Critical Currents of $YBa_2Cu_3O_{7-\delta}$ Tapes and $Bi_2Sr_2CaCu_2O_x$ Wires at Different Temperatures and Magnetic Fields

V. Lombardo, E. Barzi, D. Turrioni and A. V. Zlobin

***Abstract*—Design studies for the cooling channel of a Muon Collider show the need for straight and helical solenoids generating fields well in excess of the critical fields of state-of-the-art Low Temperature Superconductors (LTS), such as Nb_3Sn or NbTi. Therefore, High Temperature Superconductors (HTS) may be used for the manufacturing of all or certain sections of these magnets to generate and support the field levels required at the operating temperature of the new machine. In this work, two High Temperature Superconductors – Bi-2212 round wires and YBCO coated conductor (CC) tapes – are investigated to understand how their critical current density scales as a function of magnetic field and operating temperature.**

***Index Terms*— Muon Collider, High temperature superconductor, Bi-2212, YBCO, Temperature and Field dependence.**

I. INTRODUCTION

The final stage of cooling [1-5] of a Muon Collider requires solenoids generating magnetic fields in the range of 40-50T. High temperature superconductors may be used for the manufacturing of such magnets, since state-of-the-art low temperature superconductors - such as Nb_3Sn - show critical fields well below the levels required by the conceptual designs of the new machine.

At the present stage, only two high temperature superconductors show the critical current potential for application within the required field range: $YBa_2Cu_3O_{7-\delta}$ [6] and $Bi_2Sr_2CaCu_2O_x$ [7-8]. Bi-2212 is manufactured as a round wire by Oxford Superconductor Technology (OST) and therefore can be formed into Rutherford cables exactly as Nb_3Sn and NbTi wires [9]. The technology involved in cabling Bi-2212 is currently being investigated at Fermilab. Although the conductor does not show anisotropic effects with respect to field orientation, it does require a very precise heat treatment in Oxygen after which it becomes extremely brittle and therefore highly strain sensitive. On the other hand, YBCO shows better mechanical properties, does not need reaction, but shows highly anisotropic behavior, which needs to be accounted for in magnet design. Understanding how critical current scales with both magnetic field and temperature is an extremely important factor to make conductor choices depending on the geometry, field levels and operating temperatures of the magnet. In the following these aspects are analyzed in details for both conductors.

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II. CONDUCTOR PROPERTIES

In Tables I and II, the main parameters describing the conductors used in this study are summarized.

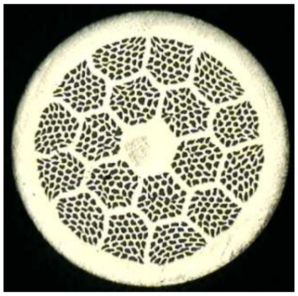
TABLE I BI-2212 WIRE PARAMETERS

Wire Manufacturer	Oxford SC. Technology
Oxford Strand ID	090306
Precursor	Nexans powder
Configuration	37x(18+1)
Diameter	0.8 mm
I_c (4.2 K, 12 T)	176 A
Fill factor	26%

TABLE II YBCO CC TAPE PARAMETERS

Tape Manufacturer	Superpower
2G HTS Tape	SCS12050
Nominal Width	12 mm
Nominal Ic(77K,SF)	330A
Nominal Thickness	0.1 mm
Stabilizer	Copper (2 x 20 µm)
Substrate	Hastelloy® C276 (50 µm)
YBCO layer thickness	1 µm

Fig. 1 shows the cross sections of the $Bi_2Sr_2CaCu_2O_x$ round wire (left) and one edge of the $YBa_2Cu_3O_{7-\delta}$ CC tape (right) investigated in this study. Bi-2212 is currently produced by OST up to 1.2 mm in diameter, whereas YBCO tapes from SuperPower have a nominal thickness of 0.1 mm and width varying from 2 mm up to 12 mm. Angular dependence for the standard 4 mm wide YBCO CC tape at 4.2 K is largely available in literature [10][11].



