The HTS Magnet R&D Program at BNL

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The performance and production lengths of High Temperature Superconductors (HTS) wire have now reached levels such that credible R&D can be carried out to address the issues related to their use in accelerator magnets. HTS offer two distinct advantages over conventional Low Temperature Superconductors (LTS) - they retain a large fraction of their current carrying capacity (a) at high fields and (b) at elevated temperatures. The first likely application of HTS could be the incorporation of a few high performance interaction region (IR) magnets in a machine to allow higher luminosity operation. At BNL, we have built and tested several short HTS (and Nb_3Sn) coils and magnets, developed several new designs, and demonstrated a new fast turn around and cost effective R&D approach. However, future R&D will become more complex; therefore, progress will depend largely on available funding.

1. Introduction

The subpanel on long range planning for U.S. High-Energy Physics has recommended (draft report, October 29, 2001) that the highest priority be given to a "*high-energy, high-luminosity, electron-positron linear collider*". It also states, "*High field magnet research is particularly important. This work is essential for upgrading the LHC, and has considerable potential for applications in high-energy and other fields, including industry. Experience with high-field magnets is needed to find the optimum design for new hadron or muon colliders*". These recommendations imply that magnet R&D should be continued and our time horizon must be long term. In this unique situation, directing resources towards innovative, high risk and high payoff R&D would be preferable over continuing to labor towards achieving incremental improvements in the designs and technologies that have been in existence for a long time. R&D on HTS-based magnets ideally fits this strategy. HTS-based magnets have the potential to influence the design and operation of future particle accelerators [1]. These magnets, if feasible, would allow a major luminosity upgrade of the LHC IR's since the magnets would attain very high fields and tolerate significant energy deposition from particles hitting the coils. This technology is also potentially useful in future hadron, electron and muon colliders.

2. High Temperature Superconductors

HTS wire (and tape) have been made in lengths exceeding 1.5 km. These long lengths are sufficient to make cable for accelerator magnets. Moreover, the performance of HTS has been continuously improving [2], [3]. At present, the critical current density (J_c) of HTS in wires of reasonable length (~100 meters) exceeds that of LTS above about 12 T (Fig. 1).

Apart from producing high fields, another significant advantage of HTS is that a few degree of temperature rise does not reduce the critical current density by a large amount. This means that, as compared LTS coils, HTS coils will be much more tolerant of local heating. A weak or local hot spot that would have caused a quench in an LTS coil would merely amount to a local increase in the heat load in an HTS coil.

We have considered using BSCCO 2212, BSCCO 2223 and YBCO as possible candidates for HTS. Although MgB_2 (a higher temperature LTS) is making rapid progress in performance, it, like YBCO, is not yet available in sufficient length to make R&D coils. Therefore, all HTS R&D coils at BNL have been made with either BSCCO 2212 or BSCCO 2223. For accelerator magnet applications, cable is preferred over tape. Rutherford cable, made with a large number of wires (strands), provides higher operating current (lower inductance) with good coupling between the wires.

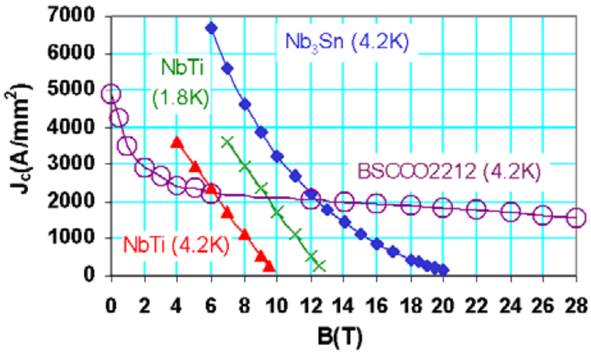

Fig 1: The performance of various superconductors in the year 2000.

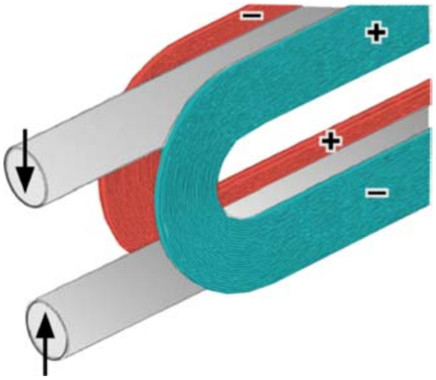

Fig. 2: The main coils of the "conductor friendly" common coil design concept.

