Electricity

Magnetostatics
Effects of force in a magnetic field

Measuring the force acting on current-carrying conductors in the field of a horseshoe magnet

Objects of the experiment

■ Measuring the force acting on a current-carrying conductor in the magnetic field as a function of the current intensity.

■ Measuring the force acting on a current-carrying conductor in the magnetic field as a function of the conductor length.

■ Measuring the force acting on a current-carrying conductor in the magnetic field as a function of the angle between the magnetic field and the direction of the current.

■ Calculating the magnetic field.

Principles

Magnetic induction, or more simply the magnetic field B, is a vector quantity. A force is exerted on a given charge q moving with a velocity v in the magnetic field B, which depends on the magnitude and direction of the velocity and on the strength and direction of the magnetic field. The following relationship applies:

$$F = q \cdot (v \times B) \tag{I}$$

The so-called *Lorentz* force F is also a vector quantity acting perpendicular to the plane defined by v and B.

The force exerted on a current-carrying conductor in a magnetic field may be understood as the sum of the individual force components acting on the moving charge carriers which make up the current. In accordance with (I), the *Lorentz* force F acts on each individual charge carrier q moving with the drift velocity v. For a straight conductor, this means a total force of

$$F = q \cdot nAs \cdot (v \times B) \tag{II},$$

as the number of charged particles in the conductor is the product of the charge-carrier density n, the conductor cross-section A and the length s of the section of the conductor within the magnetic field.

It is common to introduce the vector s, which points in the direction of the conductor section. In addition, the product $qnAv$ is equivalent to the current I. Thus, the force of a magnetic field on a straight, current-carrying conductor segment is given by the equation

$$F = I \cdot (s \times B) \tag{III}$$

and the absolute value of the force by

$$F = I \cdot s \cdot B \cdot \sin\alpha \tag{IV},$$

whereby α is the angle between the magnetic field and the direction of the current.

In this experiment, rectangular conductor loops carrying currents of up to 20 A are placed in the horizontal magnetic field of a horseshoe magnet. The force acting on the horizontal section is measured. The forces acting on the two vertical sections cancel each other out.

The conductor loops are mounted on a force sensor. This contains a bending member to which strain gauges are mounted; the electrical resistance of these elements changes under load. The change in the resistance is proportional to the originating force. A connected newtonmeter measures the change in resistance and displays the corresponding force.

Title picture: schematic illustration of the force acting on a current-carrying conductor in a magnetic field

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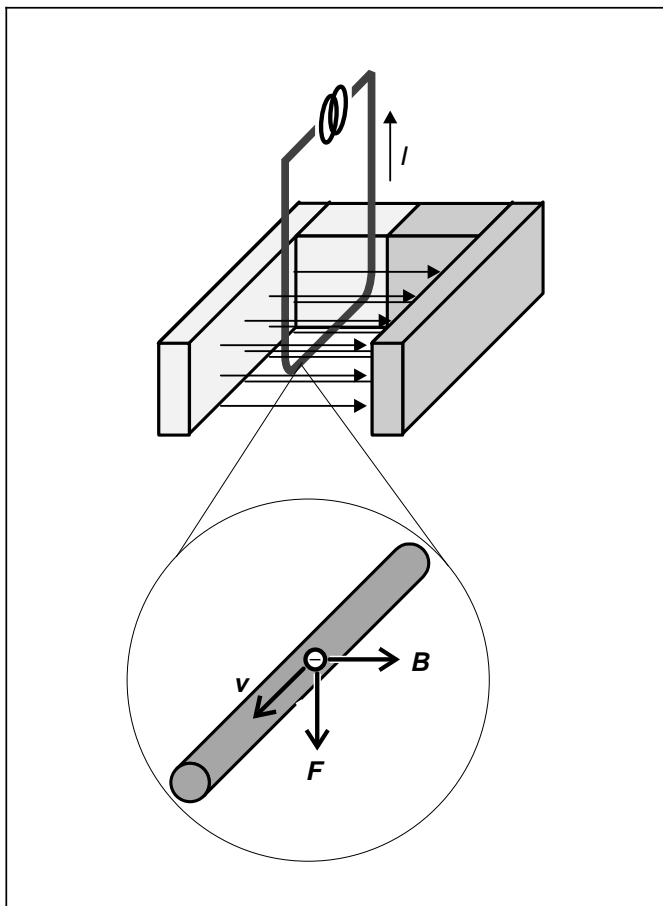
Apparatus

