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The Amsterdam high-field facility

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Abstract

A description is given of the high-field facility at the University of Amsterdam. At present, two magnets are operational in which magnetic fields which are constant within 10^{-4} can be generated with a typical duration of 0.1 s. The maximum available field is 40 T and can be reached in only one of the magnets. In this magnet, experiments can be carried out at liquid-helium temperatures and at 77 K. The other magnet, in which fields up to 30 T can be generated, can be equipped with a variable-temperature cryostat in which any temperature between 1.5 K and room temperature can be stabilized, or with a pumped ^3He cryostat for temperatures down to 400 mK. The types of experiments that can be carried out in the Amsterdam high-field facility include magnetization and magnetotransport measurements at hydrostatic pressures up to 5 kbar, measurements of quantum oscillations in the De Haas–Van Alphen and Shubnikov–De Haas effects. Special dedicated techniques have been used for non-standard measurements, like for example, time-dependent magnetic relaxation, the quantum Hall effect in thin semiconducting layers, the influence of optical irradiation on galvanomagnetic effects in semiconductors. Within the Netherlands, the Amsterdam high-field facility and the high magnetic field laboratory at Nijmegen University, where static fields up to 30 T can be realized in a hybrid magnet system, have recently joined to form the Amsterdam–Nijmegen Magnet Laboratory (ANML).

1. Introduction

The facility for high magnetic fields at the University of Amsterdam has been initiated in 1959 by G.W. Rathenau. In 1964, the first magnet with a maximum field of 20 T came into operation. In the same year, the design of a much improved magnet was started [1]. In 1969, this new magnet, capable of reaching fields up to 40 T which are constant within 10^{-4} during 0.1 s, became operational [2]. Since that time, the installation has been improved considerably. The maximum field, however, is still 40 T [3–5].

2. Principles of operation

The magnet is not energized from a stored energy source (e.g. capacitors) but from a thyristor convertor

coupled via a transformer to a 10 kV line from the mains (Fig. 1). The transformer can be overloaded during a time of the order of 1 s and delivers then a DC power of 5.8 MW on the magnet, which is about 10 times its continuous rating. The Joule heat, generated in the magnet winding, cannot be removed during the field pulse. Therefore, the coil heats up from its initial temperature of about 25 K, and its resistance increases about exponentially as a function of time. After a short time, the resistance has become so high that the convertor can no longer maintain the current, the coil still being at a cryogenic temperature of about 120 K. At this moment, the field has to decrease; the voltage of the rectifier can be reversed in order to remove the field (and the stored magnetic energy) from the coil as fast as possible, or the magnet terminals can be crow-barred by a thyristor in order to obtain a completely ripple-free slowly decaying field (Fig. 2). Before another pulse can be generated, the coil has to

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Fig. 1. Schematic overview of the thyristor convertor, the coil and the feedback circuit.

Fig. 2. Part of a recording of a De Haas–Van Alphen measurement on GdIn₃. The almost straight line represents the magnetic field, which is very smooth because the current decays freely through a thyristor parallel to the magnet coil. The wobbly curve is the almost true dHvA signal. At about 30 T is the spin flop transition, the frequencies on both sides of the transition are different.

be cooled to its initial temperature. The magnet coil can be cooled in two stages: first with liquid nitrogen to a temperature below 100 K, and subsequently down to 25 K, with liquid neon as a heat-exchange medium. To this end, neon gas in a closed system is condensed in

a cryogenerator. This liquid neon drips down into the magnet and evaporates there (Fig. 3). Since the energy converted into heat during a 40 T pulse amounts to nearly 1 MJ, the cryogenerator with its capacity of 150 W needs nearly 2 h to remove this heat. However, for pulses lower than 40 T, the cooling time is considerably shorter. The total energy is increasing about exponentially as a function of $\int J^2 dt$, where J is the current density, because of the increase of resistivity as a function of temperature. The heat generated in a maximum field of 20 T, for instance, needs only 20 min before it has been removed.

