BNL Experience with HTS and Future Possibilities

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

HTS in Accelerator Magnets

Only a decade ago, HTS in leads was considered a material of large potential benefits for special applications. Now it's being used regularly when required. To some extent, the HTS today offers similar potential for specialty magnets.

Wire is now available in lengths that is sufficient to make accelerator magnets

- BNL recently purchased wire from Showa that was 1.5 km long.

HTS wire (BSCCO 2212) now carries significant amount of current

- Even today, LHC size cable should carry ~5 kA current at high field.

… and we have made a number (14) small coils with it

- Despite being very brittle, it has been shown that it can be handled.
- So far, in the limited test, we have not seen a significant degradation.

However, for making magnets

- We need a factor of 2 (preferably 3) improvements in Jc. Also, we need to show that HTS works under high field high stress environment.

HTS Magnet R&D Program at BNL

We are developing "conductor friendly designs" for several applications based on flat racetrack coils with large bend radius. All can use HTS.

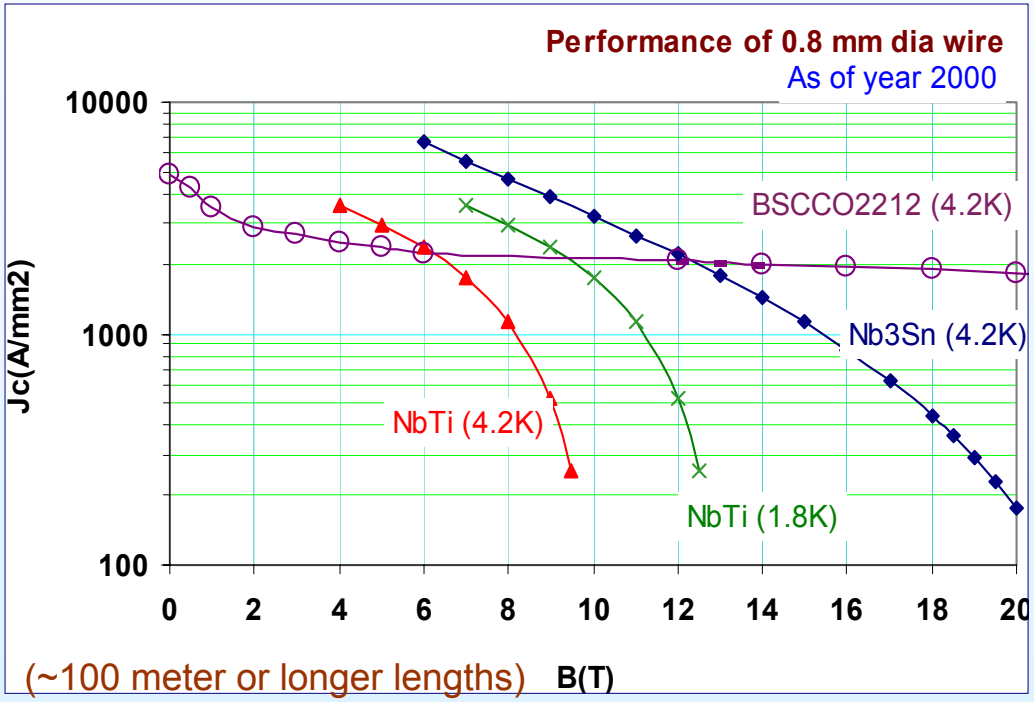
The near term goal of our R&D program is to systematically develop technology and design principle for building future HTS magnets.

10-turn coil program has been quiet successful so far. We have not seen any show stoppers in small coils at low field, low stress level.

The next step is to test these coils in high field, high stress environment. We are also going to build coils with more (~30) turns.

The longer term goal of this R&D is to show a proof of principle demonstration of the viability of HTS in high field accelerator magnets.

HTS: A High Field Superconductor



Year 2000 data for J_c at 12 T, 4.2 K

Nb_3Sn: 2200 A/mm^2

BSCCO-2212: 2000 A/mm^2

Near future assumptions for J_c at 12 T, 4.2 K

Nb_3Sn: 3000 A/mm^2 (DOE Goal)

BSCCO-2212: 4000 A/mm^2 (2X today)

Investment in 2212 has been much less than in 2223, there may be room for relatively more improvement.

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

These are quench fields, operating fields may be 10% or more lower.

Cu(Ag)/SC Ratio

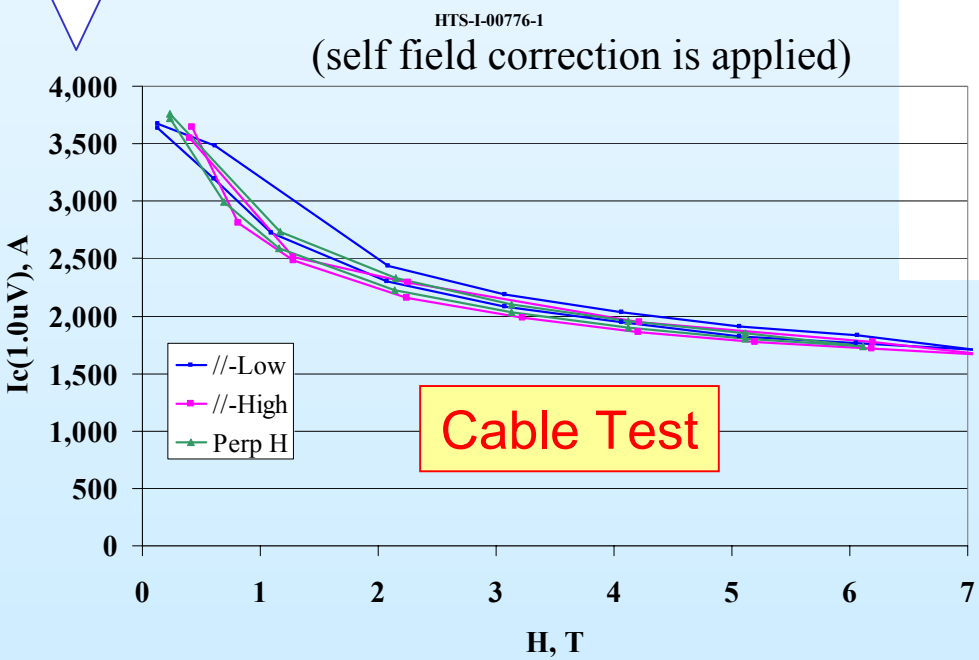
BSCCO: 3:1 (all cases)

