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Field and Temperature Dependence of Critical Currents in Industrially Manufactured High- T_c Wires and Tapes

Robert Herzog¹, Rainer Wesche and Pierluigi Bruzzone

Centre de Recherches en Physique des Plasmas, Technologie de la Fusion,
Association Euratom – Confédération Suisse,
Ecole Polytechnique Fédérale de Lausanne, CH-5231 Villigen PSI, Switzerland

Robert.Herzog@psi.ch

Abstract. In the frame of the European Fusion Technology Programme, CRPP Villigen evaluated the performance of currently available commercial High- T_c wires and tapes in view of their suitability for magnet coils in future fusion reactors. We measured the critical current of Bi-2212 round wire and Bi-2223 tapes from two different manufacturers at temperatures up to 77 K. Magnetic fields up to 12 T were applied parallel as well as normal to the plane of the tapes (always normal to the current direction) to investigate the materials' anisotropy. At temperatures up to about 50 K and in sufficiently high fields we observed that the critical current decreases exponentially with the magnetic field in the 2223 tapes. In the same regime the I_c values were significantly different for increasing and decreasing field (hysteresis), most likely related to the different magnetisation states of the samples and therefore the local magnetic fields at the grain boundaries. High- T_c tapes and particularly round wires are promising candidates for conductors in fusion magnets because of their excellent high-field properties. They also show potential for the use at temperatures above 4.2 K in the 12 to 15 T range if cooling between 20 and 50 K became an attractive alternative to helium-based refrigeration. Our measurements show that the required current densities are already available industrially.

1. Introduction

High-Temperature Superconductors (HTS) remain superconducting not only at much higher temperatures than conventional superconductors, but also at much larger magnetic fields. An important disadvantage of HTS is the fact that high-angle grain boundaries can act as barriers for the transport current. In the first generation of HTS wires and tapes, this problem was overcome by a partial melt process (BiSCCO 2212) or the formation of a c -axis texture by repeated annealing and rolling cycles (BiSCCO 2223). The brittle nature of these ceramics makes it very difficult to fabricate long lengths of conductors for practical applications. Furthermore, the layered crystal structure of these materials lead to a strong anisotropy of the physical properties. The first materials reaching industrial maturity were the BiSCCO 2212 and 2223 compounds in the form of powder-in-tube tapes,

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rolled in order to align the *ab*-planes of the platelet-like grains. First generation BiSCCO-based conductors are routinely manufactured in lengths of several kilometers.

A second generation of HTS is based on 123 compounds, e.g. $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. In these materials a biaxial texture is required to obtain strongly coupled grains. Since a few years conductors coated with 123 compounds, like YBCO, are successfully produced using biaxially textured nickel or nickel alloy substrates. In a second process an assisting ion beam or an inclined substrate help to obtain biaxial texture in the coated conductors without the need of a biaxially textured metal tape as a substrate. The merit of the second generation HTS is the possibility to reach very high current densities at 77 K even in the presence of moderately high magnetic fields. These second-generation conductors are very promising for applications if long lengths can be manufactured at reasonable cost.

The use of HTS in future fusion reactors would provide the possibility to reach higher toroidal fields and thus increased fusion power [1]. In addition, operating temperatures in the 20-30 K range may be feasible for first generation HTS. In the case of the 123 coated conductors even operating temperatures above 50 K seem achievable. Operating temperatures of 20 K and above would provide considerable savings of cooling power required for the magnets of a fusion reactor.

For the design of future fusion reactors, a detailed knowledge of the critical current performance of industrially available superconductors is essential. To permit the consideration of HTS conductors for this application four different products from three manufacturers were evaluated under a contract from EFDA. The critical current of these first generation BiSCCO 2223 tapes and 2212 round wires was measured in the temperature range of 4.2 to 50 K in fields up to 12 T. A scaling relation, first proposed by Neumüller *et al.* [2] and used to describe the performance of developmental BiSCCO 2212 wires [3], was found to fit also to the presently investigated industrially fabricated BiSCCO-based HTS wires and tapes.

