# ELECTROMAGNETIC INDUCTION. FARADAY'S LAW

## 1. Aim.

- Observe the effect of introducing a permanent magnet into a coil.
- Study what happens when you introduce a small coil into a coil in which an alternating current circulates. Analyze the effect of the frequency of the current through the coil.
- Discuss the results of these experiments using Faraday's law.
- Determine the magnetic field inside a solenoid when an alternating current passes through. Study the induced electromotive force in a small coil that is introduced into the solenoid.

## 2. Overview.

### 2.1. Faraday´s law

In the early 1830 Michael Faraday and Joseph Henry, working independently, discovered that if the flux of a magnetic field ($\Phi$) thought a conducting coil changes with time an electric current is observed in the coil. The current caused by changing magnetic flux is called *induced current*.

The induced current is caused because the change of the magnetic flux produces an *electromotive force* (emf) in the circuit. ***Faraday's law*** relates the induced emf with the change in the magnetic flux.

$$\varepsilon = -\frac{d\Phi}{dt} \qquad [1]$$

The negative sign in Faraday´s law is related with the direction of the induced emf, this is a general physical principle known as ***Lenz law***. If the magnetic flux through the circuit increases, the direction of the induced current is such that opposes to this change by trying to reduce the magnetic flux; if the flow decreases, the induced current is in such a direction as to oppose the change that produces it, trying to increase the magnetic flux through the circuit.

This is illustrated in Fig.1, which shows that when the magnet moves towards the coil, it produces a current in the indicated direction. The magnetic field due to the current induced in the loop (indicated by the dashed line) produces a flow that opposes the increase in flux through the loop due to the approach of the magnet.

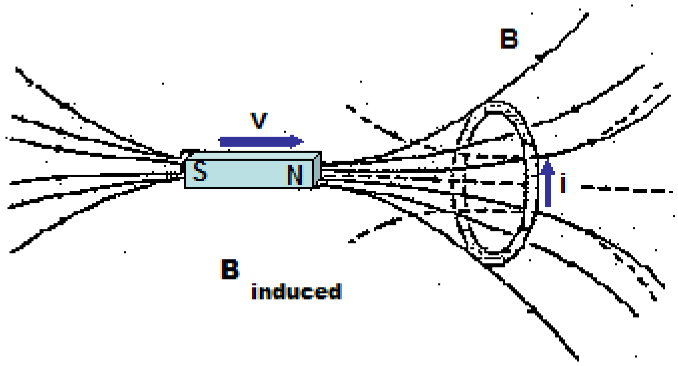



**Figure 1.**

## *2.2. Magnetic field inside a solenoid.*

A solenoid is essentially a coiled conductor thread shaped like a helix on a support usually cylindrical as shown in Fig.2.

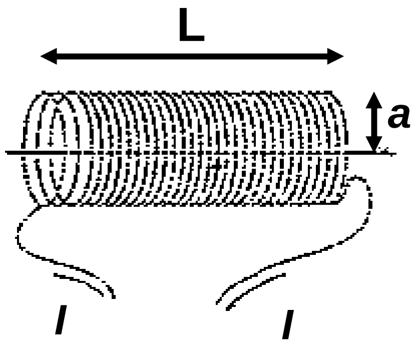



**Figure 2.**

In figure 3, you can see the magnetic field lines due to a solenoid with a current $I$ (see Fig.3 (a)) and the value of the $B$ field on the axis of the solenoid (see Fig.3 (b)) as a function of distance $x$ to the midpoint of the solenoid.

