Helmholtz coil as an environment for teaching basic properties of magnetic field by combining multimedia and real experiments

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Overview

- Motivation
- Helmholtz pair
- Past
- Present
- Students at work
- Connclusions

Motivation

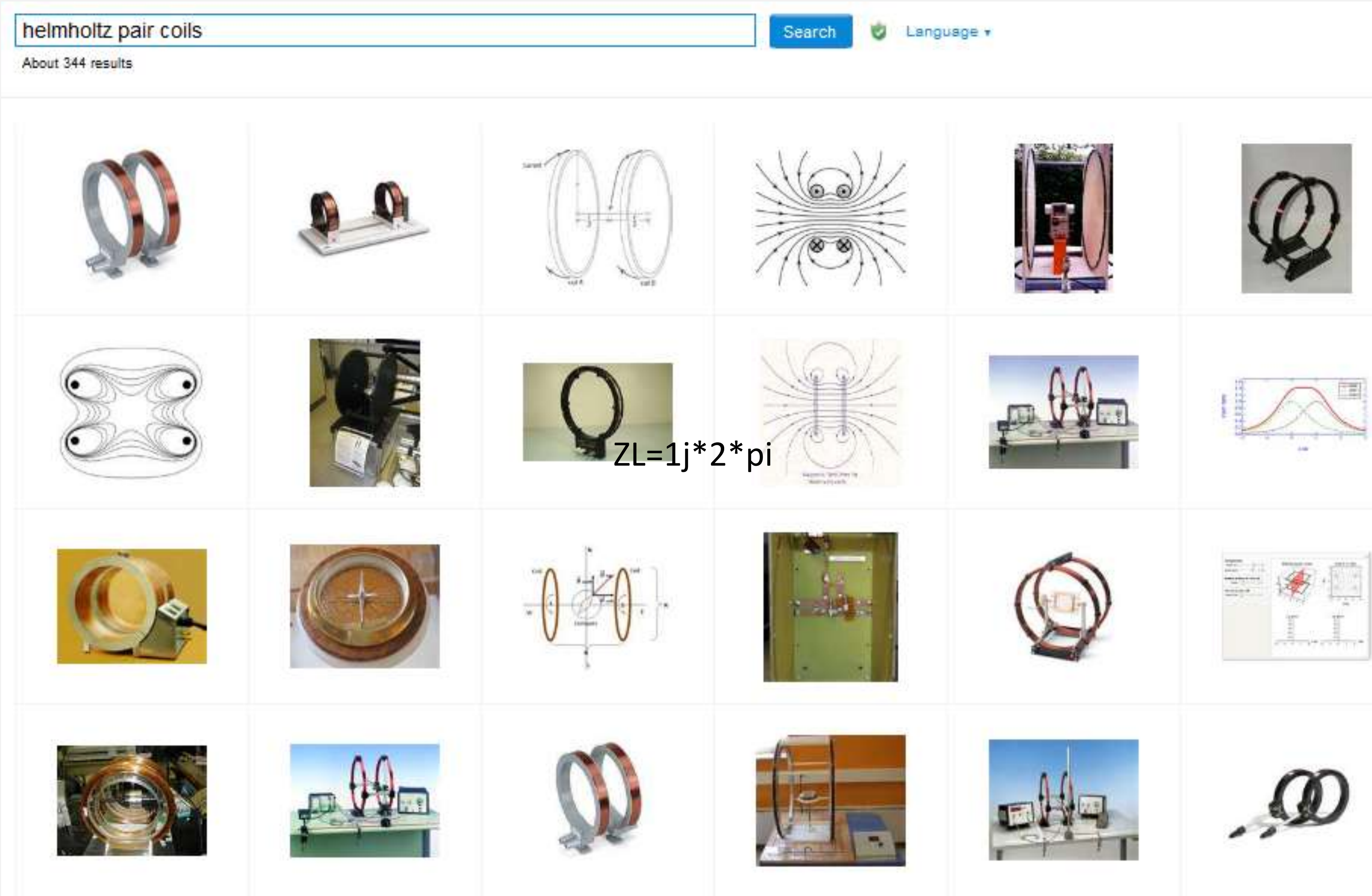
Our motivation is how to motivate students:

1. Use of modern technology

- Measurement equipment
- Computers
- Data analysis

2. Need for real (hands on) experiments

- Using equipment same as in industry !
- Experiment, that is used also in practice !



ZL=1j*2*pi

Helmholtz pair of coils

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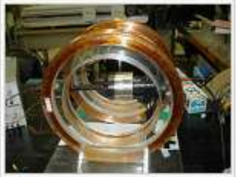
Helmholtz coil

From Wikipedia, the free encyclopedia

A **Helmholtz coil** is a device for producing a region of nearly uniform magnetic field. It is named in honor of the German physicist Hermann von Helmholtz.



A Helmholtz coil

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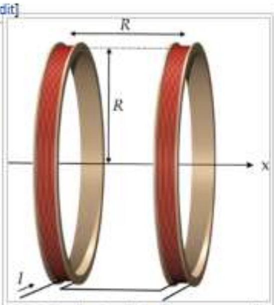
Description [edit]



Helmholtz coil schematic drawing

A Helmholtz pair consists of two identical circular magnetic coils that are placed symmetrically one on each side of the experimental area along a common axis, and separated by a distance h equal to the radius R of the coil. Each coil carries an equal electrical current flowing in the same direction.

Setting $h = R$, which is what defines a Helmholtz pair, minimizes the nonuniformity of the field at the center of the coils, in the sense of setting $\partial^2 B/\partial x^2 = 0$[1] (meaning that the first nonzero derivative is $\partial^4 B/\partial x^4$ as explained below), but leaves about 7% variation in field strength between the center and the planes of the coils. A slightly larger value of h reduces the difference in field between the center and the planes of the coils, at the expense of worsening the field's uniformity in the region near the center, as measured by $\partial^2 B/\partial x^2$.[2]

In some applications, a Helmholtz coil is used to cancel out the Earth's magnetic field, producing a region with a magnetic field intensity much closer to zero.[3]

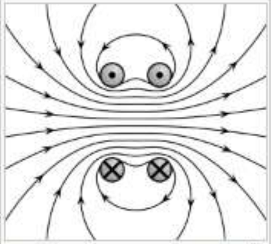
Mathematics [edit]

The calculation of the exact magnetic field at any point in space is mathematically complex and involves the study of Bessel functions. Things are simpler along the axis of the coil-pair, and it is convenient to think about the Taylor series expansion of the field strength as a function of x, the distance from the central point of the coil-pair along the axis. By symmetry the odd order terms in the expansion are zero. By separating the coils so that charge $x = 0$ is an inflection point for each coil separately we can guarantee that the order x^2 term is also zero, and hence the leading non-uniform term is of order x^4. One can easily show that the inflection point for a simple coil is $R/2$ from the coil center along the axis; hence the location of each coil at $x = \pm R/2$

A simple calculation gives the correct value of the field at the center point. If the radius is *R*, the number of turns in each coil is *n* and the current flowing through the coils is *I*, then the magnetic flux density, B at the midpoint between the coils will be given by

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R}$$

μ_0 is the permeability of free space $(1.26 \times 10^{-6}\ \mathrm{T \cdot m/A})$.



