LIST OF APPARATUS

1	Coil D with 600 Windings	1000988 (U8497430)
1	Coil D with 1200 Windings	1000989 (U8497440)
1	Transformer Core D	1000976 (U8497180)
1	Transformer with Rectifier 1/ 2/ 4/ … 14 V, 5 A @230V	1003558 (U8521112-230)
or		
1	Transformer with Rectifier 1/ 2/ 4/ … 14 V, 5 A @115V	1003557 (U8521112-115)
2	Digital Multimeter P3340	1002785 (U118091)
1	Set of 15 Safety Experiment Leads, 75 cm	1002843 (U138021)

EXPERIMENT SET-UP AND PROCEDURE

- Set up the experiment as shown in Fig. 4. The multimeter on the primary side coil should be connected in parallel across the primary coil in order to act as a voltmeter. Select the measuring range “V” and mode “AC¨.
- Inputs “COM” and “V” of the multimeter on the secondary side are to be connected to the tap terminals “0” and “1200” on the secondary coil. Select the measuring range “V” and mode “AC¨.

Note

This results in the secondary side being in open circuit (I_2 = 0), so open-circuit voltages U_{20} will be measured.

- Turn on the transformer with rectifier and adjust the supply voltages to U = 2 V, 4 V, 6 V, 8 V, 10 V, 12 V and 14 V in sequence.
- For each of these supply voltages, read off the primary volt-age and the secondary open-circuit voltage from the multimeters and enter them into Table 1.
- Now reconnect the primary-side multimeter such that it is in series with the primary coil and in a position to measure current. (Fig. 4 below). Select the measuring range “mA” and mode “AC¨.
- Inputs “COM” and “mA” of the multimeter on the secondary side are to be connected to the tap terminals “0” and “1200” on the secondary coil. Select the measuring range “mA” and mode “AC¨.

Note

This results in the secondary side being shorted through the multimeter (U_2 = 0), so the meter now measures short-circuit current I_{2C}. The multimeter itself acts as an ohmic load.

- For each of the supply voltages, read off the primary current and the secondary short-circuit current from the multimeters and enter them into Table 2.

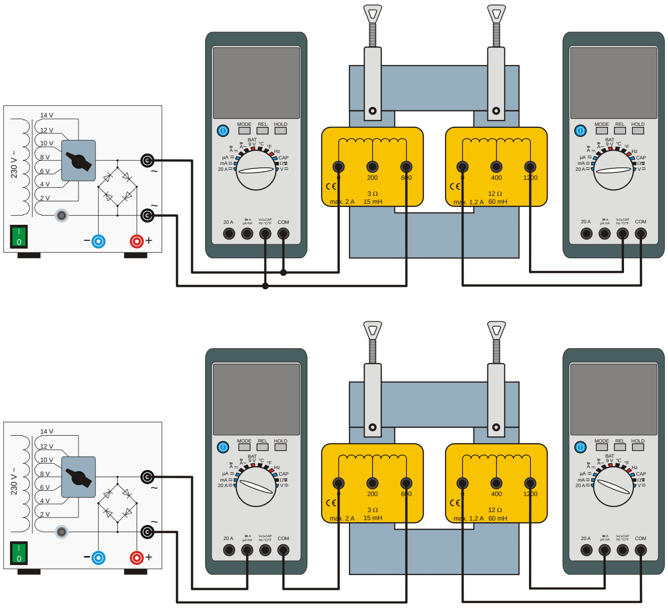


Fig. 4: Experiment set-up for transformer with no load (top) and transformer with load under short-circuit conditions (below).

SAMPLE MEASUREMENTS

Table 1: Transformer with no load (I_2 = 0). Primary voltages U_1 determined by setting supply voltage U and corresponding measurements of open-circuit voltage U_{20}, when N_1 = 600 and N_2 = 1200.

U_1 / V	U_{20} / V

Table 2: Transformer with load under short-circuit conditions (U_2 = 0). Primary currents I_1 determined by setting supply voltage U and corresponding measurements of short-circuit current I_{20}, when N_1 = 600 and N_2 = 1200.

I_1 / mA	I_{2C} / mA

EVALUATION

- Plot the open-circuit voltage U_{20} as a function of primary voltage U_1 (Table 1) and short-circuit current I_{2C} as a function of primary current I_1 (Table 2). Fit a straight line which passes through the origin to each graph (Figs. 5, 6).

