UTGAVE 25. nov. 2021

LABORATORIUM I EMNENE

TFY4155/FY1003 ELEKTRISITET OG MAGNETISME

for studenter ved studieprogrammene

MTFYMA/MLREAL/BFY/BKJ

NTNU

Våren 2022

Forord

Dette heftet inneholder tekster til laboratoriekurset til emnene TFY4155/FY1003 Elektrisitet og magnetisme.

Denne versjonen markerer restrukturing som følge av den nye XFys ferdighetstreng programmet. Laboppgavene ble fornyet for å muliggjøre mer egenstendig eksperimentering, sette fokus på dokumentasjon med labjournal og introdusere mer feilanalyse.

Christoph Brüne

25. november 2019

Innhold

Kapittel 1

LABORATORY SAFETY

The experiments in this laboratory course are safe and do not pose a danger if sensible and obvious precautions are followed and the students follow the safety instructions given below. There is always a potential danger of electric shock or fire wherever there are wall outlets, sockets, wiring or connections, which are found in all laboratories and homes. The purpose of this chapter is to provide you with general information that will prepare you to perform laboratory tests without putting yourself or others at unnecessary risk, and to describe the procedure to follow if you or anyone else nearby is in an emergency.

1.1 The electrical equipment

As stated in Ohm's law, $V = RI$, and the law of power development in a resistor, $P = VI = RI^2$, there will always be a voltage drop V over a live conductor with current I and resistor R, and it will also always heat is generated in the conductor (provided that $R > 0$).

To protect the consumer against electric shock, the outer casing of all equipment that has a conductive outer casing is permanently connected to earth. This is done through the grounding plug in the plug. If a fault occurs which causes the supply voltage to the equipment to come into contact with the conductive outer casing, the safety earthing will ensure that the voltage is connected to earth and not applied to the outer casing, with the dangers this entails. The current will thus be short-circuited to earth and normally the fuse will blow and the current will be interrupted. [1]

To avoid personal safety being dependent on the power fuses, electrical energy networks are often equipped with a so-called *nullstrømbryter*. The neutral circuit breaker can detect earth leakage currents that are much less than the hedging value of the course.

[1] It is important in this connection that the safety earth line is dimensioned so that it can withstand the current in the main supply line, ie .

The switch does this by comparing the current in the two wires of a course, ie the current into a consumer with the current returning from the consumer. Loss of electricity at the consumer is interpreted as leakage current to earth. If the zero current switch detects a difference between the phase currents that is greater than a certain preset value (eg 30 mA), then the current is interrupted.

A third method of protecting the consumer against electric shock is *dobbelt isolering* of equipment (Class II equipment, marked with a double square: ⧈). Do not attempt to ground double-insulated equipment as this will reduce contact safety.

Experience has shown that the vast majority of faults in electrical systems are earthing faults. Careful handling of earth and correct earthing of electrical equipment is a prerequisite for safe use of electrical energy and for electrical equipment to work correctly. Never plug electrical equipment that requires a grounded plug into a non-grounded electrical outlet.

1.2 Connecting electrical circuits

According to the Norwegian Electricity Regulatory Authority's regulations, all AC voltages above 25 V rms value and all ripple-free DC voltages above 60 V must be properly insulated. When connecting circuits in the laboratory, make sure that these regulations are followed.

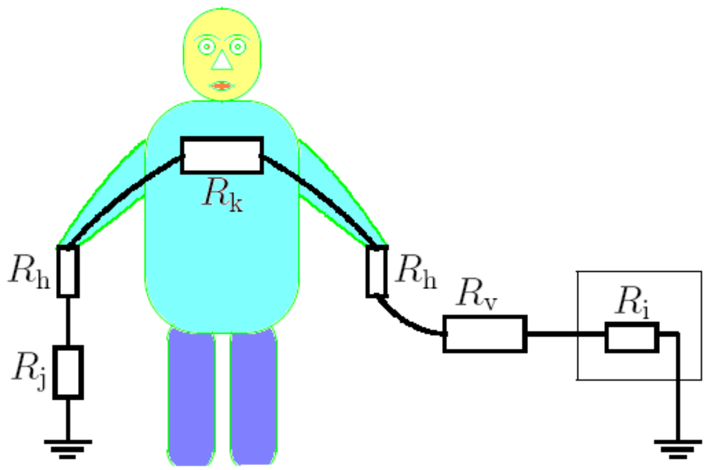
You must also make sure that the wire cross-section of the wires you use is large enough so that the wires do not heat up. Although the resistance in electrical wires is small, the value will not always be negligible. For twisted copper cables used for fixed installations in houses (with 230 V), the regulations state that a cable with a cross section 2,5 mm^2 can carry a maximum current of 16 A. As a rule of thumb in the laboratory, we can assume that 5 A/mm^2 at voltages below 300 V will be safe. The flexible laces we use for connections all have cross-sections that are larger than 1 mm^2. Streams up to 5 A will therefore not present any problem for these laces. Another factor you need to take care of is choosing a large enough cross section on your wires so that the voltage drop across the wires does not contribute to measurement errors.

Be careful not to send current through coils / drums with electrical wiring. The limit requirements described above apply to pipes in the open air with natural air cooling. If the wire is coiled tightly together, the heat development will lead to a significantly greater temperature increase which can lead to the insulation melting.

When using electrical connection equipment, it is important that you make sure that all equipment is in order. Look for damage to wires and especially connectors. It is also important that you treat the coupling material so that it is not damaged. Be sure to place the wires during use so that there is no danger of them getting caught in moving parts or getting pinched so that the insulation is damaged. The cables should also be left free so that they have sufficient cooling. When the wiring material is not in use, it should not be twisted up as heavy twisting can damage the insulation and the connection between the conductor and the socket.

1.3 Influence of electric currents on the body

The danger of electric shock is associated with the magnitude of the current flowing through the body and the current path it follows. How much voltage the body can withstand will depend on the total resistance in the circuit where the body is included. Figure 1.1 shows the human body as part of a circuit.



Figur 1.1: Menneskekroppen som del av en strømkrets, hvor R_j er isolasjonsmotstanden mellom kroppen og jord, R_h er overgangsmotstanden i huden, R_k er kroppens indre motstand, R_i er indre motstand i spenningskilden som driver strømmen i kretsen og R_v er isolasjonsmotstanden mellom spenningskildens spenningsterminal og kroppen.

Current passage can damage the body, either by damaging body tissue when heated, or by the current interfering with the electrical signals in the nervous system. The heating is given by the current I and the resistance R in the tissue being heated. A sustained flow through the tissue over time will add an increasing amount of heat energy and risk of injury. Disruption of the electrical signals in the nervous system can, among other things lead to heart fibrillation and paralysis. In particular, alternating current in the frequency range 15 to 60 Hz is dangerous for the nervous system. Our network supply of 50 Hz is therefore in the dangerous category. When the frequency of the alternating current increases, the influence on the nervous system will decrease, and for frequencies above 10 kHz the influence is almost gone. However, the heating effect is still present.

Current paths through the heart and lung region are particularly dangerous due to the vital organs that exist there. The kidneys are also particularly sensitive to current damage.

From the circuit in figure 1.1 we see that the current through the body is given by

$$I = \frac{V}{R_\mathrm{j} + 2R_\mathrm{h} + R_\mathrm{k} + R_\mathrm{i} + R_\mathrm{v}}. \tag{1-1}$$

When referring to the voltage on a supply network, the effective value of the voltage, defined as

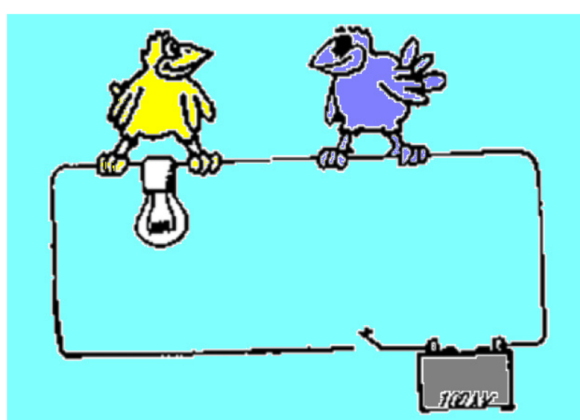
$$V_{\text{eff}} = \sqrt{\langle V(t)^2 \rangle} = \sqrt{\frac{1}{T}\int_0^T V_0^2 \sin^2\left(\frac{2\pi t}{T}\right) \mathrm{d}t} = \frac{V_0}{\sqrt{2}}. \tag{1-2}$$

This means that for a 230 volt system, the peak voltage (amplitude) is $V_0 = \sqrt{2} \times 230\,\mathrm{V} = 325\,\mathrm{V}$.

Safety precautions against electricity involve reducing the value of the current through the body to harmless values. This can be done for a given voltage V by making sure that the sum of the resistances below the fractional line is sufficiently large:

- R_v Ordinary electrical insulation of electrical equipment involves making R_v sufficiently large.
- R_k The internal resistance of the body R_k is constant and of the order of $500\,\Omega$. Note that the limit for mandatory isolation of AC voltage of 25 V effective voltage corresponds to 50 mA when we assume that the resistance in the circuit consists only of the body's internal resistance, ie worst case.
- R_h The transition resistance R_h in the skin can vary from $0\,\Omega$ for moist skin to well above $10\,000\,\Omega$ for dry skin. R_h also decreases with increasing voltage and it also varies with the frequency so that it is lowest in the frequency range around 50 Hz. This helps to make AC voltage more dangerous than DC voltage. Another factor that makes alternating voltage more dangerous than direct voltage is that the magnitude of the voltage referred to when alternating voltage is mentioned is the effective voltage. However, the peak voltage is $\sqrt{2}\times$ higher, as described in equation (1-2).
- R_j If the body is not in contact with the ground, R_j will be large. Why do the birds not die when they are on power lines (see figure 1.2)? Answer this question by modifying Figure 1.1. Now look at figure 1.3, and then answer the question asked there.

Figur 1.2: En fugl som sitter på en kraftlinje.



Figur 1.3: Hva skjer når den slås på?

In addition to the above, it is important to be aware that high-frequency electromagnetic radiation in the MHz - GHz range (microwaves - radar) can be dangerous for the body in that the electric alternating field leads to heating of the body tissue, the same effect which provides heating in a microwave. Such high-frequency heating is extra dangerous because it often takes place without normal pain functions taking effect. Persons should be shielded if the power per unit area against the body is $> 0{,}01\,\mathrm{W/cm^2}$.

Tabell 1.1: Limits of exposure[a] to static magnetic fields

Exposure characteristics	Magnetic flux density
Occupational[b]	
Exposure of head and trunk	2 T
Exposure of limbs[c]	8 T
General public[d]	
Exposure of any part of the body	400 mT

[a] ICNIRP recommends that these limits should be viewed operationally as spatial peak exposure limits.
[b] For specific work applications, exposure up to 8 T can be justified, if the environment is controlled and appropriate work practices are implemented to control movement-induced effects.
[c] Not enough information is available on which to base exposure limits beyond 8 T.
[d] Because of potential indirect adverse effects, ICNIRP recognizes that practical policies need to be implemented to prevent inadvertent harmful exposure of persons with implanted electronic medical devices and implants containing ferromagnetic material, and dangers from flying objects, which can lead to much lower restriction levels such as 0.5 mT.

1.4 Effect of static magnetic field

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) provides in its guidelines recommended limit values for exposure to electromagnetic fields (see Table 1.1). In Norway, the Radiation Protection Regulations stipulate that ICNIRP's guidelines must be followed, and that all exposure must be kept as low as practicable. For static magnetic fields, the recommended limit is 2 T for workers and 400 mT for the general population. Persons with pacemakers, ferromagnetic implants or implanted electronic components should not be exposed to magnetic fields above 0,5 mT. [2] In the experiment using the Helmholtz coils the magnetic flux density B in the immediate vicinity of the coils has a value slightly exceeding 0,5 mT for $I = 1\,\mathrm{A}$ and $R = 0{,}07\,\mathrm{m}$, where I is the current flowing in the coils and R is the average radius of the coils . But the field decreases rapidly outside the coils; the magnitude of B at a point perpendicular to the coil at a distance 0,15 m (or greater) from the center of the coil is less than 50 µT. If a current of 0,5 A is used, the field everywhere will be lower than the recommended limit for people with implants. A student with an implant that is sensitive to magnetic fields should inform the person in charge, who will ensure that this student has a partner who does not have an implant and that the partner makes the measurements.

