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Variable-temperature critical current measurements on YBaCuO coated conductors

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Abstract
The critical currents of 1 cm wide YBCO coated tapes, fabricated within the EC-funded project READY, have been measured. Critical current data as a function of temperature from 4.2 K to 77 K in magnetic fields up to 6 T, together with data at 4.2 K in fields up to 20 T, are presented. The future use of such conductors in high-field magnet-insert coils is considered through comparison of the data with those for Bi-2212, Bi-2223, NbTi and Nb_3Sn conductors at liquid helium temperatures.

1. Introduction

The highest fields of commercial superconducting magnets have been continuously increased over the last 20 years. Currently, the maximum stands at 21.1 T in 900 MHz NMR systems [1]. There is a strong demand to increase this value even further to enable the production of GHz NMR and larger magnets. To advance beyond a GHz system (central field > 23.5 T), there seems to be no alternative to employing insert coils made from high temperature superconductors (HTS) or Nb_3Al [2, 3]. The latest high-performance bismuth-based HTS conductors now appear to have the required critical currents and lengths to meet this end [4, 5]. However, much effort is now being put into developing a new generation of YBCO-based conductors that promise higher critical currents over a wide range of temperatures.

Experimental samples of YBCO conductors, produced in the EC-funded project READY [6], have been characterized to assess their potential in high-field magnet inserts and other applications. This has necessitated the development of a new critical current measurement probe that can supply large currents at variable temperatures (2–80 K). The operation of this probe is described in section 2, the test samples are described in section 3 and the measurement results in section 4.

2. Measurement system design

2.1. High current, variable-temperature critical-current probe

2.1.1. Probe design. The variable-temperature measurements described later were made using a new (non-commercial) probe specifically developed for HTS conductors with high critical currents. It uses a heat exchanger to remove heat (that conducted down the large current leads and that from resistive dissipation at the joints) away from the sample under test, enabling control of its temperature during I_C measurement.

The design of the sample holder and heat exchanger is shown in figure 1(*a*). Copper stages (2) are bolted to 1 kA brass current leads (1) near their ends. A stainless steel channel (3) is hard soldered to these copper stages, bridging the gap between them. The tape sample is adhered to this channel with vacuum grease or GE varnish. Its ends rest on the copper stages with indium strips placed over them. Current terminations are made by bolting copper blocks (4) over the tape/indium sandwiches to make low resistance pressure contacts with a surface area of (1.4 × tape width) cm^2. This technique gives contact resistances of 0.1–0.3 $\mu\Omega$ at 4 K, rising to 1–4 $\mu\Omega$ at 77 K. For tape samples, the magnetic field is oriented parallel to the tape surface (sometimes denoted as parallel to the *ab*-plane) and perpendicular to the macroscopic transport current. Voltage taps are attached with silver paint or low temperature solder. For coated conductors, narrow strips of 25 μm thick silver sheet form the contact end of the voltage taps. The sample length is 95 mm and each current joint covers a 15 mm length. Two 20 W heaters (connected in series) are placed on the back surfaces of the copper stages (2).

The heat exchanger (5) is suspended below the sample holder. This consists of two semicircular copper blocks soldered to the ends of the current leads and separated by an insulating spacer. Several slots are machined in these blocks to allow passage of cooling gas and an array of copper cooling

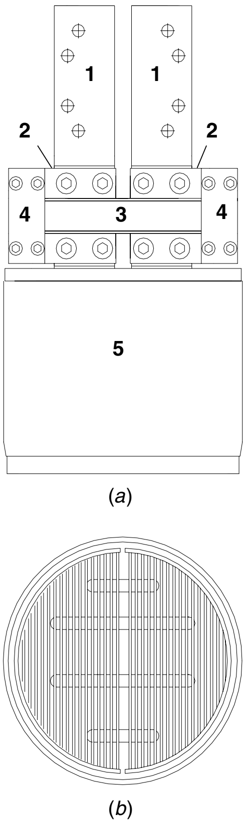

Figure 1. (*a*) A diagram of the sample mounting stage and heat exchanger for variable-temperature measurements. The outer diameter of the probe is just under 100 mm. 1: brass current leads; 2: copper stages; 3: stainless steel sample channel; 4: copper terminal blocks; 5: heat exchanger enclosed within a PTFE jacket. (*b*) A view of the heat exchanger from underneath showing the arrangement of copper cooling fins attached to the separated halves of a copper cylinder inside the PTFE jacket. The cooling slots in the 'roof' of the heat exchanger are also shown.

fins is soldered to their undersides (figure 1(*b*)). The heat exchanger is enclosed by a PTFE jacket.

