Application of HTS in Accelerator Magnets

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Brookhaven Accelerator Forum (BAF) Meeting

HTS in Accelerator Magnets Where are we now?

- **It has been 22 years since the discovery of HTS. Nobel prize came just a year after that and over 100,000 papers have been published since then.**

  So why don't we have an HTS magnet in any accelerator yet?

  - Well, building a real engineering device is usually more complex. The conductor must be available in long lengths and we must learn how to use it reliably in a magnet.
  - It took ~50 years after the discovery of the low temperature superconductor (LTS), before we had a superconducting magnet in an accelerator.

- **One needs to develop appropriate designs, build & successfully demonstrate several R&D magnets before it could be considered for a real application**
  - A variety of R&D HTS magnets with a wide range of application will be presented.
  - No other national lab has been so involved in HTS magnet R&D as BNL has been.

➢ **You will see that slowly, but surely, we are making progress !!!**

HTS in Accelerator Magnets Possible Applications

High Field, Low Temperature (~4 K) Applications

Examples: Magnets for muon colliders and upgrade of hadron colliders (e.g. LHC)

• At very high fields (~20+ T), no superconductor carries as much current as HTS can.

Low to Medium Field, Higher Temperature Applications

Examples: High Temperature Applications for FRIB, Beam Lines and unique situations

• It is much more efficient to remove large heat loads at 30-65 K in HTS magnets rather than in conventional superconducting (LTS) magnets at 4-10 K.

• With energy cost rising and HTS improving, HTS magnets operating at 30-65 K may be able to compete with 1-2 T water-cooled room temperature magnets in future.

• Now one can seriously consider HTS magnets with *nitrogen based cooling system* or cryo-coolers operating at higher temperature where they have much higher capacity.

One can relax temperature control requirements - a few degrees in HTS rather than a few tenth in LTS. This means a simpler, cheaper and more robust cryogenic system.

HTS Magnet R&D at BNL

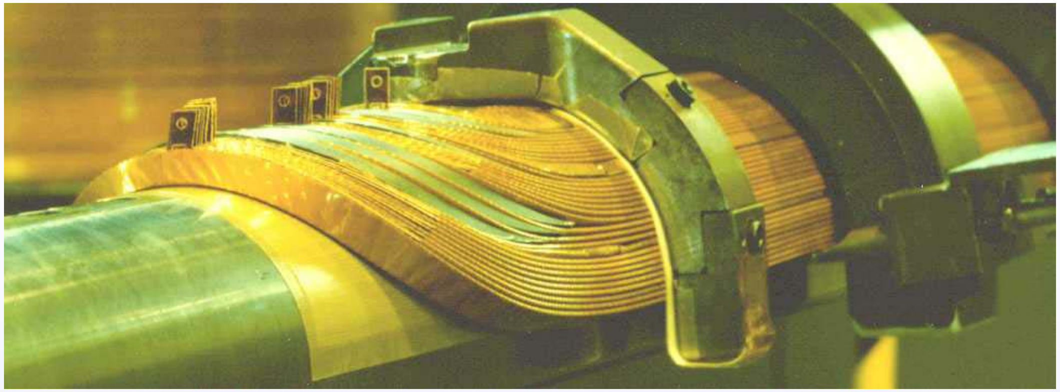
BNL has carried out a wide range of HTS magnet R&D program with a variety of High Temperature Superconductors (Bi2212, Bi223 and YBCO)

- **R&D magnets *built and tested* or *funded for construction*:**
  - Common coil 2-in-1 magnet (high field)
  - High radiation quadrupole for FRIB/RIA (medium field)
  - Solenoid for ERL (low field)
  - Solenoid for LDRD (low field)
  - 10 T and 23 T HTS solenoid for muon collider (high field)
- **Magnet proposals and magnet design studies:**
  - HTS dipole for Super Neutrino beam line (medium field)
  - HTS dipole for NSLS2 (low field)
  - Open midplane dipole for muon collider (high field)
  - Many other HTS magnet designs, e.g., ILC, LARP, dEDM, etc.

Magnet Designs for HTS

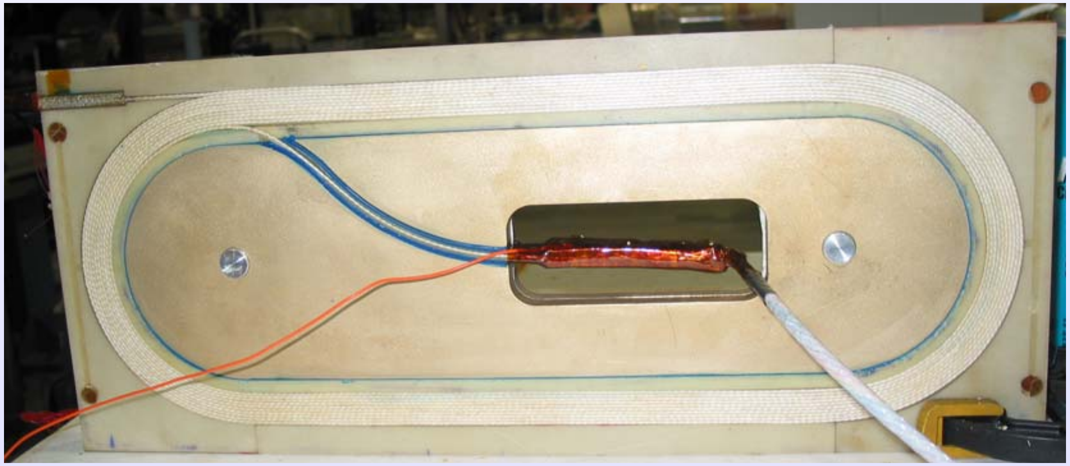
HTS are brittle.

Conventional cosine θ design with complex end geometry is not best suited for HTS.



RHIC dipole with complex 3-d geometry in the ends

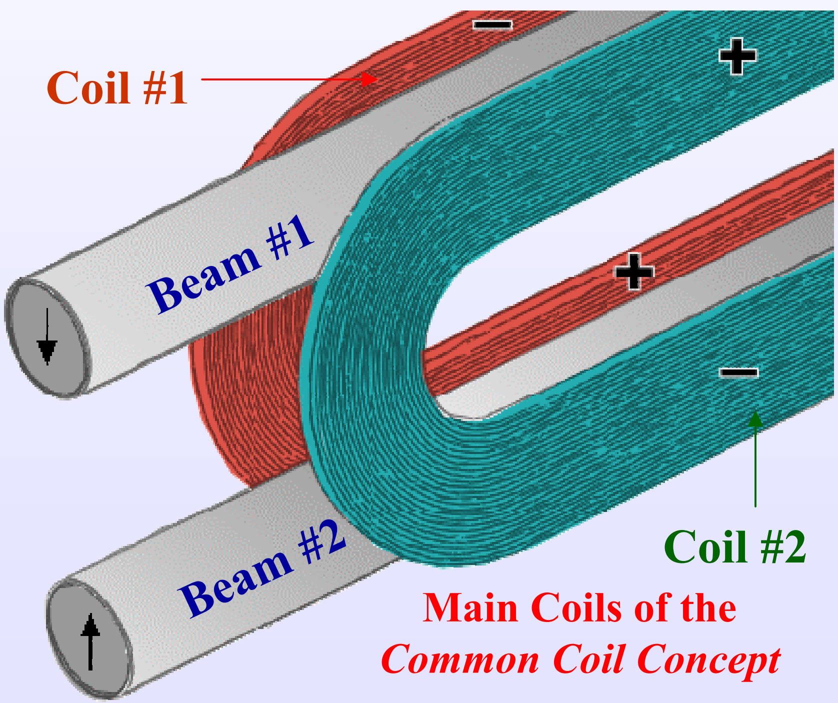
We have developed alternate "Conductor friendly" designs with racetrack coils. These designs are more suitable for high field magnets with brittle conductors (such as HTS).



Racetrack HTS coil for common coil design

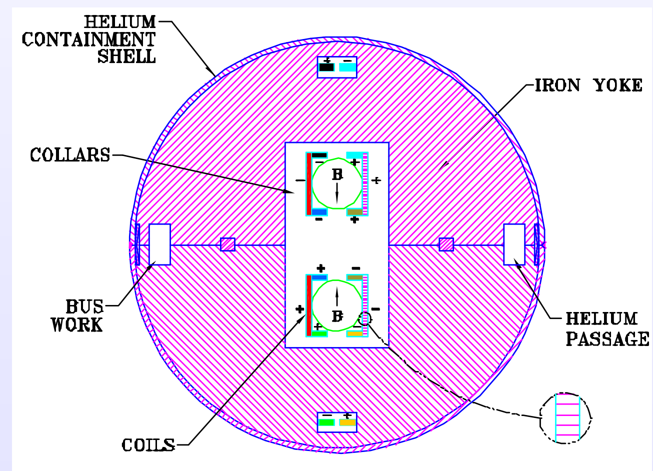
High Field 2-in-1 Common Coil Dipole Design for Colliders

- A conductor friendly design with simple racetrack Coils. No complex 3-d ends.
- Large bend radius - determined by the separation between two beams rather than the aperture itself.
- The design is suitable for coils made with brittle conductors (such as HTS).



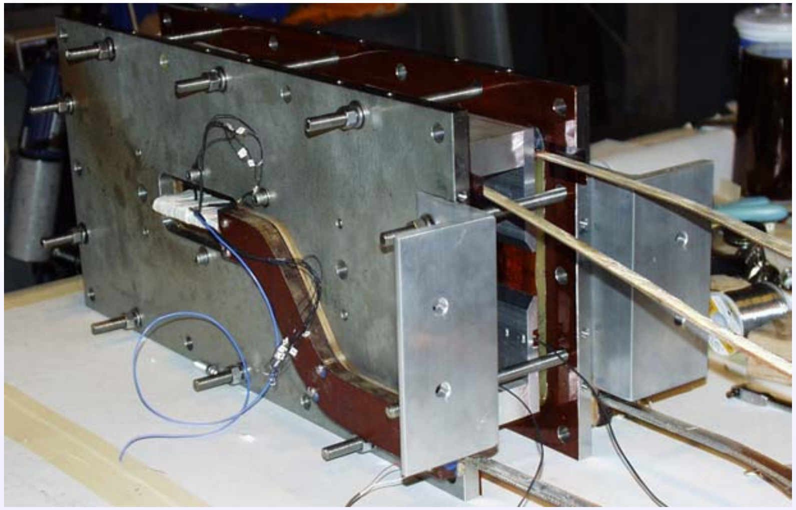
Main Coils of the *Common Coil Concept*

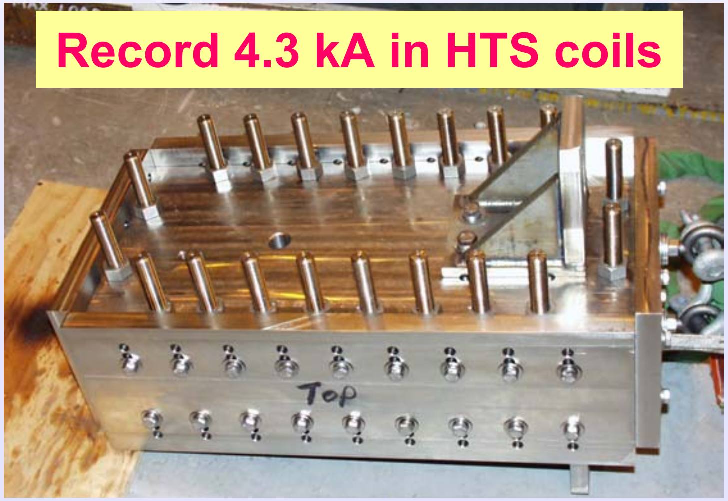
A complete cross-section of a common coil dipole



Magnets based on this design have been built at LBL and Fermilab also.

