3.

Magnetic field inside Helmholtz coil arrangement

Related Topics

Maxwell's equations, wire loop, flat coils, Biot-Savart's law, Hall effect.

Principle

The spatial distribution of the field strength between a pair of coils in the Helmholtz arrangement is measured. The spacing at which a uniform magnetic field is produced is investigated and the superposition of the two individual fields to form the combined field of the pair of coils is demonstrated.

Equipment

1	Pair of Helmholtz coils	06960.00
1	Power supply, universal	13500.93
1	Digital multimeter	07134.00
1	Teslameter, digital	13610.93
1	Hall probe, axial	13610.01
2	Meter scale, demo, l = 1000 mm	03001.00
1	Barrel base -PASS-	02006.55
1	Support rod -PASS-, square, l = 250 mm	02025.55
1	Right angle clamp -PASS-	02040.55
3	G-clamp	02014.00
1	Connecting cord, l = 750 mm, blue	07362.04
3	Connecting cord, l = 750 mm, red	07362.01

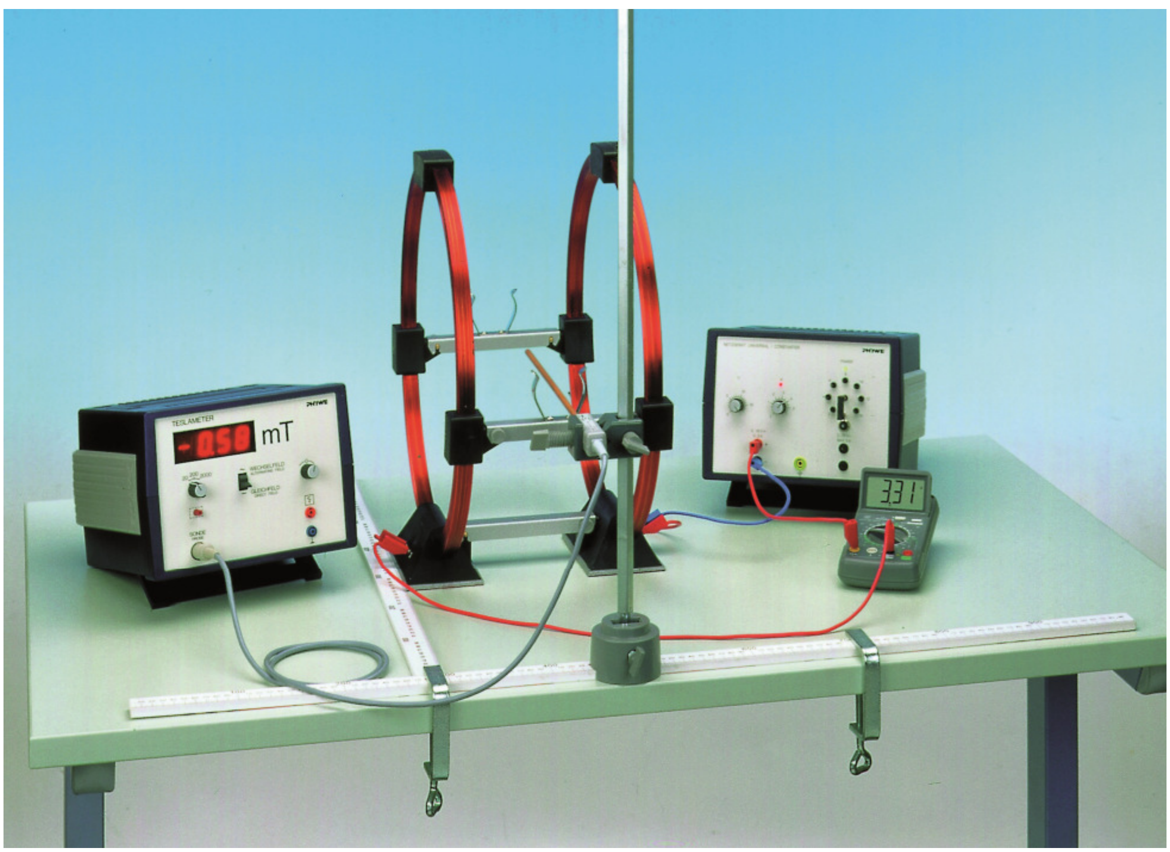

Fig. 1: Set-up of experiment P2430301

Tasks

1. Measure the magnetic flux density along the z-axis of the flat coils when the distance between them $a = R$ (R = radius of the coils) and when it is greater and less than this.
2. Measure the spatial distribution of the magnetic flux density when the distance between coils $a = R$, using the rotational symmetry of the set-up:
   a. measurement of the axial component B_z
   b. measurement of radial component B_r
