New Magnet Designs
for
Future Colliders

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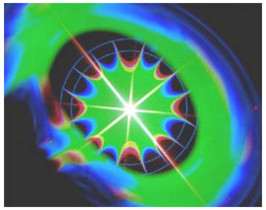


Present Magnet Design and Technology

Tevatron Dipole

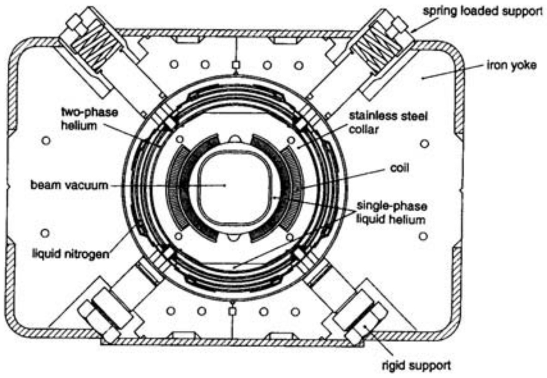
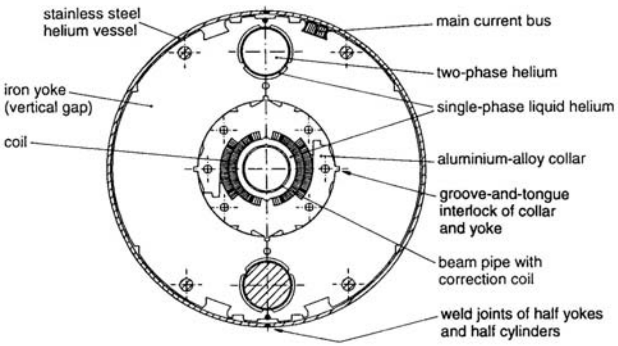
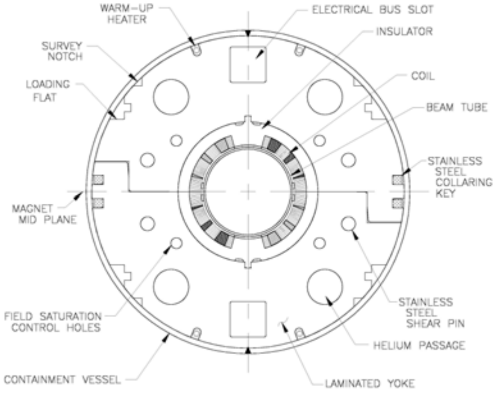


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

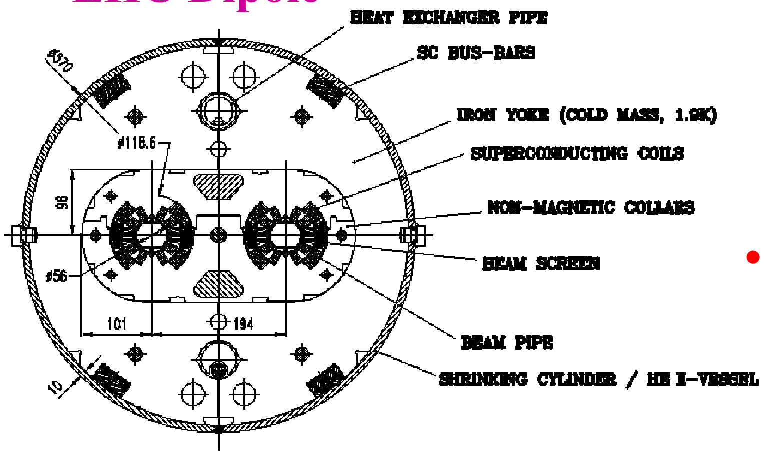
HERA Dipole



RHIC Dipole



LHC Dipole



- All magnets use Nb-Ti Superconductor.

  All designs use cosine theta coil geometry.

- The technology has been in use for decades. It has matured by now.

- The cost is "unlikely to reduce" and the "performance is unlikely to improve" significantly.

LHC Upgrade:
It may not too early to think

LHC upgrade

- Luminosity upgrade within the same layout
- Energy upgrade within the same tunnel

Both need very high field magnets

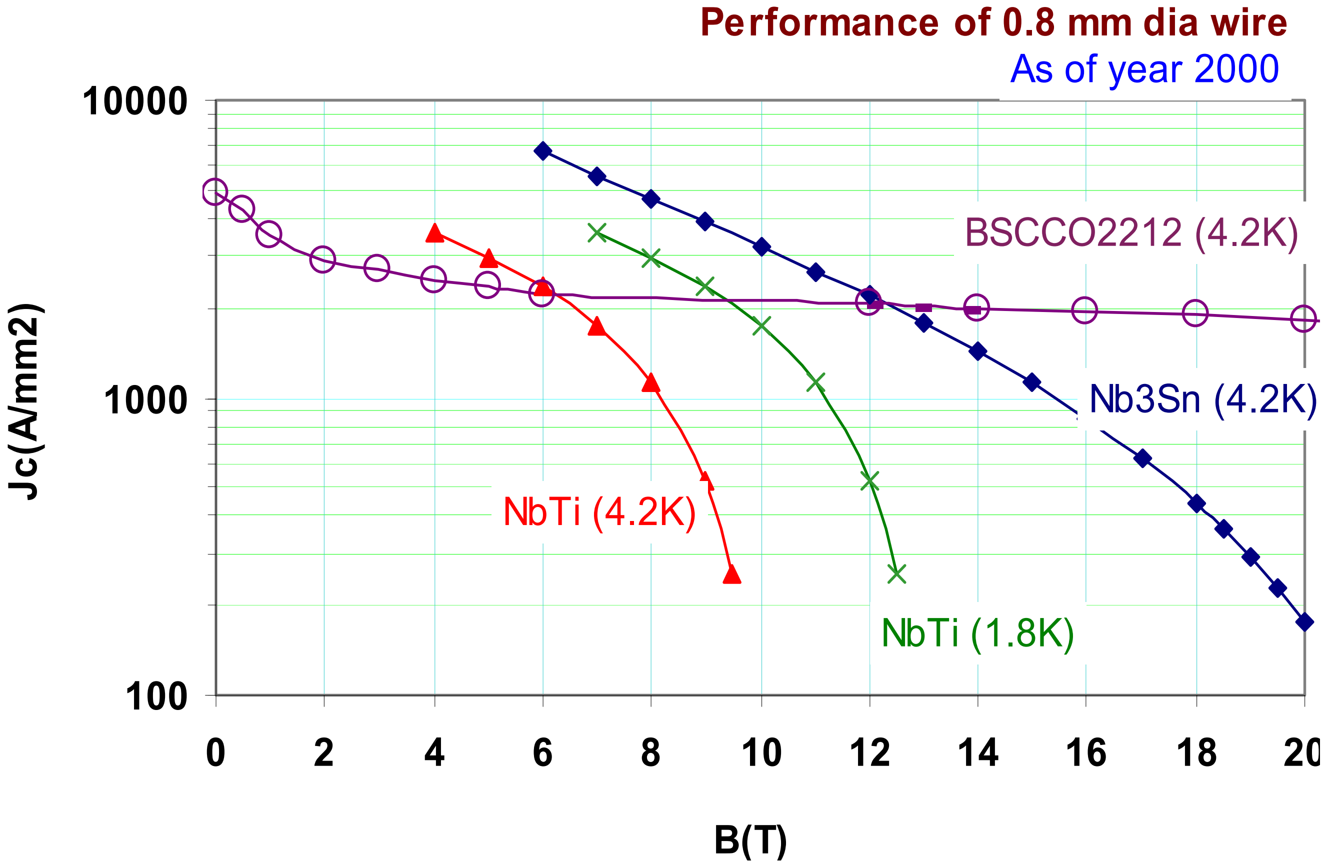
(about a factor of two over the present technology)

High Field Superconductors

Most popular conductor for high field magnet R&D: Nb_3Sn

Most interesting conductor for very high field magnet R&D: HTS

Both are brittle. Both are available in small quantities; suitable for R&D magnets only



For high field magnets, we are interested in the "Low Temperature", performance of "High Temperature Superconductors (HTS)".

Design Issues for High Field Accelerator Magnets using HTS

- Nb_3Sn & HTS are brittle

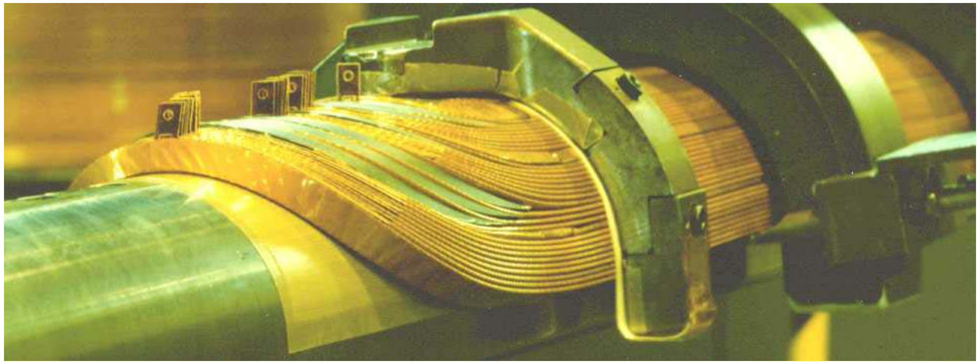
  Conventional designs are not most suitable

- Large Lorentz forces

- The required temperature uniformity during the reaction of HTS is high

  (~1/2 degree at ~890° C)

  React & Wind Approach

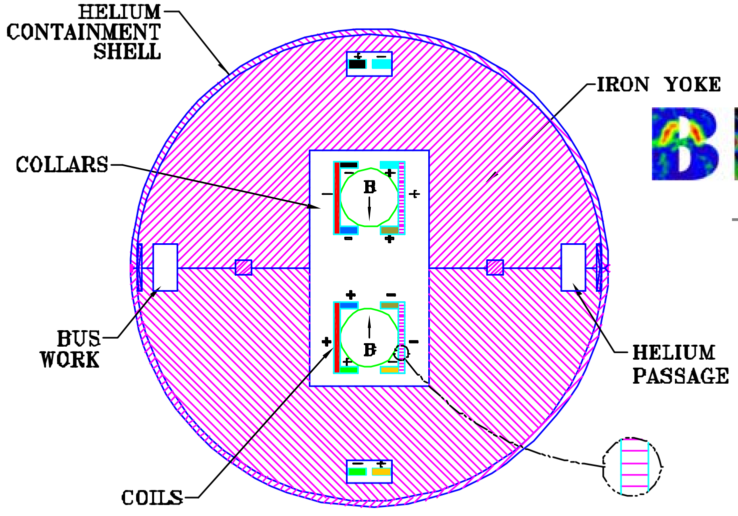


Conventional cosine θ design (e.g., RHIC magnets)

Complex 3-d geometry in the ends

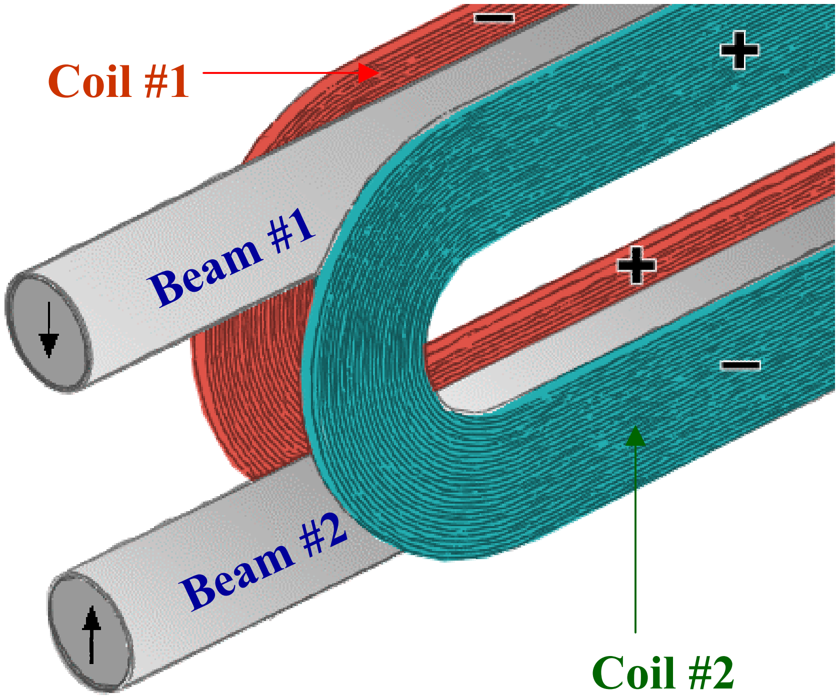
Conductor friendly racetrack coil with large bend radius

