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

Ramesh Gupta and William Sampson

***Abstract*—High Temperature Superconducting (HTS) magnets may offer an attractive alternative to both water-cooled copper and conventional low temperature superconducting magnets in many accelerators and beam lines. With energy cost rising and conductor cost falling, HTS magnets operating in the 20-60 K temperature range are gaining renewed interest for the lower cost of ownership (capital + operation). Moreover, in a few low to medium field R&D applications, HTS magnets not only provided a better technical solution but also proved to be less expensive to build and test than the magnets made with conventional Low Temperature Superconductors (LTS). In addition, HTS magnets can tolerate large energy and radiation loads and can operate with a simpler cryogenic system. This paper will present several specific examples.**

***Index Terms*— High Temperature Superconductors, HTS magnets, Facility for Rare Isotope Beams, muon colliders.**

I. INTRODUCTION

HTS magnets have been examined as a way to reduce operating cost of the large aperture medium field (~1 T to ~3 T) magnets that are usually energized by high wattage water-cooled copper coils. The technical advantages of HTS magnets have been discussed earlier [1].

HTS quadrupoles have provided a unique solution for the fragment separator region of the proposed Facility for Rare Isotope Beams (FRIB) and Rare Isotope Accelerator (RIA) where the radiation and heat loads are expected to be enormous [2]. Recent irradiation studies have shown that the YBCO is highly radiation tolerant [3] and BSCCO2223 is sufficiently tolerant [4]. Earlier energy deposition experiments have demonstrated [5] that HTS can efficiently remove large heat loads at elevated temperatures. In FRIB, the HTS magnet option has also been found to be cheaper to build than the room temperature magnets (see section II A).

In a few low field applications, HTS provided the only technical solution where neither the room temperature nor the conventional LTS could offer a comparable one. Moreover, the overall cost (design, built and test) of these short HTS magnets was found to be cheaper than the comparable LTS magnets. This is because these HTS magnets could be tested at the design field in liquid nitrogen (77 K), which is much cheaper and simpler than testing LTS magnets in liquid helium (~4K).

In some applications, where cryogen-cooled magnets are not practical, dry systems cooled by cryo-coolers become attractive. HTS (a) allow higher operating temperature where cryo-coolers have larger capacities (wattage) and (b) allow larger variation in temperature along the length of the coil which permits conduction-cooling with fewer cryo-coolers.

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II. Medium Field Applications

Five magnets are presented to illustrate a variety of possible applications of HTS medium field magnets. While the first two cases are discussed in some detail, only a brief summary is presented for the rest.

A. HTS Quadrupoles for FRIB/RIA

A large number of coils have been built and tested in a number of magnet structures [5] for FRIB and RIA. Fig. 1 shows a model HTS quadrupole. Details of the design, construction and test results of this magnet can be found elsewhere [5-7].

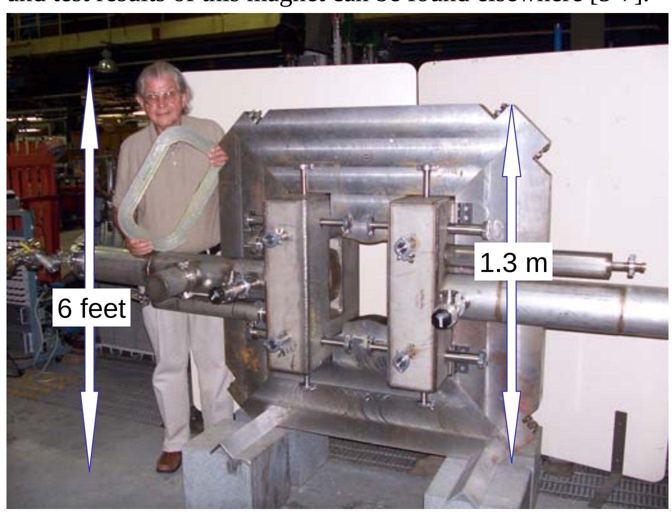

Fig. 1. A warm iron 290 mm aperture HTS quadrupole for FRIB.

