Four experiments on magnetic field at four Euros – Low-cost demonstrational experiments on Classical Electrodynamics for future physics teachers

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Introduction

Classical Electrodynamics is one of subjects studied by future high school teachers of Mathematics and Physics at Charles University in Prague in the third year of their bachelor studies. (Two more years of Master studies are required for these students to become qualified teachers but most of basic physics lectures are included in their bachelor studies.) The lecture on Classical Electrodynamics follows a basic lecture on Electricity and Magnetism (two years before) with the aim to extend and deepen students' knowledge and understanding in this field. Up to now this lecture has only been theoretical, being part of the course on Theoretical Physics for future teachers. We decided to enhance this lecture and supplement it with selected demonstrational experiments – relatively simple, low cost and not time consuming but nevertheless also quantitative ones. Though most of these experiments could be also used in the earlier lecture on Electricity and Magnetism our experience showed us that this lecture is already "overloaded" enough. So it is useful to return to many effects, formulas etc. again in Classical Electrodynamics, at a bit deeper level and with better understanding using the experience students gained in their first two years of their studies.
The article presents four experiments from the area of magnetism: Demonstration of Ampere's law, How to use an electric transformer to transform music, Dissipation of magnetic field and Simple demonstration of a multipole expansion.
The experiments use only simple and cheap instruments (ideally being the "experiments for 4 Euros") to enable future teachers to use simpler versions of selected experiments also in their future teaching at high schools.

Simple demonstration of Ampere's law

Is it possible to simply demonstrate Ampere's law of magnetic field?
Ampere's law describes the relation between magnetic field around a conductor and the current flowing through the conductor.

$$\oint_C \vec{H} \cdot d\vec{l} = I_{total} \quad (1)$$

To demonstrate the law we take a core of an electric transformer. We consider a closed curve *C* inside a core of the transformer (coinciding with a magnetic field line – see fig. 1).

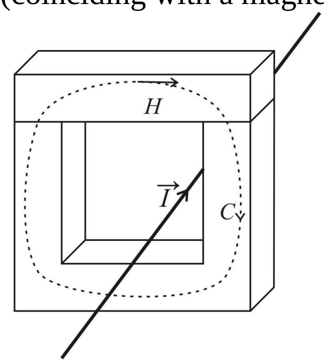


Fig. 1: Idea of Ampere's law demonstration using common school transformer

If we consider H to be approximately constant along the curve, we can take $\oint_C \vec{H} \cdot d\vec{l} = H \cdot l$,

where l is the length of the curve. The total current $I_{total} = NI$, where N is the number of turns of the coil and I is the current through the coil. We arrive at a simple formula which enables us to find out the value of H:

$$H \cdot l = N \cdot I \qquad (2)$$

Corresponding magnetic induction B is

$$B = \mu_r \mu_0 \frac{N I}{l}, \qquad (3)$$

where μ_0 is permeability of vacuum and μ_r is a relative permeability of the material of the core. If there is a thin gap between two parts of the core the value of (normal component of) B is the same in the gap as it is in the core. (Of course, the gap influences, perhaps even significantly, the value of the integral in (1) and this effect must be discussed with students. We will omit this discussion in this short article.)

All these formulas are well known to students and the theoretical reasoning indicated above is quite straightforward. Let us look how to demonstrate the dependence of B at I an N as simply as possible.

We have used a small Hall's probe to measure magnetic field inside a core of a common school transformer (see fig. 2). Hall's probe is in the centre of the gap.

The height of the Hall's probe is only 2 mm so the gap is thin enough and we can neglect it in the first approximation. (Lately we can improve our simple model and discuss with students that our first approximation is, in fact, crude enough. But it is not orders of magnitude wrong.)

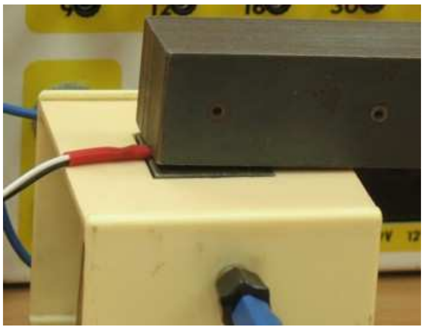


Fig. 2: Detail of the Hall's probe inside the gap of the transformer's core
(to measure the dependence of B on I)

The arrangement of the experiment you can see in fig. 3. One multimeter measures voltage at the output from Hall's probe (from which we calculate the value of B), second multimeter measures an electric current in the primary circuit. Batteries at the front are power supply for the Hall's probe. In the first experiment we have constant primary voltage for the coil (about 3 V) and change number of turns of the primary coil, which we wind from a wire.

