http://www.bnl.gov/magnets/staff/gupta

HTS in a Variety of Future Accelerator Magnets

Ramesh Gupta

LTSW 2007 @ Lake Tahoe

HTS in a Variety of Magnets

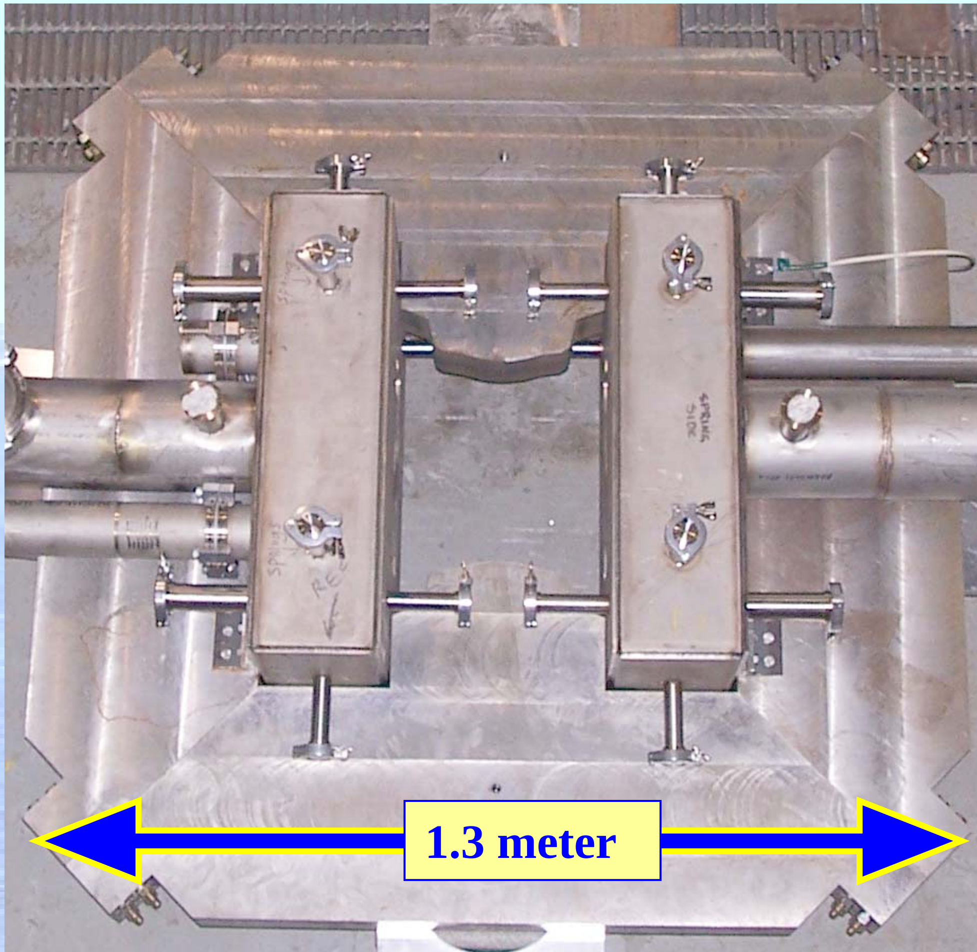
- **HTS in very high field magnets**
  - no superconductor can carry such high current density at very high fields.
- **HTS in magnets subjected to high heat loads**
  - no superconductor can tolerate such high heat loads + local temperature rise and then remove energy so efficiently.
- **HTS in energy efficient magnets**
  - low field (1-2 T) water-cooled cooper magnets for beam-lines and accelerator are becoming prohibitive to operate.

…and a combination of above.

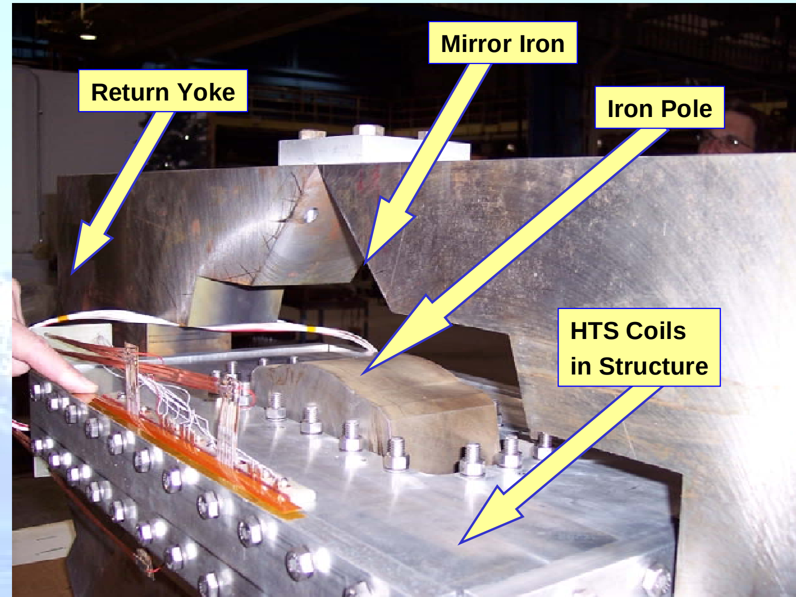
Recent Experience and Future Outlook

- **Experience with HTS R&D Magnets**
  - **RIA/FRIB Magnets (HTS for large heat loads)**
    - **made with Bi2223 tape and now with YBCO Tape**
  - **Common Coil Dipole (HTS for high field)**
    - **made with Bi2212 Rutherford Cable**
- **Future Possibilities for Accelerator Magnets**
  - **High Field Magnets**
    - **with Bi2212 cable or YBCO *wide tape*/ or *Roebel cable***
  - **Energy Efficient Magnets**
    - **with YBCO Tape**