2. Experimental details

2.1. Heat treatment of Bi2212

Since the 10 m sample of round Bi2212 wire came directly from the last stage of drawing, it was necessary to heat treat sections in pure oxygen gas, following the supplied temperature schedule precisely. Because initial trials with the steel insert of the available tube furnace led to excessive corrosion, a quartz-glass insert was designed, ordered and installed with new flanges. The 40 mm \varnothing quartz-glass tube, closed on one end, is positioned coaxially inside the 100 mm \varnothing work space of the tube furnace. Samples up to 300 mm long can be treated in oxygen, or any other gas, injected continuously into the quartz tube at the closed end through a capillary. Several trial runs with calibrated thermocouples led to the availability of a 150 mm long central zone in the quartz insert where temperatures deviate by less than 0.5 °C from the set point of the controller during the critical phase above 800 °C.

The heat-treatment of the Bi2212 samples lasted about 100 h, most at temperatures above 750 °C. The nearly identical I_c performance of samples heat treated in different runs shows that the process is controlled correctly and highly reproducible.

2.2. Critical current measurements

Most I_c measurements were carried out in a 12 T superconducting solenoid [3] with a cold bore of 80 mm, the remaining in a new 15 T magnet, recently replacing the former. A gas-tight sample holder, filled with helium gas at about 2 mbar, allowed a controller to keep temperatures up to 50 K constant while causing acceptable evaporation of the magnet's helium bath. The tapes could be mounted with their surface parallel to the magnetic field as well as normal, while the current in the tapes remained normal to the field. Measurements at 4.2 K and 77 K (in zero field) were carried out with the sample immersed in liquid helium and liquid nitrogen respectively.

A capacitive sensor and a carbon glass resistance thermometer were used to measure the temperature of the specimen. The magneto-resistance of the carbon glass resistor has been taken into

consideration using the data reported in [4]. Below 30 K the accuracy of the measured temperature is better than 1%.

3. Samples investigated

In the present study the current carrying capacity of industrially fabricated first generation HTS wires and tapes has been investigated. These first generation wires are fabricated in kilometre lengths. Bi2223 tapes have reached the maturity that they are commercially available from different companies. A disadvantage of the Bi2223 tapes is the relatively high AC loss for a time-varying field perpendicular to the broad face of the tapes. In addition, the tape geometry is disadvantageous for the fabrication of cables necessary to reach high currents. For this reason, industrially fabricated Bi2212 round wires have been included in the present study. Unfortunately, the critical temperature of Bi2212 (80-90 K) is considerably smaller than that of Bi2223 (≈ 110 K).

Table 1: Main characteristics of the investigated HTS wires and tapes.

Type / Sample	A	B high I_c^b	C high strength ^b	D
HTS Material	Bi2223	Bi2223	Bi2223	Bi2212
Shape	tape	tape	tape	round wire
Width (mm)	4.07	4.46	4.20	
Thickness / Diameter (mm)	0.22	0.25	0.23	0.81 \emptyset
Matrix	AgMg ^a	high-strength silver alloy	high-strength silver alloy	AgMg ^a
No of filaments	121	multifilament	multifilament	595
I_c (77 K, self field, $1 \mu\text{V}/\text{cm}$) ^c (A)	95	133	115	resistive
I_c (4.2 K, 12 T, $1 \mu\text{V}/\text{cm}$) ^c (A)	210 ($B \parallel ab$)	427 ($B \parallel ab$)	332 ($B \parallel ab$)	272
	145.5 ($B \perp ab$)	279 ($B \perp ab$)	221 ($B \perp ab$)	(isotropic)
Critical bending diameter (mm)	> 50	70	50	
Critical tensile strength at RT (MPa)	> 100	100	170	
Critical tensile strength at 77 K (MPa)		135	210	

^a Filaments embedded in pure silver

^b Type B and C are only distinguished by the Ag:Bi-2223 ratio

^c Measured at CRPP

4. Results and discussion

4.1. Bi2223 samples

The critical current of samples A1, A2, B and C was measured at the temperatures 4.2, 15, 20, 27, 40, 50 and 77 K at fields up to 12 T, applied parallel and normal to the tape surface. Figures 1 and 2 show typical measurement sequences where at constant temperature the field was set and the current ramped until the voltage drop on the sample reached $50 \mu\text{V}$. A least-squares fit of the data with the equation $E = E_c(I/I_c)^n$, using an electric-field criterion of $E_c = 1 \mu\text{V}/\text{cm}$, determined I_c as well as the exponent n , the indicator for the sharpness of the transition. The critical engineering current density J_{ce} was calculated by dividing I_c by the overall conductor cross section. The measurements revealed features characteristic for HTS and in particular Bi2223 tapes: anisotropy, hysteresis and a rapid drop of I_c between 0 and 1 T for B normal to the tape.