Fig. 3. Overview of the (Stirling type) cryogenerator, the neon filled heat-pipe and the magnet cryostat.

The maximum obtainable field, in our case 40 T, is limited by the huge Lorentz forces, which try to let the coil explode. These forces give rise to stresses in the windings proportional to the square of the field intensity and largely independent of the volume or the shape of the coil. If we require that the coil itself must survive many pulses of maximum intensity, we must be certain that the copper windings deform only elastically during the pulses because repeated plastic flow results in irreversible damage in the coil. The necessary internal stresses are set up by plastic deformation during the first pulse. The maximum field for a coil, wound from hard-copper band with a yield strength of about 400 MPa, is with this limitation about 40 T. Higher fields will need a much stronger material for the wires. In general, however, such a material has a much higher electrical resistivity, so that the power needed for fields above 40 T becomes soon tremendously high. Roughly speaking, one could say that every increase of the maximum field with 6 T doubles the minimum needed power [6]!

An advantage of our design over continuous-service coils is, that in the coil no cooling channels are necessary, so that a higher filling factor and a more rigid construction can be realized. Furthermore, the needed cooling capacity is reduced by a factor of 1000 or more. Besides this, the power supply can be much simpler and therefore less expensive than a supply which is able to deliver the same power during longer periods, and the energy used for the production of the magnetic fields stays negligible.

The advantage of our system over more conventional pulsed coils, using energy storage in a capacitor bank, is firstly that the pulse duration can be considerably larger: about 1 s in our case, compared to 1–10 ms. Secondly, it is possible for us to *regulate* the field, whereas with truly-pulsed coils the time dependence of the field is essentially half a sine wave. For instance in samples from a pure metal with a diameter of about 3 mm, the time constant for the decay of eddy currents induced by the changes of the field may, at liquid helium temperature, is of the order of 10 ms. Therefore, high-precision magnetic measurements require a field which is really constant during 50–100 ms. In the case of first-order phase transitions the speed of the change in field can be controlled in order to determine carefully the intrinsic hysteresis.

3. Recent developments

Since 1986, the control and regulation of the field is fully computerized [7]. A particular pulse shape is stored in the memory of a computer. The field in the magnet is measured by a pick-up coil connected to an (analogous) electronic integrator, whose output drives a 16-bit AD-converter which is read out by the computer. During the

pulse, values of the actual field are compared with the stored reference values, the differences are used to regulate the rectifier with a feedback loop. The output voltage of the thyristor rectifier is controlled by shifting the ignition moments of the various thyristors with respect to the phase of the mains frequency. This means that the necessary feed-back loop is not continuous, but only active at certain times, when a next thyristor has to be ignited. Therefore, with too high a gain, the system will always be unstable. However, using a low gain in the feed-back loop makes that the large increase in resistance of the coil introduces a considerable decrease of the current. We succeeded in designing an algorithm for the field-regulating computer which circumvents these difficulties; the resulting regulation is stable, fast (transients no longer than 10–20 ms) and accurate within 10^{-4} .

Nearly any pulse shape, i.e. a programmed field as a function of time, can be chosen by the user from a large library of field profiles. Moreover, he can construct his own field profiles if he desires so. The only limitations are the maximum field (40 T), the maximum slope of the field as limited by the maximum voltage of the convertor and the self-inductance of the coil (± 200 T/s), and the ohmic resistance of the coil as dependent on its temperature, which limits the obtainable field. 40 T can only be reached when the coil is very cold, at the start of the field profile. The increasing resistance of the coil during the pulse makes it impossible to program a field profile which gradually builds up to 40 T.