BNL Common Structures





Record 10.4 T in R&W Nb_3Sn Magnet

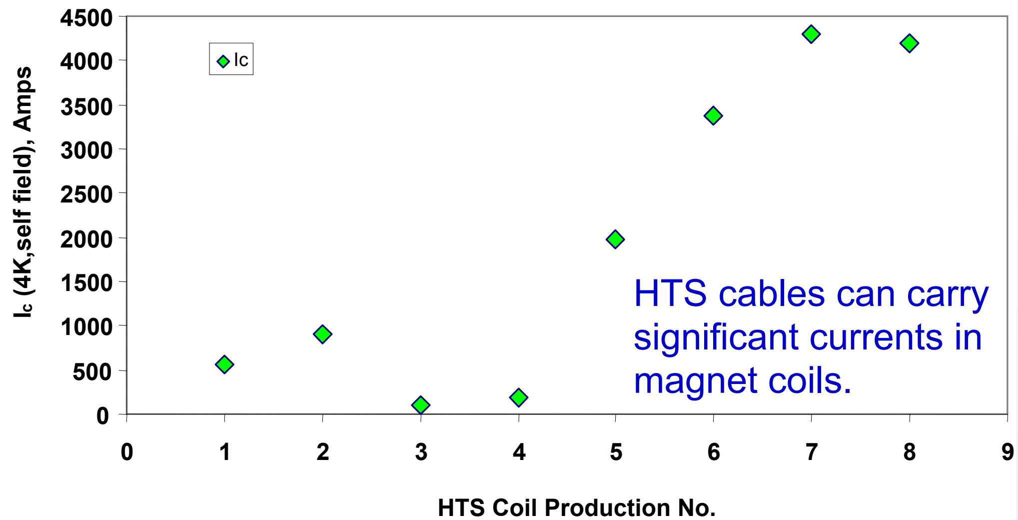
HTS Common Coil Dipole with Bi2212 Rutherford Cable

Coils and Magnets built at BNL with Rutherford Bi2212 Cable

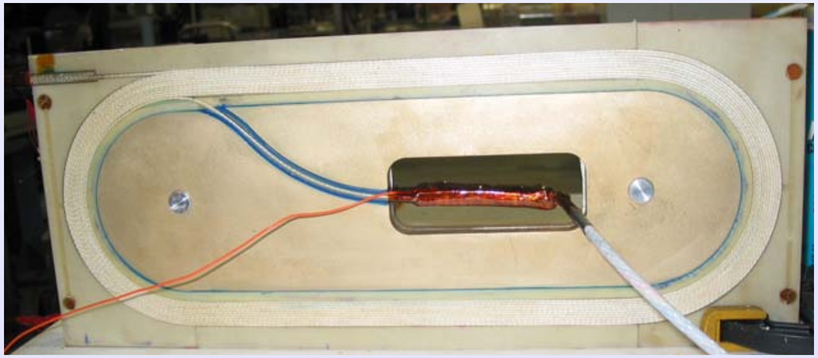
Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands	Common coil configuration	900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	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

Earlier coils
<1 kA (~2001)

Later coils
4.3 kA (2003)



Early demonstration that HTS coils with high current Rutrherford cable can be built and they can be used in a design that is suitable for coliider dipole.



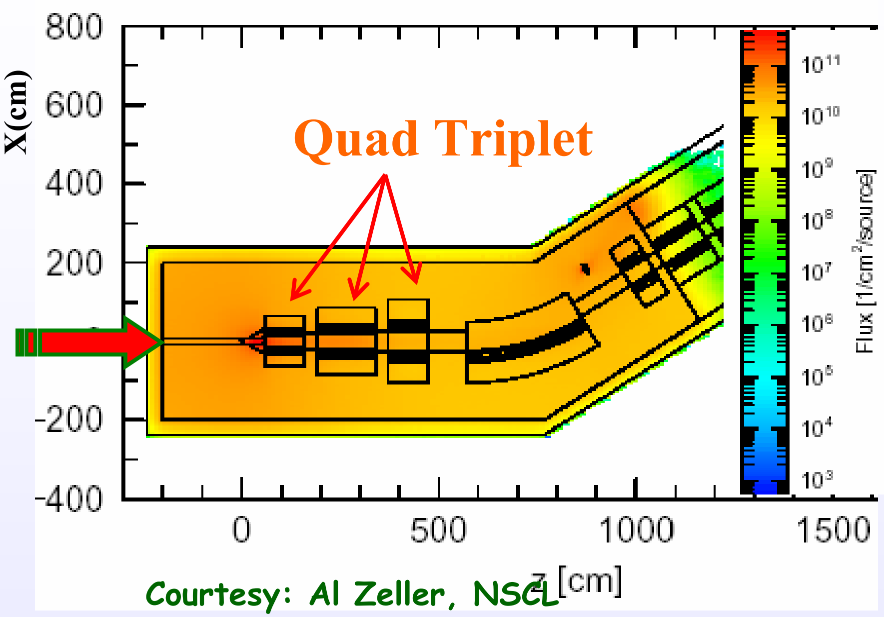
Racetrack HTS coil with Bi2212

RIA/FRIB HTS Magnet Program

- RIA R&D program has been the major source of HTS magnet R&D.
- It was set out to solve a major technical issue in RIA.
- A step-by-step R&D program was developed with key tests along the way.
- It proved that a number of HTS coils can be successfully built consistently.
- A number of magnet structures were built and tested.
- A comprehensive program included radiation damage and energy deposition studies.
- In the end we developed a solution that is not only technical superior but also turned out to be cheaper than the alternate.

HTS Quadrupoles for RIA/FRIB

400 kW beam from LINAC



- To create intense beams of rare isotopes, up to 400 kW of beam hits the target before the fragment separator.
- Quadrupole triplet is exposed to very high level of radiation and heat loads (~15 kW in the first quadrupole itself).
- HTS magnets could remove this more efficiently at 30-50 K than LTS at ~4 K.

These quads were identified as one of the most critical components of the machine.

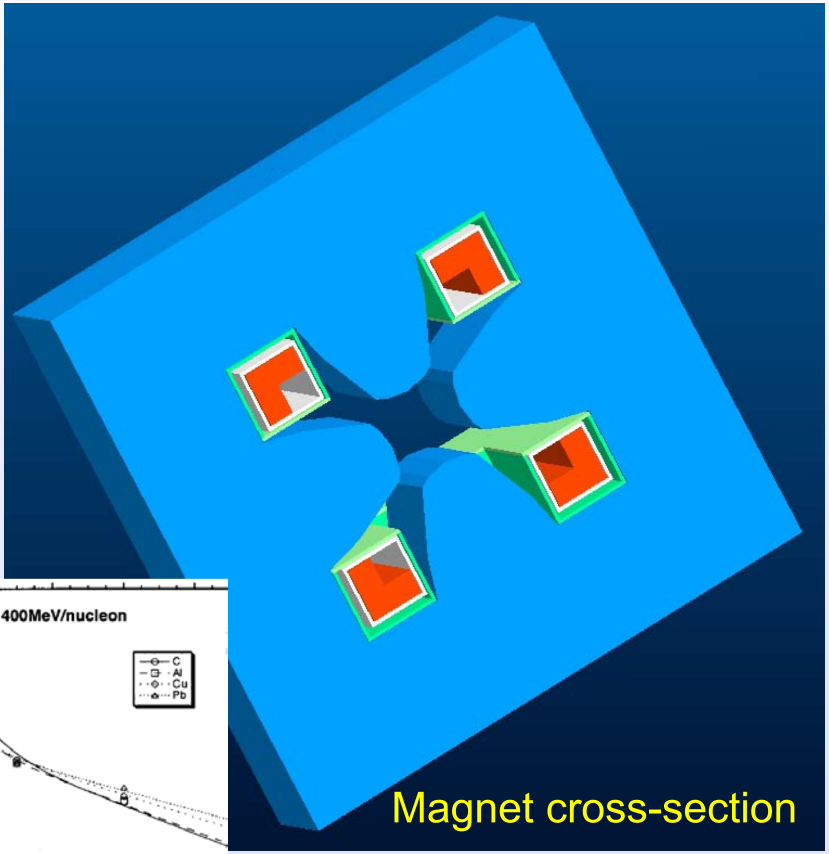
- Can these demanding requirements be met ?
- Is commercially available HTS suitable and ready for magnets ?
- Can HTS magnets be built at a cost that is affordable ?

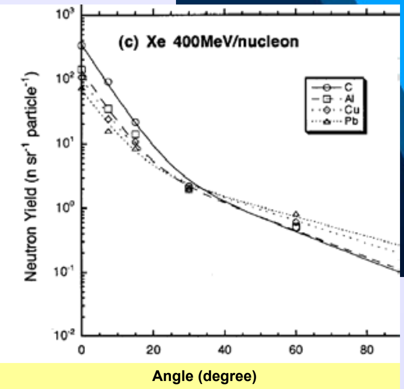
Basic Design of RIA HTS Quadrupole

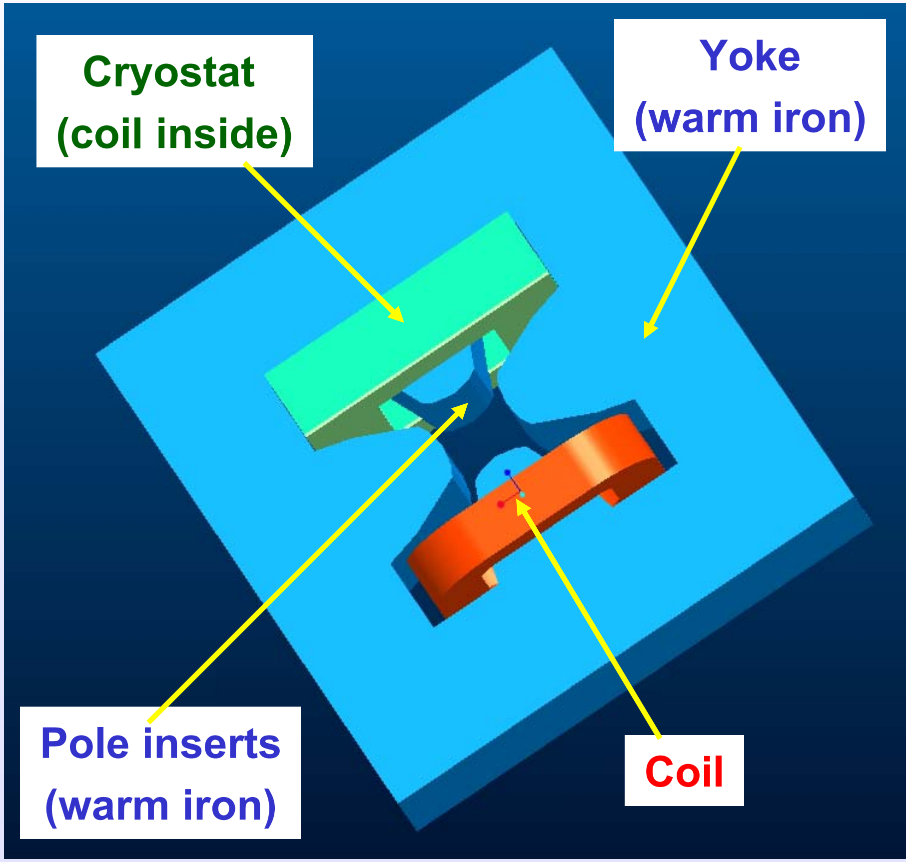
A simple warm iron super-ferric quad design with two racetrack HTS coils

Note that only a small fraction of the mass is cold (see green portion), specially in ends.

Moreover coils are moved to a larger angle where the radiation dose are low.





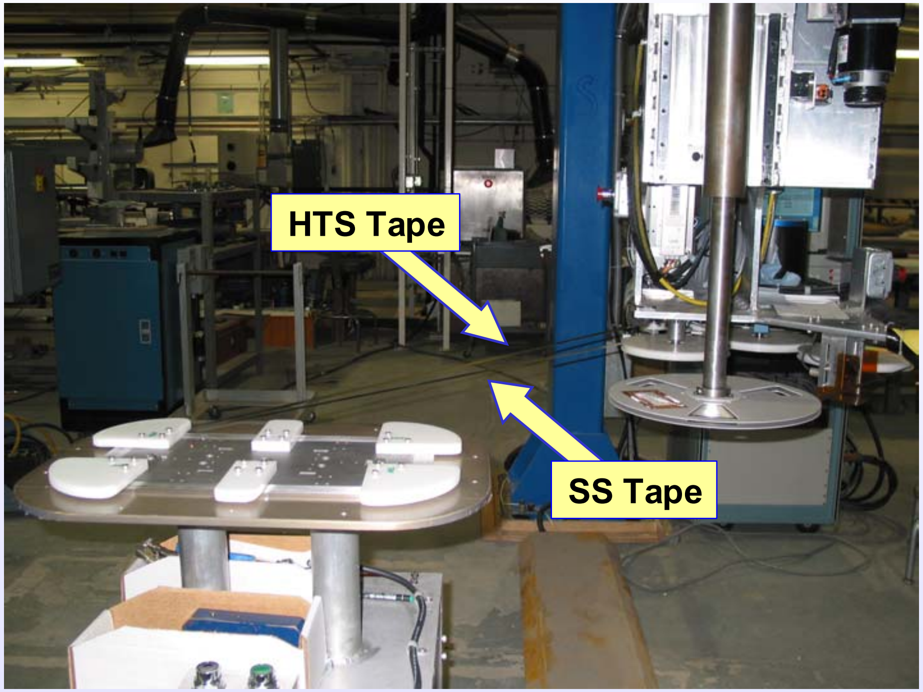


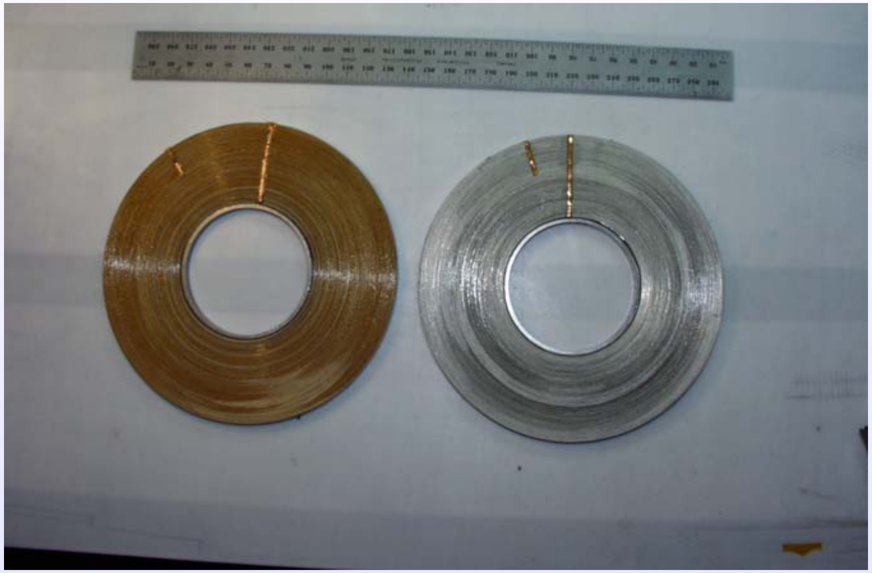
Coils inside the cryostat at the end of the magnet

Stainless Steel Insulation in HTS Coils

Radiation damage to insulation was a major issue for magnets in high radiation area.

