Homogeneity and Accuracy of the Second Critical Field B_{c2} of the NIST SRM-1457 Standard NbTi/Cu wire

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In the frame work of the VAMAS intercomparison activities the second critical field B_{c2} of the standard NIST NbTi/Cu superconductor was investigated in several laboratories in the world. In this paper the specific results obtained in the UT laboratory are reported. On a single piece of wire of 1.5 meter length the voltage is measured across 10 straight (crossing the magnet axis) and 10 bend sections (on radius 25 mm in the magnet bore). A detailed analysis of all possible errors in field, temperature and voltage is presented. The bend sections provide the best results. As a characteristic result we mention a B_{c2} (at 50%) at 4.2 K of 11.31 T with an error of 10 mT only. The variation in B_{c2} over the sections is about the same as the variation found for various runs of the same section. The B_{c2}-homogeneity of the wire over a length of 1.5 meter is extremely good ($<10^{-3}$). This accuracy is such that the B_{c2} of the standard wire could be used as a field calibrating method.

INTRODUCTION

The second critical magnetic field B_{c2} of a superconductor is an intrinsic material property. This makes the B_{c2} a good subject for an intercomparison study. The purpose of the intercomparison of the B_{c2} -measurement in the framework of the VAMAS program, is to evaluate the scattering in the measurements and to investigate the parameters involved. Moreover, information is gathered about the field accuracy of the magnet systems in the contributing laboratories. The standard NbTi multifilamentary wire and the procedure to determine the B_{c2} are both provided by the VAMAS organisation in order to increase the accuracy of the comparison. An additional investigation performed to determine the homogeneity of the B_{c2} along the supplied wire. The proposed experimental program is extended in our laboratory with a comparison of two possible shapes of the sample with respect to the magnetic field and an additional reproducibility measurement is included. An important feature of the measurements in our magnet is that the magnetic field is determined very precisely with an NMR probe in the relevant field range. This absolute field calibration provides a very good overall accuracy of the Bc2 measurement.

EXPERIMENTAL SET-UP

The transition measurements are performed in a 16 T magnet in which the investigated Nb/Ti wire is inserted. The temperature of the Helium bath of 4.23 ± 0.02 K is determined by the atmospheric pressure. The superconducting magnet is during the measurement of the resistive transition operated in the persistent mode. The magnet current control has a relative accuracy of $\pm 3 \cdot 10^{-4}$. The low voltages across the sample are measured with a Keithley 181 nano-voltmeter and scanner system with an accuracy of ± 20 nV. The magnet current, the current through the sample, and the voltmeters are controlled by a data acquisition system especially developed for monitoring the voltage current transition of superconducting wires across multiple contacts.

The field constant

The magnetic field is gauged by an NMR probe that is placed inside a temporary anti-cryostat inside the 60 mm bore of the solenoid magnet. The accuracy of the field measurement with the NMR probe is much better than the error that is made by the measurement of the magnet current (± 2 mT). The hysteresis of the magnetic field is approximately ± 12 mT in the investigated field range of 7 to 13 T. The measured field constant is 0.5 % above the value that is calculated from the room temperature dimensions which are specified by the manufacturer. This difference can be explained by the thermal contraction (≈ 0.3 %) and the mechanical tolerances (≈ 0.2 %) of the magnet. In normal operation the current of the magnet is controlled by the power supply with a slightly reduced accuracy (± 5 mT).

The sample geometry

The prescribed sample geometry is a short and straight piece of the wire, placed in a perpendicular magnetic field. The 16 T solenoid magnet that is investigated here, has a field profile that is optimised in a typical volume that is used to characterise cylindrical shaped samples. A homogeneous field, within ± 0.1%, is generated on the outer surface of a cylinder with dimensions ∅ 50 × 60 mm^2. On the central axis this uniformity is only achieved along a smaller distance of 30 mm. In order to compare the proposed straight sample geometry with a wire that is spiralled on a cylinder the sample is shaped in a deformed cylinder geometry in which both types of sample orientation are combined. The sample holder with the wire is shown in figure 1. The wire is slightly fixed by clamping it on the textolite sample holder. The voltage taken from ten straight 20 mm long sections of the wire (indicated with Str_..) are compared to the voltage of ten 40 mm long sections on the circular parts of the spiral sample (indicated with Cir_..). The length between the voltage taps on the bend sections of the sample is twice the length between the taps on the straight sections. The physical order of the sample sections is Cir_1, Str_2, Cir_2, Str_2, ... ,Str_10.

