The minimum energy required to quench a fully impregnated superconducting winding has been measured at a constant field of 5 T for various currents. Great care has been taken to match the experimental conditions with those presumed in the minimum propagating zone (MPZ) treatments of the situation. In particular the winding has been designed so that the MPZ is smaller than the heat source thus satisfying the requirement for a point disturbance. The adiabatic requirement has been met with an inductive heating technique in place of the usual resistive heating. As a consequence of these features the minimum quench energies are much smaller than those obtained in previous experiments and agree well with Wilson's theoretical treatment for a point disturbance.

Minimum heat pulse to quench a superconducting magnet

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Key words: superconductor, magnet, quench, heat pulse

The degraded performance commonly found in superconducting magnets is believed to be caused by the sudden conversion of mechanical energy stored in the windings into heat.[1] Recently, several experiments have been performed in which small pulses of heat have been applied to superconducting wires to investigate their stability.[2-5] In these experiments the aim is to simulate the sudden appearance of a point source of heat. For isolated conductors[2] the measured minimum energy to quench the superconductor agrees well with that calculated from numerical simulation of the thermal response of the system. Similar agreement has also been obtained for the case of a superconducting winding well cooled by liquid helium within the winding.[3,6] However the most widespread type of winding in superconducting magnets is fully impregnated with epoxy resin and only cooled on its outer surfaces by liquid helium. Measurements on this type of winding[4,5] have not been reconciled with theoretical results.

The aim of this paper is to present experimental measurements of the minimum energy to quench a small fully impregnated winding and show that there is good agreement with a simple theoretical model developed by Wilson.[7] The model is based on the steady state analysis of heat generation in a winding developed by Wipf.[8] An important feature of Wilson's model is that the minimum quench energy has a simple mathematical form. It is thus easy to see the influence of particular parameters on the stability of the winding.

Minimum propagating zone model

The starting point of the model[7] is the concept of a minimum propagating zone (MPZ)[8] in the winding. In the MPZ heat is generated by current flowing in the normal matrix of the composite conductor. The heat generated is in equilibrium with the heat conducted out of the zone. If heat is being generated in a region larger than the MPZ then the region inevitably grows and the magnet quenches. Conversely a region smaller than the MPZ shrinks and vanishes. The energy required to create the MPZ is taken as the minimum energy to quench the winding. At a temperature, θ, the current flowing in the matrix generates $G(\theta)$ Wm^{-3} in the composite. For temperatures less than θ_g, the generation temperature, all the current is able to flow in the superconducting part of the composite and there is no heat generation. Between θ_g and the critical temperature, θ_c, the current is divided between the matrix and the superconductor. This leads to a linear variation of generation with θ as shown by Maddock, James and Norris.[9] Above θ_c all the current flows in the matrix. The behaviour of $G(\theta)$ is illustrated in Fig. 1. In the linear region

$$G(\theta) = G_c \left(\frac{\theta - \theta_g}{\theta_c - \theta_g}\right) \qquad (1)$$

where $G_c = \rho J^2/(1-\lambda)$ for matrix resistivity ρ, current density J averaged over the composite and a fraction $(1-\lambda)$ of the composite occupied by the matrix.

The heat conduction is modelled by taking the winding to be an anisotropic continuum with thermal conductivities, k_z and k_r parallel and perpendicular to the conductor. The steady state heat balance is represented by

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_r \frac{\partial\theta}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial\theta}{\partial z}\right) + \lambda_w G(\theta) = 0 \qquad (2)$$

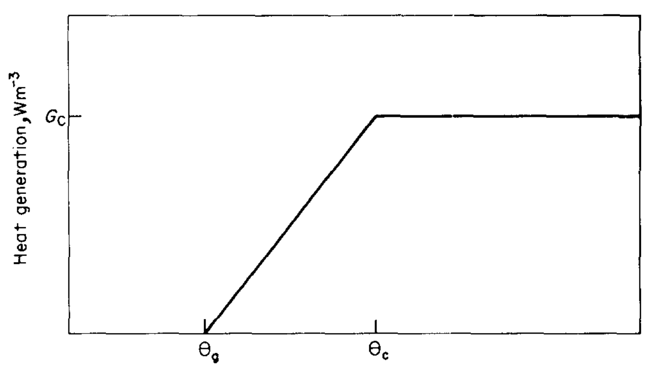

Fig. 1 Variation of heat generation with temperature at constant field and total current

