Principle

A current is passed through an electrolyte producing a magnetic field. This magnetic field inside the conductor is measured as function of position and current by determining the induction voltage.

Related topics

Maxwell's equations, magnetic flux, induction, current density, field strength, electrolyte

Tasks

Determine the magnetic field inside the conductor as a function of

1. the current in the conductor and verify the linear relationship.
2. the distance from the middle axis of the conductor and determine the position where the field inside the conductor vanishes.

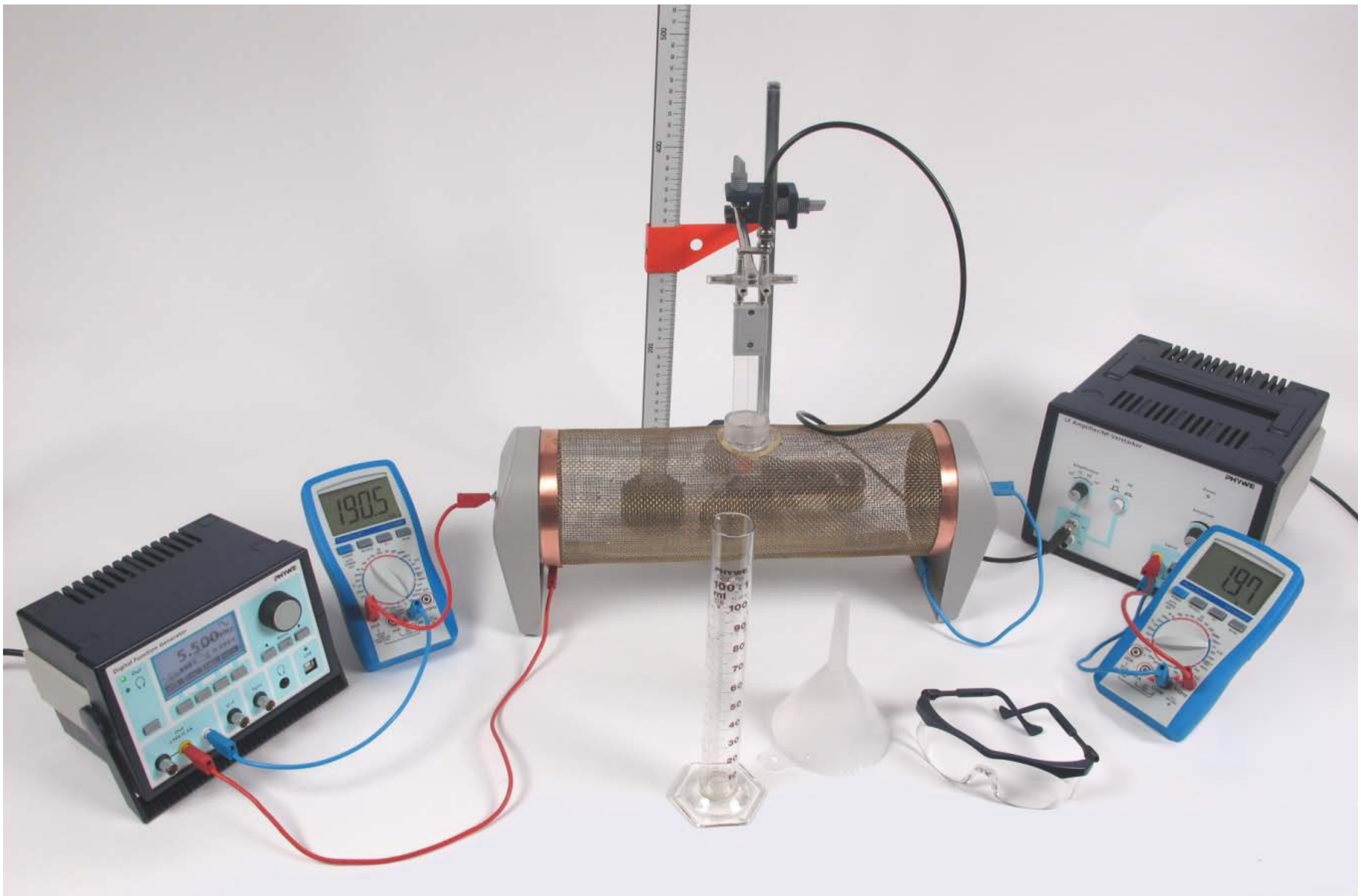

Fig 1: Experimental set-up

Equipment

1	Hollow cylinder, plexiglas	11003-10
1	Search coil, straight	11004-00
1	Digital frequency generator	13654-99
1	LF amplifier, 220 V	13625-93
2	Digital multimeter	07128-00
1	Distributer	06024-00
1	Adapter, BNC-socket/4 mm plugs	07542-27
1	Tripod base, PASS	02002-55
1	Barrel base, PASS	02006-55
1	Support rod, square, 400 mm	02026-55
1	Right angle clamp	02040-55
1	Cursors, 1 pair	02201-00
1	Meter scale, demo, 1000 mm	03001-00
3	Connecting cord, red, 250 mm	07360-01
2	Connecting cord, blue, 250 mm	07360-04
1	Connecting cord, blue, 500 mm	07361-04
1	Screened cable, BNC, 1000 mm	07542-12
1	Hydrochloric acid 1.19, 1000 ml	30214-70
1	Safety goggles	46330-00
1	Disposable gloves (medium)	46359-00
1	Filter funnel, PP	46895-00
1	Graduated cylinder, PP, 100 ml	36629-01
1	Glass beaker, 5000 ml	36272-00
1	Glass rod, 300 mm	40485-05

Safety instructions


When handling chemicals, you should wear suitable protective gloves, safety goggles, and suitable clothing. Please refer to the appendix for detailed safety instructions.

Set-up

Set up the experiment according to Fig. 1. One digital multimeter is connected in series with the digital frequency generator and the conductor in order to measure the current. To measure the induced voltage connect the second digital multimeter to the signal output of the low frequency amplifier. The search coil is connected via the screened cable to the input of the amplifier.

Procedure

