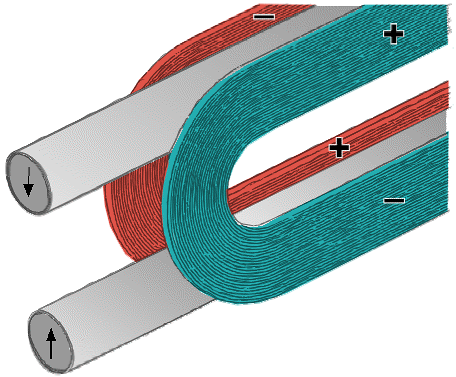

R&D for Accelerator Magnets With React & Wind High Temperature Superconductors

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Overview of the Presentation

• Why HTS in Accelerator Magnets?

Note: HTS has already invaded accelerator magnets (HTS leads in LHC magnets); Let's continue the march!

• Why Start HTS Magnet R&D Now?

•New Magnet Designs and R&D Approach

• Test Results of HTS Technology Magnets

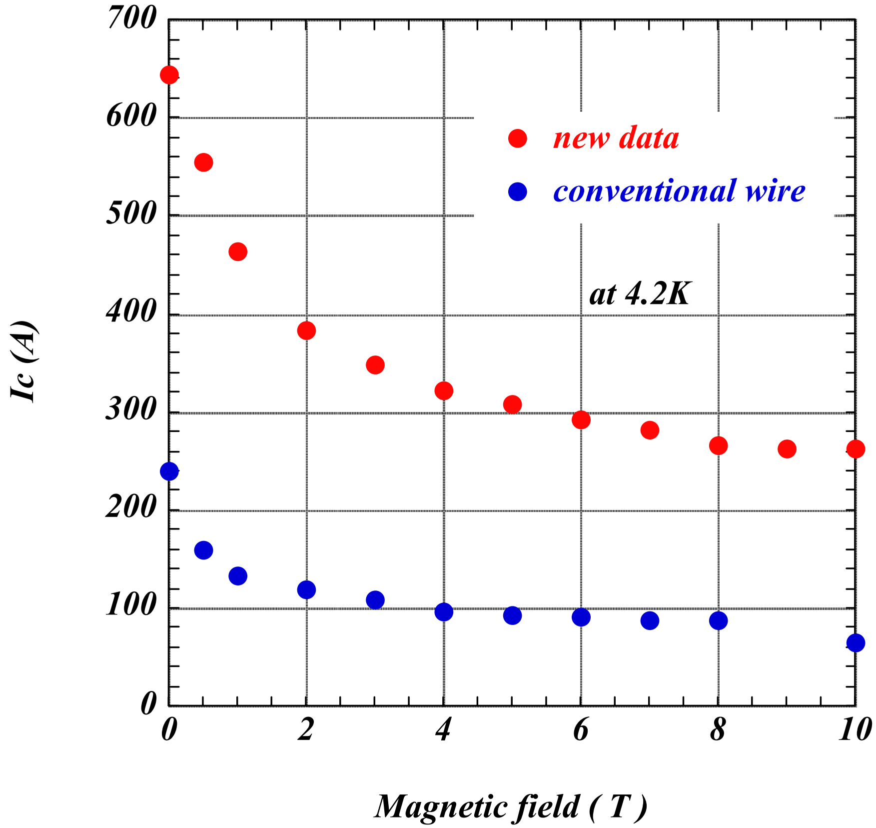
(yes we have built some test magnets)

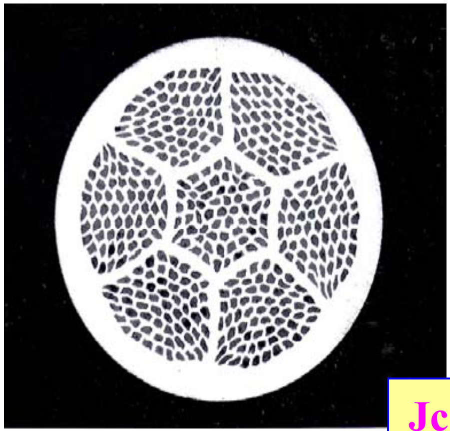
• The Next Step and the Summary

BSCCO Wire (Year 2000)

Ic-B characteristics of new wire

Showa Electric





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

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

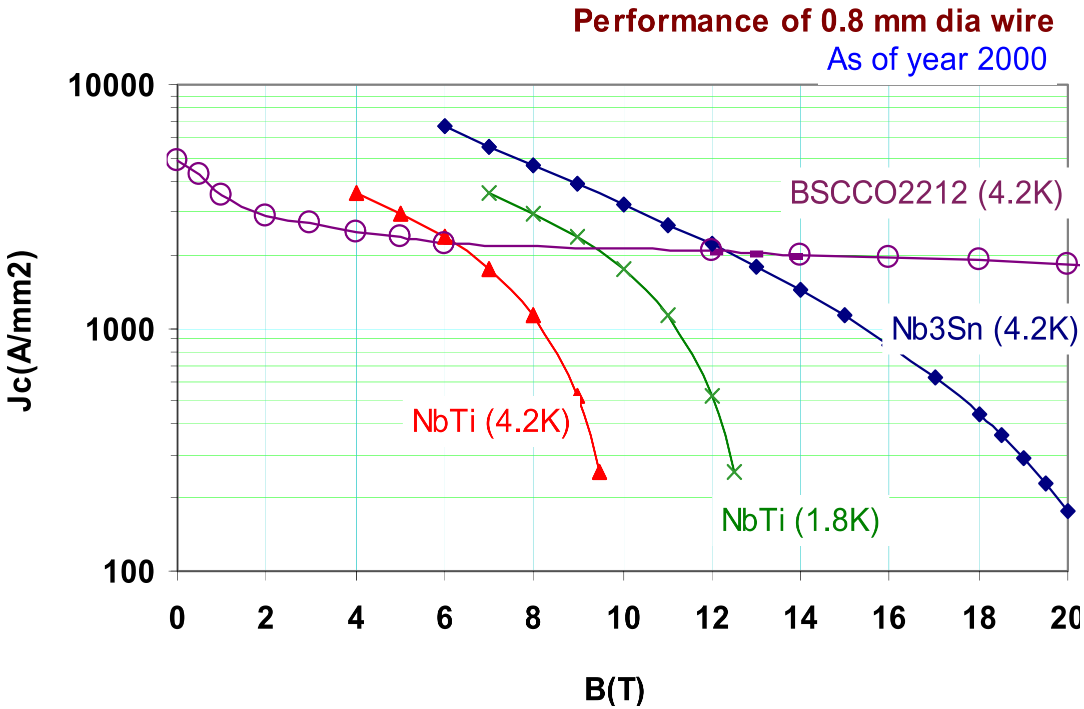
T. Hasegawa, "HTS Conductor for Magnets", MT-17, Geneva.

20/05/00

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Expected Performance of HTS-based Magnets



(performance in ~100 meter or longer lengths)

Year 2000 data for J_c at 12 T, 4.2 K

Nb_3Sn: 2200 A/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)

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

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

*20 T for Hybrid

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

Cu(Ag)/SC Ratio

BSCCO: 3:1 (all cases)

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

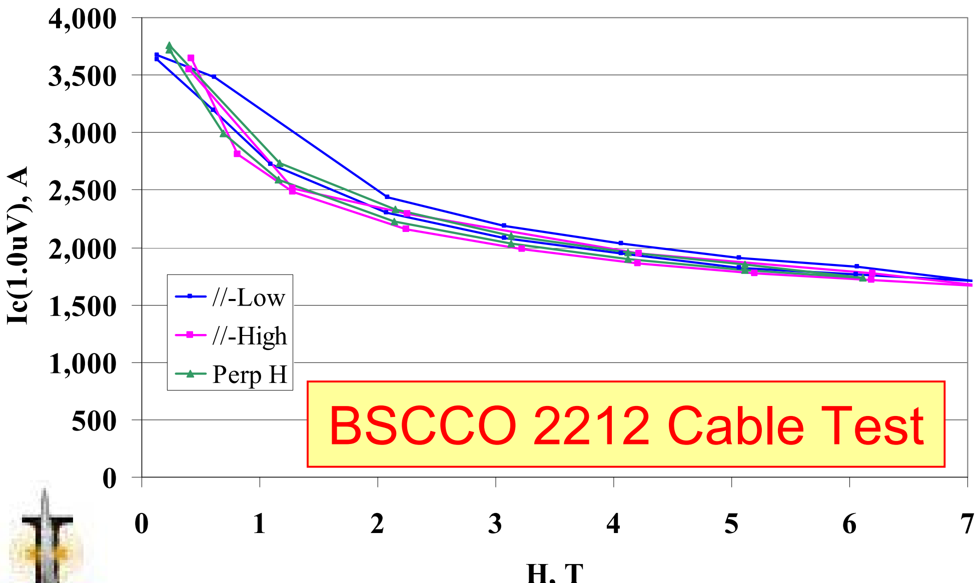
Measured Performance of HTS Cable and Tape As A Function of Field at BNL

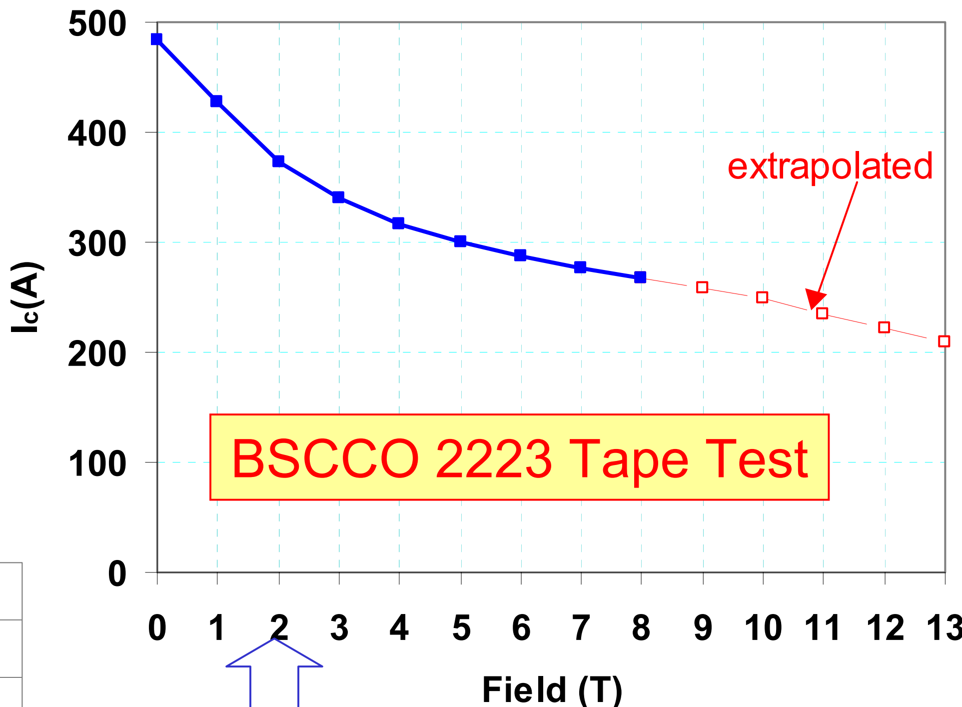
Measurements of "***BSCCO-2212 cable***" (Showa/LBL/BNL) at BNL test facility

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%)

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

- HTS materials are very brittle

  Work on magnet designs (“conductor friendly designs”).

- HTS materials are 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).

HTS and HEP

In the present situation, it appears that the progress in HTS will be driven by communities other than High Energy Physics (HEP).

The most we can do is to support industries to carry out a few small experiments that are critical to accelerator magnets and keep the kind of product that matters to us viable.

In parallel, we learn to use (develop general technology of) whatever HTS line of product becomes available.

But, looking at the progress, things are not bad for us!

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

Interaction region magnets for the next generation colliders

or luminosity upgrade of existing colliders

(LHC is existing collider for this purpose)

can benefit a lot from:

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

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

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

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

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

Why Start HTS Magnet R&D Now?

We are almost there!

Both in terms of J_c (~a factor of two) and in wire length (a factor of 5-10)

Performance has become enough to do credible magnet R&D

Cable can carry 5-10 kA and hybrid magnets can create 15^+T

It takes long time to do magnet R&D even with known NbTi technology

- Allow, at least five years for this new and challenging R&D
- Address magnet technology issues (allow new ideas to be tested)
- Address issues related to field quality, etc.

In the meantime HTS performance should improve by a factor of 2

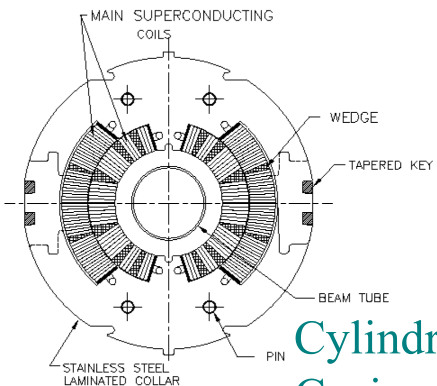
With both done in parallel, we can make an informed decision in ~5 years

To do that, the right time to start HTS magnet R&D is <u>NOW</u>!

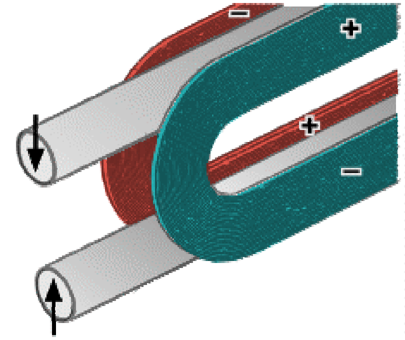
BNL Magnet R&D Program & Philosophy: Exploring an Alternate Direction to Future

Conventional | **Alternate**

Magnet Designs



Cylindrical Cosine Theta



Example:
Racetrack Common Coil

Conductors

Ductile: NbTi
Easy to make coil with

Brittle:
Nb_3Sn and (HTS)

R&D Approach

Large resources committed to developing each magnet

Experimental program:
Rapid turn around,
less expensive

BASICALLY, WE ARE TRYING TO LOOK OUTSIDE THE BOX!

