Pramāṇa – J. Phys., Vol. 25, No. 1, July 1985, pp. 11–20. © Printed in India.

Design and development of a superconducting magnet system for study of magnetoresistance in the temperature range 1·5–300 K

A K NIGAM, S SUNDARAM and GIRISH CHANDRA
Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400005, India

MS received 25 February 1985; revised 22 April 1985

Abstract. The design and fabrication of an all-metal cryostat, superconducting magnet and variable temperature sample holder insert for the measurement of magnetoresistance at temperatures in the range 1·5–300 K are described. A field of 50 kilogauss has been achieved at the centre of a one-inch bore superconducting solenoid and has a uniformity of 0·2 % over an axial distance of 20 mm around the centre of the solenoid. Also, the design and construction of vapour cooled current leads for the magnet are discussed.

Keywords. Magnetoresistance; superconducting magnet system; electrical resistivity; cryostat.

PACS No. 07·50

1. Introduction

Magnetoresistance and Hall effect measurements at low temperatures are relatively easy as compared to other thermal and magnetic measurements. The design of a cryostat is simple for such measurements if the field is applied from an electromagnet. In this case, glass dewars are conveniently used for the refrigerant, and can be easily made in the laboratory. The maximum attainable magnetic field from electromagnets is around 25 kilogauss. For measurements at higher fields, a superconducting magnet is required. The size of the cryostat increases significantly when the magnetic fields are generated by a superconducting magnet. The cryostat now houses the magnet (which is maintained at liquid helium temperature) in addition to the sample insert. This increase of dimensions of the cryostat puts an upper limit to the use of glass cryostats. Metal cryostats are conveniently used with superconducting magnets.

In this paper, we report the design and development of a superconducting magnet and the cryostat for measuring magnetoresistance in magnetic fields up to 50 kilogauss and in the temperature range of 1·5 to 300 K.

2. Design

2.1 *Cryostat*

The design details of the cryostat are shown in figure 1. The outer vacuum chamber and the liquid nitrogen shielding vessel is made of aluminium. Aluminium has been chosen because of the ease of welding and good thermal conductivity. Aluminium is also light