1 Horseshoe magnet with yoke	510 21
1 Force sensor	314 261
1 Set conductor loops for force measurement	516 34
1 Support for conductor loops	314 265
1 Newtonmeter	314 251
1 Multicore connecting cable, 6-pole	501 16
1 High current power supply	521 55
1 Stand base, small, V-shape	300 02
1 Stand rod, 47 cm	300 42
1 Leybold multiclamp	301 01

Connecting leads with conductor cross-section 2.5 mm^2

Setup and carrying out the experiment

Notes:

As the measurement quantity is very small, the measurement is easily affected by ambient interfering effects:
Avoid shocks, drafts and temperature variations in the vicinity.

The newtonmeter must warm up for at least 15 minutes before starting the experiment:
Switch on the newtonmeter with the force sensor connected using the mains switch on the rear of the device.

Subject the support and the conductor loops to loads of 20 A only for brief periods at a time (just a few minutes).

The magnetic field of the horseshoe magnet is not homogeneous:
For all measurements, center the conductor loop between the two arms of the magnet so that the effect of the magnetic field is as uniform as possible.

– Set up the experiment as shown in Fig. 1.

– To avoid short-circuits, make sure that the non-insulated cable sections of the support for conductor loops do not touch.

– Set the measuring range switch **(d)** on the newtonmeter to 2000.

The experiments are carried out using only the conductor loops without narrow section. The easiest way to set the current is to use only the current control knob **(b)**. The voltage control knob **(a)** is turned all the way to the right.

a) Measuring as a function of current:

– First, attach the 8 cm wide conductor loop to the force sensor.

– Turn the current control knob **(b)** all the way to the left and the voltage control knob **(a)** all the way to the right. Then switch on the high current power supply.

