Lecture IX

High Temperature Superconductor (HTS) Magnet Designs and Technology

Ramesh Gupta
Superconducting Magnet Division
Brookhaven National Laboratory

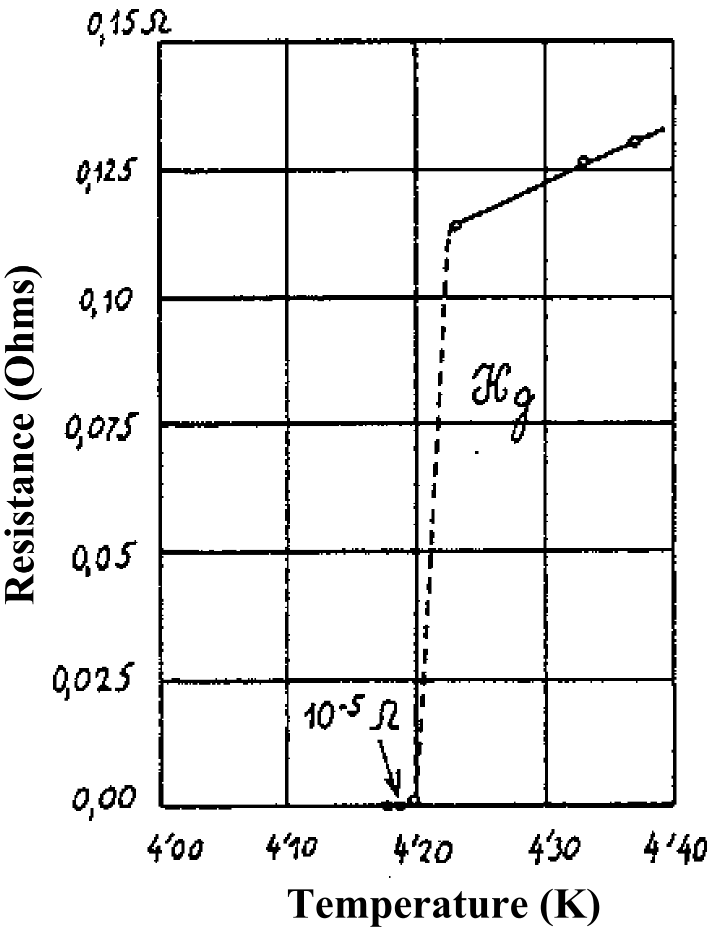
US Particle Accelerator School
Arizona State University
Phoenix, Arizona
January 16-20, 2006

ARIZONA STATE UNIVERSITY

Conventional Low Temperature Superconductors (LTS) and New High Temperature Superconductors (HTS)

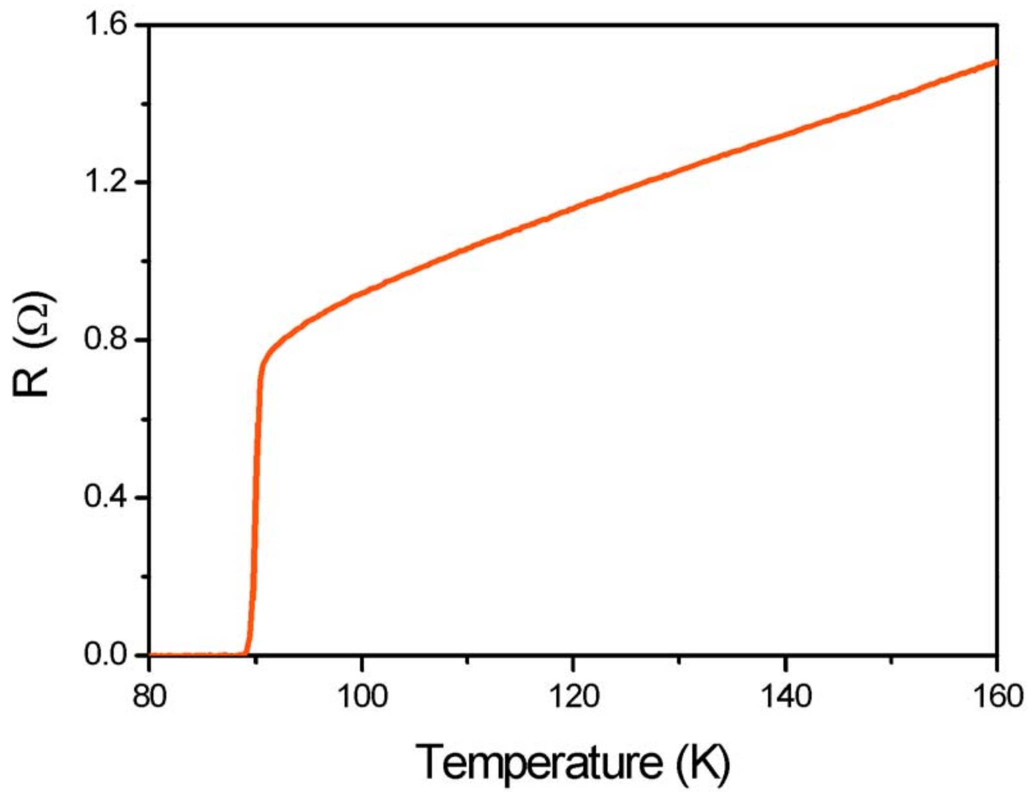
Low Temperature Superconductor Onnes (1911)

Resistance of Mercury falls suddenly below meas. accuracy at very low (4.2) temperature



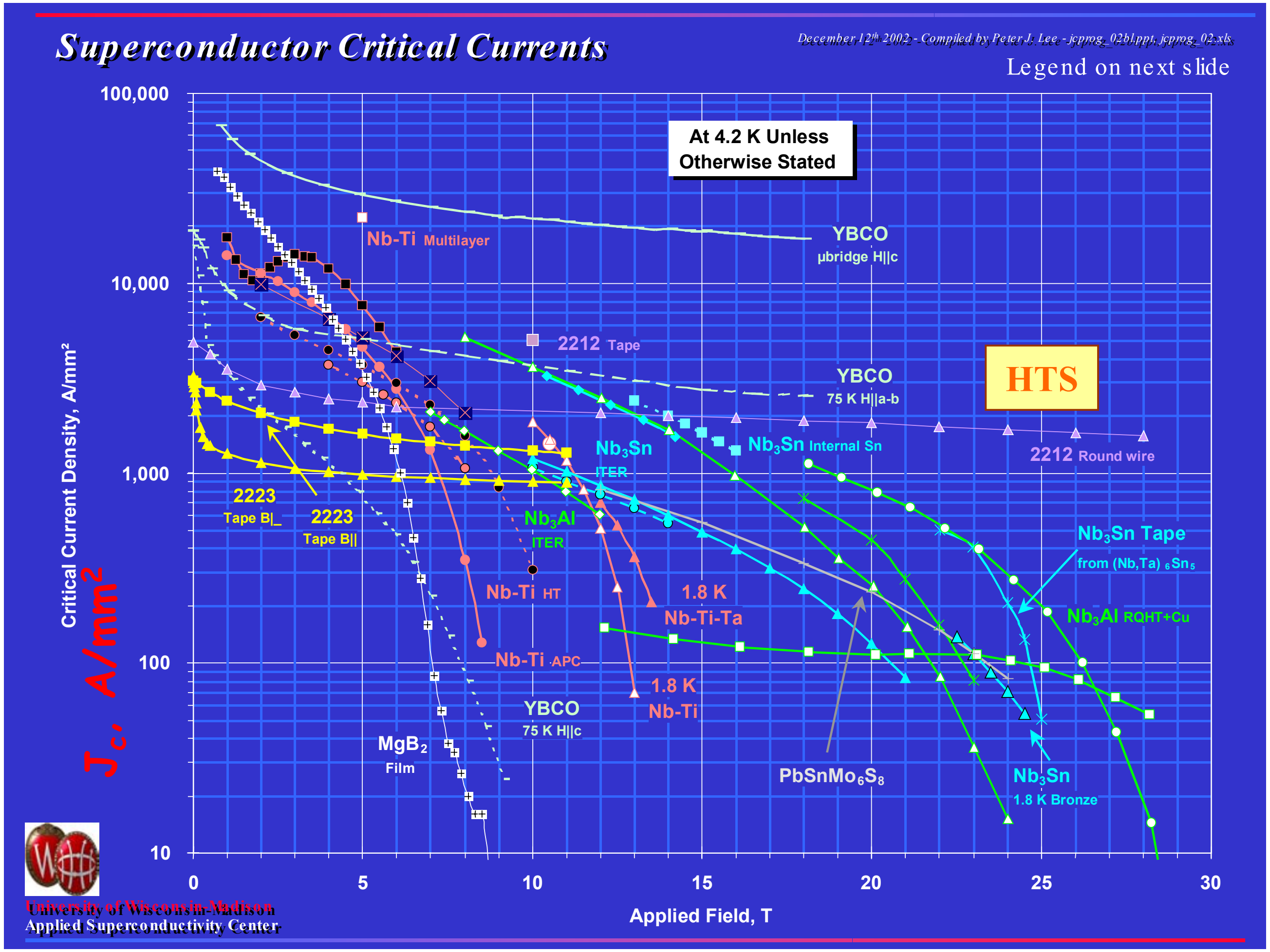
New materials (ceramics) loose their resistance at NOT so low temperatures (Liquid Nitrogen)!

High Temperature Superconductors (1986)



Another Remarkable Property of HTS
The High Field Current Carrying Capacity

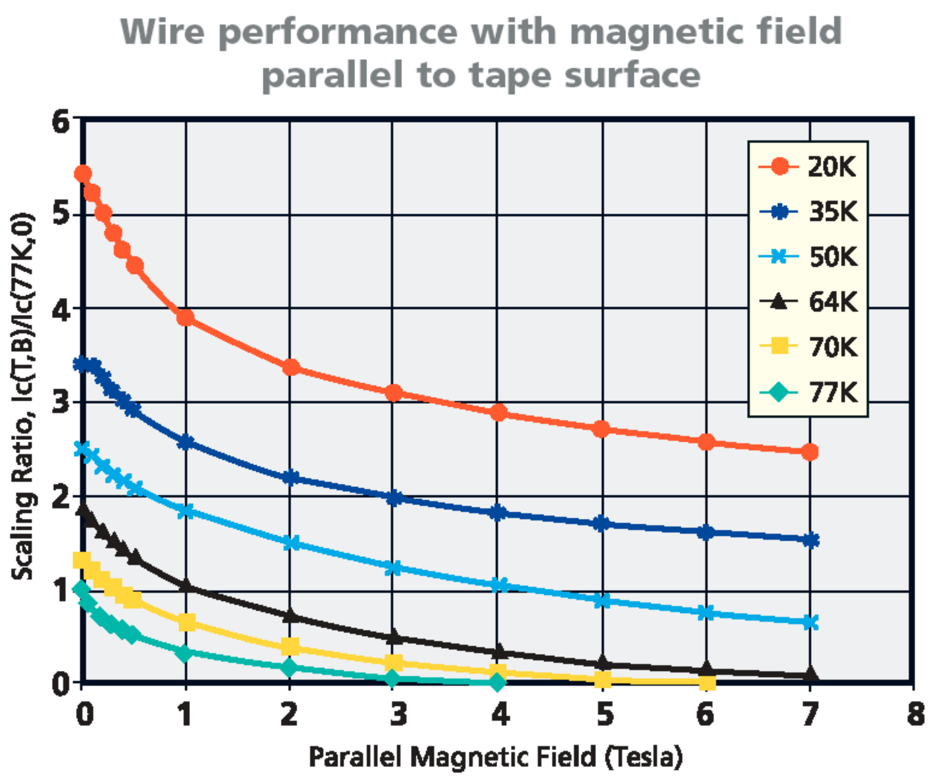
Compare J_c Vs. B between conventional Low Temperature Superconductors (LTS) and High Temperature Superconductors (HTS)

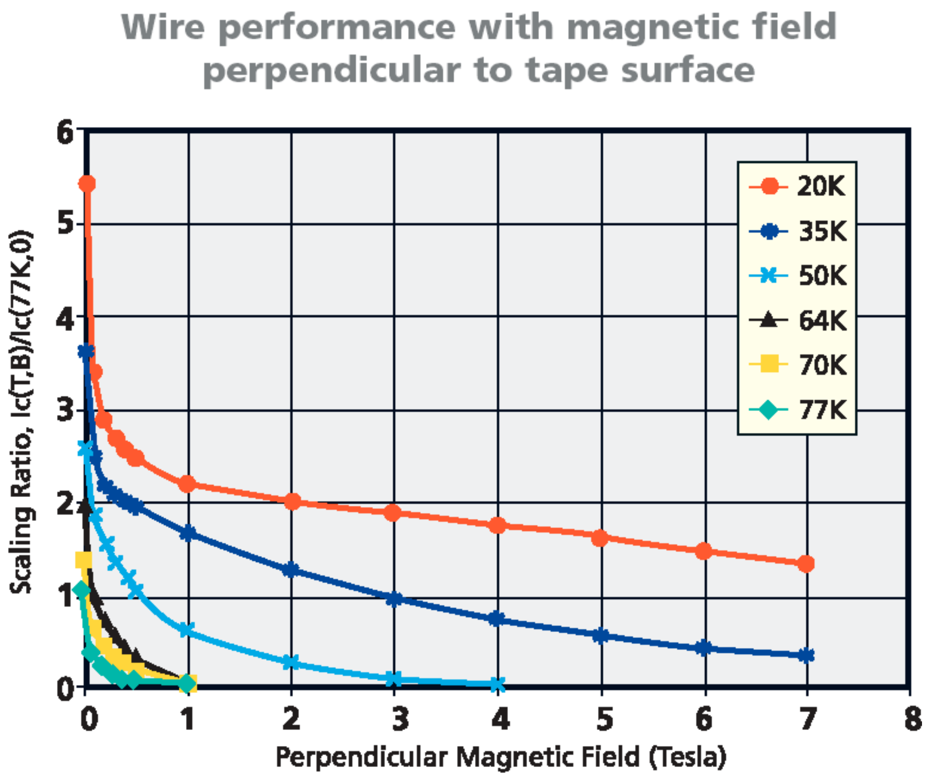


J_c, A/mm^2

Applied Field, T

Critical Current of BSCCO 2223 Tape As a Function of Field At Various Operating Temperatures





American Superconductor
REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY

Current carrying capacity of HTS depends on:

- **Temperature**
- **Magnitude of the field**

and also on the direction of the field

Advantages of using HTS in Accelerator Magnets

As compared to LTS, the critical current density (J_c) falls slowly

- as a function of temperature
- as a function of field

<u>Translate this to magnet design and accelerator operation:</u>

- HTS based magnets can operate at elevated temperatures
    - a rise in temperature from, e.g., decay particles can be tolerated
    - the operating temperature doesn't have to be controlled precisely
- HTS has the potential to produce very high field magnets

Possible Application of HTS in Accelerator Magnets

High Field, Low Temperature Application

Example: Interaction Region (IR) Magnets for large luminosity

- At very high fields (~18 T or more), no superconductor has as high a critical current density as HTS does.

Medium Field, Higher Temperature Application

Example: Quads for Rare Isotope Accelerator (RIA)

- These applications don't require very high fields.
- The system design benefits enormously from HTS because HTS offers the possibility of magnets which operate at a temperature higher than 4K, say at 20-40 K.

- In both cases, HTS magnets can tolerate a large increase in coil temperature with only a minor loss in magnet performance.
- And this temperature, moreover, need not be controlled precisely
  - One can relax about an order of magnitude in controlling temperature variations (HTS allows a few degrees, as compared to a few tenth of a degree in LTS.

Popular HTS Materials of Today

- BSCCO 2223 (T_c ~ 110 K)
- BSCCO 2212 (T_c ~ 85 K)
- YBCO (T_c ~ 90 K)

- MgB_2 is a low temperature superconductor (LTS) with critical temperature ~39 K (almost highest possible by current theories).

Of these only BSCCO2212 and BSCCO2223 (1st generation HTS) are now available in sufficient quantities to make accelerator or beam line magnets.

However, the future may lie with YBCO (2nd generation HTS) which, in principle, can be produced at a much lower cost (less Ag). Recent results from industry on 2nd generation HTS are encouraging.

HTS Wires and HTS Tapes

Popular HTS material: BSCCO 2212, BSCCO 2223 and YBCO

BSCCO 2212 is available in both wire form (round circular) and tape form (flat)

- **Rutherford cables are made with round wire. So for that only BSCCO2212 is useful.**
- **One can also make rope type cable with round wire.**
- **High field accelerator magnets are traditionally made with Rutherford cable. For quench protection purpose, it is important to have magnets running at high current. Rutherford cables, made with many wires (20-40 wires) can carry high current.**
- **The performance of this Rutherford cable does not depend on the direction of field.**

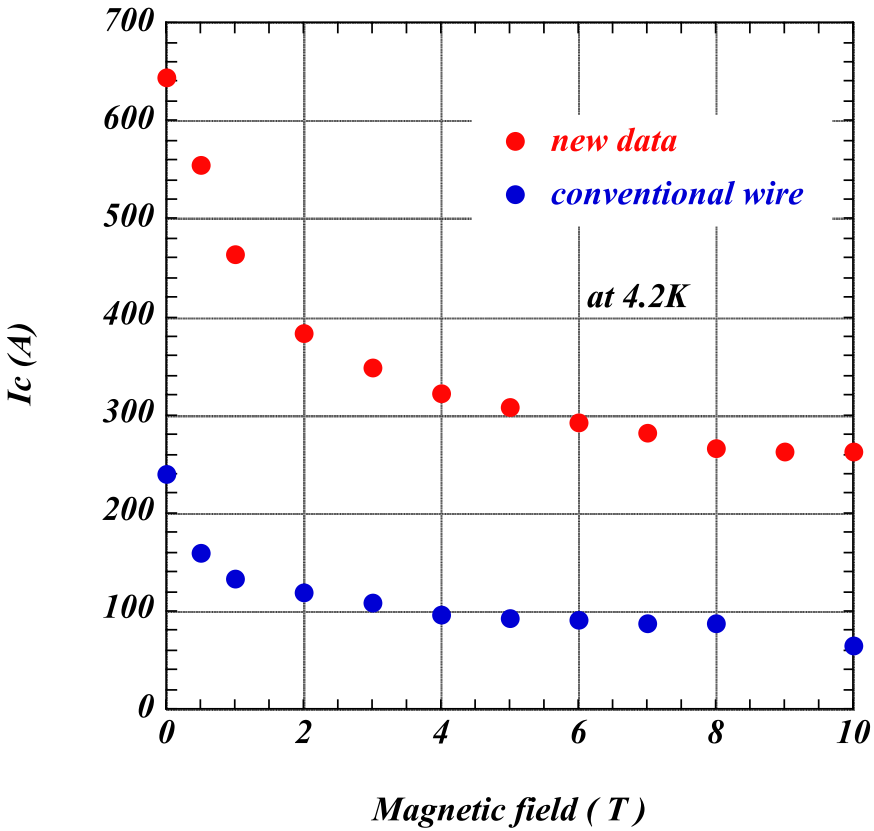
BSCCO 2223 and YBCO are available only in tape form (flat with aspect ratio ~10)

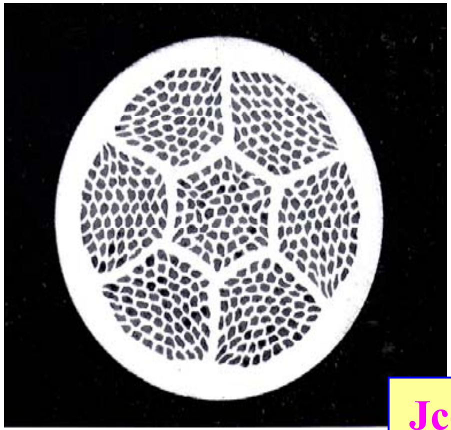
- **Interestingly, in industry this tape is referred to as wire.**
- **The performance of tape is much better in the field parallel direction compared to the field perpendicular. It can be advantageous or disadvantageous depending on the design and/or application.**
- **High current flat cables with many tapes are not common despite some attempts.**

BSCCO 2212 Wire

Ic-B characteristics of new wire

Showa Electric





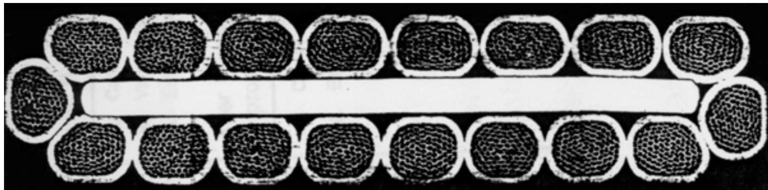
Jc(12T,4.2K) ~2000 A/mm^2

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, Showa.

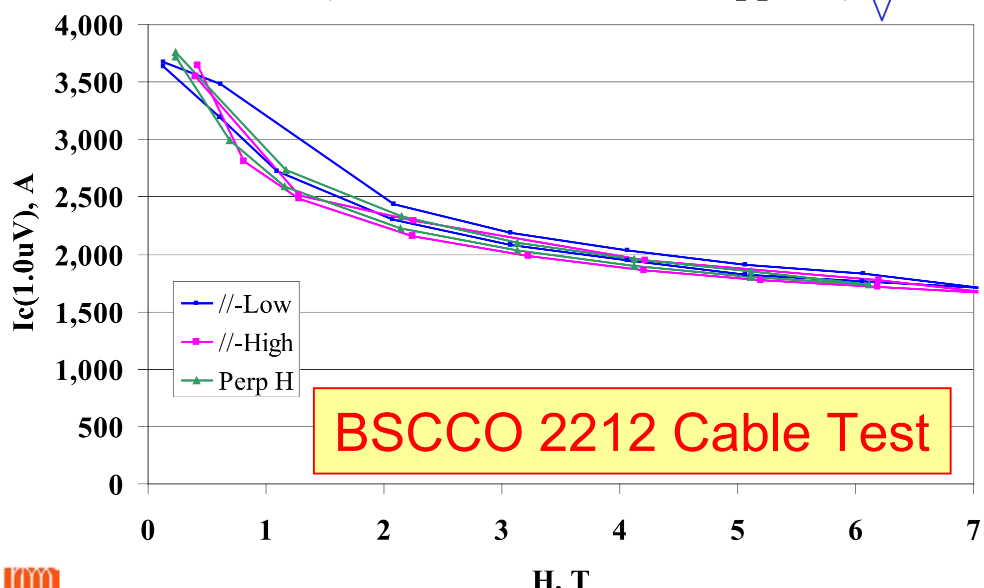
29/05/00

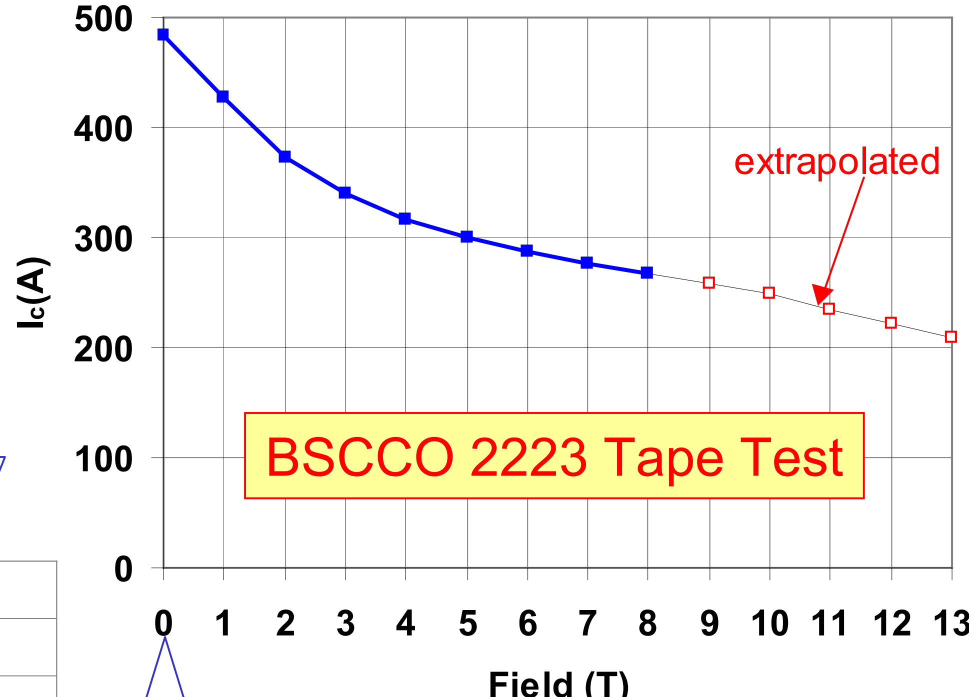
Measurements of HTS Cable and Tape at 4.2 K as a Function of Field at BNL



Measurements of "***BSCCO-2212 cable***" (Showa/LBL/BNL) @ 4.2 K at BNL test facility

(self field correction is applied)



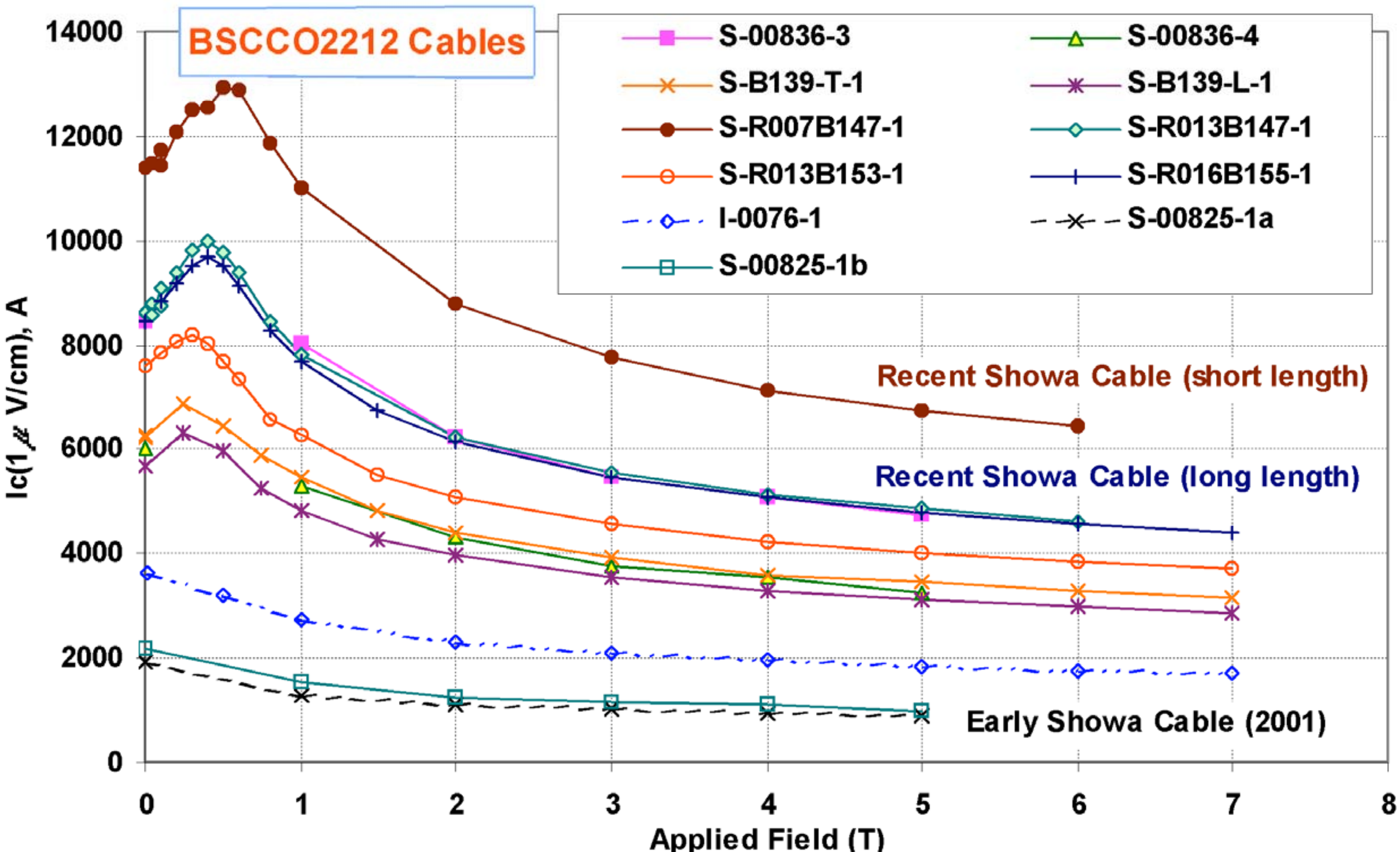


Measurements of "***BSCCO 2223 tape***" wound at 57 mm diameter with applied field parallel (1μV/cm criterion). The field perpendicular value is ~60%.

