HTS Magnets for Future Accelerators and Beam Lines

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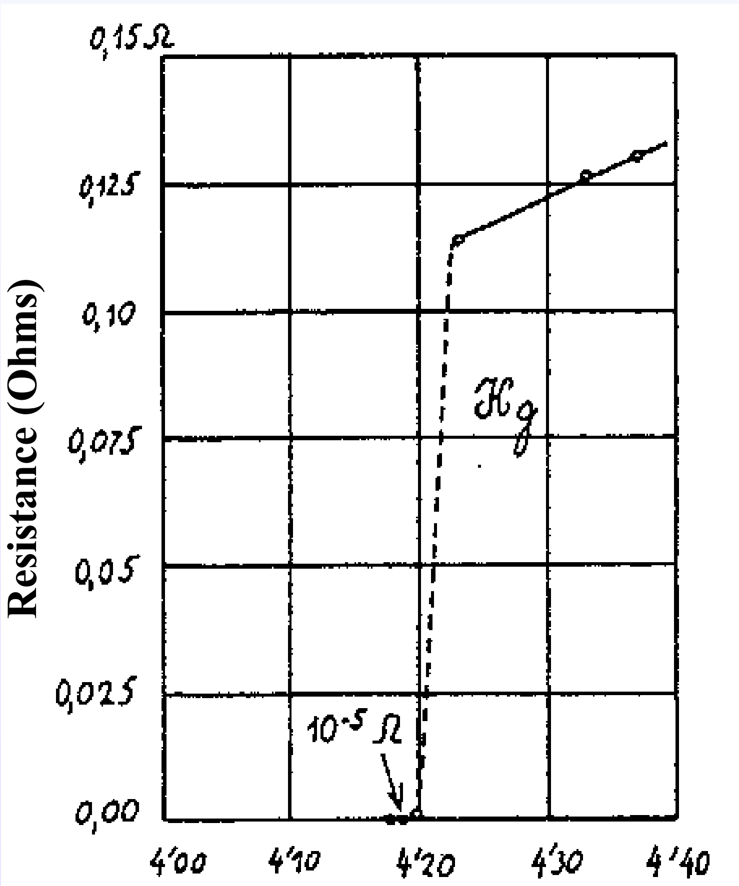
Overview of the Presentation

- **High Temperature Superconductors (HTS)**
  - ☐ Introduction
  - ☐ Advantages of using HTS in Accelerator Magnets
- **HTS R&D Magnets**
  - ☐ Summary of BNL Experience
- **Radiation damage studies of HTS**
  - ☐ An important issue in several accelerator applications, however only a limited experimental data is available
  - ☐ VECC can possibly make a world class contribution
- **Possibility of future Cryogen-free HTS Magnets**
- **Summary**

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

Low Temperature Superconductor Onnes (1911)

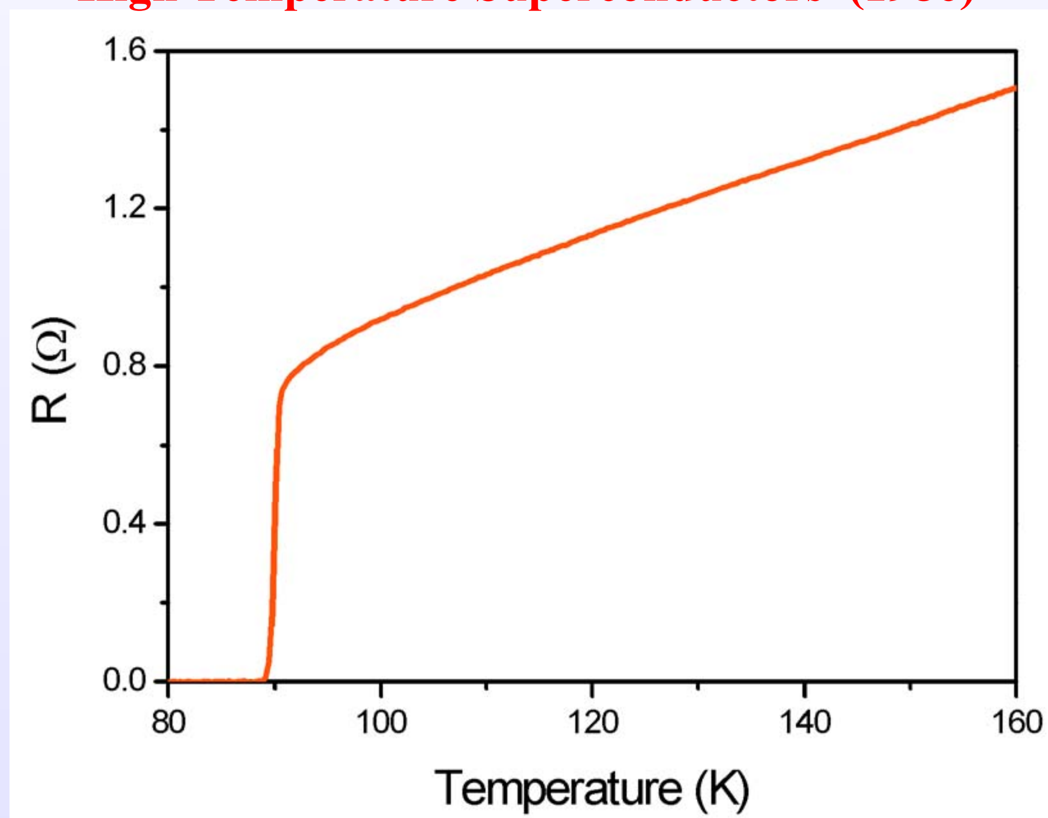
Resistance of Mercury falls suddenly below meas. accuracy at very low (4.2) temperature



Temperature (K)

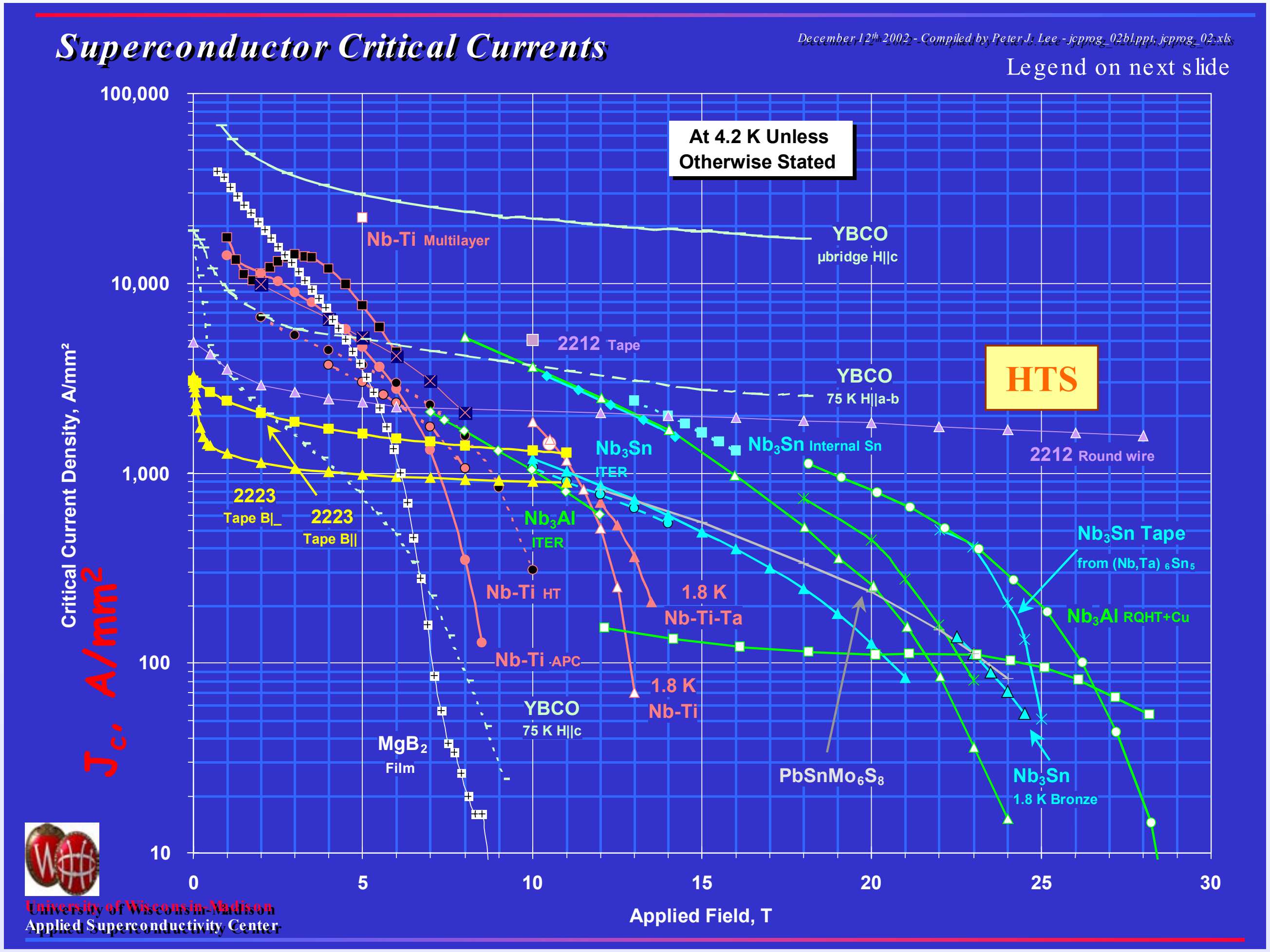
New materials (ceramics) loose their resistance at NOT so low temperature (Liquid Nitrogen)!

High Temperature Superconductors (1986)



Another Remarkable Property of HTS
The High Field Current Carrying Capacity

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



Applied Field, T

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

Translate this to magnet design and accelerator operation:

- 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 has a potential to produce very high field magnets

Operation of HTS Based Accelerator Magnets

• HTS based magnets don't appear to quench in a normal way.

• One (or even a few) weak spot (s) won't limit the ultimate performance of the magnet. That would only cause the local temperature to rise a bit but the magnet will continue to operate.

• This becomes more a question of the heat load rather than the weak spot limiting the performance of the whole magnet.

• This is a major difference from the LTS based magnets where a single weak spot limits the performance of the entire magnet.

Popular HTS Materials of Today

- BSCCO 2223 $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$
- BSCCO 2212
- YBCCO

  □MgB_2 is technically a low temperature superconductor (LTS) with critical temperature ~39 K.

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

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

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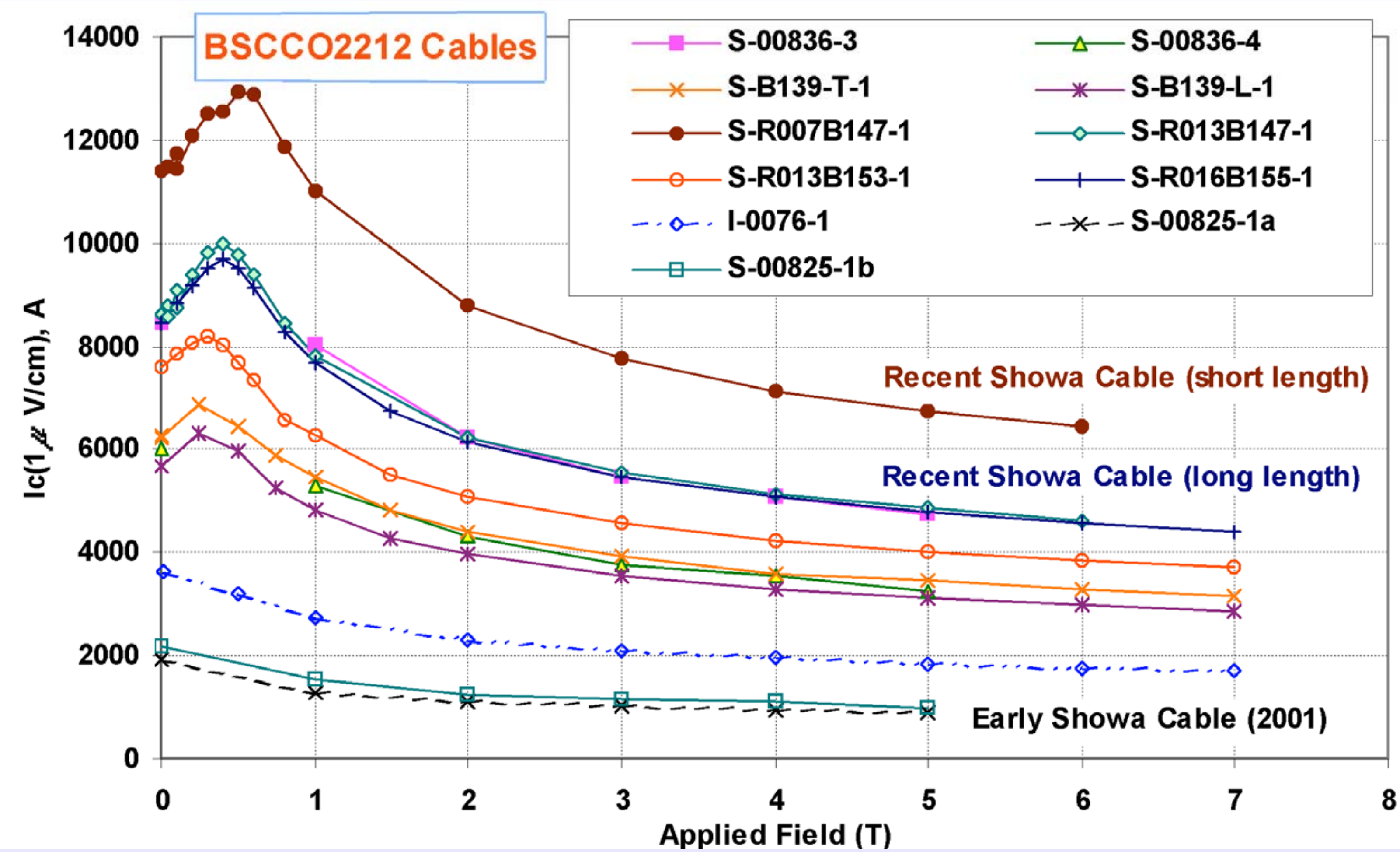
HTS Cables: A Remarkable Progress



Significant self-field at high currents.

HTS Cables Tested at BNL Short Sample Test Facility

⇒ **Modern HTS Cables Carry A Significant Current.**

Possible Applications of HTS in Accelerator Magnets

High Field, Low Temperature Application

Example: Interaction Region (IR) Magnets for large luminosity upgrade or very high field main ring dipoles to achieve highest possible energy in existing given tunnel.

• At very high fields (>15 T), no superconductor can have as much critical current density as HTS can.

Medium Field, Higher Temperature Application

Example: Quads for Rare Isotope Accelerator (RIA)

• These applications don't require very high fields.

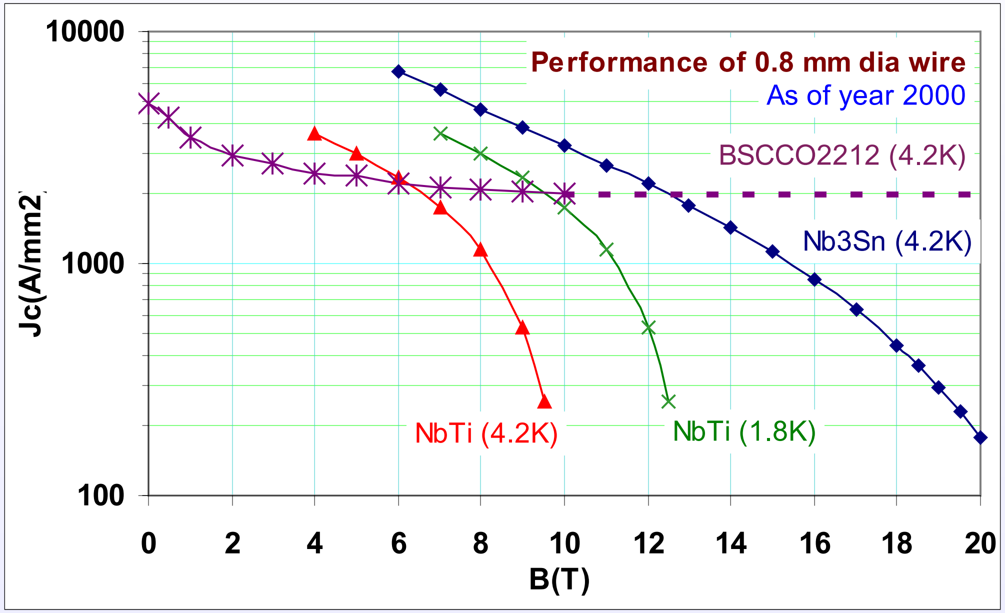
• The system design benefits enormously because the HTS offers the possibility of magnets to operate at higher than 4K, say at 20-40 K.