[2] http://www.icnirp.de/documents/emfgdl.pdf [*Health Physics* **96** (2009) 504–519.]

1.5 Common sense in handling electrical equipment

In addition to the usual risks associated with electricity, some laboratories have high voltage equipment [3] Which poses an even greater potential hazard. Students should be extra careful with such equipment, and should learn how to disconnect the power source in an emergency. Here are some rules that must be followed when working with and near electricity.

1. Do not work with electricity if your hands, feet, or other parts of your body are wet, or if you are standing on a wet floor.
2. Inspect electrical equipment (with power off and unplugged) for broken wires and damaged connections. If such a thing is detected, do not use the equipment. Then report it to the person in charge so that the equipment can be repaired.
3. Never attempt to repair electrical equipment yourself — this must be done by qualified personnel.
4. If you are subjected to even a mild shock from any equipment, it will be repaired immediately.
5. Do not use or store extremely flammable liquids near electrical equipment. Some substances, such as ether, can be ignited by sparks from electrical equipment.
6. Always use earthed sockets in earthed wall sockets. Never attempt to insert a grounded electrical outlet into an unearthed wall outlet.
7. Extension cords should not be used instead of permanent wiring; they should only be used temporarily and they should not be pulled under doors, across hallways, through windows or holes in walls, around pipes or near sinks.
8. Do not overload circuits by using branch outlets on a standard outlet.
9. Do not remove or change safety measures on high voltage equipment. Remember they are there to protect you.
10. Make sure that the power is switched off during connection or when making changes to the circuit.
11. Make sure that all equipment is set with the correct settings according to the measurement to be performed before the circuit is made live.
12. Make sure that the components used are of a rating that can withstand the applied current and voltage.
13. Replace broken fuses with new ones of the correct type and with the correct specifications.
14. *Hvis du tror noen har vært utsatt for et kraftig elektrisk sjokk*:

[3] For our purposes, it will be sufficient to consider any voltage higher than 50 V as high voltage.

- do not remove the injured person from the electrical source until the power has been switched off.
- if you do not turn off the power, use an insulator such as a dry rope, cloth or broom handle to pull the person away from the power.
- check if there is contact.
- check if there is breathing.
- secure free airways.
- when injured do not breathe or in cardiac arrest, call 113 AMK control panel.
- provide cardiopulmonary resuscitation (CPR) 30 compressions and 2 breaths. Continue until healthcare professionals arrive.
- breathes the injured person himself, puts the person in a stable side position.
- look for burns and cool burns with water and treat them as third-degree burns.
- All injured persons must be supervised after first aid has been given. Do not leave unconscious persons. Conscious people should be talked to. Personal injuries must be treated further by medical personnel.
- persons sent to the Emergency Room by taxi / private car must be followed all the way in and out. Bring any HSE data sheets!
- all accidents / approaches to accidents are to be regarded as deviations in relation to normal operation, and must be reported on the deviation form.

In the experiment with Coulomb's law, the high-voltage cannon used to charge the bullets 25 kV when activated. However, the current is limited to 75 µA. Such currents usually have no physiological effect on the body, but still: *Behandle kanonen som om den var livsfarlig.*

Kapittel 2

STATIC MAGNETIC FIELD

Goal

You are going into this lab assignment

- develop your skills in documenting laboratory work with the lab journal
- set up and carry out physical measurements
- perform basic error analysis
- learn to measure magnetic fields with Halleffekt gaussmeter,
- study the magnetic field around a short coil, Helmholtz coil and solenoid,
- use Python or Excel spreadsheets to compare calculated and measured results.

2.1 Theoretical background

Biot-Savart's law is presented here. Some theory is presented in the text for the calculation tasks in section 2.2. Otherwise, reference is made to the textbook and the lectures in electromagnetism.

2.1.1 Biot-Savarts Law

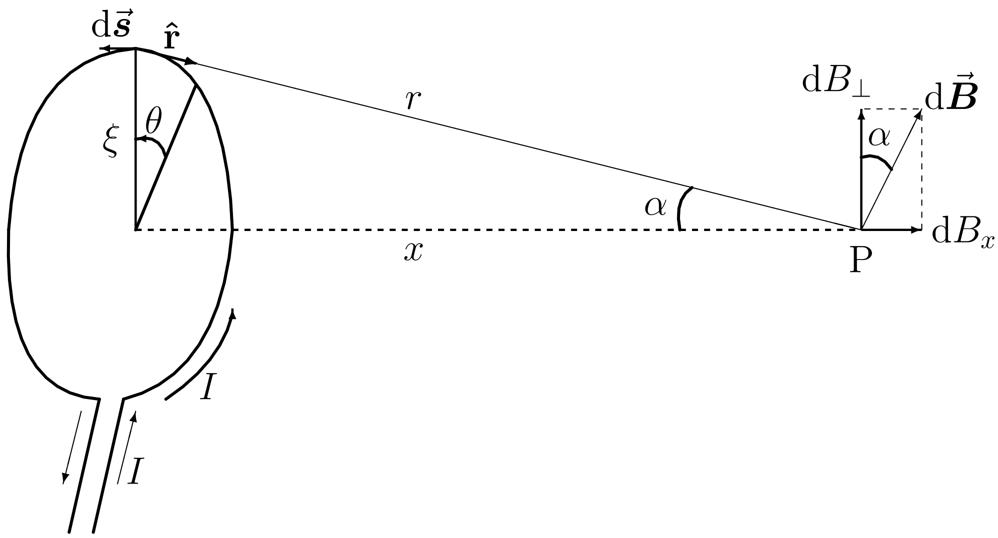
Electric fields are generated around any electric charge while magnetic fields are generated around electric charges that move. In 1820, Jean-Baptiste Biot and Félix Savart performed magnetic field experiments on live conductors and set up the following expression for the magnetic field contribution $\mathrm{d}\vec{\boldsymbol{B}}$ at a point P in space from the current I in a wire element $\mathrm{d}\vec{\boldsymbol{s}}$,

$$\mathrm{d}\vec{\boldsymbol{B}} = \frac{\mu_0}{4\pi}\frac{I\,\mathrm{d}\vec{\boldsymbol{s}} \times \hat{\mathbf{r}}}{r^2}, \tag{2-1}$$

where $\vec{\boldsymbol{r}}$ is the position vector of the point P measured from the current element $I\,\mathrm{d}\vec{\boldsymbol{s}}$, $\hat{\mathbf{r}} = \vec{\boldsymbol{r}}/r$ is the unit vector along $\vec{\boldsymbol{r}}$ and μ_0 is the magnetic permeability in empty space. Note the r^{-2} dependence, the same as for the electric field strength in Coulomb's law. The superposition principle applies to magnetic fields, and consequently the total field strength $\vec{\boldsymbol{B}}$ at point P from the whole conductor can be found by integrating the whole over the length of the conductor s:

$$\vec{\boldsymbol{B}}(\vec{\boldsymbol{r}}) = \frac{\mu_0 I}{4\pi}\int_s \frac{\mathrm{d}\vec{\boldsymbol{s}} \times \hat{\mathbf{r}}}{r^2}. \tag{2-2}$$

In the experiment, you will examine the magnetic field along the axis of circular coils. The simplest circular spool you can make consists of a simple wire loop as shown in Figure 2.1.



Figur 2.1: Magnetfeltet på aksen til en sirkulær trådslynge.

The magnetic field on the axis of the sling will have a component in the axis direction x and a component normally on this. According to Biot-Savart's law, the normal component will be zeroed out by contributions (integration) over the entire loop, as the symmetry of the system gives equal strength in all directions. For the x component we get by inserting $r^2 = x^2 + \xi^2$ and using $\sin\alpha = \xi/r$,

$$\begin{aligned} \mathrm{d}B_x &= \frac{\mu_0 I}{4\pi}\frac{\mathrm{d}s}{x^2+\xi^2}\sin\alpha \\ &= \frac{\mu_0 I}{4\pi}\frac{\xi\,\mathrm{d}\theta}{x^2+\xi^2}\frac{\xi}{\sqrt{x^2+\xi^2}}, \end{aligned} \tag{2-3}$$

where θ is the integration angle around the loop circle. Integrated over the loop with $\int \mathrm{d}\theta = 2\pi$ gives this result

$$B_x = \frac{\mu_0 I}{4\pi}\frac{2\pi\xi^2}{(x^2+\xi^2)^{3/2}} = \frac{\mu_0 I}{2\xi}\left(1+\frac{x^2}{\xi^2}\right)^{-3/2}. \tag{2-4}$$

For $x = 0$ (middle of the loop) becomes $B_x = \mu_0 I/2\xi$ and for $x \gg \xi$ (far away from the loop) becomes $B_x = \mu_0 I\xi^2/2x^3$.

2.2 Calculation tasks

2.2.1 Calculation and documentation

To perform calculations and to create tables / diagrams, you can freely choose between suitable programs (for example Python, Matlab, Origin, Excel or similar). Data and results must be documented in the lab journal (for example by pasting printouts of the tables and diagrams in the lab journal or by entering results). The program code and the original files used for calculation must be available in case of questions. The program code can be pasted into the lab journal.

2.2.2 Short Coil

The magnetic field from a short coil with N windings can be seen far from the coil (in relation to the extent of the coil) as the sum of the magnetic field from N current loops given in equation (2-4). The magnetic field on the axis at a distance x from the middle center of the coil is then according to equation (2-4) given by

$$B(x) = \frac{N\mu_0 I}{2R}\left(1 + \frac{x^2}{R^2}\right)^{-3/2}, \tag{2-5}$$

where R is the average radius of the current loops.

Assume that you have a short coil with $N = 330$ viklinger and an average radius $\langle R \rangle = 70\,\text{mm}$ with a constant current $I = 1{,}00\,\text{A}$ through the windings.

1A. Make a table of the magnetic flux density $B(x)$ on the axis of the coil in the area $-20\,\text{cm} < x < 20\,\text{cm}$.

A suggested table is shown in Figure 2.2. Constants are entered in rows under the heading. This is followed by table values where each column must have a descriptive text.

1B. Present the result in a graph.

Discuss the calculation of the magnetic field of a short coil when the extent of the coil is taken into account.

The program or spreadsheet in Excel can also be used to calculate expected magnetic field strengths as a result of Biot-Savart's (2-4) law and subsequent comparison with experimentally measured magnetic field strengths in section 2.3.

1C. Include a column for measured value of B and a column for deviation between measured and calculated value given in %, and also prepare to show the deviation graphically. (A suggestion is given in the table in figure 2.2.)

Take a control bill by hand from one of the calculated B. Check the calculated difference by entering the hand-calculated value.

Tabell 1. Beregnede og målte verdier av magnetfeltet B på aksen til en kort spole s.f.a. avstanden x fra spolens midtplan

Magnetisk permeabilitet for tomt rom, μ_0	1,26E-06 H/m
Antall viklinger, N	330 #
Spolestrøm, I	1,00 A
Gjennomsnitts spoleradius, R	0,07 m

Posisjon på målestav (cm)	x (m)	Beregnet B 1 (gauss = 10^{-4} T)	Målt B 2 (gauss)	Differanse B 2-B 1 (%)
24,5	-0,25	0,581		-100,0
29,5	-0,20	1,068		-100,0
34,5	-0,15	2,241		-100,0
39,5	-0,10	5,588		-100,0
44,5	-0,05	15,965		-100,0
47,5	-0,02	26,339		-100,0
48,5	-0,01	28,745		-100,0
49,5	0,00	29,629		-100,0

Figur 2.2: Utdrag fra en Excel-tabell for magnetfelt på aksen til tynn spole.

En nøtt for de som har god tid:

The actual spool you are going to use in the problem has 22 windings in 15 layers with an effective wire diameter equal to 0,93 mm, wound with inner diameter equal to 126 mm and outer diameter equal to 154 mm.

2. How do you think the real magnetic field near the coil will differ from the magnetic field calculated from equation (2-5)? [1]

3. If you were to take into account the extent of the coil during the calculations of the field, how would you proceed? [2]

2.2.3 Helmholtzspoler

So-called Helmholtz coils consists of two identical, short series-connected coils set up parallel on the same axis at a distance a as shown in figure 2.3. The axial magnetic field on the axis is given by equation (2-5) for each coil. According to the superposition principle, we find the total field at a distance x from the center plane between the coils

[1] TIP: Look at the extent of the coil as an error in x and estimate the corresponding error ΔB in $B(x)$.