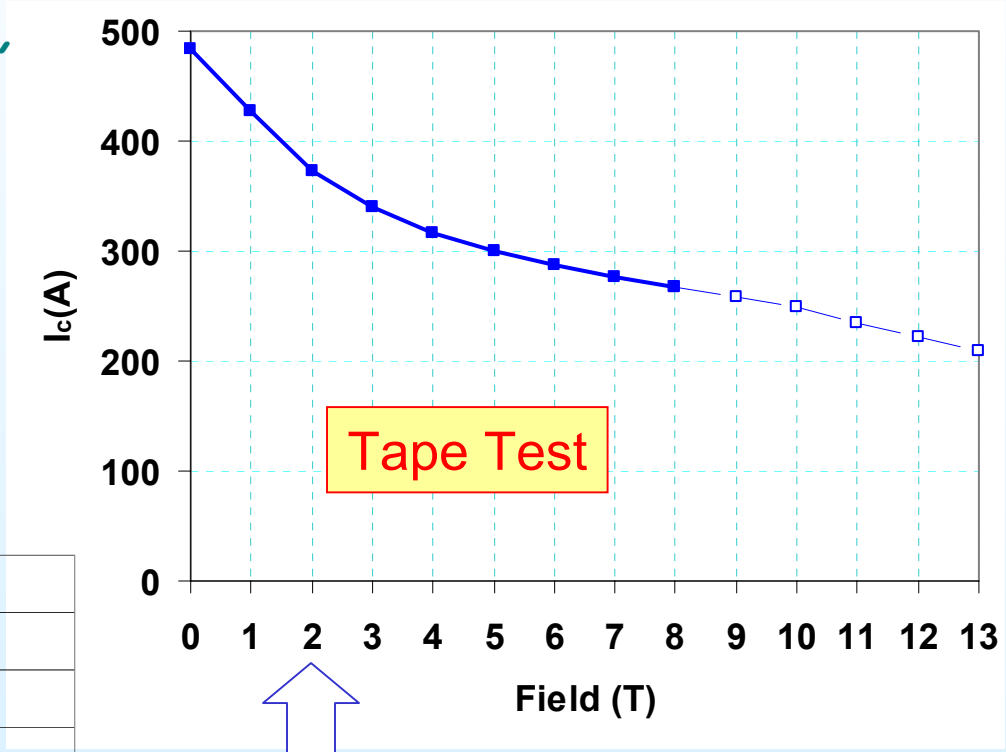
Nb_3Sn: 1:1 or J_{cu}=1500 A/mm^2

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

Measurement of "*BSCCO-2212 cable*"
Showa/LBL/BNL collaboration

Today's HTS cable can carry large currents. This was a narrow cable. LHC size cable will carry much more. Moreover, Ic is better by over a factor of two now.





Measurement of "*BSCCO 2223 tape*" wound at 57 mm diameter with applied field parallel (1μV/cm)
(field perpendicular value is ~60%)

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

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

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

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

IR Magnet Design Considerations

Differences between the IR magnets and main magnets:

- Only a few IR magnets as compared to a large number of main magnets.
- A few magnets may make a large difference in luminosity performance.
- The cost of material is a fraction of the overall cost of R&D and production.

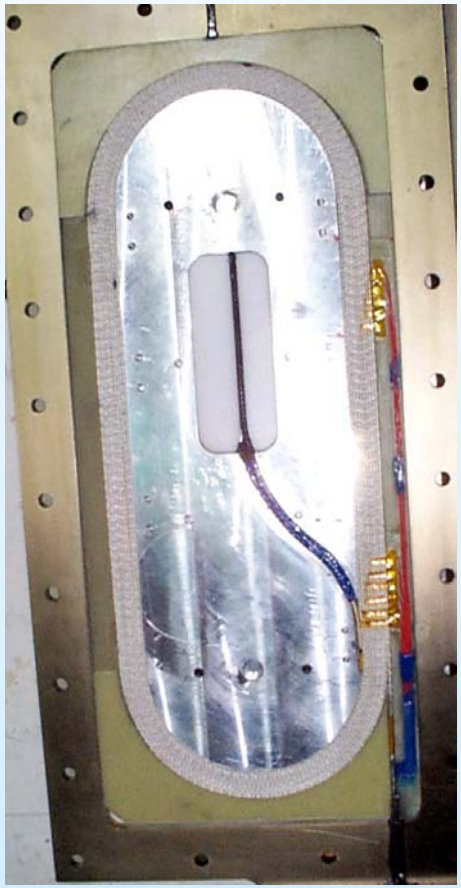
These contrasts suggest that we are open to adopting different design strategies for IR magnets as compared to what we do in main magnets.

- They can use much more expensive materials.
- They can be more complicated in construction, as we need only a few.

⇒This makes a good case for HTS in IR magnets.

HTS Test Coils and Magnets at BNL

BNL has built many test coils (14) and magnets with HTS cable and tape.



HTS Cable Coil

HTS Cable Coils in support structure

Two HTS tape coils in common coil configuration

HTS Test Coils

BNL has made a number of short test coils -- 16 with brittle pre-reacted material and of them five are made with HTS cable (in addition many more are made with HTS tapes). The purpose of this program is to to systematically develop this new and challenging technology in a rapid turn around and cost effective manner.

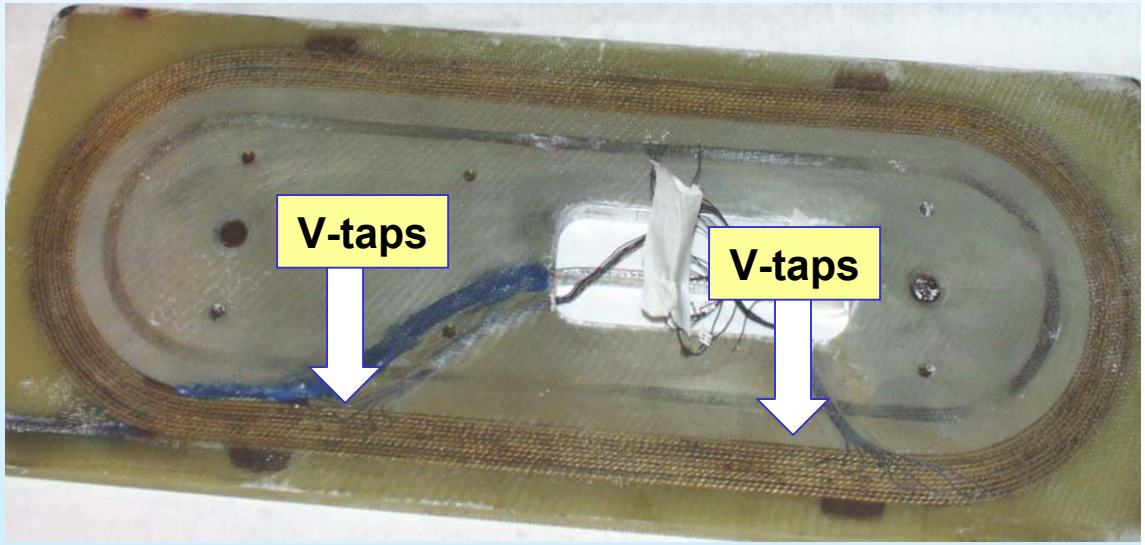
Coil #	Magnet #	Impreg #	Conductor	Conductor pedigree	Insulation type	Bobbin	Process additions
CC001	None	001	Nb_3Sn	ITER chrome	3 mil glass wrap	Iron	First impreg, single ended
CC002	DCC001&2	002	Nb_3Sn	ITER chrome	2 mil glass wrap	Iron	Double hole impreg
CC003	DCC002	003	Nb_3Sn	ITER chrome	2 mil glass wrap	Iron	Double hole impreg
CC004	DCC003 & 8	005	Nb_3Sn	ITER chrome	2 mil glass wrap	Stainless steel	V taps added
CC005	DCC003 & 8	006	Nb_3Sn	ITER chrome	2 mil glass wrap	Stainless steel	V taps added
CC006	DCC004	004	HTS	Low performance	Tube braided glass	Aluminium	
CC007	DCC004	007	HTS	Low performance	Tube braided glass	Stainless steel	
CC008	DCC005	010	Nb_3Sn	LBL RD3 cable	2 mil glass wrap	Stainless steel	
CC009	DCC005	011	Nb_3Sn	LBL RD3 cable	2 mil glass wrap	Stainless steel	
CC010	DCC006	008	HTS/Ag	2 BSCCO, 16 Ag	2 mil glass wrap	Brass	Teflon tape on mold faces
CC011	DCC006	009	HTS/Ag	2 BSCCO, 16 Ag	2 mil glass wrap	Stainless steel	
CC012	DCC008	012	HTS	High Performance	2 mil glass wrap	Aluminium	New mold plates
CC013	None	013	Nb_3Sn	ITER NEEWC	NEEW braided	Stainless steel	Removable bobbin test
CC014	None	014	Nb_3Sn	ITER NEEWC	2 mil glass wrap	Stainless steel	First vacuum bag impreg
CC015	None	015	Nb_3Sn	ITER NEEWC	2 mil glass wrap	Stainless steel	First kevlar string clamping
CC016	DCC009	016	Nb_3Sn	LBL RD3 cable	2 mil glass wrap	Brass	Kevlar string clamping