Design Issues for High Field Accelerator Magnets using HTS

- HTS is very brittle

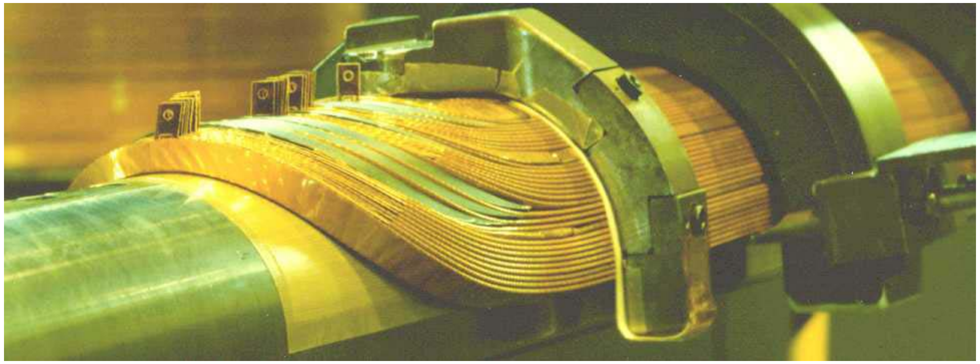
  Conventional designs are not the most suitable

- Large Lorentz forces

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

  (~1/2 degree at ~890^o C)

⇒ React & Wind Approach

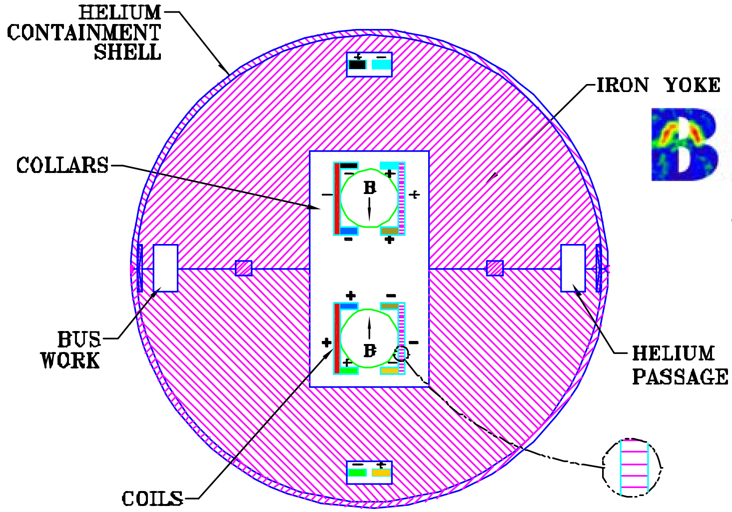


Conventional cosine θ design (e.g., RHIC magnets)

Complex 3-d geometry in the ends

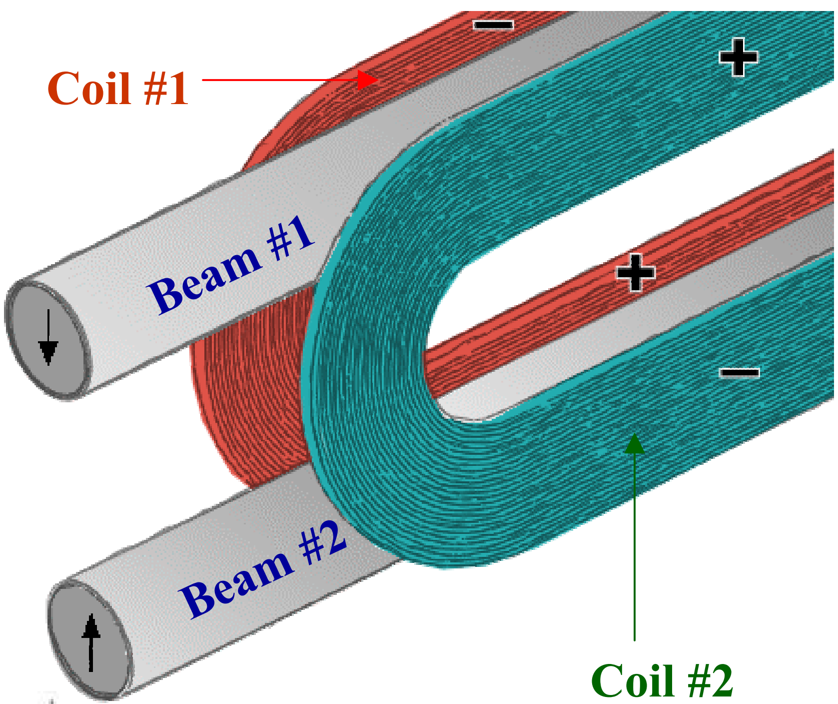
Conductor friendly racetrack coil with large bend radius

Suitable for high field magnets with brittle material



Common Coil Design

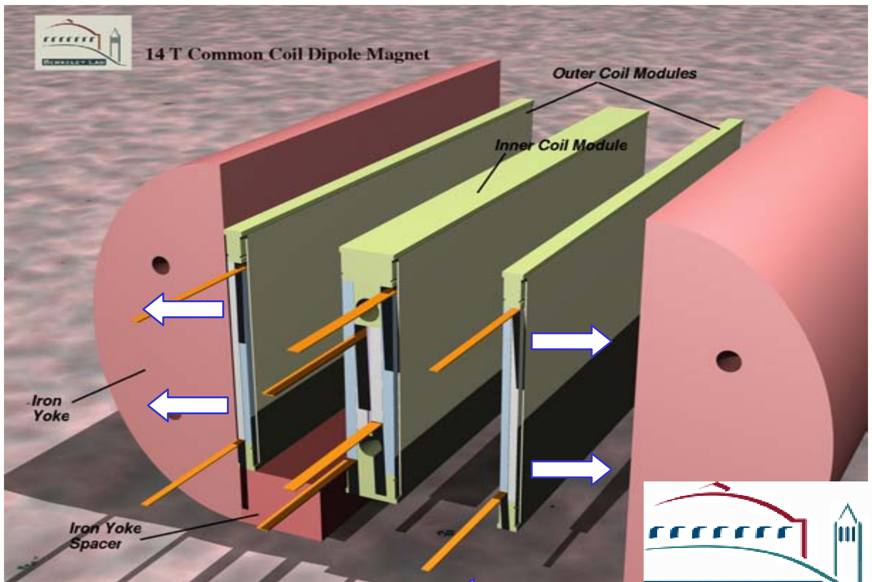
- **Simple 2-d geometry with large bend radius** (determined by spacing between two apertures, rather than aperture itself)
- **Conductor friendly (no complex 3-d ends, suitable for brittle materials - most for H.F. are - Nb_3Sn and HTS)**
- **Compact (quadrupole type cross-section, field falls more 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**



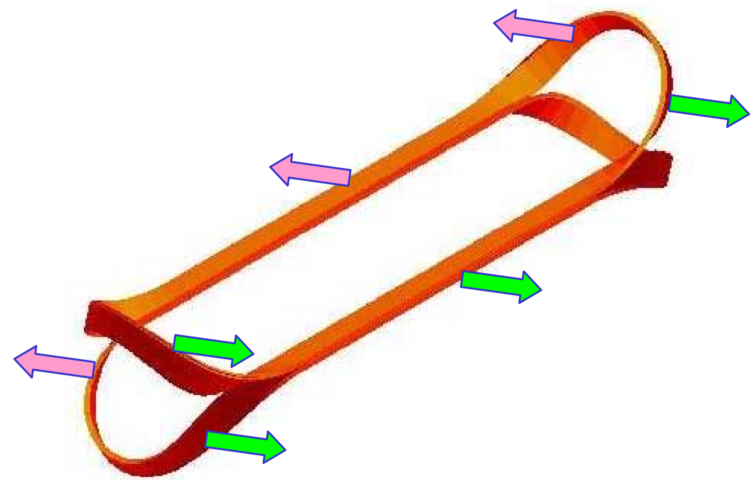
Main Coils of the *Common Coil Design*

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

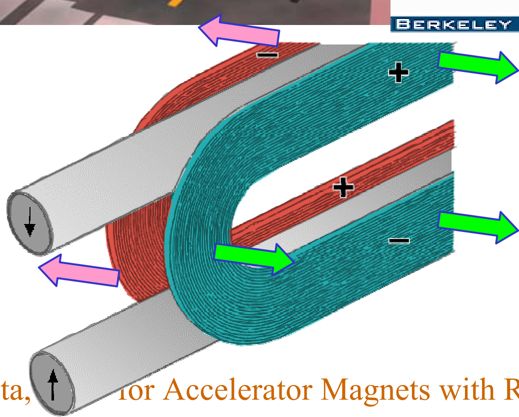
In common coil design, geometry and forces are such that the impregnated solid volume can move as a block without causing quench or damage (over 1 mm motion in LBL RT1 common coil test configuration).



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.

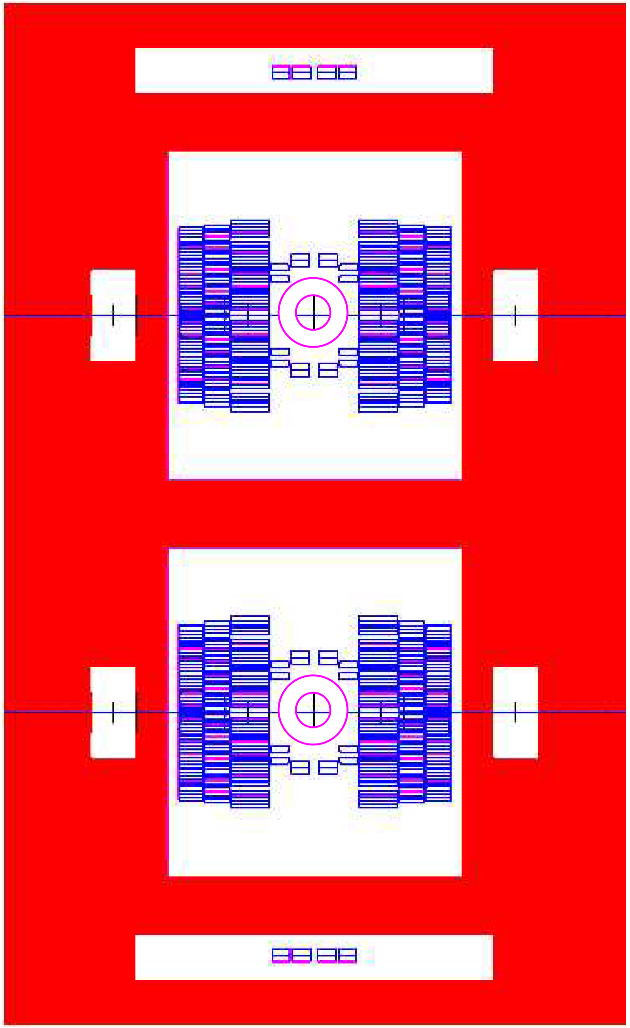


Horizontal forces are larger



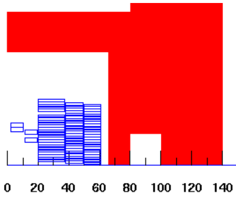
We must check how far we can go in allowing such motions in the body and ends of the magnet. This may significantly reduce the cost of expensive support structure. Field quality optimization should include it (as was done in SSC and RHIC magnet designs).

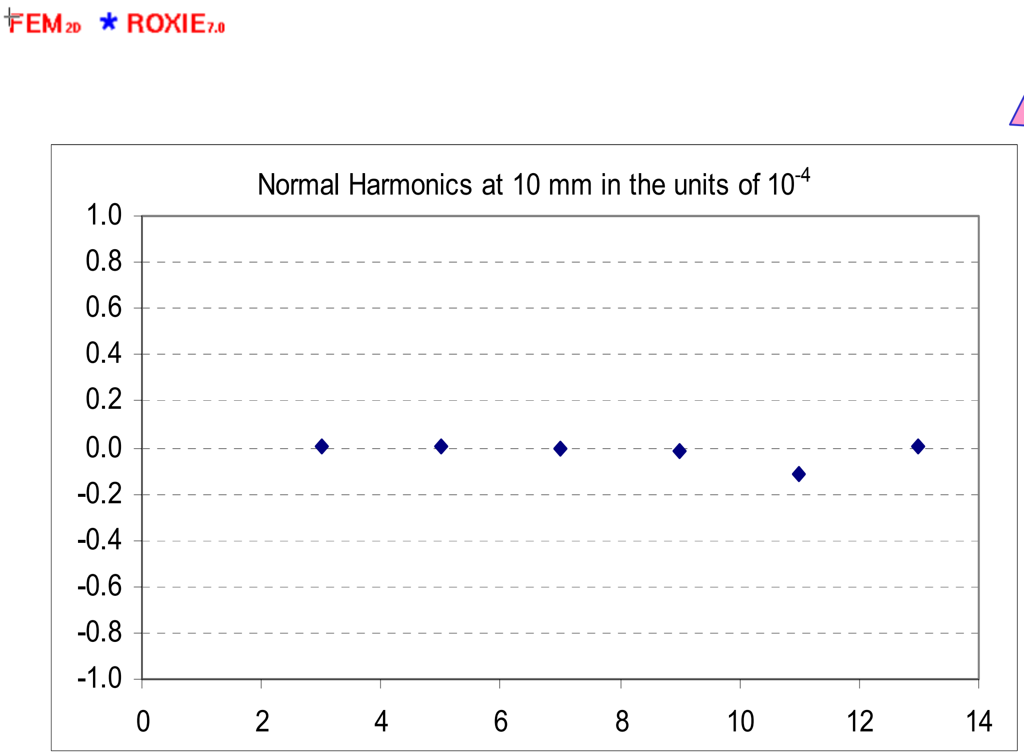
Field Quality: Small Geometric Harmonics



Typical Requirements:
~ part in 10^4, we have part in 10^5

(from 1/4 model)



