IE2

Modul Electricity

Magnetic field and permeability of vacuum

In this experiment, the magnetic field of a coil is measured. The vacuum permeability μ_0 can be determined from the data. This experiment serves as a basic introduction to the basics of magnetostatics.

Versuch IE2 - Magnetic field and permeability of vacuum

In this experiment, the magnetic field of a coil is measured. The vacuum permeability μ_0 can be determined from the data. This experiment serves as a basic introduction to the basics of magnetostatics.

1.1 Preliminary Questions

- Electric fields are produced by electric charges. However, what is generated by magnetic fields?
- What are the similarities and what are the differences of electrical and magnetic field lines?
- Why does the superposition principle apply for electric and magnetic fields? (One example: it is a mathematical argument).
- Sketch the magnetic field/magnetic flux density through a current conductor.
- With which physical law can calculated the course of this field or this flux?
- What understands one with the permeability of the vacuum and how is this defined?
- What is the relationship between magnetic flux density B and magnetic field strength H and which role does the permeability μ play?
- What is the magnetic susceptibility and how is this related together with the permeability?
- What do the terms ferromagnet, diamagnet, and paramagnet mean and how do these terms go together with permeability?
- What happens when a para-, dia-, or ferromagnet is in a coil, as it is used in this experiment? How does the magnetic flux density change?
- What is the relationship between ferro- and paramagnets?
- What does the term hysteresis mean? Sketch an example of the hysteresis curve of a ferromagnetic and describe the four characteristic points of this curve with the appropriate terms.

1.2 Theory

1.2.1 Fundamental Magnetostatics

Generally magnetic fields are produced by moving charges. A static current flows through an electrical conductor, so it generates a stationary magnetic field, which in a vacuum by the so-called MAGENTIC FLUX DENSITY $\vec{B}$ is characterized as. However, looking at magnetic fields in matter, which is characterized as MAGNETIC FIELD POWER and designated as $\vec{H}$. The relationship between quantities is given by the so-called PERMEABILITY it applies:

$$\vec{H} = \frac{\vec{B}}{\mu} = \frac{\vec{B}}{\mu_r \mu_0} \tag{1.1}$$

Here, mu_0 is the permeability of the vacuum and is also designated as the magnetic field constant. μ_r is the relative permeability and unlike mu_0, it is not one constant of nature, but a material constant, which, where appropriate, further parameters such as temperature may depend on. For different materials can μ_r can assume both positive and negative values. This is essential for the classification of magnetic materials in parameters, diagnostic, and ferromagnets. In this experiment, the magnetic flux density of a coil is measured in order to subsequently determine the permeability of the vacuum. The magnetic flux density has the SI unit Tesla:

$$[B] = 1\,T = 1\,\frac{V \cdot s}{m^2} \tag{1.2}$$

The permeability of a vacuum is defined as:

$$\mu_0 = 4\pi \cdot 10^{-7} \frac{Vs}{Am} \tag{1.3}$$

1.2.2 The Law of Biot-Savart

In the experiment, the field of a copper coil is measured. However, what is expected from the theoretical side of this box? In fact, you can calculated the field or the magnetic flux density of the coil. In general, the magnetic flux density of a current carrying conductor of any shape can be calculated with the LAW OF BIOT-SAVART. In the case of a constant, steady flow, it reads:

$$\vec{B} = \frac{\mu_0 \cdot I}{4\pi} \int_L \frac{d\vec{s} \times \vec{r}}{r^3} \tag{1.4}$$

Here, the flow is called the current I, and $d\vec{s}$ is an infinitesimal path element, which shows the direction along the current, and $\vec{r}$ is the spatial coordinate in relation to an arbitrary origin (often referred to as a reference point). Analytical solutions of the Biot-Savart law indices are obtained usually only at very symmetrical conductor geometries. If an analytical solution is not possible, the solution must be numeric that is carried out by the computer.
In the case of a long straight coil with a constant number of turns, you get the following analytic solution:

$$B = \mu_0 \cdot I \cdot \frac{N}{L} \tag{1.5}$$

where N denotes the number of turns of the coil and L is the length[1]. This formula applies to the interior of the considered coil. Thus, inside the coil the magnetic flux density is homogeneous. In fact, it can be compared that such coils generate relatively homogenous fields. However, there are still better geometries in order to realize homogeneous magnetic fields, e.g. the Helmholtz coil, which in another experiment of this course is performed.