Stainless steel tape serves as an insulator which is highly radiation resistant.





Stainless steel tape can be used to provide additional strength, when needed.

HTS Coils for RIA/FRIB Model Magnet

- RIA quad is made with 24 coils, each using ~200 meter of HTS.
- This gives a good opportunity to examine the reproducibility in coil performance.

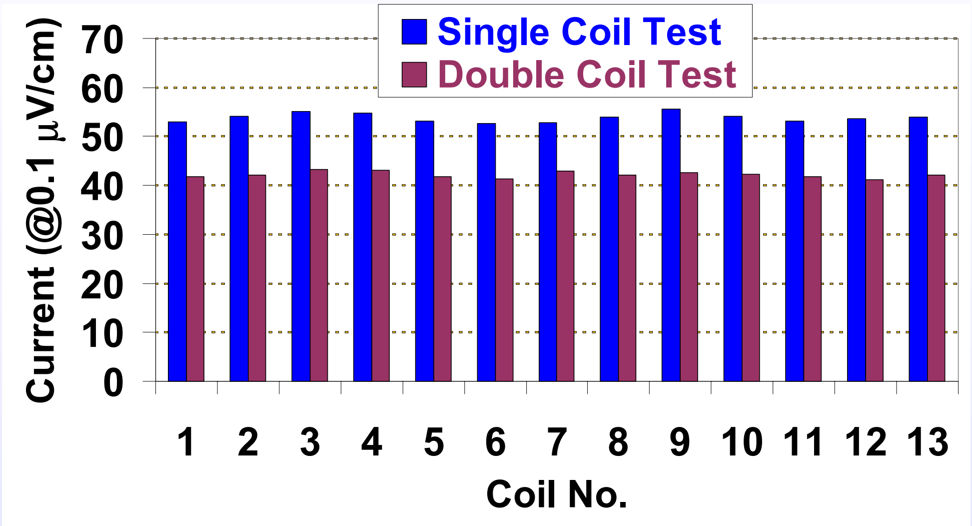
Over 5 km of HTS tape has been purchased for RIA/FRIB

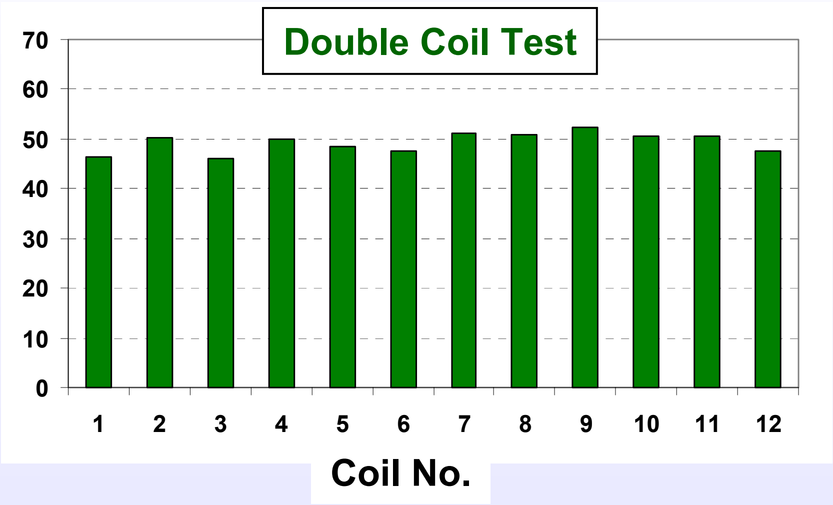
Courtesy/Contributions
Jochen

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)





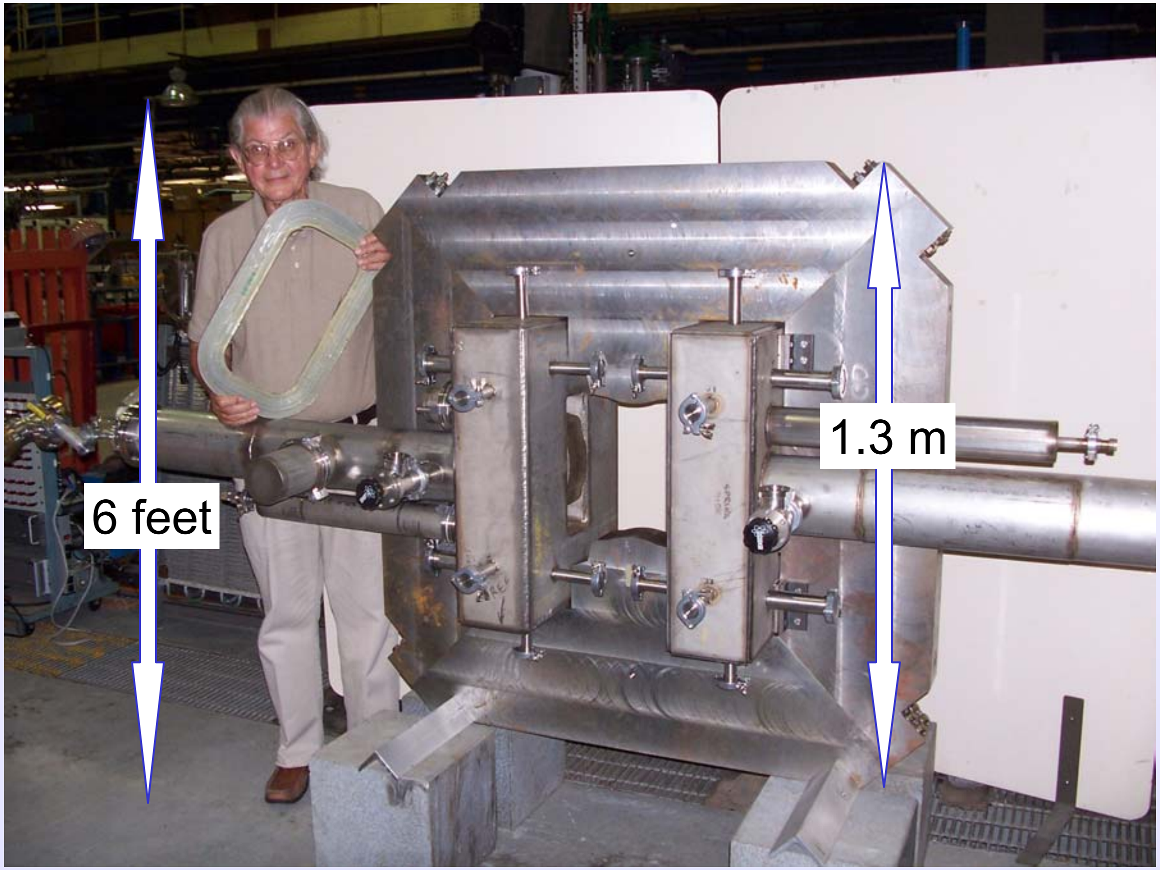
Coil performance generally tracked the conductor performance very well.

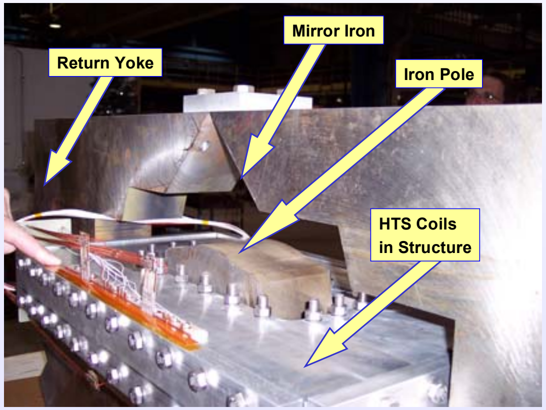
Note: A uniformity in performance of a large number of HTS coils.
It shows that the HTS coil technology is now maturing !

Various Magnet Structures of RIA Quad (a part of step by step R&D program)

Unique Features of RIA HTS Quad :

