Magnetic Field of a Cylindrical Coil

DETERMINE THE MAGNETIC FIELD GENERATED BY COILS OF VARIOUS LENGTHS.

- Determine the magnetic flux density B inside a cylindrical coil as a function of the current I.
- Measure the magnetic flux density B inside a cylindrical coil with variable number of windings per unit length as a function of the current I.
- Determine that for long coils, the magnetic flux density is proportional to the density of the windings.

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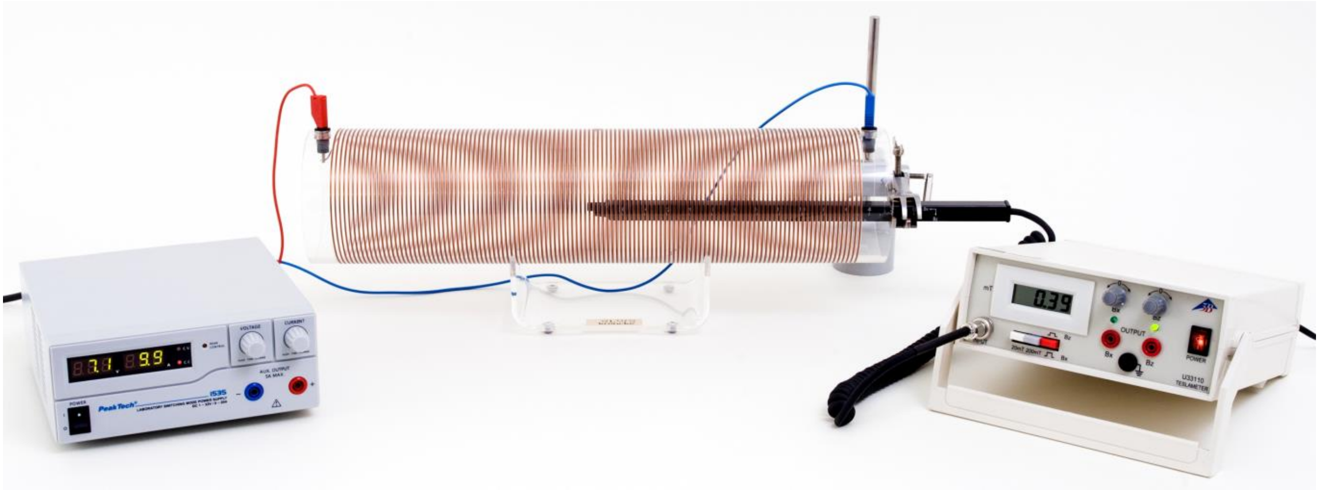

Fig. 1: Measurement set-up.

GENERAL PRINCIPLES

The Biot-Savart law describes the relationship between magnetic flux density *B* and electric current *I* through a conductor of any arbitrary geometry. The calculation involves adding the contributions of infinitesimally small sections of conductor to find the overall magnetic flux density. The overall field is then determined by integrating over the geometry of the conductor. In some cases, e.g. for a long cylindrical coil, there is a simple analytical solution to this integration.

According to the Biot-Savart law, an infinitesimally small section of conductor d**s** through which a current I is flowing, generates the following magnetic flux density at the point **r**

$$(1)\quad \mathrm{d}\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\cdot I\cdot\frac{\mathrm{d}\mathbf{s}\times\mathbf{r}}{r^3}\,.$$

B: magnetic flux density

$\mu_0 = 4\pi\cdot 10^{-7}\,\frac{\mathrm{Vs}}{\mathrm{Am}}$: permeability of free space

Inside the cylindrical coil, the magnetic flux density is aligned parallel to the axis of the cylinder and is given by the following expression:

$$(2)\quad B = \mu_0\cdot\frac{N}{L}\cdot I\,.$$

N: number of windings, L: length of coil

This applies as long as the length of the coil is much greater than its radius. The magnetic flux density does not therefore depend on the diameter of the coil and is proportional to the density of the windings, i.e. the number of windings per unit length, and the current through the coil.

The experiment involves using an axial teslameter to measure the magnetic flux density inside long coils for currents of up to 20 A. It demonstrates that the flux density does not depend on the coil diameter but is proportional to the current and the winding density. In order to prove the latter, a coil is provided which allows the windings to be moved closer together or farther apart, i.e. varying the number of windings per unit length.

