CHARACTERIZATION OF REBCO COATED CONDUCTORS FOR HIGH FIELD MAGNETS*

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Abstract

Magnet applications for high energy physics has long been an important driver for the development of superconducting technology. New high temperature superconductors (HTS), which have very high values of the upper critical field H_{c2}, show promise for magnets generating fields greater than 25 T, such as those required for muon cooling [1]. (Rare Earth)$Ba_2Cu_3O_y$ (REBCO) coated conductor is an HTS material which is well suited to these needs; however it requires characterization in the low temperature (4.2 K), high magnetic field regime. We are proposing to measure electro-mechanical and magnetic properties, including angular field dependence of commercially available REBCO conductor. Here we present results of initial testing to characterize commercially available REBCO coated conductors at 77 K, including critical current and quench testing to calculate minimum the quench energy (MQE) and normal zone propagation velocity (NZPV).

INTRODUCTION

HTS conductors have evolved rapidly in recent years and several varieties of HTS conductors are sufficiently developed to be available commercially. These include Bi2212 ($Bi_2Sr_2CaCu_2O_x$), Bi2223 ($Bi_2Sr_2Ca_2Cu_3O_z$), and REBCO ((Rare Earth)$Ba_2Cu_3O_y$).

The Bi2212 conductor is available as a wire that can be easily incorporated into a round cable. It has the very nice property that the J_c dependence upon B is isotropic. This is a very advantageous property for accelerator magnets since the magnetic field can be oriented in less than optimum directions particularly in the end regions of magnets. The primary disadvantage of Bi2212 is that the conductor is very strain sensitive and it has to be wound into the desired coil configuration and then reacted in an oxygen environment at a uniform temperature of nearly 900 °C. The final performance is quite sensitive to the heat treatment, and in particular to the peak temperature and the amount of time above the melt temperature. Bi2212 conductor has relatively low strain tolerance which can cause micro-cracking in the conductor that irreversibly degrades its performance.

The REBCO conductor is available in tape form only and has the largest critical current density of the commercial HTS conductors. The SuperPower version of REBCO conductor consists of an YBCO layer deposited on buffer layers on top of a Hastelloy substrate and sandwiched between copper layers. The Hastelloy substrate provides the conductor with strength while the copper layers add thermal stability. A disadvantage to the REBCO conductor is that its critical current density is very sensitive to the orientation of the magnetic field. This has a significant effect on how it may be used in magnets. The Bi2223 conductor has largely been superseded by the REBCO conductor and is becoming less available from vendors. Here we examine REBCO coated conductor from three manufacturers at 77 K.

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EXPERIMENTAL SET-UP

Conductor was obtained from SuperPower (SP), American Superconductor (AMSC) and a third vendor, to be named Manufacturer X (Man X). Table 1 lists relevant physical and electrical properties of the received conductors; the final row normalizes the critical current to a 1 cm wide tape. Critical current has been defined using a 1 μV/cm criterion.

Table 1: Physical and electrical properties of REBCO coated conductor at 77 K.

Manufacturer	SP	AMSC	Man. X
Conductor	YBCO	YBCO	GdBCO
Conductor name	SCS4050	344C	
Manufacturer I_C [width] (A [mm])	112 [4]	>90 [4]	580 [10]
Measured $I_{C,AVE}$ [width] (A [mm])	118 [4]	106 [4]	272 [5] 185 [3.2]
I_C/cm-w (A/cm)	295	265	544

Preparation of Samples

Due to the high critical current of some of the full width conductors and limitations of probes and power supplies, it was required reduce the overall critical current I_C. We investigated various methods to reduce I_C while maintaining high critical current density J_C and these are presented below.

A K&S 780 dicing saw featuring a 40 μm wide Ni blade with 4 μm diamond grit was used to dice the sample lengthwise. Man. X was diced from 10 mm to 5 mm, 3.3 mm, and 2.5 mm for testing at NCSU. After dicing, the critical current of the samples was tested to ensure no degradation.

A wet chemical etching technique can also be used to reduce the current carrying portion of the conductor [2]. To begin, nail varnish was applied to the surface to protect areas not to be etched. The conductor was then submersed in the following etchants to remove any copper, silver, and REBCO on exposed areas, rinsing with water between each solution: ammonium persulfate (APS) Cu etchant, a solution of ammonium hydroxide (15%), hydrogen peroxide (15%) and water (70%), and finally a 30 % nitric acid solution. The critical current of the samples was tested to verify etching success. Figure 1 shows a 4 mm wide piece of SuperPower YBCO etched into a 1.5 mm wide "dogbone".