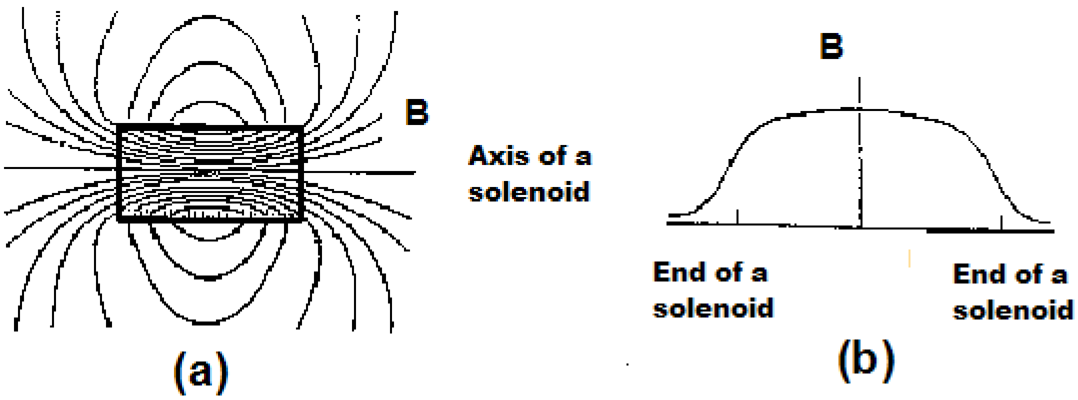



**Figure 3.**

In these figures we can see that the magnetic field *B* inside the solenoid is approximately uniform and parallel to the axis of the solenoid and it becomes smaller as we approach the edges, and continues to decrease outside. It can be shown that in a solenoid of length *L* and radius *a* (see Fig.2), the magnitude of the magnetic field *B* at a distance *x* from its center is given by the expression:

$$B_0 = \frac{\mu_0 nI}{2}\left(\cos\beta_2 - \cos\beta_1\right) \qquad [2]$$

where $\mu_0$ is the permeability of free space, $\mu_0 = 4\pi\cdot 10^{-7}$ H/m, *n* is the number of turns per unit length of solenoid, $n = N/L$ (*N* is the number of turns in the solenoid and *L* its length)

$$\cos\beta_1 = -\frac{\frac{L}{2} - x}{\sqrt{\left(\frac{L}{2} - x\right)^2 + a^2}}$$

$$\cos\beta_2 = +\frac{\frac{L}{2} + x}{\sqrt{\left(\frac{L}{2} + x\right)^2 + a^2}} \qquad [3]$$

The field *B(x)* on the axis of the solenoid is shown in Fig.3 (b). When the solenoid is very long, inside the solenoid and far from the edges *B* is approximately constant and its value, using (2), is approximately:

$$B = \mu_0 nI \qquad [4]$$

## *3. Learn more…*

- **TIPLER, PA & MOSCA, G. "Physics" 4th edition Ed W.H Freeman and company 1999. Chapter 30 "Magnetic Induction"**
- **SERWAY, RA & JEWETT, JW. "Physics" Volume 2. 3th edition Ed Thomson 2003.**