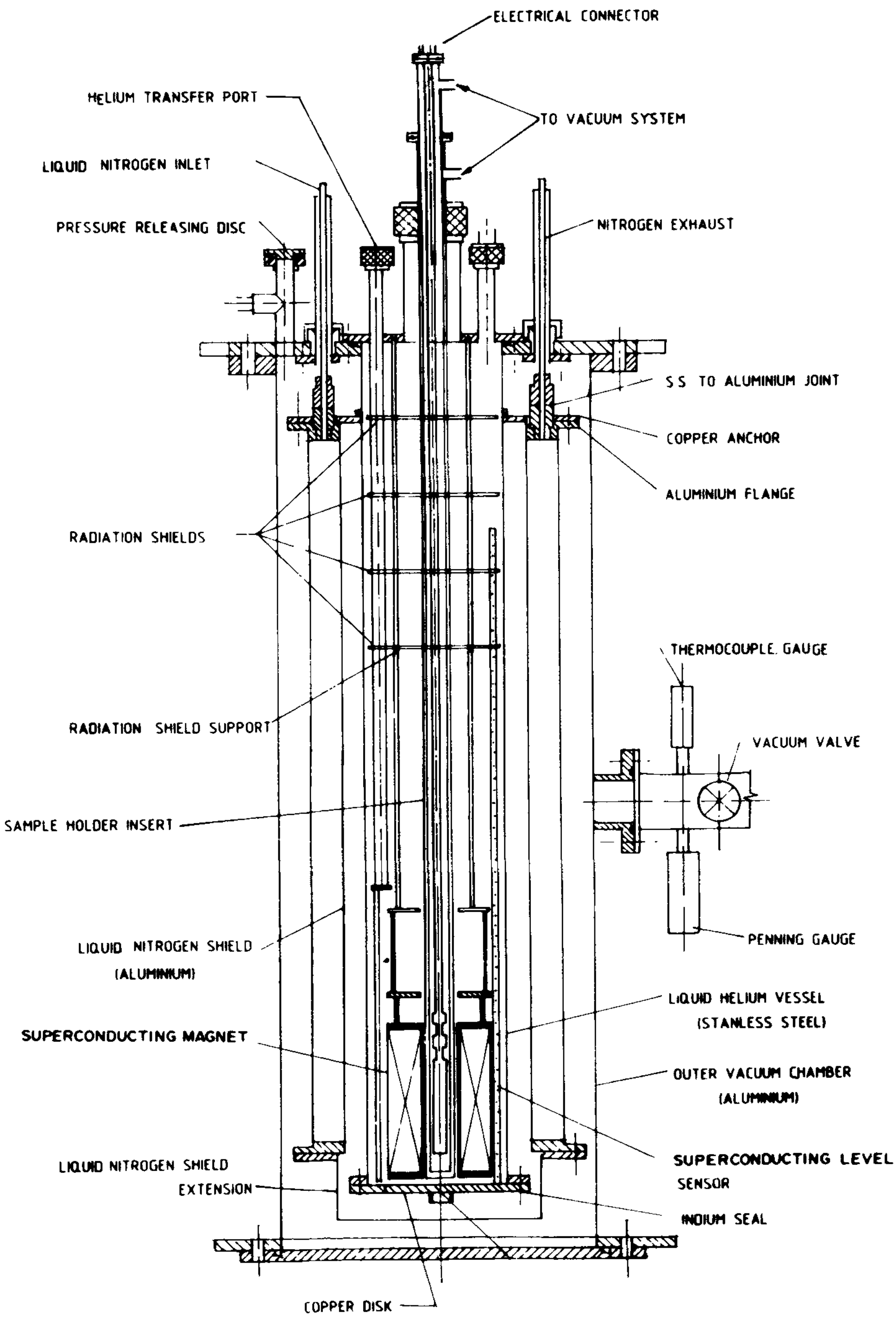

Figure 1. Schematic diagram of the complete magnetoresistance set-up.

weight and cheaper as compared to stainless steel which is conventionally used in the construction of metal cryostats. It is known that commercial aluminium is quite satisfactory for applications above 77 K. Stainless steel has been chosen for the liquid helium chamber due to its good weldability and low thermal conductivity. The helium chamber is made of a 125 mm diameter stainless steel tube and has a capacity of 6 litres of liquid. More details about the design of the cryostat are described by Sundaram and Girish Chandra (1983).

2.2 *Superconducting magnet*

The dimensions of the magnet are calculated for a one-inch clear bore magnet. For the solenoid configuration shown in figure 2, the following expression is used to calculate the magnetic field at the centre of the solenoid (Montgomery 1969)

$$H_{oo} = \frac{a_1 F(\alpha, \beta) i}{A}, \tag{1}$$

where i is the current through the solenoid, A is the cross-sectional area per turn, and

$$F(\alpha, \beta) = \frac{4\pi\beta}{10} \ln \frac{\alpha + (\alpha^2 + \beta^2)^{1/2}}{1 + (1 + \beta^2)^{1/2}}, \tag{2}$$

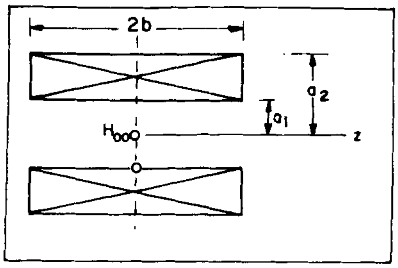

Figure 2. Coordinate system of coil configuration.

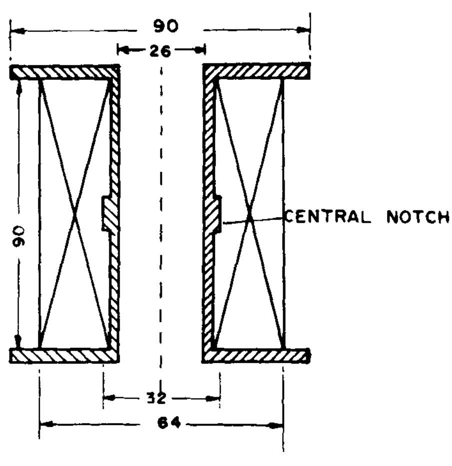

Figure 3. Notched coil-form used in the construction of the superconducting magnet for improved homogeneity (all dimensions in mm).

with $\alpha = a_2/a_1$ and $\beta = b/a_1$.
The function $F(\alpha, \beta)$, called the Fabry factor, can be calculated from (1) if the bore diameter, magnet current and A are known.

The length of the superconducting wire required is given by

$$L = \frac{2\pi a_1^3 \beta(\alpha^2 - 1)}{A}. \tag{3}$$

Thus, by knowing $F(\alpha, \beta)$ from (1) and the available length of the superconducting wire, one could calculate, from (2) and (3), α and β or, in turn, the dimensions of the superconducting coil.