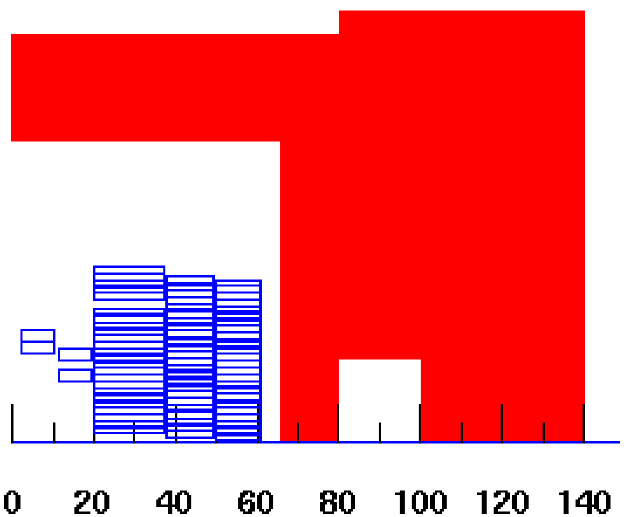


Coil Aperture = 40 mm

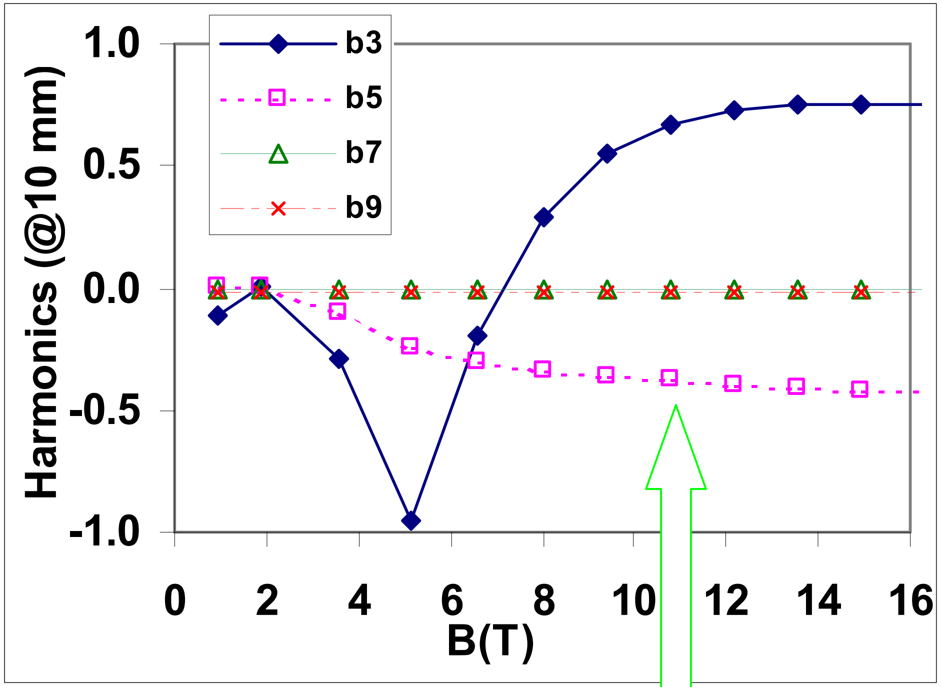
BNL design uses very small spacing between modules. Above design is consistent with that.

Field Quality: Small Saturation-induced Harmonics

Use cutouts at strategic places in yoke iron to control the saturation.



New designs: ~ part in 10^4
Satisfies general accelerator requirement



Low saturation induced harmonics up to 15 T with a single power supply

Field Quality: Small Harmonics in Ends

Proof:

End harmonics can be made small in a common coil design.

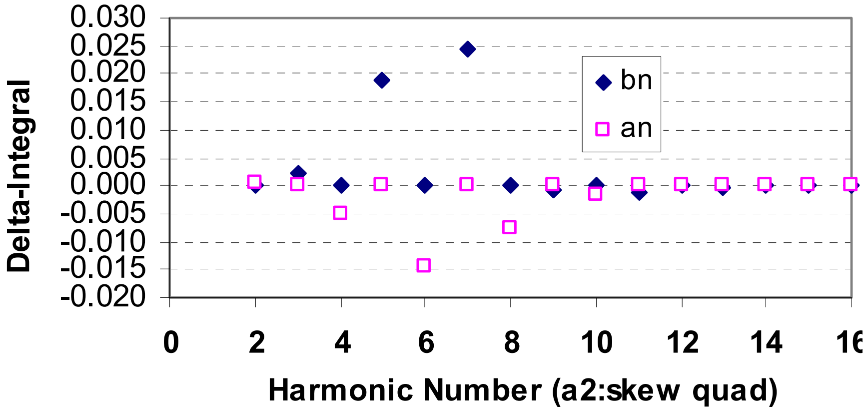
(Very small)

End harmonics in Unit-m

n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00

Contribution to integral (a_n,b_n) in a 14 m long dipole ($<10^{-6}$)

n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000

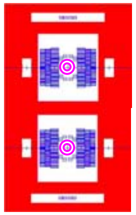


Field Quality: Persistent Current Induced Harmonics in HTS Coil

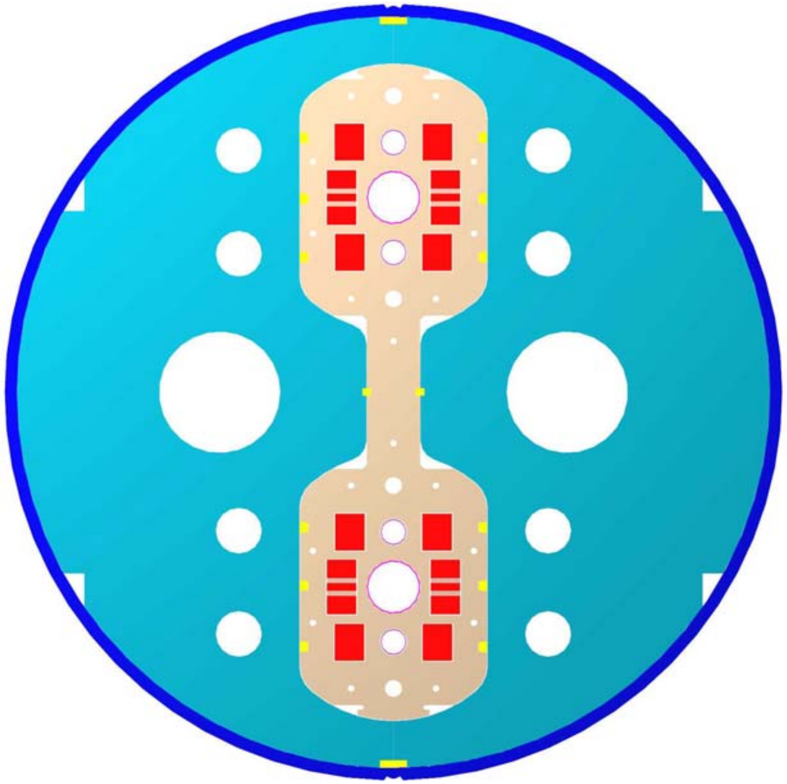
We have started measuring persistent current induced harmonics in HTS coils.

Mitigate the problem in "smart designs" :

Some design concepts from Fermilab and LBL



Status of R&D on Common Coil Magnets



Fermilab Design of Common Coil Magnet for VLHC-2

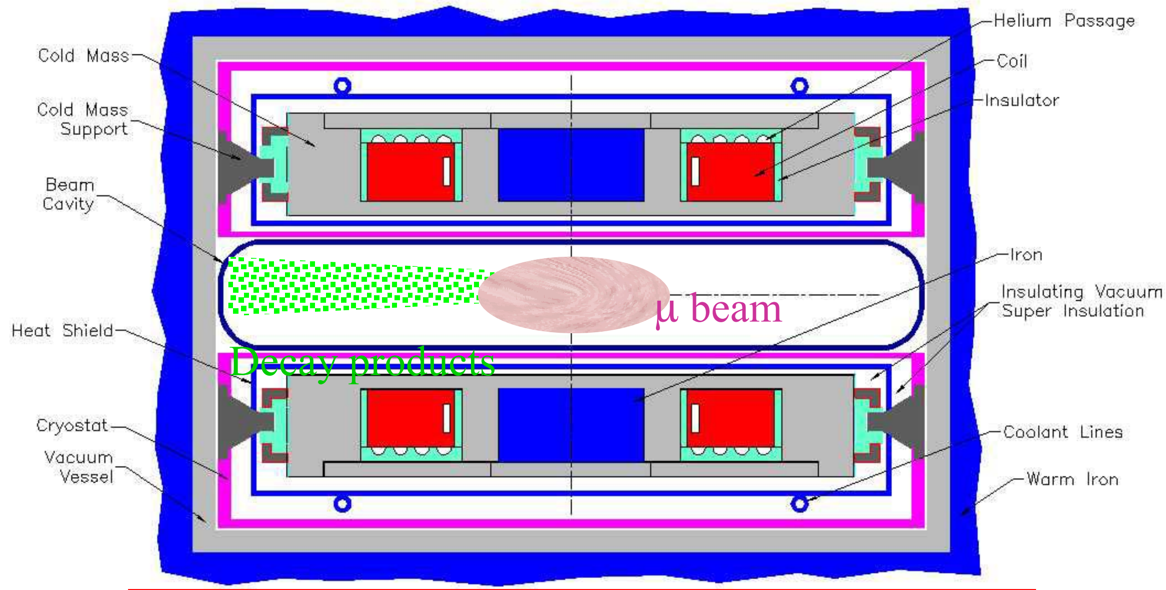
- A large number of papers (20-40) written (number of designs with good field quality shown)
- All three major US labs are working on this design
- A significant number (10+) of R&D test magnets built in last few years
- Record magnetic field is obtained (14.7 T @LBL)
- New material (HTS) introduced in accelerator magnets

Magnet Design for ν Factory

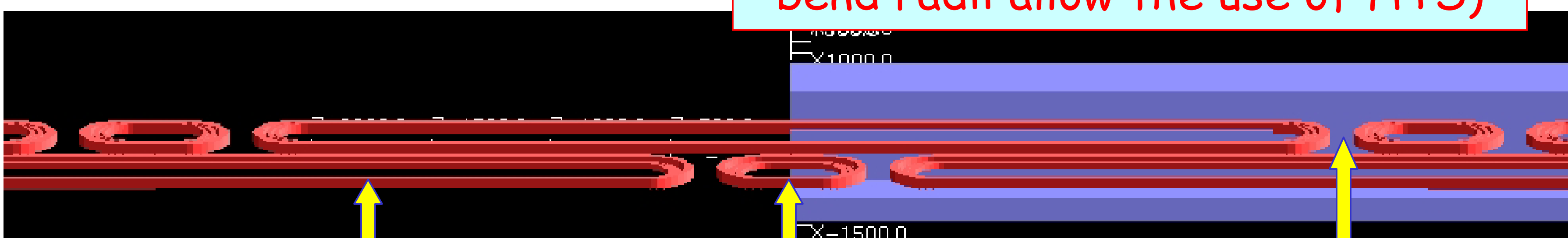
Decay products clear superconducting coils

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)



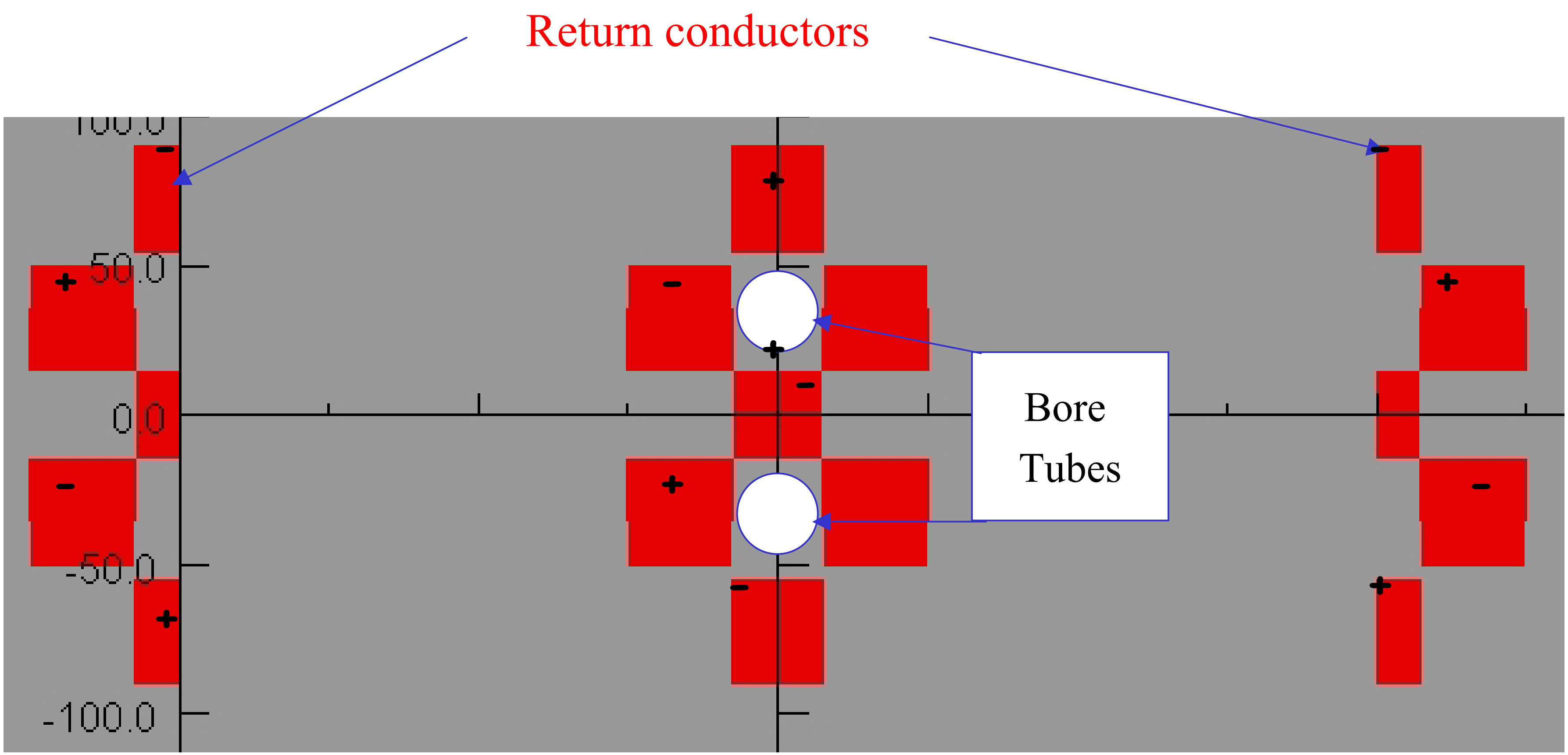
Normal Coils Dipole

Reverse Coils Skew Quad

One Coil 1/2 & 1/2

VLHC-2 Interaction Region Magnet Design (Preliminary)

Conductor friendly IR quad design



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

HTS Magnet R&D and Test Program at BNL

HTS Tape Coil Program:

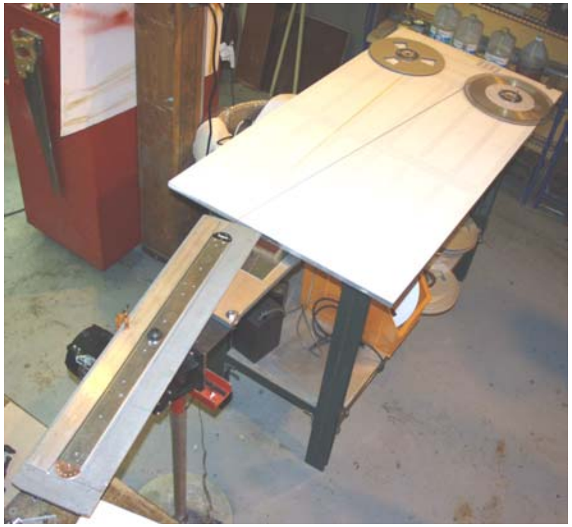
- Started ~ 3 years ago
- Six 1-meter long coils built and tested

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 ~1 1/2 year ago
  - 10 coils built and tested (4 HTS, 6 Nb_3Sn)

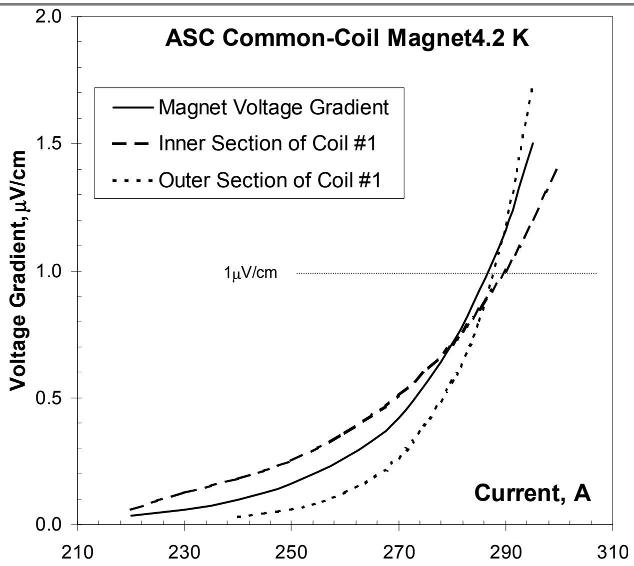
Common Coil Magnets With HTS Tape

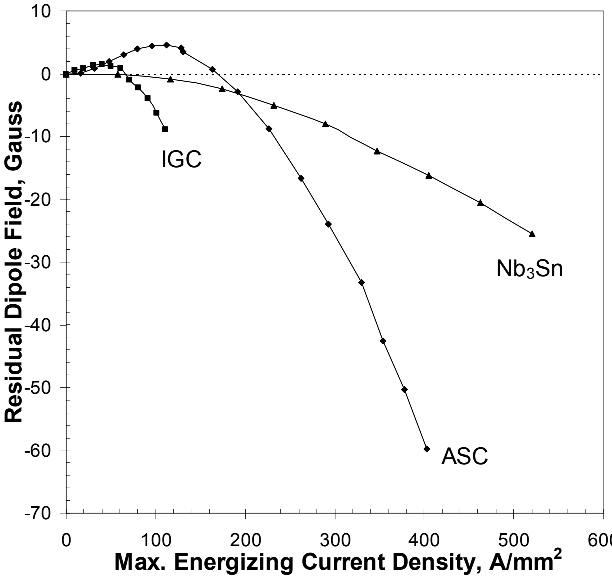
(Field quality in 74 mm aperture to be measured soon)



A coil being wound with HTS tape and insulation.

Two HTS tape coils in common coil configuration





Status of HTS tape coils at BNL

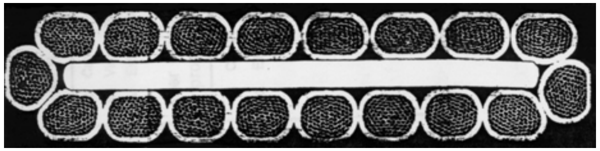
	Size, mm	Turns	Status
Nb_3Sn	0.2 x 3.2	168	Tested
IGC	0.25 x 3.3	147	Tested
ASC	0.18 x 3.1	221	Tested
NST	0.20 x 3.2	220	Under construction
VAC	0.23 x 3.4	170	Under construction

HTS Cable Magnet Program

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

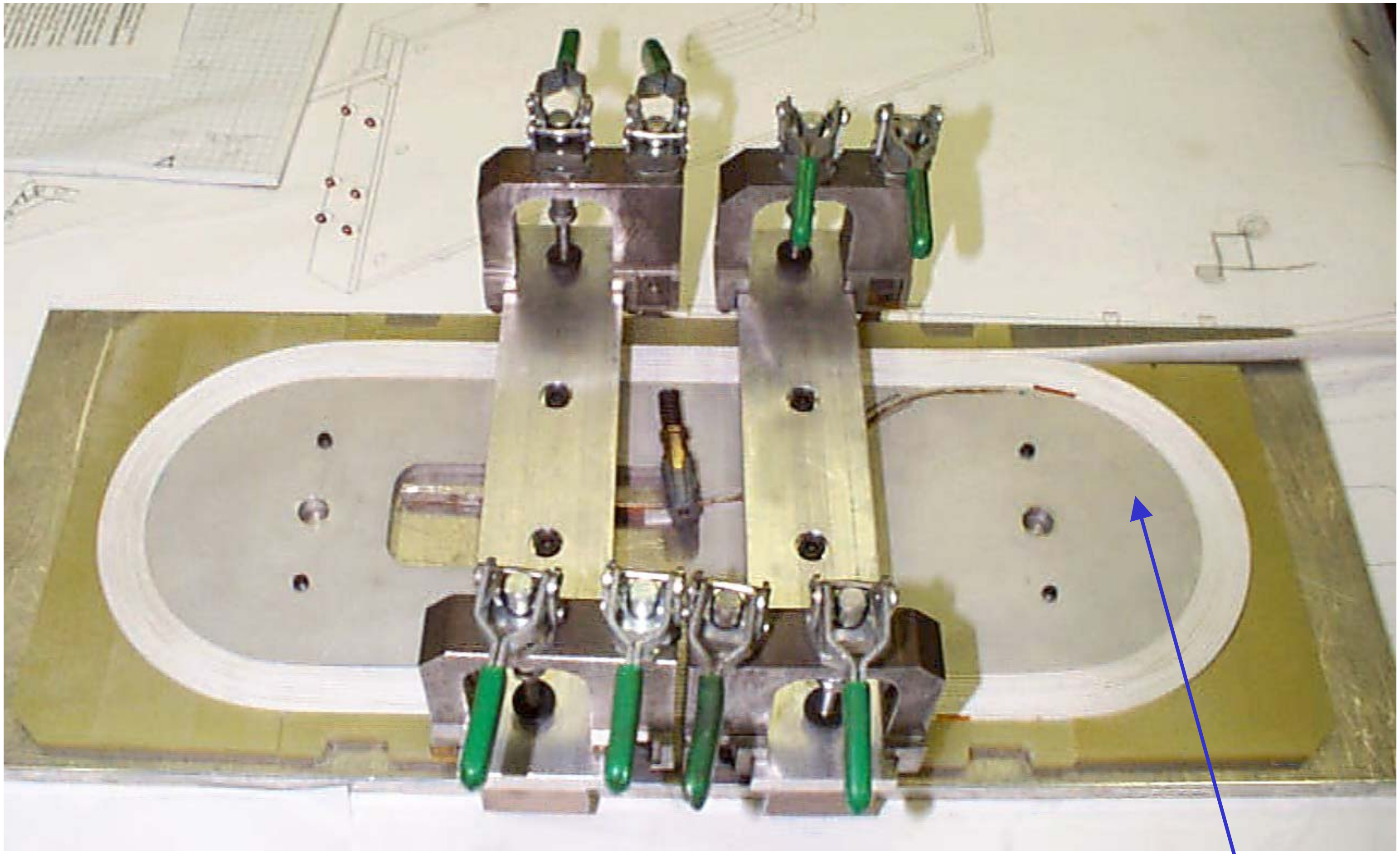
- Higher current for operating accelerator magnets
- Plus all standard reasons for using cable

HTS Cable



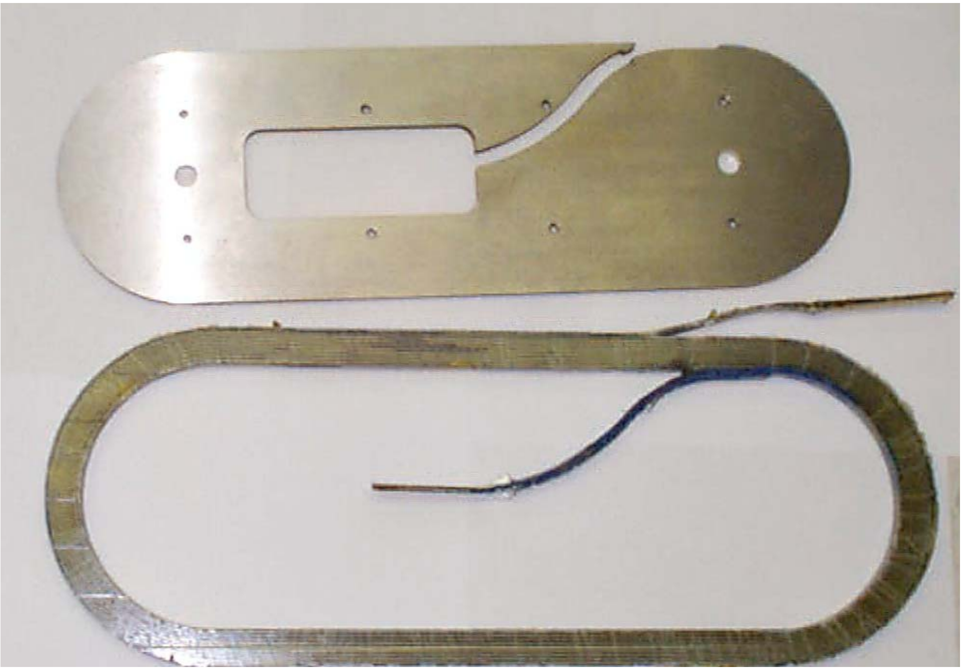
A good and productive collaboration has been established between labs (BNL, LBL) and industries (IGC, Showa).

HTS Coil Wound by Hand



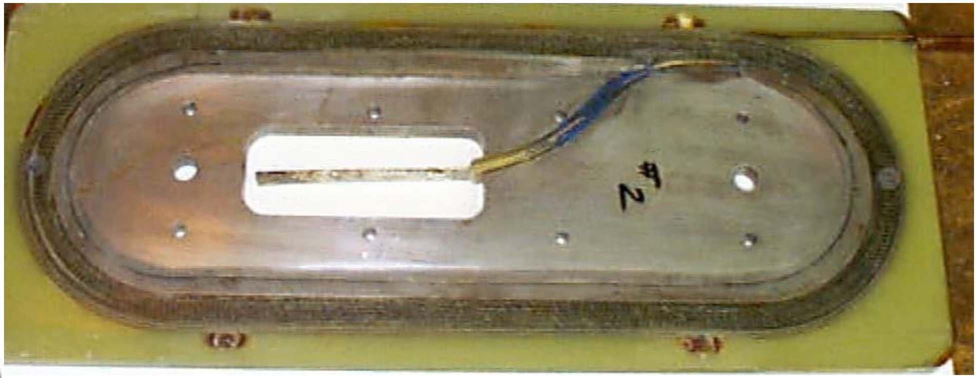
Al Bobbin (70 mm radius)
(also used, Fe, SS and brass bobbins)

The Bobbin and the 10-turn Coil



The bobbin
(the coil is wound on it)

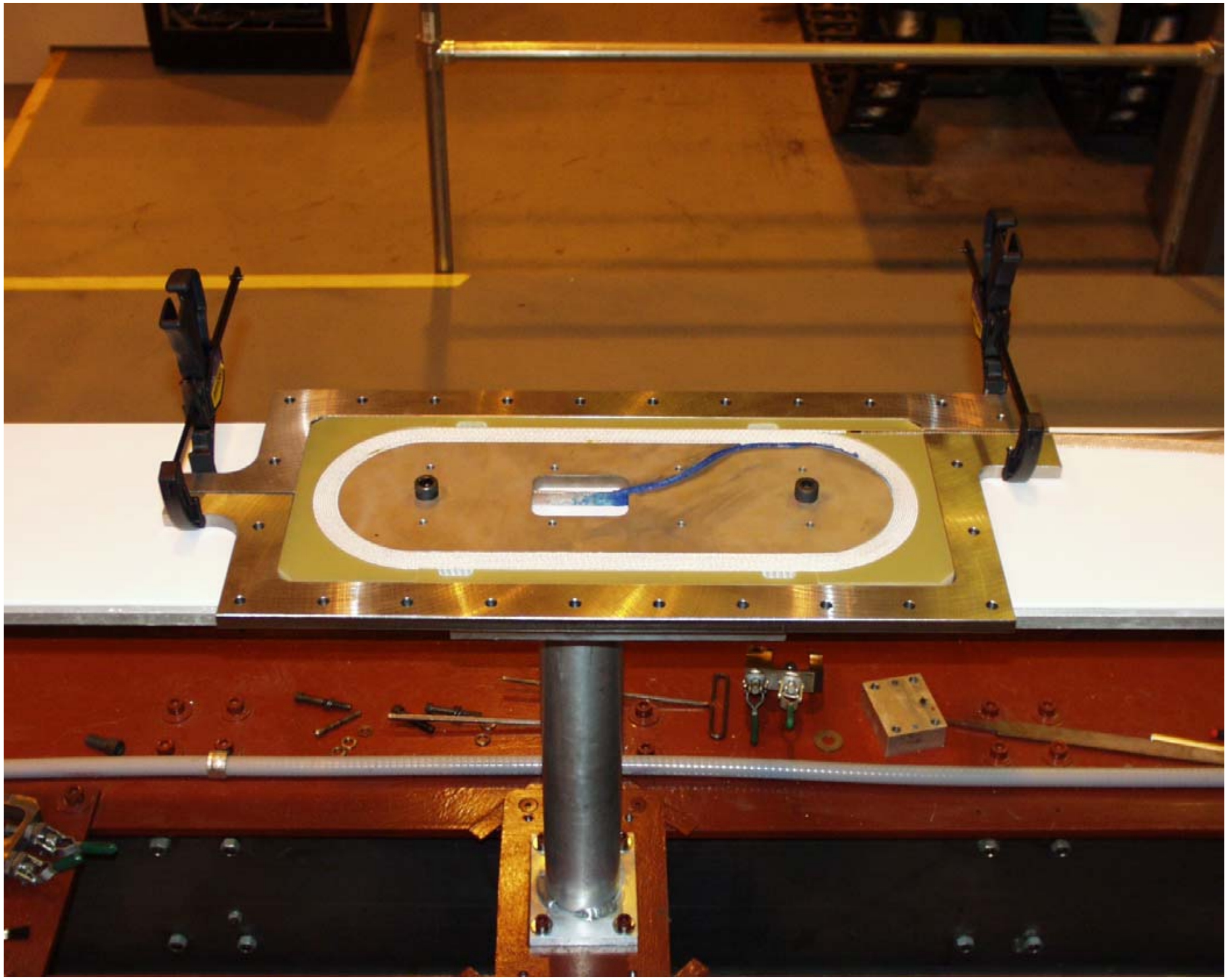
The first 10-turn practice coil
(removed from bobbin after impregnation)