• The HTS can tolerate a large increase in temperature in superconducting coils (caused by the decay particles) with only a small loss in performance.

• Moreover, the temperature need not be controlled precisely (Think about an order of magnitude relaxation in temperature variations, as compared to the LTS used in current accelerator magnets).

High Field Magnet Designs with HTS

NOTE: High Temperature Superconductors (HTS) are uniquely suitable for generating very high fields since, unlike in conventional Low Temperature Superconductors (LTS), the reduction in critical current density as a function of field is much smaller at very high fields.



Applications Under Considerations

- Common Coil 2-in-1 Dipole Design for Hadron Colliders
- Neutrino Factory Storage Ring/Muon Collider Dipole (and Quads) Design
- Interaction Region Magnets (Dipole and Quadrupoles) for High Luminosity Colliders (e.g. for LHC Luminosity Upgrade)

Design Issues for High Field Accelerator Magnets using HTS

• HTS is very brittle

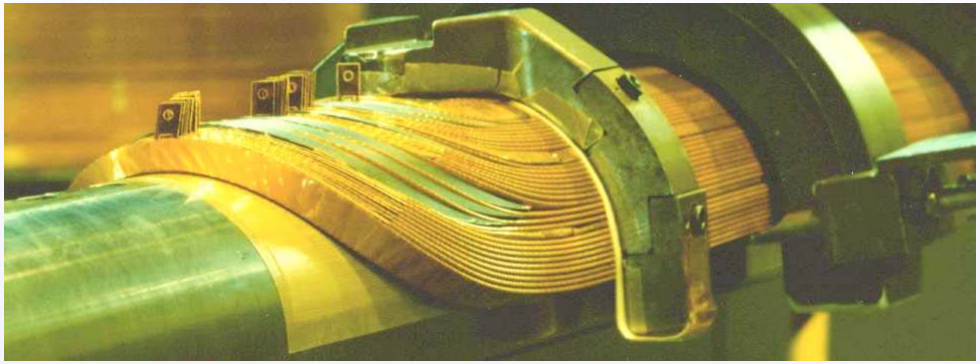
Conventional designs are not the most suitable

• Large Lorentz forces

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

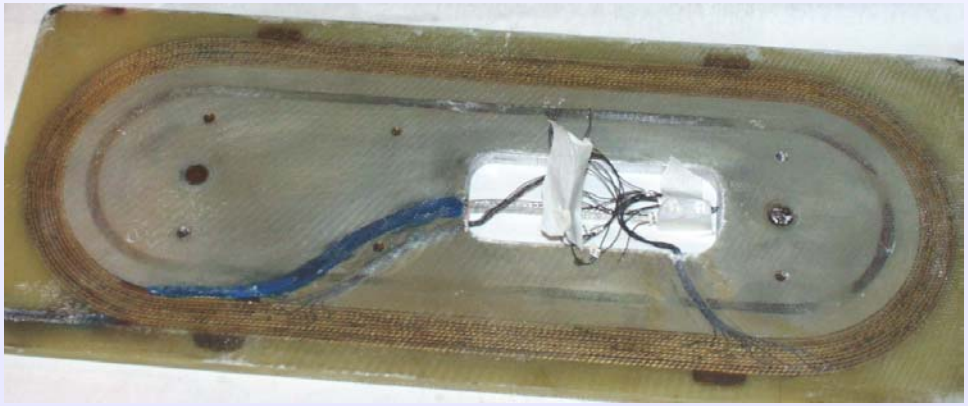
(~1/2 degree at ~890^o C)

⇒ React & Wind Approach



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

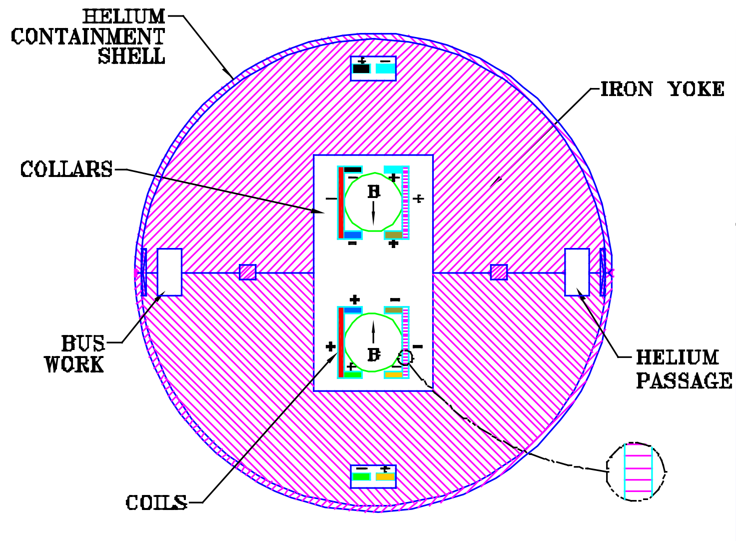
Complex 3-d geometry in the ends

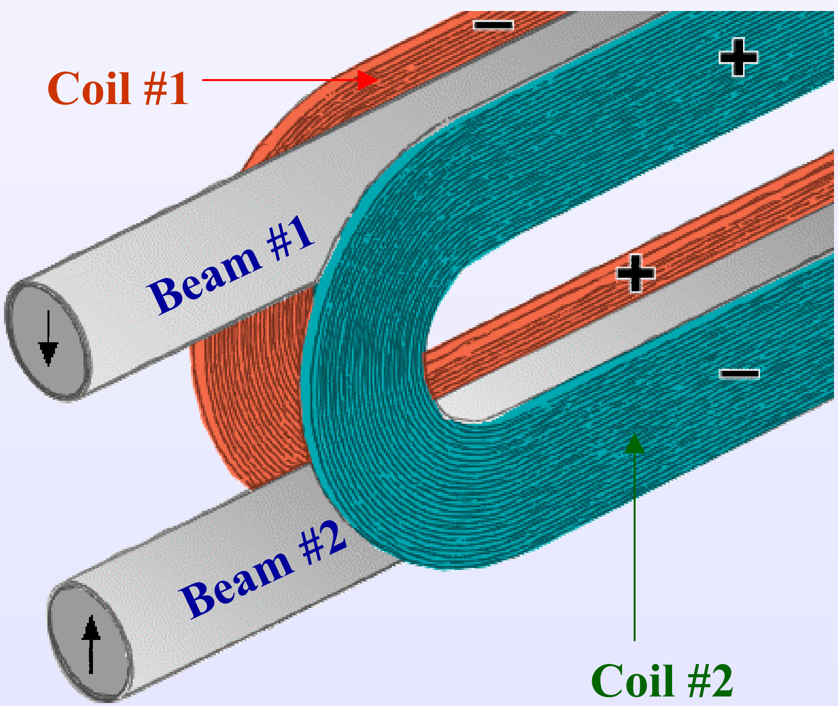


"Conductor friendly" racetrack coil with large bend radius

Suitable for high field magnets with brittle material

Common Coil Design

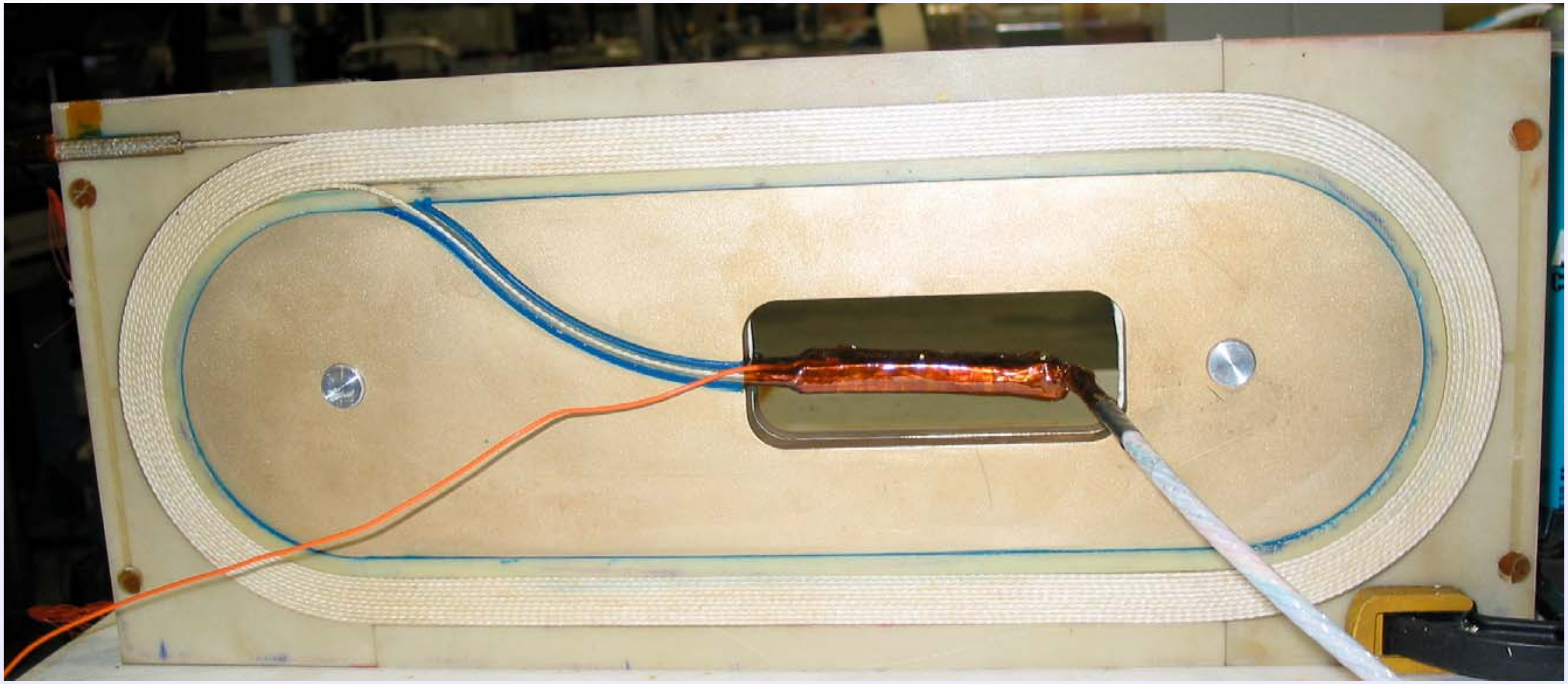




Main Coils of the *Common Coil Design*

- 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

High Temperature Superconductors (HTS) in Accelerator Magnets



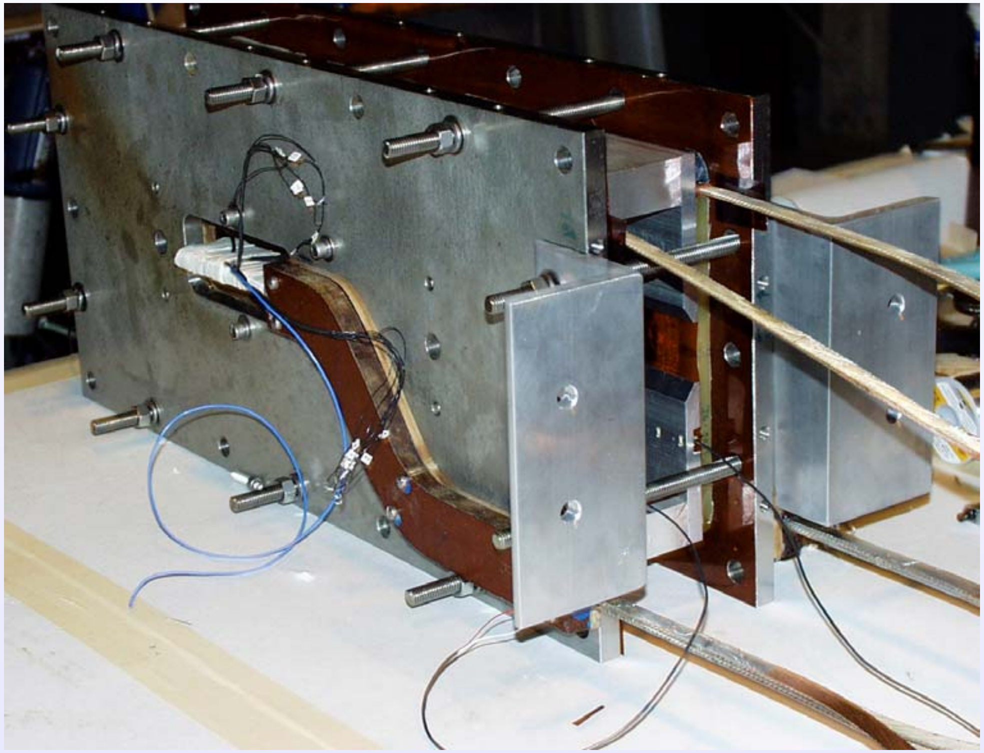
This coil carried a record 4+ kA.