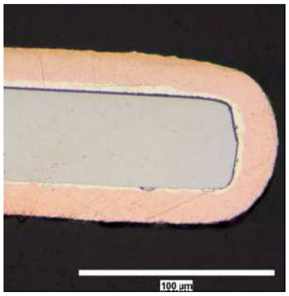


Fig. 1. (a) Cross section of Bi-2212 wire. Picture courtesy of OST. (b) Cross section of YBCO tape. Picture courtesy of SuperPower.

III. Experimental Setup

In order to evaluate critical current of both wires and tapes, a 38 mm sample holder was used. The overall length of the sample was determined by the available space within a variable temperature insert (VTI) equipped with a needle valve and a heater, both used to regulate the sample temperature. The samples were mounted on a G-10 support and soldered at both ends on 12 mm copper joints for current transfer. The setup is shown in Fig. 2. The copper leads used for this experiment were designed to carry up to 2 kA, whereas the available power supply limited the maximum sample current to 1.8 kA.

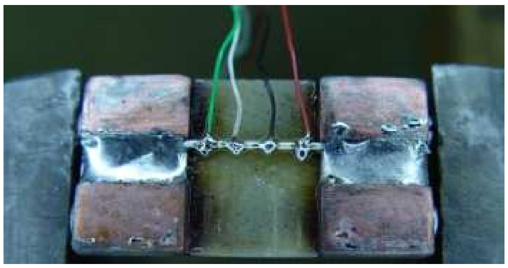


Fig. 2. Example of a Bi-2212 short sample mounted on a 38 mm sample holder for in-field testing. Voltage development is monitored using two pairs of voltage taps over 5 mm and 10 mm of wire respectively.

In Fig. 3, a V-I curve from the innermost taps is plotted for a Bi-2212 sample. The acquired voltage data is fitted and used to evaluate critical current values using a 1 µV/cm criterion. Voltage data is recorded up to 10 µV/cm and used to compute *n-values* for each transition. All the results shown in this study have been obtained according to this protocol.

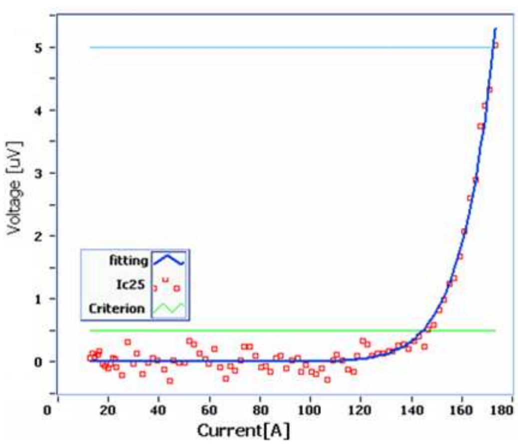


Fig. 3. Example of a V-I curve from the innermost taps (5 mm), showing real data and numerical fitting of the curve for accurate computation of both I_c and *n-values*.

The samples were mounted horizontally to avoid temperature gradients along the length and the temperature was closely monitored using calibrated Cernox sensors down to 1.9 K. A PID-based control system was used to regulate the voltage across the heater and therefore warm up the helium around the sample to the desired temperature (Fig. 4). The helium flux through the needle valve was kept constant for the duration of the tests.

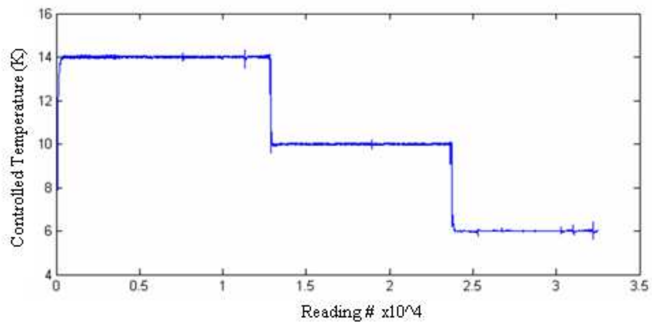


Fig. 4. Example of temperature stability around set-point during testing. The spikes are due to quench of the conductor at every current ramp.