The axial field homogeneity of the magnetic field is achieved either by having a suitable notch at the centre of the coil or by having additional compensating coils near the ends of the winding. In the present magnet, a centrally notched coil form has been used. A sketch of the coil form is shown in figure 3. It is made out of aluminium, and the notch has a width of 1 cm and a thickness of 0·2 cm.

2.3 *Current leads of the magnet*

In superconducting magnets, a high current is passed through it while maintaining it at liquid helium temperature. The magnet current leads constitute a dominant source of heat leak into the cryostat. There are two sources for this heat leak:

(a) Thermal conduction across the leads due to the temperature gradient across it— one end at room temperature connected to the power supply and the other at liquid helium temperature connected to the magnet.
((b) The heat leak due to ohmic heating of the leads when the magnet is energised. It is, therefore, required to optimize both the thermal conduction and ohmic loss. The following expression has been used to find the optimum cross-section of the leads (Rose–Innes 1970).

$$A_{\text{opt}} = i \cdot 4 \times 10^{-4}\ \text{cm}^2, \tag{4}$$

where i is current through the leads in amperes. Using (4), the optimum cross-section for the current leads were calculated.

In order to minimize the evaporation loss of liquid helium in the cryostat, it is always desirable to avail of the maximum possible cooling capacity of the liquid helium. That is, besides the latent heat of vapourization of liquid helium, the enthalpy of the evaporated gas should be utilized as it warms up to room temperature. This has been achieved by so designing vapour cooled current leads that a major portion of the heat generated within the leads is carried away by the evaporated cold helium gas. This also helps to further reduce the cross-section of the current leads than the optimum one given by (4). Figure 4 shows a drawing of the vapour cooled current leads.

2.4 *Variable temperature sample holder assembly*

A schematic drawing of the sample holder insert is shown in figure 5. This has a double-walled construction in order to have a thermal isolation of the sample region from that of the magnet region which is always maintained at 4·2 K. This insert is made up of two concentric thin-walled stainless steel tubes, the interspace between which is evacuated according to the requirement of maintaining a desired temperature of the specimen.

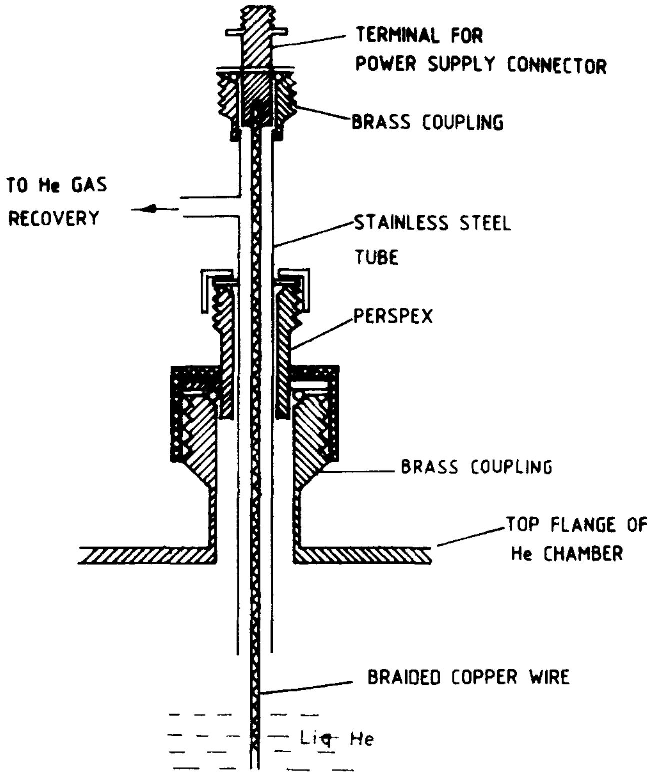

Figure 4. Schematic diagram of the vapour cooled current leads for the superconducting magnet.

This type of construction also provides the advantage of changing the sample when the system is at liquid helium temperature.

3. Construction

The outer jacket and liquid nitrogen chamber are made by argon arc welding of aluminium. The liquid nitrogen chamber is suspended from the top flange by small diameter stainless steel tubes *via* friction welded stainless steel/aluminium transition joints. The liquid helium chamber is made by argon arc welding of the stainless steel tube to the end stainless steel flanges. The bottom end of the helium chamber is blocked by a copper flange with indium O-ring seal. The top plate of the chamber is made of brass and has ports for liquid He transfer, sample insert, current leads, etc. The outer jacket, liquid nitrogen chamber and the liquid helium chamber are isolated from each other by a vacuum space.

