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Development of a Cryogenic Synchrotron Magnet with High Purity Aluminium Coils

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Abstract

Small iron magnets with aluminium exciting coils varying in purity have been tested at 4.2 K and 20.4 K in magnetic fields up to 30 kG. Resistivity ratio and magnetoresistance results are reported for pancakes wound from aluminium ribbon. At 4.2 K the relative resistivity increase $\Delta\rho/\rho$ due to the magnetoresistance tends to a saturation value of 1.5 at 30 kG, independent of the sample purity which is given by the pancake resistivity ratio in zero field and was measured to be 8000 for the best and 1500 for the worst material investigated. At 20.4 K $\Delta\rho/\rho$ becomes purity dependent in contradiction to Kohler's rule and was found to be 3.6 for the best and 1.5 for the worst material at 30 kG.

Questions concerning the appropriate conductor material and configuration, temperature of operation and cooling performance are discussed.

Zusammenfassung

Kleine Eisenmagnete mit Erregerspulen aus Aluminium unterschiedlichen Reinheitsgrades wurden bei 4.2 K und 20.4 K in Magnetfeldern bis 30 kG getestet.

Ergebnisse zum Widerstandsverhältnis und Magnetowiderstand werden für Flachspulen aus Aluminiumband berichtet. Bei 4.2 K zeigt die relative Widerstandszunahme $\Delta\rho/\rho$ aufgrund des Magnetowiderstandes Sättigungstendenz bei dem Wert 1.5 in einem Feld von 30 kG, unabhängig von der Probenreinheit. Der Reinheitsgrad ist durch das Widerstandsverhältnis der Flachspule im Nullfeld bestimmt; 8000 wurde für das beste und 1500 für das schlechteste der untersuchten Materialien gemessen. Bei 20.4 wird $\Delta\rho/\rho$ im Widerspruch zur Kohler'schen Regel abhängig vom Reinheitsgrad: 3,6 für das beste und 1.5 für das schlechteste Material bei 30 kG.

Fragen, die sich auf das geeignete Leitermaterial und die Leiterkonfiguration, die Betriebstemperatur und die Kühlung beziehen, wurden diskutiert.

Introduction

The generation of high magnetic fields by conventional techniques leads to high ohmic losses in the coils, which are in the megawatt region for a big magnetsystem like a synchrotron of several 10 GeV. To reduce these losses, that is to reduce the conductor resistivity, two ways can be seen to date promising an economic improvement. These are to use either a superconductor or a normal conductor of high purity at low temperatures to achieve a remarkable decrease in resistance. For DC-magnets one would of course prefer a superconductor, but in a pulsed synchrotron magnet this is still an open question on account of the AC-losses in a superconductor, therefore a cryogenic normal conductor may be competitive in this case. The convenient conductor material for normal conducting cryomagnets is aluminium, which was proposed and used already by Danby et al. [1] for a cryomagnet. It can be purified by zone melting to a high degree thus giving a resistivity decrease of about four orders of magnitude between room temperature and 4.2 K. A second important reason for its applicability is the fact that the magnetoresistance approximately tends to a saturation value in high magnetic fields.

The well known data of high purity aluminium are not sufficient to construct a synchrotron bending magnet, because these data result from short sample measurements. There is little information about the behaviour of the resistivity ratio when the material is wound into a coil and powered in a magnet at low temperatures. Therefore we have built a small iron magnet of the window frame type with exciting coils of high purity aluminium to investigate questions which are of importance in the design of cryomagnets, such as problems concerning the resistivity ratio and cooling performance. We have chosen the window frame type magnet to attain high magnetic fields by low power consumption.