IV. Results for YBCO Tapes

Using the sample mounting technique showed in Fig. 2, an un-doped 12 mm wide YBCO CC tape from SuperPower was mounted and instrumented. Extreme care was put into soldering the sample ends to the leads to avoid conductor damage or high resistive joints that would cause excessive Joule heating during testing. The sample holder was rotated so that the magnetic field generated by the external Nb_3Sn/NbTi magnet would be perpendicular to the ab-plane of the tape. This configuration was chosen to limit the current in the sample and avoid the need to reduce the width of the tape. Before testing the sample in liquid helium, a cooling cycle in nitrogen was performed. The test showed a critical current value of 332 A, which is within the nominal range provided by the manufacturer. The tests were run starting from 15 T down to self field. In Fig. 5, test results are shown in terms of critical current as a function of external field and as a function of temperature up to 33 K. Low field tests were limited by the maximum current available (1.8 kA). Only data points corresponding to complete transitions are shown in Fig. 5.

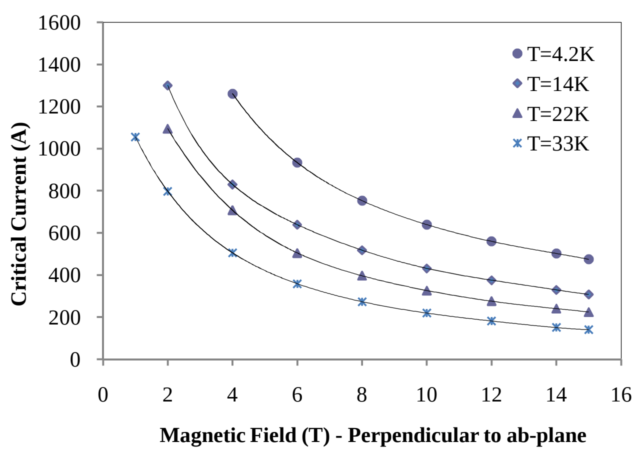


Fig. 5. $YBa_2Cu_3O_{7-\delta}$ critical current as a function of field (perpendicular to the ab-plane of the tape) and temperature.

In Fig. 6 the same set of data points is plotted in terms of critical current versus temperature for several magnetic fields perpendicular to the ab-plane of the YBCO tape.

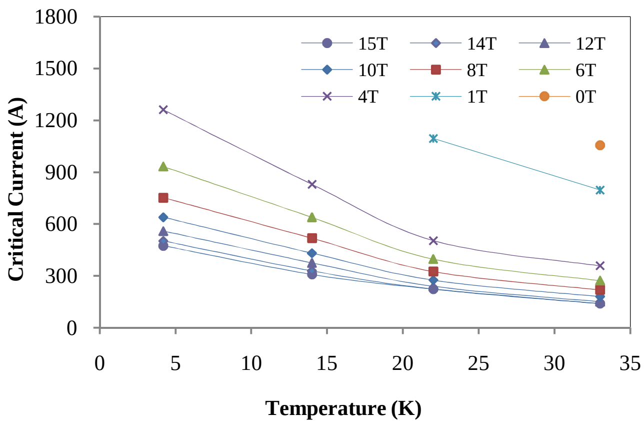


Fig. 6. $YBa_2Cu_3O_{7-\delta}$ critical current as a function of temperature, plotted at different fields perpendicular to the ab-plane of the tape.

V. Results for Bi-2212 Wires

Whereas YBCO CC tapes do not require any reaction, Bi-2212 wires do. For this particular billet, the heat treatment in Oxygen was performed by OST according to the cycle shown in Fig. 7.

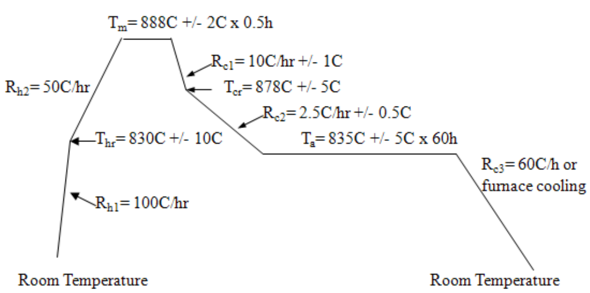


Fig.7. Summary of Bi-2212 heat treatment cycle used for this study. The heat treatment was performed at OST.

Before proceeding with the complete battery of tests on the same short sample, critical current homogeneity was investigated along the length of the available virgin wire to address any problem due to possible temperature unbalances at the ends of the sample during the heat treatment. The length of the original sample was 200 mm.