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

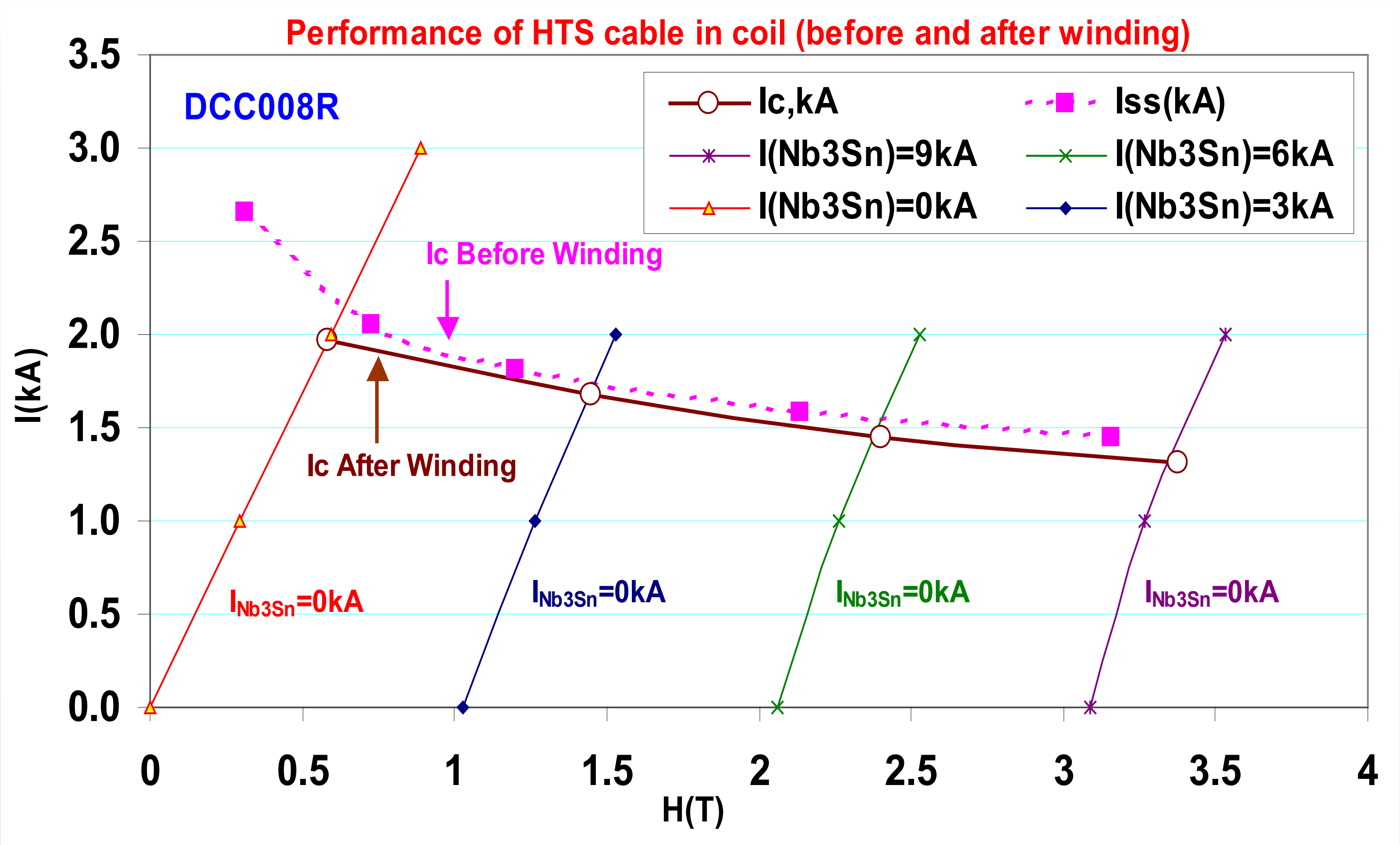
(need a factor of 2-4 improvement in J_c for 12-20 T range)

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

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

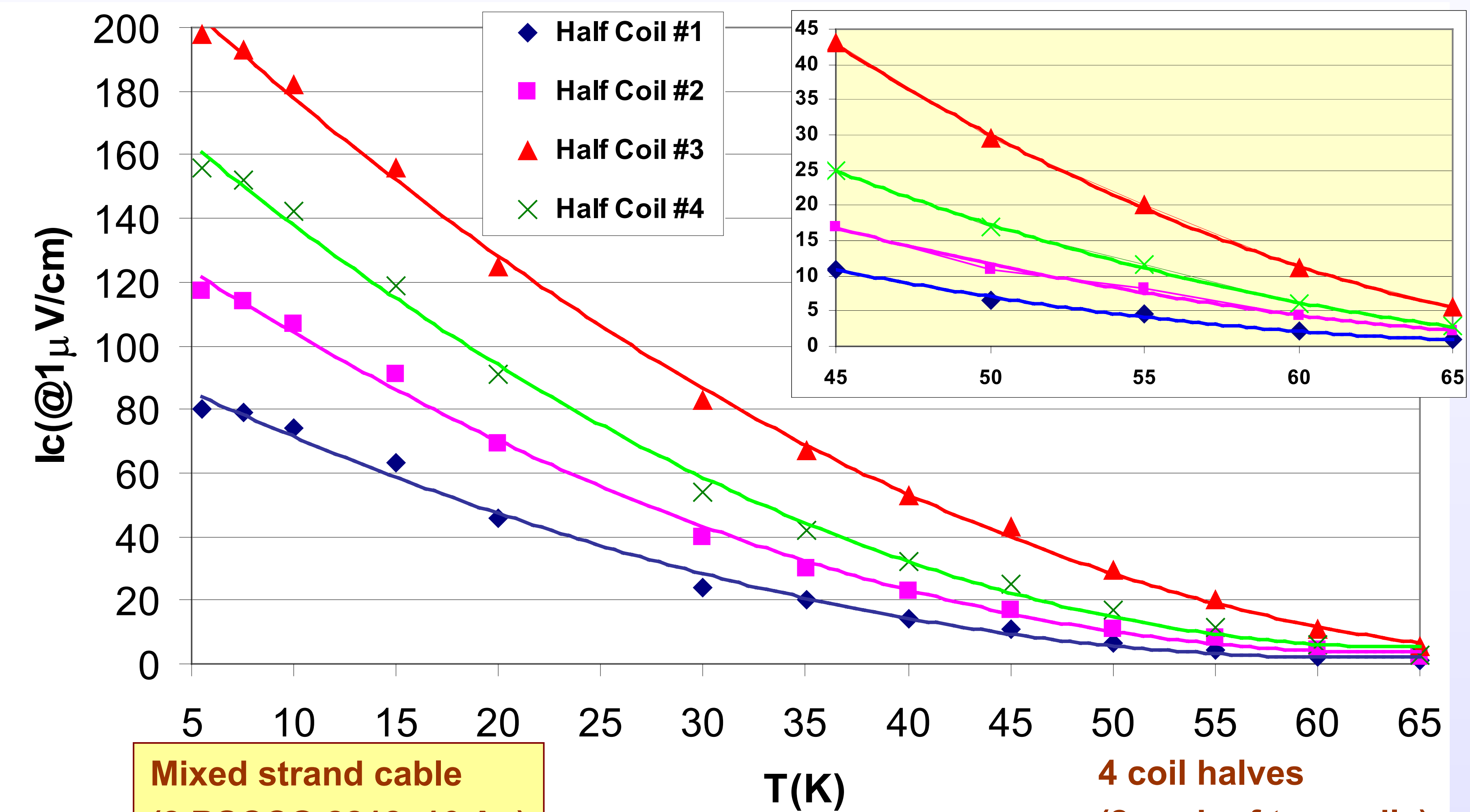


Performance of HTS Coil in the Background Field of Nb_3SN Coils



The background field on HTS coil was varied by changing the current in "React & Wind" Nb_3Sn coils (HTS coil in the middle and Nb_3Sn on either side).

Measured Critical Current as a Function of Temperature



Mixed strand cable
(2 BSCCO 2212, 16 Ag)

4 coil halves
(2 each of two coils)

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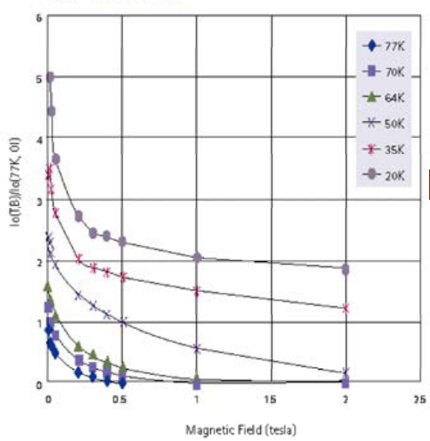
Medium Field HTS Magnets

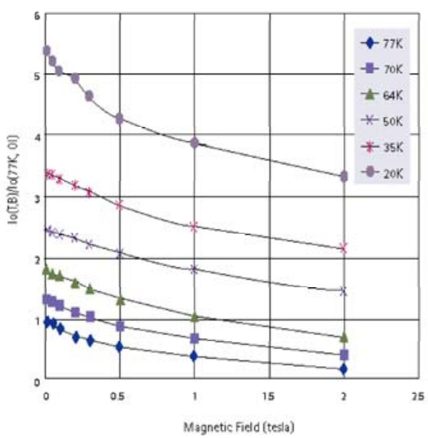
Critical current as a function of field at different operating temperature

HTS Properties



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.

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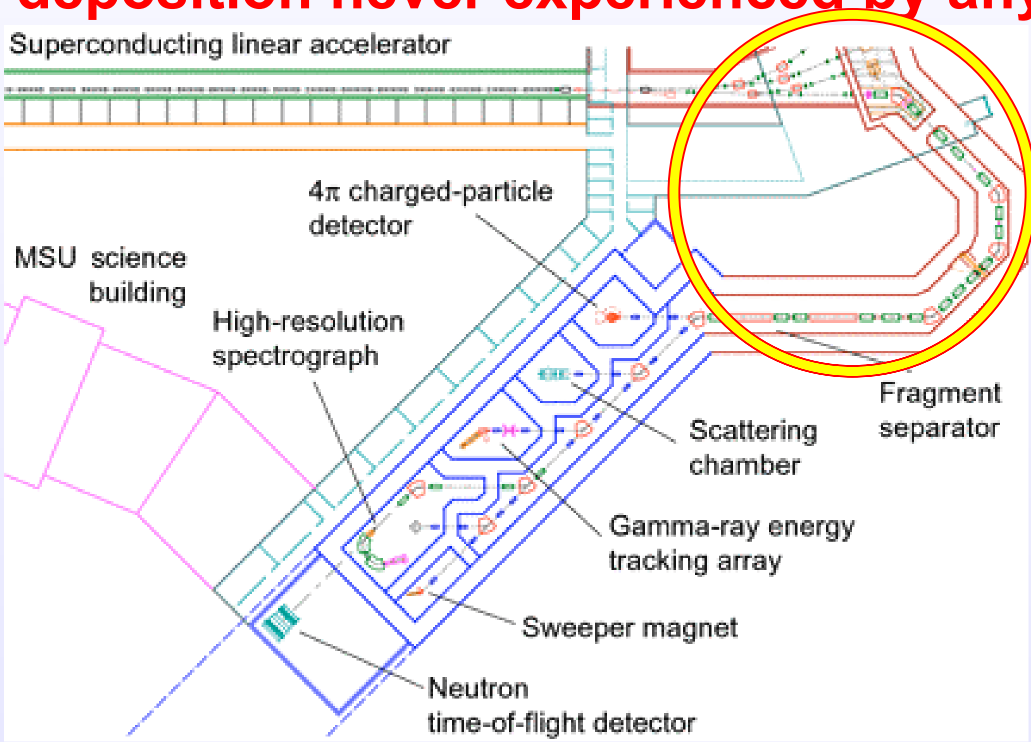
ASCHTS-PS-0003-02 October 1999

Medium field (few Tesla) HTS super-ferric magnets operating at ~35K (or even higher temperature) is an interesting possibility for future beam line and accelerator magnets.

One such application is the quadrupole magnets for the “Fragment Separator” of the proposed Rare Isotope Accelerator (RIA)

Fragment Separator Region of RIA

Magnetic elements (quads) in 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 high radiation level of fast neutrons.

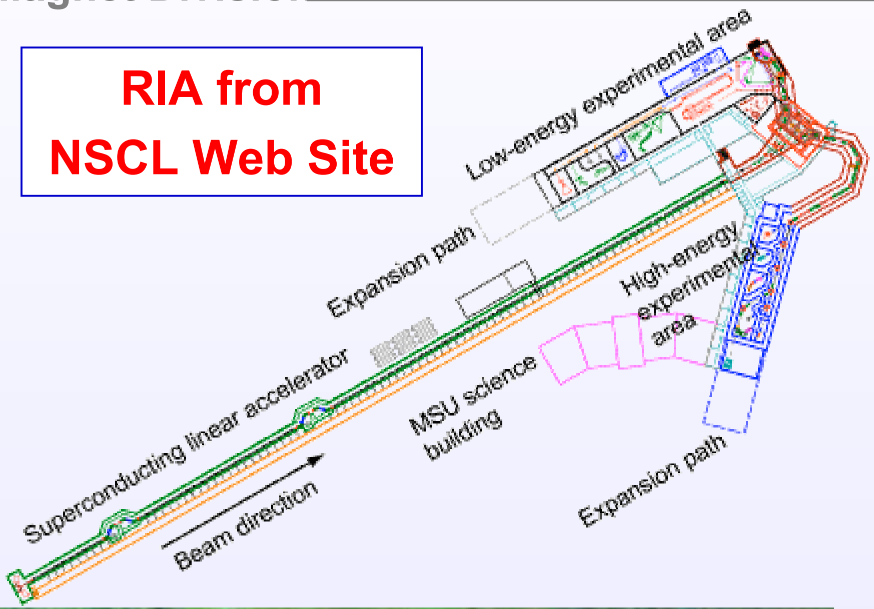
Room temperature, water cooled copper magnets produce lower gradient and/or lower aperture, reducing acceptance and making inefficient use of beam intensity.

Basically, we need *"radiation resistant"* superconducting quads, that can withstand large heat loads. There are many short and long time scale issues!

Superconducting
Magnet Division

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

RIA from NSCL Web Site

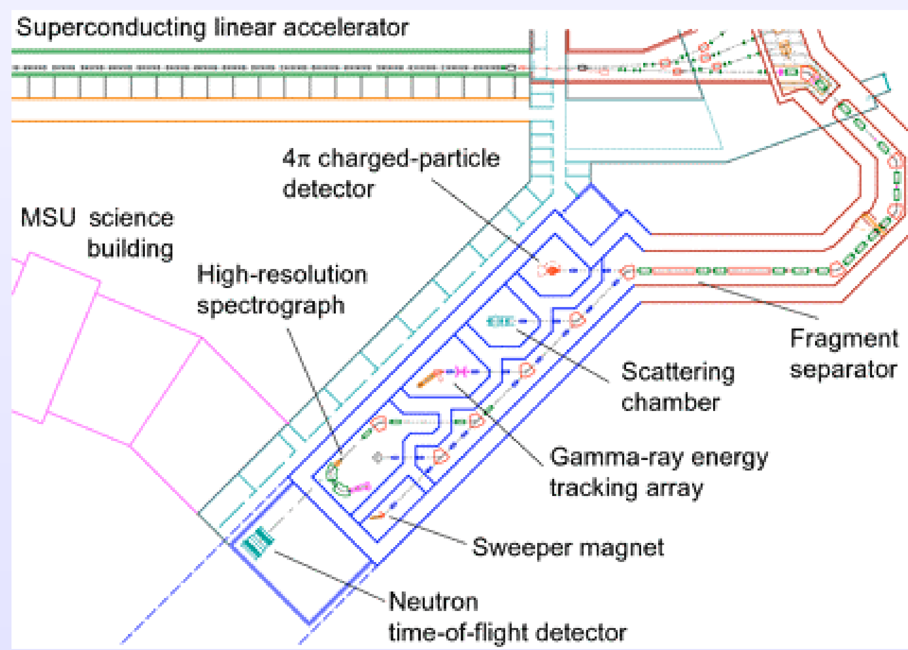


NSCL
NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY
AT MICHIGAN STATE UNIVERSITY

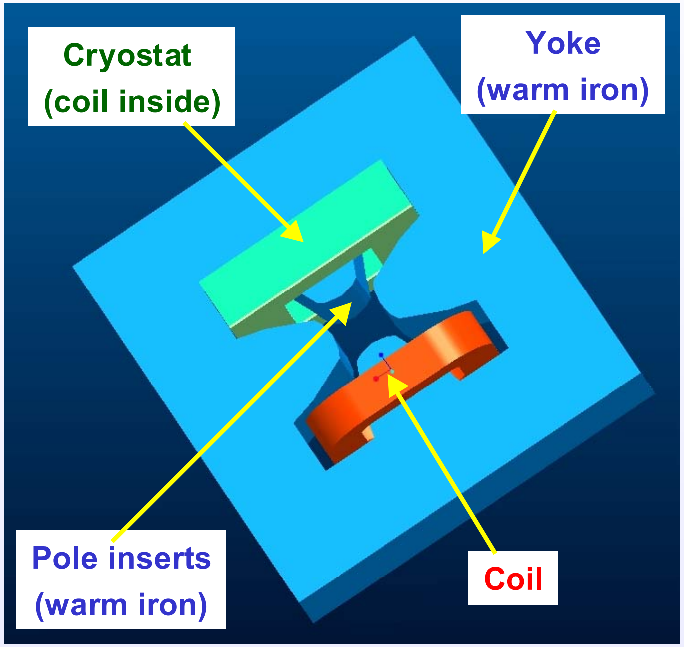
BNL/NSCL Collaboration:

BNL will do HTS magnet design, test and construction.

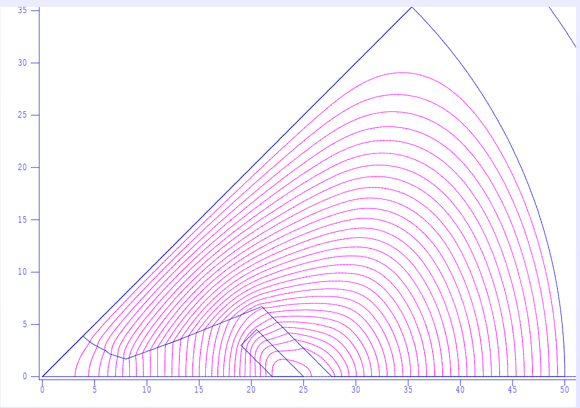
NSCL will do radiation damage studies.