From equation (3) the magnitude of the voltages would be as follows:

$$U_{20} = \frac{N_2}{N_1} \cdot U_1 .$$

Similarly the short-circuit current values are derived from equation (6):

$$I_{2C} = \frac{N_1}{N_2} \cdot I_1 .$$

This means the gradients of both the lines found in Fig. 5 and Fig. 6 are determined by the ratio of the number of windings $N_2/N_1 = 2$ or $N_1/N_2 = 0.5$. The line fitted to the above results in the no-load case comes out to be $N_2/N_1 = 1.90$ and that for the short-circuited case comes out to be $N_1/N_2 = 0.46$.

The values deviate from the ideal values of 2 and 0.5 because real coils are always subject to loses. These losses consist of so-called iron and copper losses, as well as losses due to scattering of the magnetic flux. Iron losses arise from the hysteresis as the iron core becomes demagnetised and from eddy currents within the core itself. Copper losses arise from ohmic resistance in the copper wires of the coils. Scattering losses are caused because not all of the magnetic flux Φ generated by the current I flowing in the primary coil passes through the secondary coil.

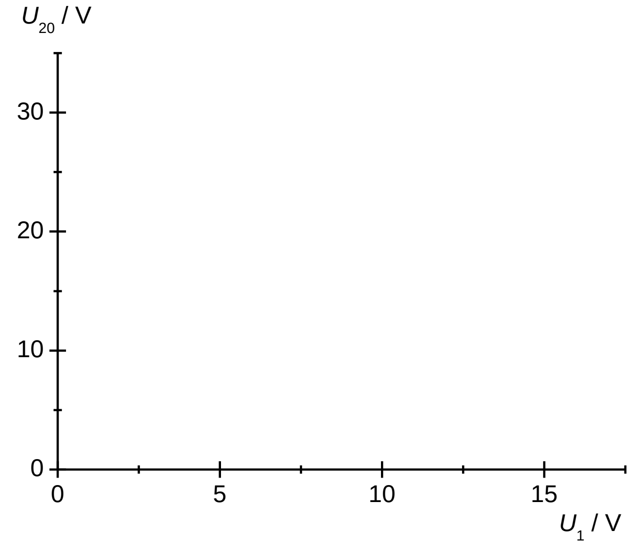


Fig. 5: Transformer without load ($I_2 = 0$). Open-circuit voltage U_{20} as a function of primary voltage U_1, with winding numbers $N_1 = 600$ and $N_2 = 1200$.

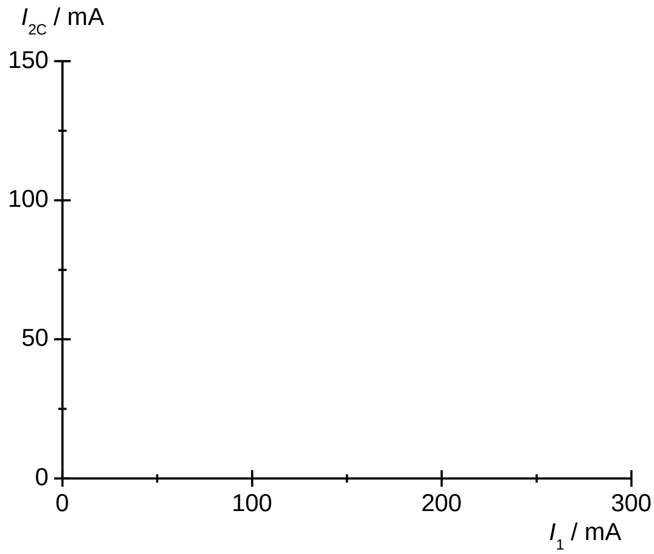


Fig. 6: Transformer with load under short-circuit conditions ($U_2 = 0$). Open-circuit voltage I_{2C} as a function of primary current I_1 with winding numbers $N_1 = 600$ and $N_2 = 1200$.

PHYSICS EXPERIMENT

Charging and Discharging a Capacitor (6)

INVESTIGATION OF HOW THE VOLTAGE ACROSS A CAPACITOR CHANGES OVER TIME WHEN THE CAPACITOR IS CHARGING OR DIS-CHARGING.

- Measure the voltage across a capacitor as it charges and discharges when the DC supply voltage to a circuit is turned on and off.
- Determine the half-life period for charging and discharging.
- Investigate how the half-life period depends on the capacitance and the resistance.