RIA HTS Model Quadrupoles



Warm iron R&D quadrupole with twenty four coils in two cryostats

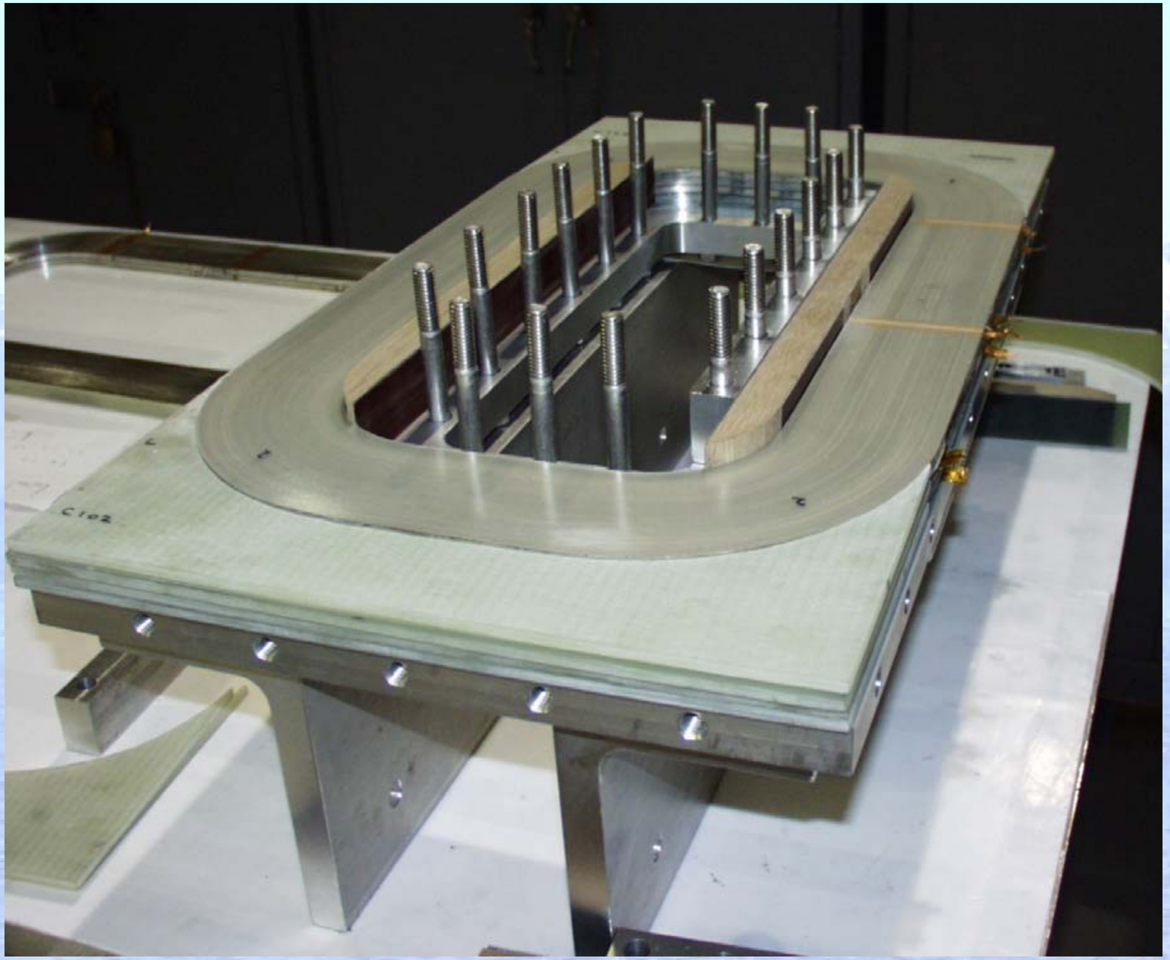


Cold iron mirror model

Warm iron mirror

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Bi2223 Coils in RIA Quads



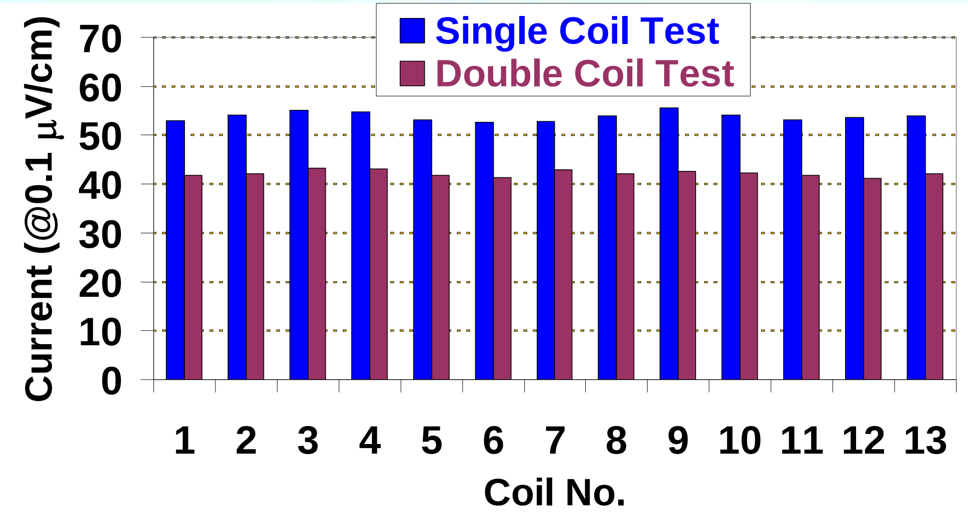
RIA quad is made with 24 coils with each using ~200 meter of commercially available HTS wire (tape).

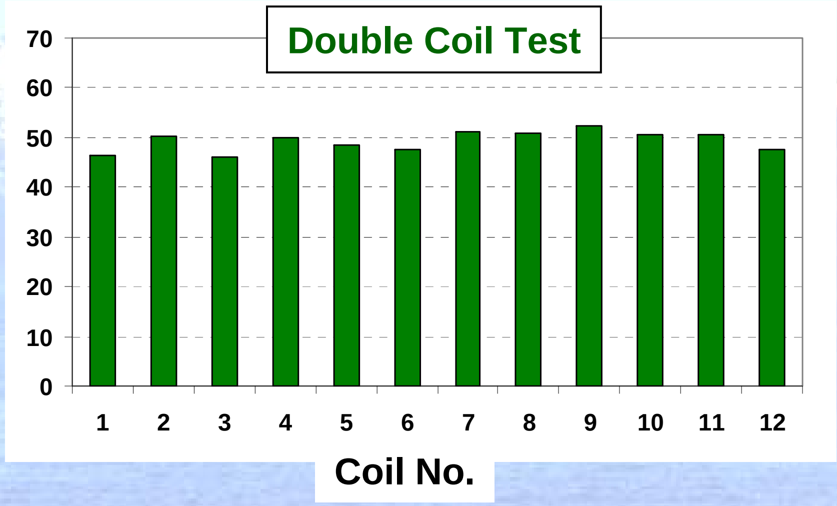
This gives a good opportunity to examine the reproducibility and reliability in performance of number of coils (number grows every year).

LN_2 (77 K) Test of 25 BSCCO 2223 Coils

13 Coils made earlier tape
(Nominal 175 turns with 220 meters)

12 Coils made with newer tape
(150 turns with 180 meters)



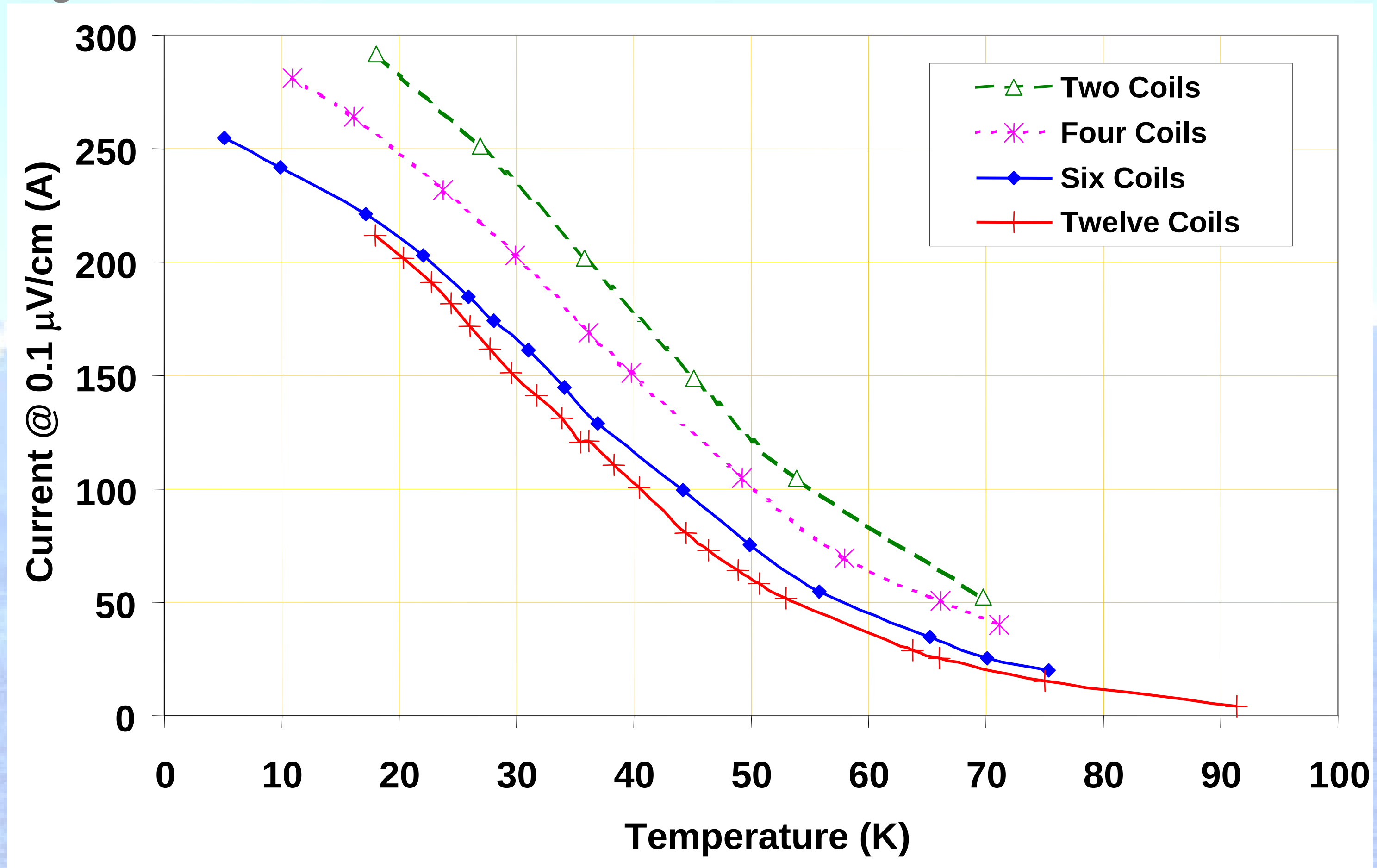


Coil performance generally tracked the conductor performance very well.