Suitable for high field magnets with brittle material



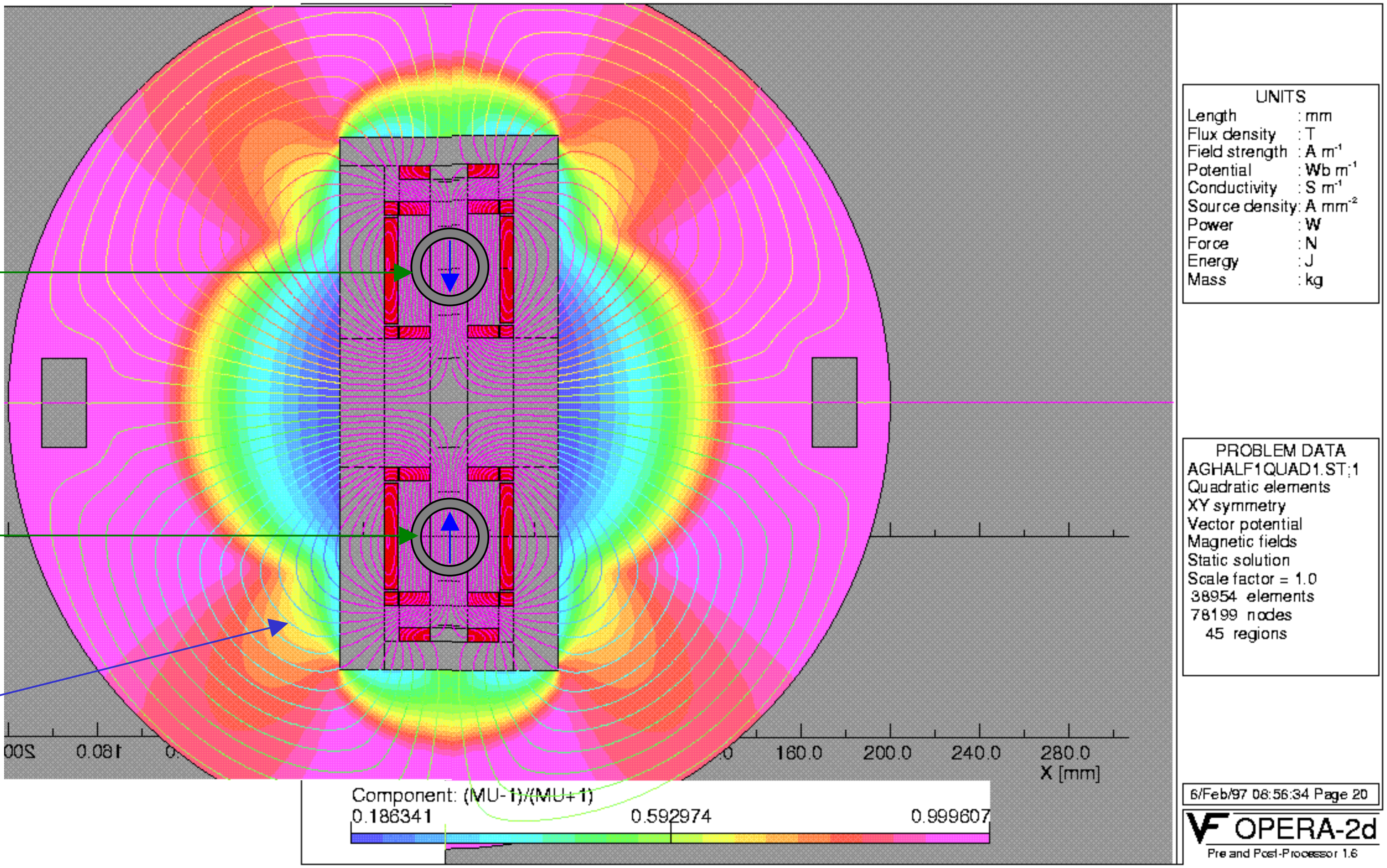
Common Coil Design

- **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



UNITS
Length : mm
Flux density : T
Field strength : A m^{-1}
Potential : Wb m^{-1}
Conductivity : S m^{-1}
Source density: A mm^{-2}
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
AGHALF1QUAD1.ST;1
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 1.0
38954 elements
78199 nodes
45 regions

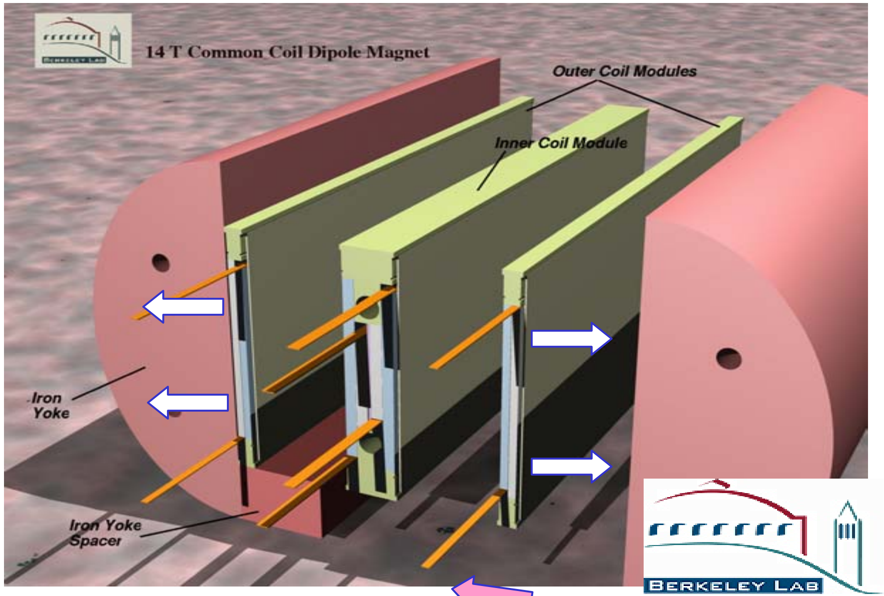
Aperture #1

Aperture #2

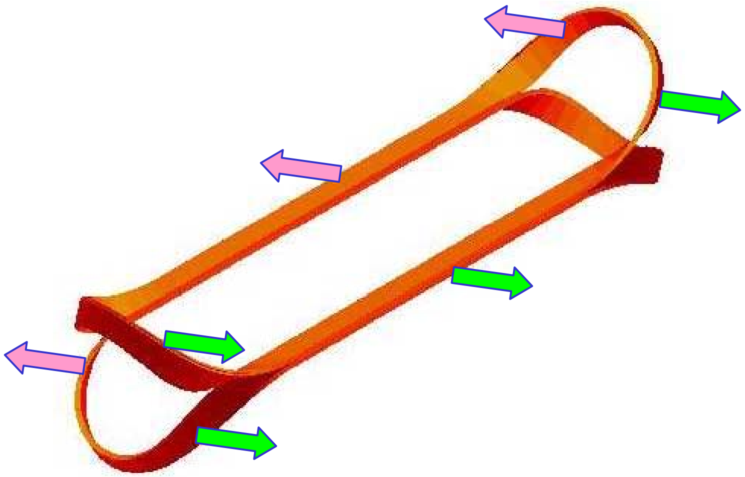
Place of maximum iron saturation

Common Coil Design in Handling Large Lorentz Forces in High Field Magnets

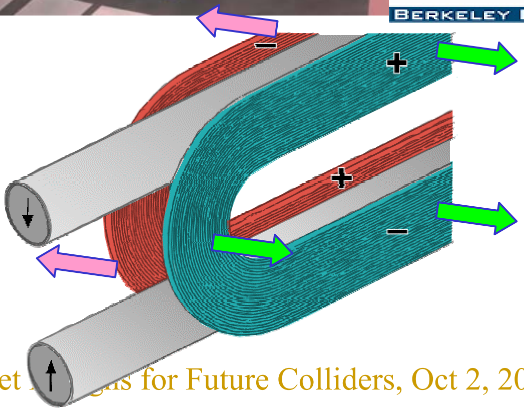
In common coil design, geometry and forces are such that the impregnated solid volume can move as a block without causing quench or damage. Ref.: over 1 mm motion in LBL common coil test configuration).



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.

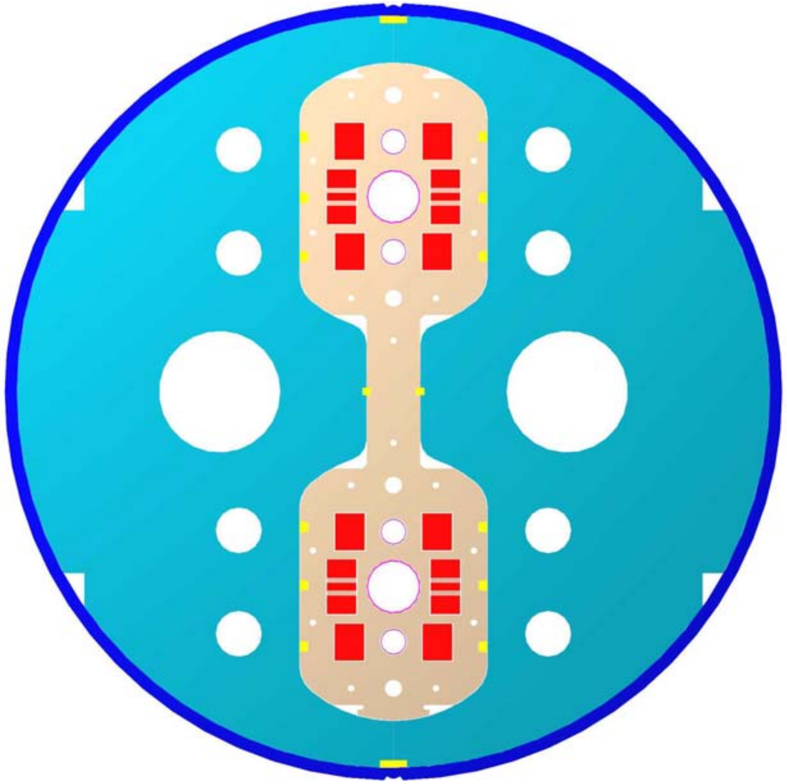


Horizontal forces are larger



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).

Status of R&D on Common Coil Magnets



Fermilab Design of Common Coil Magnet for VLHC-2

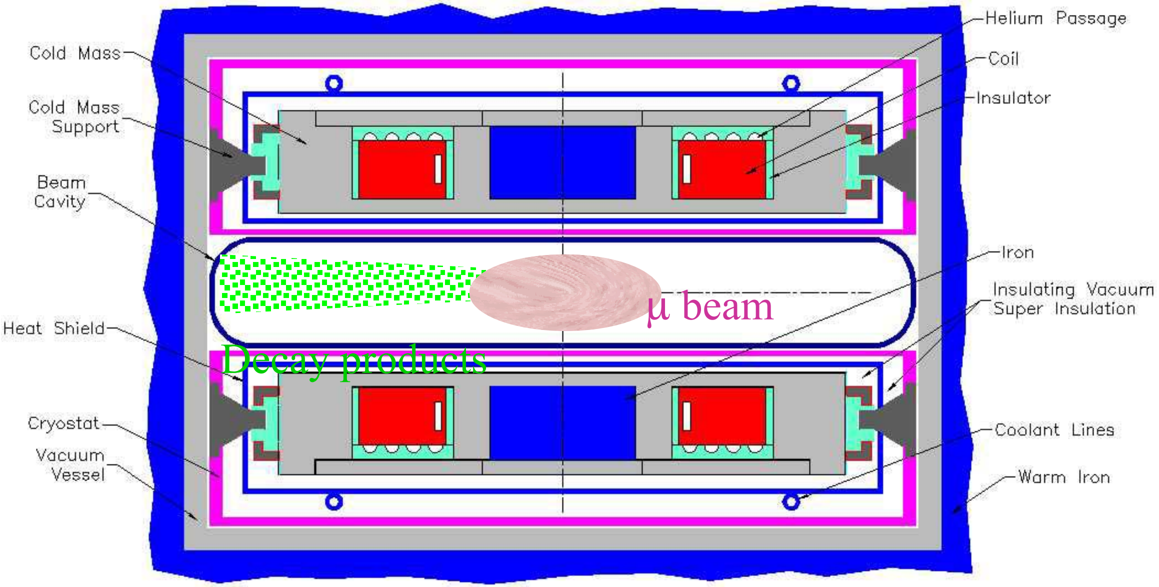
- A large number of papers (20-40) written (number of designs with good field quality shown)
- All three major US labs are working on this design
- A significant number (10+) of R&D test magnets built in last few years
- Record magnetic field is obtained (14.7 T @LBL)
- New material (HTS) introduced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

Magnet Design for ν Factory

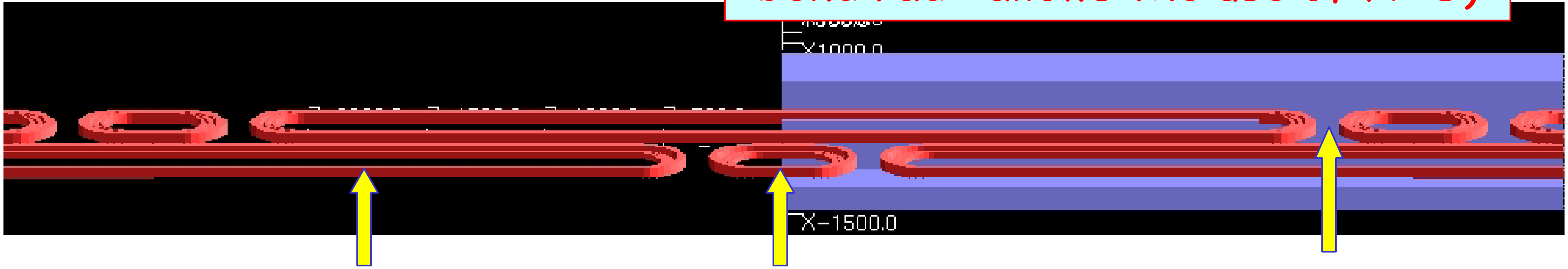
Decay products clear superconducting coils

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 allows the use of HTS)



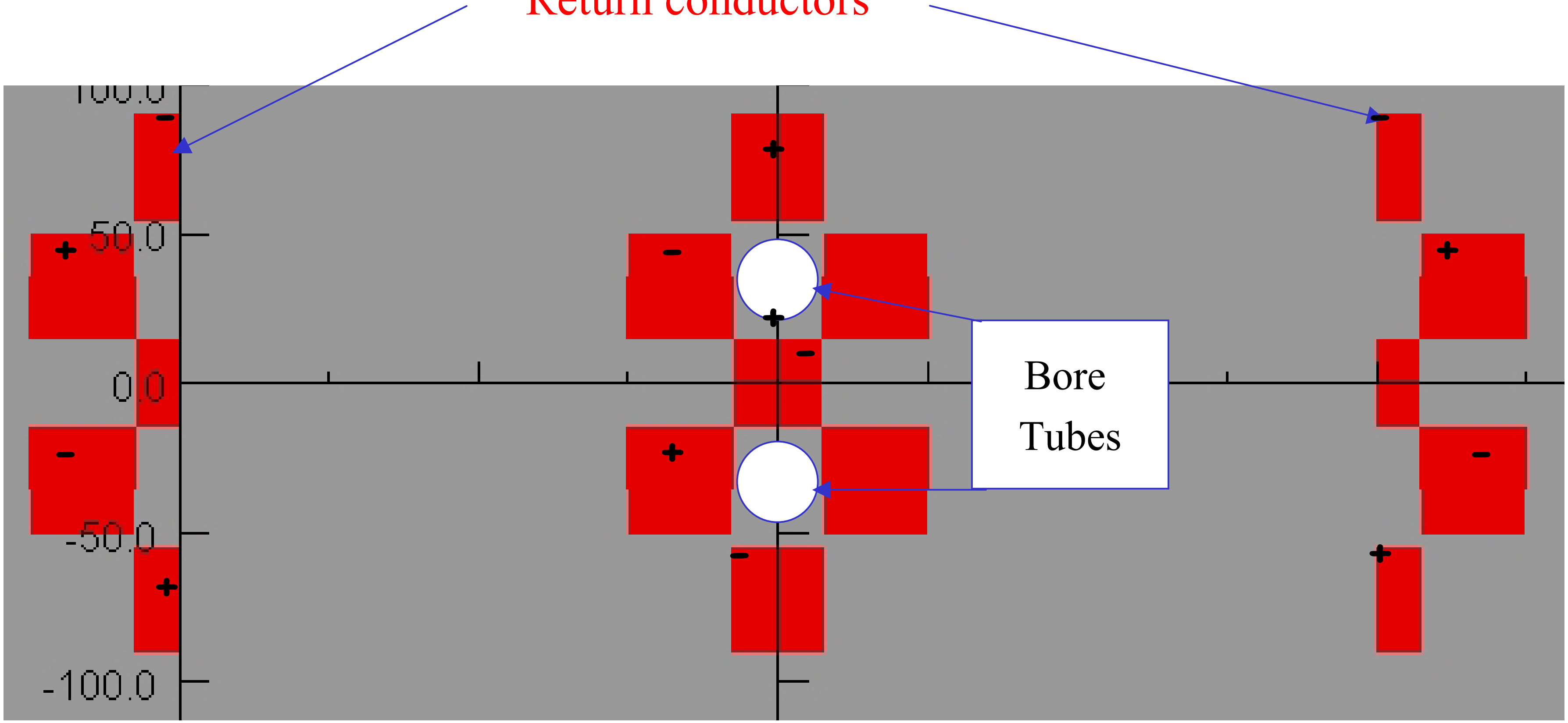
Normal Coils
Dipole

Reverse Coils
Skew Quad

One Coil
1/2 & 1/2

VLHC-2 Interaction Region Magnet Design (Preliminary)

