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STABILITY OF FLUX MOTION IN SUPERCONDUCTING CYLINDERS AND COILS

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STABILITY OF FLUX MOTION IN SUPERCONDUCTING CYLINDERS AND COILS

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ABSTRACT

Flux flow in a high current density type II superconductor may become unstable, and the limit of stability can be calculated by balancing the energy dissipated in an adiabatic flux jump against the enthalpy of the superconductor. Calculations of the limiting field which may be screened by a cylinder are discussed and compared with experimental results. The method is then extended to the calculation of the limit of stable current in a coil, which is related to the degradation commonly observed in superconducting coils.

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Kim, Hemstead and Strnad[1] have shown that flux flow can occur in a high current density type II superconductor which is in the critical state. For example, flux may penetrate continuously to the centre of a superconducting cylinder which is situated in an increasing axial magnetic field[2]. In some circumstances, however, flux flow may become unstable, leading to a discontinuous change in the flux distribution. This instability is associated with the decrease in critical current density that can be carried by a superconductor as temperature increases, and occurs when the energy dissipated in a flux jump heats the superconductor so that it can no longer support the local magnetic field gradient.

A simple calculation[3], based on a one dimensional model of an adiabatic flux jump, gives the maximum field which may be applied to a semi-infinite block of superconductor before such an instability occurs as

$$H_s = \sqrt{8\pi s \rho T_0} \qquad \ldots (1)$$

where T_0 is a temperature less than the critical temperature of the superconductor and is defined by $T_0 = - J/(\partial J/\partial T)$, s is the specific heat and ρ the density. A similar calculation by Swartz and Bean[4], based on the same model but giving a more complete analytical solution, leads to the same result except for a numerical factor $(\pi^2/8)^{\frac{1}{2}}$. These calculations show that the limit of stability is independent of the critical current density but is a function of the specific heat, and both of these effects have been demonstrated experimentally[3,5].

More extensive calculations have been made by computer using the same model but including the temperature variation of both the specific heat and current density. The limit of stability is not so well defined in these calculations, especially at low temperatures where the instability does not grow to the point at which the superconductor enters the normal state but, because of the rapid increase of specific heat with temperature, the flux motion is stabilized again at a temperature below the transition temperature. This effect was observed experimentally[5] with Nb_3Sn cylinders at temperatures below about 5.5 $^{\circ}$K.

Although it has only been possible to compare the computed and experimental results over a limited range of variables, the calculations appear to predict that instabilities should occur at fields which are as much as 40% lower than the fields at which they are actually observed. It is thought that this is due to the fact that flux jumps are localized and take a finite time to develop so that some of the dissipated energy is lost by thermal diffusion. This is supported by recent measurements on a Nb_3Sn cylinder which was subjected to a steadily increasing magnetic field on which small pulses ($\sim 75\ O_e$) were superimposed in order to initiate the instability more uniformly around the cylinder. The instability occurred in this case at a field 30% lower than the corresponding field without superimposed pulses.

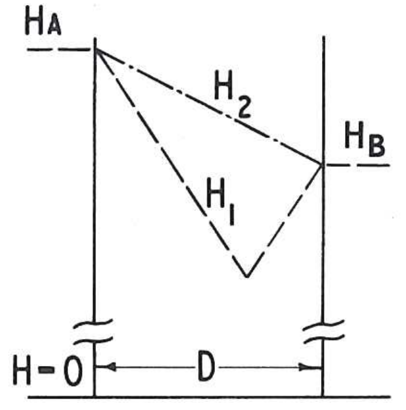
Encouraged by the agreement between theory and experiment for cylinders the stability calculations has been extended to simple coils. Each layer of the winding is considered as a sheet of superconductor which experiences both an increasing external magnetic field and an increasing current. Since the sheet is generally thin the calculation is simplified by averaging the energy change over the cross-section, in which case the winding is stable up to its full critical current provided

$$J D \leqslant \sqrt{3 s \rho T_o/4\pi} \qquad \ldots (2)$$

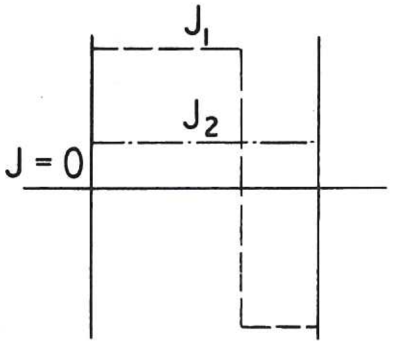
where D is the thickness of the layer.

Equation 2 predicts that below a certain critical current density a superconducting wire is stable when used in a coil. Since current density generally decreases with increasing magnetic field it follows that materials of high current density may be stabilised by the presence of a field, an effect already used successfully in coil construction.