Note: A uniformity in performance of a large number of HTS coils made with commercially available superconductor (ASC).

It shows that the HTS technology is now maturing !

RIA HTS Mirror Model Test Results (operation over a large temperature range)



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, six and twelve coils in the magnetic mirror model. In each case voltage first appears on the coil that is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for two coils.

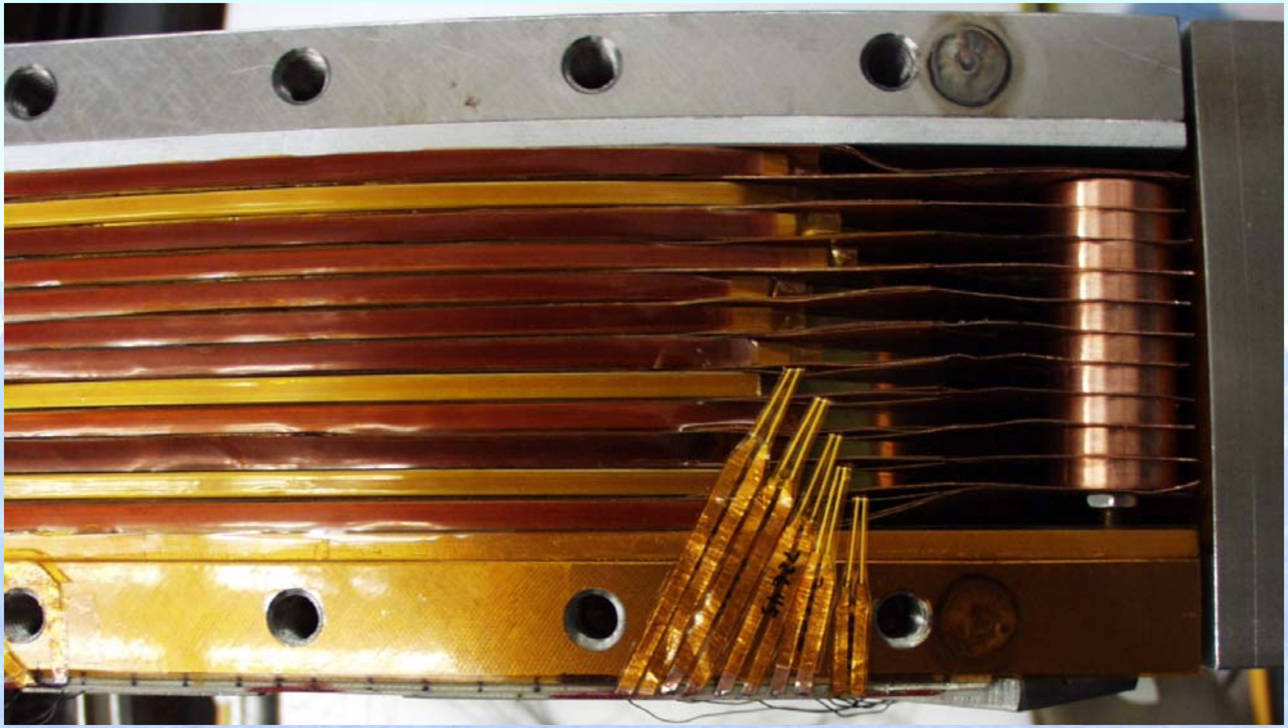
Advantages of using HTS in RIA/FRIB

- Up to 400 kW of beam power hits the target producing a variety of isotopes. ~15 kW of the above is deposited in the first quadrupole itself.
- Removing these large heat loads at ~30 K (as in high temperature superconductors) instead of ~4K (as in low temperature superconductors) is over an order of magnitude more efficient.
- HTS can tolerate a large local increase in temperature in superconducting coils caused by the non-uniform energy deposition.
- Moreover, in HTS magnets, the temperature need not be controlled precisely. It can be relaxed by over an order of magnitude as compared to that for the present low temperature superconducting magnets (few kelvin rather than a few tenth of a kelvin). This simplifies the design and reduces cost of the cryogenic system.
- Therefore, HTS would facilitate a magnet system for fragment separator that will be robust and economical to operate.

Energy Deposition and Cryogenic Experiments

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Stainless steel tape heaters for energy deposition experiments

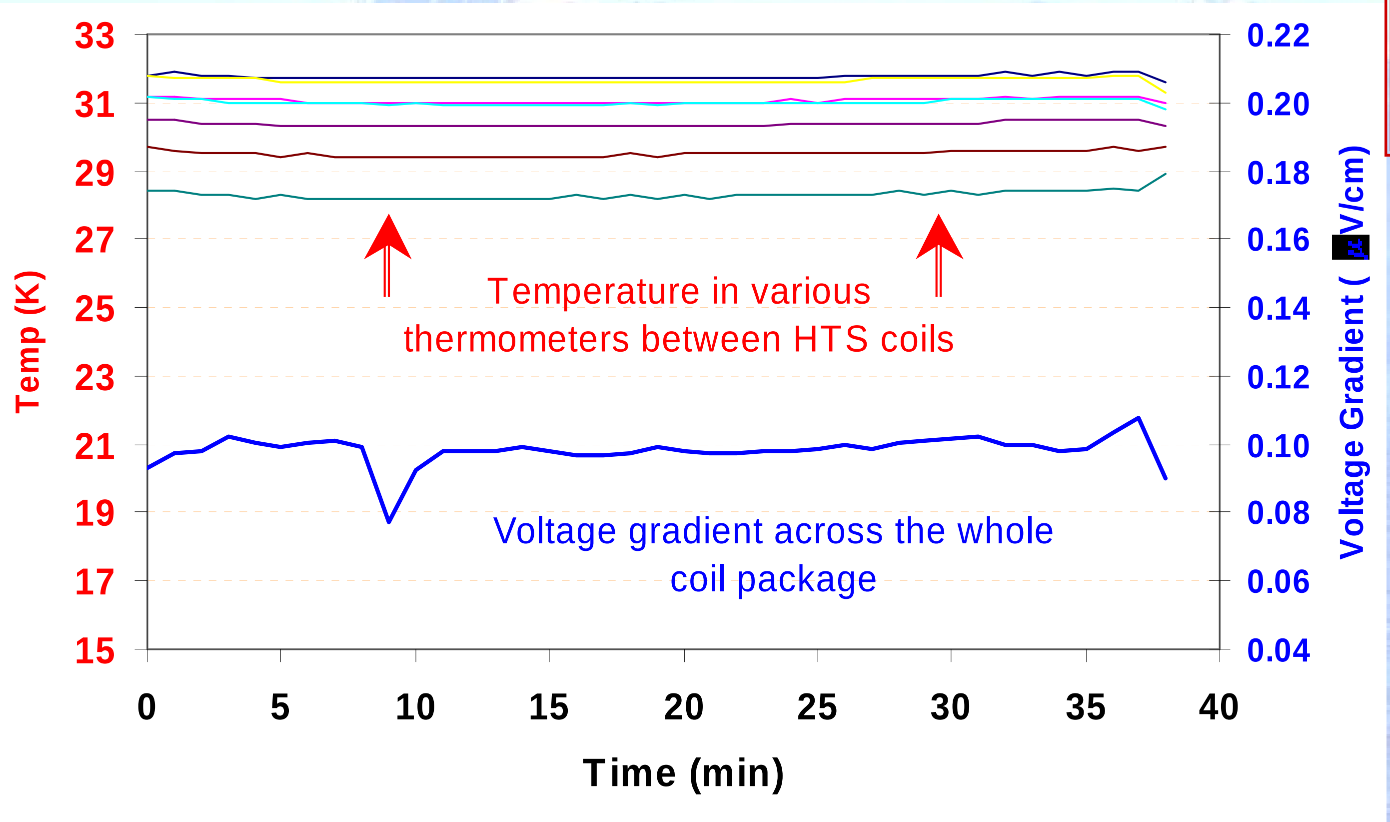


Copper sheets between HTS coils with copper rods and copper washers for conduction cooling