The superconduction magnet solenoid are wound with multifilamentary Nb-Ti superconducting wire (Vacryflux 5001, Vacuumschmelze, West Germany). The aluminium coil form was anodized before winding so as to provide safety electrical insulation.

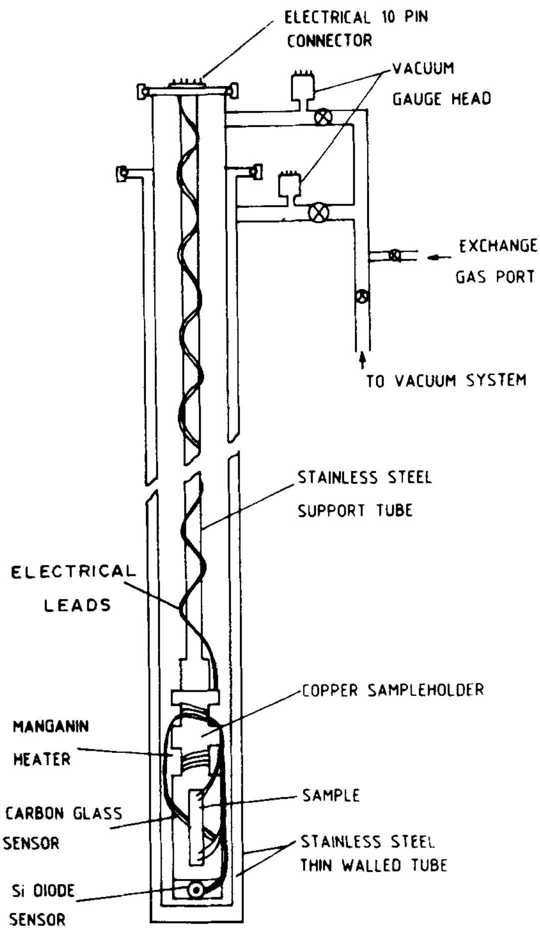

Figure 5. Sample holder insert assembly for magnetoresistance study.

An interlayer insulation of mylar was used to prevent voltage breakdown between the winding layers. The length of wire used for winding was nearly 1000 m. The dimensions of the coil are shown in figure 3. To make the terminal connections of the wire, the leads are taken out of the winding in smooth bends of sufficient radius to prevent a permanent set in the wire which would otherwise degrade the superconducting characteristics of the wire. The magnet terminals are made out of copper and are kept a few centimetres away from the maximum field area of the magnet, since the current carrying capacity of the joints is lower than that of the wire. A 1 ohm, 30 W resistor is connected across the magnet terminals in order to dissipate the magnetic energy through it in the event of magnet quenching.

The current leads of the magnet are shown in figure 4. The current carrying part is made out of copper braid of a shielded cable, and has uniform cross-section throughout. The cross-sectional area of the wires carrying the current is approximately 0·014 cm^2. This value is less than 0·024 cm^2 as calculated from (4) because of the vapour cooling of the leads. The braid is surrounded by a stainless steel tube which is connected

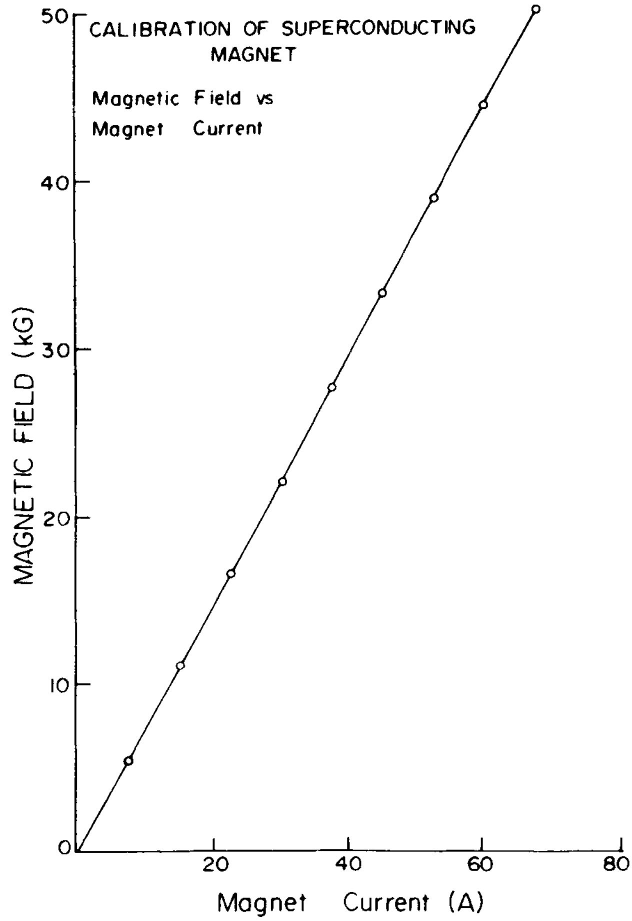

Figure 6. Field calibration of the superconducting magnet against magnet current.