HTS Cables: A Remarkable Progress

Measurements at 4.2 K

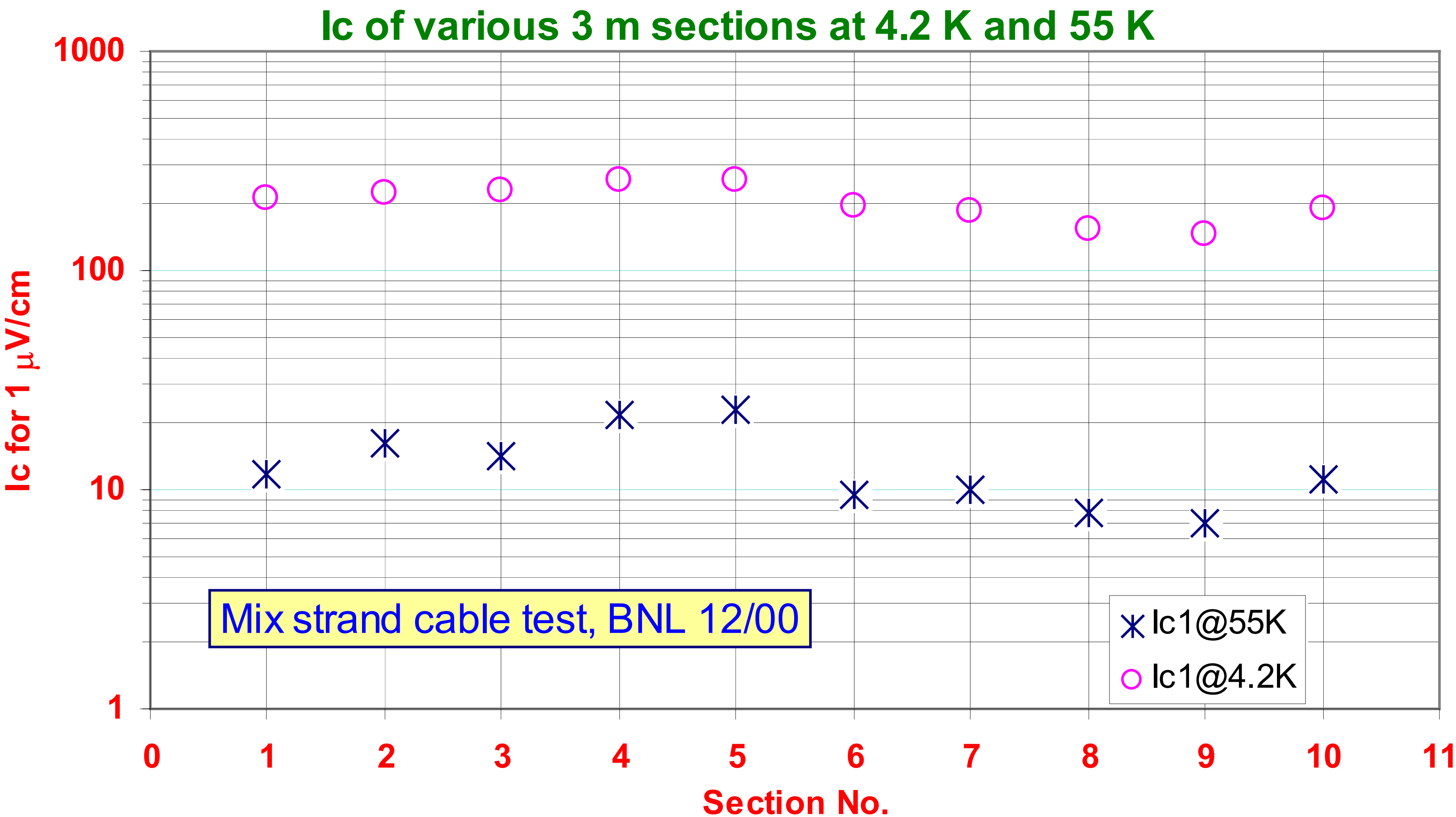
Modern HTS Cables Carry Significant Current.



Significant self-field at high currents.

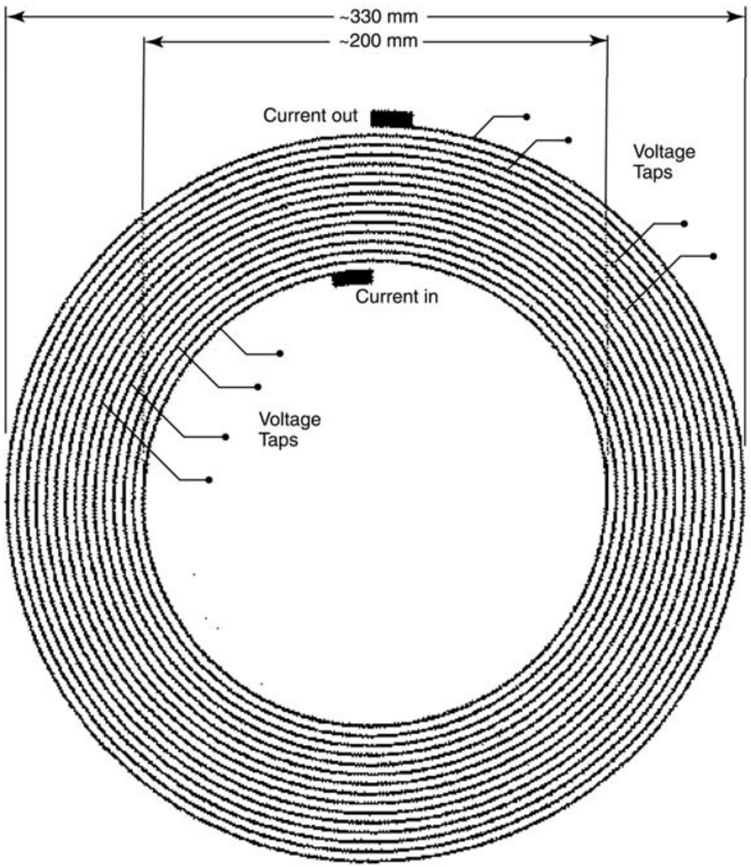
HTS Cables Tested at BNL Short Sample Test Facility

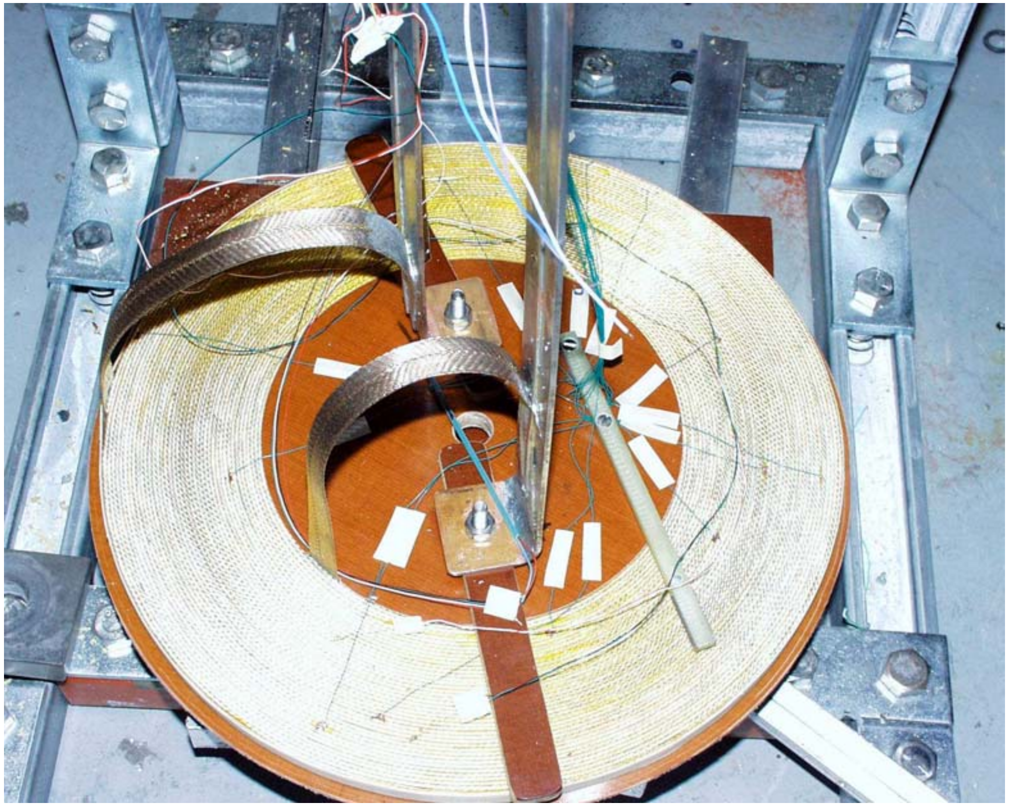
Ic Tracking Between 4.2 K and 55 K



BSCCO-2212 Cable "Pancake Coils"

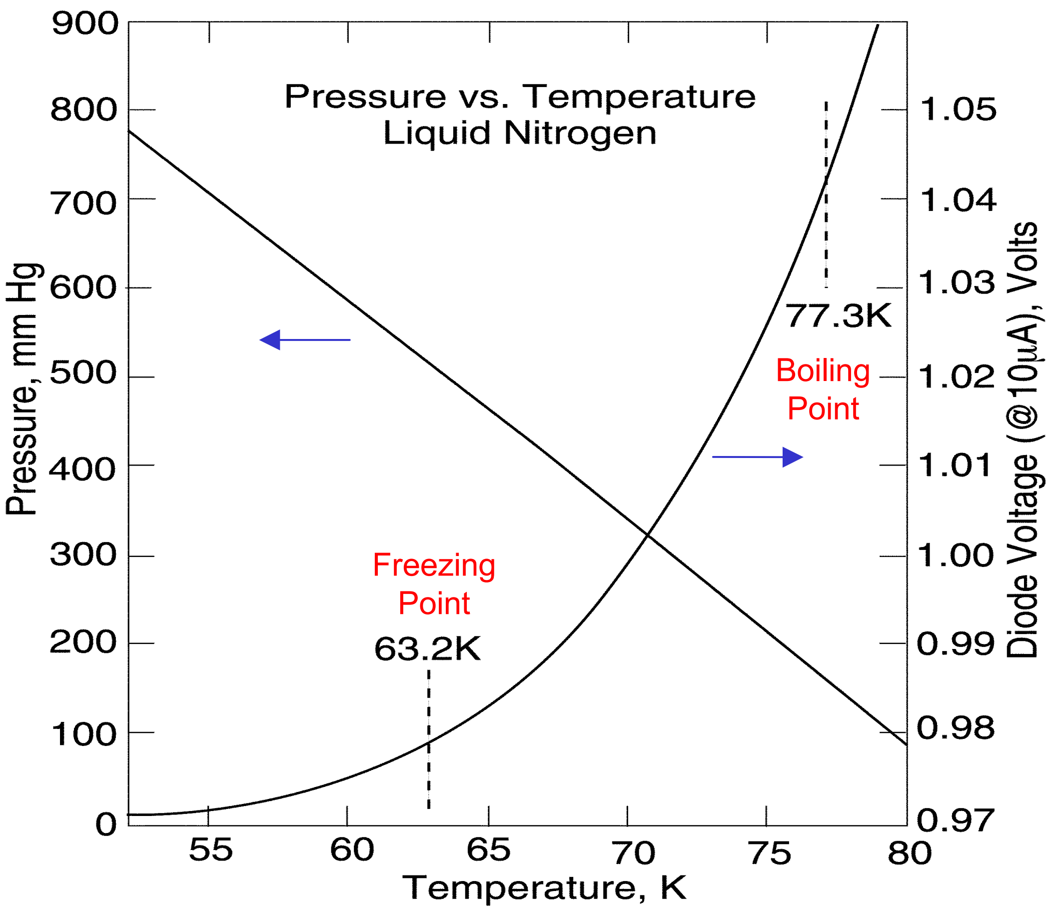
HTS cable carefully wound in a large radius pancake coil for testing at liquid nitrogen (LN_2) temperatures





HTS Cable and Coil Test at Liquid Nitrogen (LN_2)

Testing at LN_2 temperature is a simple, inexpensive and powerful QA tool even for applications where magnets would operate at lower temperatures.



- Good correlation has been observed between 77K (LN_2 testing) and 4K measurements.

Test/operating temperature can be reduced by reducing pressure - a simple and useful tool. We have gone as low as ~55 K at which point nitrogen was frozen.

Design Issues for High Field Accelerator Magnets using HTS

- HTS is very brittle

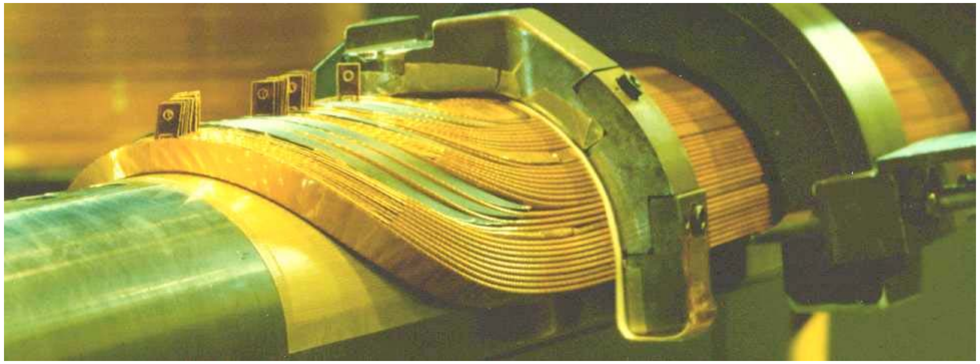
  Conventional designs are not the most suitable

- Large Lorentz forces
- The required reaction temperature and required uniformity over the whole area is very high:

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

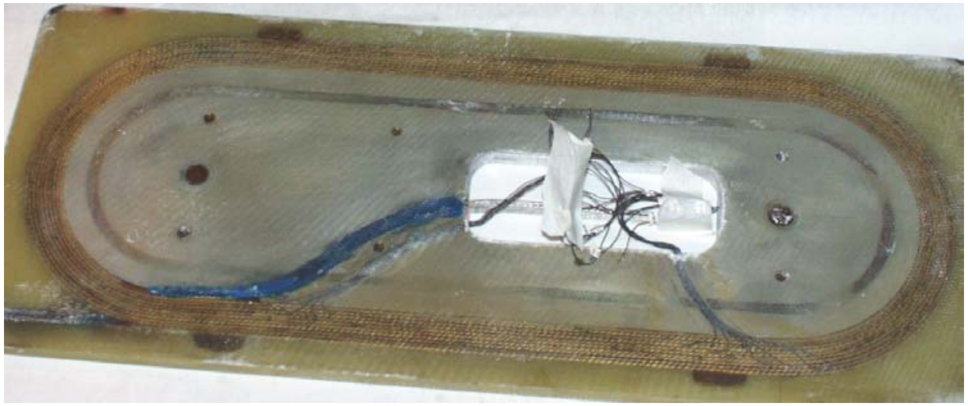
⇒This implies that "Wind and React" Technology is not suitable.

➢ **Develop "React & Wind" Magnet Designs and technology.**



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

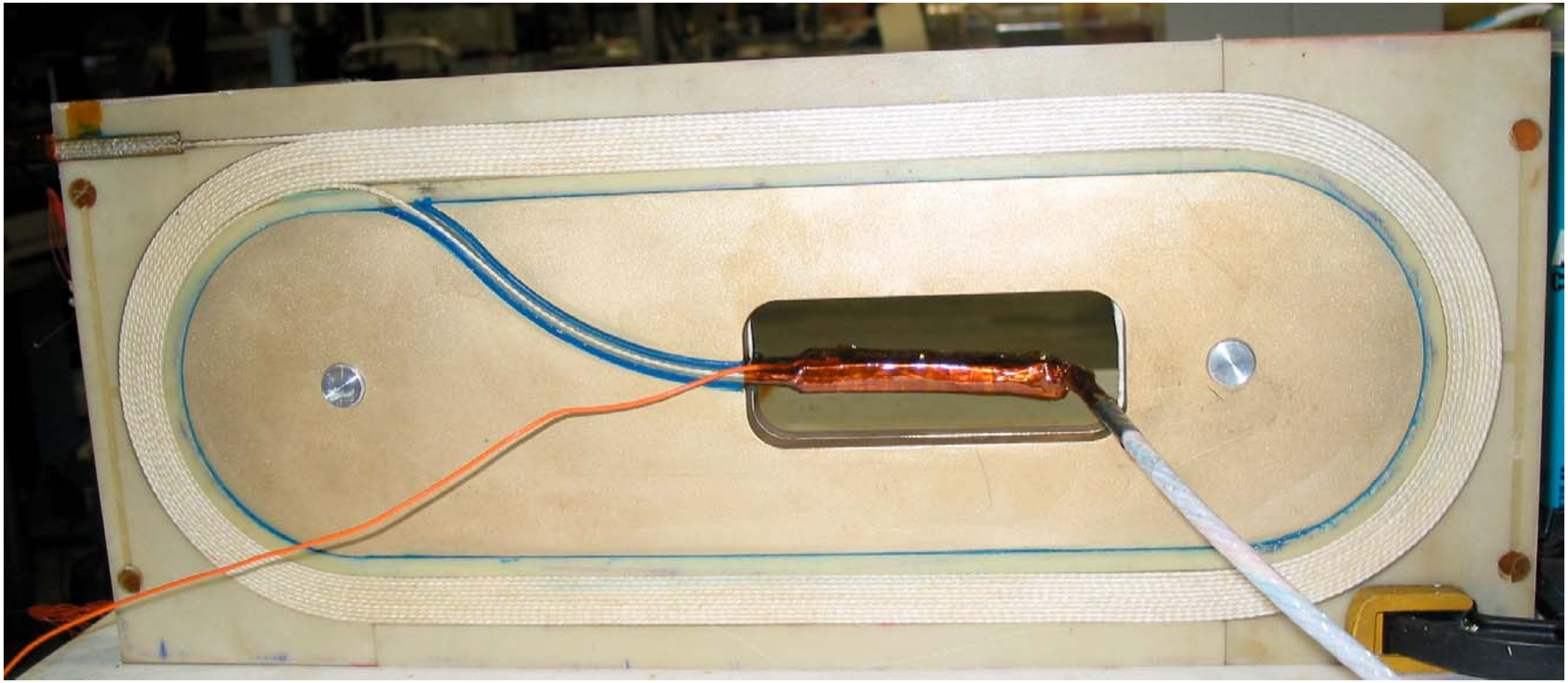
Complex 3-d geometry in the ends



"Conductor friendly" racetrack coil with large bend radius

Suitable for high field magnets with brittle material

High Temperature Superconductors (HTS) in Accelerator Magnets



This coil carried a record 4+ kA.

At present no superconductor can carry such engineering current density at ~25 T or more.