Conductor friendly IR quad design



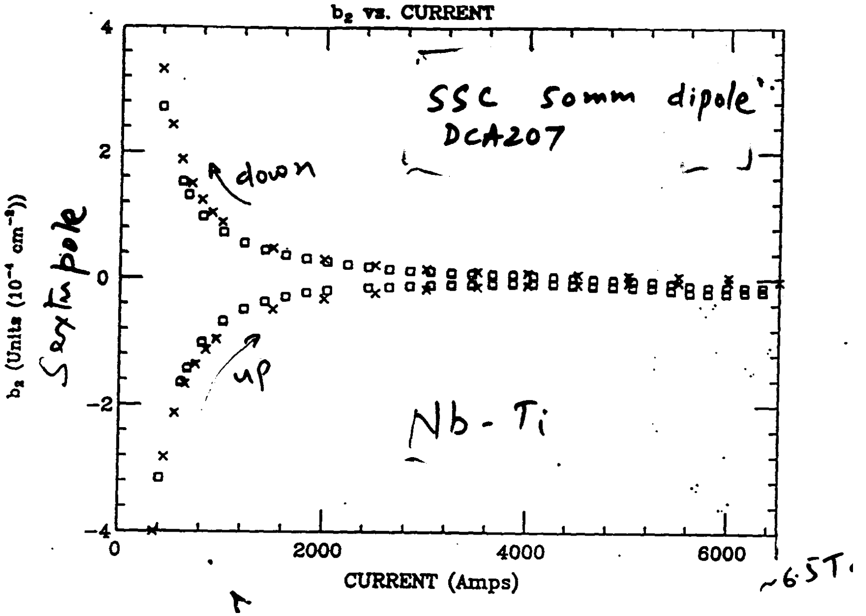
(simple racetrack coils with large bend radii allows the use of HTS)

Persistent Current-induced Harmonics
(may be a problem in Nb_3Sn magnets, if done nothing)

Nb_3Sn superconductor, with the technology under use now, is expected to generate persistent current-induced harmonics which are **a factor of 10-100 worse** than those measured in Nb-Ti magnets.

In addition, a snap-back problem is observed when the acceleration starts (ramp-up) after injection at steady state (constant field).

Measured sextupole harmonic
in a Nb-Ti magnet



Measured sextupole harmonic
in a Nb_3Sn magnet

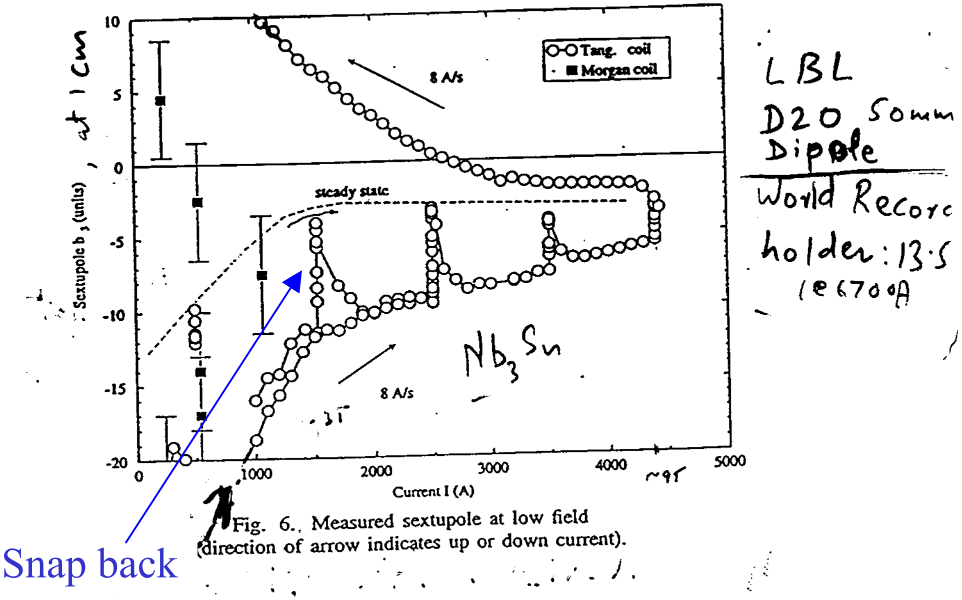


Fig. 6., Measured sextupole at low field (direction of arrow indicates up or down current).

Snap back

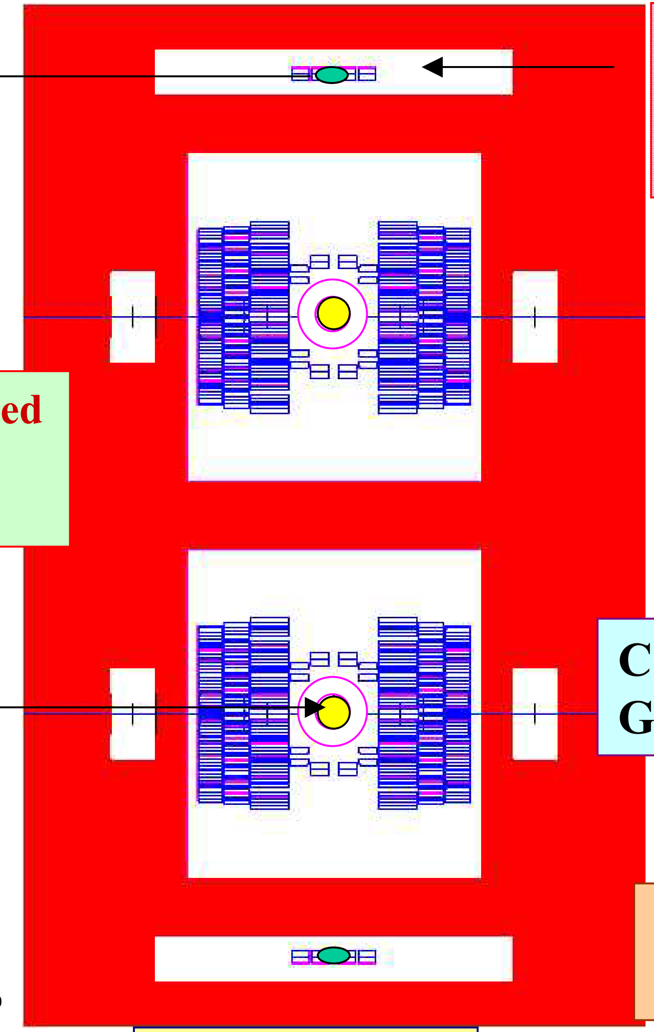
The iron dominated aperture in a common coil magnet system overcomes the major problem associated with magnets using Nb3Sn superconductor.

A Common Coil Magnet System for VLHC

A Solution to Persistent Current Problem

May eliminate the High Energy Booster (HEB)

A 4-in-1 magnet for a 2-in-1 machine



Inject in the iron dominated aperture at low field and accelerate to medium field

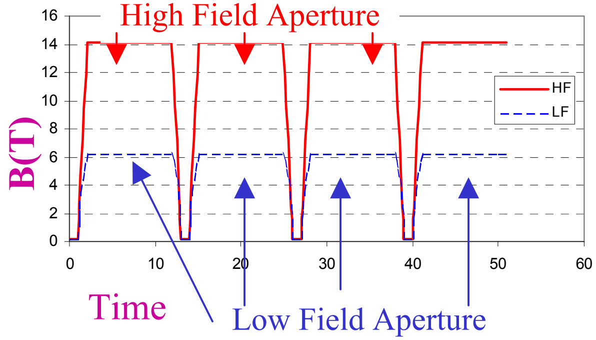
Injection at low field in iron dominated aperture should solve the large persistent current problem associated with Nb3Sn

Transfer to conductor dominated aperture at medium field and then accelerate to high field

Conductor dominated aperture Good at high field (1.5-15T)

Iron dominated aperture Good at low field (0.1-1.5T)

Field profile with time



Compact size

AP issues? Compare with the Low Field Design.

Common Coil Magnet System
(Estimated cost savings by eliminating HEB)

SSC: 20+20 TeV;
VLHC: 50+50 TeV

Based on 1990 cost in US$

2 TeV HEB Cost in SSC (derived):
$700-800 million

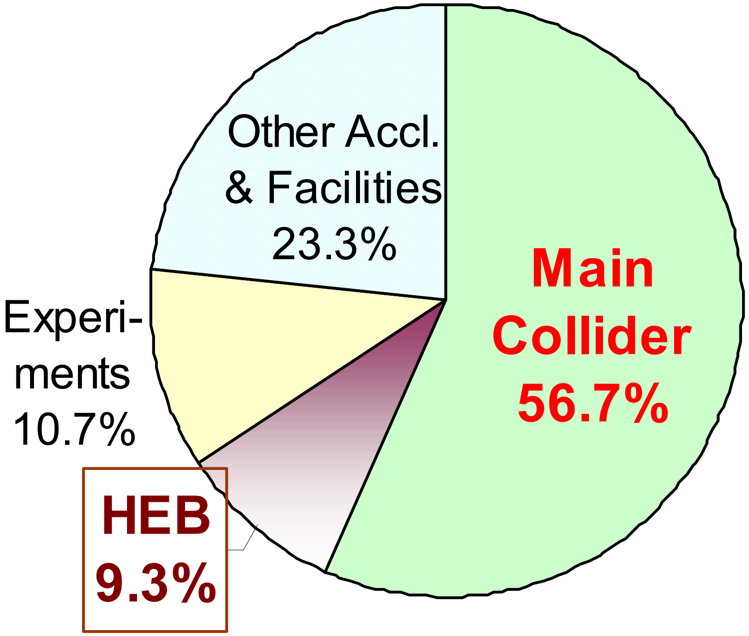
Estimated for 5 TeV (5-50 TeV vlhc):
~$1,500 million (in 1990 US$)

A part of this saving (say ~20-30%) may be used towards two extra apertures, etc. in main tunnel. Estimated savings ~ $1 billion.

Cost savings in equivalent 20xx $?

Cost Distribution of Major Systems

(Reference SSC Cost: 1990 US $7,837 million)



(Derived based on certain assumptions)

Advantages of Common Coil Magnet System with 4 Apertures (2-in-1 Accelerator)

- **Large Dynamic Range**

~150 instead of usual 8-20.

May eliminate the need of the second largest ring. Significant saving in the cost of VLHC accelerator complex.

- **Good Field Quality (throughout)**

Low Field: Iron Dominated
High Field: Conductor Dominated.

Good field quality from injection to highest field with a single power supply.

- **Compact Magnet System**

As compared to single aperture D20, 4 apertures in less than half the yoke.

- **Possible Reduction in High Field Aperture**

Beam is transferred, not injected
- no wait, no snap-back.

Minimum field seen by high field aperture is ~1.5 T and not ~0.5 T.

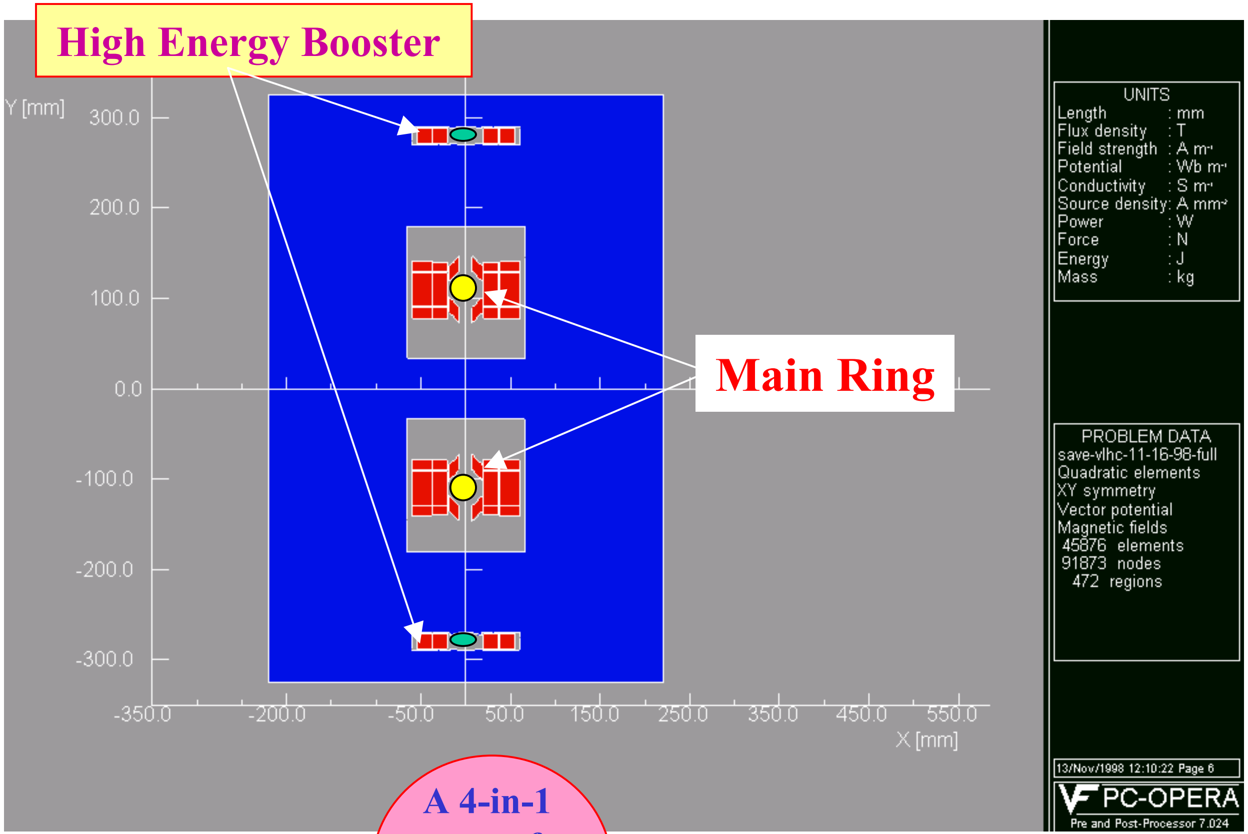
The basic machine criteria are changed!
Can high field aperture be reduced?