The assembly is placed inside a variable-temperature insert (VTI) that is located in the bore of a 6 T magnet. The outer diameter of the PTFE jacket has been sized so that, after allowing for thermal contraction, the heat exchanger just fits inside the 100 mm bore of the VTI. Cernox temperature sensors are placed at several locations: the bottom of the VTI, on the sample channel (3), on the back of the copper stages (2) and suspended in the gas stream over the sample.

2.1.2. Probe operation. Cold helium gas enters the VTI through the needle valve at its lower end and is removed at the top by a pump. The gas is forced to flow between the cooling fins of the heat exchanger, removing heat dumped into them, then across the sample, cooling it. Each measurement temperature is obtained with appropriate settings of the heater output, needle valve and pump flow rate. It is monitored and controlled during the I–V measurement using an Oxford Instruments ITC3. For measurements at 4.2 K, liquid helium is collected inside the VTI until the sample is submerged. At temperatures just above 4.2 K (i.e. 5–10 K) there is only a small difference in the temperatures of the cooling gas and sample. This makes it difficult to maintain a stable temperature during high current measurements since heating from the terminations is more than can be compensated for by reducing the sample heater output. This means that at 10 K, heating of the sample occurred with currents higher than 100 A. For sample temperatures of 4.2 K, 20 K, 40 K, 60 K and 77 K, critical currents up to 800 A, 640 A, 450 A, 280 A and 180 A, respectively have been measured to date without sample heating—indicated by the cernox sensors on the sample channel and copper stages.

2.1.3. Angular measurements. With the heat-exchanger probe head described above, HTS tapes can only be measured in parallel magnetic fields (perpendicular to the transport current). For I_C measurements at other field orientations, an alternative sample holder is bolted onto the ends of the current leads in place of the heat-exchanger probe. For this angular probe head, the stainless steel channel holding the sample can be manually rotated (at room temperature) to the desired orientation. It is only suitable for measurements in liquid helium and the sample must be further constrained to cope with Lorentz forces.

2.2. Critical current measurements in high magnetic fields

Critical current measurements in magnetic fields higher than 6 T were made with an Oxford Instruments 20/21 T magnet system at the Clarendon Laboratory, Oxford University [7]. The samples were inserted directly into the 40 mm cold bore of the magnet, immersed in 4.2 K liquid helium. The sample mount was not optimized for coated conductors (for which contacts can only be made on one surface) and the restricted sample length caused difficulties in making low resistance current joints. The contact surface area at each end was only 0.5 cm^2. Previous measurements on solder joints to YBCO conductors predict contact resistances of 0.5–1.0 $\mu\Omega$ in this situation. The V–I characteristics of YBCO coated conductors are very sensitive to contact length and resistance [8]. With this set-up, measurements could not be made on coated conductors above 200 A without quenching, often leading to burnout. Silver-clad bismuth-based HTS conductors could be measured up to the limit of the power supply (500 A).

3. Description of conductor samples under test

Five YBCO tapes, produced in the EC-funded project READY, have been tested. YBCO films of varying thickness were deposited by THEVA GmbH onto CeO-buffered 10 mm wide Ni-alloy RABiTS^{TM} substrates supplied by IFW (Dresden) [5, 9, 10]. The film widths were 9 mm and each tape had a protective coating of gold, 0.1–0.2 μm thick. Useful parameters of the four samples, labelled A–D are given in table 1. The self-field J_C at 77 K of the samples varied from 0.4–1.2 MA cm^{-2}.

Sample A was non-uniform along its length. Its properties were measured over four 1 cm sections. One of the end sections had a very low J_C and was resistive for the most part of each V–I measurement. The data from the medium quality section out of the remaining three is reported here. One of the other

Table 1. Dimensions and critical current values of the YBCO tape samples (A-D) and the Bi-2223 tape (ASC, with and without stainless steel reinforcement).