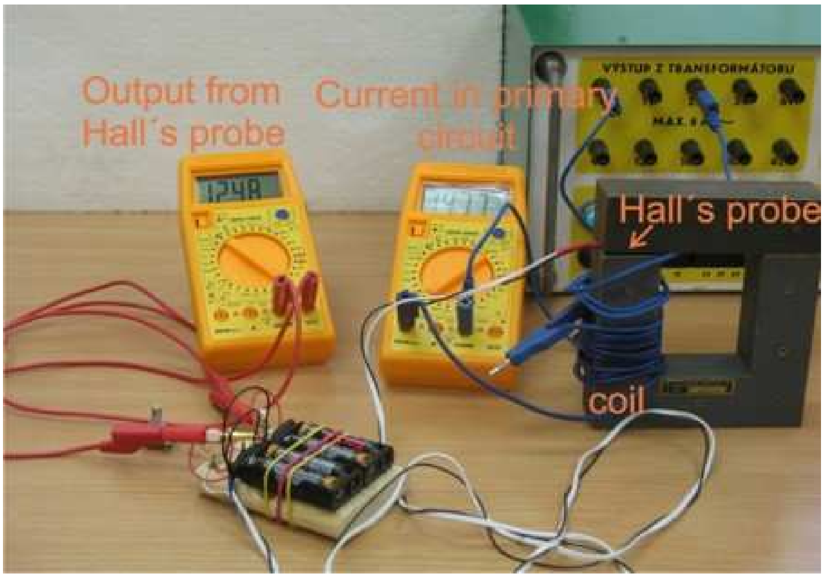
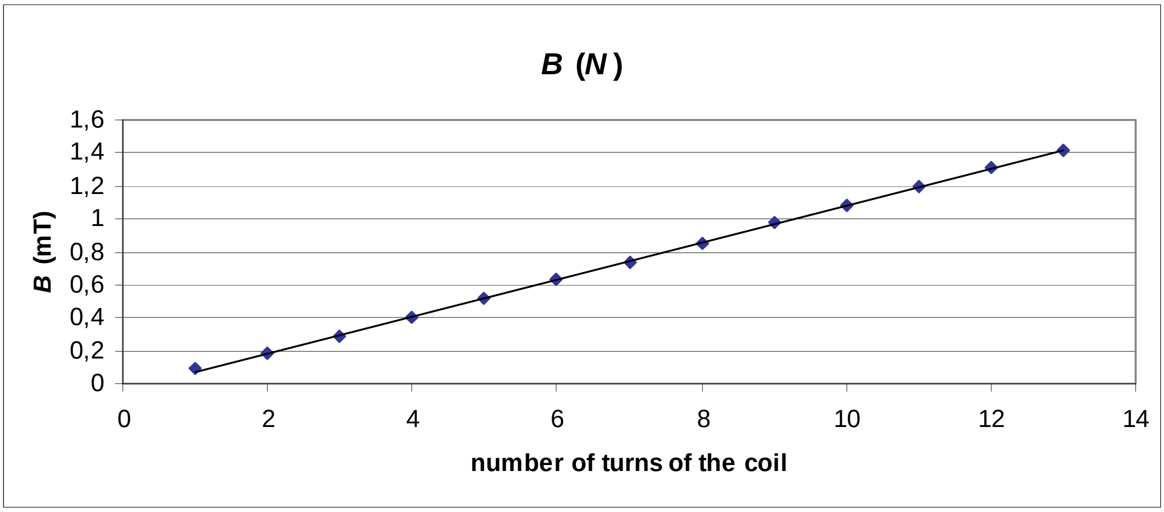


Fig. 3: Arrangement of the experiment
(to measure the dependence of *B* on number of turns of the coil)

In the second experiment we have coil with 300 turns and change current in the coil. Minimum current we use was 55 mA, maximum about 260 mA.