Reduction in high field aperture => reduction in conductor & magnet cost.

A Combined Function Common Coil Magnet System for Lower Cost VLHC

In a conventional superconducting magnet design, the right side of the coil return on the left side. In a common coil magnet, coil from one aperture return to the other aperture instead.

- A combined magnet design is possible as the coils on the right and left sides are different.
- Therefore, combined function magnets are possible for both low and high field apertures.
- Note: Only the layouts of the higher energy and lower energy machines are same. The “Lattice” of the two rings could be different.



UNITS

Length : mm
Flux density : T
Field strength : $A\,m^{-1}$
Potential : $Wb\,m^{-1}$
Conductivity : $S\,m^{-1}$
Source density: $A\,mm^{-2}$
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA

save-vlhc-11-16-98-full
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
45876 elements
91873 nodes
472 regions

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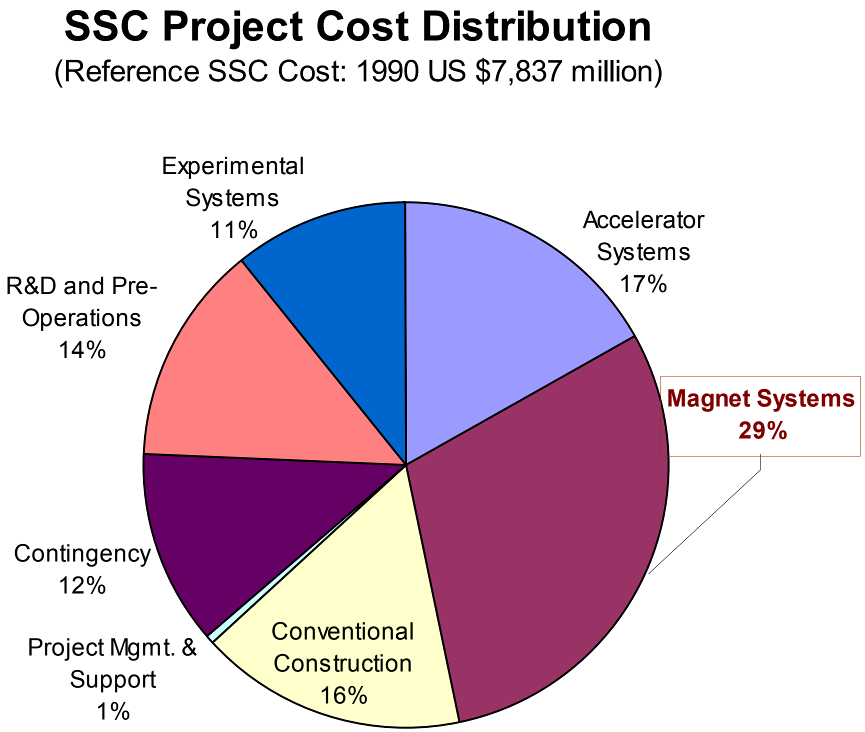
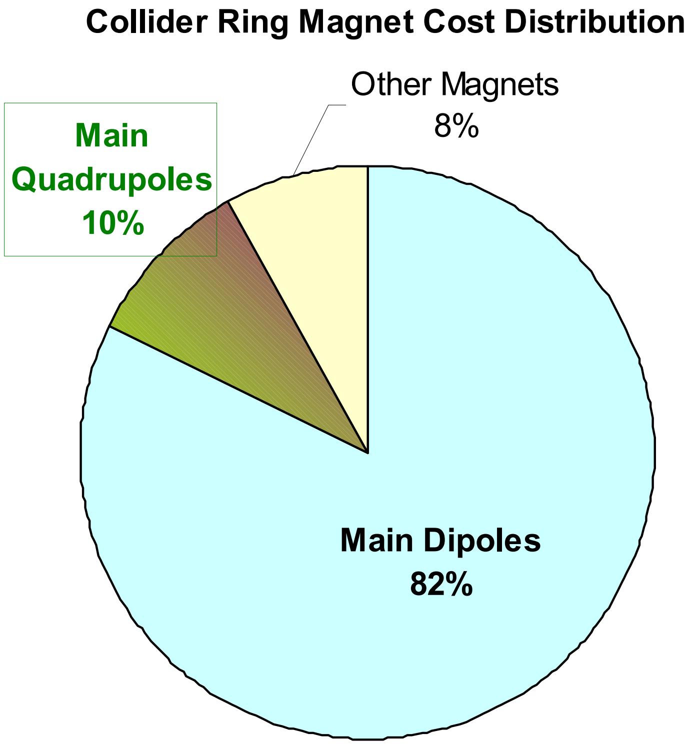
A 4-in-1 magnet for a 2-in-1 machine

A Combined Function Magnet Option (Estimated cost savings for VLHC)





Total:
$2,037 million

AP Challenge:

Retaining the benefits of the *Synchrotron Damping* in the *High Field Magnet* vlhc option.

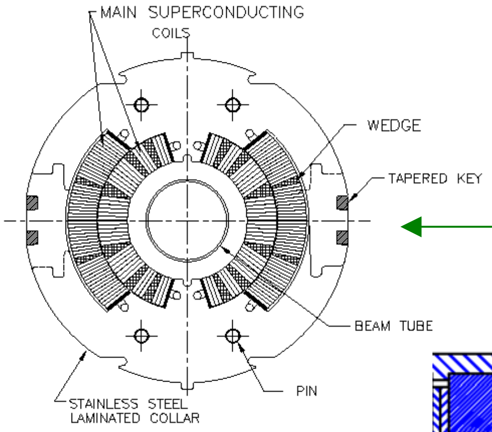
SSC (20 TeV) Main Quads: ~$200 million; VLHC (50 TeV) Main Quads: ~$400 million (x2 not 2.5).

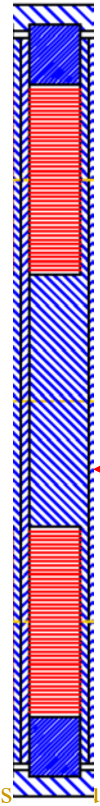
Additional savings from tunnel, interconnect, etc.

Estimated potential savings: ~$0.3-0.5 billion (1990 US$).

Cost savings in equivalent 20xx $?

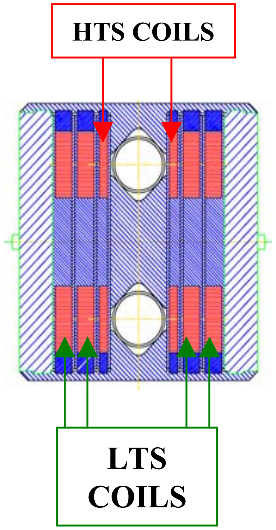
Take Advantage of Simple Structure in Manufacturing, etc.





- **Reduce steps and bring more automation in magnet manufacturing**
- **Current procedure : make cable from Nb-Ti wires => insulate cable => wind coils from cable => cure coils => make collared coil assembly**
- **Possible procedure : Cabling to coil module, all in one automated step - insulate the cable as it comes out of cabling machine and wind it directly on to a bobbin (module)**

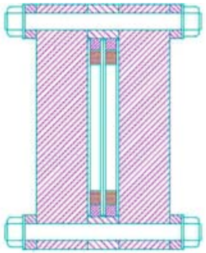
Common Coil Magnet R&D at BNL



Primary Goal of the Program:

Design and build a ~12.5 Tesla, "React & Wind" Common Coil Magnet with HTS playing a major role (outer coils: Nb_3Sn).

R&D Plan to Develop Technology:



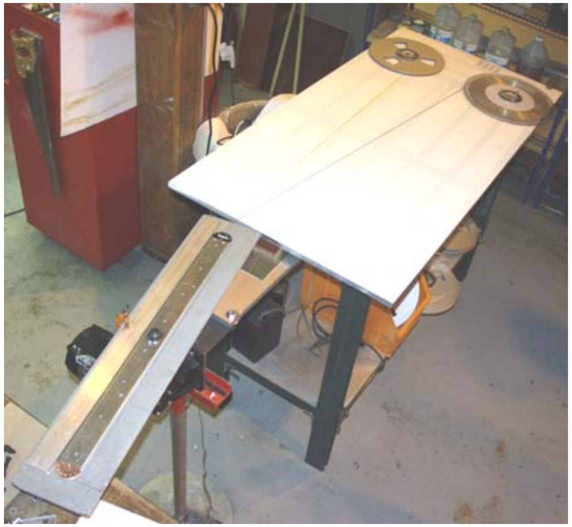
A "*mini 10-turn magnet R&D program*" to systematically develop and test new ideas, designs and technologies (React & Wind HTS) in a time and cost effective manner.

At this rate, we can afford to built many coils and afford to see some destroyed in an attempt to understand and develop new technology and find a limit of others.

That philosophy is in-built in the "Program Design"!

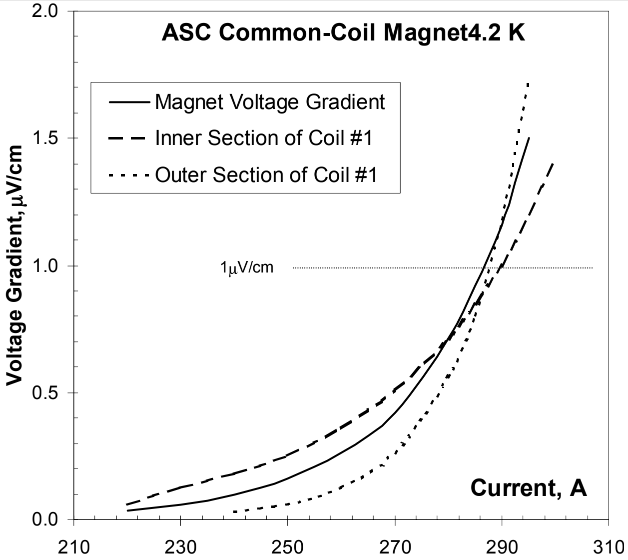
Common Coil Magnets With HTS Tape

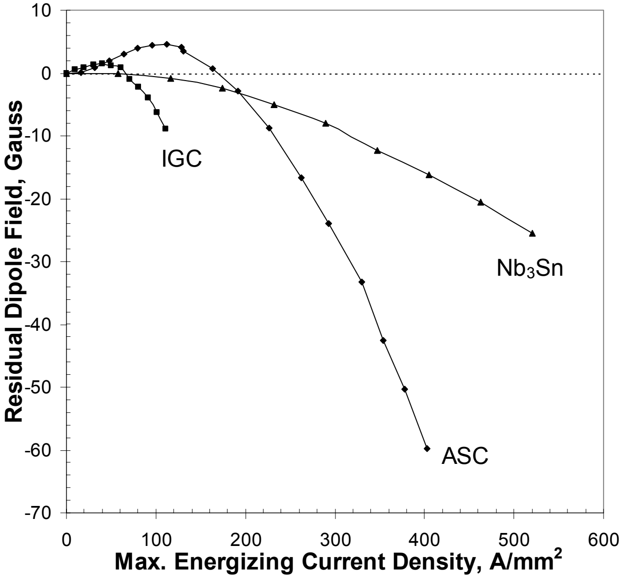
(Field quality in 74 mm aperture to be measured soon)



A coil being wound with HTS tape and insulation.