LIST OF EQUIPMENT

1	Field Coil, 100 mm	U12252	1000591
1	Field Coil, 120 mm	U12253	1000592
1	Coil with Variable Number of Turns per Unit Length	U8496175	1000965
1	Stand for Cylindrical Coils	U8496150	1000964
1	Teslameter	U33110	1003313/4
1	DC Power Supply 1 – 32 V, 0 – 20 A	U11827	1012857/8
1	Set of 15 Experiment Leads 2,5 mm²	U13801	1002841
1	Barrel Foot, 1000 g	U13265	1002834
1	Stainless Steel Rod, 250 mm	U15001	1002933
1	Universal Clamp	U13255	1002830
1	Universal Jaw Clamp	U13261	1002833

SET-UP AND PROCEDURE

Note:
By way of example, the experiment is carried out with 100 mm field coil (diameter D = 10 cm).

- Set up the experiment as shown in Fig. 1.
- Connect the field coil (D = 10 cm) to the 0 – 20 A output on the rear of the DC power supply. Do not turn on the power supply yet.
- Position the magnetic field probe by setting up the stand in such a way that the axial Hall probe (Fig. 2) is precisely in the centre of the coil.

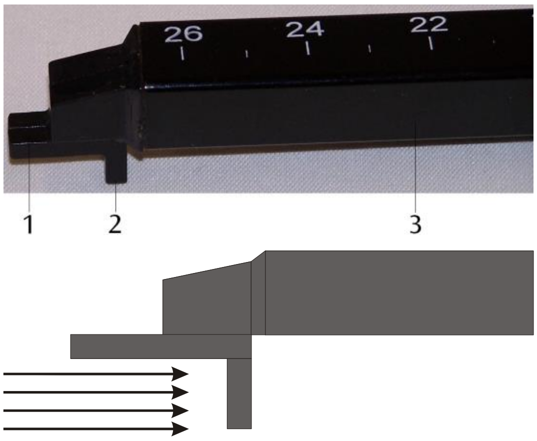

Fig. 2: Top: Magnetfeldsonde, 1 tangential Hall probe (z-direction), 2 axial Hall probe (x-direction), 3 probe carrier. Bottom: Measurement of axial magnetic fields.

The axial Hall probe measures the component of magnetic induction B along the axis of the probe. If the field B points along the axis of the probe (Fig. 2 below), the value displayed will be positive, whereas if it points the other way the value shown will be negative.

- Connect the magnetic field probe to the corresponding sockets of the teslameter (Fig. 3).

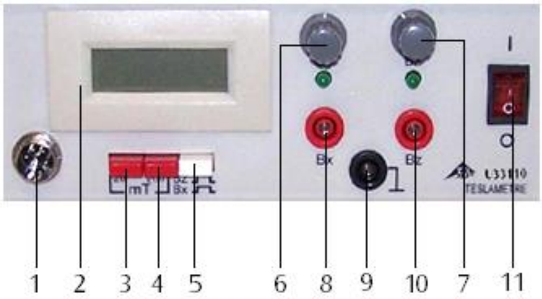

Fig. 3: Controls for teslameter:

1 Connecting socket for magnetic field probe
2 Digital display
3 Measurement range selector, 20 mT
4 Measurement range selector, 200 mT
5 Measurement mode switch, axial (B_X) and tangential (B_Z)
6 Zero adjustment knob for B_X with LED indicator
7 Zero adjustment knob for B_Z with LED indicator
8 Output socket for axial mode B_X
9 Earth (ground) socket
10 Output socket for tangential mode B_Z
11 On/off switch

- Turn on the teslameter, select a measuring range of 20 mT and turn the measuring mode delector switch to axial (B_X).
- Calibrate the zero point by turning the zero point calibration knob B_X until the display shows 0 or the lowest value achievable.
- Turn on the DC power supply. Increase the current from 0 up to 20 A in steps of 1 A. For each of these steps, read off the magnetic flux density B_X, entering this value into Table 1 along with the current I set for that measurement.

Safety instruction:

- For a set current 10 A < I ≤ 20 A, only allow the current to flow for a brief period.
- Replace the field coil (D = 10 cm) by the coil with variable turns per unit length (Fig. 4).
- Set the lengths of the coil to be L = 7, 12, 17, 22, 27 and 32 cm, with each symmetrical around the centre of the coil. Repeat the measurement procedure described above for each of these lengths and enter all the values into Table 2.