- Large Aperture, Radiation Resistant

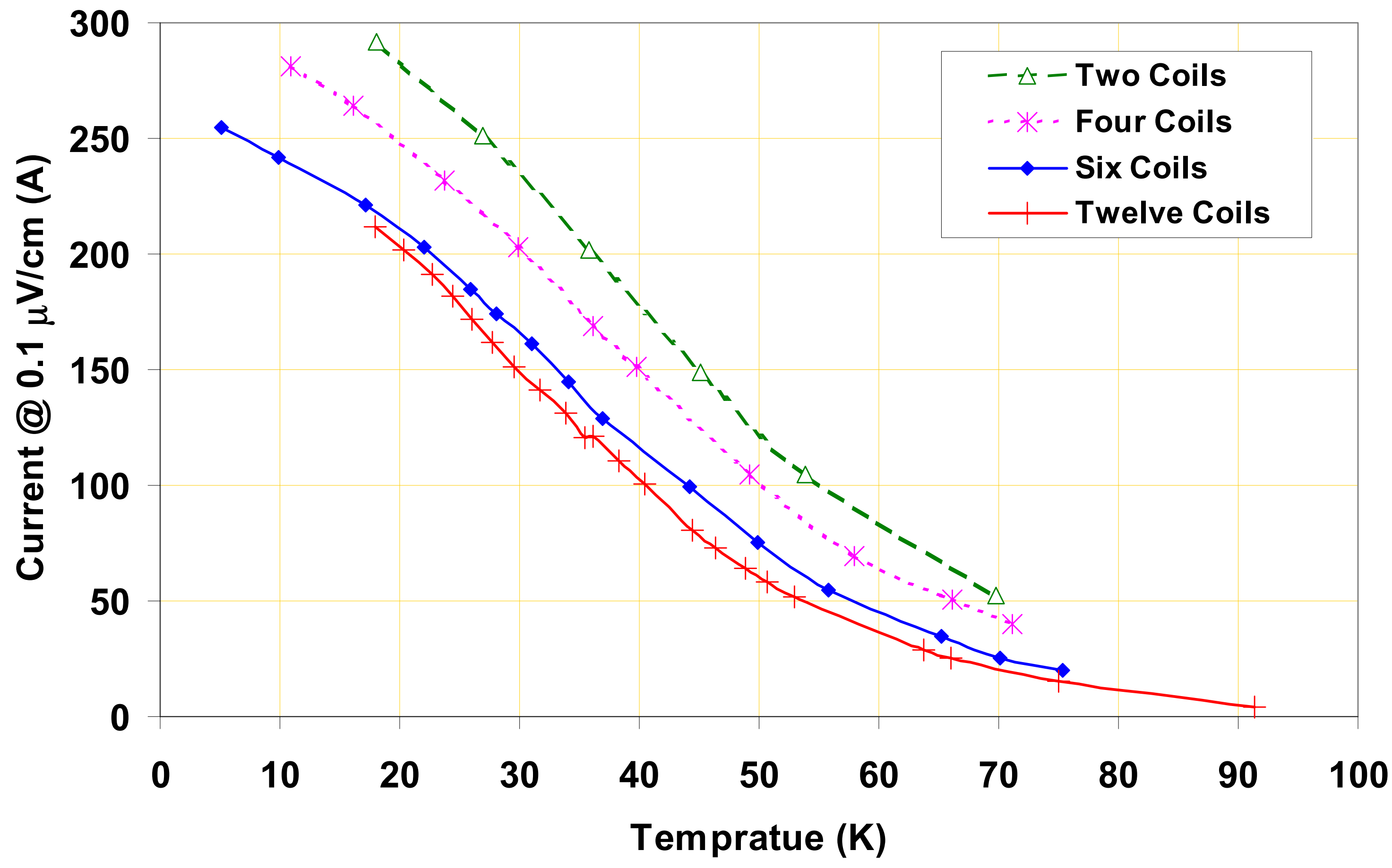




Courtesy/Contributions

Anerella, Dilgen, Ince, Jochen, Kovach, Schmalze

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

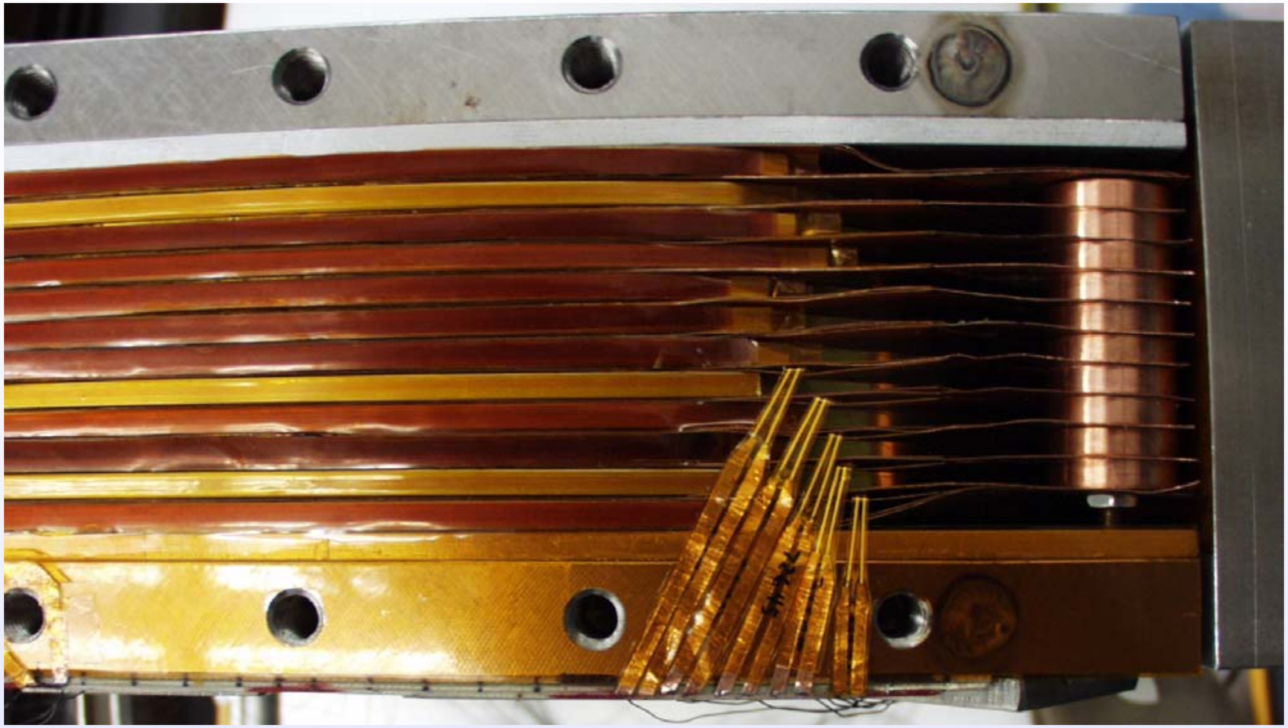


More coils create more field and hence would have lower current carrying capacity

Courtesy/Contributions Sampson

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.

Energy Deposition and Cryogenics Experiments



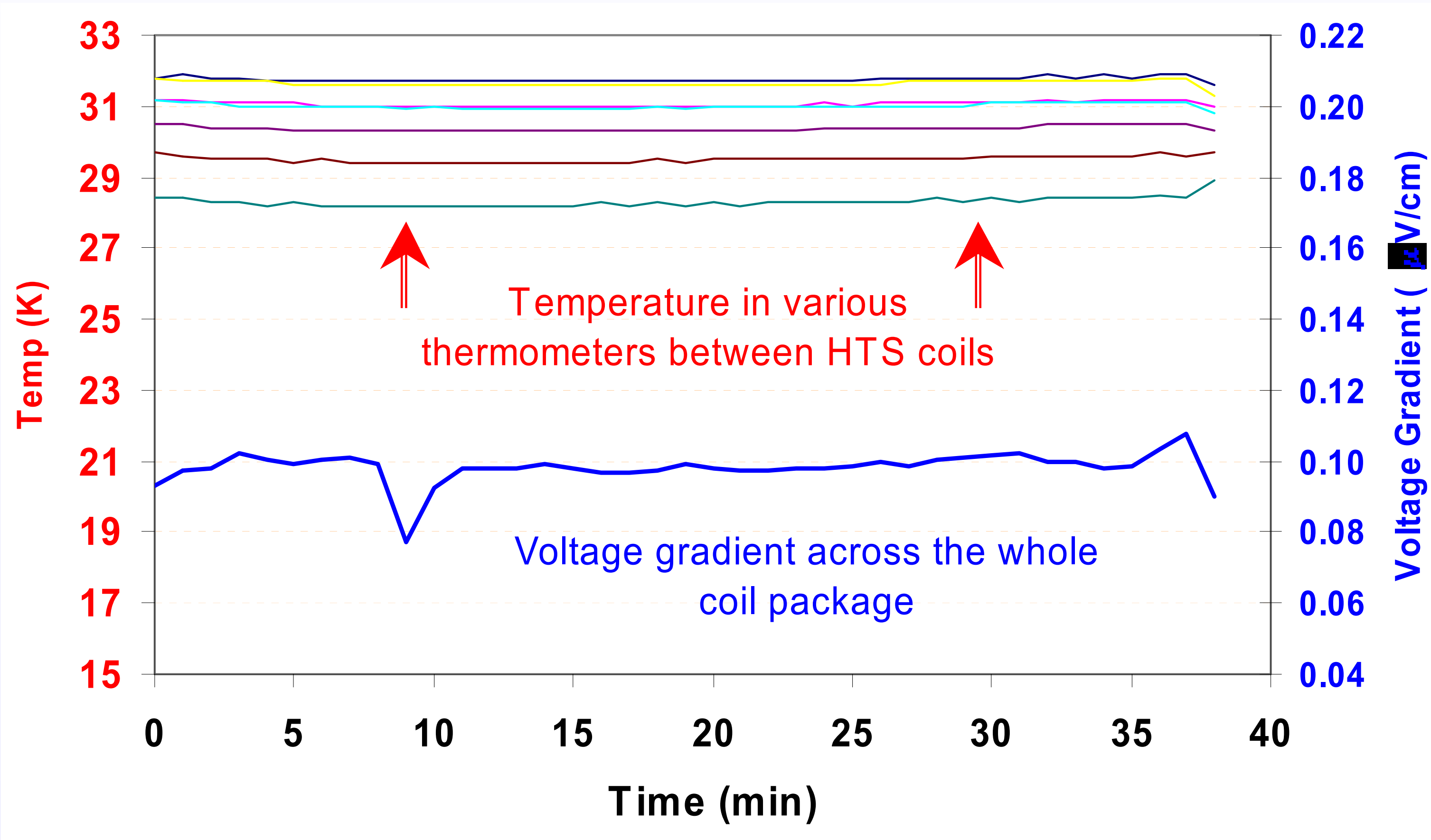
Stainless steel tape heaters for energy deposition experiments

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.
- Energy deposition in magnet worked well in both cases.

Large Energy Deposition Experiment

Magnet operated in a stable fashion with large heat loads (25 W, 5kW/m^3) at the design temperature (~30 K) at 140 A (design current is 125 A).



Stable operation for ~40 minutes

Voltage spikes are related to the noise

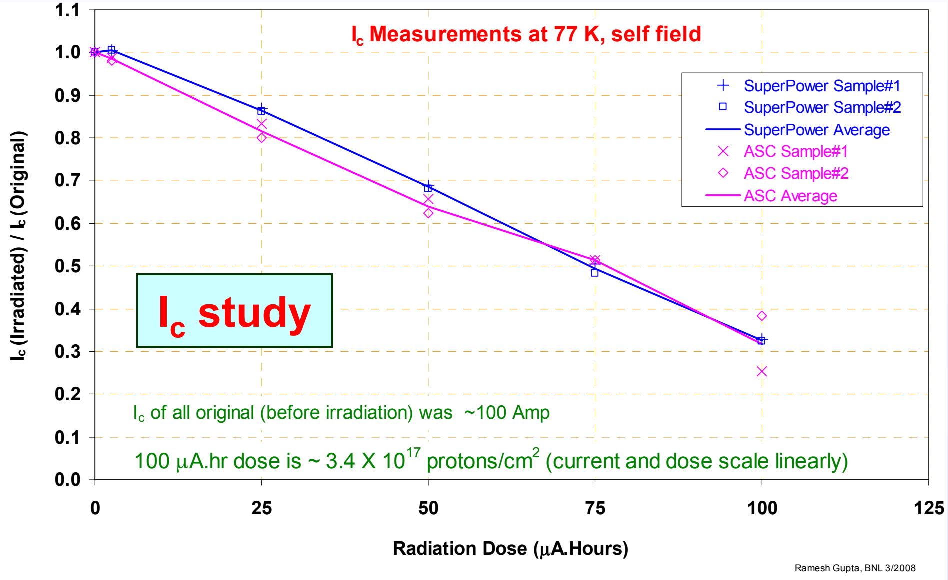
Impact of Large Irradiation on YBCO

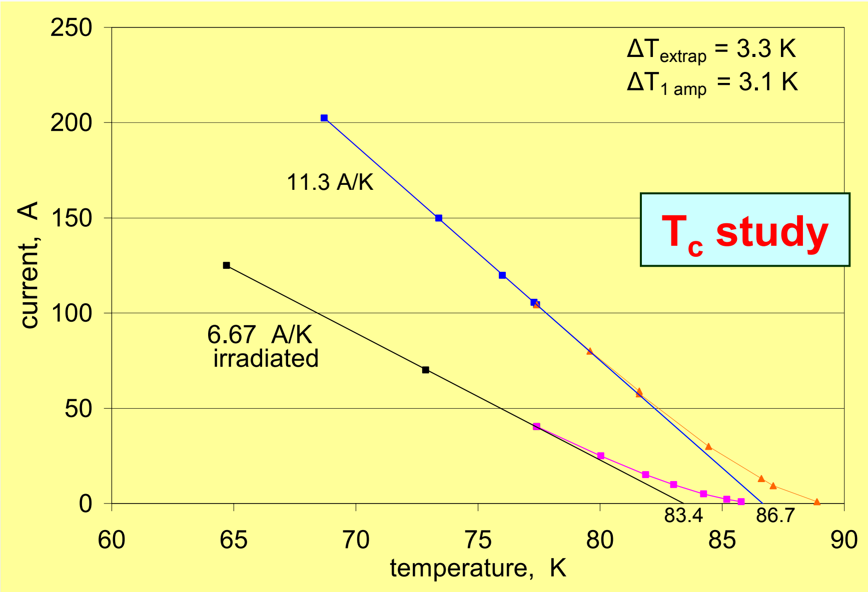
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Note: The following doses are order of magnitude more than what would be in FRIB

• Radiation damage studies at this level has never been done before !

Courtesy/Contributions: Garber





Bottom line – YBCO is robust against radiation damage:

- **Negligible impact on FRIB performance even after 10 years (Al Zeller, MSU).**
- **This allows even more efficient design where quads can be brought closer.**

YBCO seems to be more robust than Bi2223, studies on Bi2212 are underway.

Cost Comparison Between Resistive Copper and HTS Magnet for RIA

Comparison of large aperture, radiation resistant resistive copper and HTS quadrupole options for RIA (A. Zeller, MSU)

Magnet Type	Current Density (A/mm2)	Power (kW)	Iron (ton)	Coil (ton)	Coil Cost (M$)
Resistive	~2	~160	~38	~7	~1.0
HTS	~50	~3	~10	~0.2	~0.3

- **HTS solution consume much less power**
- **HTS magnet is much smaller in size and weights much less**
- **And in this case, radiation resistant HTS magnet even cost less than the radiation resistant water-cooled room temperature magnet**

- Conventional Low Temperature Superconductor (NbTi or Nb_3Sn) can not tolerate these large heat loads and removing that energy at 4-10 K would be very costly.

FRIB HTS Magnet R&D Program

Summary of Phase I Program

- RIA/FRIB HTS program with first generation (1G) has been very successful.
- It has solved a major technical issue with a design that is superior and cheaper.