Two HTS tape coils in common coil configuration

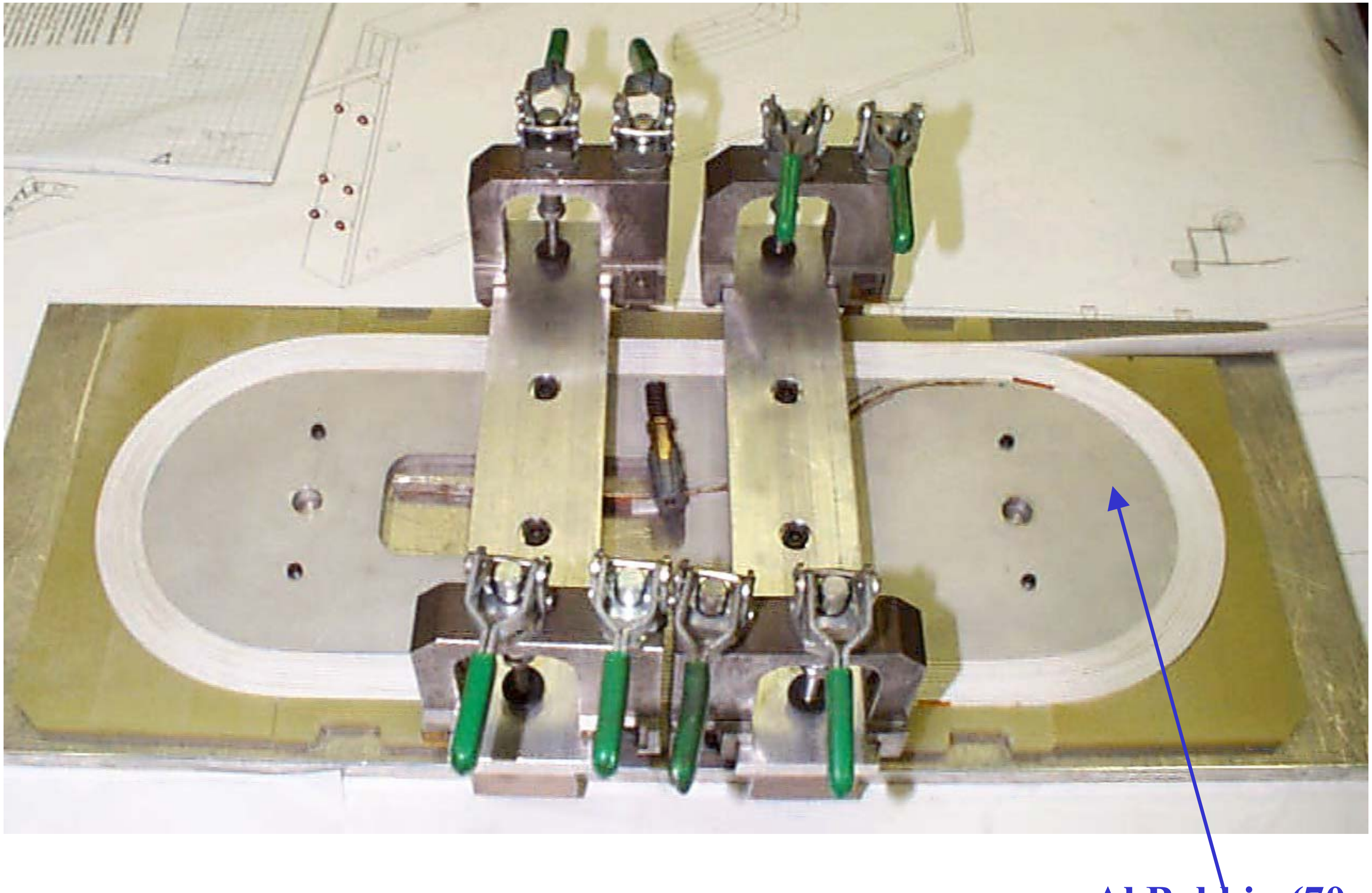




Status of HTS tape coils at BNL

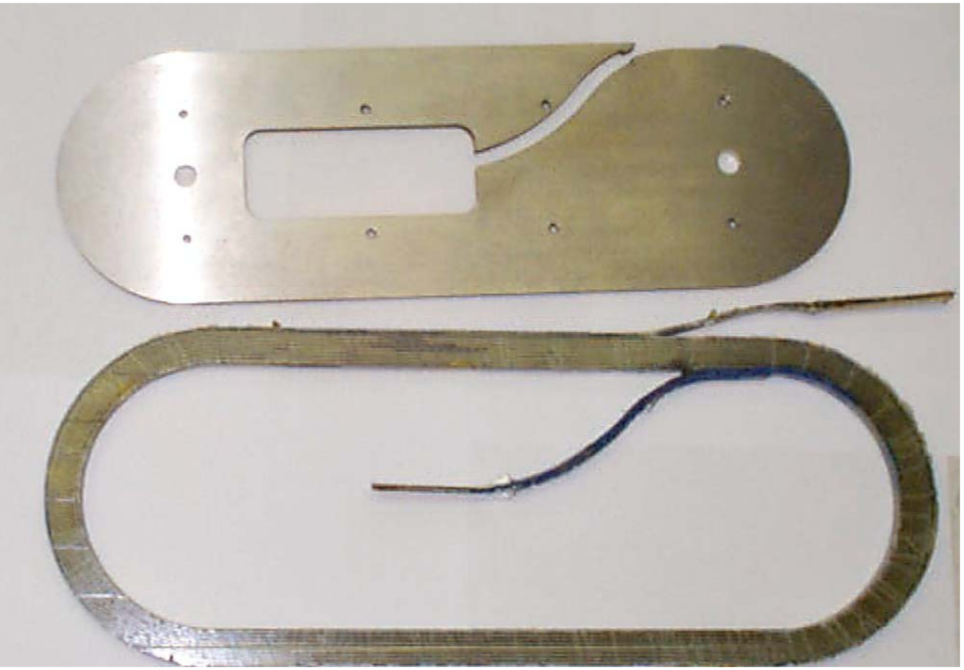
	Size, mm	Turns	Status
Nb_3Sn	0.2 x 3.2	168	Tested
IGC	0.25 x 3.3	147	Tested
ASC	0.18 x 3.1	221	Tested
NST	0.20 x 3.2	220	Under construction
VAC	0.23 x 3.4	170	Under construction

HTS Coil Wound by Hand



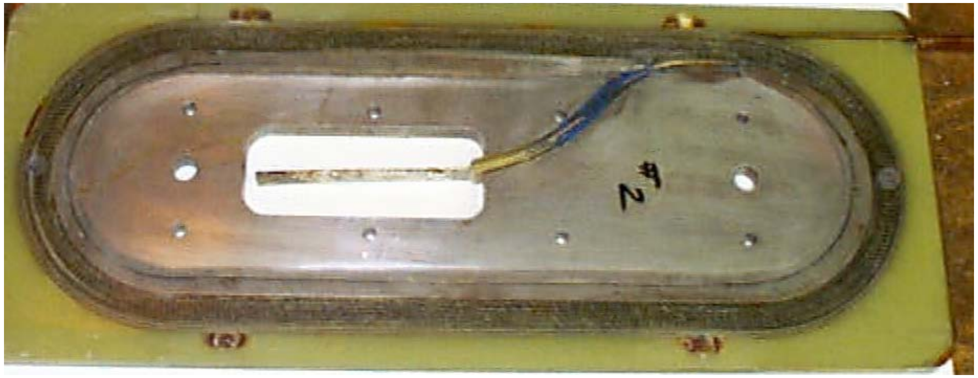
Al Bobbin (70 mm radius)
(also used, Fe, SS and brass bobbins)

The Bobbin and the 10-turn Coil



The bobbin
(the coil is wound on it)

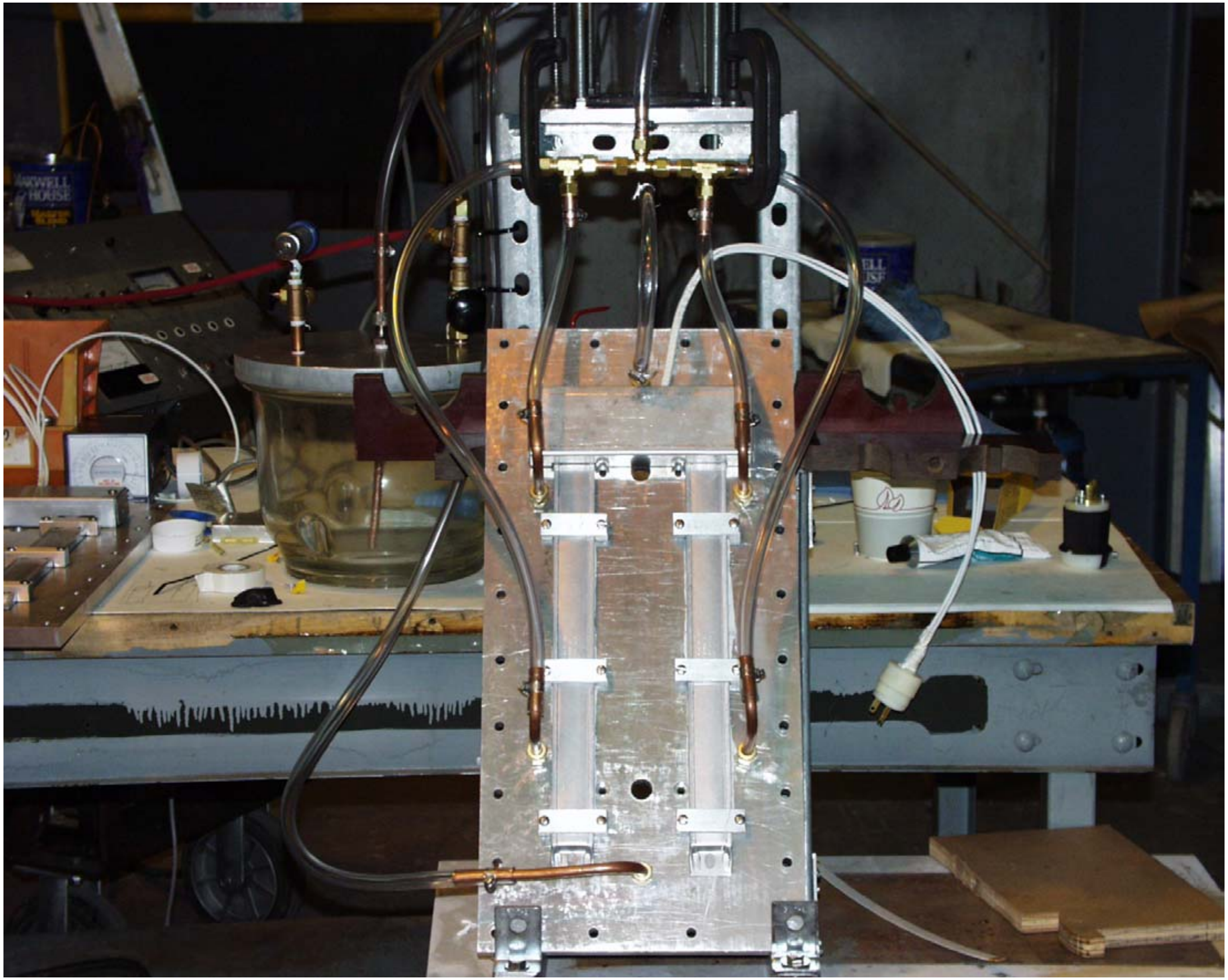
The first 10-turn practice coil
(removed from bobbin after impregnation)



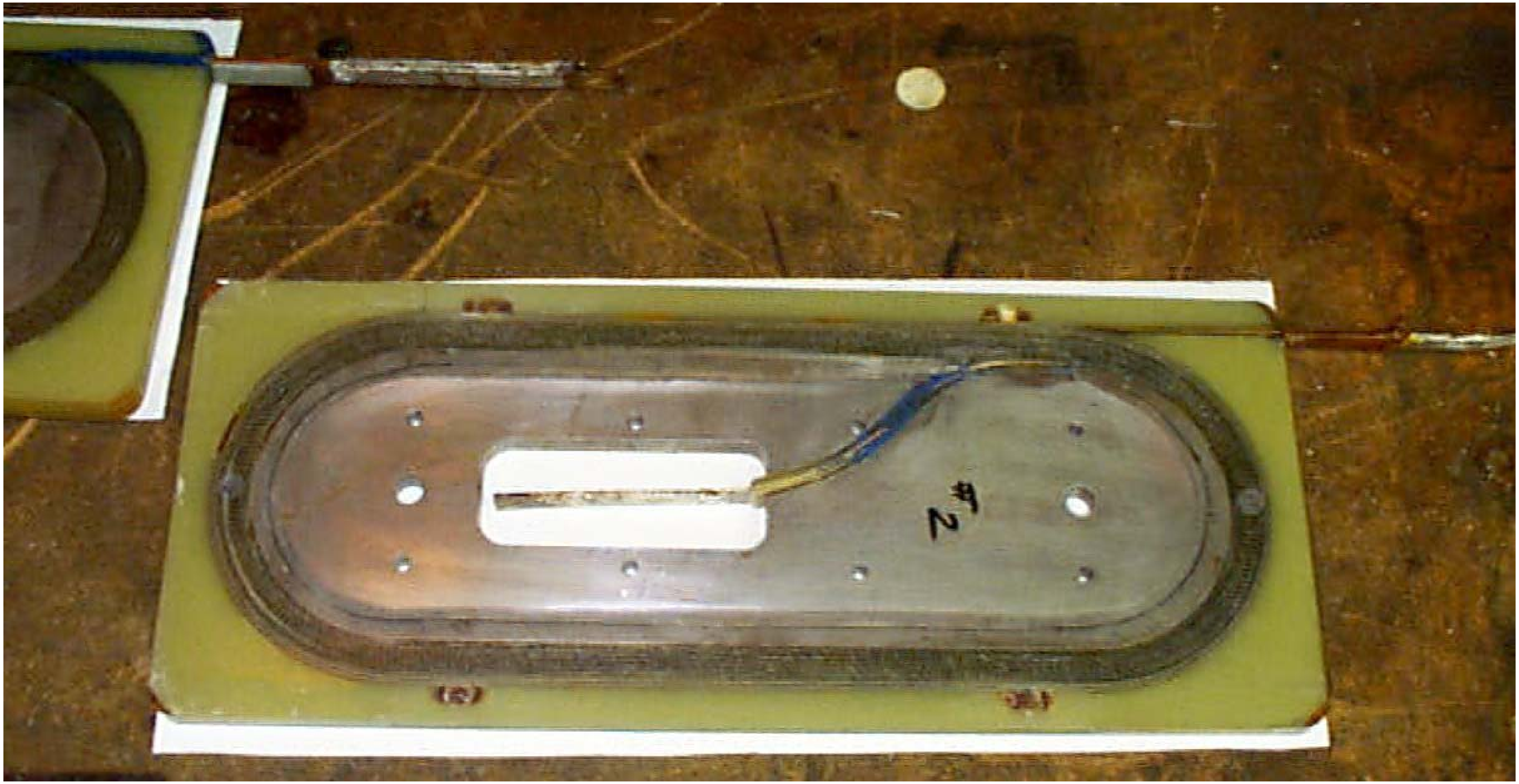
The complete cassette module
(vacuum impregnated coil in bobbin)

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

Vacuum Impregnation Setup



Vacuum Impregnated Coils



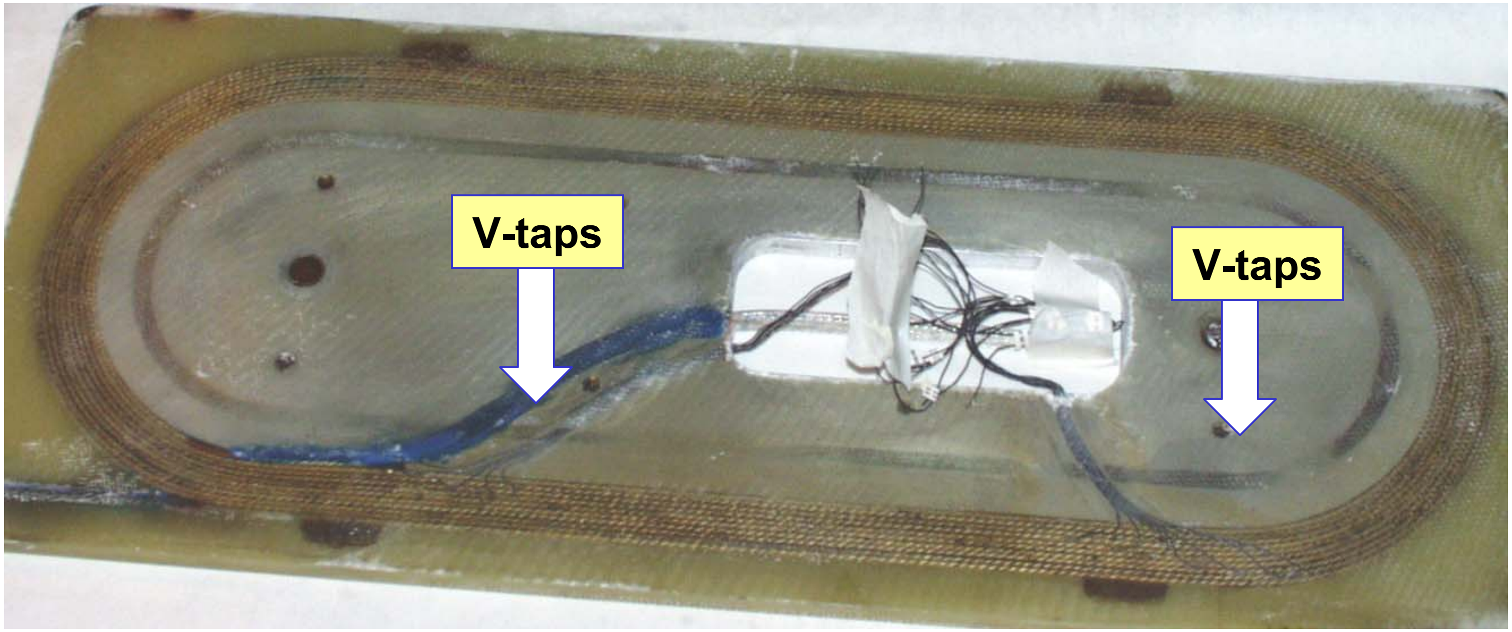
Vacuum impregnated coils made after “react and wind” technique.