to the recovery line of the helium gas. This assembly (ss tube + copper braid) is electrically insulated from the rest of the system by a perspex coupling.

In the sample holder insert, the sample holder is made of a cylindrical copper block (figure 5). Nearly half of its length is machined to provide a plane rectangular surface which gives a good thermal contact to the specimen. A thin tissue paper soaked in GE varnish (Oxford Instrument, UK) is used to electrically insulate the specimen from the copper block. A manganin wire heater is wound on the copper block to vary the specimen temperature between 4·2 and 300 K. Two precalibrated temperature sensors *viz*, a Lakeshore carbon glass resistor and a Lakeshore silicon diode, are mounted on the copper block to monitor the specimen temperature in the range 4·2 K–100 K and 100 K–300 K, respectively. The sample holder is rigidly attached to a thin-walled stainless steel tube which extends up to the top of the cryostat. The electrical leads coming from the sample holder are connected near the top of the insert to a 10-pin gold plated connector (Oxford Instruments). The electrical leads attached to the sample are of copper and are usually spot welded.

4. Operation and performance

The outer chamber (at ambient temperature), the liquid nitrogen chamber and the liquid helium chamber are thermally isolated from each other by vacuum better than 10^{-5} torr. Care is taken during the fabrication to see that no part of any section touches the colder part of the other section. The evaporation of liquid helium during the cool down of the cryostat from 77 K to 4·2 K is about 2·5 litres. The level of the liquid helium in the cryostat is monitored with a superconducting level sensor (American Magnetics, USA) (figure 1). The hold time of the cryostat without any electrical load is approximately 24 hr.

The power supply (model 75-M from Intermagnetics General Corp., USA) used for charging the magnet is a 75A/5V current source with a ramp generator. The magnet is usually energised with a sweep rate of 7·5 A/min. The magnet has been calibrated at 4·2 K with an axial Hall probe. The calibration curve—magnet current *vs* magnetic field at 4·2 K, is shown in figure 6. The field profile along the axis of the magnet was measured by moving the Hall probe up and down around the centre of the magnet, and the results are shown in figure 7. It is found that the field is uniform to within 0·2 % over 20 mm length along the axis around the centre of the magnet. The observed homogeneity is in conformity with the calculated value.

Longitudinal magnetoresistance was measured up to fields of 45 kilogauss in the temperature range 4·2 to 300 K. The specimen temperatures above 4·2 K are obtained by passing a current through the heater wound on the sample holder. This current is controlled by a Lakeshore temperature controller (model 520). In order to use optimum heater power and to achieve good temperature stability, the vacuum in the interspace between the sample chamber and helium bath is maintained at different levels at different temperatures. The interior space (around the sample holder) is usually filled

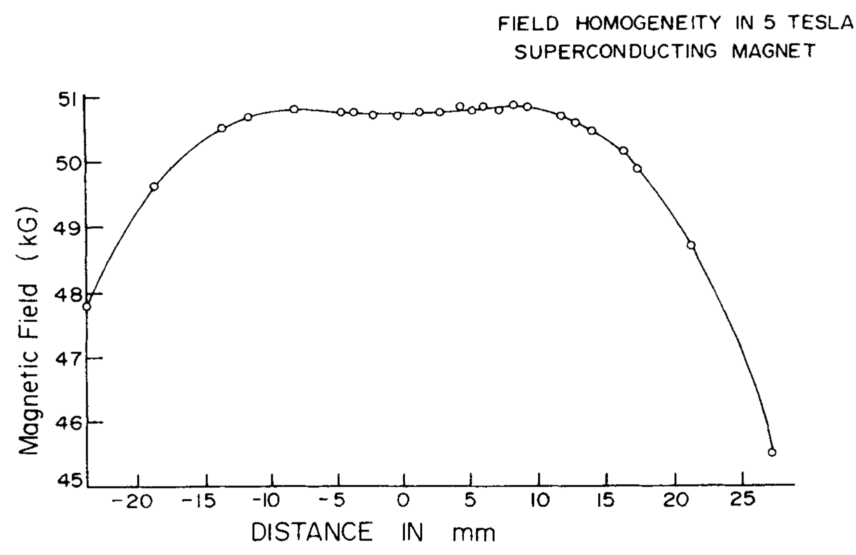

Figure 7. Magnetic field profile along the axis of the superconducting magnet solenoid. Note that the field has a homogeneity of about 0·2 % over a length of 20 mm around the centre.