Magnetic field lines in a plane bisecting the current loops. Note the field is approximately uniform in between the coil pair. (In this picture the coils are placed one beside the other: the axis is horizontal)

Derivation [edit]

Start with the formula for the on-axis field due to a single wire loop [1] (which is itself derived from the Biot-Savart law):

$$B = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}$$

Where:

μ_0 = the permeability constant = $4\pi \times 10^{-7}\ \mathrm{T \cdot m/A} = 1.257 \times 10^{-6}\ \mathrm{T \cdot m/A}$

I = coil current, in amperes

... radius, in meters

n.wikipedia.org/wiki/Main_Page

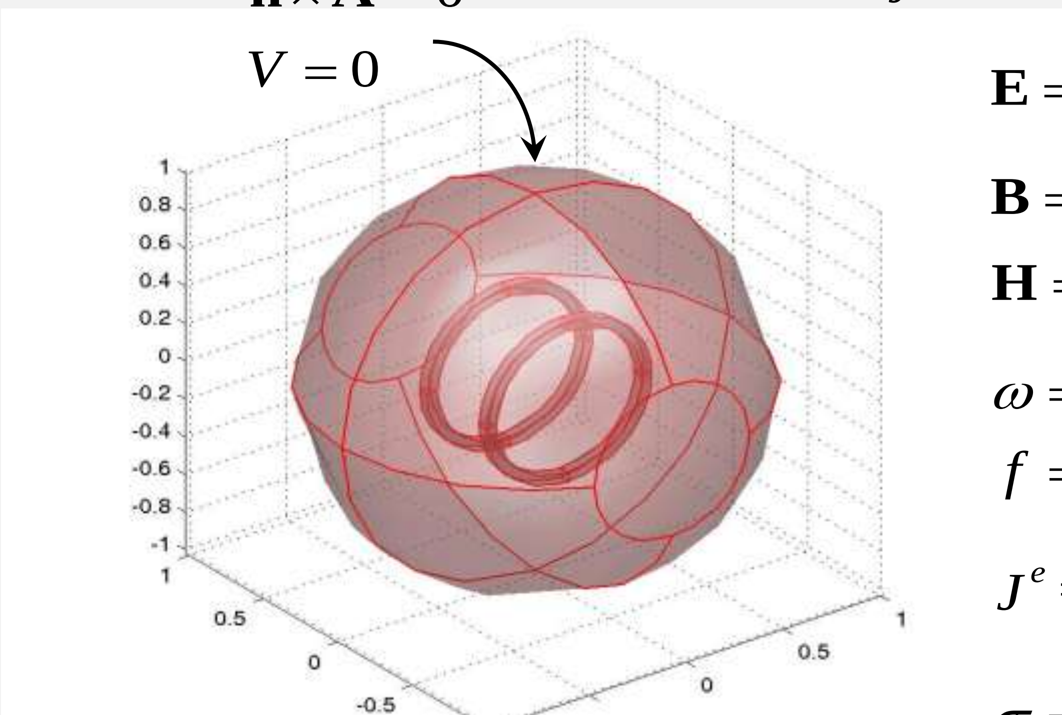
Domain equations and boundary conditions

$$-\nabla \cdot \left(j\omega\sigma\mathbf{A} + \sigma\nabla V - \mathbf{J^e} \right) = 0$$

$$j\omega\sigma\mathbf{A} + \nabla \times \left(\mu^{-1} \nabla \times \mathbf{A} \right) + \sigma\nabla V = \mathbf{J^e}$$

$$\mathbf{n} \times \mathbf{A} = 0$$

$$V = 0$$



$$\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{H} = \mu^{-1}\mathbf{B}$$

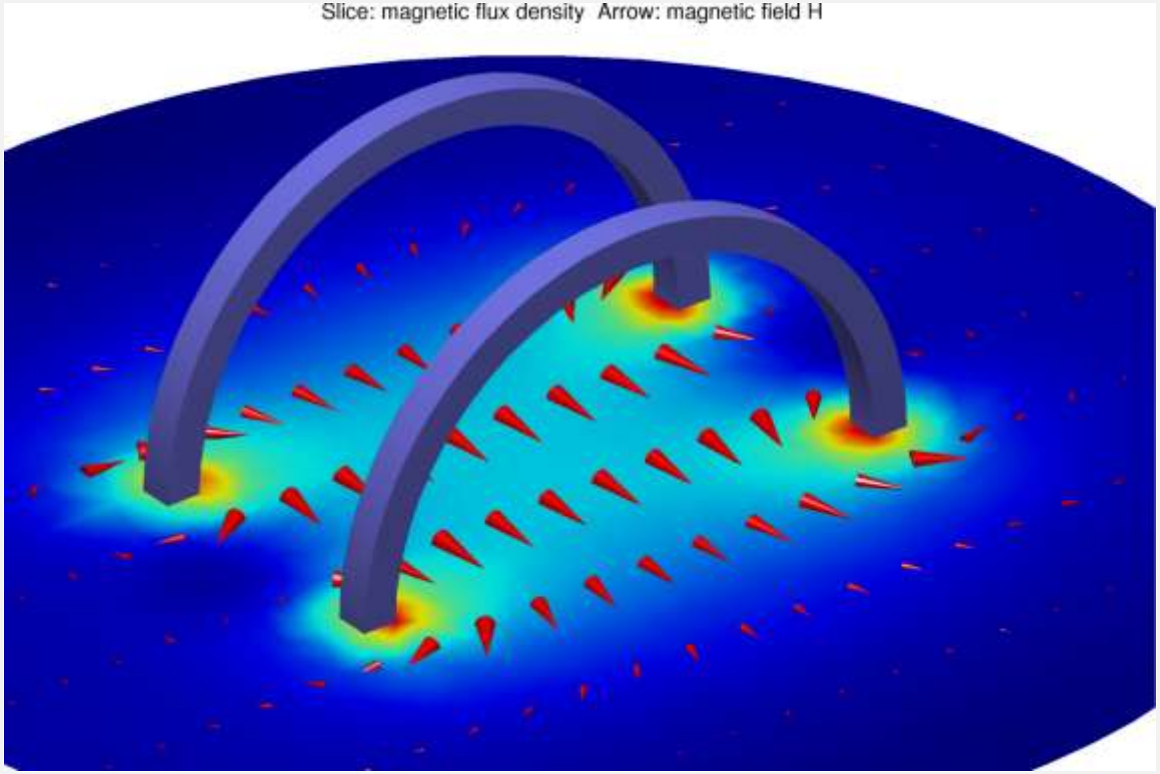
$$\omega = 2\pi f \text{ (radians/s)}$$

$$f = 50 \text{ (Hz)}$$

$$J^e = \begin{cases} 1 & \left[\mathrm{Am^{-2}}\right] \\ 0 & \end{cases}$$ *(in coil)*

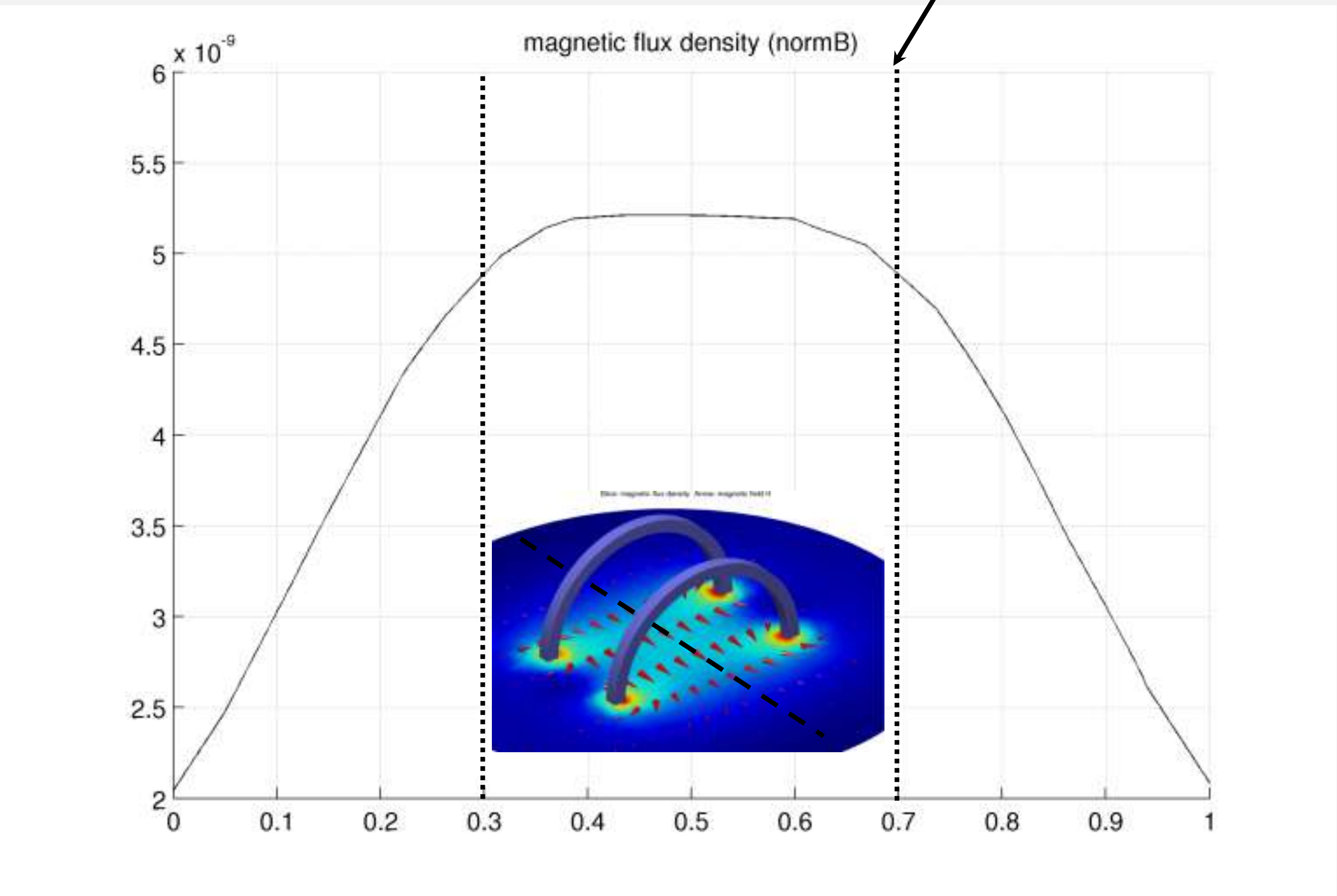
$$\sigma = 1 \quad \left[\mathrm{Sm^{-1}}\right]$$