**In internet:**

http://hyperphysics.phy-astr.gsu.edu/hbase/electric/farlaw.html

http://www.phys.unsw.edu.au/PHYS1169/beilby/magnetism2.htm

## 4. Equipment.

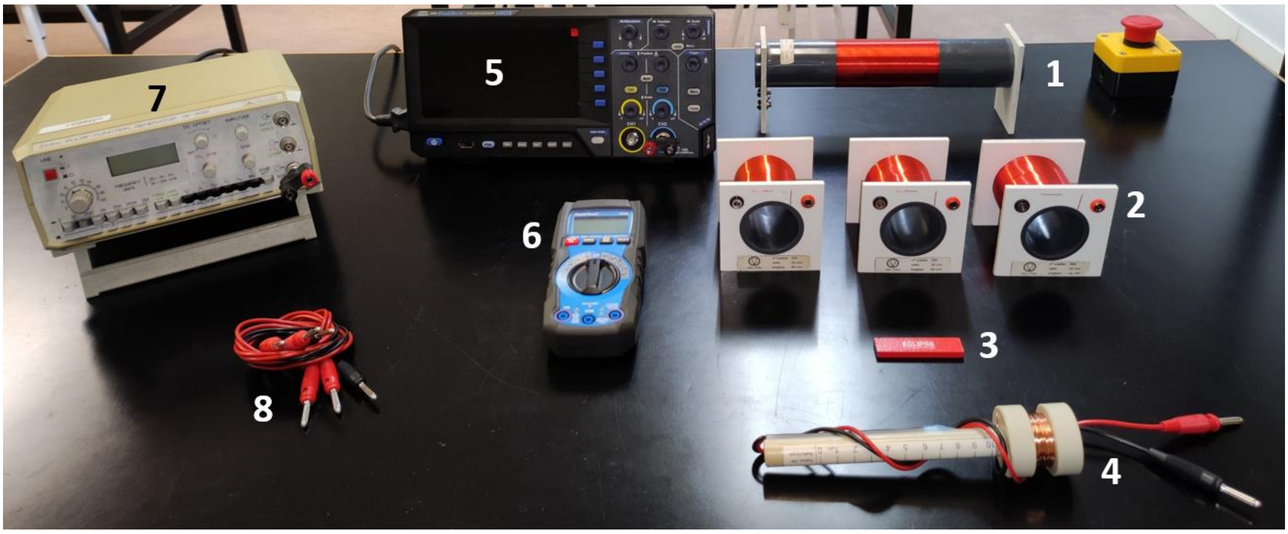



**Figure 4**

1. Solenoid
2. 200, 500 and 1000 turns coils.
3. Magnet.
4. Small coil.
5. Oscilloscope.
6. Multimeter.
7. Frequency generator.
8. Connectors.

## 5. Experimental procedure

### 5.1. Electric current induced by a magnet in a coil.

1. Connect the 200 turns coil to the oscilloscope. The oscilloscope shows the **emf** in the coil. The electromotive force should be zero initially.
2. Quickly enter the magnet inside the 200 turns coil. Do you see any electromotive force in the coil? Record your observations.
3. Place your magnet inside the coil and take out it rapidly. What happens to the signal?

4. Repeat the test with the other pole of the magnet. Does an induced **emf** appear? What is its direction?

5. Move the coil with the magnet at rest, inside the coil. Do you see an induced **emf**?

6. Repeat the above steps with coils of 500 and 1000 turns, respectively. What differences do you see?

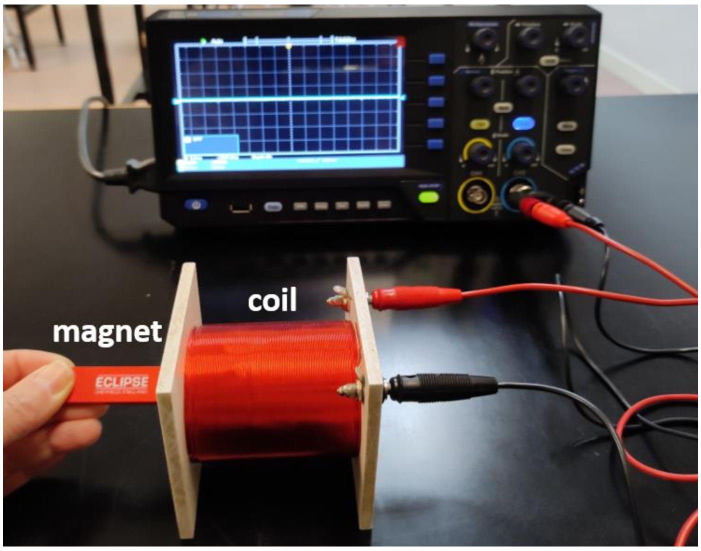
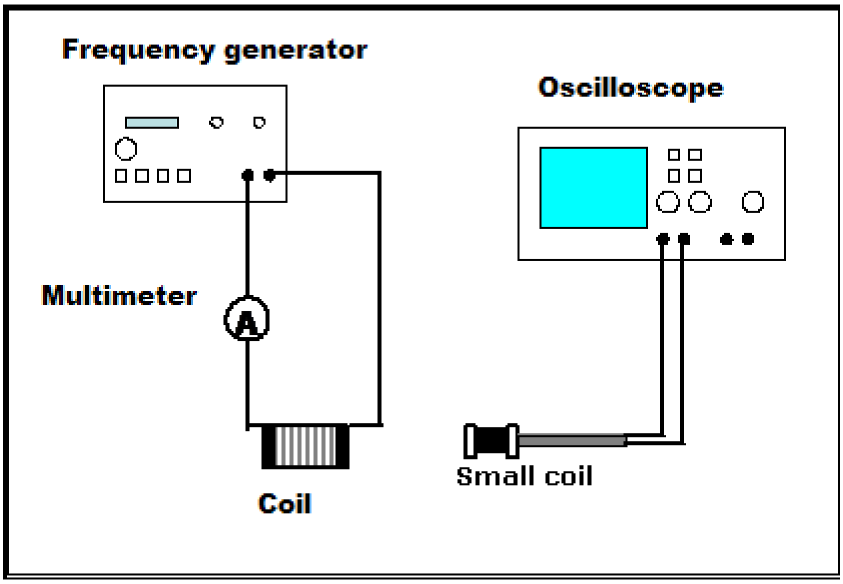