- In conduction cooling mode, helium flows through top and bottom plates only.
- In direct cooling mode, helium goes in all places between the top and bottom plates and comes in direct contact with coils.

Large Energy Deposition Experiment

Goal was to demonstrate that the magnet can operate in a stable fashion at the expected heat loads ($5 mW/cm^3$ or $5 kW/m^3$ or 25 W on 12 short HTS coils) at the design temperature (~30 K) with some margin on current (@140 A, design current is 125 A).



Voltage spikes are related to the noise

Stable operation for ~40 minutes

- **We use 0.1 μV/cm as the definition of I_c.**
- **Temperature differences may be partly real and partly calibration mis-match.**
- **As such HTS can tolerate such temp variations with small margin.**

FRIB/RIA with YBCO (2G)

The goal is to move to 2nd generation (2G) wire because:

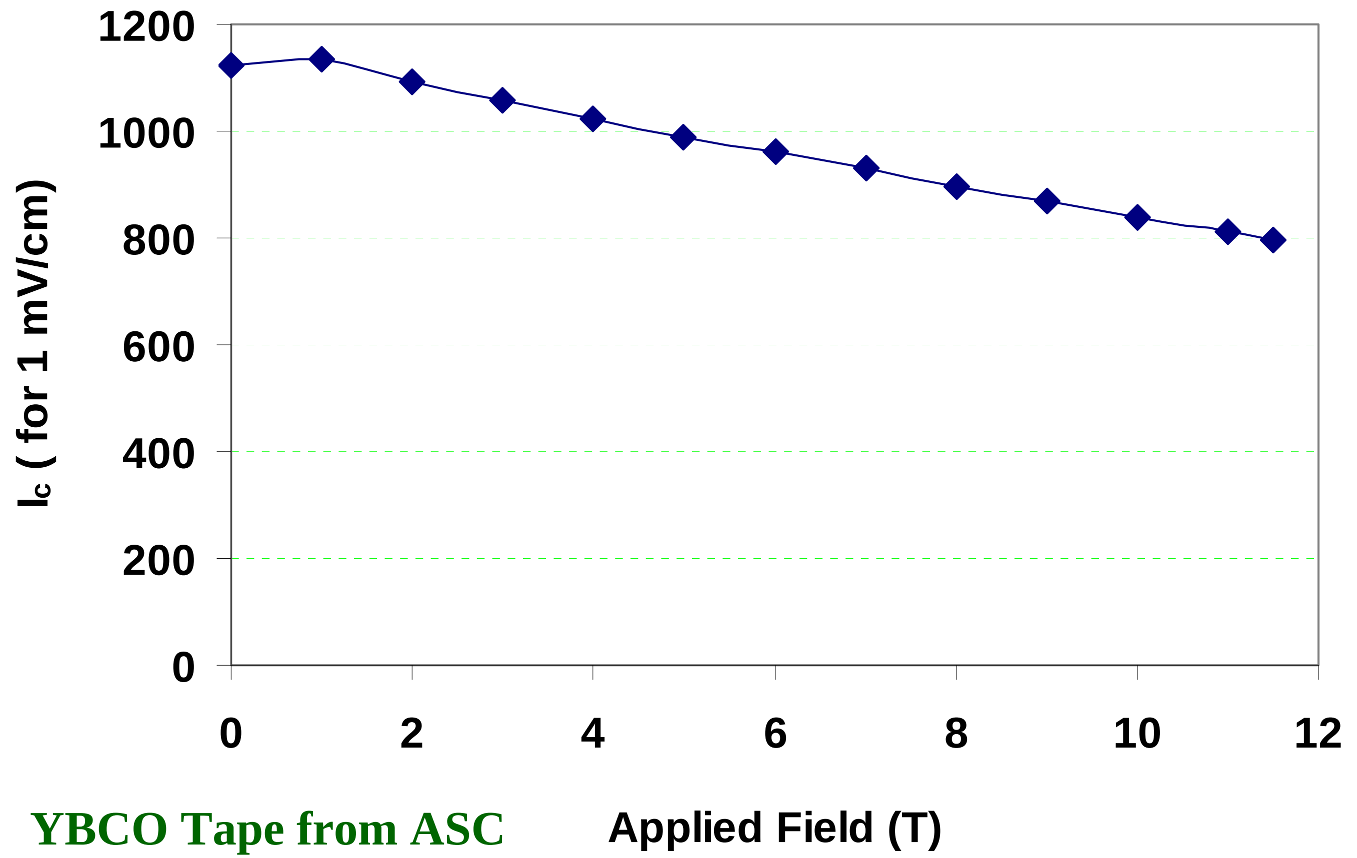
- 2G is expected to allow operation at 50 K (or above), which would provide even more saving in operation.
- 2G is expected to be less expensive.

Coil made with 2G wire

Current YBCO Program

- 3 coils each with ~100 m of 2nd generation wire (initial plan was to make two coils only but the price conductor dropped that allowed us to re-scope the program).
- 2 coils with wire from ASC and 1 from SuperPower.
- 1 coil made with ASC wire (tape) has been built and tested (over a large range of temperature).