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where λ_w is the fraction of the winding volume occupied by conductor. A solution of this equation can be found if the variation of thermal conductivity with temperature is ignored.[7] The MPZ is an ellipsoid with its major axis parallel to the conductor and a ratio of minor to major axes given by $\alpha = (k_r/k_z)^{1/2}$. The boundary of the MPZ is defined by the surface at temperature θ_g. This surface has a major radius,

$$R_g = \pi \left(\frac{k_z(\theta_c - \theta_g)}{\lambda_w G_c}\right)^{1/2} \tag{3}$$

The energy required to create the MPZ from a winding initially at θ_0 (the bath temperature) is calculated from the detailed temperature distribution found from the solution of (2). The energy has the form

$$E = E_0 e(\theta_g, \theta_0) \tag{4}$$

where $E_0 = 4\pi\alpha^2 R_g^3 H_0/3$ and H_0 is the average specific enthalpy of the winding at θ_0. Fig. 2 shows the form of e as a function of the dimensionless parameter $\beta = (\theta_g - \theta_0)/\theta_0$. Assuming a linear variation of θ_g with current, I, leads to

$$\theta_g = \theta_c - (\theta_c - \theta_0)(I/I_c) \tag{5}$$

where I_c is the critical current at θ_0 and field, B. Substituting this value of θ_g into (3) gives R_g for a known winding. The minimum quench energy can then be calculated from Fig. 2 and the energy normalising factor E_0 given by (4). The solid line in Fig. 3 shows the values calculated for a test coil with the parameters of Table 1.

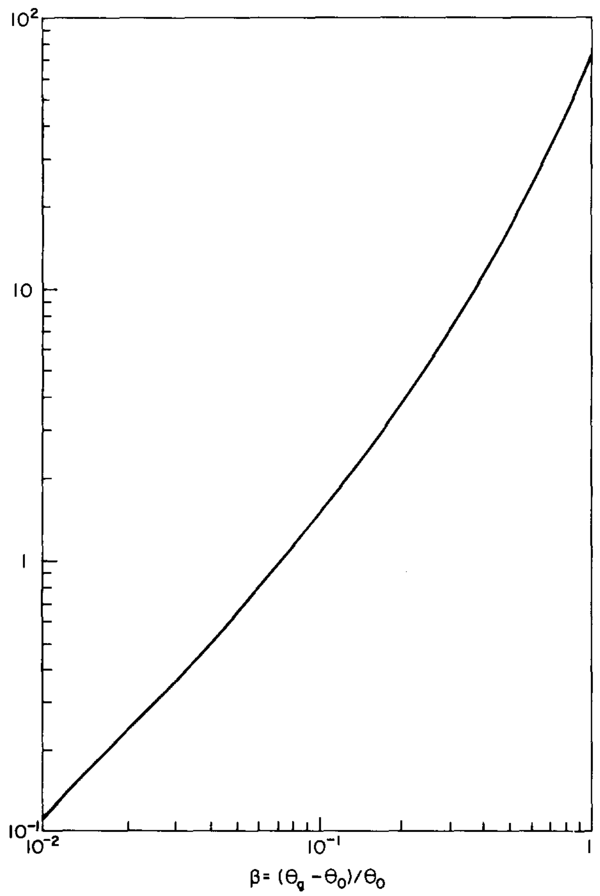

Fig. 2 Variation of normalised energy with generation temperature parameter

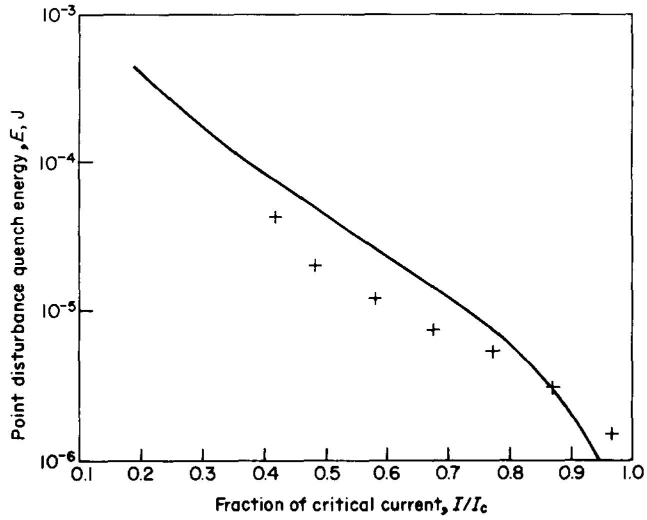

Fig. 3 Quench energy as a function of normalised current for a test coil at a constant field of 5 T. The solid line shows the calculated values and the crosses show experimental points