3. Magnet Designs

All present high field superconductors, such as HTS and Nb_3Sn, which can generate fields well above 10 T, are brittle. We are developing a number of alternate magnet designs that are based on "conductor friendly" racetrack coil geometry with a "large bend radius" (see, for example, the common coil design shown in Fig. 2). Though we would examine "Wind & React" approach for small aperture quadrupoles, we prefer "React & Wind" technology as the required temperature control of ~0.5 degree at ~850 degree Celsius over the entire coil volume may be very difficult. The "React & Wind" approach has the further advantages that one does not have to deal with the differential thermal expansions of various materials in the coil and that one can use a variety of insulation schemes since the insulation does not go through the high reaction temperature. However, the "React & Wind" approach requires one to deal with the brittle materials during coil winding without causing significant degradation in handling the pre-reacted cable.

Brittle superconductors, such as HTS and Nb_3Sn, are prone to large degradation when the bending strain exceeds a critical value. The following "*conductor friendly*" designs have been developed to make "React & Wind" technology attractive for high field magnets:

- Common Coil Dipole Design for Hadron Colliders [4]
- Open Midplane Dipole Design for Muon Collider [5]
- Interaction Region Quadrupoles for High Luminosity IR's [6]

These block-type designs for dipole and quadrupole magnets are also advantageous in containing the large Lorentz forces associated with high fields.

In Table 1, we compare the two versions of a series of dipole designs (optimized for various fields) where Nb_3Sn coils are replaced by BSCCO 2212 coils. The current density in the copper is kept at 1500 A/mm^2 (or lower in HTS magnets to keep the Ag/SC ratio at least 3:1). The large amount of silver that accompanies the superconductor reduces the engineering current density now, but would not be a limiting factor in future magnets as the critical current density goes up. Table 1 is based on the critical current density available in the year 2000 (2200 A/mm^2 in Nb_3Sn and 2000 A/mm^2 in HTS) and extrapolation for future (3000 A/mm^2 in Nb_3Sn and 4000 A/mm^2 in HTS). The critical current density values are given at 12 T and 4.2 K. Expected future values could be realized in 2-5 years depending on the level of effort.

Table I: Computed fields in dipoles when HTS coils replace the Nb3Sn coils.

Year 2000 Conductor		**Expected Future Conductor (2-5 Year)**	
All Nb_3Sn Coils	**All HTS Coils**	**All Nb_3Sn Coils**	**All HTS Coils**
12 T	**5 T**	**12 T**	**11 T**
15 T	**13 T**	**15 T**	**16 T**
18 T	**19 T**	**18 T**	**22 T**

4. BNL Magnet Program Overview and Philosophy

The primary goal of this R&D program is to investigate the feasibility of and develop the technologies needed for building accelerator magnets using HTS materials. To develop the new HTS magnet technology in an experimental manner, a rapid turn around program has been instituted [7], [8]. We have adopted the "React & Wind" approach and are developing this and other associated technologies. Magnets with both HTS tapes [9] and cables [2] have been built and tested. The magnet structures (two structures for tape coils and two for cable coils) have been simple and yet versatile enough to allow a variety of tests in various configurations.

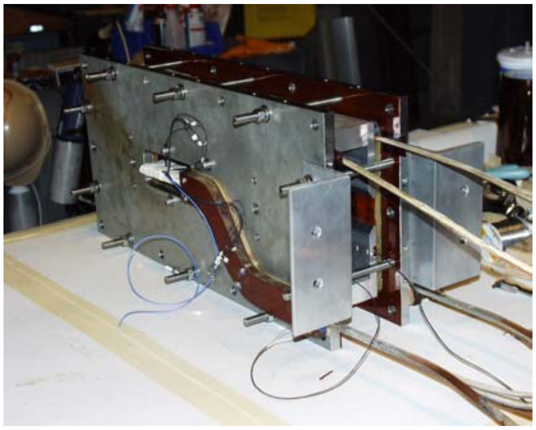

Fig. 3: The common coil magnet DCC006 made with HTS coils. It has an aperture of 74 mm to allow field quality measurements.