The experimental apparatus

Fig. 1 shows a cross section through the whole arrangement. The iron yoke of the small magnet is laminated for pulse experiments. Four pancakes of aluminium tape are mounted in the window of the iron yoke. In the middle and on both sides of the coil arrangement vertical cooling channels provide for a removal of the generated heat out of the interior of the coil by convection cooling in liquid helium or hydrogen. The magnet is suspended at a flange by means of thin stainless steel sticks and mounted in a metallic cryostat. Two radiation shields reduce the heat input. A styropor insulation fills the space between the shields and the wall of the cryostat, thus the evaporated helium flows through the electrical current leads cooling them at the same time.
The electrical current leads consist of a copper pipe with copper fins at the inner and outer side to lead the gas flow along the enlarged surface. A safety valve avoids a dangerous pressure rise in the vapor above the liquid. The central magnetic field is measured by a low temperature Hall generator*).
A flattened carbon resistor**) was embedded between two pancakes to observe the temperature rise in the coils by the decrease of its resistance. This resistor and a second one placed in the central magnetic field were parts of a symmetrical Wheatstone bridge in order to compensate partially the magnetoresistance of the carbon resistor.

Experimental results

The aluminium tape with 12 x 0.3 mm^2 in cross section was wound into pancakes by a simple winding machine. The pancakes have an inner and an outer diameter of 4 cm and of about 12 cm, respectively. The windings were insulated by a 25 µ thick Hostaphan foil.

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*) Siemens RHY 18
**)Allen Bradley resistor 100 Ω, 0.1 Watt

Four pancakes were put together to a magnet coil, electrically connected in series. Potential connections are installed at both ends of the exciting coil and at the connections between the individual pancakes to evaluate the resistance of the entire coil and of the four pancakes separately. The current was measured by the voltage drop of a normal resistor of $10^{-4}\Omega$. At our investigations we observed at low temperatures a remarkable contact resistance between the connections of the pancakes. Thus to get reliable potential measurements one had to prepare the potential connections carefully and had to place them away from the current contacts.

Fig. 2 shows the resistance of one pancake versus the central coil magnetic field at the temperatures of liquid helium and liquid hydrogen. The aluminum* of this pancake was purified by zone melting and annealed at $500^{o}C$ for one hour and cooled down for about 10 hours after having been cold rolled to the ribbon of the desired geometry. The resulting short sample resistivity ratio was about 9000. In the pancake we found a resistivity ratio of 8000. Due to the magnetoresistance the resistance of the pancake increases with increasing magnetic field. At 4.2 K the magnetoresistance tends to a saturation value. At 20.4 K the resistance shows no tendency towards saturation up to fields of about 30 kG and the magnetoresistance effect is obviously greater than at 4.2 K. The average increase of the resistance at a central field of about 20 kG amounts to a factor of 4.3 at 20.4 K. This latter result is not in agreement with Kohler's rule of the magnetoresistance given for aluminum by several authors [2]. Our results for aluminum indicate not only a temperature dependence of the magnetoresistance but also a dependence on purity.

Fig. 3 shows a Kohler plot at 4.2 K and 20.4 K for 3 aluminum tape wound pancakes differing in purity. The relative increase of the resistance $\Delta\rho/\rho$ in the self-field is plotted versus the argument $(\rho_{295}/\rho_T) \times H$ (H = central coil field) as it is usually done. These ribbons are heat treated in the same manner as

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* delivered by VAW, Bonn, Germany

mentioned above. In the upper curve it can be seen that at 4.2 K the experimental values of the different materials are grouped along a common mean curve. At 20.4 K, on the other hand, there are significant differences in the behaviour of the different materials, as shown in the lower curve. The magnetoresistance increases with increasing purity. At 20.4 K and for a field of 30 kG in the coil center we found a relative increase in resistance of 3.6 for the best material and 1.5 for the worst material investigated. The corresponding curve at 4.2 K is repeated for comparison and shows a noticeable lower magnetoresistance.

As our pancake measurements are performed in the self generated magnetic field we have to regard a temperature rise by the dissipated power which had an upper level of about 60 watts at 4.2 K and of 180 watts at 20.4 K. The temperature in the exciting coils approaches a stationary value within a minute. The observed increase of temperature was low, at 4.2 K in the order of $5 \cdot 10^{-2}$ K and at 20.4 K in the order of $5 \cdot 10^{-1}$ K (the absolute values of the temperature rise are not quite reliable as the carbon resistors were influenced by the magnetic field). At 4.2 K in the region of the residual resistance there is only a small influence of temperature rise on the resistance. From measurements of Dorey [3] the temperature increase in the heated coils should not exceed 0.3 K in the case of nucleate boiling being the common cooling condition in channels. At 20.4 K on the other hand the resistance has a strong dependence on temperature, thus a small temperature rise leads to an appreciable increase in resistance. Supposing Kohler's rule to be valid the observed additional resistance at 20.4 K and 30 kG for the material of highest purity corresponds to a temperature rise of 6 K according to a T^5-law temperature variation of the resistivity at 20.4 K. This value is too high in comparison with our experimental value. There is still another argument, which shows that our observation will be no heating effect. The material with the higher resistivity shows a smaller increase in resistance in spite of its higher Joule heating. In agreement with measuremnts of Borovik et al. [4]

there exists a considerable deviation from Kohler's rule for high purity aluminum at 20.4 K.