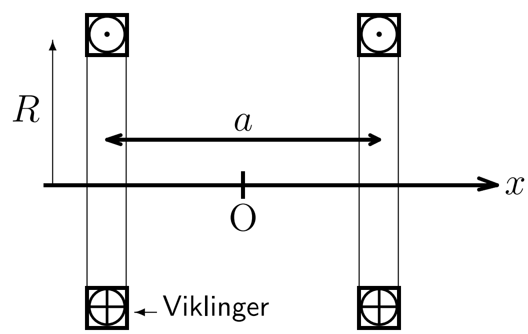
[2] TIP: Divide the coil into e.g. three coils with 110 windings each and calculate the field from each of the coils and superimpose the effect. The best thing you can do is treat each winding separately, and in practice, that means integration over each winding.

to be equal

$$B_x(x) = \frac{N\mu_0 I}{2R}\left[\left(1+\frac{(x-a/2)^2}{R^2}\right)^{-3/2}+\left(1+\frac{(x+a/2)^2}{R^2}\right)^{-3/2}\right]. \tag{2-6}$$

Here the average radius of the coils is equal to R, the current through the coils is equal to I and we have neglected the extent of the coils.

If you derive equation (2-6) with respect to x you will find that at $x = 0$ $\mathrm{d}B/\mathrm{d}x = \mathrm{d}^2B/\mathrm{d}x^2 = \mathrm{d}^3B/\mathrm{d}x^3 = 0$ is when $a = R$. This means that when $a = R$ you have a geometry that gives you a particularly good homogeneous magnetic field in the area between the coils. Such Helmholtz coils are used to set up homogeneous magnetic fields in many situations.



Figur 2.3: Helmholtzspoler består av to tynne spoler i en gitt avstand a mellom spolene.

Suppose you have Helmholtz coils with $N = 330$ viklinger on each coil, $R = 70\,\mathrm{mm}$ and send a constant current $I = 1{,}00\,\mathrm{A}$ through the windings.

4A. Make a table of the magnetic flux density $B(x)$ on the axis of the Helmholtz coil in the range $-20\,\mathrm{cm} < x < 20\,\mathrm{cm}$ for each of the three different values $a = R/2, R$ and $2R$.

A suggested table is shown in Figure 2.4.

4B. Present the result in a curve diagram

The spreadsheet shall also be used for the calculation of expected magnetic field strengths as a result of Biot-Savart's law (2-4) and subsequent comparison with experimentally measured magnetic field strengths in section 2.3.

4C. Include a column for measured value of B and a column for deviations between measured and calculated value given in $\%$ for $a = 2R$. Repeat this for the other two values of a. Prepare to display the deviation graphically. (A suggestion is given in the table in figure 2.4.)

Take a control bill by hand from one of the calculated B. Check the calculated difference by inserting some imaginary measured values.

Tabell 2. Målte og beregnede verdier av magnetfeltet *B* på aksen til en Helmoltzspole s.f.a. avstanden *x* fra spolens midtplan

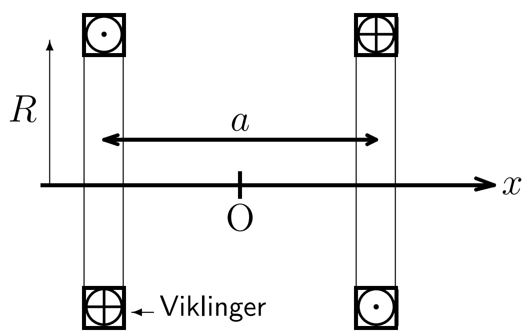
Magnetisk permeabilitet for tomt rom,	1,26E-06 H/m
Antall viklinger, N	330 #
Spolestrøm, I	1,00 A
Gjennomsnitts spoleradius, R	0,07 m
Avstand mellom spolene, a	a=2R, R eller R/2

Posisjon på målestav (cm)	x (m)	a=2R Beregnet B1 gauss	a=R Beregnet B1 gauss	a=R/2 Beregnet B1 auss = 10^{-4}	a=2R Målt B2 gauss	a=2R Differanse B2-B1 (%)	a=R Målt B2 gauss	a=R Differanse B2-B1 (%)	a=R/2 Målt B2 gauss	a=R/2 Differanse B2-B1 (%)
30	-0,20	3,626	2,454	2,213		-100,0		-100,0		-100,0
35	-0,15	9,286	5,478	4,719		-100,0		-100,0		-100,0
40	-0,10	24,643	14,549	11,996		-100,0		-100,0		-100,0
43	-0,07	32,279	26,258	22,393		-100,0		-100,0		-100,0
45	-0,05	30,129	35,312	33,160		-100,0		-100,0		-100,0
47	-0,03	24,981	41,063	45,054		-100,0		-100,0		-100,0
48	-0,02	22,821	42,105	49,866		-100,0		-100,0		-100,0
49	-0,01	21,429	42,382	53,017		-100,0		-100,0		-100,0
50	0,00	20,951	42,402	54,108		-100,0		-100,0		-100,0

Figur 2.4: Utdrag fra tabell for magnetfelt på aksen til Helmholtzspoler.

2.2.4 Anti-Helmholtz Coil

Anti-Helmholtz coils consist of two identical, short series-connected coils set up parallel on the same axis at a distance a as shown in figure 2.5, with different directions on the magnetic field. How do you find the field in this configuration?



Figur 2.5: Anti-Helmholtzspoler består av to tynne spoler i en gitt avstand a mellom spolene.

5A. Make a table of the magnetic flux density $B(x)$ on the axis of the Anti-Helmholtz coil in the area $-20\,\mathrm{cm} < x < 20\,\mathrm{cm}$ for each of the three different distances $a = R/2, R$ and $2R$.

5B. Present the result in a graph.

The spreadsheet shall also be used for the calculation of expected magnetic field strengths as a result of Biot-Savart's law (2-4) and subsequent comparison with experimentally measured magnetic field strengths in section 2.3.

5C. Include a column for measured values of B and a column for discrepancies between measured and calculated values given in % for $a = 2R$. Repeat this for the other two values *of a. Prepare the spreadsheet to display the deviation graphically.* (A suggestion is given in the table in Figure 2.4.)

Make a control calculation by hand of one of the calculated B. Check the calculated difference by entering the hand-calculated value.

2.2.5 Solenoid

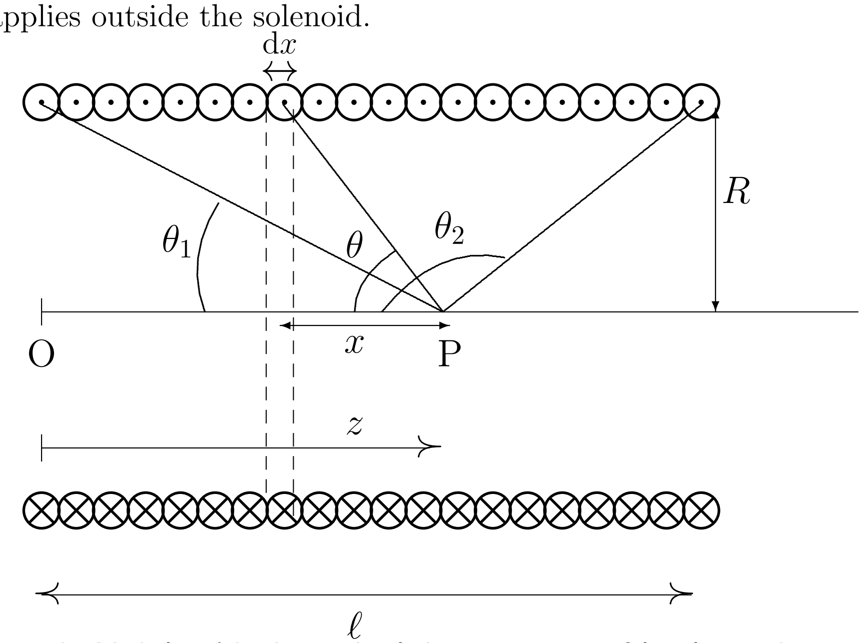
The magnetic field at a point P on the axis of a solenoid can be found from Biot-Savart's law, and the result is

$$B = \frac{N\mu_0 I}{2\ell}(\cos\theta_1 - \cos\theta_2), \tag{2-7}$$

where ℓ is the length of the solenoid and the angles θ_1 and θ_2 are defined in Figure 2.6 or analytically:

$$\cos\theta_1 = \frac{z}{\sqrt{z^2+R^2}}, \qquad \cos\theta_2 = -\frac{\ell - z}{\sqrt{(\ell-z)^2+R^2}}, \tag{2-8}$$

where R = inner radius of the solenoid and z is the axis distance from the left end of the solenoid to the point. Inside the solenoid are $\theta_1 \in \langle 0, \pi/2\rangle$ and $\theta_2 \in \langle \pi/2, \pi\rangle$. The formula also applies outside the solenoid.



Figur 2.6: Solenoide. Vinkelen θ brukes ved utledning av magnetfeltet langs aksen, se teksten.

Vi spanderer et bevis for likning (2-7)*:* In equation (2-4) we have found magnetic fields on the axis at a distance x from a single loop. In a solenoid we have many loops close together, we define current per unit length as $IN/\ell = In$, where n is the number of windings per length. Flux density at a point P on the axis then receives a contribution from the thin current loop $\mathrm{d}I = In\,\mathrm{d}x$ in position x, and according to the first part of equation (2-4) the flux density is equal

$$\mathrm{d}B = \frac{\mu_0\,\mathrm{d}I}{4\pi}\frac{2\pi R^2}{(x^2+R^2)^{3/2}} = \frac{\mu_0 In}{2}\frac{R^2}{(R^2+x^2)^{3/2}}\,\mathrm{d}x\,. \tag{2-9}$$

With θ as the angle at point P between the solenoid axis and the periphery at position x (figure 2.6) we see that $\tan\theta = R/x$, and derivation of $x = R/\tan\theta$ gives

$$\mathrm{d}x = R\frac{-1}{\tan^2\theta}\frac{1}{\cos^2\theta}\,\mathrm{d}\theta = -R\frac{1}{\sin^2\theta}\,\mathrm{d}\theta\,. \tag{2-10}$$

We notice that

$$\sin^3\theta = \frac{R^3}{(R^2+x^2)^{3/2}}, \tag{2-11}$$

so that

$$\mathrm{d}x = -R\frac{1}{\sin^3\theta}\sin\theta\,\mathrm{d}\theta = -R\frac{(R^2+x^2)^{3/2}}{R^3}\sin\theta\,\mathrm{d}\theta \tag{2-12}$$

and by substituting $\tan\theta = R/x$ in equation (2-9) and inserting boundaries θ_2 (right end, lowest x) to θ_1 (left end, highest x), we will get

$$B(x) = -\frac{\mu_0 I n}{2}\int_{\theta_2}^{\theta_1}\sin\theta\,\mathrm{d}\theta = \frac{\mu_0 I n}{2}(\cos\theta_1 - \cos\theta_2), \tag{2-13}$$

to be displayed.

5. What is the expression of the magnetic field deep inside the solenoid, and what is it at the end of the solenoid? Catalog TIP: What are θ_1 and θ_2 at these positions?

Suppose you have a solenoid with $N = 397$ viklinger, $\ell = 420\,\mathrm{mm}$, $R = 50\,\mathrm{mm}$ and current $I = 1{,}00\,\mathrm{A}$.

6A. Make a table of the magnetic flux density $B(z)$ on the axis of the solenoid in the area $-10\,\mathrm{cm} < z < 50\,\mathrm{cm}$ where $z = 0$ at the left edge of the solenoid.

A suggested table is shown in Figure 2.7.

Tabell 3. Målte og beregnede verdier av magnetfeltet *B* på aksen til en solenoide s.f.a. avstanden *z* fra ene ende

Magnetisk permeabilitet for tomt rom, μ_0	1,26E-06 H/m
Antall viklinger, N	397 #
Spolestrøm, I	1,00 A
Indre radius i solenoiden, R	0,05 m
Lengde, l	0,42 m

Posisjon på målestav (cm)	z (m)	cos θ1	cos θ2	Beregnet B1 gauss	Målt B2 gauss	Differanse B2-B1 (%)
60	-0,10	-0,894	-0,995	0,600		-100,0
55	-0,05	-0,707	-0,994	1,707		-100,0
53	-0,03	-0,514	-0,994	2,848		-100,0
52	-0,02	-0,371	-0,994	3,696		-100,0
51	-0,01	-0,196	-0,993	4,736		-100,0
50	0,00	0,000	-0,993	5,899		-100,0
49	0,01	0,196	-0,993	7,062		-100,0

Figur 2.7: Utdrag fra tabell for magnetfelt på aksen til Helmholtzspoler.