(need a factor of 2-4 improvement in J_c for 12-20 T range)

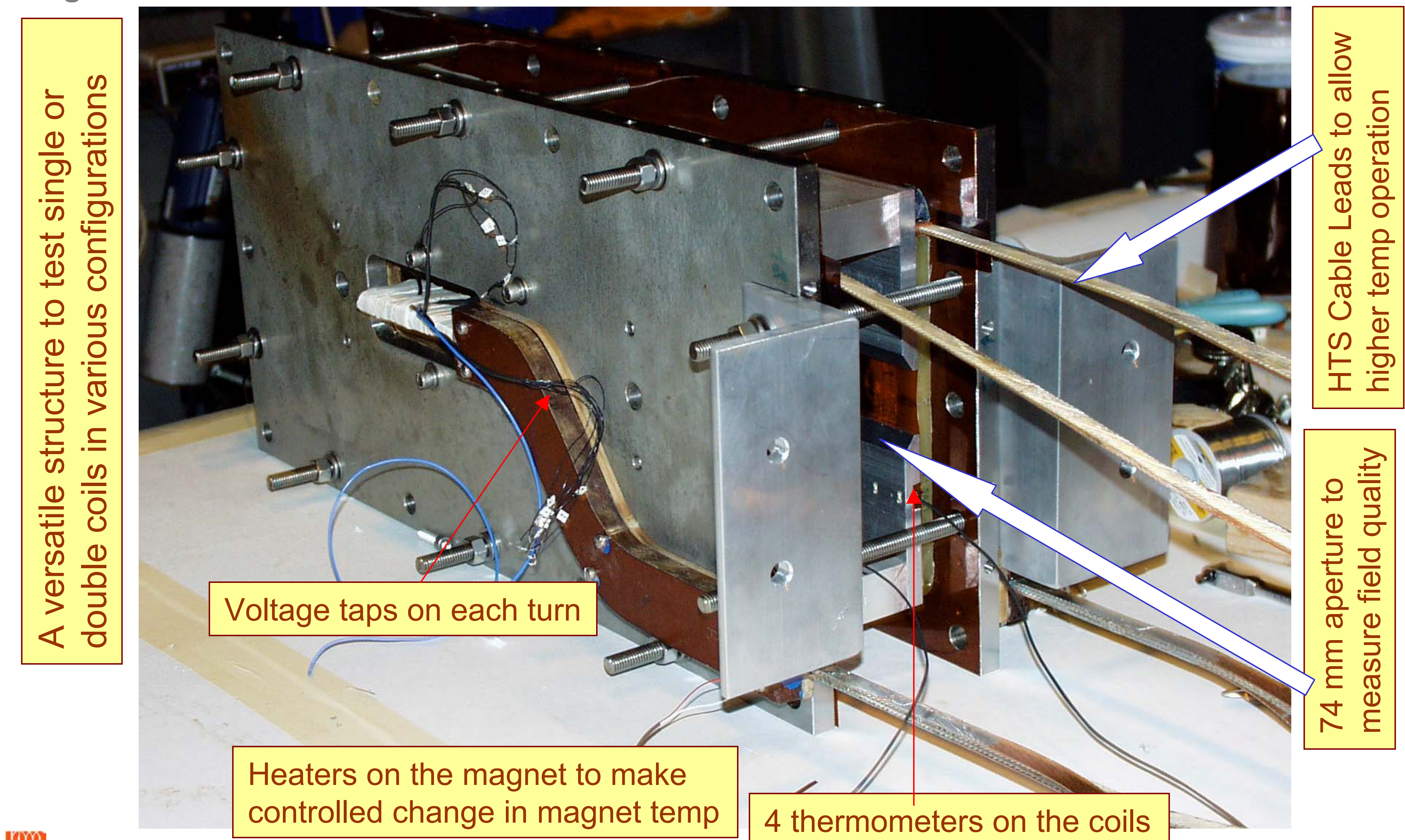
HTS Common Coil R&D Test Magnets (A High Field Magnet Design)

Made with HTS Tape

Made with HTS Cable

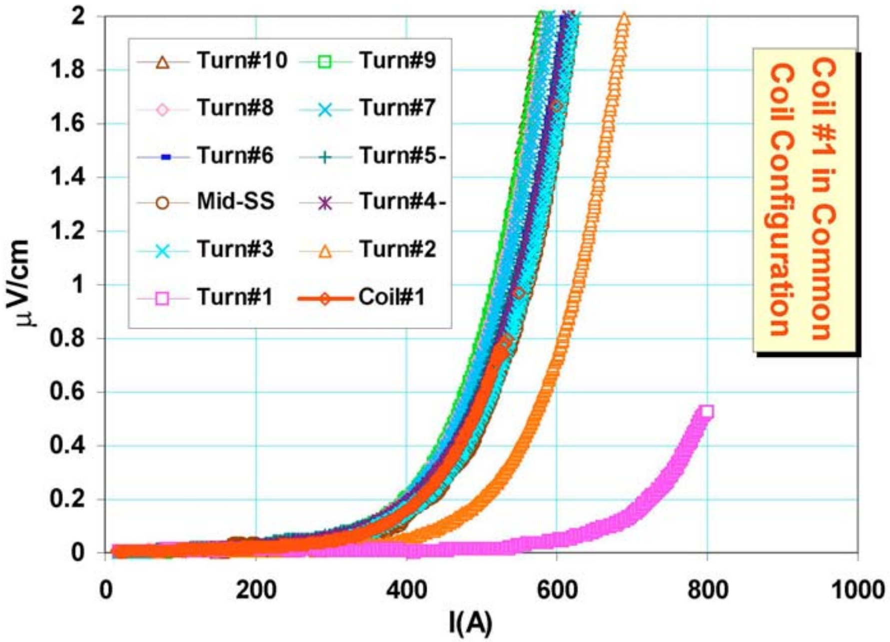
HTS Dipole with 74 mm Aperture

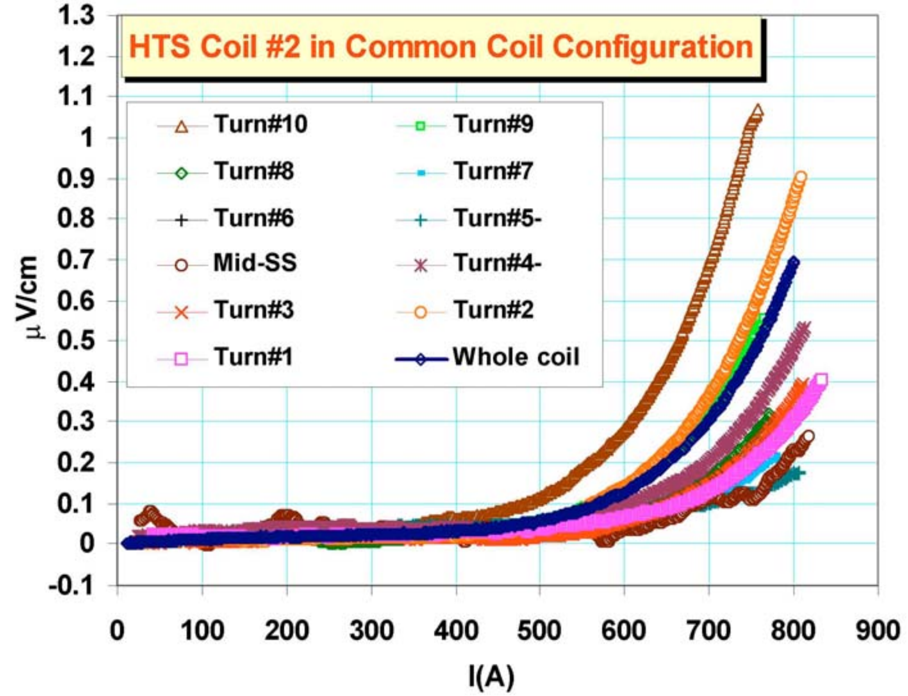
(Sufficient aperture to measure field harmonics)



Performance of Coil #1 and Coil #2 in Common Coil Test Configuration in Magnet (DCC004)

Voltage difference between each consecutive turn and on each coil





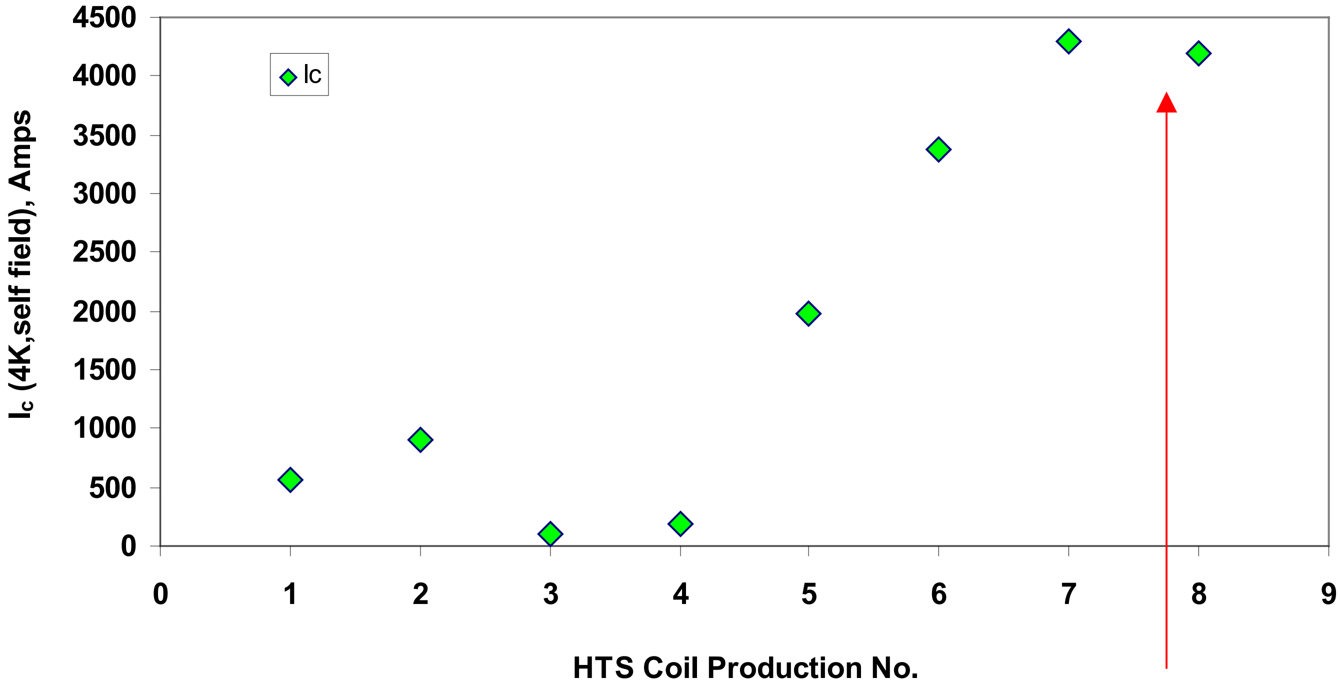
Turn-to-turn differences in critical current come from

- Differences in field at various turns
- Variation in the performance of initial conductors along the length (modern conductors show much better uniformity)

4.2K Test Results of Various HTS Coils

Earlier coils
<1 kA (~2001)

Latest coils
4.3 kA (10/03)



Self-field
<0.05 T

Self-field
~ 1.85 T

Measurements in self-field

Note:

HTS cables now carry significant currents in magnet coils.

TABLE II

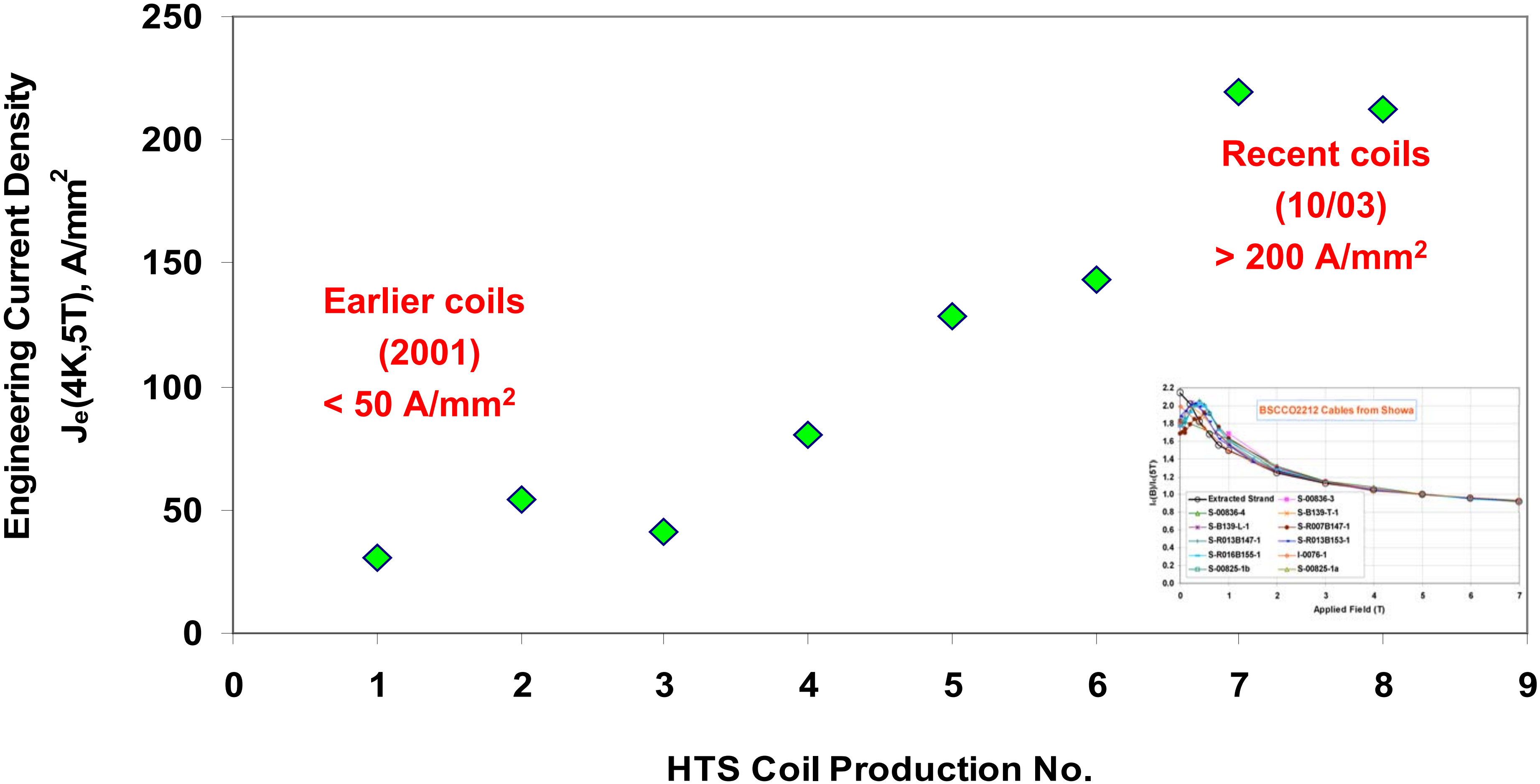
COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. I_c IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

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	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

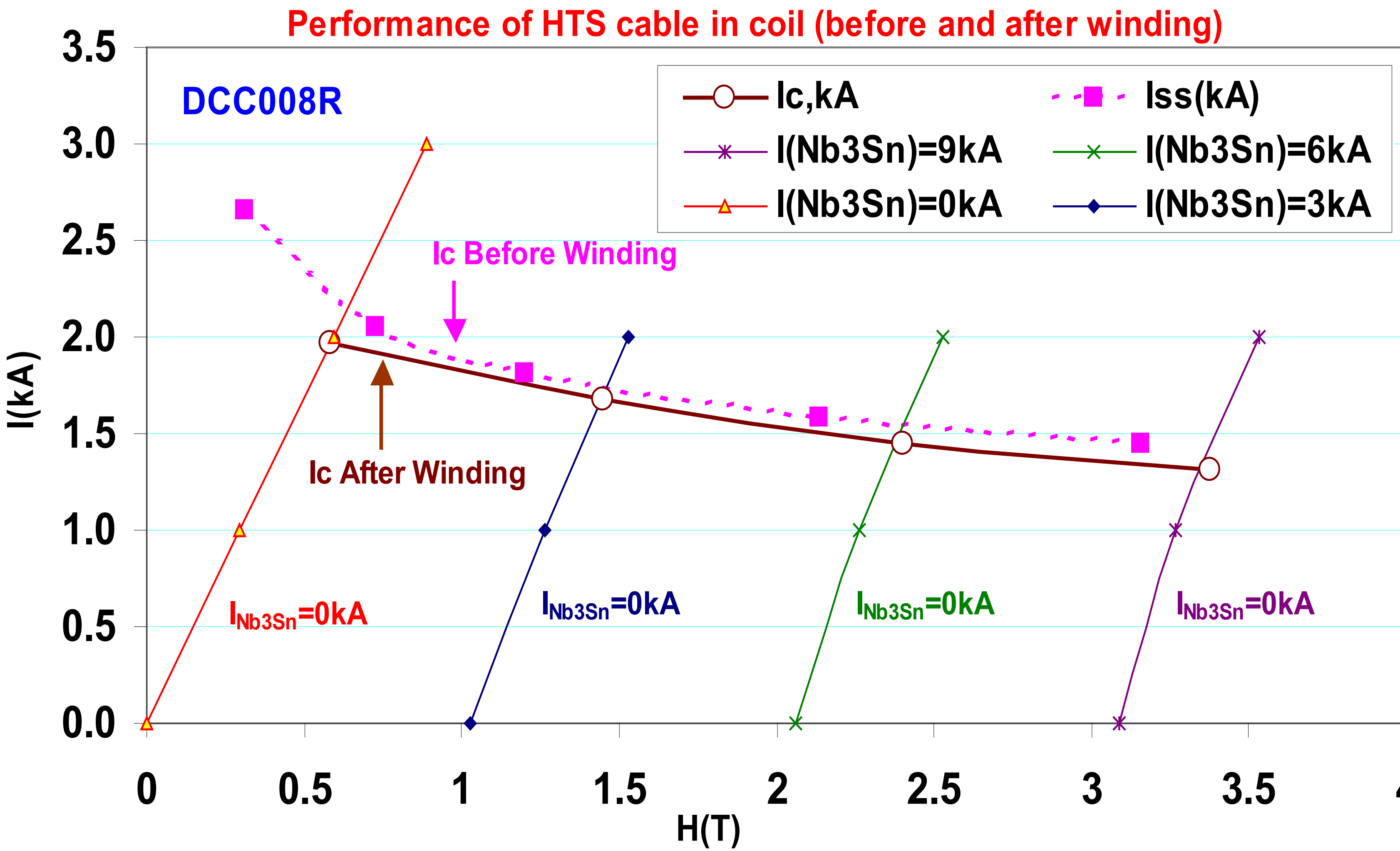
Test Results of HTS Coils at 4K Normalized to 5T

Self-field measurements, normalized to 5 T (small change in J_e at higher fields).

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

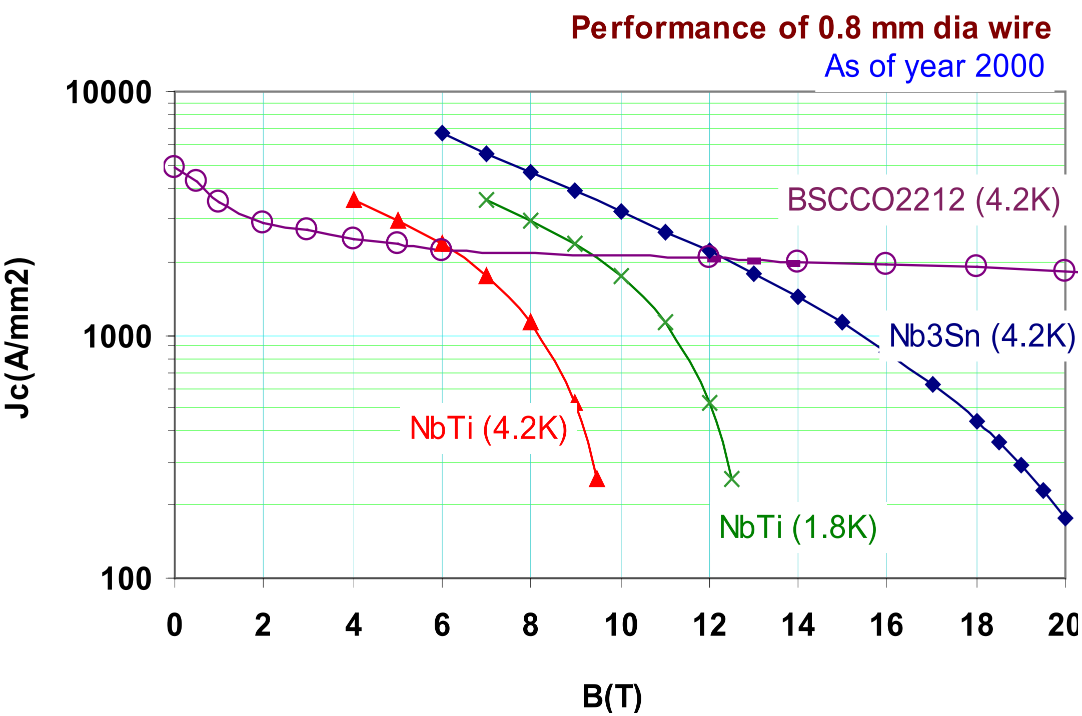


Performance of HTS Cables & Coils



Proof that despite the brittle nature of HTS cable, coils can be wound without causing significant degradation in performance.

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)

HTS (BSCCO/YBCO) : 4000 A/mm^2 (2X today)

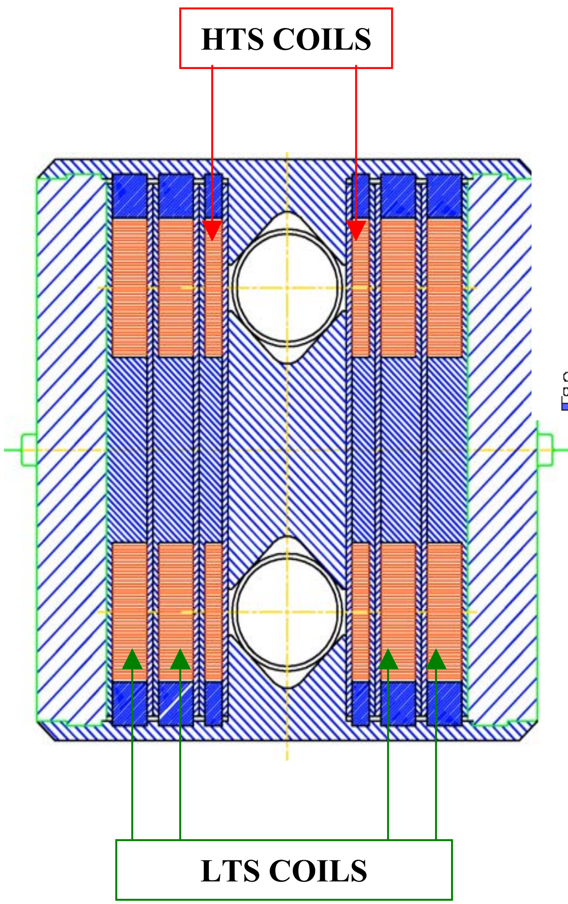
Expected performance of all Nb_3Sn or all HTS magnets at 4.2 K for the same amount of superconductor:

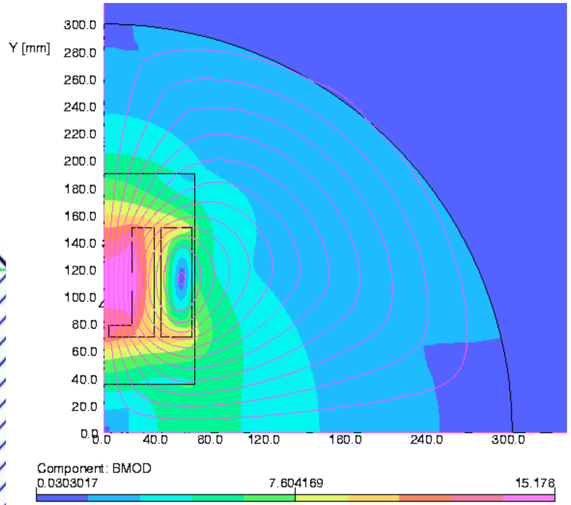
Year 2000 Data	
All Nb_3Sn	All HTS
12 T	5 T
15 T	13 T
18 T	19 T*

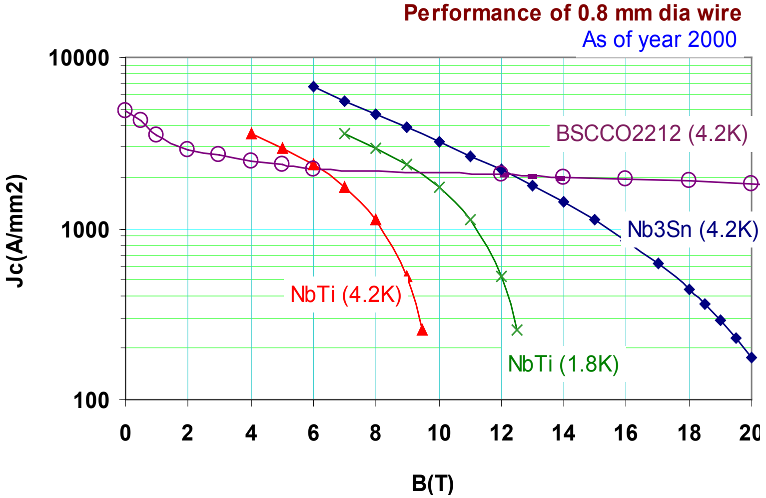
*20 T for Hybrid

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

Use of HTS with LTS for High Field Hybrid Magnet Designs

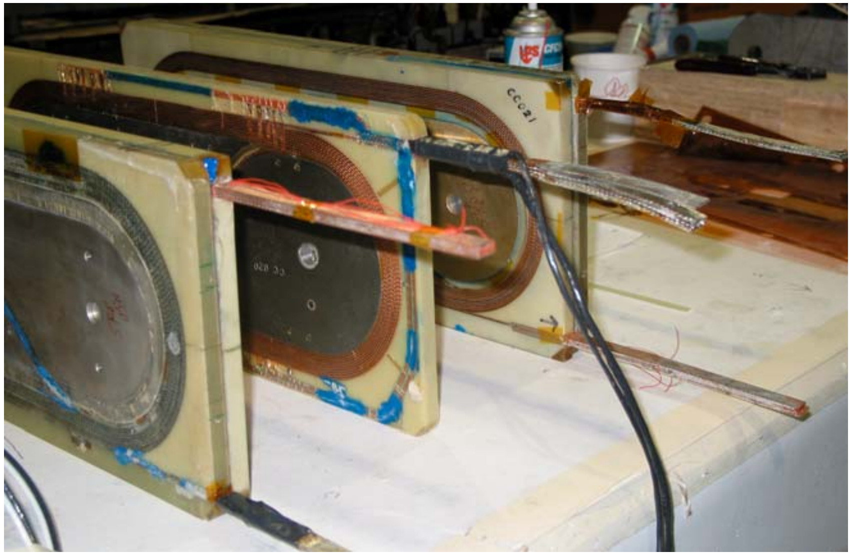






- At present, HTS alone does not provide the best solution for generating very fields.
- Make inner coils with HTS coils where the field is really high and outer coils with LTS (Nb_3Sn) where the field is somewhat lower.
- This facilitates designs with the highest possible current densities both in very high field regions (use HTS) and a relatively lower field region (use Nb_3Sn).
- This principle is used in all types of high field magnets.

An Example of HTS Coils in a Hybrid Magnet Structure

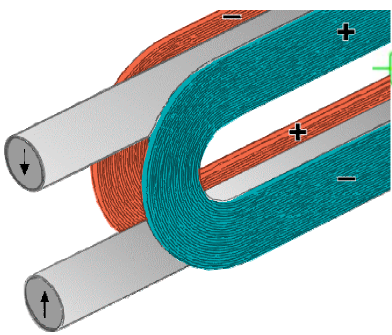


We make racetrack coils as modular components. These modules (cassettes) can be mixed and matched in a common coil magnet structure for a variety of experiments with a rapid turn around.