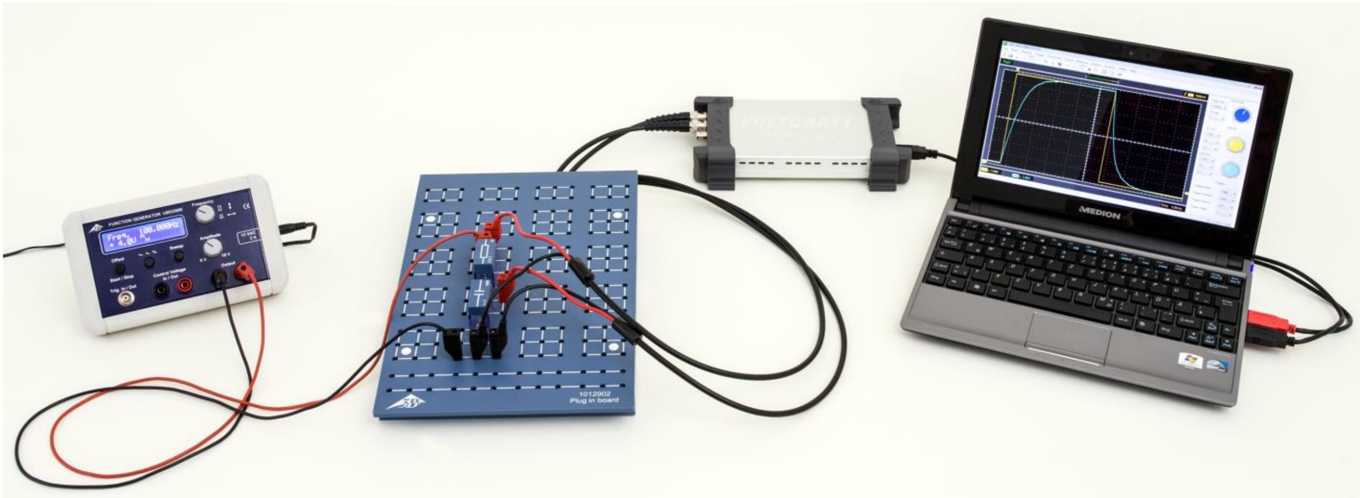


Fig. 1: Measurement set-up.

GENERAL PRINCIPLES

In a DC circuit, current only flows through a capacitor at the point in time when the power is turned on or off. The current causes the capacitor to charge up until the voltage across it is equal to the voltage applied. When the power is switched off, the capacitor will discharge till the voltage across it drops to zero. A plot of the capacitor voltage against time can be shown as an exponential curve.

For a DC circuit featuring a capacitance C, resistance R and a DC voltage U_0, the following applies when the supply is turned on:

$$(1) \quad U(t) = U_0 \cdot \left(1 - e^{-\frac{t \cdot \ln 2}{T_{1/2}}}\right)$$

The following applies when the power supply is switched off:

$$(2) \quad U(t) = U_0 \cdot e^{-\frac{t \cdot \ln 2}{T_{1/2}}}.$$

where

$$(3) \quad T_{1/2} = \ln 2 \cdot R \cdot C$$

$T_{1/2}$ is the half-life period, i.e. the voltage across a discharging capacitor will halve within a time $T_{1/2}$. The same period elapses when the voltage drops from a half to a quarter and from a quarter to an eighth.

These aspects will be investigated in the experiment. How the capacitor voltage changes over time is recorded using a storage oscilloscope. Since the DC voltage U_0 is set to 8 V, it is easy to read off a half, a quarter and an eighth of that value.

LIST OF EQUIPMENT

1	Plug-In Board for Components	U33250	1012902
1	Resistor 470 Ω, 2 W	U333022	1012914
1	Resistor 1 kΩ, 2 W	U333024	1012916
1	Resistor 2,2 Ω, 2 W	U333026	1012918
3	Capacitor 1 µF, 100 V	U333063	1012955
1	Function Generator FG 100	U8533600	1009956/7
1	USB Oscilloscope, 2x50 MHz	U112491	1017264
2	HF Patch Cord, BNC/4 mm Plug	U11257	1002748
1	Set of 15 Experiment Leads	U13800	1002841
1	Set of 10 Jumpers	U333093	1012985

Additionally required:

1 Computer running Win XP, Vista or Win7 operating system

SET-UP AND PROCEDURE

- Set up the apparatus for the measurement as shown in Fig. 2.
- Set up the circuit shown in Fig. 3 on the plug-in board.
- For the oscilloscope, select a time base of 1 ms, 1 V for the vertical deflection of CH1 and CH2, set the trigger mode to edge and and trigger sweep to auto. The source of the trigger should be CH1 and with a threshold of around 600 mV.

