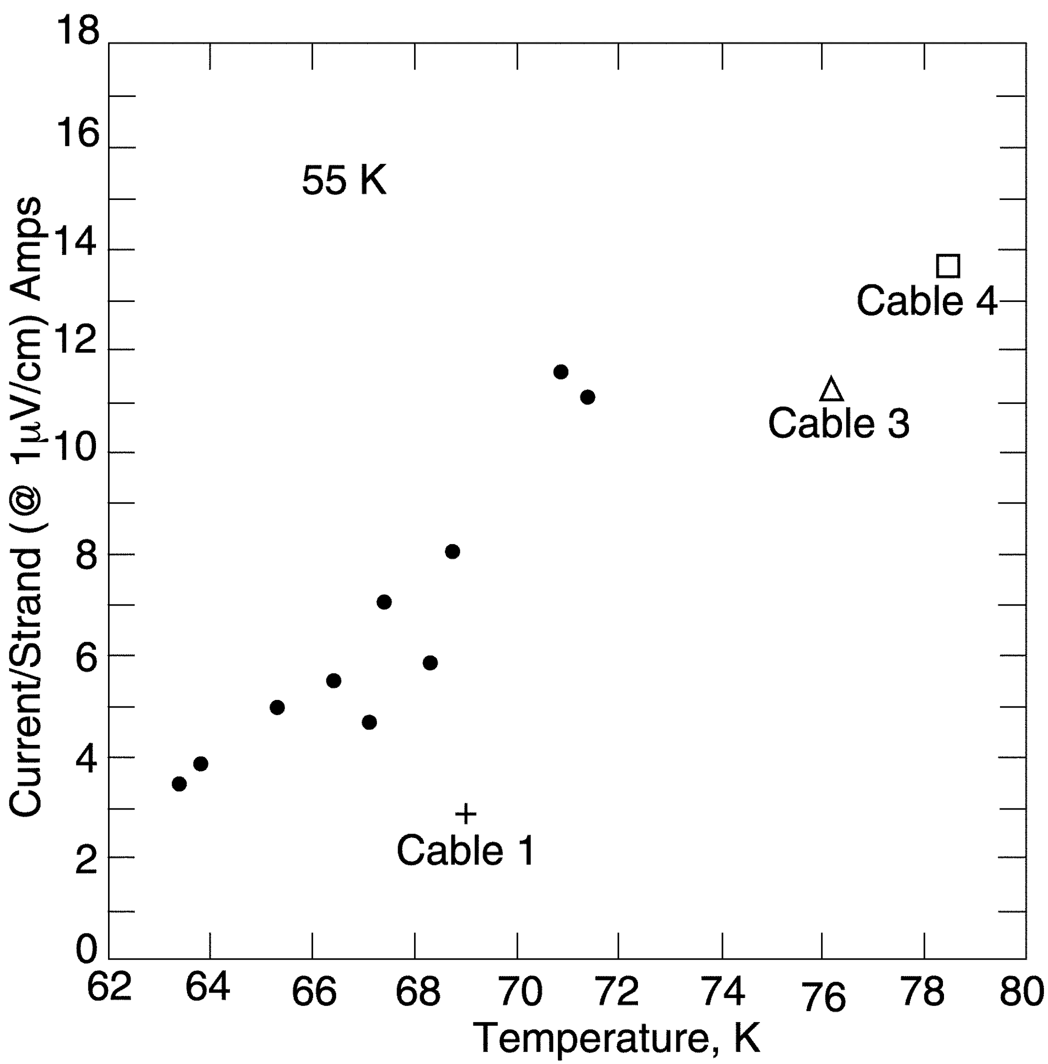


BNL Measurements of Various Cables from Showa (Note: Continuous progress in cable performance)



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

Correlation between T_c and I_c



In ealier cases we found that the cables with higher T_c also have better I_c at 4K.

- However, this has not been the case in the last test. The two cables had about the same I_c at 77 K but ~20% different at 4K.
- This is an inconvenient warning about the limitations of LN_2 test.
- And also that improving I_c may have a different recipe then that for improving T_c.

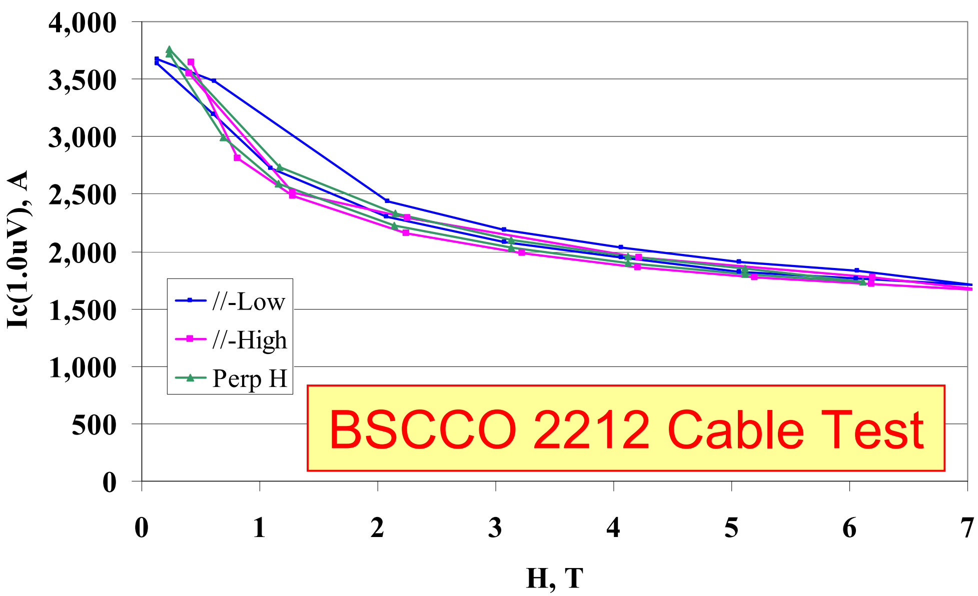
Measured Performance (@4K) of HTS Cable and Tape As A Function of Field at BNL

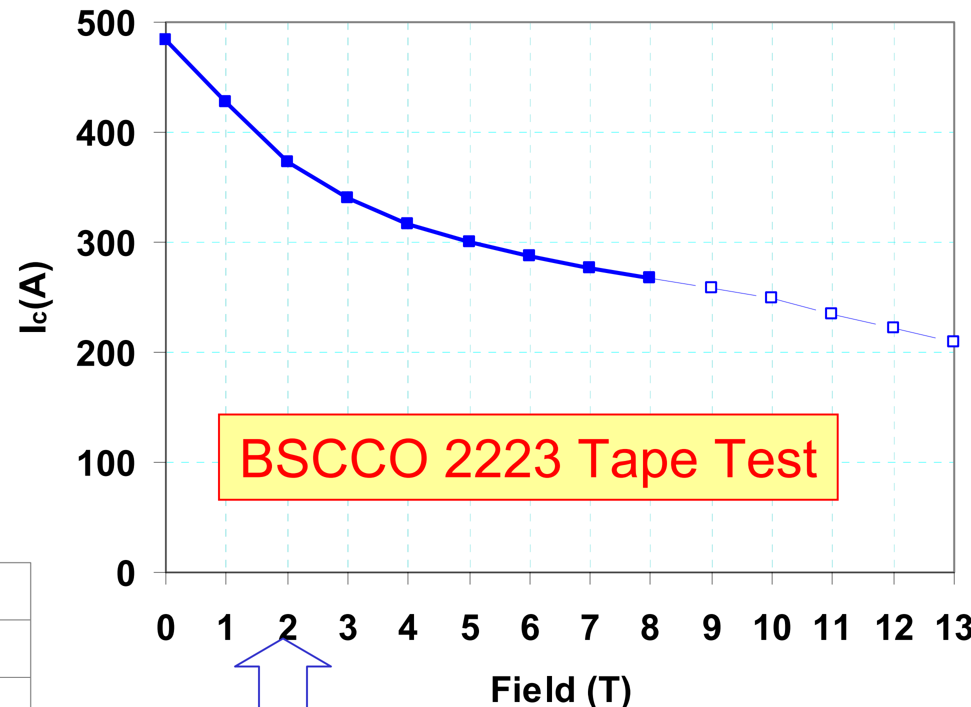
Measurements of "***BSCCO-2212 cable***" (Showa/LBL/BNL) at BNL test facility

This is the plot from an early test.

Modern HTS cable carry much higher current. In this reporting the self field correction is applied. This is not been the situation in all cases.

(self field correction is applied)

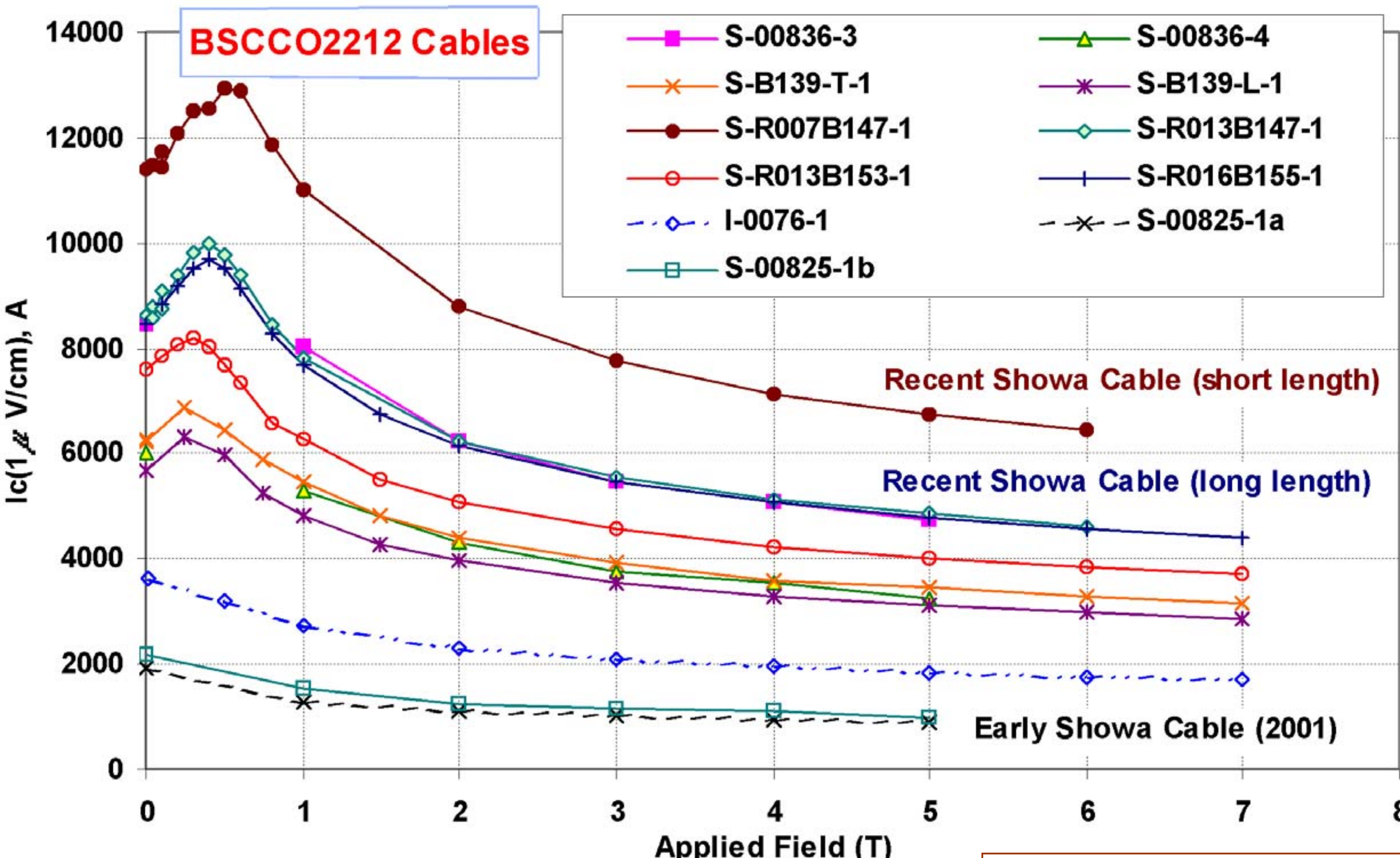




Measurements of "***BSCCO 2223 tape***" wound at 57 mm diameter with applied field parallel (1μV/cm criterion)

(field perpendicular value is ~60%)