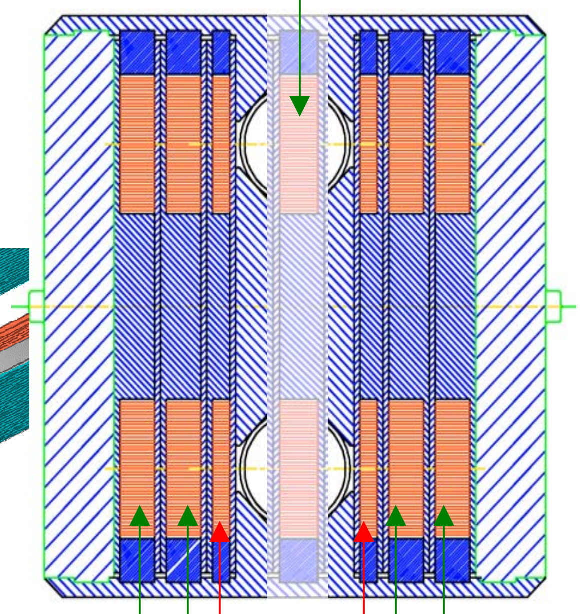
- A versatile support structure that can accommodate up to six coils. The width of the coils need not be the same.
- The structure has been used for hybrid magnet with the number of HTS coils from 1 to 2 and Nb_3Sn coils from 2 to 4.
- Nb_3Sn coils provide adjustable background field on the HTS Coils.

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

Common coil design



Strand, cable or insert coil

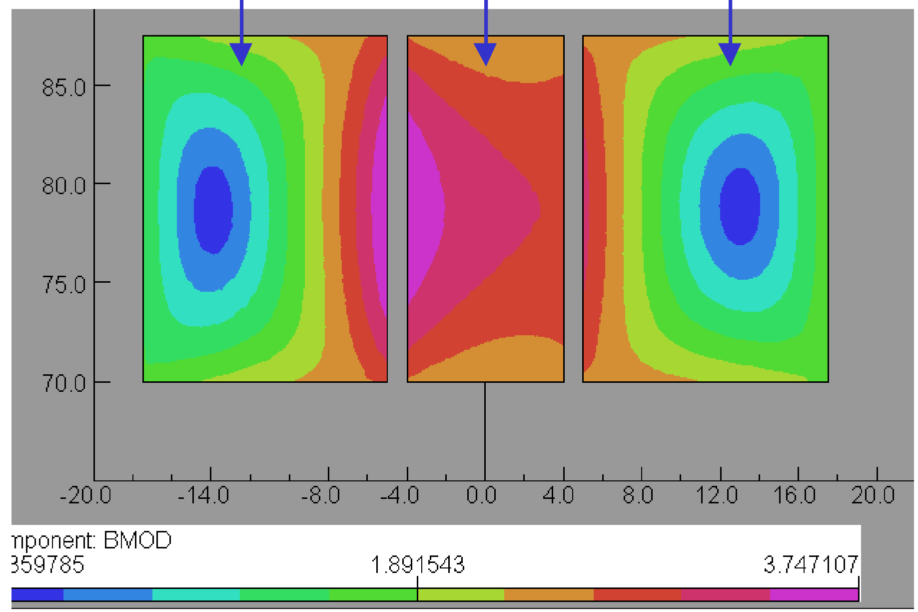


Original coils

Background field test configuration

Field in various coils

Nb_3Sn HTS Nb_3Sn

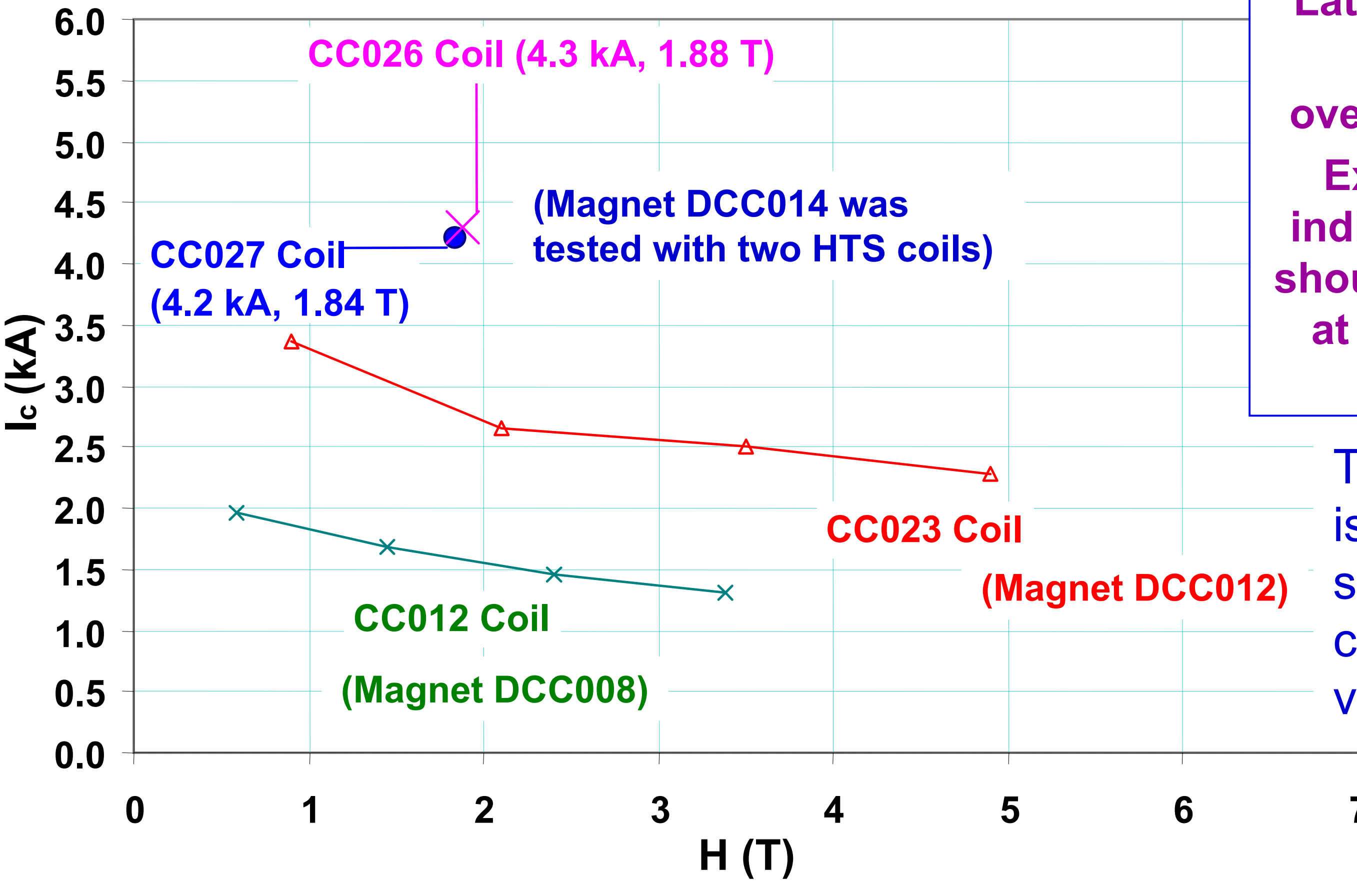


Nb_3Sn coils provide a background field on HTS coil in a common coil hybrid design

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).

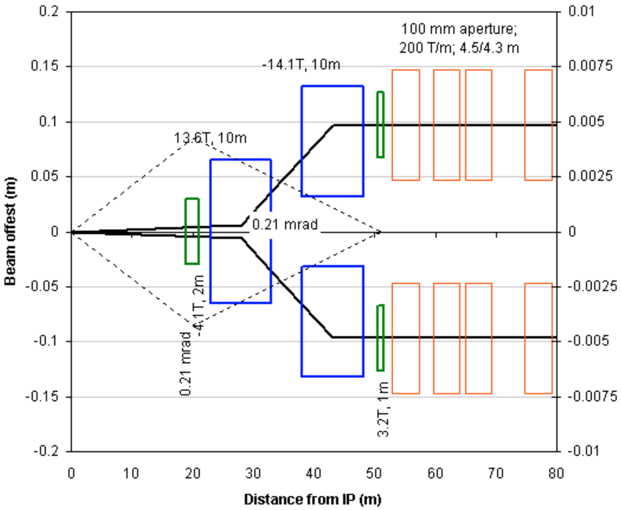
Continuous progress is noteworthy.

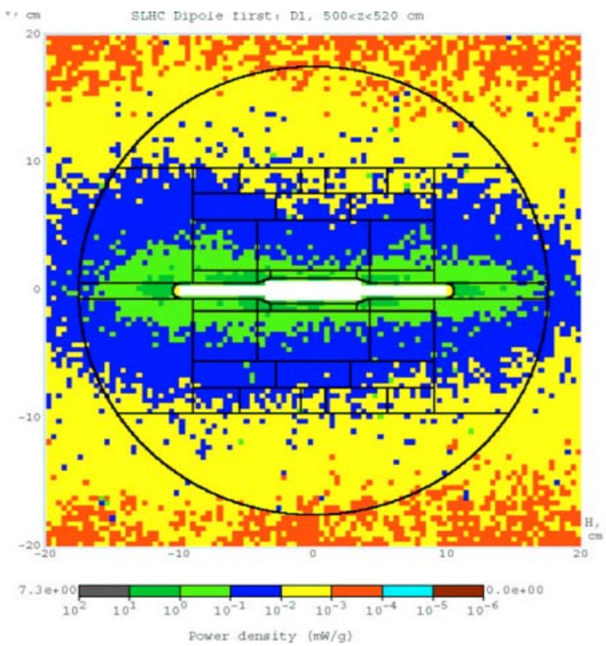


Latest coils were tested for over 4 kA at ~2 T. Extrapolations indicate that they should carry ~3 kA at any arbitrary high field.

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

Use of HTS in Interaction Region (IR) Magnets





The use of HTS in interaction region magnets for next generation of hadron colliders can benefit a lot from:

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

→ For a very high luminosity IR, a few magnets determine the ultimate machine performance. Hence, the magnet performance, not the conductor cost, should be the driver.

Medium Field High Operating Temperature Applications of HTS

- These applications don't require very high fields.
- The system design benefits enormously from HTS because HTS offers the possibility of magnets which operate at a temperature higher than 4K, say at 20-40 K.

There are two class of potential applications:

Small scale, special magnet application

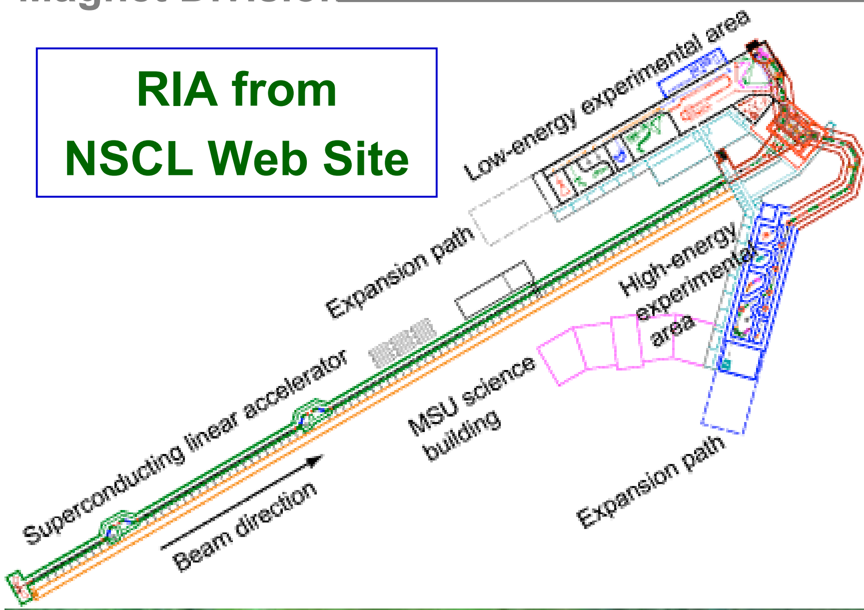
- Here the use of HTS is determined by its unique advantage of large temperature margin. The system is optimized for performance and not necessarily for cost.

Large scale, general magnet application

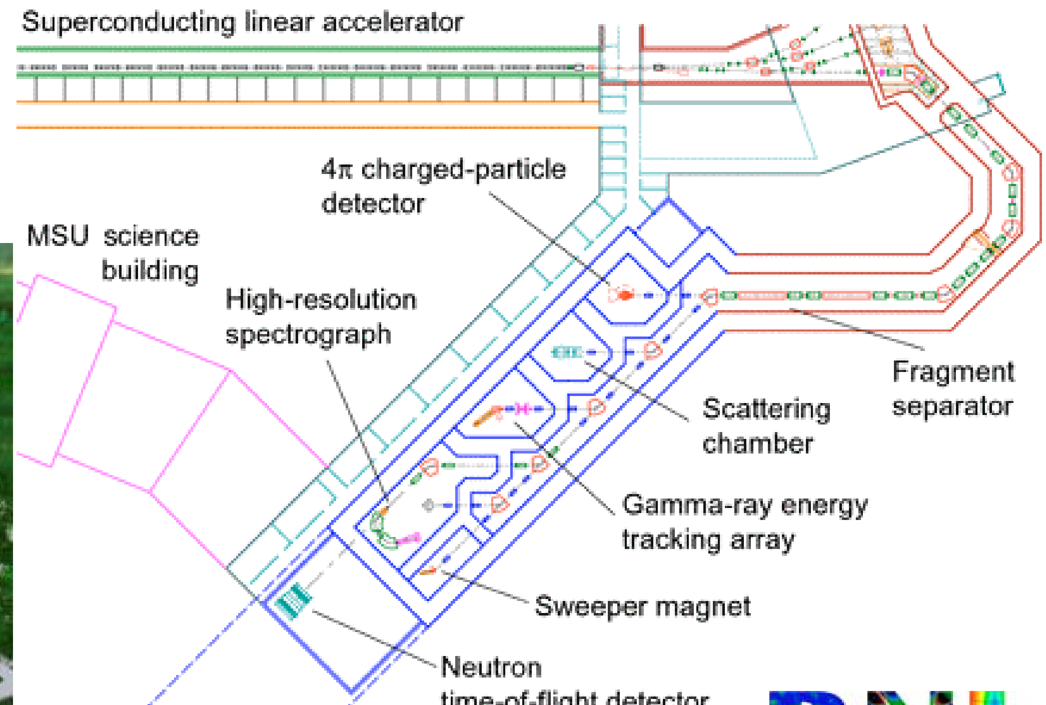
- Here the use of HTS should reduce the cost of ownership (construction + operation). In this case one must compare these costs with room temperature water-cooled magnets or with conventional low temperature superconducting magnets.
- It's challenging but if successful it may make a significant impact in the field.

High Temperature Superconductor (HTS) Quads in Fragment Separator Region of RIA

RIA from NSCL Web Site



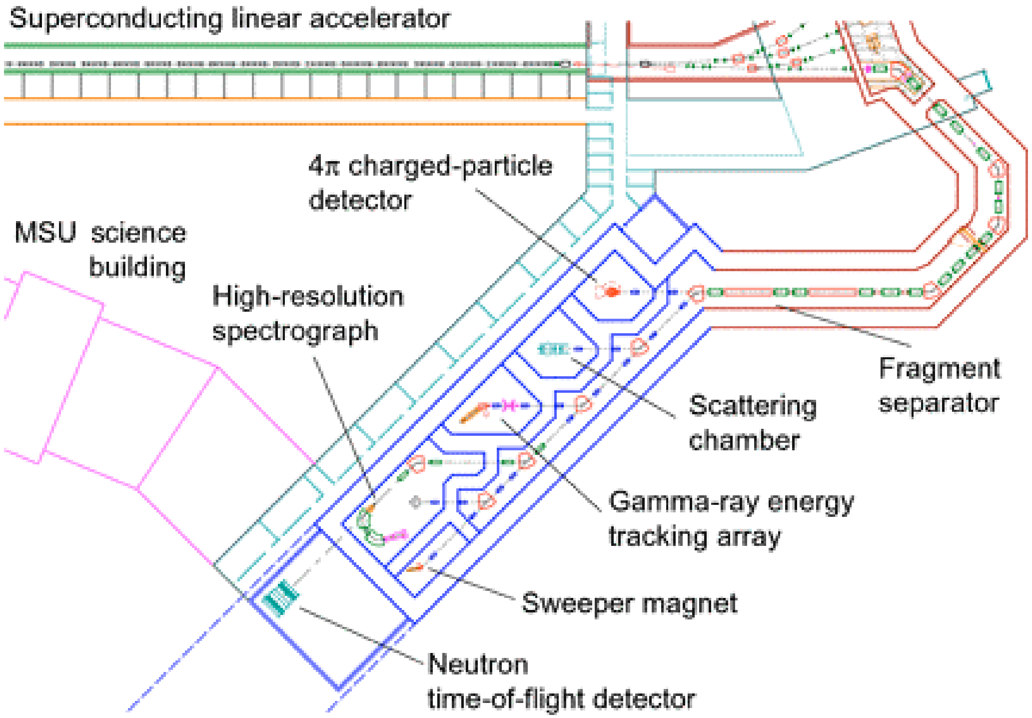
In the Rare Isotope Accelerator (RIA), a high energy, high intensity proton beam will hit the target to produce intense secondary beams. The fragment separator region (consisting of dipole and quadrupole magnets) will then select a copious amount of the desired rare isotopes, focus, and send this beam further down.



NSCL NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY AT MICHIGAN STATE UNIVERSITY

Fragment Separator Region of RIA

Magnetic elements (quads) in the 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 a high radiation dose 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!

Short Time Scale Issues

Conventional low temperature (e.g. NbTi) superconducting magnets will quench if a large amount of energy is dumped on their coils (> several mJ/g).

In addition, there is a large constant heat load on the cryogenic system

- The temperature increase must be controlled within the tolerances of the superconductor used.
- The large amount of heat deposited must be removed economically.

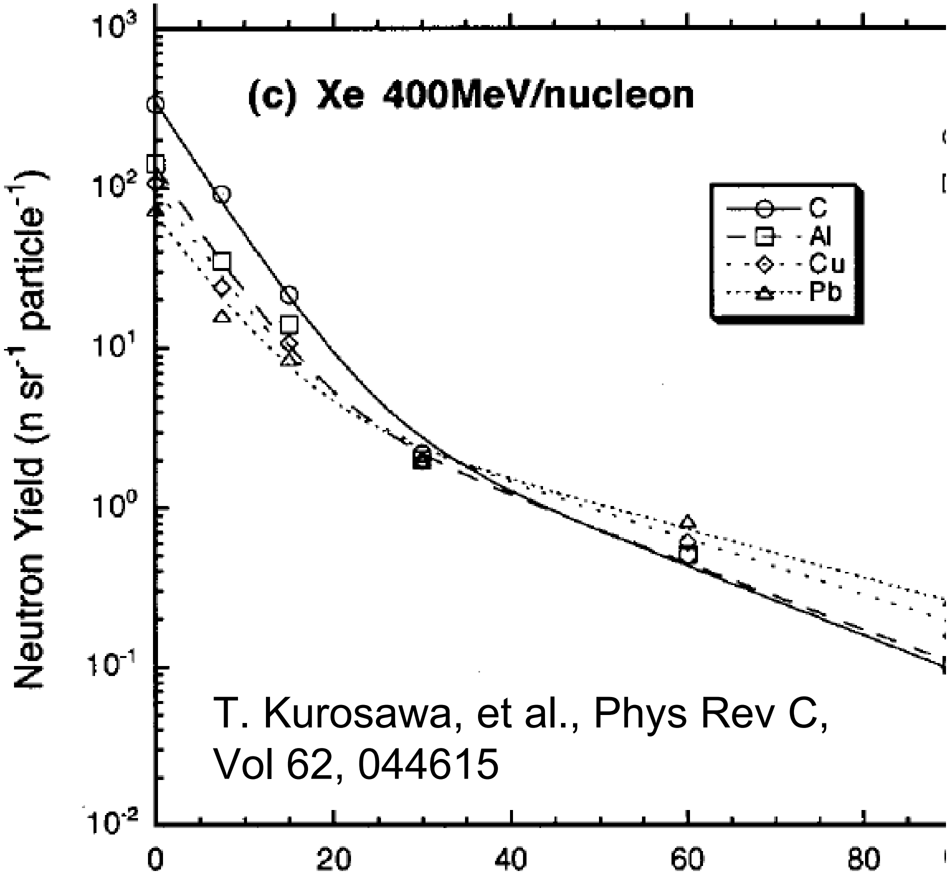
High Temperature Superconductors (HTS) offer an attractive solution.

Advantages of using HTS in Magnets for the Fragment Separator

- As compared to conventional Low Temperature Superconductor (LTS), the critical current density (J_c) of High Temperature Superconductor (HTS) falls slowly as a function of temperature.
- The magnet system benefits enormously from the possibility of magnets operating at elevated temperature (20-40 K instead of conventional ~4 K).
- HTS can tolerate a large local increase in temperature in superconducting coils caused by the decay particles.
- Moreover, the temperature need not be controlled precisely. The temperature control can be relaxed by over an order of magnitude, compared to that for present superconducting accelerator magnets.

Significant Reduction in Neutron Fluence at Larger Angle

BNL/MSU collaboration



The plot on the left shows a typical neutron dose as a function of angle, away from the target.

One must look at the impact on the material properties of such a high radiation dose over the magnet life time.

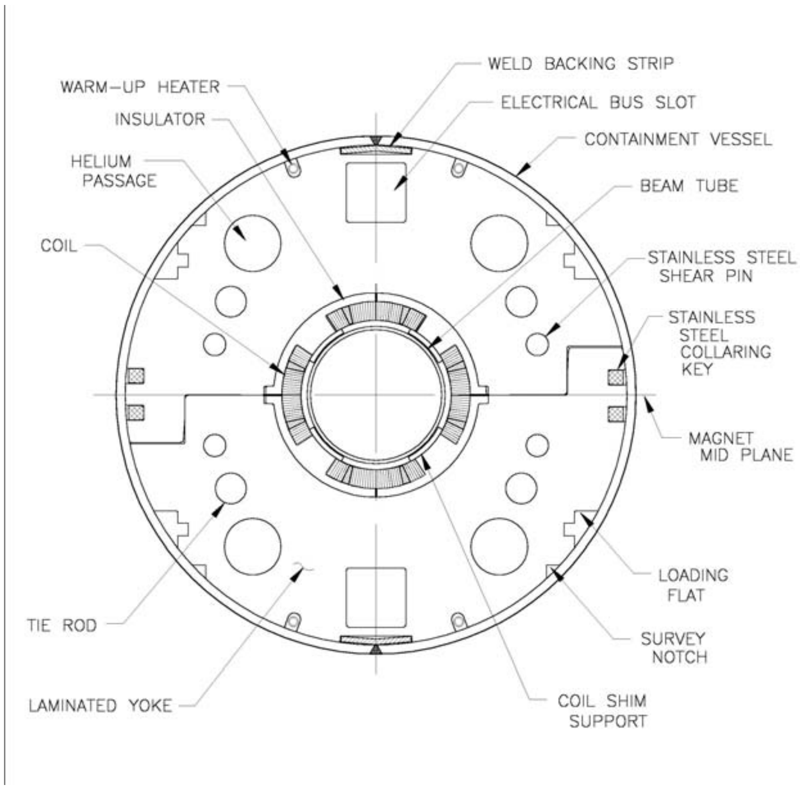
Estimated value in ~12 year period:

10^{19} neutrons/cm^2 in 0^o to 30^o region.