3. Measure the radial components B_r‘ and B_r’’ of the two individual coils in the plane midway between them and to demonstrate the overlapping of the two fields at $B_r = 0$.

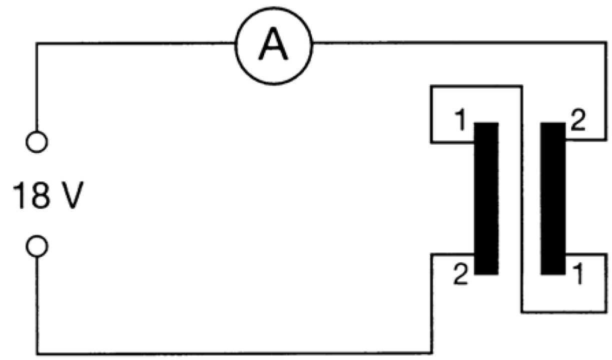

Fig. 2: Wiring diagram for Helmholtz coils.

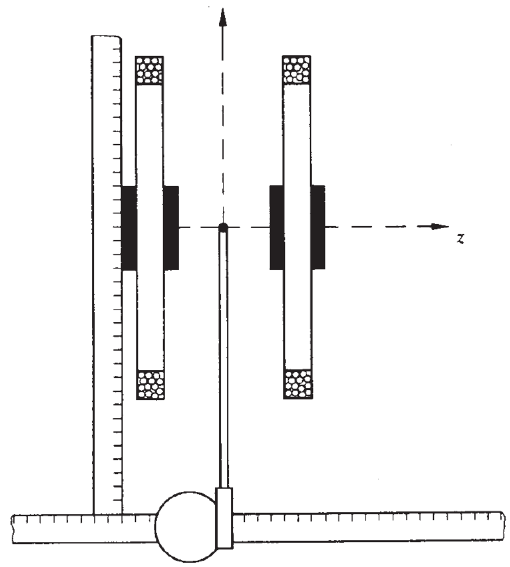

Fig. 5: Measuring B_r (z, r).

Set-up and Procedure

Connect the coils in series and in the same direction, see Fig. 2; the current must not exceed 3.5 A (operate the power supply as a constant current source). Measure the flux density with the axial Hall probe (measures the component in the direction of the probe stem).

The magnetic field of the coil arrangement is rotationally symmetrical about the axis of the coils, which is chosen as the z-axis of a system of cylindrical coordinates (z, r, Φ). The origin is at the centre of the system. The magnetic flux density does not depend on the angle Φ, so only the components B_z (z, r) and B_r (z, r) are measured.

Clamp the Hall probe on to a support rod with barrel base, level with the axis of the coils. Secure two rules to the bench (parallel or perpendicular to one another, see Figs. 3–5). The spatial distribution of the magnetic field can be measured by pushing the barrel base along one of the rules or the coils along the other one.

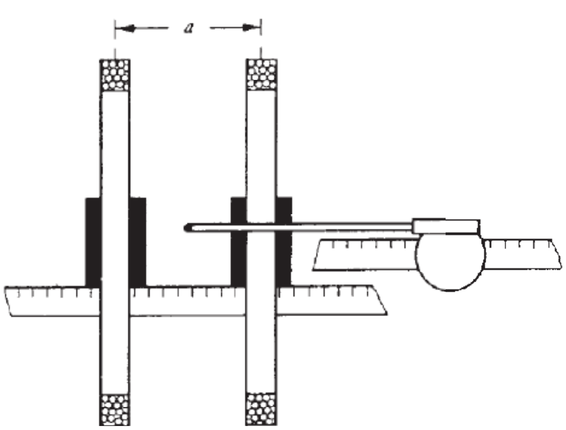

Fig. 3: Measuring B (z, $r = 0$) at different distances a between the coils.

