Status of High Temperature Superconductor Magnet R&D at BNL

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HTS R&D Program at BNL

- Test HTS tapes, wires and cables.
- Build and test coils made with HTS tapes and HTS cables.
- Develop accelerator magnet designs that can use HTS.
- Material science R&D for understanding and developing HTS.

The primary focus of this presentation will be on the recent test results with HTS cables and the coils made with them.

We have been carrying out these activities for ~5 years.

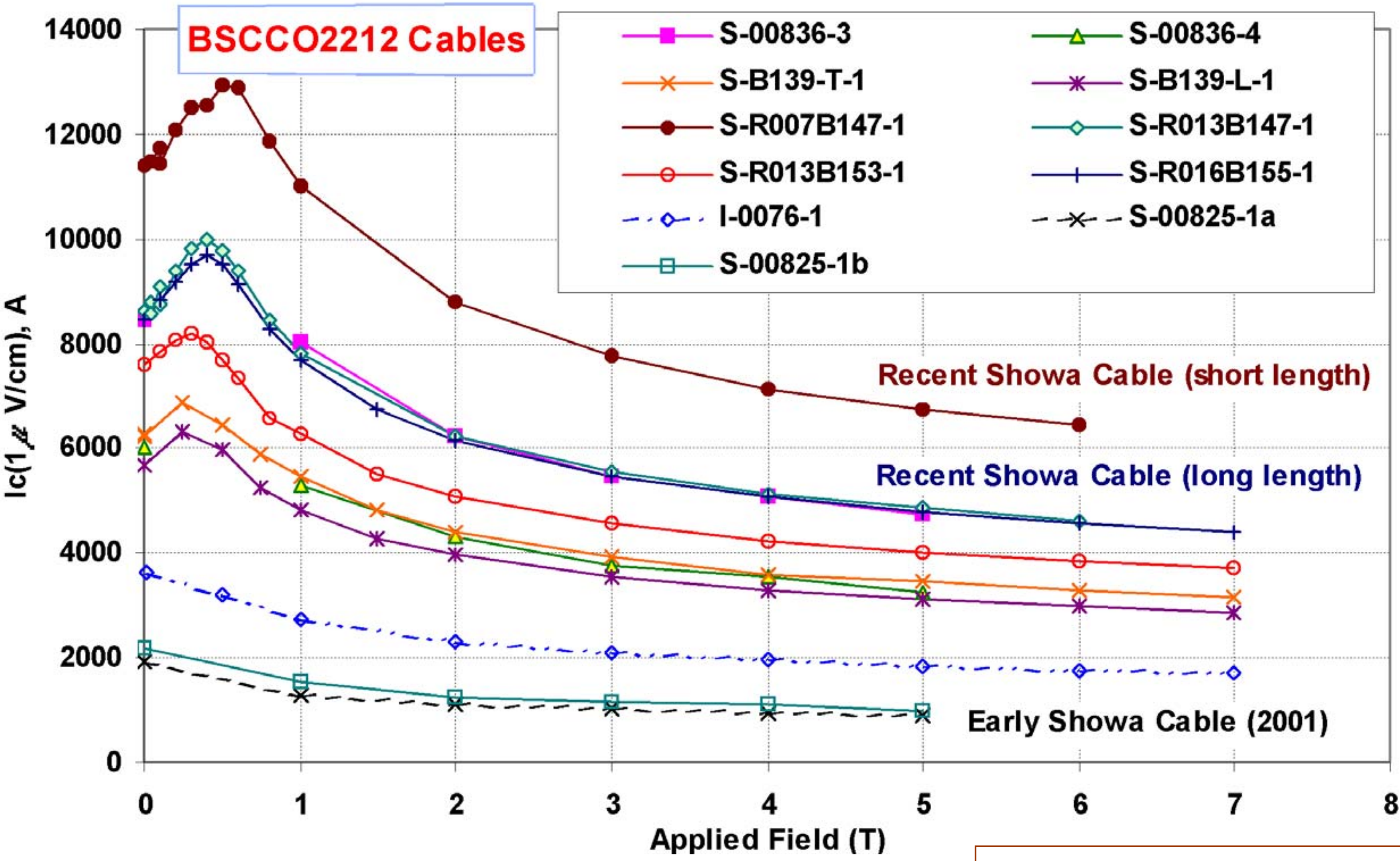
Acknowledgements

- Most pre-reacted wires and cables for this R&D were provided by Showa Electric Wire & Cable Corporation, Japan.

- BSCCO 2212 development at Showa is sponsored by Chubu Electric Power Co., Japan. We appreciate their interest and support to this exciting technology.

- Most cables used in this R&D were made at Lawrence Berkeley National Laboratory (LBNL), USA.

HTS Cables: A Remarkable Progress



Significant self-field at high currents.

HTS Cables Tested at BNL Short Sample Test Facility

Modern HTS Cables Carry A Significant Current.

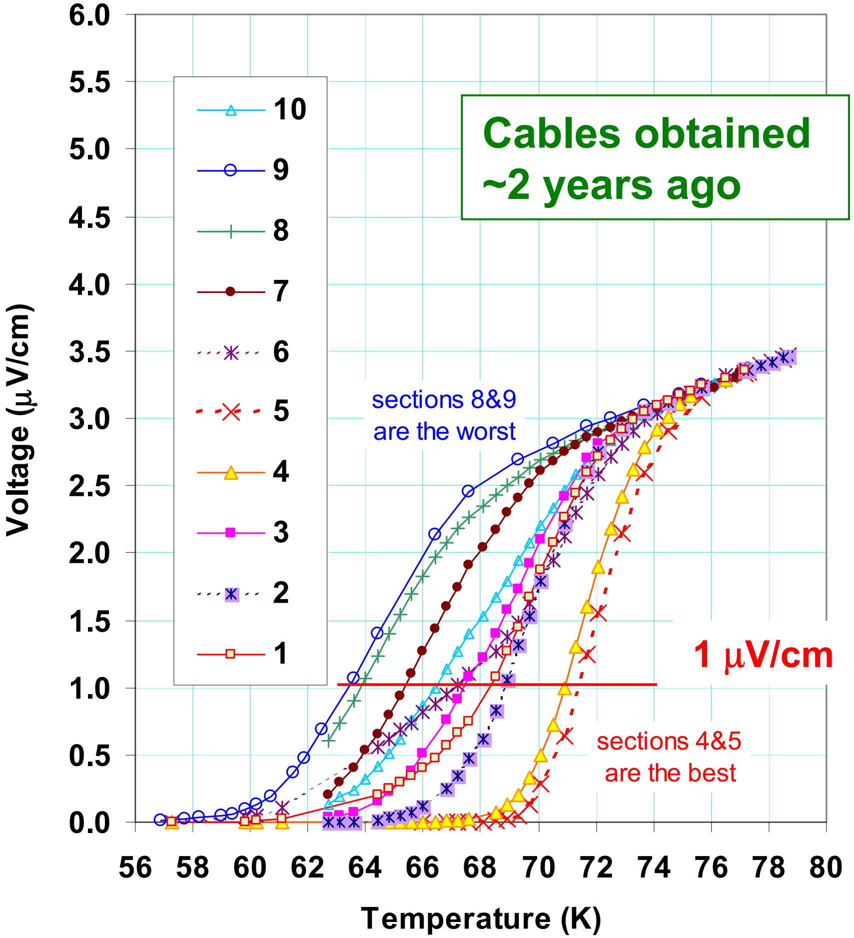
Talk by Dr. Hasegawa (Showa), Thursday (4C-p07).

