Medium and Low Field HTS Magnets for Particle Accelerators and Beam Lines

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HTS Magnets May be Attractive for Medium and Low Field Applications

- With the energy cost rising, HTS magnets (include MgB_2) may compete with large water-cooled copper and conventional NbTi/Nb_3Sn superconducting magnets for *"lower cost of ownership (capital + operation)".*

- With the performance of the 2G HTS improving and the cost decreasing, medium field (1 T – 3.5 T) HTS magnets operating at 50 K – 65 K, may compete in overall cost with NbTi magnets operating at ~4 K due to simpler and cheaper cryogenic system.

- In some low field (< 1 T) applications, where s.c. magnets must be used, HTS magnets may compete with NbTi magnets in overall cost of building and testing since ~77 K LN_2 testing is much cheaper than ~4 K LHe testing.

- HTS magnets offer several technical advantages over LTS magnets, such as ability to deal and remove large heat loads cheaply at higher temperature.

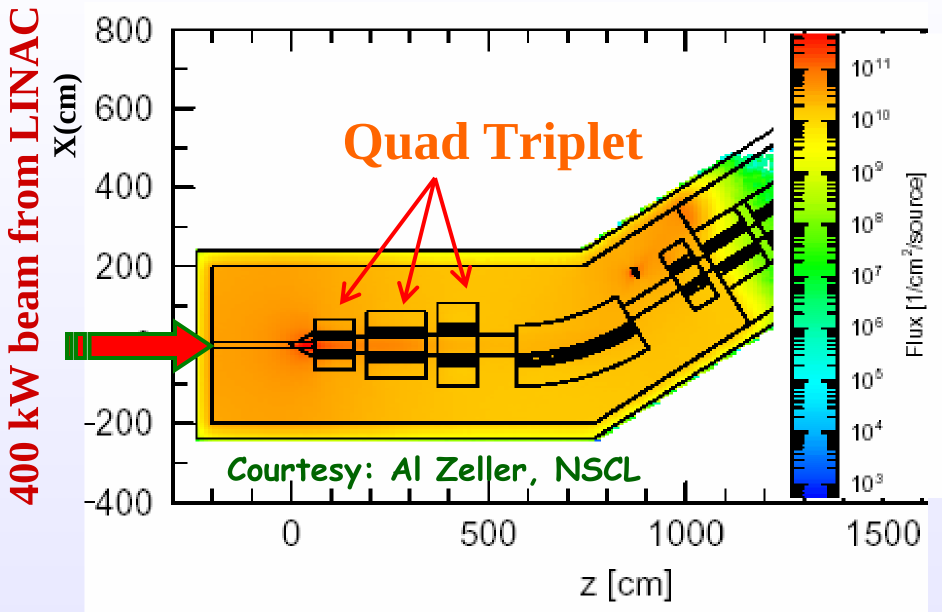
- Above points will be illustrated with the help of a few specific examples

  (not discussed here: high field applications of HTS/HFS).

HTS Quadrupoles for RIA/FRIB

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

- A comprehensive HTS magnet R&D has practically solved the problem.



Courtesy: Al Zeller, NSCL

- ➢ 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.

- *Can HTS magnets meet these demanding requirements ?*
- *Can HTS magnets be made at a cost that is affordable ?*

