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QUENCH PROPERTIES OF HIGH CURRENT SUPERCONDUCTORS*

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Summary

A technique has been developed which allows the simultaneous determination of most of the important parameters of a high current superconductor. The critical current, propagation velocity, normal state resistivity, magnetoresistance, and enthalpy are determined as a function of current and applied field. The measurements are made on non-inductive samples which simulate conditions in full scale magnets. For wide, braided conductors the propagation velocity was found to vary approximately quadratically with current in the 2 to 5 kA region. A number of conductors have been tested including some Nb₃Sn braids which have critical currents in excess of 10 kA at 5 T, 4.2K.

Introduction

A number of properties of a high current superconductor are of importance in regard to its performance in a large scale device such as an accelerator magnet. Besides the quench current as a function of temperature and field one is also interested in the current at some effective resistivity, say 10^{-12} ohm cm, the normal state resistance, and the enthalpy of the conductor. Other properties, which depend on the conductor's environment as determined by the device construction, are also important. Examples of these are the quench propagation velocities both along the conductor and between neighboring conductors, and the energy needed to initiate a quench. The foregoing properties all play a role in determining the maximum operating current of the device, the dissipation during transient operation, stability against disturbances, and the ability to withstand accidental quenches without damage.

In this paper we describe short sample apparatus and techniques by means of which all of the properties mentioned above may be determined. The illustrative results given are for flat braided conductor made of twisted, multifilamentary wire, either of NbTi as used in the construction of ISA magnets¹ or of Nb₃Sn as has been used in making a prototype dipole.² However, the techniques described may be used with cabled or monolithic conductor as well.

Short Sample Apparatus

Two sample configurations have been used. The simpler of these, illustrated schematically in Fig. 1, is formed by soldering together two lengths of insulated conductor to form a straight, flat, non-inductive sample. The braided conductor dimensions are approximately 16.3 x 0.61 mm. The bifilar sample thus formed is held in a slotted clamp which prevents mechanical motion. Bifilar sample lengths of ~0.5 m have usually been used although lengths up to 1 m are possible. Voltage taps are soldered at several positions along the conductor edges. One or more heaters are placed against an outer surface of the sample. These are constructed of 13 μ m thick stainless steel and cover an area of the sample surface approximately 10 mm x 16 mm.

In order to study conductor turn to turn effects an elaboration of the sample described is used. A

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bifilar sample some 10 to 20 m in length is wound around a 0.5 m long mandrel to form a race track shaped coil. Any convenient number of adjacent conductor layers may thus be built up. A sample of this form is described below in greater detail (see Fig. 5).

The experiments are carried out in a vertical dewar, in pool boiling helium. The external field is applied by means of a superconducting dipole of 75 mm bore and 1 m length.³ The sample probe is oriented so that the magnetic field is perpendicular to the flat surface of the conductor. The ends of the sample are connected to a pair of gas cooled leads to a 6000 A power supply.

Quench Current as a Function of B and T

Samples of either form, Fig. 1 or Fig. 5, may be used. The simpler of these is convenient for quality control tests of large numbers of samples. Measurements of quench current at 4.2K have been made by ramping the current at a rate of 100A/S. Critical current, defined as that at which ρ (effective) = 5×10^{-12} ohm cm, is determined by observing the voltage drop across probes separated by 0.20 to 0.30m. Variations in braid characteristics over several sections of the bifilar sample are determined. For ISA type braid these variations are generally 2% or less in a given sample. The critical current is usually 8 to 10% less than the take-off current, which is typically 4.7 to 5kA at 5T. The use of a soldered joint, resistance $\leq 3 \times 10^{-9}$ ohm, leads only to a reduction in the observed quench voltage, but as the voltage is a very steep function of current at this point there is very little difference in the observed take-off currents. This observation is made by comparing a sample employing a tight hairpin turn with one having a solder joint.

Fig. 1. Schematic of bifilar braid sample with voltage probes and heater. A magnetic field is applied perpendicular to the flat surface of the conductor. Lower photo shows the observed voltage and current for a quench initiated by a heat pulse. Current is shut off at the right by an electronic level detector.