*Not listed here are (a) DCC007, an HTS tape and (b) an earlier NbTi cable common magnet.

Magnet DCC002: 1st HTS Dipole/Quad

Given the aggressive R&D and learning nature of the program, we instrument the magnet, as much as we can.

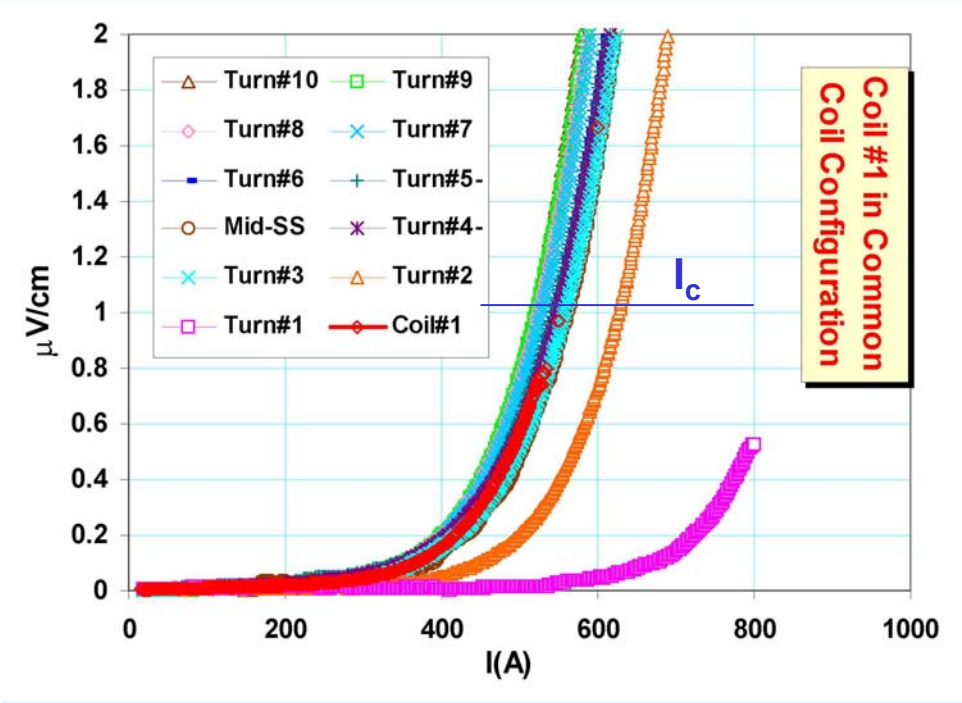
We put at least one voltage tap on each turn

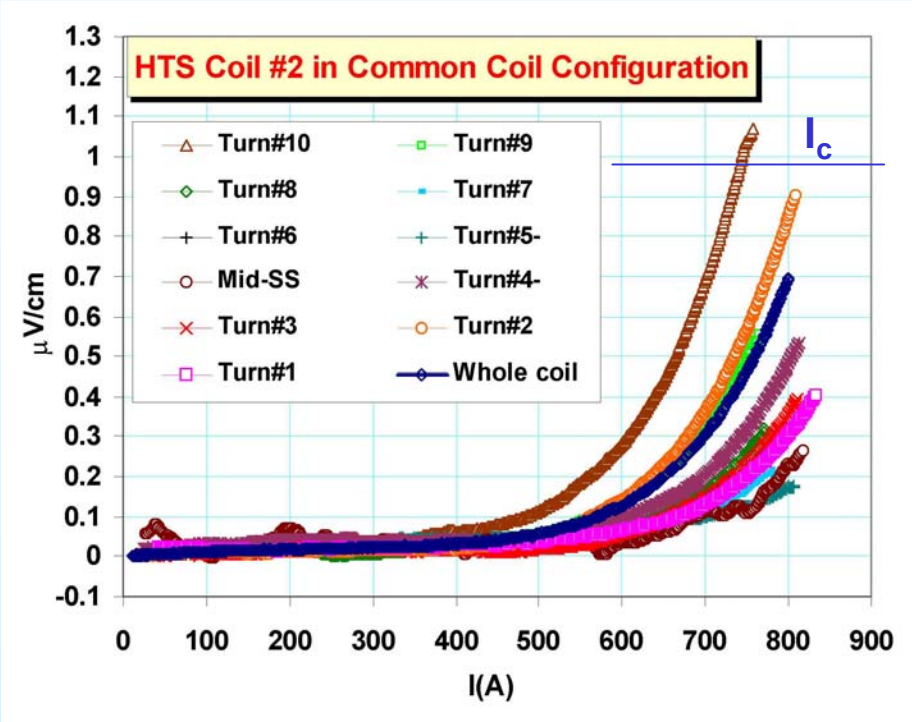


Coils are assembled for a flexible and extensive testing. Four leads are taken out of the cryostat.