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

Cables made at LBL.

Improvements in the Uniformity of the HTS Cables

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

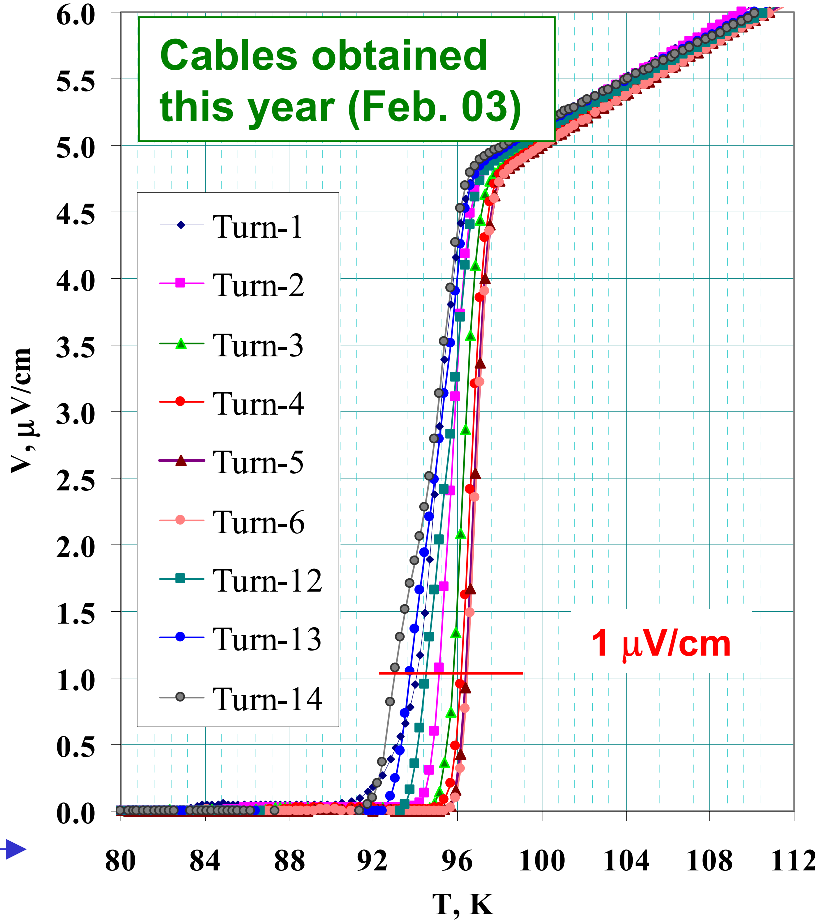


Cables obtained ~2 years ago

sections 8&9 are the worst

1 μV/cm

sections 4&5 are the best



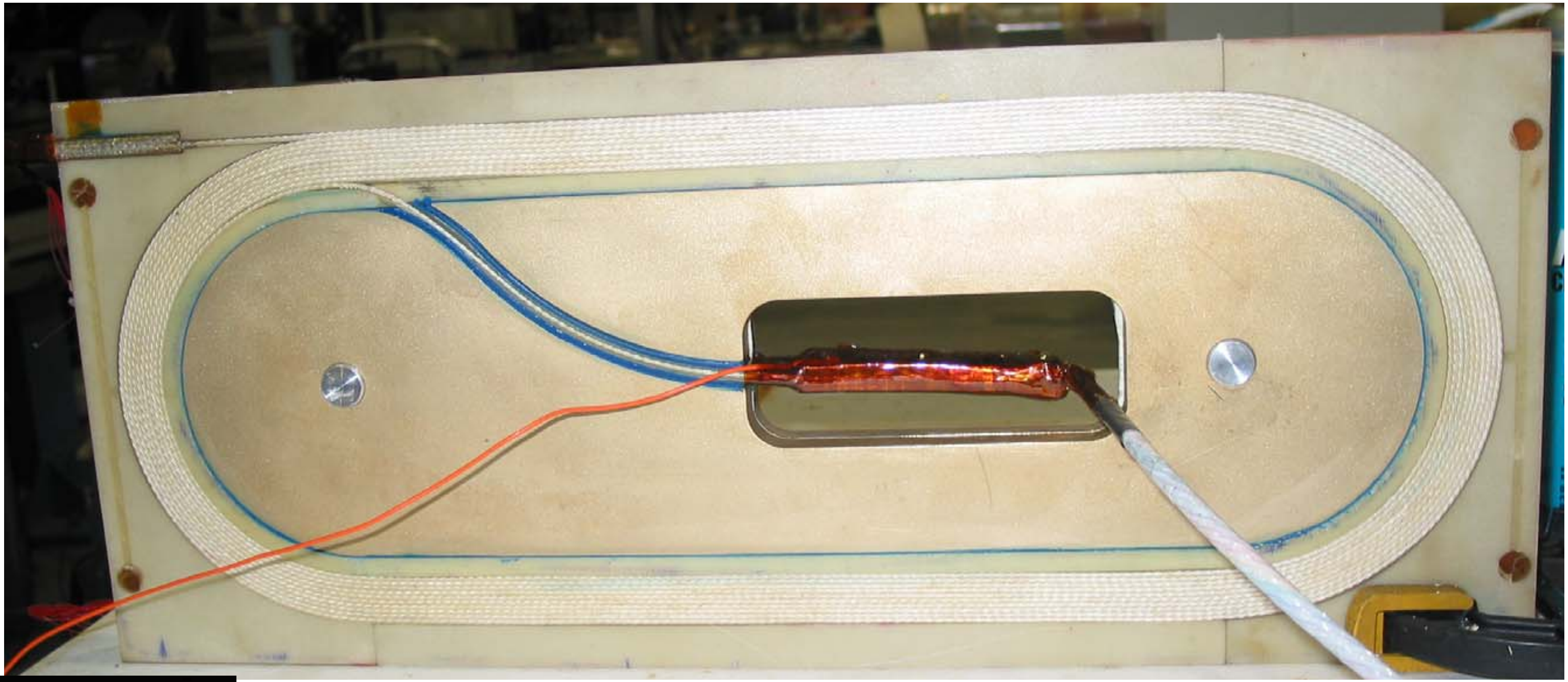
Cables obtained this year (Feb. 03)

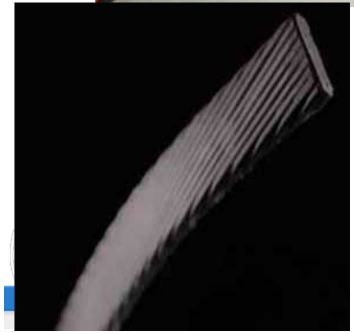
1 μV/cm

Similar improvements in I_c (increase in value and decrease in variation).