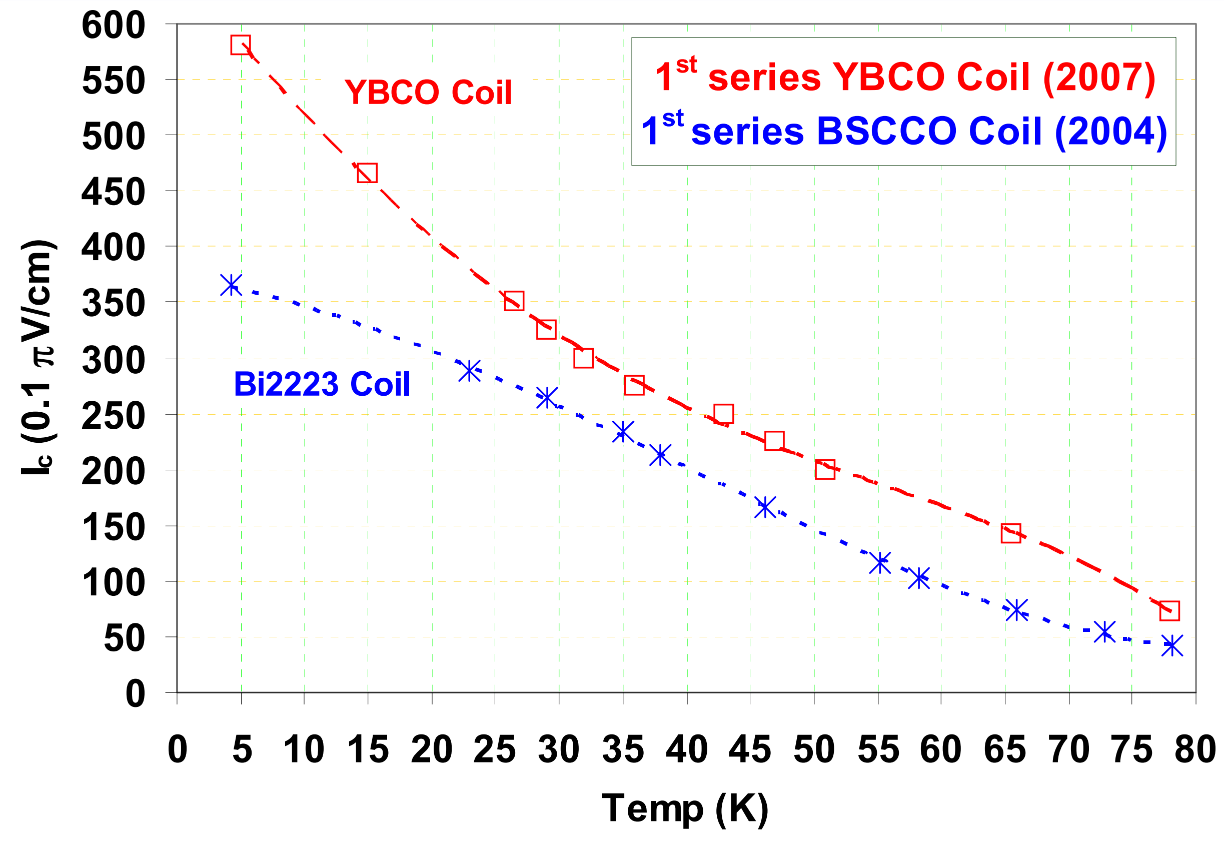
Possible Phase II Program and Future Outlook

- We have developed a new design that allows magnet to come closer to the target.
- This allows ~30% increase in capture efficiency – a major boost when you are dealing with hundreds of MW beam Power.
- We have started using second generation HTS (2G - YBCO) which would allow this large energy to be removed at 50+ K rather than at ~30 K in first generation or ~4 K in LTS (significant saving due to increased efficiency).
- HTS magnets have been found to be suitable in other places in FRIB beam line.

However, above is our vision (and record).

Our exact role in future FRIB program is yet to be established.

Initial R&D with 2G HTS in Support of Next Generation FRIB Design



YBCO (2G):
Early stages

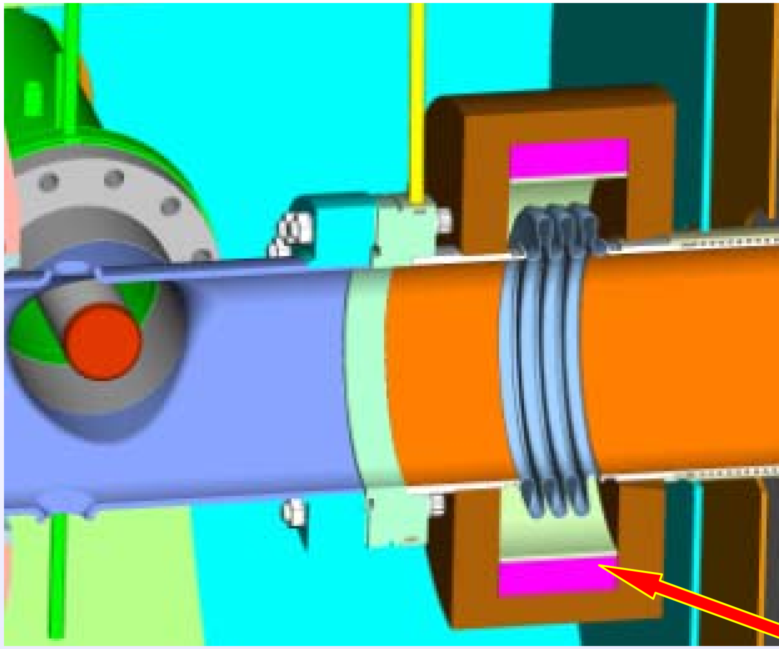
Bi2223 (1G):
Older technology

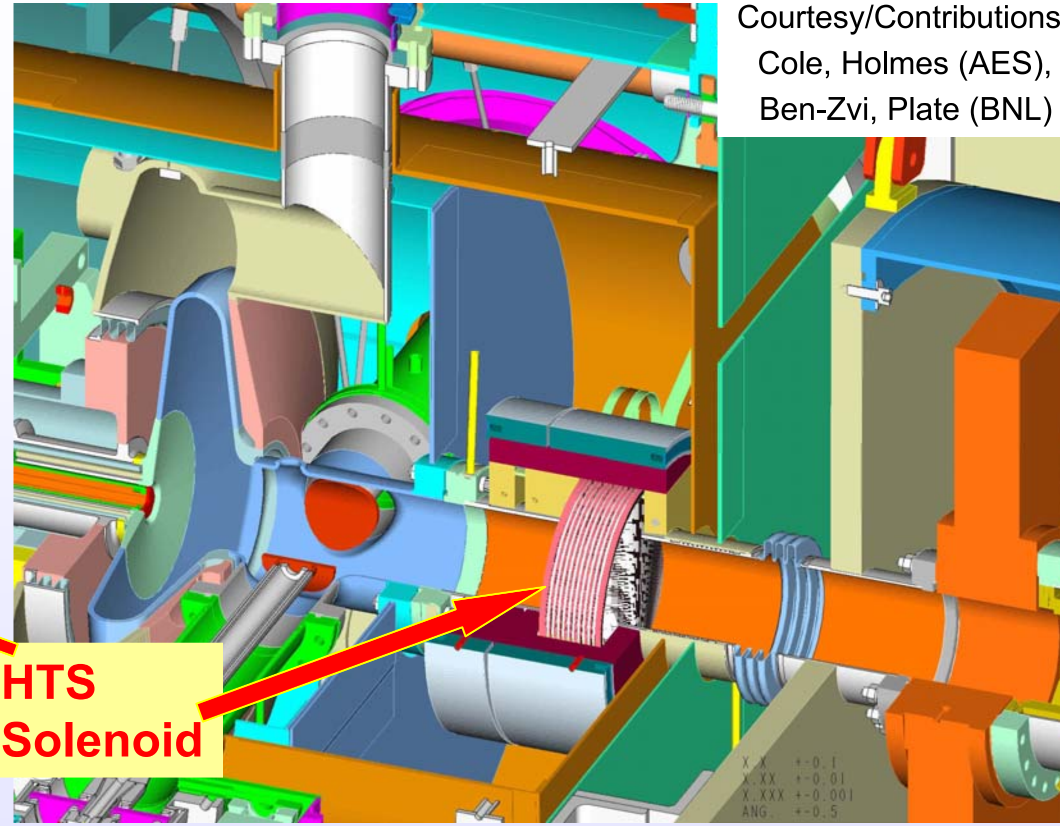
- 2G coil has higher performance at any temperature.
- Alternatively 2G coils can operate at 10-20 K higher temperature than 1G coils for the same performance

Expect more gains in 2G coils in future

Low Field Applications at BNL where HTS Provided Unique and Cheaper Overall Solution

HTS Solenoid for the Proposed ERL (Electron Recovery Linac) at BNL (1)





Courtesy/Contributions
Cole, Holmes (AES),
Ben-Zvi, Plate (BNL)

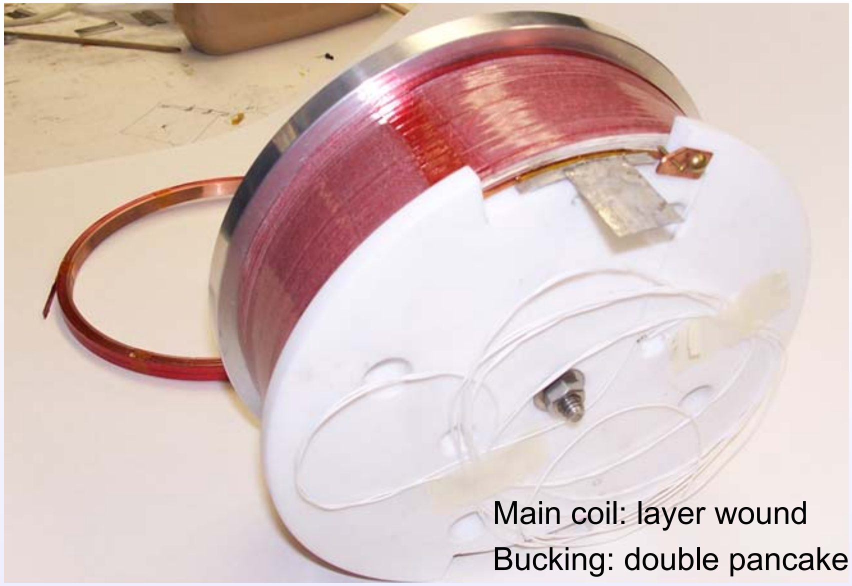
HTS Solenoid

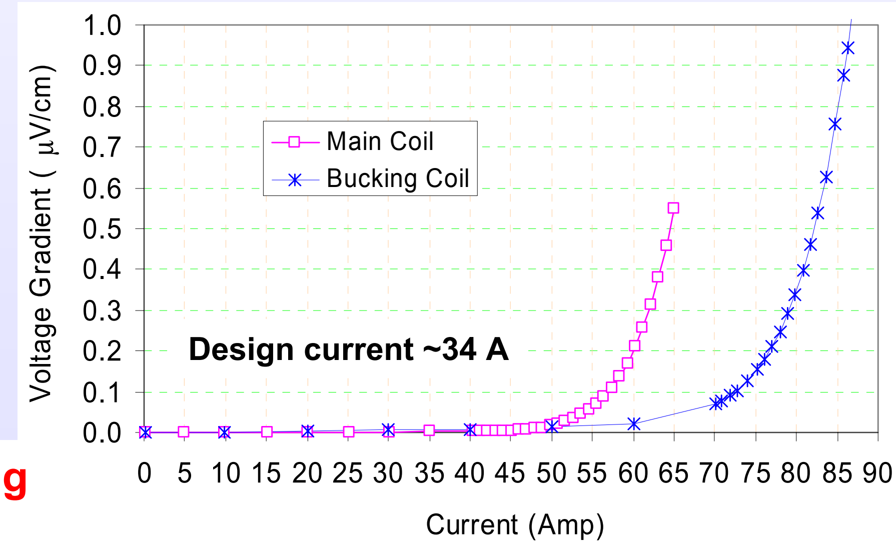
HTS solenoid magnet is placed over the bellows before the gate valve in cold to warm transition region (~20 K)

- HTS solenoid provides a unique technical solution.
- Reached design current at 77 K – LN2 rather than He provides savings in QA testing.

HTS Solenoid for the Proposed ERL (Electron Recovery Linac) at BNL (2)

Parameters	Value
Coil Inner Diameter	175 mm
Coil Outer Diameter	187 mm
No. of Turns in Main Coil	180
No. of Turns in Bucking Coil	30 (2X15)
Coil Length (Main Coil)	55 mm
Coil Length (Bucking Coil)	9 mm
Conductor Type	BSCCO2223 (1G)
Insulation	Kapton
Total Conductor Used	118 meter
Nominal Integral Focusing	~1 T^2. mm (axial)
Nominal Current	~34 A
Yoke Inner Radius	55 mm
Yoke Outer radius	114 mm
Yoke Length (Main + Bucking)	147 mm

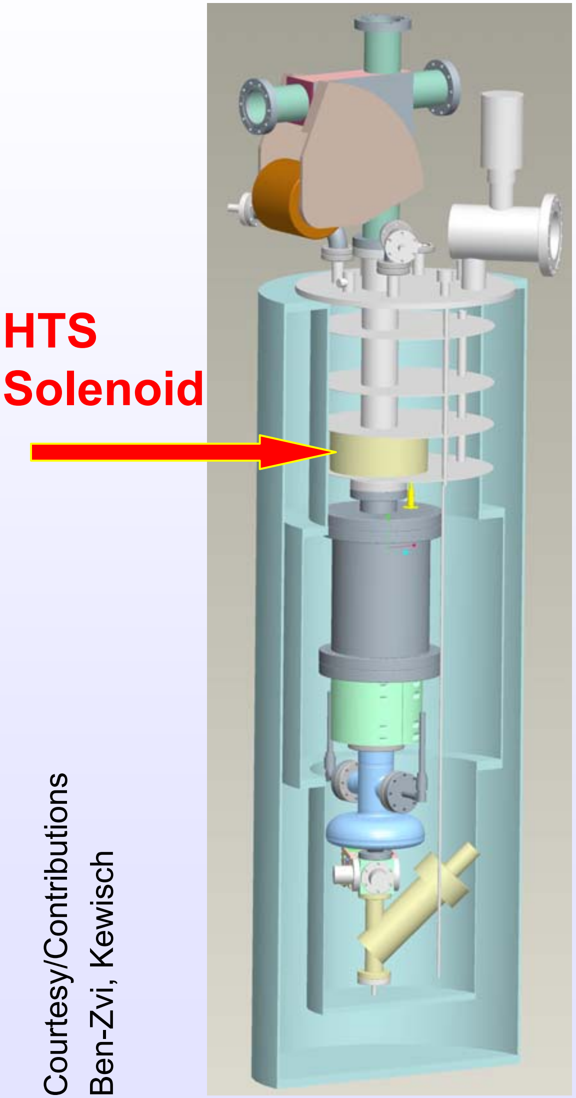




Well above design current is obtained @77 K in the liquid nitrogen testing itself.