4.1.1. Anisotropy In these highly textured materials I_c depends strongly on the direction of applied fields. It is largest if the field is parallel to the tape surface, and hence aligned with the ab -plane of the Bi2223 crystals, because here flux pinning is most effective. The least pinning occurs with the field

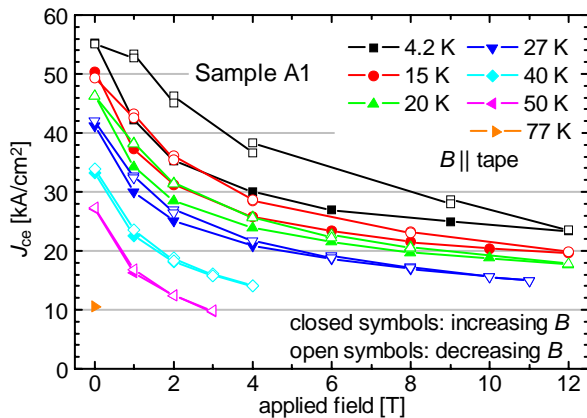


Figure 1. J_{ce} of Sample A1 with $B \parallel$ tape, first measured in increasing, then in decreasing field.

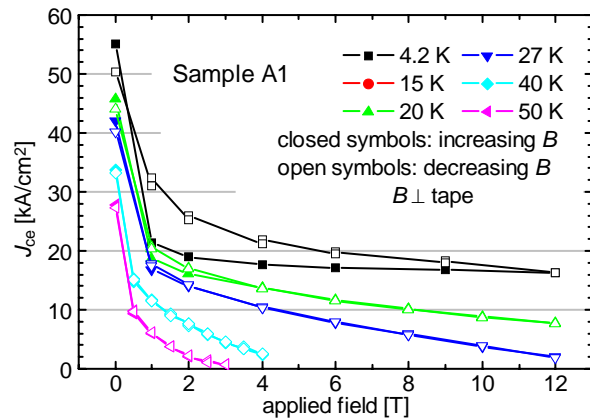


Figure 2. J_{ce} of Sample A1 with $B \perp$ tape.

normal to the tape surface, i.e. parallel to the crystal c -axis. Depending on the local field direction in a coil winding $I_c(B \perp ab)$ may limit the overall performance of the conductor. Figure 3 shows a comparison of the values measured in Sample A1. For $B \perp ab$ J_{ce} drops by about 2/3 from 0 to 1 T but then stays remarkably constant up to 12 T at low temperatures. This behavior may arise from a cross-over between an inter-granular weak-link limited I_c at low fields to a regime where flux pinning inside the grains determines I_c . At higher temperatures thermal activation of the pinned flux lines leads to an exponential reduction of I_c with B (see scaling laws below).

4.1.2. Hysteresis Figure 4 shows a sequence (indicated by arrows) of I_c measurements, where the field was first increased ($0 \rightarrow 1 \rightarrow 2 \rightarrow 4 \rightarrow 6$ T) and then decreased. At each field-step the current was ramped to I_c five times. The observation that the I_c values are smaller for increasing than for decreasing field can be explained by a superposition of the applied field with the one generated by intergranular shielding currents at the location of grain boundaries, which determine the transport I_c . In increasing applied field the local field there is enhanced, while it is reduced in decreasing field [5]. Subsequent ramps of the sample current to I_c appear to reduce the intra-grain currents, resulting in a 'closing' of the hysteresis loop [6]. The hysteresis effect disappears at about 27 K for $B \perp ab$ and at 40 K for $B \parallel ab$ (see figures 1 and 2).