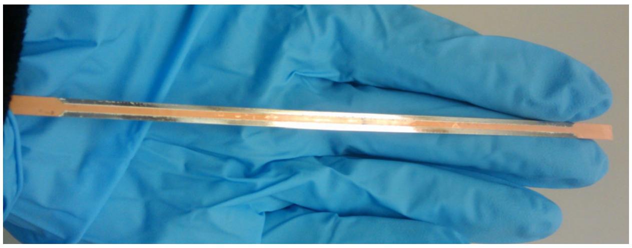

Figure 1: Etched SuperPower YBCO

Experiment Instrumentation

For critical current and quench testing, a 15 cm length of conductor was soldered to copper current leads on the cold head of a probe. A 6 cm length was monitored and instrumented with voltage taps (V1-V5 and V_ETE) and thermocouples (T1-T5). Quench was induced with a heat pulse from a heater wire located in the center. Figure 2 shows the layout of Man. X conductor ready for testing. The voltage taps and thermocouples were monitored using Keithley 2001 and 2700 digital multimeters; the transport current was supplied to the probe by an HP 6680A power supply and the heater power for quench testing was provided by a KEPCO 50-4D power supply.

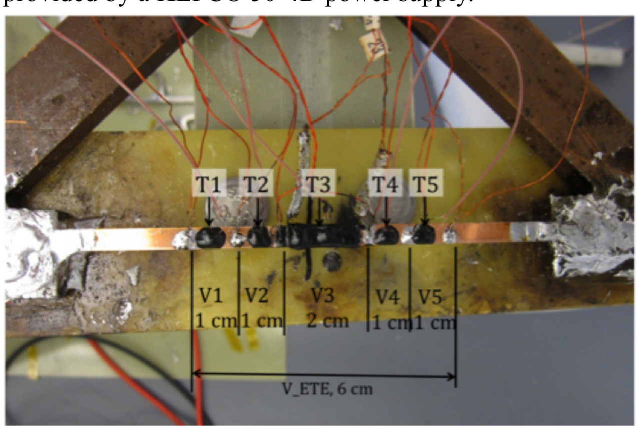

Figure 2: Experimental set-up for Man. X GdBCO conductor

EXPERIMENTAL PROCEDURE

Critical Current Testing

The testing probe was instrumented as shown above and submersed in liquid nitrogen. A transport current was pushed through the conductor and gradually ramped until monitoring end-to-end voltage taps revealed an electric field of 5 μV/cm and the power supply was automatically shut off.

Quench Testing

After the I_C of each sample was measured, quench testing was performed on conductors from SuperPower and Man. X, as they had the most promising behaviors for our application, i.e. the highest I_C. To start, the transport current was held at 60% of I_C for 3 s and a small (10 V) pulse was applied through the heater wire for 0.3 s. The heater energy was increased incrementally until the power supply limit (50 V) was reached, or a quench initiated. If no quench propagation was observed, the transport current was increased to 80% of I_C and the sequence was run again. The transport current, transport current length, and heater pulse length were increased until the quench propagated throughout the monitoring length of the sample.

RESULTS AND DISCUSSION

Critical Current Testing

The critical current I_C was measured for all conductors and compared to the vendor specifications. Critical current testing was also performed to verify that the dicing and etching processes were successful and did not degrade the conductor. Figure 3 shows the critical current of all conductors normalized to a 10 mm width, with a 1 μV/cm criterion. It can be seen that the conductor from Man. X has nearly twice the critical current as the SuperPower and AMSC conductors.

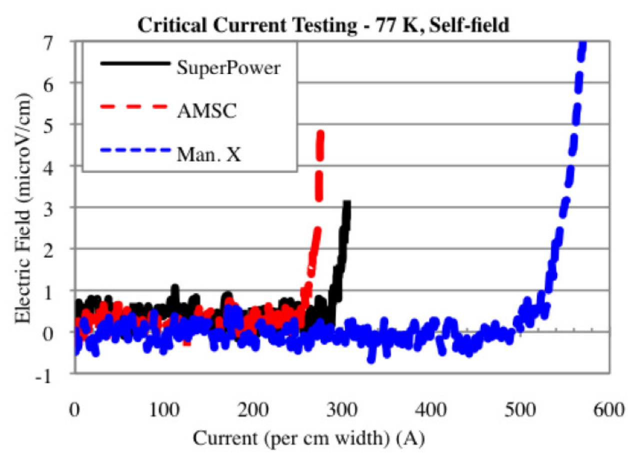

Figure 3: E-I curve for three REBCO conductors at 77 K.