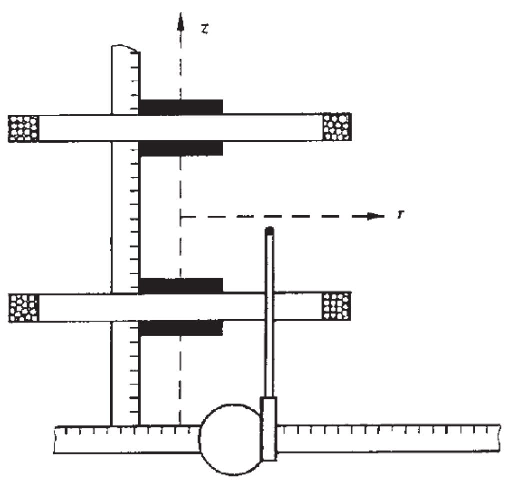

Fig. 4: Measuring B_z (z, r).

Notes

Always push the barrel base bearing the Hall probe along the rule in the same direction.

1. Along the z-axis, for reasons of symmetry, the magnetic flux density has only the axial component B_z. Fig. 3 shows how to set up the coils, probe and rules. (The edge of the bench can be used instead of the lower rule if required.) Measure the relationship B (z, r = 0) when the distance between the coils $a = R$ and, for example, for $a = R/2$ and $a = 2R$.
2. When distance $a = R$ the coils can be joined together with the spacers. a) Measure B_z (z, r) as shown in Fig. 4. Set the r-coordinate by moving the probe and the z-coordinate by moving the coils. Check: the flux density must have its maximum value at point (z = 0, r = 0). b) Turn the pair of coils through 90° (Fig. 5). Check the probe: in the plane z = 0, B_z must = 0.
3. Short-circuit first one coil, then the other. Measure the radial components of the individual fields at z = 0.

Theory and evaluation

From Maxwell's equation

$$\oint_K \vec{H} d\vec{s} = I + \int_F \int \vec{\dot{D}} d\vec{f} dt \qquad (1)$$

where K is a closed curve around area F, we obtain for direct currents ($\dot{D}$= 0), the magnetic flux law

$$\oint_K \vec{H} d\vec{s} = I \qquad (2)$$

which is often written for practical purposes in the form of Biot-Savart's law:

$$d\vec{H} = \frac{I}{4\pi} \frac{d\vec{l} \times \vec{\rho}}{\rho^3} \qquad (3)$$

where $\vec{\rho}$ is the vector from the conductor element $d\vec{l}$ to the measurement point and $d\vec{H}$ is perpendicular to both these vectors.

The field strength along the axis of a circular conductor can be calculated using equation (3). (Fig. 6).

The vector $d\vec{l}$ is perpendicular to, and $\vec{\rho}$ and $d\vec{H}$ lie in, theplane of the sketch, so that

$$dH = \frac{I}{4\pi\rho^3} dl = \frac{I}{4\pi} \cdot \frac{dl}{R^2 + z^2} \qquad (4)$$

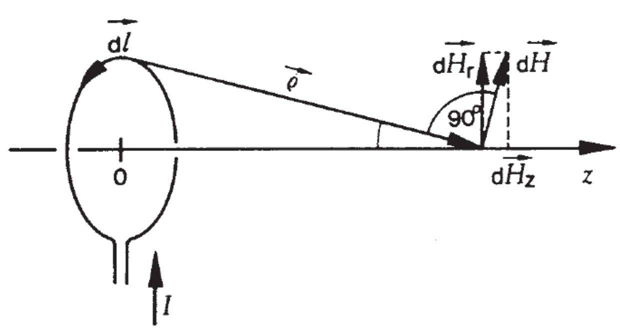

Fig. 6: Sketch to aid calculation of the field strength along the axis of a wire loop.