	Sample					
	A	B	C	D	ASC	ASC
					3-ply	No S/S
Film thickness (μm)	1.9	0.7	0.57	0.7		
Overall dimensions (mm)		10×0.08			4×0.3	4×0.2
Voltage tap distance (mm)	10	30	40	20	40	40
Self-field I_C at 77 K (A)	110	50	62	25	135	135
Self-field J_C at 77 K (A mm^{-2})	6433	7937	12 086	3968	430	430
Self-field J_E at 77 K (A mm^{-2})	134	61.8	76.8	30.9	112	168
Factor increase in self-field I_C on cooling to 4 K		7.5	8.8	7.4	5.7	5.7
I_C (6 T, 4 K), (A)		341	514	144	480	480
J_E (6 T, 4 K), (A mm^{-2})		421	637	178	382	573

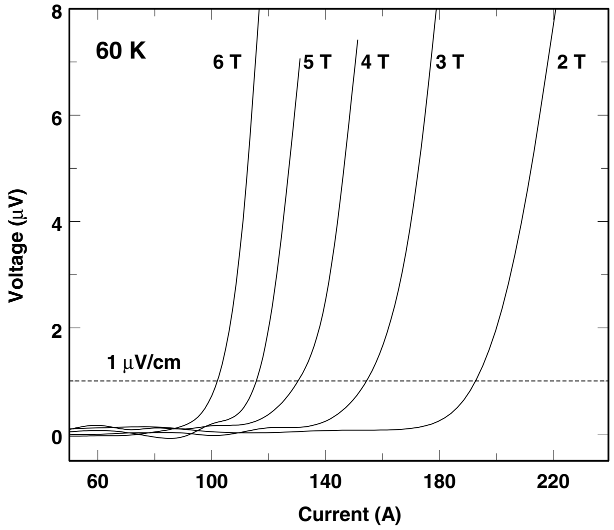

Figure 2. Example I–V traces measured with the heat-exchanger probe from sample A at 60 K. Traces at parallel fields of 2, 3, 4, 5 and 6 T are shown. The dashed line indicates the criterion used to calculate the critical current.

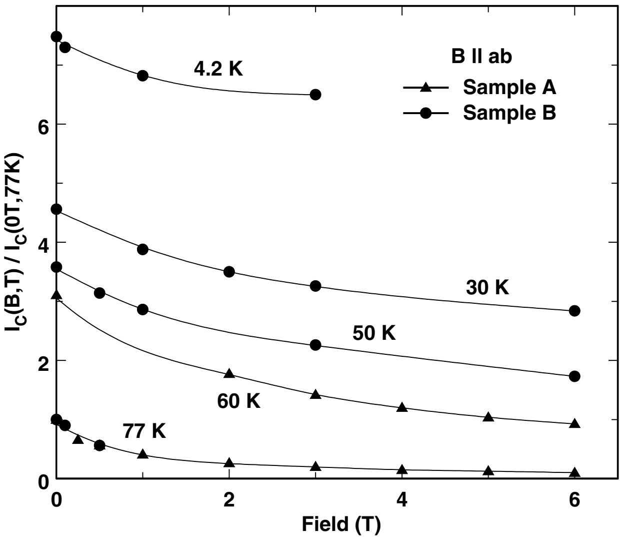

Figure 3. Critical currents of samples A (1.9 μm, triangles) and B (0.7 μm, circles) in parallel fields up to 6 T and at temperatures between 4 K and 77 K. The I_C values are normalized to those at 77 K in self-field (110 A for sample A and 50 A for sample B).

sections had a higher I_C that could not be measured in low fields without quenching the sample and the remaining section had an I_C that was 8% lower.

Data from commercially available Bi-2223 tapes, measured with the same test rig, have been used to compare with the YBCO tapes performances. The Bi-2223 samples were cut from a length of 3-ply reinforced tape from the American Superconductor Corporation; overall dimensions were 4 mm wide by 0.3 mm thick. This thickness included the two 50 μm thick stainless steel reinforcement strips. The most useful sample parameters are listed in table 1. The data used in this table for the Bi-2223 tape are from a sample of average quality. Some sections exhibited critical currents that were 30% higher. For better comparison with the YBCO samples, the predicted performance of this tape with the stainless steel strips removed is also given.

4. Measurement results

4.1. Critical current as a function of temperature in magnetic fields up to 6 T

Variable-temperature I_C measurements in a parallel field have been made on samples A and B. Figure 2 shows typical V–I traces from sample A at 60 K. The base noise level in all voltage measurements was ± 0.2 μV. Figure 3 plots critical current data from both samples normalized to their self-field values at 77 K. Whilst attempting to do further measurements at 60 K, the resistive section of sample A was burnt out, destroying the sample.