RIA: Rare Isotope Accelerator
FRIB: Facility for Rare Isotope Beams

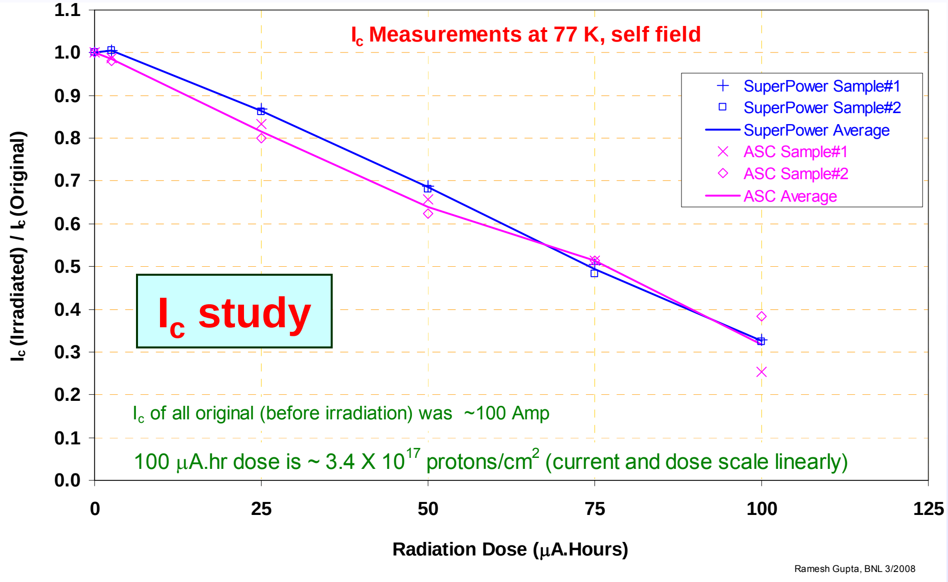
Impact of Large Irradiation on YBCO

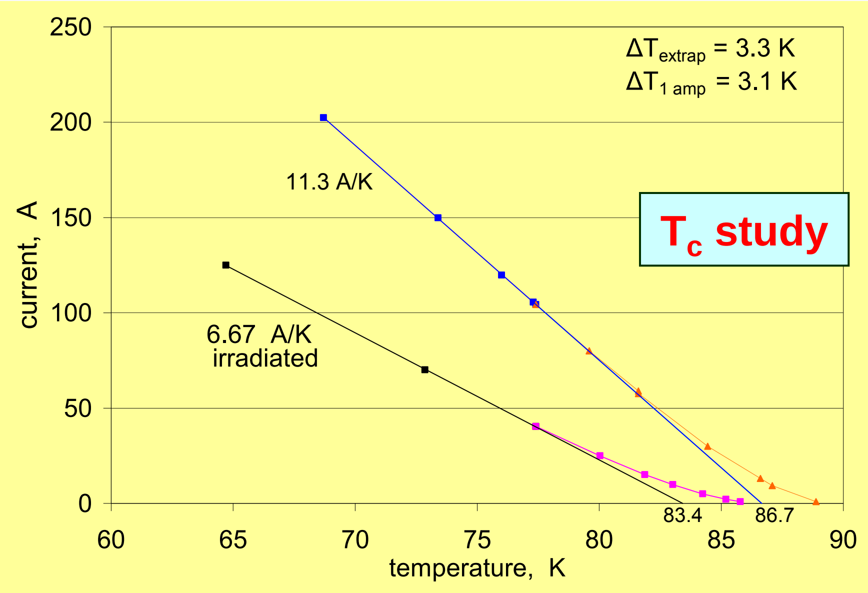
Note: The following doses are <u>order of magnitude more than what would be in FRIB</u>

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

(for details see paper 1MPH03)

Courtesy/Contributions: Garber





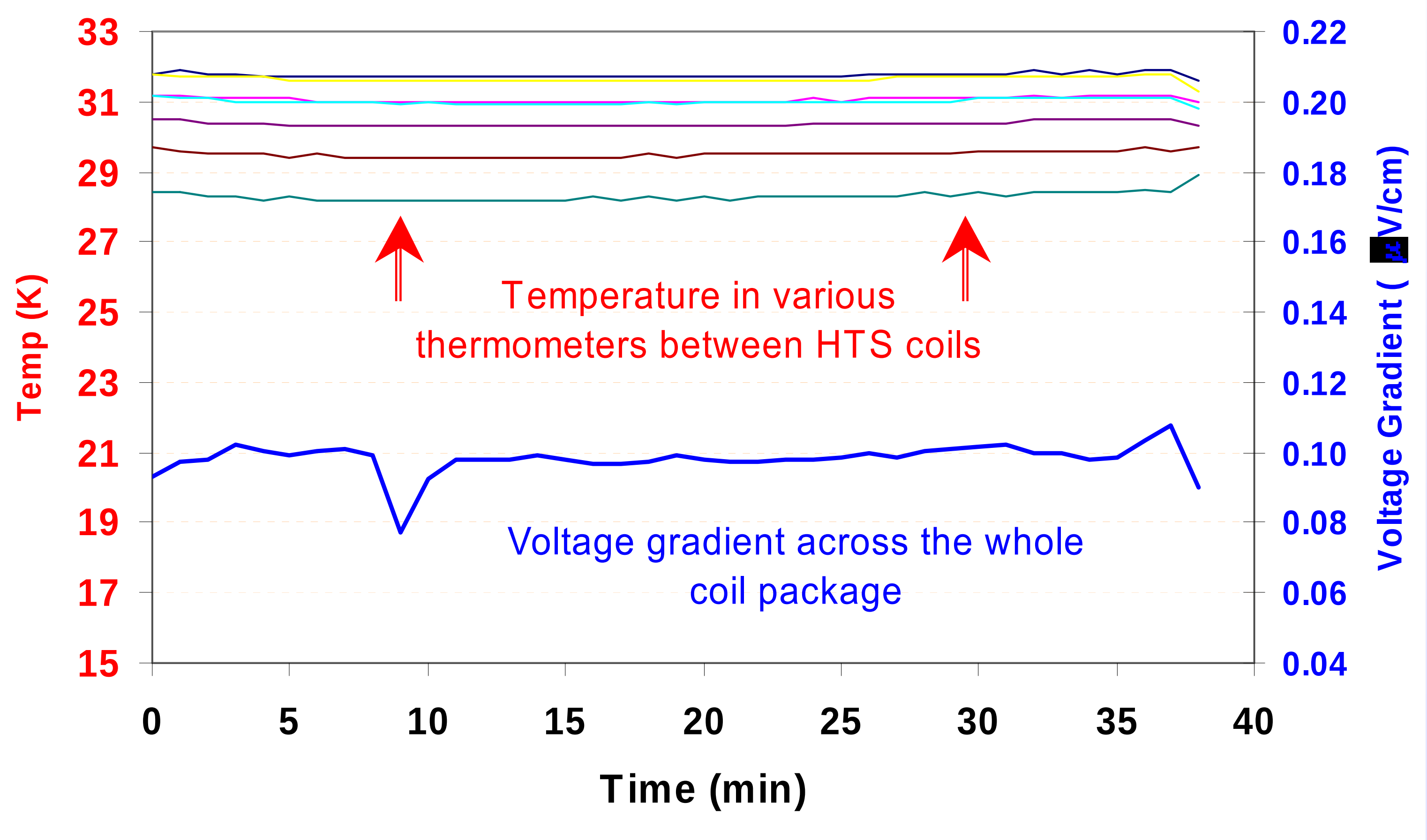
<u>Bottom line – YBCO is robust against radiation damage</u>:

- **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.