The short sample magnetoresistance effect will still be higher than our results show, as in our experimental arrangement we measured a magnetoresistance averaged over the decreasing magnetic field of the pancake.

Up to now we have tested the aluminum under DC-conditions, but in the next stage we will apply cyclic powering. To date we observed no change in the zero field resistance of the exciting coils after several magnetic cycles up to fields of about 30 kG. The magnetic pressure acting on the windings was calculated to be about 36 atm.

Discussion

We have used the high purity aluminum conductor in an arrangement comparable to that in a future technical application. The geometrical dimensions of the aluminum ribbon, especially the thickness of 0.3 mm, were chosen to keep the eddy current losses and the size effect small at 20.4 K, this means in a limit of 10% of the ohmic losses*. At 4.2 K these additional losses would be remarkable greater for the same ribbon because of its higher conductivity.

In our experimental apparatus we tried to generated magnetic fields as high as possibel. The power input in liquid helium was limited by the cooling performance of the cooling channels. At an electrical power of 59 watts in liquid helium we get a heat flow of 0.29 watts cm^{-2} through the walls of the cooling channels which corresponds to the critical heat flow for our channel length of about 9.5 cm measured by Wilson [5]. In liquid hydrogen we did not attempt to approach the upper limit of the cooling performance

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*The eddy current losses were calculated from the usual relation $P = (1/2\ 4)\cdot\sigma\ \omega^2\ d^2\ B^2$ [watts/cm^3] with the assumptions: central peak field 40 kG, $2\pi/\omega = 3$ sec period and a resistivity ratio $\sigma 20/\sigma 295$ of 1000.

for safety reasons. From ordinary theories of cooling in channels [5] one can expect a cooling capacity in liquid hydrogen ten times greater than in liquid helium because of the higher latent heat.

In the next stage we will build a window frame magnet for 40 kG with a length of 40 cm and an iron yoke saturated up to a magnetic flux density of 18 kG. The exciting coils will be cooled down together with the iron return yoke. The magnet will be placed vertically for applying convection cooling. From our present results we expect a power dissipation of about 350 watts at 20.4 K at a current density of about $4.5 \cdot 10^{+3}$ amps/cm^2. The winding section will be 4×10 cm^2 and the magnet gap will have a cross section of 4×7 cm^2.

In correlation with thermodynamical considerations our measurements indicate that liquid hydrogen is an economic cooling agent. The overall gain in power calculated from ordinary formulas* will be 12 at 20.4 K and 6.5 at 4.2 K. The temperature dependent magnetoresistance may lead to another optimal temperature. Therefore we will spent more attention to this problem in the next time by studying the temperature and purity behaviour of the magnetoresistance.

It is a difficult technical problem to bend the coil ends of a tape wound race track coil out of the coil plane. This is necessary for the applicability of a window frame magnet to get access to the magnet gap. We are studying technical possibilities of bending tape wound coils. Another way is to use a twisted and transposed cable of many insulated thin aluminum wires, also under study.

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* Thermodynamical gain $G = (\rho_{295}/\rho(T,H))\left(1 + \frac{1}{\zeta}\frac{T_o - T}{T}\right)^{-1}$. T_o is room temperature and ζ is the overall efficiency of the refrigerator relative to the ideal thermodynamic efficiency. It may be taken to be about 0.3 at 20.4 K and 0.15 at 4.2 K.