Table 1. Parameters of the test coil

Conductor type	IMI A61/25 (niobium titanium)
Matrix/superconductor ratio $(1-\lambda)/\lambda$	1.35
Critical current at 4.2 K in 5 T field, I_c	31 A
Critical temperature, θ_c, at 5 T	6.9 K
Resistivity of matrix at 5 T	$3.6 \times 10^{-10}\ \Omega$m
Fraction of winding occupied by wire, λ_w	0.49
Longitudinal thermal conductivity, k_z	81 $\mathrm{Wm^{-1}\,K^{-1}}$
Transverse thermal conductivity, k_r	0.2 $\mathrm{Wm^{-1}\,K^{-1}}$
Specific enthalpy of winding at 4.2 K, H_0	2825 $\mathrm{Jm^{-3}}$
Wire diameter	0.25 mm
Heated length of wire	3.5 mm
Coil internal diameter	18 mm
Coil external diameter	25 mm
Coil length	8.5 mm
Coil impregnation	MY740 100 HY906 80 parts by wt DY062 0.5 (Ciba-Geigy resins)

Measurements of minimum quench energy

The measurements were made by heating a short length of wire in a test coil using an eddy current heating technique.[10] As far as possible the conditions were chosen to match those assumed in the theory. In particular the wire diameter and heated length were chosen to be smaller than the expected minor and major diameters of the MPZ. Table 1 shows the parameters of the test coil. For this coil the MPZ was calculated to have a length of 8.4 mm and a diameter of

0.42 mm at the quench current. At lower currents the MPZ was larger since from (3) and (5) $R_g \propto I^{-1/2}$. Hence the heated volume was about $(8.4/3.5) \times (0.42/0.25)^2 = 7$ times smaller than the smallest MPZ volume; a reasonable approximation to a point source.

The coil was bifilar wound so that its current made no contribution to the field within the winding. A field of 5 T transverse to the wire was provided by mounting the coil in the bore of a solenoid. Interlayer insulation was omitted from the winding in order to preserve the symmetry about the conductor assumed in the theoretical model.

Initially heat pulses were generated in the test winding by passing current through a resistance wire wound round a short length of the superconductor. However the minimum quench energies were larger than expected and delays of several hundred microseconds were observed between the end of the heating pulse and the appearance of a voltage across the coil. This indicated a long thermal time constant between the heater and the superconductor, presumably because of poor thermal contact. The results presented here were all obtained with an eddy current heating technique.[10] A 0.1 mm diameter copper wire was wound round a short length of the superconducting composite to form a close wound coil. The test winding was arranged so that this coil was embedded in the centre of the winding cross-section. A small inductor was connected in series with the heating coil and a decaying oscillatory current was generated by switching a charged capacitor into the circuit. An SCR (silicon controlled rectifier) was used for the switch. The capacitor and inductor were chosen to give an oscillation frequency of 250 kHz. At this frequency the skin depth in copper is 19 μm and is similar to the mean thickness of the copper shell on the outside of the composite (Fig. 4). Thus the circumferential eddy currents induced by the longitudinal field of the coil heated the outer shell of the superconducting composite. Typically the time constant of the oscillatory decay was about 10 μs. Measurements of the voltage across the test coil (Fig. 5) showed that the time-scale for the growth and decay of the disturbance within the coil was a few milliseconds. Hence the eddy current technique easily satisfied the adiabatic condition assumed in the theory.