The above magnet was built with 24 coils using ~4.5 km of the first generation (1G) HTS (BSCCO2223) from ASC [16]. 1G HTS allowed operation at ~30 K rather than ~4 K for conventional LTS. Second generation (2G) HTS (YBCO) could allow operation at even higher temperature (~50 K) where the removal of large heat loads is even more economical. Test results of the first of many coils made with 1G HTS (~175 turns) and 2G HTS (~95 turns, conductor from SuperPower [15] and ASC [16]) are shown in Fig. 2. It may be noted that 2G HTS is in the early stages of development and still has room for significant improvements.

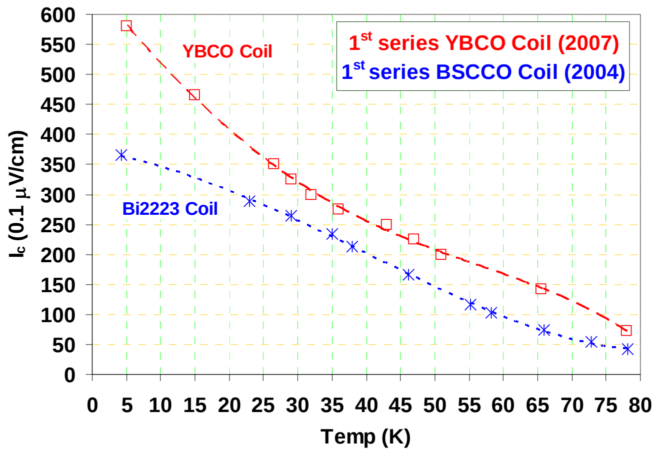

Fig. 2. Performance of one of the first series of coils made with BSCCO2223 (1G) and one of the second series of coils made with YBCO (2G).

In table I, the HTS magnet option is compared with the radiation resistant room temperature magnet option [8]. In this case, the HTS magnet option was cheaper to build, cheaper to operate, had superior performance (the room temperature option did not create an equivalent gradient) and weighed less as well. The 2G HTS has also been found to be highly radiation resistant [3] beside operating at ~50 K.

TABLE I COMPARISON OF THE RADIATION RESISTANT ROOM TEMPERATURE AND HTS QUADRUPOLE OPTIONS FOR FRIB [3].

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

B. HTS Dipoles for Super Neutrino Beam Proposal

A design study was carried out for the HTS magnet option for the beam transport line for the Super Neutrino Beam Facility proposal [9]. An earlier proposal was based on 1.55 T, 3.7 meter long room-temperature magnets. The HTS magnet design was optimized to reduce cost and then to do the cost of ownership comparison with the room temperature magnets. With the rapid AGS cycle rate, the beam line operating continuously with room temperature magnets, the estimated consumption was ~3MW of power (~$2K/day) or about $250K for a nominal 5 month run. Room temperature magnets also incur significant infrastructure costs that include a longer tunnel, cooling water, high current power supplies, etc.

The proposal based on HTS magnet technology was expected to significantly reduce the operating cost of the primary proton beam transport line. It may also have reduced the overall capital/construction cost and provided an enhancement in the performance by allowing a shorter primary beam transport line, or a longer decay channel (hence a larger neutrino beam intensity) or both. In the overall cost comparisons, the cost of cryo-coolers, etc. must be included.

A conceptual design based on cryo-cooler is shown in Fig. 3. A primary proton beam transport constructed from such HTS magnets, operating at a temperature of ~50K with second generation conductor, will be much more compact than room temperature magnets. They may be either cooled by plug-in cryo-coolers or alternatively by a local re-circulating helium gas based cooling system run entirely by cryo-coolers. HTS magnets can significantly reduce or potentially eliminate the beam line cooling water system. The magnets will operate at a few hundred amps, about a factor of ten lower than the current required for room temperature magnets. The estimated HTS cost is ~$50K based on either the present cost and performance of 1G operating at ~30 K or the expected cost and performance of 2G by year 2009 operating at ~50 K. This is about 1/3 of the total estimated cost of the equivalent room temperature magnet.

