HIGH TEMPERATURE SUPERCONDUCTORS FOR HIGH FIELD SUPERCONDUCTING MAGNETS

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ABSTRACT

Ionization cooling, a method for shrinking the size of a muon beam, requires a low Z energy absorber, high field magnets, and high gradient radio frequency cavities. The use of high temperature superconductors (HTS) for the high field superconducting magnets is being considered to realize a helical muon cooling channel using hydrogen refrigeration. A test stand was set up at Fermilab to perform critical current (I_c) measurements of HTS wires under externally applied perpendicular and parallel fields at various temperatures. A description of the test setup and results on $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (BSCCO-2223) tapes and $Bi_2Sr_2CaCu_2O_8$ (BSCCO-2212) round wires are presented. Finally, the engineering critical current density, J_E, of HTS and Nb_3Sn were compared in the application's field and temperature range of interest.

KEYWORDS: High temperature superconductor, BSCCO, DC measurement.
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INTRODUCTION

First generation multi-filamentary HTS are composites of silver or silver alloy matrix and BSCCO. The combination of fine filaments with the metal matrix reduces crack formation and allows critical strain, whether tensile or compressive, in a range of several tenths of a percent [1]. BSCCO conductors are typically produced in the form of tapes and, more recently, of round wires. Tapes are anisotropic and exhibit the highest critical current when the magnetic field is applied parallel to the tape face and the lowest one when the field is perpendicular.

Figure 1 shows the geometrical configuration of a tape and relative directions of magnetic field. The longitudinal direction is along the length of the tape. The transverse direction, orthogonal to the length of the tape, which is parallel to the tape width, is also called "ab-trans" or "lateral" or "long transverse". The transverse direction, orthogonal to the length of the tape, which is perpendicular to the tape face, is also called "c-axis" or "normal" or "short transverse". Magnetic fields having longitudinal or long transverse directions are both parallel to the tape surface. A magnetic field having short transverse direction is perpendicular to the tape surface. In their manufacturing process, the rolling of a wire to tape provides an environment where the superconductor can grow preferentially such that the c-axis of the crystal is mostly perpendicular to the tape face. In the case of the a,b plane there is only a slight difference between the a direction and the b direction (the crystal is nearly tetragonal but slightly orthorhombic) and also there is no preference within the plane of the tape for preferential growth. Because there is little difference in the a and b axis and since there is no preference for growth within the plane, the tape exhibits a nearly isotropic effect in this plane. Critical stresses, determined by the silver alloy sheath, typically range from 50 MPa (for pure silver) up to 130 MPa [2]. For applications where high tensile stresses are encountered, such as high field magnets, stainless steel (SS) reinforcements provide larger stress tolerances. For instance the High Strength BSCCO-2223 tape by American Superconductor (AMSC) withstands up to 265 MPa [1]. Round wires are isotropic, there is no crystallographic texture normal to the wire axis. This is an attractive characteristic because in a magnet configuration the wire will be found in both a perpendicular and a parallel configuration. After reaction the wire is very brittle. High strength tape is commercially available in lengths greater than 100 m, the round wire is available in a range of round sizes and in particular 300 m lengths are available at 0.8 mm diameter.

Results on some earlier BSCCO-2223 and BSCCO-2212 tapes tested at various temperatures can be found in [3]. In [4] critical current and n-value measurements were obtained on BSCCO-2223 tapes, under externally applied perpendicular and parallel magnetic field up to 5 T and temperature between 20 K and 100 K. Results that are available on AMSC web site [5] provide critical currents in a temperature range between 20 K and 77 K and at fields up to 7 T. Dc measurements results on BSCCO-2212 round wire were obtained by Oxford Superconducting Technology (OST) at 4.2 K and at field up to 16 T [6]. For the present application, the choice in temperature ranges from 4.2 K to about 35 K, with the highest possible magnetic field.

EXPERIMENTAL SETUP

Samples Description

A High Strength BSCCO-2223 tape, produced by AMSC, and a BSCCO-2212 round wire of 0.8 mm diameter, produced by OST, were tested. Samples specifications are given in Tables 1 and 2 and their cross sections are shown in Figure 2.