6B. Present the result in a curve diagram

The spreadsheet shall also be used for the calculation of expected magnetic field strengths as a result of Biot-Savart's law (2-4) and subsequent comparison with experimentally measured magnetic field strengths in section 2.3.

6C. Include a column for measured value of B and a column for deviations between measured and calculated value given in %. (A suggestion is given in the table in Figure 2.7.)

2.2.6 Python Data Analysis

The previous tasks can be done in Python, for example. It is advisable to save the data in text files. Here we use comma separated files as shown below.

```
# Posisjon (m), B-felt (Gauss)
0.245,0.0
0.295,0.623
...
```

Here, the first column represents *Posisjon på målestav*, and the second column represents *Målt B2* in Figure 2.2. The remaining columns can be calculated in Python. To read the data, we create the following code:

```python
# - * - coding: utf-8 - * -
import numpy as np


def main ():
    filename = 'short_spool.csv'
    data = np.loadtxt (filename, delimiter = ',')
    xe = data [:, 0]
    Be = data [:, 1]

if (__name__ == '__main__'):
    main ()
```

In the `main` function, the text file *kort_spole.csv* is read. The position data, located in the first column, is stored in the variable `xe` and the data for the measured magnetic field is stored in the variable `Be`.

The next thing we need to do is implement a function that calculates the magnetic field according to equation (2-5). We can do this as follows:

```python
def B_field_short_coil (x):
    prefactor = N * mu_0 * I0 / (2 * R)
    return prefactor * (1.0 + (x / R) ** 2) ** (- 1.5)
```

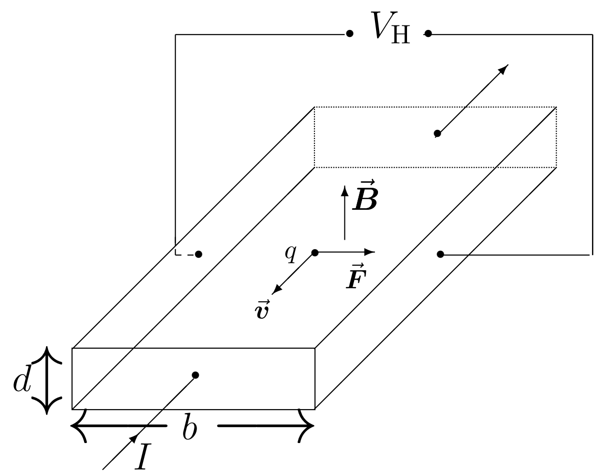
To plot the result for the calculated field, we add some lines in the `main` function. We also need to define some parameters used in the calculation. The whole program then looks like this:

```
# - * - coding: utf-8 - * -
import numpy as np
from matplotlib import pyplot as plt


N = 330 # [] number of windings
I0 = 1.0 # [A] current
mu_0 = 4.0 * np.pi * 1e-7 # [H / m] permeability in empty space
R = 0.07 # [m] radius
x0 = 0.400 # [m] center of coil

def B_field_short_coil (x):
    prefactor = N * mu_0 * I0 / (2 * R)
    return prefactor * (1.0 + (x / R) ** 2) ** (- 1.5)

def main ():
    filename = 'short_spool.csv'
    data = np.loadtxt (filename, delimiter = ',')
    xe = data [:, 0] - x0 # position, centered around x0
    Be = data [:, 1] # measurement data

    # Calculate the B field
    xb = np.linspace (xe [0], xe [-1], 100) # multiple data points
    Bb = B_field_short_coil (xb) * 1e4 # calculated B-field (Gauss)

    # Plot the results
    plt.plot (xb, Bb, label = 'Calculated')
    plt.plot (xe, Be, '.', label = 'Measurement data')
    plt.xlabel ('Distance from center of coil (m)')
    plt.ylabel ('Magnetic field (Gaussian)')
    plt.legend ()
    plt.show ()

if (__name__ == '__main__'):
    main ()
```

You can now create more functions to plot the results for a Helmholtz coil and a solenoid. Remember that it often pays to divide the program into smaller functions. This makes the code easier to read, but also allows you to reuse much of the code for other purposes. More examples of plotting can be found here: https://nbviewer.jupyter.org/urls/www.numfys.net/media/notebooks/basic_plotting.ipynb.

2.2.7 Hall effect probe

When electrons move at speed $\vec{\boldsymbol{v}}$ in a semiconductor located in a magnetic field $\vec{\boldsymbol{B}}$ as shown in Figure 2.8, the electrons will bend to one side. The deflection is given by the Lorentz force $\vec{\boldsymbol{F}} = q(\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}})$, where $q = -e$ for electrons.



Figur 2.8: Halleffekt i en halvlederprobe. Strøm I påtrykkes mellom de to minste endevegger.

The Lorentz force acts normally on the current direction and normally on B and the deflection due to this causes the electron concentration to become stronger against one wall of the semiconductor. An electric field $\vec{\boldsymbol{E}}$ thus builds up in the conductor with the same direction as the Lorentz force, and this field gives an additional force $\vec{\boldsymbol{F}} = q\vec{\boldsymbol{E}}$ on the electrons. An equilibrium will quickly arise where electrostatic force and Lorentz force are equal so that

$$\vec{\boldsymbol{F}} = q\vec{\boldsymbol{E}} + q(\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}) = \vec{\boldsymbol{0}} \quad \Rightarrow \quad \vec{\boldsymbol{E}} = -\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}. \tag{2-14}$$

The speed v of the electrons through the semiconductor is determined by the current at the expression $I = nqvA$, where n is the density of electrons and $A = bd$ is the cross section in the conductor direction. This gives

$$v = \frac{I}{A}\frac{1}{nq} = \frac{I}{bd}R_{\mathrm{H}}, \tag{2-15}$$

where we have defined the Hall constant $R_{\mathrm{H}} = 1/nq$.

With b equal to the width of the probe, the voltage $V_{\mathrm{H}} = Eb$ will form across the side walls. If we disregard the sign and use that $\vec{\boldsymbol{v}} \perp \vec{\boldsymbol{B}}$ we get the following expression for Hallspenningen V_{H}:

$$V_{\mathrm{H}} = Eb = vBb = \frac{R_{\mathrm{H}}I}{d}B, \tag{2-16}$$

where d is the thickness of the Hall probe that the magnetic field B acts over. The hall constants R_{H} and d are constants for a given probe and the current I is kept constant.

Figur 2.9: Probegeometrier: (1) Aksial probe, (2) transversal probe.

The magnetic flux density B normally on the probe will then be proportional to the Hall voltage V_H which is measured with a voltmeter.

The hall effect is used i.a. in Gaussian meters for measuring magnetic fields. A Hall Power Gaussmeter will essentially consist of a current source that provides a constant current I through a probe, and a voltmeter. The probe is placed in the magnetic field to be measured. Through a calibration process, the relationship between the measured Hall voltage and the magnetic field can be established and the voltage reading unit is graded directly in $\mathrm{T} = \mathrm{Wb/m^2}$ or gauss $= 10^{-4}\,\mathrm{T}$.

In practice, the extent of a Hallprobe is of the order of a few mm^2. Two different probe geometries are common: transverse probes and axial probes, as shown in Figure 2.9.

Typical value for the electron density in a doped semiconductor is $n = 10^{20}\,\mathrm{elektroner/m^3}$. By comparison, copper has $n = 10^{28}\,\mathrm{elektroner/m^3}$. In our Gaussian meters are $I = 20\,\mathrm{mA}$ and $d = 1{,}0\,\mathrm{mm}$. Assume that the magnetic field varies from 1 to 100 gauss.

7A. What measuring range must the Gaussmeter voltmeter have to measure in this magnetic field range? (Assume at $n = 10^{20}\,\mathrm{elektroner/m^3}$.)

7B. Why do you think semiconductors are used in magnetic field probes? Explain why e.g. copper will not be a suitable material.

7C. Also explain why an insulator will not be a suitable material in a magnetic field probe.

2.2.8 Magnetic scattering fields

In the laboratory, the magnetic scattering field forms a background that can interfere with magnetic field measurements. The spreading fields have three main sources:

- the earth magnetic field,
- magnetic fields from magnetic materials in building structures and fixtures,
- induced magnetic fields from i.a. 230 V power cords.

The earth's magnetic field, which is constant and of the order of magnitude 1 gauss, is believed to originate from convection currents of electric charges in the earth's liquid core. Assume that in the middle of the earth's interior there is a current loop perpendicular to the earth's axis of rotation. Let the radius of the current phase be $R = R_\mathrm{j}/4$, where $R_\mathrm{j} = 6371\,\mathrm{km}$ is the radius of the earth. The axial component of the magnetic field in position x on the axis of such a current loop is given by equation (2-4).

8. How large must the current in the loop be for the magnetic field on the earth's surface at the pole ($x = R_{\mathrm{j}}$) to be equal to $1\,\mathrm{gauss}$?

Contributions to the current magnetic field from the building and the inventory will depend on the building and construction materials used. You will evaluate the contributions to this in the laboratory through your own measurements.

Contribution to the spreading field from the currents in non-shielded wires can be estimated by calculating the field set up by a long straight conductor leading the current I. The azimuthal component of the magnetic field at a distance r from a long conductor can be found from [3] Biot-Savarts Law (2-2)

$$B_\theta(r) = \frac{\mu_0 I}{2\pi r}. \tag{2-17}$$

9. How large is the magnetic flux density at a distance $5\,\mathrm{cm}$ from a long $230\,\mathrm{V}$ mains lead due to a current $1\,\mathrm{A}$ in this wire?

2.2.9 Magnetic field-free room

The permanent magnetic field on the earth's surface leads to problems with zeroing of Gaussian meters. However, magnetic fields can be shielded by using materials with high permeability. Pure iron can be used. There are also special alloys that have even higher permeability μ and thus shields even better. An example is mymetal [4]. Gauss meters are usually zeroed by inserting the Gauss meter probe into a chamber that shields it from the ground magnetic field during zeroing.

2.3 Experimental

2.3.1 Equipment

The experiment uses PASCO's data logging system (Capstone) with interfaces and sensors for magnetic fields and position. The following instruments are included in the line-up:

- **Grensesnitt.** PASCO 550 Universal Interface.
- **Magnetfelt sensor.** PASCO Magnetic Field Sensor CI-6520A. Measuring range: 0,01 G - 100 kG. Resolution: 50 mG. Accuracy: 10 % of reading
- **Nullfeltkammer.** PASCO Zero Gauss Chamber EM-8652.

[3] Derivation e.g. i [1], Kap. 23.5.

[4] Mymetal is an alloy of 77 % nickel, 15 % iron plus some copper and molybdenum. It got its name due to very high value for magnetic permeability, μ.

- **Posisjonssensor.** PASCO Rotary Motion Sensor PS-2120A. Catalog Resolution: 0,09°. Radii on the three pulleys: 10 mm, 29 mm, 48 mm.

- **Korte spoler.** 330 Vikings, 22 Vikings / Team $\times$ 15 Teams Inner diameter 126 mm, Outer diameter 154 mm. Wire: lacquer-insulated copper, diameter 0,75 mm, maximum coil current: 1,0 A.

- **Solenoide.** 368 windings, length $\sim$ 400 mm, inner diameter 100 mm. Wire: lacquer-insulated copper, diameter 1,0 mm, maximum solenoid current 1,0 A.

- **Multimeter.** Escort Mod. EDM 168A, or equivalent.

- **Diverse utstyr:** Meter, screwdriver.