HTS Cables: A Remarkable Progress in the State of Art



HTS Cables Tested at BNL Short Sample Test Facility

A significant self field at high currents

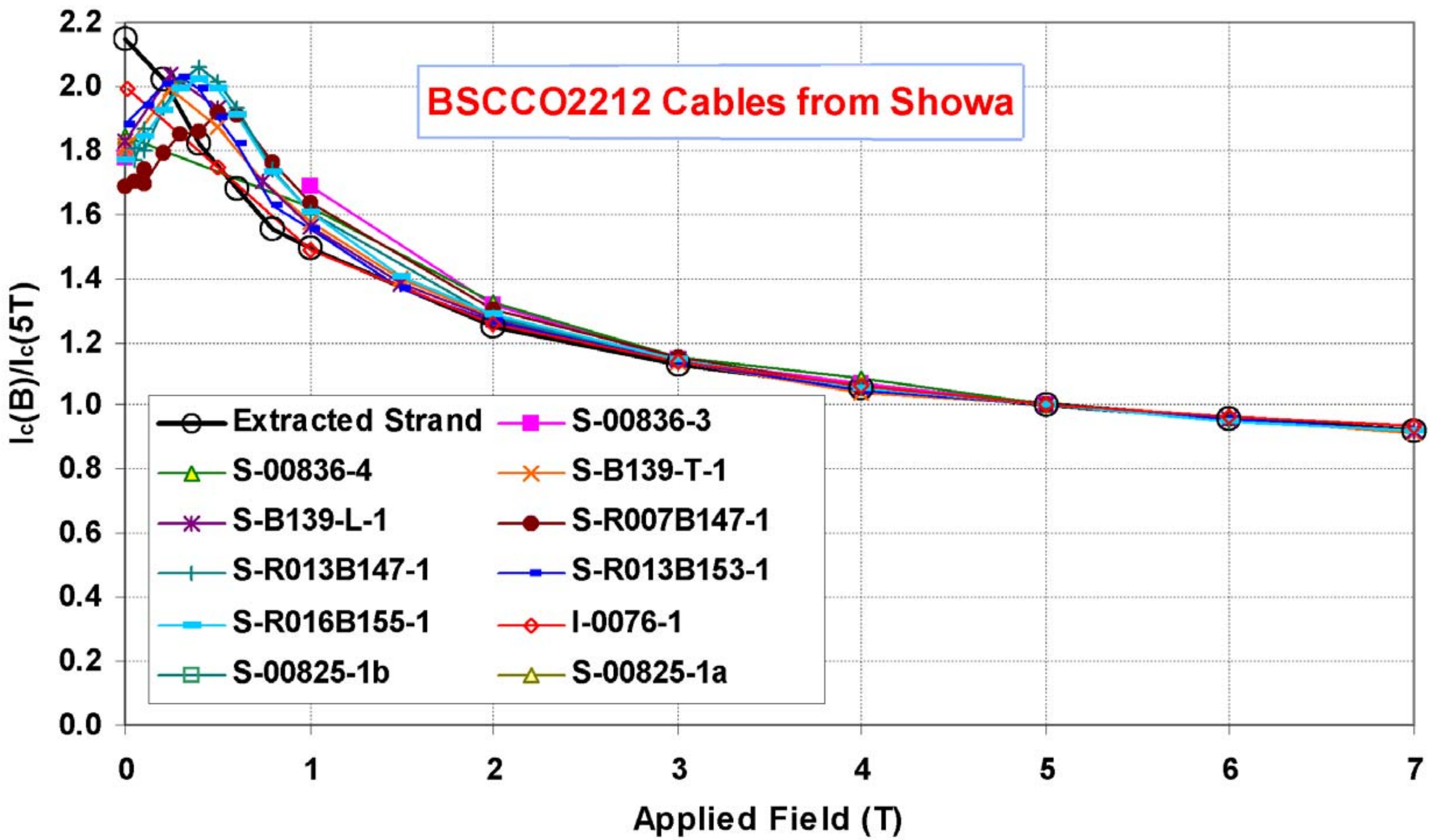
Modern HTS Cables Carry A Significant Current.

See talk by Dr. Hasegawa, on Thursday (4C-p07 @MT18)

All HTS from Showa (sponsored by Chubu Electric for SMES program)

Cable made at LBL

Relative Field Dependence in Various Cables and Extracted Strand from Cable

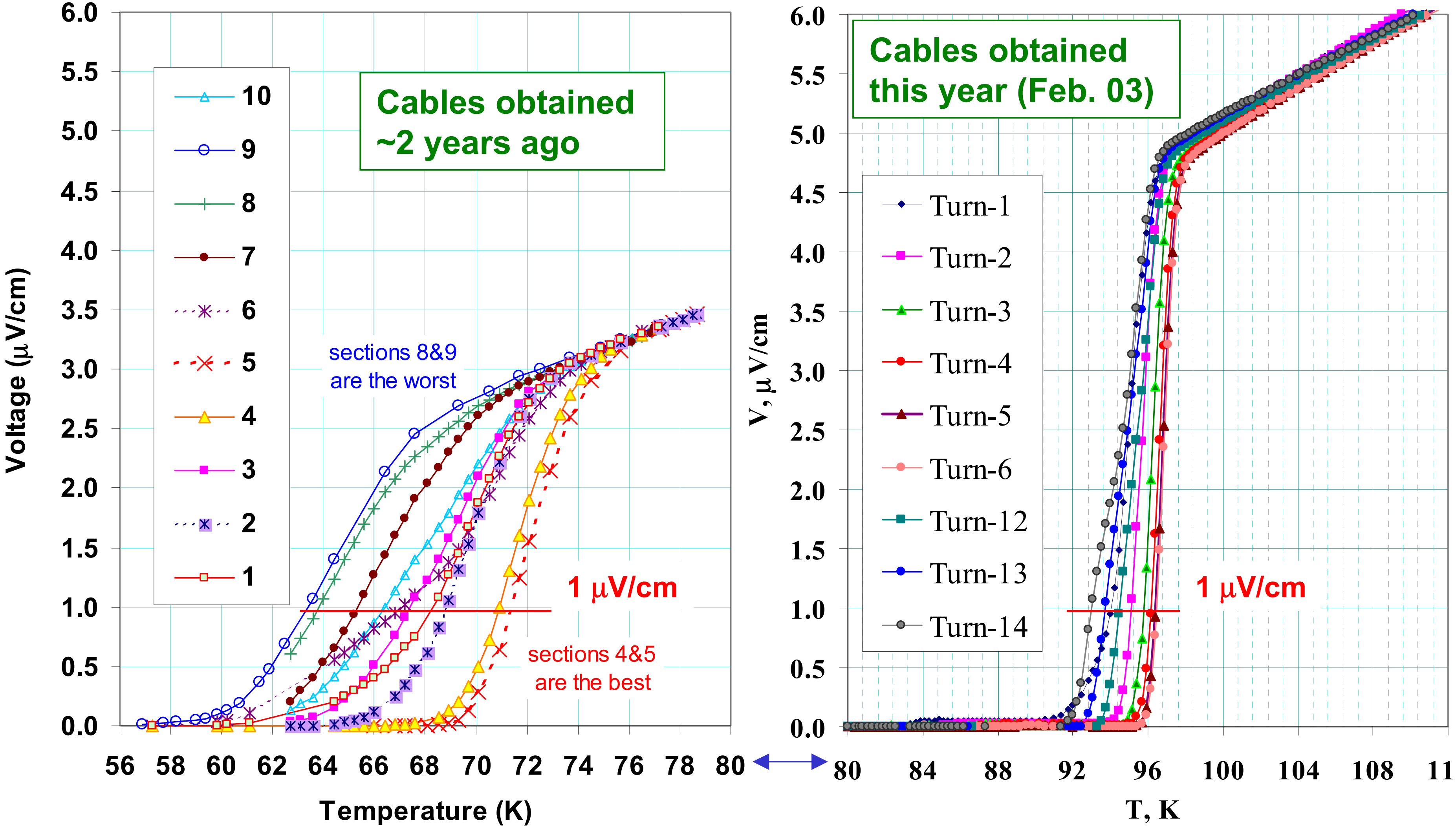


A generally similar field dependence except at low fields where self field correction will be significant in high performance cables.

Relative field dependence is normalized at 5T (a good value for specification).

Improvements in Uniformity of Recent HTS Cables from Showa

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



HTS Coil and Magnet Test Results

HTS Coils and Magnets Made with Showa Cable

TABLE II

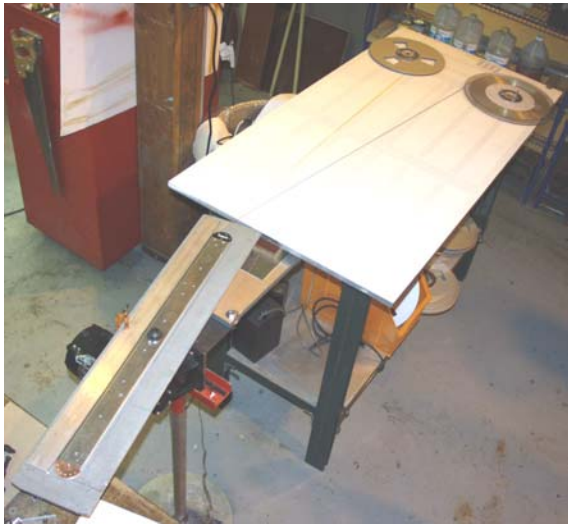
COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. I_c IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

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

The results of three most recent magnets will be discussed in more details.

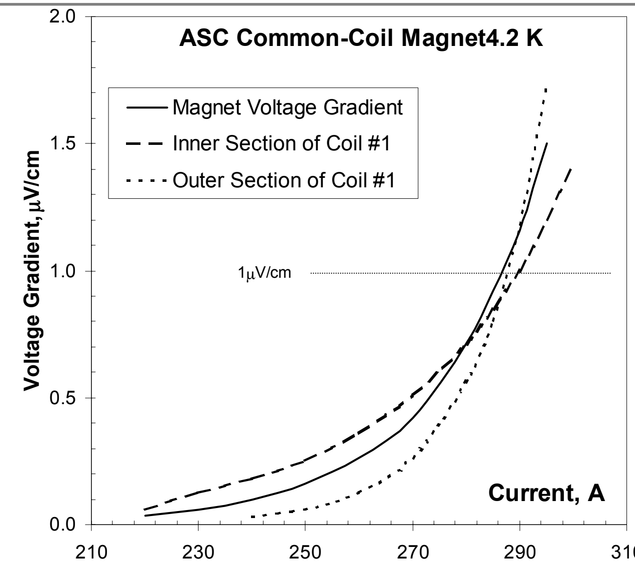
Common Coil Magnets With HTS Tape

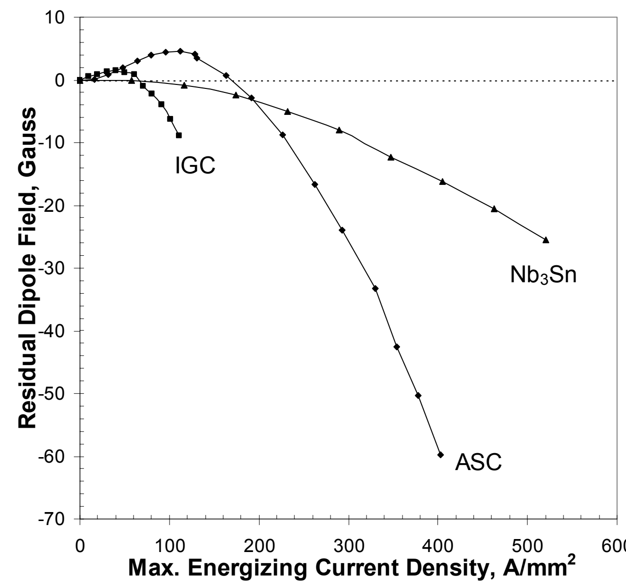
(Field quality in 74 mm aperture to be measured soon)



A coil being wound with HTS tape and insulation.