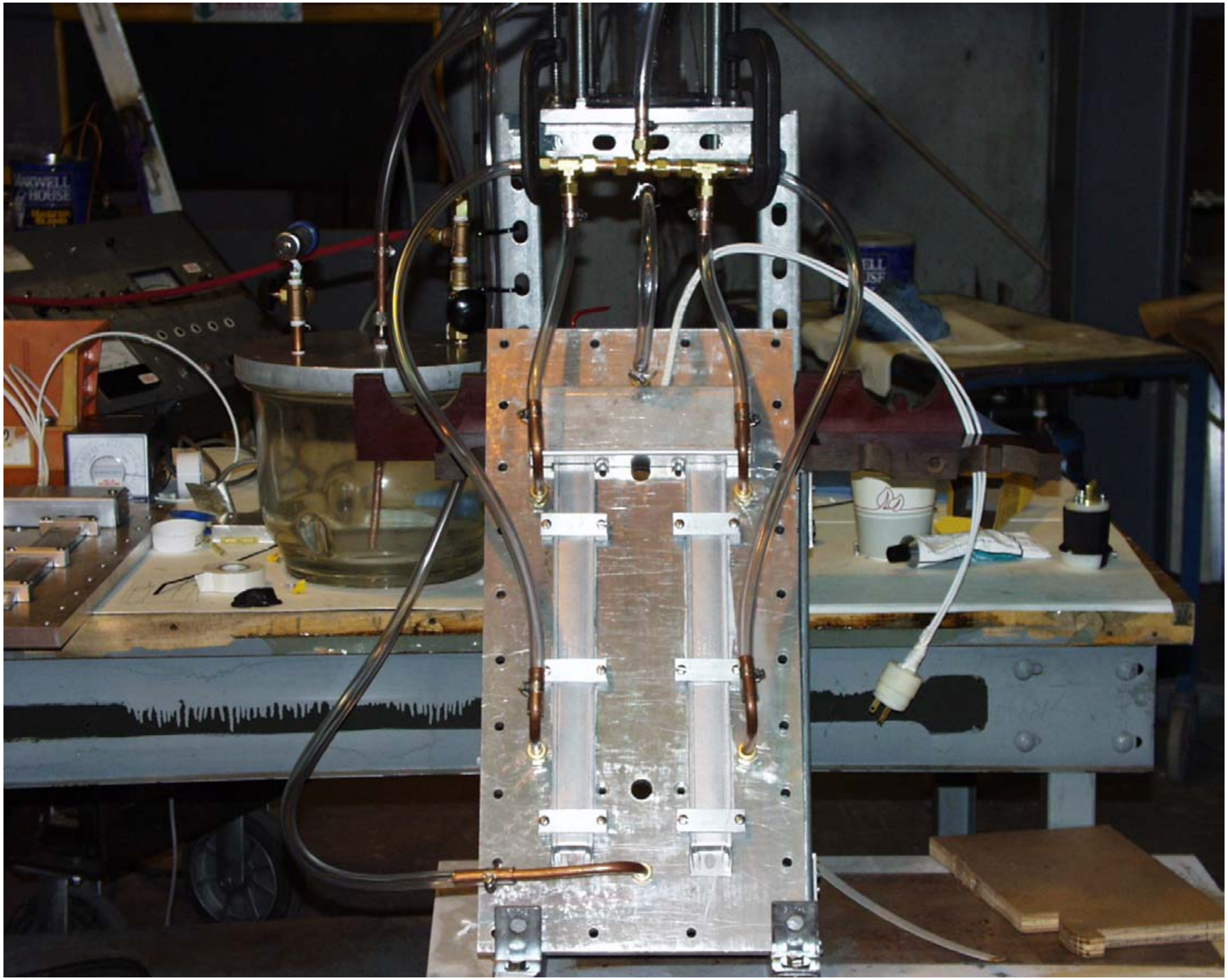
The complete cassette module
(vacuum impregnated coil in bobbin)

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

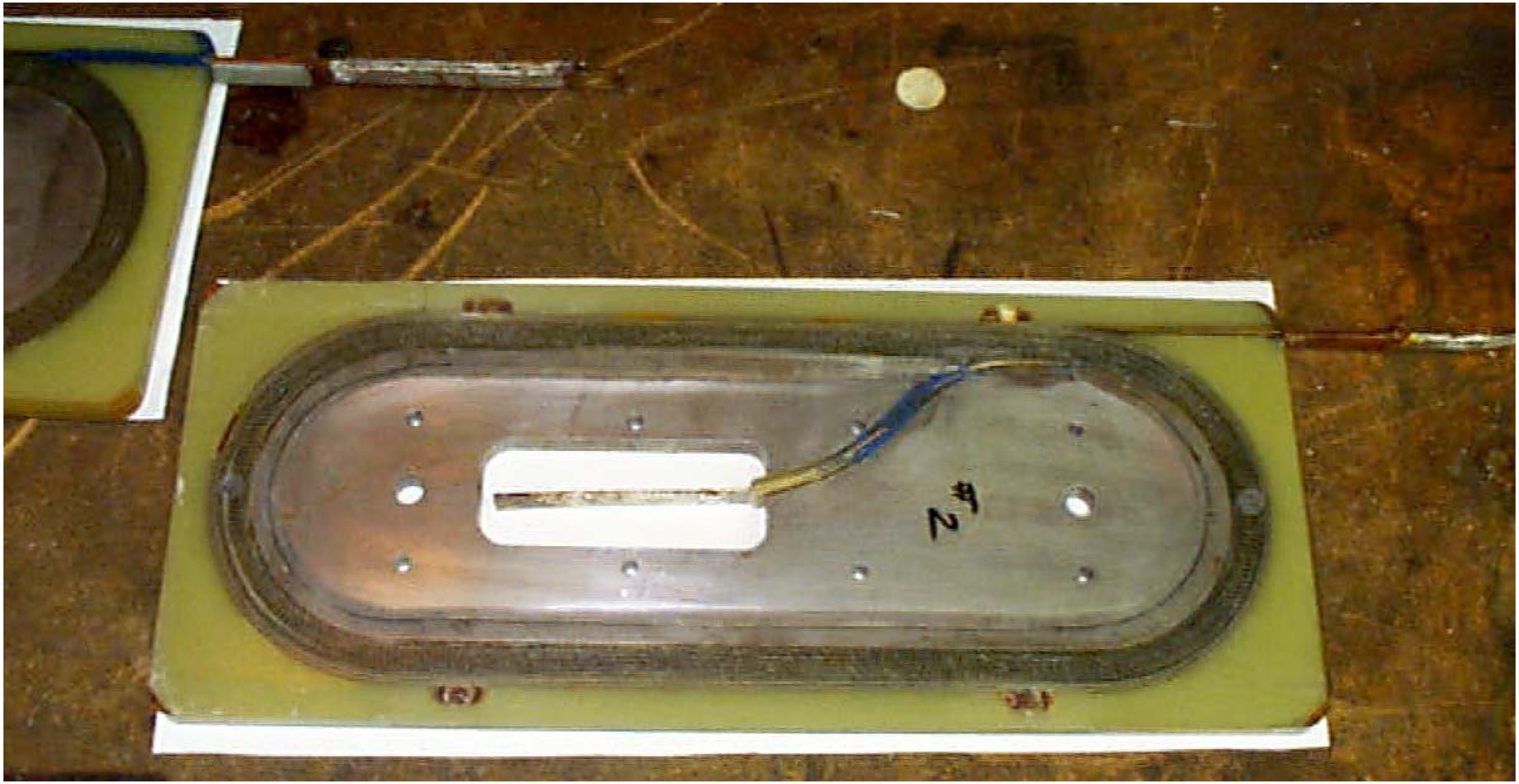
10-turn Coil Being Prepared for Vacuum Impregnation



Vacuum Impregnation Setup



Vacuum Impregnated Coils



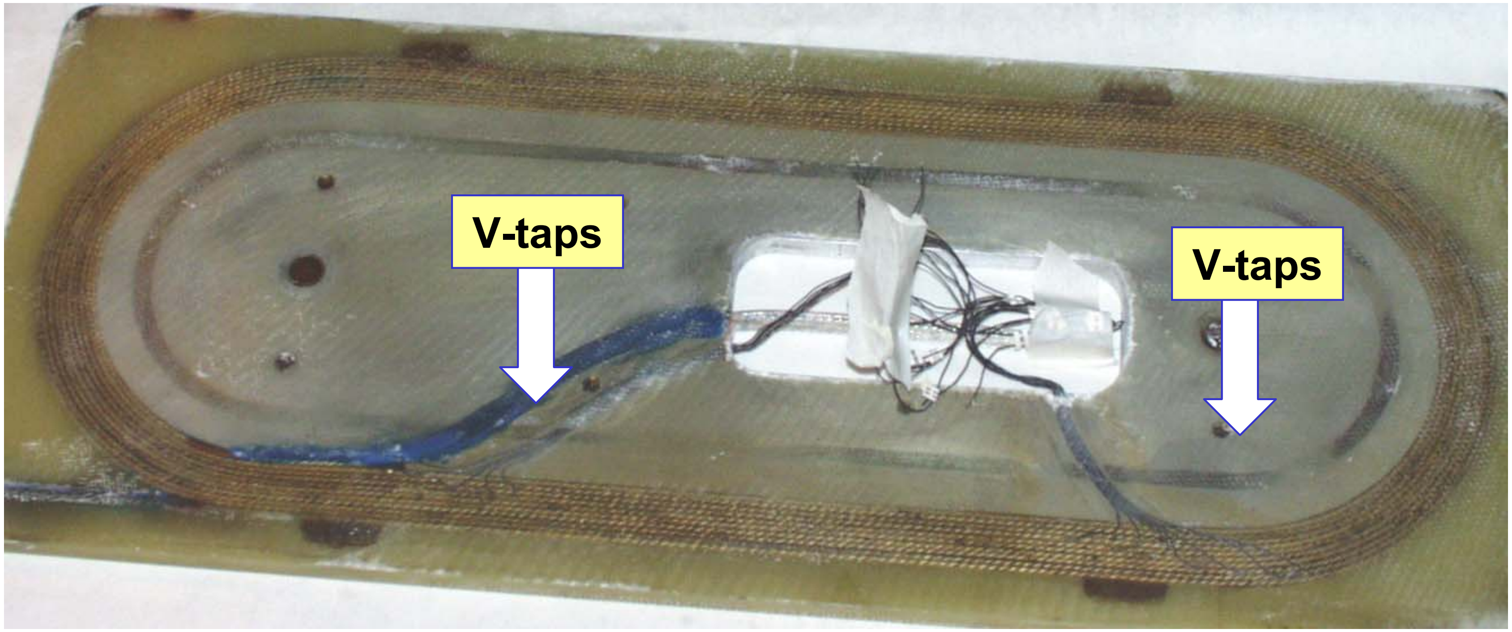
Vacuum impregnated coils made with the "react and wind" technique.

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.

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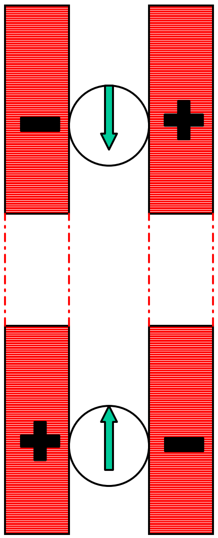
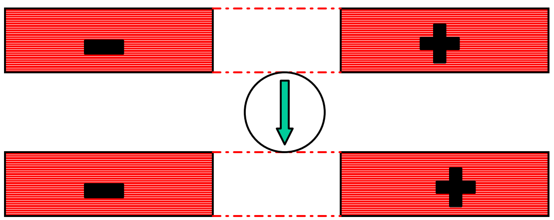
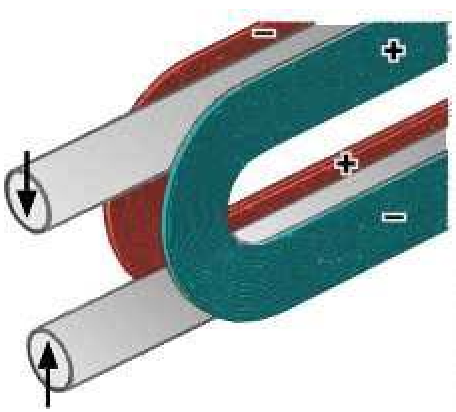
Common Coil and Muon Collider Test Configurations

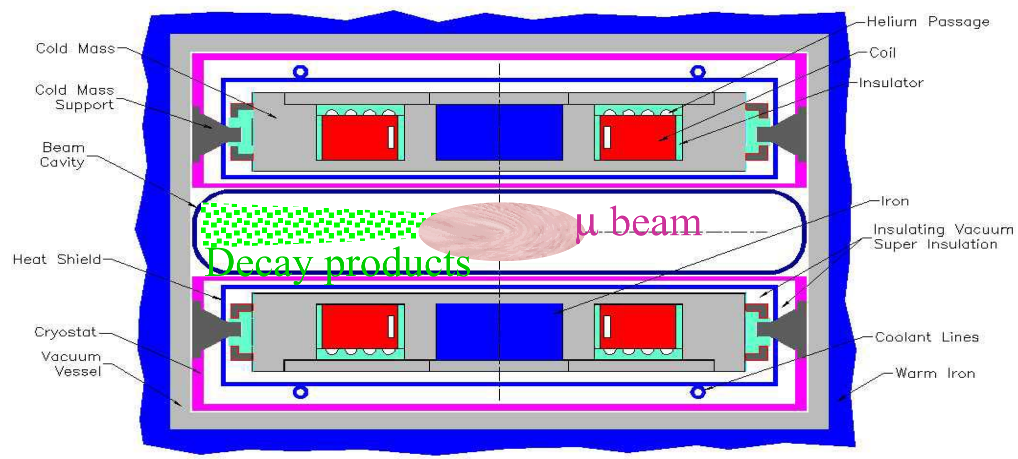
Common Coil configuration **muon collider configuration**