- **Kraftforsyning.** Mascot Type 719. Range: 0- 30 V, 30 mA - 2 A. This is a combined power-controlled / voltage-controlled power supply. That is, it can supply a constant current or a constant voltage, up to a certain maximum load. The box has two adjustment buttons, one for voltage marked "0 $\rightarrow$ 30 V"and one for current marked "30 mA $\rightarrow$ 2 A". **Strømstyrt kraftforsyning (strømkilde)** we have if the voltage adjustment is set to maximum. The current is regulated with the current adjustment knob. **Spenningstyrt kraftforsyning (spenningskilde)** we have if the power adjustment is set to maximum. The voltage is regulated with the voltage adjustment knob. If the box is used current-controlled, the maximum current 2 A can be given to an equivalent output resistance of maximum $R = U/I = 30\,\mathrm{V}/2\,\mathrm{A} = 15\,\Omega$. The box also has a button marked range"which can limit the maximum voltage to 15 V instead of standard 30 V. If 15 V is selected, the maximum output resistance will be $R = U/I = 15\,\mathrm{V}/2{,}0\,\mathrm{A} = 7{,}5\,\Omega$. At higher output resistance, the output voltage will be kept at maximum value and the current will be lower. Corresponding maximum regulation is for voltage-controlled power supply. 30 V maximum voltage can be given down to a resistance of $R = U/I = 30\,\mathrm{V}/2{,}0\,\mathrm{A} = 15\,\Omega$. At lower resistance, the supply will not be able to provide enough current so that the voltage will drop.

2.3.2 Calibration of Hallprobe

It is difficult to produce Hall probes with exactly the same Hall constants. The hall voltage that occurs at a given magnetic field and current may therefore vary slightly from probe to probe. In order to be able to use several probes for the same Gaussmeter, each probe has often assigned a calibration number which is used to adjust the gain of the Gaussmeter's voltmeter so that the meter shows the correct magnetic field. PASCO's sensors are adjusted and a calibration is not normally needed. Before use, the sensor must be reset.

Nullstillingsprosedyre:

- Set the area knob on the sensor to position 1x and axial.

- Insert the probe into the zero field chamber and press the zero adjustment button.

MERK: When changing the measuring range, make a new reset!

Enheter og fortegn for Hallproben:

- The meter shows the magnetic flux density, B, of the device you select in Capstone.
- The Gaussian meter shows **positivt** signs when the field lines have direction **inn** of the cylindrical tip of the probe.

2.3.3 Magnetic scattering fields

Task: *Undersøk de magnetiske strøfeltene i laboratoriet og svar på følgende spørsmål:*

- How does the measured direction of the earth's magnetism correspond to the assumed direction of our latitude? [5]
- Compare the results with results from the other groups. Is there variation of the measured earth magnetism within the laboratory?
- Will the magnetic field from the iron in the laboratory tables be able to interfere with the measurements?

2.3.4 Statistical error in measurements

Reading magnetic field strengths from Hallproben will give a somewhat varying result. You can use this to find the statistical error.

Task: *Undersøk statistisk feil i målinger:*

- Connect the sensors in the PASCO interface and the computer interface. Start Capstone and get ready for data sampling.
- Reset and sample data in 10 s. Select data and perform a statistical analysis with built-in functionality in Capstone. What will be the standard deviation of the data? What standard deviations do you get if you sample in 1 s and 100 s? How many samples should you use?
- Use the standard deviation as an error in your data from Hallproben.

2.3.5 Magnetic field in short coil

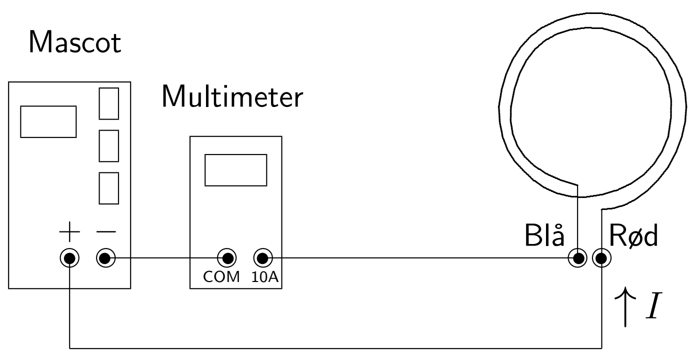
Task: *Kartlegg magnetfeltet på aksen til en kort spole sfa. avstanden fra spolen.*

[5] The magnetic north pole is located near the geographical south pole. Magnetic field lines are closed curves and have direction from magnetic north pole to south pole outer set and from south pole to north pole inside the magnet.

To measure the magnetic field, you can either hold the coil and move the Hallproben or you can attach the Hallproben and move the coil. Which of these is best to use? Motivate!

Framgangsmåte:

- Mount the rotation sensor on the stand.
- Connect the sensors to the interface and the interface of the computer. Start Capstone and get ready for data sampling.
- Mount a short spool on the movable carriage.
- Adjust the position of the magnetic field sensor so that it rests on the coil axis. Use a spirit level.
- Connect the coil circuit as shown in figure 2.10. IMPORTANT: The power supply must be switched off during connection. Select current measurement on both the power supply and the multimeter. Use the 10A input on the multimeter. Catalog - Ask the lab supervisor to approve the connection.
- Reset the magnetic field sensor. (It is safest to break the coil circuit during zeroing.)



Figur 2.10: Spolekrets. Mascot kraftforsyning, multimeter og spolen er vist. Merk deg vikleretningen for spolen, spolen er sett mot siden med koplingsbøssingene.

- Measure the magnetic field $B(x)$ along the axis of the coil sfa. the distance x from the center plane of the coil Remember: maximum coil current is 1,0 A; Check that you do not have an operation in the measurement.

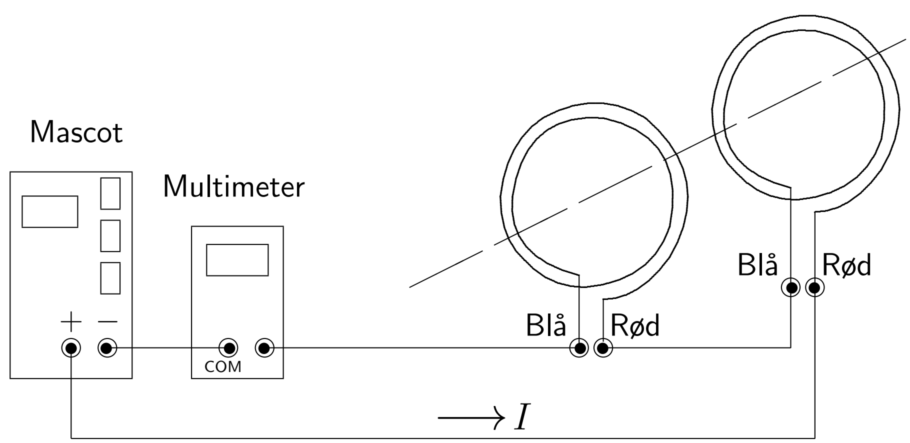
Analyze the results and compare measured and calculated value. Print out the table and graph and paste in the journal.

2.3.6 Magnetic field in Helmholtz coil

Task: *Kartlegge magnetfeltet på aksen mellom to korte spoler sfa. avstanden fra spolens midtplan og avstanden mellom spolene.*

Framgangsmåte:

- Mount on the movable trolley two short coils at a distance $a = R$ from the center plane to the center plane.
- Measure the magnetic field $B(x)$ along the coil axis as a function of the distance x from the center plane between the coils with e.g. $I = 1{,}00\,\mathrm{A}$ and gradually enter the results in the spreadsheet table for the Helmholtz coil. Measure a piece outside the end of the spool.
- Repeat the measurement with coil distances $a = 2R$ and $a = R/2$.
- Analyze the results and compare measured and calculated value. Print out the table and graph and paste in the journal.



Figur 2.11: Oppkopling av Helmholtzspoler. For å få spolene nærme hverandre nok må du montere spolene slik at koplingsbøssingene peker utover for begge spoler. Pass på at strømretningene i hver spole er den samme.

2.3.7 Magnetic field in Anti-Helmholtz coil

Task: *Gjør samme eksperiment som over for Anti-Helmholtzspoler.*

2.3.8 Magnetic field in solenoid

Task: *Kartlegg magnetfeltet på aksen til en solenoide.*

Framgangsmåte:

- Mount the solenoid on the movable carriage and connect the circuit.
- Measure the magnetic field $B(x)$ along the axis of the solenoid as a function of the distance x from the end plane of the solenoid and enter the results in the spreadsheet table gradually.
- Analyze the results and compare measured and calculated value. Print out the table and graph and paste in the journal.

2.3.9 Magnetic field in short coil - extra assignment

Task: *Kartlegg magnetfeltet parallelt en kort spole (y-aksen) sfa. avstanden fra spolen.*

Here the coil is mounted so that the magnetic field sensor passes parallel to the coil. How does the field vary? (Note: field direction.) Explain why the curve looks the way it does.

2.3.10 General Discussion

- Carry out error analysis of the results and discuss possible systematic deviations
- Discuss discrepancies between measurement results and the modeling you have included in the calculation section. Where are the biggest differences? What is the reason?
- Discuss possible applications of the physical effects observed in the experiment.

2.3.11 End

Switch off all appliances, unplug all cables and leave the space in at least as good an order as you found it.

Kapittel 3

LORENTZKRAFTEN

Goal

You are going into this lab assignment

- document experiment in the lab journal
- perform error analysis of the experiment.
- use numerical methods to model the experiment
- study forces on electrons in homogeneous and constant electric and magnetic fields,
- determine the ratio e/m between the charge of the electron e and the mass m (the Thomson experiment),

3.1 Theoretical background

The theory is presented in connection with the presentation of the calculation tasks below. Reference is also made to the textbook and the lectures in electromagnetism.

3.2 Calculation tasks

3.2.1 Lorentzkraften

The force from electric and magnetic fields on charged particles is often called the Lorentz force. The force of a charged particle with charge q moving at velocity $\vec{v}$ in an electrostatic field $\vec{\boldsymbol{E}}$ and a magnetostatic field $\vec{\boldsymbol{B}}$ is given by

$$\vec{\boldsymbol{F}} = q\vec{\boldsymbol{E}} + q\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}. \tag{3-1}$$

To create a fast electron beam, electric fields are always used to accelerate the electrons. However, the expression for Lorentz power shows that both electric and magnetic fields give a power effect on charged particles.

1. Explain from the expression of the Lorentz force why magnetic fields (as opposed to electric fields) can not give a charged particle increased kinetic energy.

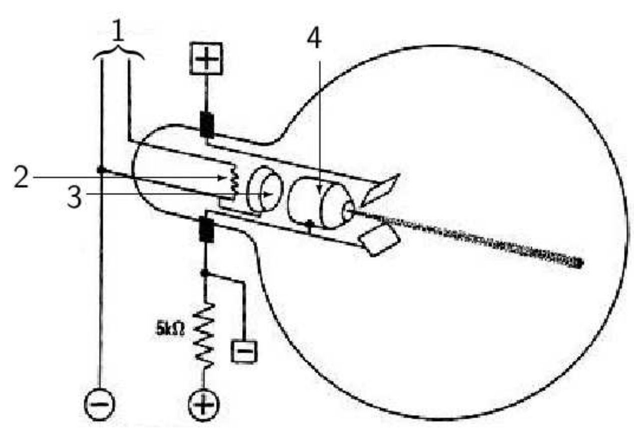
3.2.2 Charges in $\boldsymbol{E}$ field

A homogeneous electric field is most easily set up between two parallel plate electrodes. This geometry provides an electric field $E = U_\mathrm{a}/\ell$ where U_a is the voltage between the plates and ℓ the distance between them. A charged particle with charge q and mass m is accelerated with an acceleration during passage between the plates

$$a = \frac{qE}{m} = \frac{qU_\mathrm{a}}{m\ell}. \tag{3-2}$$

This is used in sources of charged particle beams.

Figure 3.1 shows how an electron beam source can be made. A tungsten filament is heated by electric current passing through it. When it is red hot, it emits electrons from the surface. The filament is placed just behind a plate electrode with holes in it. Voltage is applied between the filament and the plate electrode. The electrons are accelerated towards the plate electrode and the electrons passing through the hole go out in a beam on the other side of the plate. Another way to make electrons in electron sources is to use an oxide cathode that is heated indirectly by a filament. This construction provides better field conditions during acceleration, and it is this version that is shown in figure 3.1.



Figur 3.1: Prinsippskisse for elektronstrålekilde. (1) Vekselspenning (5-10 V) til (2) glødefilament varmer opp (3) oksidbelegget. Akselerasjonsspenning mellom filamentet og (4) anoden akselerer elektronene.

Assume that an electron is accelerated from a standstill to a voltage of 30 V in a static electric field.