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

Voltage Taps, etc.

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

- Given the aggressive R&D nature of the program we instrument is 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

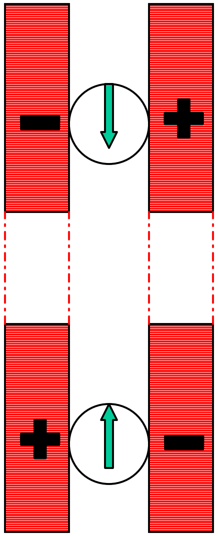
Coils are heavily instrumented. There is a voltage tap after each turn. Data were recorded from all 26 voltage taps.

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”.

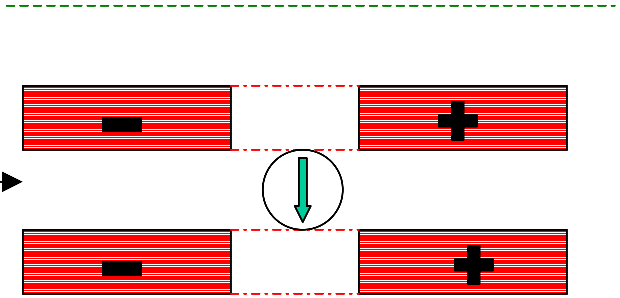
Two hall probes (in between two coils and at the center of two coils) also recorded the central field.

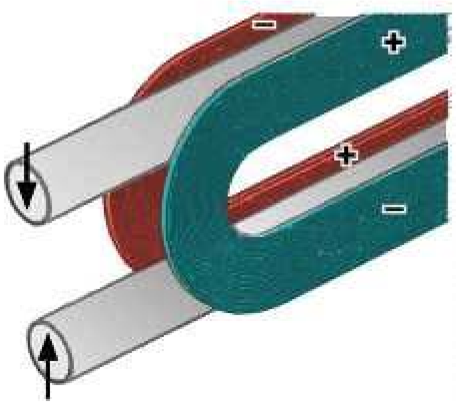
Common Coil and Muon Collider Test Configurations

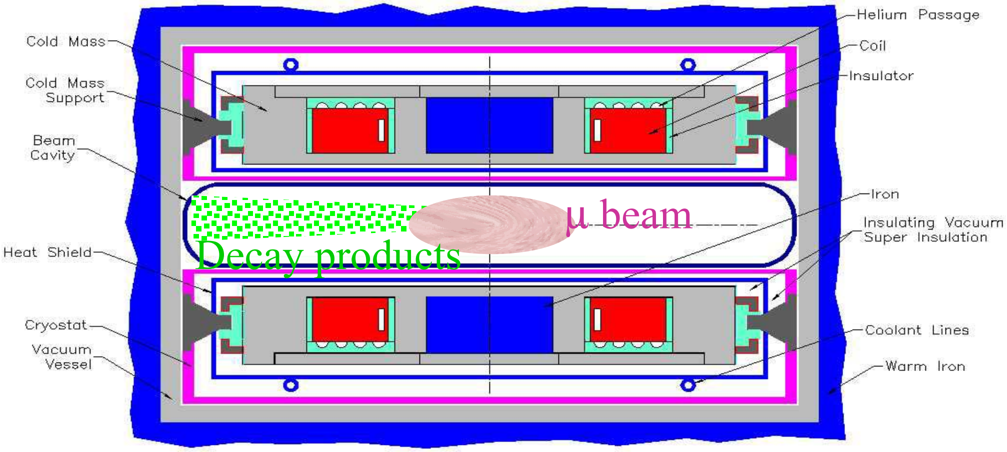
Common Coil configuration **muon collider configuration**



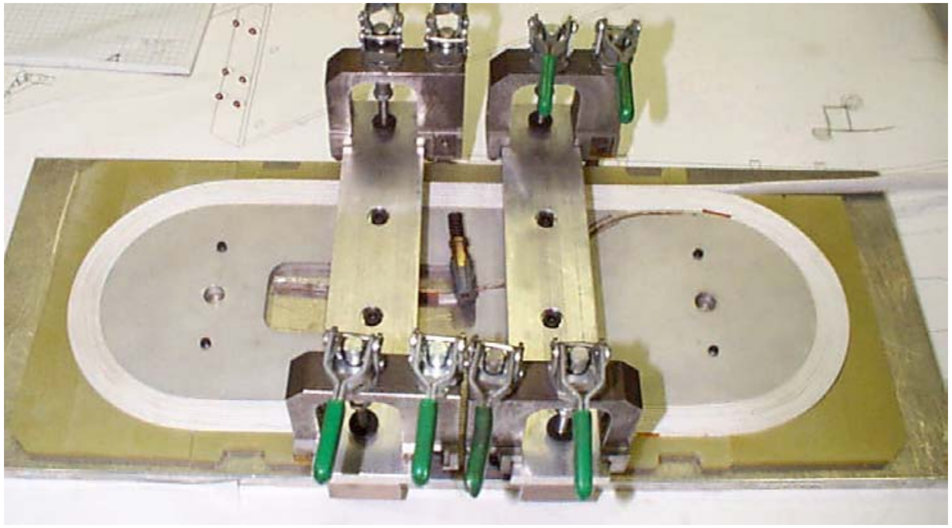
← Powering differently changes common coil design test to muon collider design test →







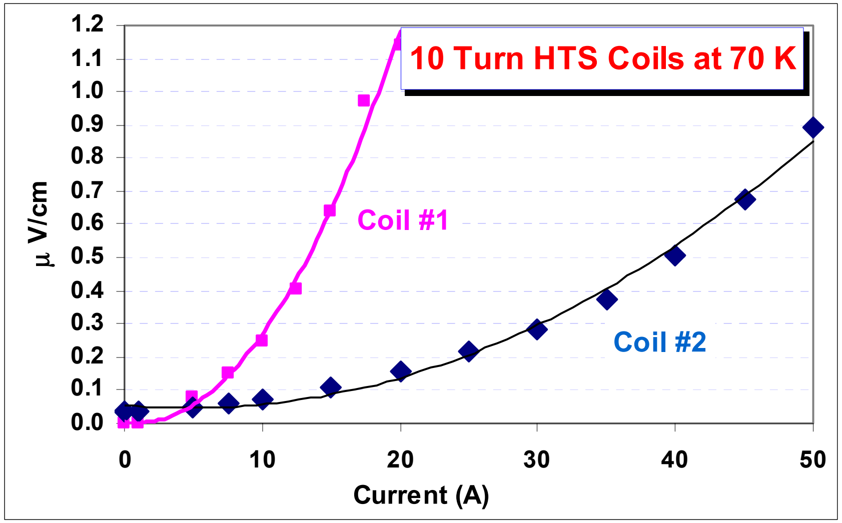
Common Coil Magnets With HTS Cable



HTS cable coil prior to vacuum impregnation

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

Two coils were tested in Liquid Nitrogen

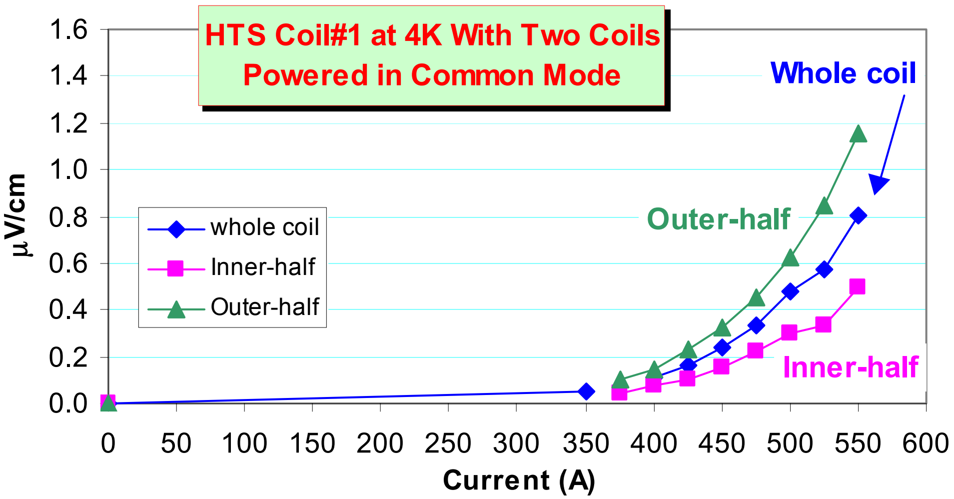


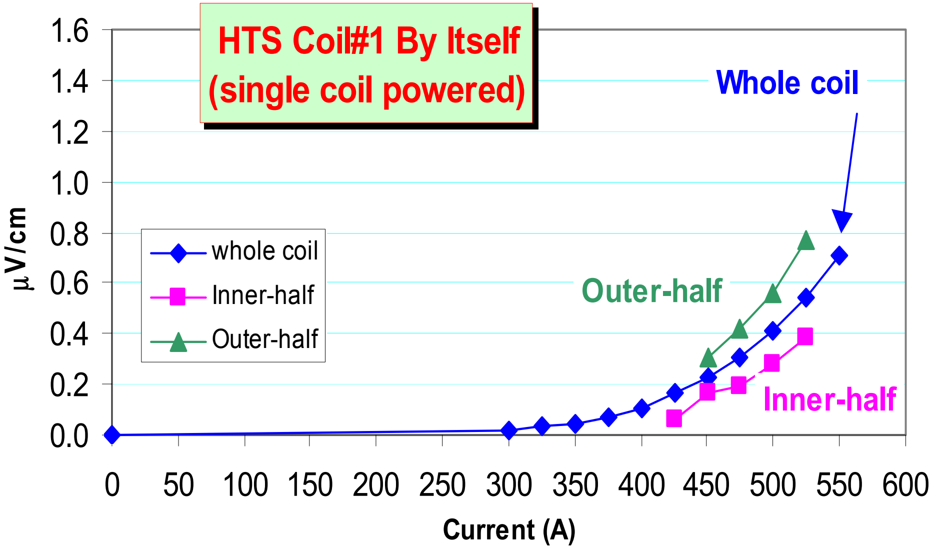
The HTS cables were from two different batches. They behaved differently:

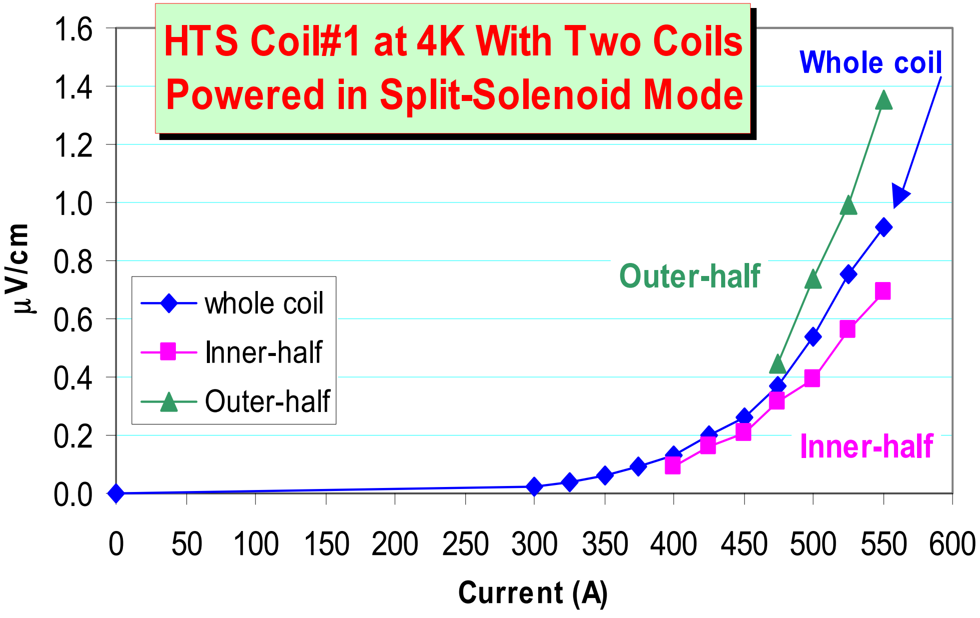
- Different Ic
- Different Tc

Based on preliminary analysis, no large degradation is observed.