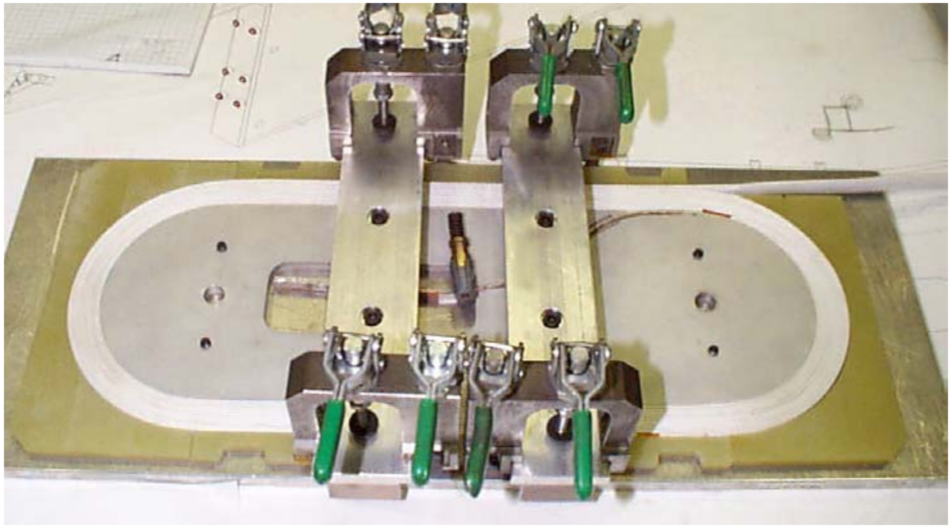
Powering differently changes a common coil design test to a muon collider design test





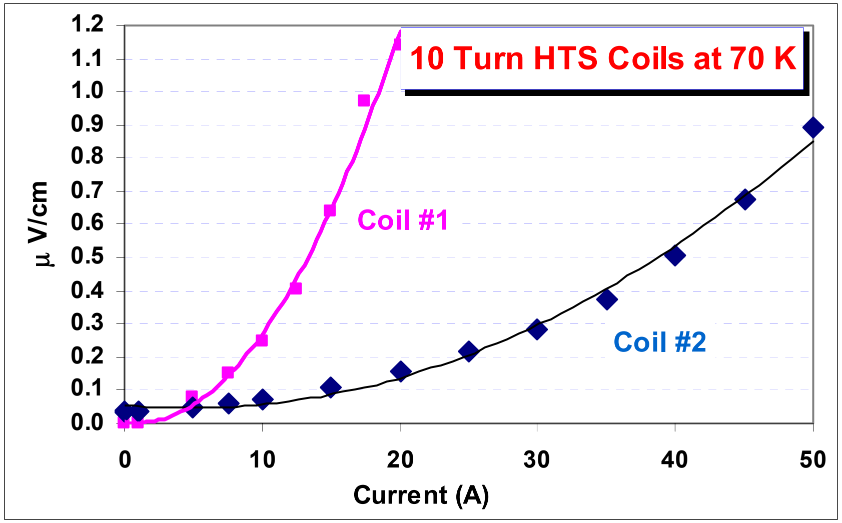


Common Coil Magnets With HTS Cable



HTS cable coil prior to vacuum impregnation

Two coils were tested in Liquid Nitrogen



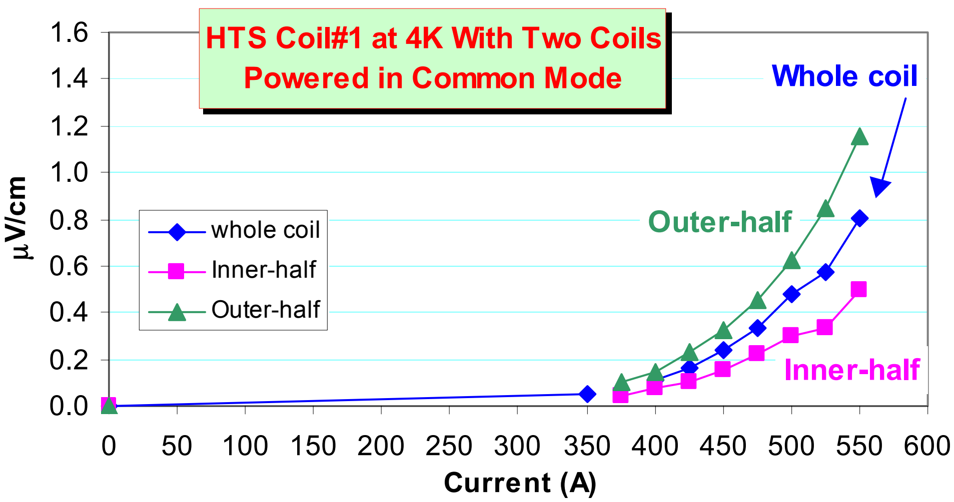
A coil cassette made with HTS cable after vacuum impregnation and instrumentation

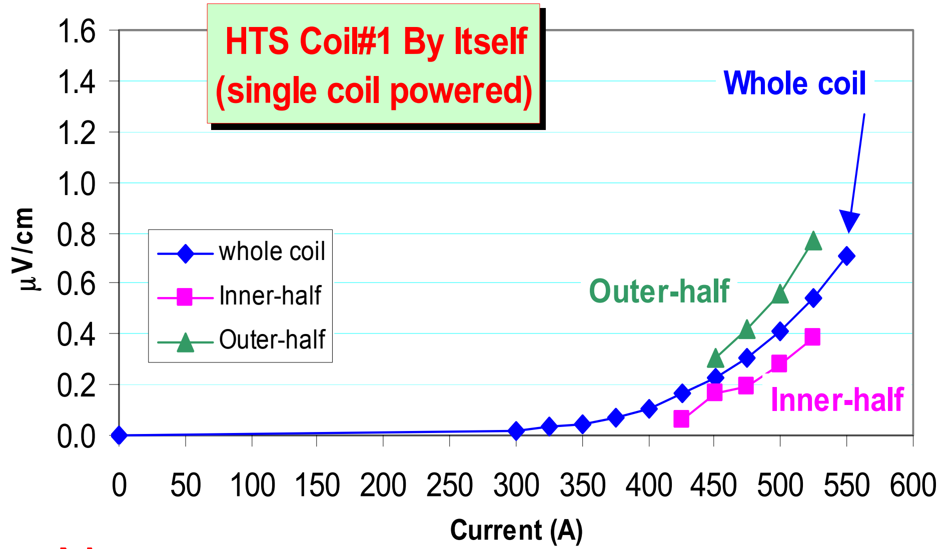
The HTS cables were from two different batches. They behaved differently:

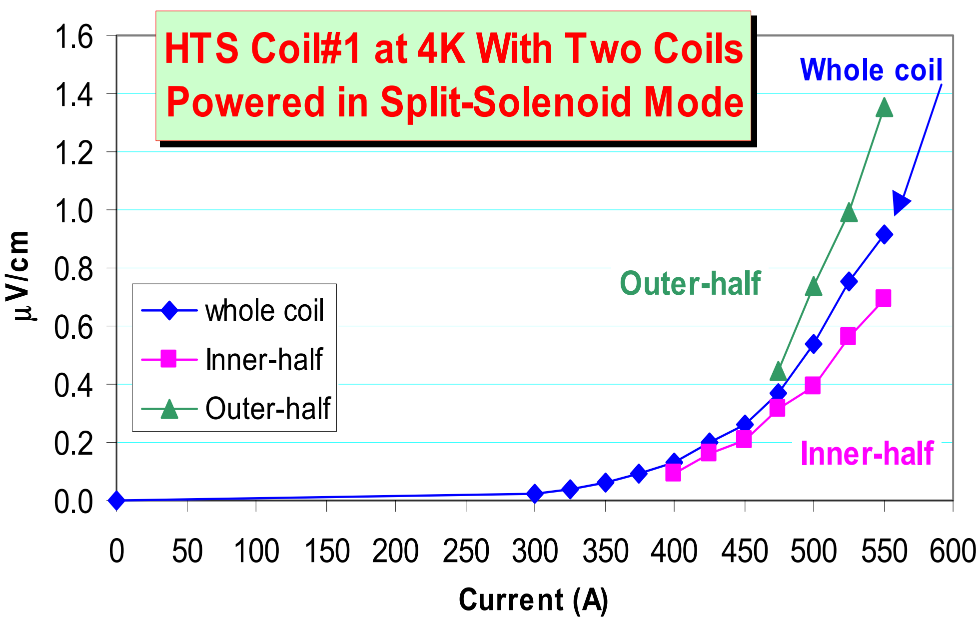
- Different Ic
- Different Tc

Based on preliminary analysis, no large degradation is observed.

4K Performance of 1st Common Coil HTS Magnet





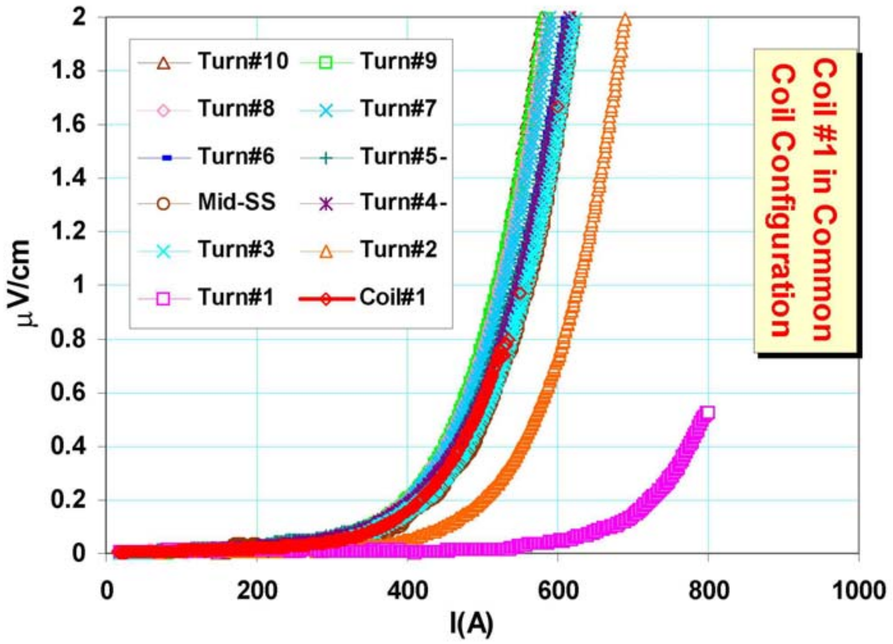


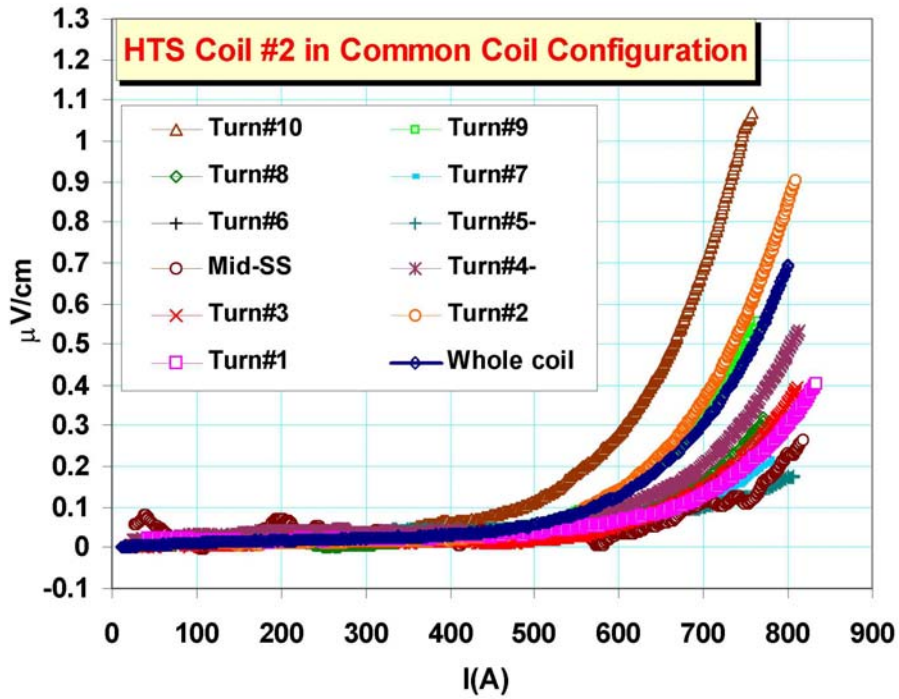
Notes:

- The cable in coil#2 was better than that used in coil #1; no clear onset of resistive state was observed up to 550 A. See results of next tests at higher current.
- Observed performance of coil#1 is line with expectation (no large/significant degradation was observed).
- The inner coil half (smaller bend radius) has better performance. It was made with the better part of cable - as per LN2 measurements. This means that the cable performance rather than degradation during manufacturing is determining the performance --- an encouraging result indeed.