Literatur

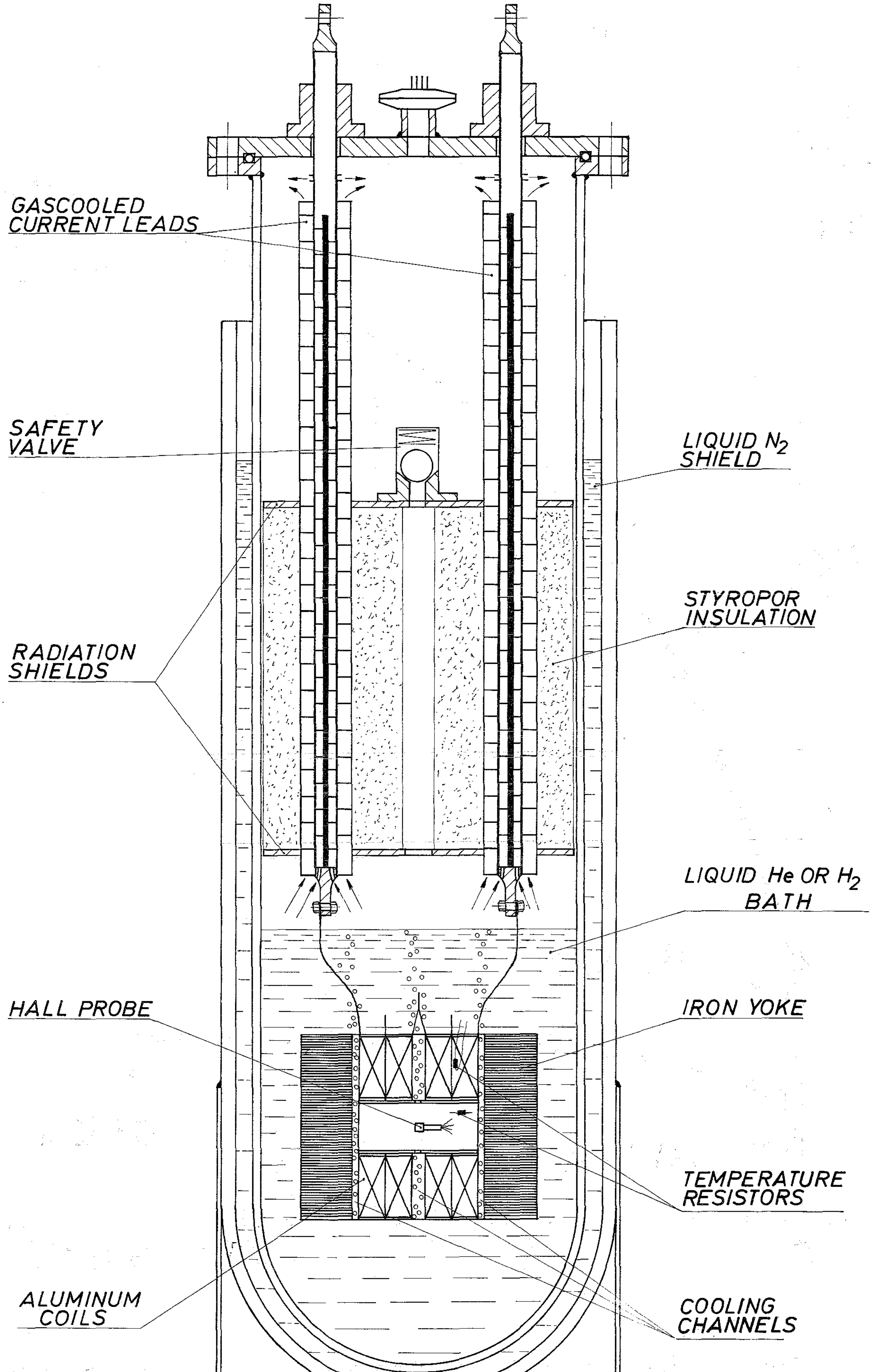
[1] J. Allinger, G. Danby, J. Jackson, I. Polk, A. Prodell
IEEE NS 16, 728 (1969)

[2] B. Lüthi, Helv. Phys. Acta 33, 161 (1960);
V. Arp, Brookhaven 1968 Summer Study, p. 1095