Prepare the electrolyte under the exhaust hood. Use the safety goggles and the protective gloves while preparing and handling the electrolyte. First fill 4 l of destilled water into the glass beaker. Then add 200 ml of the hydrochloric acid while carefully stirring the electrolyte with the glass rod. Use the funnel and the graduated cylinder to measure the acid. When filling the prepared electrolyte into the hollow cylinder, take care to still protect your eyes with the safety goggles.

The experiment does not need to be carried out under the exhaust hood. The aperture must not be tightly closed so that gases being released (H_2, O_2) can escape. Do not allow any open fire in the vicinity of the experiment.

The various connection sockets on the hollow cylinder permit separate measurements on the electrolyte and on the jacket (hollow cylinder). Account must be taken of the fact that the magnetic field strengths to be measured lie in the µT range, i.e. the cables carrying the current – especially the return lead – also produce magnetic field strengths of same order of magnitude.

For the field strength measurement in the electrolyte the return lead for the current is the grid, as a current in the wall of the hollow cylinder produces no magnetic field inside the cylinder. With this connection there is no resultant field in the space outside the cylinder.

To carry out the experiment choose a frequency ν < 6 kHz and a sinusoidal signal. In order to tune the current you have to tune the voltage amplitude of the signal from the digital function generator. The maximum current is limited by the chemical process of electrolysis taking place in the hollow cylinder. The amplification should be of the order of 10^3.

Task 1

Position the search coil so that it is just completely immersed into the electrolyte – or that it reaches the bottom of the hollow cylinder. Tune the amplitude of the signal at the frequency generator to change the current between 0.2 A and 1 A. Record the induced voltage for at least six different values of current.

Task 2

Set the current to an intermediate value and record the induced voltage for all positions between the bottom and the upper edge of the hollow cylinder. Proceed in intervals of 50 mm.

Theory

Maxwell's first equations

$$\oint_C \vec{B}\,\vec{\mathrm{d}s} = \mu_0 \int_A \vec{J}\,\mathrm{d}\vec{A} \tag{1}$$