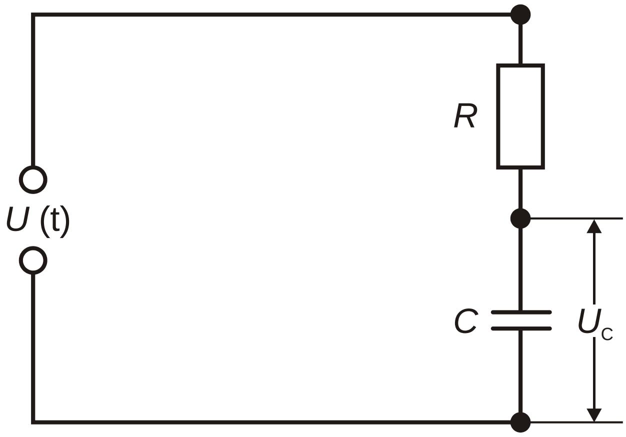


Fig. 3: Sketch of circuit.

Time to reach half-way when charging and discharging

- Plug a resistor of 1 kΩ and a capacitor of 1 µF into the plug-in board as sketched in Figs. 2 and 3.
- Set s frequency of 100 Hz on the function generator and selct a square waveform.
- Select an amplitude which will result in a signal with a peak to peak voltage U = 8 V, corresponding to ±4 divisions with a setting of 1 V/div.
- Read off from the oscilloscope the times $T_{1/2}$ it takes the voltage to halve as the capacitor discharges from voltages of U = 8 V down to U = 4 V, from U = 4 V down to U = 2 V and from U = 2 V down to U = 1 V and enter these values into Table 1.
- Read off from the oscilloscope the times $T_{1/2}$ it takes the voltage to reach the various half-way points when charging up to U = 8 V, i.e. U = 0 V up to U = 4 V, U = 4 V to U = 6 V and U = 6 V to U = 7 V. Enter these values into Table 2.

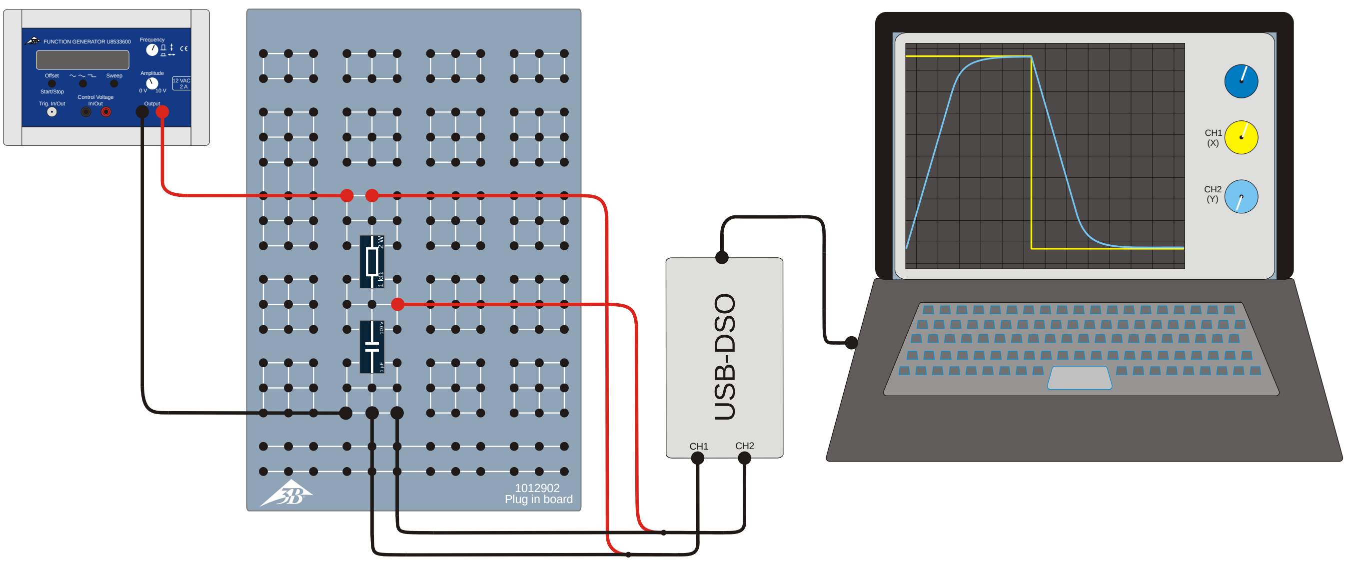


Fig. 2: Sketch of measurement set-up.