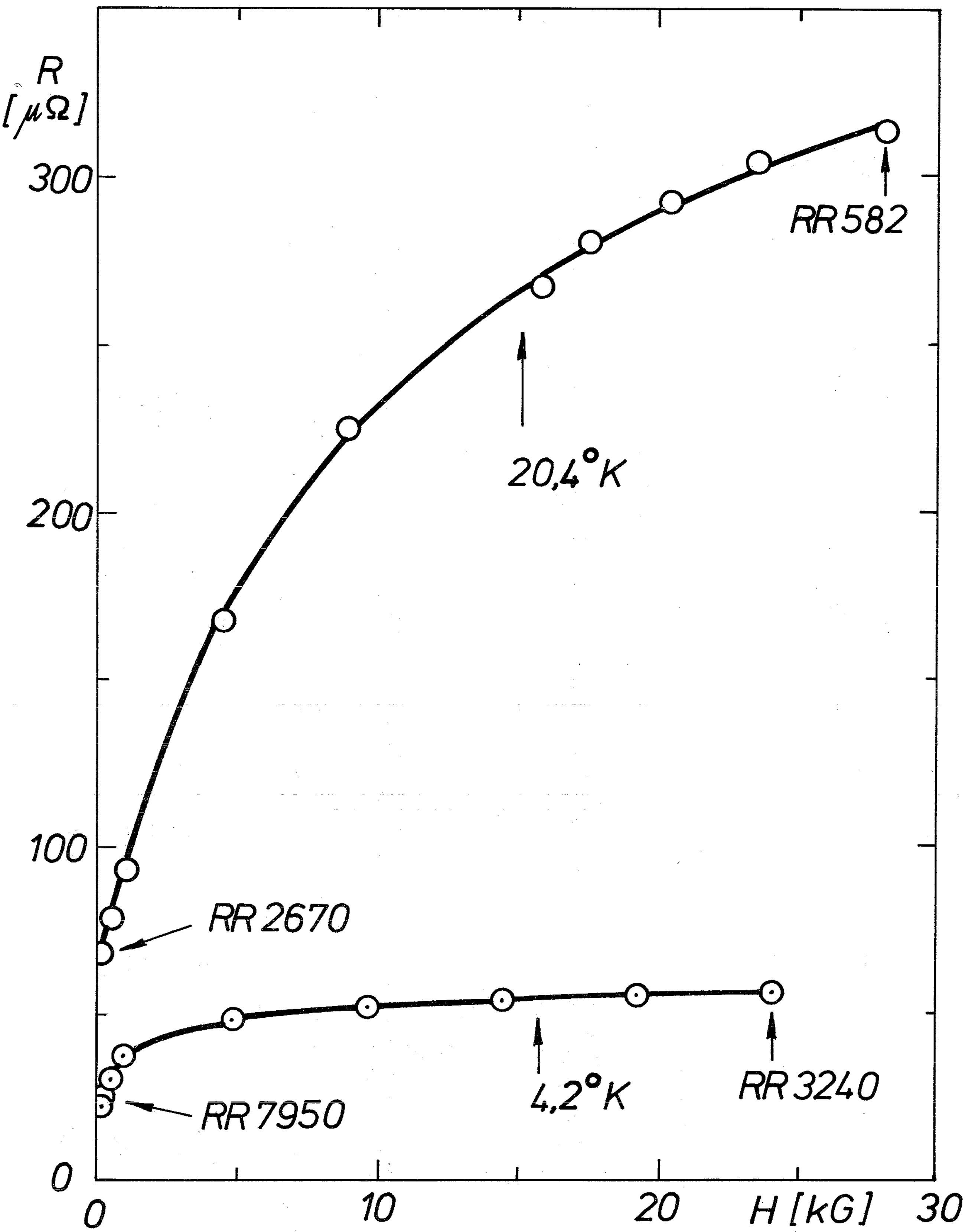
[3] A. P. Dorey, Cryogenics 5, 146 (1965)

[4] E.S. Borovik, V. G. Volotskaya, N. Ya. Fogel
J. Exp. Theor. Phys. (USSR) 45, 46 (1963)

[5] M.N. Wilson, Bull. I.I. R. Annex 5, 109 (1966)