HTS QUAD for RIA Fragment Separator



Coils inside the cryostat at the end of the magnet



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

➤ **Can be achieved with the commercial HTS.**

- **HTS Quads can operate at a higher temperature (20-40 K instead of 4K). Higher operating temperature makes large heat removal (few hundred kW) more economical.**
- **In HTS magnets, the control of operating temperature can be relaxed by an order of magnitude. This simplifies cryogenic system.**
- **A warm iron yoke brings a major reduction in amount of heat to be removed at lower temperature.**
- **The coils are moved outward to significantly reduce the radiation dose.**
- **Insulation is a major issue. We plan to use stainless steel which is radiation resistant.**

Influence of Radiation Damage on HTS

A relatively small and controlled dose of radiation brings enhancement in J_c from radiation. However, given the amount of dose relevant to this application, J_c is expected to go down. Need to determine that experimentally, even though the design is optimized to minimize the effects.

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

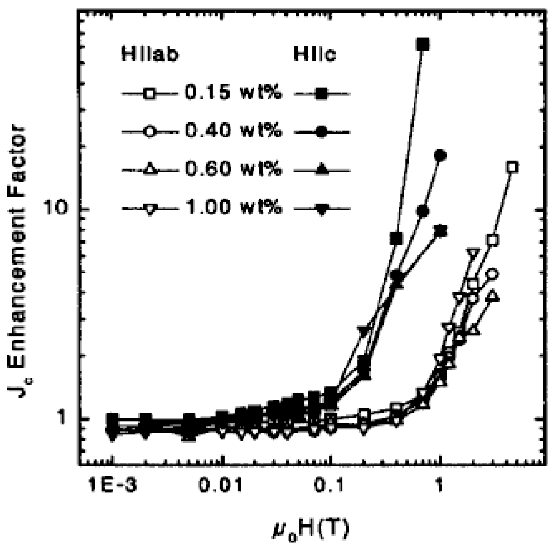


Figure 2. Enhancement of the critical current densities for samples with different amounts of uranium at 77 K, but at fixed track density.

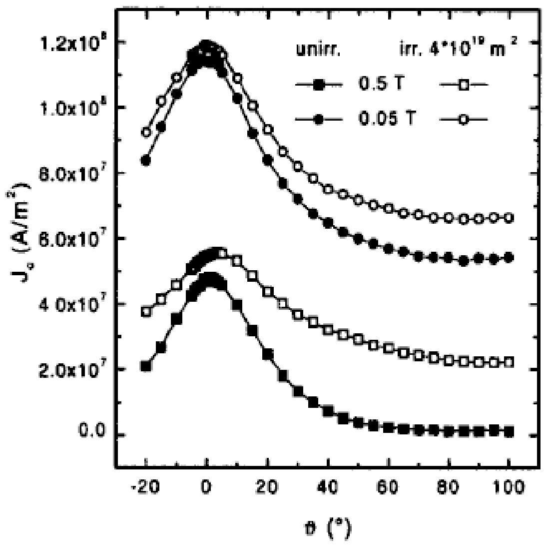


Figure 3. Anisotropy of J_c before and after irradiation to $4{*}10^{19}$ m^{-2} at 77 K and 0.5 T.

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

Equivalent dose from lower energy proton or ions?

This study is a part of NSCL/BNL collaborations.

Possible Radiation Damage Studies at Cyclotron

In RIA HTS is subjected to a very high radiation dose: 10^{19} neutrons/cm^2.

(high energy neutrons : ~500 MeV)

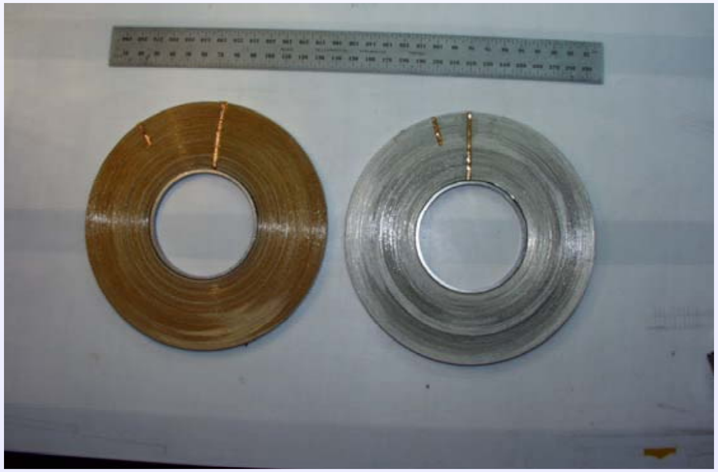
• Variable Energy Cyclotron Center (VECC) may possibly participate in radiation damage studies on HTS and other materials. If interested, one can explore the possibility of such a collaboration. This would be carried out with NSCL playing a major role.

• Equivalent radiation dose on HTS (and other materials) can perhaps be provided (?) at VECC. The critical current of HTS will be measured at VECC before and after irradiating the sample at VECC.

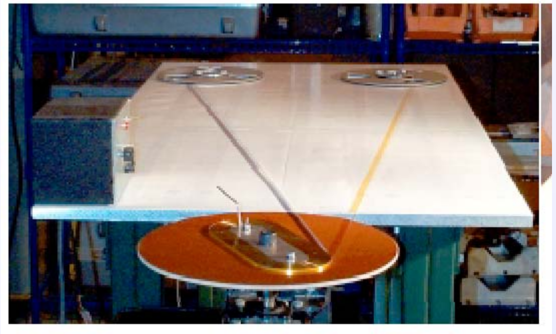
• This will be a world class research that could have a major implications on various future facilities. There are very few places where such studies are being currently carried out.

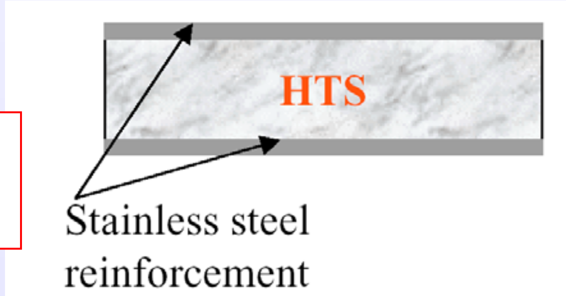
Stainless Steel Insulation in HTS Coils

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.





Will the bonded SS tape on either side of HTS be adequate, or use extra ~1 mil SS tape?

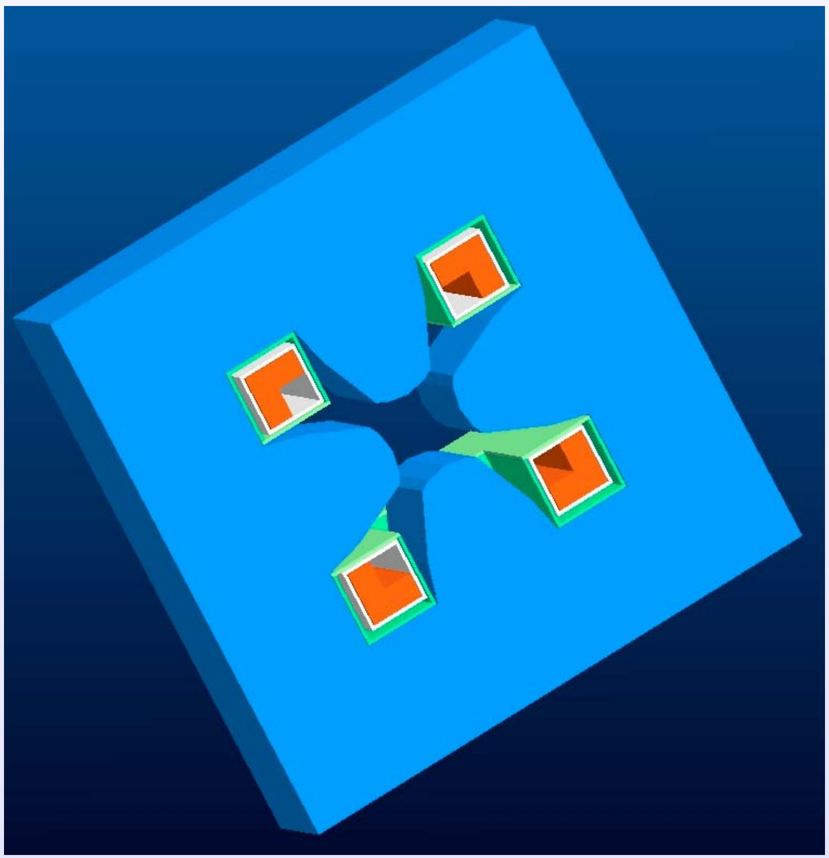
- **Plan to use extra, at least in initial coils.**

Basic Design of RIA HTS Quadrupole

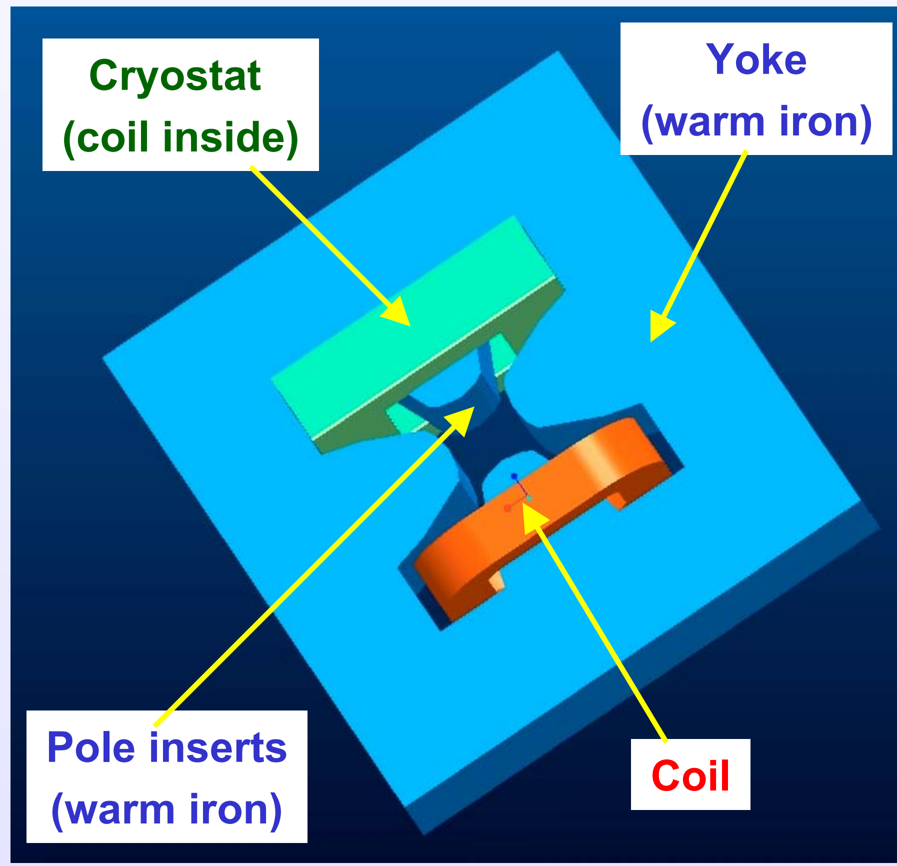
A simple warm iron super-ferric quad design with two racetrack HTS coils

Note that only a small fraction of 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

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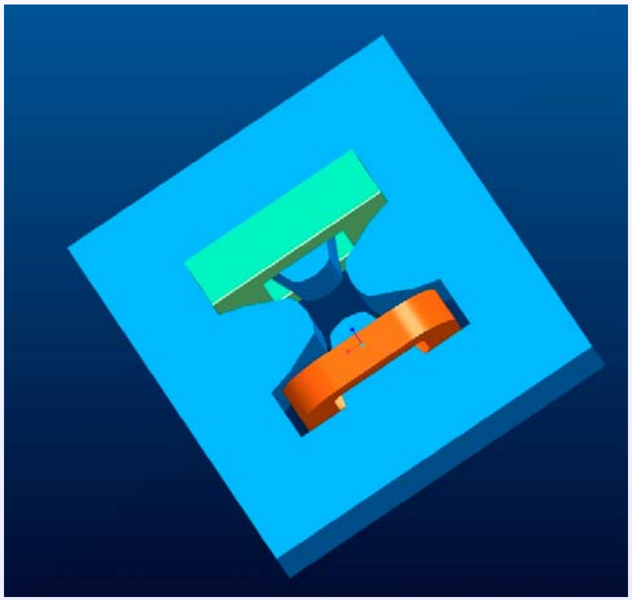
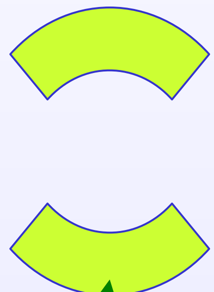
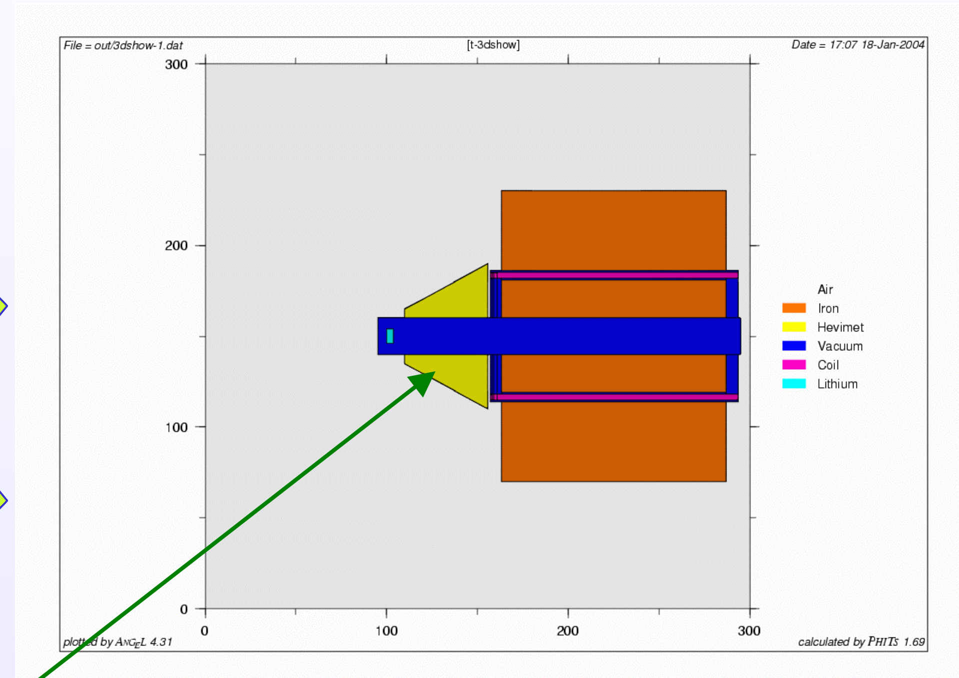
Heat Load and Shielding

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.