Magnetic flux density and H-field vectors



Axial profile

coil position



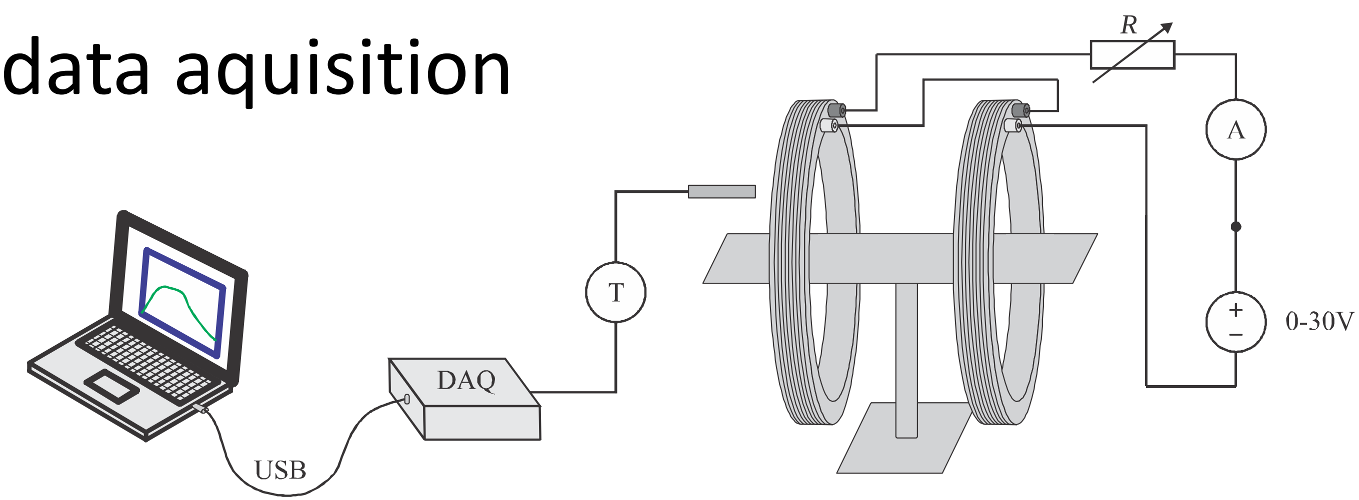
Past

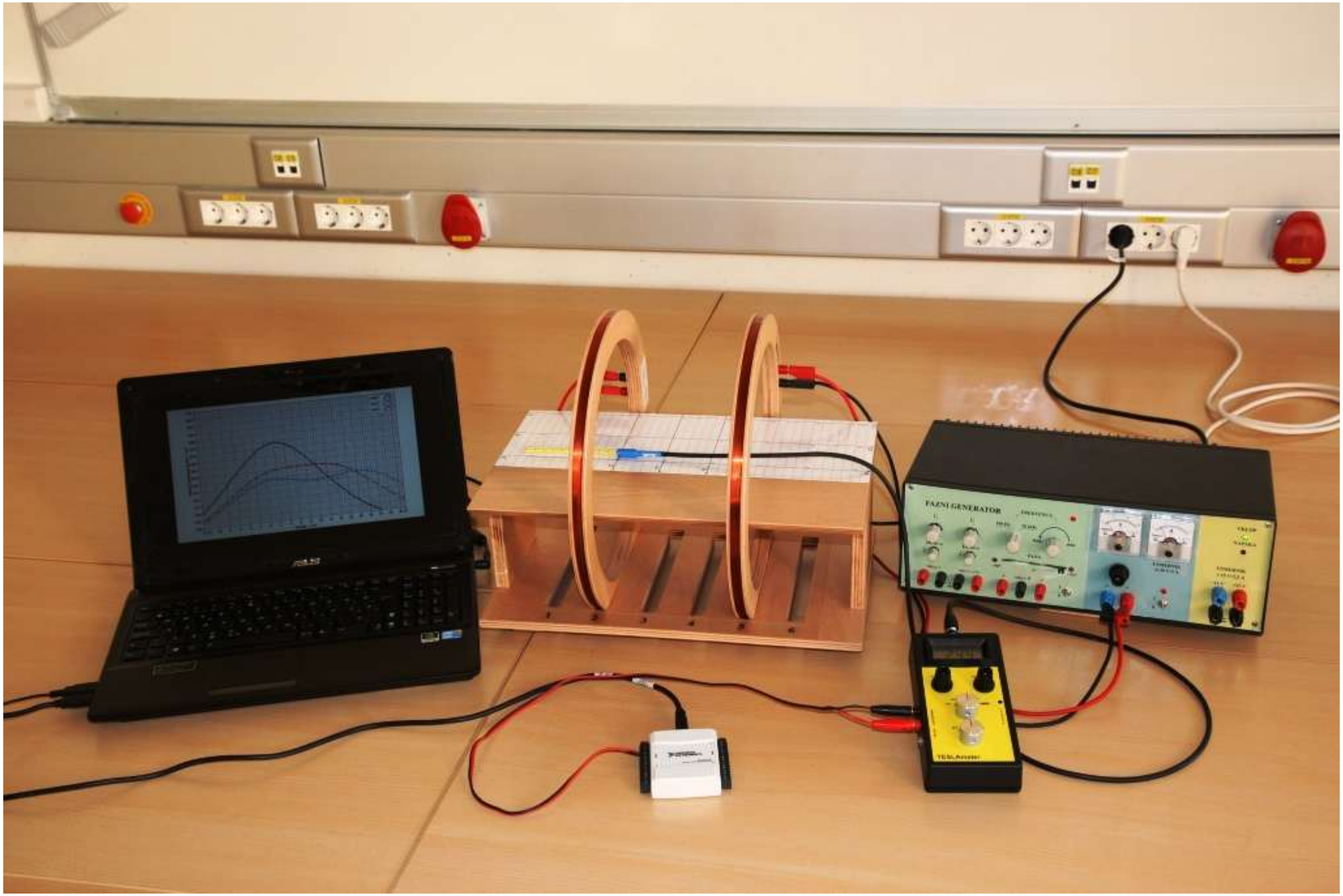
Investigation of magnetic field in the vicinity of a one big coil:

- manual reading from a Teslameter
- writting data manually into a table
- manually plotting the graphs

Today

- Voltage/current source
- Two coils (Helmholtz configuration)
- Ampermeter
- Teslameter with a Hall element
- Computer assisted measurement, analysis, …
- DAQ for data aquisition



