CLM-P163

United Kingdom Atomic Energy Authority
RESEARCH GROUP
Preprint

ENTHALPY STABILIZED SUPERCONDUCTING MAGNETS

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1968

UNCLASSIFIED
(Approved for publication)

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(Submitted for publication in the Proceedings of the Intermag Conference, Washington, 3-5th April, 1968).

ABSTRACT

An essential requirement for complete stabilization of a superconducting magnet is adequate circulation of liquid helium in the winding, resulting in a low average current density. In partially stabilized magnets the size of the cooling channels is reduced, but access for liquid helium is still considered necessary. With enthalpy stabilization, however, the need for helium penetration into the winding is eliminated, resulting in better packing of the conductors and a higher average current density.

A small enthalpy stabilized magnet has been tested which was fully impregnated with epoxy resin, and operated at a current density above 10^4 A cm^{-2}. The basis of the design of such magnets is discussed, with particular reference to the choice of conductor size and its effect on average current density in the magnet. Possible applications of this technique are also discussed.

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February, 1968. (MB)

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1. INTRODUCTION

Stability against the effects of degradation in a superconducting magnet can be achieved in several ways. In large magnets complete stability is obtained by the use of composite conductors with a large cross-section of a good normal conductor, such as copper, and by also providing wide cooling channels around each conductor for the circulation of liquid helium. With this construction magnets are stable up to the critical current of the superconductor, and may even be operated at currents slightly above the critical current with the excess current flowing in the normal material. Whilst this gives the advantages of safety in operation and protection against a wide variety of failures, the overall current densities achieved are low, being in the range 10^3 to 5×10^3 A cm^{-2}.

In medium size magnets higher average current densities are often required, in which case it is necessary to reduce the cross-sectional area of normal material in the composite conductor and limit the size of the cooling channels. Such coils operate at average current densities around 10^4 A cm^{-2} and are partially stabilized - that is, they are stable against small internally generated fluctuations such as flux jumps, but not necessarily stable against large externally applied disturbances. The criterion for stability in these coils is their Minimum Propagating Current, which is the current below which any normal region induced in the winding will not propagate throughout the whole magnet. The presence of liquid helium in the winding is still essential for this type of stabilization, and if the magnet were operated in gas the minimum propagating current would be halved and its performance degraded.

An alternative concept is that of enthalpy stabilization. In this case the thermal capacity of the composite conductor is increased to the point at which unstable flux jumping cannot occur in the superconductor. Such a magnet is again only partially stabilized since it may be quenched by large externally applied disturbances, but it is stable against internal fluctuations. Since no part of the winding is driven into the normal state it is not necessary to have a high minimum propagating current, and liquid helium cooling throughout the whole of the winding is no longer required. In many cases the magnet may be fully impregnated with epoxy or silicone resins for added mechanical strength, and may be operated equally successfully in liquid or gaseous helium.

2. THE MECHANISM OF ENTHALPY STABILIZATION

It has been shown by several authors (1-3) that a simple thermodynamic argument can be used to predict the limit of stable flux motion in a semi-infinite block of superconductor. If a magnetic field is applied to such a block of superconductor the flux penetrates slowly until an instability causes complete penetration and quenching of the superconductor. The critical field for this instability is

$$H_S = \sqrt{8\pi c \rho T_o} \qquad \ldots (1)$$

where T_o is a characteristic temperature equal to $-J/(dJ/dT)$. This critical field does not depend on the critical current density of the superconductor J, but is determined mainly by the specific heat c.

A similar calculation can be made of the limit of stable flux motion in a wire or strip wound magnet, by approximating each layer of the winding to a thin sheet of superconductor which experiences both an increasing external magnetic field and an increasing current. In this case, however, a limited instability can be tolerated provided the heating effect of the flux motion does not cause the critical current density to fall below the value required to support the current flowing in the superconductor. It is found that this limit is determined by the enthalpy $\int c.dT$ of the superconductor, and that by increasing the enthalpy a magnet may be stabilized against the effects of unstable flux motion.

Fig.1 shows possible magnetic field distributions across the superconductor. Whilst flux motion is stable the superconductor will be in the critical state and there will be a field minimum as in distribution (a). If flux motion is unstable the superconductor will be heated and the critical current density will fall, leading to a new field profile (b). In the limit the current density may be reduced to the point at which the superconductor can only just carry the current, corresponding to distribution (c). Since the field variations across the conductor are small compared with the externally applied field the current density may be considered to be independent of the field during a flux jump, and a function of temperature only. It will also be assumed that the thermal diffusivity across the conductor is greater than the magnetic diffusivity, and therefore that both the temperature and the field gradient will be uniform.