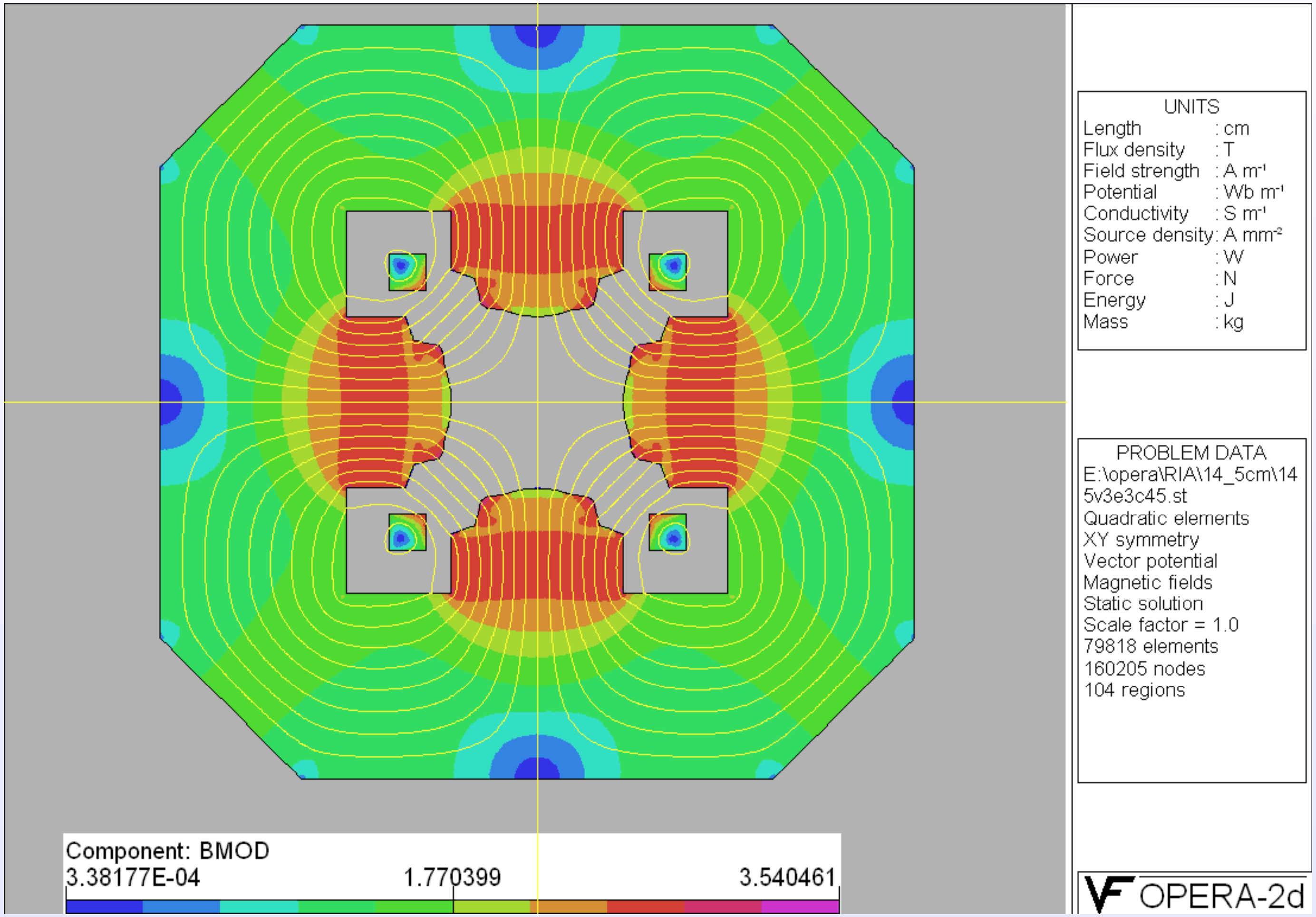
Iron heat load = 9 kW ☆

Coil heat load = 130 W ☆

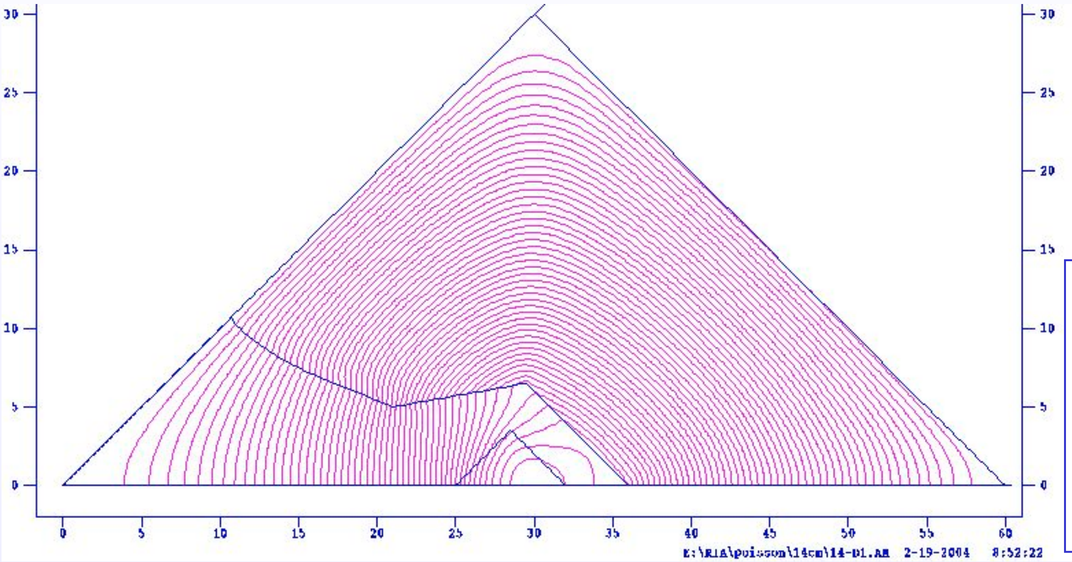
Coil dose rate (assumed to be silver) = 1 MGy/year

(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



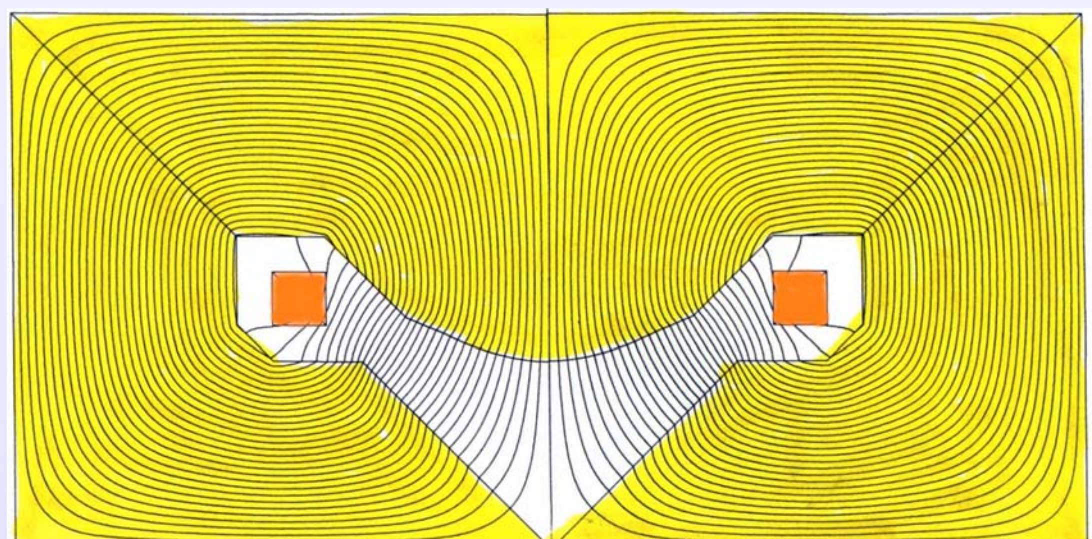
Operating Temperature ~30 K;
Coil current density ~100 A/mm²

Present HTS cost : $200/kA/m

Total HTS cost in magnet: ~$400K

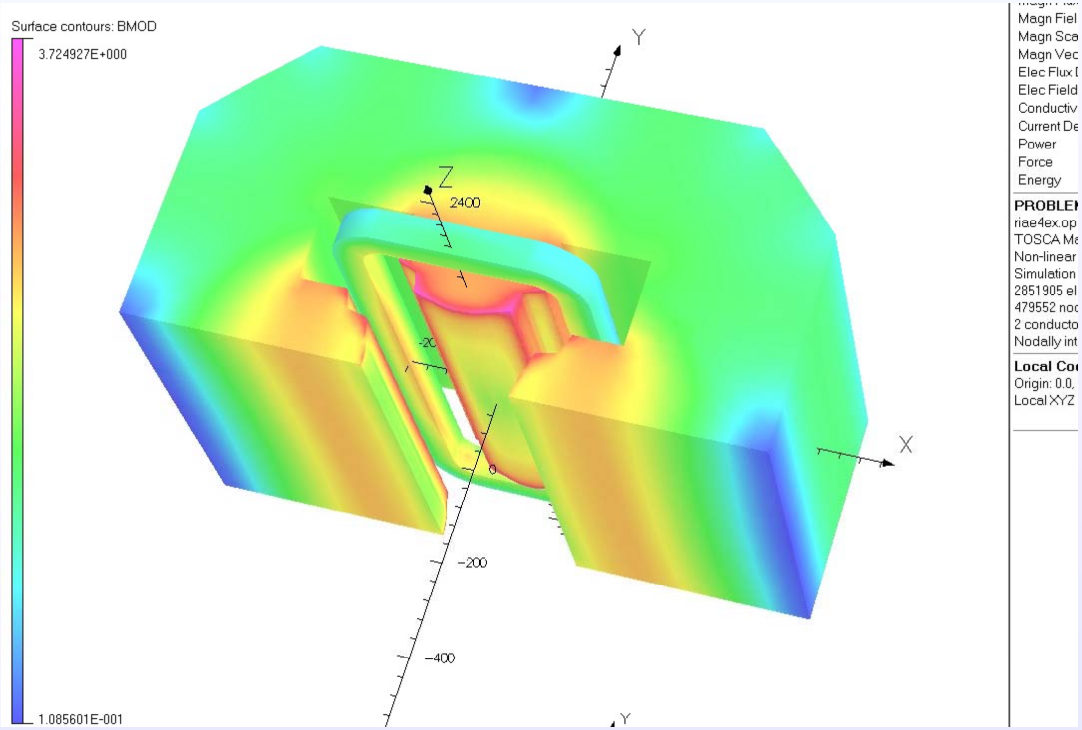
According to American Superconductor corporation, the cost is expected to go down by a factor of ~3 in ~5 year.

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



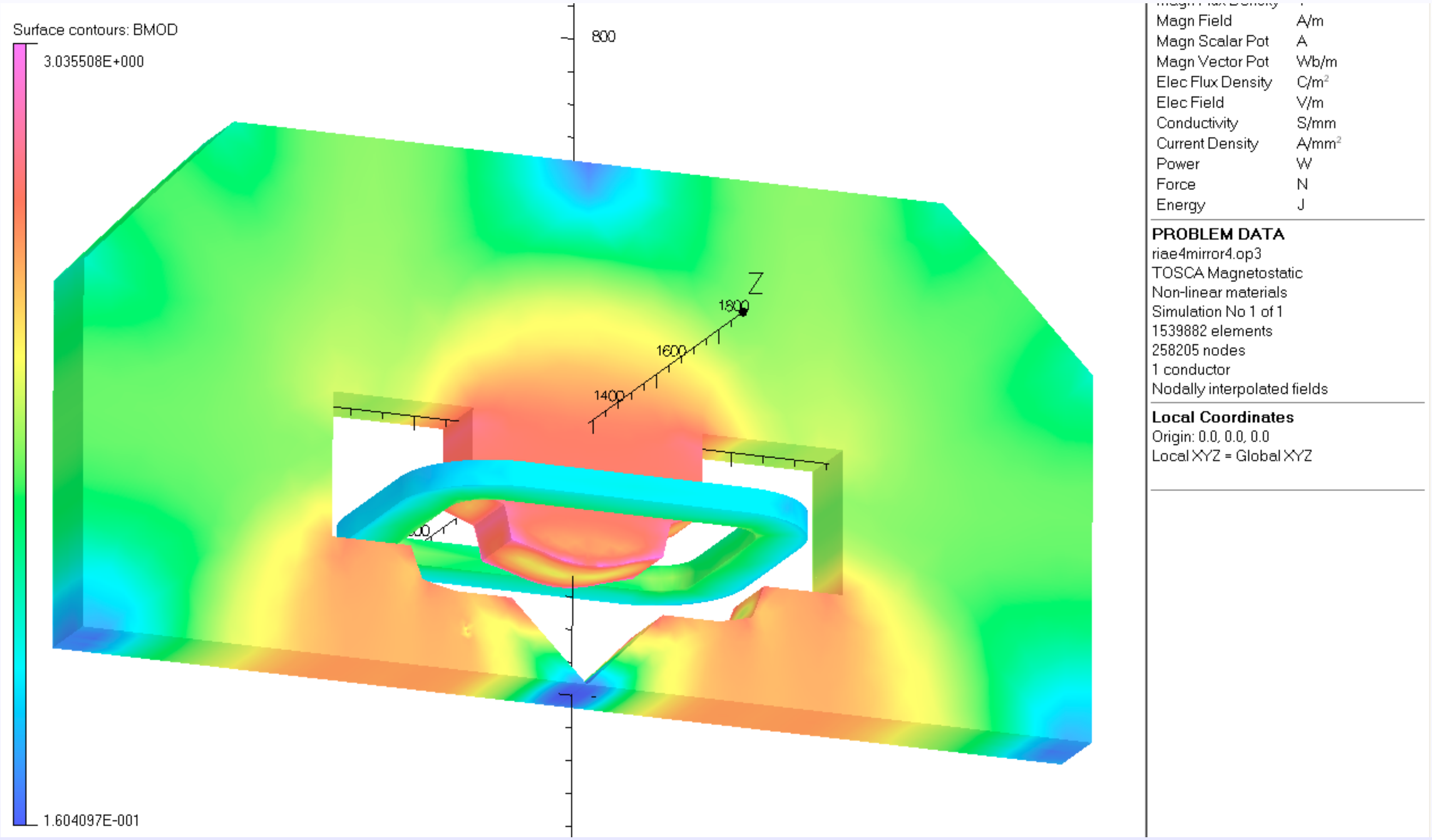
The basic design of RIA HTS quad has been demonstrated by building and testing a magnetic mirror configuration.

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.

