Analysis of the anisotropic critical current behaviour of HTS coated conductors

P M Leys, M Klaeser, F Schleissinger and Th Schneider
Karlsruhe Institute of Technology, Institute for Technical Physics, Hermann-von-Helmholtz Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

E-mail: pauline.leys@kit.edu

Abstract. In order to generate fields of more than 20 T using pure superconducting magnets, the implementation of HTS coated conductors (CCs) is an option. Amongst the characteristics of the REBCO is its intrinsic anisotropy which means its critical current, $I_c$, varies as a function of its orientation with respect to the external magnetic field, $\Phi$, as well as being dependent on external field, $B$, and temperature, $T$. For the design of the high field insert coils for the experimental magnet facility HOMER II, the behaviour of $I_c$ at fields of about 24 T and at $\Phi$ approximately 80 ° is required. Within our JUMBO facility it is possible to measure the $U(I)$ behaviour of commercial CCs at liquid helium and liquid nitrogen temperatures. The free bore available is 100 mm at 4.2 K; the applied magnetic field can be varied up to 10 T, and $\Phi$ can be set between 0 and 180 °. Measurements were carried out on commercially available CCs with emphasis on $\Phi$ values near to 90 °. The critical current was determined by means of a power law function fitted to the resulting $U(I)$ curves using specially written Matlab® programs. A number of different three dimensional functions were fitted to the measurement data and compared with each other.

1. Introduction
REBCO high temperature superconductor (HTS) coated conductors can be used for energy applications at 77 K and, due to their excellent low temperature current carrying capabilities at high fields, they are ideal candidates for operation at 4.2 K. Having studied the dependence of the critical current, $I_c$, of an HTS on the angle, $\Phi$ (defined as the angle between the magnetic field and the normal vector to the conductor tape) at different magnetic fields and temperatures in a previous paper [1], we wanted to further develop our analysis of mathematical models or functions that would fit the three dimensional surface plot of $I_c(B, \Phi, T)$ measurement data at both 4.2 K and 77 K.

All high field insert coils have a maximum radial field, $B_r$, component at their outer edges where the angle $\Phi$ is greatest. For an optimal design we need to know the $I_c$ anisotropy for each conductor to be used in developing our HOMER II facility, NMR projects and all other high field applications at 4.2 K. Anisotropy is also an important feature at 77 K. Here the $B_r$ component must be considered in project design as well, but in this case, due to the strong $I_c(B)$ decrease, only low fields are considered. Therefore the aim of this paper is to present an analysis and comparison of the critical current data for the HTS samples at both liquid helium and liquid nitrogen temperatures.

2. Experimental Details
The conductor used in the experiments was a coated conductor from the company SuNAM [2]. We tested two conductor types: type I with copper plating and type II with copper plating and brass lamination. The conductor width was approximately 4.1 mm and its thickness 0.11 mm (type I) or...
0.19 mm (type II). The $I_c$ values are 130–190 A at 77 K and 1160–1230 A at 4.2 K self-field, dependent on conductor type. Measurements were made across the complete conductor width of 4.1 mm for the two conductor samples at 4.2 K and at 77 K and the angle $\Phi$ was adjusted between $0 – 180 ^\circ$. At both temperatures the experiments followed the same procedure as described in [1] with more measurements at $\Phi = 76 -104 ^\circ$ in steps of $\geq 2 ^\circ$, as this range is most relevant to magnet design. Each set of measurements was made with a different conductor sample.

At 4.2 K we measured the voltage-current ($U(I)$) characteristics [1] for the samples at fields from 3–10 T. Measurements at fields below 3 T were not made due to the high critical current at low fields, and also our area of interest at this temperature is high field operation. At 77 K we measured $U(I)$ in fields from 0–4 T with steps of 0.1 T being made between 0 and 1 T in consideration of the usual operational range at this temperature.

3. Theoretical Background

The intrinsic anisotropy of HTS CC’s leads to an angular dependency of the critical parameters, in particular $I_c$ and $n$[3]. $I_c(B, \Phi, \Gamma)$ was determined from measured $U(I)$ curves by means of a power law fit with $E_c$ defined as 0.1 $\mu$V/cm.

The first mathematical model considered for the dependence of $I_c$ on $B$ was that according to [3] and combined with anisotropy from [4] as already used in our previous paper [1], given as

$$I_c(B, \Phi) = I_c0 \cdot \left(1 + \varepsilon(\Phi) \cdot \left(\frac{B}{B_0}\right)^\gamma\right)^{-1}$$

This was adapted to form the following equation:

$$I_c(B, \Phi) = I_c0 \cdot \left(1 + \varepsilon(\Phi) \cdot \left(\frac{B}{B_0}\right)^\alpha\right)^{-1}$$

A second model considered was the so-called Percolation model according to [5] which states that the current flows by percolation through the weak-link network of the conductor. Combining this model with the anisotropy gives:

$$I_c(B, \Phi) = I_c0 \cdot \left(\delta + \exp\left[-\varepsilon(\Phi) \cdot \left(\frac{B}{B_0}\right)^\beta\right]\right)$$

A third function considered is given in [6] where the magnetisation of superconducting wires was studied and a remarkably good fit with the following function (which has been expanded to include the anisotropy and further mathematical fit parameters) was found:

$$I_c(B, \Phi) = I_c0 \cdot \exp\left[\lambda - \varepsilon(\Phi) \cdot \left(\frac{B}{B_0}\right)^\beta\right]$$