Half-way values for a fixed capacitor

- Use two capacitors with capcitance C = 1 µF in parallel to create a network with capacitance C = 0.5 µF.
- Set up circuits with resistance values of R = 0.47, 1, 1.47, 2.2 und 2.67 kΩ in succession. For those values which cannot be achieved using a single resistor, use two resistors in series.
- For each of these resistance values R, read off from the oscilloscope the time $T_{1/2}$ its takes the voltage value to reach half way and enter the results into Table 3.

Half-way values for a fixed resistor

- Use an ohmic resistor of value R = 470 Ω.
- Set up circuits with capacitance values of C = 0.33, 0,5, 0.67, 1, 1.5 und 2 µF in succession. For those values which cannot be achieved using a single capacitor, use multiple capacitors of value C = 1 µF in series or parallel.
- For each of these capacitance values, read off from the oscilloscope the time $T_{1/2}$ its takes the voltage value to reach half way and enter the results into Table 4.

SAMPLE MEASUREMENT

Fig. 4 shows an example oscilloscope trace for the charging and discharging of a capacitor. The yellow exhibits how the voltage across the ohmic resistance changes with time (CH1), while the blue curve represents the change in voltage across the capacitance (CH2).

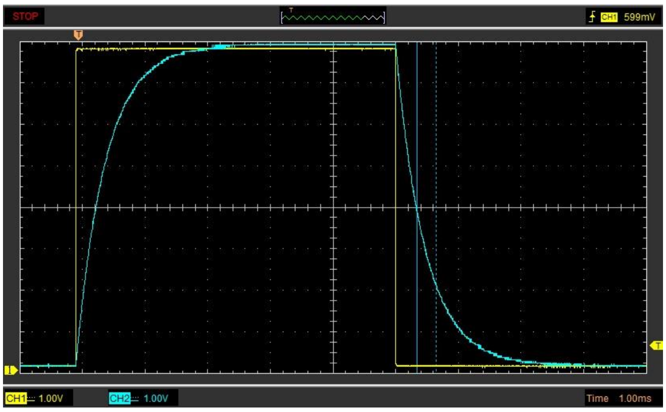


Fig. 4: Traces of voltage across a capacitor while charging and discharging recorded with an oscilloscope.

Tab. 1: Times $T_{1/2}$ for voltages to halve when a capacitor C = 1 µF discharges through a resistor R = 1 kΩ

$T_{1/2}(8\,\mathrm{V} \rightarrow 4\,\mathrm{V})$	$T_{1/2}(4\,\mathrm{V} \rightarrow 2\,\mathrm{V})$	$T_{1/2}(2\,\mathrm{V} \rightarrow 1\,\mathrm{V})$

Tab. 2: Times $T_{1/2}$ for voltage to reach half way when a capacitor C = 1 µF charges via a resistor R = 1 kΩ

$T_{1/2}(0\,\mathrm{V} \rightarrow 4\,\mathrm{V})$	$T_{1/2}(4\,\mathrm{V} \rightarrow 6\,\mathrm{V})$	$T_{1/2}(2\,\mathrm{V} \rightarrow 7\,\mathrm{V})$

Tab. 3: Times $T_{1/2}$ for voltage to reach half way when a capacitor C = 0.5 µF charges or discharges in circuits with various resistance values R.

$\frac{R}{\mathrm{k\Omega}}$	0.47	1.00	1.47	2.20	2.67
$\frac{T_{1/2}}{\mathrm{ms}}$					

Tab. 4: Times $T_{1/2}$ for voltage to reach half way when a capacitors C charge or discharge in circuits with a fixed resistance R = 470 Ω.

$\frac{C}{\mathrm{\mu F}}$	0.33	0.50	0.67	1.00	1.50	2.00
$\frac{T_{1/2}}{\mathrm{ms}}$						

EVALUATION

Half-way values when charging and discharging

The agreement between the times it takes voltage to reach half way at various parts of the charging and discharging curves (Tables 1 and 2) confirms the expected exponential relationship, see equations (1) and (2).