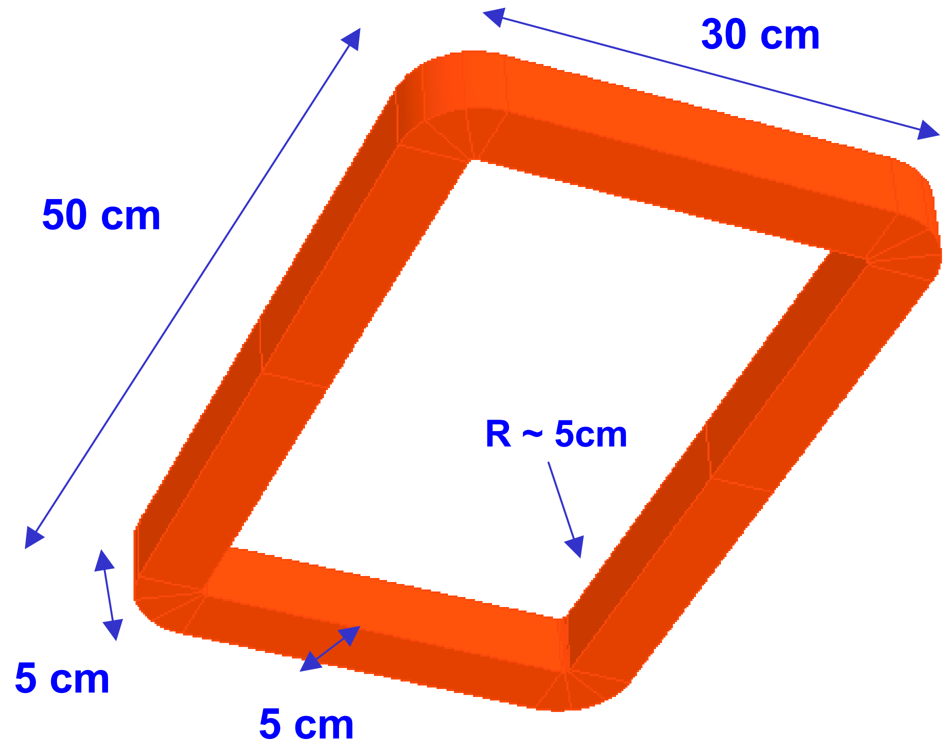
HTS Coil Design

- 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

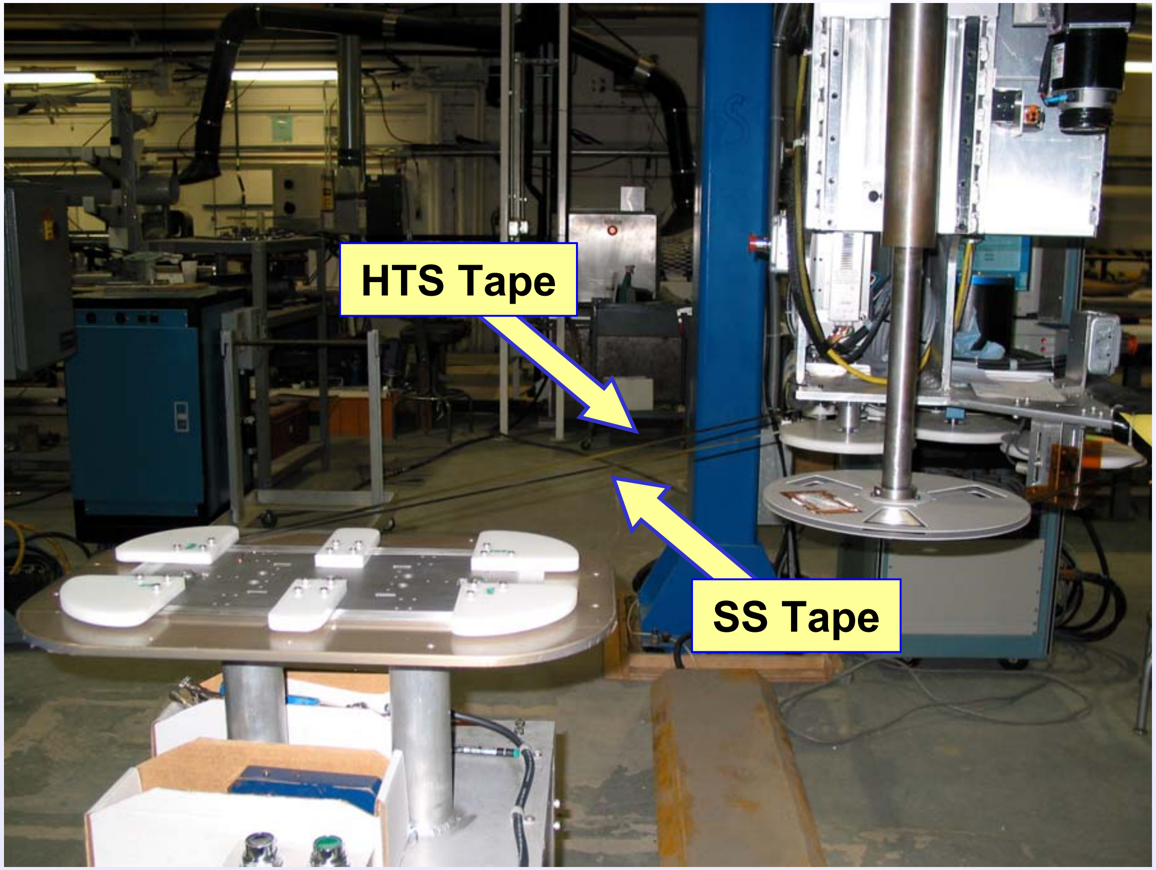
Specifications:

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

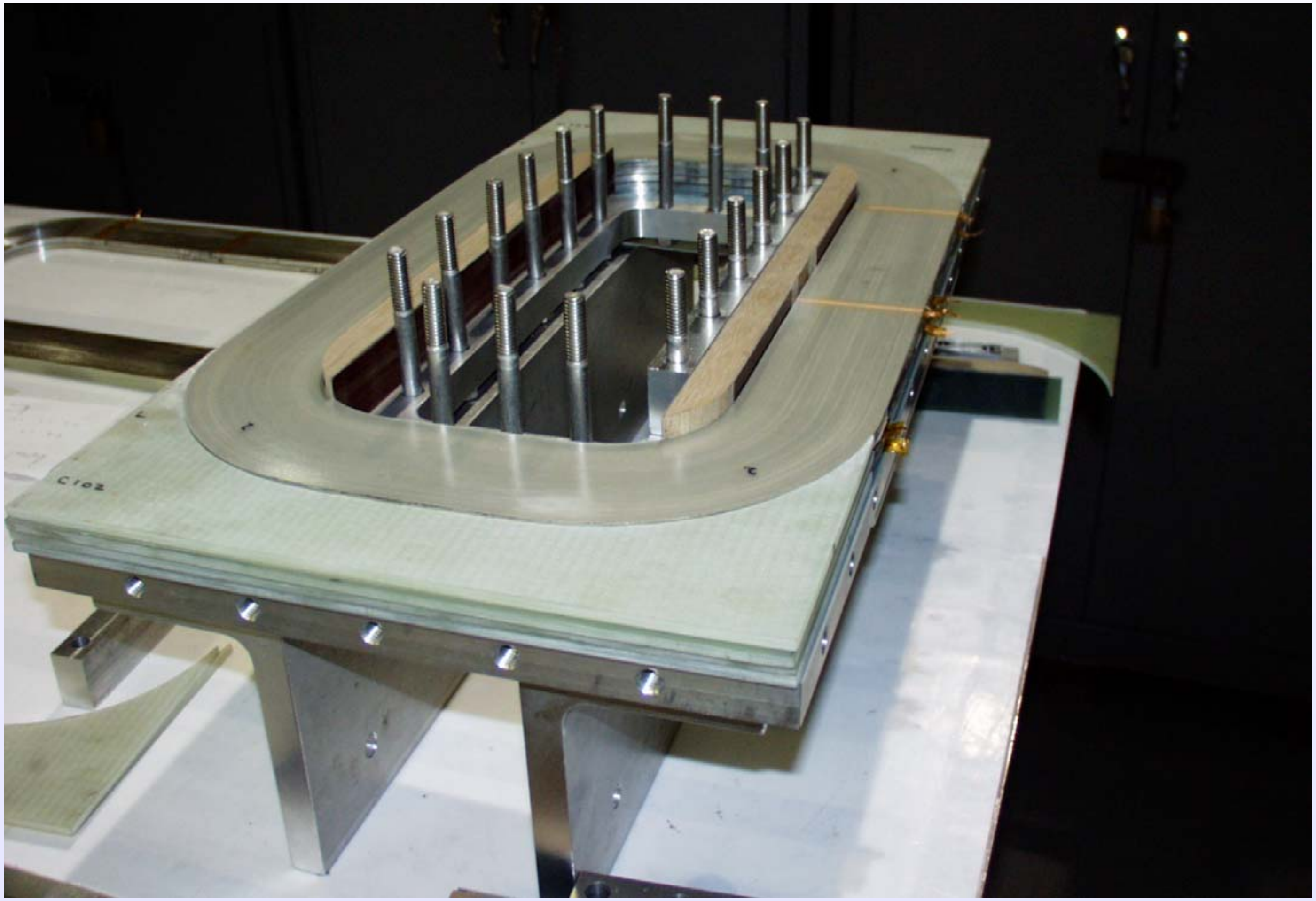


A coil being wound in a computer controlled winding machine.

HTS Coils for Magnetic Mirror Model

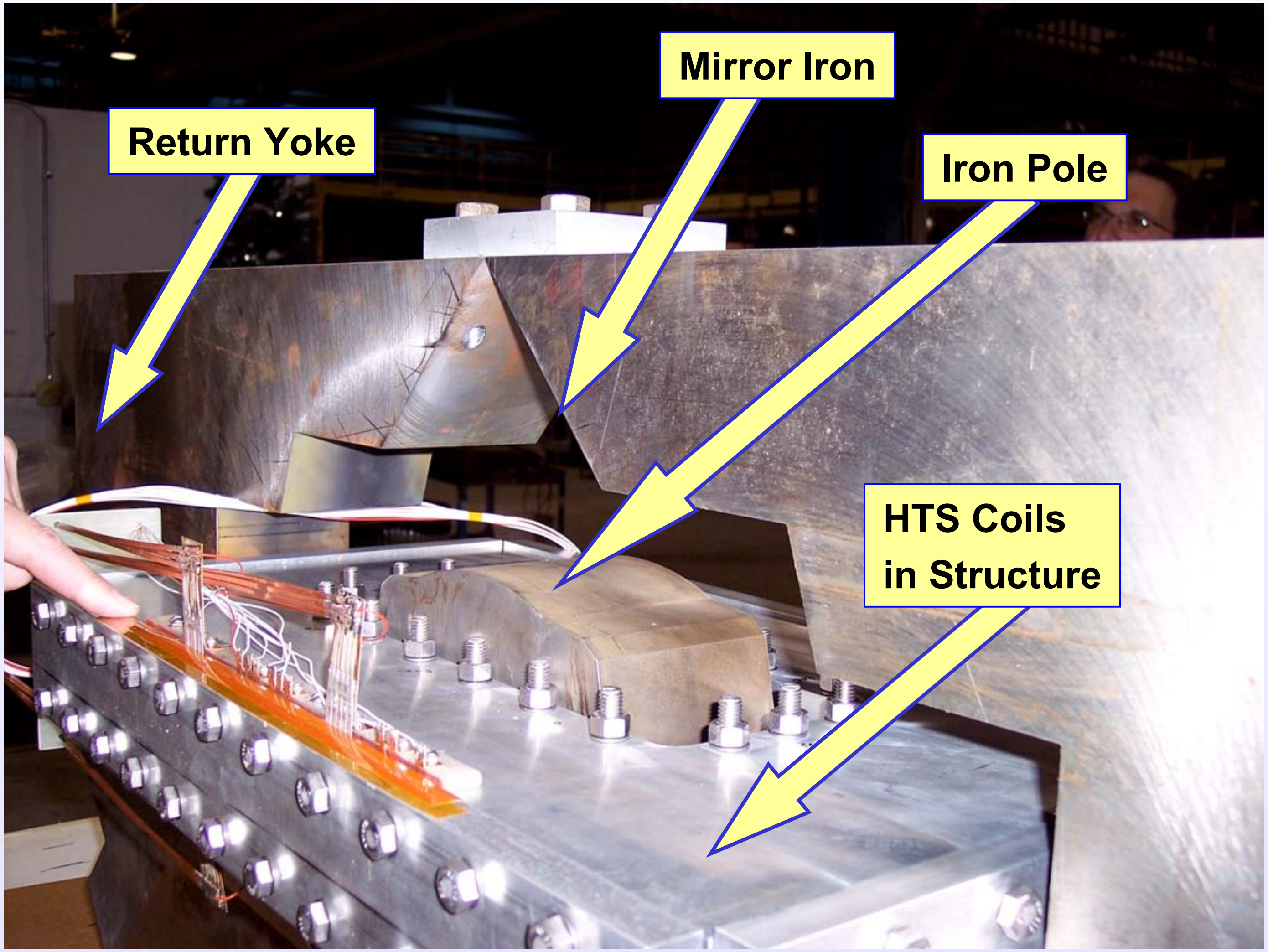
Three pairs of coils (six coils). These coils are made with HTS tape (nominal 4.2 mm wide and 0.3 mm thick) and insulating stainless steel tape (nominal 4.6 mm wide and 0.04 mm thick).

Assembled Coils with Internal Splice



Three pairs of coils during their assembly a support structure.

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.

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).

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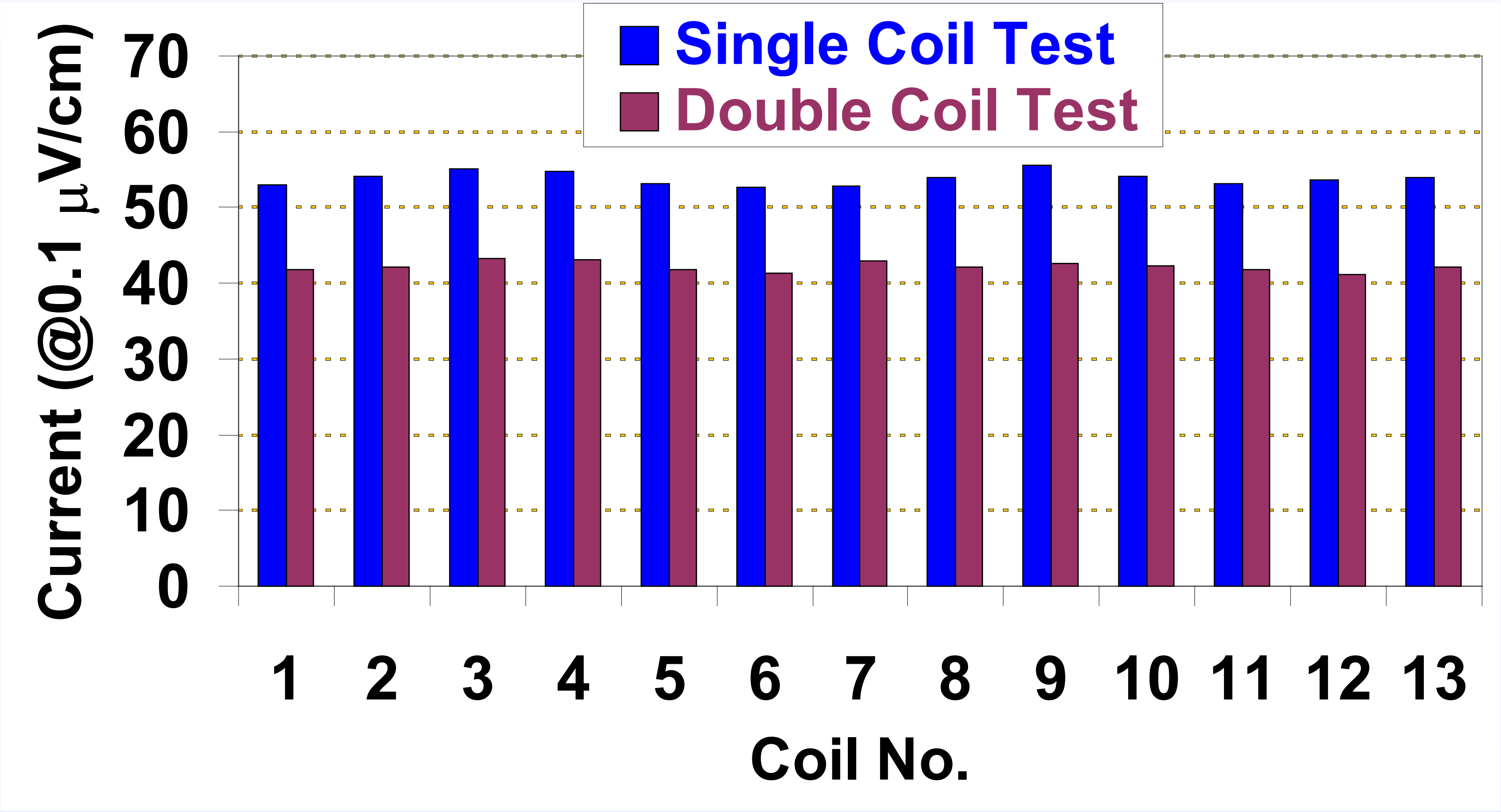
Magnetic Mirror Model with Top Hat

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.