$\mathrm{d}\vec{H}$ can be resolved into a radial $\mathrm{d}H_r$ and an axial $\mathrm{d}H_z$ component. The $\mathrm{d}H_z$ components have the same direction for all conductor elements and the quantities are added; the $\mathrm{d}H_r$ components cancel one another out, in pairs. Therefore,

$$H_r = 0 \tag{5}$$

and

$$H = H_z = \frac{I}{2} \cdot \frac{R^2}{(R^2 + z^2)^{3/2}} \tag{6}$$

along the axis of the wire loop, while the magnetic flux density

$$B(z) = \frac{\mu_0 \cdot I}{2R} \cdot \frac{1}{\left(1 + \left(\frac{z}{R}\right)^2\right)^{3/2}} \tag{7}$$

The magnetic field of a flat coil is obtained by multiplying (6) by the number of turns N. Therefore, the magnetic flux density along the axis of two identical coils at a distance α apart is

$$B(z, r = 0) = \frac{\mu_0 \cdot I \cdot N}{2R} \cdot \left(\frac{1}{\left(1 + {A_1}^2\right)^{3/2}} + \frac{1}{\left(1 + {A_2}^2\right)^{3/2}} \right) \tag{8}$$

where

$$A_1 = \frac{z + \alpha/2}{R}, \quad A_2 = \frac{z - \alpha/2}{R}$$

When $z = 0$, flux density has a maximum value when $\alpha < R$ and a minimum value when $\alpha > R$. The curves plotted from our measurements also show this (Fig. 7); when $\alpha = R$, the field is virtually uniform in the range

$$-\frac{R}{2} < z < +\frac{R}{2}$$

Magnetic flux density at the mid-point when $\alpha = R$:

$$B(0.0) = \frac{\mu_0 \cdot I}{2R} \cdot N \cdot \frac{2}{\left(\frac{5}{4}\right)^{\frac{3}{2}}} = 0.716\, \mu_0 \cdot N \cdot \frac{I}{R}$$

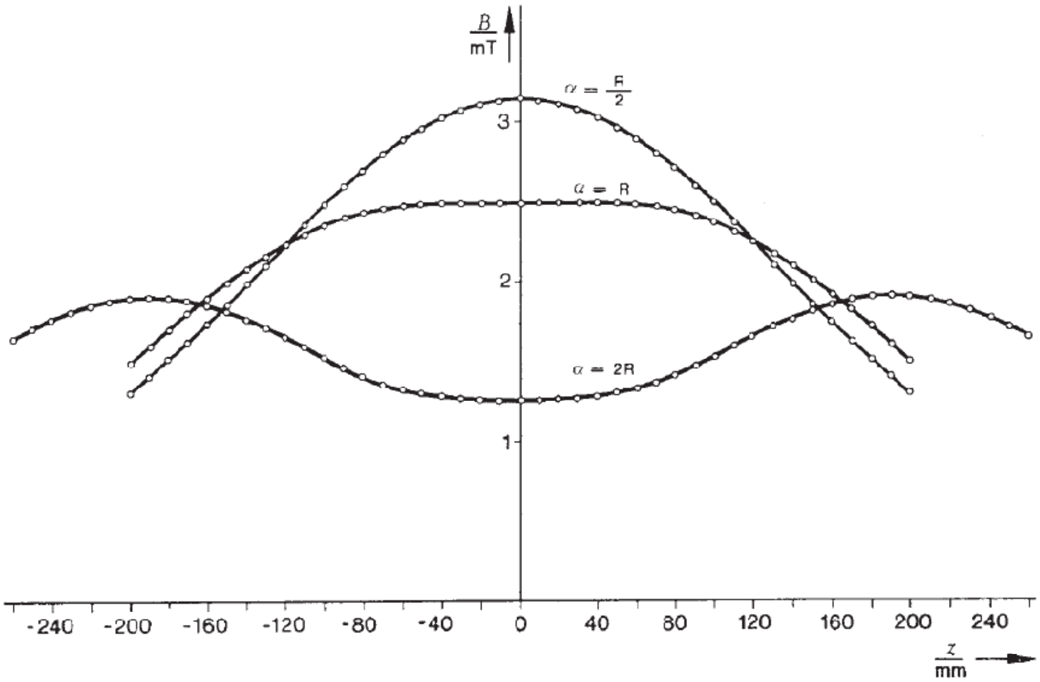

Fig. 7: B (r = 0) as a function of z with the parameter α.

when N = 154, R = 0.20 m and I = 3.5 A this gives:

B (0.0) = 2.42 mT.