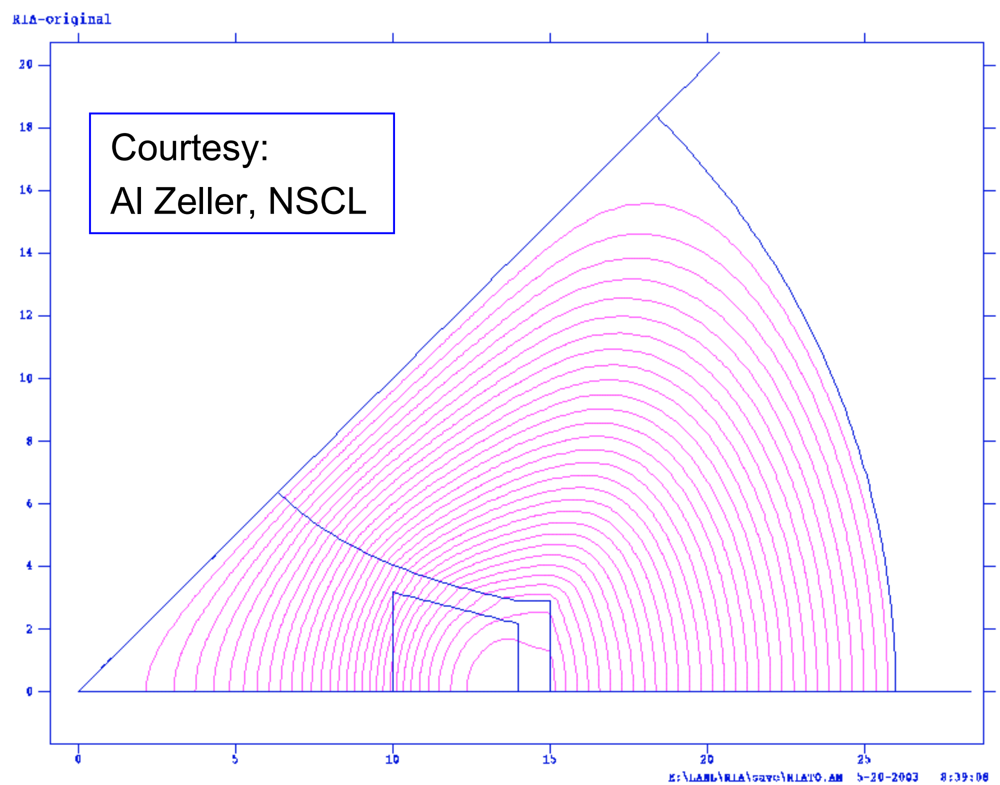
Note: Log scale and 50 X difference in value between 0^o and 30^o

Conventional Designs of Superconducting Quadrupoles for the Fragment Separator

A Cosine theta Design with NbTi (LTS) Superconductor



A Cold Iron Super-ferric Design with NbTi (LTS) Superconductor



BROOKHAVEN NATIONAL LABORATORY

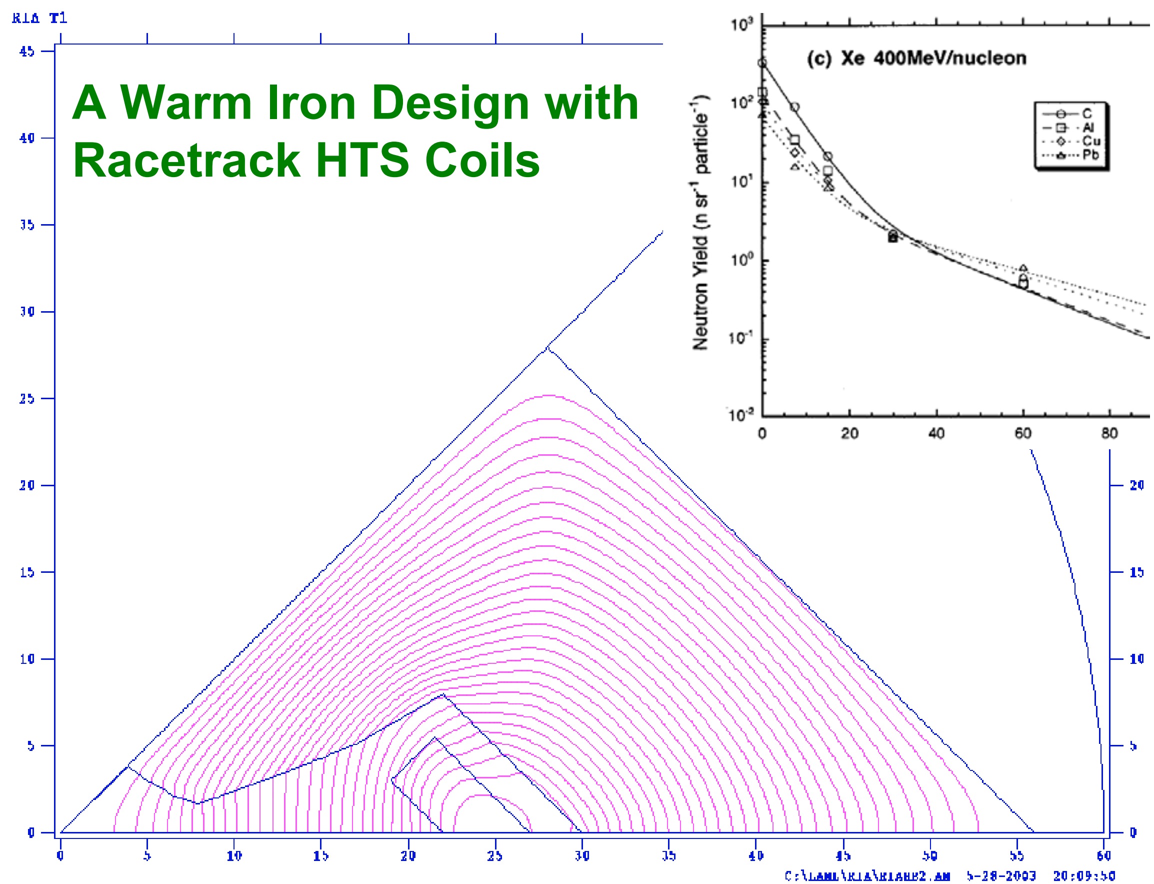
Superconducting Magnet Division

Proposed Design Concept for the 1st RIA Quad in the Triplet of the Fragment Separator

A Super-ferric design with yoke making significant contribution to field. Simple racetrack coils, yoke starts at R_{yoke} = 5.5 cm. Gradient = 32 T/m.

- Coils are moved further out to reduce radiation dose.
- The magnet is designed with warm iron and a compact cryostat to reduce the amount of coldmass on which the heat and radiation are deposited. This design reduces the heat load on the system by a large amount.
- Field lines are funneled to the pole to create a larger pole tip field, and gradient.

A Warm Iron Design with Racetrack HTS Coils

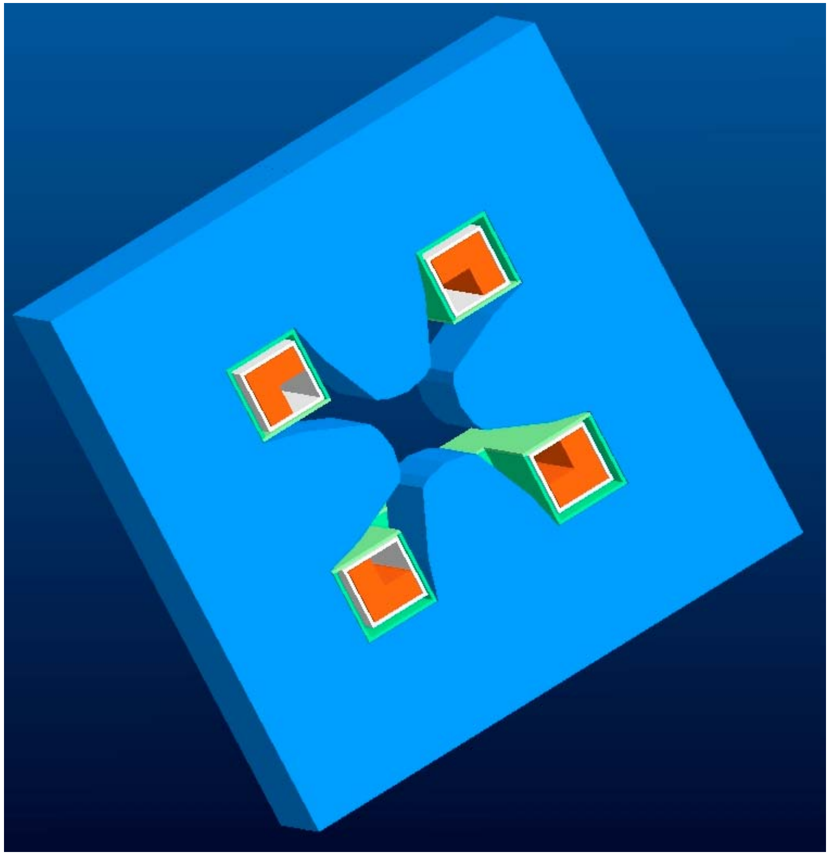


Basic Design of RIA HTS Quadrupole

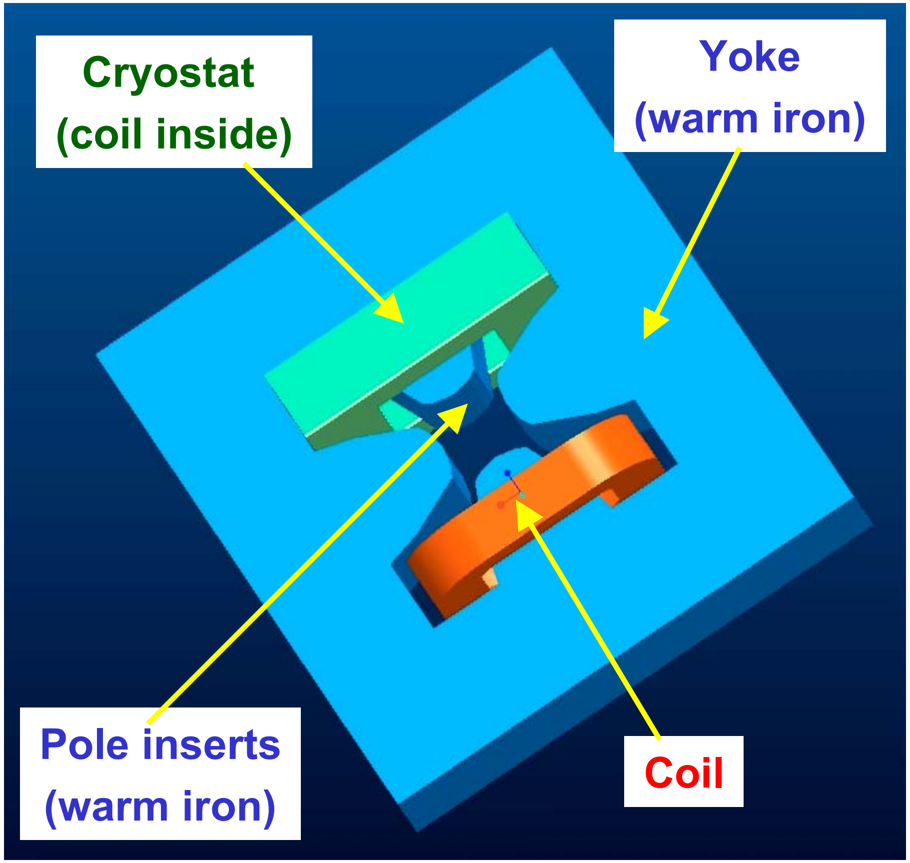
A simple warm iron super-ferric quad design with two racetrack HTS coils

Note that only a small fraction of the mass is cold (see green portion), and also that it is at a large solid angle from the target .

Also two (NOT four) coils means lower heat and radiation load at the ends.



Cutout at the middle of the magnet



Coils inside the cryostat at the end of the magnet

Long Time Scale Issues

• One must look at the impact on the material properties of such a radiation dose over the life time (estimated 10^{19} neutrons/cm^2 in the region of 0 to 30 degrees in ~12 years).

• Iron and copper are expected to be able to withstand about ~100 times the above dose.

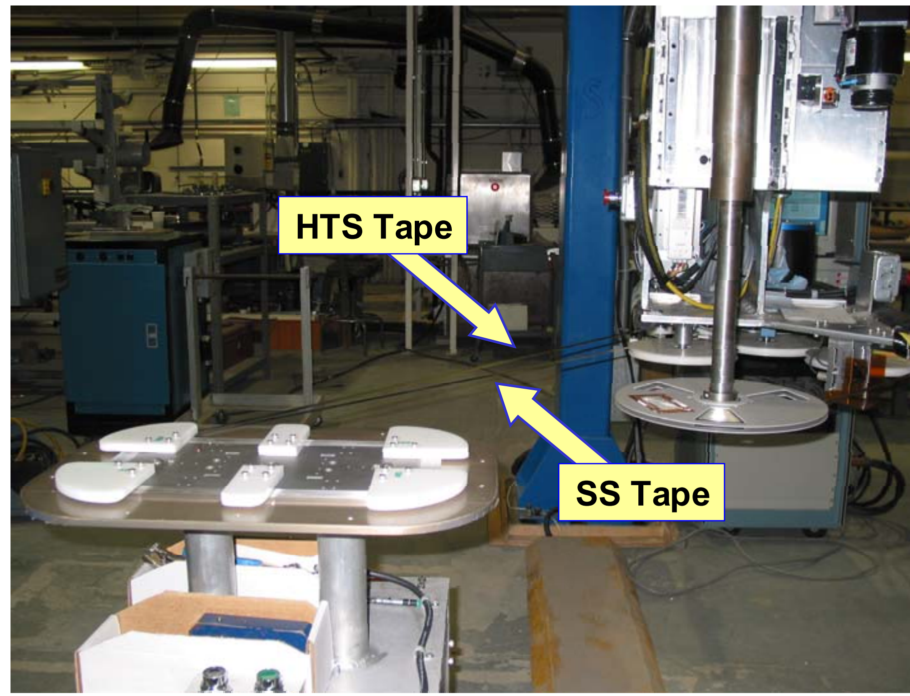
Note: Normal water cooled electromagnet cannot generate the required field gradient.

Stainless Steel Insulation in HTS Coils

Radiation damage to insulation is another major issue for magnets in high radiation area. Relatively speaking, metal (stainless steel) is an insulator. It is also highly radiation resistant. BNL (Sampson) has made use of stainless steel as the insulation material between turns.

Two coils, one with kapton insulation and the other with stainless steel.

Stainless steel reinforcement



HTS tape, used here, itself comes with stainless steel tape on either side of HTS tape.

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

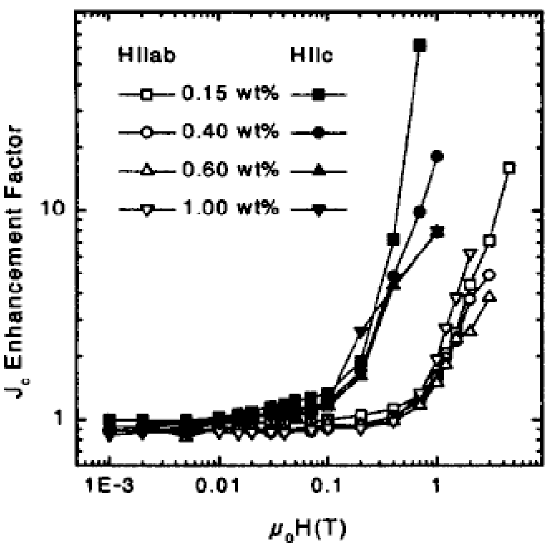


Figure 2. Enhancement of the critical current densities for samples with different amounts of uranium at 77 K, but at fixed track density.

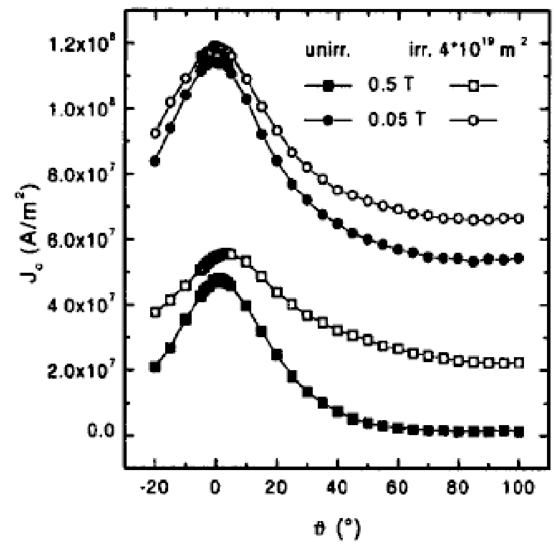


Figure 3. Anisotropy of J_c before and after irradiation to $4{*}10^{19}$ m^{-2} at 77 K and 0.5 T.

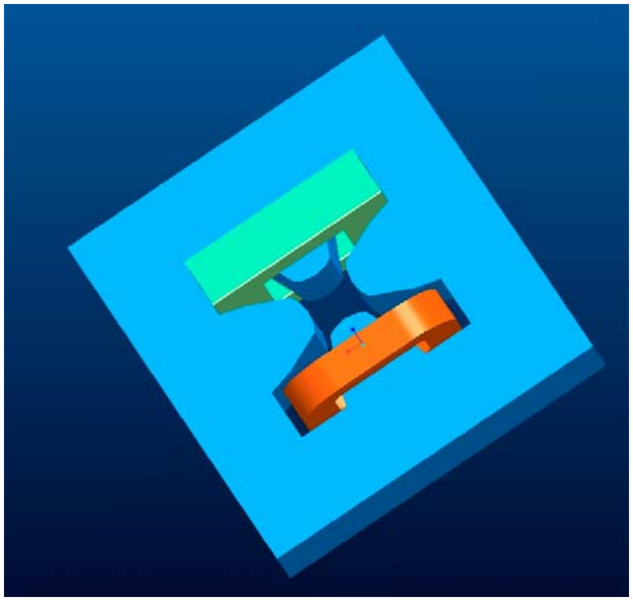
Need to study radiation damage on HTS from a large dose (few kW) of ~500 MeV neutrons.

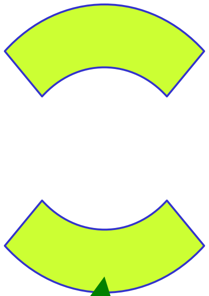
Equivalent dose from lower energy proton or ions?

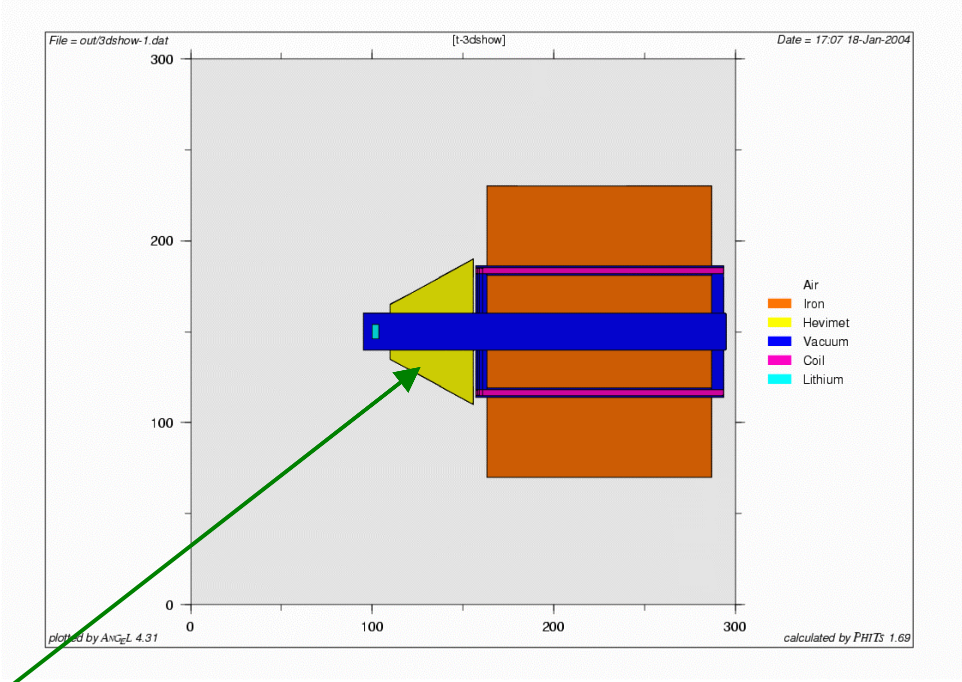
A few samples of HTS tapes have been irradiated at LBL by NSCL. Need to wait several months so that radiations level at a safe level to study the damage.

Heat Load and Shielding

BNL/NSCL Collaboration







Heat Load on Tungsten ~3.3 kW

Note: The volume (and hence cost) of Tungsten shield can be significantly reduced because coil ends do not cover the entire annulus.

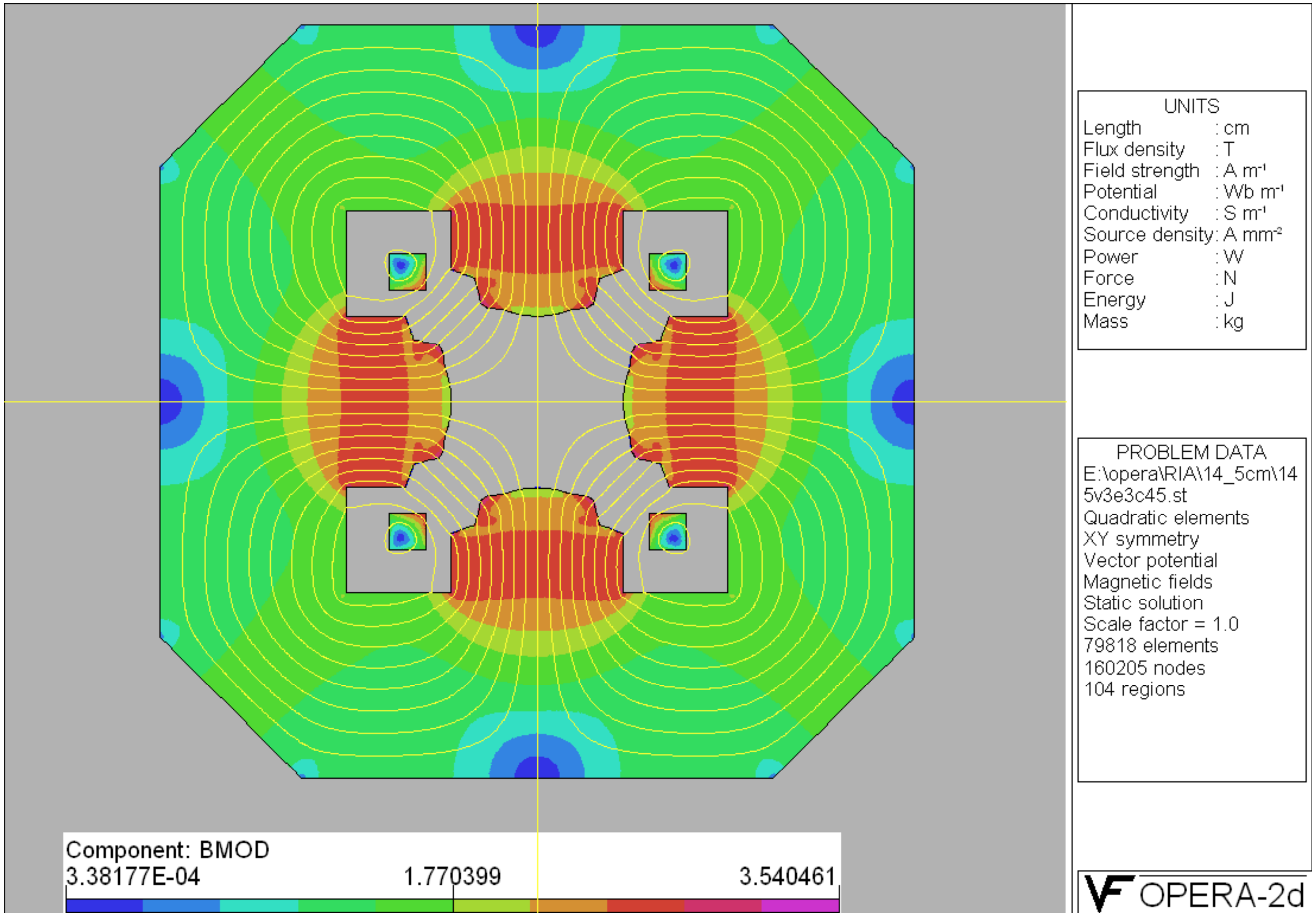
Iron heat load = 9 kW ☆

Coil heat load = 130 W ☆

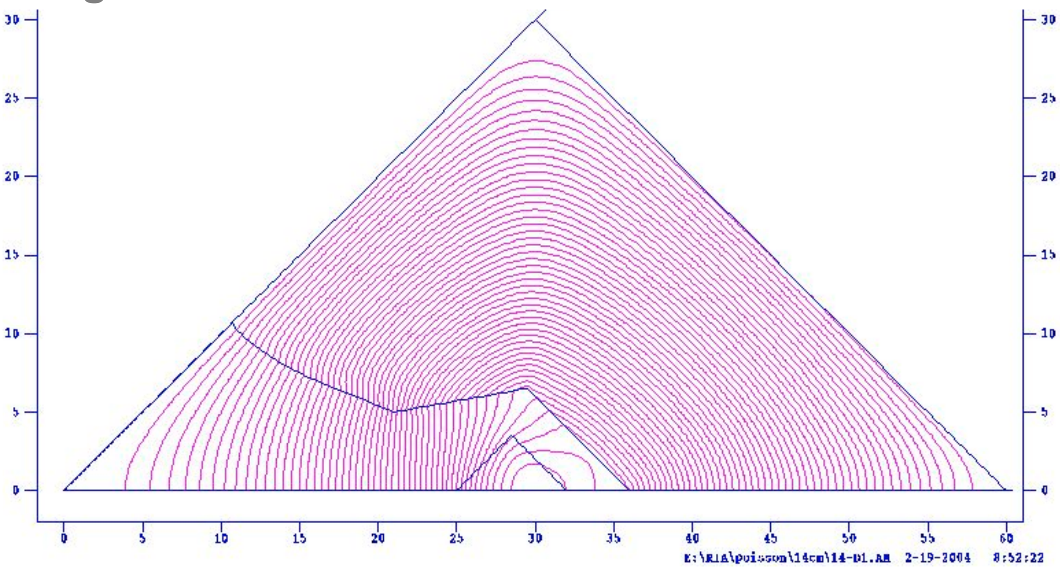
Coil dose rate (assumed to be silver) = 1 MGy/year

(organic materials would be a factor of 200 times more)