Nitrogen testing at 77 K rather than Helium testing at 4 K for NbTi provided a significant savings.

HTS Solenoid for LDRD on SRF Electron Gun (1)



- No room for solenoid in Liquid Helium (LHe)
- Aluminum baffles prevent cooling
- Temperature between the first set of baffles is ~20 K
- Thus NbTi/Nb_3Sn superconductors can not be used
- Copper solenoid would generate ~500 W heat as against the ~5 W heat load of the entire cryostat
- Copper solenoid outside the cryostat will be too far away and will not provide the desired focusing and will result in a large deterioration in performance

- **HTS solenoid provided a technical solution that was not possible with either with copper or with conventional low temperature superconductors.**

HTS Solenoid for LDRD on SRF Electron Gun (2)

HTS Solenoid also provided an overall cheaper solution (design + build + test)

- Testing at ~77 K in LN_2 is much cheaper than testing at ~4 K in LHe
- The solenoid reached the design current at ~9 A with a few hundred percent margin - $I_c(0.1\ \mu V/cm) \sim 35$ A, operated in stable manner at ~46 A
- The maximum current in the system is limited by feed-thru (<20 A)
- The solenoid itself was built with small leftover end pieces of HTS wire from previous projects

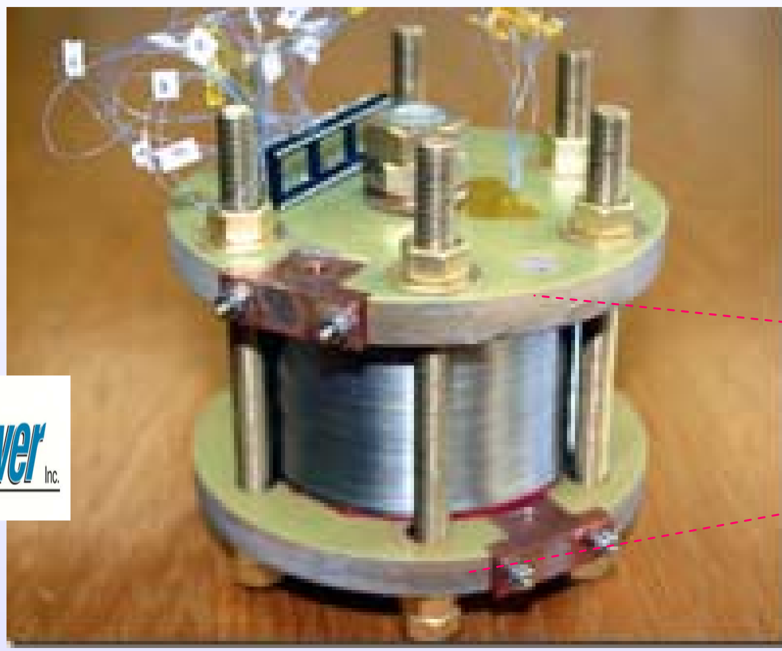
Courtesy/Contributions: Dilgen, Ince

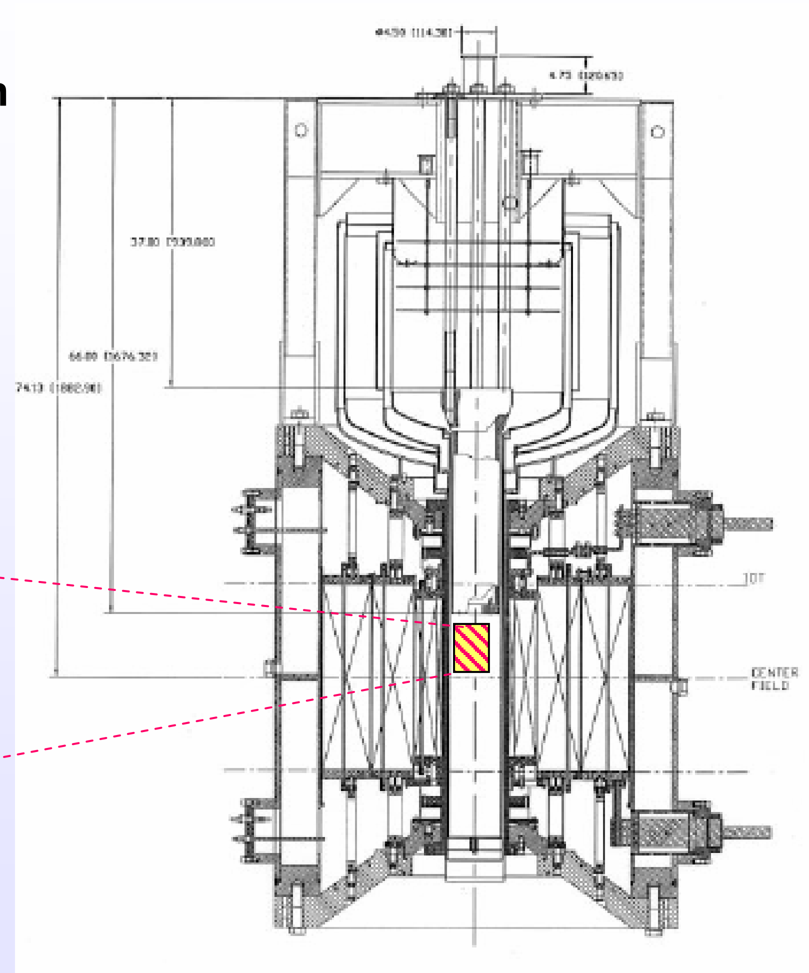
High Field HTS Solenoid Design (SBIR with Particle Beam Lasers)

- An SBIR has been funded with PBL with BNL developing an HTS solenoid.
- The original proposal was for a 10 T solenoid with 66.5 mm inner diameter.
- It stated that diameter can be increased to 87.2 mm for twice the conductor.
- However, now we are planning to build 110 mm solenoid – thanks to the improvement in the superconductor performance.
- Moreover, in collaboration and with contributions from SuperPower, we are now planning for a 22-25 T solenoid with ~29 mm bore. This will be the highest field HTS solenoid.
- This R&D should put us on a good trajectory to very high field HTS magnet work with 30-40 T solenoid within grasp and possibly going to ~50 T.
- This should also help us and the community in developing high field HTS dipoles and quadrupoles for various accelerator applications.
- We shall also study performance of the solenoid as a function of temperature as the eventual goal of the SBIR is a 10 T, 100 mm solenoid operating at ~30K.

SuperPower HTS Solenoid inside the NHMFL 19 T Solenoid (providing the background field)

SuperPower made a ~10 T small aperture HTS solenoid with its own conductor and tested it in NHMFL's unique, 19-tesla, 20-centimeter bore, 20-megawatt Bitter magnet (solenoid)





SuperPower Inc.

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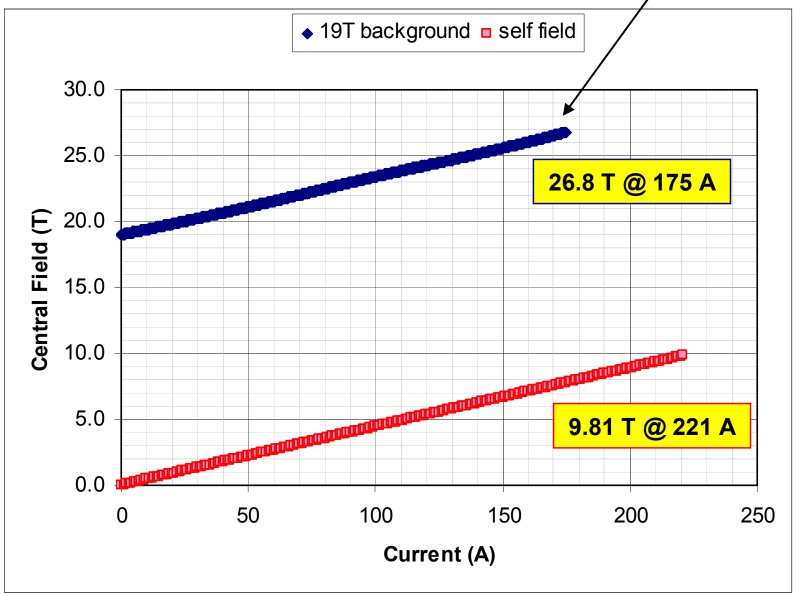
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY - LOS ALAMOS NATIONAL LABORATORY - UNIVERSITY OF FLORIDA

SuperPower/NHFML YBCO Solenoid

High field insert coil achieves world records for highest HTS field, highest magnetic field by a SC magnet

Peak hoop stress ~ 215 MPa, well below tape limit



Ic of Wires in Coil	72 A – 82 A (77K, sf)
4.2 K Coil Ic - self field	221 A
4.2 K Amp Turns @ Ic-self field	612,612
4.2 K Je @ Ic, self field	346.7 A/mm^2
4.2K Peak Radial Field @ Ic, self field	3.2 T
4.2 K Central field – self field	**9.81 T**
4.2 K Coil Ic – 19 T background (axial)	175 A
4.2 K Amp Turns @ Ic – 19 T background (axial)	485,100
4.2 K Je @ Ic, 19 T background (axial)	274.6 A/mm^2
4.2 K Peak Radial Field @ Ic, 19 T bkgd (axial)	2.7 T
4.2K Central Field – 19 T background (axial)	**26.8 T**

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SuperPower Inc.

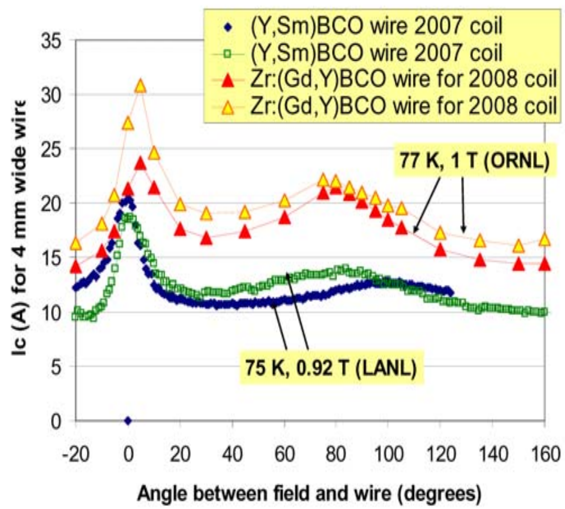
Low Temperature Superconductivity Workshop, 10/29/07

– 19 –

Solenoid with Improved Conductor

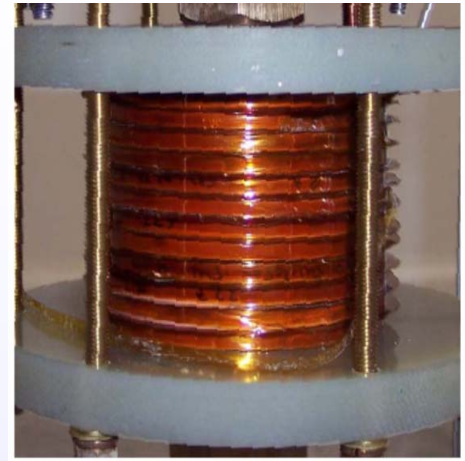
SuperPower

30% Higher Field Achieved Using 2G with Improved In-field Performance



Temperature (K)	Coil current (A)	Max Central Field (T)
77.4	22.7	**0.95**
70.25	44	1.84
65.8	54	2.26
64.5	57	**2.39**
63.8	58	2.43

Temperature	2008 coil with Zr-doped (Gd,Y)BCO	2007 coil with (Y,Sm)BCO	Improvement
77 K	0.95 T	0.73 T	30%
65 K	2.39 T		



Will this 77 K improvement in performance be retained at ~4 K?