It's possible to demonstrate that dependence of magnetic field on a number of turns of the coil and on electric current is approximately linear (see fig. 4). Deviation from linear dependence can be caused by the fact that relative permeability of the ferromagnetic material of the core is not constant but changes with *H*. In the more detailed treatment students can find that this effect is diminished by an air-gap. If the influence of the air-gap is neglected (as in our derivation above), the experiment can be taken rather as an approximate demonstration of Ampere's law, not as an accurate quantitative measurement.



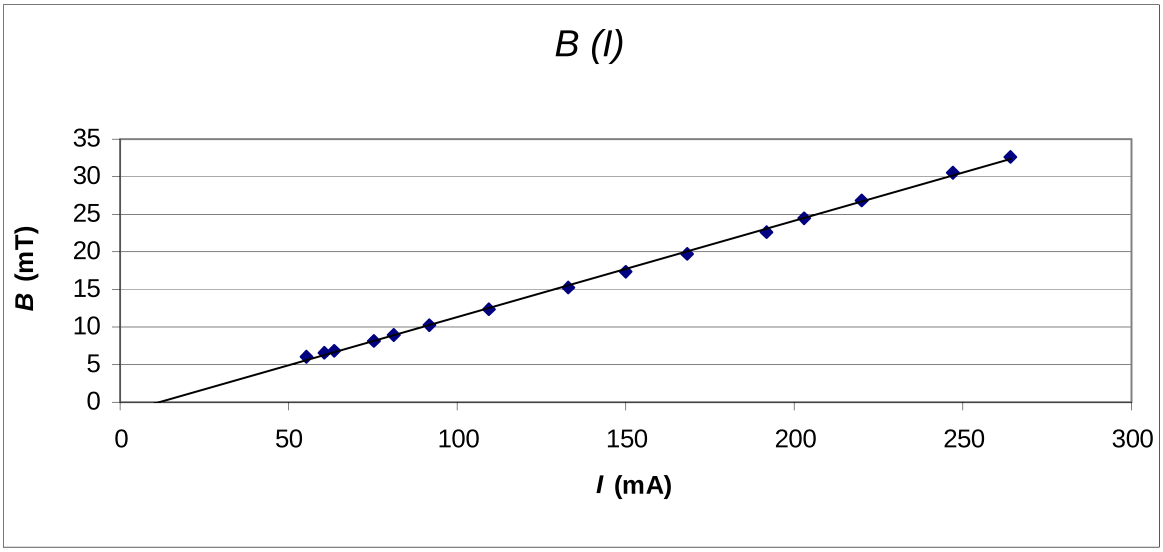


Fig. 4: Dependence of magnetic field: a) on number of turns of the coil, b) on an electric current

"Transforming music"

When demonstrating the principle of an electric transformer one usually transforms only harmonic alternate voltage and uses only coils made from wire. Could it be possible to use something else instead of a wire? And is it possible to transform something more interesting than harmonic voltage?

In the following experiment we transform music and, to make the experiment more surprising for students, we can even use our fingers instead of wire in a "coil" (with just one turn).

You can see the arrangement of the experiment in figure 5.

We use music from a small cassette-recorder. Amplified signal from this recorder powers primary coil (of 600 turns) of a transformer. In a first version of the experiment we use one turn of wire as a secondary coil. The second amplifier connected to a secondary coil is a simple amplifier with one transistor; its output is connected to the input of a sound card of a computer.