YBCO Tape at 4K : I_c Vs. $B_{parallel}$



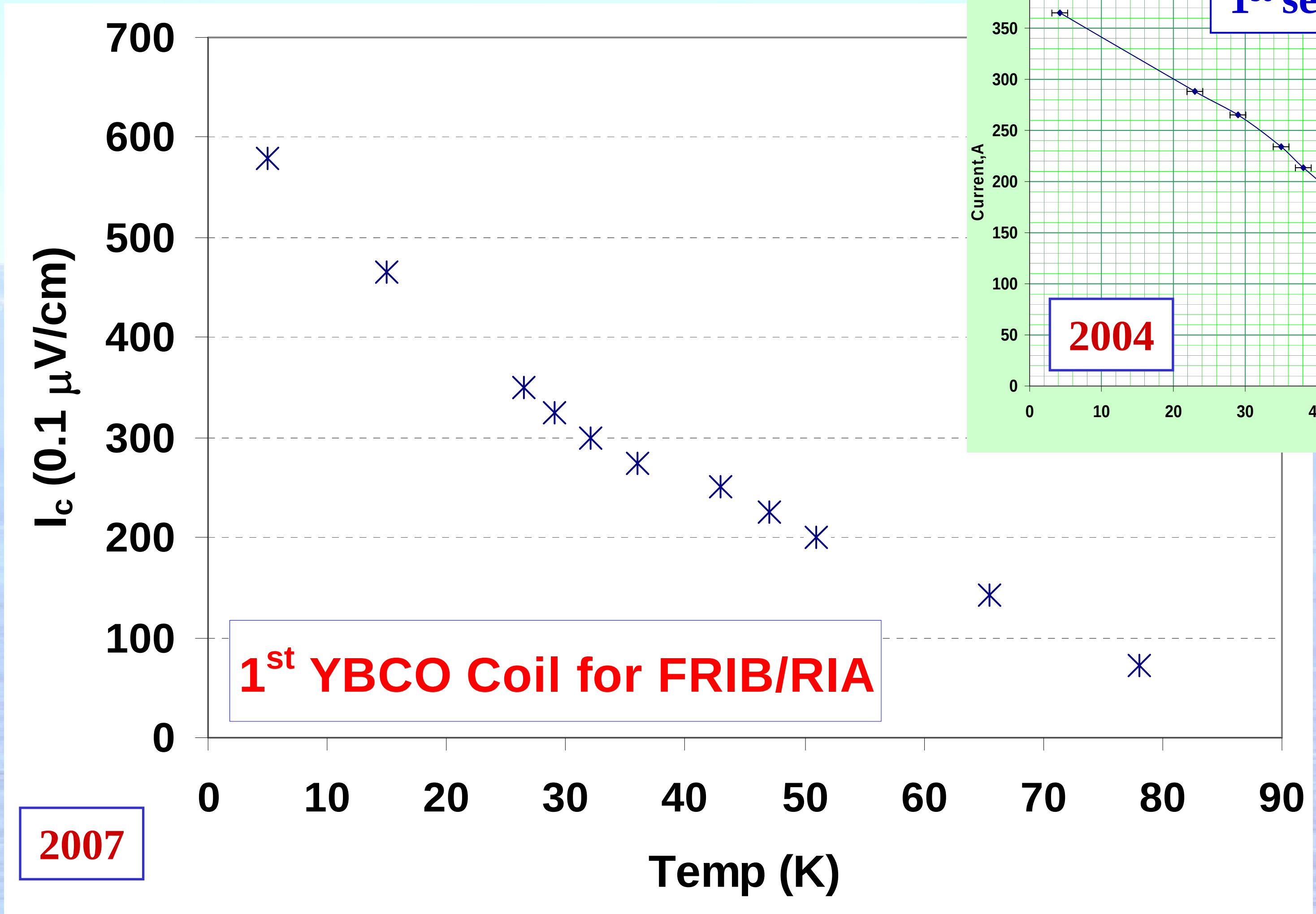
YBCO Tape from ASC

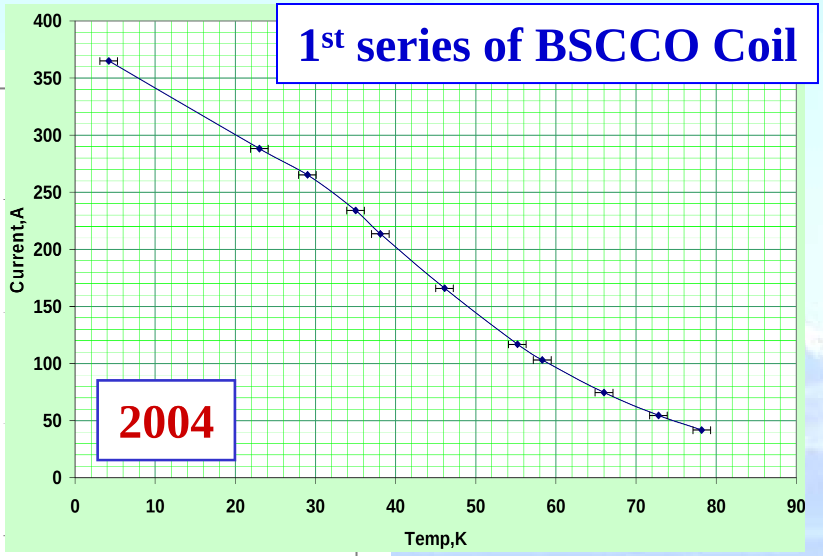
Small field dependence in field parallel direction.

Somewhat worse dependence in field perpendicular direction, however, nothing compared to that in LTS.

Measurements courtesy Ghosh and Sampson

I_c Vs. T Over a Large Range of Temperature in RIA Coils Made with YBCO and Bi2223



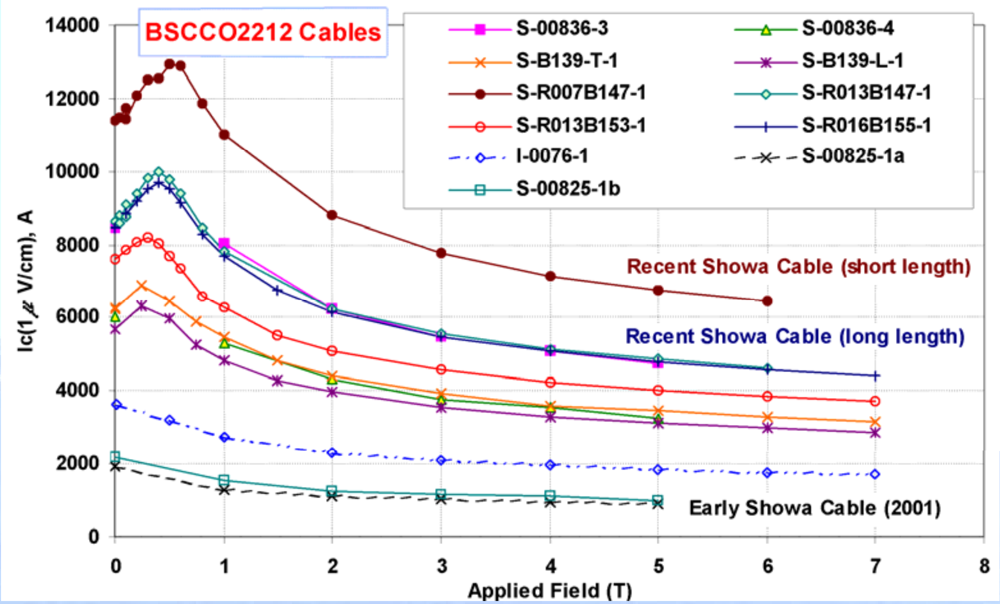


Note: YBCO is already better than BSCCO.

And there is still a significant potential for improvements.

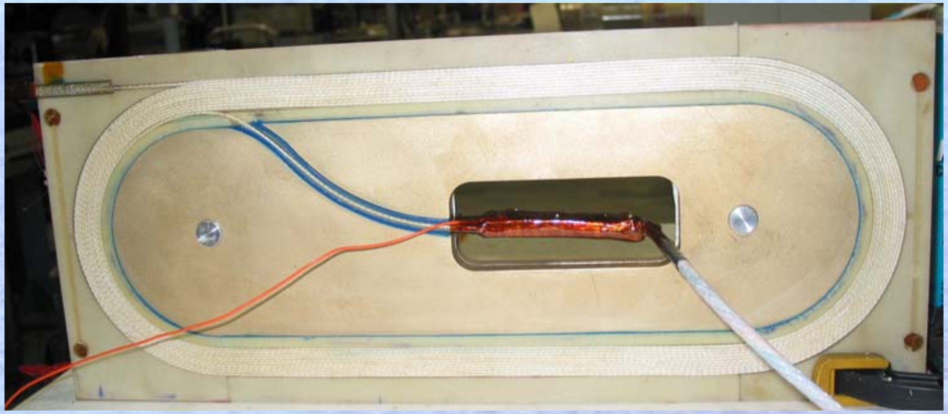
BSSCO and YBCO Tapes from ASC

HTS for High Field Magnets with Rutherford Cable

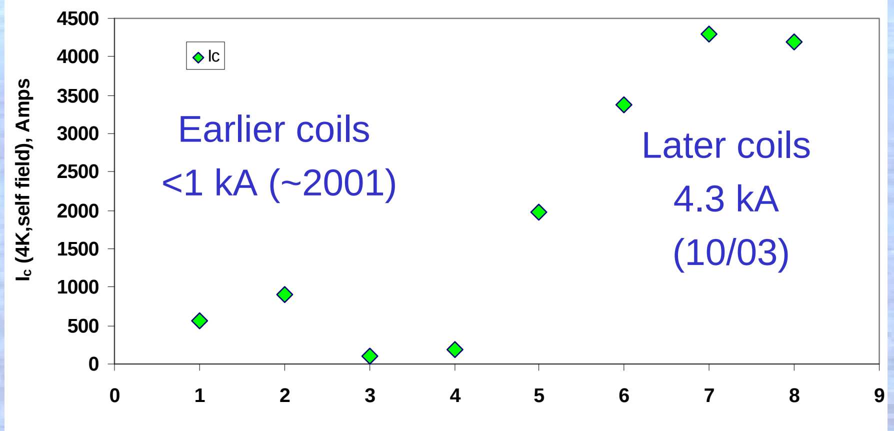


Cable made at LBL, reacted at Showa, tested at BNL

HTS cables, coils & magnets can carry a significant current.