HTS Coil for Accelerator Magnets

We use “Rutherford cables” in “conductor friendly” accelerator magnet designs using “racetrack coils” and “React & Wind technology”.





A 10-turn racetrack R&D coil recently built and tested at BNL.

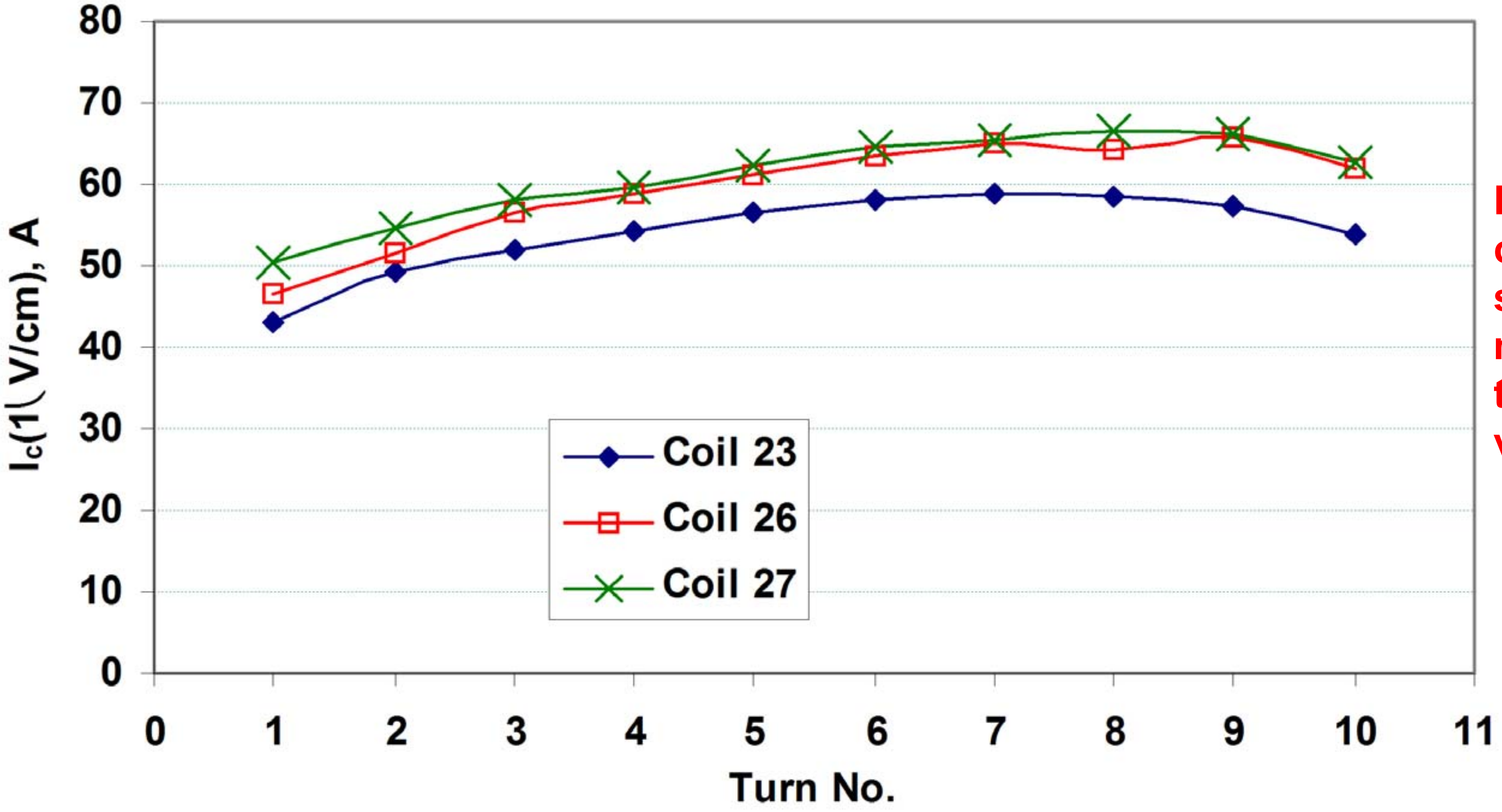
Minimum bend radius 70 mm; Cable thickness ~1.6 mm.

Bending strain 1.4% or 0.7% depending on whether the wires in the cable are sintered or not.

77K Test Results of HTS Coils Made at BNL

(Measurements of I_c of individual turns with V-taps pre-installed)

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



Earlier HTS coils showed a much larger turn-to-turn variations.

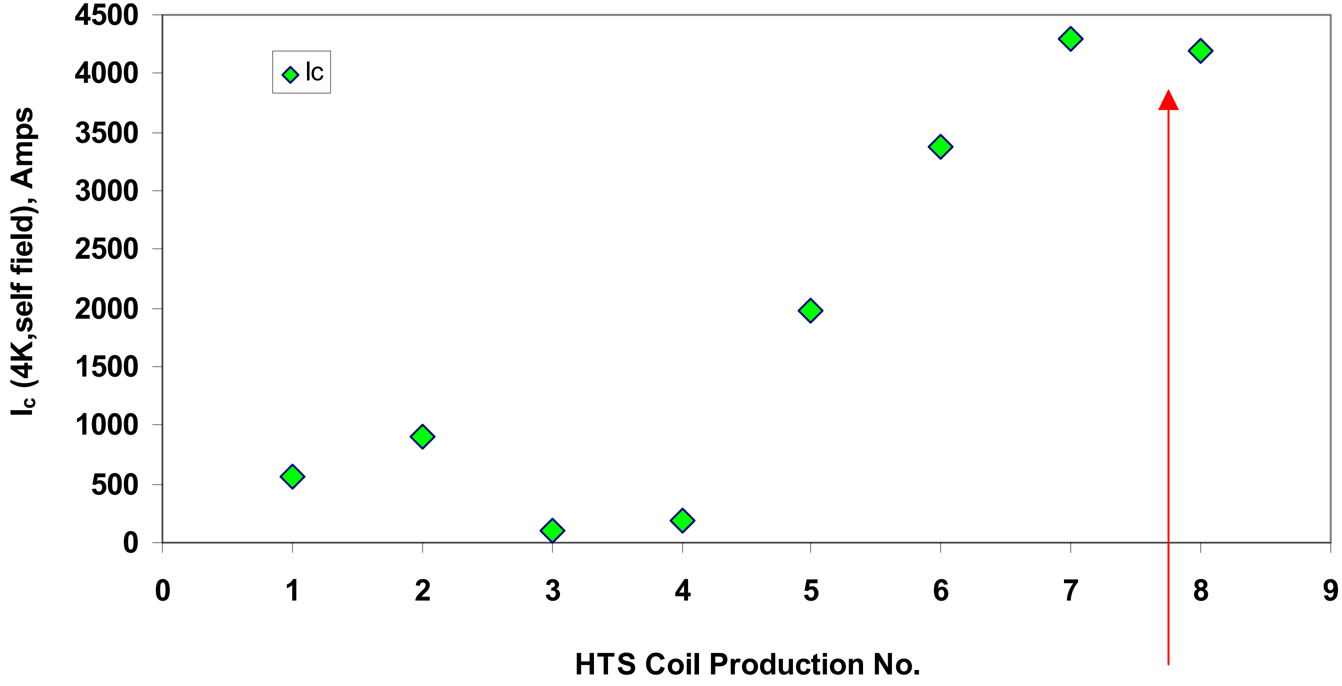
Liquid Nitrogen (63-77K) tests are inexpensive and useful Quality Assurance (QA) method - something unique to HTS.