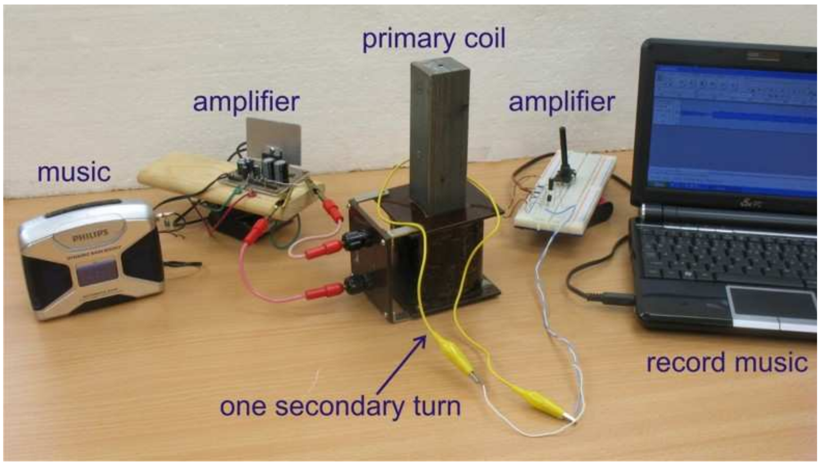


Fig. 5: Arrangement of the experiment

The notebook then acts as a speaker and a recording device. Output signal can be recorded for example by a program Audacity (you can see the output at fig. 6). One turn of secondary coil is enough to produce clear signal at the output. We can show that changing the diameter of the secondary turn does not change significantly the amplitude of the output signal. If we use two turns instead of one the amplitude grows twice.

In the second version of the experiment we use our fingers as a secondary coil instead of wire. Output is very noisy in this case, but the music can be clearly distinguished.

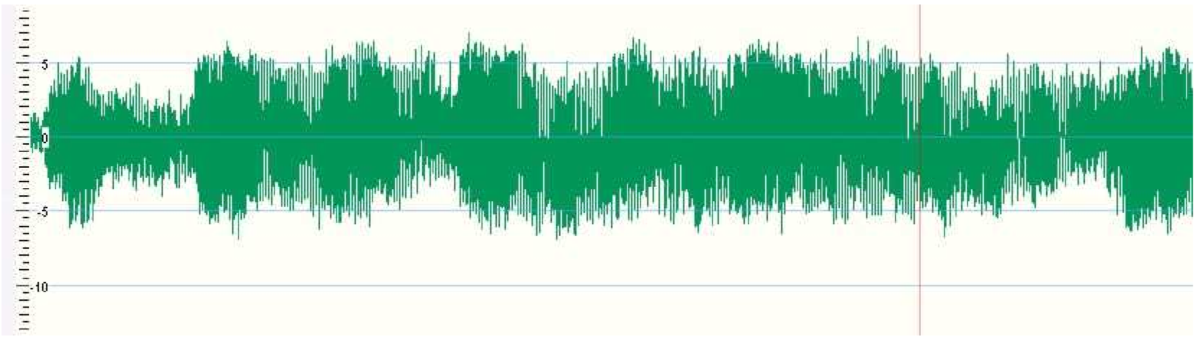


Fig. 6: Transformed music – output from the Audacity

Dissipation of magnetic field

In most of usual school experiments with electric transformer we can see that not all magnetic flux flows inside the core of a transformer. Part of the magnetic flux dissipates around the core. As a consequence of this dissipation we can for example induce small voltage in one turn of wire which is near the electric transformer but not around the core.

The question can arise how large this dissipation is, i.d. what is the value of the magnetic induction outside the core.

For the experiment we use a core of a common school transformer which is built from two parts – the “U core” and the “I core”. There is a small gap between these cores, which is not usually present in commercial transformer’s cores. Using small Hall’s probe we measured magnetic field near the transformer’s core. To “power the transformer” we used a coil with 300 turns connected to the power source of 12 V AC.

Results of our measurement are shown in figure 7. In both measurements – at the top of the core and at the right side of the core – the Hall’s probe was very close to the core (it touched it). We measured the component of magnetic induction normal to the surface of the core. Let us note that we measured the dissipated magnetic field only at the central part of the top side, not near the front edge or the back edge of the core.

At the top of the core the value of magnetic field of the dissipated flux falls down from the left to right-hand side. The field starts to rise again close to the right-hand edge of the core. We found the maximum of the dissipated magnetic field at 0.5 cm from the left-hand edge of the core; its value was about 0.6 mT.

At the right-hand side of the core the dissipated magnetic field was nearly constant in the central part of the core (about 0.4 mT), rapidly increased near the gap of the core (to more than 1.6 mT) and slightly grew near the lower edge of the core.

The purpose of this experiment is rather to describe qualitatively or semi-quantitatively how the magnetic field dissipates from a core – precise quantitative explanation of this effect would be out of the scope of the lecture Classical Electrodynamics for future physics teachers.