**Figure 5.**

### *5.2. Electric current induced in a small coil by another coil.*

1. Take the small coil and a 1000 turns coil, and prepare the setup shown in Figure 6. The coil is connected to the frequency generator and the small coil to the oscilloscope, in this way, the oscilloscope measures the electromotive force on the small coil.

**Schematic procedure.**



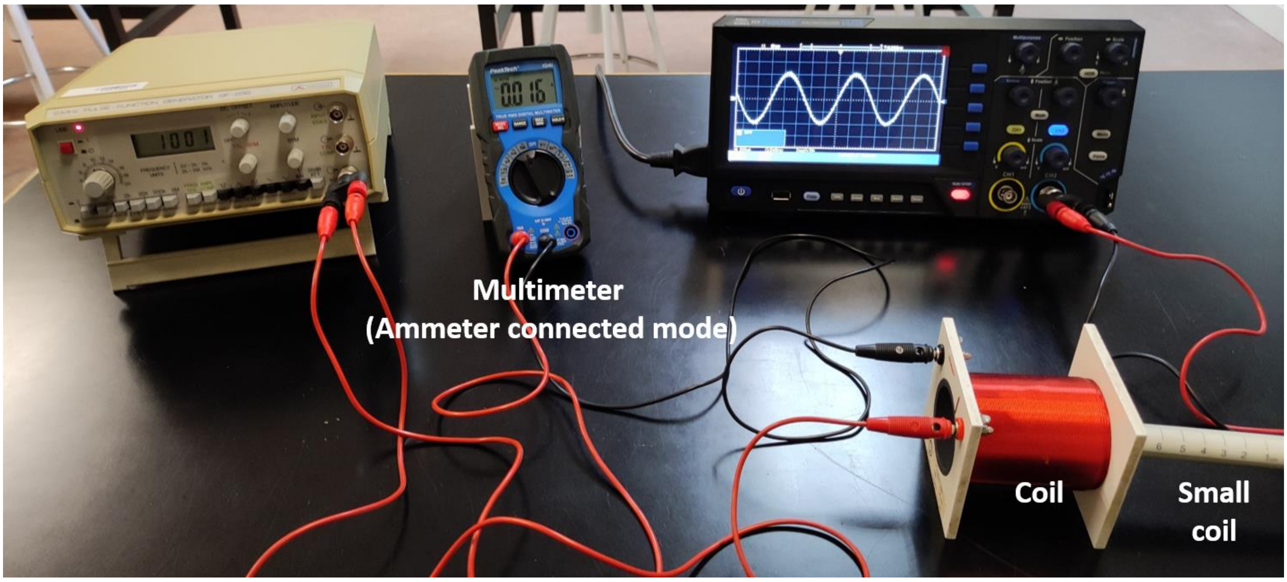



**Figure 6**

2. Turn on the frequency generator and select a sinusoidal output of frequency $f$=4 kHz. An intensity $I = I_0 \cos\omega t$ circulates through the coil, where $\omega=2\pi f$ is the angular frequency. Record the value of the current in the coil, as measured in the multimeter (Note: Although the coil is carrying an alternating current $I = I_0 \cos\omega t$, the value measured on the multimeter is the **rms current**, $I_{rms} = I_0 /\sqrt{2}$).

   When driving a current through the coil, it creates a magnetic field inside approximately uniform and proportional to the current:

$$B = \mu_0 nI = B_0 \cos\omega t \qquad \textbf{[5]}$$

   where $n$ is the number of turns per unit length of the coil and $B_0=\mu_0 n I_0$.