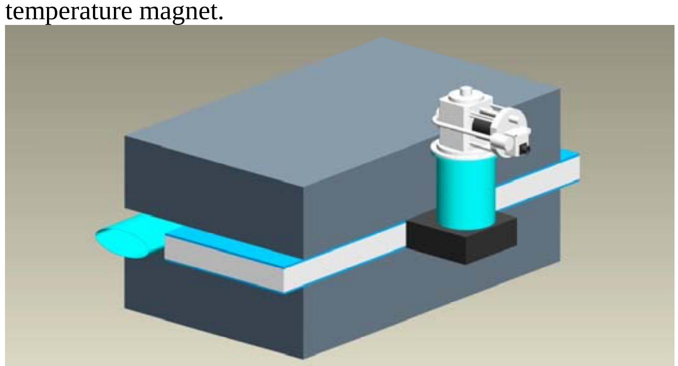

Fig. 3. Conceptual design of HTS magnet with cryo-cooler for Super Neutrino Beam Line at AGS at BNL.

C. HTS Dipole for NSLS2

HTS dipole magnets were considered for the NSLS-II [10] as a way to deal with the increasing cost of electricity. ~1T and 0.4 T designs were examined with 0.4 T as the final choice for machine physics reasons. Fig. 4 shows one of several magnetic designs evaluated for developing a low cost design of this dipole. However, at 0.4 T field, the cost of ownership (capital + operation) of HTS magnets was not favorable compared to water-cooled copper magnets, and therefore, the HTS option was not pursued further.

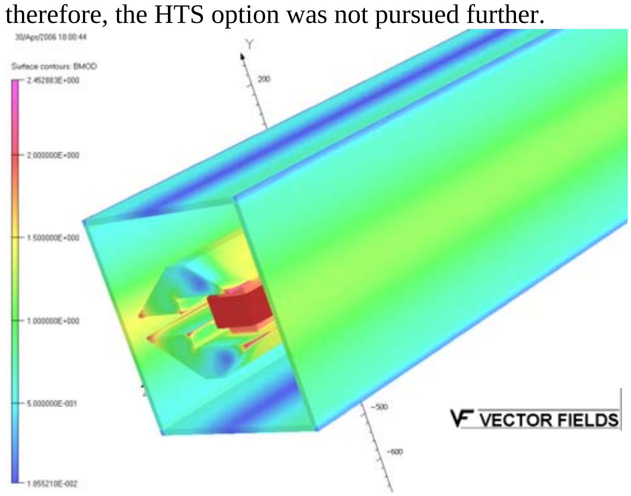

Fig. 4. Preliminary magnetic design of a possible 0.4 T HTS dipole that was once considered as an option for NSLS2.

D. HTS Quadrupole for ILC

This HTS quadrupole (QFEX4B-4E) was designed for one of the extraction lines [11] of ILC (International Linear Collider). The quadrupole has a good field radius of ~85 mm, field gradient of ~13 T/m and the entire magnet must fit with 400 mm outer radius while meeting the small fringe field requirements. A preliminary magnet design was developed with 2G HTS. The operating temperature was ~65 K, which could be either achieved with cryo-coolers or sub-cooled liquid nitrogen. As compared to the room temperature magnets, HTS magnets would be more compact (easily fit within the restricted space), would be energy efficient and allow much larger temperature excursion compared to conventional LTS magnets.

E. *HTS Quadrupole for LHC Upgrade*

A superferric quadrupole with a radius of 34 mm and a gradient of 230 T/m was examined for one of the optics of LHC IR upgrade [12]. This quadrupole, operating at ~20 K, could be embedded in TAS and the HTS coils would be inside the copper which removes major radiation and heat. The radiation and heat loads in this case are large but comparable to those present in RIA/FRIB. Since this permits the quadrupole closer to the interaction point, it provides efficient focusing. However, this case was not considered as a serious contender for upgrade optics and therefore was not pursued in detail. Nevertheless, HTS magnets could play a significant role in various LHC upgrade scenarios.

III. Low Field Applications

In this section, two low field HTS magnet applications are discussed. Both are solenoids.

A. *HTS Solenoid for SRF Electron Gun*

A solenoid is needed after the Superconducting Radio Frequency (SRF) electron gun to focus the diverging beam [13]. The electron gun resides in a 100 liter cryostat with no room for a solenoid in the liquid helium. As shown in Fig. 5, the heat shield to the top consists of compartments separated by aluminum plates (baffles). The plates prevent heat transport by circulation of the helium gas. The estimated temperature between the first set of plates is ~ 20 K. The HTS solenoid is placed in this region. The solenoid should create an integrated axial field of ~2.5 T•mm.