Our measurements gave B (0.0) = 2.49 mT.

Figs. 8 and 9 shows the curves B_z (z) and B_r (z) measured using r as the parameter; Fig. 10 shows the super-position of the fields of the two coils at B_r = 0 in the centre plane z = 0.

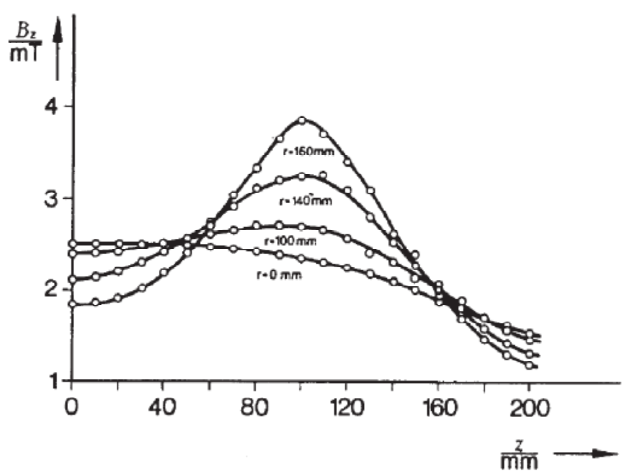

Fig. 8: B_z (z), parameter r (positive quadrant only).

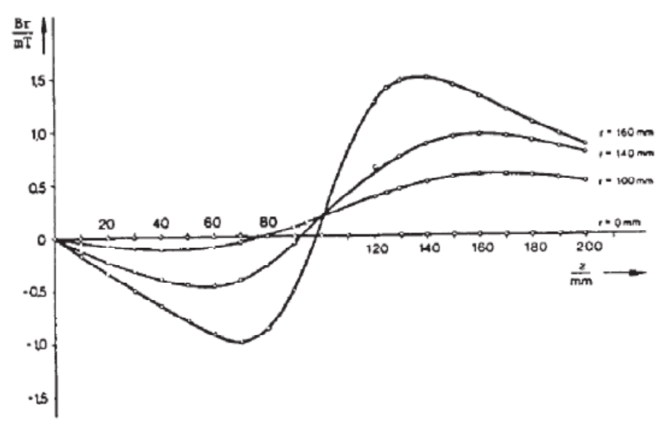

Fig. 9: B_r (z), parameter r (positive quadrant only).