   What is now observed on the oscilloscope? Measure the period of the oscillations and determine their frequency. Check that it coincides with the frequency of the current in the coil (f =4kHz). Determine the peak to peak voltage $V_{pp}$ and the small coil amplitude $\varepsilon_0$, $\varepsilon_0 = V_{pp} /2$.

3. Repeat the measurements for 500 Hz, 1 kHz, 2 kHz and 3 kHz frequencies. Regulate the amplitude in the generator until the current measured by the multimeter is approximately equal to the previous case, so we are sure that the amplitude of the current $I_0$ that circulate through the coil is the same than before. Measure the amplitude and frequency of the oscillations of the **emf** in the small coil in all cases.

### *5.3. Measure the magnetic field inside a solenoid*

Suppose we have a solenoid such as the one you can see on Figure 7, of radius ***a*** and length ***L***, through which an alternating current $I = I_0 \cos\omega t$ flows. When varying I with time, the field $B$ due to the solenoid will also vary respect to time and according to equation [2], its value at a point on its axis at a distance $x$ from the center of the solenoid can be written as:

$$B = B_0 \cos\omega t \qquad \textbf{[6]}$$

where $B_0$ is the magnetic field amplitude $B$ at this point, given by:

$$B_0 = \frac{\mu_0 n I_0}{2}\left(\cos\beta_2 - \cos\beta_1\right) \qquad \textbf{[7]}$$

with $\cos\beta_1$, $\cos\beta_2$ given by the relation [3].

If we place a small coil inside the solenoid, with its axis coinciding with the axis of the solenoid (see Fig.7), there will be a variation of magnetic flux through the turns of the small coil and, therefore, an induced **emf** will appear in the small coil.

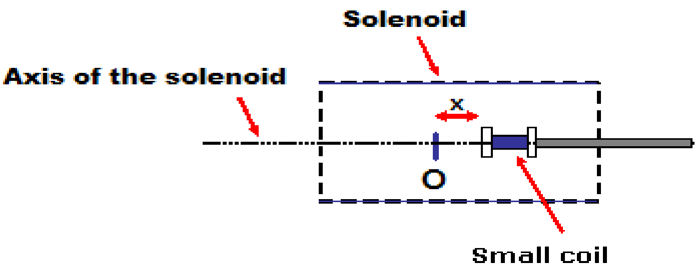



**Figure 7**

In a first approximation, as the small coil is small compared to solenoid, the magnetic field B due to the solenoid can be considered constant within the cross section of the small coil. Therefore, the flow $\Phi$ through the turns $N_c$ of the small coil is:

$$\Phi = N_c A_c B = N_c A_c B_0 \cos\omega t \qquad \textbf{[8]}$$

Where $A_c$ is the area of each turn of the small coil and $B$ the magnetic field due to the solenoid at point x where is located the small coil, $B = B_0\cos\omega t$, with $B_0$ at that point given by (7). Using Faraday's law, it can be deduced that the emf induced in the small coil will be:

$$\varepsilon_{ind} = \varepsilon_0 \sin\omega t \qquad \textbf{[9]}$$

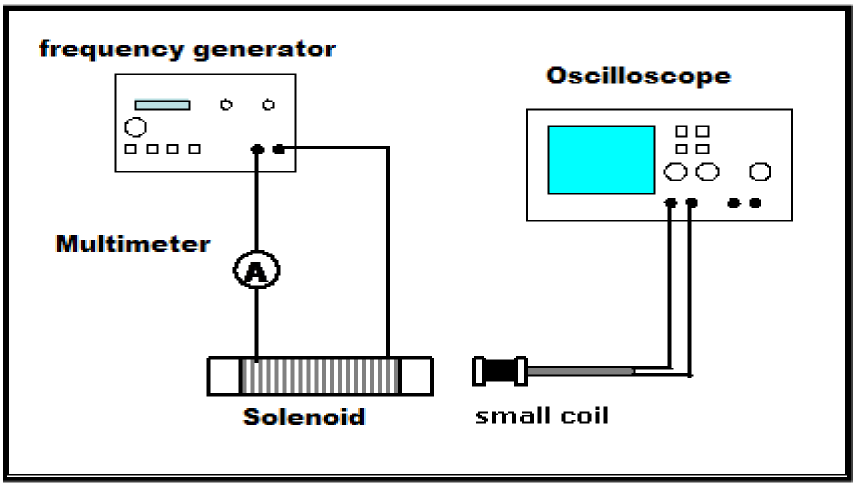
with $\varepsilon_0$, the amplitude of the induced emf, given by $\varepsilon_0 = N_c A_c \omega B_0$. Therefore, if we measure the amplitude $\varepsilon_0$ of the induced emf in the small coil at a point x axis of the solenoid, we can calculate the amplitude $B_0$ at that point of the magnetic field due to the solenoid:

$$B_0 = \frac{\varepsilon_0}{N_c A_c \omega} \qquad \textbf{[10]}$$

To do it, we follow these steps:

1. Annotate the number of turns of the solenoid and the small coil. Measure the length $L$ of the solenoid. Write down the radius of the small coil in order to calculate the area $A_c$ of each turn of the small coil.

2. Prepare the setup of Figure 8 and put the small coil inside the solenoid, taking into account that when the small coil is in the center of the solenoid the distance x measured with the ruler attached to the small coil is 0 cm.




**Schematic procedure.**

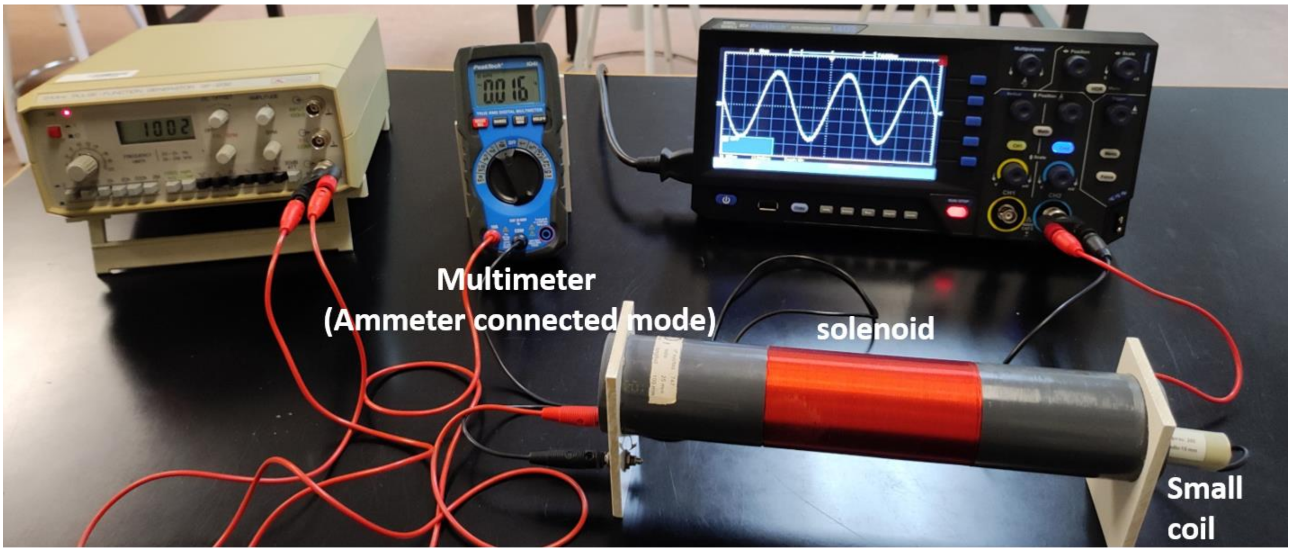



**Figure 8**

3. Select from the generator the frequency 1 kHz and increase its amplitude in order to see clearly the emf induced in the small coil on the oscilloscope.

4. Record the peak to peak voltage $V_{pp}$ and calculate the amplitude $\varepsilon_0 = V_{pp}/2$ of the emf induced in the small coil.

5. Record the value of current in the solenoid indicated on the multimeter. Remember that, although the solenoid is carrying an alternating current $I = I_0 \cos\omega t$, the value measured on the meter is the effective current $I_{rms} = I_0/2^{1/2}$.

6. Repeat the above steps by varying the distance *x* from the small coil to the center of the solenoid in 1 cm steps.

7. Plot theoretical and experimental values of $B_0$ as a function of x.

8. Discuss plot results.