4.2K Test Results of HTS Coils

Earlier coils
<1 kA (~2001)

Latest coils
4.3 kA (10/03)

Measurements in self-field



Self-field
<0.05 T

Self-field
~ 1.85 T

Note:

HTS cables now carry significant currents in magnet coils.

TABLE II

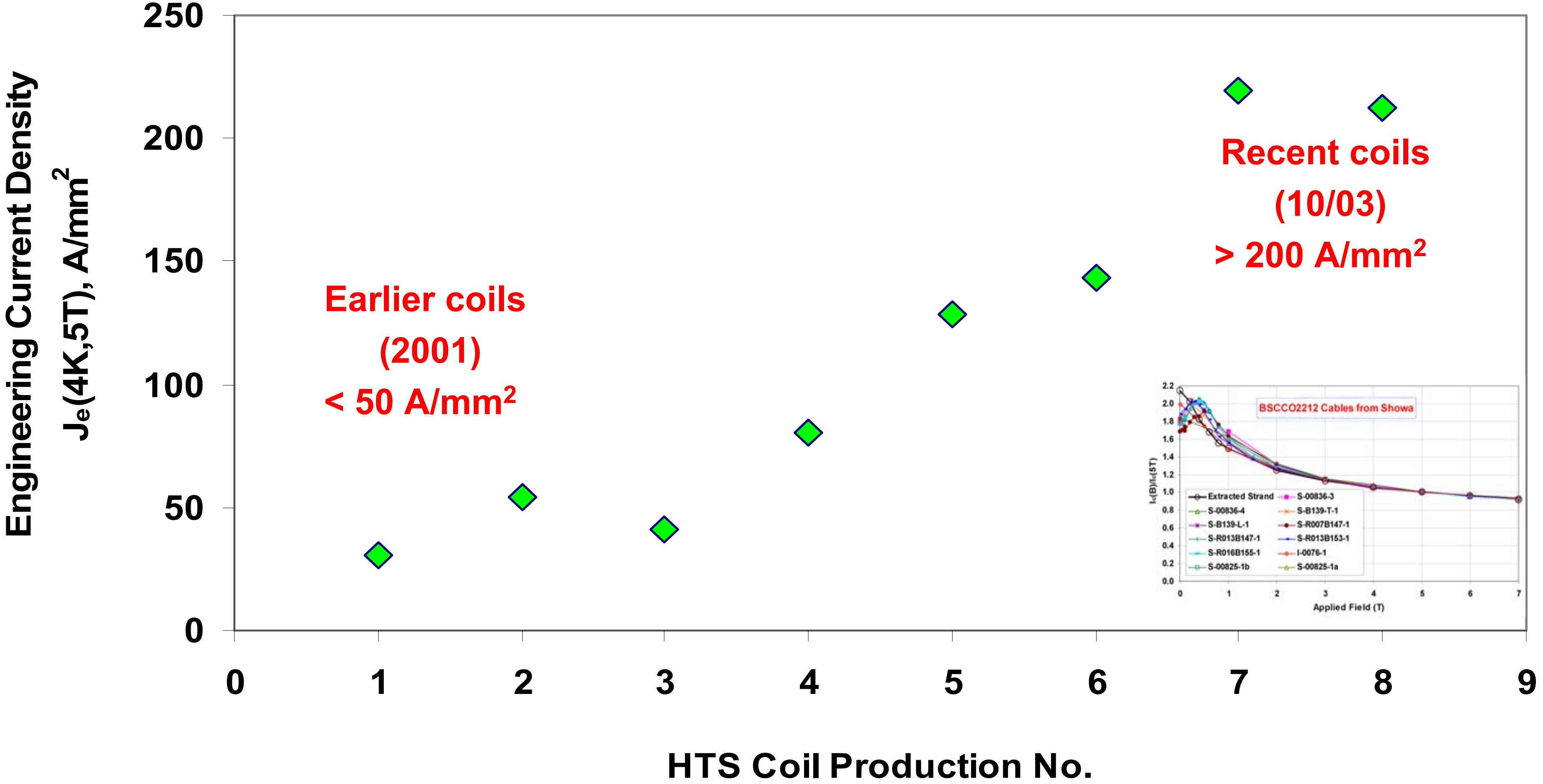
COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. I_c IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

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 Common coil configuration	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands		900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	2 HTS coils (mixed strand) 74 mm spacing Common coil	94	91 [41]	0.023
CC011 DCC006	0.81 mm wire, 2 HTS, 16 Ag		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 2 HTS, 4 Nb_3Sn coils (total 6 coils)	4300	278 [219]	1.89
CC027 DCC014	0.81 mm wire, 30 strands		4200	272 [212]	1.84

Test Results of HTS Coils at 4K Normalized at 5T

Self-field measurements, <u>normalized at 5 T</u> (small change in J_e at higher fields).

Note the progress in the Engineering Current Density in HTS Cables.

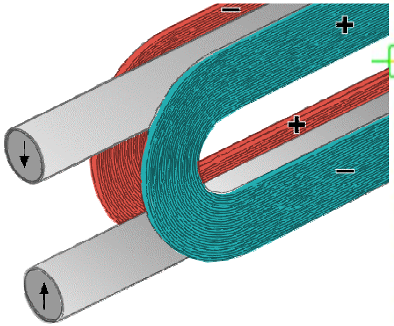


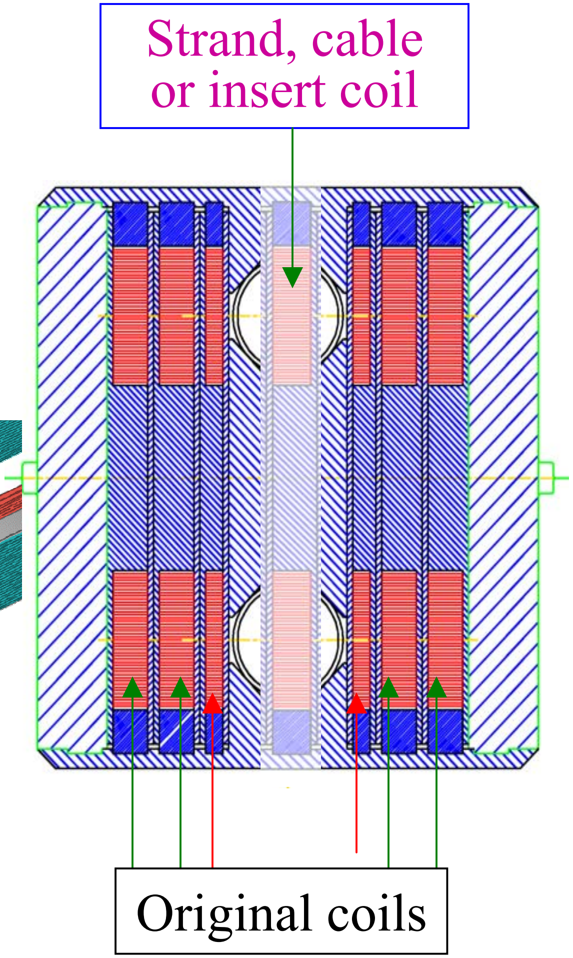
Earlier coils
(2001)
< 50 A/mm^2

Recent coils
(10/03)
> 200 A/mm^2

Test Results at Higher Fields Using the Common Coil Magnet as the Background Field Test Facility