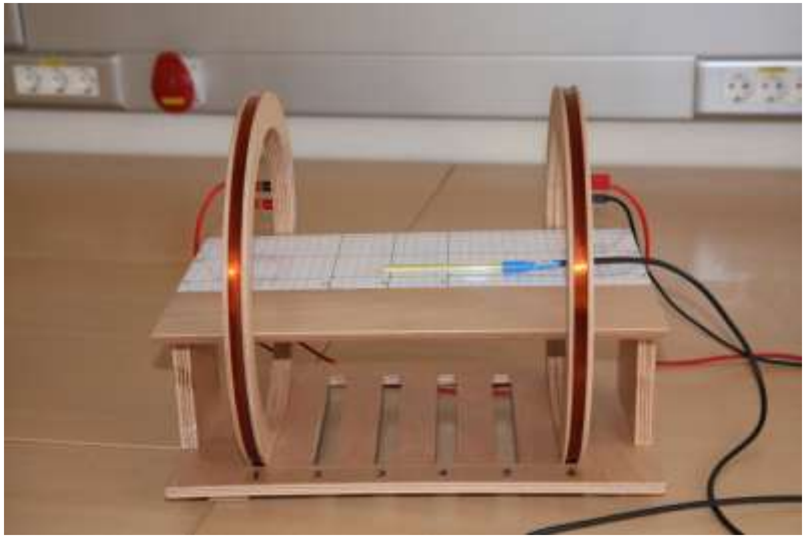

FAZNI GENERATOR

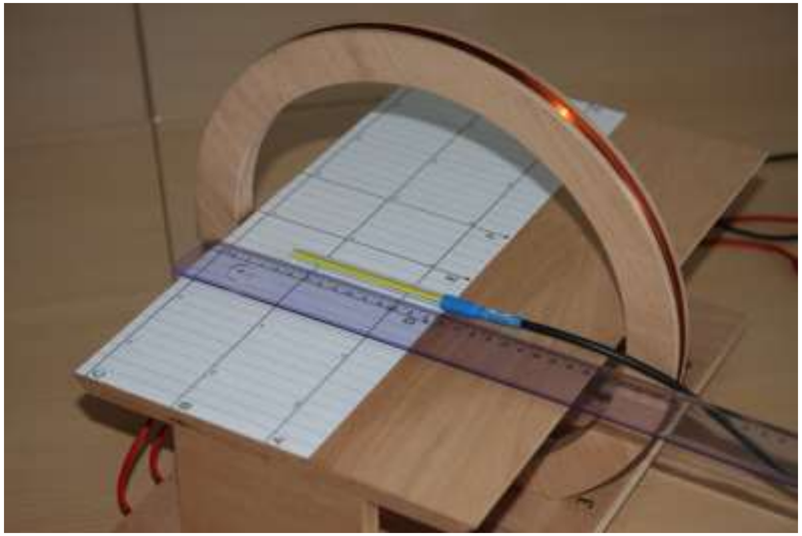
In practice

- Preparatory work (1,5 hour)
  - Introducing the purpose and goal of the experiment
  - Explaining the equipment and its use
  - Video „hands-on„ demonstration
  - Demonstration of use of a computer for calculation, analysis and plotting (Matlab, Octave, Matematica, *Python*)

- Homework
  - Homework consists of several calculations of magnetic field around the coil and the current loop.
  - They use their own computer to plot and insert the calculations and graphs in the prepared laboratory textbook used also later in the laboratory
  - They are encouraged to do some extra effort and use some numerical scripts to calculate the field distributtion numerically and plot it.

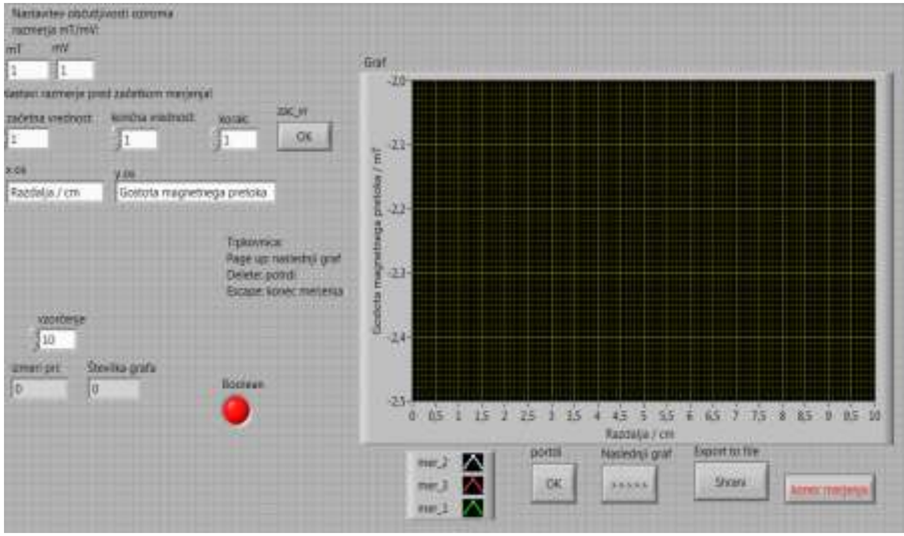
- Laboratory work (1,5 hour)
  - Two students per course
  - Študent sam poveže inštrumente in opravi meritve po navodilih v skripti
  - Pomoč asistenta in demonstratorja
  - Rezultate shranijo v datoteko z rezultati, v kateri dopišejo še nekaj ugotovitev in odgovorijo na vprašanja
  - Na koncu semestra oddajo skripto in priložene rezultate v pregled
  - Ocena laboratorijskega dela se prišteje k oceni kolokvijev





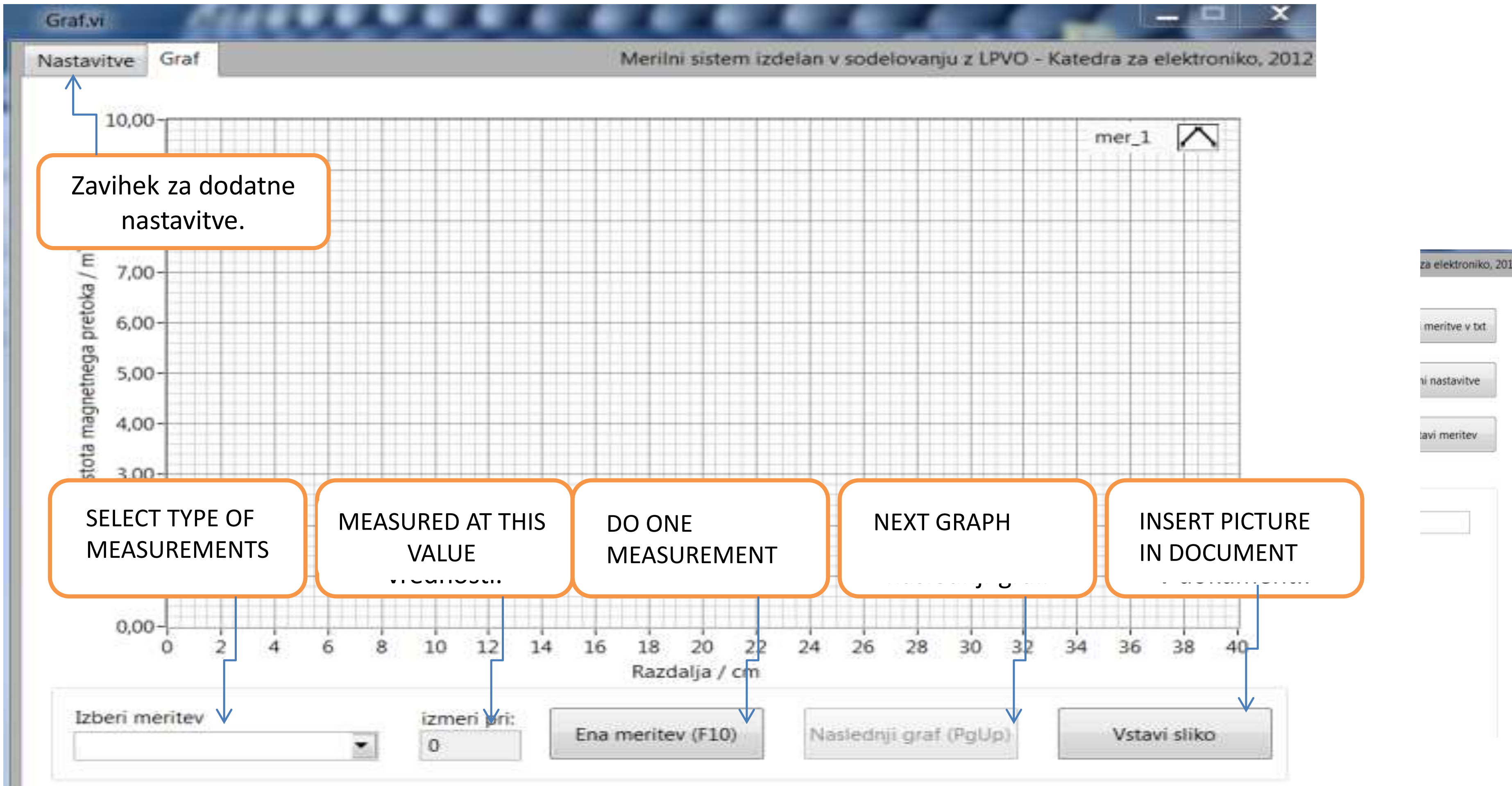
Computer software

- LabVIEW with DAQ
- LabVIEW is a standard for rapid prototyping of measurement setup