Magnet DCC002: 1st HTS Dipole/Quad

Voltage difference between each consecutive turn and on each coil at 4.2 K



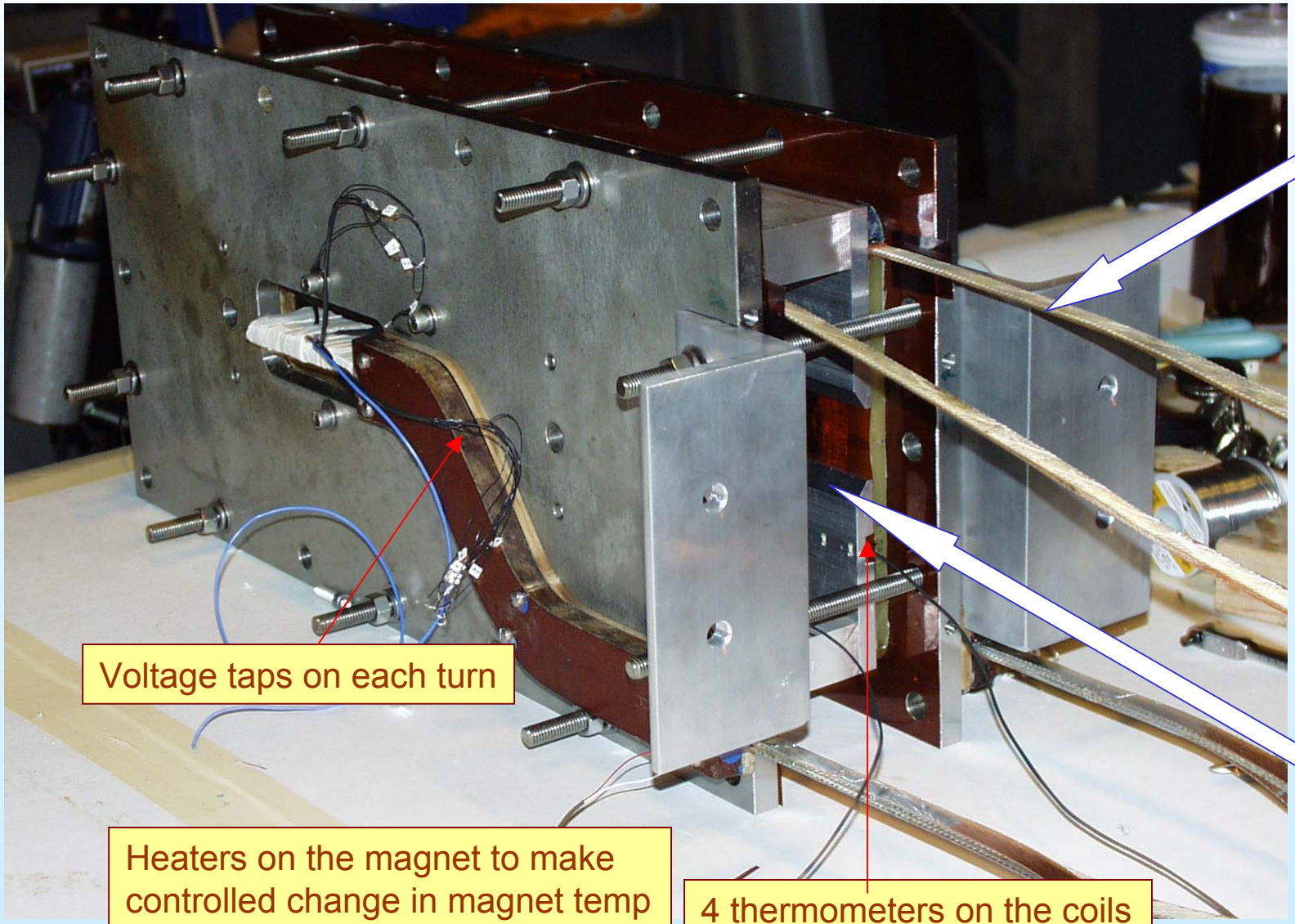


- This test magnet was made with cable from early wire
- The state-of-the-art wire is now about a factor of five better

Magnet DCC006: 2nd HTS Dipole

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

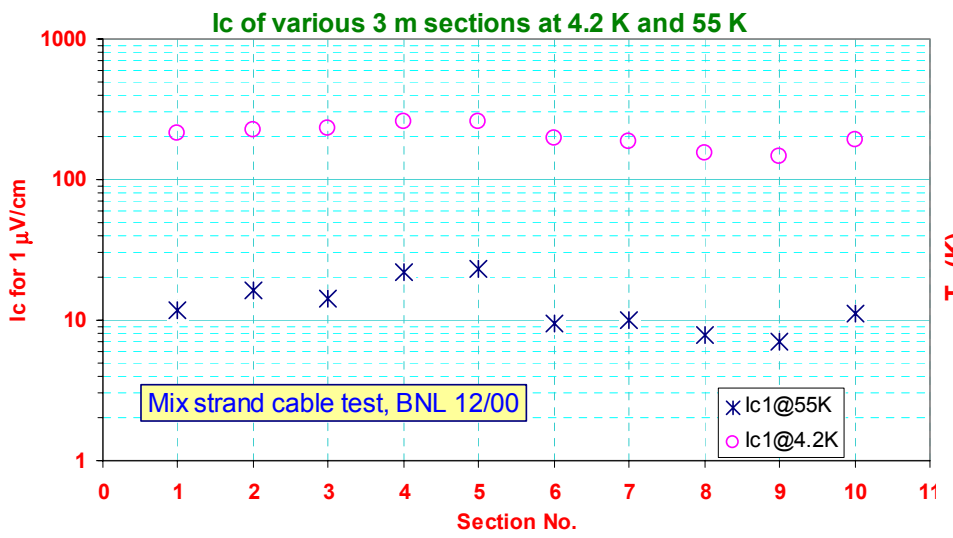
A versatile structure to test single or double coils in various configurations

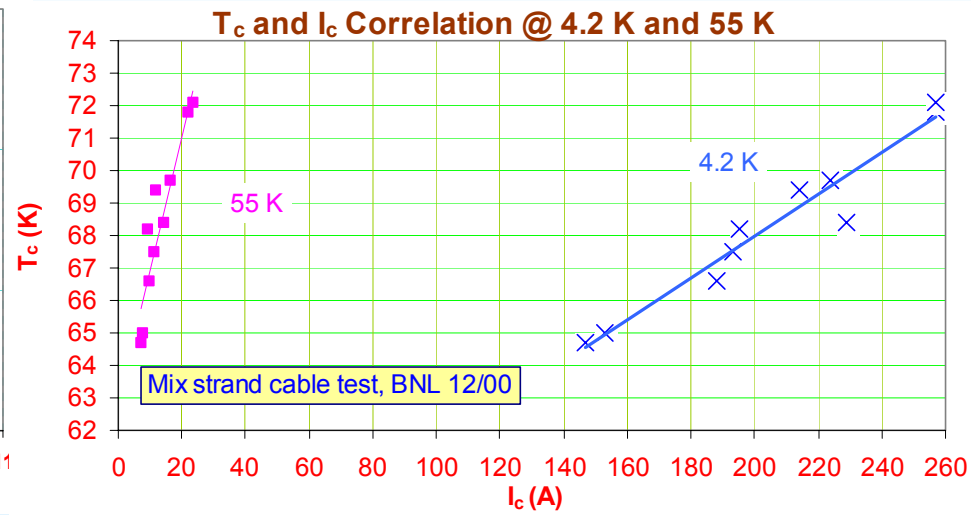


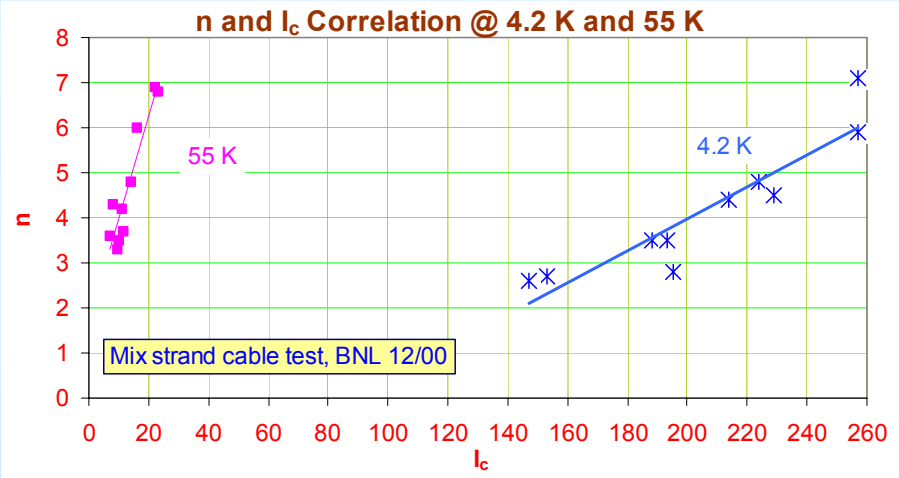
HTS Cable Leads to make high temp measurements