2. What is the speed of the electron after the acceleration?

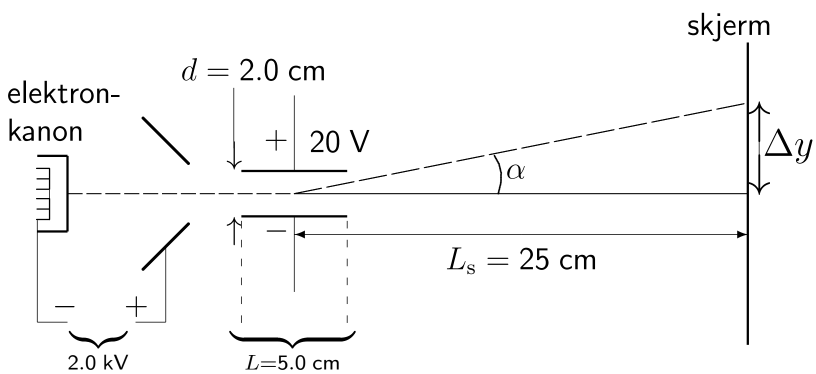
In particle accelerator physics, the energy unit electron volt"is abbreviated eV. A particle charge with an elementary charge gets the energy 1 eV when it is accelerated through a voltage drop of 1 V.

3A. How many joules is equivalent to $1\,\mathrm{eV}$*?*

3B. What is the energy of an electron that is accelerated to a voltage of $30\,\mathrm{V}$ *expressed in the unit* eV*?*

An electron beam from an electron source with zero potential is accelerated to a potential U_a can be deflected in a transverse electric field $E = U_\mathrm{d}/d$ over a distance L as shown in figure 3.2. The deflection angle α is given by

$$\tan\alpha = \frac{1}{2}\frac{U_\mathrm{d}}{U_\mathrm{a}}\frac{L}{d}. \tag{3-3}$$



Figur 3.2: Avbøyning av elektronstråle i et elektrisk felt. Tallverdier i figuren brukes i oppgaven.

Equation (3-3) describes the physical laws that form the basis of the oscilloscope, which is an instrument for measuring electrical voltage. The voltage to be measured is placed between the transverse deflection plates and the deflection of the electron beam observed on a phosphorescent screen is a measure of the voltage.

Assume the electrons are accelerated by a $2\,\mathrm{kV}$ acceleration potential and the other parameters are as shown in Figure 3.2.

4. How much deflection Δy *does the beam on the screen get if the deflection voltage is* $20\,\mathrm{V}$*?*

3.2.3 Charges in B field

When an electron moves in a space free of electric field but with a magnetic field B, the Lorentz force at all times acts normally on the path of the path (unless the path is parallel to the magnetic field). Let's assume the electron is shot into the B field at velocity perpendicular to the field, the Lorentz force then becomes $F_\mathrm{B} = evB$ and constitutes the centripetal force. The electron orbit becomes a circle of radius r with centripetal acceleration $a_s = v^2/r = F_B/m$. The speed v can be determined from the kinetic energy of the electron given by $\frac{1}{2}mv^2 = eU_a$. By putting these equations together, we get the following expression for the radius

$$r = \frac{1}{B}\sqrt{\frac{2U_a}{e/m}}. \tag{3-4}$$

5. Set up in a curve diagram curve intersections over r *sfa.* B *in the range* $0 < B < 15$ gauss *for* $U_a = 20$, 40 *and* $60\,\mathrm{V}$. Use, for example, Python or Matlab.

3.2.4 Determination of e/m (Thomson Experiment)

In 1897, Thomson discovered extremely light, negatively charged particles - which later turned out to be electrons. That same year, he used deflection in static electric and magnetic fields to find the relationship between their charge and mass. The expression (3-4) can be rewritten to

$$\frac{e}{m} = \frac{2U_a}{B^2r^2}. \tag{3-5}$$

The ratio e/m can thus be determined by measuring the radius r in the electron path in a magnetic field B perpendicular to the path of electrons accelerated above a voltage U_a.

You will repeat Thomson's experiment in the laboratory. The size of the equipment limits the diameter of the largest electron orbit to approx. 8 cm.

6. Use the curve cutter that you set up in the problem above to estimate the favorable magnetic field B *for three different acceleration voltages* $U_a = 20$, 40 *and* $60\,\mathrm{V}$*.*

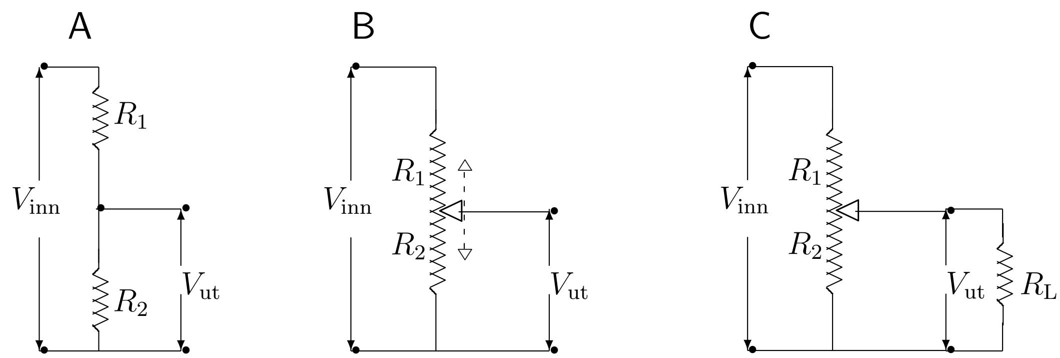
When rewriting (3-5) you get

$$m = \frac{qB^2r^2}{2U_a}, \tag{3-6}$$

showing that the mass m of a charged particle with a known charge q that has been accelerated to a known potential U_a can be determined by measuring the magnetic flux density B and the orbital radius r of the particle in a magnetic field. This is the idea behind the magnetostatic mass spectrometer which is one of the most important instruments for determining atomic and molecular particle masses. With his work, Thomson laid the foundation for this technique.

3.2.5 Voltage components

The so-called voltage divider is among the most common electrical connections. You must use it in the experiment. In its simplest form, the voltage divider looks like in figure 3.3 A.



Figur 3.3: Spenningsdeler. (A) Med faste motstander. (B) Med variabel motstand med midttapping (skyvemotstand/potensiometer). (C) Med potensiometer og last $R_{\rm L}$.

Through the coupling, the voltage $V_{\rm inn}$ can be reduced to $V_{\rm ut}$. To find the size of $V_{\rm ut}$ sfa. $V_{\rm inn}$ you can look at the current I through the resistors R_1 and R_2 which according to Ohm's law are equal

$$I = \frac{V_{\rm inn}}{R_1 + R_2}. \tag{3-7}$$

Use Ohm's law again on R_2:

$$V_{\rm ut} = IR_2 = \frac{R_2}{R_1 + R_2} V_{\rm inn}. \tag{3-8}$$

The voltage divider can be made variable by replacing R_1 and R_2 with a resistor with variable center tap (sliding resistance) as shown in figure 3.3 B. Together with a fixed voltage source, this provides an opportunity to create a cheap variable voltage source.

However, the voltage divider has a disadvantage.

7. Can you find what disadvantage? Catalog TIP: What happens to $V_{\rm ut}$ when you start drawing power from the output (center tapping)? See Figure 3.3 C. The resultant resistance across the parallel connection of R_2 and $R_{\rm L}$ is denoted $R_2||R_{\rm L}$ and is equal to $(R_2R_{\rm L})/(R_2 + R_{\rm L})$.

3.3 Experimental

3.3.1 Equipment

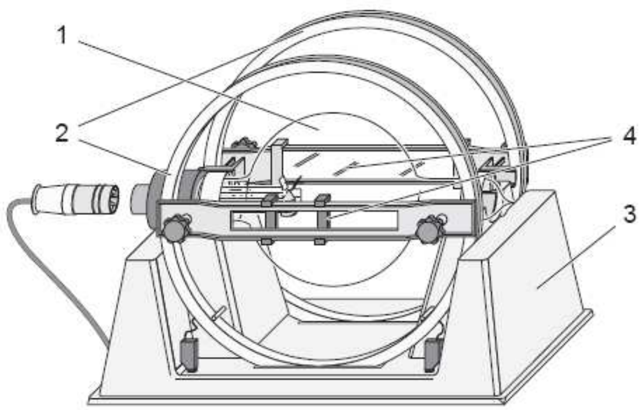
- **Elektronstrålerør.** Leybold Hereaus 555 571.
- **Kraftforsyning for elektronakselerasjonen og fokuseringselektrode.** Leybold Didactics 521 651 Tube power supply 0 ... 500 V.
- **Kraftforsyning for Helmholtzspoler.** Mascot, type 719. Used as a power source. Range: 0- 15 V, 30 mA - 2 A.
- **Multimeter for spolestrøm.** Escort EDM168A, 3 digits, or equivalent.

- **Multimeter for akselerasjonsspenning.** Escort EDM168A, 3 digits, or equivalent.

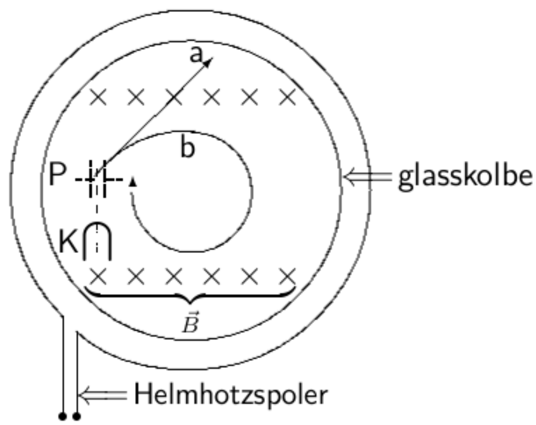
  Catalog

- **Koplingsboks B med spenningsdeler.**

- A quantity **ledninger** of different lengths.



Figur 3.4: Leybold apparat med elektronkanonen innen glasskolbe (1), Helmholtzspoler (2), holder (3), og radiusmåler (4).



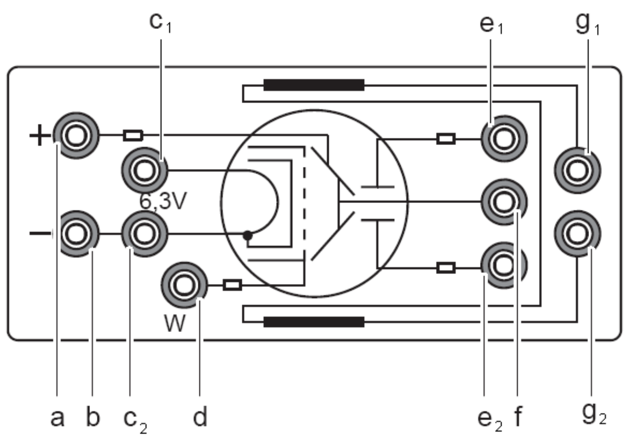
Figur 3.5: Prinsippskisse. Elektronkanonen (K), avbøyning av elektronstrålen mellom avbøyningsplater (P). Magnetfelt er markert med kryss $\times$ *inn i* papirplanet og elektronstrålen er vist uten (a) og med B-felt (b).

The apparatus is shown schematically in Figures 3.4 and 3.5. The electron gun (K) emits electrons that can be deflected in a static electric field between the parallel deflection plates (P) and / or in a static magnetic field from the Helmholtz coils. The glass flask around the electron gun is filled with thin hydrogen gas to a pressure of approximately 10^{-5} atmospheres 1 Pa. Shock between the electrons and the gas will excite the electrons in the gas molecules which then dexcite and emit light (same phenomenon as in the northern lights). The trace of the electrons then becomes visible as a blue-green stripe.

Study the electron gun through the glass flask. Also study the disassembled cannon from an old pipe laid out in the laboratory.