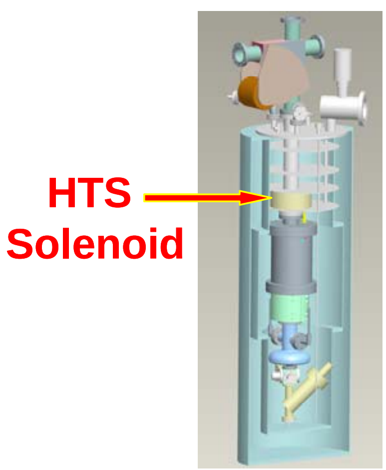

Fig. 5: HTS solenoid with SRF Gun.

Use of a conventional low temperature superconducting solenoid was not possible because of the high (~20 K) temperature. A copper solenoid magnet was calculated to produce 500 W of heat. This is in contrast to the measured ~5 W heat load of the entire cryostat without the solenoid. In principle a warm magnet could be placed outside the cryostat but that brings a large deterioration in the performance as the distance to the first focusing solenoid becomes too large for the diverging beam.

Fig. 6 shows the HTS solenoid, as installed, between the first set of aluminum plates. The solenoid has an inner diameter of 133.5 mm and outer diameter of 173.5 mm. It consists of two double pancake coils having a total of 220 turns. Each of the four coils used 26.5 m of 4 mm wide BSCCO2223 tape, and was made with the pieces left over from other projects. The solenoid ran in liquid nitrogen (~77 K) in a stable fashion up to a current of 46 A, well above the critical current of ~35 A (defined for a gradient of 0.1 μV/cm). The operating current in the system is limited by the feed through to <20 A. The design performance (2.5 T•mm) is achieved at only ~9.07 A. Liquid nitrogen testing of the solenoid before incorporating it in the system was significantly less expensive than testing of equivalent conventional LTS solenoid in helium based cryo-system. In fact, it has been found that in such small scale low field applications, the cost of designing, building and testing an HTS solenoid is significantly cheaper than the equivalent conventional LTS solenoid in a helium based cryo-system.


Fig. 6. HTS solenoid between the aluminum baffles. SRF Gun will be situated below this assembly.

B. *HTS Solenoid for ERL*

An HTS solenoid has been built and tested for the SRF gun of the proposed Energy Recovery Linac (ERL) to decrease the emittance of the electron beam [14]. The solenoid is placed between the superconducting gun cavity (see Fig. 8) and the gate valve. Compared to a room temperature magnet, the HTS solenoid makes overall design much simpler and technically superior. With the smaller beam pipe size possible, HTS significantly reduces the amount of material needed to make the coil and greatly reduces the power needed to drive the magnet and subsequently the heat generated during its operation. The solenoid is situated in the transition region (4K to room temperature) where the temperature is expected to be too high for a conventional low temperature superconductor.

In addition to the main coil, the solenoid consists of a bucking coil to minimize the field on the superconducting RF cavity. Additional shielding between the solenoid and cavity ensure very low field. In fact, assuring that the trapped field is below the milli-Gauss level on the superconducting cavity has been a major design consideration.

The main coils are placed over the bellows, so little additional space is consumed. The majority of the field is generated by the iron which has a much smaller inner radius than the coils (see Table II). The main coil is a layer-wound coil with 180 turns in 15 layers and the bucking coil is a double pancake coil with a total of 30 turns (Fig. 7). All coils were made with helically wrapped Kapton insulated 1G tape supplied by American Superconductor Corporation [16]. Major parameters of the solenoid are given in Table II.

TABLE II MAJOR PARAMETERS OF HTS SOLENOID FOR ERL

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

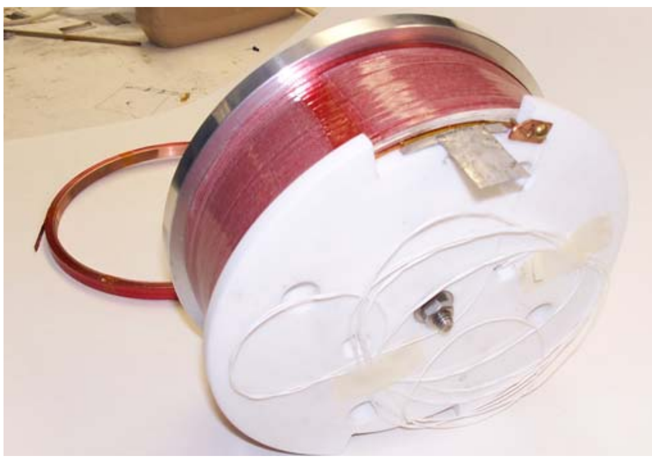

Fig. 7. HTS solenoid for the proposed ERL project.

