Pulsed critical current measurements of NbTi in perpendicular and parallel pulsed magnetic fields using the new Cryo-BI-Pulse System

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Abstract. Rapid transport current versus high magnetic field characterisation of high-irreversibility type II superconductors is important to maximise their critical parameters. HTS conductors are already used to produce insert coils that increase the fields of conventional magnets made from NbTi, (Nb,Ta)\textsubscript{3}Sn and Nb\textsubscript{3}Al wires. There is fundamental interest in the study of HTS tapes and wires in magnetic fields higher than 21 T, the current limit of superconducting magnets producing a DC field. Such fields can be obtained by using pulse techniques. High critical currents cannot be routinely measured with a continuous current applied at liquid helium, hydrogen or neon temperatures because of thermal and mechanical effects. A newly developed pulsed magnetic field and pulsed current system which allows rapid $J_c(B,T)$ measurements of the whole range of superconducting materials was tested with a multifilamentary NbTi wire in perpendicular and parallel orientations.

1. Experimental

Measurements were conducted with the new Cryo-BI-Pulse system (figure 1). A current pulse of 4 ms with a peak value up to 700 A was generated during a magnetic field pulse of 15 ms length with a peak value up to 30 T. The pulse durations and relative start times were always the same; only the amplitude was changed. The potential difference across the sample was measured with the conventional 4-point measurement technique. Similar measurements have been previously reported on Bi\textsubscript{2}Sr\textsubscript{2}CaCu\textsubscript{2}O\textsubscript{8+\delta} tapes [1] and reaction-textured MgO/Bi\textsubscript{2}Sr\textsubscript{2}CaCu\textsubscript{2}O\textsubscript{8+\delta} composite conductors [2, 3] but with less clear voltage signals.

The sample was a commercial NbTi wire with 60 filaments in a copper matrix (figure 2). The cross-sectional area of the whole wire was 0.053 mm\textsuperscript{2}, of which 0.024 mm\textsuperscript{2} was NbTi. The orientation of the sample was either perpendicular or parallel to the external magnetic field. The voltage contact separations were 5 mm and 23 mm for the perpendicular and parallel orientations respectively.
2. Results and discussion

Figure 3 shows the voltage signals for two current pulses with peak values below and above the critical current in applied magnetic fields of 2 T and 10 T. The wire is perpendicular to the field, in the so-called Lorentz force configuration, where the Lorentz force acting on the flux lines is maximal. For all current values there is an initial increase of the voltage when the current pulse starts. This inductive voltage is not related to the transition to the normal state. If the current exceeds the critical value, a voltage peak arises at the maximum of the current pulse. This is a clear indication of the sample reaching the normal state. This transition from the superconducting to the normal state can be defined with accuracy of approximately 0.5 A.

Figure 4 shows transitions for the same magnetic fields with the wire parallel to the field. As expected, the critical currents are much higher in this so-called Lorentz force-free configuration than for $I \perp B$, but the voltage peak indicating the transition to the normal state occurs when the current is already decreasing.

The reason for this behaviour is not yet fully understood, but some explanation can be provided. If the magnetic field is parallel to the current, helical flux lines nucleate from the surface since the self-field of the current, which is perpendicular to the external field, is superposed. When the force-free current flows, these helices are sheared torsionally [4] and moved to the centre. It is perhaps possible that flux line cutting (the intersection and cross-joining

Figure 3. Typical voltage signals for transport currents $I$ close to the critical current $I_c$ with the wire perpendicular to the magnetic field; a) $B = 2$ T, b) $B = 10$ T. The deviation from the grey curve depicted by the black curve represents the transition to the normal state. (For clarity, only one current curve is shown. The currents differ only in amplitude.)
of adjacent vortices) occurs [5], which increases the repulsive forces between the flux lines. As soon as the current decreases, the compressive force is suddenly released, and dissipation occurs as the flux lines approach their equilibrium positions. Some authors argue that flux cutting is unlikely because of the high energy threshold [6], but most of the theoretical treatments of flux cutting and the Lorentz force-free configuration do not consider short pulsed currents or even superconductors with strong pinning centres which could facilitate flux cutting [7].

Figure 5 shows the critical current $I_c$ versus magnetic field $B$ with the values determined by the method described above. The reference curve for the perpendicular orientation is measured by a DC transport current method. The $I_c$ curve measured with the pulsed technique shows very similar results to the reference curve. However, the obtained values are 5 to 7 A higher than the reference values. This deviation does not depend on the field, indicating a systematic experimental shift.

The measured $I_c$ values for the parallel orientation show a broad maximum at approximately 1 T. This maximum has been reported before for cold drawn single-core NbZr and TiTa wires, but at higher fields of about 2.5 T due to more effective pinning by elongated precipitates [8]. This behaviour can be derived by a model which assumes that the current flows parallel to the helical flux lines [9]. As the sample consists of filaments which constrict the helical current flow, the maximum in the NbTi wire is less pronounced.

The measured self-field value in the parallel orientation is less than the value in the perpendicular orientation. This seems to be caused by the arrangement of the current tracks on the sample holder. For the parallel orientation, the current track is parallel to the sample and hence the magnetic field of this track, which is perpendicular to the sample, influences the measurement. For the perpendicular orientation, the magnetic fields of the two current lines are in opposite directions and cancel each other out.

Figure 6 shows the voltage versus current during the increasing part of the current pulse for the perpendicular orientation at $B = 2$ T. The higher the peak value of the current the lower the slope of the voltage. As the length of the pulse is always the same, these differences must be caused by the time-derivative of the current, which increases proportionately with the peak value. As shown elsewhere [10] the $n$ value of the $V(I)$ characteristic decreases for higher currents because the current sharing between NbTi and the copper matrix becomes more important. As the current decreases, the voltage decreases in direct proportion to the current; the sample does not instantaneously return to the superconducting state at $I = I_c$ due to the rapid rate of change of current.
3. Conclusions

Critical currents have been successfully measured in a wide range of magnetic fields using the new Cryo-BI-Pulse system. The pulsed measurement technique could contribute to the basic understanding of the flux flow state in a type II superconductor. However, to clarify the complex flux dynamics processes during pulsed measurements in the Lorentz force-free configuration, further investigation should be conducted on twisted multifilamentary NbTi wires because of the helical flux lines. Additionally, one has to take into account that the physical picture is further complicated by the fact that the sample is a filamentary wire which normally is not considered in theoretical treatments. Moreover, improvements to the measurement techniques have to be made as there are still artefacts, e.g. the different $I_c$ for zero applied field in perpendicular and parallel orientations.

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