Half-way value for a fixed capacitor

- Plot the “half-way” values $T_{1/2}$ from Table 3 against the resistance R on a graph and join up the points with a straight line through the origin (Fig. 5).
- To verify equation (3), determine the capacitance C from the gradient of the line m_C.

(4) $T_{1/2} = m_C \cdot R$ where $m_C = \ln 2 \cdot C$

$$\Rightarrow C = \frac{m_C}{\ln 2} = \frac{\qquad}{\ln 2} = \qquad .$$

The value determined by measurement is very well in agreement with the nominal capacitance value C = 0.5 µF.

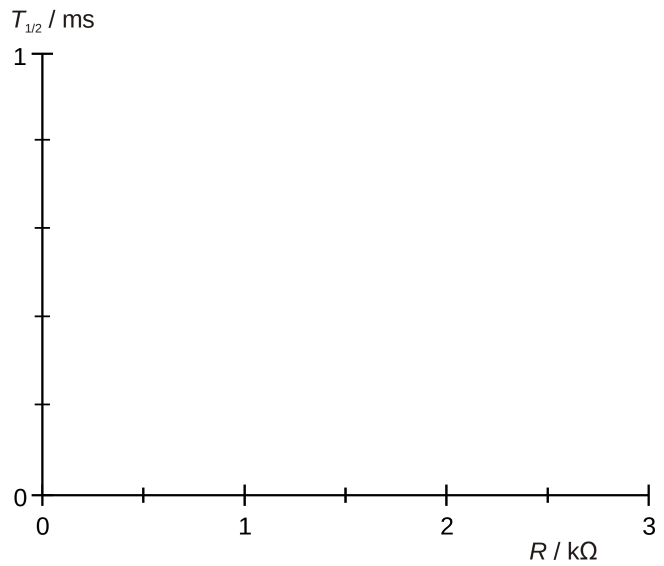


Fig. 5: Half-life $T_{1/2}$ as a function of resistance R.

Half-way value for a fixed resistor

- Plot the "half-way" values $T_{1/2}$ from Table 4 against the capacitance C on a graph and join up the points with a straight line through the origin (Fig. 6).
- To verify equation (3), determine the resistance R from the gradient of the line m_R.

(5) $T_{1/2} = m_R \cdot C$ where $m_R = \ln 2 \cdot R$

$$\Rightarrow R = \frac{m_R}{\ln 2} = \frac{0.32}{\ln 2} = 0.46\ \mathrm{k\Omega}.$$

The value determined by measurement is very well in agreement with the nominal resistance value R = 470 Ω.

- Multiply the values for the ohmic resistance R from Table. 3 with that of the capacitance C = 0.5 µF and alsoi multiply the capcitance values C from Table 4 with the resistance value R = 470 Ω. Enter these values for the product $R \cdot C$ alongside the corresponding "half-way" from Tables 3 and 4 into Table 5.

Tab. 5: Half-way times $T_{1/2}$ for products $R \cdot C$, as calculated from the values in Rables 3 und 4.

$R \cdot C$ / kΩ · µF	$T_{1/2}$ / ms
0.16	
0.24	
0.24	
0.31	
0.47	
0.50	
0.71	
0.74	
0.94	
1.10	
1.34	.

- Plot the "half-way times $T_{1/2}$ from Table 5 against the prodcts $R \cdot C$ on a grph and join the points with a straight line through the origin (Fig. 5).
- To verify equation (3), determine the resistance use the gradient of the line m to determine that the coefficient of proportionality is ln2.

(6) $T_{1/2} = m \cdot R \cdot C$ where $m = \ln 2$

The value obtained by measurement m = 0.67 is very well in agreement with the theoretical value ln2 = 0.69.

