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Liquid Helium cooled Coils for making intense transient Magnetic Fields

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Abstract. The very economical production of transient magnetic fields above 10^5 Oersted with coils immersed in liquid helium is discussed. Graphs are given to facilitate calculation of coil heating.

Work here on the magnetoresistance effect at low temperatures requires magnetic fields of about 10^5 Oersteds. It is well known that steady fields of this order can only be produced by the use of solenoids dissipating hundreds of kilowatts. *Transient* fields of this magnitude may, however, be produced comparatively easily with either batteries, a generator (Kapitza[1])[2])) or condensers (Wall[3])) as the power source. This technique has recently been employed by several workers[4–10]), and very complete and useful design data are available in papers by Cockroft[11]) and Champion[8]).

Cooling of the coils with liquid hydrogen or helium causes an enormous improvement in the electrical efficiency. This was first used by de Haas and Westerdijk[12]) who report producing fields of 250,000 Oersted for periods up to 0·1 second in helium and hydrogen immersed coils fed from a bank of batteries. This technique which provides a very convenient tool for low temperature research is at present in use here, and it is the purpose of this note to discuss some of the design considerations involved. In our case condensers now provide the current.

Calculation of field.

The magnetic field which may be generated by discharging a condenser of capacity C microfarads charged to a potential V volts through a coil is given (Champion[8])) by

$$H = \left\{\frac{20\,C}{l}\right\}^{1/2} \frac{V}{a_1} \cdot S\,J \tag{1}$$

where a_1 and a_2 are the internal and external radii of the coil, and

$2\,l$ is its length. S and J are two factors less than unity. S depends on the fraction of the field energy actually within the coil, and is a function only of the shape of the coil, i.e. of a_2/a_1 and of l/a_1. J depends on the amount of energy dissipated as heat in one cycle, and is a function of RP/L where R and L are the resistance and inductance of the coil, and P is the period of oscillation of the system. CHAMPION gives charts showing S and R/L for a wide range of shapes of coil, and a table for J. J is seen to decrease rapidly with increasing values of RP/L.

Equation (1) may also be written in the slightly different form

$$CV^2 = H^2 \cdot \frac{a_1^2\, l}{20\, SJ} \,. \tag{2}$$

From this it may be seen that when S and J are constant CV^2 (and hence approximately the cost of the condensers) is proportional to the volume in which it is intended to produce the magnetic field. It is therefore clear that for simple experiments, where the specimen or arrangement being exposed to the field is small, a considerable saving can be made by having the magnet coil placed directly round the specimen rather than placing it outside the cryostat containing the experimental equipment. For the arrangement used by us the saving is at least of the order of 10^2.

The gain achieved by reducing the size of the coil is, however, accompanied by an increase of R/L, which varies as a_1^{-2}, and therefore by a decrease in the value of J. To avoid this decrease in J, either P, the period of the oscillation, or the specific resistivity of the material from which the coil is wound must be reduced. Fortunately an adequate reduction in resistance is achieved by immersing the coil in liquid helium. For good commercial copper wire this reduction is of the order of one hundred times.

Heat generation.

The total heat generated in discharging the condensers, $\frac{1}{2}\,CV^2$, will mainly go to heating the coil, and thus increase its resistance. The total amount of this increase may of course by calculated by equating $\frac{1}{2}\,CV^2$ to the change of heat content of the copper. The heat rise at intermediate points of the cycle may be calculated by equating the amount of Joule heat $I^2\,\varrho\,dt$ produced in the time dt to the resultant change in heat content $C dT$. Here I is the current density, ϱ the resistivity, and C the specific heat of the copper. On integrating we obtain

$$\int I^2\, dt = \int \frac{C}{\varrho}\, dT\,. \tag{3}$$

The value of the integral on the right hand side of (3) is only a function of the temperature and the residual resistance, and may be calculated from published specific heat and resistance data. When this has been done a knowledge of $\int I^2\, dt$ allows the temperature increase and hence the change in resistance to be determined.

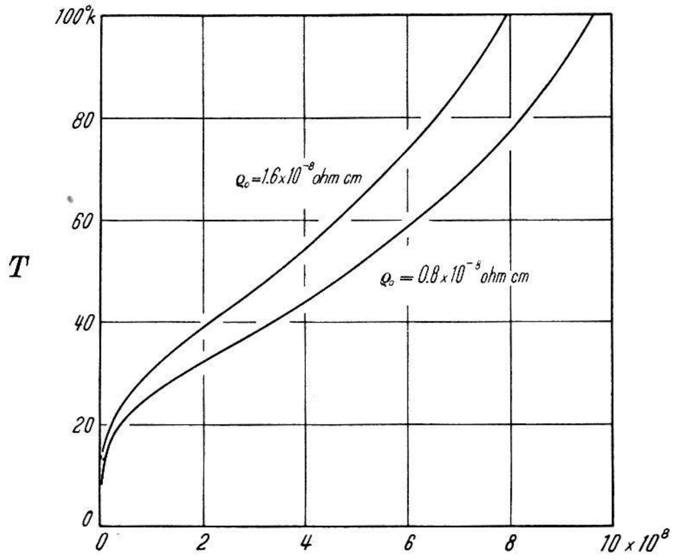

Fig. 1.