- DAQ – data acquisition device NI USB 6009

Programing in LabView



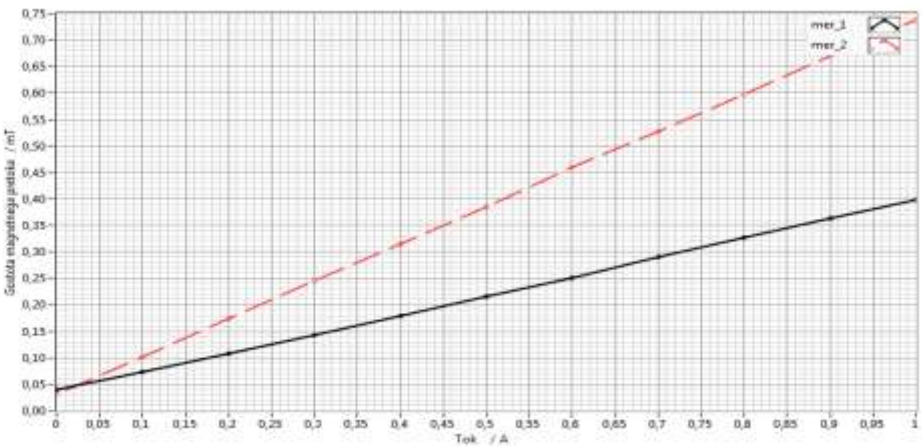
Students at work

Some experiments

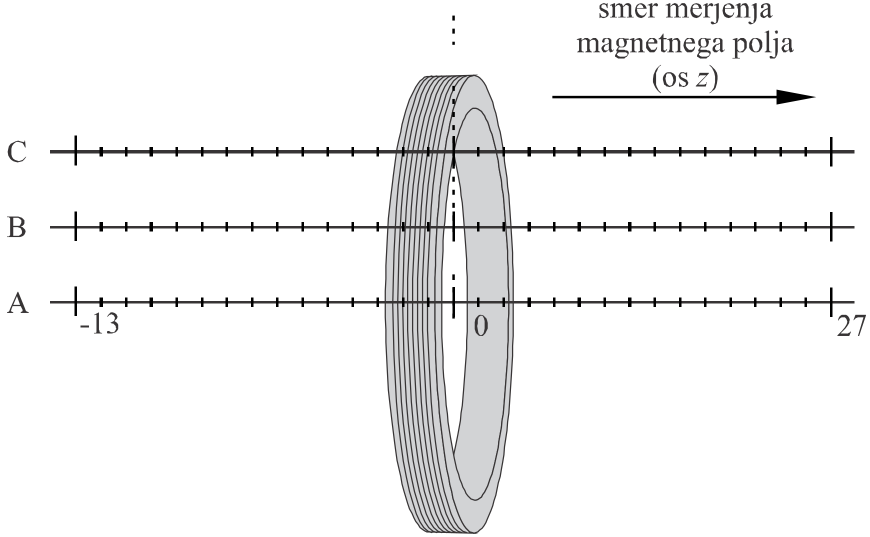
Measuring dependance of magnetic field on the current in one coil

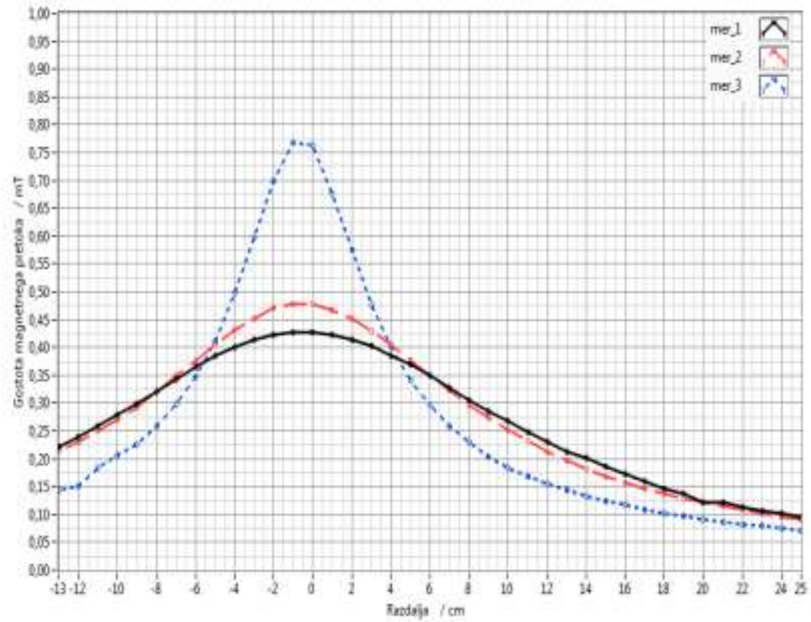
Merjenje odvisnosti magnetnega polja od toka v tuljavi (Graf 1)

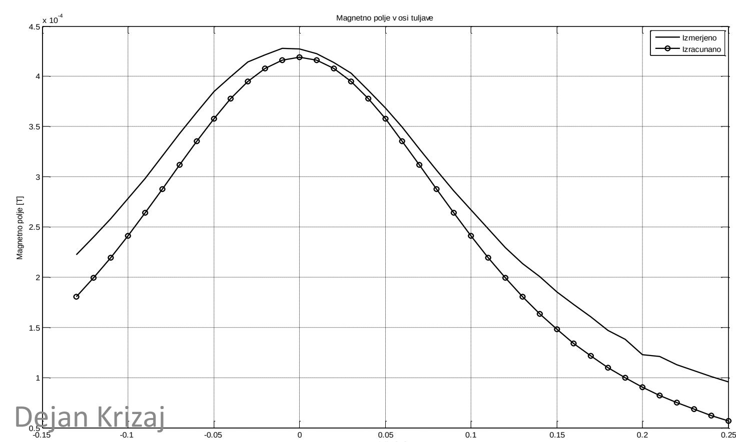
1. Tuljavo vstavite v ležišče 2 in jo povežite z inštrumenti kot kaže merilna shema. Enosmerni napetostni vir naj bo priključen preko ampermetra (v pušo za merjenje v merilnem območju amperov) in (drsnega) upora, na katerem nastavite upornost približno 10 Ω. Na ampermetru je potrebno ročno nastaviti merilno območje na ampere. Vklopite napetostni vir in nastavite napetost (tok) na 0 V (A).
2. Sondo teslametra postavite (približno) v središče tuljave v smeri osi tuljave.
3. Zaženite program Meritve_Graf in v izbirnem meniju izberite *nastavitve_Graf1*.
4. Izvedite meritve s povečevanjem toka od 0 do 1 A s korakom 0,1 A. To izvedete tako, da povečujete tok do želene vrednosti (preverite na priključenem ampermetru) in ob pritisku na tipko Meritev v programu izvedete eno meritev, ki se prikaže tudi na grafu. Opravite meritve za vse prednastavljene vrednosti.