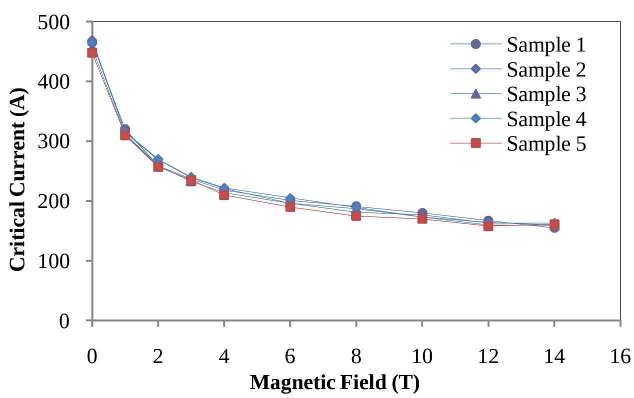


Fig.8. Critical current of five Bi-2212 short samples tested in liquid helium.

Five short samples were cut out of the available length of conductor and tested independently for critical current in liquid helium. No major I_c variation was found along the length of the original strand as shown in Fig. 8. The critical current values of the central sample are plotted against magnetic field at six different temperatures in Fig. 9.

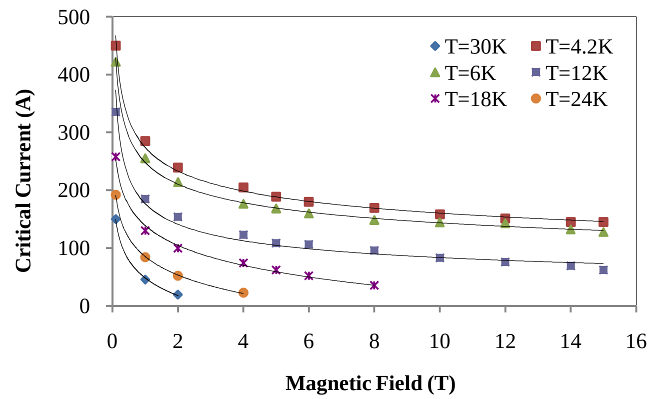


Fig. 9. Bi-2212 critical current as a function of magnetic field, plotted at different temperatures.

Plotting the same data points versus temperature for the available magnetic fields, one can see how critical current scales almost linearly at all fields, showing lower critical temperature values with respect to YBCO tapes (Fig. 6).

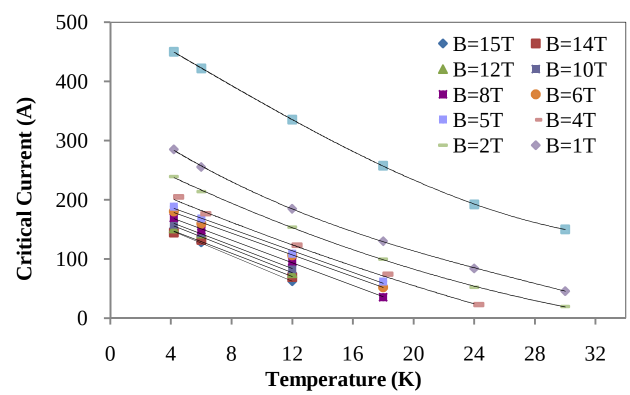


Fig. 10. Bi-2212 critical current as a function of magnetic field, plotted at different temperatures.

VI. Engineering Critical Currents Comparison

In order to compare the two conductors, the available data is shown in Fig. 11 in terms of engineering current density J_e.

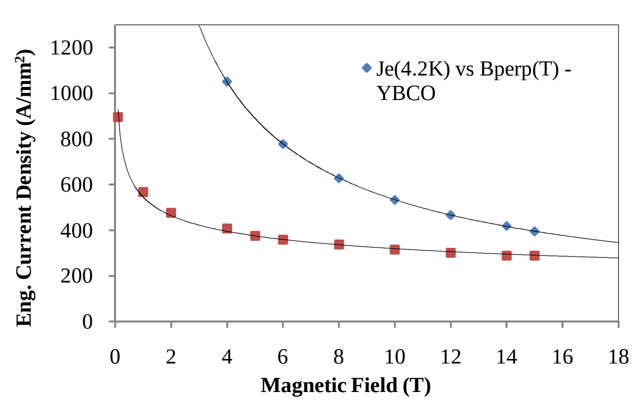


Fig. 11. Bi-2212 and YBCO J_e comparison at 4.2 K as a function of magnetic field (perpendicular to the *ab-plane* for the YBCO tape).

