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Indigenous design and fabrication of a 6.5 T superconducting magnet and a magnetotransport measurement set-up

P KHATUA[1] and A K MAJUMDAR[1,2,*]
[1]Department of Physics, Indian Institute of Technology, Kanpur 208 016, India
[2]S.N. Bose National Centre for Basic Sciences, Sector III, Block-JD, Kolkata 700 098, India
[*]Corresponding author. E-mail: akm@bose.res.in

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Abstract. A low-cost apparatus for measuring Hall effect and magnetoresistance is designed and built indigenously. This includes a 6.5 T superconducting magnet and a variable temperature sample holder assembly. A superinsulated liquid helium dewar with a low liquid helium boil-off rate is chosen as the low-temperature bath for doing magnetotransport measurements. A pair of high-T_c superconducting leads for energizing the magnet reduces the liquid helium consumption further and makes it economically beneficial, especially for laboratories with limited budget. The performance of the apparatus is tested over a wide range of temperatures (4.2 to 300 K) and fields up to 6.5 T. Reproducible magnetotransport data are obtained with excellent temperature and field stability.

Keywords. Magnetotransport set-up; superconducting magnet; Hall effect; magnetoresistance.

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1. Introduction

Performing experiments like Hall effect and magnetoresistance in liquid nitrogen-shielded helium cryostats is costly due to the higher consumption rate of liquid helium. To make the experiments economically more cost-effective, a home-made superconducting magnet and a variable temperature sample holder assembly are inserted in a superinsulated helium dewar. The maximum field obtained with this magnet at its centre at liquid helium temperature (4.2 K) is as high as 6.5 T. Special attention is given in designing the superconducting magnet assembly since there are limitations regarding the size of the mouth of the dewar itself. The shape and size of the superconducting magnet assembly are designed in such a way that it can fit in the superinsulated liquid helium dewar, having a storage capacity of ∼60 l. The biggest advantage of doing experiments in such superinsulated dewars is that it holds liquid helium for a couple of weeks and therefore one can have a number of runs with a full dewar.

In this paper, we described in details the design of the magnetotransport set-up and the 6.5 T superconducting magnet. Scientists at the National Physical Laboratory (NPL), New Delhi, made a 3 T superconducting magnet operated inside a 100 l LHe storage dewar in 1999. Recently, a 7.1 T (at 200 A) superconducting magnet with a working bore of 46 mm and a field uniformity of $\pm 0.1\%$ has been designed and fabricated [1]. It is wound using a NbTi multifilamentary conductor. The magnet is of insert type and is suited for a standard 100 mm neck liquid helium storage dewar.

2. System design and description

The magnet system assembly comprises of a home-built 6.5 T superconducting magnet, a magnet support stand along with helium vapour-cooled high-T_{c} current leads (made of bismuth cuprate tapes with a current carrying capacity of 300 A at 77 K), a variable temperature sample holder assembly, and a superinsulated liquid helium dewar, as shown schematically in figure 1a. The superconducting magnet is suspended in the liquid helium dewar by means of the support stand. Its structure is such that it uses a brass flange at the top, a non-magnetic stainless steel tube brazed with the magnet-mounting flange that is coupled with the magnet at the bottom, and some radiation baffles for minimizing heat transfers into the liquid helium bath, respectively. The high-T_{c} current leads run from the top of the magnet assembly flange all the way down to the Cu leads of the magnet as shown clearly in figure 1a. The Ohmic heat loss for each of the two Cu leads (3 mm diameter and 0.5 m length) is about 2 W at 30 A current. The heat load due to the thermal conduction is $\mathrm{d}Q/\mathrm{d}t \sim kA\ \mathrm{d}T/\mathrm{d}L = 6$ W for each lead using thermal conductivity k for Cu = 400 W/mK, area A and effective length $\mathrm{d}L$ from the dimensions, and $\mathrm{d}T = 200$ K. So the total heat load for both the Cu leads = $(2 + 6) \times 2 = 16$ W whereas it is $\sim$0.2 W (through heat conduction only) for the high-T_{c} current leads. A detailed design of the superconducting magnet and the associated sample holder assembly is described below.