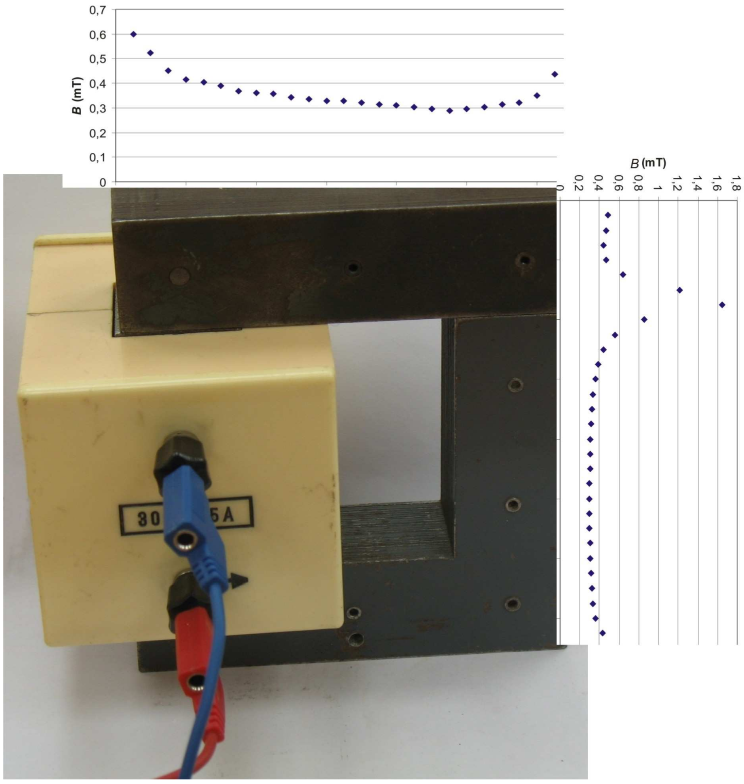


Fig. 7: How large is the dissipation of magnetic field around the core?

Magnetic quadrupole, dipole…and monopole?

As a motivation to this experiment we can ask two or three questions:

1) Is it possible to demonstrate the idea of multipole expansion in a simple way?
2) Is it possible to demonstrate how the field of magnetic monopole would behave?
3) Is it possible to do such demonstrations quantitative and to obtain sufficiently precise (or at least convincing) values of powers in the dependence on distance?

Students learn in the lectures on Classical Electrodynamics that electric or magnetic field of monopole, dipole, quadrupole etc. falls down with increasing distance r from the multipole as

$$\frac{1}{r^{k+2}}, \tag{4}$$

where k = 0, 1, 2… (k = 0 for monopole, k = 1 for dipole, k = 3 for quadrupole, etc. Of course, students learn that there are no magnetic monopoles.).This knowledge follows from a theoretical derivation. Can we support the theory by some simple measurement?

As a magnetic quadrupole we can use two pairs of small thin neodymium magnets (1 cm in diameter and 2 mm in height). Members of each pair are at both sides of a paper sheet, the pairs are beside each other (see fig. 8a). The pairs of magnets have an opposite orientation. As a magnetic dipole we can use just two small magnets with a paper sheet between them (see fig. 8b). Magnets attracts together. These magnets have the same parameters as the magnets we used for the quadrupole.
We can even create the configuration which produces magnetic field that behaves (to some distance) like a magnetic monopole! As such a magnetic “monopole” we can use a small steel ball with attached rod composed of long thin neodymium magnets (see fig. 8c). In our case the magnetic rod consisted of 10 magnets 2.5 cm long and about 0.5 cm in diameter.

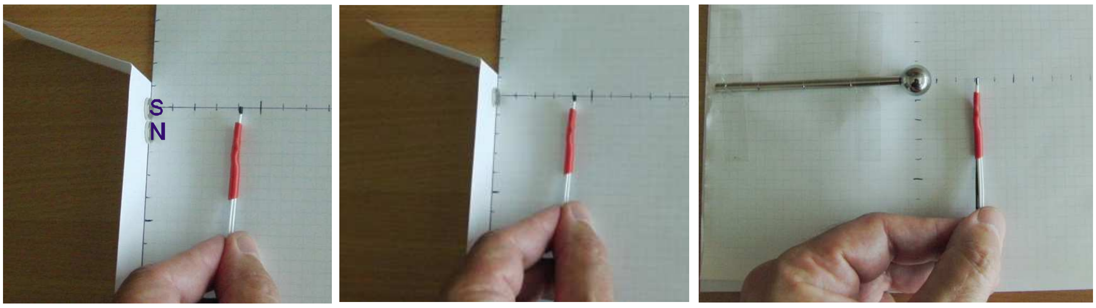


Fig. 8: a) magnetic quadrupole, b) magnetic dipole, c) magnetic “monopole”