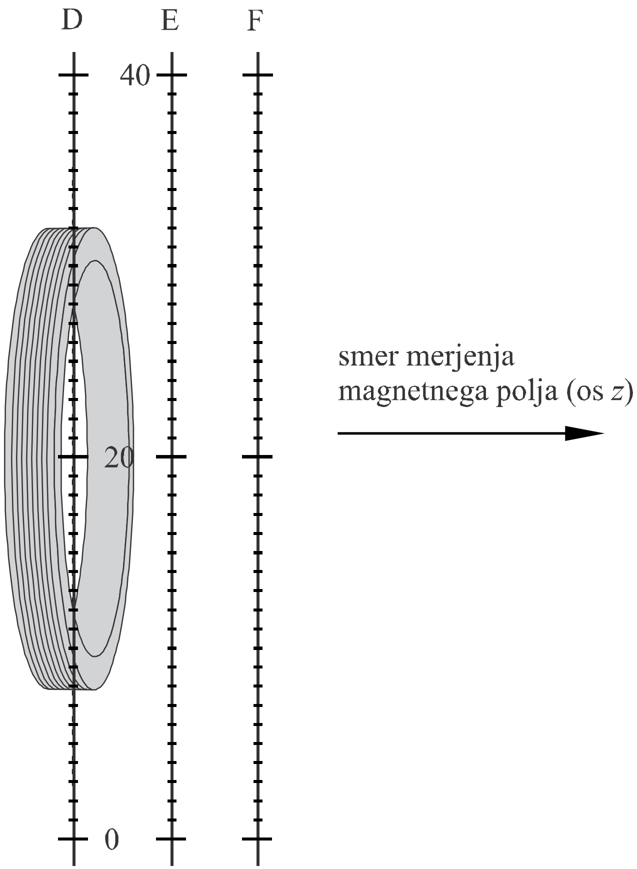
Magnetic field along lines parallel to coil axis

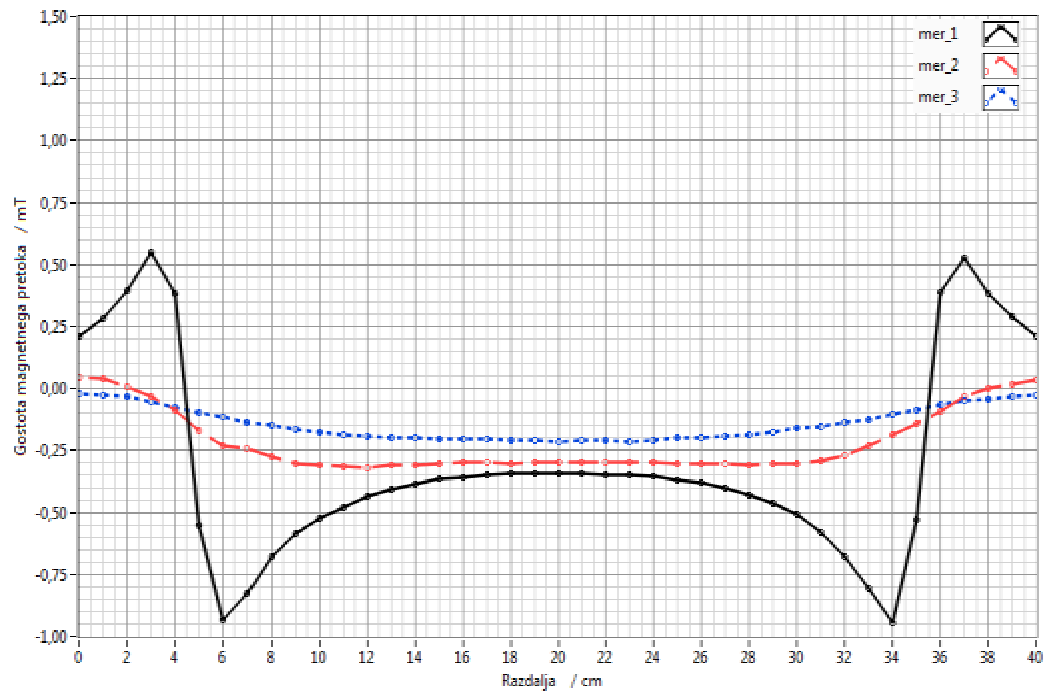




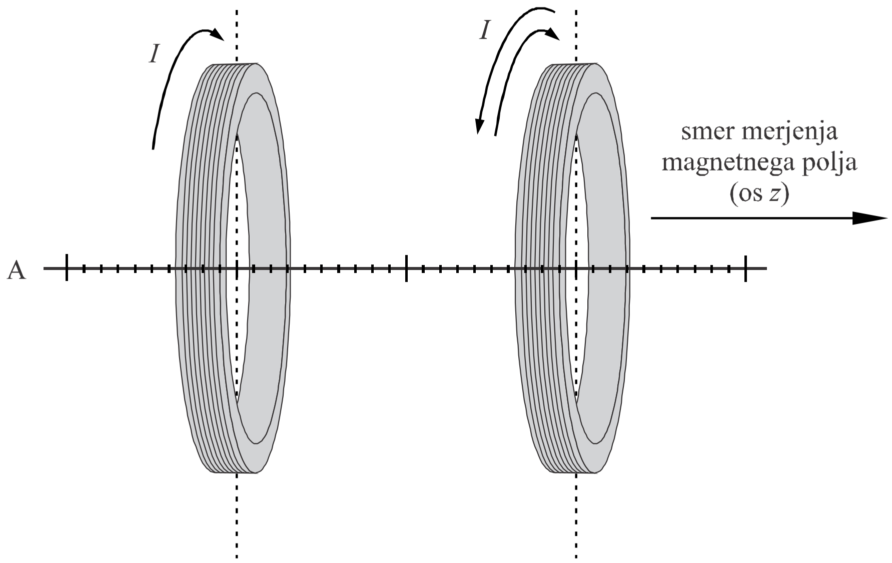


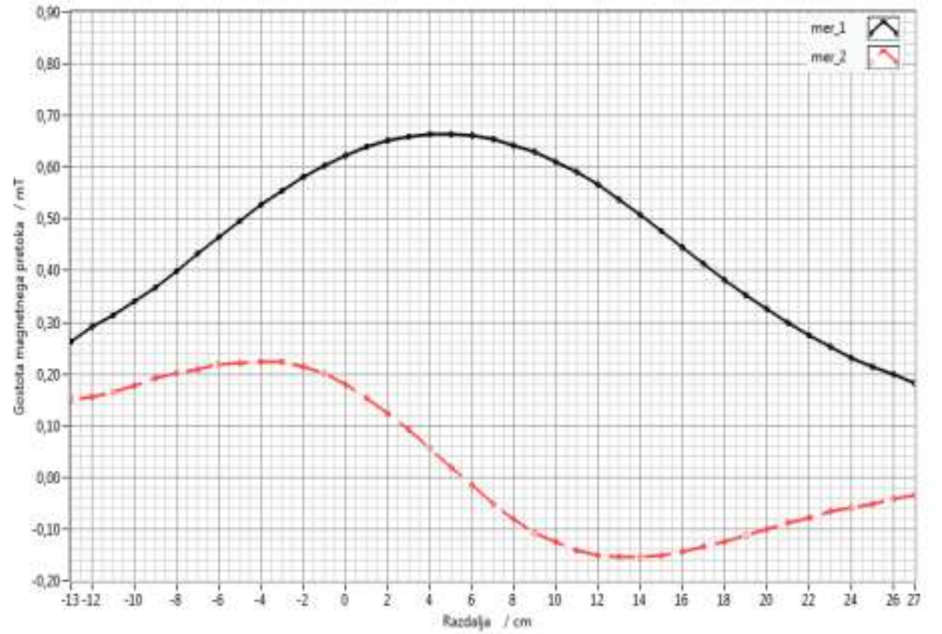
Magnetic field along the line perpendicular to the coil axis