2-d Magnetic Model of The RIA Quad



Magnetic Mirror Model of RIA HTS Quadrupole magnet



Operating Temperature ~30 K;
Coil current density ~100 A/mm^2

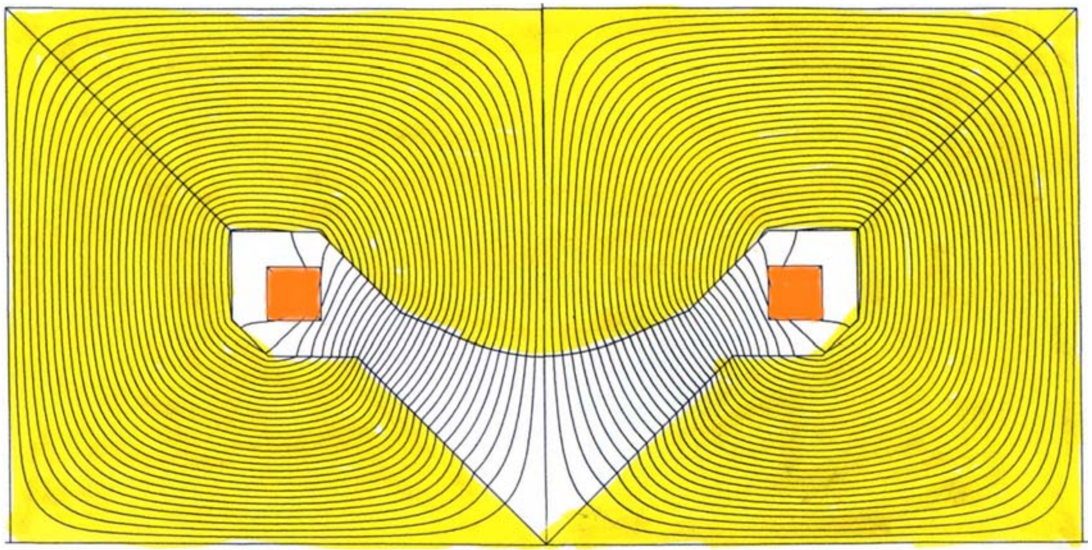
Present HTS cost : $200/kA/m

Total HTS cost in magnet: ~$400K

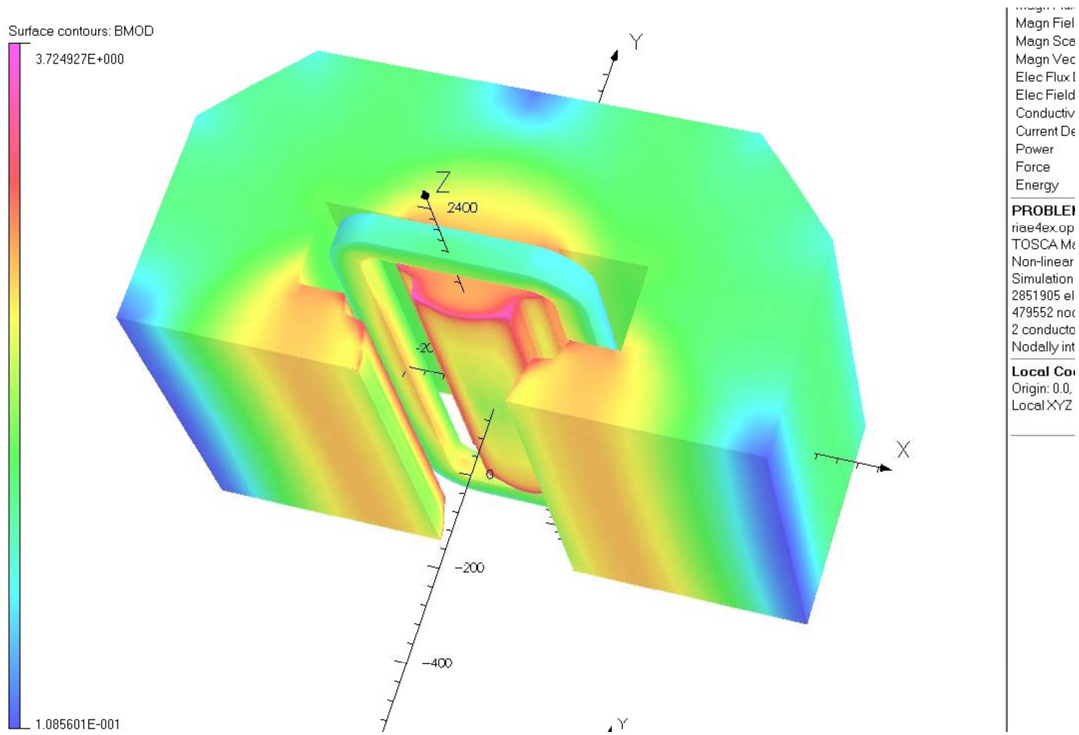
According to American Superconductor corporation, the cost is expected to go down by a factor of ~3 in ~5 year.

Magnetic Mirror model is cheaper as it requires ¼ number (six layers) of expensive HTS coils.

The basic design of RIA HTS quad has been demonstrated by building and testing a magnetic mirror configuration.

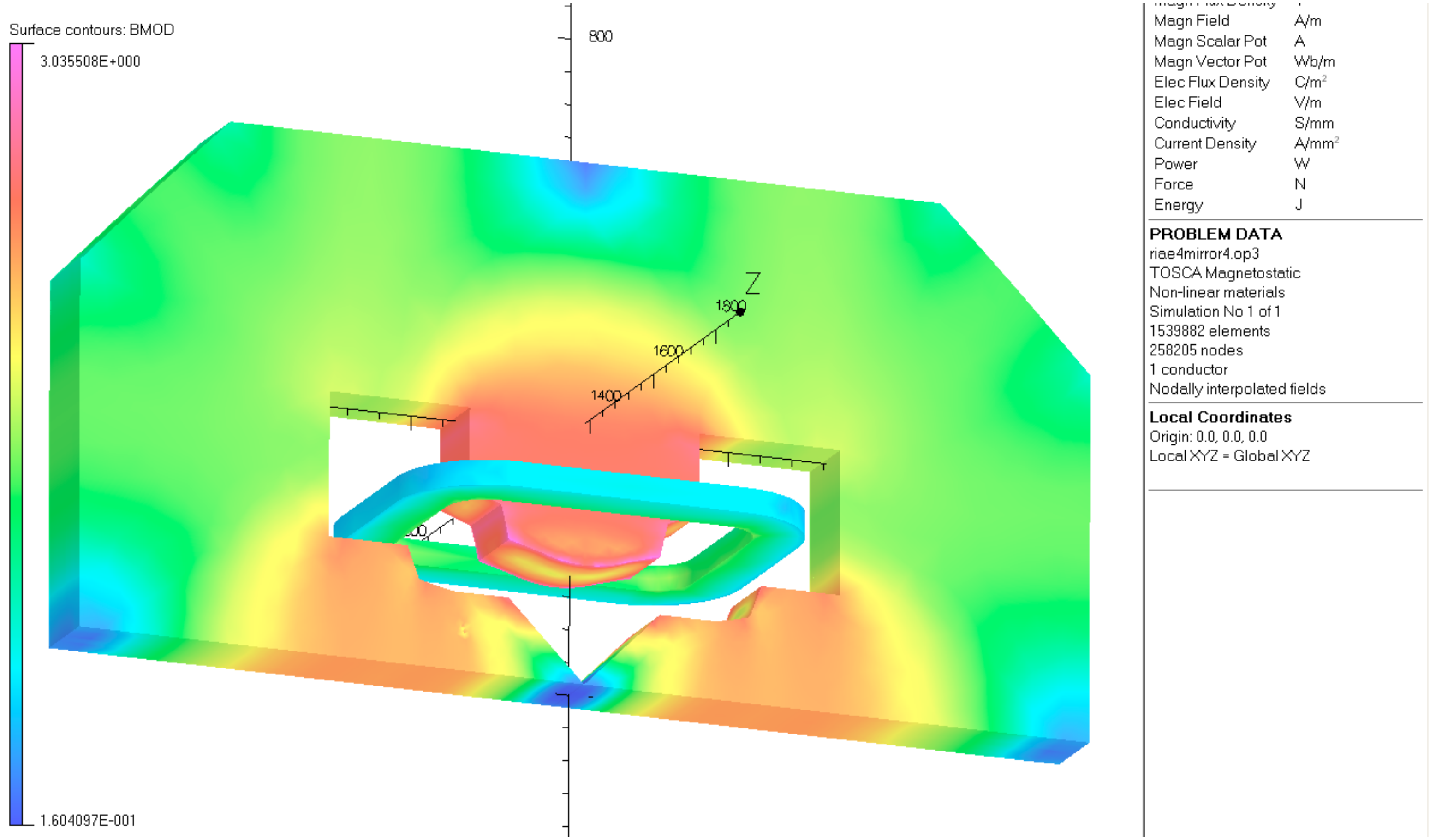


3-d Model of RIA Quad



An OPERA3d model of the 280 mm aperture super-ferric quadrupole design for RIA. Color indicates the field intensity on the surface of coil and iron regions. The model shows only one symmetric half the complete magnet. The magnet is designed such that two coils create the quadrupole symmetry.

3-d Model of Magnetic Mirror Design

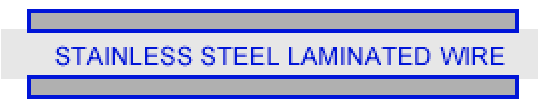


An OPERA3d model of the magnetic mirror design. Color indicates the field intensity on the surface of coil and iron regions.

HTS Coil Design

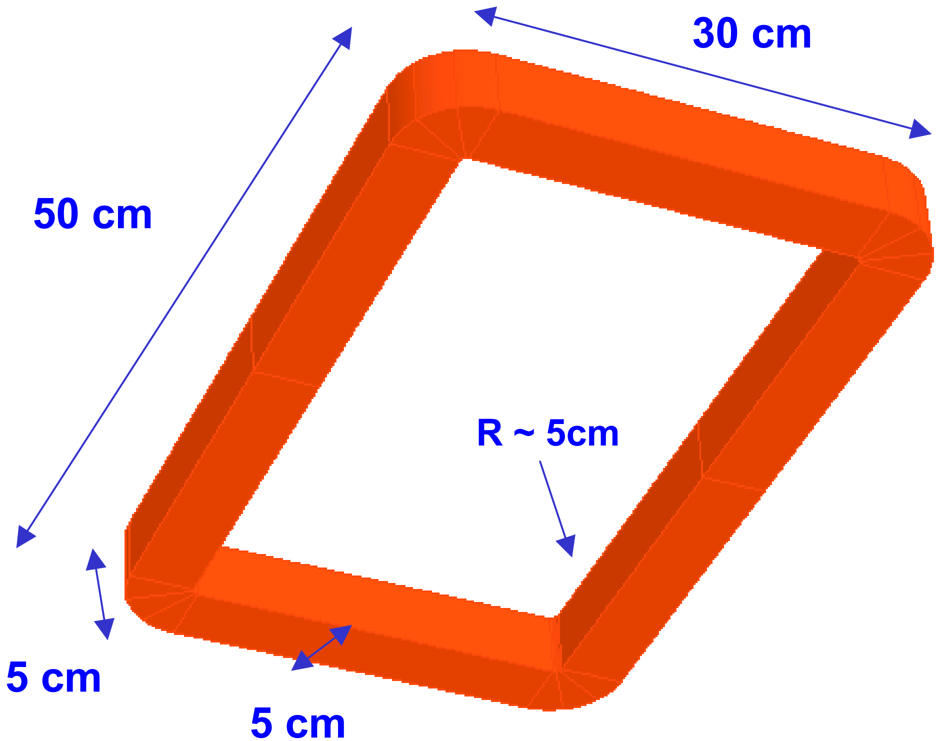
- 12 layers of coils, each layer co-wound with HTS and SS Tape.
- HTS tape will include stainless backing tape on either side.

HTS HIGH STRENGTH WIRE



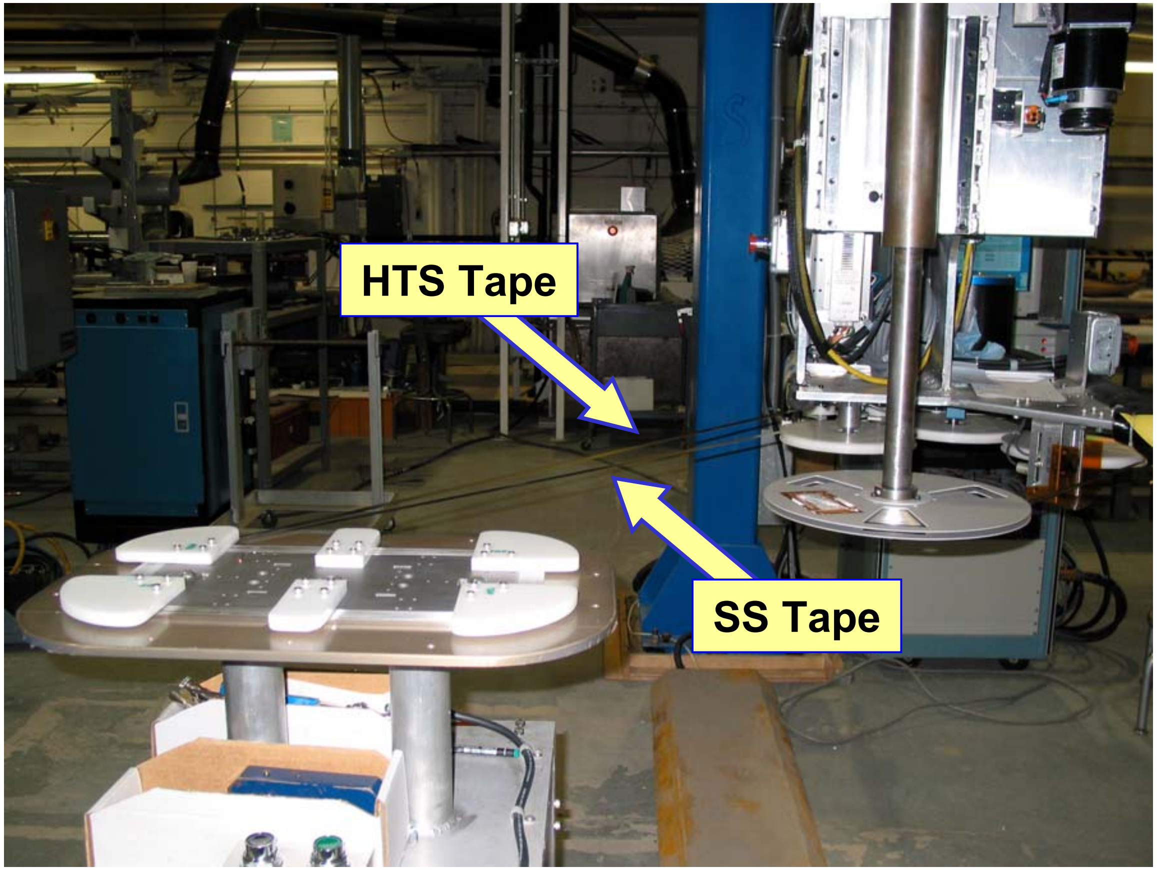
Specifications:

Average Thickness:	0.31(+/-0.02mm)
Average Width:	4.2(+/-0.2mm)
Min. Critical Bend Diameter:	70mm**
Min. Critical Tensile Stress:	265MPa*,**
Min. Critical Tensile Strain:	0.4%*,**



Parameters are chosen partly for cost, and partly to fit various test facilities.

Coil Winding

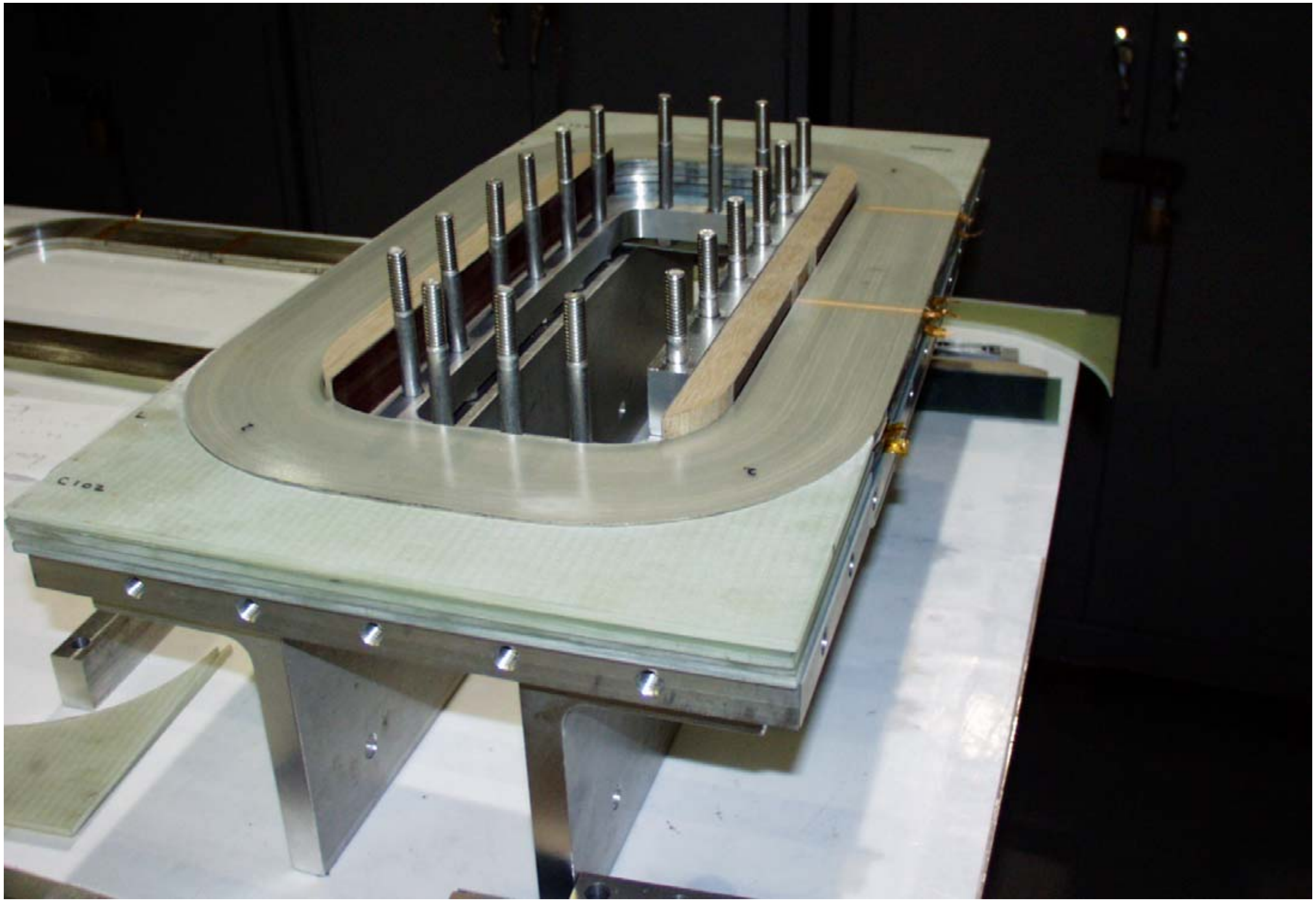


A coil being wound in a computer controlled winding machine.

HTS Coils for the Magnetic Mirror Model

Three pairs of coils (six coils). These coils are made with HTS tape (nominal 4.2 mm wide and 0.3 mm thick) and insulating stainless steel tape (nominal 4.6 mm wide and 0.04 mm thick).

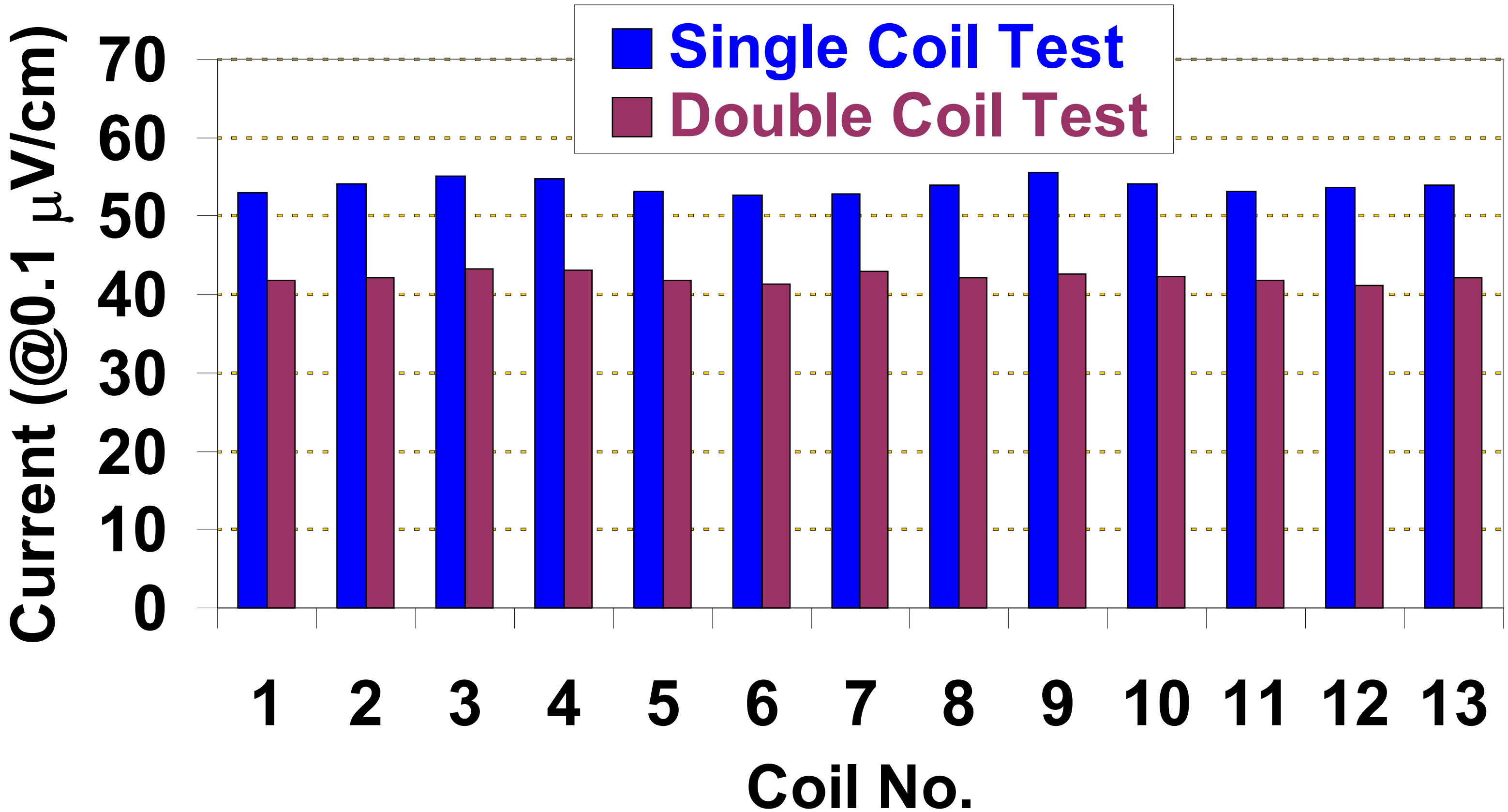
Assembled Coils with Internal Splice



Three pairs of coils during their assembly a support structure.