74 mm aperture to measure field quality

Mixed Strand Cable for DCC006 (tested prior to winding coil)



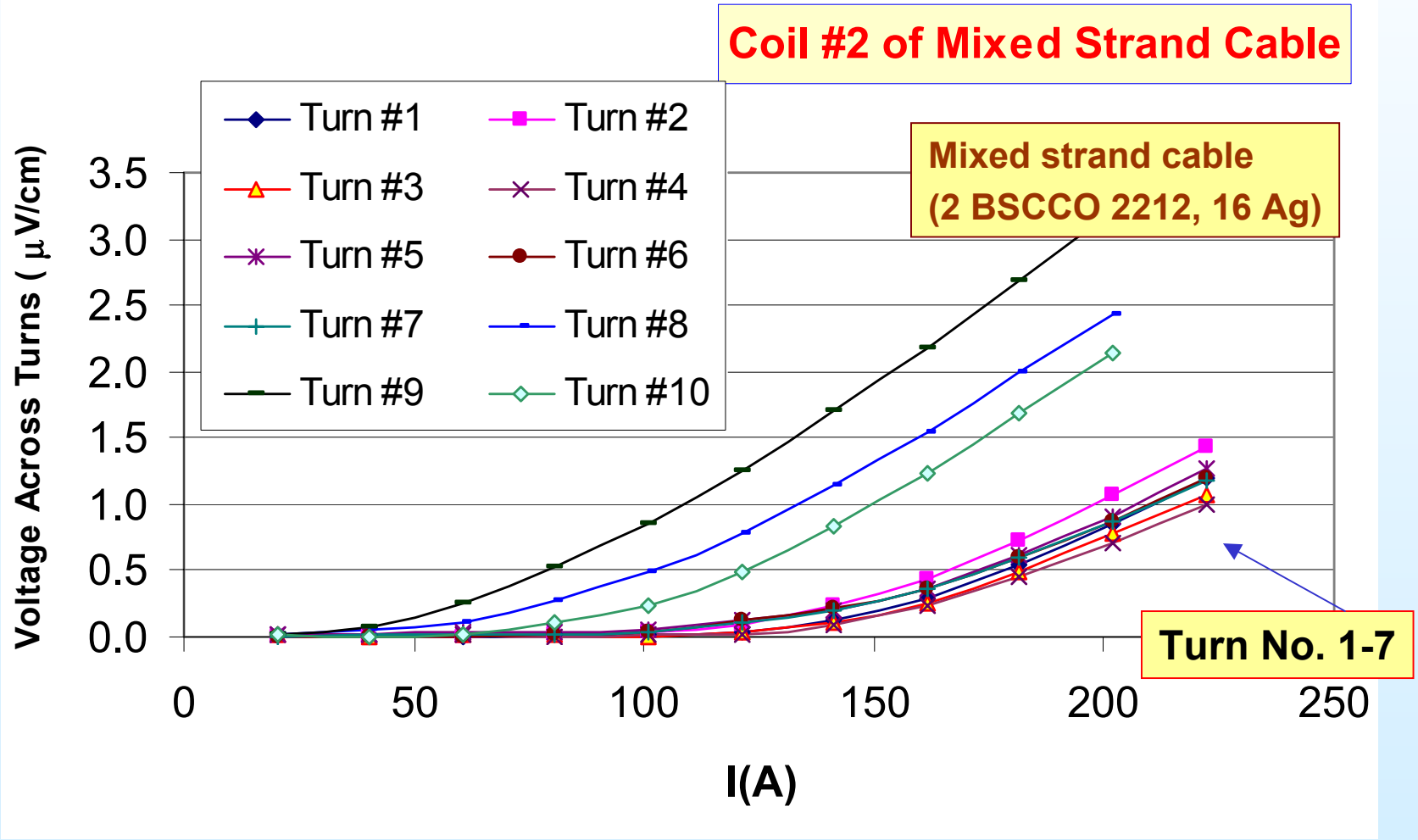




Notes:

1. A good correlation between LN_2 and LHe measurements offer a valuable QA technique for industry.
2. Better cable has better Tc
3. I_c and "n value" improve together.

Measured I_c of Various Turns of Common Coil Magnet DCC006



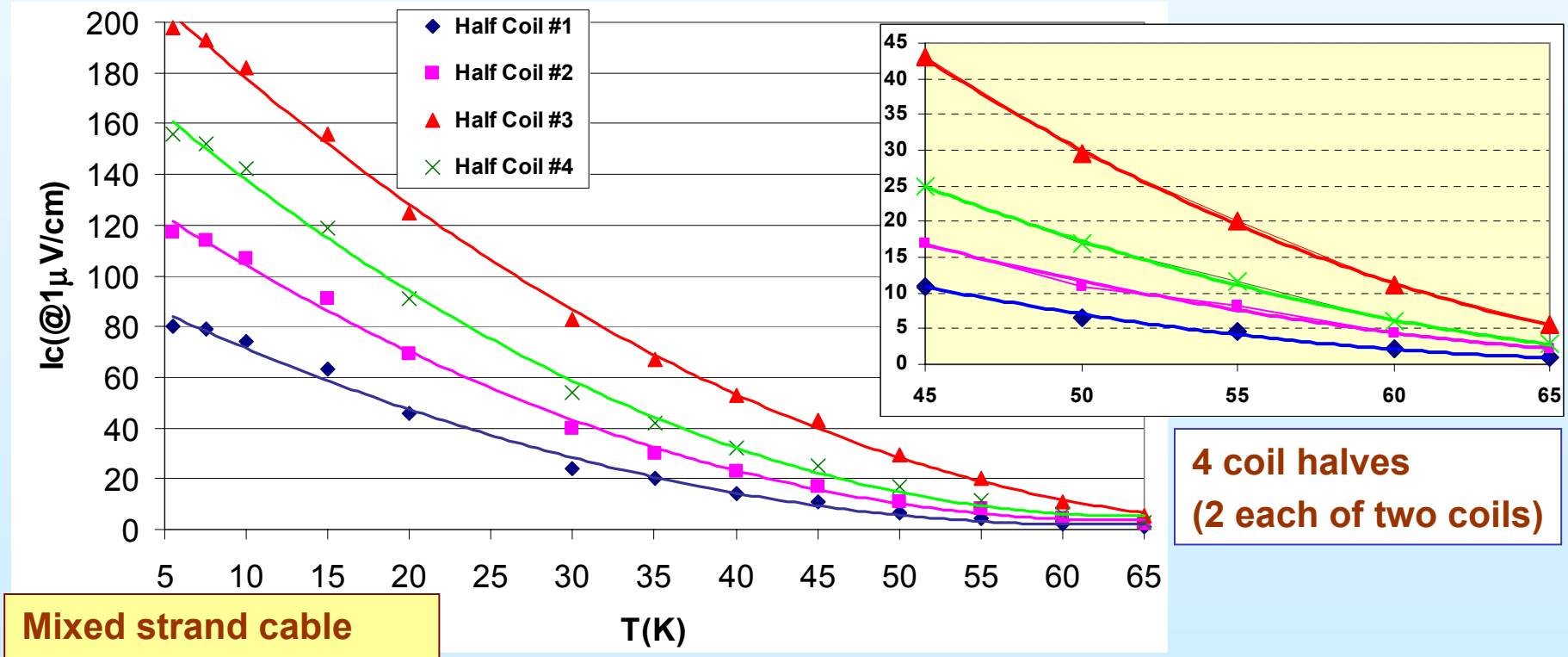
Turns No. 1-7 show an I_c close to the best measured in cable prior to winding.