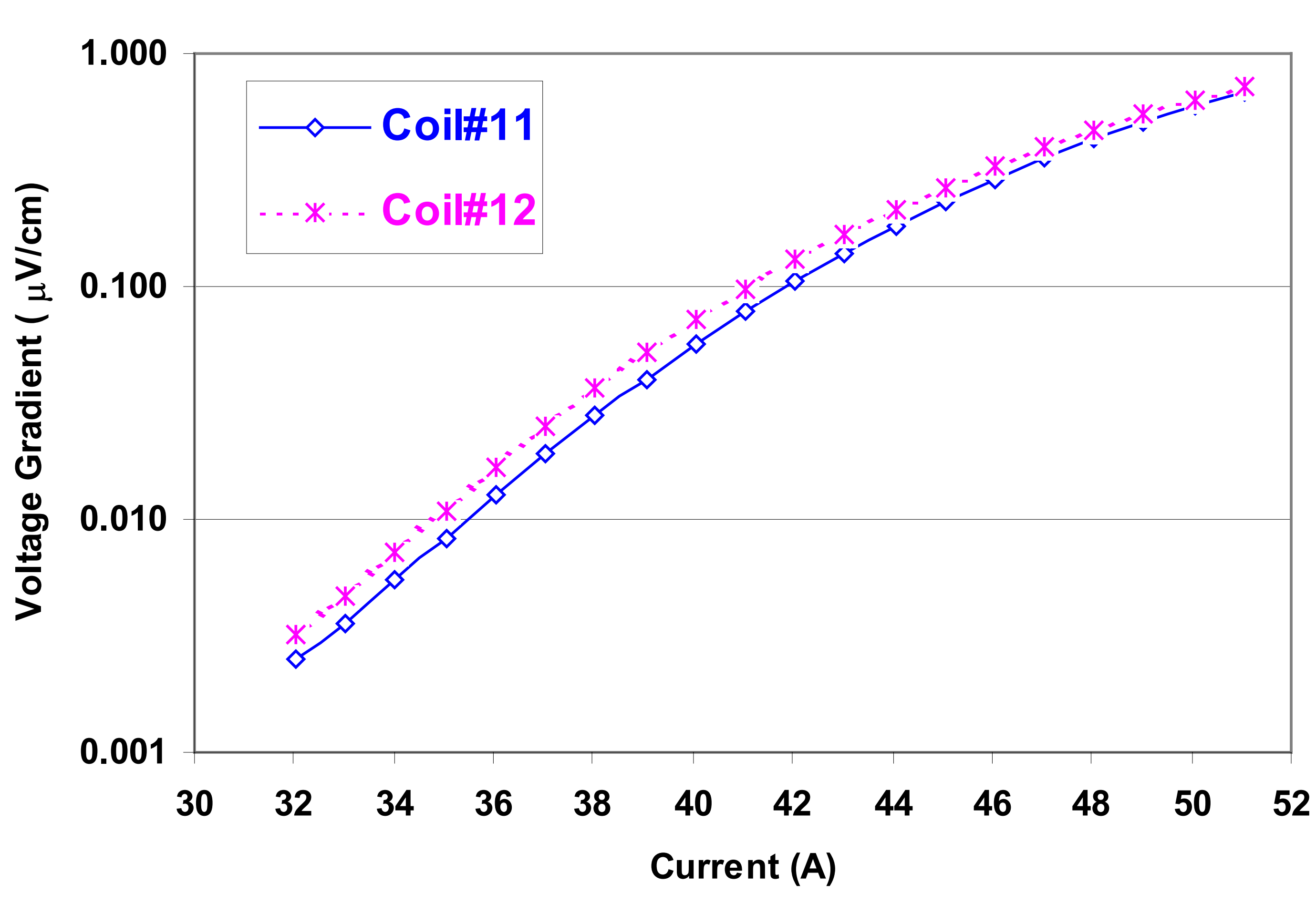
Performance of 13 Coils (Tested at 77 K in Liquid Nitrogen)

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



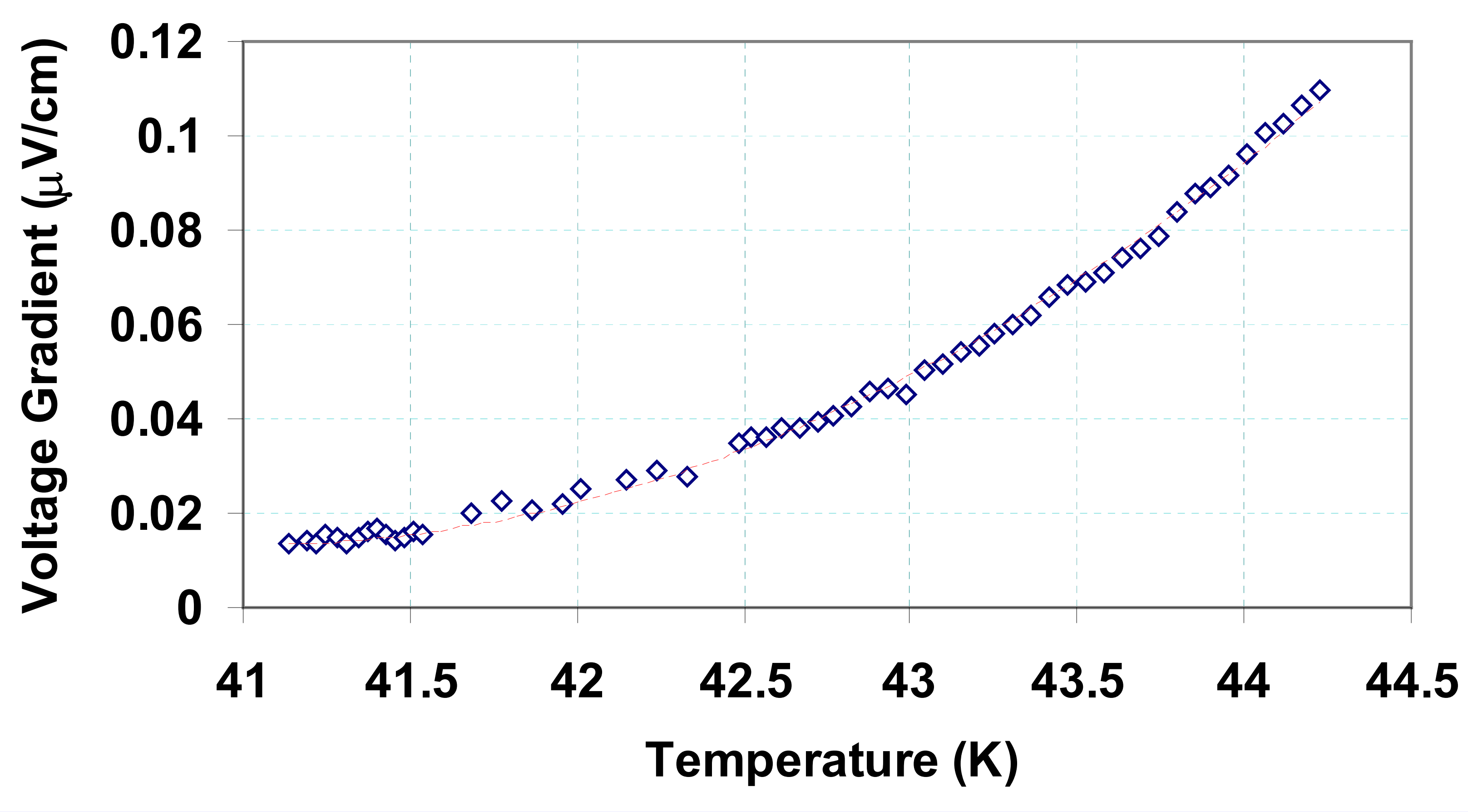
The current at a voltage gradient of 0.1 μ V/cm (10 μ V/meter) over the total length of the coils at 77 K.

Typical Test Results of HTS Coil (Voltage Vs. Current to Determine I_c)



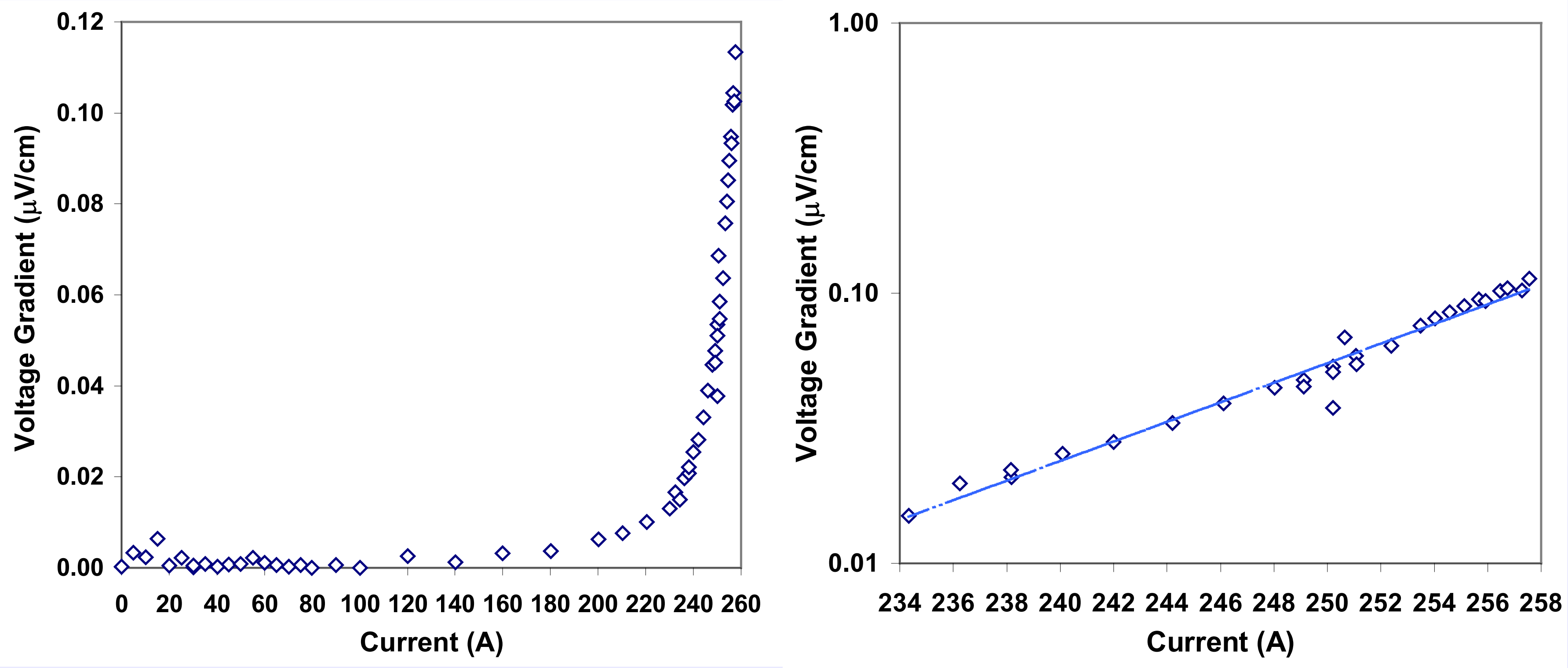
Typical voltage gradient vs. current curves for a pair of coils operated in series in liquid nitrogen bath.

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



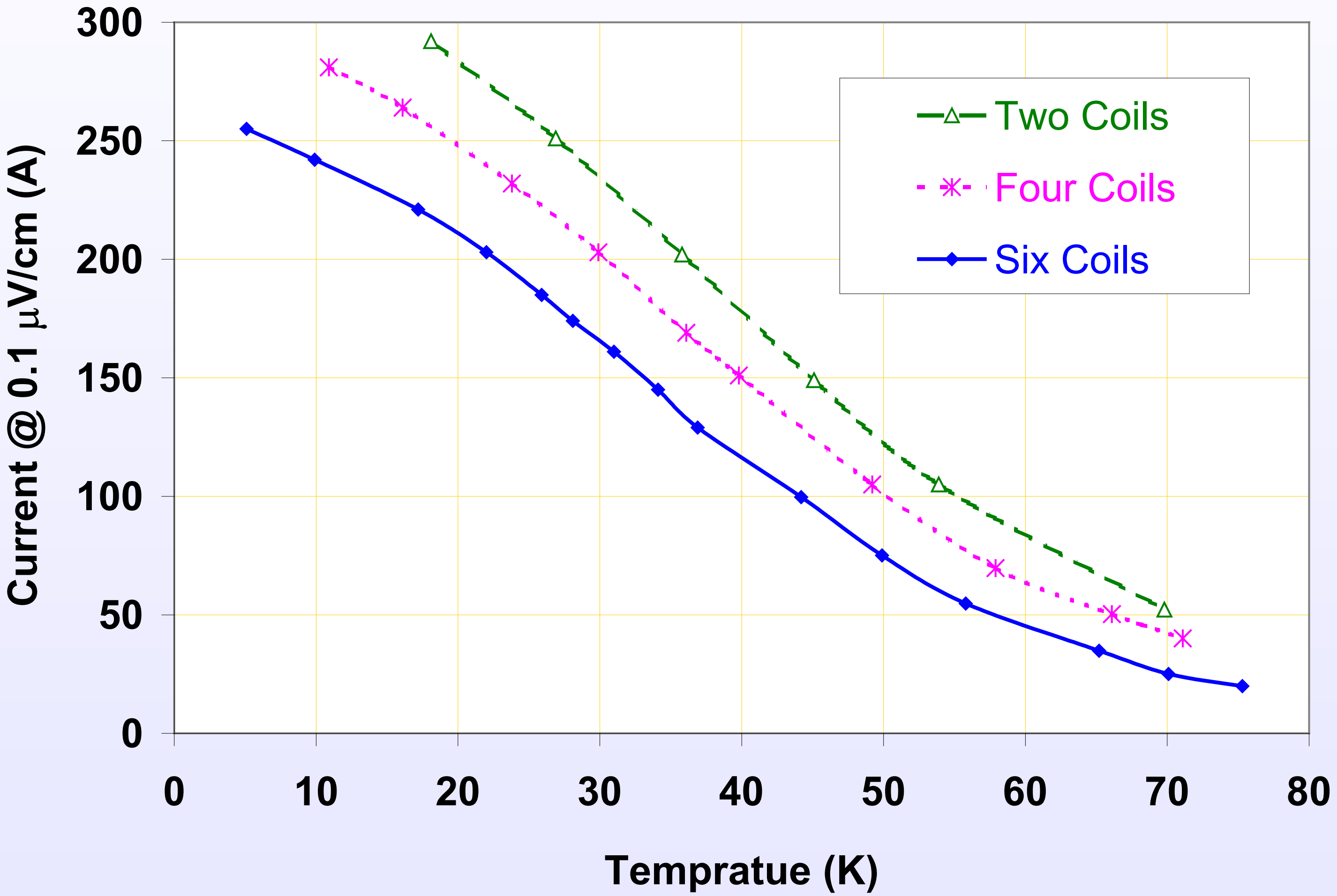
Voltage gradient as a function of temperature for the magnetic mirror model at a constant current of 100 A.

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.