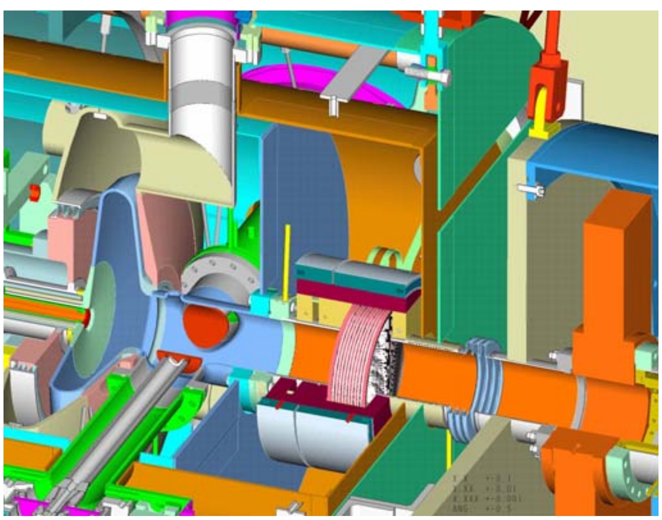

Fig. 8. Main coil (layer-wound, in front) and bucking coil (double pancake, in back) of the HTS solenoid for the ERL project.

Fig. 8 shows the voltage current characteristics of the main and bucking coils when the measurements are carried out at 77 K (liquid nitrogen). The main coil has an I_c of 54 A and the bucking coil 72 A respectively when I_c is specified for a gradient of 0.1 μV/cm. The lower I_c in the main coil is due to the higher field. In the actual magnet structure, iron would make the field more parallel to the HTS tape which would increase I_c of both coils. Clearly both coils are well above the design value of ~35 A. The margin in operating conditions will actually be much greater as the temperature will be well below 77 K. The solenoid could, in principle, have been designed with fewer turns but the desire to use 50 A HTS leads motivated an ~35 A operating current and a larger number of turns to reach the required Amp-turns. In this case the strength of the solenoid is determined by the iron that has a smaller inner radius than the coil.

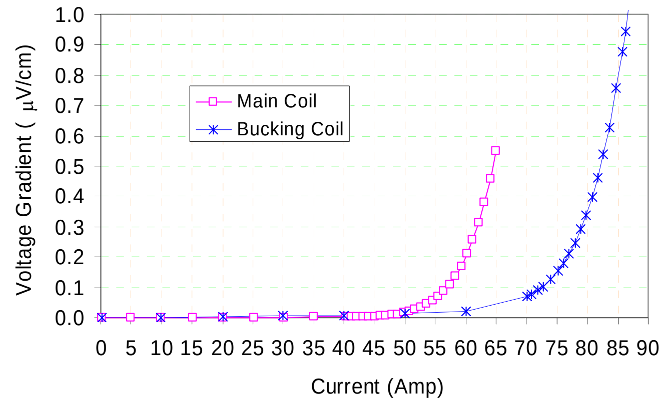

Fig. 9. Measured voltage gradient at 77 K of the main coil (l80 turns) and the bucking coil (30 turns) HTS solenoid for the proposed ERL project. Both coils reach well above the design current of ~35 A.

IV. CONCLUSIONS

In the several applications presented in this paper, HTS magnets have been found to provide unique technical solution. In a few cases HTS magnets have also been found to provide an overall cheaper solution compared to the water-cooled room temperature copper magnets and/or conventional low temperature superconducting magnets. With the in-field performance of the second generation HTS (YBCO) improving and the cost decreasing [15, 16], HTS must be considered in future accelerator and beam lines. With energy cost increasing, the medium field magnets operating at ~65 K offer an attractive option.

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