2.1 *The superconducting magnet*

In our magnet design, the superconducting magnet coil is wound using a special type of superconducting wire which comprises of many fine filaments of niobium–titanium (NbTi) alloy embedded in copper matrix. The former on which the coils are wound is made of a thin-walled non-magnetic stainless steel tube with two brass flanges brazed at its both ends in a bobbin shape. The inner diameter of this tube is the same as that of the support stand, which in turn becomes the bore diameter of the magnet.

Though the impregnation with epoxy resin [2] has been the most popular technique in coil winding, we do not use epoxy resin or any kind of spacer materials (such as glass fibre mat or coil winding paper) between successive coil layers in our

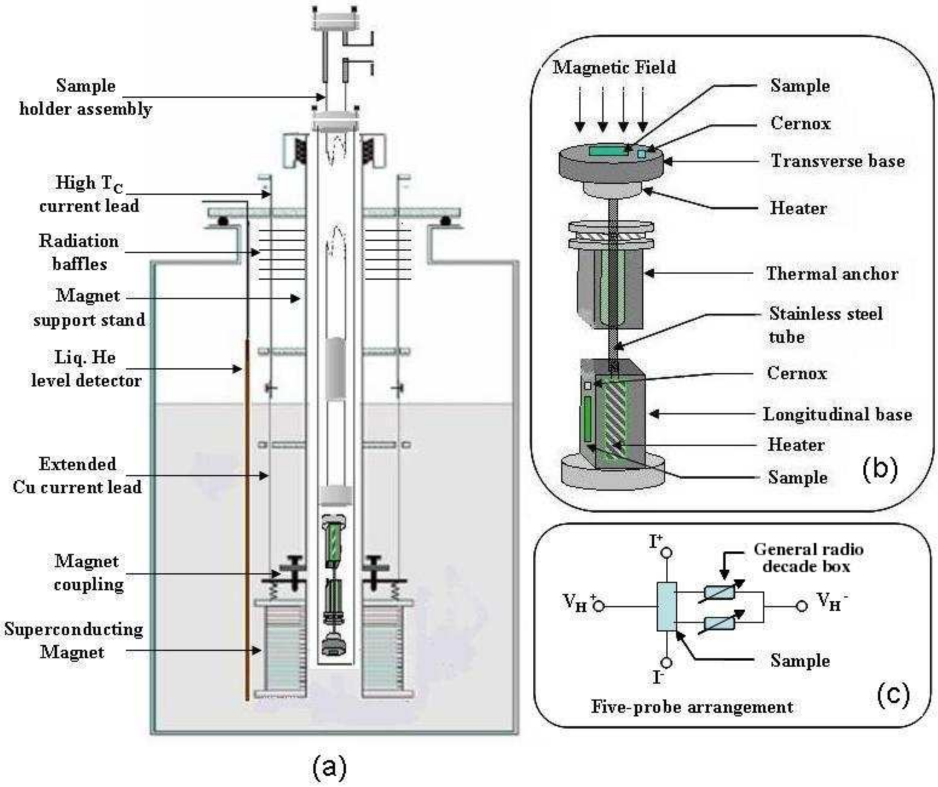

Figure 1. Schematic diagram of (**a**) the magnetotransport set-up consisting of a 6.5 T superconducting magnet and a variable temperature sample holder assembly, (**b**) a detailed design of the sample holder for electrical measurements in longitudinal and transverse orientations of the samples with respect to the magnetic field and (**c**) a five-probe arrangement for Hall effect measurements.