Temperature T as function of $\int I^2\, dt$ for copper with two values of the residual resistivity ϱ_0. I is the current density in Amperes per cm² in the metal, and t the time in seconds.

In figure 1 and 2 we show the temperature and resistance plotted as a function of $\int I^2\, dt$ for copper for two values of residual resistance. These values correspond to 1% and 0·5% of the room temperature resistance. The curves have been calculated from resistance and specific heat data taken from literature.

Example of actual use of coils.

Our supply of current comes from a 3,000 μFd bank of electrolytic condensers which can be charged to 360 volts. This is fed into a coil 15 mm long, 4 mm internal and 9 mm external diameter. The windings are made of 750 turns 0·2 mm enamelled commercial copper wire embedded in glue. At present no external strengthening is given to the coil since fields of up to only 150,000 Oersted are used. No tendency for the coil to burst has been found, nor does the residual resistance show any noticeable increase as would be expected in the case of serious straining.

The resistance of the external circuit requires close attention if it is not to be large compared with the resistance of the coil (in our case 0·07 Ω) at helium temperature. Switches with solid contacts are undesirable since arcing occurs which interferes seriously with delicate measurements. A mercury switch with a large contact area has been found quite satisfactory here, although an electronic device may provide a more elegant solution.

The coil arrangement above gives fields of ca. 130,000 Oersted*) when the condensers are discharged from 300 volts. This is rather

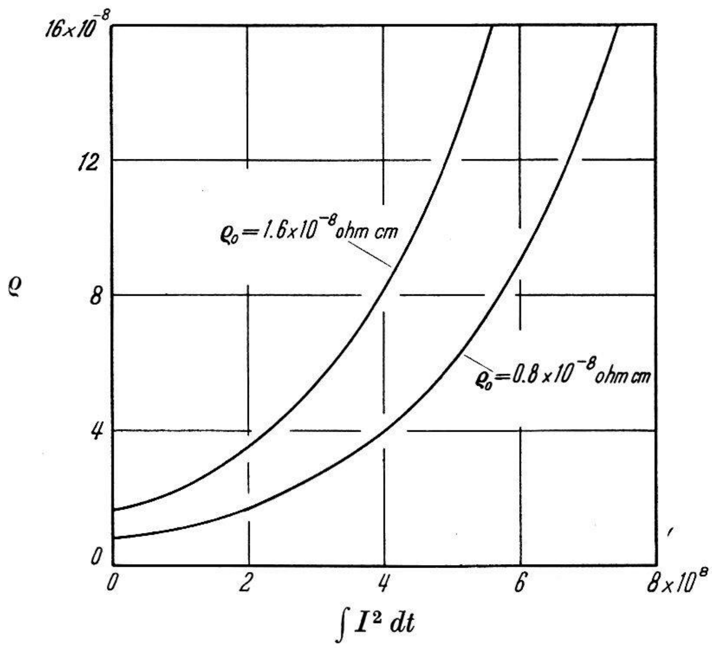

Fig. 2.

Resistivity ϱ in ohm cm as function of $\int I^2\,dt$ for two values of the residual resistivity ϱ_0. I is the current density in Amperes per cm^2 in the metal and t the time in seconds.

less than predicted by equation (1) which gives 180,000 Oersted when the resistance 0·12 Ω of the external circuit is taken into account. The magneto-resistance in the inner windings increases the resistance of these windings by approximately a factor 6, but this is somewhat difficult to allow for.

If all the energy of the condensers is dissipated in the cryostat then ca. 75 cm^3 of liquid helium should be evaporated. The evaporation observed lies about 50 cm^3 per discharge.

*) After 2·5 millisecond.

In early experiments using a 24 volt battery as power source feeding into a coil of 4 mm internal and 18 mm external diameter and 15 mm length wound with 930 turns of 0·3 mm diameter copper wire a maximum of 75,000 Oersted was reached after 30 milliseconds. Some difficulty was, however, found in limiting the evaporation of helium owing to inadequate arrangements for breaking the circuit early enough. The information contained in figures 1 and 2 may be used for predicting the performance of coils for this case too.

Conclusion.

A glance at figures 1 and 2 shows that the electrical efficiency is not greatly different whether helium or hydrogen is used as refrigerant. The main advantage to be gained by the method lies in the reduction in volume to be filled with magnetic field energy, and in the economy achieved, which may be decisive in the preliminary stages of a research project.

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