This suggest a low level of degradation!

High Temperature Performance of HTS Coils Built at BNL

A few degree increase in temperature, either from energy deposition of decay particles, or from mechanical motion, has a small effect on critical current.

HTS magnets will not quench easily, they can tolerate much more beating!

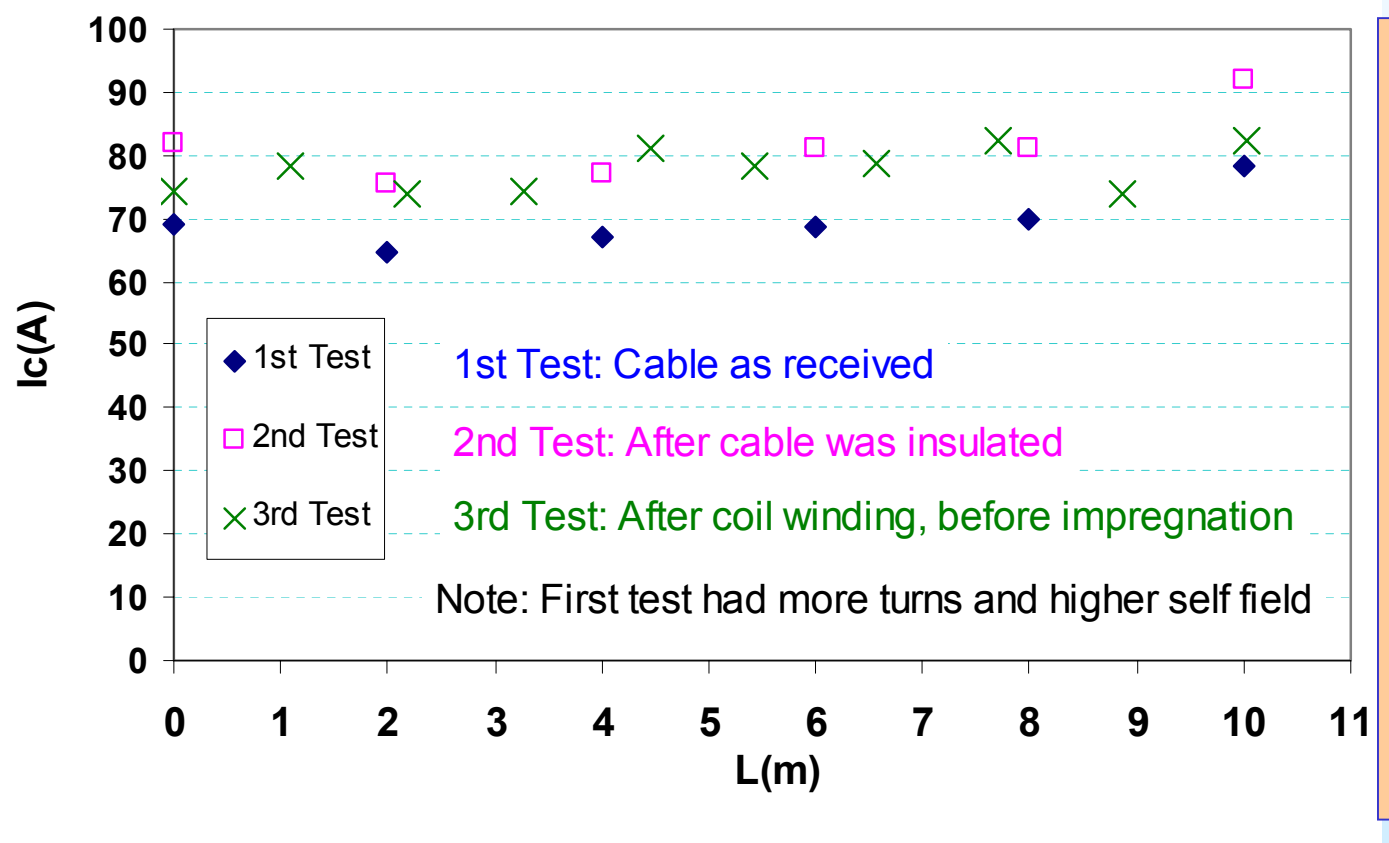


4 coil halves
(2 each of two coils)

Mixed strand cable
(2 BSCCO 2212, 16 Ag)

Systematic Test during the steps of making High Performance HTS coil for DCC008

The coil CC012 is made with the best HTS delivered to date (best claimed is about a factor of 2 better). We want to study degradation, if any, in each and every step of the process. The following LN_2 measurements track the process.



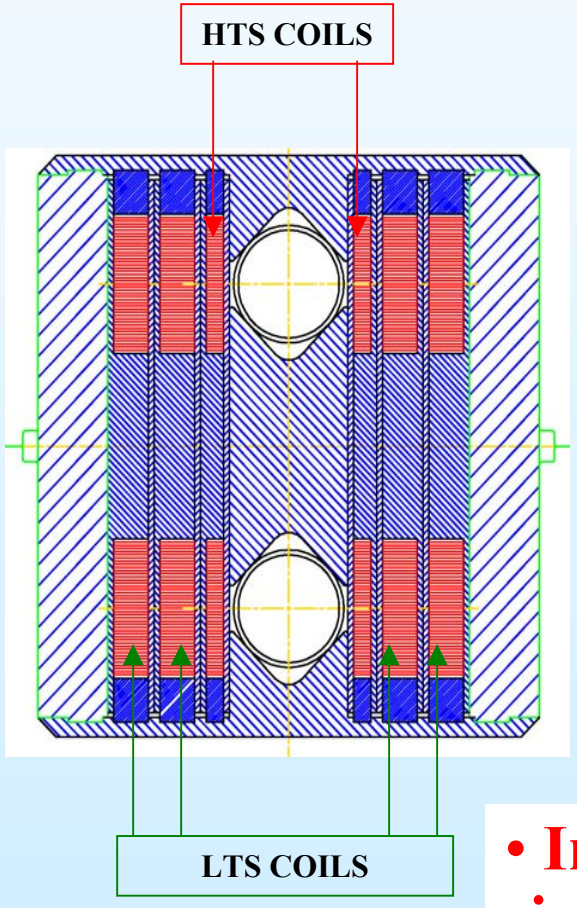
Next Magnet Test

Measure the performance of this coil at 4 K and ~4 T. Background field created by Nb_3Sn coils.