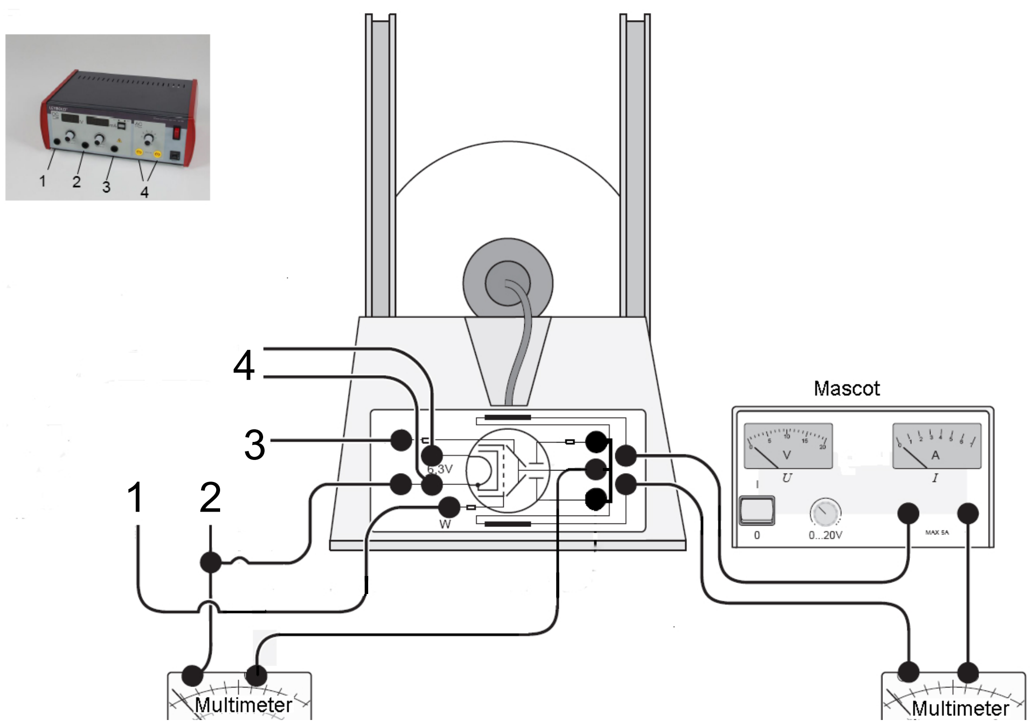
3.3.2 Connection of voltages to the electron gun

Figures 3.6 and 3.7 show schematically the electrical connections for the electron gun. Note the common ground point (output 2 on Leybold Power supply)



a: anodespenning,
b: jordingspunkt,
c: glødespenning til katoden,
d: Wehneltsylinder,
e: avbøyningsspenning (øvre og nedre),
f: punkt for måling anodespenning,
g: strømtilførsel Helmholtzspoler.

Figur 3.6: Elektrisk tilkoplingskjema på apparaturens sidekant.



Figur 3.7: Koplingsskjema for elektronkanonen. Kraftforsyning Leybold, multimeter for måling av anodespenning.

There are several alternative ways to connect the electron gun, but it is important to connect directly. However, it is not difficult to break a couple of fuses if you connect incorrectly, so ask the supervisor if you are in doubt.

Connect the glow circuit according to figure 3.7.

Notes and tips:

- You must connect socket 4 to the unit. Which one you use is irrelevant but one is grounded via contacts b and c $_1$ in figure 3.6.
- The unit must be switched off during connection.
- Ask the lab supervisor to approve the connection.
- Switch on the unit and adjust the glow voltage to "6"(V) and observe that the wire glows. This assumes that the ceiling lighting is switched off and the table lighting is dimmed. Note that the glow voltage can be lowered to 5 V during the experiments.
- Switch off the unit again.

To extract an electron beam from the cathode, the electrons must be accelerated as explained above in the theory section. This is done by applying an acceleration voltage between the cathode and the anode.

Connect the acceleration voltage according to figure 3.7.

Notes and tips:

- Make sure that the power supply is switched off and that the power and voltage adjustment knobs are turned all the way down when connecting.
- Connect Leybold output 3 to "a"and output 2 to b".
- Preliminary deflection potential $U_\mathrm{d} = 0$, therefore the two deflection plates (e $_1$ and e $_2$) are connected together and possibly grounded or connected to the anode, to prevent charge from building up on them.
- To avoid measurement errors due to voltage drop across the series resistor, you can connect the voltmeter directly to the anode instead of f". Use measuring range 1000 V DC. Check the value of the Leybold unit. How big a measurement error do you get and what determines the size of the error?
- The series resistors mounted internally in the equipment are inserted for safety reasons to avoid excessive current in the circuit in the event of an internal short circuit (eg a gas discharge).

Now it is ready to turn on all voltages and see that the electron beam is displayed:

- Ask the lab supervisor to approve the connection.
- Switch on the glow voltage.
- Check that the filament starts to glow.

- Increase the acceleration voltage slowly until you (at 20–30 V or slightly higher if your eyes have not waited until dark) see the trace of the electron beam in the hydrogen gas as a blue-violet stripe out of the electron gun.
- Observe how the beam changes when you change the acceleration voltage.
- Why does the beam not reach the glass wall at low acceleration? At higher voltages, quite abruptly, the beam will meet the wall, then lower the voltage slightly. This happens at different voltages at the different setups, follow closely with around 100 V, and possibly upwards to approx. 150 V.
- NOTE: If the anode starts to glow, turn off the appliance and let it cool down. Never use higher acceleration voltages than necessary to avoid glowing.

Lag en skisse av strålegangen for forskjellige akselerasjonsspenninger.

Procedure for **slå av apparaturen**:

- Switch off the glow plug.
- Reduce the acceleration voltage to zero and switch off the power supply.

NOTE: It is not dangerous to have on acceleration voltage and magnetic field without having on glow voltage, but it is not good to have on glow voltage without acceleration voltage. Therefore, always switch off the glow voltage when you have short and long breaks.

In an electron beam, all the particles have the same sign of charge. The beam will therefore have a tendency to diverge due to internal Coulomb power. If the focusing ring (Wehnelt cylinder) in front of the cathode is placed slightly negative, this will have a focusing effect on the beam.

Connect the Wehnelt cylinder according to figure 3.7. Output 1 to "W". Notes and tips:

- Check that the power supply is switched off and that the power and voltage adjustment knobs are turned down completely before connecting it.
- After connecting the Wehnelt cylinder and switching on the power supply. Adjust the voltage on the focusing electrode (Wehnelt cylinder) if you think the beam is poorly focused. Use maximum 10 V.

3.3.3 Deflection in $\boldsymbol{E}$ field

Task: *Du skal studere avbøyningen av en elektronstråle i et elektrostatisk felt.*

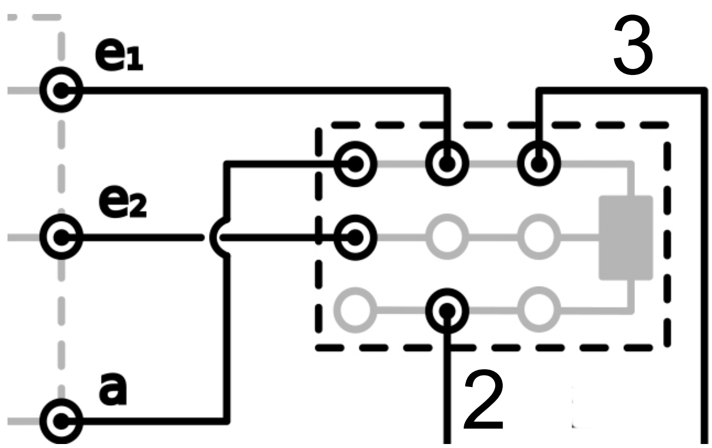
In the setup so far, you have laid both deflection plates at the same voltage, namely the anode voltage U_a. To obtain deflection, one plate is placed on a somewhat lower voltage. In practice, we do this by taking voltage division from the anode voltage. The principle of voltage division is shown in Figure 3.3. Here you have to make changes to the connection. The anode voltage (3) should now be connected with a junction box according to the diagram in figure 3.8 shows changes you must make from the connection in figure 3.7 where the deflection potential was zero. The connection between e $_1$ and e $_2$ is removed.

The voltage divider consists of a precision potentiometer (Helipot) and is mounted on junction box B. The acceleration voltage U_a is connected across the potentiometer. From the center tapping, we take out a voltage that varies with the position of the potentiometer button, which needs 10 revolutions to turn from top to bottom. The deflection voltage is taken out between the top outlet (which is at potential U_a) and the middle outlet at potential xU_a, where x can vary from 0 to 100 %. This means that one deflection plate is at the anode voltage U_a and the other at xU_a. The deflection stress then becomes

$$U_\mathrm{d} = U_\mathrm{a} - xU_\mathrm{a} = (1-x)U_\mathrm{a}. \tag{3-9}$$

If you connect incorrectly and take out voltage division to the ground potential, the electron beam will be braked sharply and easily disappear. You can find out which record should have lower potential by thinking, or by trial and error.

Connect the deflection potential according to figure 3.8.



Figur 3.8: Kretsdiagram for inkopling av spenningsdeler.

Notes and tips:

- Set the potentiometer to 100 % so that the center tap has the same potential as the anode voltage.
- Switch on glow, focusing voltage and acceleration as described previously.
- Vary the deflection by turning the potentiometer knob.

Forklar det du observerer ut i fra uttrykket for Lorentzkraften i likning (3-1).

Sketch the beam for different deflection stresses, e.g. U_d equals $\frac{1}{2}U_\mathrm{a}$ and $\frac{4}{5}U_\mathrm{a}$.

3.3.4 Deflection in $\boldsymbol{B}$ field

Task: *Du skal studere avbøyningen av en elektronstråle i et statisk magnetfelt.*

Kople oppstillinga i henhold til figur 3.7. Note that the connection of the voltage divider in the previous step is not necessary for the tests to be performed here

Connect the circuit to the magnets with the Mascot unit in (g) .

Notes and tips:

- Check that the power supply for the Helmholtz coils is switched off and that the control buttons for current and voltage are turned down completely.
- Set the power supply to the power source (METER: A and the control knob for voltage up 1/2 revolution) and set RANGE to 15 V.
- Use the multimeter (6) for current measurement
- Turn up the power to approx. 1 A, and check that the circuit is working. NOTE: The coils can withstand max. 2 A. Then turn the power down again.
- Switch on the electron beam as described earlier.
- Adjust the acceleration voltage to approx: 100 V and the magnetic current to 0,75 A.

Gi en forklaring på det som skjer forankret i uttrykket for Lorentzkraften.

Ask the lab supervisor to help you twist the electron beam tube in storage until the beam describes a helical path.

Sketch the beam and explain the reason for the helical path.

3.3.5 The Thomson Experiment: Measurement of e/m

Problem: *Du skal bestemme forholdet e/m mellom elektronets ladning og masse fra likning (3-5) by measuring the acceleration voltage U_a, the radius r in the electron orbit and the magnetic field B.*

The magnetic field is pre-calibrated against the current in the coils. The result is given in a calibration curve attached to the apparatus and as an empirical expression of the magnetic field as a function of the measured coil current found from the calibration curve. Alternatively, this expression can be used:

$$B = \mu_0 \cdot (\frac{4}{5})^{3/2} \cdot \frac{n}{R} \cdot I \tag{3-10}$$

R: Radius of the coils, n: number of turns = 130 per coil.

Notes and tips:

- Align the tube so that the beam becomes a circle and not a helix.
- Set the multimeter for voltage measurement in the range 0- 1000 V DC voltage.
- Ask the lab supervisor to show you how to measure the diameter of the electron path using the parallax mirror behind the electron beam tube and a ruler.
- It is possible to photograph the electron path and analyze in TRACKER to get the diameter of the path. Note that you must have a scale (ruler) in the image then.

Analysis and Discussion of the Thomson Experiment

- Determine e/m for the electron based on your measurements of U_a, r, I and the calibration curve or formula for $B(I)$.
- Repeat if you have time the provision for another set of values for U_a and I.
- Estimate the errors in the measured quantities and find the measurement error in e/m. Which sources of error dominate?
- Compare the measured value of e/m with the table value.
- What is the correspondence between the measurement results from different values of U_a and I and your error estimate?
- Discuss possible applications of the physical effects that have been observed in the experiment.

3.3.6 Closing

Switch off all appliances, unplug and clean all cables. Leave the place in at least as good an order as you found it.

Kapittel 4

POWER ON POWER CONDUCTOR

Goal

You are going into this lab assignment

- develop your skills in documenting laboratory work with the lab journal
- study the force between a live conductor and a constant magnetic field,
- gain experience in producing results from precision measurements,
- perform data processing of the measurement results using regression analysis in Python (least squares method).

4.1 Theoretical background

4.1.1 Power on a leader

An electron with charge $q = -e$ moving at a speed $\vec{\boldsymbol{v}}$ in a conductor located in a magnetic field $\vec{\boldsymbol{B}}$ will be affected by a force according to the Lorentz force

$$\vec{\boldsymbol{F}} = q\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}. \tag{4-1}$$

The total force on a live conductor in a magnetic field becomes the resulting force on all the electrons in the conductor:

$$\vec{\boldsymbol{F}} = q(\vec{\boldsymbol{v}}_d \times \vec{\boldsymbol{B}})nA\ell, \tag{4-2}$$

where ℓ is the length of the conductor, A is the cross-sectional area, n is the electron density and consequently $nA\ell$ is equal to the total number of electrons in the conductor.