Common coil design



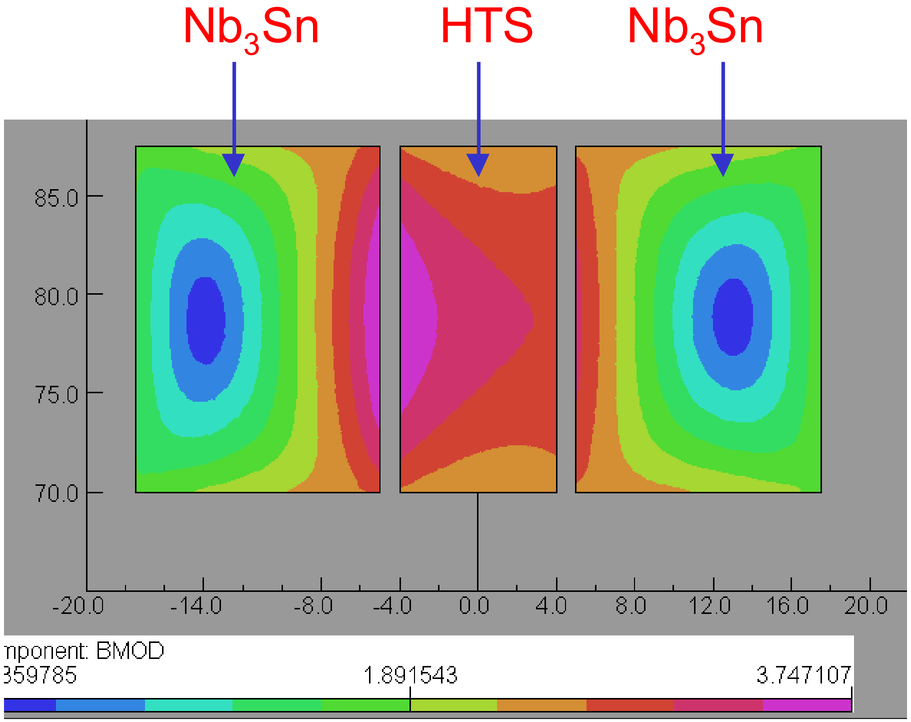


Strand, cable or insert coil

Original coils

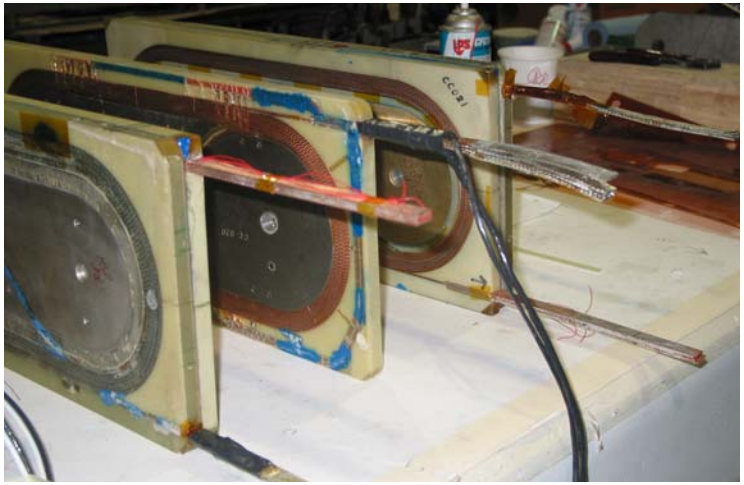
Background field test configuration

Field in various coils

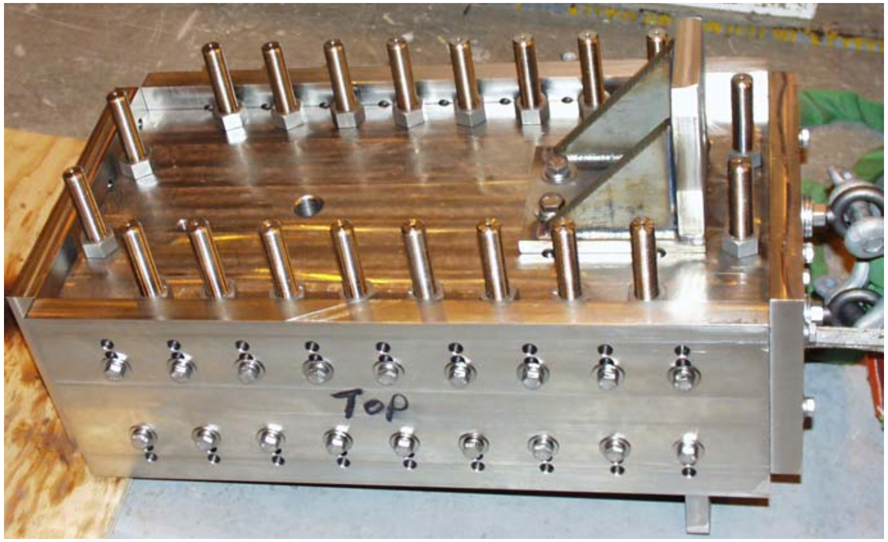


Nb_3Sn coils provide a background field on HTS coil in a common coil hybrid design

An Example of HTS Coil in a Hybrid Magnet Structure



We make racetrack coils as the modular component. These modules (cassettes) can be mixed and matched in a common coil magnet structure for a variety of experiments with a rapid turn around.