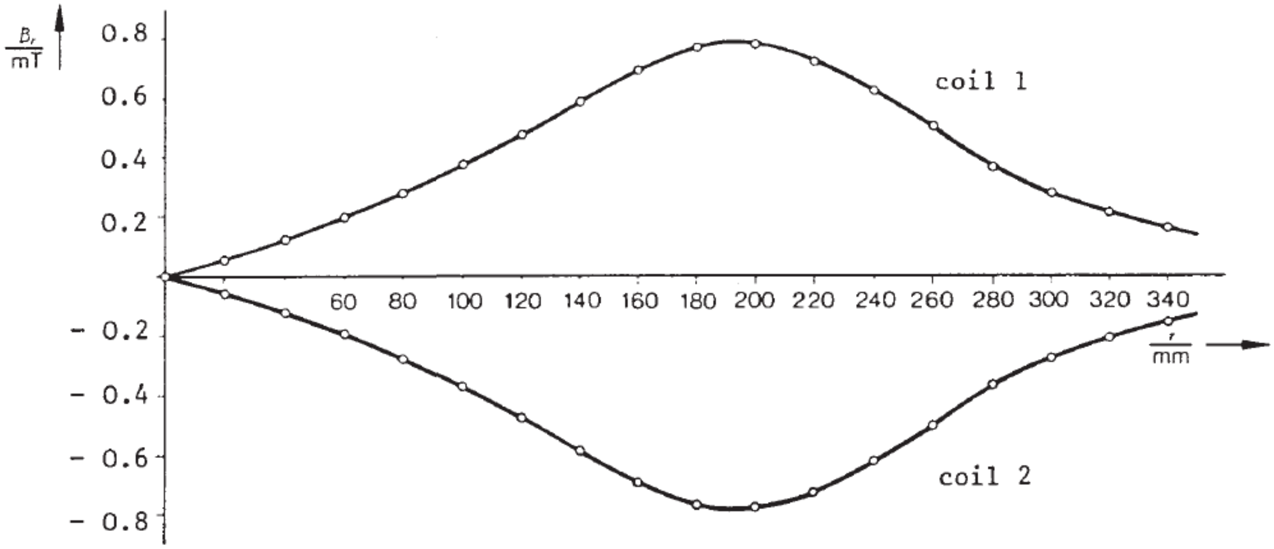

Fig. 10: Radial components $B_r'(r)$ and $B_r''(r)$ of the two coils when $z = 0$.

Teslameter, digital
Hall probe, axial
Hall probe, tangential

13610-90…99
13610-01
13610-02

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Operating instructions

The unit complies with the corresponding EC guidelines.

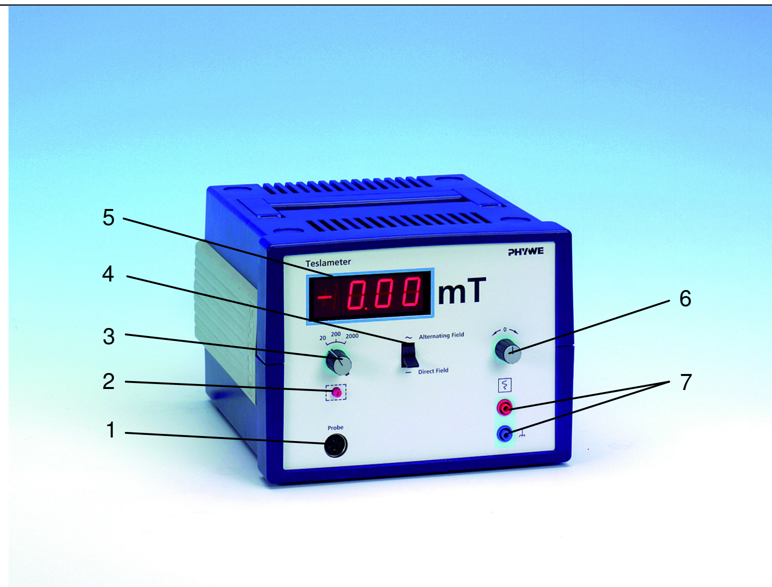

Fig. 1: 13610-90…99 Front view of the Teslameter, digital

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1 SAFETY PRECAUTIONS

Caution!

- Carefully read these operating instructions before operating this instrument. This is necessary to avoid damage to it, as well as for user-safety.
- Check that your mains supply voltage corresponds to that given on the type plate fixed to the instrument.
- Install the instrument so that the on/off switch and the mains connecting plug are easily accessible.
- Do not cover the ventilation slits.
- Only use the instrument in dry rooms in which there is no risk of explosion.
- Only use the instrument for the purpose for which it was designed.

2 PURPOSE AND CHARACTERISTICS

The teslameter is suitable for measuring magnetic flux density (induction) *B* accurately. Two hall probes are supplied for use as sensors. One of them is specially designed for measuring fields oriented axially in relation to its rod-shaped stem (axial probe, order no. 13610-01). It is suitable for measuring fields inside coils for instance. The stem is 30 cm long to allow measurements to be taken easily even in the middle of long coils. The second probe measures fields perpendicular to its stem (tangential probe, order no. 13610-02), which is extremely thin and flat for measurements in narrow air gaps down to about 1 mm.
The meter has 3 switchable measuring ranges:

0 to…20 mT (accuracy 0.01 mT)
0 to…200 mT (accuracy 0.1 mT)
0 to…1000 mT (accuracy 1 mT)

3 FUNCTIONAL AND OPERATING ELEMENTS

The plugs for connecting the mains lead supplied with the meter and the power switch are to be found on the back of the meter.
Fig. 1 shows the teslameter with the controls and functional elements on the front panel:

1 *Input*
socket for connecting the hall probes 13610-01 and 13610-02.
2 *Adjusting screw*
for rough zeroing.
3 *Stepping switch*
for selecting the measuring range.
4 *Changeover switch*
for selecting the „ALTERNATING FIELD“ and „DIRECT FIELD“ measurement modes.
5 *Digital display*
for displaying the values measured. 3 digit display with sign for the direction of the field and decimal point.
6 *Adjusting knob* for fine zeroing
7 *Output*
for connecting an external measuring instrument, e.g. a recorder. Output voltage: 1 mV per digit.

4 HANDLING

The teslameter is connected to the AC mains with the lead supplied and switched on with the power switch on the back of the case. Changing the primary safety fuse: The fuse holder is in the upper part of the mains socket of the instrument, and so is only accessible when the connecting cord is not plugged in. Unplug the connecting cord, open the fuse holder using a screwdriver, take out the defect fuse and replace it with a new one (first check the specification of this against the data on the type plate), then fit the fuse holder back in the mains socket.
Should this fuse blow when the instrument is switched on, never replace it with a more resistant fuse! A defect is indicated and the instrument must be returned to the Phywe service department for repair.

4.1 Using the probes

The component of the magnetic induction in the direction of the axis of the probe is measured with the axial probe. The measuring point is right at the end of the stem. The direction of direct fields can also be detected: if the field is directed towards the handle of the probe (e.g. in front of the north pole of a bar magnet) the value displayed is positive, whereas it is negative when the field is in the opposite direction.
The tangential probe is provided with a protective tube that has to be removed before any measurements are taken. The Hall sensor is embedded in a flat plastic stem about 1 mm thick. Its position (measuring point) in the stem is clearly visible. In this case the component of the magnetic induction perpendicular to the face of the probe is measured. The direction of the field can also be detected when direct fields are being measured: a positive reading indicates that the field enters the probe from the direction of the surface of the handle that carries the nameplate, whereas a negative value indicates that the field has the opposite direction.
The probes generally have to be positioned accurately for precise measurement. They are easily held using a stand. The bosshead order no. 02040-55 is ideal. To avoid damaging them the probes should always be held by the metal tube provided for the purpose at the end of the handle rather than clamping the stem.

4.2 Zeroing

This procedure as described below is only necessary when direct fields are to be measured. In the case of alternating fields the meter is zeroed automatically within a few seconds, although a display of 1 digit (10^{-5} T) is unavoidable in the 20 mT range.
The mode switch (***4***) is to be brought into the „DIRECT FIELD“ (Gleichfeld) position. Once the hall probe selected for the measurement has been connected to input (***1***), but before any field is applied to it, the display is set on zero with the adjusting knob (***6***). Should this prove impossible the knob is turned to the middle position and the value displayed minimised by turning the adjusting screw (***2***) with a screwdriver; fine adjustment is then repeated with the adjusting knob (***6***).
We recommend zeroing in the most sensitive range (20 mT) to avoid the need for re-adjustment when higher ranges are subsequently selected.
It should be noted that the earth’s magnetic field alone can produce a reading of ± 4 digits (40 μT) in this range. If no compensation for this field is to be made during zeroing the zero adjustment knob is to be set so that turning the probe through 180° only results in the sign, and not the absolute value of the field strength displayed, changing.
When the fields of conductors carring a current are to be measured, before zeroing we recommend positioning the probe at the measuring point to be used with the magnetic field current switched off; this eliminates any interference from static stray fields at the same time.
When measuring in the 20 mT range zeroing is to be checked in the first few minutes after the meter is switched on and corrected if necessary. We recommend switching it on about ten minutes before starting to take measurements, by which stage zero drift is insignificant.

4.3 Measuring direct fields

Once the meter has been zeroed it is ready to take measurements. The mode switch (***4***) must be in the „DIRECT FIELD“ position. The value „1“ displayed without leading zeros indicates overranging and hence the need to switch to a higher range. The direction of the field is also indicated in this case.