Up till now, we limit ourselves to field profiles consisting of several different constant fields. Very popular among the users are step-wise pulses in which consecutively constant fields (e.g. 35, 30, 25, ..., 5 T) (Fig. 4) are generated, separated by quick transitions. Each constant-field period has a duration of typically 60–70. Also “sloped” fields, increasing or decreasing linearly with time, are used. More complicated profiles, for instance a field which is a quadratic or hyperbolic function of time, can in principle be generated with only slight modifications to the regulation software. During the pulse, the values of the actual field and of the measured quantity (e.g. the magnetic moment of a sample) are stored. In most cases a low rate of data sampling (300 points/s) is sufficient; for fast changing signals, as obtained, for instance, during a measurement of the De Haas–Van Alphen effect, the sampling rate can be enhanced to 50 000 points/s. After the pulse, the (binary) data are read from the memory, converted to a more suitable format, and written to a file, which can subsequently be analyzed by one or more dedicated programs, depending on the type of measurement.

It was experienced as inefficient that the facility could not be used during the time that one has to wait for the cooling of the coil. Since we were in the possession of

Fig. 4. Longitudinal magneto resistance of single-crystalline UNiGe along the *b*-axis. Most of the disturbances due to the changing field decay during the time the field is constant.

a spare coil, which probably will not be needed, we decided some years ago to install this spare coil in the same room, and connect it to the same power supply and measuring and regulating computer. The switching of the power between the two coils is done automatically with two power thyristors, one of which is conducting. Unfortunately, we do not possess a spare cryogenerator. Therefore, this second coil, which is identical to the first one, is now cooled with liquid nitrogen only. Since its ohmic resistance remains too high for the highest fields, this spare coil is able to generate fields up to 30 T only. It is, however, a very welcome addition to the facility, since many measurements, among them preliminary ones, do not require a field of 40 T and can therefore be done in the 30 T coil, while at the same time other measurements in the 40 T coil are being done. We provide this new coil with a helium bath cryostat. A variable temperature insert allow measurements at any temperature between 4.2 K and room temperature. An insert with pumped ^3He can realize temperatures as low as 400 mK.

4. Experimental set-ups

The types of experiments that can be carried out in the Amsterdam high-field facility can roughly be divided into four groups:

(A) Magnetization measurements, mostly done on metallic specimens. The sample consists of bulk material or powder that fits into a cylindrical teflon sample holder of 3 mm diameter and 15 mm length. The magnetic moment

is measured with a special pick-up coil described elsewhere [8], which is insensitive to all fields generated by currents *outside* the pick-up coil, but has a high and homogeneous sensitivity for magnetic matter *inside* the coil. The signal from the pick-up coil is still for the largest part caused by the change of the field, and not by the change of the very small magnetic moment of the sample. The first-mentioned contribution can, however, be subtracted in an analogous way before the remaining signal is integrated with a special low-noise electronic integrator. The output of this integrator is digitalized with a 16-bit ADC and sent to the computer. In this way, changes of the magnetic moment can be detected with a resolution of about $5 \times 10^{-6} \text{ Am}^2$. In order to measure small change in saturated ferromagnetic samples one can measure with the integrator at very high sensitivity. To avoid overload under this condition the sample is saturated in a weak field (of e.g. 1.3 T) before the integrator is connected.

(B) Galvanomagnetic measurements. Up till now, magnetoresistance and Hall effect are being measured with essentially the same set-up in which two current wires and two voltage wires are connected to a conducting specimen. Changes of the DC voltage down to $0.5 \mu\text{V}$ can be detected within the “noisy” surrounding of an energized magnet coil, if special care is taken that neither the sample nor the voltage wires can move during the pulse and the enclosed flux is reduced to a strict minimum.

(C) The De Haas–Van Alphen effect can be measured very accurately if the magnet coil is crow-barred after it has reached the highest field. In the nearly exponential

decrease of the field, the noise level is much lower than when the convertor is operating. The De Haas–Van Alphen signal is measured with a very small (not very well compensated) measuring coil and a special analogous integrator. Since we are in this case interested only in relatively high frequencies, this integrator rejects very low frequencies and is therefore less easily overloaded.

(D) Special dedicated techniques have been used for non-standard measurements, as, for example, time-dependent magnetic relaxation, the quantum Hall effect in semiconducting thin layers, the influence of optical irradiation on galvano-magnetic effects in semiconductors, etc.

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