Large Energy Deposition Experiment

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



Temperature in various thermometers between HTS coils

Voltage gradient across the whole coil package

Stable operation for ~40 minutes

Voltage spikes are related to the noise

HTS Coils for RIA/FRIB Model Magnet

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

Over 5 km of HTS has been purchased for RIA/FRIB (1G from ASC and 2G from ASC & SuperPower)

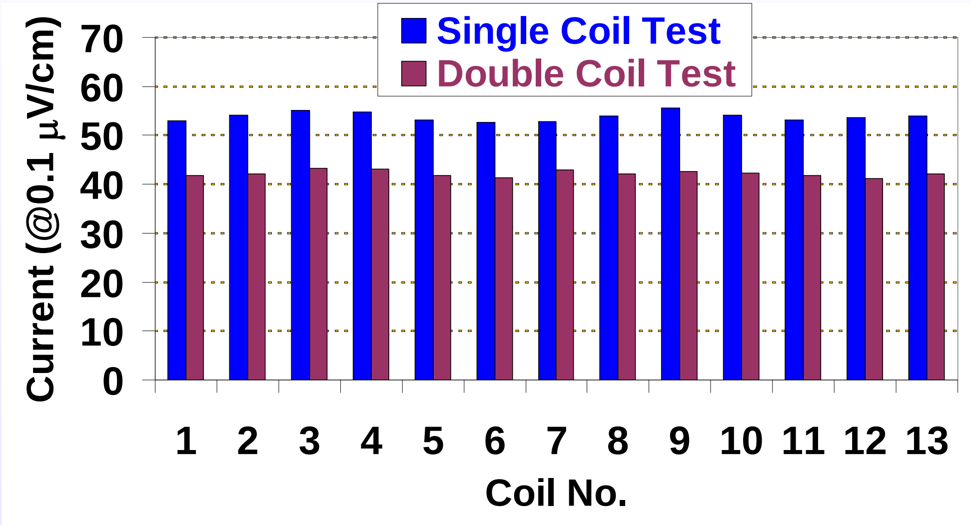
Radiation resistant SS tape insulation

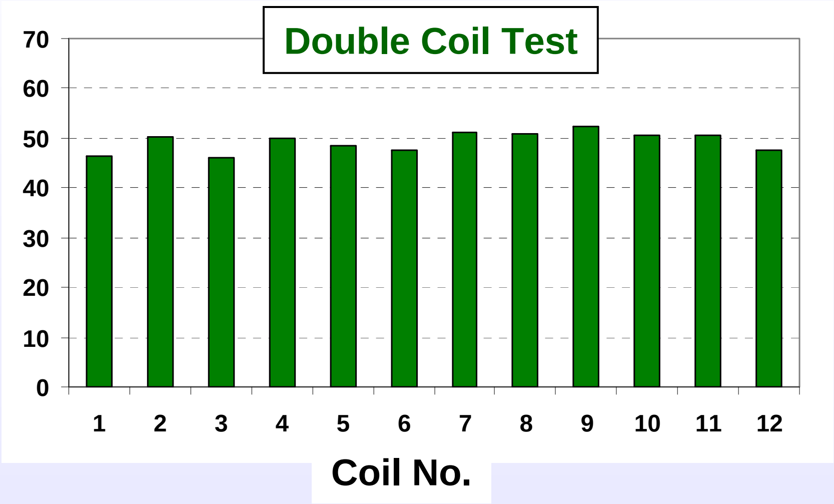
Courtesy/Contributions
Jochen

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.

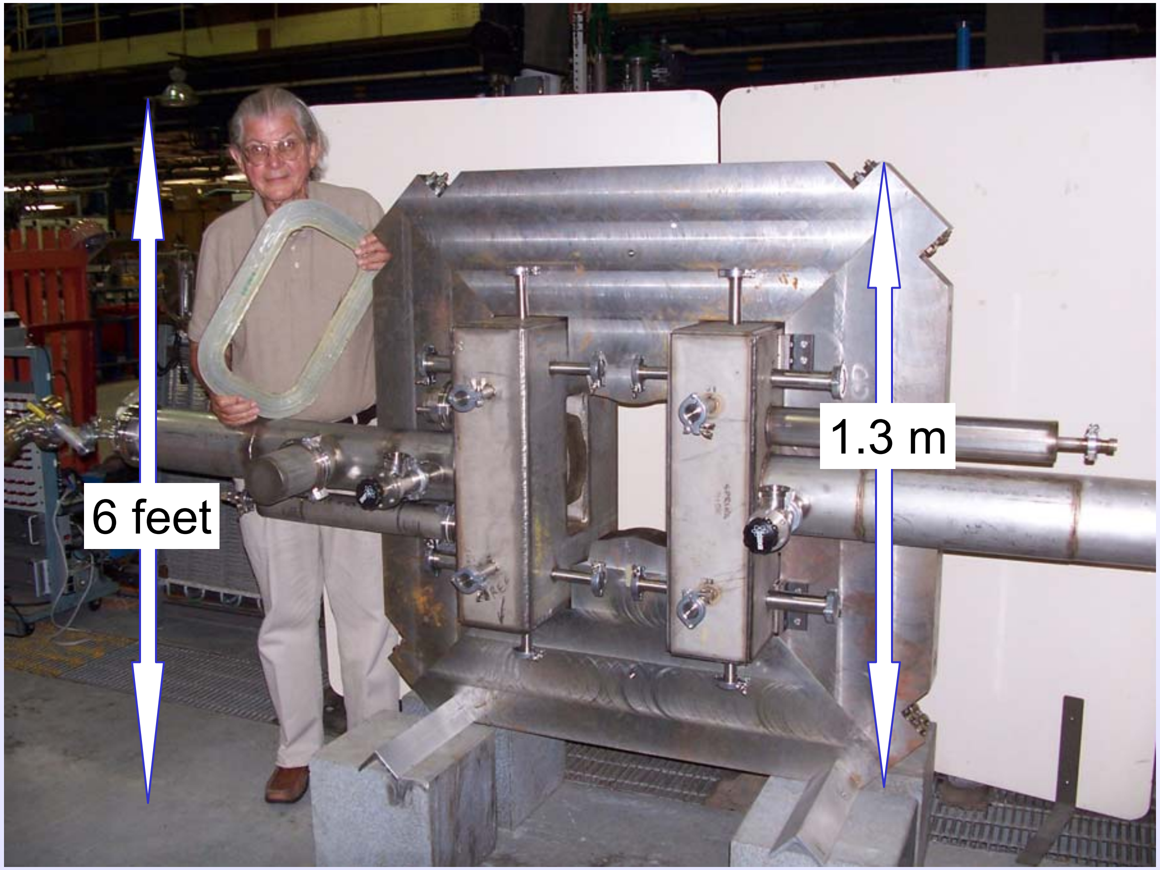
Note: A uniformity in performance of a large number of HTS coils made with commercially available 1G superconductor from ASC.