The hybrid magnet is assembled and is being prepared for the test.

Rutherford cable made with 18 strands of BSCCO2212. Strand diameter = 0.8 mm.

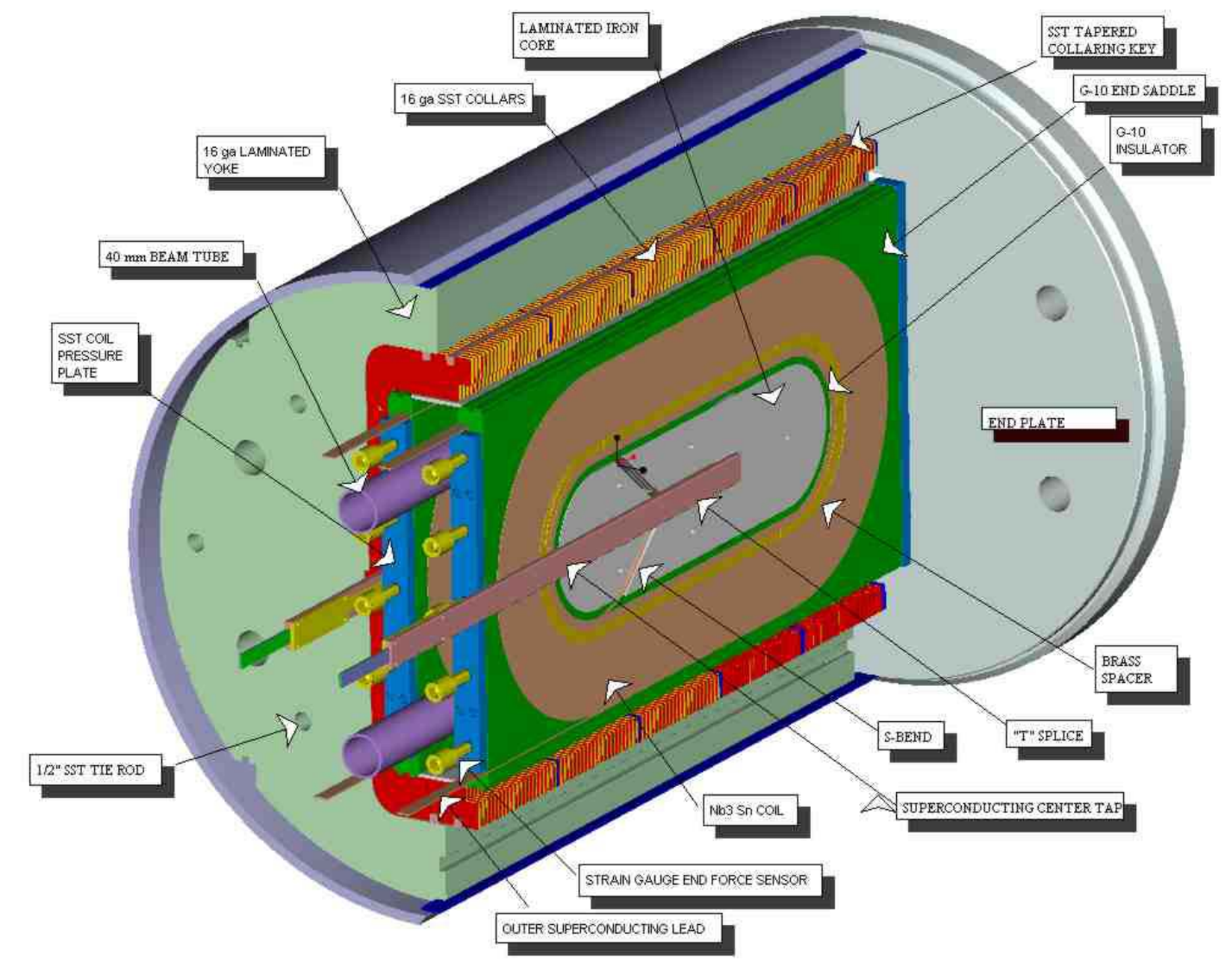
12 T Background Field Magnet: The Next Step in HTS R&D Program



- 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.

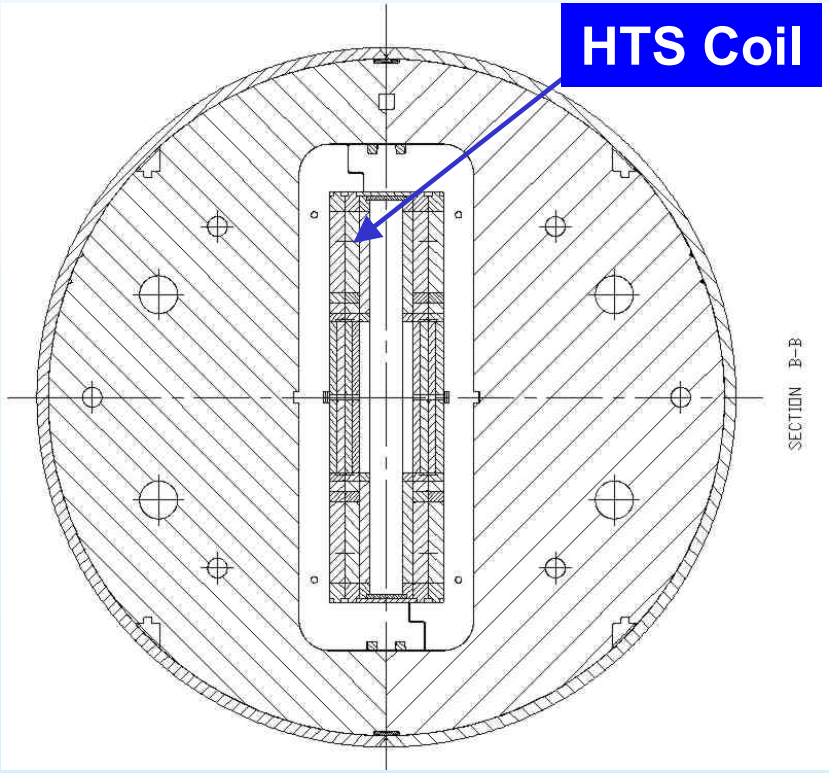
BNL 12 T Nb_3Sn Common Coil Background Field Dipole