An additional study has been performed on the two conductors in order to explore boundaries in terms of both magnetic field and temperature. The J_e data in Fig. 12 were obtained at the maximum available background field (15 T) and up to the highest reachable temperatures. YBCO CC in a 15 T background field perpendicular to the ab-plane was superconducting up to more than 60 K, whereas Bi-2212's current dropped to zero slightly below 20 K.

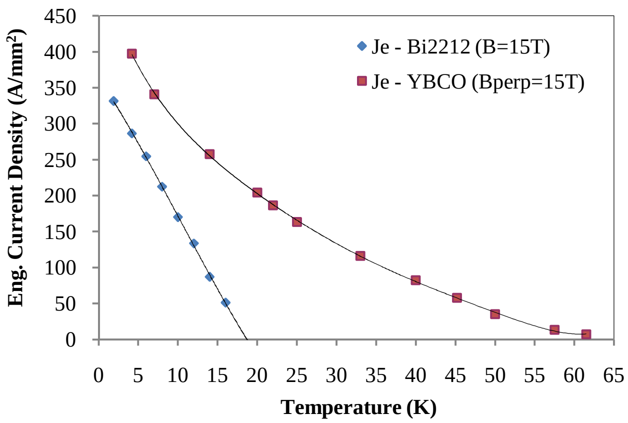


Fig. 12. Bi-2212 and YBCO J_e comparison at the maximum achievable field (15T) as a function of temperature from 1.9 K up to 62 K.

The Bi-2212 sample was finally tested in super-fluid helium (1.9 K), showing an additional gain in critical current, which maintains its linear trend versus temperature as shown in Fig. 12. Previous studies have shown that YBCO tapes exhibit no gains in terms of I_c when operated at 1.9 K [12]. In fitting the data for critical current, *n-values* were also computed. In Fig. 13, *n-values* are plotted for both conductors at 15 T as a function of temperature. *N-values* for YBCO tapes closely follow the trend of the critical current from Fig. 12, whereas for Bi-2212 they seem to flatten around 10, except for a small spike when tested in super-fluid regime.

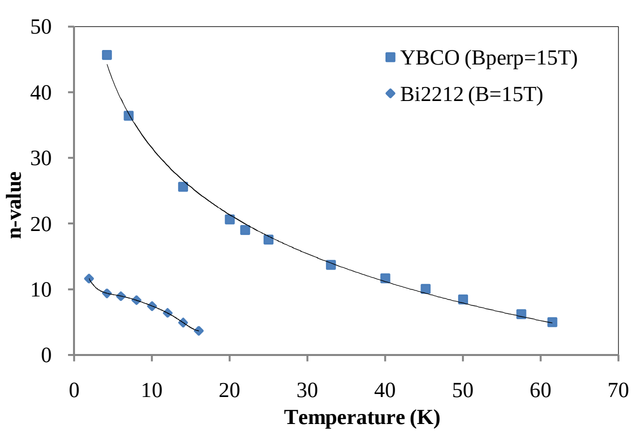


Fig. 13. Bi-2212 and YBCO *N-value* comparison at the maximum achievable field (15T) as a function of temperature from 1.9 K up to 62 K.

Conclusions

In this paper, 12 mm wide YBCO CC tapes by SuperPower and Bi-2212 wires from OST have been extensively investigated in terms of critical current as a function of both magnetic field from 0 to 15 T and temperature from 1.9 K to 62 K. The Bi-2212 billet used for this study was chosen because already available from work done on Bi-2212 Rutherford cable technology at Fermilab [13]. Since the *VHFSMC (Very High Field Superconducting Magnet Collaboration)* is working with several different Bi-2212 billets, next steps may include the extension of this study to other Bi-2212 wires from such Collaboration. Also, numerical fits of collected data can be provided as inputs for quench development simulations.

Acknowledgment

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