4.2. Critical current and n-value at 4.2 K in parallel and perpendicular fields

Sample C was measured at 4.2 K in parallel and perpendicular field directions up to 6 T using the variable-angle probe head. Of all the measured YBCO samples, this one had the highest J_C but not the best engineering current density (J_E) at 77 K. Figure 4 plots J_E for the two field orientations at 4.2 K. With Bi-based tapes, the critical current is lowest when the field is perpendicular but this may not be the case with the YBCO tapes [11, 12], where a sweep of field angle is needed to confirm the position of the I_C minimum. The corresponding n-values were calculated by fitting power-law curves, $E = aJ^n$, to the data between $E = 0.1$ μV cm^{-1} and $E = 10$ μV cm^{-1}. They are plotted in figure 5.

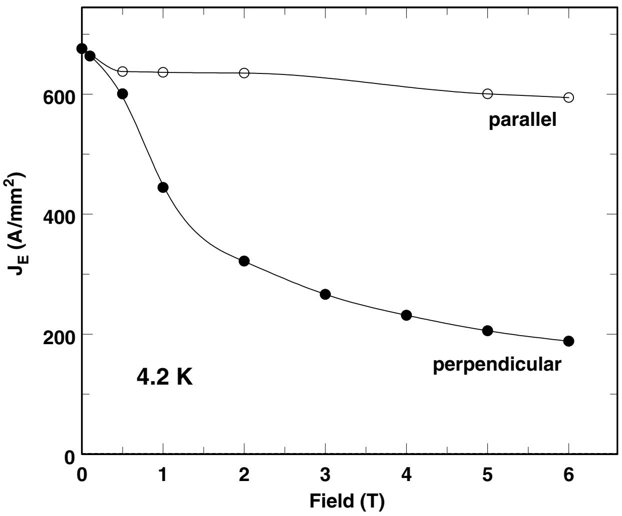

Figure 4. The engineering critical current density of sample C, in parallel and perpendicular fields up to 6 T at 4.2 K, measured with the variable-angle probe head in liquid helium.

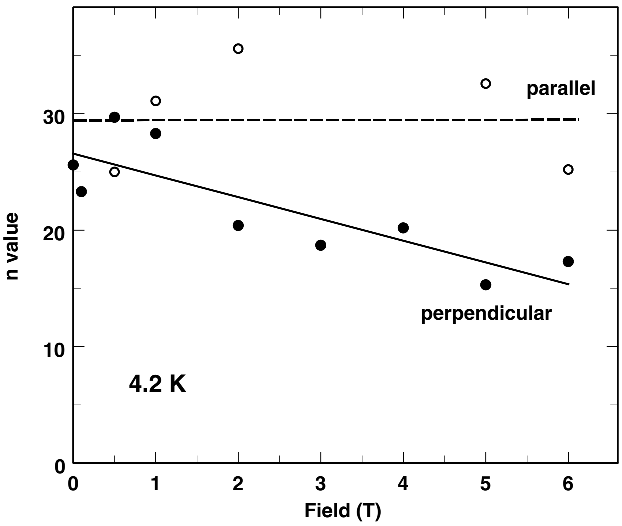

Figure 5. The power index, n-values of sample C versus parallel and perpendicular field. They were calculated by fitting power functions between $E = 0.1\ \mu$V cm^{-1} and $E = 10\ \mu$V cm^{-1} of the measured E–J traces at 4.2 K.

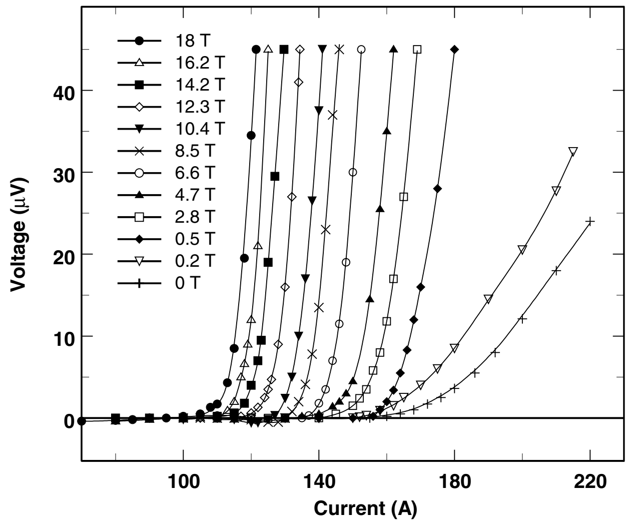

Figure 6. I–V traces of sample D, measured at 4.2 K in the 21 T magnet system at the Clarendon Laboratory, Oxford University. Selected traces over the parallel field range of 0–18 T are plotted. These traces have been transcribed from hardcopy chart-plotter output. The symbols show selected data points used in the 'digitization process'.

