A POSSIBLE SOURCE OF INSTABILITY IN "FULLY STABILIZED" MAGNETS

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The purpose of this brief note is to draw attention to a problem which could affect the performance of fully stabilized magnets made from wide strip conductor.

The fully stabilized conductor is designed by assuming that the full transport current may flow in the normal metal and equating the power dissipation to the surface heat transfer with, typically, a safety factor of 2.

This safety factor may, however, be insufficient to cope with the power dissipation during a flux jump, since in the lower field regions of the coil the superconductor can support a magnetization current density which is much higher than the peak transport current density.

An approximate quantitative estimate of this effect may be obtained as follows:

1) In addition to the transport current, the conductor throughout most of the coil is filled with magnetization currents. When the superconducting filaments are connected by low resistance metal, the finite rate of rise of field will in general be sufficient to cause these currents to flow around the entire composite, instead of being confined within the individual filaments (Fig. 1). The magnetic energy associated with this current distribution is

$$Q = \frac{2\pi}{3} \frac{J^2 \ell^2}{10^9} \qquad (\mathrm{J/cm^3}) \quad , \tag{1}$$

where J is the over-all current density.

2) Since J increases as H decreases, the maximum value of $J\ell$ will occur approximately at the field which just achieves complete penetration of the strip. Let this occur at $J_1 \ell = H_1$, say. Let the over-all current density be J_p at the peak field H_p, and assume $J \propto 1/H$, so that $J_1 \sim H_p J_p / H_1$. Then

$$H_1^2 \sim (J_1 \ell)^2 \sim H_p J_p \ell \tag{2}$$

which is the value to be inserted in (1), and also

$$J_1^2 \sim J_p^2 \times (H_p / J_p \ell) \quad . \tag{3}$$

3) To see what these equations could mean in practice, consider a specific example of a large coil with H_p = 60 000 G, and suppose a superconductor-copper composite with J_p = 1500 A/cm^2, and 2ℓ = 8 cm. Then $J_1^2 \sim 10\, J_p^2$ at $H_1 \sim$ 19 000 G. If, during a flux jump in this part of the coil, all the superconductor in the cross section became resistive, the magnetization currents would transfer to the normal metal, and decay with an initial power dissipation about 10 times as great as the design value (neglecting the reduction in magnetoresistance).

The time constant for the decay of these currents is approximately $(16/10^9\pi)(\ell^2/\rho)$; which in this case is about 2 sec. The thermal time constant, $S\ell^2/2k$ (S in J/cm^3, k in $W/cm\cdot{}^oK$) is about 10^{-3} to 10^{-2} sec, so that uniform heating can be assumed; the total energy released, given by (1), is about 0.7 J/cm^3.

4) Since only part of this energy can be transferred immediately to the liquid helium there will be a rise in temperature, which in this case could amount to 15-25°K. Thus, the example we have considered would appear to be reasonably safe, since a temperature rise of this order would cause very little increase in the resistivity of the copper, the transport current would still be stabilized, and the conductor would recover. There remains, however, the possibility that the increased heat transfer rate associated with the higher temperature might be sufficient to vaporize the liquid helium in the (narrow) cooling channel, after which the transport current would no longer be stabilized. This appears difficult to assess with any certainty.

These effects could, of course, become more serious with wider conductors, higher peak fields and lower-enthalpy materials such as aluminum. They are, however, unlikely to be observed in lower field coils such as those for the Argonne bubble chamber.

The preceding calculations are based on some apparently rather pessimistic assumptions: firstly that the length of conductor involved in the flux jump is sufficiently great for longitudinal and radial heat conduction to be negligible, and secondly that a complete flux jump occurs, whereas in practice it may well be partially or completely extinguished by the electromagnetic and thermal damping provided by the copper.

An approximate estimate of the conditions under which normal metal may prevent flux jumping has been made by Chester[1] for the case of thin sheets of superconductor embedded in a good thermal conductor. Using the same approach we obtain the following criterion for absence of flux jumping in a composite containing circular filaments of diameter d (cm):

$$d^2 \leq (T_o k/\rho)\ (1/J_m J_c) \qquad (4)$$

where $T_o = J_c/(-\,dJ_c/dT) \simeq 3^oK$,

k = thermal conductivity of superconductor, $\sim 10^{-3}$ $(W/cm\cdot{}^oK)$,

ρ = resistivity of normal metal, $\simeq 2 \times 10^{-8}$ $(\Omega\cdot cm)$,

J_c = current density in superconductor (at appropriate field value),

J_m = mean current density in composite (at appropriate field value).