At any temperature T, and corresponding current density J, the distance of the minimum in the field distribution in a conductor of thickness D from either surface is

$$Z = D(1 \pm J_2/J)/2 \qquad \ldots (2)$$

where J_2 is the current density which would just support the current if it flowed uniformly in the conductor.

If the temperature increases by dT and the current density changes by dJ, the magnetic flux entering the superconductor from the two surfaces is

$$d\Phi = -\pi D^2 \ (1 \pm J_2/J)^2 \ dJ/2 \qquad \ldots (3)$$

and the energy dissipated on either side

$$dQ = -\pi J D^3 \ (1 \pm J_2/J)^3 \ dJ/6 \qquad \ldots (4)$$

If the temperature before and after the flux jump corresponding to the distributions (a) and (c) are T_1 and T_2 and current densities J_1 and J_2, the total energy dissipated is

$$Q_F = \pi D^3 J_1^2 \left\{ 1 - (J_2/J_1)^2 + 6(J_2/J_1) \ \ell n \ (J_1/J_2) \right\} /6 \qquad \ldots (5)$$

and in the limit of stability this must not exceed the increase in enthalpy

$$Q_T = \rho D \int_{T_1}^{T_2} c dT \qquad \ldots (6)$$

so that the criterion for a stable flux jump is

$$\pi D^2 \left\{ J_1^2 - J_2^2 + 6J_2^2 \ \ell n \ (J_1/J_2) \right\} \leqslant 6\rho \int_{T_1}^{T_2} c dT \qquad \ldots (7)$$

The solution of this equation must generally be obtained numerically rather than analytically since the current density and the specific heat of the superconductor are both functions of temperature and magnetic field. A typical solution for a copper plated superconducting wire is illustrated in Fig.2, which shows the critical current $I_c = \pi J_1 D^2/4$ and the calculated degraded current $I_d = \pi J_2 D^2/4$.

In this case the conductor is understabilized and if it were used to construct a magnet degradation might be observed due to unstable flux jumps in the low field region of the winding.

3. THE DESIGN OF STABILIZED COILS

In the previous section two prerequisites for enthalpy stabilization were given. Firstly, the enthalpy of the composite conductor must be sufficient to fulfil equation (7) throughout the relevant range of magnetic field; and secondly, the thermal diffusivity across the conductor must be greater than the magnetic diffusivity so that the energy dissipated by the flux motion is averaged through the conductor.

The first of these requirements can be fulfilled in two ways without adversely affecting the overall current density in the magnet. If the diameter of the conductor is reduced the energy dissipated by flux motion is also reduced and stabilization is improved. However with this approach, sometimes known as intrinsic stabilization, conductors of diameter less than 0·1 mm are generally required so that fabrication of both the conductor and the magnet is difficult. The alternative is to increase artificially the enthalpy of the conductor by adding a material of high specific heat such as mercury, lead, or cadmium. The overall current density obtained this way is not so high, but a more practical conductor can be used. In the examples discussed below, lead is used for stabilization and it will be seen that current densities above 10^4 A cm^{-2} are easily obtained.

The second requirement for enthalpy stabilization is that the energy dissipated by flux motion is averaged over the cross-section of the conductor. To achieve this it is necessary to subdivide the superconductor which has a poor thermal conductivity and form a composite conductor with a normal material such as copper which has a high thermal conductivity and also a high electrical conductivity to provide some damping of the flux motion.

As an example of an enthalpy stabilized conductor, the calculated degraded performance of a lead coated conductor is shown in Fig.3. The 0·5 mm diameter core of the conductor is a composite of Niobium-Titanium and copper with a copper to superconductor ratio of 1·5:1, which is the highest proportion of superconductor which can conveniently be incorporated in a multi-stranded conductor. Eighteen strands of superconductor, each approximately 0·08 mm diameter, are used to give good heat transfer properties. Lead is then electroplated to any required thickness and hardened to improve its mechanical strength and the conductor is either wrapped with terylene yarn or insulated with an enamel. Fig.3 shows the calculated degraded performance of three conductors in which the lead to core ratios are 1:1, 2:1, and 3:1. On the basis of these calculations a 30 kG magnet constructed from any of these conductors should operate at the critical current of the superconductor, giving overall current densities of $2{\cdot}8 \times 10^4$, $1{\cdot}9 \times 10^4$, and $1{\cdot}4 \times 10^4$ A cm^{-2} respectively.

In general the design of an enthalpy stabilized conductor is mainly determined by the overall current density required in the magnet. If a low current density is acceptable a large conductor can be used, but if it is important to obtain the highest possible current density a small conductor must be used. A comparison of several conductors of similar construction but of varying diameters is given in Table I. The core of each of these conductors has a copper to superconductor ratio of 1·5:1, but the proportion of lead is varied to give the same degree of stabilization.