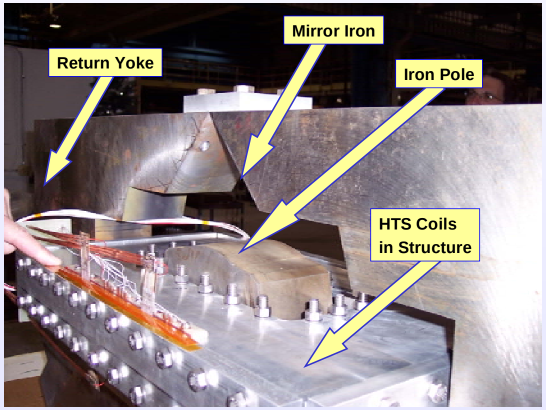
It shows that the HTS coil technology is now maturing !

RIA Quad is a Large Magnet

Unique Feature of RIA HTS Quad :

- Large Aperture, Radiation Resistant





Courtesy/Contributions

Anerella, Dilgen, Ince, Jochen, Kovach, Schmalze

Cost Comparison Between Resistive Copper and HTS Magnet for RIA

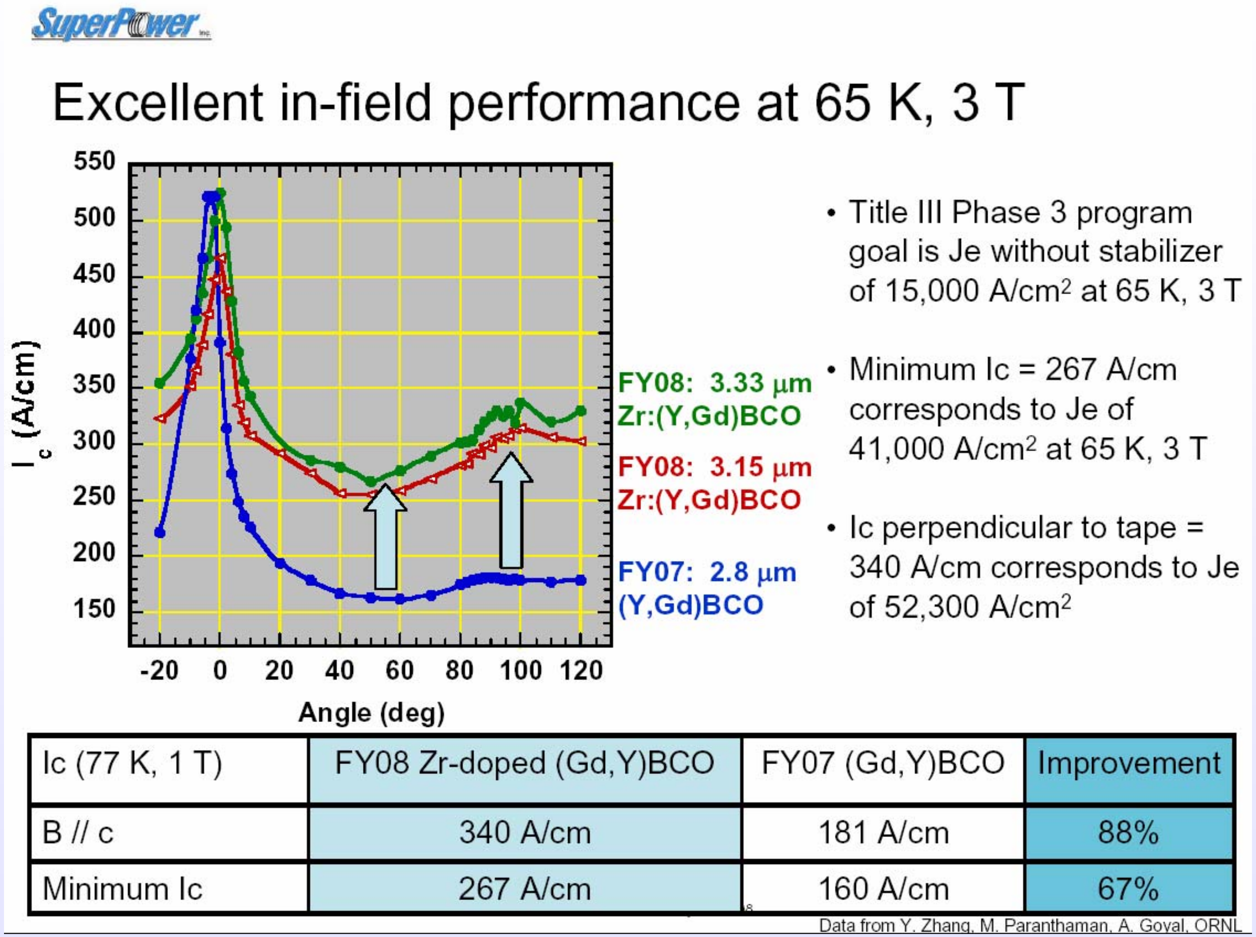
Comparison of large aperture, radiation resistant resistive copper and HTS quadrupole options for RIA (A. Zeller, MSU)

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.