The speed $\vec{\boldsymbol{v}}_d$ must be understood as the average speed (operating speed) of the electrons. The electric current in a conductor is defined as

$$I = nqv_dA, \tag{4-3}$$

and consequently the power can be expressed

$$\vec{\boldsymbol{F}} = I\vec{\boldsymbol{\ell}} \times \vec{\boldsymbol{B}}, \tag{4-4}$$

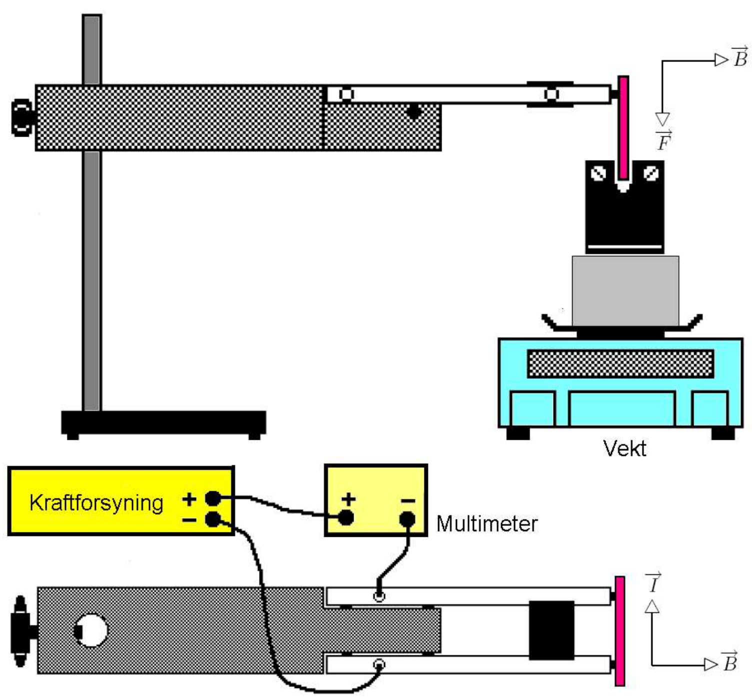
where $\vec{\boldsymbol{\ell}}$ must be perceived as a vector with direction along the conductor in the current direction. Printed in scalar form, the equation is

$$F = I\ell B \sin\theta, \tag{4-5}$$

where θ is the angle between the magnetic field and the positive current direction in the conductor. When the conduction direction is perpendicular to the magnetic field direction is $\theta = \pi/2$, and equation (4-5) is simplified to

$$F = I\ell B. \tag{4-6}$$

The force on a live conductor in a magnetic field can be measured with the arrangement in figure 4.1. The magnet rests on the scale, while the live conductor is fixed independently



Figur 4.1: Prinsippskisse for oppstilling for måling av kraft på en strømførende leder. Øverst vises oppsettet sett ifra siden, og nederst vises oppsettet sett ovenfra.

of the scale. The force effect between the conductor and the magnet will be registered as a result of the weight. However, the weight is calibrated and graded to measure mass M in grams as a certain value for gravitational acceleration g is assumed. As is well known, the connection between power and mass is given by

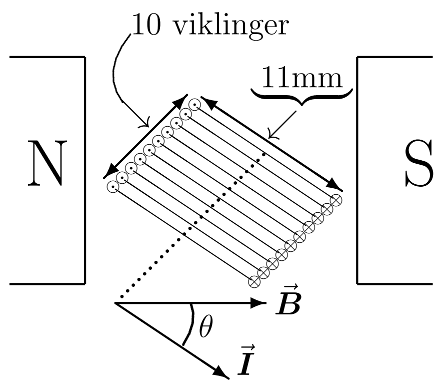
$$F = Mg, \tag{4-7}$$

so that from equation (4-5) we will express the weighting result:

$$M = \frac{I\ell B}{g} \sin\theta. \tag{4-8}$$

4.1.2 Kraft sfa. angles

You replace the conductor with a coil as shown in figure 4.2 where the angle between the coil axis and the magnetic field direction is variable. The coil has $N = 10$ rectangular windings with side lengths 11 mm and only the lower part of the coil lies in the magnetic field so that the force only acts on the lower horizontal part of the windings, ie total length 110 mm. The angle between the current direction and the magnetic field is θ and is included in the equation for calculating the force.



Figur 4.2: Dreibar spole plassert i magnetbrønnen, sett ovenfra. Kun den nedre delen av spolen ligger i magnetfeltet og de vertikale lederne (markert med $\times$ og $\cdot$ på figuren) er påvirket av krefter i horisontal retning og som innbyrdes nuller hverandre ut.

4.2 Preliminary Tasks

Familiarize yourself with the linear curve fitting script located on the Blackboard (Jupyter notebook). Two examples of data sets that can be used for testing are distributed.

4.3 Experimental

4.3.1 Equipment

The following instruments are included in the line-up:

- **Elektromagnetisk vekt.** Mettler Mod. PM480. Range: 0- 400 g. Precision: ±1 mg, or Mettler Mod. PB-SDR / FACT. Range 0- 60 g ± 1 mg / 70- 310 g ± 8 mg.
- **Stativ for strømbaner.** Pasco SF-8607.
- **Faste strømbaner** and **magnetbrønn** with variable magnetic field from 125 G to 750 G in steps of 125 G. Make and type: Pasco SF-8607. Max 5A

- **Roterbar spole** with 10 rectangular windings horizontal, dimension 11×23 mm, with associated magnetic well with magnetic field equal to approx. 250 G. Max 5A. Make and type: Pasco SF-8608.
- **Kraftforsyning.** Fredriksen Mod. 364000. Area: 0- 24 V 0- 10 A. Used as a power source.
- **Multimeter.** Keithley 175A or GW plug GDM-8246.
- **Gaussmeter.** Magnetic Instruments RFL, Mod. 912.
  Measuring range: 0,01 G − 100 kG. Catalog
  Precision: ± (0.4 % of reading + 0.1 % of range + 1 in the last digit). Catalog
  Transversal probe. Catalog
- **Skyvelære.**

The scale is a precision instrument that you must handle with care. Take special care to avoid shocks to the weighing pan during assembly and disassembly of the stand. The scale is based on an electromagnetic weighing method according to the compensation principle so that the weighing pan does not change position during weighing. This is important for our measurements.

The conductors used in the experiments are built up as modern electronic circuit boards with narrow current paths of copper steamed on fiberglass-reinforced polyester sheets. To prevent oxidation of the copper surface, it is covered with tin. In total, the instrument set-up contains six fixed current paths of different lengths, of which four are single and two are double.

As a magnetic field source, a magnetic well built up of six identical permanent magnets is used. The field in the well can be varied by removing the magnets one by one.

To investigate the power sfa. the angle between field direction and current direction is used in the last experiment a rotatable coil with its own magnetic well.

4.3.2 Kraft sfa. the electricity

Task: *Undersøk hvordan kraften mellom en tynn strømførende leder og et magnetfelt med retning vinkelrett på lederen avhenger av strømmen i lederen.*

Suggested procedure:

- Select one of the current paths and measure the length ℓ and the width t of the current path with calipers. (Be careful not to damage the current path with the caliper.) Preliminarily define the length of the current path as the outer dimension in the longitudinal direction. Later you will have the opportunity to reconsider this definition.
- Prepare the power supply: Check that it is switched off and the current and voltage are set to 0.

- use the multimeter to measure the current
- Connect the circuit as shown in figure 4.1. .
- Check the weight level (back level, adjust feet) and then turn on the weight.
- Place the magnetic well in the middle of the scale with the perforated cylinder between the magnetic well and the scale. (The perforated cylinder is inserted to increase the distance between the magnetic well and the weight to avoid the magnetic field from the magnetic well interfering with the weight.)
- Adjust the position of the conductor relative to the magnetic well so that it is in the center of the magnetic field.
- Reset the weight. NOTE: To be absolutely sure that no current is flowing in the circuit during the reset, disconnect the circuit by unplugging one of the connectors while resetting.

The measurement can now be started. The power supply must be power-controlled, but the power supply can deliver up to 10 A while *strømbanen tåler maksimalt 5 A*. It is your responsibility to make sure that the power line is not overloaded! Keep an eye on the electricity meter!

the measurement should provide answers to the following:

- What is the relationship between the weight $M = F/g$ sfa. the current I in the range 0- 5 A? Document the measurement results in the lab journal and in a data file.
- What happens when you change the polarity of the current path? Do you get an expected result?
- What happens when you turn the magnet? Do you get an expected result?
- Show in a sketch current directions and force directions and identify the magnetic poles.
- Finally measure the magnetic field B in the magnetic well with the Gauss meter.

Analysis / Discussion:

- Adjust measurement data to $M^* = a_0 + a_1 I$. Find the beststraight line through the measuring points using. linear regression and determine the slope a_1 and the uncertainty Δa_1.
- Calculate the expected slope number a_1' for $M(I)$ using measured values for ℓ and B and equation (4-8). Also find the uncertainty $\Delta a_1'$.
- Is the value of a_1' equal to the slope number a_1 from the experimental curve within the uncertainty? If not, can you explain the discrepancy?

- Plot the deviation between measured values and values from linear regression for the force as a function of current. Does it look like there is a linear relationship between power and current? (Hint: Look at how the measurement points are distributed around the regression line.) If you assume that there is a linear relationship, does the size of the deviations correspond to the measurement accuracy of the weight?

- Can you, when you take into account the results of the error analysis, claim that you have verified equation (4-8)?

- Print curve diagrams and graphs and paste in the journal along with comments.

4.3.3 Kraft sfa. lengths

Task: *Undersøk hvordan kraften på en tynn leder i et magnetfelt med retning vinkelrett på lederen avhenger av lengden av lederen.*

- Set-up and measurement of the force takes place as in the task above. IMPORTANT: Reduce the current in the circuit to zero each time you change the conductor.

- Measure the length and width of each circuit as accurately as possible. Use external dimension for the length. Note that two of the current paths are double.

- Document the results in the lab journal and in a data file as you measure.

Analysis / Discussion:

- Match measurement data to $M^* = b_0 + b_1\ell$. Find the beststraight line through the measuring points using. linear regression and determine the slope b_1 and the uncertainty Δb_1.

- Calculate the expected slope number b_1' for $M(\ell)$ using measured values for I and B and equation (4-8). Also find the uncertainty $\Delta b_1'$.

- Is the value of b_1' within the uncertainty $b_1 \pm \Delta b_1$ from the experimental curve? If not, can you explain the discrepancy?

- Based on your results here, possibly revising your definition of leader length.

- When you take into account the results of the error analysis, can you claim that you have verified equation (4-8)?

- Print curve diagrams and graphs and paste in the journal along with comments.

4.3.4 Kraft sfa. angles

Task: *Undersøk hvordan kraften på en tynn strømførende leder avhenger av vinkelen mellom lederen og magnetfeltet.*

Procedure:

- Place the swivel spool on the stand and use the corresponding magnetic well.
- Measure weight M sfa. the angle θ between the coil and the magnetic field at fixed current (eg 2 A).
- Document the results in the lab journal and in a data file as you measure.
- Create a regression curve of the shape $M^* = c_0 + c_1 \sin\theta$ for your results. Note that we can use linear regression to adjust a sine if we use $\sin\theta$ as x values.
- Carry out the same analysis / discussion as for previous measurements.

4.3.5 General Discussion

- Discuss the measurement accuracy of the experiment and its influence on the possibilities for comparison with the theory.
- Discuss the most correct way to specify the length of the leader in exercise 4.3.3. Do you have the ability to calculate an effective length based on experimental data?

4.3.6 Closing

- Switch off all appliances, unplug all cables and leave the space in at least as good an order as you found it.

Bibliografi

[1] E. Lillestøl, A. Hunderi og J.R. Lien, 2001 *Generell fysikk for universiteter og høgskoler. Bind 2: varmelære og elektrisitetslære*, Universitetsforlaget.

[2] G.L. Squires, 1985, *Practical Physics*, Cambridge University Press, Cambridge.

[3] N.C. Barford, 1985, *Experimental Measurements: Precision, Error and Truth* (2nd edn), Wiley, Chichester.