BNL is soon receiving this solenoid to study 4K–80 K measurements

We are planning to optimize the performance of our solenoid with a strategic use of various dopings to partially align enhancement with the direction of field

Baseline Design of the Solenoid

✓ **Baseline design has a reasonable margin to assure success : 10 T @ 4K**

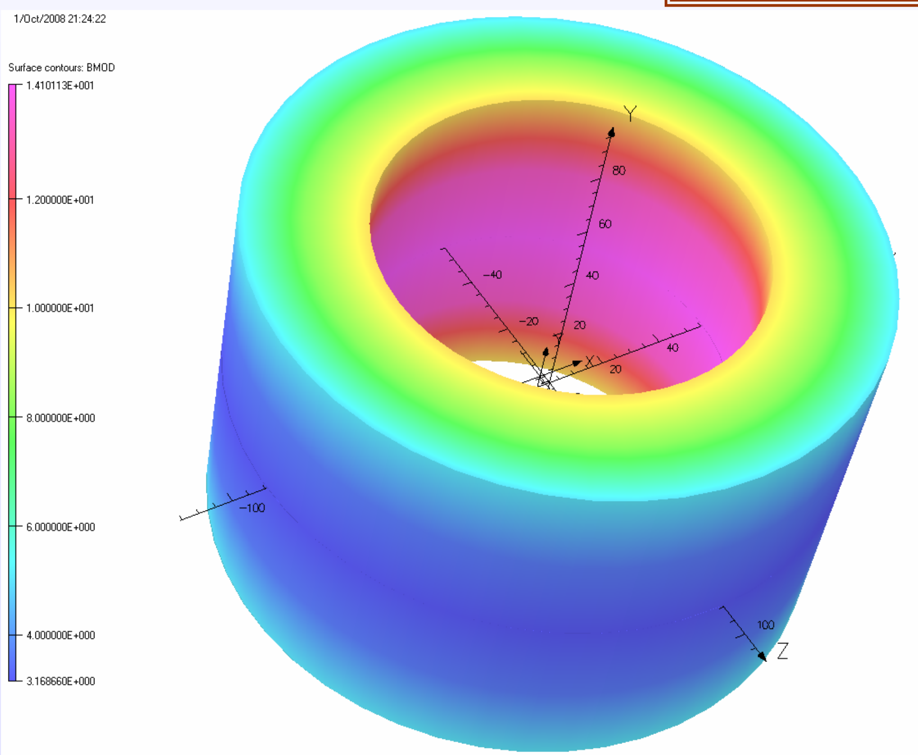
- Je in coil : ~450 A/mm^2

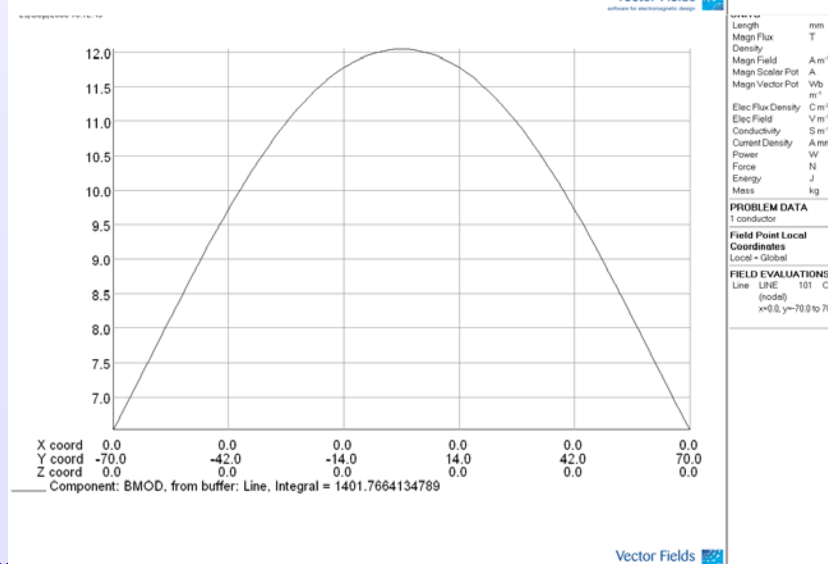
(30% improvement assumed)

- ➢ Solenoid coil i.d. : 110 mm
- Clear bore i.d. : 100 mm

B_o ~ 12 T

B_{pk} ~ 14 T

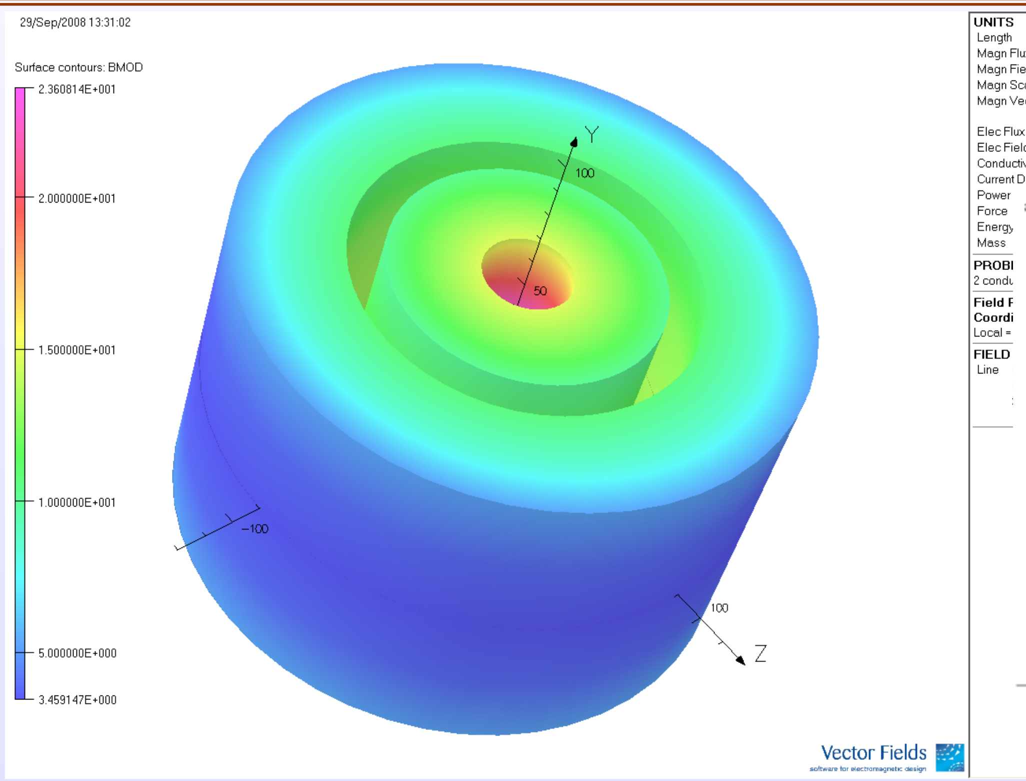


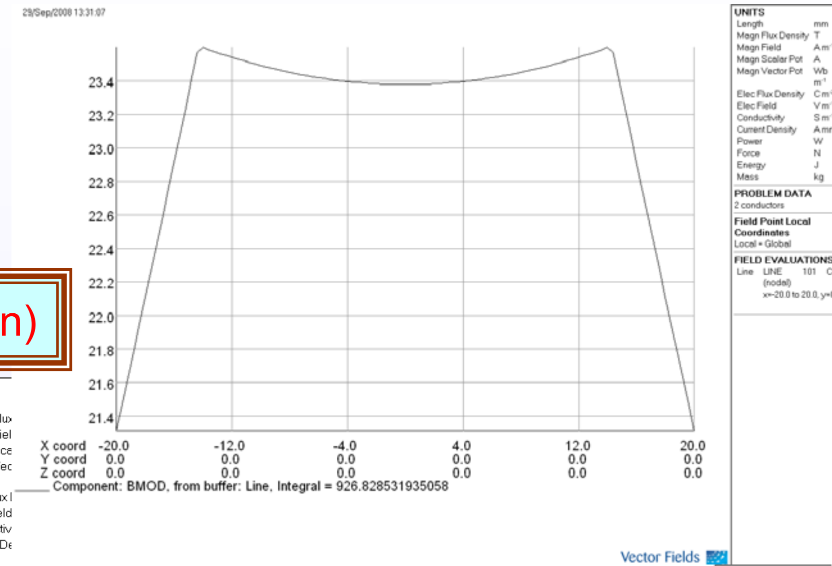


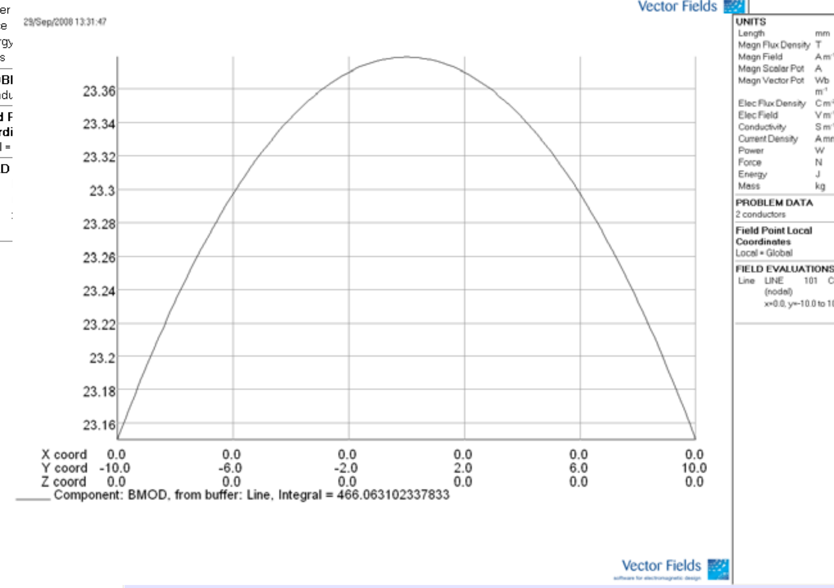
HTS Solenoid with SupePower Insert

- Je in our solenoid : ~450 A/mm^2
  - Je in SuperPower solenoid: ~350 A/mm^2
- i.d. of our solenoid : 110 mm
  - i.d. of SuperPower Solenoid : 28.6 mm

Bo ~ 23 T (22 T – 25 T depending on the optimization)