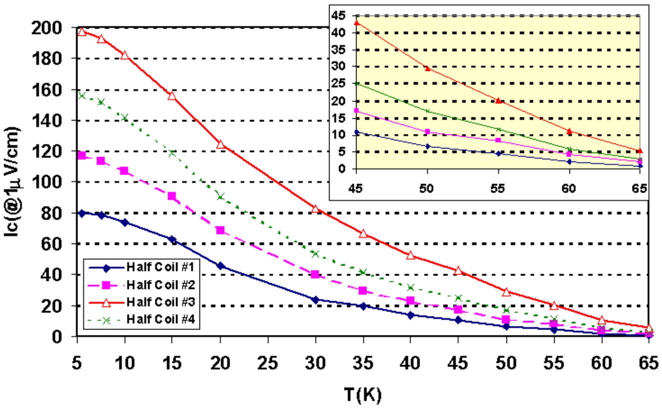

Fig. 4: Critical current measurements of HTS (BSCCO 2212) cable coil as a function of temperature.

The first series of cable magnets (Fig. 3) has only 10 turns in each coil and the straight section is only 30 cm long to minimize the use of expensive HTS for developing the basic techniques.

The choice of these parameters, coupled with a rapid turn around program, allows us to carry out cost effective R&D where a number of ideas can be tested and iterated in a short period of time. This philosophy encourages both systematic and innovative R&D. We have been able to develop and test several new techniques with the help of thirteen cable coils (five HTS and eight Nb_3Sn) built in ~2 years. Ten tape coils (eight HTS and two Nb_3Sn) have also been built and tested.

In addition to developing designs, the BNL program will continue to address the major technical issues associated with High Field HTS magnets. The following items have been identified for this ongoing R&D:

(a) HTS cable performance
(b) strain degradation in HTS cable when wound in a coil
(c) degradation in HTS coils under large Lorentz forces generated in high field magnets
(d) HTS coil under heat load
(e) react and wind technology
(f) high field magnet structure
(g) cable insulation
(h) vacuum impregnation

5. Test Results

A variety of tests are being performed to develop and understand the technology in a systematic manner based on experimental results. This includes the testing of tape and cable [10] before and after they are wound in the magnet. The conductor performance is also measured in intermediate steps. It is encouraging to note that so far we have not observed a large amount of degradation in HTS coils. The magnets themselves are tested in a variety of configurations. We have performed seven sets of cable magnet/coil tests in liquid helium and many more in liquid nitrogen. The coils were tested in a temperature range of 4-77 K (4-65 K in liquid helium and 55-77 K in liquid nitrogen). The results of such measurements are shown in Fig. 4, Fig. 5 and Fig. 6 and are discussed in more detail later. We have also started making field quality measurements.

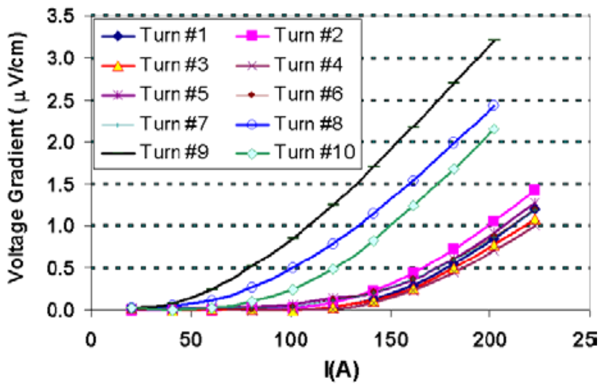

Fig. 5: Voltage Gradient across each turn in a 10-turn mixed strand HTS cable (16 Ag, 2 BSCCO 2212) coil to determine I_c of the wire at 4.2 k.

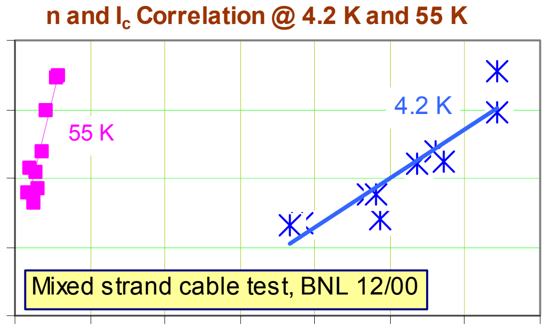

Fig. 6: Correlation between "n value" and I_c.