Two HTS tape coils in common coil configuration



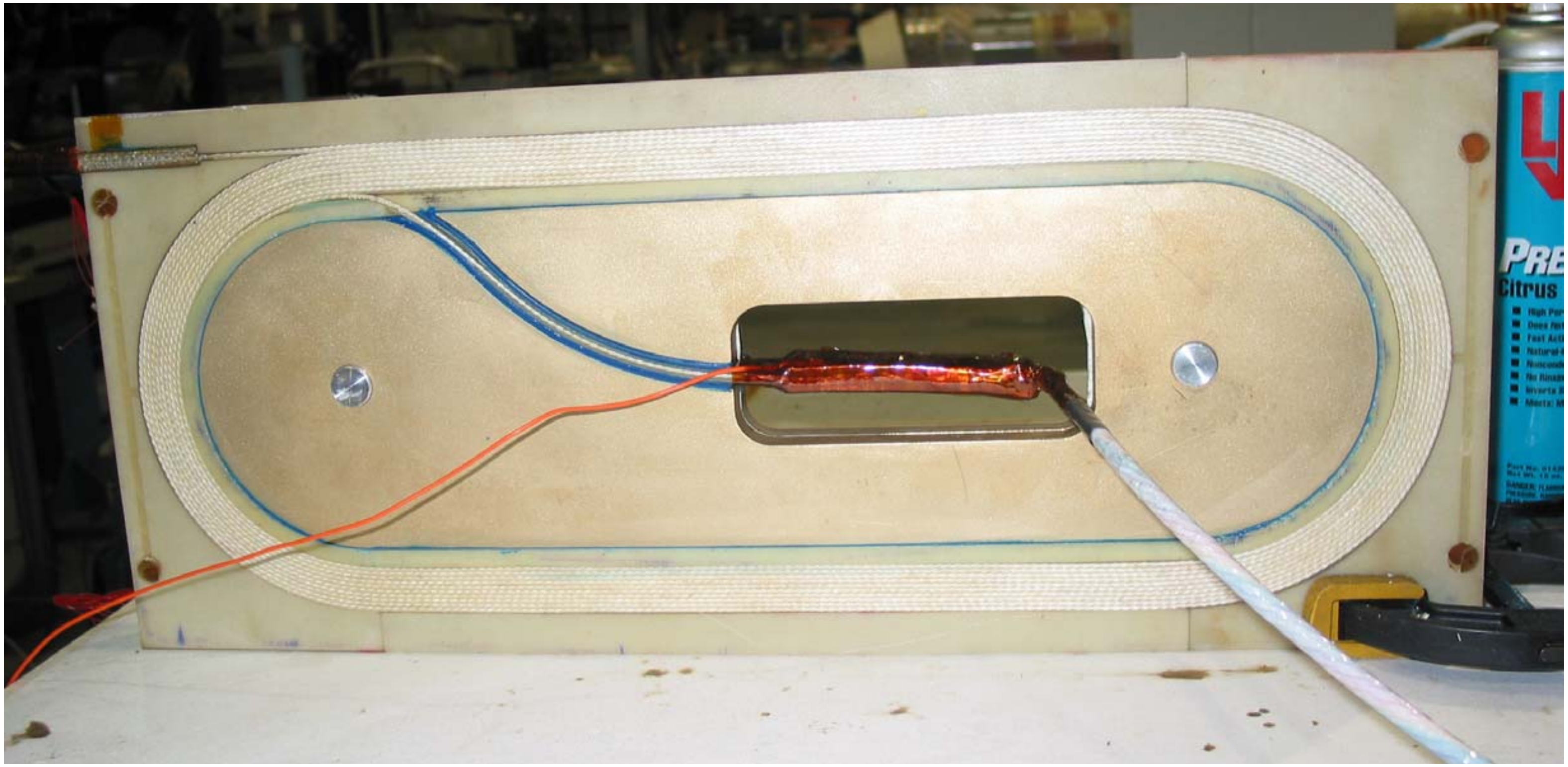


Status of HTS tape coils at BNL

	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

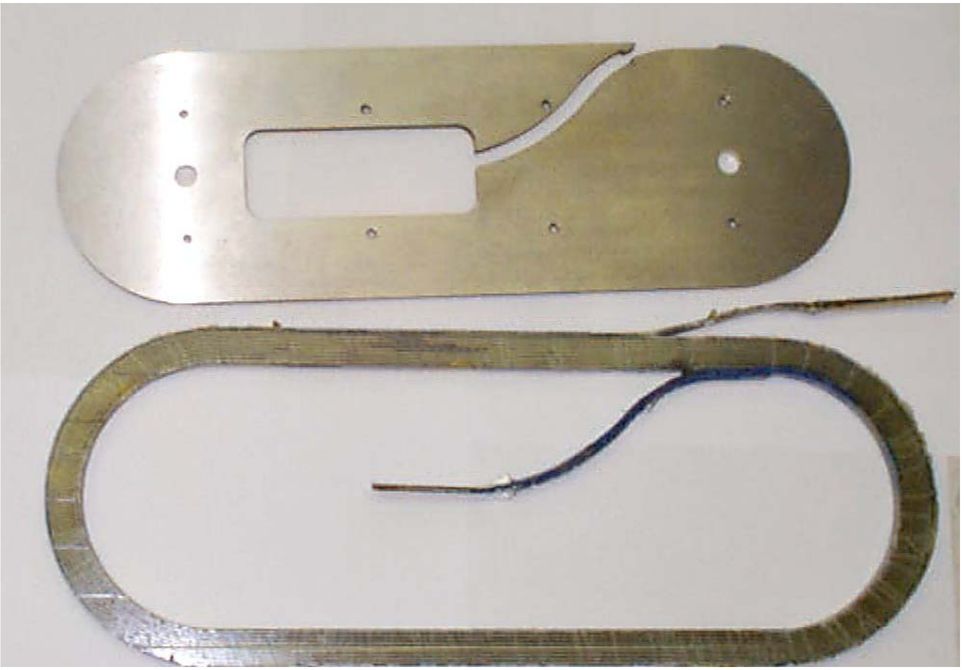
HTS Coils for Accelerator Magnets

We propose to use these HTS cables in accelerator magnets made with conductor friendly racetrack coils using React & Wind technology.



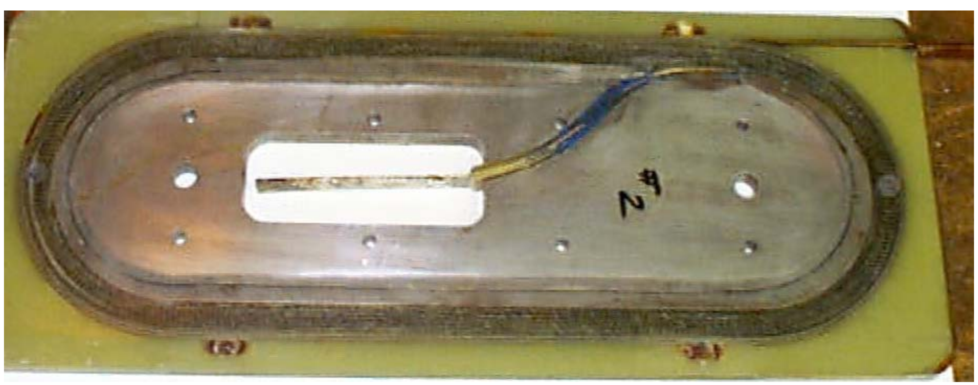
An example of racetrack coil recently built and tested at BNL.

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)

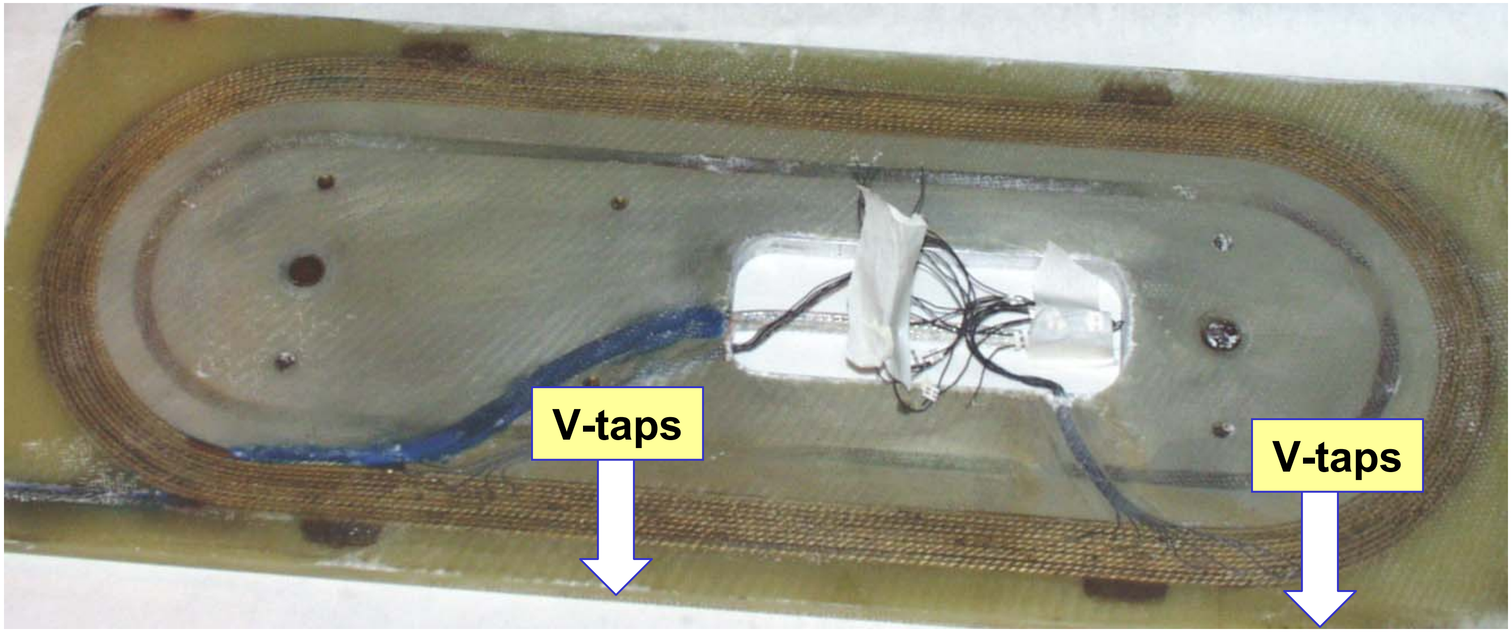


The complete cassette module
(vacuum impregnated coil in bobbin)

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)

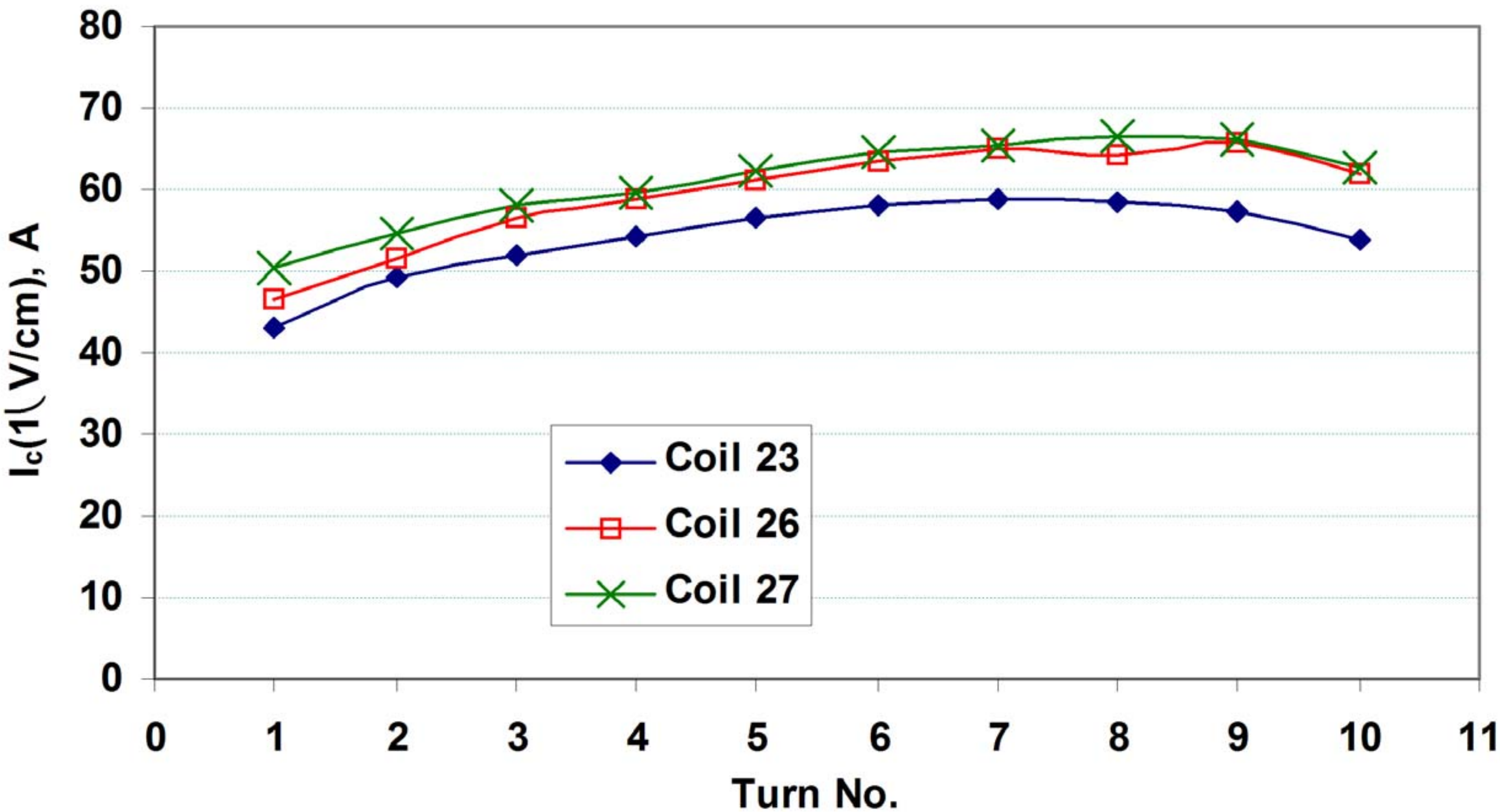


This is an old coil, now we do things a bit differently.

But the basic principle remains the same.