DETERMINING THE B_{c2}

The magnetic field is swept step-by-step between 10 and 13 tesla. After each step in magnetic field the sample current is changed stepwise to the prescribed values of 0.01, 0.03, 0.1, 0.3 and 1 A respectively. At a constant current and field, with the magnet switched to the persistent mode, the differential voltages of 8 sections are scanned and compared to the voltage offset by switching the sample current to zero. The field is first swept up in order to start every voltage measuring at the same magnetic history and then the two field sweeps down and up are recorded in order to include any magnetic hysteresis effects in the analysis. The 18 measured $R(B)$ points, nicely distributed over a single transition, are fit to a piece-wise linear dependence between R and B covering the three field intervals.The transition is described by 5 independent parameters C_i:

$$
\begin{aligned}
0 < B < B_1 &\Rightarrow R(B) = C_1 \\
B_1 < B < B_2 &\Rightarrow R(B) = C_2 + C_3 B \\
B_2 < B \quad &\Rightarrow R(B) = C_4 + C_5 B
\end{aligned}
$$

where the constants B_1 and B_2 are determined by the condition of continuity in the $R(B)$ transition. The values for C_i are determined by a numerical least square method. The mid-point of the transition is defined than as B_{c2} (50%)= $(B_1 + B_2)/2$. Moreover the offset, the 10 %, the 90 % and the onset values of the B_{c2} can be calculated. An example of the result from this method of B_{c2} determination is presented in figure 2. The accuracy of the numerical fit, typically ± 2 mT, is better than the determination of the field present in the magnet. Finally the mean value is calculated from the two different B_{c2} values that are measured in both the field down and up sweeps. The influence of the sample current on the B_{c2} determination is significant. If the current is reduced from 1 to 0.01 A, the B_{c2} shifts typically to a 100 mT lower value. If the current is reduced to 0.01 A, the voltage noise becomes larger than the deviation in the B_{c2} determination due to the sample current. The B_{c2} values that are presented in this study are therefore determined at a current of 0.03 A.

In figure 3 a characteristic result is shown of the B_{c2} (50 %) of the 20 sections on the sample as function of the sample current. Note that the B_{c2} of the straight sections are slightly above those of the circular sections.

Reproducibility

The twenty different section of the wire sample are investigated in three runs. Three straight sections are investigated two or three times within a few weeks. Moreover after a few months one series was repeated.

The maximum deviation that occurred between the different B_{c2} determinations is 20 mT. This is approximately the maximum error that can be expected based on the variations in the temperature of the bath (± 7 mT), the determination of the magnet current (± 5 mT) and the fitting error (± 2 mT).

Homogeneity

In order to investigate the homogeneity of the B_{c2} along the investigated wire precisely several geometrical factors determining the average field on a specific section are taken into account to enable a fair comparison:

- Some of the straight samples are slightly misaligned which implies a maximum correction in field of 0.07 %.
- The straight samples are placed in a slightly non uniform field that causes a maximum correction of 0.80 %.
- The circular samples are located in a more uniform field which means a maximum correction of 0.30 %.

All these different corrections are based on the field profile that is calculated by the magnet dimensions as specified by the magnet manufacturer. The accuracy of the geometrical corrections is estimated at 0.03 %, which implies an additional inaccuracy in the determination of the field of only ± 3 mT. The maximum variation in B_{c2} that is detected along the investigated samples is 34 mT at an absolute value of 11.31 T which means a variation of only 0.1%. The differences found between he various sections are not significantly larger than the absolute maximum experimental error of ± 17 mT.

Shape of the sample

As mentioned previously there are some significant differences between the two different types of section: straight and circular. These differences result also in a small difference in the determination of the B_{c2}. The maximum variation as well as the mean values are slightly different among both the section types:

Straight sections: B_{c2} (50 %) = 11.317 ± 0.013 mT,
Circular sections: B_{c2} (50 %) = 11.307 ± 0.007 mT.

The better accuracy of the B_{c2} determination of the circular sample sections can be explained by the larger section length and a better approximation of the geometrically determined field errors which are smaller in that case. The physical order of the sample sections makes it unlikely that the larger variations found in the straight sections are due to spatial variations of the B_{c2} along the wire. With this assumption it is concluded that the circular sections provide more accurate information and thus a better approximation of the homogeneity of the B_{c2} along the supplied Nb/Ti wire sample of less than 10 mT.

CONCLUSIONS

1. The mid value of the $R(B)$ transition is used to determine the upper-critical field of a standard Nb/Ti wire sample at B_{c2} = 11.31 ± 0.02 T.
2. The variations along the supplied wire sample are smaller than the experimental accuracy of ± 10 mT.
3. A comparison between the straight and the circular shaped sample sections gave the conclusion that in the circular samples the Bc2 determination is much more accurate. This is probably caused by a better alignment and less inhomogeneity of the magnetic field. A second effect can be the sample length that is two times larger than in the straight sections.4. The accuracy of the B_{c2} determination is so good (0.2%) that it enables an accurate comparison of the field constants between different magnets.