HTS coil wound & tested in a common coil magnet at BNL



Self-field <0.05 T

Self-field ~ 1.85 T

Recent Experience and Future Outlook

- **Experience with HTS R&D Magnets**
  - **RIA/FRIB Magnets (HTS for large heat loads)**
    - **made with Bi2223 tape and now with YBCO Tape**
  - **Common Coil Dipole (HTS for high field)**
    - **made with Bi2212 Rutherford Cable**
- **Future Possibilities for Accelerator Magnets**
  - **High Field Magnets**
    - **with Bi2212 cable or YBCO *wide tape*/ or *Roebel cable***
  - **Energy Efficient Magnets**
    - **with YBCO Tape**

Prospects of HTS in Future Accelerator Magnets

HTS now and in near future:

- **Progress in US Bi2212 wire in last few years, and expected future support from DOE should make a significant difference**
- **Recent progress in YBCO is relevant to future prospects**
  - ➢ Prices continue to fall and are likely to be well below what's expected from BSCCO
  - ➢ YBCO tape in many ways has superior performance to Bi2223
    - ✓ better mechanical properties
    - ✓ smaller bending radius possible with low degradation
    - ✓ expected higher engineering current density
    - ✓ Operating current of ~10 kA looks possible with wider tape (up to 40 mm rather than 4 mm) and/or with ***Roebel cable***

R&D on Roebel Cable in Europe (1)

Coupling and higher current (somewhat similar to that in Rutherford cable)

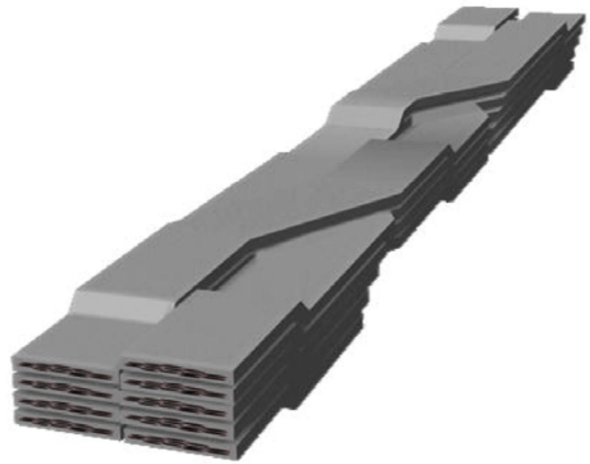
SIEMENS

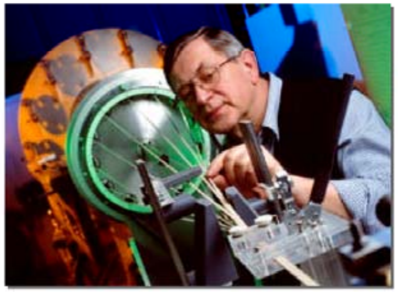
CORPORATE TECHNOLOGY

Technical HTS-Conductors & HTS-Windings
High Current Assemble

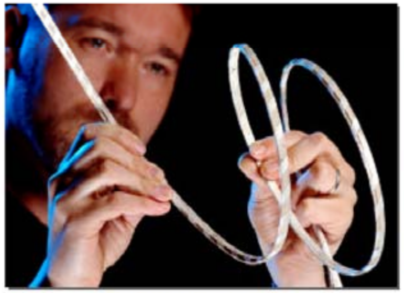
Roebel bar conductor

- modular concept for high-current conductors
- transposed strands for low ac-loss
- insulated strands - thin coated plastics
- flexibility for coil winding
- long-lengths production - semiautomatic
- developed for HTS transformers
- presently not applicable for YBCO

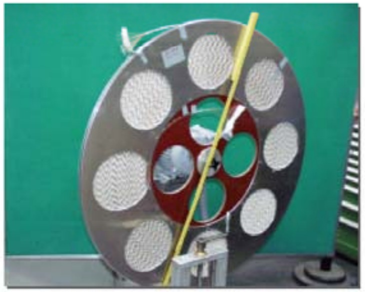




Laboratory Cabling Facility LARA



Flexible conductor



13-strand conductor, length=160m

Power & Sensor Systems
Power Components & Superconductivity

This was the case with BSCCO.

Expect similar in case of YBCO.

R&D on Roebel Cable in Europe (2)

EHTS
European High Temperature Superconductors
A member of Bruker Biospin

Home | About us | Products | Applications | News/Career/Publications | Contact | Links

Products

- HTS-Tapes
- Current Leads
- Coils
- Roebel Conductors

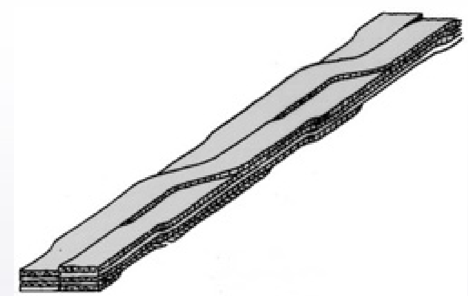
Downloads

- BSCCO Data Sheet
- BSCCO AgAu Data Sheet
- YBCO Data Sheet
- EHTS Company Profile

Search

Roebel Conductors

are designed for high total currents. The transposition adds the advantage of equivalence of elementary tapes. This is of benefit for magnets as well as for AC applications (low loss). The Roebel conductors may be made by an odd number of transposed tapes, bare or insulated, the actual transposition scheme is usually designed to fit the requirements of the application. This cable has the advantage of high mechanical flexibility and high current at the same time.



Helical winding with Roebel cable

R&D on Roebel Cable in Europe (3)

Roebel cable with YBCO

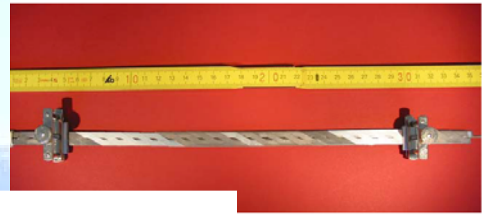
(SuperPower + Forschungszentrum)

- Small bending radius (>11mm) possible

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Institut für Technische Physik, Superconducting materials, Wilfried Goldacker 8-200

2. Step Full 16 strand DyBCO-RACC sample (35 cm length)



pressed Indium sandwich contacts

contact length 5 - 6 mm

No interstrand connection for first test

Parallel ext. Cu stabilizer with 5 mm^2

Mixture of 2 CC batches: different Ag c

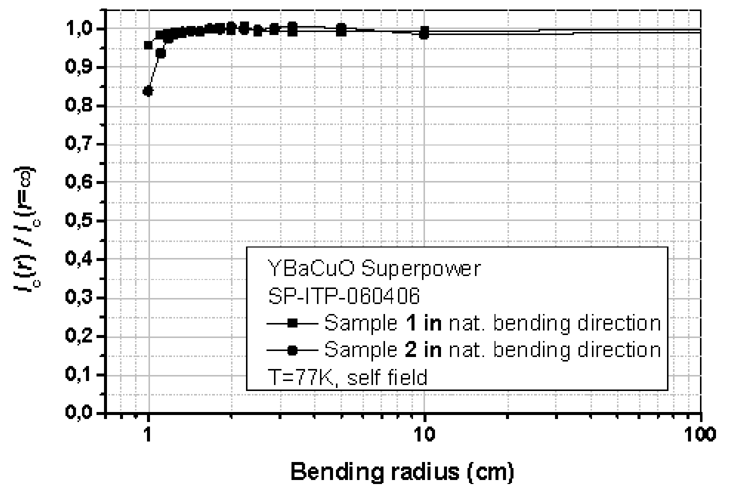


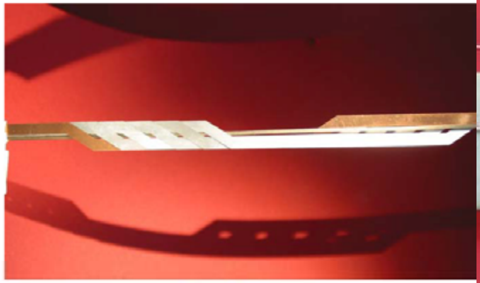
Fig. 3 Critical current of MOCVD SP CC with bending applied at 77 K