Putting $J_c = 2 \times 10^5$ A/cm^2, and $J_m = 5 \times 10^3$ A/cm^2, (4) gives $d \leq 1.2 \times 10^{-2}$ cm (0.005 in.).[2] The approximate derivation we have used is uncertain by various factors of order 2, and also assumes the copper to be a perfect heat sink, which assumption may not be valid if the perturbation initiating the flux jump is large. There is at present no experimental confirmation of this theory, and the predictions which it makes for copper-clad Nb_3Sn tapes, typically that superconducting layers less than $\sim 10\ \mu$ thick should be stable, are in evident disagreement with observation.

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1. P.F. Chester, Rep. Progr. Phys. 30, Pt. 2, 361 (1967).
2. Note that this criterion refers only to flux motion across the entire composite, and not to flux jumping in the individual filaments. These criteria are considered in more detail in a separate paper in these Proceedings (p. 913).

In the present state of knowledge, therefore, one cannot be at all confident of specifying a fully stabilized composite in which low field flux jumping is absent, but the preceding calculations suggest that even in extreme cases the heating effects only just begin to reach a dangerous level.

On balance, there seems to be a reasonable chance that no instabilities of this kind will be encountered in any of the large magnets now being planned. Nevertheless, in view of the importance and high cost of such projects, some experimental reassurance appears desirable before finalizing their design.

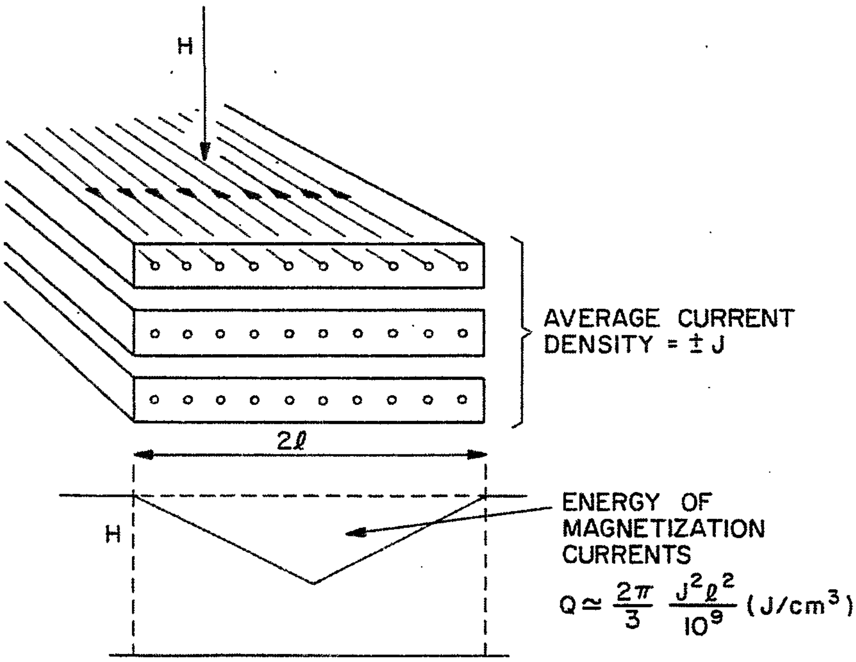

Fig. 1. Energy of magnetization currents.

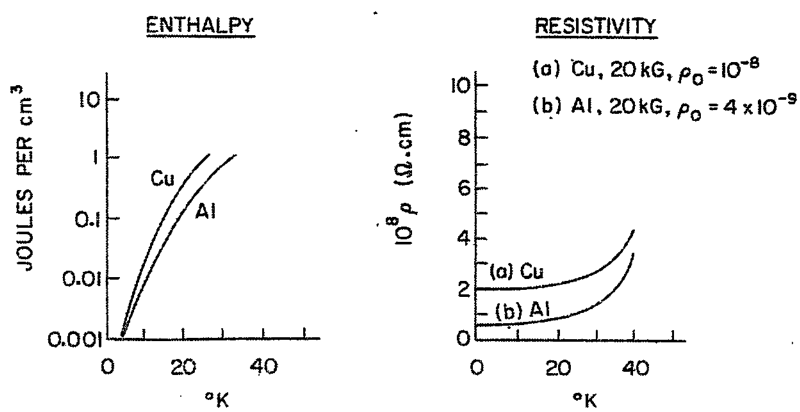

Fig. 2. Typical temperature variation of enthalpy and resistivity for copper and aluminum.