TABLE I

Comparison of enthalpy stabilized conductors of varying size.

Core diameter (mm)	Overall diameter (mm)	Current at 30 kG (A)	Overall current density at 30 kG (A cm^{-2})
0·75	2·0	335	$0{\cdot}8 \times 10^4$
0·50	1·0	150	$1{\cdot}4 \times 10^4$
0·36	0·60	78	$2{\cdot}0 \times 10^4$
0·25	0·35	38	$2{\cdot}7 \times 10^4$
0·20	0·24	24	$3{\cdot}4 \times 10^4$

4. THE APPLICATION OF ENTHALPY STABILIZATION

Preliminary tests of enthalpy stabilized magnets suggest that the principles outlined in the previous sections can be applied to practical magnets. The first small magnet constructed in this way consisted of 24 layers of 1·0 mm diameter composite conductor with a copper to superconductor ratio of 1·5:1 and a lead to core ratio of 3:1, and generated 26 kG in a 1·5 cm bore. This magnet was fully impregnated with epoxy resin and operated at 162 A, which was the critical current of the superconductor, when run in either helium liquid or helium gas at 4·2°K. The overall current density was $1{\cdot}25 \times 10^4$A cm^{-2}. A similar coil using the same conductor but without the lead plating quenched repeatedly as 34 A, confirming the value of the lead in stabilizing a magnet. Further magnets using lead coated conductors are in the course of construction to show that higher current densities are possible and that the larger magnets may be stabilized in this way.

The main advantage of this form of stabilization is that the operation of magnets is no longer limited to systems immersed in liquid helium. Enthalpy stabilised magnets will work equally well in liquid, gas, or even in vacuum if suitable refrigeration is provided. A novel application currently being considered is in a plasma physics "levitron" experiment where a current carrying ring is required which will be held in place in a vacuum system only by its own magnetic field, without any mechanical supports. Existing experiments of this type using a copper ring are limited to pulsed operation due to resistive current decay, but the use of a superconducting ring would allow almost continuous levitation. For such an application, however, the use of liquid helium in the ring is a severe embarrassment because of the difficulty of introducing it through the vacuum system by means of a demountable transfer tube, and also because the ring must be contained in a pressure vessel to protect the system if the superconductor should ever quench. The use of an enthalpy stabilized winding, on the other hand, which can be fully impregnated and cooled by conduction appears quite attractive.

An alternative application where impregnation of the winding might be advantageous is in magnets where a high degree of mechanical stability is required either for periods of many years or in the presence of thermal cycling or varying mechanical forces.

Finally, perhaps the most interesting aspect of enthalpy stabilization is simply that it offers a new approach to stabilization and a new freedom in magnet design.

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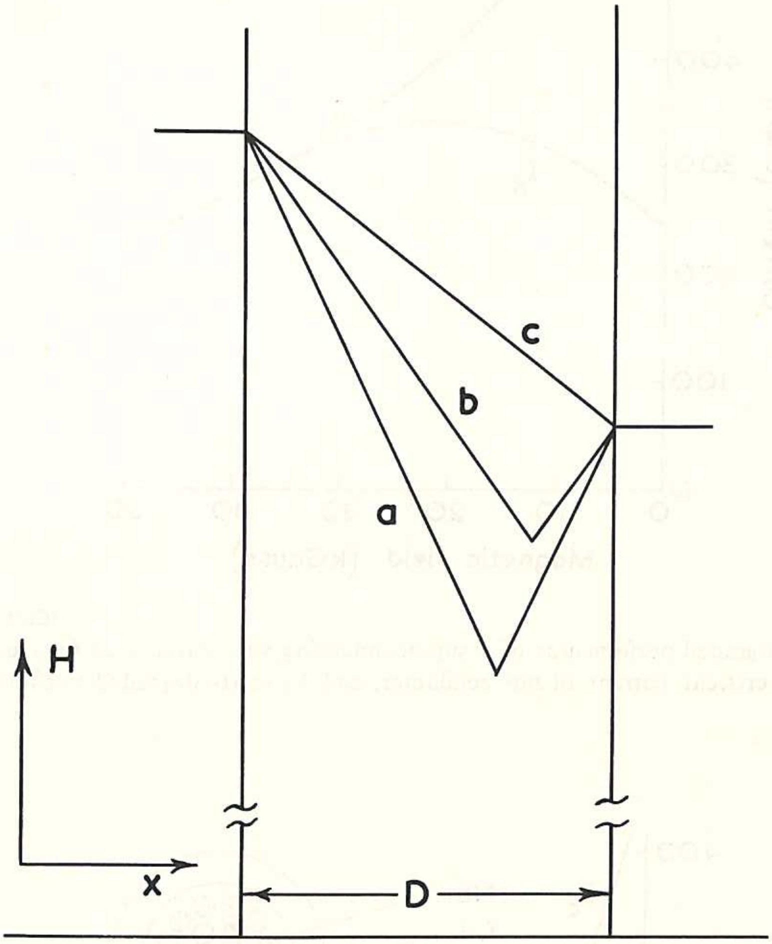