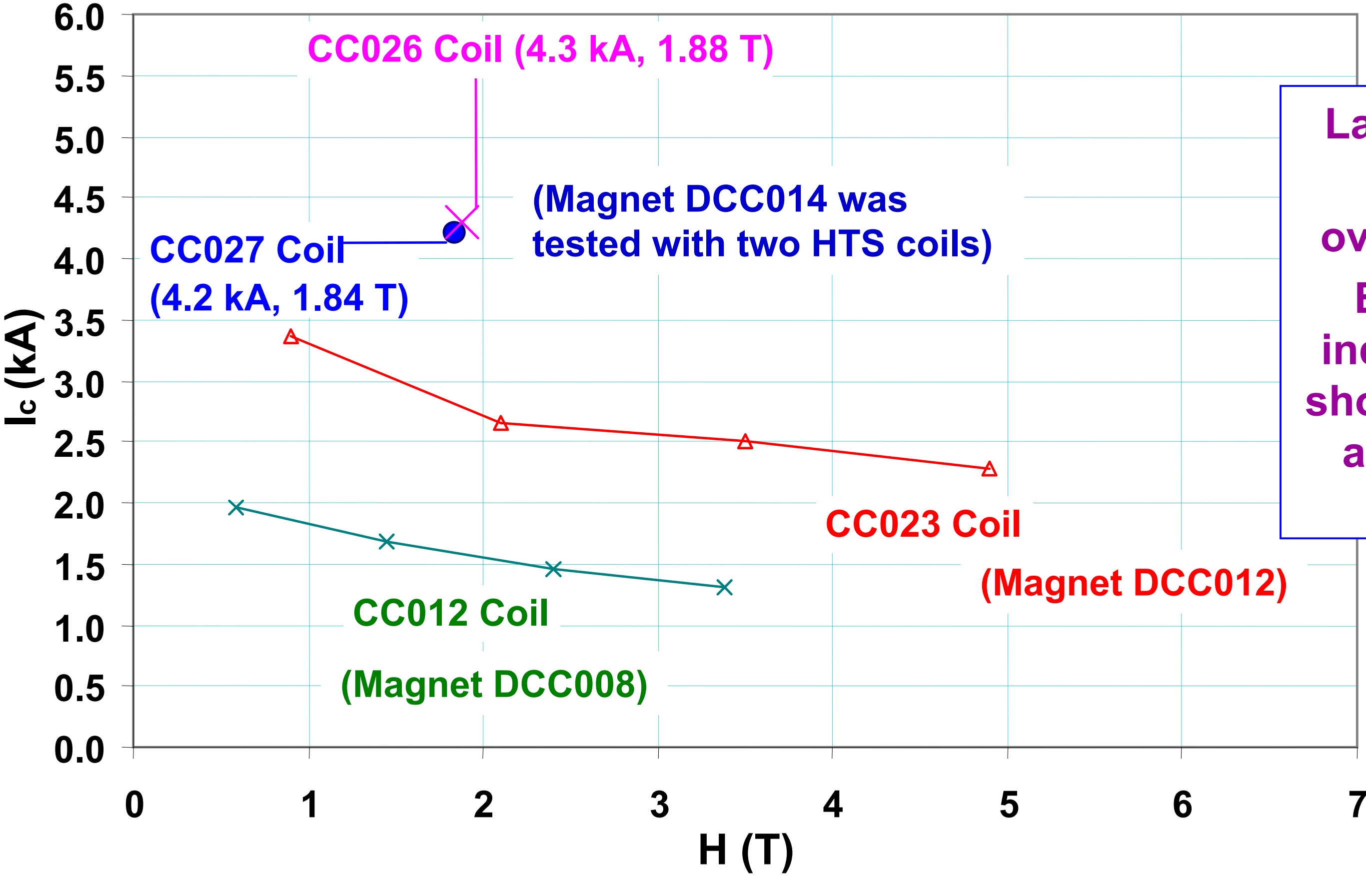


- A versatile support structure that can accommodate up to six coils. The width of the coils need not be the same.
- The structure has been used for hybrid magnet with the number of HTS coils from 1 to 2 and Nb_3Sn coils from 2 to 4.
- Nb_3Sn coils provide adjustable background field on the HTS Coils.

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.



CC026 Coil (4.3 kA, 1.88 T)

(Magnet DCC014 was tested with two HTS coils)

CC027 Coil (4.2 kA, 1.84 T)

CC023 Coil

(Magnet DCC012)

CC012 Coil

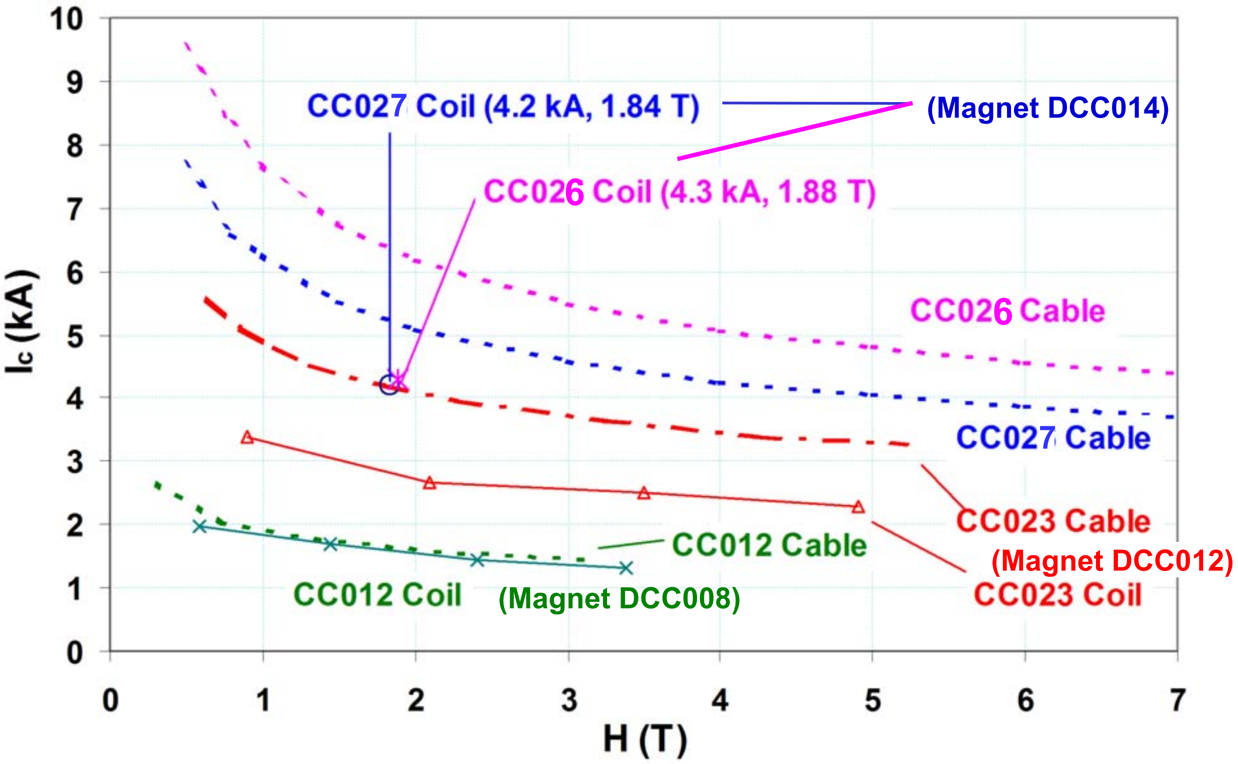
(Magnet DCC008)

Latest coils were tested for over 4 kA at ~2 T.

Extrapolations indicate that they should carry ~3 kA at any arbitrary high field.

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).

A Damaged HTS Coil in DCC014

The background field test could not be performed in DCC014 as one of the two HTS coils was damaged (burnt-out) during the test after two quenches.