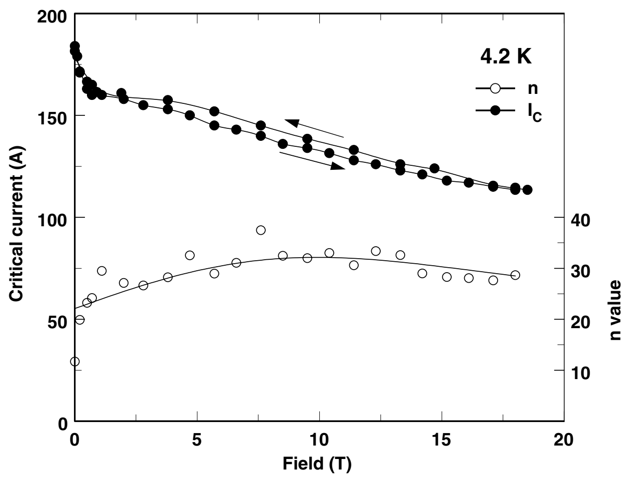

Figure 7. The critical currents and n-values of sample D at 4.2 K, calculated from the I–V traces in figure 6. The filled circles plot I_C using the left-hand y-axis with increasing and decreasing parallel field. The open circles plot the n-values with increasing field using the right-hand y-axis.

4.3. Critical current at 4.2 K in parallel fields up to 20 T

The critical current of sample D was measured in parallel fields up to 18.5 T using the measurement system at the Clarendon Laboratory. Figure 6 shows selected V–I traces from the whole field range. The traces are very flat before any transition, showing no signs of thermally induced or current transfer voltages. The critical current and n-values are plotted in figure 7.

4.4. Comparisons with other superconductors

Figures 8 and 9 compare the data of samples C and D to alternative high current superconductors used in high-field magnets. In both figures the data from sample D (obtained with the 21 T magnet at the Clarendon in which higher quality YBCO tapes could not be measured) have been multiplied by a factor of 3.2. This allows a lower estimate of the high-field performance of the better quality sample C. Since the field dependence of a conductor usually improves as J_C increases, it is likely that the performance of sample C would be better than this estimate.

Figure 8 compares the J_E values at 4.2 K of the two YBCO samples to those of samples from an American Superconductor Corporation 3-ply Bi-2223 tape, measured with the same test systems. There was some variation in the critical current along this ASC tape and the data in this figure are from tape sections with *average* performance levels. Also plotted is the estimated J_E of the ASC tape with the stainless steel reinforcement removed. This provides better comparison with the YBCO tapes that have no reinforcement and little stabilization.

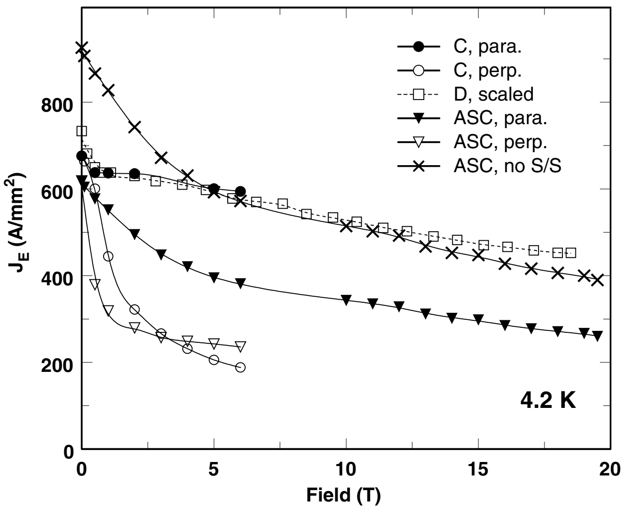

Figure 8. Engineering critical current densities of samples C, D and an average quality ASC tape in parallel and perpendicular fields at 4.2 K. The data for sample D have been scaled by a factor of 3.2 to provide an estimate of the high-field performance of sample C. The estimated parallel field data for the ASC tape with its stainless steel strips removed are also plotted.