Fig. 1   Experiment setup for measuring the force acting on current-carrying conductors in a magnetic field
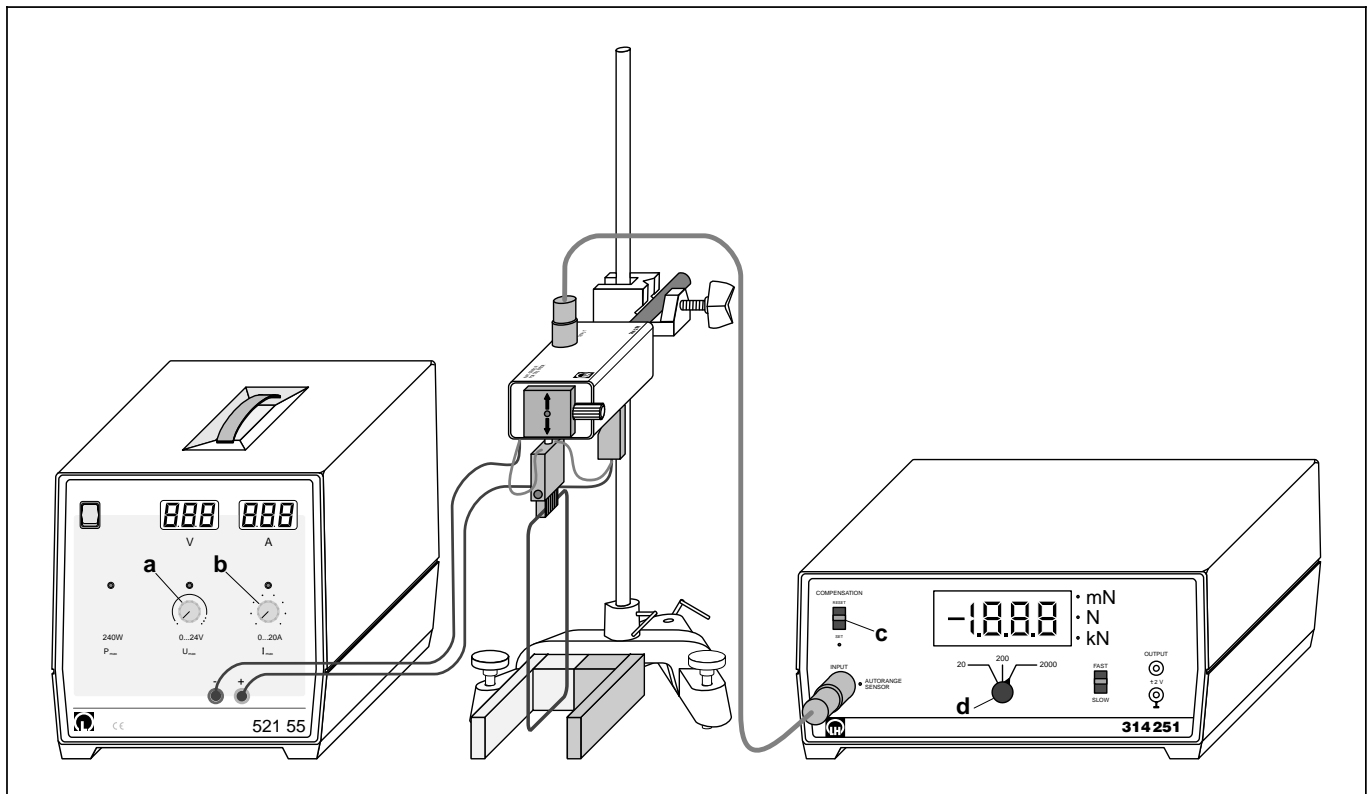
– To compensate the zero point of the newtonmeter, select the SET position with the COMPENSATION switch **(c)**.

– Using the current control knob **(b)**, increase the current to 20 A in steps of 2 A; for each current level, read off the force from the newtonmeter and write these values in your experiment log.

– Set the current to $I = 0$ A and check the zero point of the force display.
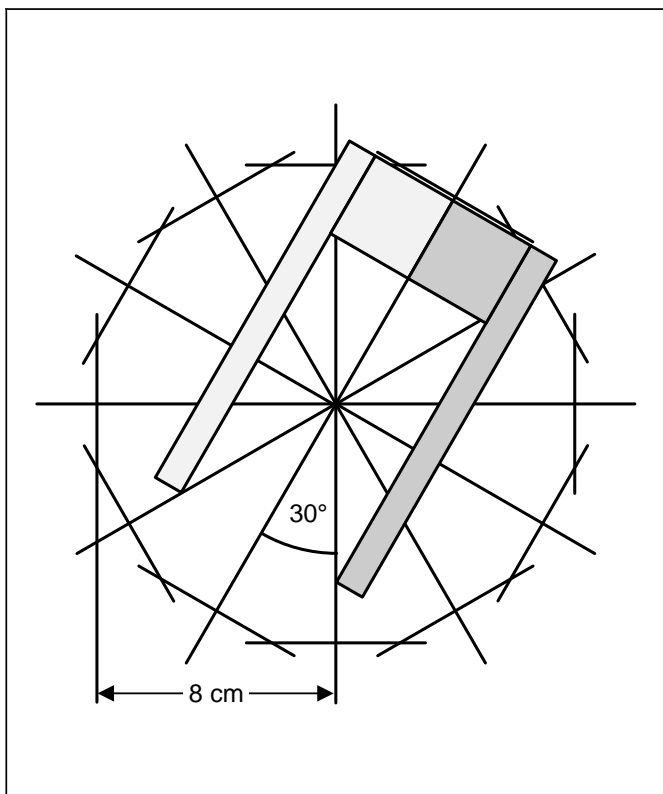
b) Measuring as a function of the conductor length:

– Attach the 4 cm wide conductor loop to the force sensor.

