BITTER MAGNETS FOR 20 T

B.E. Mulhall
International Research & Development Co. Ltd.,
Newcastle upon Tyne, U.K.

Abstract

To generate the highest steady fields, solenoids of the Bitter type are almost always used. Considerations of power density and stress in the windings show that beyond a certain point nested windings must be used, though these are more expensive to produce and less efficient in terms of power consumption. A single coil to produce 20 T in a 28 mm bore should be feasible, and such a magnet has already been operated at 18 T.

I Introduction

In discussing the design of water-cooled copper magnets for producing steady fields it is convenient to distinguish three types, namely (i) iron cored magnets, (ii) high field air core solenoids, and (iii) ultra high field magnets.

The first class, iron magnets, is suitable only for fields up to about 2 T (possibly extending to 5 T in small volumes) and will not be considered further.

High field solenoids, the second class, have been constructed successfully to produce fields of 15 T or more at several laboratories and described on a number of occasions. At the highest field levels mechanical and thermal problems become increasingly severe, until eventually more complicated types of winding have to be adopted. The field at which this occurs is, as discussed below, around 20 T but at and above this level experience is rather limited.

II High field magnets

The most important design considerations in high (as distinct from ultra high) field magnets are efficiency (that is, obtaining the maximum field for a given power dissipation and useful volume), reliability, and ease of construction. Bitter's well known contribution was to invent a construction which goes far to meeting all requirements, and though some aspects of the discussion below may be more general we shall be concerned particularly with Bitter magnets.

A discussion of efficiency is best illustrated by the well known Fabry formula,

$$H_o = G\sqrt{\frac{W\lambda}{r_o\,\rho}} \qquad .....(1)$$

Of course, in Bitter magnets the value to be used for the space factor, λ, is an equivalent value which depends on the particular arrangement of the cooling passages. In discussing the limitations on field, the following additional formulae are useful:

$$H_o = J_o\, r_o\, K \qquad .....(2)$$

where K, like G in *Eq. 1*, is a factor dependent only on the geometry of the solenoid, and

$$\sigma_o = B_o\, J_o\, r_o \qquad .....(3)$$

$$= \frac{B_o H_o}{K}$$

where σ_o is a measure of the mechanical stress in the coil. It is convenient to illustrate the significance of these formulae by plotting contours of K as well as the more usual contours of G. Examples are shown in *Fig. 1* for a Bitter coil (that is, with current density inversely proportional to radial distance from the axis) of rectangular cross section (length $2\alpha\, r_o$ and outer diameter $2\beta r_o$).

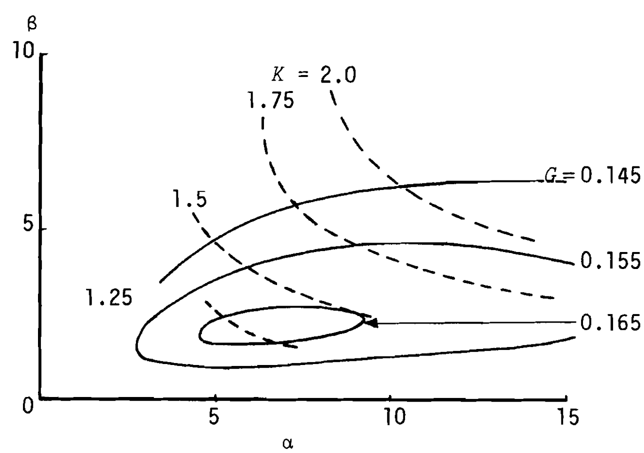

Fig. 1 *K* and *G* for Bitter coils

The factors determining the highest field which can be reached are the intensity of cooling and the tolerable stresses. *Equation 3* gives an upper limit to the tensile stress in the conductors of a Bitter magnet. If the typical values $B_o = 20$ T and $K = 1.25$ are used, the stress is 2.5×10^8 N/m^2, which is close to the ultimate tensile strength of hard worked pure copper. A more detailed analysis, based for example on the methods discussed by Leon[1], gives appreciably higher values. Thus, in the case of a coil for which $\alpha \simeq 12$ and $\beta \simeq 4$, and for which the cooling holes are ignored, the hoop stress is approximately doubled. Since magnets of such dimensions work it is presumed that the conductors deform so as to be under stress when at zero field, though one would then expect the life to be limited by metal fatigue at the highest fields.

Further considerations[2] of localised stresses at the contact area of the conductors are more complex, but in general can be neglected if the conductors are sufficiently thin, as tends to be the case with the magnet resistances (say 10-20 mΩ) commonly required for operation at power levels of up to 5 MW.

Cooling of Bitter magnets has been discussed extensively, and a number of similar designs of conductor have been developed. The holes are distributed so that each cooling passage carries off the same amount of heat and the limiting rating is obviously determined by the greatest density of cooling holes that can be manufactured.

III Particular magnet designs

One satisfactory design of high field magnet, with which a great deal of experience has been obtained, is that developed at RRE, Malvern[3], and now being manufactured at IRD. Manufacture is clearly more economic if the number of different parts is as small as possible, and thus a standard hole pattern is used. It is based on a 40 mm bore disc with 2.5 mm cooling holes, which are convenient to produce and, incidentally, give near optimum cooling under typical conditions. The larger bore magnets have the centre of the 40 mm conductors cut out, and so have fewer cooling holes.