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It is possible to raise the temperature of a small region of the braid by means of the surface heater and thus to measure the quench current at temperatures above ambient. For the purpose of illustration, Fig. 2, we have selected data obtained for a Nb₃Sn braid. Quench current is determined as a function of heater power, P_H , for each of a series of applied magnetic fields. The curves obtained are linear, except for very low currents, and we assume that the peak local temperature is proportional to P_H . The intercept of the line for $B = 0$ with the P_H - axis corresponds to the critical temperature of the sample; $T_c = 17.7\text{K}$ in this case. This serves to calibrate P_H in terms of temperature. With the aid of this calibration, then, we obtain the curves of Fig. 3. Points corresponding to currents in excess of the power supply limit are obtained by linear extrapolation of the curves of Fig. 2. A reasonable estimate of the 4.2K capability of this braid is obtained even though it is not possible to drive it normal with the available field and power supply. A typical ISA NbTi braid is included in Fig. 3, as well as the ISA dipole B-I curve. For the developmental Nb₃Sn braid 40% higher field is possible than with the optimized NbTi braid.

Longitudinal Propagation Velocity

Quenches which occur at currents less than critical, such as occur during training, propagate with a well defined velocity which may be determined by the technique illustrated in Fig. 1. By means of a current pulse applied to the heater a quench is initiated which (except for currents below a few hundred amperes) propagates in either direction away from the heater. Typically a 0.1 or 0.2 joule pulse of 3 ms duration is used. The signal observed across a pair of voltage probes shows an initial linear portion which corresponds to the passage of the normal-superconducting interface between the probes. The time for this passage and the probe separation give the velocity. The voltage rise at the end of this initial period corresponds to the normal state RI drop of the section of braid, at ~ 10 to 20K . Thus the residual resistance of the braid is determined as a function of magnetic field. For ISA NbTi braids this resistance is typically about $2\ \mu\text{ohm cm}$. The region of the voltage curve after the linear rise corresponds to normal state heating and is discussed further below (see Fig. 8).

Longitudinal velocity data for typical ISA NbTi braid is shown in Fig. 4. For fields between 3 and 5T and for currents between 1 and 4kA the velocity varies approximately at I^2 . The behavior is insensitive to the cooling conditions in this region as the ohmic heating driving the quench is large. Unpublished analyses by M. Barton and J.D. Jackson have shown that the observed velocities are in good agreement with theory,⁴ using the observed critical current data obtained by the method described previously.

Transverse Propagation Velocity

Transverse propagation of quenches between adjacent conductors of a device is equal in importance to the longitudinal propagation. As mentioned before layered samples are fabricated by winding a long bifilar sample around a race track shaped former. Although the forces and stored energy in this type of sample coil are quite different from those in a magnet we can expect these coils to simulate accurately the transverse propagation of quenches by using fabrication techniques similar to those used in the magnet. Thus the sample braids are insulated with a fiberglass wrap and the coil turns are bonded together with B-

Fig. 2. Quench current for a braided Nb₃Sn conductor as a function of steady state heater power.

Fig. 3. Quench current vs. field for Nb₃Sn braid for several temperatures and for NbTi braid at 4.2K. The ISA dipole load line shows the increased field possible with this developmental Nb₃Sn conductor.

stage epoxy under heat and pressure. The coil is then banded with fiberglass-epoxy rings to restrain mechanical motion. An example of this type of sample in finished form is shown in Fig. 5. Voltage probes on the conductor edges, and heaters between coil turns are installed as before. Quenches are initiated by heat pulses. The times at which various pairs of coil layers begin to show resistance are measured with the aid of a 2 channel digital oscilloscope. In general the quench jump time between any adjacent pair of layers is the same throughout the structure, for a given current and field.