<u>Fig.1:</u> Cross section through the experimental apparatus



<u>Fig.2:</u> The measured resistance of one pancake in various magnetic fields at the temperature of liquid helium and liquid hydrogen; RR = resistivity ratio $\rho_{295}/\rho_{T,H}$

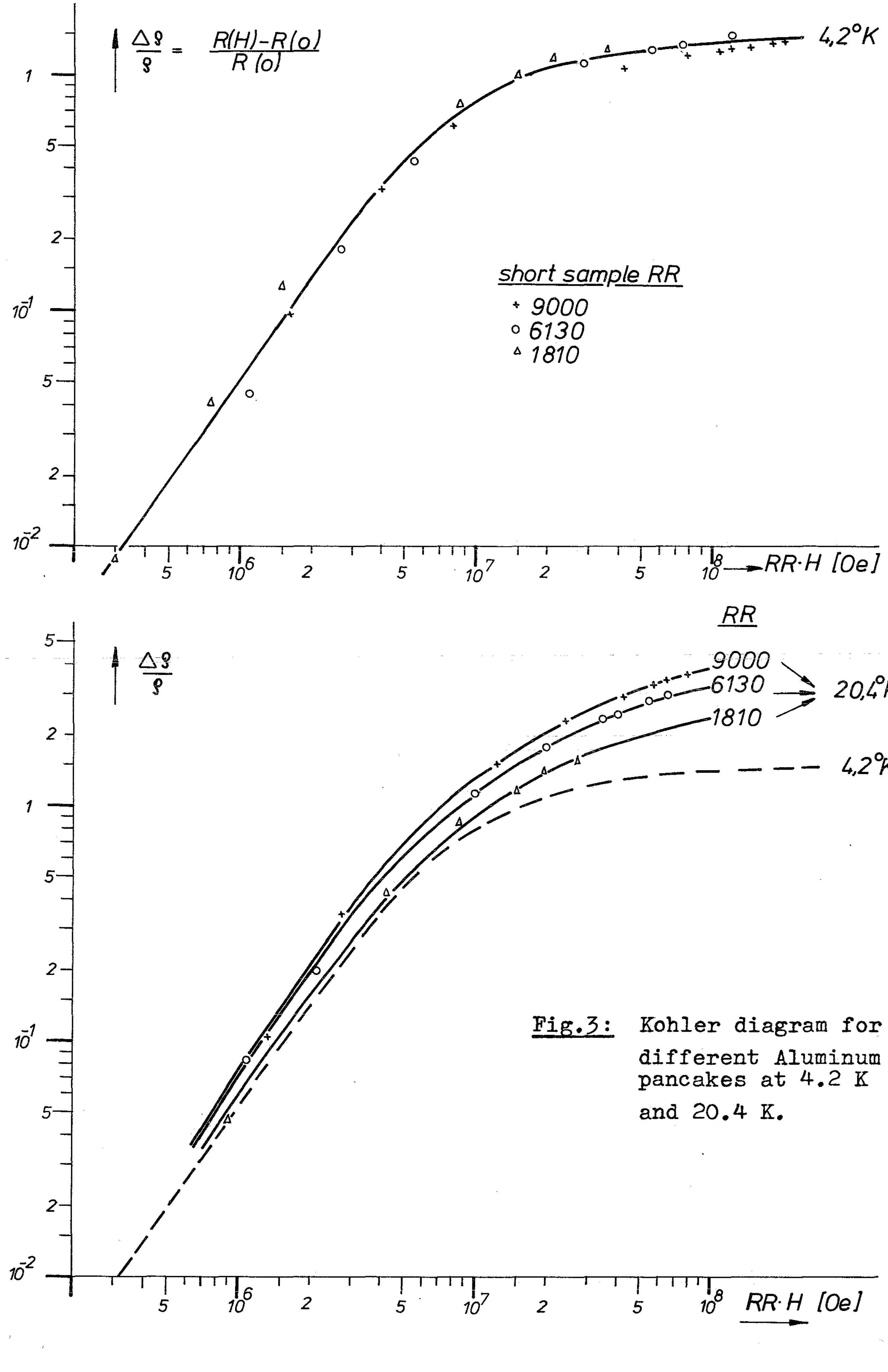


Fig.3: Kohler diagram for different Aluminum pancakes at 4.2 K and 20.4 K.