Sample Holders

These HTS critical current measurements were performed at Fermilab at the Short Sample Test Facility. Measurements were obtained at various temperatures in a Variable

Temperature Insert (VTI) with an inner diameter of 49 mm, within a 15/17 T magneto cryostat (Teslatron) by OST.

The minimum critical bending strain for reacted tapes is 50 mm [5]. To avoid sample stress due to bending the tape was tested in the form of straight samples 45 mm long. The wires were provided after reaction in oxygen by OST as straight samples 10 cm long, and they were cut to size. Figure 3 shows the sample holder used to test the BSCCO-2212 wire (left) and the BSCCO-2223 tape (right) in perpendicular and parallel configurations. The tape was tested separately in each configuration. As can be see in Figure (right), for the test in parallel field a force-free configuration was chosen. Sample extremities are soldered directly on the current leads while the central part rests on a G-10 structure. In the design of the sample holders, the length of the soldered junction was chosen [7] to control contact resistance and heating power. The splice length of 12 mm that was used on each side of the sample produced a contact resistance at 4.2 K of ~0.3 μΩ in the case of the tape, most of which due to the SS, and of ~0.1 μΩ in the case of the wire. The current transfer length [8] determined the distance between the voltage taps, which was of 5 mm for the wire, and 10 mm for the tape.

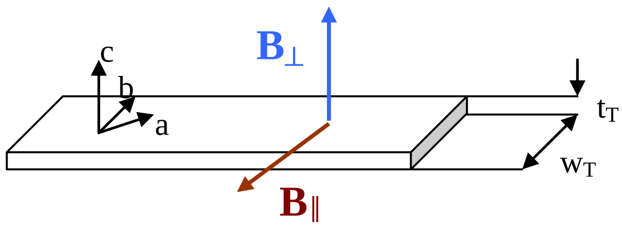

FIGURE 1. Geometrical configuration of a BSCCO tape and relative directions of magnetic field.

FIGURE 2. Transverse cross section of High Strength BSCCO-2223 tape showing 55 filaments of BSCCO-2223 embedded in a metal matrix of silver alloy and 37 μm strips of stainless steel on top and bottom of tape (left). Transverse cross section of unreacted BSCCO-2212 OST 85 × 7 wire (right).

TABLE 1. AMSC Tape Specifications

High Strength BSCCO-2223 Tape	
Min I_c (77 K, self-field, 1 μV/cm)	122 A
Average thickness	0.31 mm ± 0.02 mm
Average width	4.16 mm ± 0.02 mm
Stainless steel strip thickness	$37 \cdot 10^{-3}$ mm
Max. rated tensile strain (95% I_c retention)	0.35 %
Min. critical bend diameter	50 mm

TABLE 2. OST Round Wire Specifications

BSCCO-2212 Round Wire	
I_c (4.2 K, self-field, 1 μV/cm)	770 A
Average diameter	0.8 mm
Fill factor	28 %
Critical Strain	0.3 %

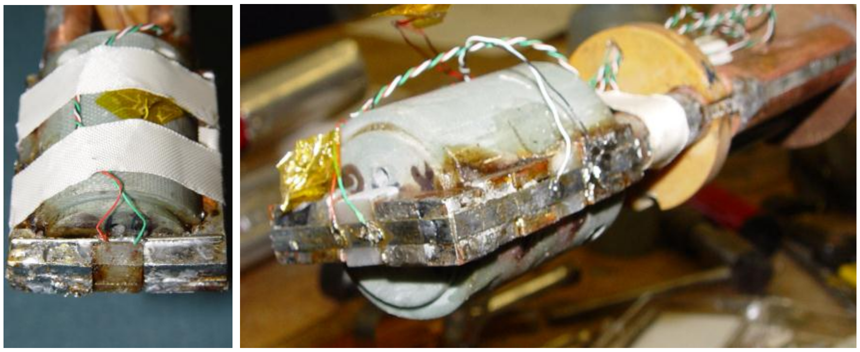

FIGURE 3. Sample holder used to test BSCCO-2212 round wire (left), and sample holder used to test BSCCO-2223 tape in perpendicular and parallel configurations (right).