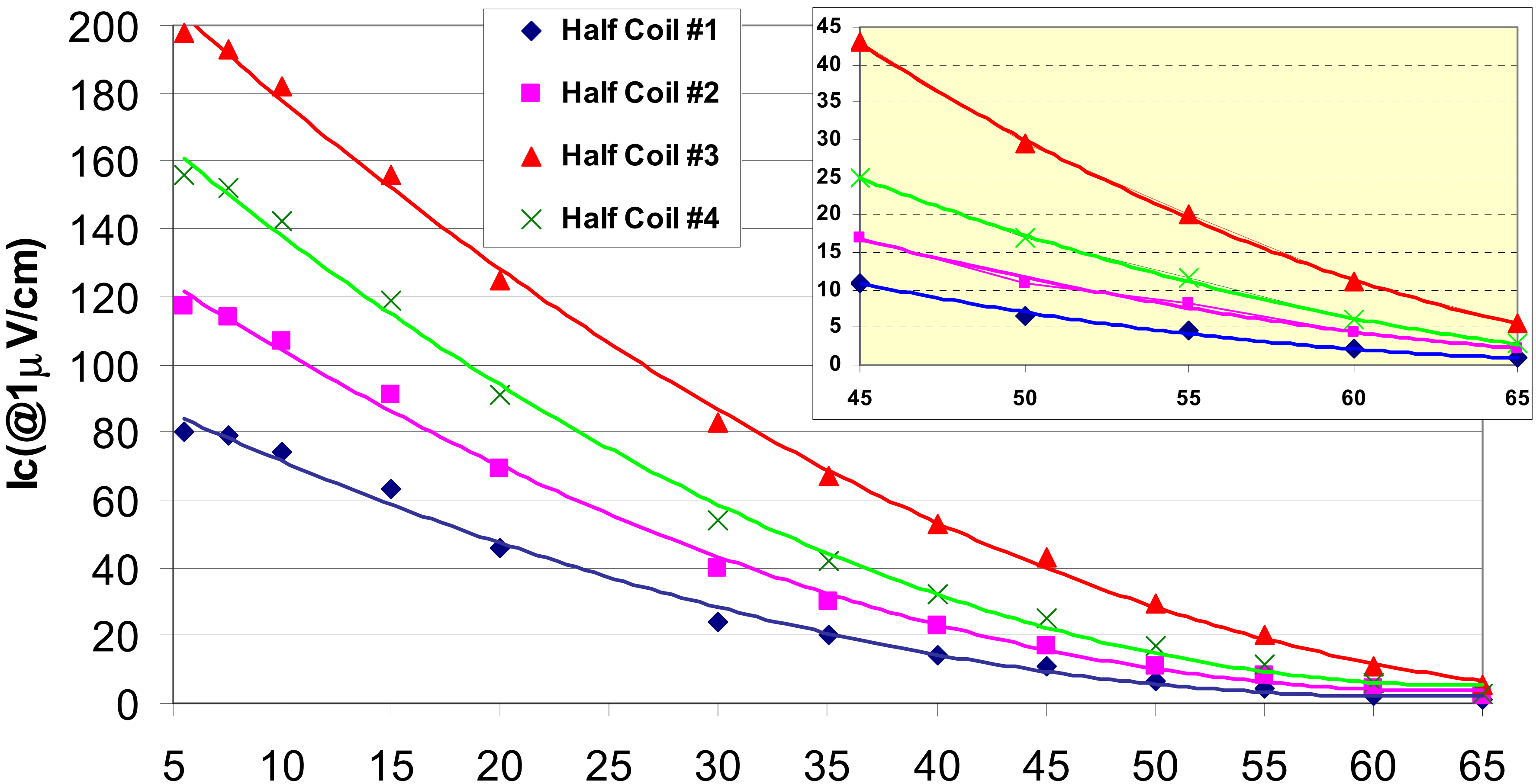
Measurements of HTS Coils at 77 K (Liquid Nitrogen)

An inexpensive and very useful quality assurance technique - unique to HTS



Variation in I_c is primarily due to field variation in the self field

Measured Critical Current as a Function of Temperature



Mixed strand cable
(2 BSCCO 2212, 16 Ag)

4 coil halves
(2 each of two coils)

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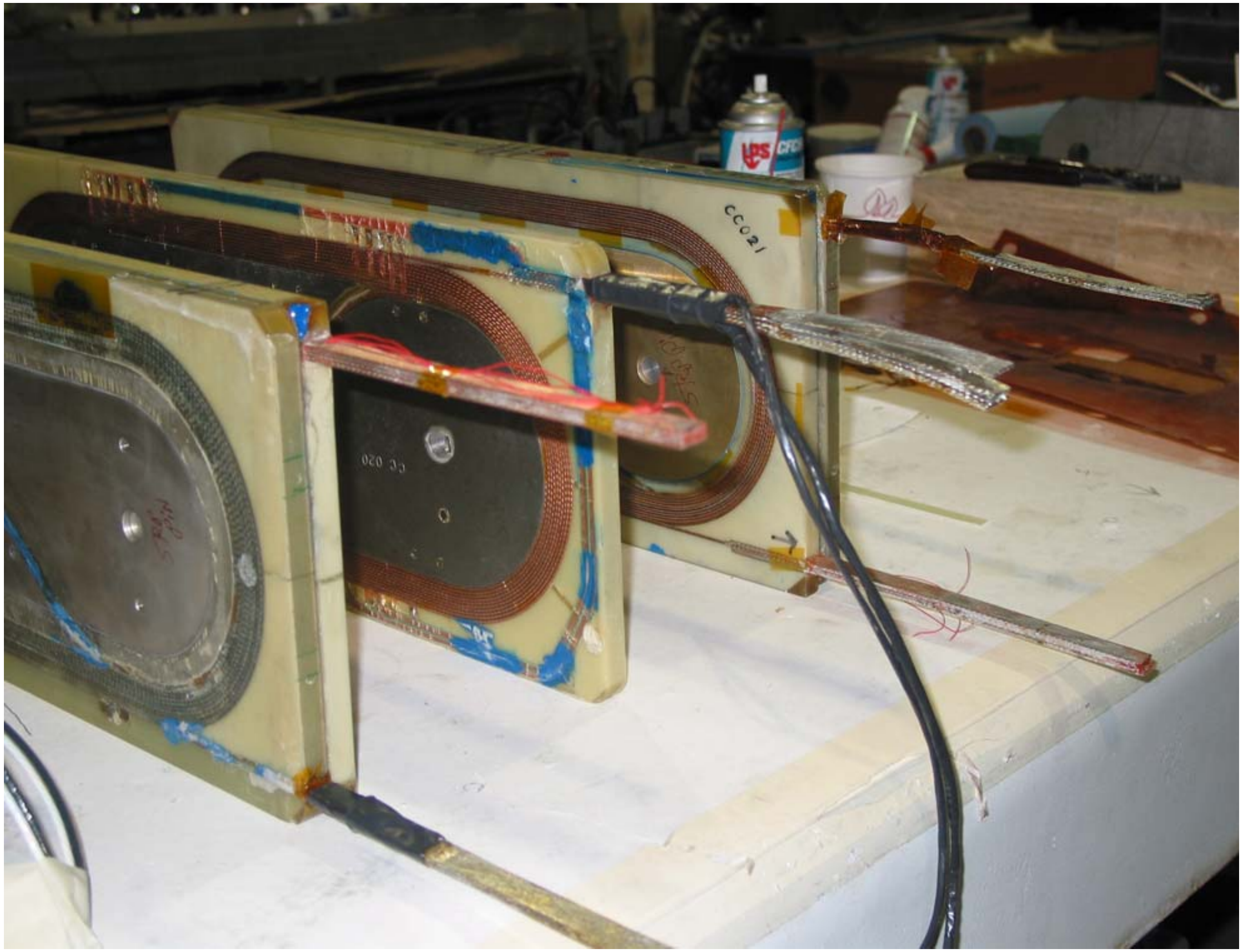
Racetrack Coil Cassettes for Rapid Turn Around Magnet R&D Facility



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.

5 cassettes (racetrack coils) for a hybrid magnet test

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.

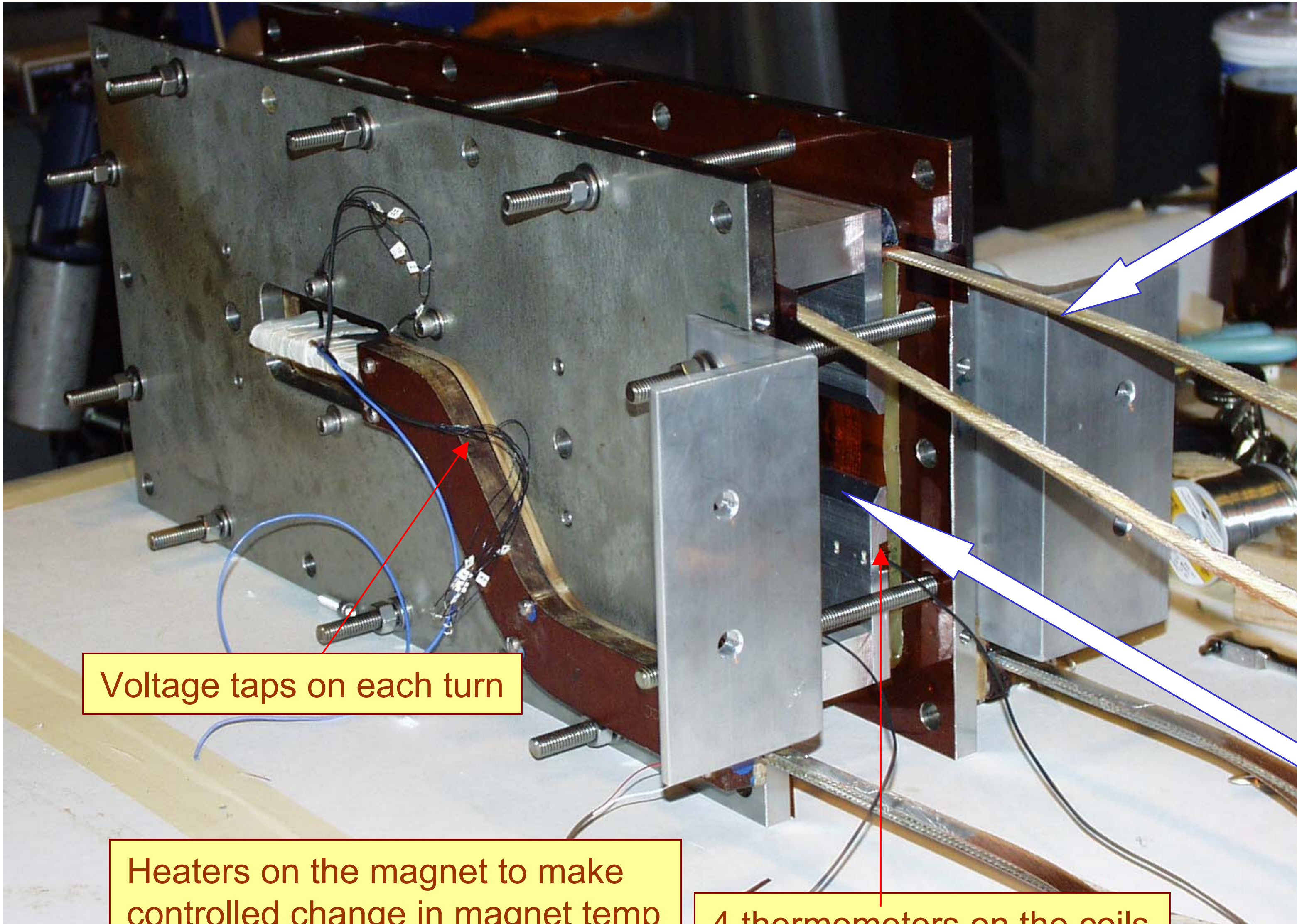
Coils are assembled for the most flexible and extensive testing. Four leads are taken out of the cryostat. During the test the coils were powered separately and together in “common coil” and “split-pair solenoid mode”.