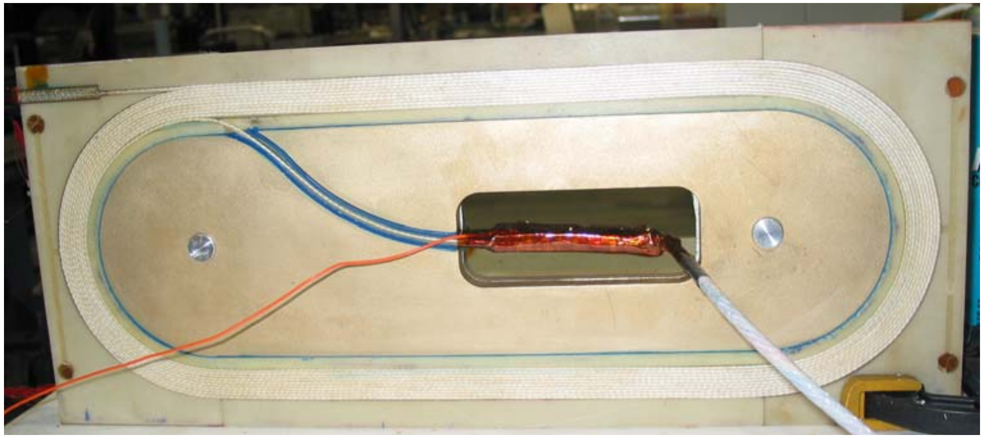
The quench protection (as used in LTS coils) was unable to protect the high performance HTS coil.

We had continued to operate the coil despite a small section going beyond 1 μV/cm. This is what we have done in the past to obtain I_c (as per 1 μV/cm definition) of some what weaker sections.

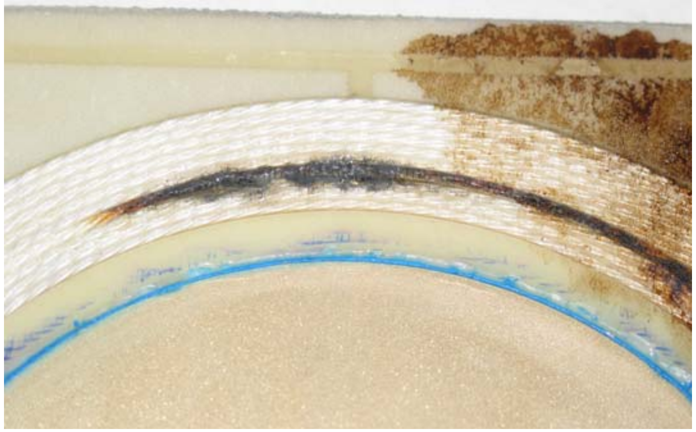
All previous coils were able to recover from the quench.

However, this time perhaps because of 50% higher operating current, one of the two coils did not recover. No good deed goes unpunished!

Before Test



After Test



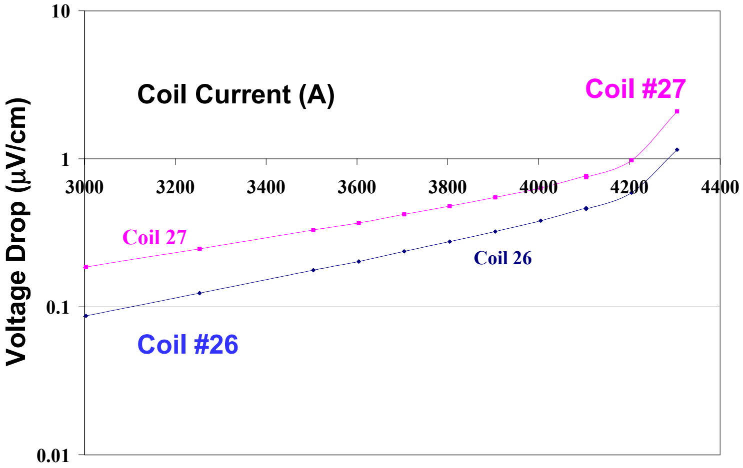
Quench Protection in Present HTS Coils

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 Future HTS Coils

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

has higher “n-values”

- □ faster transition from superconducting state to normal state

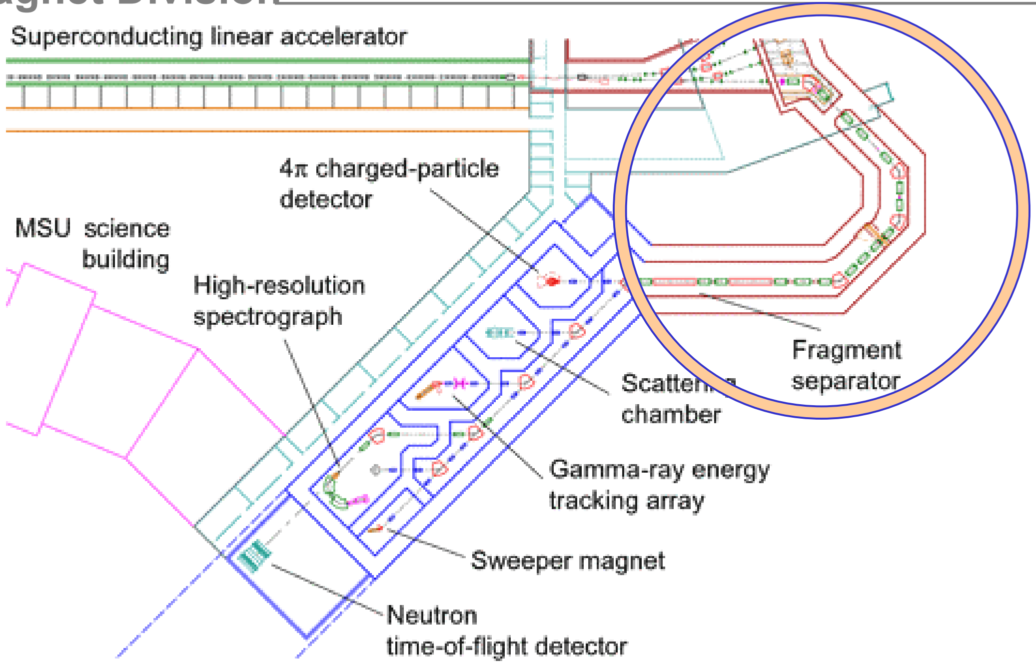
becomes more uniform

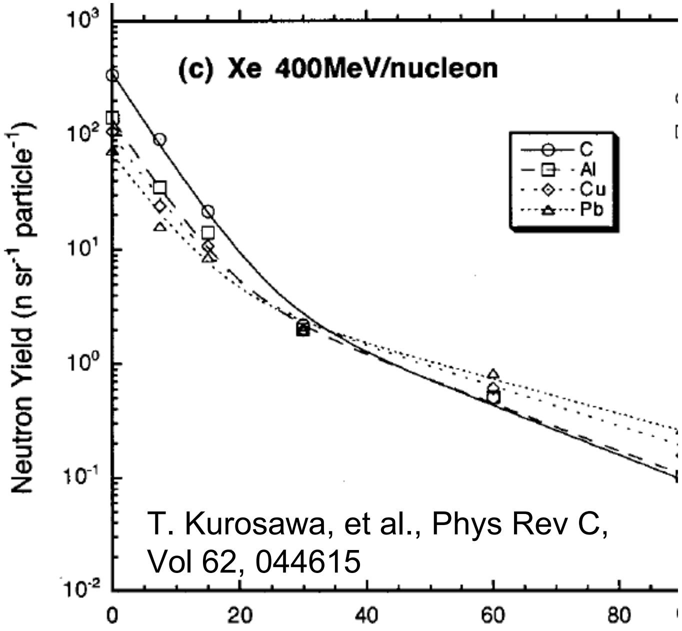
- □ absence of local “hot spot” which could have gone undetected

→ But in the mean time we need to be careful. In particular, when using long lengths of high performance cable in a system operating at 4 kelvin.