4.4 Measuring alternating fields

The mode switch (***4***) is moved to the „ALTERNATING FIELD“ (Wechselfeld) position. The display returns to zero within a few seconds when there is no field acting on the probe. The meter is then ready for use immediately. It should be noted that in this mode the meter responds to changes in the field strength within about 3 s. The rms value of the value of the magnetic induction, which is assumed to be sinusoidal, is displayed. The meter is calibrated for an alternating field frequency of 50 Hz. However extremely accurate measurements are possible at frequencies of up to 500 Hz (limit frequency 5 kHz). The value „1“ displayed without leading zeros indicates overranging and hence the need to switch to a higher range. Positive values are always displayed in this mode. Turning the probe through 180° at a fixed measuring point does not affect the value displayed.

4.5 Using the analog output

External measuring instruments can be connected to the pair of 4 mm sockets (***7***). In addition to yt and xyt recorders possibilities include computer-aided measuring systems (e.g. COBRA3 Basic-Unit 12150-50).
The output voltage corresponds to the digital display. It is 1 mV per digit; the limits of the indicating range correspond to

the output voltage of ± 1.999 V (positive polarity only with alternating field measurements). The measuring instrument connected should have an internal resistance of at least 20 kΩ.

5 NOTES ON OPERATION

This high-quality instrument fulfills all of the technical requirements that are compiled in current EC guidelines. The characteristics of this product qualify it for the CE mark.

This instrument is only to be put into operation under specialist supervision in a controlled electromagnetic environment in research, educational and training facilities (schools, universities, institutes and laboratories).

This means that in such an environment, no mobile phones etc. are to be used in the immediate vicinity. The individual connecting leads are each not to be longer than 2 m.

The instrument can be so influenced by electrostatic charges and other electromagnetic phenomena that it no longer functions within the given technical specifications. The following measures reduce or do away with disturbances:

Avoid fitted carpets; ensure potential equalization; carry out experiments on a conductive, earthed surface, use screened cables, do not operate high-frequency emitters (radios, mobile phones) in the immediate vicinity. Following a blackout failure, operate the on/off switch for a reset.

6 TECHNICAL DATA (TYPICAL FOR 25°C)

Operating temperature range 5...40°C	
Relative humidity < 80%	
Measuring range	10-5 to1 T
Indicating range	10-5 to 2 T
Accuracy	
Direct field	± 2%
Alternating field 50 to 500 Hz	± 2%
Alternating field 500 to 1000 Hz	± 3%
Material of the Hallsensors	GaAs, monocrystalline
Temperature coefficient	
(10 to 40°C)	≤ 0.04%/K
Limit frequency	
(measurement of alternating field)	5 kHz
Analog output	
Voltage range	0 to ± 2 V
Calibration factor	1 mV/digit
Protection class	I
Connecting voltage	see type plate
(+6%/-10%)	
Mains frequency	50/60 Hz
Power consumption	10 VA
Mains fuse	see type plate
(5 mm x 20 mm)	
Case dimensions	225 x 235 x 170 mm
Weight	approx. 3.75 kg
Hall probe, axial	
Probe length (without handle)	300 mm
Diameter of the stem	6 mm
Weight	approx. 0.38 kg
Hall probe, tangential	
Dimensions of the stem	
(without handle)	75 x 5 x 1 mm
Weight	approx. 0.20 kg

7 EXPERIMENTAL LITERATURE

Handbook Laboratory Experiments Physics 16502-32

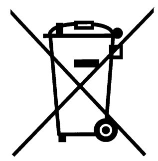
8 NOTES ON THE GUARANTEE

We guarantee the instrument supplied by us for a period of 24 months within the EU, or for 12 months outside of the EU. Excepted from the guarantee are damages that result from disregarding the Operating Instructions, from improper handling of the instrument or from natural wear.

The manufacturer can only be held responsible for the function and technical safety characteristics of the instrument, when maintenance, repairs and alterations to the instrument are only carried out by the manufacturer or by personnel who have been explicitly authorized by him to do so.

9 WASTE DISPOSAL

The packaging consists predominately of environmentally compatible materials that can be passed on for disposal by the local recycling service.



Should you no longer require this product, do not dispose of it with the household refuse.

Please return it to the address below for proper waste disposal.

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