Measurement Procedure

The current was provided to the sample using 1000 A current leads. Voltage-current (VI) characteristics were measured in He (liquid or vapor) at a magnetic field up to 15 T. The I_c was determined from the VI curve using the 1 μV/cm criterion. The n-values were determined in the $V(I_c)$ to $10 \cdot V(I_c)$ range by fitting the VI curve with the power law $V \sim I^n$. In the case of the tape, critical current measurements were also performed at zero magnetic field in liquid nitrogen at 77 K.

Table 3 shows the results of the I_c measurement error analysis at 4 T. The effects that were considered include temperature variations, magnetic field variations (only for vertical samples, as for the horizontal ones this effect is negligible), self-field, noise. The read-back accuracy of the power supply is 0.1 % + 0.6 A. In addition, an accuracy of 1 mm in placing voltage taps leads to $\Delta I_c/I_c =$ 0.6 to 10 % for n-values ranging from 34 to 2.

TABLE 3. Results at 4 T of I_c measurement error analysis

ΔI_c / I_c	At 4.2 K	At 14 K	At 22 K	At 38 K
Due to ΔT @ 4 T	- 0.14 %	-0.15 %	- 0.26 %	- 1.66 %
Due to ΔB @ 4 T for vertical samples	- 0.06 %	- 0.07 %	- 0.08 %	- 0.1 %
Self-field effect @ 4 T	0.6 %	0.7 %	0.8 %	0.9 %
Noise effect @ 4 T	0.17 %	0.28 %	0.69 %	0.22 %

RESULTS AND DISCUSSION

BSCCO-2223 Tape

Figures 4 and 5 show I_c results as a function of magnetic field for the BSCCO-2223 tape, in the parallel and perpendicular field configuration respectively, tested from 4.2 K up to 34 K. The I_c test results in nitrogen at 77 K were of 125 A for the tape tested in parallel configuration and of 127 A for the tape tested in perpendicular configuration.

Figures 6 and 7 show I_c results as a function of temperature at various fields, in the parallel and perpendicular field configuration respectively.

Figure 8 shows n-value results as function of applied field at various temperatures in the perpendicular configuration.

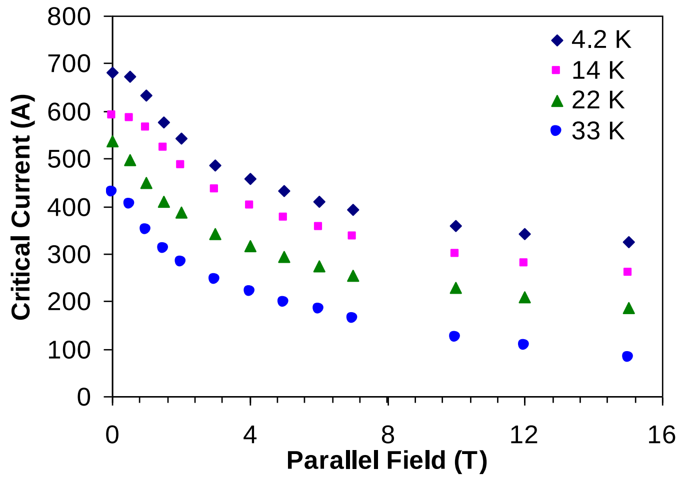

FIGURE 4. AMSC BSCCO-2223 High Strength tape I_c results as a function of applied magnetic field at various temperatures in parallel configuration.

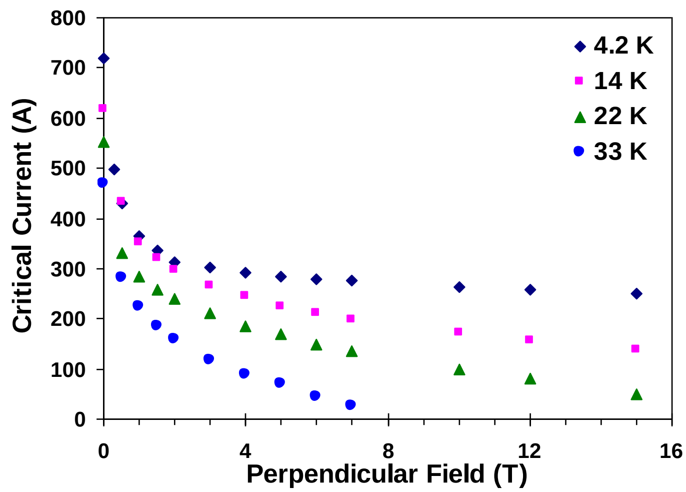

FIGURE 5. AMSC BSCCO-2223 High Strength tape I_c results as a function of applied magnetic field at various temperatures in perpendicular configuration.