– To compensate the zero point of the newtonmeter, select the SET position with the COMPENSATION switch **(c)**.

– Set the current level $I = 20$ A, read off the force from the newtonmeter and write this value in your experiment log.

– Set the current to $I = 0$ A and check the zero point of the force display.

– Repeat the measurement for the 2 cm and the 1 cm conductor.

c) Measuring as a function of the angle between the magnetic field and the direction of the current:

Recommendation: to compensate for the non-homogeneous nature of the magnetic field, and to set the proper rotational angle, make a template (see Fig. 2). This makes positioning the horseshoe magnet easier and more accurate.

– Turn the current control knob all the way to the left and attach the 4 cm wide conductor loop to the force sensor.

– Place the template underneath the conductor loop so that the center of the template is exactly underneath the midpoint of the horizontal conductor section and one of the template lines is parallel to this conductor section.

Fig. 2   Using the template as an aid in positioning the horseshoe magnet

– Set up the horseshoe magnet so that the magnetic field and the conductor section are parallel.

– To compensate the zero point of the newtonmeter, select the SET position with the COMPENSATION switch **(c)**.

– Set the current level $I = 10$ A.

– Turn the magnet through 360° in steps of 30° and read off the force from the newtonmeter for each angle.

– Set the current to 0 A and check the zero point of the force display.

Measuring example and evaluation

a) Measuring as a function of current:

Table 1: Force F as a function of the current I $(s = 8$ cm$)$

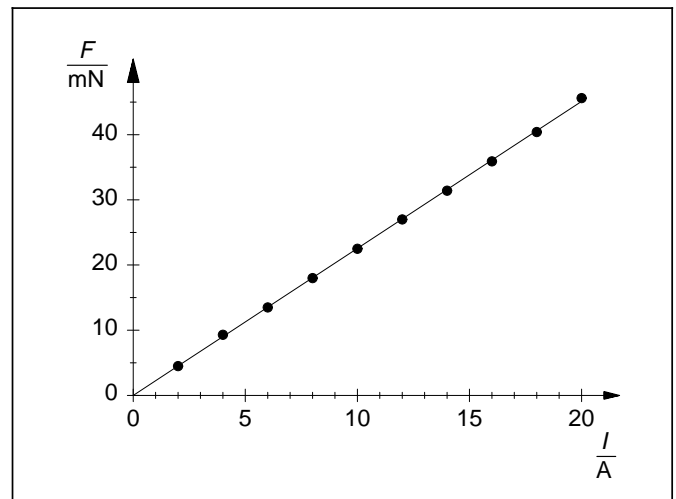| $\dfrac{I}{\text{A}}$	$\dfrac{F}{\text{mN}}$
0	0.0
2	4.5
4	9.3
6	13.5
8	18.0
10	22.5
12	27.0
14	31.4
16	35.9
18	40.4
20	45.6

Fig. 3   Force F acting on a current-carrying conductor as a function of the current I (cf. Table 1)

In the graph in Fig. 3, the measured values show a close approximation of a straight line with the slope

$$\frac{F}{I} = 2.26 \frac{\text{mN}}{\text{A}}$$

Given that $\sin 90° = 1$, equation (IV) gives us the following value for the magnetic field:

$$B = \frac{F}{I \cdot s} = \frac{2.26 \text{ mN}}{\text{A} \cdot 0.08 \text{ m}} = 28.5 \text{ mT}$$

The linear relationship between the force and the current for a constant conductor length formulated in equations (III) and (IV) is confirmed.