Together with Maxwell's fourth equation

$$\int_A \vec{B}\,\mathrm{d}\vec{A} = 0 \tag{2}$$

gives the relationship between the steady electric current I flowing through the area A

$$I = \int_A \vec{J}\,\mathrm{d}\vec{A} \tag{3}$$

producing the magnetic field $\vec{B}$ Here, C is the boundary of the enclosed area A, $\vec{J}$ is the

electrical current density and μ_0 is the magnetic field constant with $\mu_0 = 1.26 \cdot 10^{-6} \frac{\text{Vs}}{\text{Am}}$.
From (1) and (2) one obtains

$$B = \frac{\mu_0}{2\pi} \cdot \frac{I}{|\vec{r}|} \qquad (4)$$

for a long straight conductor, where $|\vec{r}|$ is the distance of point P, at which the magnetic flux is measured, from the middle axis of the conductor.
Since the current density $\vec{J}$ is uniform in the electrolyte, the current I flowing through the area A can be expressed as a function of the current I_{tot} flowing through the whole cross-section of the electrolyte, from (3), as

$$I = I_{tot} \frac{r^2}{R^2}$$

So (4) yields

$$B = \frac{\mu_0}{2\pi} \cdot I_{tot} \frac{|\vec{r}|}{R^2} \qquad (5)$$

B is measured with an induction coil, so we obtained

$$U_{ind} = n \cdot A \cdot 2\pi \cdot \nu \cdot B_0 \cdot \sin(\omega t + \phi) \qquad (6)$$

With the number of turns n = 1200, the effective area A = 74.3 mm^2 and the frequency ν.

Note: The digital multimeters measure the rms-values. The phase displacement is irrelevant for these measurements. Therefore the sine-term in eq. (6) can be ignored.

Evaluation and results

In the following the evaluation of the obtained values is described with the help of example values. Your results may vary from those presented here.
In order to obtain the magnetic field strengths, use eq. (6).

Task 1

From the regression line in Fig. 2 the following linear relation between current and magnetic field is obtained (compare eq. 5):

$$B/\text{mT} = 0.51 \cdot I_{tot}/\text{A} + 0.28$$

There the term $|\vec{r}|/R^2 \approx 1$ as the search coil was positioned at the very edge of the conductor during the measurements. The correlation coefficient R = 0.998 verifies the linear relationship with high confidence.

Task 2

From the regression lines in Fig. 3 follows

$$B_{\mathrm{lh}}(x)/\mathrm{mT} = -5.2\cdot 10^{-3}\, x/\mathrm{mm} + 1.4$$

for the lower half of the conductor and

$$B_{\mathrm{uh}}(x)/\mathrm{mT} = 5.5\cdot 10^{-3}\, x/\mathrm{mm} - 1.45$$

for the upper half.
The position where the field vanishes can be calculated by computing the point of intersection x_0 of both regression lines where $B_{\mathrm{lh}}(x_0) = B_{\mathrm{uh}}(x_0)$.
We obtain x_0 = 267 mm with a minimum field strength B_0 = 15 µT. This magnetic field can be attributed to errors due to the surroundings and especially to the unscreened cables connecting the digital multimeter to the LF amplifier. To reduce these errors one can try to screen the cables and the connection sockets (which typically are the main source of such "noise") with aluminium foil.