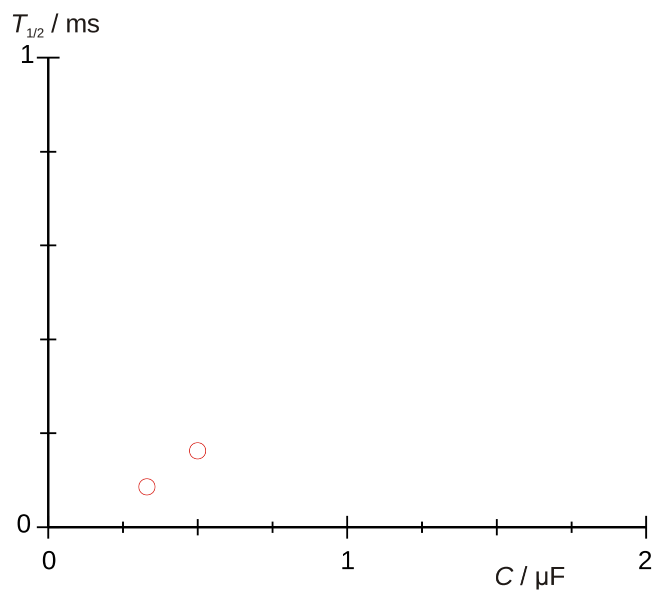


Fig. 6: Half-life $T_{1/2}$ as a function of capacitance C.

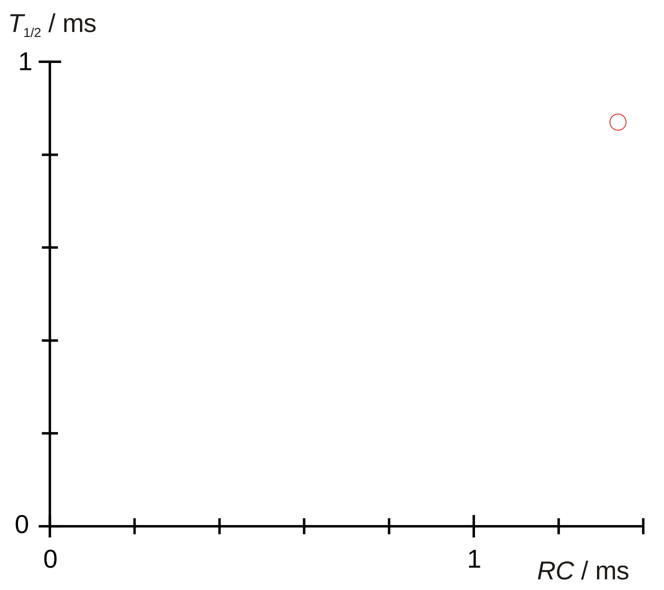
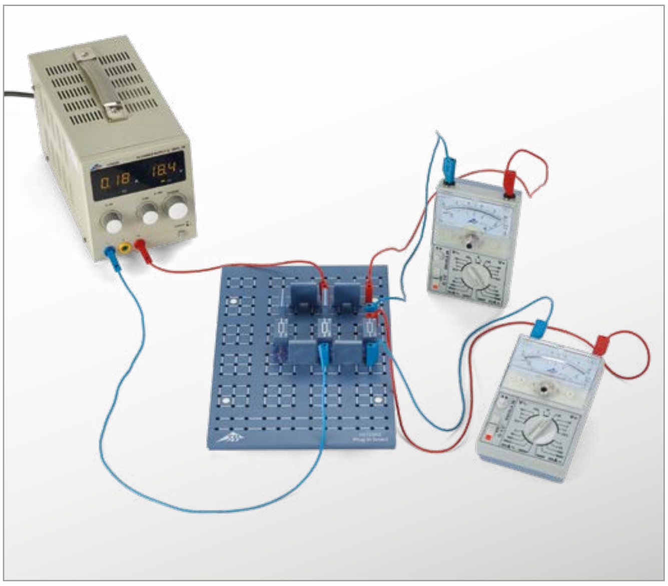
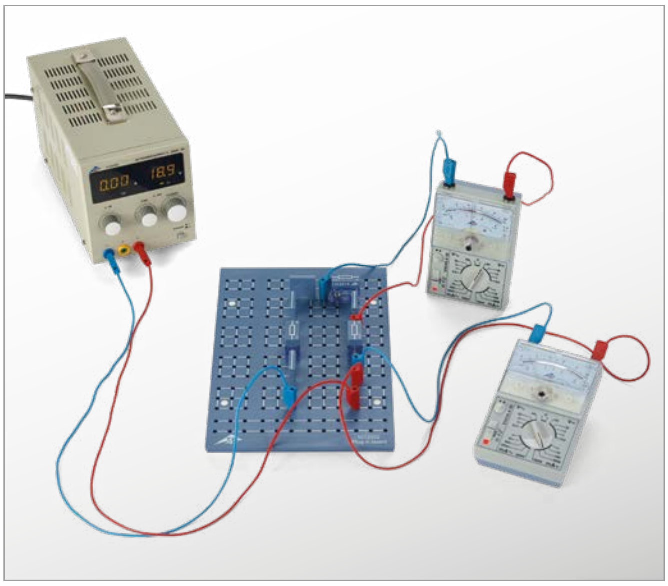


Fig. 7: Half-life $T_{1/2}$ as a function of the product of R*C.

