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Ramesh Gupta

A discussion on the potential of 2G conductors in more HTS magnet applications in accelerators and medical sciences

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2G HTS Magnet R&D





Possible Applications of HTS in Accelerator Magnets

Low to Medium Field, Higher Temperature Application

- Example: Quadrupoles for the Facility for Rare Isotope Beams (FRIB)
- The system design benefits enormously from HTS because HTS offers the possibility of magnets which operate at a temperature higher than 4K, say at 20-77 K.
- Now one can seriously consider nitrogen based cooling system or cryo-coolers operating at higher temperature where they have much higher capacity (wattage)

High Field, Low Temperature Application

Example: Interaction Region (IR) Magnets for large luminosity

• At very high fields (~20 T or more), no superconductor has as high a critical current density at ~4 K as HTS does.

• In both cases, HTS magnets can tolerate a large heat/energy deposition and increase in coil temperature with only a minor loss in magnet performance.

- The coil temperature, moreover, need not be controlled precisely
 - One can relax the requirements on temperature variations (HTS allows a few degrees, as compared to a few tenth of a degree in LTS).

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This means a simpler, cheaper and more forgiving cryogenic system.
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HTS Magnets May be Attractive for Medium and Low Field Applications

- With the energy cost rising, HTS magnets may compete with large watercooled copper magnets for *"lower cost of ownership (capital + operation)"*.
- With the performance of the 2G HTS improving and the cost decreasing, one can imagine that low to medium field 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.
- One can imagine that the cryogenic system for 2G magnets can be based on LN2 or sub-cool nitrogen rather than helium – a major technical and cost saving departure from the present superconducting magnet technology.
- Even in cryo-cooler based cooling, the system benefits from the higher performance/efficiency of cryo-coolers at higher temperatures.
- HTS magnets offer several technical advantages over LTS magnets, such as ability to deal and remove large heat loads cheaply at higher temperature.
- Many of above arguments apply to accelerator and beam line magnets in both research laboratories and in magnets for medical facilities.





HTS Quadrupoles for RIA/FRIB

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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 <u>radiation</u> and <u>heat</u> 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.

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

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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 has been purchased for RIA/FRIB (1G from ASC and 2G from ASC & SuperPower)

Courtesy/Contributions Jochen

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Stainless Steel Insulation in HTS Coils

Radiation damage to insulation is 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.

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LN₂ (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 !

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RIA Quad is a Large Magnet

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Unique Feature of RIA HTS Quad :

• Large Aperture, Radiation Resistant



Courtesy/Contributions Anerella, Dilgen, Ince, Jochen, Kovach, Schmalze



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Energy Deposition and Cryogenic 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.
- Magnet worked well in both cases.

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Magnet operated in a stable fashion with large heat loads (5kW/m³) at the design temperature (~30 K) at 140 A (design current is 125 A).





Impact of Large Irradiation on YBCO

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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 !
(for details see paper 1MPH03)



Bottom line – YBCO is robust against radiation damage:

- Negligible impact on FRIB performance even after 10 years (AI 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.

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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 Nb₃Sn) can not tolerate these large heat loads and removing that energy at 4-10 K would be very costly.

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2G Based R&D for FRIB Magnets

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• Now 2G carry significant I_c/J_e in wire at high temp. – 0.1 mm thick >250 A/mm².

- Energy removal is the key concern in RIA/FRIB.
- 2G allows it to be removed at higher temperature - ~50 K rather than ~30 K – where it is much more efficient.

•2G wire is also expected to be cheaper. This would allow HTS magnets to become competitive at more places in FRIB.

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Excellent in-field performance at 65 K, 3 T



This remarkable high temperature in-field performance of YBCO opens door for many HTS magnet applications operating with sub-cool nitrogen based cooling system. Alternatively, cryo-coolers offers better cooling efficiency at higher temperature.

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



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

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Proposed Study of Doping in 2G Conductor in Actual Coils

- As a part of FRIB R&D we want to make coils with 2G having different doping.
- We want to study performance these coils as a function of temperature (as performed earlier).
- This should be an interesting study as in coil conductor faces field in all orientations.
- These results should be useful elsewhere as well and may also provide productive feedback in conductor development.
- Three coils with three different dopings??



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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)

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

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





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).

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Some Low Field Applications where HTS Provided Unique and Cheaper Overall Solution

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HTS Solenoid for SRF Electron Gun (1)

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- No room for solenoid in Liquid Helium (LHe)
- Aluminum baffles prevent cooling
- Temperature between the first set of baffles is ~20 K
- Thus NbTi/Nb₃Sn 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.

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HTS Solenoid for SRF Electron Gun (2)

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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

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- 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.

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

1.0 0.9

0.8

0.7

0.6 0.5 0.4 0.3 0.2 0.1 0.0

Voltage Gradient (μ V/cm)

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	$\sim 1 \text{ T}^2$. 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.

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Main Coil

Bucking Coil

Main coil: layer wound Bucking: double pancake



At very high fields (~20 T or more), no superconductor has as high a critical current density at ~4 K as HTS does !!!