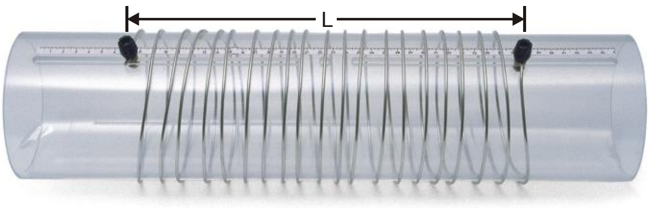

Fig. 4: Coil with variable number of windings per unit length.

Note:
The coil can optionally be mounted by its ends from two 1000964 stands. This means that it does not need to be taken off its stand every time the length is adjusted and that the magnetic field sensor does not need to be repositioned either.

SAMPLE MEASUREMENT

Tab. 1: Magnetic flux density B as a function of current I through a field coil of diameter D = 10 cm.

I / A	B / mT
0	0.00
1	0.31
2	0.62
3	0.93
4	1.24
5	1.55
6	1.85
7	2.17
8	2.47
9	2.78
10	3.10
11	3.41
12	3.72
13	4.03
14	4.34
15	4.65
16	4.96
17	5.27
18	5.58
19	5.90
20	6.21

Tab. 2: Magnetic flux density B as a function of current I for various lengths of coil L.

I / A	B / mT					
	L = 7 cm	L = 12 cm	L = 17 cm	L = 22 cm	L = 27 cm	L = 32 cm
0	0.00	0.00	0.00	0.00	0.00	0.00
1	0.29	0.26	0.20	0.17	0.14	0.12
2	0.58	0.52	0.40	0.34	0.27	0.23
3	0.88	0.78	0.60	0.51	0.41	0.36
4	1.18	1.04	0.80	0.68	0.55	0.47
5	1.48	1.30	1.00	0.85	0.68	0.60
6	1.78	1.56	1.20	1.02	0.83	0.72
7	2.07	1.84	1.40	1.19	0.97	0.84
8	2.37	2.12	1.61	1.36	1.10	0.96
9	2.67	2.37	1.81	1.53	1.25	1.08
10	2.96	2.66	2.01	1.70	1.38	1.20
11	3.26	2.93	2.21	1.88	1.52	1.32
12	3.56	3.20	2.42	2.05	1.67	1.45
13	3.86	3.46	2.62	2.22	1.80	1.57
14	4.17	3.74	2.83	2.39	1.94	1.70
15	4.47	4.02	3.04	2.57	2.08	1.81
16	4.77	4.28	3.24	2.73	2.23	1.94
17	5.07	4.59	3.45	2.91	2.36	2.06
18	5.38	4.86	3.65	3.08	2.51	2.19
19	5.66	5.15	3.85	3.26	2.65	2.31
20	5.96	5.44	4.06	3.43	2.79	2.43

EVALUATION

- Plot the measurements in Table 1 in a graph of B against I (Fig. 5).

This verifies that the magnetic flux density B is proportional to current I through the coil as predicted by equation (2).

Note:
A corresponding measurement using a coil of diameter 120 mm (D = 12 cm) can demonstrate that the magnetic flux density B remains proportional to the current I through the coil regardless of the coil’s diameter.

- Plot the measurements from Table 2, incorporating the various lengths as a parameter, in a graph of B against I (Fig. 6).

This verifies that the magnetic flux density B is proportional to current I through the coil as predicted by equation (2) for any length of coil.

Due to the inverse proportionality of the magnetic flux density B to the coil length L, the gradient of the lines decreases as the length gets longer.

- Knowing the number of turns on the variable length coil is N = 30, calculate the winding turns per unit length N/L and enter the results into Table 3.
- Take the magnetic flux densities B when current I = 20 A for each of the N/L values calculated from Table 2 and enter them in the corresponding cells of Table 3.
- Plot the measurements from Table 3 in a graph of B against N/L (Fig. 7).
- The flux density is confirmed to be proportional to the turns per unit length as long as the length of the coil is more than three times its radius. The diameter of the coil with variable turns per unit length is D = 10 cm.

Tab. 3: Magnetic flux density *B* as a function of number of windings per unit length *N*/*L* when *I* = 20 A. Number of windings *N* = 30.