solenoid. The present magnet is designed for a 2-inch neck superinsulated liquid helium dewar. The space limitations at the mouth (diameter of mouth ~51 mm) of the superinsulated liquid helium dewar has put a restriction on the volume of the conductor that could be wound. Keeping in mind the limitations of the critical current (I_C) vs. field (B_C) behaviour of the present conductor, we try to exploit the maximum magnetic field just by increasing the volume fraction of the conductor (i.e. number of turns) for the given geometry of the magnet coil. Great care is taken during the process of winding of the magnet since no spacer layer is used between two successive layers. The magnet coil is covered by winding a separate layer of enameled copper wire to protect the magnet coil and also to provide a good thermal contact with the surrounding coolant that is necessary during an unexpected field quench. After completing the coil winding, in order to avoid degradation and training [3,4], we carried out wax impregnation by vacuum impregnation technique which in turn provides additional mechanical stability to the magnet coil as well.

Table 1. Specifications of NbTi ($T_c \sim 10$ K) multifilament superconducting wire.

Specifications	Value
Composition	NbTi/Cu
Cu/SC ratio	1.3
Diameter of the conductor (insulated)	0.33 mm
Filament diameter	25 μm
No. of filaments	54
Critical current	45 A at 7 T and 4.2 K

Table 2. Specifications of the magnet coil.

Specifications	Value
Inner diameter of the coil	22 mm
Outer diameter of the coil	49 mm
Coil length	150 mm
Total number of turns	17910
Number of layers	41
Effective wire length	1997 m
Wire volume fraction	75.6%
Coil constant	145.9 mT/A
Coil inductance	2 H
Stored energy	1.92 kJ
Central field (maximum)	6.5 T at 44.6 A
Homogeneity	5 cm <1%
Highest ramping rate for energizing the magnet	0.45 T/min
High T_c current leads	Made of bismuth cuprate tapes (current carrying capacity of 300 A at 77 K)
Cu coil at the outermost layer	

The critical parameters of the magnet design are the radial access diameter, central field strength, and field homogeneity. The field strength of a magnet coil depends on the number of turns and the current while the field homogeneity varies with the shape function (geometric) of the magnet coil. Detailed specifications of the NbTi wire and the magnet are given in tables 1 and 2, respectively. A close-packed solenoid of ~17910 turns is wound on the bobbin so that the volume fraction of the conductor in the magnet coil becomes ~75.6%. The coil has an inner diameter of 22 mm, an outer diameter of 49 mm and a length of 150 mm. With these dimensions the inductance of the magnet coil is calculated to be ~2 H.

2.2 *Field calibration and quench protection*

Before doing the actual field calibration of the magnet experimentally, the field strength is calculated theoretically using Biot-Savart integral [5,6] and the coil

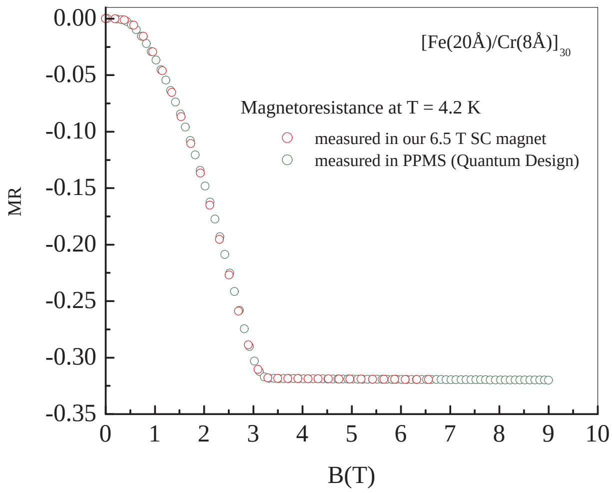

Figure 2. Magnetoresistance vs. $B(T)$ of a Fe/Cr GMR multilayer sample measured using our 6.5 T magnet system and a commercial 14 T quantum design PPMS for comparison. The excellent match between the two plots shows the degree of accuracy of the field calibration of our superconducting magnet.

constant is found to be 145.9 mT/A. From the theoretically calculated field profile, the field at the end point of the solenoid is found to be essentially half of that at the centre of the solenoid, as expected. Field homogeneity (better than 1% over 50 mm distance) is obtained over 22 mm DSV (the diameter of spherical volume) at the centre of the solenoid and it falls off axially away from the centre.