We used a small Hall’s probe to measure field around these multipoles. The field around the “monopole” and the dipole was measured at distances from 20 mm to 100 mm, the field around the quadrupole was possible to measure only at distances between 30 mm and 60 mm. (The field near the quadrupole at distances less than 30 mm did not correspond to theoretical values for point-like quadrupole. This is natural because the distances in this case are the size of the magnets. Due to the fact that a magnetic field around the quadrupole falls down as a r^{-4} the magnetic field at distances longer than 60 mm is too small to be possible to measure it by our simple probe.)
Results of measurements can be seen in the graph in figure 9. The interpolations done by Excel show that a magnetic field we measured falls down like $r^{-3,96}$ for the quadrupole, like $r^{-2,94}$ for the dipole and like $r^{-2,03}$ for “monopole”, in surprisingly well agreement with theory, (To take into account the final size of magnets could improve the agreement but even without such corrections the results seem to be sufficiently convincing – so we prefer to let the experiment and the processing of measured data as simple as they are in their current form described above.)

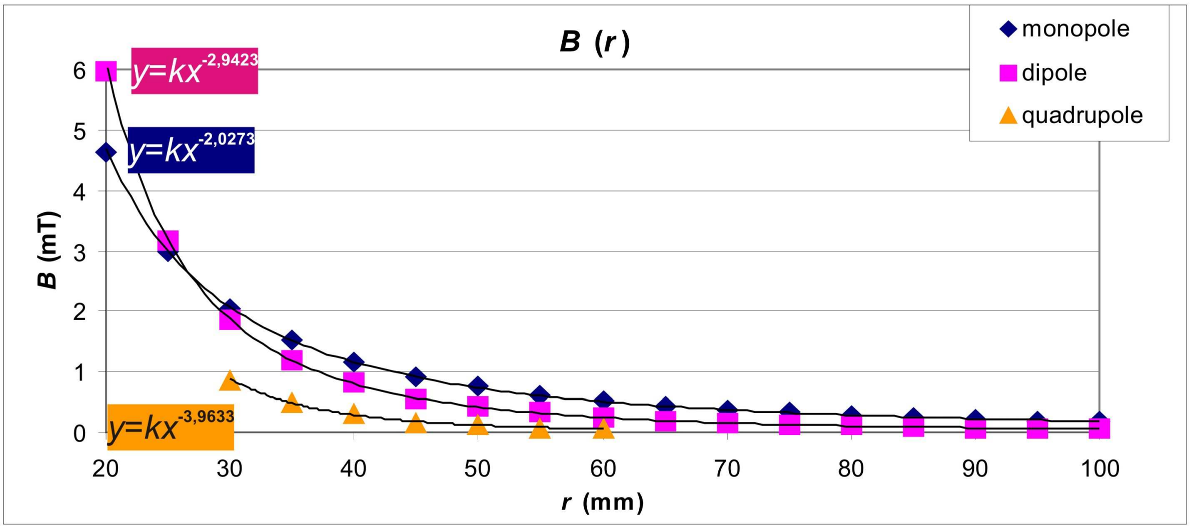


Fig. 9: Results of measurements of magnetic field near a quadrupole, dipole and a “monopole”

Conclusions

We developed simple, low-cost and not time consuming but still quantitative demonstrational experiments that can enrich formerly only theoretical lecture on Classical Electrodynamics. Especially some non-traditional experiments may enhance motivation of students and – not only for future physics teachers – elucidate connections between theoretical formulas and reality. We plan to describe some of these experiments in more details elsewhere – and to continue in the development of similar simple experiments that can help in students' understanding of physical theory and its relation to reality.

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References

[1] Jackson, J. D.: Classical Electrodynamics, 3rd ed.1998.