Future R&D for RIA/FRIB Magnets



Excellent in-field performance at 65 K, 3 T

- Title III Phase 3 program goal is Je without stabilizer of 15,000 A/cm² at 65 K, 3 T
- Minimum Ic = 267 A/cm corresponds to Je of 41,000 A/cm² at 65 K, 3 T
- Ic perpendicular to tape = 340 A/cm corresponds to Je of 52,300 A/cm²

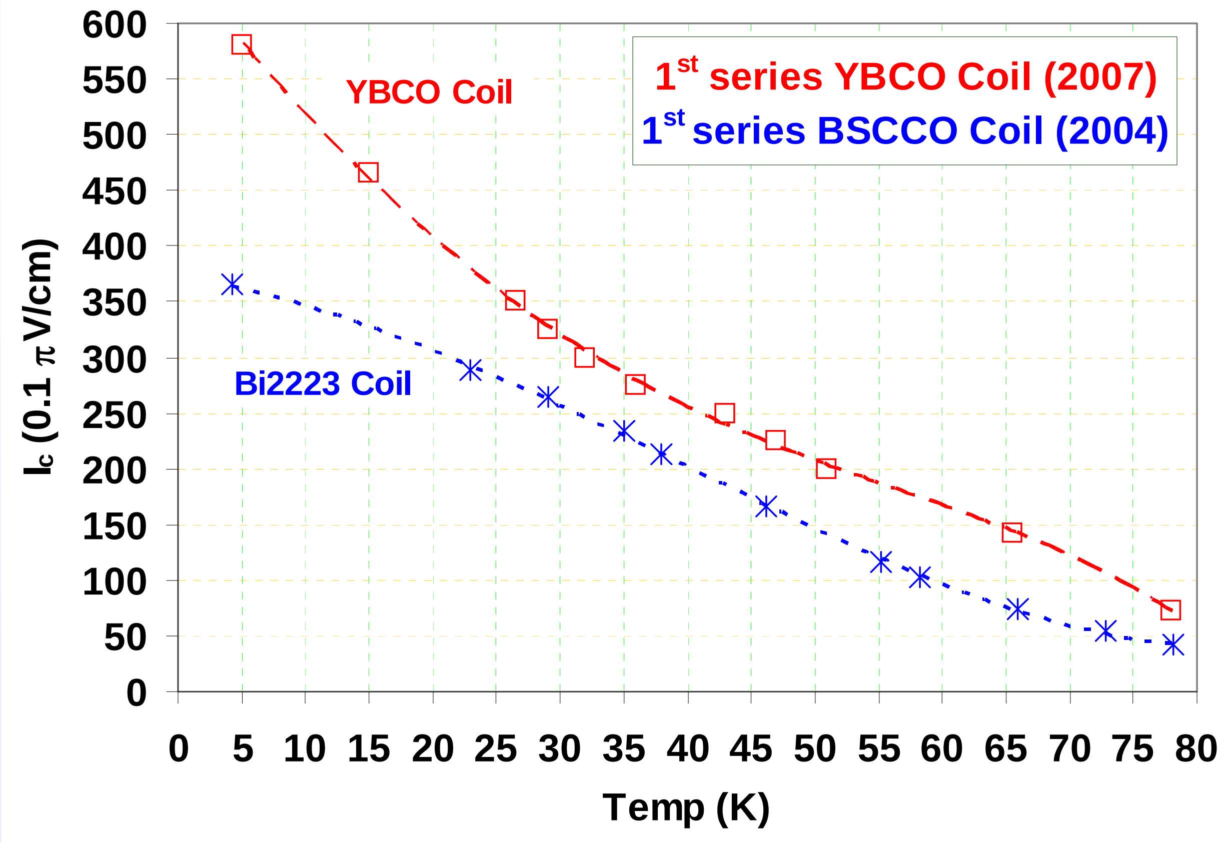
Ic (77 K, 1 T)	FY08 Zr-doped (Gd,Y)BCO	FY07 (Gd,Y)BCO	Improvement
B // c	340 A/cm	181 A/cm	88%
Minimum Ic	267 A/cm	160 A/cm	67%

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

- In the fragment separator magnets of RIA/FRIB, large energy removal is the key concern.
- Removing energy at higher temperature (~50K) will be even more efficient.
- Second generation (2G) YBCO allows energy to be removed at much higher temperature.
- Significant J_e in wire – 0.1 mm thick >250 A/mm²
- There is still room for significant improvements.

This remarkable high temperature in-field performance of YBCO opens door for many HTS magnet applications operating with sub-cool nitrogen based cooling system or with cryo-coolers which have much higher efficiency at higher temperature.