Quench Testing

The parameters used to characterize primary quench behavior are typically the minimum quench energy (MQE), and the normal zone propagation velocity (NZPV). Table 2 lists these and other relevant test parameters for both conductors. Note that the NZPV for Man. X was nearly twice that of SuperPower; this is largely due to a much higher transport current during the test. However, these values for NZPV are nearly two orders of magnitude slower than low temperature superconductors NbTi and Nb3Sn, which typically have NZPV on the order of 1 to 2 m/s. This makes quench detection very difficult in HTS conductors, and we are investigating quench detection schemes elsewhere [3]. Figures 4 and 5 show voltage response for SuperPower and Man. X for the runs from which NZPV was calculated.

Table 2: Relevant quench parameters for SP and Man. X

Manufacturer	SP	Man. X
Transport current (A)	110	240
Transport current time (s)	6	5
Heater output voltage (V)	50	32.3
Heater pulse time (s)	0.5	0.4
MQE (J)	50	34
NZPV (mm/s)	0.24	0.43
Peak temperature (K)	415	185

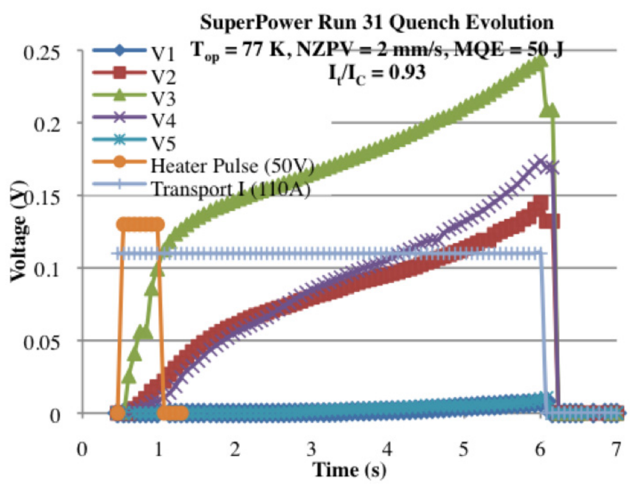

Figure 4: Voltage response of SuperPower quench test Run 31.

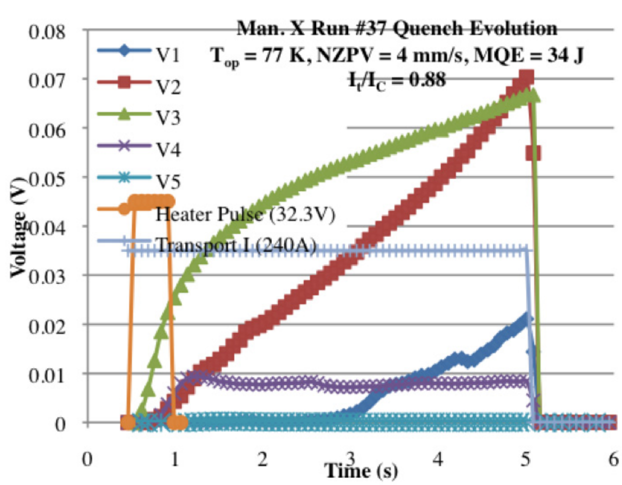

Figure 5: Voltage response of Man. X quench test Run 37.

SUMMARY

We have found the I_C of three commercially available REBCO coated conductors and performed quench characterization on two of these conductors, SuperPower YBCO and Man. X GdBCO. We have also presented techniques to reduce I_C of the conductors by dicing and wet chemical etching. Future studies will include measuring the critical current as a function of magnetic field and magnetic field angle at 4.2 K, strain measurements, and further quench analysis using magneto-optical imaging. Additionally, a fiber optic quench detection scheme is being developed for HTS conductors.

REFERENCES

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2. Mbaruku, A.L. and J. Schwartz, *Fatigue Behavior of Y-Ba-Cu-O Coated Conductor at 77 K.* IEEE Transactions on Applied Superconductivity, 2008. **18**(3): p. 1743-1752.
3. Hunte, F., *Fiber Bragg Optical Sensors for YBCO Applications*, in *PAC09*. 2009: Vancouver, Canada.