HTS Quads for Rare Isotope Accelerator

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



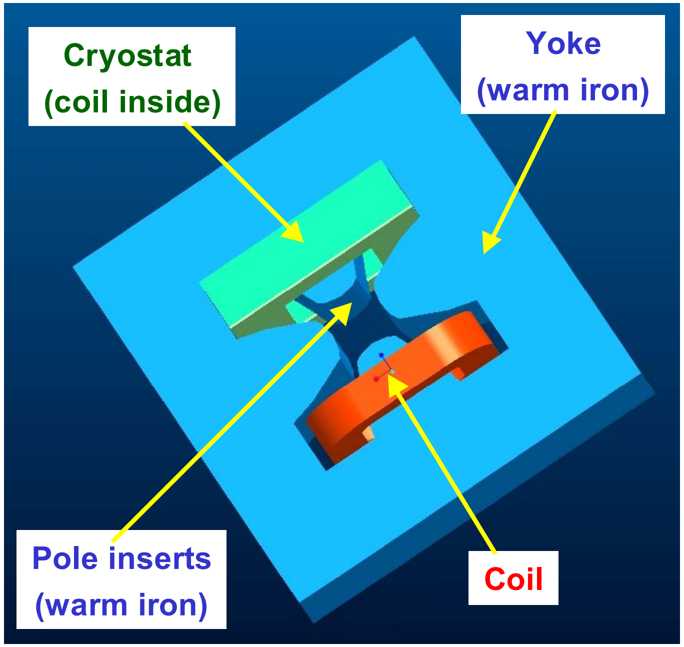


T. Kurosawa, et al., Phys Rev C, Vol 62, 044615

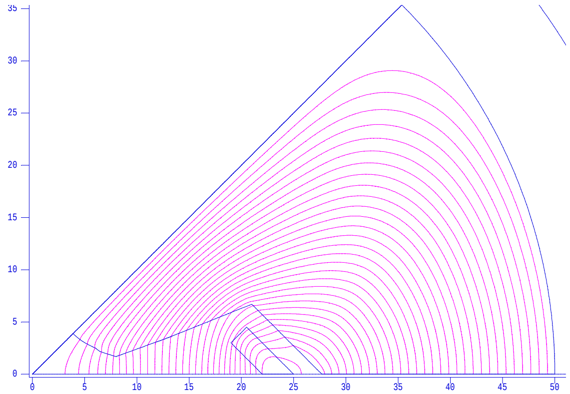
- ➢ Beam loses 10-20% of its energy (several hundred kW) in the production target. This produces several kW of fast neutrons with yield peaking strongly at the forward angle.
- ➢ Quads are exposed to very hostile environment with a level of radiation (10^{19} neutrons/cm^2 in 0^o to 30^o region) and energy deposition (15 kW in the first magnet) never experienced by any magnet system before.

Need *“radiation resistant”* sc magets, that can withstand large heat loads.

HTS QUAD for RIA Fragment Separator



Coils inside the cryostat at the end of the magnet



Requirements: ~3 T field, operating at >20K.

✍ Can be achieved with the commercial HTS.

- HTS Quads can operate at a higher temperature (20-40 K instead of 4K). Higher operating temperature makes large heat removal (few hundred kW) more economical.
- In HTS magnets, the control of operating temperature can be relaxed by an order of magnitude. This simplifies cryogenic system.
- 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.
- Insulation is a major issue. We plan to use stainless steel which is radiation resistant.

Influence of Radiation Damage on HTS

A relatively small and controlled dose of radiation brings enhancement in J_c from radiation.

However, given the amount of dose relevant to this application, J_c is expected to go down. Need to determine that experimentally, even though the design is optimized to minimize the effects.

S. Tönies et al. / Physica C 341–348 (2000) 1427–1430 1429

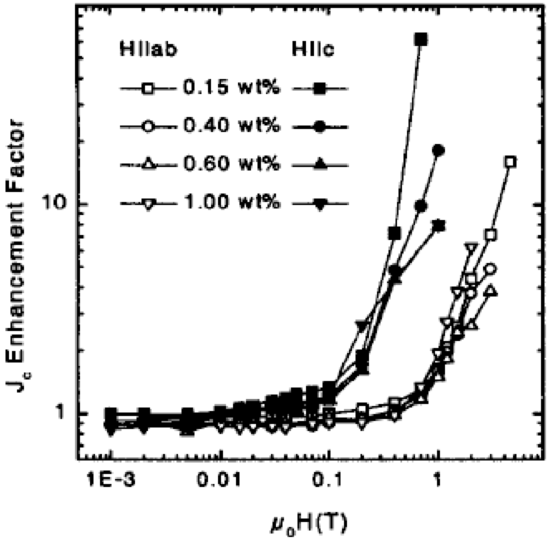


Figure 2. Enhancement of the critical current densities for samples with different amounts of uranium at 77 K, but at fixed track density.

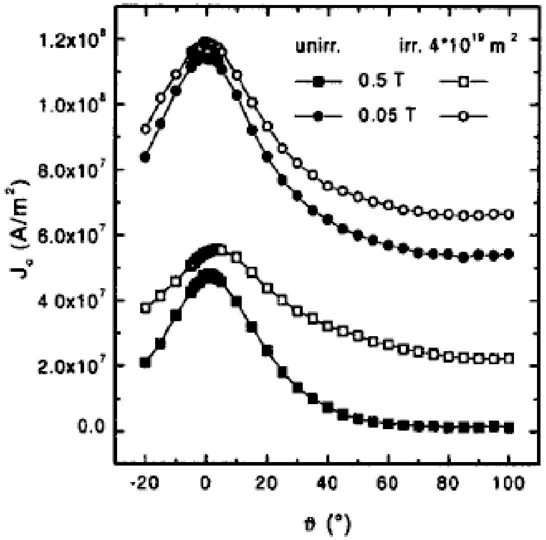


Figure 3. Anisotropy of J_c before and after irradiation to $4{*}10^{19}$ m^{-2} at 77 K and 0.5 T.

Need to study radiation damage on HTS from a large dose (few kW) of ~500 MeV neutrons.

This study is a part of NSCL/BNL collaborations.

SUMMARY

- HTS cables and HTS coils have made significant progress. They have been shown to carry a respectable current in magnet coils (~ 4 kA).

- Quench protection of HTS coils will be somewhat different than that used for LTS coils. More R&D is needed.

- HTS offer unique opportunities in the “high field low temperature” and “low field high temperature” applications.