1G and 2G Coil Performance As a Function of Temperature



YBCO (2G):

Early stages

Bi2223 (1G):

Matured technology

- Even then 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

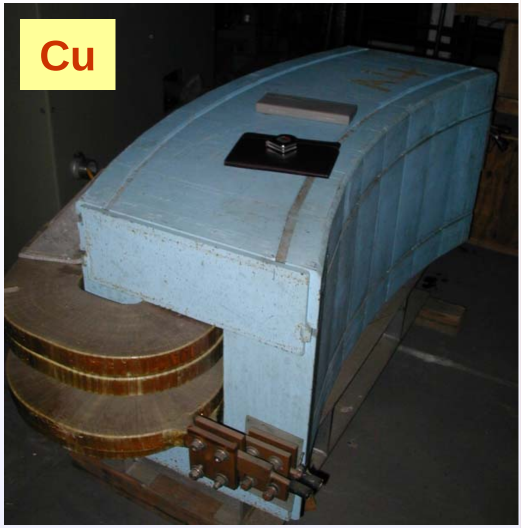
Expect relatively much more gain in 2G coils in future

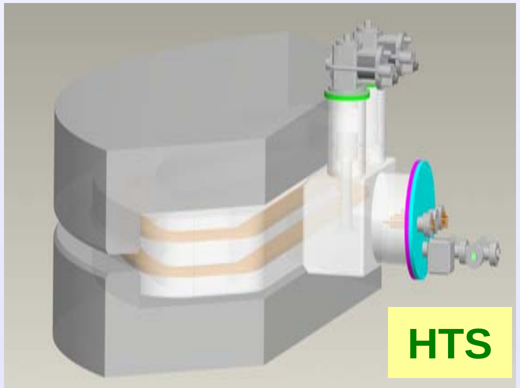
HTS Dipoles for a Super Neutrino Beam Facility Proposal

- 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





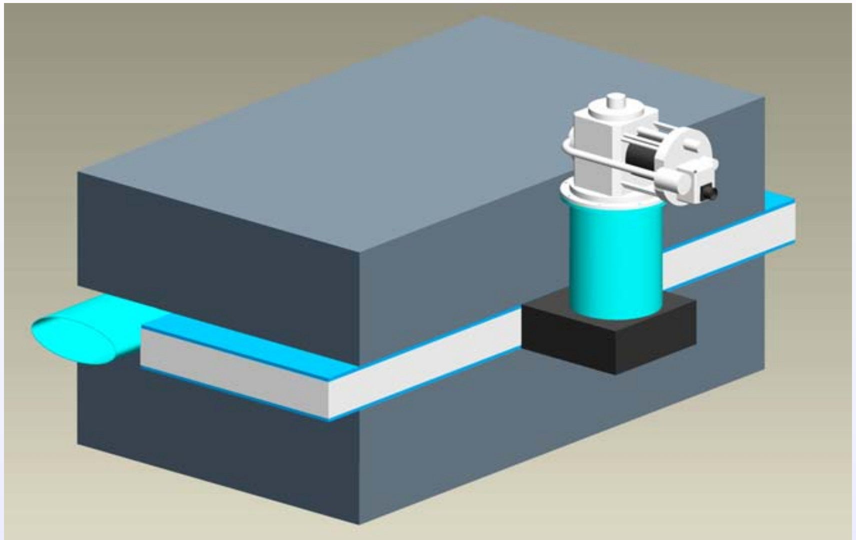
Courtesy/Contributions:
Mike Harrison

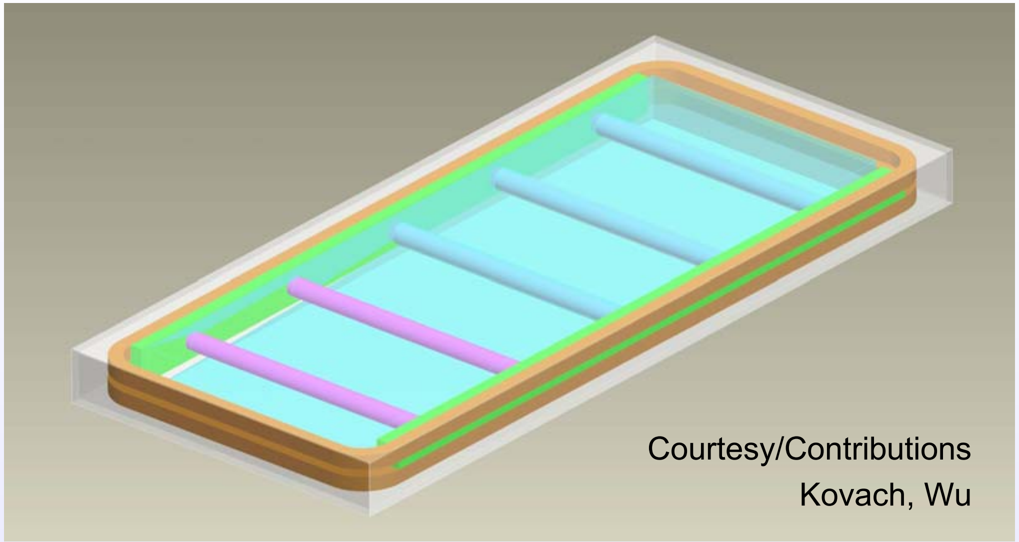
Cost of ownership must include all costs. Some outstanding:

- 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)