4.1.3. Scaling laws To describe the I_c dependence on B and T in as large a range as possible, empirical scaling laws are useful [3]. Fits with equation (1) reproduced the data above 4 T – the region interesting for applications – with errors smaller than 10 %, if the data for $B \perp ab$ and $B \parallel ab$ was treated

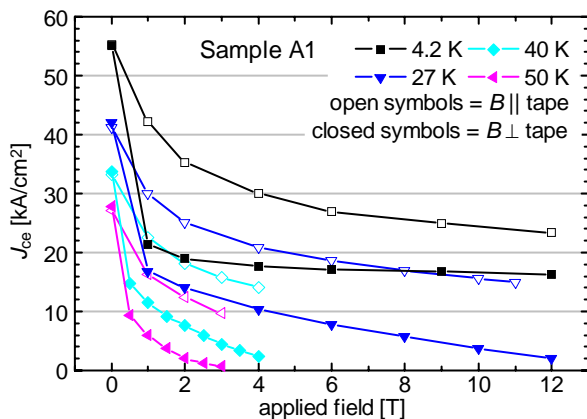


Figure 3. Anisotropy: J_{ce} strongly depends on the direction of an applied field (B increasing only).

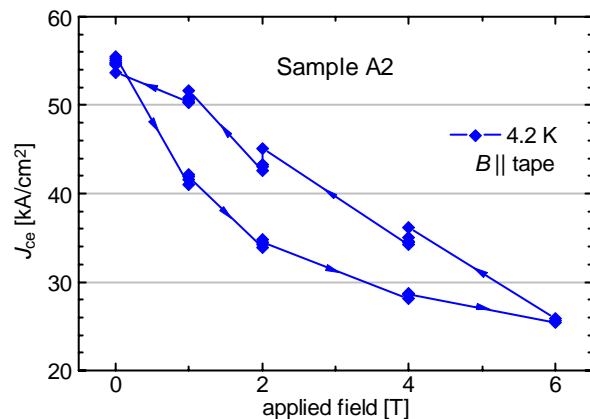


Figure 4. Hysteresis: J_{ce} depends on the history of the applied field and of the conductor current.

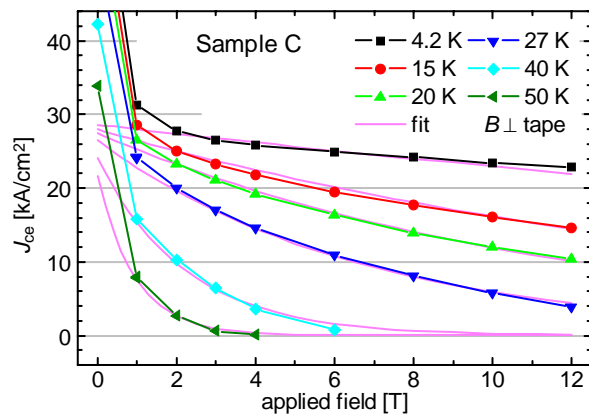


Figure 5. Fit of the measured data above 2 T.

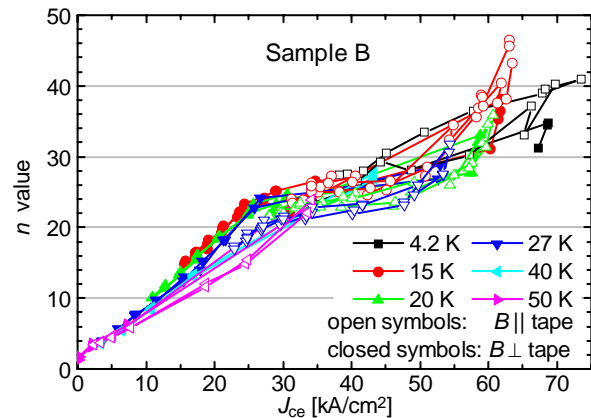


Figure 6. Correlation between n values and J_{ce} .

separately. Figure 5 shows a typical fit result, while table 2 summarizes the obtained fit parameters. The scaling current, field and temperature (I_{sc} , B_{sc} , and T_{sc}) are free parameters, T_c was estimated.

$$I_c = I_{sc} \cdot \left(1 - \left(\frac{T}{T_c} \right)^\beta \right) \cdot \exp \left(-B \cdot \left(B_{sc} \exp \left(\frac{-T}{T_{sc}} \right) \right)^{-1} \right) \quad (1)$$

4.1.4. n -values The exponent n , used to fit the I - V curve of the superconducting transition, is strongly correlated to J_{ce} in all investigated Bi2223 samples, independent of T , B and even field direction (see figure 6). n increases linearly with J_{ce} until a near-plateau is reached at about 22 (observed for example at 15 K with 4 T $B \perp ab$ and with 12 T $B \parallel ab$). Equation (1) and the n - J_{ce} correlation provide full information of the superconducting transition in a wide range of T and B , useful e.g. for simulations of conductor behaviour in a coil.