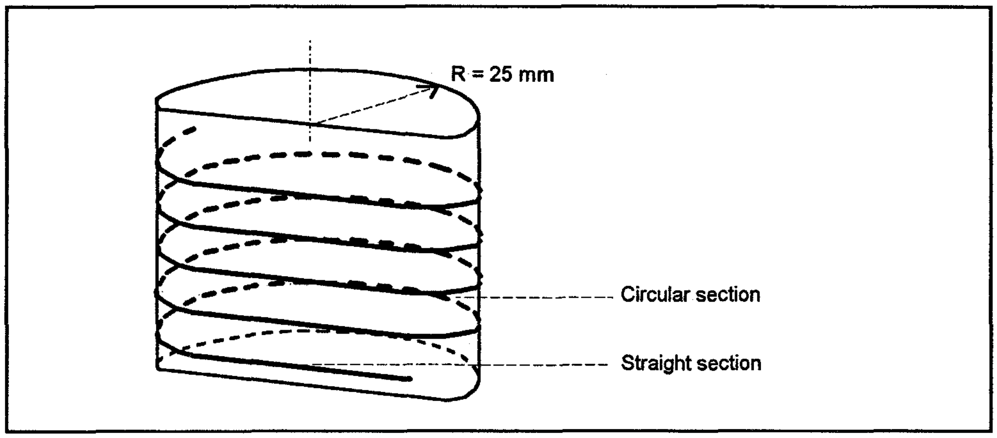

Figure 1 The geometry of the sample with the straight and circular shaped sections indicated

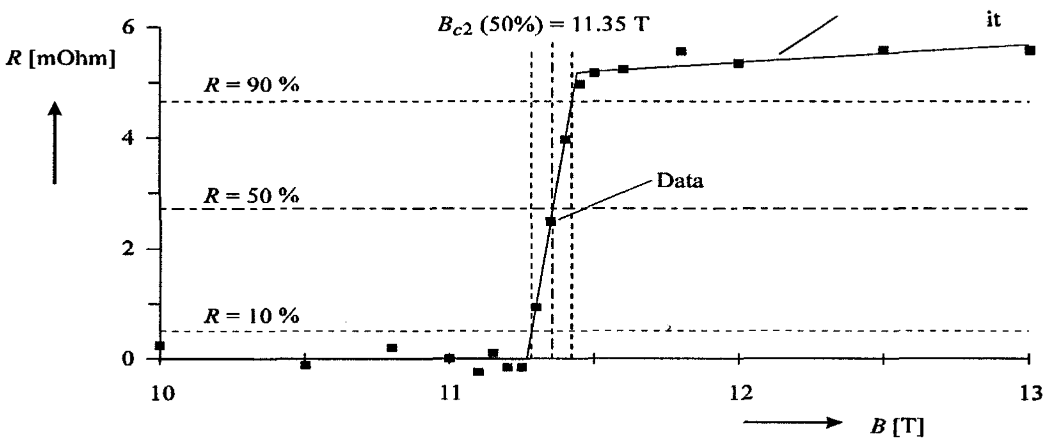

Figure 2 An example of the numerical five parameter fit that is used to determine the B_{c2} value

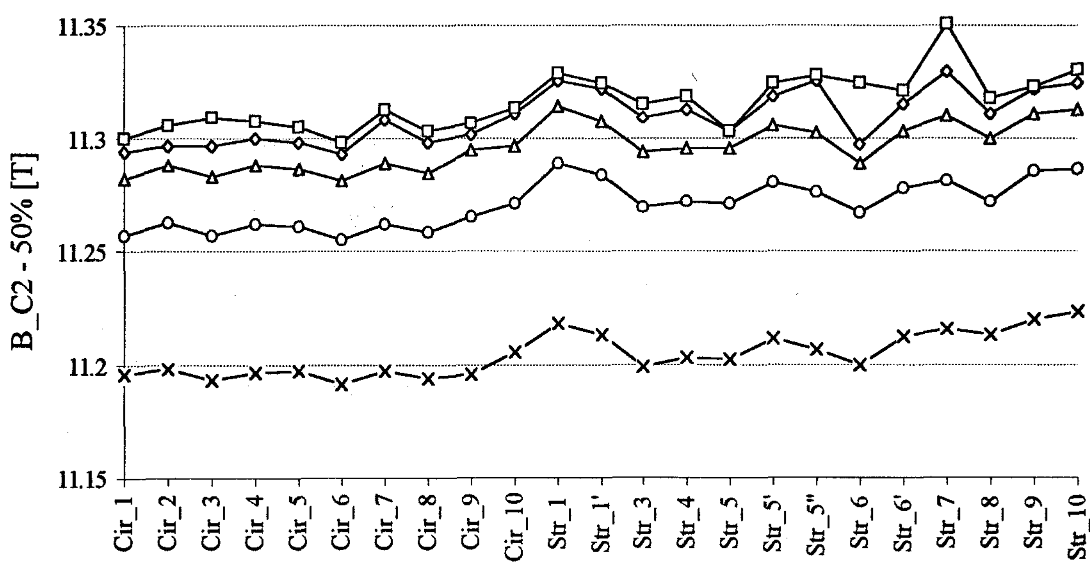

Figure 3 The B_{c2} (50 %) of all straight (Str_#) and circular (Cir_#) sections at 0.01,0.03,0.10,0.30 and 1.00A