According to this theoretical prediction, the resultant magnetic flux density is proportional to the current I flowing through the coil. Whereas the magnetic flux density is inversely proportional to the length of the coil. Thus, one would expect a larger flux density for shorter coils, however, the approximation used in the derivation is poor and thus, it is accepted that the above formula 1.5 is no longer valid. This is also indicated by that of infinite, small lengths L, the magnetic flux density according to this formula tends to infinity.
Furthermore, it can also be seen in the above formula that the magnetic flux density directly proportional to the number of turns of the coil. The three pictures before this formula predicted dependencies which will be checked in the following experiment.

[1] The calculation of this formula requires mathematical knowledge, which is not available in the first semester. Therefore, reference is made at this point to the lectures in Physics 2 or electrodynamics

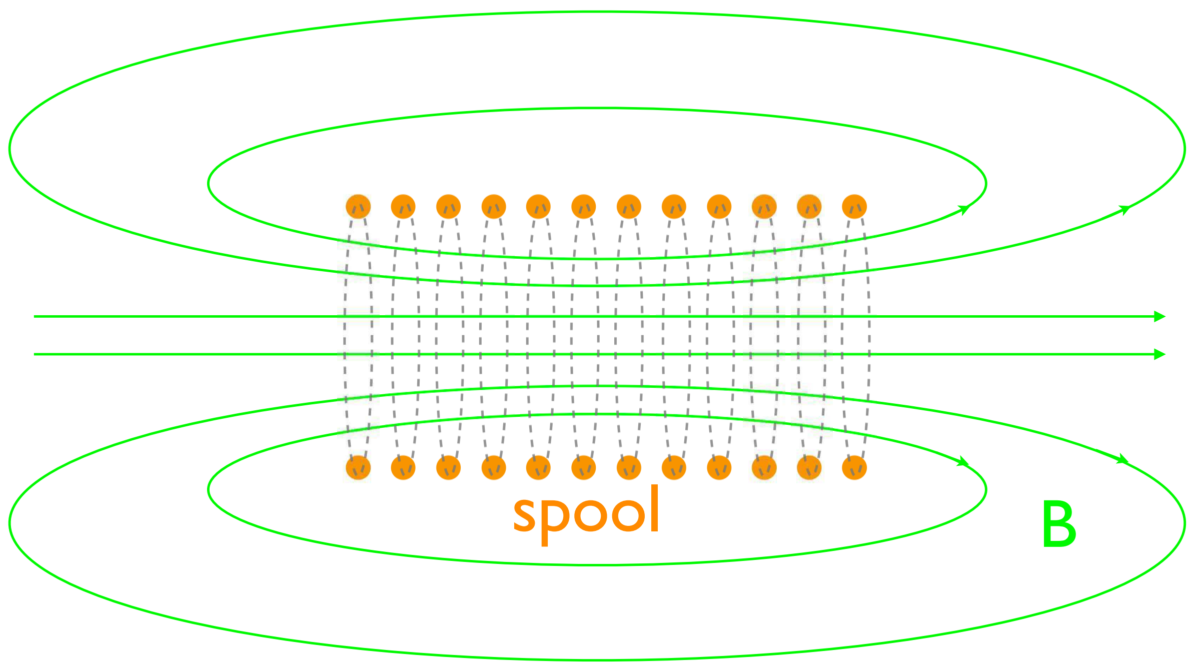

Figure 1.1: This figure schematically shows the course of the magnetic flux density B of a straight coil. Due to the limited space, some field lines are not shown closed although the field lines should be closed.

1.3 Experiment

In this experiment, the magnetic flux density of a straight copper coil with constant turns will be measured. The experiment will be available in the disassembled state and the students should build the apparatus in accordance with these instructions and adjust accordingly. In this experiment, relatively high currents are used (up to 20A), so everyone here should react responsibly. Course misconduct and endangering others or hazards may lead to exclusion from the practicum!

1.3.1 Accessories

Components	quantity
Coil	1
High current power supply	1
Teslameter	1
Axial B probe	1
Connection cable, 6-pole	1
Base, stand of the coil	1

1.3.2 Experimental Setup and Adjustment

At the beginning of the experiment, one must first connect the high-current power supply and the coil, and two cables are needed. Then the B-probe must be mounted to the corresponding pedestal and are connected to the associated teslameter. The connection serves the 6-pin cable which is at the experimental setup. Since those are an axial B-probe, it must be aligned parallel to the axis of symmetry of the coil.
Now, both the AC adapter and the Tesla meter can be turned on. It is shown that the teslameter

should indicate mT. Optionally, the range that should be implemented is switched. Should the teslameter already show something, even though no current is flowing through the coil, the Teslameter can be set manually to 0. This process will be eventually repeated between each series of measurements, therefore, always check before each series of measurements that the device displays such an offset to have a more accurate measurement.