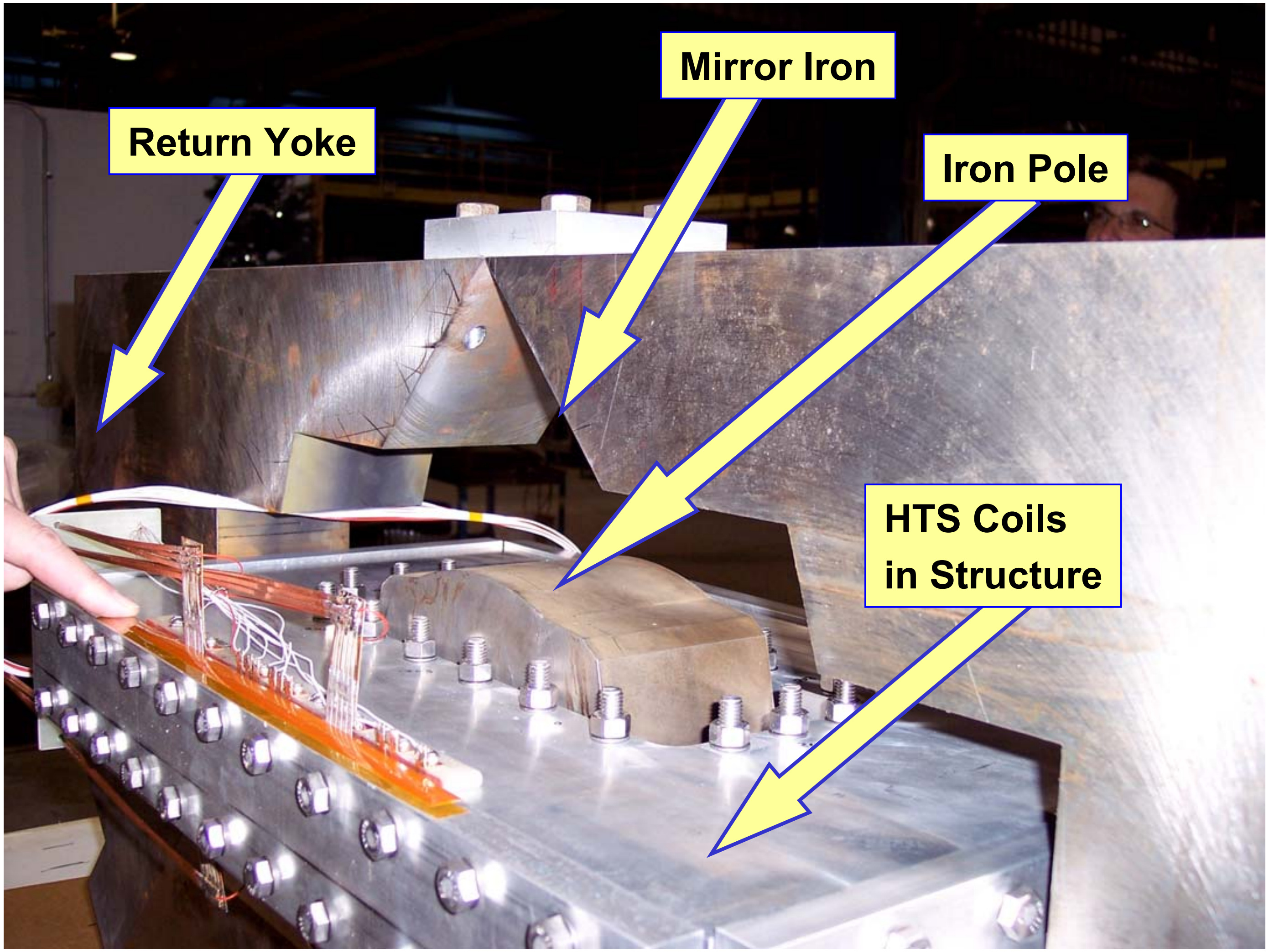
Performance of 13 Coils (Tested at 77 K in Liquid Nitrogen)

This is a fast QA Test. All coils show a sort of uniform performance.



The current at a voltage gradient of 0.1 μ V/cm (10 μ V/meter) over the total length of the coils at 77 K.

Magnetic Mirror Model



Coils in their bolted support structure, with the pole iron (in the middle, inside the structure), magnetic mirrors (two on the upper side with 45 degree angles on either side of the vertical axis) and iron return yoke.

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Magnetic Mirror Model

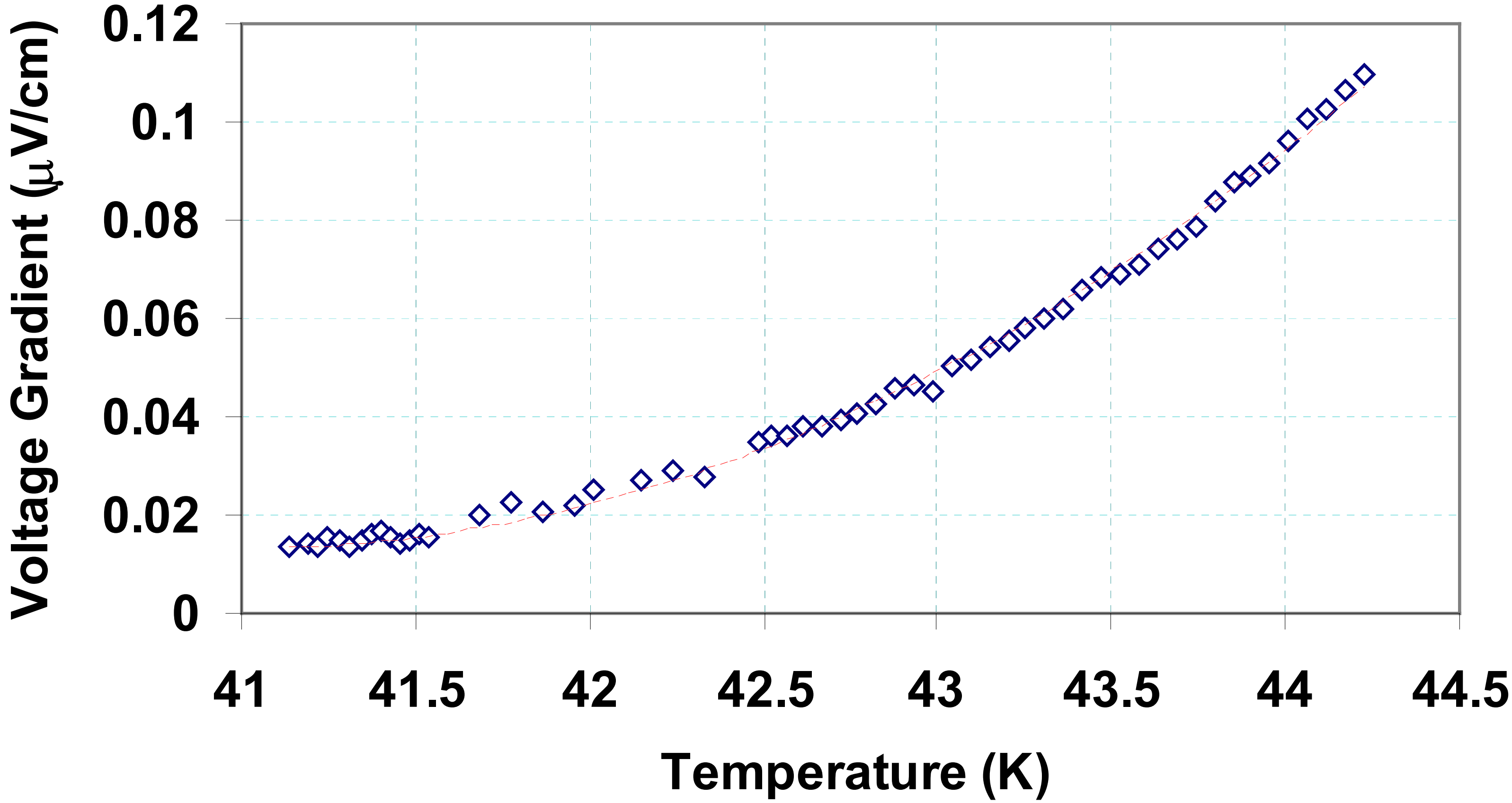
Magnetic mirror model magnet, just before the test. At the test facility, the magnet can be tested in a wide range of temperature (4.2 K to 80 K).

Magnetic Mirror Model with Top Hat

Magnetic mirror model magnet with top hat (top) during its transport to the test station. At the test facility, the magnet can be tested in a wide range of temperature (4.2 K to 80 K).

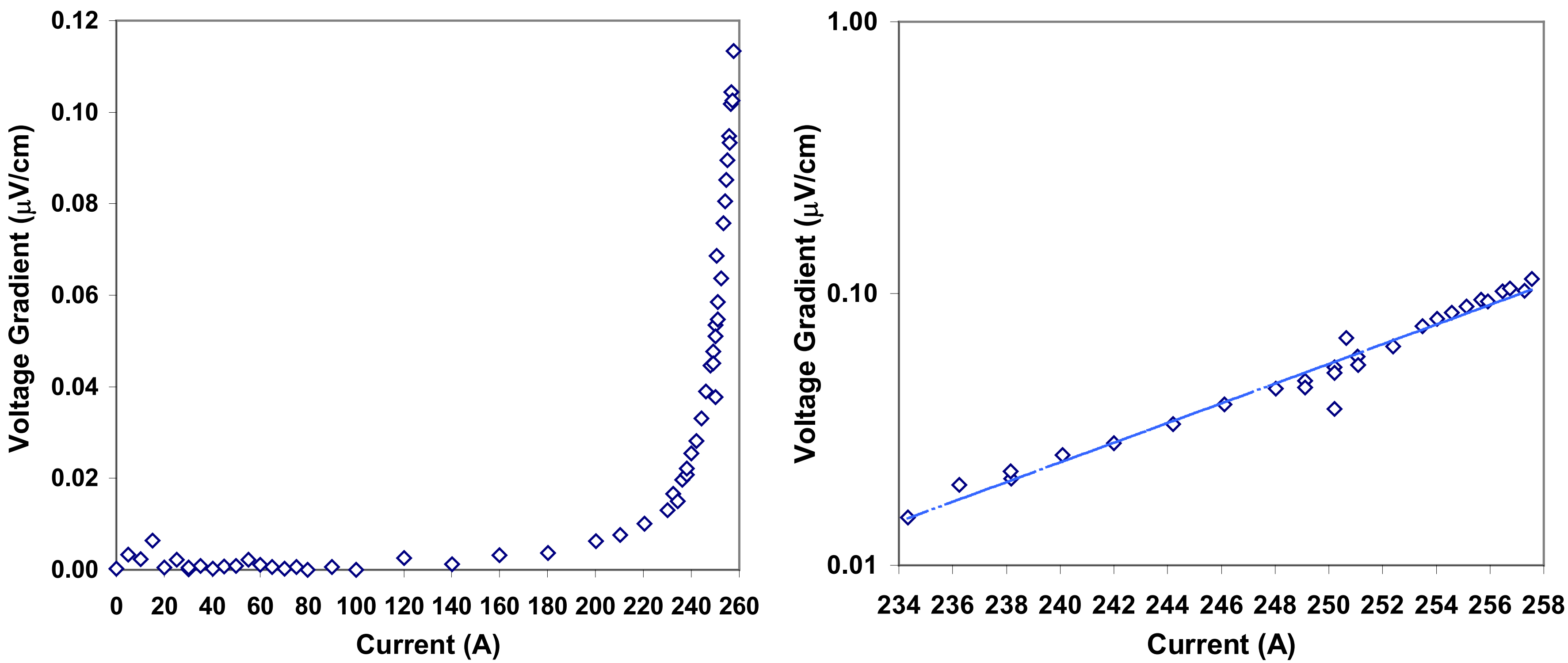
A higher operating temperature translates in to a significant reduction in operating cost.

Typical Test Result of An HTS Coil (Voltage Vs. Temp. to Determine T_c)



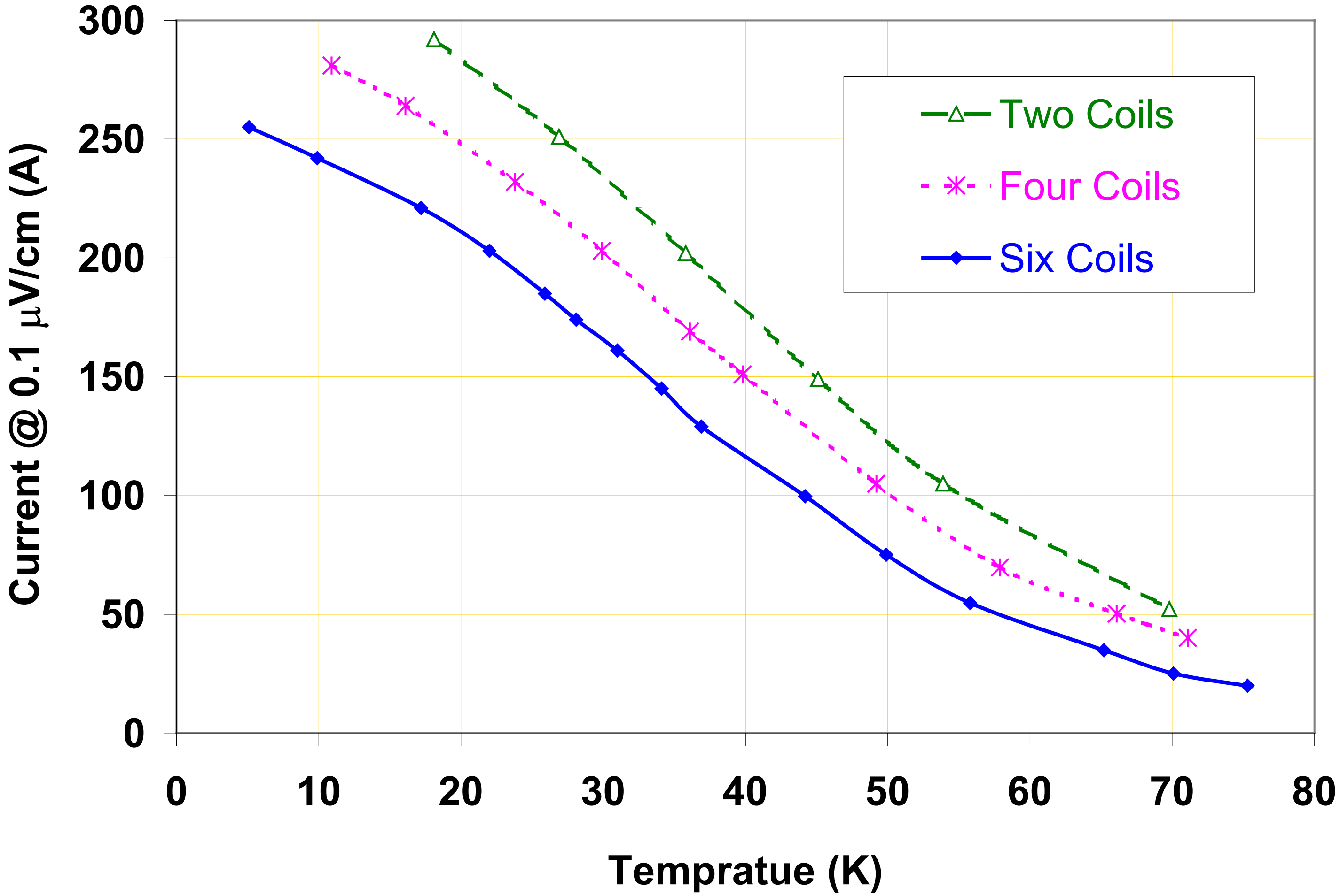
Voltage gradient as a function of temperature for the magnetic mirror model at a constant current of 100 A.

Test Results of RIA HTS Magnetic Mirror Model Magnet



Voltage Gradient as a function of current at ~5 K in RIA magnetic mirror model with six coils. We use a voltage gradient of 0.1 μV/cm as a definition of transition from superconducting state to normal state.

RIA HTS Model Magnet Test Results for Various Configurations



More coils create more field and hence would have lower current carrying capacity

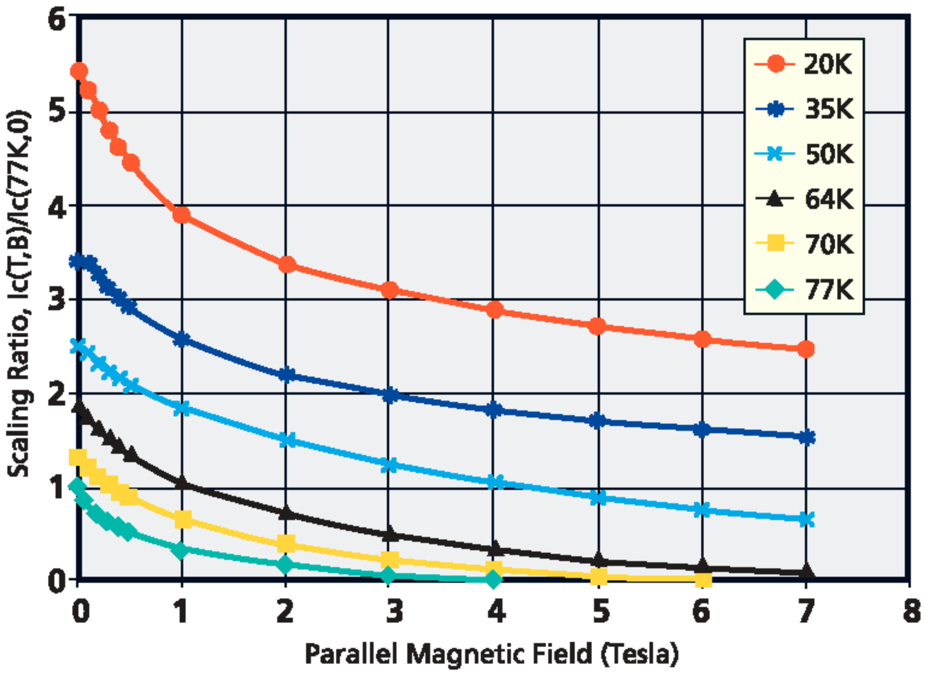
A summary of the temperature dependence of the current in two, four and six coils in the magnetic mirror model. In each case voltage appears on the coil is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for four coils.

RIA HTS Magnet Experience

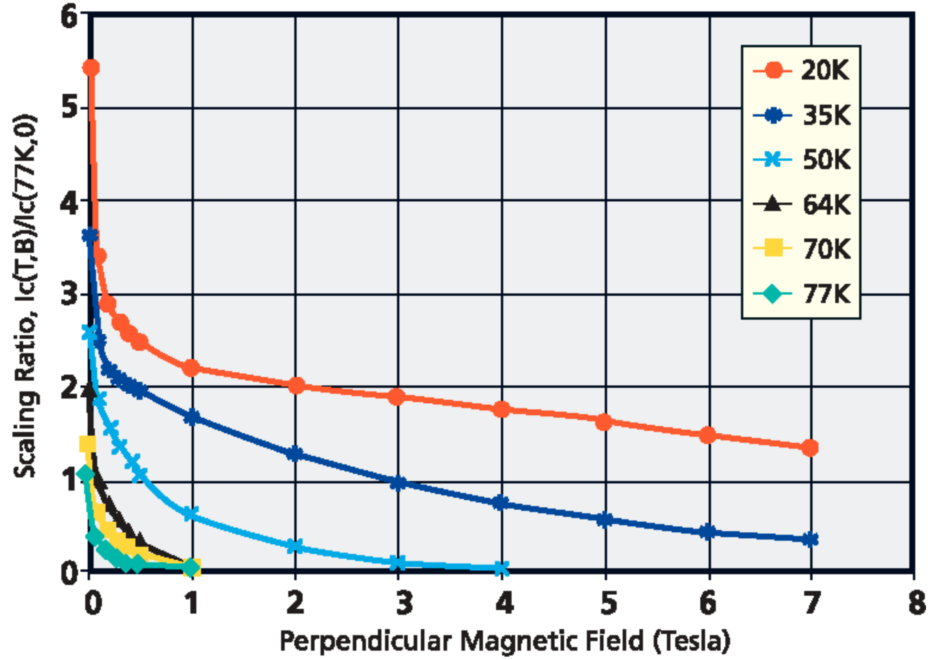
- A magnetic mirror model built with commercially available high temperature superconductor has achieved the desired performance (~150 A at ~30 K).
- It meets the RIA requirements with a margin.
- Stainless steel tape between the turns has provided the necessary insulation. The successful test of this magnet is the first significant step towards demonstrating that HTS-based magnets can provide a good technical solution for one of the most critical items of the RIA proposal.
- At present, no magnet made with HTS is in use in any accelerator.
- The mirror model test magnet for RIA proves that despite its brittle nature, the technology to build magnets with HTS can be developed.

HTS Magnet Designs to Provide the Required Performance at Nitrogen Temperatures

Wire performance with magnetic field parallel to tape surface



Wire performance with magnetic field perpendicular to tape surface



American Superconductor

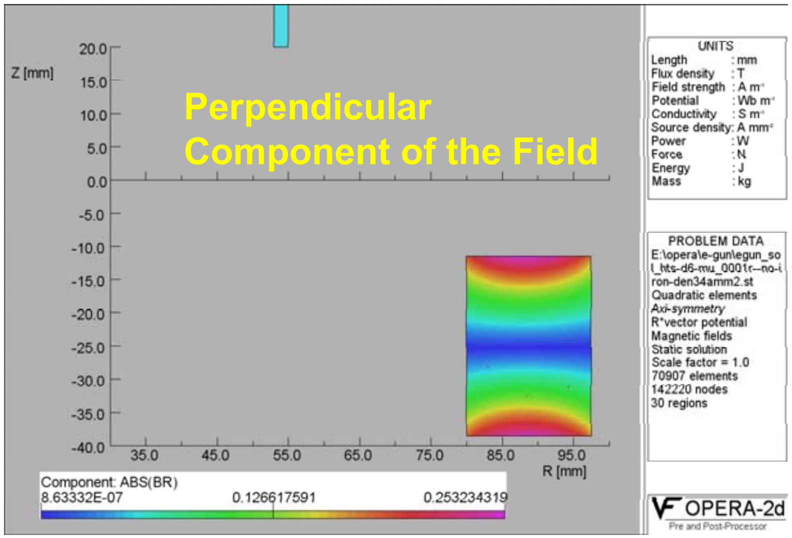
For HTS magnets to operate at nitrogen temperatures, it is very important to minimize the perpendicular component of the field on HTS.

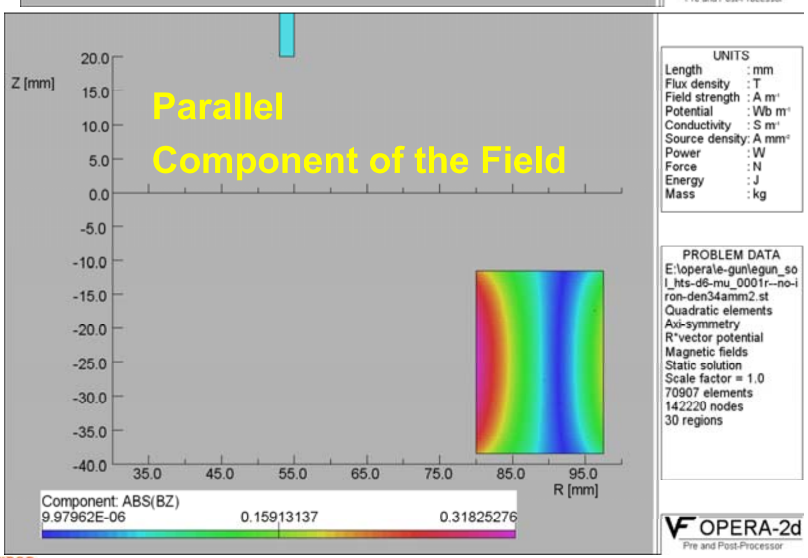
Current carrying capacity of HTS depends on:

- **Temperature**
- **Magnitude of the field**

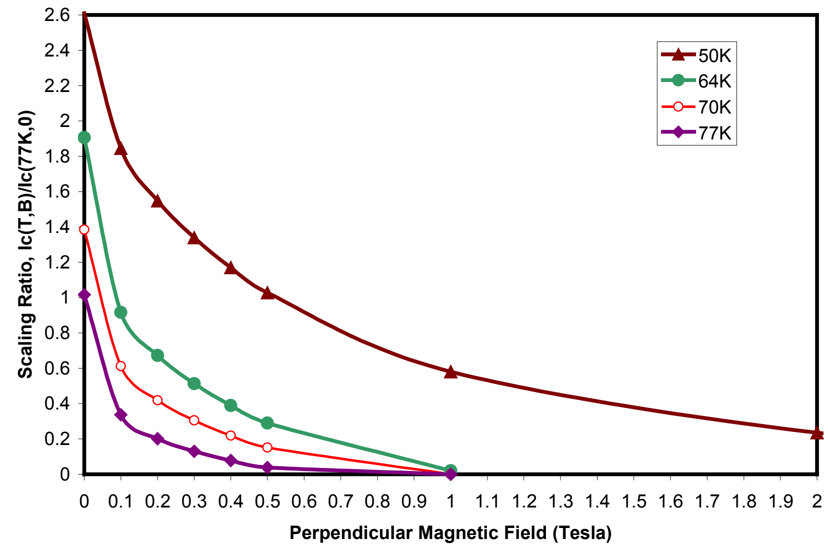
and also on the direction of the field

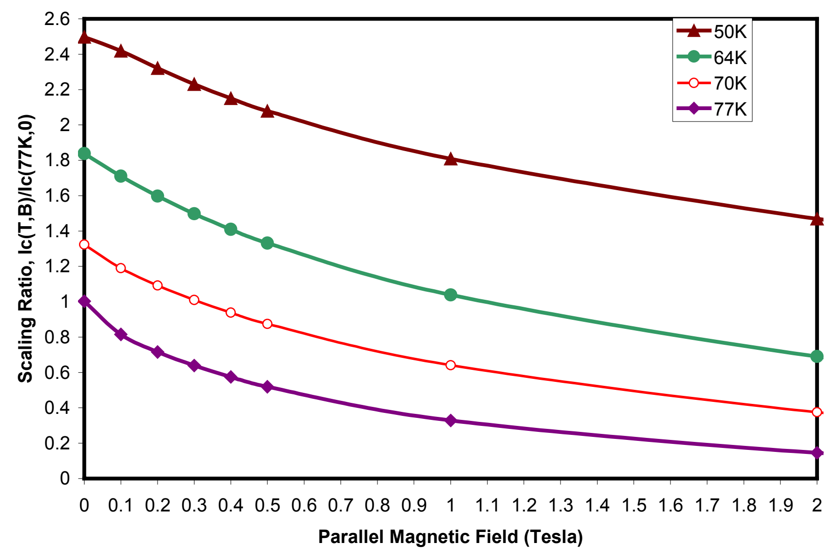
HTS Solenoid Design Without Iron Yoke Over Coil