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

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



Voltage taps on each turn

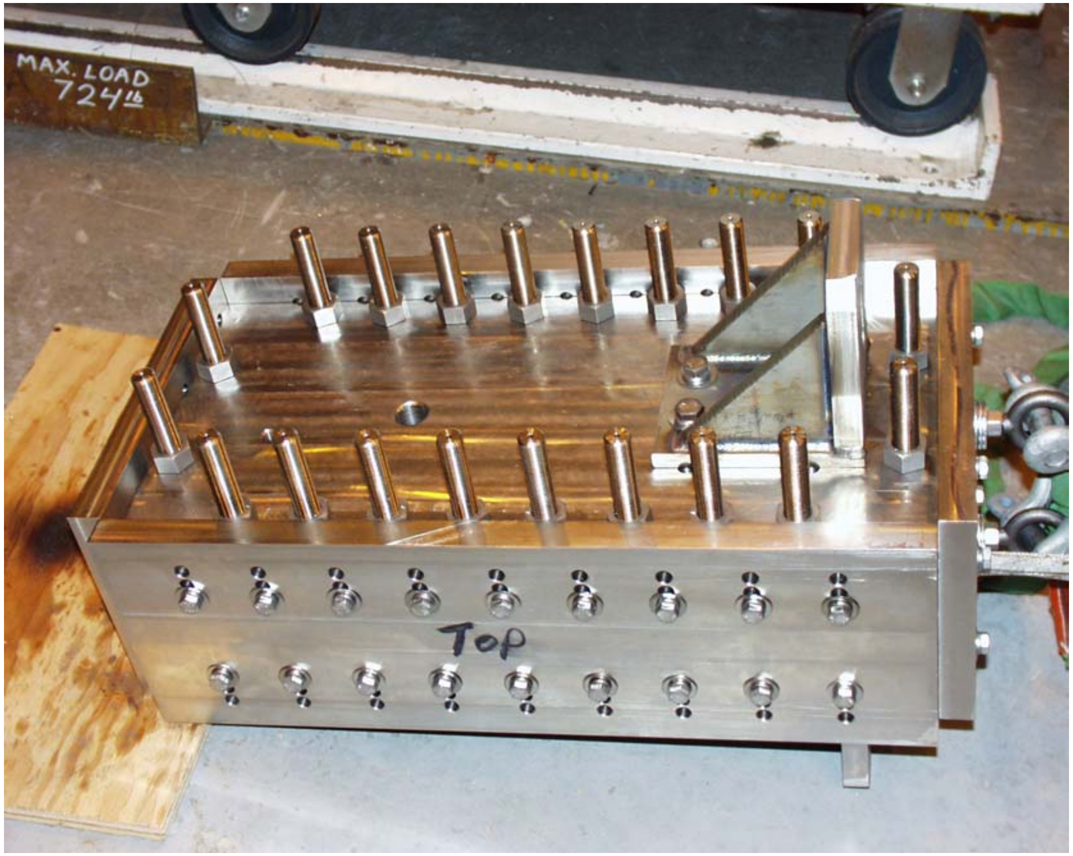
Heaters on the magnet to make controlled change in magnet temp

4 thermometers on the coils

HTS Cable Leads to make high temp measurements

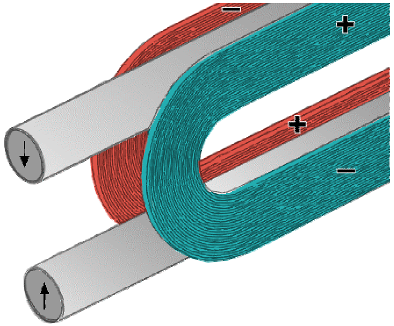
74 mm aperture to measure field quality

HTS Coil Test Magnet

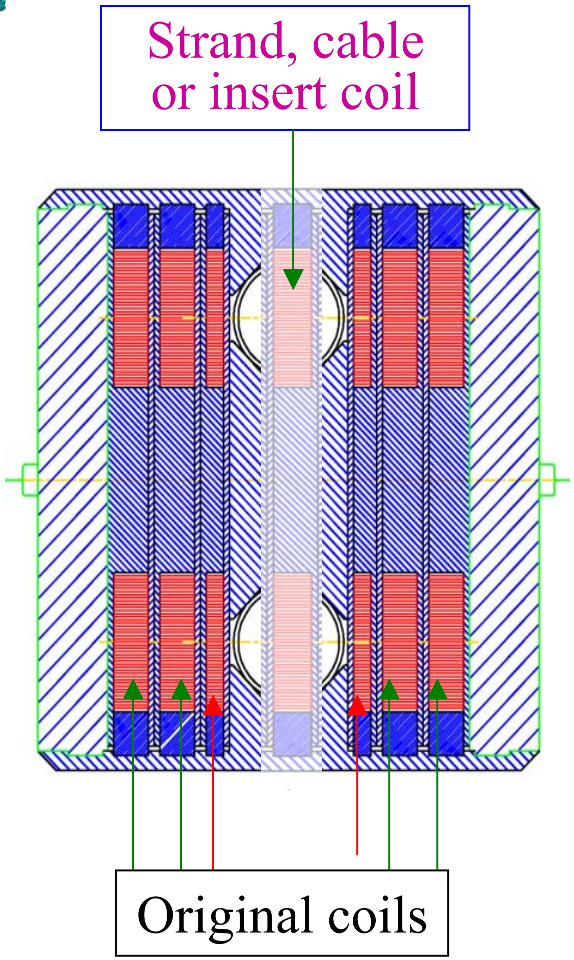


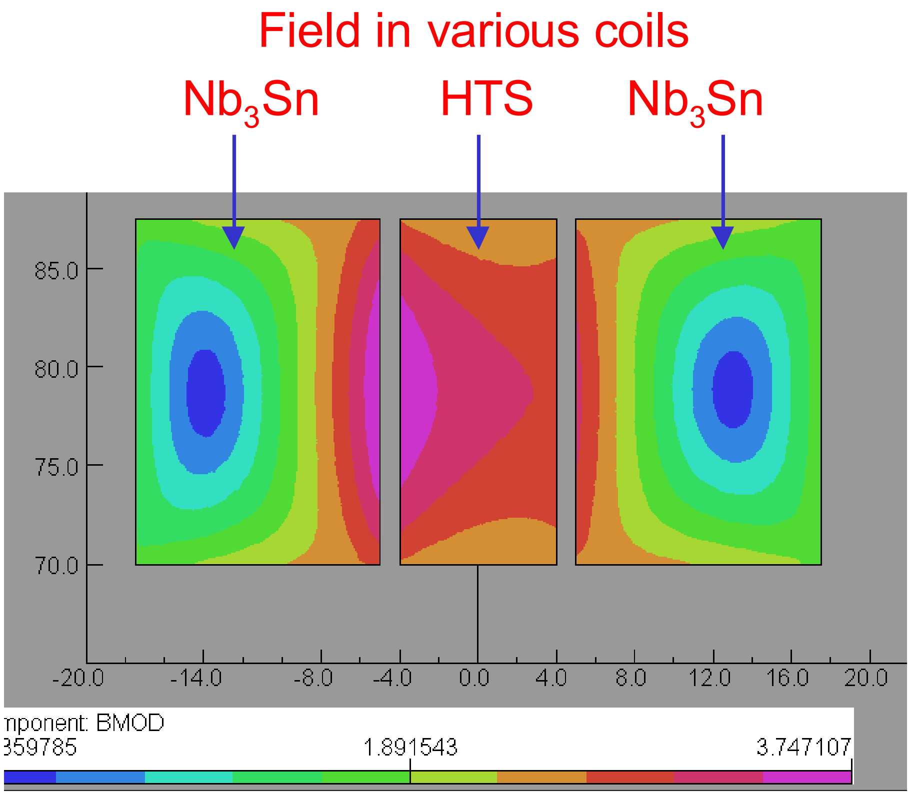
- DCC012 is a hybrid magnet made with five coils (one HTS and four Nb_3Sn); Nb_3Sn coils provide background field on the HTS Coil.
- Vary current in Nb_3Sn coils (background field) to study HTS coil performance at different field level.

Common Coil Magnet As A Test Facility



Nb3Sn coils provide a background field on HTS coil in a hybrid design





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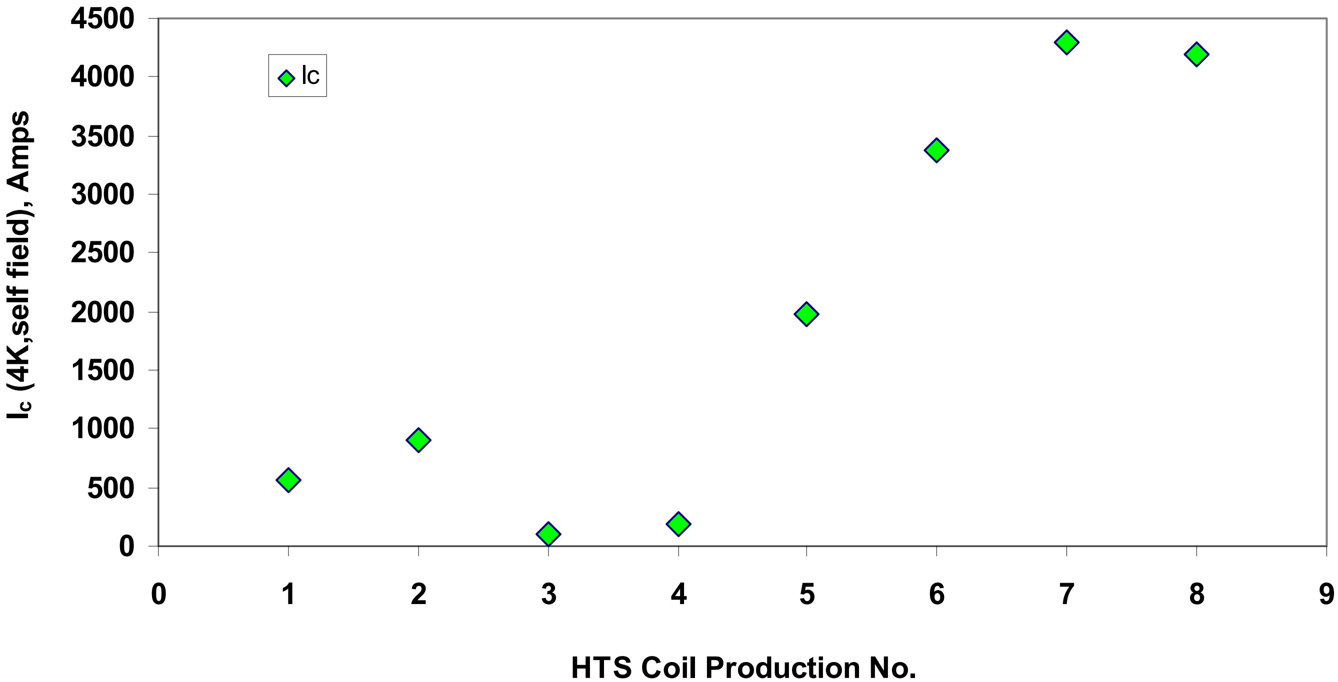
HTS (BSCCO2212) Cable Now Carry A Significant Current in Magnet Coil

Earlier coils (~2001)

Latest coils (Oct., 2003)



These measurements are in self field

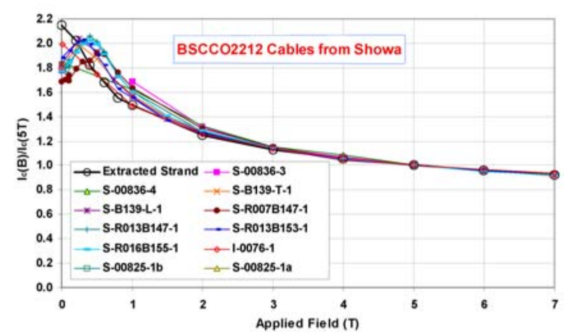
TABLE II

COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. I_c IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

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

Self-field <0.05 T

Self-field ~ 1.85 T



All HTS from Showa
Cable made at LBL

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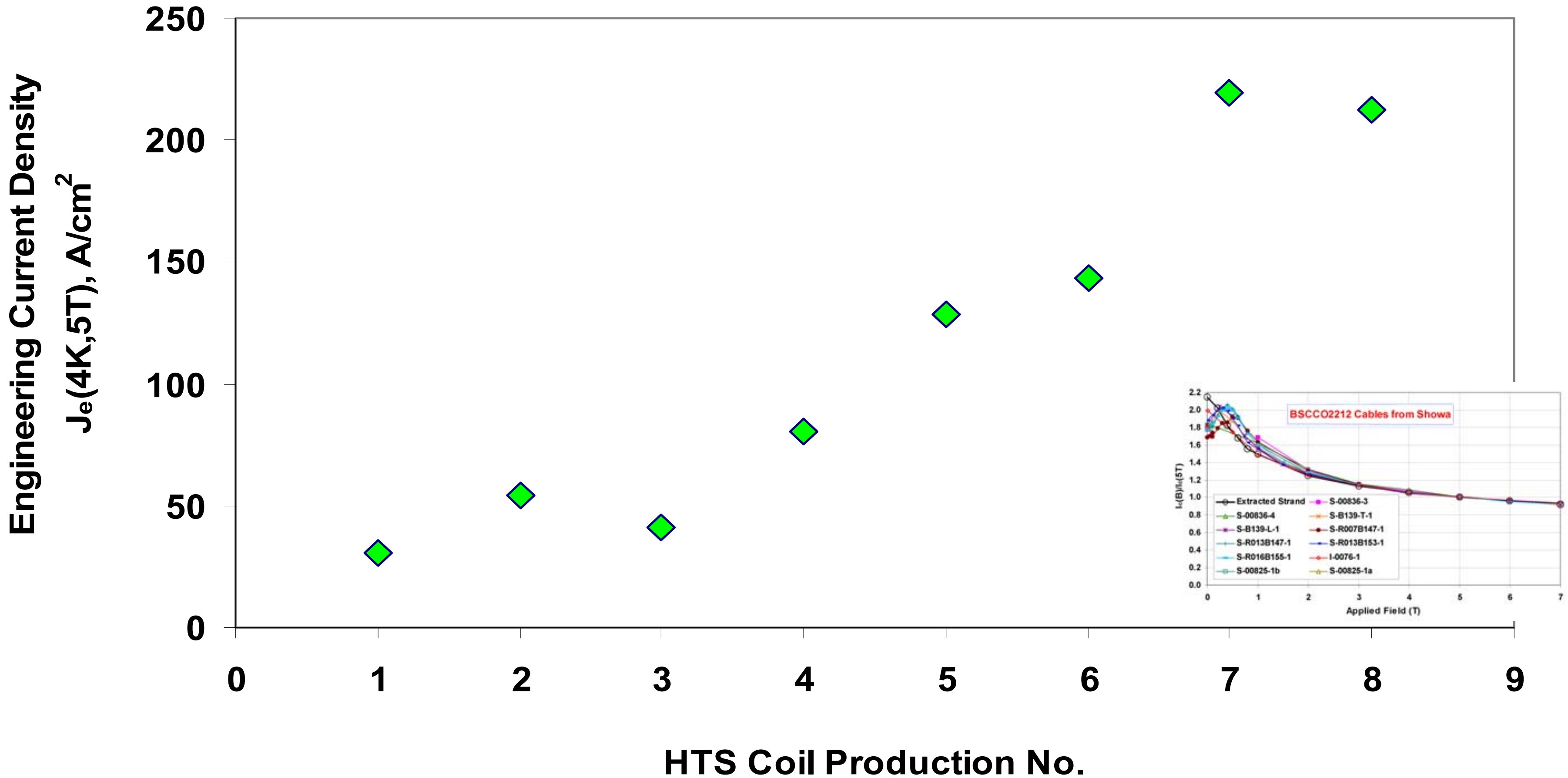
Progress in Engineering Current Density of HTS Cable in Coil