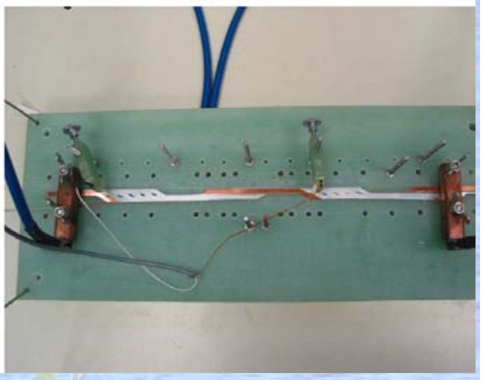
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

1. Step RACC – Cable with 5 CC – Strands + 1 Cu - strand

Results

- Measured transport current I_c slightly above 300 Amps (approx. 305 Amps.)
- Calculated I_c was 294 A
- I_c onset was detected at 300 A (current source limit)
- Slight transport current increase through stabilising Cu strand ?
- Current sharing works !
- Ag cap layer (0.4 microns) seems to work sufficiently !
- External shunt of 1 mm^2 Cu ok !





ROEBEL Cable
An Interesting Topic for SBIR, etc.

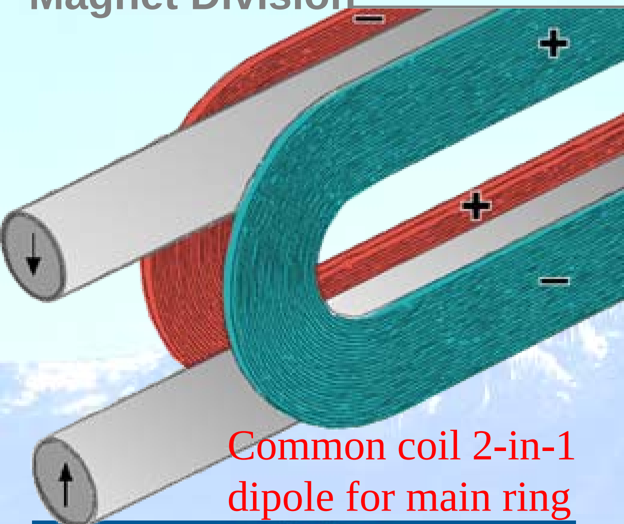
• Roebel cable may make YBCO tape much more attractive for accelerator and other type of magnets

• Roebel cable allows higher operating current and coupling between a number of wires (somewhat analogous to Rutherford cable with round wires)

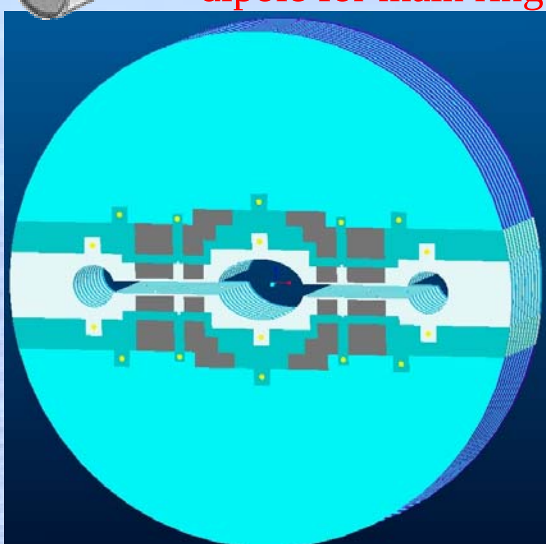
• Roeble cable seems to be more attractive in racetrack coil designs. One can reference this cable R&D with various such designs (listed in next slide)

• Evaluate flexibility of Roebel cable with bending (in reference to cosine theta designs)

High Current, High Field, HTS Magnet Designs with Bi2212 Rutherford Cable and YBCO Roebel Cable

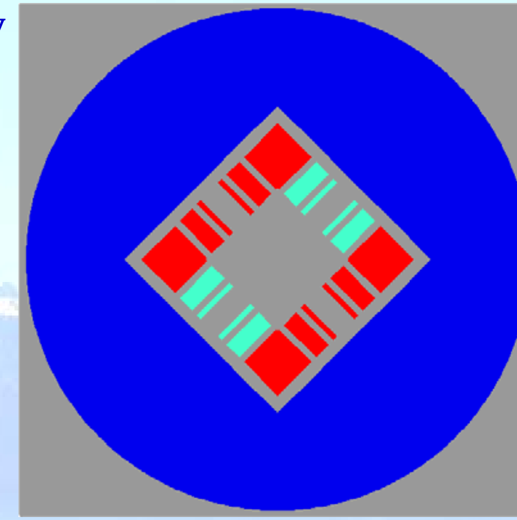


Common coil 2-in-1 dipole for main ring

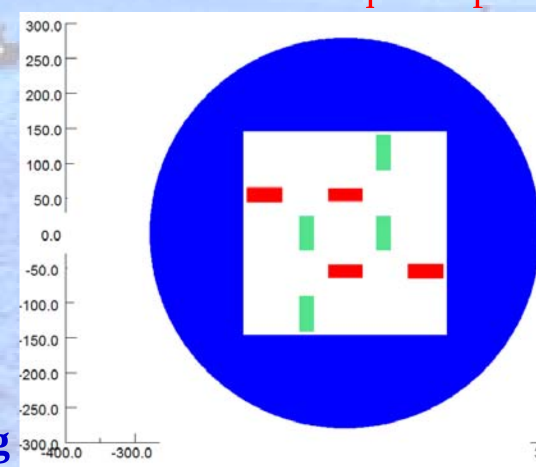


Open midplane dipole for muon collider or LHC IR upgrade

- **HTS is particularly attractive in very high field magnets – may be as an hybrid option in 20 T – 30 T designs.**
- **For React & Wind technology, racetrack coil magnet designs are more attractive.**
- **Possible designs :**
  - **Common coil 2-in-1 dipole**
  - **Single aperture dipole with lifted ends to clear bore tube**
  - **Open midplane dipole**
  - **Race-track coil quad**
  - **Racetrack coil modular design**
- **For high luminosity IR, HTS is particularly attractive to face large energy deposition (RIA experience).**
- **For a few critical IR magnets, driving force should be performance and not the cost of the conductor.**