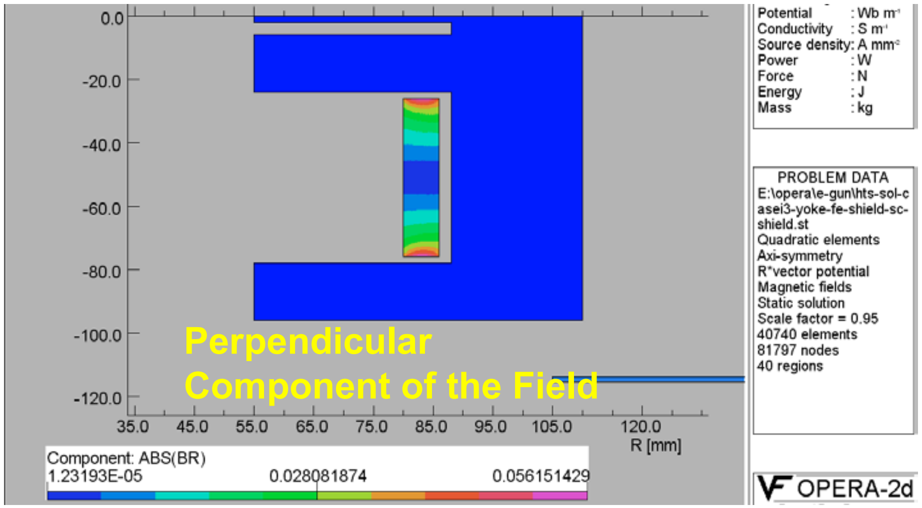
Note: Field parallel and field perpendicular components are about the same

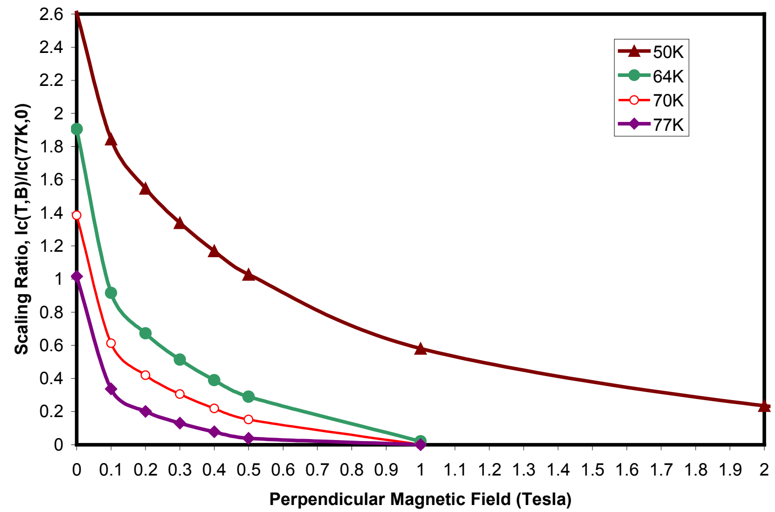


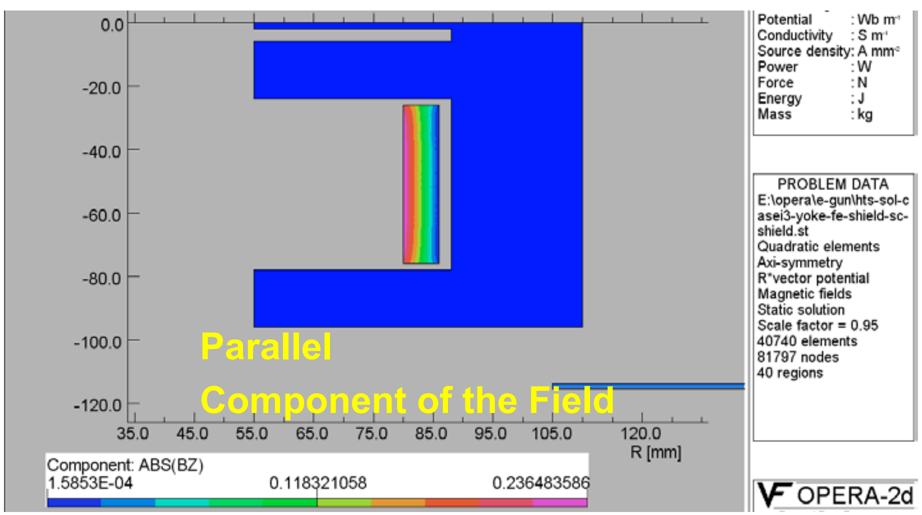


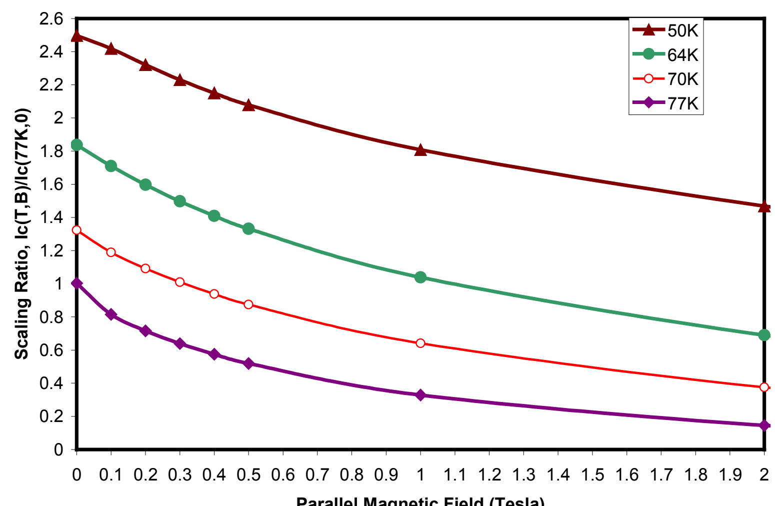
HTS Solenoid Design With Iron Yoke Over Coil

Magnetic model has been optimized to reduce the perpendicular field in the superconductor



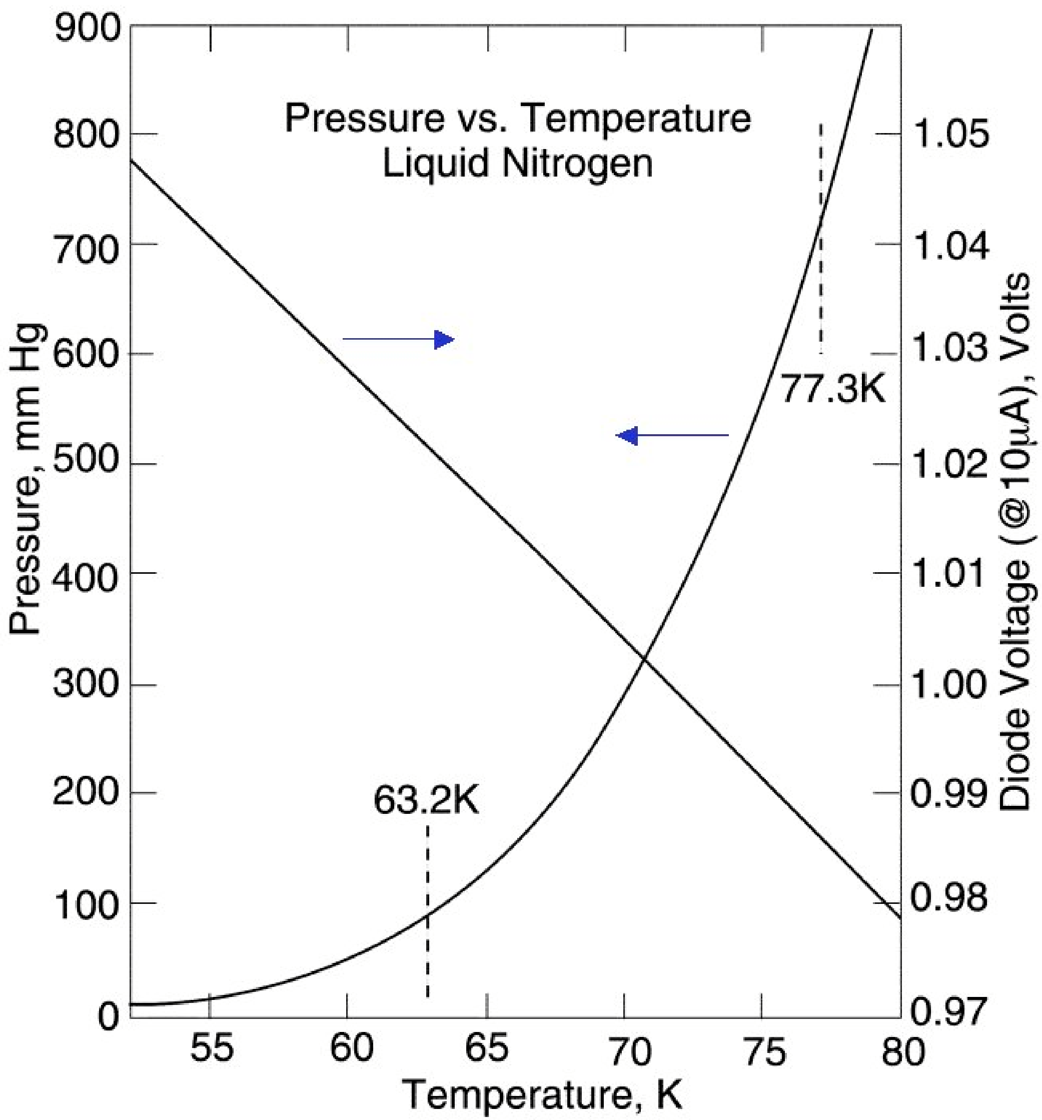






Note: Perpendicular component is less than ¼ of field parallel

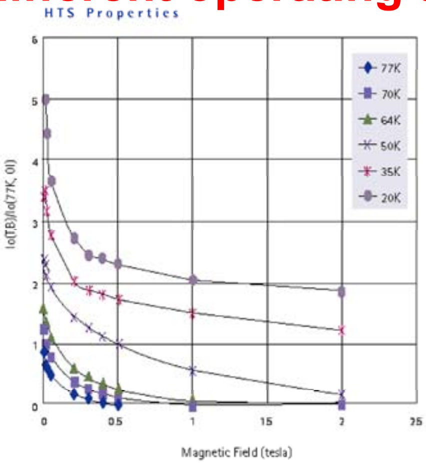
Bath Temperature of Nitrogen can be Lowered by Pumping



- In some low field applications, one can perhaps operate HTS magnets with nitrogen only.
- One can reach significantly lower temperature than 77 K by reducing the pressure.
- This means that the superconducting (HTS) magnets can be operated without helium.
- This is a major advantage in many situations.

Future of Medium Field HTS Magnets in Accelerators and Beam Lines

Critical current as a function of field at different operating temperature

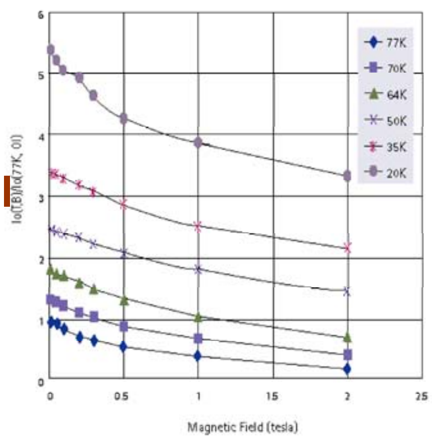


Field Perpendicular

Bi-2223 performance at different temperatures and fields compared to the performance at 77K for field perpendicular to the tape surface.

Medium field (1-3 Tesla) HTS super-ferric magnets operating at ~35K (or even higher temperatures) are an interesting possibility for future beam line and accelerator magnets. If it is a few magnet system, then one can operate them with a few cryo-coolers only (no cryogenic plant needed).

Field Parallel



Bi-2223 performance at different temperatures and fields compared to the performance at 77K for field parallel to the tape surface.

American Superconductor

All specifications subject to change without notice from American Superconductor.

A million dollar question?

Can future HTS magnets compete with water cooled copper (room temperature) magnets in terms of the cost of ownership (capital + operation) in a number of years?

Cost Comparison of Copper and HTS Dipole

HTS magnets are beginning to look attractive for special applications. The details of one such application (RIA) were discussed here. However, before HTS magnets can become attractive for large scale use, consider the following:

Copper Magnets:

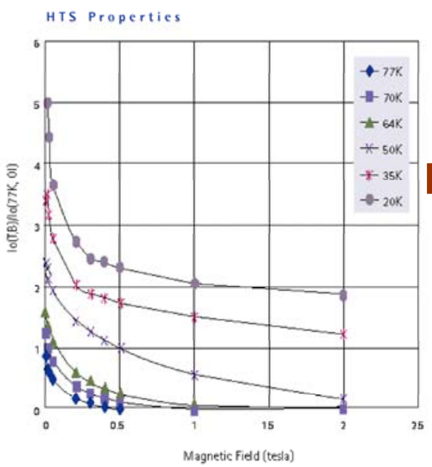
- Better known costs (order of 100k$ for ~3 meter long, 15cm X 8cm (H X V) aperture ~1.4 T magnet)
- Cost of individual components like coil, yoke, etc., is well understood
- Need "higher current" (a few kA) power supply (higher cost)
- Need "low thermal conductivity water cooling plant"
- High operating costs (a significant issue as the electric costs are rising)
- Maintenance issues (cost, downtime): water leak etc.

Goals for Future HTS Magnet:

- Develop magnet designs and construction techniques such that the cost of HTS magnets becomes comparable to similar water cooled room temperature copper magnets
- Develop designs such that cost of HTS in magnets is 1/3 or less of the total production costs
- Lower current (a few hundred Amp) power supply (cheaper)
- Cost of cryo-coolers (compare with infrastructure cost of Low Thermal Conductivity Power Plant)
- Lower operating costs (wall power of cryo-cooler?)
- Maintenance issues (cost, downtime): cryo-coolers
- Can future HTS magnets with economical design operate at Nitrogen temperatures?

HTS Magnets with Cryo-coolers

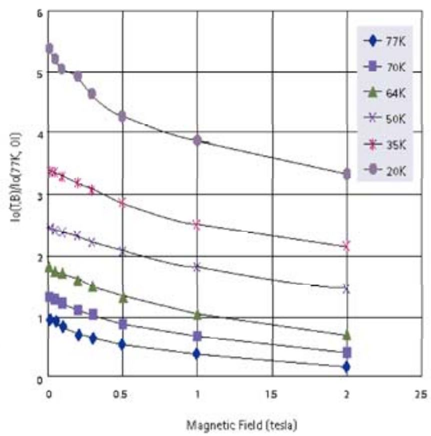
Critical current as a function of field at different operating temperature



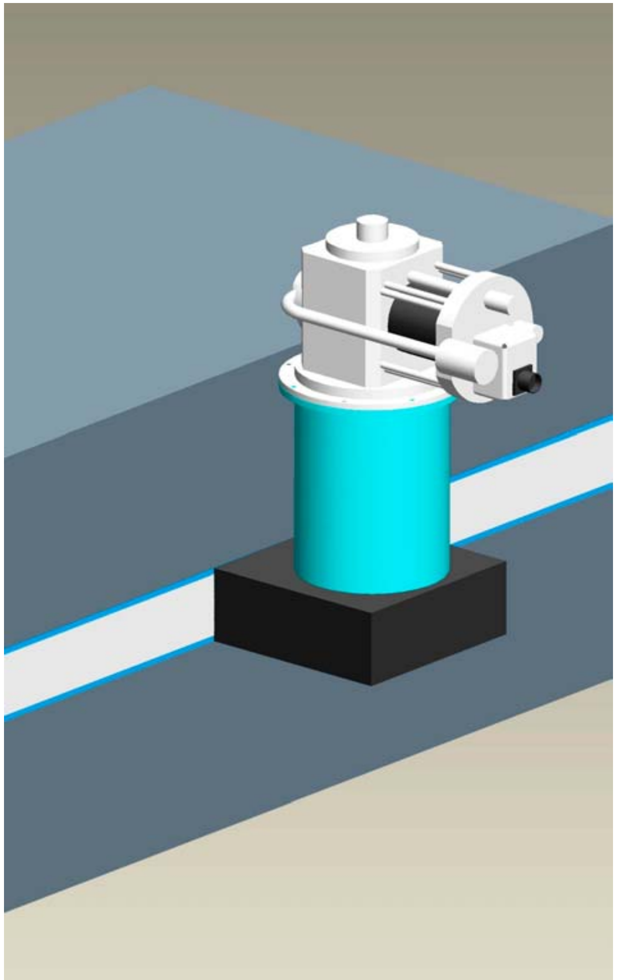
Field Perpendicular

Bi-2223 performance at different temperatures and fields compared to the performance at 77K for field perpendicular to the tape surface.

Field Parallel



Bi-2223 performance at different temperatures and fields compared to the performance at 77K for field parallel to the tape surface.



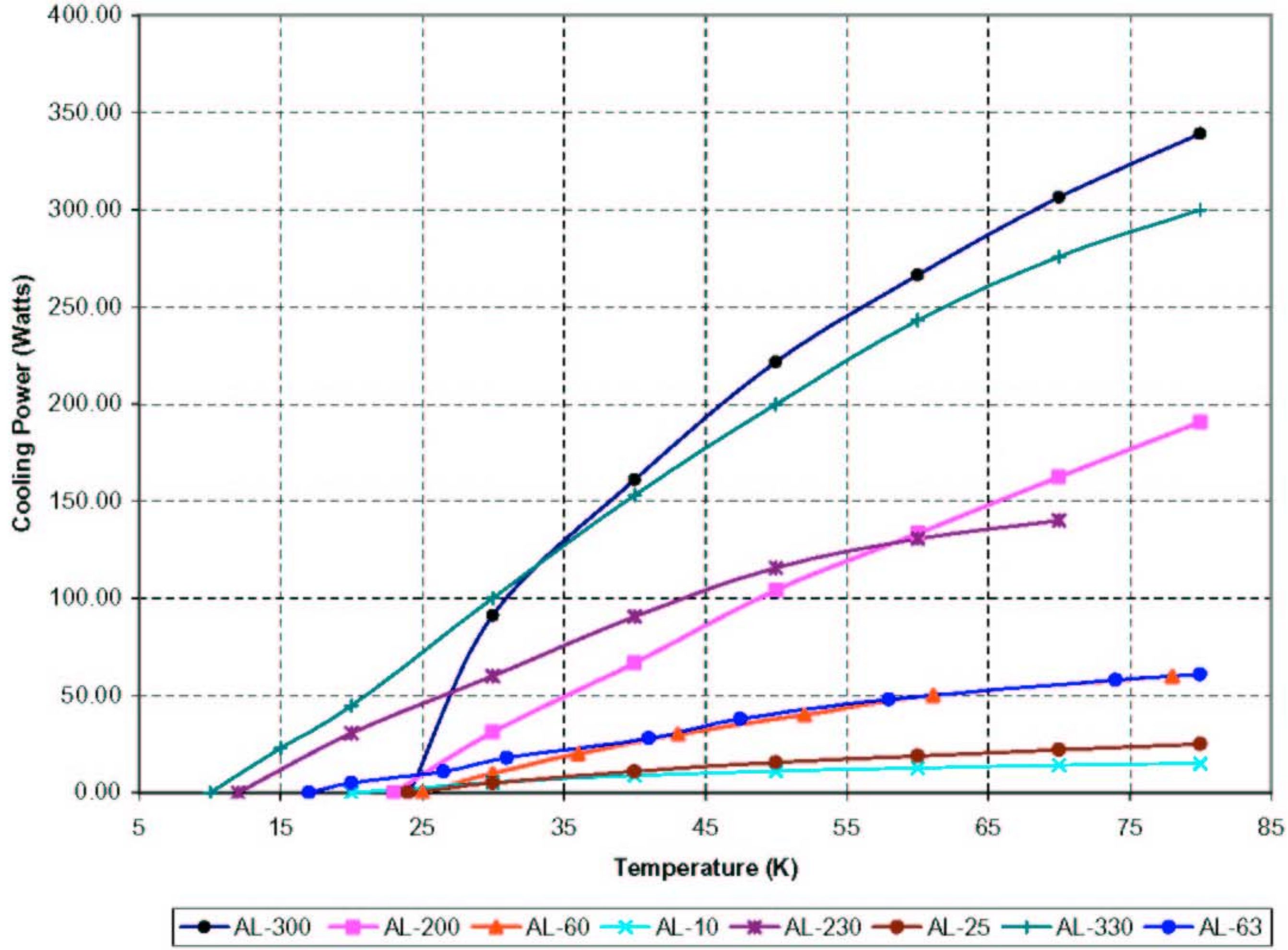
American Superconductor
REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY

Two Technology Drive
Westborough, MA 01581-1727
Ph: 508.836.4200
Fax: 507.836.4714
website: www.amsuper.com

American Superconductor Europe GmbH
Rathausstraße 7
41564 Kaarst, Germany
Ph: 49.2131.766051
Fax: 49.2131.668734

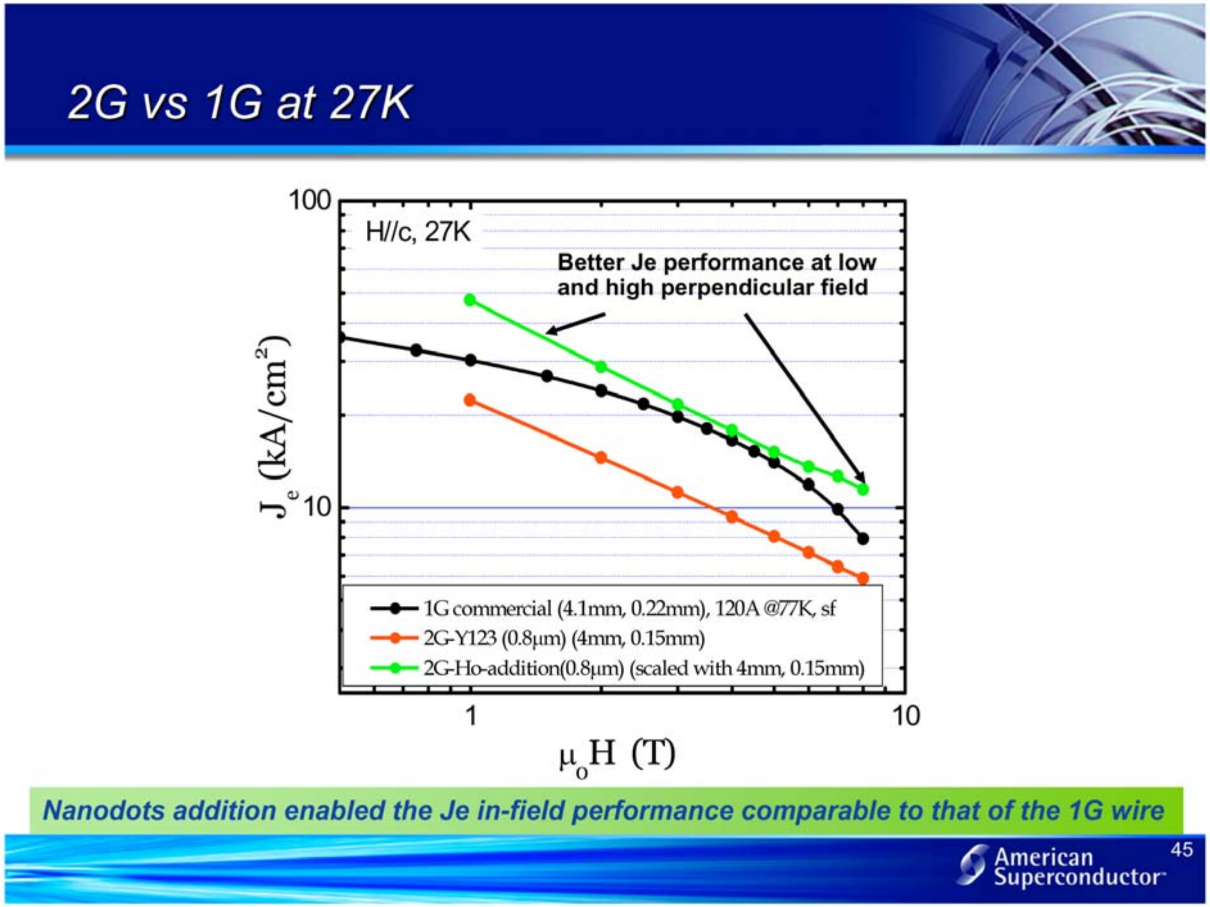
Capacity of Cryo-coolers as a Function of Temperature

Performance curve of some cryo-coolers from CRYOMECH



HTS Wire in the Future

2nd Generation (2G) YBCO wires have lower material cost



SUMMARY

- **HTS can make a significant impact in certain applications**
  - HTS magnets can operate at elevated temperature which need not be controlled precisely.
  - HTS magnets can generate very high fields.
- **HTS have reached a level that one now can use them in medium field magnets and can do a meaningful R&D for high field magnets**
  - Results from Brookhaven over several years have been encouraging.
  - HTS offer the potential of good technical and economic operational solution for RIA fragment separator quadrupole triplet.
- **With rising energy costs, HTS magnet technology may offer a lower cost ownership solution in many future accelerator and beam line applications**
  - However, for this to happen, HTS magnet costs must become comparable to water cooled copper magnet costs.

You are welcome to join this exciting R&D!