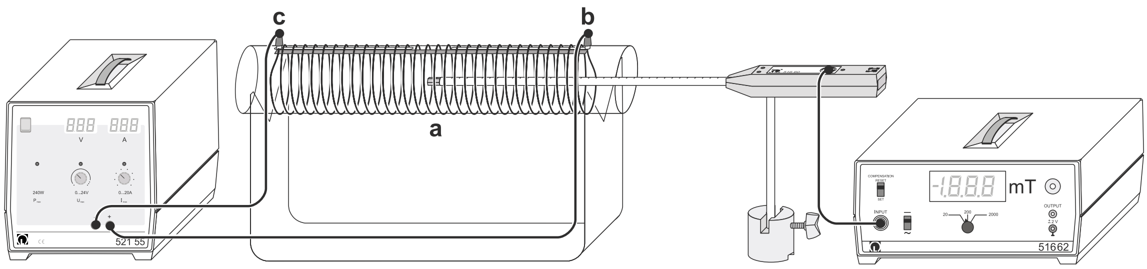

Figure 1.2: This illustration shows the experimental setup. In the middle of the coil, it can be seen the terminals a and b, and the power supply (left). On the right side is the B probes and the associated teslameter, with which the actual measurements are to be made. (Source: LD Didactic)

Before starting the actual measurement, the experimental setup should be shown to the appropriate assistant.

1.3.3 Procedure

- **Measurement of magnetic flux density as a function of the current** I: for this measurement, direct the B-probe so that it is exactly measured in the center of the coil. Point the Tesla meter to the measuring range 20 mT. Now, vary the current strength in increments of 0.5 A, however, take at least 40 readings. These measurements should be carried out for three different coil lengths, for example, a) 7 cm, b) 15 cm, and c) 26 cm. In order to vary the length of the coil, the power supply must be set to 0 and separated from the reel! The number of turns of the coil is measured for all three rows $N = 30$.
  It can be measured up to 20 A. Should the current already be at a stagnant smaller value, the internal current limit of the connected device should be switched on. In this case, the assistant should be consulted to check the relevant distance. After the series of measurements has been completed, the offset should be checked again with the teslameter. Estimate an error for both B and for I.

- **Measurement of** B **as a function of length** L: the length of the coil may vary in range from 7 cm to 27.5 cm. Take at least 10 measurements at maximum amperage and in the middle position of the B probe of B as a function of length L. Between individual measurements, the offset should be repeatedly checked with the teslameter. Estimate an error for both B and L.

- With a constant current and coil length, the B-probe can slowly move from the center of the coil to the edge of the coil. Describe your observations and note the measured flux densities B as a function of displacement on a sheet of paper. (Take a minimum of 15 readings).

1.3.4 Tasks for Evaluation

- B **as a function of** I**:** Make a plot of $B(I)$ with your estimated errors as error-bars. Make a customized linear fit to the displayed function. As the slope of this line is proportional to μ_0, you can choose μ_0 to be a fit parameter since all other quantities are known. Determine the error propagation of this function. Compare the determined values for μ_0 to each other. Explain observed differences? Which value is the most precise? Compare the obtained values of μ_0 with its literature value.

- B **as a function of** L**:** Make a plot of $B(L)$ with your estimated errors as error-bars. According to equation 1.5 is $B \approx 1/L$, hence fit the function $f(x) = a/x$ to your data set, where a is a constant factor. This constant factor a can be calculated from equation 1.5. Compare theoretical value to the result of your fit. Are there deviations? If so, in which sector and why?
  Alternatively one can define the number of turn density $n = N/L$ Calculate this number of turns density for your data set and plot $B(n)$. This leads to a linear correlation as well. Determine the vacuum permeability from this linear relation.

- B **as a function of the position of the** B**-probe:** Discuss your results by comparing them to the literature values. Do you observe deviations from the model concept? Display the absolute value of magnetic flux density, calculated from your data, along the axis of the spool.

Literature

- Demtröder Band 2 - *Elektrizität und Optik*, 6. Auflage: Abschnitt 3.2 und 3.5

- *Gerthsen Physik*, 22. Auflage oder neuer: Abschnitt 7.3.1+7.3.2 sowie Abschnitt 7.5.1-7.5.4 (Für die Beantwortung der Fragen zur Vorbereitung)