6. Impact of Heating and Coil Resistivity

Apart from maintaining significant critical current density at high fields, HTS magnets can operate over a large temperature range without a significant loss in performance. This range could be a few degrees rather than a few tenth of a degree as required in conventional LTS magnets. This will significantly simplify the cryogenic system and its control. Moreover, HTS coils can tolerate significant local heating generated either internally from the coil or externally from decay particles.

HTS coils could operate in a semi-resistive mode with a low level of resistivity because of a high critical temperature. In the present stage of HTS conductor development, the transition from the superconducting to normal phase is slow. This is shown in Fig. 5, where the voltage gradient in the HTS cable is plotted as a function of current. We define the critical current density in HTS as the current density when there is a 0.1 μV/cm (instead of the industry standard 1 μV/cm) average gradient in the voltage along the length of the conductor. This would create a 20 W/m heat load in a 100-turn, 2-in-1 magnet operating at 10 kA. Such a large heat load would cause a temperature rise of only 1-2 Kelvin [11] in a 10 meter long magnet based on typical VLHC/LHC IR upgrade parameters. This means that the above HTS resistivity is primarily an issue of heat load on the cryo-system, limited by its capacity. Such increase in temperature (1-2 K) does not reduce the critical current or magnet performance significantly. This heat load on the cryo-system is expected to reduce significantly as the conductor performance improves. A parameter that tells how fast the transition from superconductor to normal phase occurs is called the "n-value" and comes from an empirical equation: $V=k I^n$, where V is the voltage measured along the length of the cable at a current I and k is a constant. In Fig. 6, we plot the measured "n-value" as a function of critical current for various sections of an HTS wire. Fig. 6 suggests that as the conductor performance (I_c) improves, the difference in I_c arising from different thresholds will become smaller. This means that in defining I_c, a lower threshold of resistivity may be used, which in turn means that the heat load on the coils would become smaller as the conductor performance improves. A similar situation was faced during the early R&D on low temperature superconductors.

7. Future Plans of HTS Magnet R&D at BNL

The next step of the HTS R&D program at BNL will be to build a 12 T, Nb_3Sn background field magnet where ~40-turn HTS coils can be tested. These tests will address most technical issues related to high field HTS magnets, as the HTS coil will be subjected to large forces in a high field environment. In this section we lay out a 5-year R&D plan that can be carried out with modest funding. A successful outcome of this R&D will direct us towards detailed work on high performance IR magnets, whose designs will continue to be developed in parallel. These magnets can be used in a high luminosity machine where the requirement on the pole tip field is high and the energy deposition in the superconducting coils is large.

In the coming years, we propose to build 4-6 HTS coils/year with the number of turns ranging from 30-50. In parallel we will continue to build a larger number of 10-turn coils. We will conduct 8-10 tests/year in a variety of configurations (dipole, quadrupole, hybrid, all HTS, etc.). Most of these tests will address issues pertaining to HTS coil performance; however, some will involve field quality measurements as well. We will also simulate conditions of large energy depositions on the HTS coils. The designs and technologies developed will be such that in most cases they can be used in building full-scale accelerator magnets.

8. Conclusions

HTS is an attractive option where the performance of a few magnets rather than the cost of conductor determines the future upgrade of colliders. HTS wire with reasonable performance is presently available in sufficient lengths to perform credible magnet R&D. Initial results of the BNL program are encouraging. Since HTS is a new and challenging technology, a reasonable level of magnet R&D should be started now to allow sufficient time (~5 years) for developing the designs and techniques. Results of the R&D would then be available in time for choosing a direction for luminosity upgrades of then-existing machines. The outcome of the proposed HTS R&D at BNL would help the HEP community make a more informed decision about the potential of HTS in accelerator magnets. Apart from providing a hefty luminosity upgrade of machines existing at that time, HTS based magnets may change the design and performance of some proposed accelerators.

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