- Two variety of magnet applications are being considered
 - > High field dipoles and quadrupoles
 - > High field solenoids
- We prefer racetrack coil magnet designs with the cable that can carry large currents
 - > Rutherford cable for round wire
 - > Roebel cable (???) for tapes





Conventional Shell and Alternate Racetrack Coil Designs

Conventional shell (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 materials such as HTS







High Field HTS Magnet Designs

- A few possible designs based on racetrack coils:
 - 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 muon colliders and high luminosity IR, HTS is particularly attractive to face large energy deposition (FRIB/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 SuperPower, September 9, 2008

Common coil 2-in-1 dipole for main ring

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Open midplane dipole for muon collider or LHC IR upgrade

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HTS Coils for Accelerator Magnets

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A 10-turn racetrack HTS coil with Rutherford cable built and tested at BNL.



• Rutherford cables are good solution for round wire conductor as they provide high current in the cable and coupling between various wires.

• Roebel cable may be the equivalent answer for tape conductor.

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HTS Magnets with Rutherford Cable



Cable for these coils were mostly provided free of cost by Showa as a part of R&D collaboration where BNL provided the test results on cable samples.



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High Field Magnet R&D at BNL with HTS Tapes







Two HTS tape coils in common coil configuration

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A coil being wound with HTS tape and insulation.



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74 mm Aperture HTS Tape Dipole

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OL

versatile

Cable Leads to allow configurations operation structure to test single higher temp coils in various HTS 2 quality **t** aperture field double Voltage taps on each turn measure 4 E E E E 4 Heaters on the magnet to make controlled change in magnet temp 4 thermometers on the coils

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Roebel Cable for High Current and Magnetic Coupling

Roebel cable with YBCO

(SuperPower + Forschungszentrum)

• Small bending radius (>11mm) possible

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)

Forschungszentrum Karlsruhe





pressed Indium sandwich contacts

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

1. Step RACC – Cable with 5 CC – Strands + 1 Cu - strand contact length 5 - 6 mm No interstrand connection for first test Parallel ext. Cu stabilizer with 5 mm² Results Mixture of 2 CC batches: different Ag c Measured transport current I_c 1,0slightly above 300 Amps (approx. 0,9 305 Amps.) 0,8 Calculated I_c was 294 A 0.7 (v) / (′=∞)° 0,6 I_c onset was detected at 300 A 0.5 (current source limit) 0,4 YBaCuO Superpower Slight transport current increase 0,3 SP-ITP-060406 through stabilising Cu strand ? —=— Sample 1 in nat. bending direction 0,2 — Sample 2 in nat. bending direction 0,1 T=77K, self field Current sharing works ! 0.0 Ag cap layer (0.4 microns) seems 10 100 Bending radius (cm) to work sufficiently ! External shunt of 1 mm² Cu ok ! Fig. 3 Critical current of MOCVD SP CC with bending applied at 77 K

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SBIR - Muon Collider/Neutrino Factory

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- Current (funded) SBIR from Particle Beam Lasers (PBL).
- PBL will purchase superconductor and do other accelerator physics and technology studies.
- BNL will build and test ~10 cm, 10 T solenoid. A part of the test plan is to measure its performance as a function of temperature as solenoid benefits by operating at a higher temperature.
- We would like to build this solenoid in a way such that:
 - it can be used for testing future HTS samples (measure critical current as a function of temperature, magnitude of the field and orientation of the field).
 - allow insert HTS coils to reach 20+ T .





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SuperPower Solenoid (that was tested at NHFML)



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BNL Solenoid – No Split (Superpower solenoid should fit inside)



Coil parameters (NO split or spacing): i.d. = 106 mm, o.d. = 190 mm, height = 80 mm Je = 450 A/mm² (1,512 kA.turns, 2450 meter)

> Coil parameters of earlier Superpower solenoid: i.d. = 19 mm, o.d. = 87 mm, height = 51.6 mm Je = 346.8 A/mm² (607kA.turns, 458 meter)





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Conductor Testing Resources at BNL

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- Strand Testing
 - 8T/10T (4.2/1.9K) 60 mm bore solenoid
 - 12T 50 mm bore solenoid
 - Testing barrel for Nb3Sn strands
 - Test current 1500 A
- SEM, Optical Microscope, at CMPMSD
- Magnetometer for magnetization tests to 5T
- Heat treatment facility for Nb₃Sn strand & cable
 - Tube furnaces at CMPMSD
 - Large furnace at SMD

Cable Testing

- 7.5T, 75mm bore dipole magnet
- Test current 25 kA
- Can be used for Rutherford/Roebel cable



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$I_c(B)$ Measurements of Rurtherford Cable

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Bi2212 Cables from Showa over a period of time

Significant selffield at high currents.

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Field and Temperature Dependent Test

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This facility can be used for testing high performance (high current) wire or Roebel Cable

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77 K Testing to Field over 1 T



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- High field all HTS solenoid (Superpower inner, BNL outer).
- Measurements of the performance of conductor as a function of temperature, field and direction of field. This is particularly important for doping studies. In order to better characterize the conductor we should have continuous curves with several points.
- Study of the performance of coils as a function of temperature for the coils made with the conductors having different dopings.
- Identifying applications and developing magnet designs where HTS would play a significant role (and if we can find source of funding, then build and test the system as well).



Concluding Remarks

- There are several possible areas where HTS magnets can be attractive.
- However, being a new technology, not many are aware of the benefits of HTS and/or comfortable and convinced of the 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.
- Current second generation conductors should make 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 could become a larger volume application in accelerator and medical sciences.
- In very high field applications (20+ T), HTS is the only High Field Superconductor (HFS). Now is the time to build demonstration magnets.

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