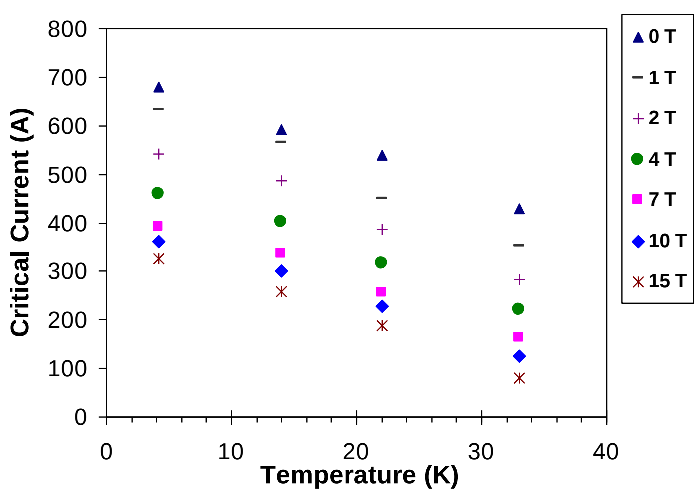

FIGURE 6. AMSC BSCCO-2223 High Strength tape I_c results as a function of temperature at various applied magnetic fields in parallel configuration.

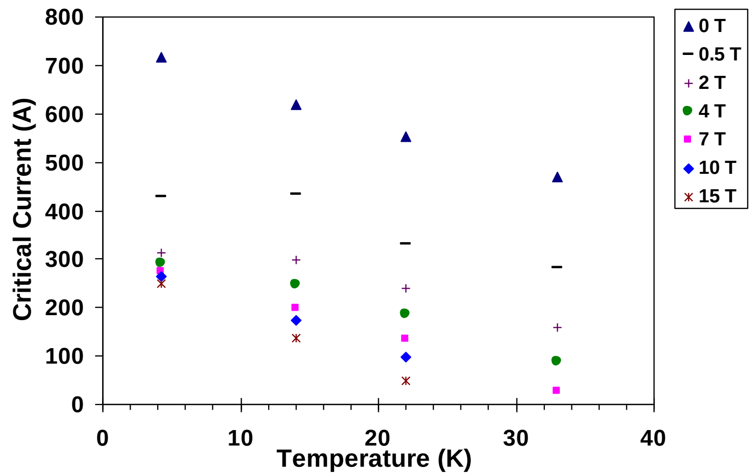

FIGURE 7. AMSC BSCCO-2223 High Strength tape I_c results as a function of temperature at various applied magnetic fields in perpendicular configuration.

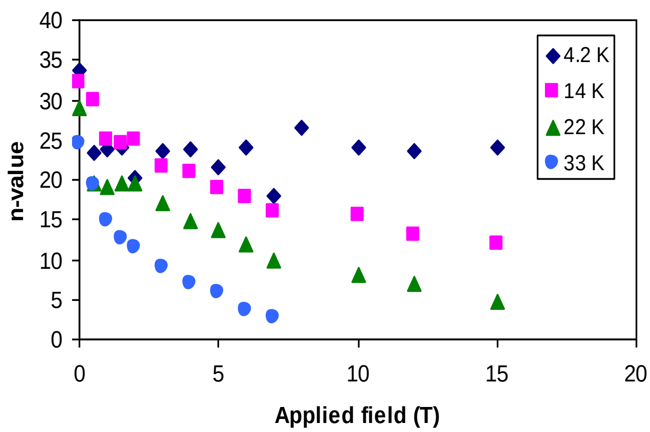

FIGURE 8. AMSC BSCCO-2223 High Strength tape n-value results as a function of applied magnetic field at various temperatures in perpendicular configuration.