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

HTS dipole conceptual design for a super-neutrino beam line facility proposal





Courtesy/Contributions
Kovach, Wu

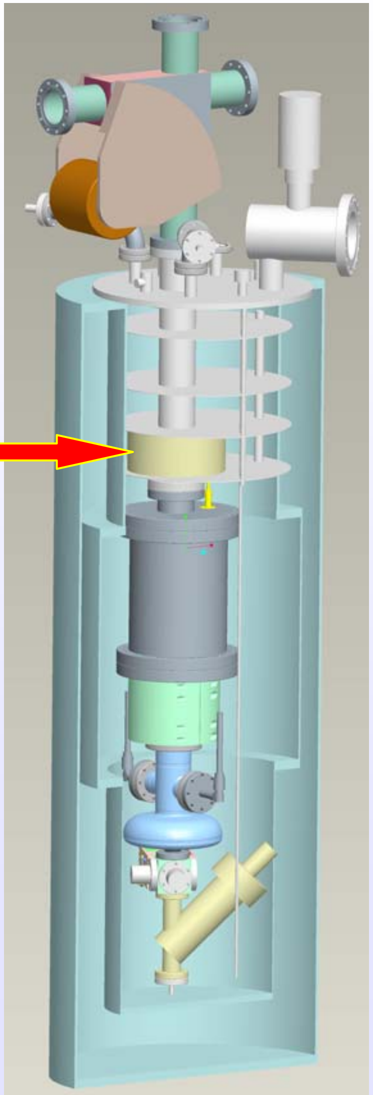
An attempt was made to develop a lower cost HTS magnet design

- **As compared to Cu magnets, HTS magnets can generate higher fields, which reduces tunnel cost and provides better technical solution.**
- **As compare to NbTi magnets, HTS magnets do not need helium.**
- **With the cost of electricity increasing and the cost of second generation HTS decreasing (in-field $A/m), there is a good possibility for future HTS magnets competing with cu and NbTi magnets for 1.5 T - 3 T (or more).**

Low Field (<0.1 T) HTS Magnets for Accelerators and Beam Lines

(a previously overlooked area)

HTS Solenoid for SRF Electron Gun (1)



Courtesy/Contributions
Ben-Zvi, Kewisch

- 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.**

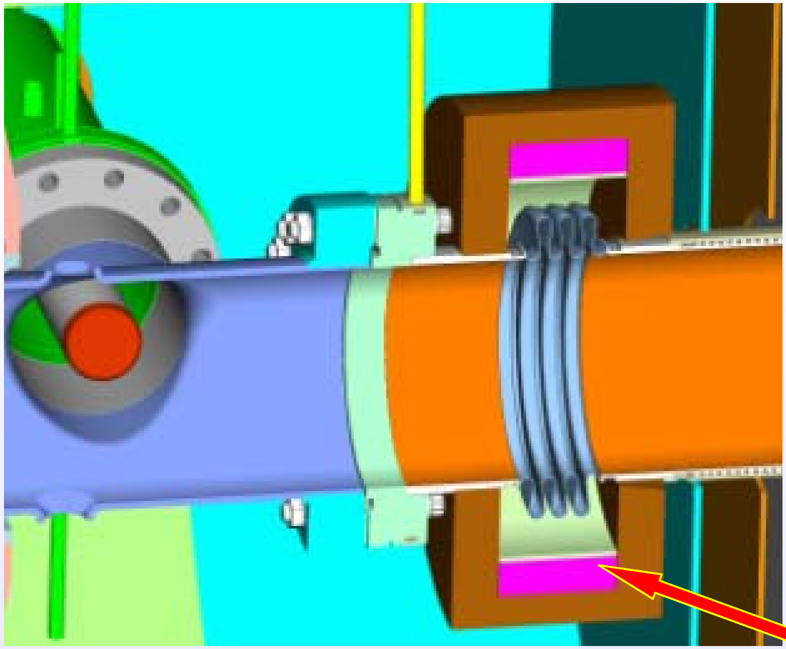
HTS Solenoid for SRF Electron Gun (2)