Performance of Coil #1 and Coil #2 in Common Coil Test Configuration

Voltage difference between each consecutive turn and on each coil





Measurements in HTS Magnet DCC002 at 4.2 K

HTS Coil Test Magnet #2

The previous test magnet was made with cable from early wire

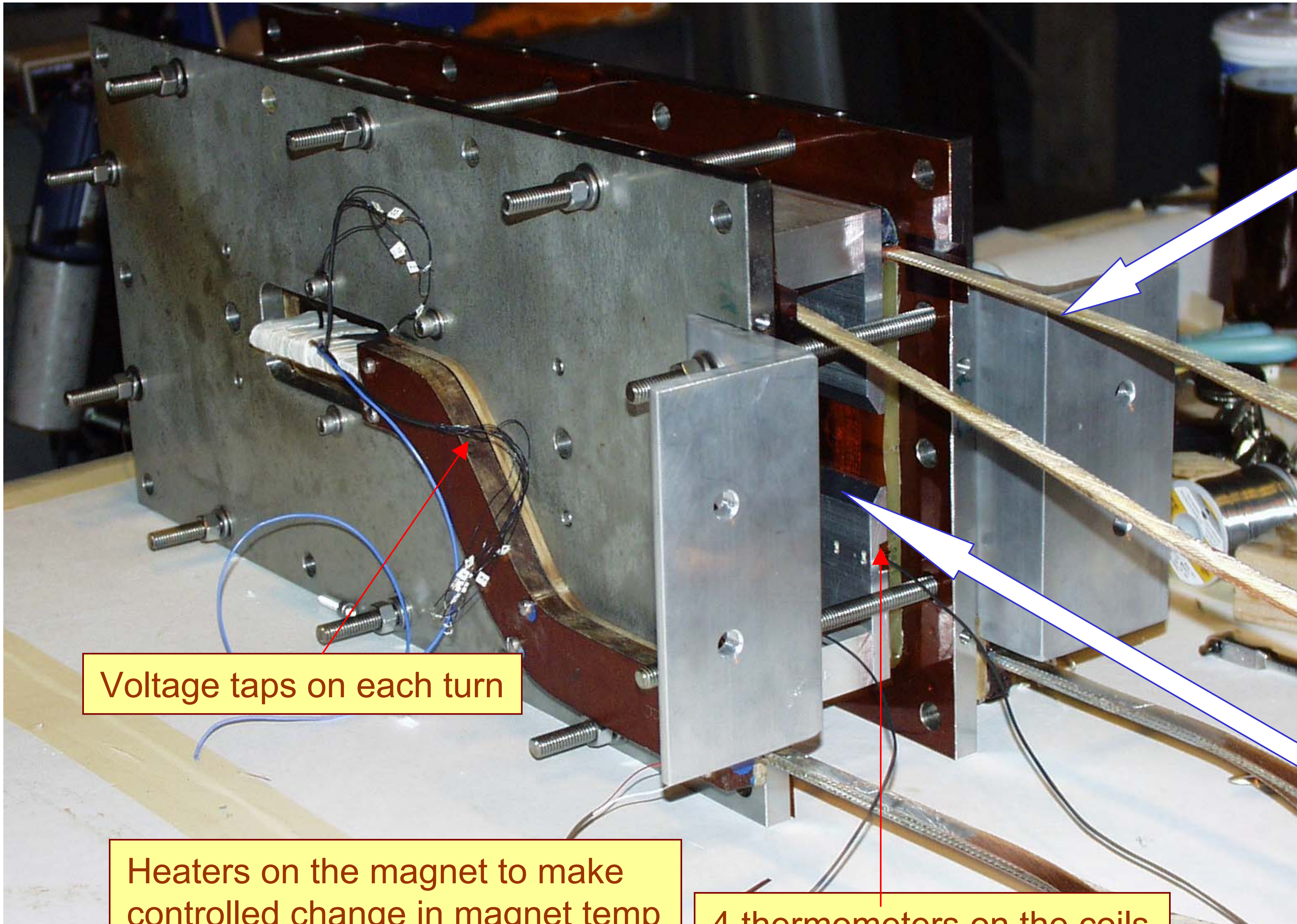
The state-of-the-art wire is now a factor of three better

Next magnet is made with coils from better wire/cable
(not state-of-the-art yet)

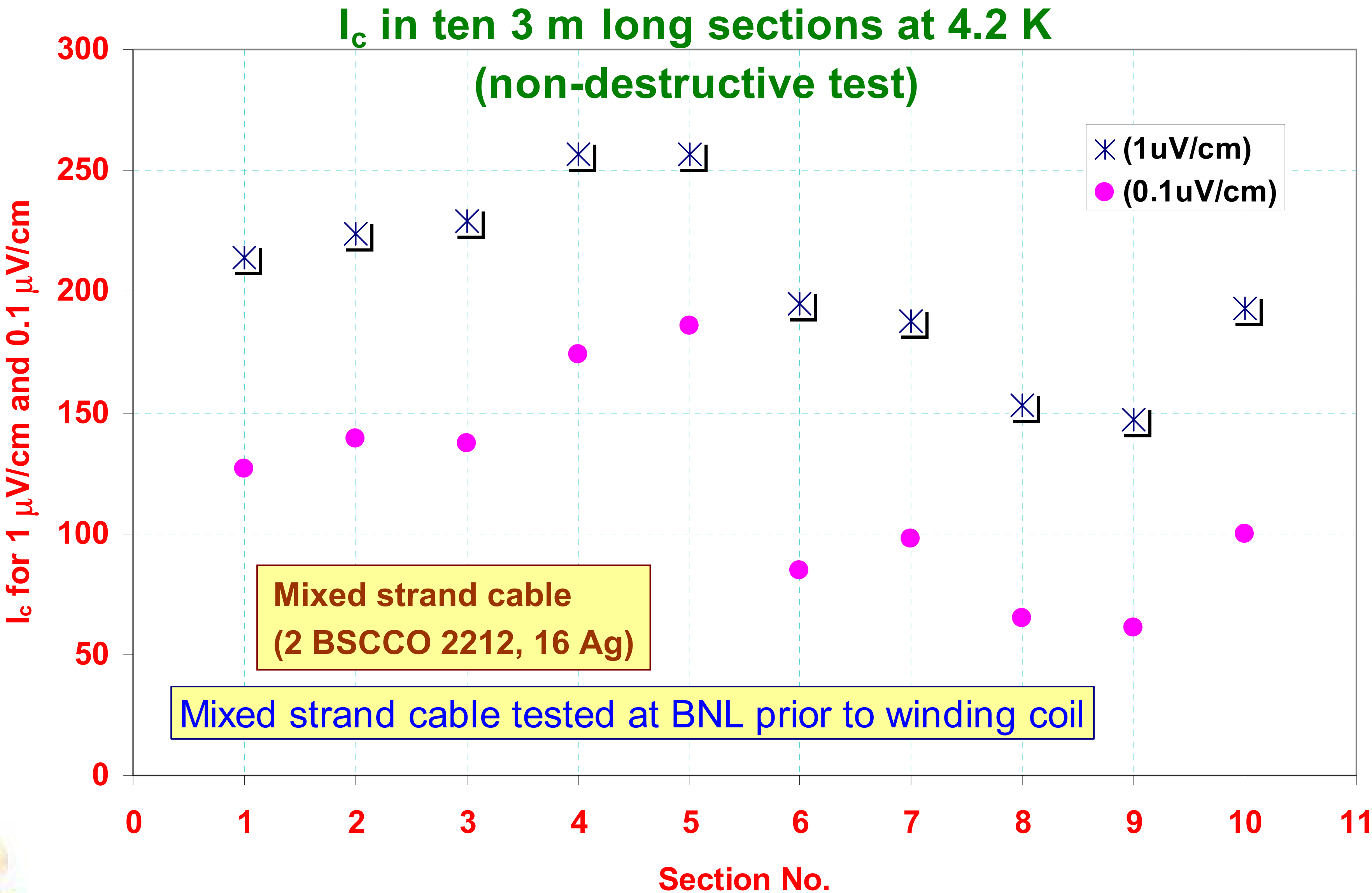
Cable has only 2 HTS strands; remaining 16 are made of Silver

Magnet DCC006: 2nd HTS Dipole

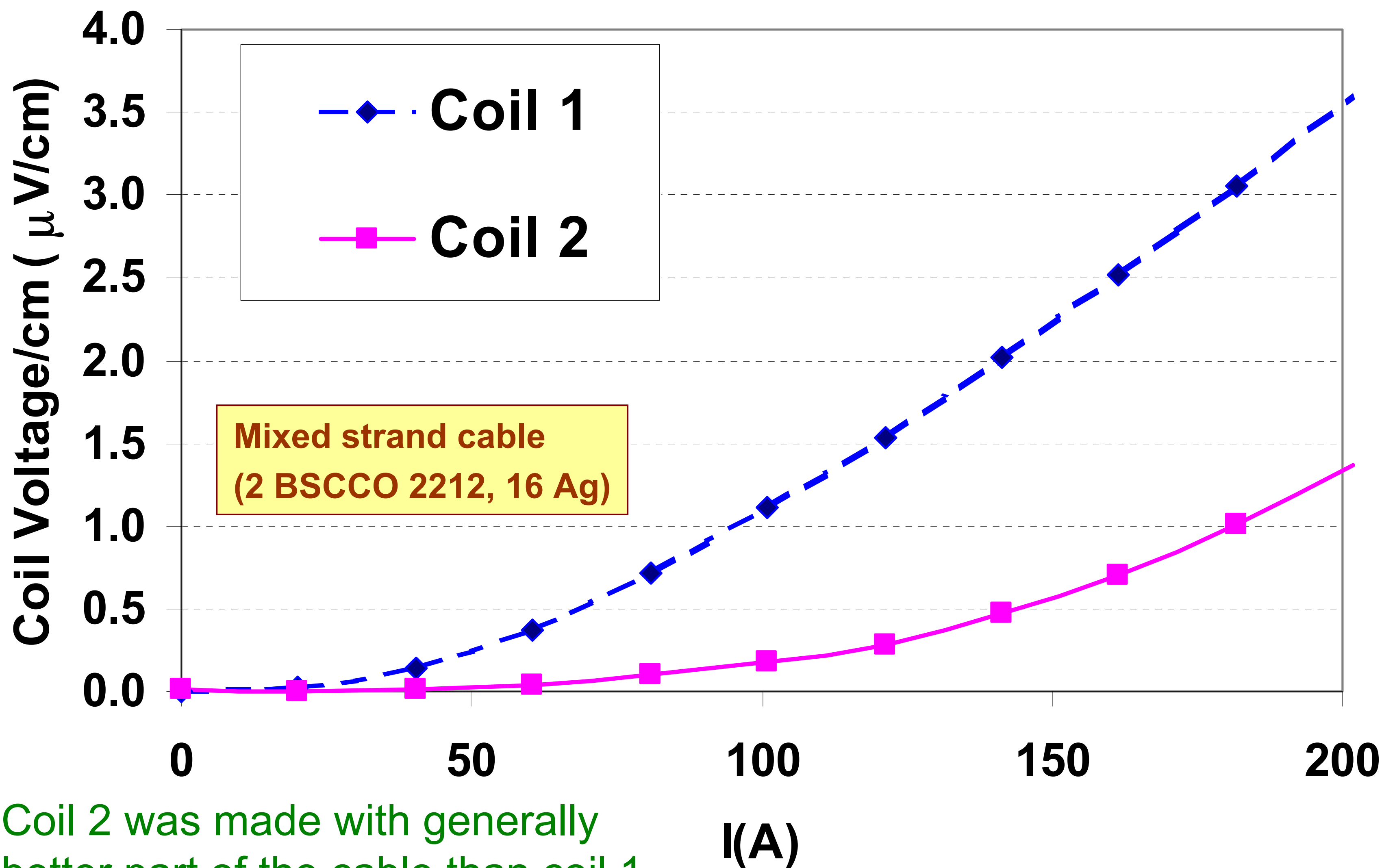
(Magnet No. 6 in the common coil cable magnet series)



Critical Current in Mixed Strand Cable



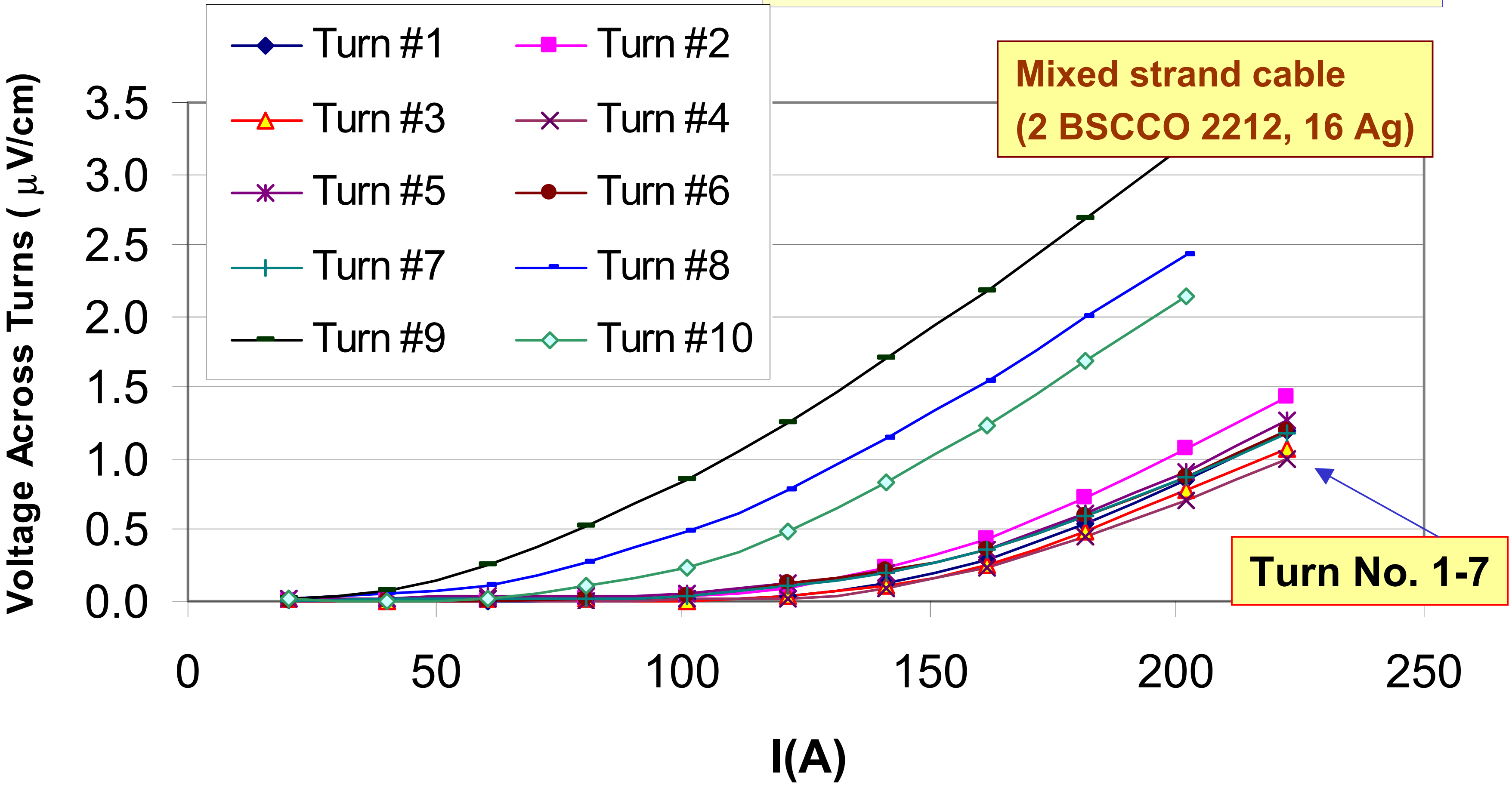
Performance of 2 Coils in Muon Collider Dipole Configuration