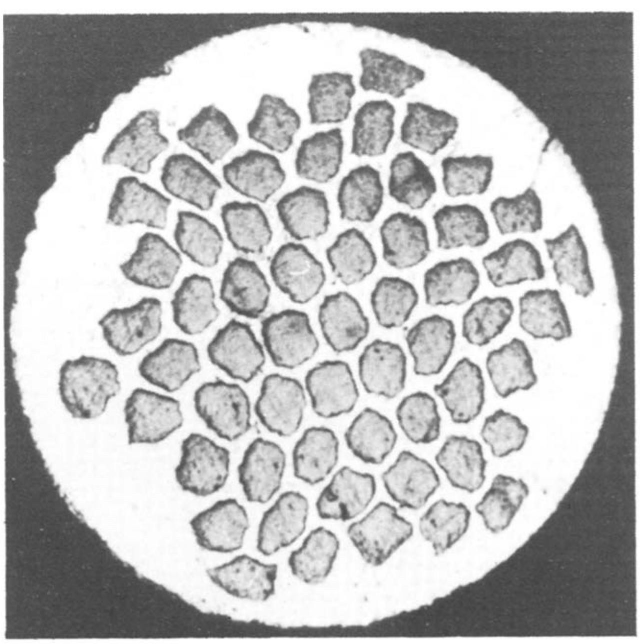

Fig. 4 Cross-section of superconducting composite, diameter 0.25 mm, IMI type A61/25 (copper matrix)

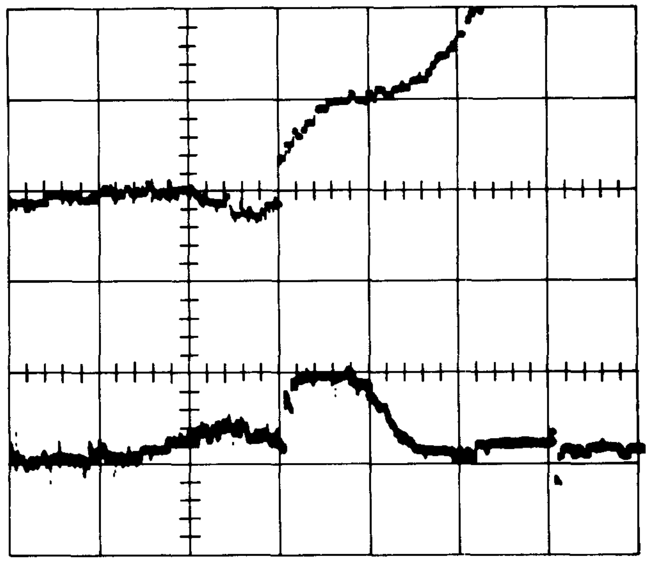

Fig. 5 Time dependence of voltage across test coil for pulses just greater and just smaller than the minimum quench energy. Vertical scale 1 mV/division, horizontal scale 1 ms/division, current 18 A

The experimental procedure was to set the current in the test coil and then gradually increase the initial voltage on the capacitor until the heat pulse quenched the coil. The energy in the pulse was calculated from the initial voltage on the capacitor and the decay time constant of the oscillatory current.[10] For currents up to 24 A it was possible to see a transient voltage in the winding for pulse energies below that which caused a quench (lower trace in Fig. 5). The minimum energies to quench the coil at a field of 5 T, a bath temperature of 4.2 K and a range of currents are shown as crosses in Fig. 3.

Discussion

The experimental quench energies show the same general fall with increasing current that the theory predicts and are of similar magnitude. The greatest discrepancy between theory and experiment is about a factor of two. This should be regarded as very reasonable agreement considering the approximations made in the theory and the difficulty in determining some of the parameters needed in the calculation.

Two parameters are especially difficult. Firstly the critical current, I_c, is fundamental to the calculation. However real superconducting filamentary composites show a broad transition from apparently zero resistance to a finite resistance rather than the sharp transition to the current sharing regime assumed here. The experimental results have been interpreted by making the arbitrary assumption that the coil quench current is a reasonable approximation to I_c. Secondly the theoretical minimum quench energy is directly proportional to the transverse thermal conductivity, k_r. However k_r is difficult to estimate reliably for a winding because it depends on the geometry of the small spaces between the wires. Ideally, k_r should have been obtained from a measurement on a model winding rather than from a calculation based on the thermal conductivity of the resin.

There is also a difficulty with the interpretation of the measurements. As well as the heat deposited on the surface of the conductor by the decaying eddy currents, there is some heat generated in the small coil wrapped round the conductor. On a sufficiently long time-scale this should be included in the disturbance. However the observation of long time delays in the initial experiments mentioned earlier suggests that it is reasonable to ignore this contribution.

Conclusions

The experiment has shown that steady state theory provides an acceptably accurate description of the minimum point disturbance required to quench fully impregnated superconducting magnets. Since the disturbance spectrum is unknown this result cannot be applied directly to predict the training performance of magnets. However the effects of changes in the conductor design can be predicted in cases where the design change is not expected to alter the disturbance spectrum. An example of this is the substitution of aluminium for copper as stabilising material in the composite.

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