4K Performance of 1st Common Coil HTS Magnet





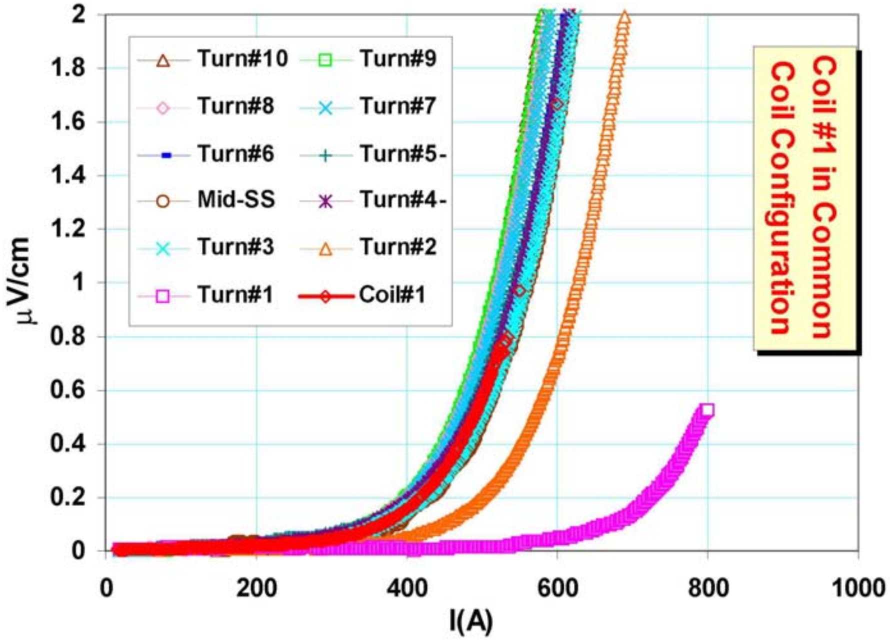


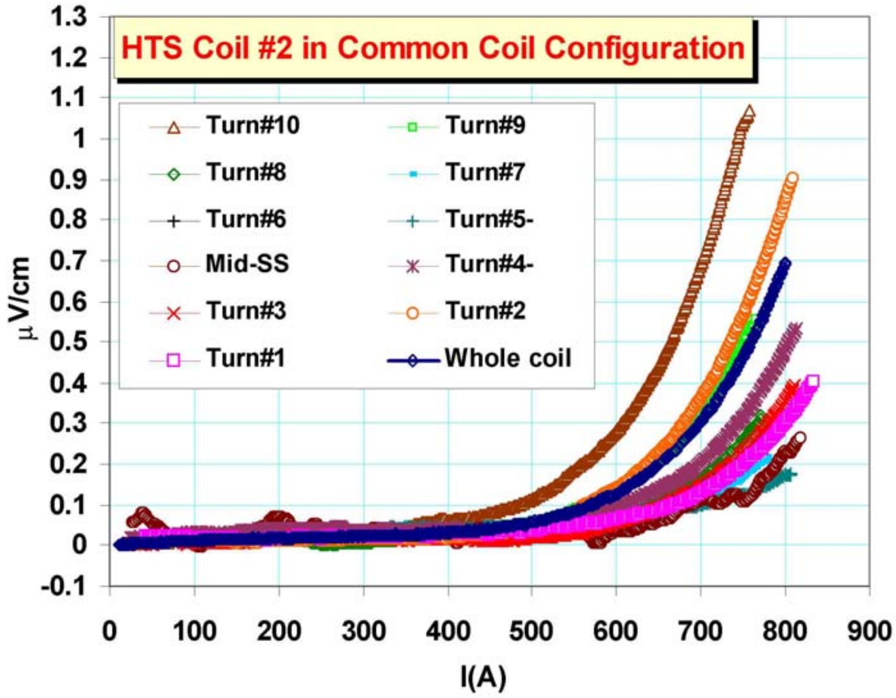
Notes:

- 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

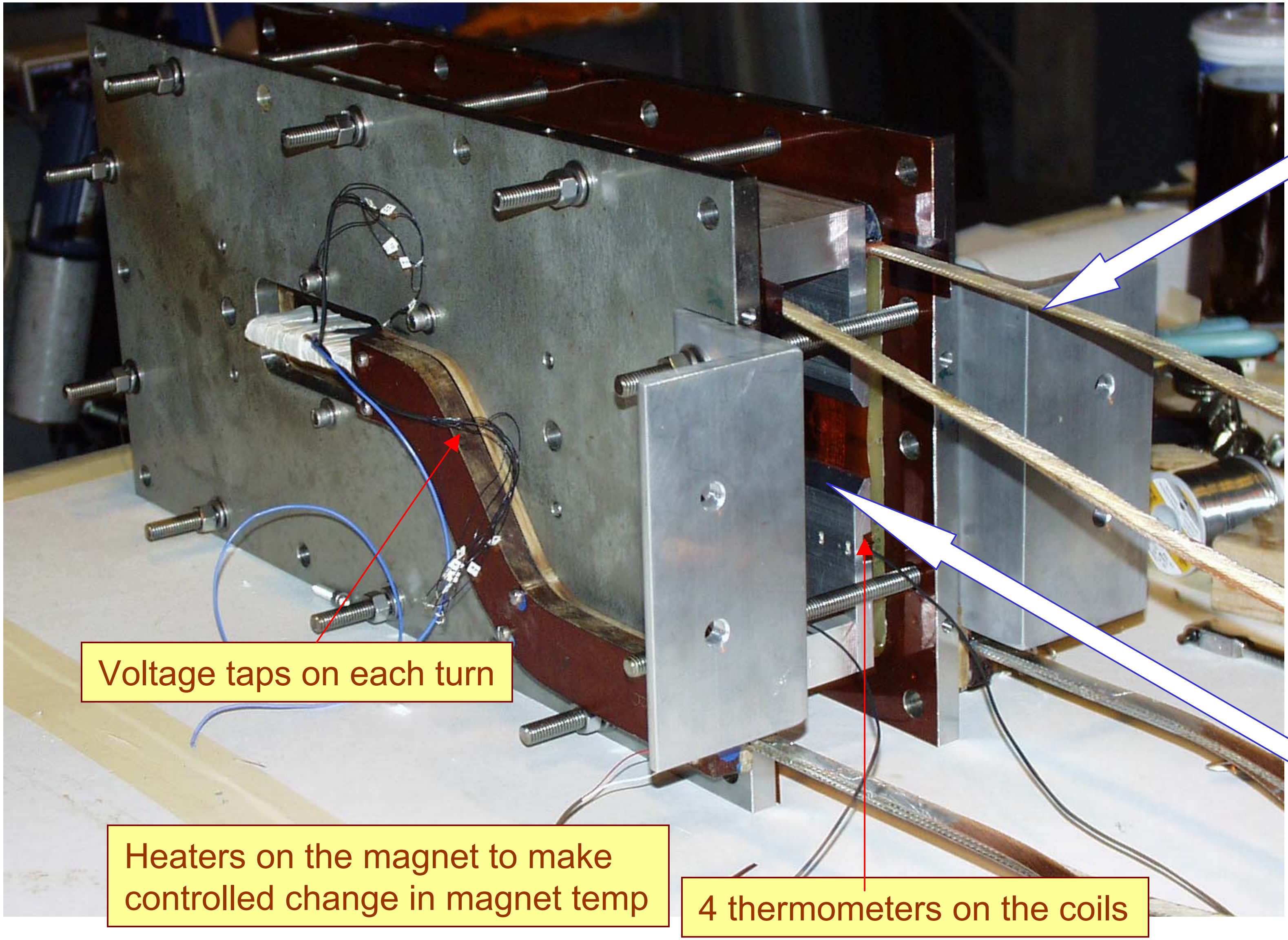
The state-of-the-art wire is now a factor of three better

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: 2^{nd} 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

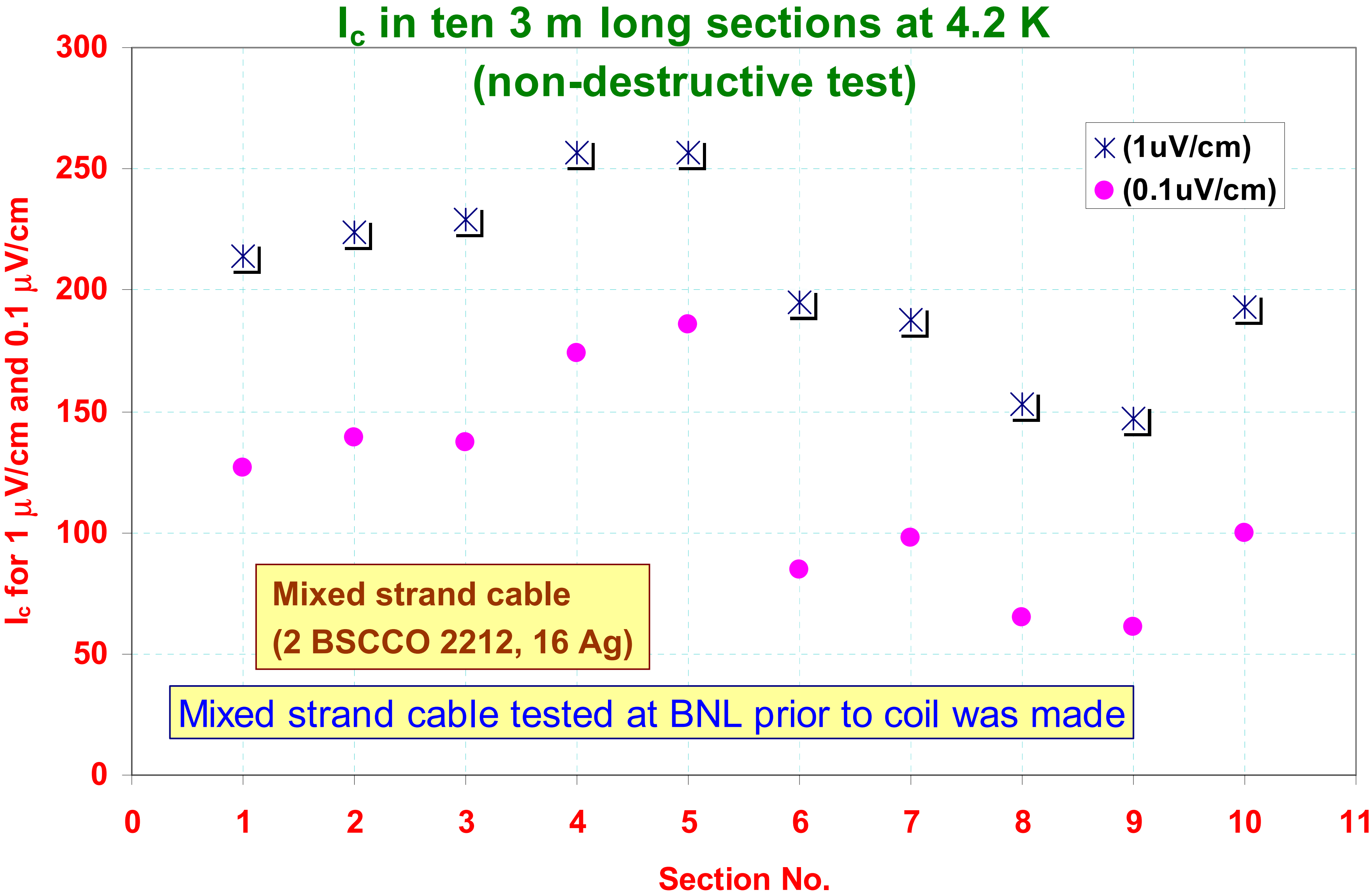
74 mm aperture to measure field quality

Voltage taps on each turn

Heaters on the magnet to make controlled change in magnet temp

4 thermometers on the coils

Critical Current in Mixed Strand Cable



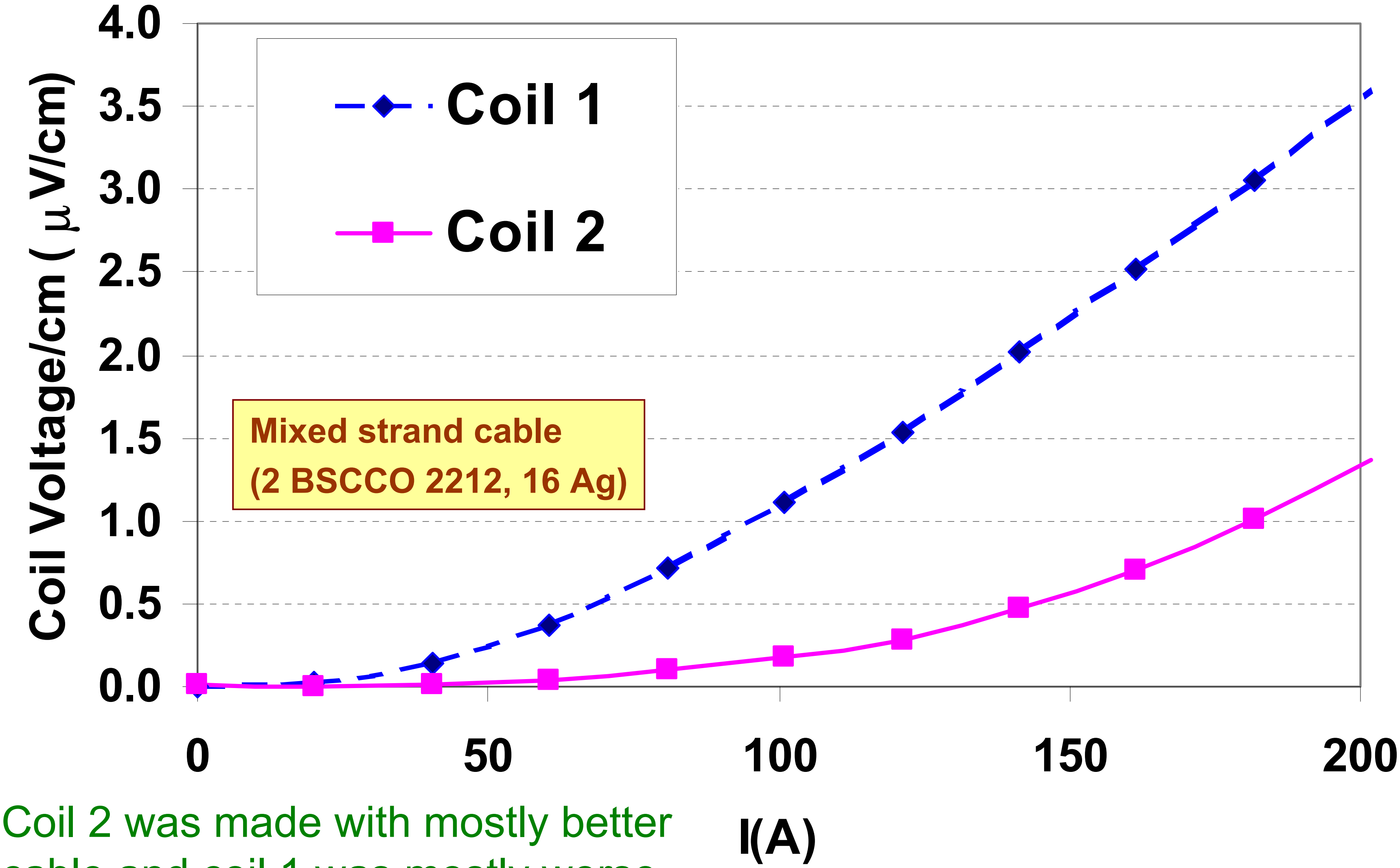
I_c in ten 3 m long sections at 4.2 K

(non-destructive test)