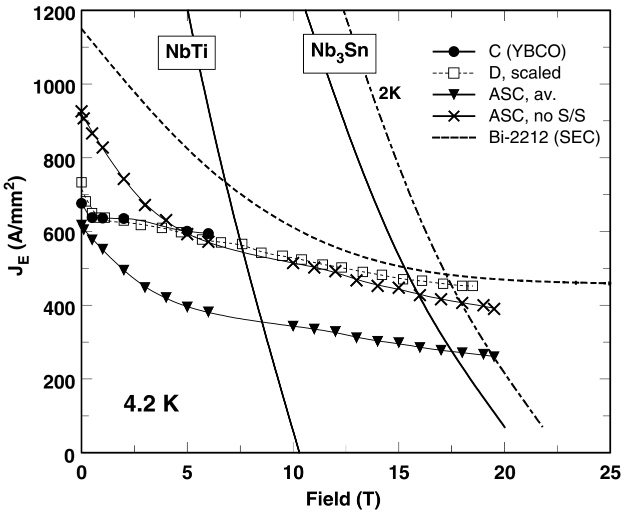

Figure 9. The engineering critical current densities of samples C, D (scaled as in figure 8) and the ASC tape in parallel fields at 4.2 K, compared to those for state-of-the-art multifilamentary Nb_3Sn, NbTi and Bi-2212 wires. The Bi-2212 data are for a 1 mm diameter wire manufactured by Showa Electric Company [3].

The parallel field performances of these YBCO and Bi-2223 tapes are compared to NbTi, Nb_3Sn and Bi-2212 wires at 4.2 K in figure 9. The data for Bi-2212 have been extracted from a published graph of I_C versus field for a 1 mm diameter wire made by Showa Electric Company [3]. The significant increase in J_E of a Nb_3Sn wire in cooling to 2.2 K is also indicated in this figure. In contrast, the J_E of HTS conductors increases very little at this lower temperature.

5. Conclusions

We make the following conclusions about the measured performance of the YBCO coated conductors compared to other materials:

1. The critical current of the YBCO tapes decreases more slowly with low parallel field compared to Bi-based tapes. On decreasing the temperature from 77 K to 4 K, I_C increases by a higher factor than with Bi-2223 tapes.
2. Sample A was the best sample measured at 77 K with $J_E = 134$ A mm^{-2}. It could not be measured at 4 K, but if it had scaled with temperature and field in a similar way to the other samples, we could expect it to have had a self-field I_C of 800–1000 A (J_E = 975–1220 A mm^{-2}) at 4.2 K, dropping to 480–600 A (J_E = 580–730 A mm^{-2}) at 20 T.
3. The thinner film of sample C had the highest J_C (12 kA mm^{-2} at 77 K), but with such conductor geometry this does not correspond to the highest J_E which is the more important parameter for magnets.
4. When HTS tapes are used in insert coils in high background fields (<20 T), radial fields are expected to be relatively low. For Bi-2223 tapes, the parallel field performance is likely to be the limiting parameter. However, for YBCO there is not yet sufficient data to allow this assumption. The anisotropy may vary strongly with sample quality and more detailed angular measurements at 4 K on high quality tapes are required.
5. Figure 9 shows how necessary it is to use HTS conductors to generate fields much above 20 T, whereas at lower fields Nb_3Sn and NbTi are still the superior superconducting wires.
6. If the assumption used in figure 8 is valid (that the $J_E(B)$ data of sample D can be scaled to represent the possible performance of sample C at high fields), then these experimental YBCO tapes predict good potential for high J_E conductors in magnets at 4.2 K. This predicted performance (for 'medium' quality tapes) is close to that of existing, non-reinforced Bi-2223 and Bi-2212 conductors. It must be remembered however, that I_C of the Bi-2212 wire manufactured by Showa Electric is isotropic with respect to magnetic field.
7. State-of-the-art Bi-2223 and Bi-2212 conductors are available now in lengths of several hundred metres with a performance suitable for use in high-field magnets. To displace first generation HTS wires in these applications, YBCO tapes must be supplied in similar lengths with additional stabilizing material, which have a higher J_E. For the same substrate thickness, it may be possible to double J_E by coating both sides (though to our knowledge, this has not yet been successfully demonstrated). Promisingly, recent reports of coated conductors with YBCO multilayers [13] suggest an alternative approach that has the potential to significantly increase the J_E of future YBCO conductors.
8. Whether it is the first or second generation, it is clear that HTS conductors of one type or another will be needed to produce research or NMR magnets with fields much in excess of 20 T.

Acknowledgments

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