In each case, the anisotropy function $\varepsilon(\Phi)$ was defined as

$$\varepsilon(\Phi) = \sqrt{g^2 \cdot \cos^2(\Phi) + \sin^2(\Phi)}$$

with the parameters to be fitted by the Matlab® software grouped into the physical fit parameters $I_{c0}$, $B_0$, $\delta$, $\lambda$ and $g$ and the mathematical fit parameters $\alpha, \beta$ and $\gamma$

4. Analysis of the results

The measurements showed that the angle at which $I_c$ has its maximum value deviated slightly from $90 ^\circ$ at both 4.2 K and 77 K. Therefore an extra variable must be included in the anisotropy function $\varepsilon(\Phi)$ in equation (5) and $\Phi$ becomes $\Phi + \Delta \Phi$. One theory is that this off-set arises due to the crystal structure of the HTS and is specific to the conductor sample tested. In the above equations $I_{c0}$ was determined by extrapolating the value of $I_c(B)$ at the angle at which the maximum measurement values were found to $B=0$. Once $\Delta \Phi$ was determined by equation (1), it was fixed at this value (see table 1).

Taking the normal operating range of the conductor into consideration, the fits were made for the liquid nitrogen data at 0–1 T. For the liquid helium data the fits were made over the range 3–10 T as a basis for extrapolation to $B > 20$ T. The best fit was determined by comparing the values of the Mean value of the Absolute Difference (MAD) between the $I_c$ values from our measurement data and the corresponding $I_c$ values determined by the fit function as a percentage of the average measured $I_c$. 

---

11th European Conference on Applied Superconductivity (EUCAS2013) IOP Publishing
Journal of Physics: Conference Series 507 (2014) 022013 doi:10.1088/1742-6596/507/2/022013
value. The three dimensional surfaces resulting from the best of the fit models at 77 K and 4.2 K are shown in figures 1 and 2 respectively for the conductor type II and the fit parameters in table 1.
In order to better illustrate the dependence of $I_c$ on $\Phi$ and $B$ individually, figures 3 - 6 show the normalised partial derivatives of $I_c(B, \Phi, \Theta)$ for the functions at 77 K and 4.2 K up to the maximum $I_c$ value. From figure 3 it can be seen that at 77 K varying $\Phi$ has no effect on $I_c$ at zero field, as expected, but rises quickly to a maximum at around 90° as soon as an external field is applied. Figure 5 clearly shows that at extremely low fields a slight increase in the external field results in a rapid decrease in $I_c$ at 77 K which is even more apparent as the field strength increases. This means that the peak in figure 2 becomes increasingly sharper at higher fields. Figure 6 illustrates that at 4.2 K $I_c$ changes more rapidly with $B$ when the field lies parallel to the conductor ($\Phi = 90°$) than when it is perpendicular ($\Phi = 0°$).

All fits made using equations (1) – (4) gave an MAD value of less than 10 %. Equation (2), the modified version of equation (1), improved the MAD value of equation (1) by almost 50 %. Table 1 summarises the results of the best fit functions for the individual sets of measurement data. The MAD percentage error value shows a good correlation with the $R^2$ value generated by the Matlab® software.

| Temp. (K) | CC-type | $\Delta \Phi$ (°) | Equation | Fit Parameters | MAD (%) |
|----------|---------|------------------|----------|----------------|---------|
| 4.2      | II      | 1.84             | 3        | $L_0$ (A) $B_0$ (T) $g(-)$ $\alpha(-)$ $\beta(-)$ $\delta(-)$ | 3.52    |
| 4.2      | I       | 5.10             | 3        | 1222           20.28 53.96 0.65 0.77 0.15 | 3.02    |
| 77       | II      | -1.64            | 2        | 138            0.38 13.03 0.42 1.46 - | 3.89    |
| 77       | I       | 3.28             | 2        | 187            0.34 14.32 0.38 1.47 - | 4.01    |

5. Conclusion
We have made $I_c(B, \Phi, \Theta)$ measurements at 4.2 K and 77 K for CC’s from SuNAM and analysed a number of possible three dimensional fit functions. The variation in $\Delta \Phi$ was possibly due to pinning structure variations between the individual samples. We found that all functions studied gave a suitable fit of the measurement data and that whilst the fit function based on [3] used in our previous paper [1] was still valid (equation (1)), we were able to reduce the percentage error of the function in some cases by up to 50% by introducing new parameters. The best fits gave an error of less than 5 %. At both liquid nitrogen and liquid helium temperatures the error was minimised in all our fits due to the large number of $I_c$ measurements made in the range 76 -104° and, in the case of 77 K, the consideration of the magnetic field range at which the HTS would be likely to be operating. At 4.2 K the functions used can be extrapolated to higher fields, as required.

6. References
[1] Leys P, Klaeser M, Schleissinger F and Schneider Th 2013 Angle-dependent U(I) measurements of HTS coated conductors IEEE Transactions on Applied Superconductivity 23 3 3800604
[2] www.i-sunam.com
[3] Kim Y B, Hempstead C F and Strnad A R 1962 Critical persistent currents in hard superconductors Phys. Rev. Letters 9 7 306-9
[4] Blatter G, Feigelman M V, Geshkenbein V B, Larkin A I and Vinokur V M 1994 Vortices in high-temperature superconductors Rev. Mod. Phys. 66 1125
[5] Doyle T B 1993 Morphology-dependent intergranular behaviour in high-Tc superconducting Y-Ba-Cu-O Phys. Rev. B 47 8111-8
[6] Fietz W A, Beasley M R, Silcox J and Webb W W 1964 Magnitization of Superconducting Nb-25%Zr wire  Phys. Rev. 136 2A 335-345