Table 2. Fit parameters for equation (1) of all samples

		T_c	T_{sc}	I_{sc}	B_{sc}	β
A1	$B \parallel ab$	105	14.88	253.3	100.2	2.24
	$B \perp ab$	105	11.52	176.8	68.9	2.7
A2	$B \parallel ab$	105	16.8	247.3	86.4	1.91
B	$B \parallel ab$	105	15.24	494.6	111.8	1.79
	$B \perp ab$	105	11.6	344.4	65.7	1.9
C	$B \parallel ab$	105	15.35	396.5	121	1.75
	$B \perp ab$	105	11.84	276.8	64.9	1.9
D		80	8.28	622.2	59.45	0.33

4.2. The Bi2212 sample

The round Bi2212 wire, heat treated at CRPP, reached very high current densities at 4.2 K, but much smaller ones at temperatures as low as 15 K. Figures 7 and 8 summarize the temperature dependence of all samples investigated at 8 T and 12 T respectively. Above 20 K J_{ce} of the Bi2212 Sample D is smaller than J_{ce} of the Bi2223 samples with $B \perp ab$. Interestingly only a very small hysteresis effect appeared in the Bi2212 wire, even at 4.2 K, indicating a better coupling at the grain boundaries.

5. Conclusions

Design studies for a first commercial fusion reactor indicate that conductors reaching at least 15 kA/cm² [1] in fields between 13 and 13.6 T [7] may be candidates for the TF coil winding. At 4.2 K the round Bi2212 wire easily fulfils this requirement, while the Bi2223 tapes are also suitable, independent of their orientation to the field. At 20 K and above, where the heat capacity of metals and

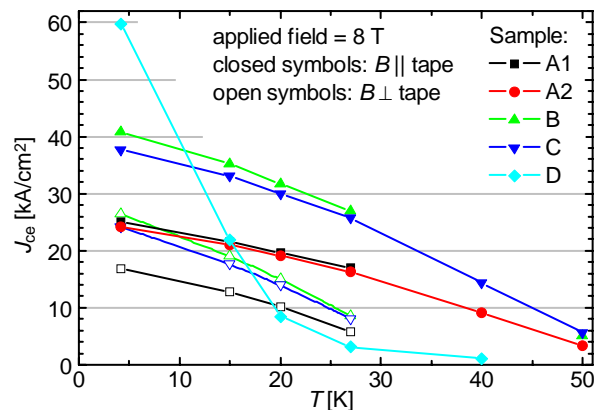


Figure 7. T dependence of J_{ce} at 8 T applied field for all samples and both orientations. Sample D, the round wire, is isotropic.

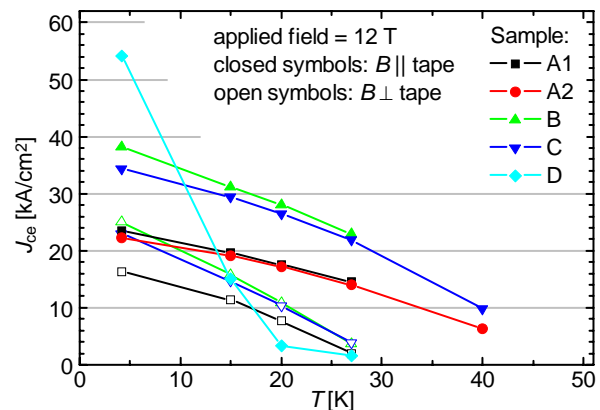


Figure 8. T dependence of J_{ce} at 12 T applied field for all samples and both orientations. Sample D, the round wire, is isotropic.

thus the quench stability of the superconductor are substantially higher, only conductors made of Bi2223 tapes, carefully crafted to assure that $B \perp ab$ remains below about 3.5 T [8], could prove attractive if a suitable cooling system is available.

A scaling relation, based on an exponential field dependence of the critical current, describes the high field performance of the conductors well. The scaling laws, obtained for the presently investigated Bi2212 and Bi2223 wires and tapes, are useful for future conceptual design studies of DEMO considering the possibility to make use of HTS. As soon as the second generation high- T_c tapes will be available in long lengths at reasonable cost they may be even more attractive superconductors for fusion magnets. The 123 coated conductors are the only materials offering the possibility to operate future fusion magnets at temperatures of 50 K or above.

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