Fig. 1 (CLM-P 163)
Magnetic field distributions across a superconductor in the presence of both an applied field and a current

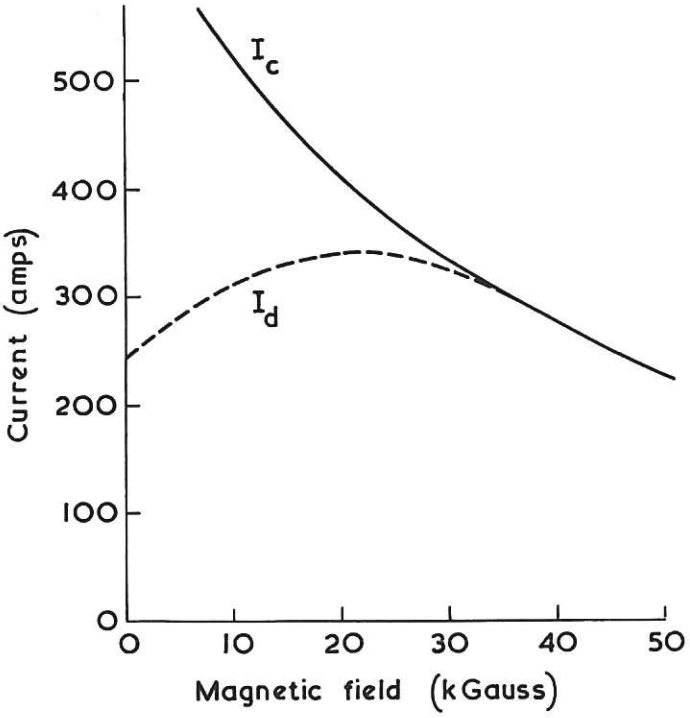

Fig. 2 (CLM-P163)
Typical degraded performance of a superconducting wire calculated from eqn.(7). I_c is the critical current of the conductor, and I_d is its degraded performance

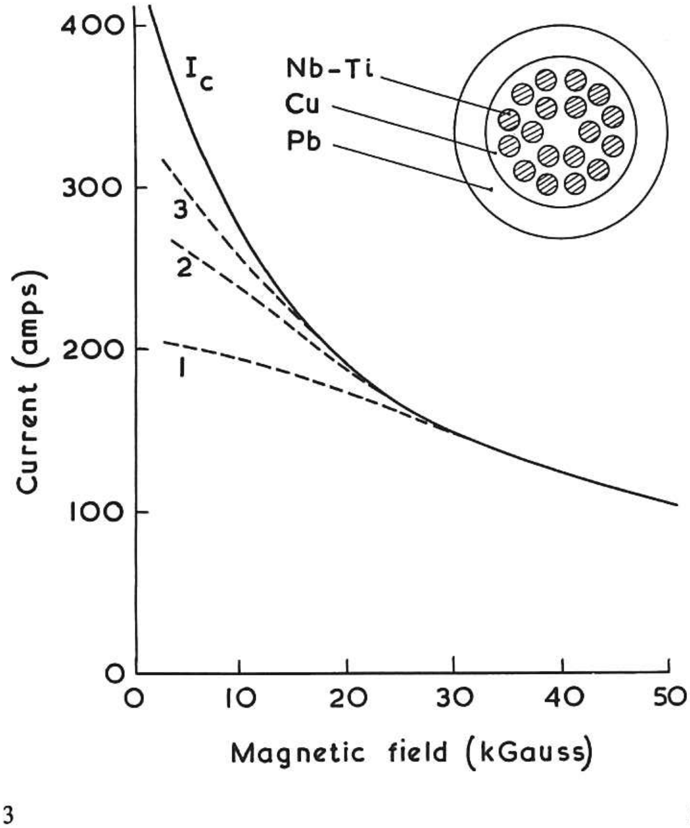

Fig. 3 (CLM-P163)
Calculated degraded performance of a lead coated multi-strand composite conductor. I_c is the critical current, and the three lower curves are for three thicknesses of the lead coating