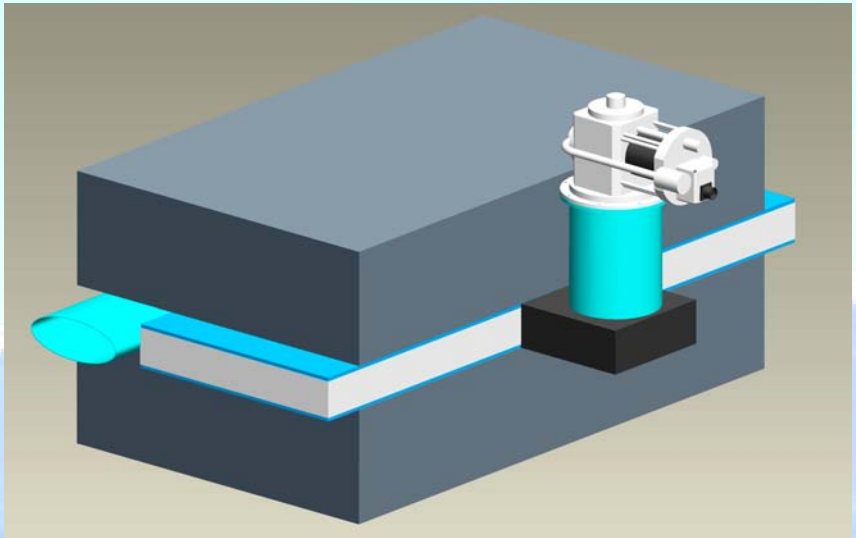


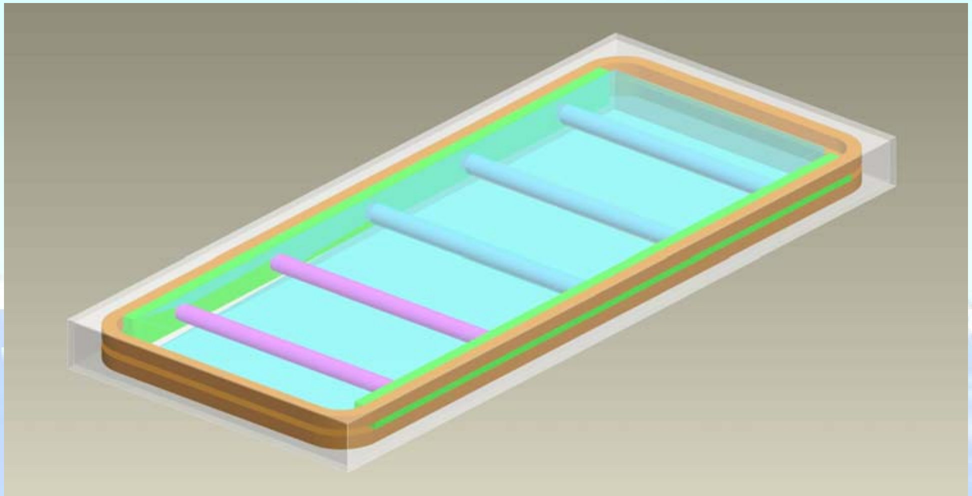
Racetrack coil quadrupole

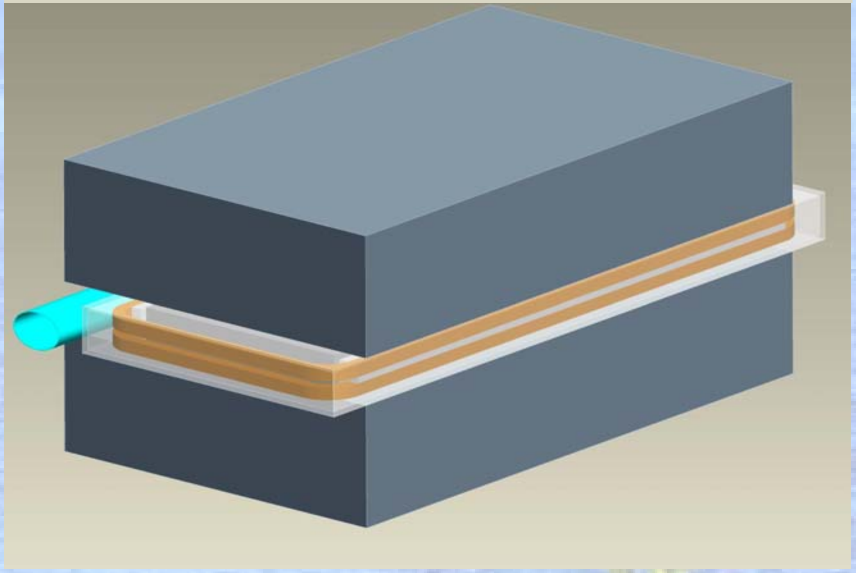


Modular design for high gradient quadrupole

Medium field (1.5 T-3 T) Energy Efficient HTS Magnets







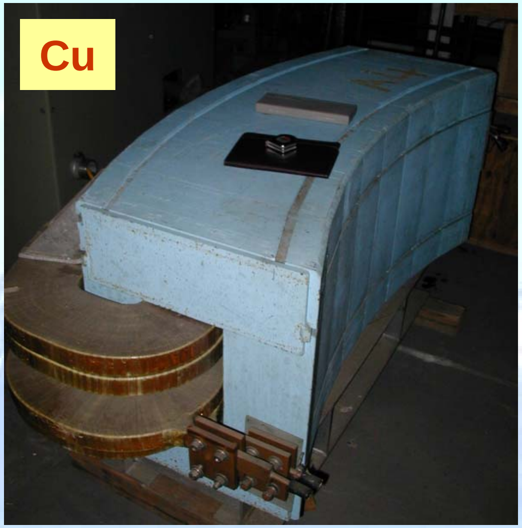
- Consider the cost of ownership – capital cost for purchasing magnets and operating cost in light of increasing energy costs.
- With the cost of second generation conductor dropping, we have a good shot at this option if we can develop designs and technology that allows a lower cost magnet construction.

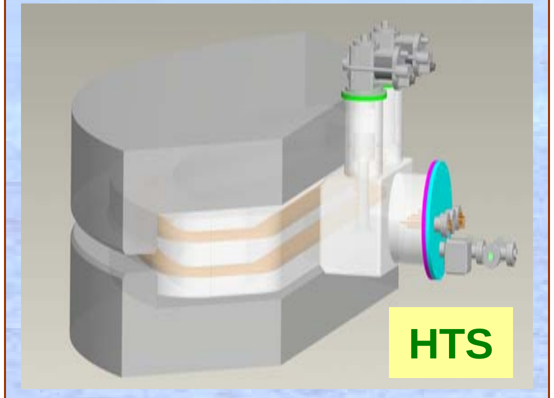
A Case Study for Cost Comparison of Copper and HTS Dipole for Neutrino Facility

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Design Parameters:
- B = 1.55 T
- L = 3.73 m
- Pole width = 153 mm
- Pole gap = 76 mm

Copper Magnets:
- Better known costs (estimated : ~150k$ each for this magnet)
- Cost of individual components like coil, yoke, etc., is well understood
- High operating costs (estimated ~3 MW total)
- Low thermal conductivity water cooling plan
- Higher current (a few kA) power supply (higher cost)
- Maintenance issues (cost, downtime): water leak etc.





Desired cost of support structure and cryostat in this HTS magnet: < 20 K$

HTS Magnets:
- Develop designs to reduce cost (goal : ~150k$/magnet for equivalent integral field)
- Cost of HTS as per present price: ~35 k$ (only ~1/4, lower in future)
- Need to include cost of other components like iron (low and well understood), support structure, cryostat (major driver unless better designs developed)
- Lower operating costs (wall power of cryo-cooler?)
- Cost of cryo-coolers (compare with infrastructure cost of Low Thermal Conductivity Power Plant)
- Lower current (a few hundred Amp) power supply (cheaper)
- Maintenance issues (cost, downtime): cryo-coolers

Summary and Outlook

• Successful construction and test of a number of coils and various configurations should encourage use of HTS in accelerator magnets.

• RIA R&D has demonstrated that HTS magnets can be designed, built and operated in presence of a large heat load environment.

• At present, HTS is particularly attractive for special applications (such as high field magnets, magnets that must deal with large energy deposition, etc.). These applications are driven by magnet performance and not the cost of the conductor.

• A larger scale application of HTS may lie in the magnets for beam-lines, low energy machines (such as injectors, neutrino factories and synchrotron radiation sources to save operating costs – electricity) and magnets for a number of medical applications.

• Second generation conductor should make HTS magnets much more attractive (higher J_e, lower cost and higher temperature operation).