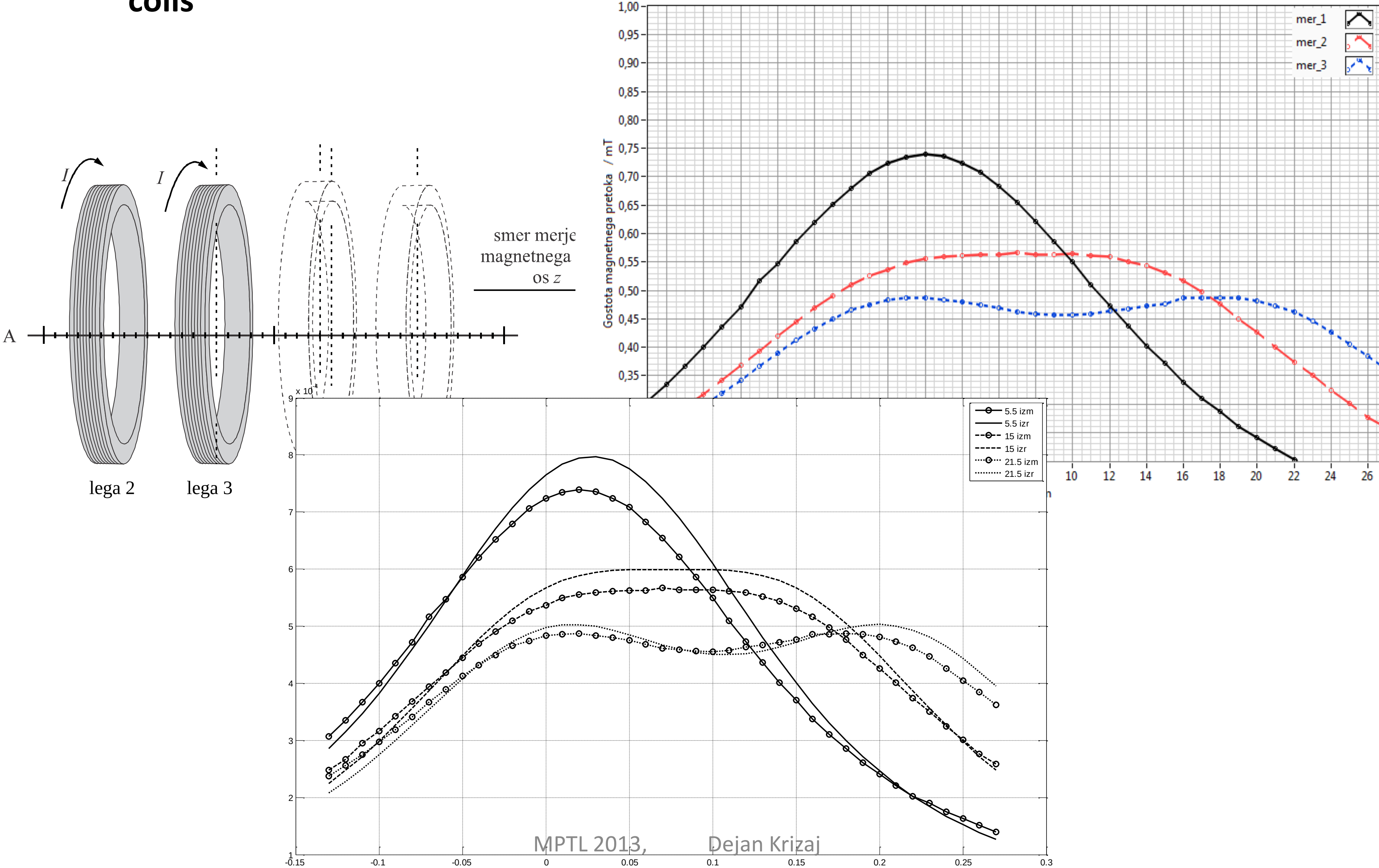


Magnetic field along the coil axis for current reversal

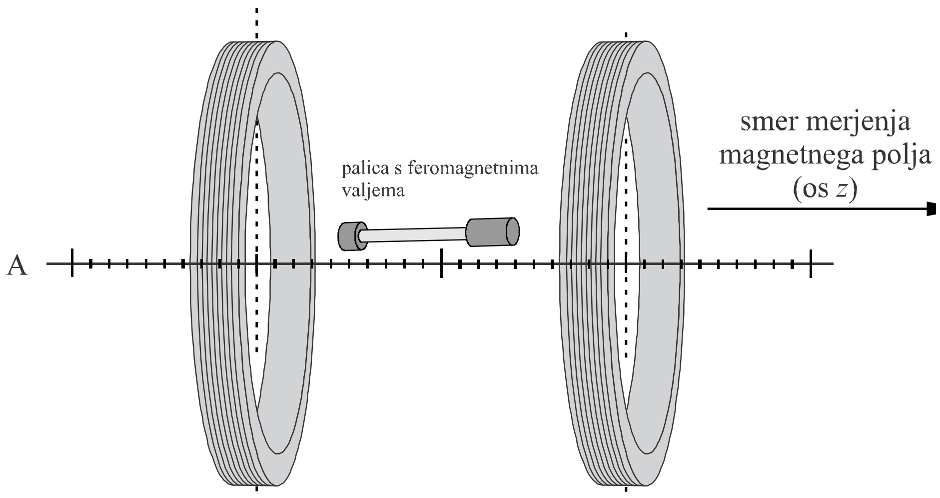


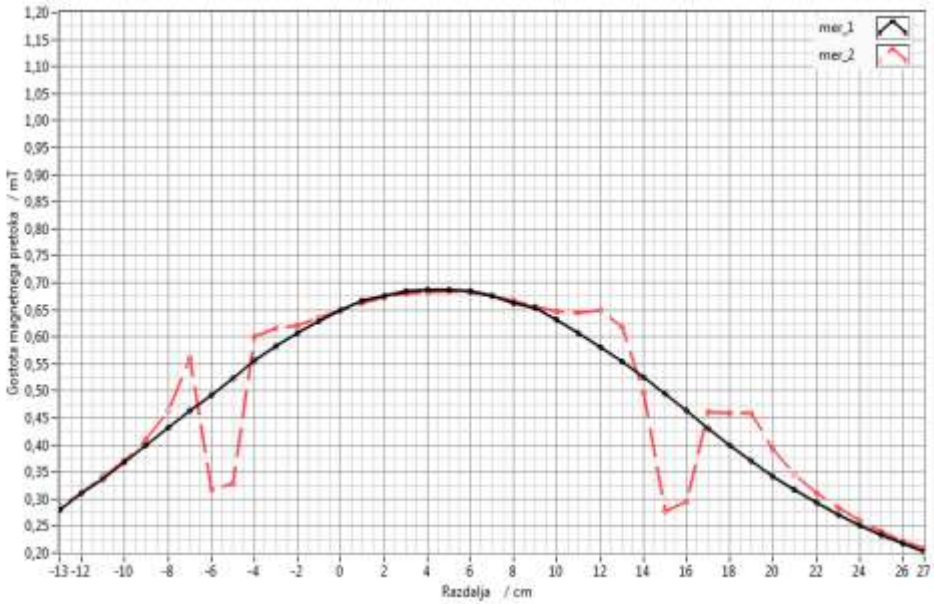


Magnetic field along coil axis for three different distances between the coils

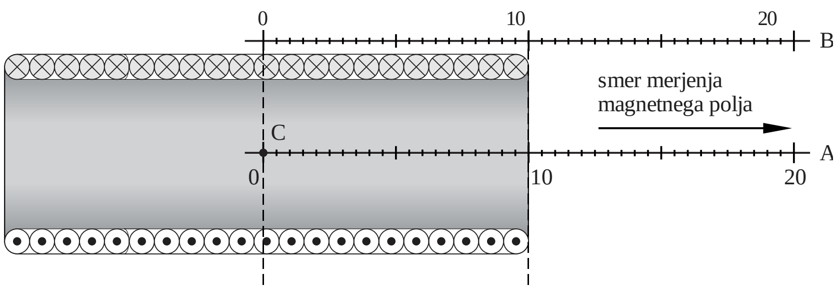


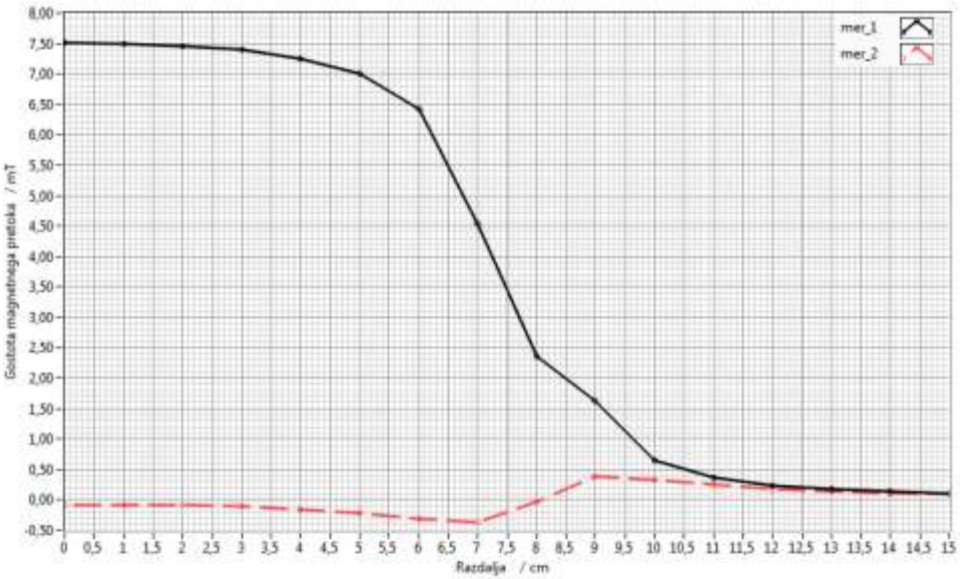
Magnetic field along axis and a ferromagnetic stick between the coils