The remaining design variables are thus coil length and conductor thickness. The latter can be varied with axial position in the coil, either to give slightly better efficiency (thin plates in the centre) or to give greater uniformity of field (thick plates in the centre), but is determined essentially by the magnet resistance needed. The scope for improvement in efficiency is rather limited, as the thermal conditions discussed below are more severe with the thinner conductors.

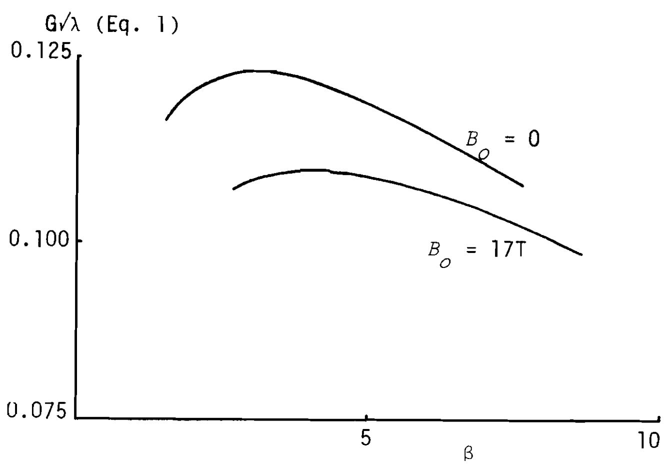

Fig. 2 Magnet efficiency versus length for 33 mm bore conductors

The length is chosen in the first instance to optimise efficiency (see *Eq. 1*), but, because the resistivity, ρ, of the copper depends on the mean conductor temperature, and hence on the heat flux, and hence again on the coil length, the optimum varies with field level. This is illustrated by *Fig. 2.* Ultimately, the length is governed mainly by the critical heat flux, above which vapour blanketing of the cooled surfaces occurs. This heat flux (about 1 kW/cm^2) is rather insensitive to water flow conditions and thus the magnet rating depends on the wetted area, which is proportional to magnet length. *Fig. 3* illustrates this for a number of different bore magnets.

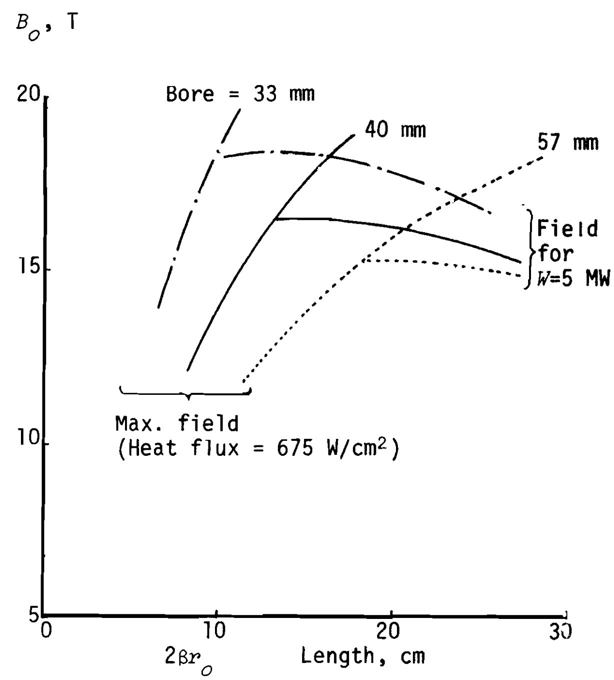

Fig. 3 Limiting ratings of Bitter solenoids

Increasing the magnet length has the further benefit of increasing K (or, in other words, of decreasing the current density corresponding to a given field, as may be seen from *Eq. 2* and *Fig. 2*), and hence of decreasing the stress level in the windings. Thus, up to a certain (not yet completely evaluated) extent, the maximum fields given by the thermal analysis are close to those set by mechanical considerations. Beyond this the current density at the inner edge must be reduced, and an arrangement of nested windings becomes inevitable.

As well as considering the field limit of the existing designs, the possibility of reducing the bore was studied. The hole pattern was extrapolated to a bore of about 33 mm, at which the packing density of the cooling holes is as great as is practicable, and curves for this are included in *Fig. 3.* This was done at the request of Prof. Justi of the new High Field Facility of the Technical University of Braunschweig, where d.c. power of over 5 MW and very high stability is available. The working bore of 28 mm is just sufficient for many purposes, and allows a field approaching 20 T to be reached with a relatively limited power. To date just over 18 T has been generated with a power dissipation of 4.75 MW.

IV Conclusion

Figure 3 shows that on the basis of thermal considerations it should be possible to generate fields close to 20 T in suitably long Bitter coils. However, these coils are close to the limits of permissible mechanical stress, and their efficiency (in terms of $T/W^{\frac{1}{2}}$) is falling appreciably. There also remain points of detail design, such as stresses around the contact area and criteria for plate slippage, to be re-examined. Thus eventually nested magnet systems will have to be adopted, though probably only at power levels beyond the capability of most existing or projected High Field Laboratories.

Nomenclature

B_o = $\mu_o H_o$ flux density at origin, T

G = Fabry efficiency factor (*Eq. 1*)

H_o = field at origin, A/m

J_o = current density at inner radius of winding, A/m^2

K = current density factor (*Eq. 2*)

r_o = half winding bore, m

W = power dissipated in winding, W

α = ratio of outer to inner radius of winding

β = ratio of length to bore of winding

λ = effective fraction of winding occupied by conductor

ρ = resistivity of conductor, Ω m

σ_o = mechanical stress in winding, N/m^2

References

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