Measurements at 4.2 K in self-field, normalized to 5 T value

(J_e remains practically flat at higher field)



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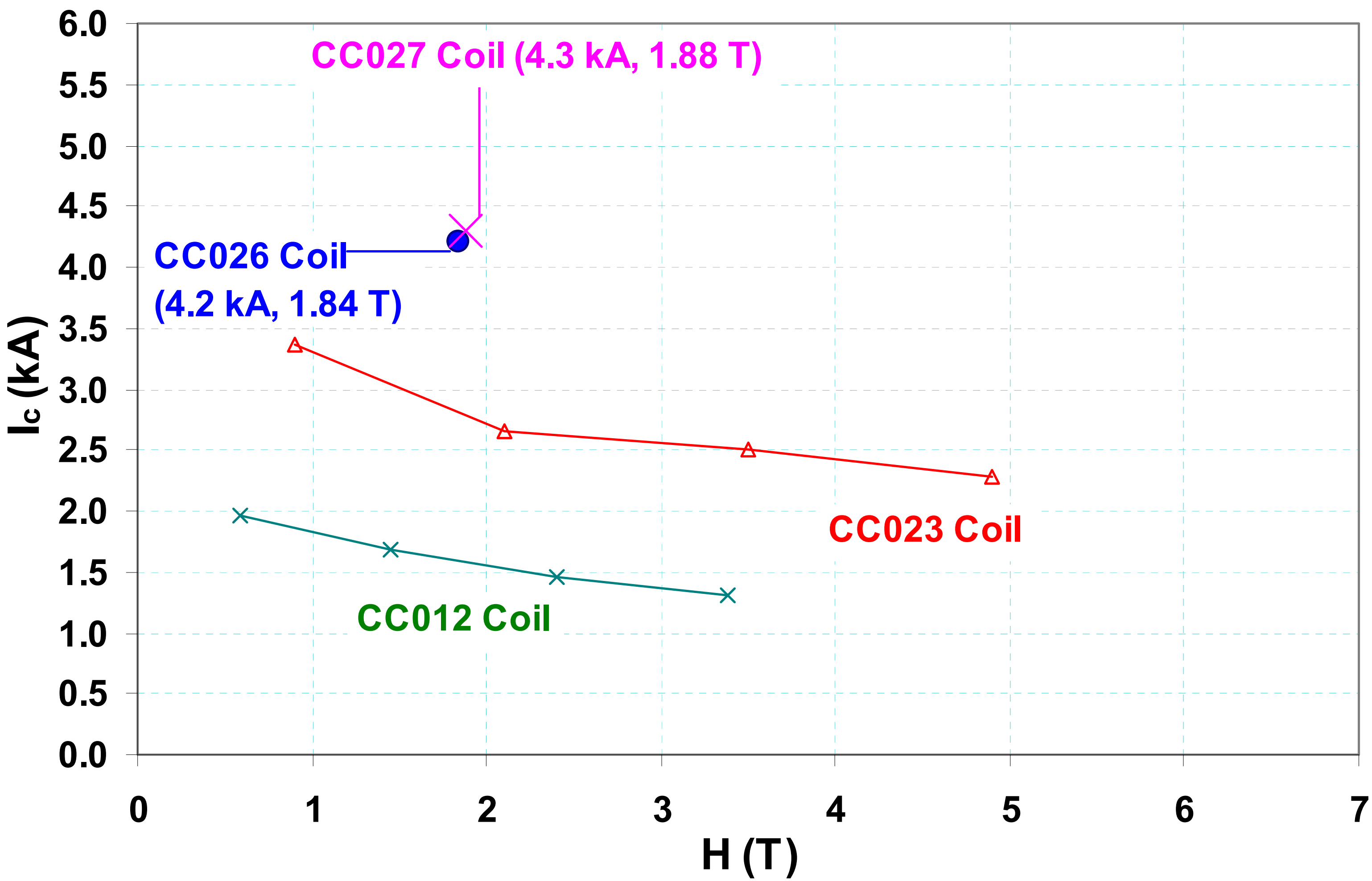
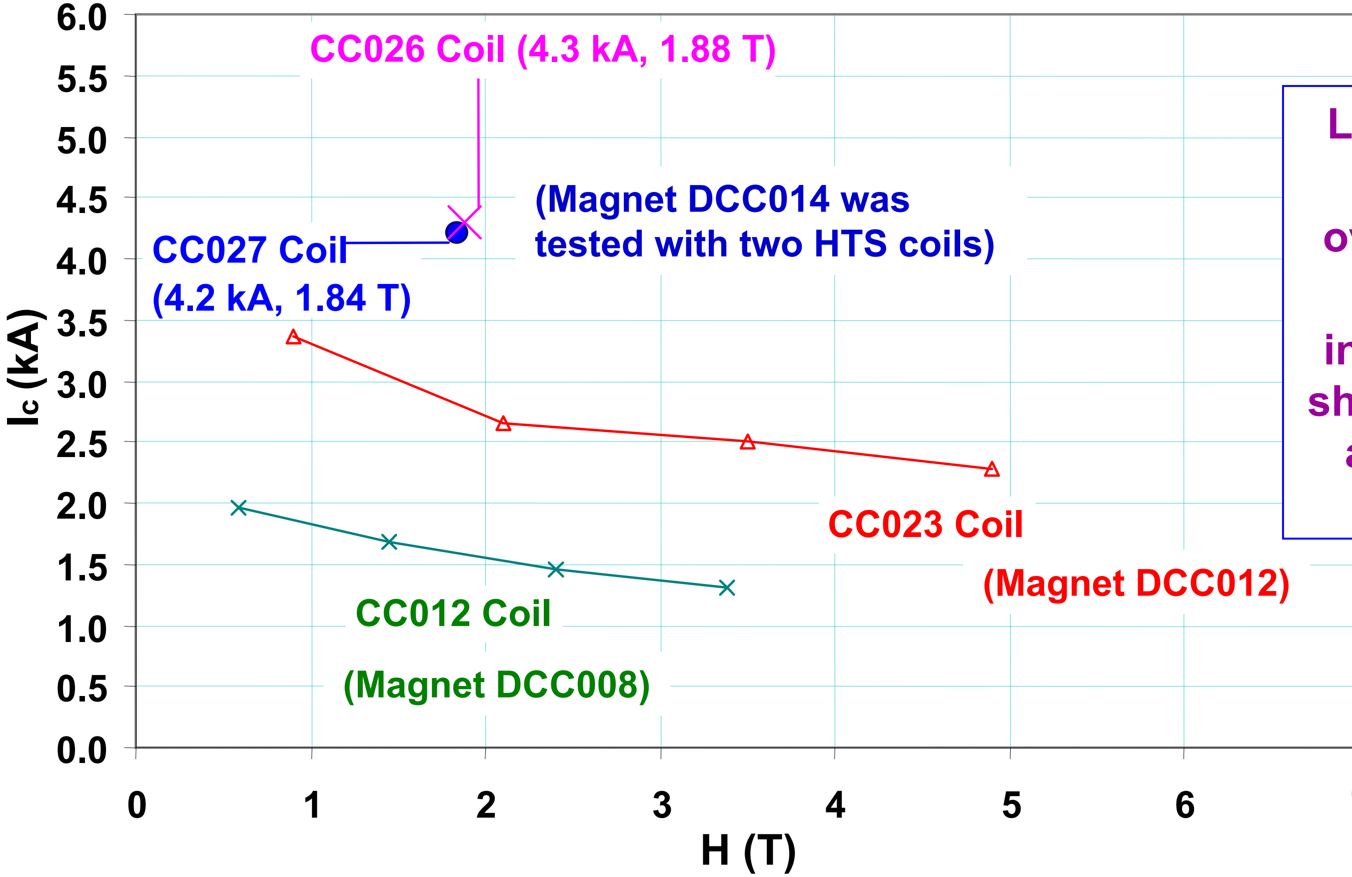
Progress in the Current Carrying Capacity of HTS Coils



Progress in the Current Carrying Capacity of HTS Coils at Higher Fields

HTS coils can now be made with the cable carrying a respectable current at higher fields (Note that the current carrying capacity does not fall much beyond 5 T).

A continuous progress is noteworthy.



Latest coils were tested for over 4 kA at ~2 T. Extrapolations indicate that they should carry ~3 kA at any arbitrary high field.

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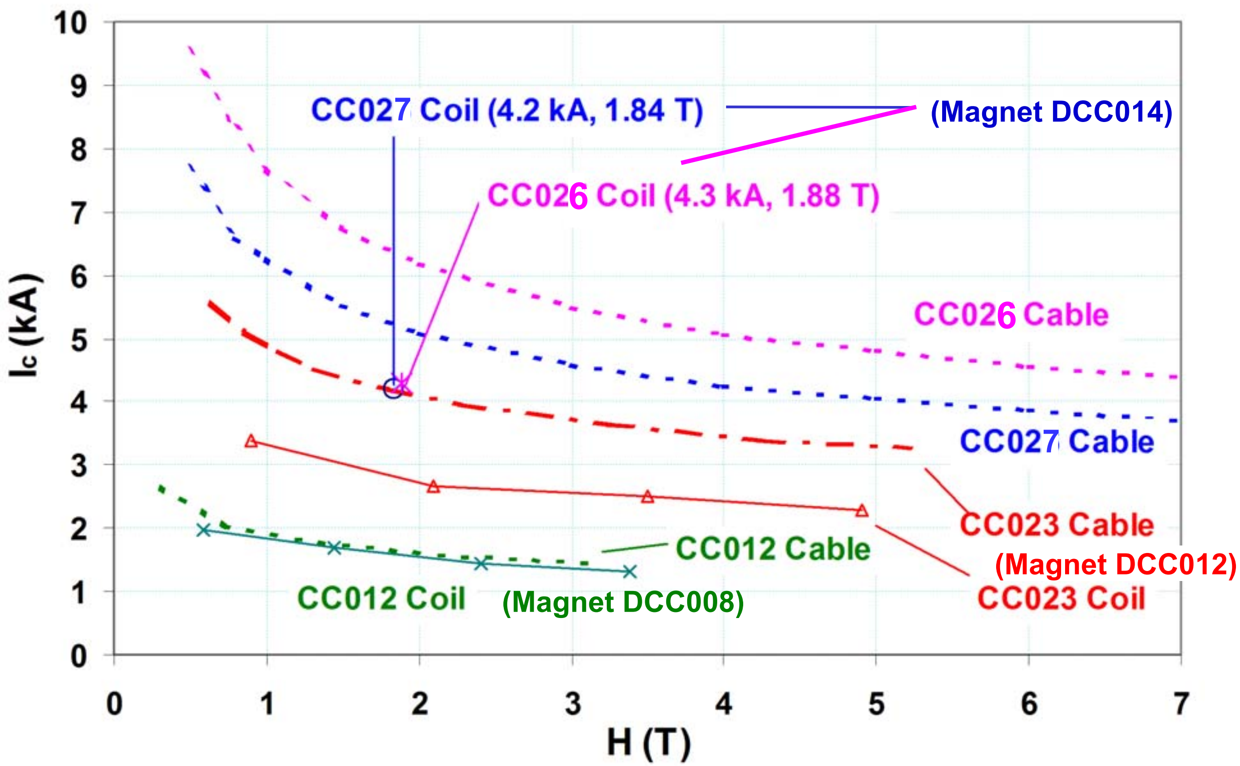
Future Potential of HTS Coils

HTS Coils in 3 Most Recent Hybrid Magnets (background field was provided by Nb_3Sn).



We have not yet obtained the same I_c in the coil as in the cable (Although Showa says it matches their expectations).