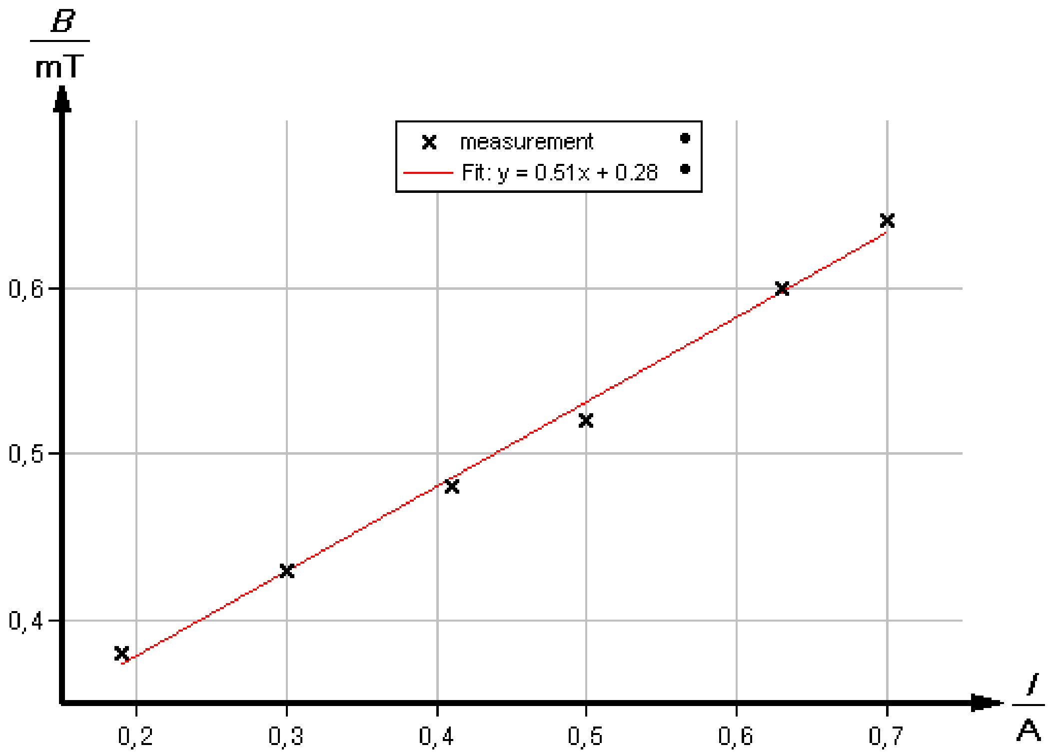

Fig. 2: Measurements for Task 1. The linear relationship between current density and magnetic field is obvious

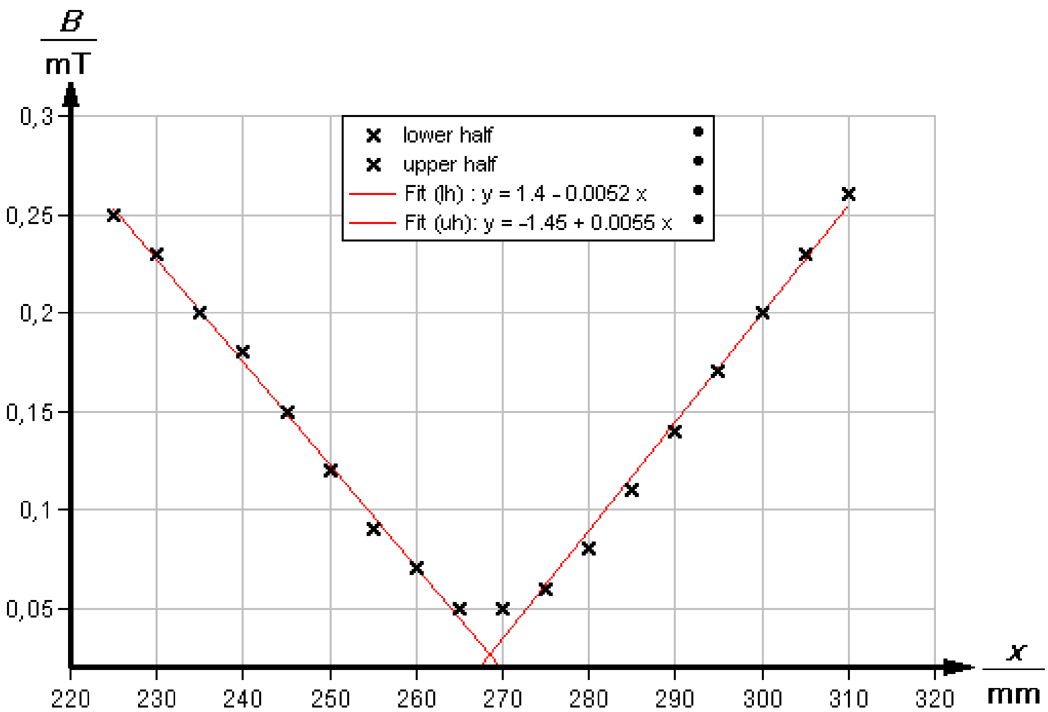

Fig. 3: Measurements for Task 2: magnetic field strength as function of position inside the conductor

Appendix

Hazard symbol, signal word	Hazard statements	Precautionary statements
Hydrochloric acid (HCl)		
	H314-335 causes severe skin burns and eye damage, toxic, irritating	P260: do not inhale P301+330+331: If swallowed, rinse the mouth, do not induce regurgitation P303+361+353: at contact with skin/clothing, rinse the skin thoroughly, take off contaminated clothing P305+351+338: at eye contact rinse for several minutes, take off eventual lenses 405: Keep locked. 501 Use the appropriate containers for disposal