The final field calibration is done with an ion-implanted GaAs (Lakeshore Cryotronics) Hall sensor (of sensitivity $\sim$10 μV/Oe at 5 mA DC excitation) by moving it to various axial positions and the measured coil constant is found to be very close to the theoretical value. In order to crosscheck the field calibration, the magnetoresistance (MR) of a giant magnetoresistive (GMR) Fe/Cr multilayer sample having a GMR of $\sim$32% at 4.2 K is measured using this magnet and then compared with previous measurements by quantum design PPMS (physical property measurement systems). An excellent match of the MR vs. field $B(T)$ curves (see figure 2) is observed where both the curves are found to be almost overlapping over the common field range, showing the high degree of accuracy of the field calibration of our superconducting magnet.

In order to protect the magnet from any kind of damage and also to prevent any big loss of liquid helium, a safety circuit is designed. It consists of two parallely connected power diodes (of high current rating $\sim$100 A) in series with a combination (all connected in parallel among themselves) of small resistors ($\sim$1 Ω). This unit is connected in parallel to the magnet so that when a quench occurs, the voltage developed across the magnet makes either of the diodes to conduct and allows dissipation of the stored energy through the small resistors. This is how any serious damage to the magnet is avoided.

2.3 *Sample holder assembly for magnetotransport measurements*

A schematic diagram of the variable temperature sample holder assembly for Hall effect (especially for metallic samples) and magnetoresistance measurements is shown in figure 1a. The assembly is inserted into the magnet by a simple O-ring arrangement at the end of the extended part of the magnet support stand. In order to make the use of the cryostat handy, a 1-m long vacuum can is designed to encapsulate the sample zone. Inside the vacuum can, there is a sample holder support assembly, at the end of which the sample stage is attached. All the electrical leads from the sample zone come out through a vacuum seal arrangement on the brass connector and are finally attached to a 25-pin connector. A number of teflon spacers are used to isolate the inner support assembly from the outer vacuum can.

The main sample stage is coupled to the inner adjustable support assembly by means of a thin-walled non-magnetic stainless steel tube of outer diameter 4 mm, as shown in figure 1b. Two specially designed separate copper bases are brazed with this tube in suitable orientations for the longitudinal and transverse measurements, respectively. Each of the sample bases is separately equipped with a calibrated CERNOX thermometer and a heater (Nichrome heater wire of 40 Ω resistance) for measuring the sample temperature and its control. A weak heat link to the sample holder is established by attaching a thin copper strip with the copper anchor fixed at the middle of the supporting tube of the sample base which directly touches the vacuum can (in contact with liquid helium bath).

In the standard four-point probe DC Hall measurements, the misalignment voltage (which is actually the additional longitudinal voltage superposed on the transverse Hall voltage because the Hall contacts may not be on the same Ohmic equipotential) is usually taken care of by reversing the magnetic field direction. In order to avoid the field reversal, the five-point probe DC technique is used to measure the Hall voltage. In this method, we measure Hall voltage with fairly good accuracy but with far less effort. A voltage divider arrangement is made by using two general radio decade resistance boxes (Model 1432N), as shown in figure 1c. This artificially produces one terminal from the two on one side (V_H^-) and the contact on the other side becomes the second terminal (V_H^+). They together now form the Hall probe arrangement. The misalignment voltage is adjusted to zero (to the noise level of the circuit) by simply changing the resistance in the decade boxes in zero fields. In order to measure the Hall voltage at different temperatures, the misalignment adjustment must be done at each temperature before applying the magnetic field, since it is strongly temperature-dependent.