Possible Sources:

- Degradation during winding (e.g. bending strain ~1.2%)
- Non-uniformity of cable

~20% potential gain

Long cable don't have the same I_c as the short cable

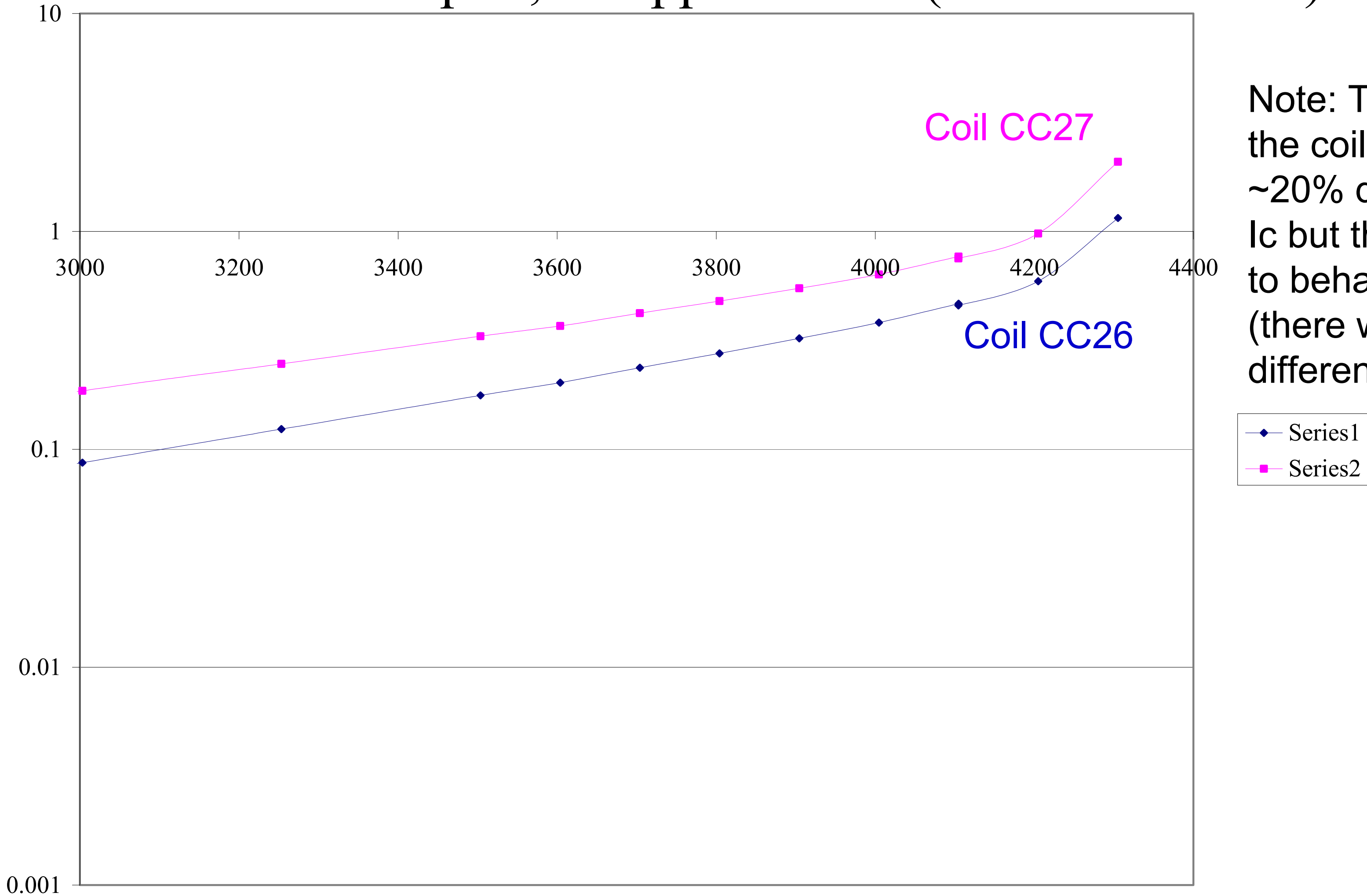
~20% more gain

The desired goal is to have a similar size cable carry ~10 kA at very high fields.

This implies a factor of ~3 improvement in the performance of the coil (about half of may come from the improvements in wire J_c and half from cable/coil).

HTS Coils CC026 and CC027

Coils tested in pair, no applied field (self field >1.8 T)



Note: The cables in the coils have ~20% difference in Ic but they seems to behave similarly (there was also difference in pitch)

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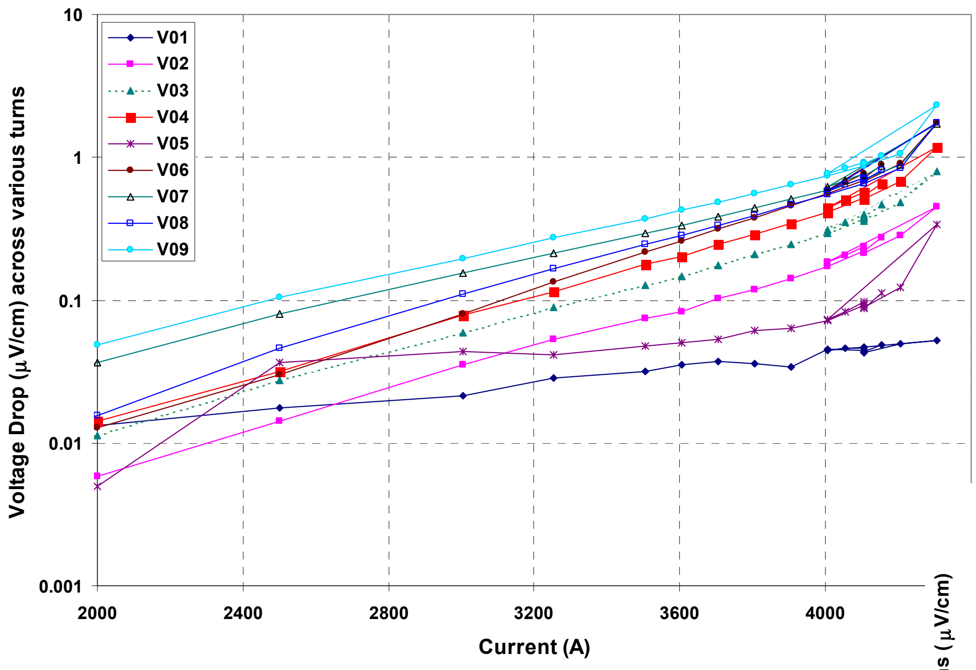
The Differences in the Performance of Individual Turns



A variation in performance of different turns.

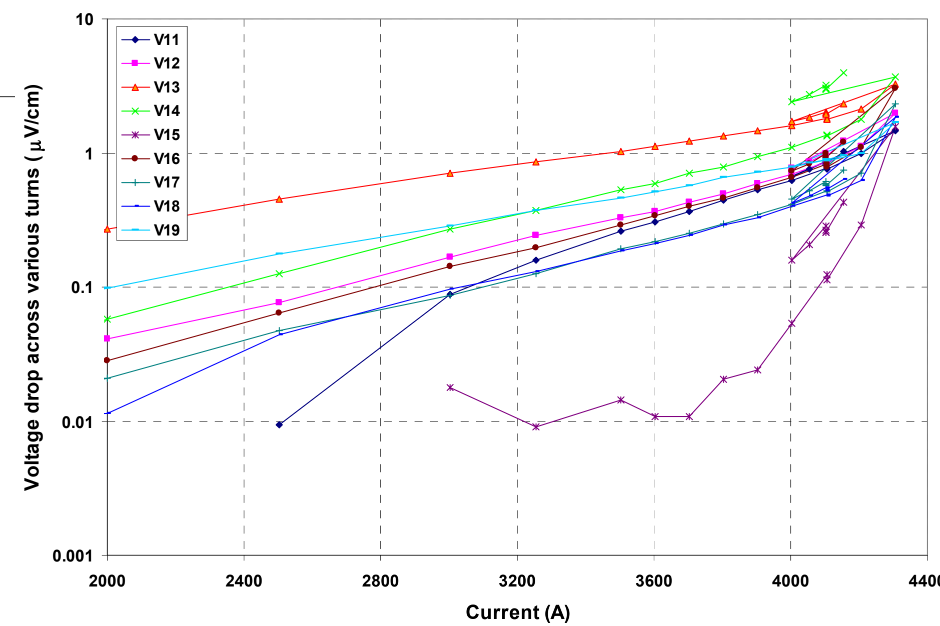
Possible causes:

- Difference in bending radius
- Difference in field
- Variation in cable Ic

Ideal performance based on short piece of cable: ~ 5 kA and ~6 kA

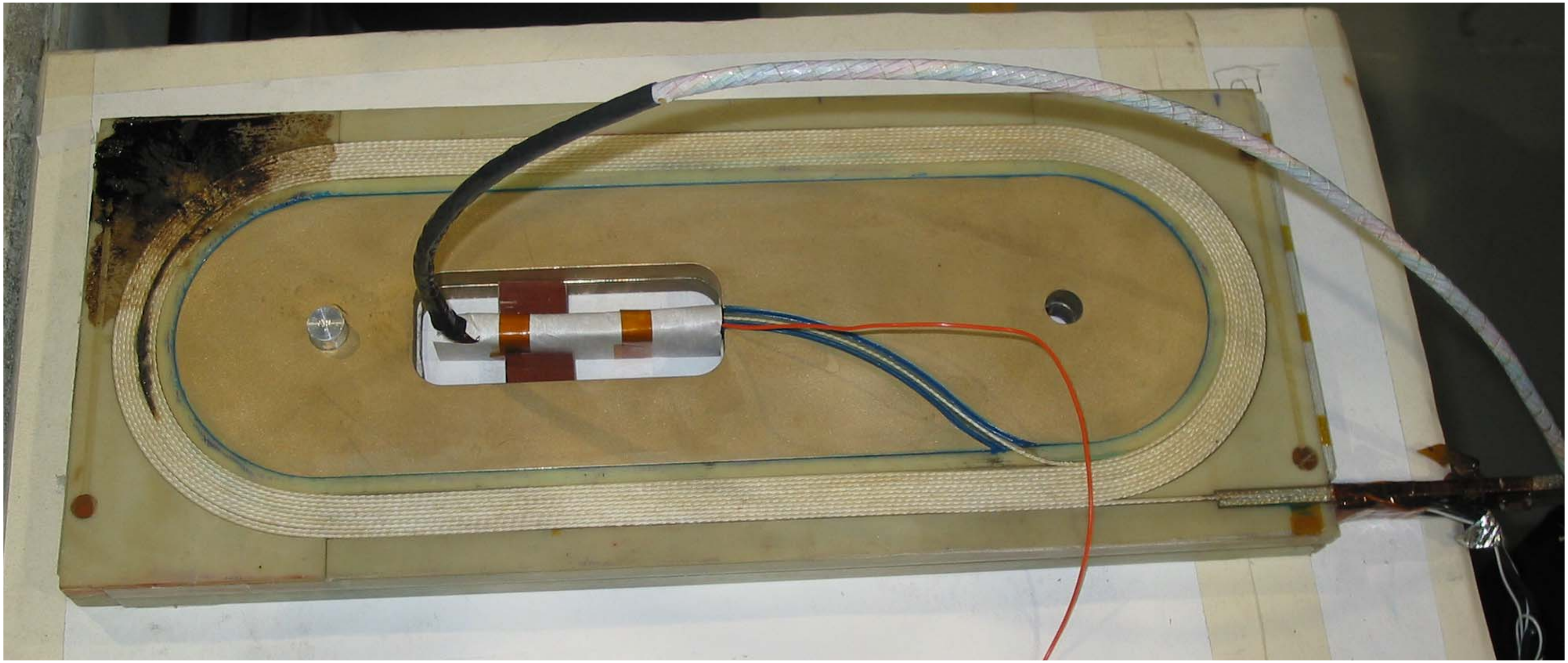
Using a long length, high performance HTS cable with 1 μV/cm may be risky.

Use lower threshold 0.5 or 0.1 μV/cm and then extrapolate (see linearity when plotted in log scale).