Results for the sample of Fig. 5 are given in Fig. 6. The spacing between turns is approximately 0.7 mm. Using this distance the observed times may be converted to transverse velocities. For currents between 3 and 4kA and fields between 3 and 5T the transverse velocities were approximately 50 times

slower than the longitudinal.

An alternative method for determining the transverse quench jump times is illustrated in Fig. 7. In this method the voltage across the entire sample coil is observed. As the quench jumps from layer to layer the rate of increase of voltage changes discontinuously. A kinked voltage wave form is observed. The time between kinks gives the transverse quench time. The results obtained by this method are in very good agreement with those obtained by direct measurement. The second method is far simpler provided noise pick up can be kept low. Moreover it can be applied to magnets or coils in which it is impossible or undesirable to introduce internal probes.

Normal State Enthalpy; Temperature Rise Following a Quench

Returning to Fig. 1, we consider the behavior following the passage of the normal superconducting interface through the section of braid under observation. If the current is allowed to continue as in the illustration the section of braid will heat up until such time that the power supply is turned off, say by a voltage level detector. During the heating

Fig. 4. Longitudinal quench propagation velocity in a NbTi braid at 4.2K.

Fig. 6. Transverse quench propagation: jump time between turns vs current. NbTi braided conductor, $T = 4.2K$.

Fig. 5. Bifilar race track coil sample used for determining turn to turn propagation. This sample contains 10 turns (5 bifilar turns) of NbTi braid. It is wound on a G-10 mandrel and banded by nine epoxy-fiber-glass rings. The view is edge on to the braid.

Fig. 7. Observation of transverse quench propagation. The voltage across the entire racetrack sample coil following the start of a quench is shown. The segmented appearance is due to the propagation of the quench across successive sample turns. The jump time in this case is 2.7 ms.

portion the power input is VI . It may be determined from the observed $V(t)$ and $I(t)$ signals. For a current of 3kA ohmic dissipation is about 20W per centimeter of braid. It increases rapidly to values of the order of 100 to 200 W/cm as the temperature increases or if larger sample currents are used. As these voltages are large compared with heat flow along the braid or outward through its surface the sample section is heated in a nearly adiabatic manner. The enthalpy change is obtained by integrating $dH = VI dt$, using the observed data. At the same time the resistance of the braid, which is a known, measured function of temperature, serves as an ideal thermometer. It also is determined from the observed signals: $R = V/I$. Thus, it is possible from the observed V , I data to construct the $H(T)$ curve for the conductor.

In Fig. 8 the $H(R)$ graph is shown as obtained for a number of different quenches. As can be seen, consistent results are obtained over a wide range of heating rates. The calibrated temperature values for the braid are also shown. The method is applicable for temperatures above about 40K. Calculated values of $H(T)$ based on the imprecisely known relative amounts of the various components of the braid and their Debye θ 's are about 20% greater than the measured values in this case. Following Maddock and James⁵ we may write:

$$f(T) = \int_0^T dH/R = \int_0^T I^2 dt.$$

The maximum temperature rise following a quench is given implicitly by the left hand equation, with the value of f for a given quench being determined by the quantity $\int I^2 dt$. Typically, for data such as that of Fig. 8 a value of $f(T) = 3.5 \times 10^6 \text{ As}^2$ gives a temperature rise of approximately 400K. The $f(T)$ function varies somewhat with the residual resistance ratio of the braid. In the present case the value of this quantity was approximately 30.

Fig. 8. Normal state enthalpy of a braided NbTi conductor vs. normal state resistance. Results are independent of the currents used to heat the sample. The upper temperature scale is derived from the $R(T)$ curve of the conductor.

Further Work

Apparatus of the type depicted in Fig. 5 lends itself to determination of the factors which enter into the stability of a superconductive coil. Thus, the energy necessary to initiate a quench and the way it is affected by insulation, bonding pressure, and porosity to refrigerant are under study. In addition the effect of varying the material and the shape of coil components such as spacer wedges and dummy turns are also being studied. Apparatus of the type shown in Fig. 1 is appropriate for quality control. A number of important properties are obtained easily and quickly.

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