BSCCO-2212 Round Wire

Figure 9 shows I_c results as a function of magnetic field for the BSCCO-2212 round wire, tested from 4.2 K up to 34 K. Figure 10 shows I_c results as a function of temperature at various fields. Figure 11 shows n-value results as a function of applied field at various temperatures.

Figure 12 shows the J_E results obtained at 4.2 K for three different samples and the value obtained by the company [6]. These data provide a measure of reproducibility when testing identical samples, and of consistency with the company's results.

Comparison with LTS

Figures 13 and 14 show a comparison between HTS, Nb_3Sn and NbTi performance in form of J_E as a function of field at 4.2 K and 14 K respectively. The wire shows lower critical current but higher J_E than tapes, also because of the stainless steel strips reducing the transport current area. At 4.2 K Nb_3Sn performs better at least up to magnetic fields of 17 T, while the superiority of the HTS materials is obvious at higher temperatures.

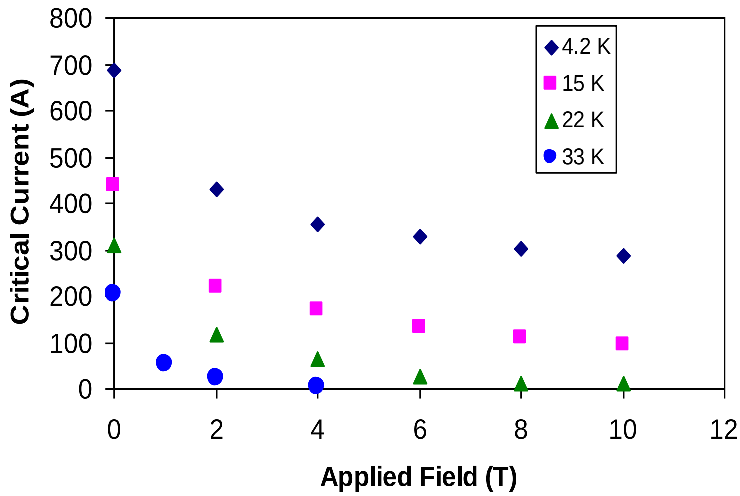

FIGURE 9. OST BSCCO-2212 round wire I_c results as a function of applied field at various temperatures.

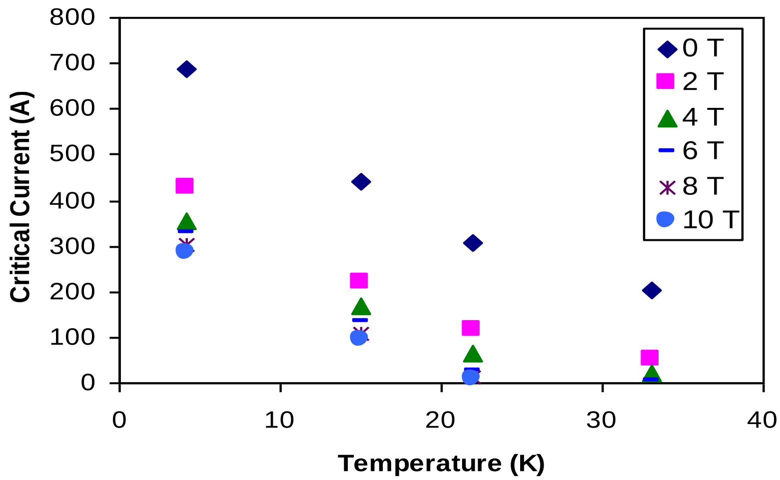

FIGURE 10. OST BSCCO-2212 round wire I_c results as a function of temperature at various applied fields.

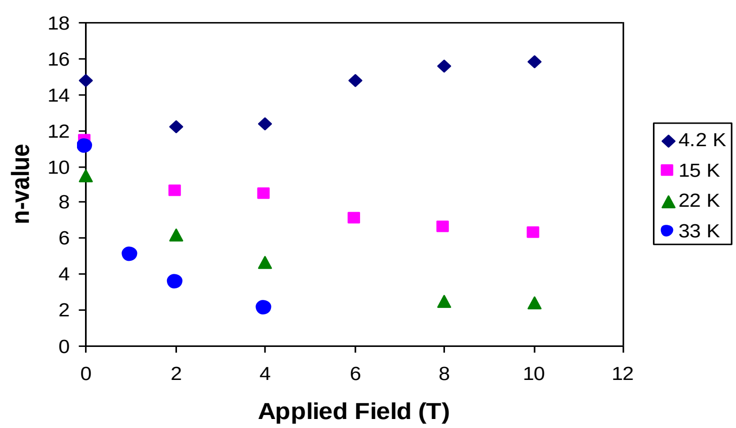

FIGURE 11. OST BSCCO-2212 round wire n-value results as a function of applied field at various temperatures.