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

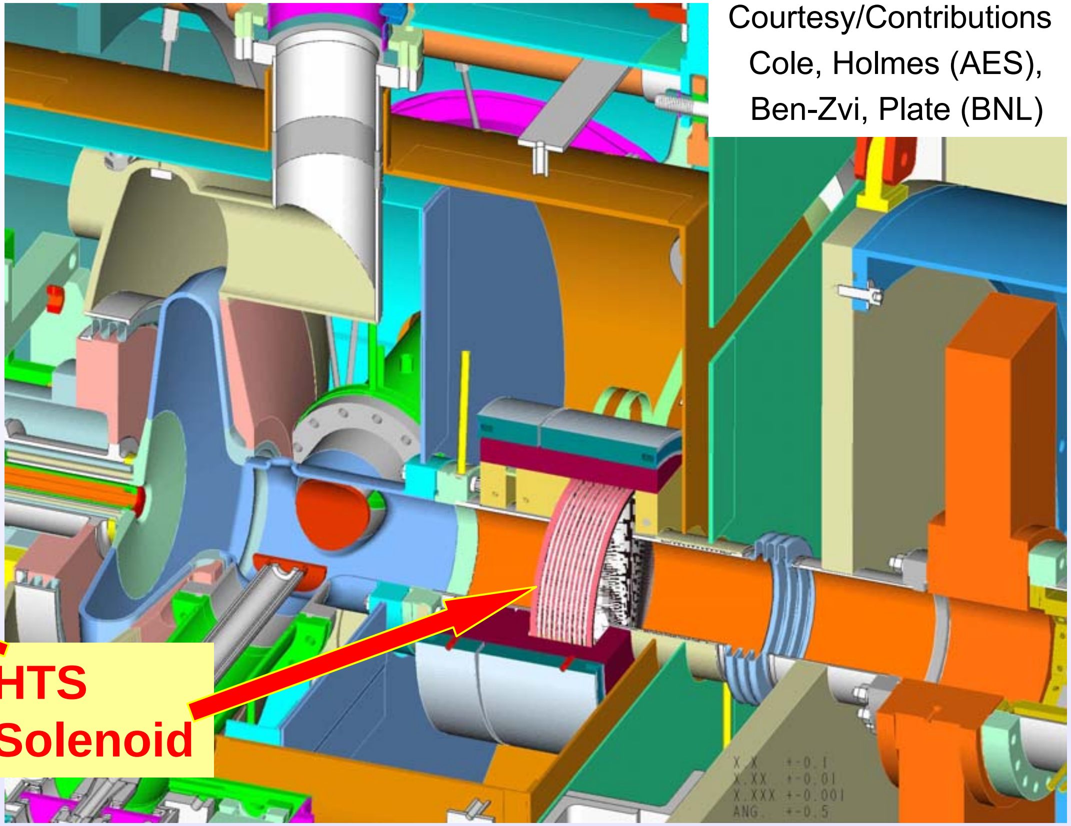
Courtesy/Contributions: Dilgen, Ince

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



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

HTS Solenoid

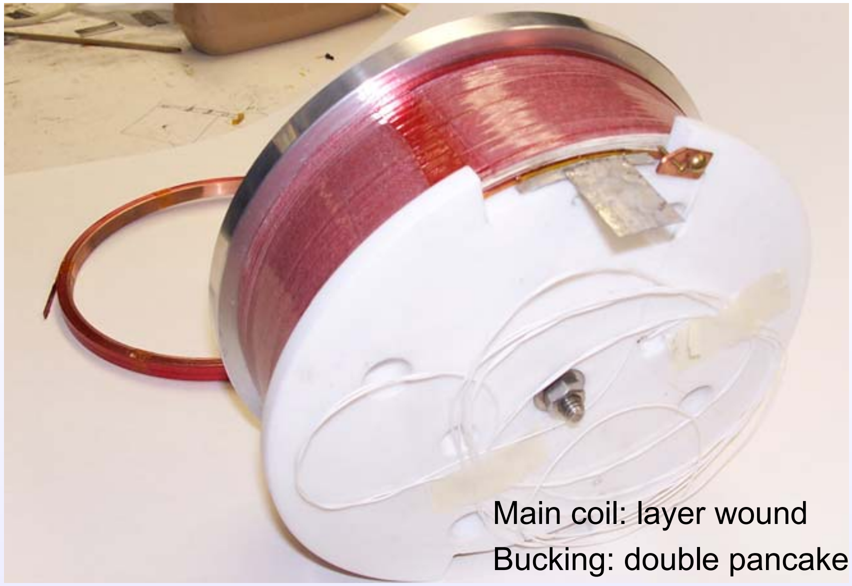


Courtesy/Contributions
Cole, Holmes (AES),
Ben-Zvi, Plate (BNL)

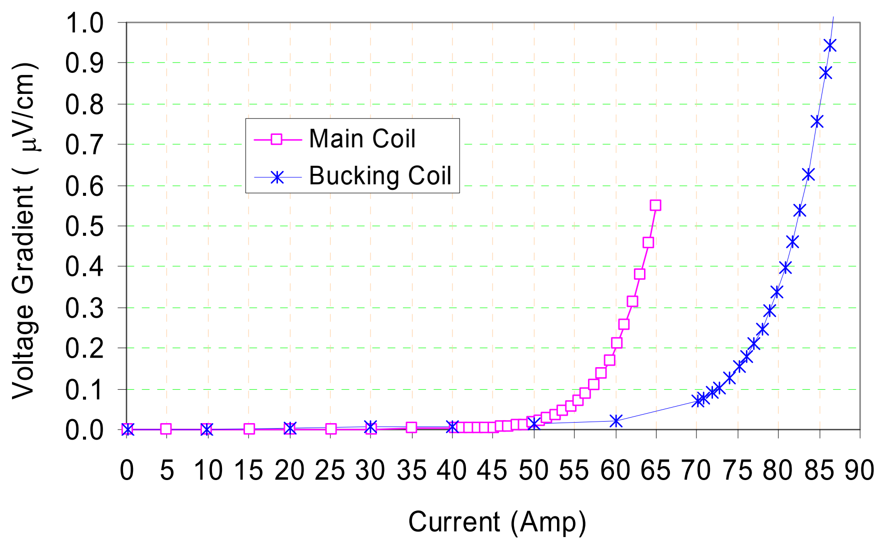
- HTS solenoid provides a solution that was not possible otherwise (a variation of the arguments presented earlier). Design performance at 77 K - savings in QA testing.
- The integral focusing strength of the solenoid is determined by iron. Keeping low field on superconducting cavity was a major design consideration.

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



Main coil: layer wound
Bucking: double pancake



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

Summary and Outlook

- **HTS magnets have provided a unique technical solution in a number of applications.**

- **In some cases, they have also been found to be cost attractive over conventional NbTi magnets when overall costs (design construction and test) are taken into account.**

- **With energy cost rising, HTS magnets may become more competitive in "cost of ownership" for large medium field copper magnets.**

- **Second generation conductor should make HTS magnets much more attractive because of (a) higher "in-field" J_e (b) lower conductor cost and (c) higher operating temperature.**

- **Medium field applications operating at 50-65 K could become a larger volume application in accelerator and medical sciences.**

Acknowledgement

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