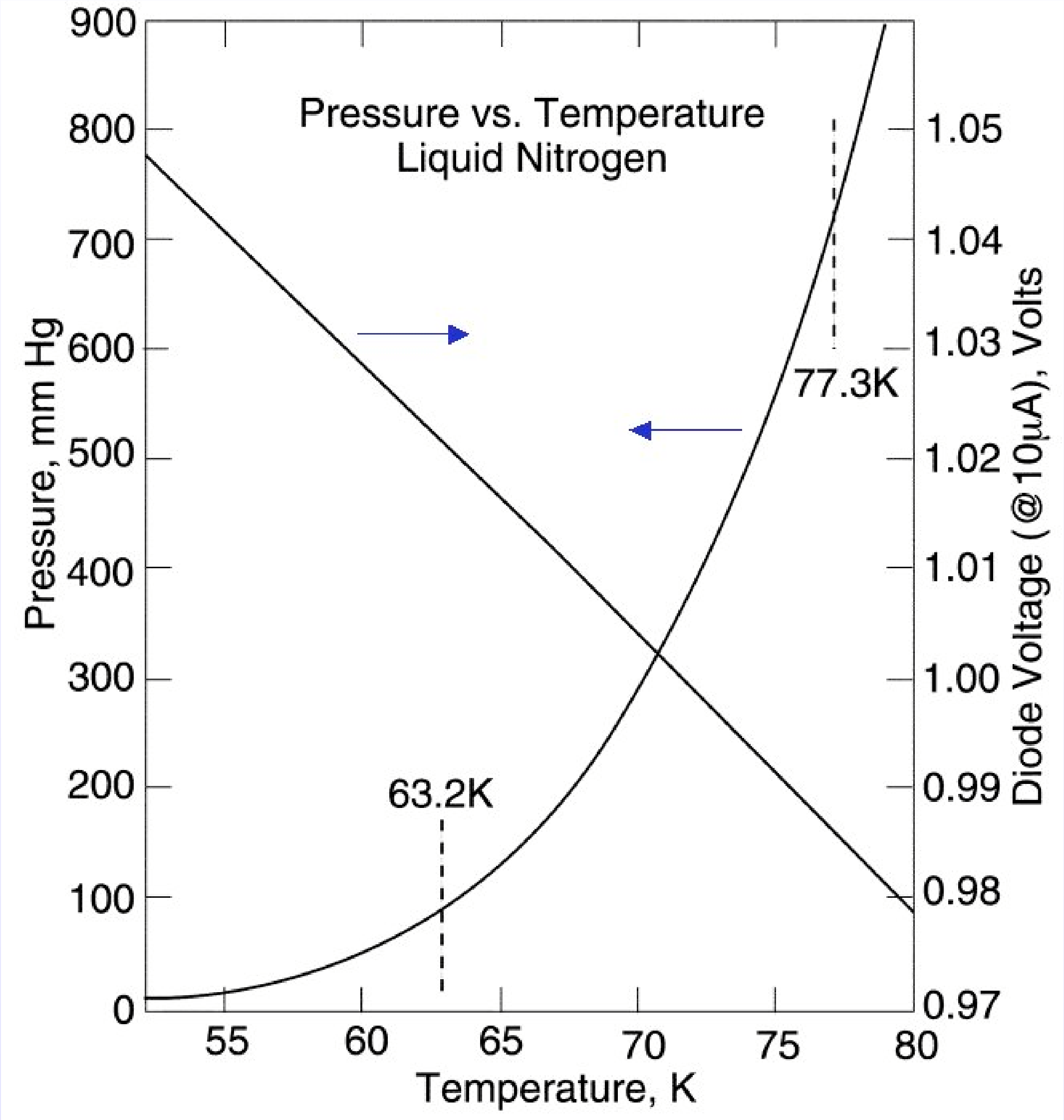
RIA HTS Model Magnet Test Results for Various Configurations



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.

Bath Temperature of Nitrogen can be Lowered by Pumping



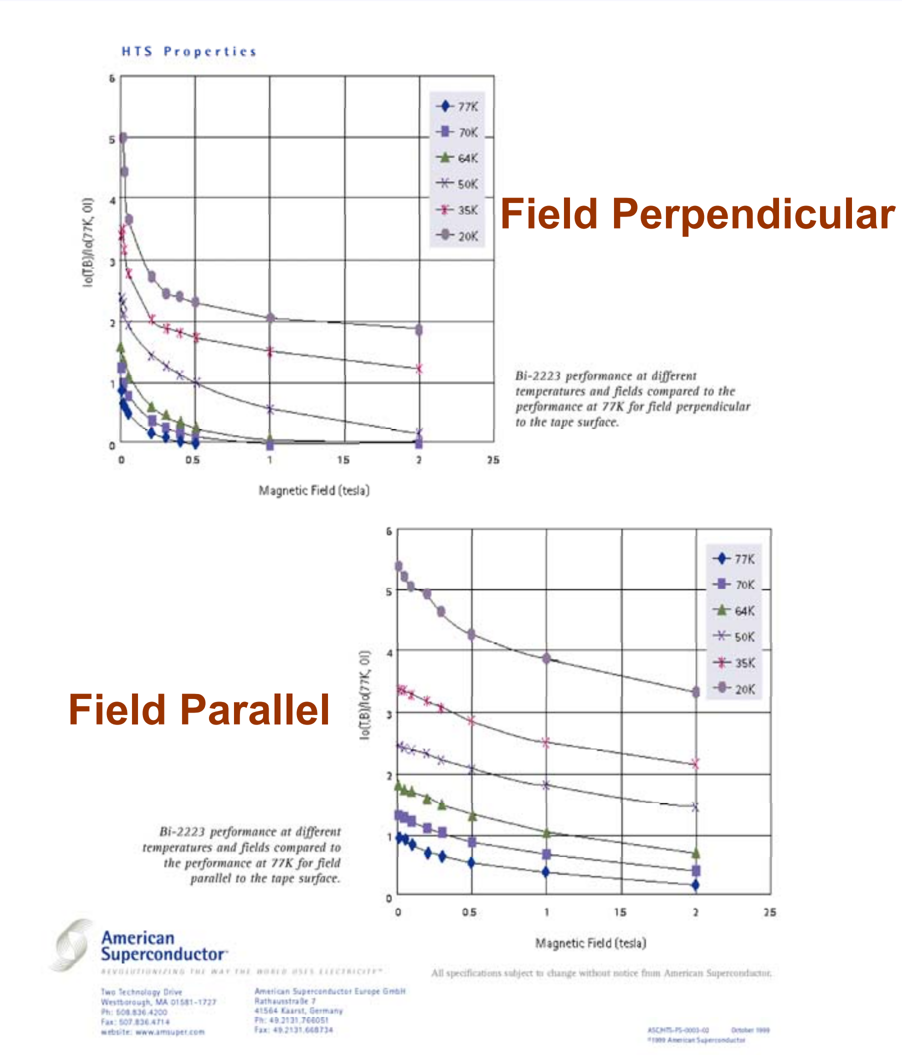
In some low field applications, one can perhaps operate HTS magnets with nitrogen only.

This means that the superconducting (HTS) magnets can be operated without helium.

This is a major advantage in many situations.

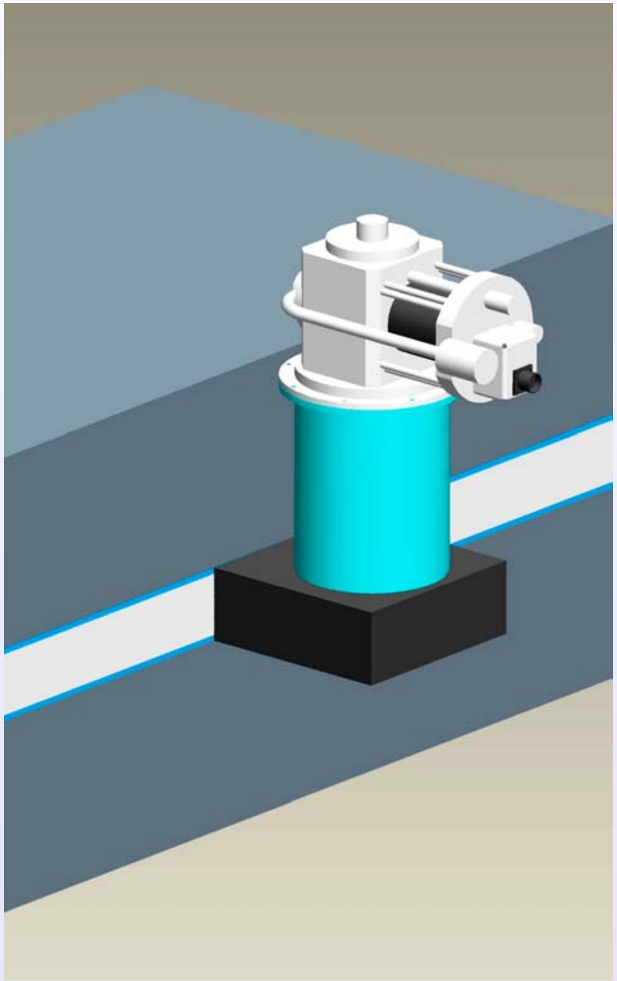
HTS Magnets with Cryo-coolers

Critical current as a function of field at different operating temperature



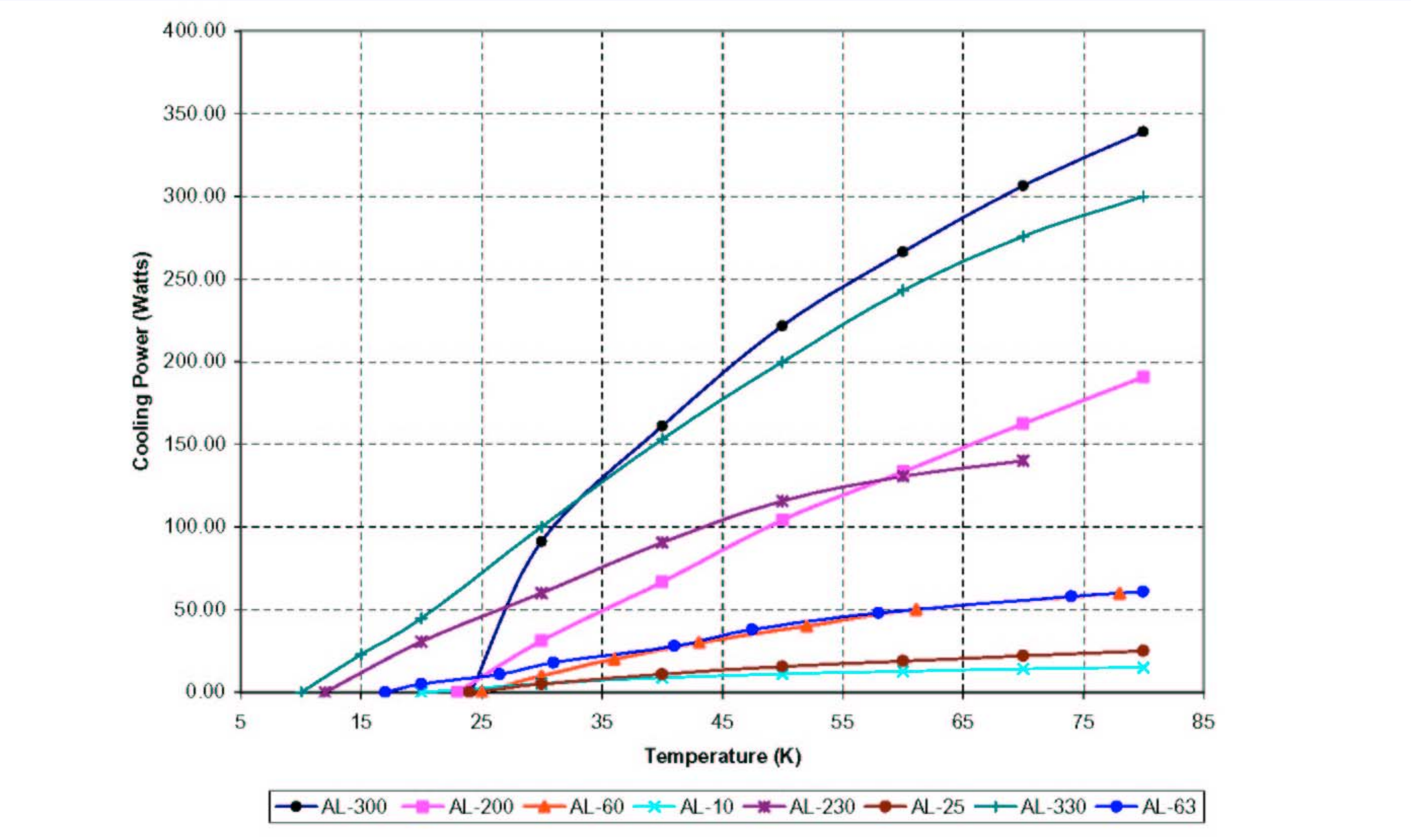
Field Perpendicular

Field Parallel



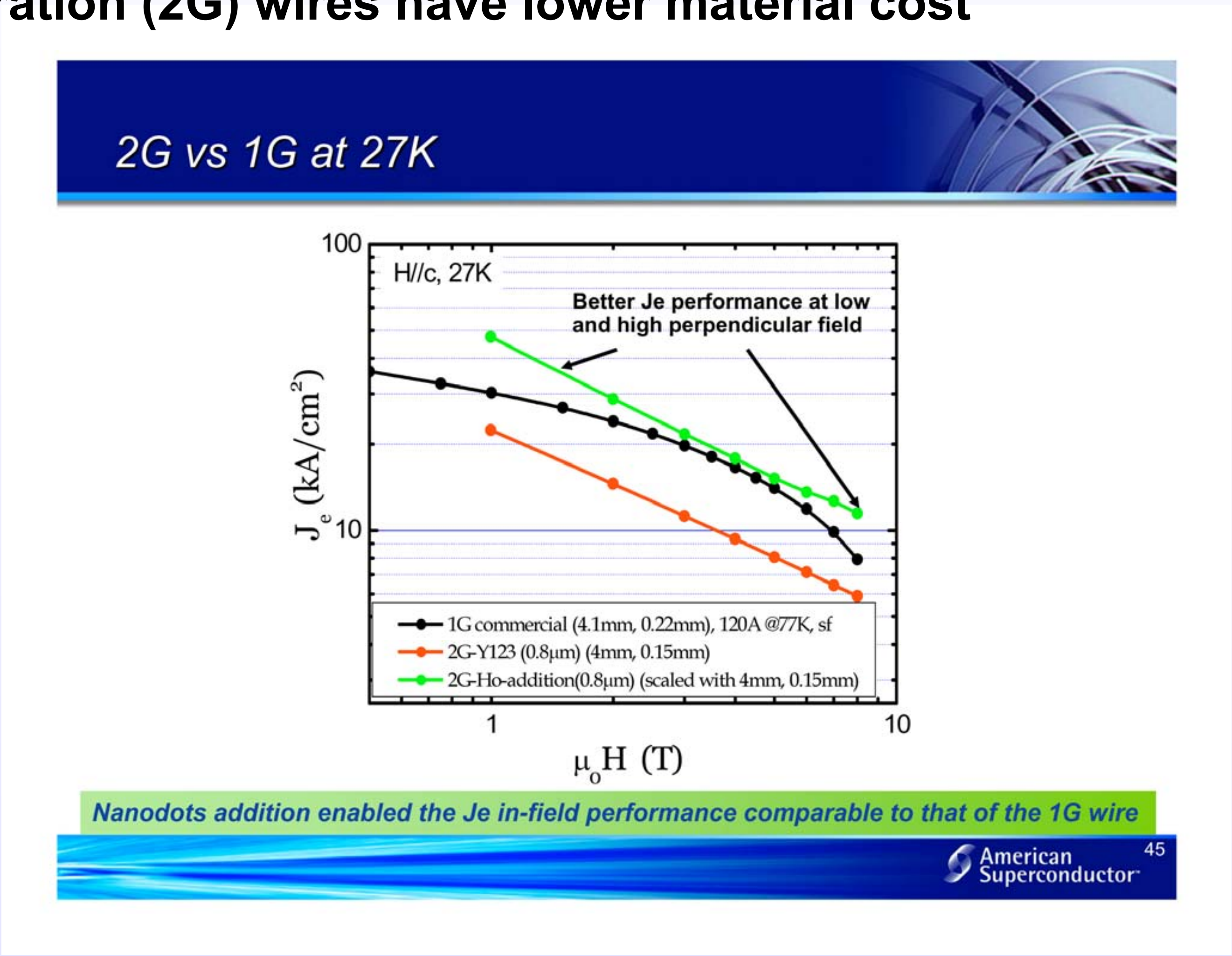
Capacity of Cryo-coolers as a Function of Temperature

Performance curve of some cryo-coolers from CRYOMECH



HTS Wire in Future

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



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 result presented here proves that despite its brittle nature, the technology to build magnets with HTS can be developed. HTS based accelerator magnets offer several unique advantages.

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 can do meaning magnet R&D and system design to address various technical issues**
  - Results from Brookhaven over several years have been encouraging.
  - HTS offer a potential of good technical and economic operational solution for RIA fragment separator quadrupole triplet.
- **The next step for RIA Quad**
  - Examine the impact of large dose of radiation on superconductor and insulation material.
  - Demonstrate HTS magnet technology in a complete magnet.
- **HTS magnet Technology may be useful in many future accelerator and beam line applications.**