with helium gas at a pressure of 1 torr. This helium gas provides good temperature uniformity across the specimen. Temperatures below 4·2 K are obtained by pumping over the liquid helium bath.

The resistivity of the specimen is measured by using the standard four-probe d.c. technique. The current through the specimen is drawn from a Hewlett–Packard constant current source (model 6177C). The voltage across the specimen is measured by a Keithley digital nanovoltmeter (model 181). The magnetic field is applied in steps and the resulting change in sample voltage is detected on the nanovoltmeter. The magnetoresistance defined as the ratio of the change in resistivity (due to field) to the zero-field resistivity, is calculated for each value of incremental field. A typical plot of

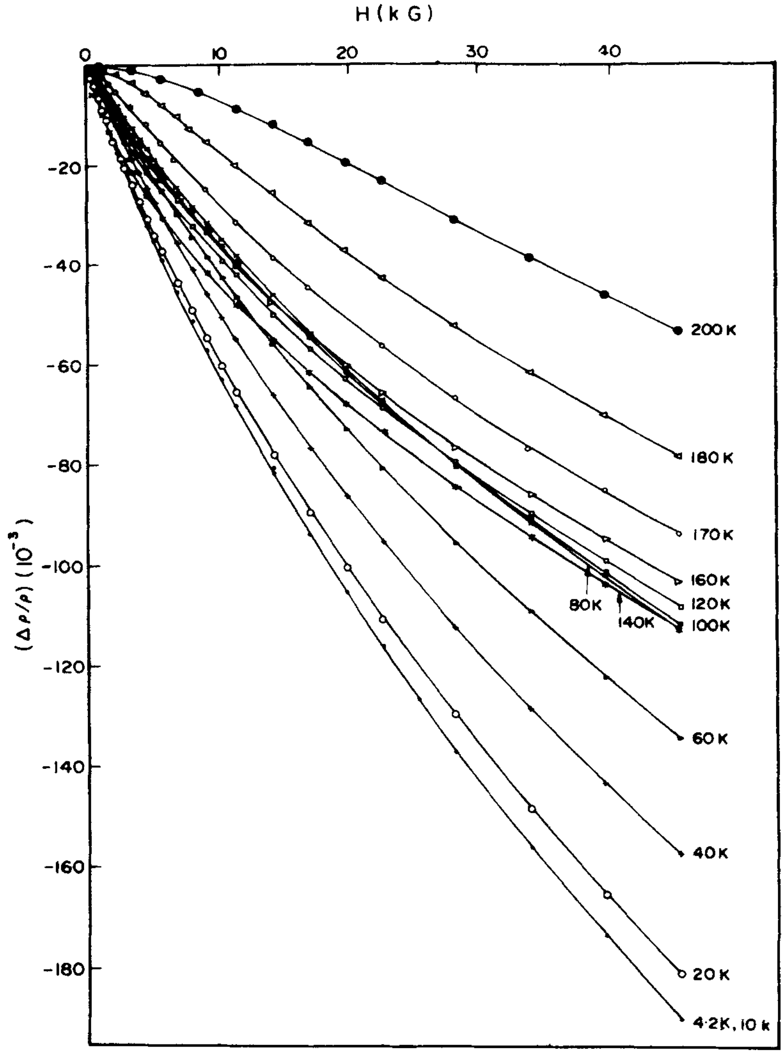

Figure 8. Variation of magnetoresistance with field at various temperatures in the range 4·2–200 K, as measured in the present set-up.

magnetoresistance ($\Delta\rho/\rho$) *vs* magnetic field (H) at different temperatures is shown in figure 8 for AuFe (18 at %) alloy.

Measurements of critical field of superconductors have also been carried out.

References

Montgomery D B 1969 *Solenoid magnet design* (New York: Wiley Interscience) p. 134
Rose–Innes A C 1970 *Low temperature techniques* (London: The English Universities Press) p. 48
Sundaram S and Girish Chandra 1983 *Indian J. Cryogenics* **8** 270