A more interesting calculation using the same model is that of the energy dissipated by unstable flux flow in a degraded coil. As before, the rapid increase of specific heat with temperature may limit the growth of an instability, and provided the wire is still capable of carrying current during the development of the instability a transition from an unstable to a stable state may occur. The limiting case of this is illustrated in Fig.1, in which a transition occurs from a highly diamagnetic state (designated by suffix 1) to the state in which transport current flows uniformly through the whole cross-section of the conductor (designated by suffix 2). Balancing the energy dissipated in flux flow against the increase in thermal energy gives the criterion for a stable transition, and if the superconductor is



Magnetic field distribution



Current distribution

Figure 1. Magnetic field and current distributions in a superconducting sheet before (suffix 1) and after (suffix 2) unstable flux flow.

not to be driven normal

$$\frac{1}{v}\iint E\cdot J(T)\cdot dt\cdot dv \leqslant \rho\int_{1}^{2} s\cdot dT \qquad \ldots (3)$$

In the case of a thin sheet, and assuming the current density to be independent of the magnetic field strength, this reduces to

$$\pi D^2\left[J_1^2 - J_2^2 + 6J_2^2\,\ell n\left(J_1/J_2\right)\right]\Big/6 \leqslant \rho\int_{1}^{2} s\cdot dT \qquad \ldots (4)$$

In practice the degradation of a coil will not be as serious as predicted by equation 4 since, as before, a one dimensional adiabatic model has been used whereas flux jumps will only occur in short lengths of wire and longitudinal heat flow may occur. On the other hand in large coils effects due to interaction between layers can occur, allowing energy dissipated in one layer to be coupled electromagnetically into an adjacent layer and thus increasing degradation. This latter effect could be reduced by the use of thin metallic screens between layers such as are commonly used in large magnets.

Neither of these effects are present in small coils which are uniformly subjected to small magnetic pulses, as, for example, in the experiments of Iwasa and Montgomery[6]. In these experiments a single layer coil of 0.25 mm diameter Nb/Zr wire was subjected to magnetic pulses of amplitude 10 to 100 O_e. Pulses with an amplitude above a certain threshold caused severe degradation of the current carrying capacity of the wire. Using the specific heat data of Bindari and Litvak[7] and approximating for the effect of magnetic field on $\partial J/\partial T$, equation 4 has been evaluated for this material and the predicted limit of stability is compared with the experimental results in Fig.2.

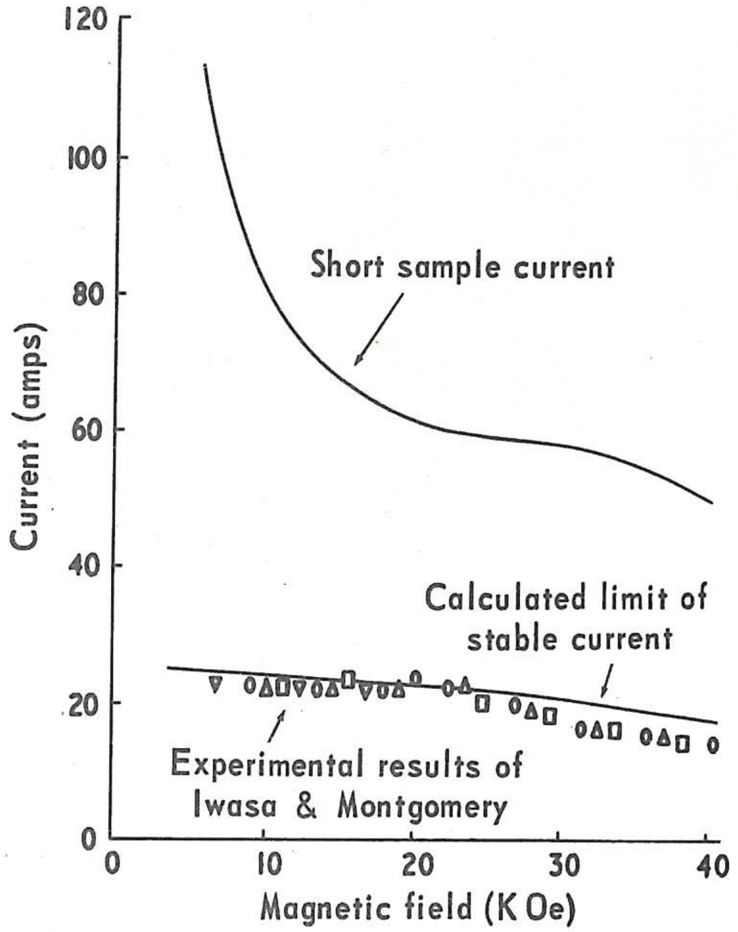


Figure 2. Comparison of calculated degradation in a coil of 0.25 mm Nb/Zr wire with the experimental results of Iwasa and Montgomery.

The close agreement in Fig.2 between theory and experiment supports the view that unstable flux flow is a major cause of coil degradation.

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