Theoretically, the sign of the charge carriers is determined by applying the Lorentz force law to the charge carriers under the influence of an external magnetic field. Experimentally, it is confirmed by measuring the Hall effect of a pure Ni sample in the same configuration of the magnetic field direction, the sample current direction, and the voltage probe connections to the micro/nanovoltmeter. Once the Hall configuration is standardized, the Hall effect on all the samples are measured by keeping the configuration unaltered in this Hall set-up.

Finally, the system is automated with LabView software for data acquisition by attaching an NI-card (National Instruments, USA) to a PC for making a link between the set-up and the IEEE 488-interfaced measuring instruments.

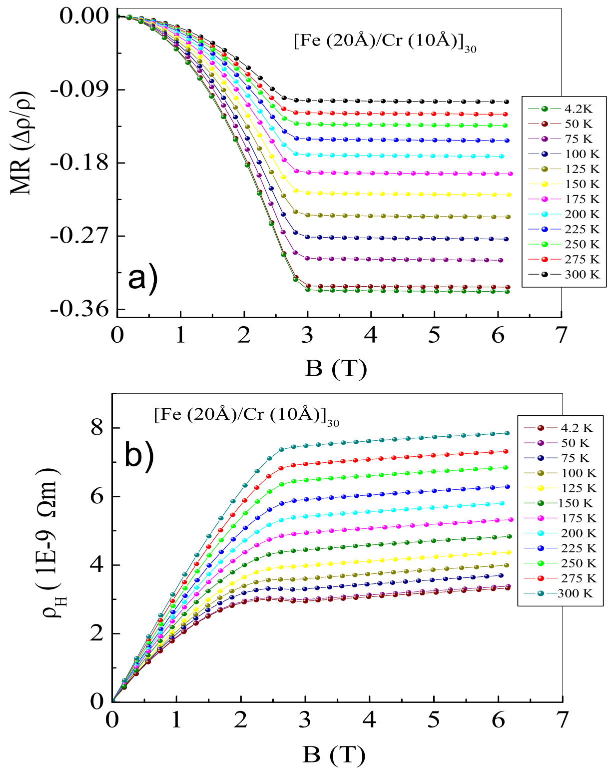

Figure 3. Plots of (**a**) magnetoresistance (MR) vs. field $B(T)$ and (**b**) Hall resistivity (ρ_{H}) vs. field $B(T)$, measured at various temperatures on a Fe/Cr GMR multilayer sample. The solid lines are just guides to the eye.

2.4 *Performance of the Hall set-up*

The performance of the Hall set-up and hence the magnet is tested by measuring Hall effect and magnetoresistance (both in transverse and longitudinal orientations) on various types of samples. Figure 3 shows typical plots of magnetoresistance (MR) vs. field $B(T)$ and Hall resistivity (ρ_{H}) vs. field $B(T)$, measured at various temperatures on one ion-beam sputtered Fe/Cr GMR multilayer sample. We find that both sets of curves saturate at nearly the same applied magnetic field of ∼3 T. The MR is ∼32% at 4.2 K. In the above measurements, the Ohmic and the Hall voltages are measured with relative accuracy of 1 in 10^5 and 1 in 3000, respectively. Further, both the above, namely, magnetoresistance MR (B, T) and Hall resistivity ρ_{H} (B, T) in Fe/Cr multilayers of variable Cr thickness have been interpreted very satisfactorily in terms of spin-dependent electrical transport [7] and quantum mechanical side-jump effect [8], respectively.

In conclusion, we presented here the fabrication of a physical property measurement system which is a low-cost apparatus, designed and built indigenously in India. The feasibility of a home-made 6.5 T superconducting magnet is also successfully demonstrated. The performance of the apparatus is tested by measuring Hall effect and magnetoresistance on various types of samples, up to 6.5 T between 4.2 and 300 K and is found to be as good as that of the commercial PPMS of quantum design. The second noteworthy feature is the use of a pair of high-T_c superconducting leads for energizing the magnet to reduce the liquid helium consumption. Lastly, all the details of the design are provided for possible replication.

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