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b) Measuring as a function of the conductor length:

Table 2: Force F as a function of the length s ($I = 20$ A)

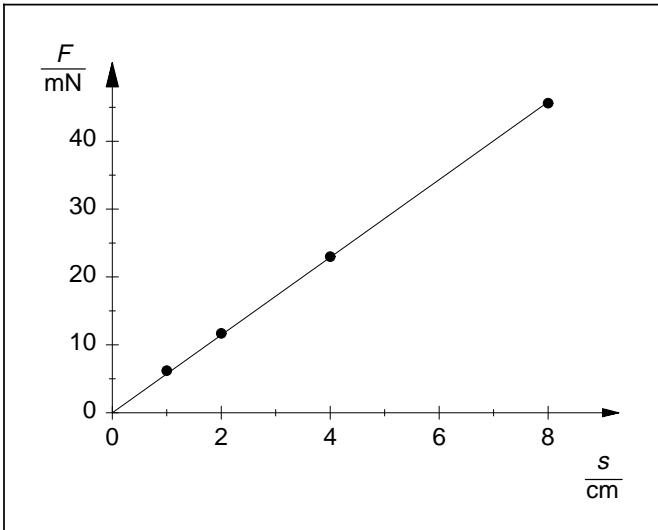| $\dfrac{s}{\text{cm}}$	$\dfrac{F}{\text{mN}}$
8	45.6
4	23.0
2	11.7
1	6.2

Fig. 4   Force F acting on a current-carrying conductor as a function of the conductor length s (cf. Table 2)

In Fig. 4, the measured values are also a close approximation of a straight line through the origin with the slope

$$\frac{F}{s} = 572 \frac{\text{mN}}{\text{m}}$$

For the magnetic field, we obtain the value

$$B = \frac{F}{s \cdot I} = \frac{572 \text{ mN}}{\text{m} \cdot 20\,\text{A}} = 28.6\,\text{mT}$$

The linear relationship between the force and the conductor length for a constant current formulated in (III) and (IV) is confirmed.

c) Measuring as a function of the angle between the magnetic field and the direction of the current:

Table 3: Force F as a function of the angle α ($s = 4$cm, $I = 10$A)

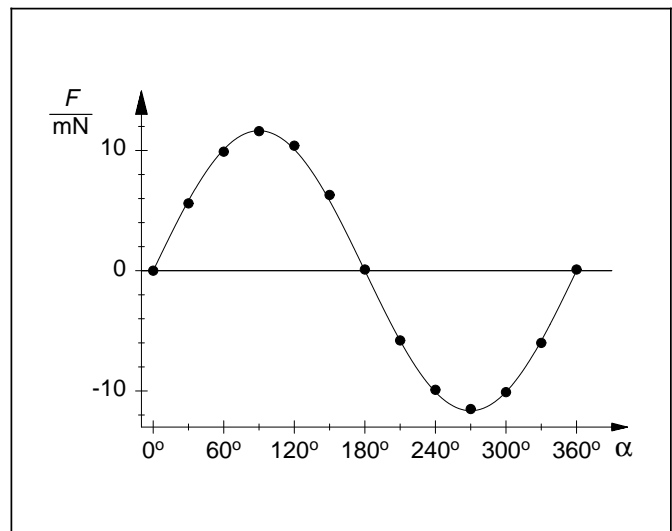| α	$\dfrac{F}{\text{mN}}$
0	0.0
30	5.6
60	9.9
90	11.6
120	10.4
150	6.3
180	0.1
210	-5.8
240	-9.9
270	-11.5
300	-10.1
330	-6.0
360	0.1

Fig. 5   Force F acting on a current-carrying conductor as a function of the angle α between the magnetic field and the direction of current (cf. Table 3)

The measured values in Fig. 5 are a close approximation of a sine curve calculated using (IV) for a magnetic field $B = 28.5$ mT.