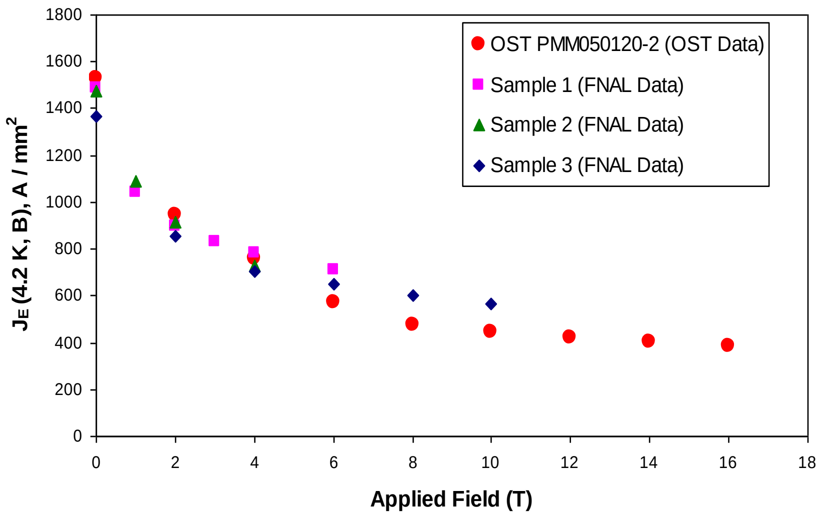

FIGURE 12. OST BSCCO-2212 round wire J_E results as a function of applied field at 4.2 K for three different samples and comparison with company's data.