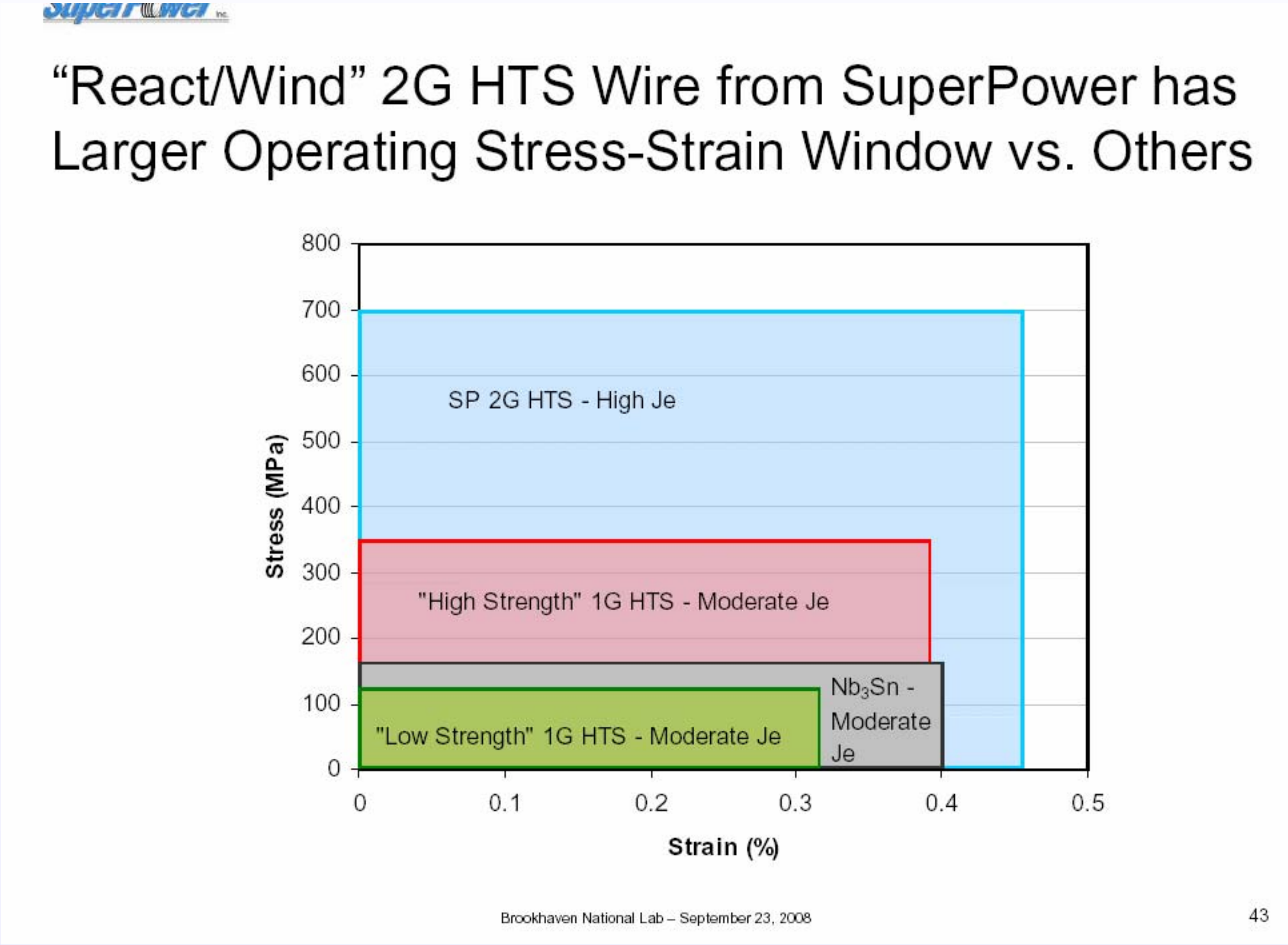




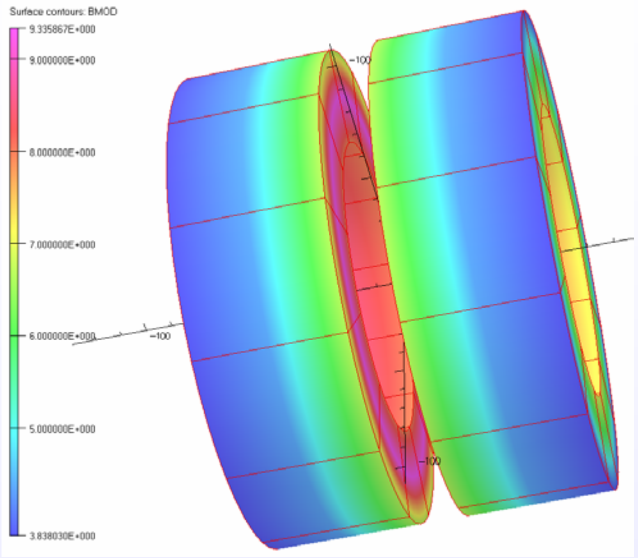


Strength of YBCO

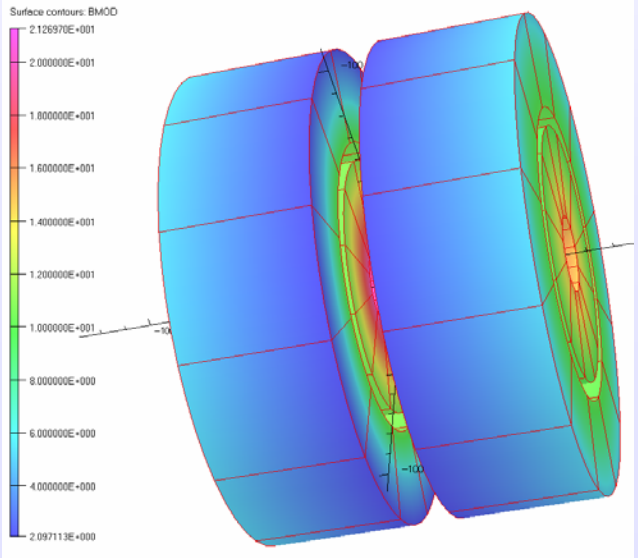
- **Question: can YBCO take these large stress associated with high fields ?**
- **Yes it can! But we will have stainless steel wrap also !!!**



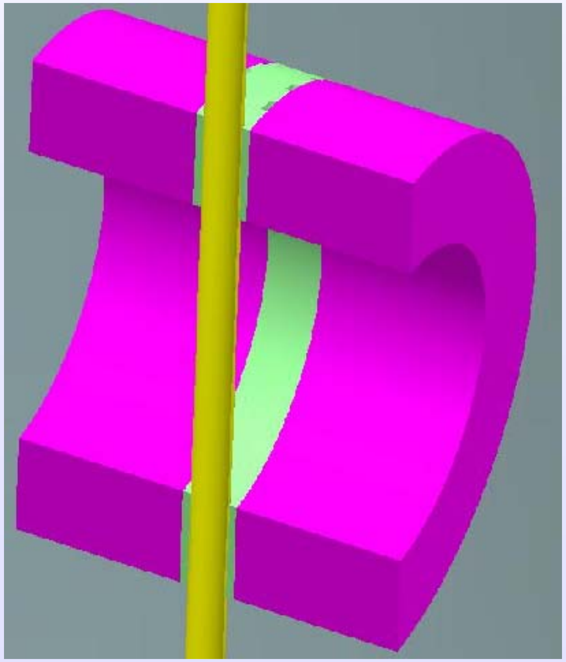
Converting HTS Solenoid to a Unique and Useful Facility



- At present there is no good facility which permits low temperature measurements of I_c as a function of both the magnitude and the direction of field.
- This information is useful in optimizing both the conductor and the magnet. A split-pair solenoid using these coils, can create a unique test facility for such measurements (10 T in 10 cm and ~20 T in 2 cm).



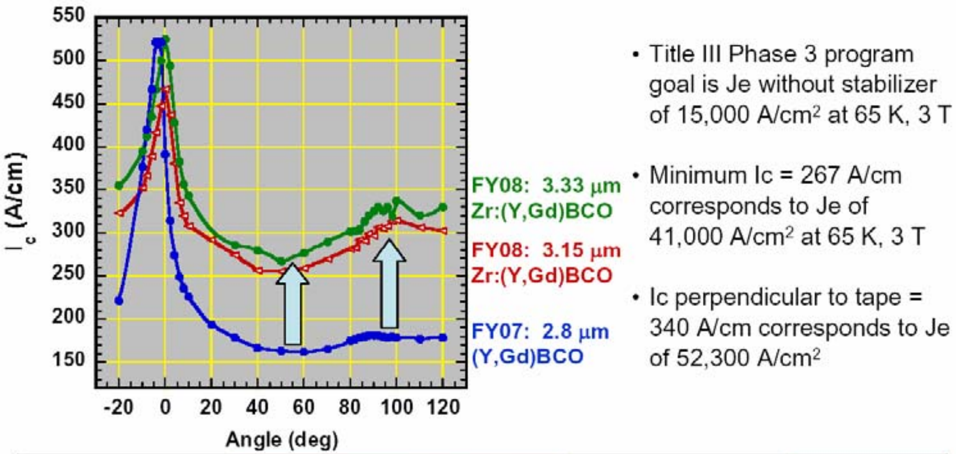
In addition to varying field angle, one may also be able to vary temperature with on-board heaters. This will allow a continuous and systematic 4 K – 80 K measurements as a function of the magnitude and the direction of the field.



HTS Magnets May be Attractive for Medium and Low Field Applications

SuperPower

Excellent in-field performance at 65 K, 3 T



Ic (77 K, 1 T)	FY08 Zr-doped (Gd,Y)BCO	FY07 (Gd,Y)BCO	Improvement
B // c	340 A/cm	181 A/cm	88%
Minimum Ic	267 A/cm	160 A/cm	67%

Data from Y. Zhang, M. Paranthaman, A. Goyal, ORNL

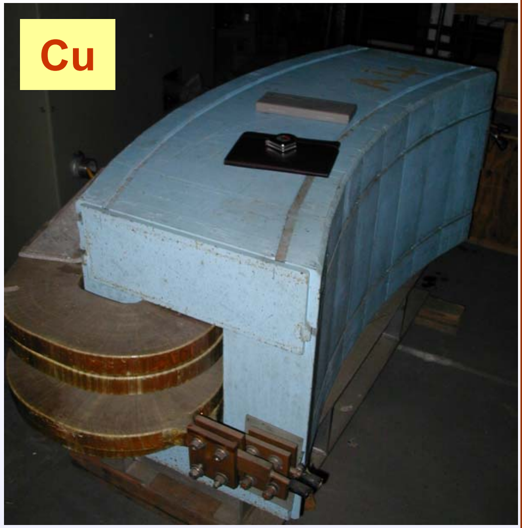
Above **65 K**, 3T HTS J_e is already in the same ball-park as **4K**, 3T NbTi J_e used in AGS snake magnet (and is still improving).

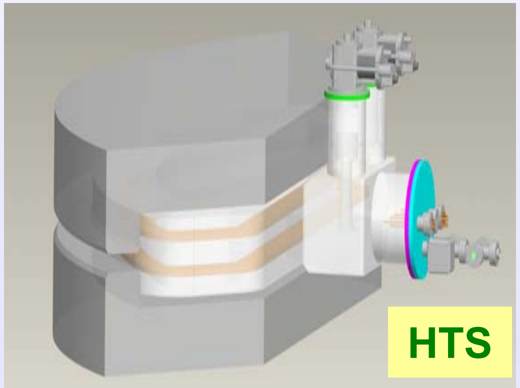
- With the energy cost rising, HTS magnets may compete with large water-cooled copper magnets for *"lower cost of ownership (capital + operation)"*.
- With the performance of the 2G HTS improving and the cost decreasing, medium field HTS magnets operating at ~65 K, may compete in overall cost with NbTi magnets operating at ~4 K due to simpler and cheaper cryogenic system.

Cryogenic system for 2G HTS magnets can be now be based on sub-cool nitrogen rather than helium – a major technical departure with a significant cost saving potential over the present superconducting magnet technology.

HTS Dipoles for a Super Neutrino Beam Facility Proposal

- An earlier proposal was developed with room temperature, water-cooled copper magnets.
- The question: Can an HTS magnet design be developed, which provides enough savings in operating cost to off-set its higher initial cost ?





Design Parameters:

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

Courtesy/Contributions:
Mike Harrison

Cost of ownership must include all costs. Some outstanding:

- Operation- Cu magnets have large power consumption ~3 MW, >$250 k/year for a 5 month run. HTS magnets: <$50 k/year.
- Cooling- Cu: Low thermal conductivity water plant based cooling system. HTS: Either Cryo-cooler based or sub-cool nitrogen based cooling system. For HTS magnets operating at ~60 K, the two may be within a factor of 2.
- Conductor- Cu: ~$10 k, HTS: ~$50 k (depends on temp., in-field cost $/A may reduce significantly in future)
- Cryostat, support- Almost none in Cu, large in HTS (but some creativity may bring large savings). only ~1/4, lower in future)
- Iron, weight- less in HTS
- Power supply- less in HTS (~100 A in HTS rather than a few thousands in Cu)
- + others (need to make a complete list)

Low Field (<1 T) and Medium Field (1-3 T) HTS Magnet Design Studies

HTS magnet design studies have been carried out for the following proposals:

- **Super Neutrino beam line dipole (~1.6 T)**
- **NSLS2 dipole (0.4 T and 1 T)**
- **ILC quad**
- **LARP quad**
- **Common coil dipole for dEDM**

• Improvements in conductor performance with reduction in cost would make helium-free HTS magnets more attractive over (a) water-cooled copper magnets on one side and (b) conventional LTS magnets on other side.

• Innovative magnet designs would also help as cryo costs are not insignificant.

Challenges and Open Issues with HTS Magnets

Cost

- The cost of HTS is still order of magnitude more than that of LTS. It continues to decrease rapidly but will always be more than LTS. Thus savings in simpler cryogenic system operating at higher temperature must off-set the higher conductor cost.

Quench Protection

- Since quench propagation in HTS is slow, it is harder to detect in the same time frame as in LTS magnets. One needs to develop a dependable quench protection system.
- HTS has a large temperature margin. HTS magnets can operate well above the quench criterion before a thermal run-away. In addition to the voltage rise, detection of the local temperature rise could play a significant role in protecting HTS magnets.

Still in R&D Phase

- Only a limited number of short R&D magnets have been built and tested. There is not enough statistics on the reliability, etc. However, this is a general challenge with any new technology. There is no substitute for building and testing more coils and more magnets. Moreover, use whatever one can from the experience of LTS magnets, but often innovate ideas brings major progress. One should optimize the design and technology that takes advantage of this remarkable superconductor.

Acknowledgement

The work presented here is made possible due to important contributions from a large number of colleagues.

In particular we wish to acknowledge M. Anerella, I. Ben-Zvi, J. Cozzolino, T. Dilgen, J. Escallier, G. Ganetis, A. Ghosh, G. Greene, M. Harrison, P. Joshi, D. Ince, G. Jochen, J. Kewisch, P. Kovach, J. Muratore, B. Parker, S. Plate, W. Sampson, J. Schmalzle, P. Wanderer and K.C. Wu at BNL, A. Zeller at National Superconducting Cyclotron Laboratory, and M. Cole and D. Holmes at Advanced Energy Systems (AES).

ASC, Showa and SuperPower not only provided the HTS but also the technical information that was used during the course of this work.

Concluding Remarks

- There are several possible areas where HTS magnets can be attractive.
- Current second generation conductor makes HTS magnets more attractive because of (a) higher "in-field" J_e (b) lower cost and (c) higher operating temperature.
- Low to medium field applications operating at 50-65 K has a potential to become a larger volume application in accelerator and medical sciences.
- In very high field applications (20+ T), HTS is the only viable conductor. In these applications performance, not the cost, is the driving force.
- However, being a new technology, not many people are aware of the benefits of HTS and/or comfortable and convinced of its reliability.
- Our job is (a) to identify the potential applications and (b) build and test as many magnets as possible to make a more convincing case.