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

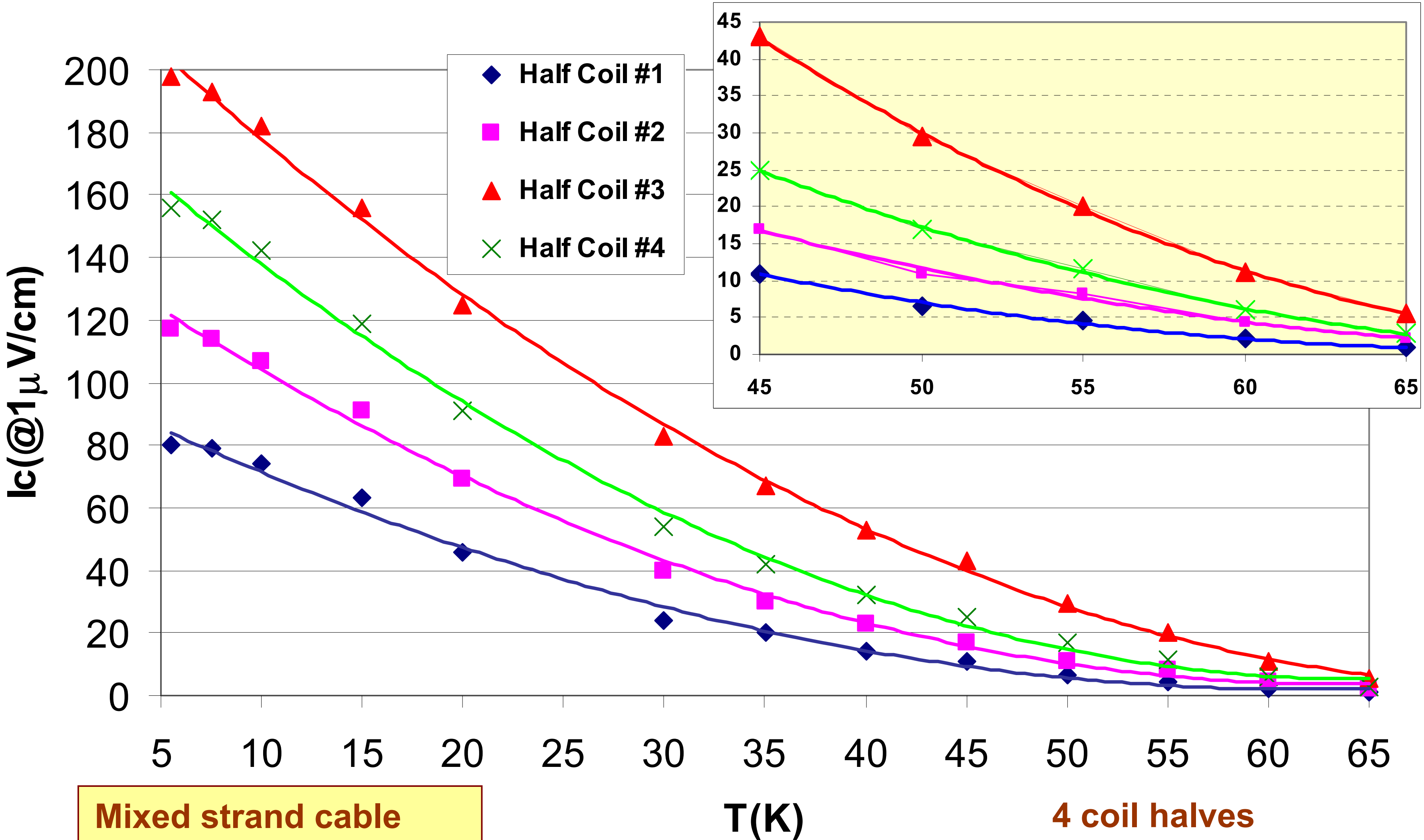
Measured Ic of Various Turns

Coil #2 of Mixed Strand Cable



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

Measured Critical Current as a Function of Temperature

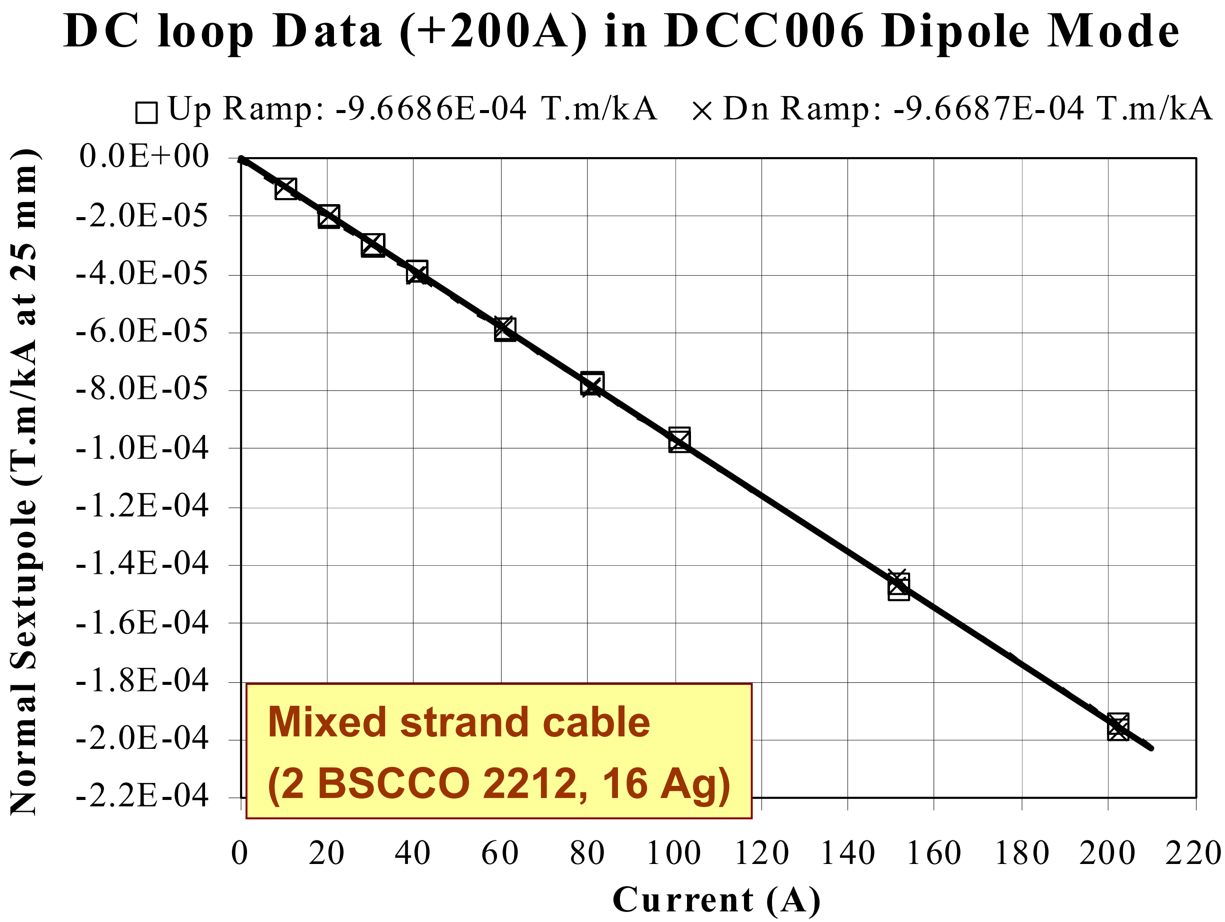


Mixed strand cable
(2 BSCCO 2212, 16 Ag)

4 coil halves
(2 each of two coils)

Field Quality Measurements

Sextupole Harmonic

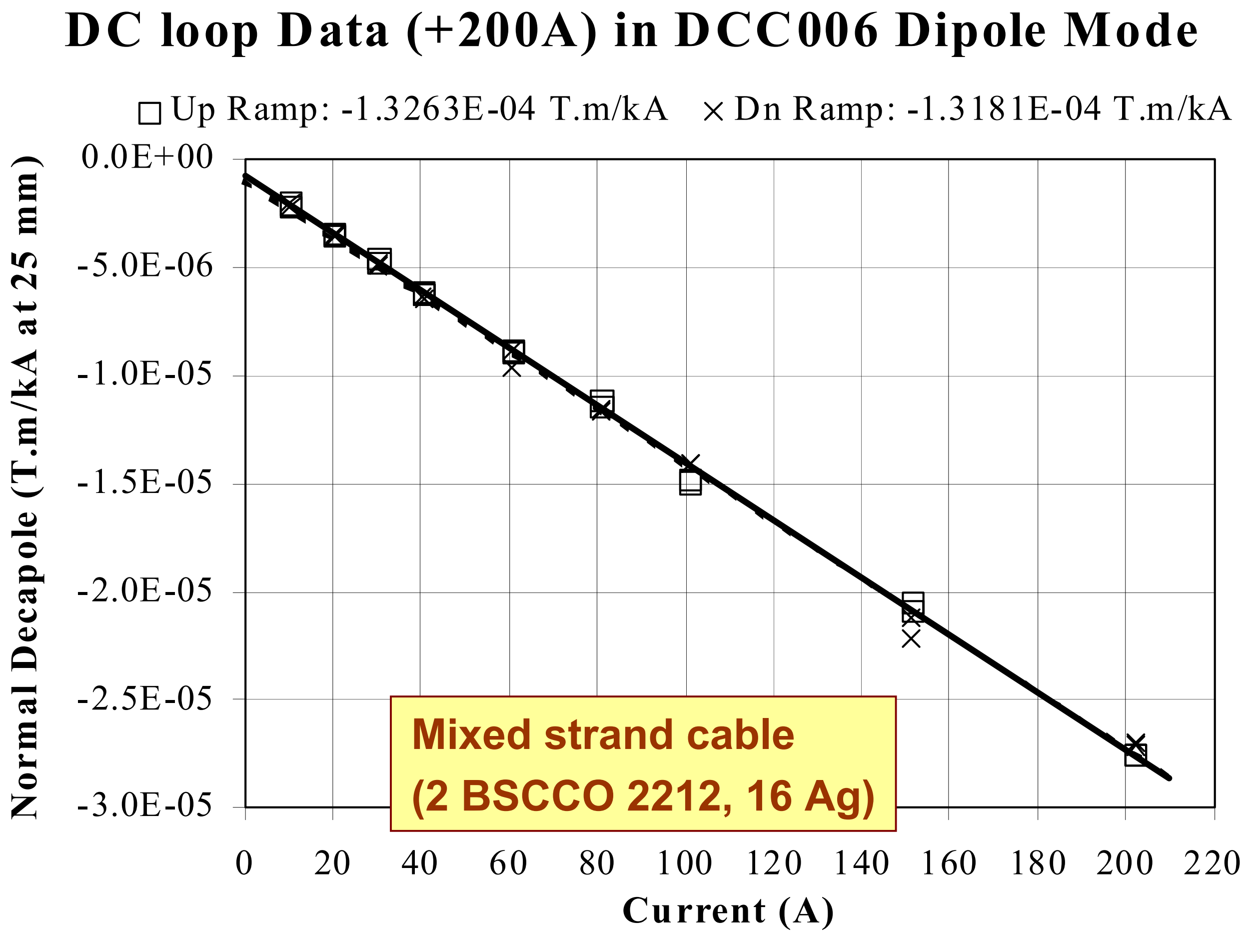


Difference between up and down ramp values is within measurement errors.

Max field on conductor was only ~550 Gauss. Expect a relatively less measurement when the total current is high in an all HTS cable.

Field Quality Measurements

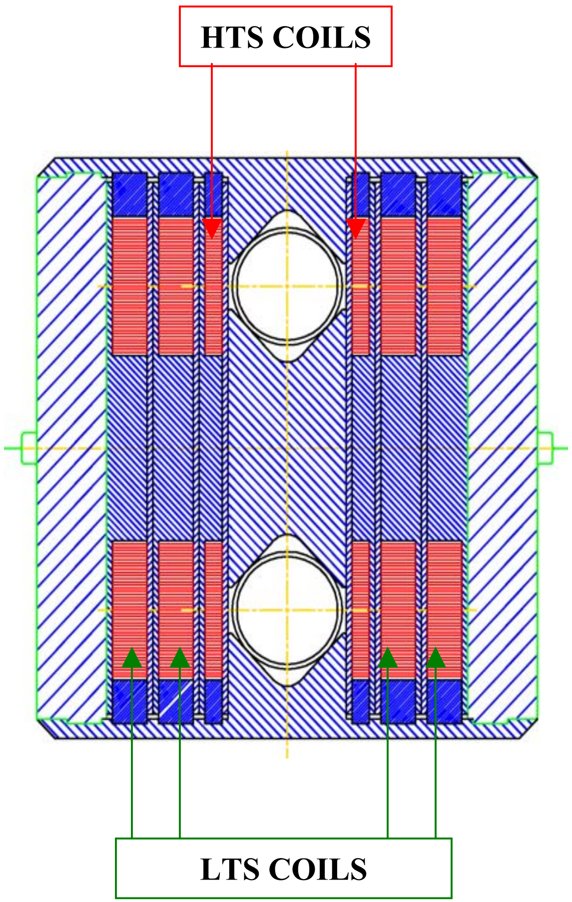
Decapole Harmonic



Difference between up and down ramp values is within measurement errors.

Max field on conductor was only ~550 Gauss. Expect a relatively less measurement when the total current is high in an all HTS cable.

HTS in a Hybrid Magnet



- Perfect for R&D magnets now. HTS is subjected to similar forces that would be present in a future high performance all HTS magnets. Therefore, several technical issues will be addressed.
- Field in outer layers is ~2/3 of that of the 1st layer. Use HTS in the 1st layer (high field region) and LTS in the other layers (low field regions).
- Possible design for specialty magnets where the performance, not the cost is an issue. Possible design for main magnets if cost of HTS comes down.

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.

SUMMARY

- **HTS has potential to make a significant impact on IR Design**
  - Can generate high fields
  - Can work at elevated temperature

- **New "conductor friendly designs" allow HTS "React & Wind" technology to be incorporated in accelerator magnets**

- **HTS has reached a level that one can do meaningful magnet R&D and address various technical issues**
  - The recent test results from Brookhaven are encouraging.

- **Time to start HTS magnet R&D is now so that we can make a better informed decision (in 5+ years) about the feasibility of HTS in next project or upgrade of existing one at that time**