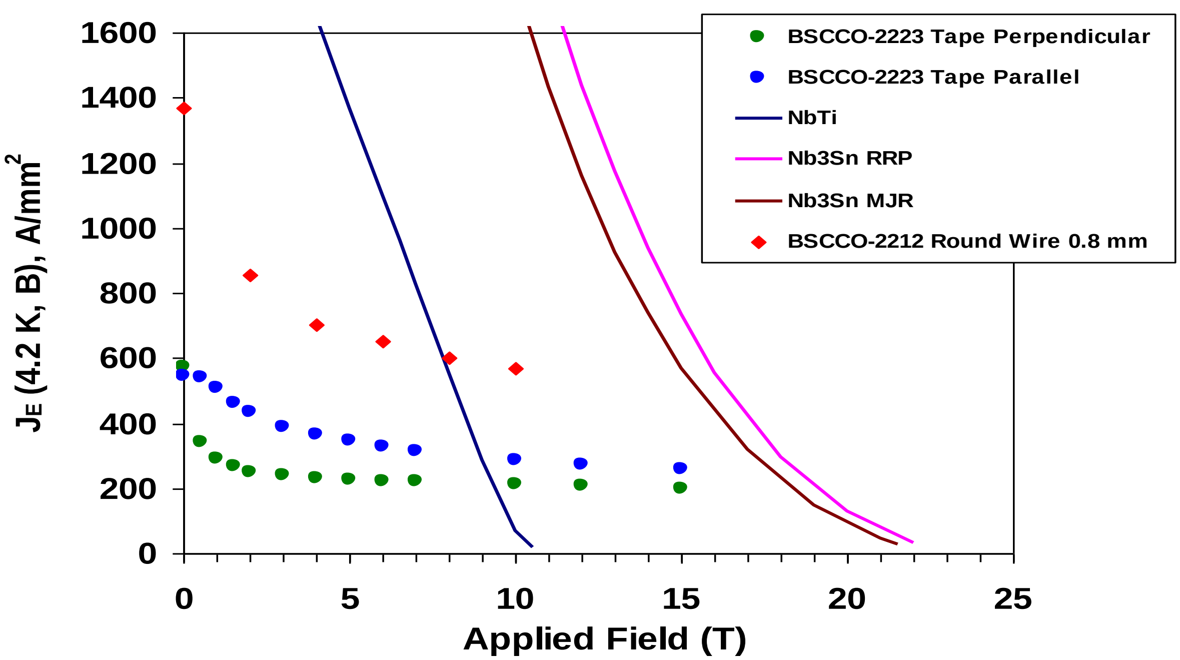

FIGURE 13. J_E comparison at 4.2 K between NbTi, Nb_3Sn, BSCCO-2212 wire and BSCCO-2223 tape as a function of applied magnetic field.

CONCLUSIONS

A measurement apparatus was set up to measure the dc characteristics of HTS tapes and wires under applied magnetic fields at various temperatures. Test temperatures from 4.2 K to 34 K were achieved for BSCCO-2223 tapes and a BSCCO-2212 round wire while providing up to 1000 A of current and magnetic field magnitudes up to 15 T. The data acquired from the measurements performed using the designed sample holders are consistent with similar measurements performed by AMSC [5] and OST [6]. A comparison between HTS, Nb_3Sn and NbTi was obtained in the range of temperature and field of interest to help choose the most adequate superconductor for the magnets of a muon cooling channel application.

Studies of strain effects on the superconducting properties will also be performed to determine whether a React&Wind or Wind&React technology should be used. Once the operation temperature and magnetic field operation range of the magnets will have been specified, magnetization measurements might also be of interest.

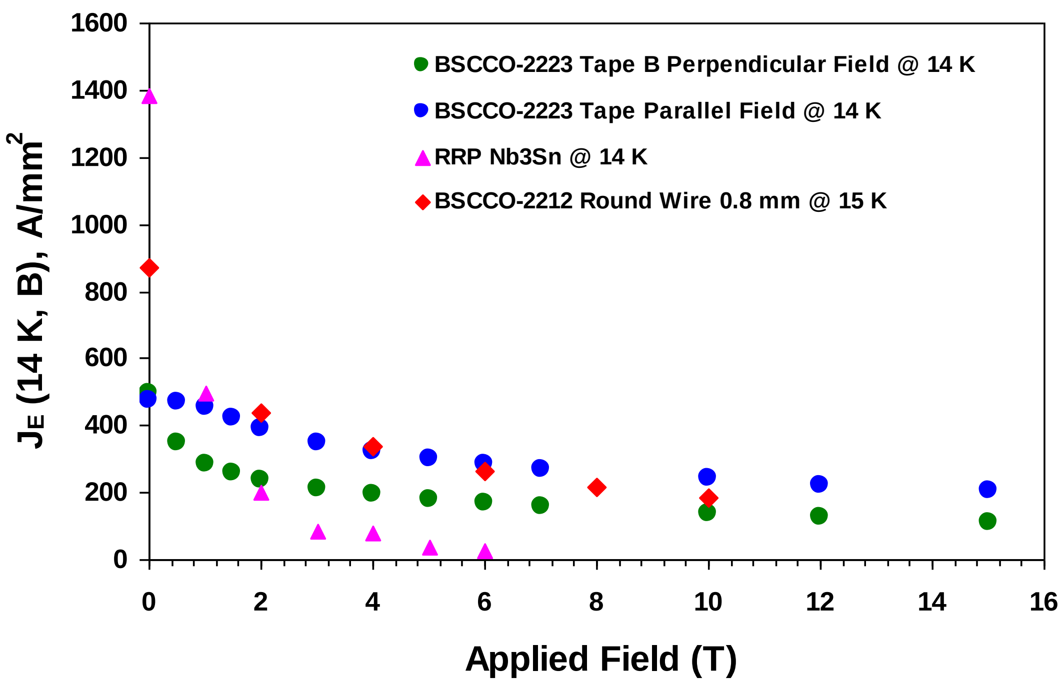

FIGURE 14. J_E comparison at 14 -15 K between Nb_3Sn, BSCCO-2212 wire and BSCCO-2223 tape as a function of applied magnetic field.

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