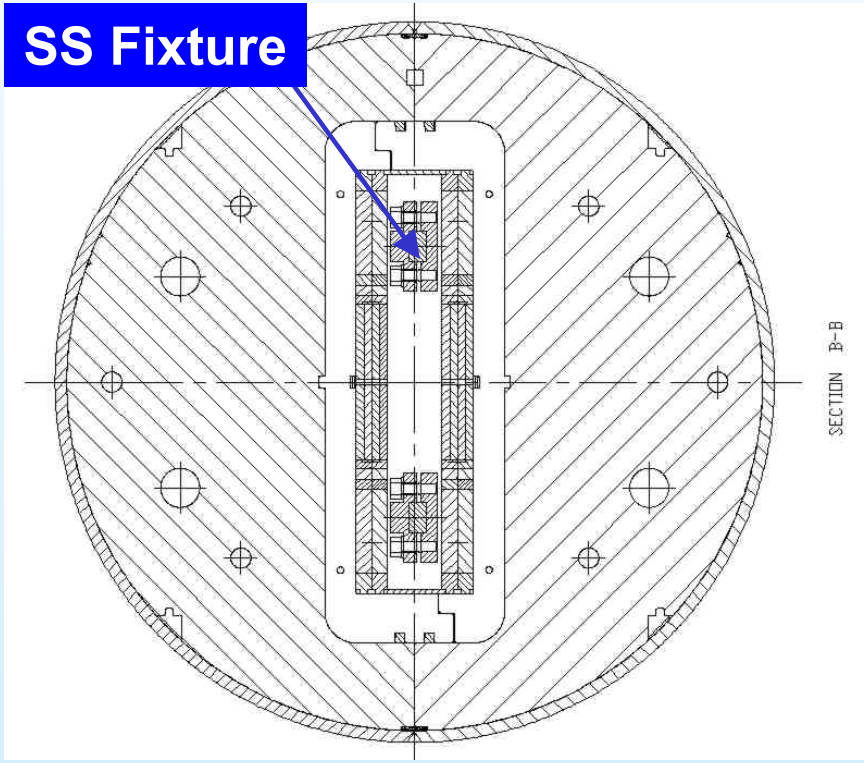
Nb_3Sn conductor for both inner and outer layers is provided by OST

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.



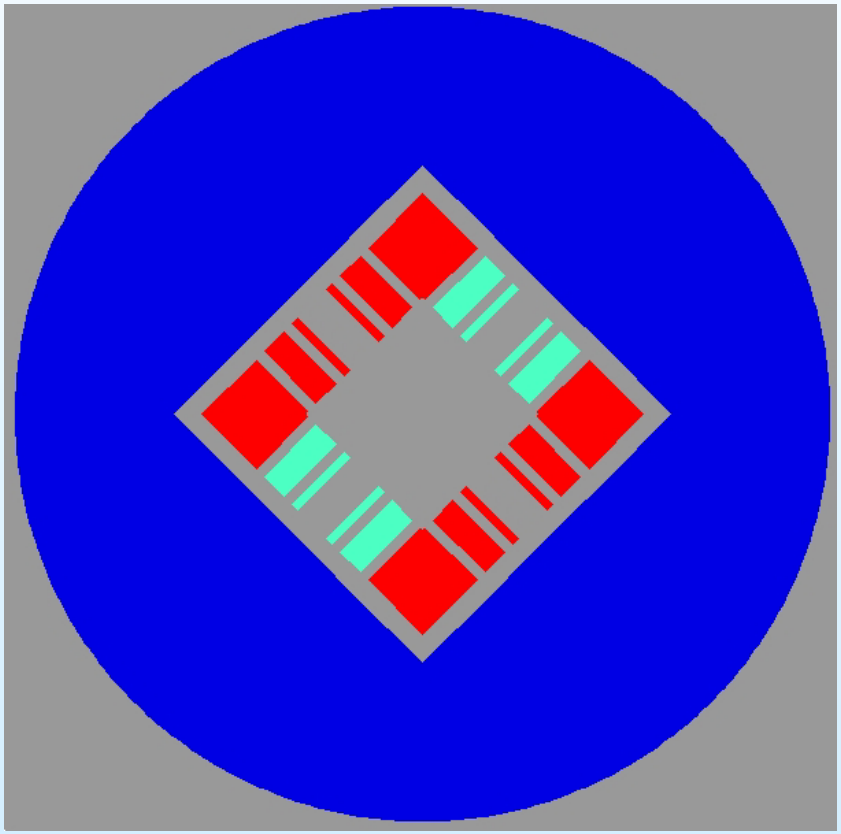
HTS insert coil test configuration

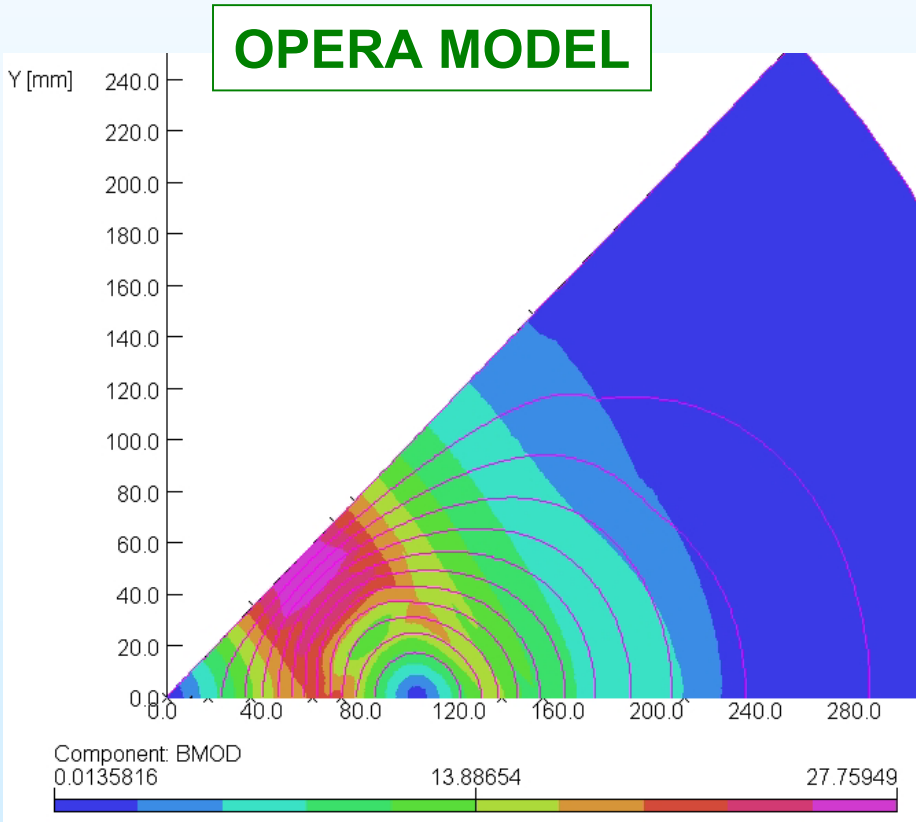


Short sample test configuration

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

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





Note: Peak field is not a major concern in HTS quadrupole designs.

Summary

We have demonstrated that small HTS coils can be made without large degradation.

This is a significant progress (real & psychological) as it reduces "the intimidation factor" of brittle HTS materials.

We have to extend this technology to long coils with many turns.

We need to demonstrate that these coils will have small degradation in high field, high stress environment.

…and what we would like from you is …

Expectations from Conductor Manufactures

We hope from you to

- Start BSCCO 2212 wire R&D
- Match Showa's performance (J_c and length) in short time
- Deliver BSCCO 2212 for our short and long coils
- Carry out small R&D experiments that are critical to HEP applications
- Improve J_c by a factor of 2-3 in ~ 5 years

Investment in 2212 has been much less than that in 2223. There must be room for more improvement.