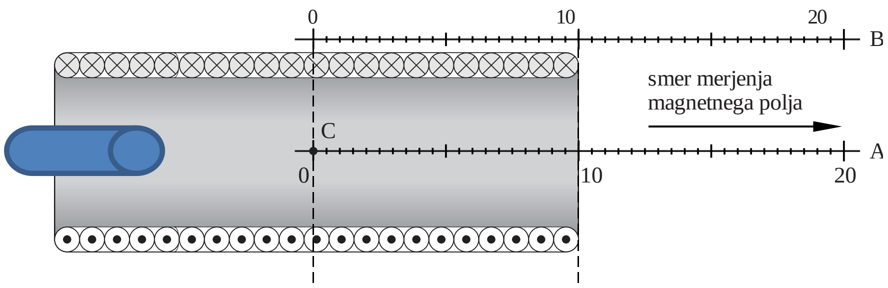


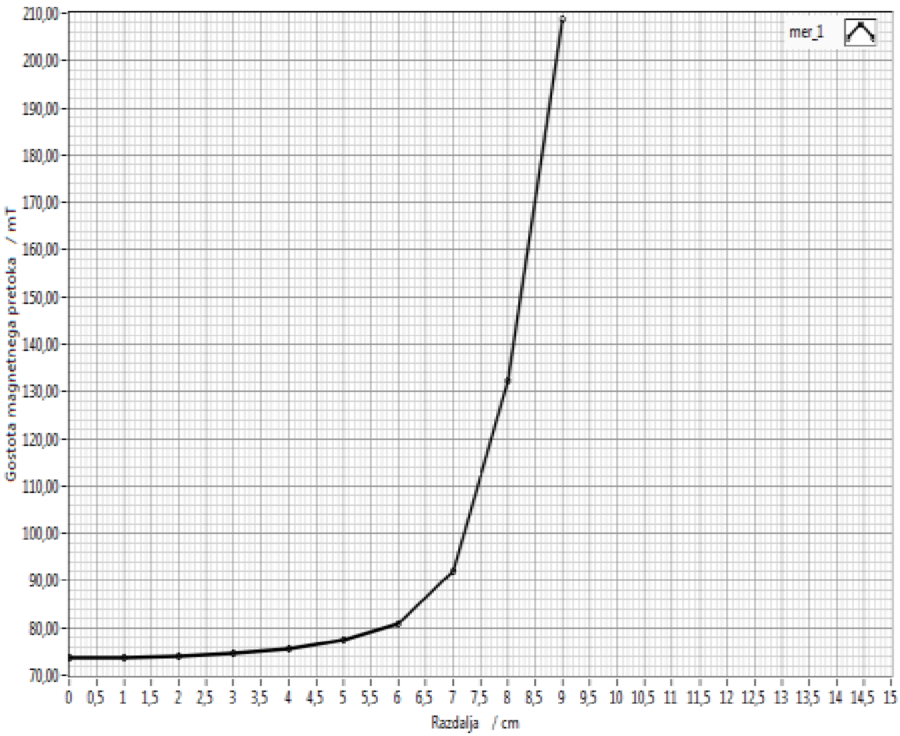
Magnetic field inside and outside a long coil (solenoid)



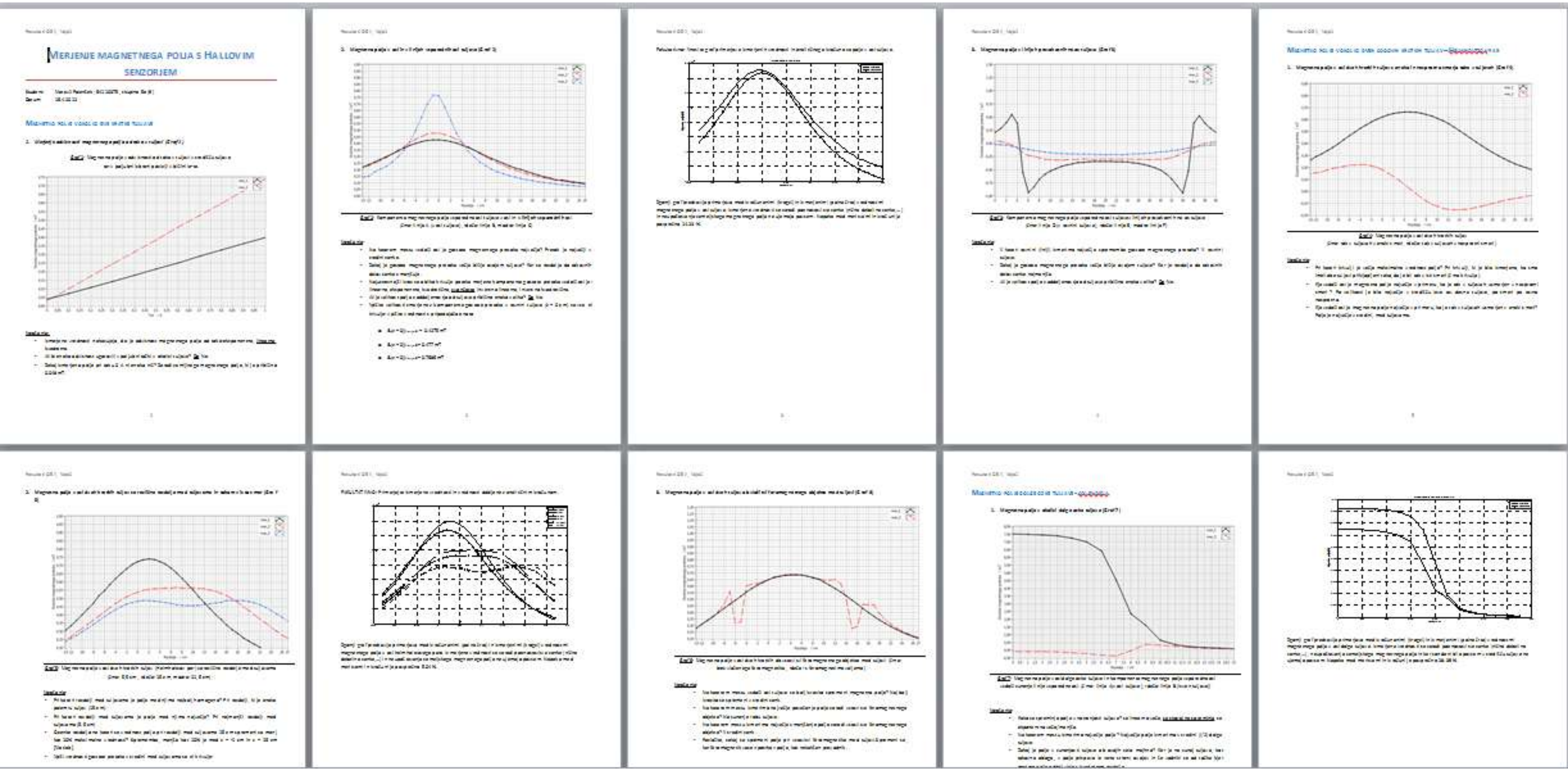


Magnetic field inside the center of the coil at insertion of a ferromagnetic stick inside the coil





FINAL REPORT



Conclusion

- Modernisation of laboratory excercises
  - Using modern IT technologies
  - Using measurement equipment that is used in practise: in laboratories as well as in industry
- Students response is positive
- What next ?