L / cm	*N*/*L* / 1/cm	*B* / mT
7	4.29	5.96
12	2.50	5.44
17	1.76	4.06
22	1.36	3.43
27	1.11	2.79
32	0.94	2.43

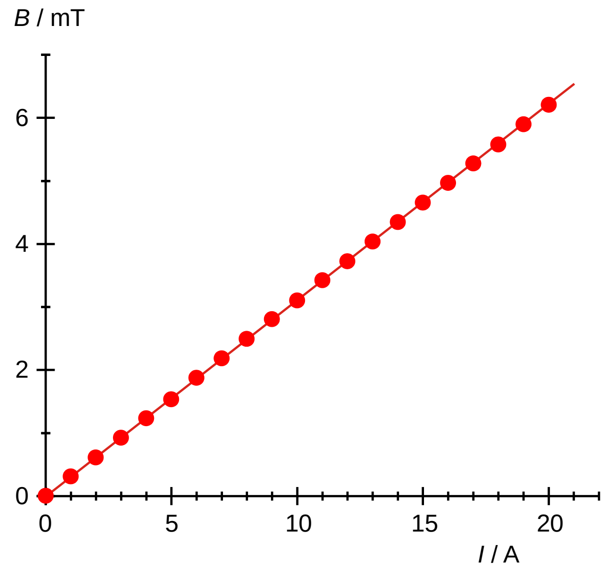

Fig. 5: Magnetic flux density *B* as a function of current *I* through a field coil of diameter *D* = 10 cm.

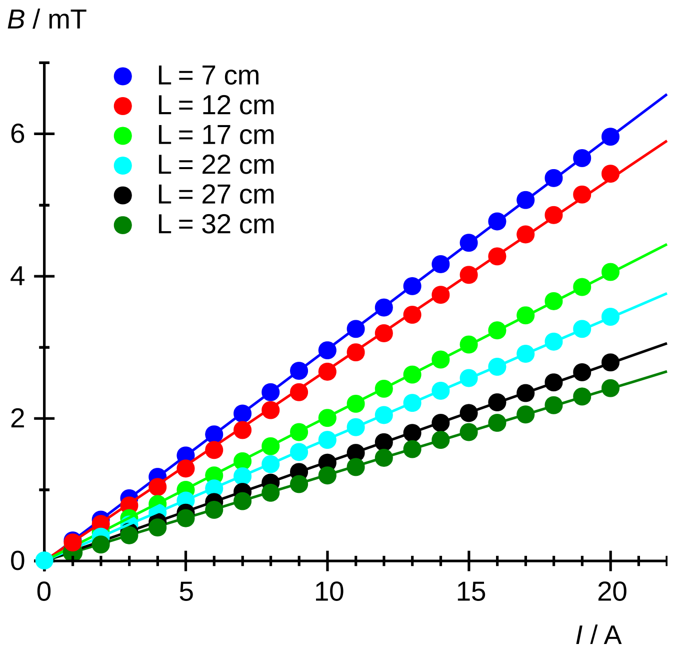

Fig. 6: Magnetic flux density *B* as a function of current *I* using the coil with a variable number of windings per unit length for various lengths of coil *L*.

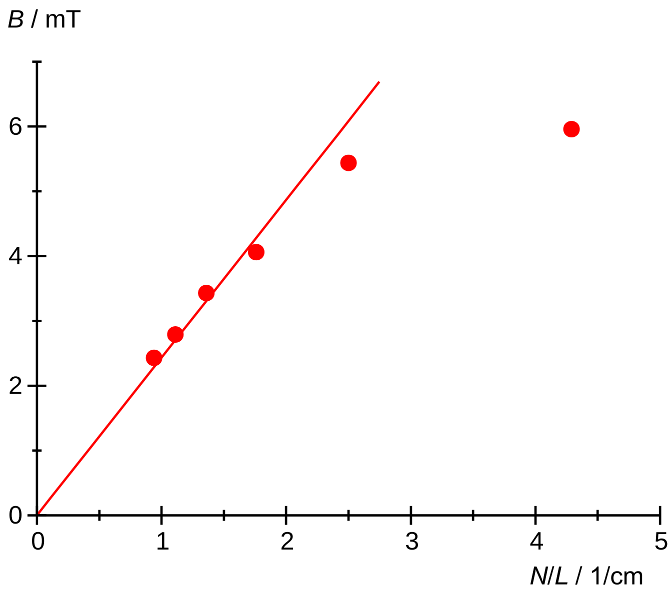

Fig. 7: Magnetic flux density *B* as a function of number of windings per unit length *N*/*L* when *I* = 20 A.