Mixed strand cable
(2 BSCCO 2212, 16 Ag)

Mixed strand cable tested at BNL prior to coil was made

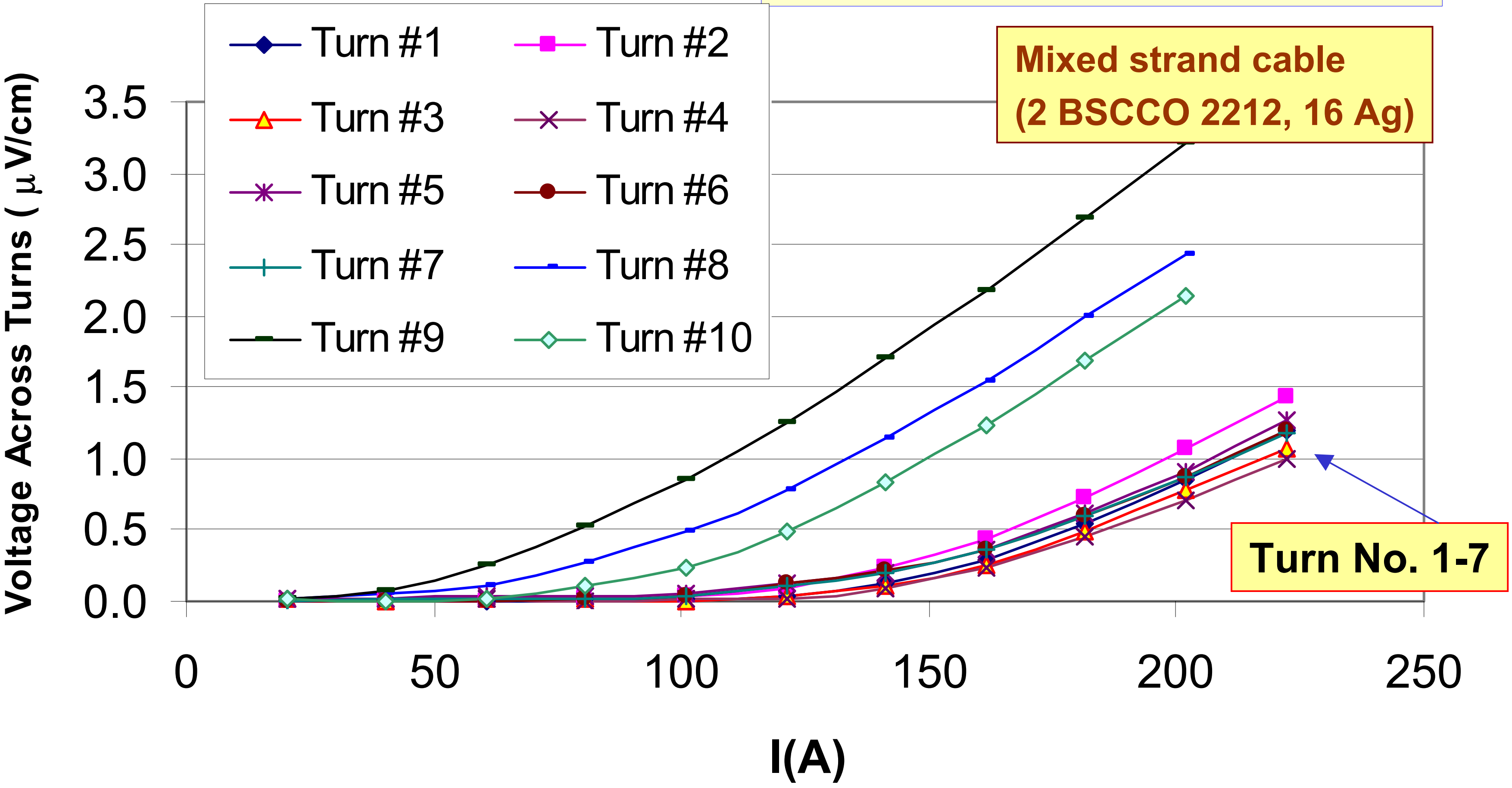
Performance of 2 Coils in Muon Collider Dipole Configuration



Mixed strand cable
(2 BSCCO 2212, 16 Ag)

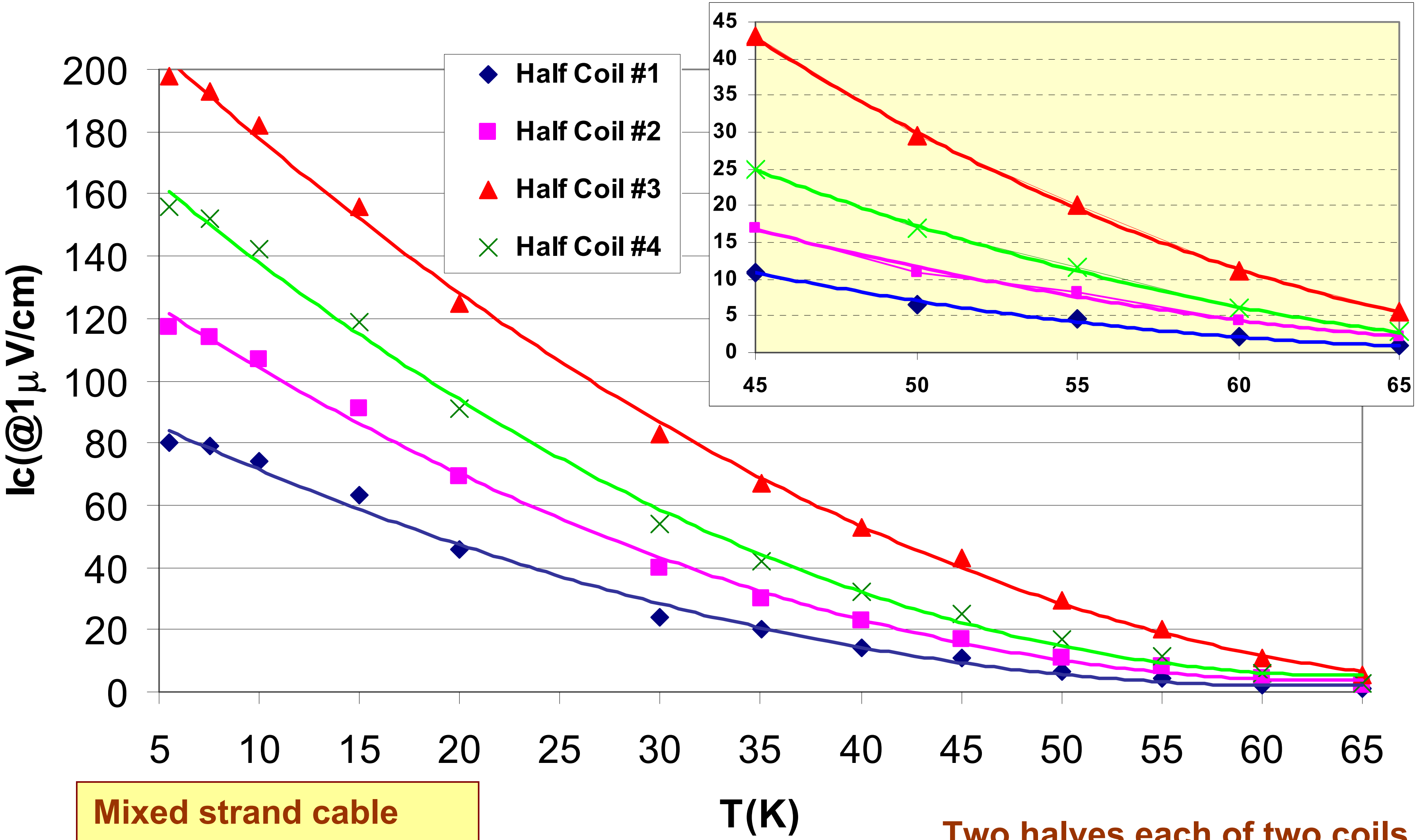
Coil 2 was made with mostly better cable and coil 1 was mostly worse

Measured I_c of Various Turns



Turn No. 1-7 in coil have Ic close to the cable measurements before the coil was made

Measured Critical Current as a Function of Temperature



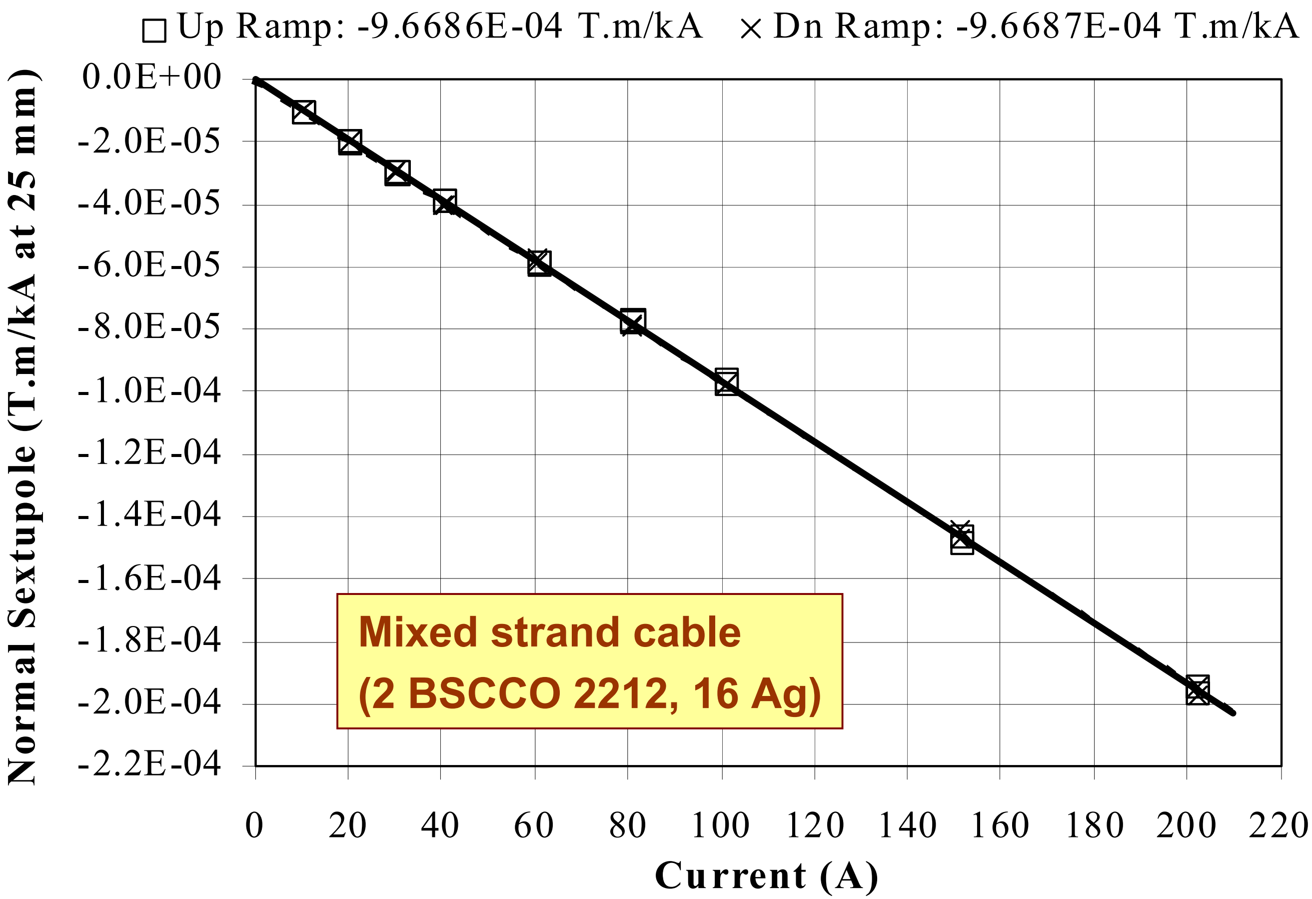
Mixed strand cable (2 BSCCO 2212, 16 Ag)

Two halves each of two coils

Field Quality Measurements

DC loop Data (+200A) in DCC006 Dipole Mode

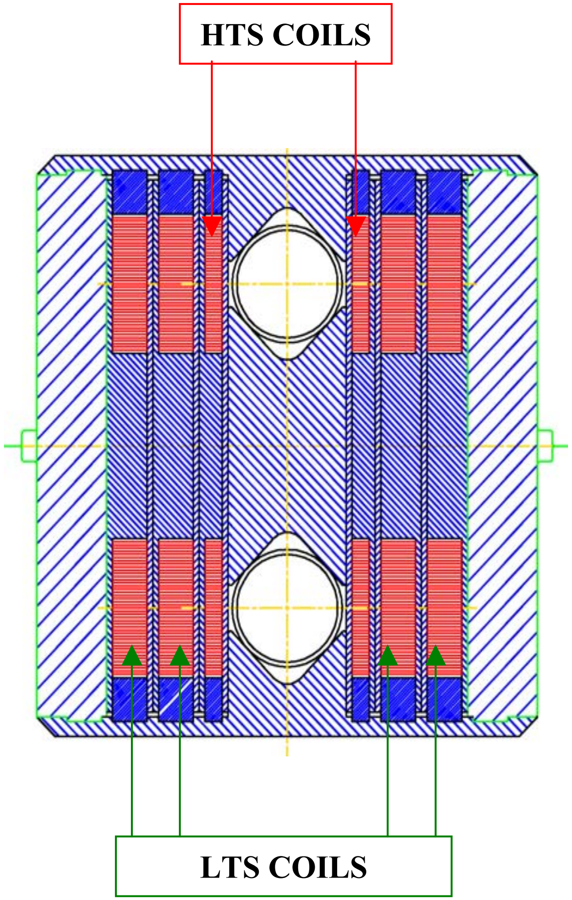
Sextupole Harmonic



Mixed strand cable
(2 BSCCO 2212, 16 Ag)

Difference between up and down ramp values is within measurement errors.
(Max field on conductor only ~550 Gauss. Better signal on all HTS cable).

HTS in a Hybrid Magnet



- **Perfect for R&D magnets now.**

  HTS is subjected to the similar forces that would be present in an all HTS magnet. Therefore, several technical issues will be addressed.

- **Field in outer layers is ~2/3 of that in 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 magnet

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