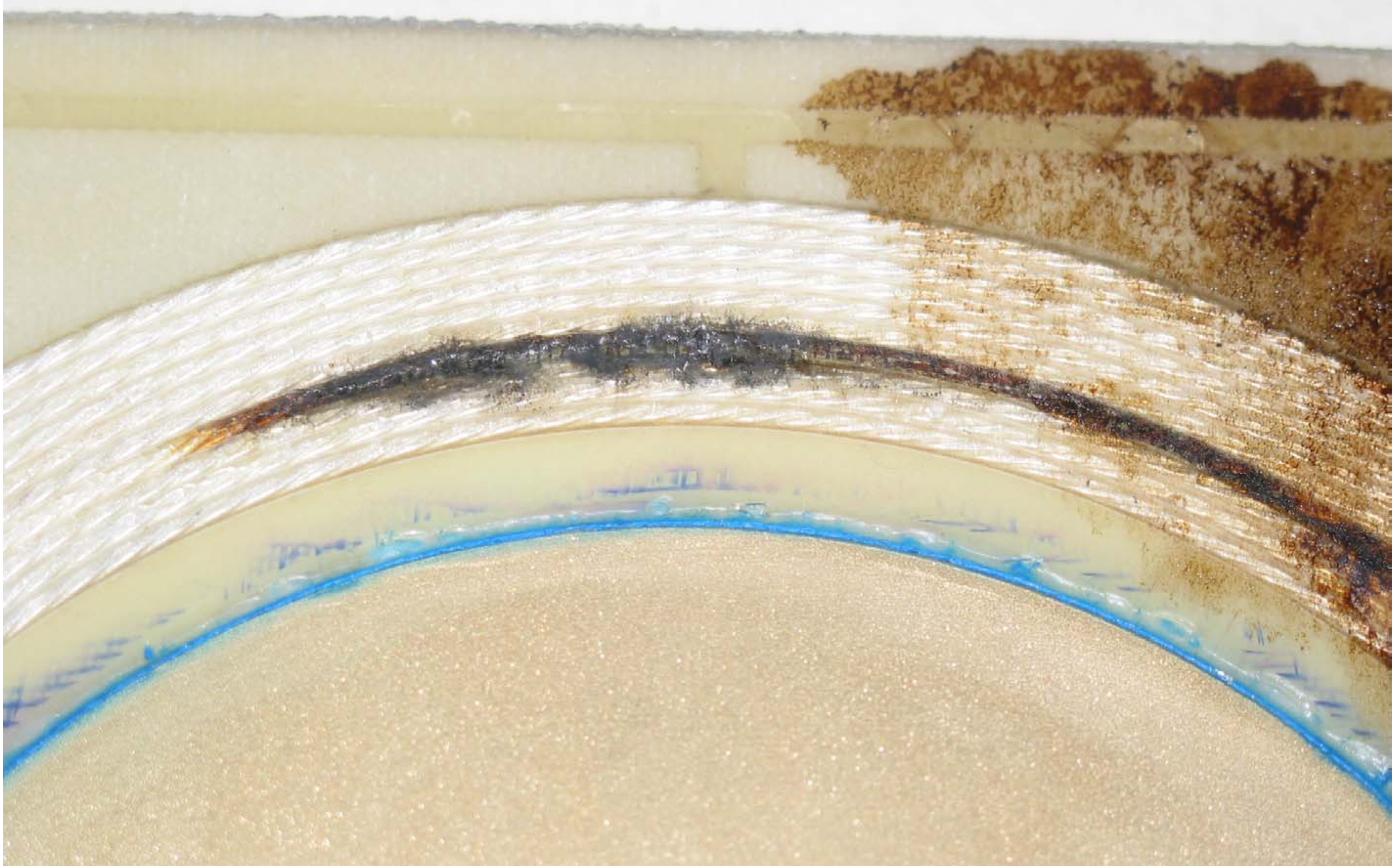


The HTS Coil After Damage

- The improvements in HTS coil performance were such that the coil did not recover after going a bit over 1 μV/cm in a small section (no good deed goes unpunished.
- The LTS type quench protection system, in place at the time of test, are not adequate to protect the HTS coils.

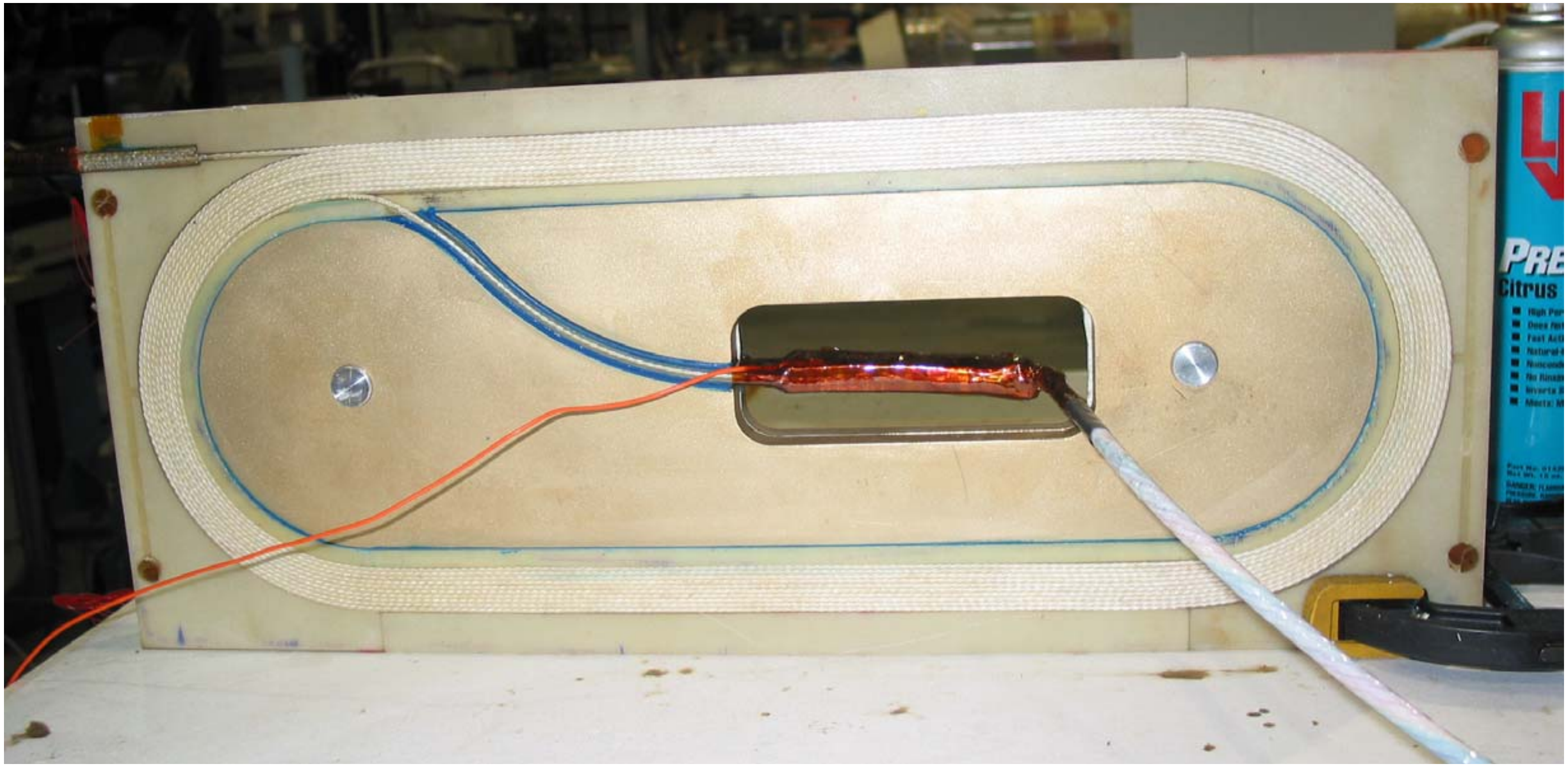


A Section in More Details



Impression on Insulation

Remember: It used to be a nice coil !



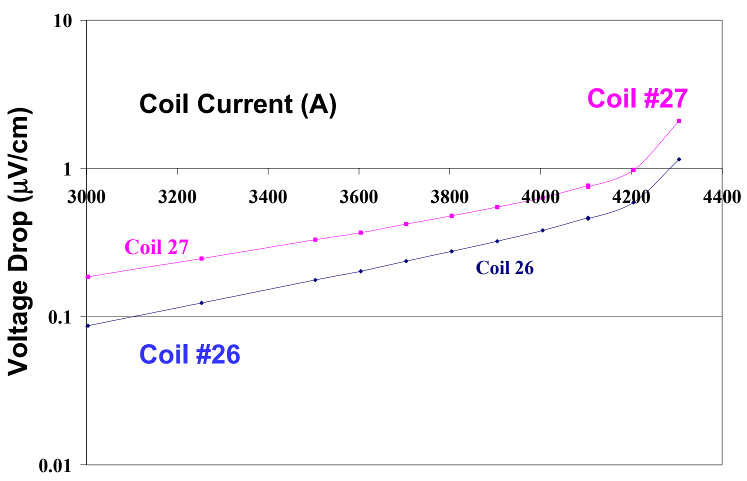
Quench Protection in Present HTS Coils

Characteristics of the present day HTS (that are different from LTS)

- **Slow transition from superconducting to normal state. For a range of operating current, the present HTS remains in a resistive state (very low resistive state).**
- **Low quench propagation velocities in HTS operating at 4K temperature.**

These properties makes the normal LTS quench detection methods unsuitable for HTS, unless modified.

→ *A preliminary plan is already developed for protecting future HTS coils.*



We need to reduce quench detection thresholds.

Moreover, for the systems that uses long lengths of HTS cables, 1μV/cm (conventional definition of I_c) is too liberal (dangerous) to operate a coil on.

Quench Protection in HTS Coils

The coil was partially burnt because we continue to operate it despite a small section going beyond 1 μV/cm. This is what we did in the past to obtain I_c (1 μV/cm definition) of some what weaker sections. All previous coils were able to recove from quench. However, because of larger current, one of these two did not. The normal quench protection was unable to protect the coil.

Significant properties of present day HTS (that are different from LTS)

- **Transition from superconducting state to normal state is slow and for a range of current the present HTS remains in a very low resistive state.**
- **The quench propagation velocity is very low in HTS.**

These properties makes the normal LTS quench detection methods unsuitable for HTS, unless modified. BNL, having built the most recent superconducting accelerator (RHIC), has a significant experience in protecting a large systems.

$\rightarrow$ A preliminary plan is already developed for protecting future HTS coils.

Quench Protection in HTS Coils (Contd.)

The situation is expected to improve in future when (like LTS):

- HTS cable has higher “n-value”
    - faster transition from superconducting state to normal state
- HTS cable is more uniform
    - absence of local “hot spot” which could have gone undetected

→ But in the mean time we need to be very careful for HTS coils made with long cable and operating at low temperature.

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Future BNL Plans with HTS

Near Term:

Continue with the cable and 10-turn coil testing to help improve performance

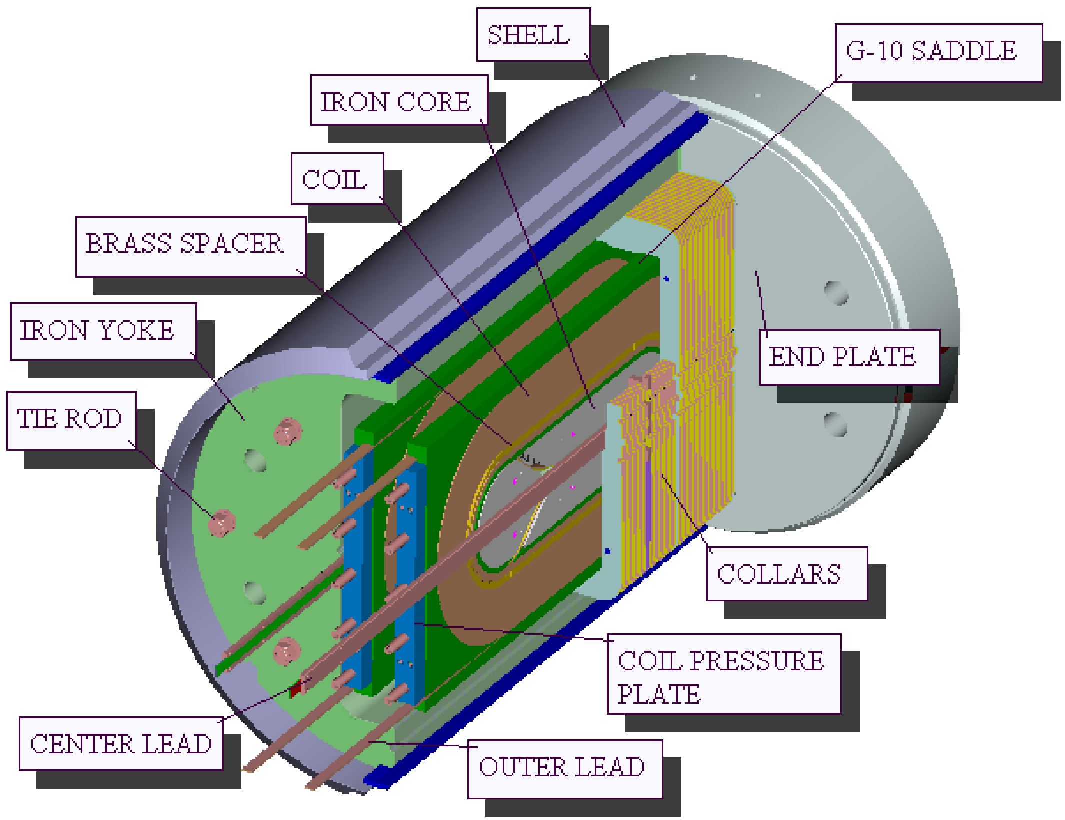
Medium Term:

Build a hybrid magnet with ~12 T from Nb3Sn coils and additional ~5 T from 40-50 turn HTS coil.

Long Term:

Build an all HTS magnet for accelerator application

Cut-away View of the 12 T Background Field Magnet



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• Discussions with Dr. Hasegawa have been very beneficial.

• Thanks to Dr. Scanlan (LBNL) for his cabling work.

• We understand that this development has possible because of the sponsorship of Chubu Electric Power Co. We appreciate their interest and support to this exciting technology.

• Thanks to a number of technical and scientific staff at Brookhaven National Lab (BNL) for their expert contributions in various areas. We hope this collaboration is mutually beneficial.

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 HTS coils have made significant progress in a relatively short time -- thanks in a large part to Showa**
  - Now it appears more likely that it can be used in accelerator magnets
  - However, there is a still room for improvement
- **We appreciate a productive collaboration with Showa**
  - There are many areas where we continue to work together and to help advance state-of-art.