KIRCHHOFF'S LAWS (7)





› EXPERIMENT PROCEDURE

- Verify Kirchhoff's laws for a circuit featuring resistors in series.
- Determine the overall resistance of a series circuit.
- Verify Kirchhoff's laws for a circuit featuring resistors in parallel.
- Determine the overall resistance of a parallel circuit.

OBJECTIVE

Measure voltage and current in circuits featuring resistors in series and in parallel

SUMMARY

Kirchhoff's laws are of key importance for calculating current and voltage in various parts of a circuit with multiple branches. In this experiment, Kirchhoff's laws will be verified by measuring voltage and current in various parts of circuits featuring resistors in series and parallel.

REQUIRED APPARATUS

Quantity	Description	Item Number
1	Plug-In Board for Components	1012902
1	Resistor 220 Ω, 2 W, P2W19	1012912
1	Resistor 330 Ω, 2 W, P2W19	1012913
1	Resistor 470 Ω, 2 W, P2W19	1012914
1	Resistor 1 kΩ, 2 W, P2W19	1012916
1	Resistor 6.8 kΩ, 2 W, P2W19	1012921
1	Resistor 10 kΩ, 0.5 W, P2W19	1012922
1	Resistor 100 kΩ, 0.5 W, P2W19	1012928
1	Set of 10 Jumpers, P2W19	1012985
1	DC Power Supply 0 – 20 V, 0 – 5 A (230 V, 50/60 Hz)	1003312 or
	DC Power Supply 0 – 20 V, 0 – 5 A (115 V, 50/60 Hz)	1003311
2	Analog Multimeter ESCOLA 30	1013526
1	Set of 15 Experiment Leads, 75 cm, 1 mm^2	1002840

BASIC PRINCIPLES

In 1845 *Gustav Robert Kirchhoff* formulated laws describing the relationship between voltage and current in electric circuits which include multiple branches. Kirchhoff's 1st law (current law or junction rule) states that at every point where a circuit branches the sum of the currents flowing towards the junction are equal to the sum of currents flowing away from it. His 2nd law (voltage law, loop or mesh rule) states that, for any loop in any closed circuit, the sum of the voltages in all the branches is equal to the overall voltage provided by the source to that loop. For such loops, a direction of flow is defined. Currents flowing around the loop in the defined direction and voltages which cause such current to flow are considered to be positive, whereas if the currents flow in the opposite direction they are considered to be negative, along with the voltages driving them. These rules can, for example, be applied to circuits featuring resistors in series or in parallel.

In a circuit with *n* resistors in series, the current *I* is identical at every point in the circuit. According to Kirchhoff's second law, the sum of the voltages across each resistor will be equal to the voltage of the source to which they are connected.

(1) $$U = U_1 + \ldots + U_n$$

Therefore the following applies with respect to the overall resistance R_{ser}:

(2) $$R_{ser} = \frac{U}{I} = \frac{U_1 + \ldots + U_n}{I} = R_1 + \ldots + R_n$$

For a circuit featuring resistors in parallel, so-called nodes or junctions arise for the current. Measurements at those nodes show that the sum of the current flowing towards them is equal to the sum of the currents flowing away from them. The voltages at each of these nodes are identical. Kirchhoff's 2nd law makes it possible to determine unknown currents at a node. The sum of the currents flowing through the resistors in each branch is equal to the overall current *I*, whereby the following is true:

(3) $$I = I_1 + \ldots. + I_n$$

Therefore the following applies with respect to the overall resistance R_{par}:

(4) $$\frac{1}{R_{par}} = \frac{I}{U} = \frac{I_1 + \ldots + I_n}{U} = \frac{1}{R_1} + \ldots + \frac{1}{R_n}$$

In this experiment, series and parallel circuits both featuring three resistors are investigated. To verify Kirchhoff's laws, the overall current and the current in each section will be measured along with the overall voltage and the voltage in each section.

EVALUATION

From the measurements on the series and parallel circuits, the overall resistance *R* is first to be calculated and then compared with the theoretical values obtained from equations (2) and (4).

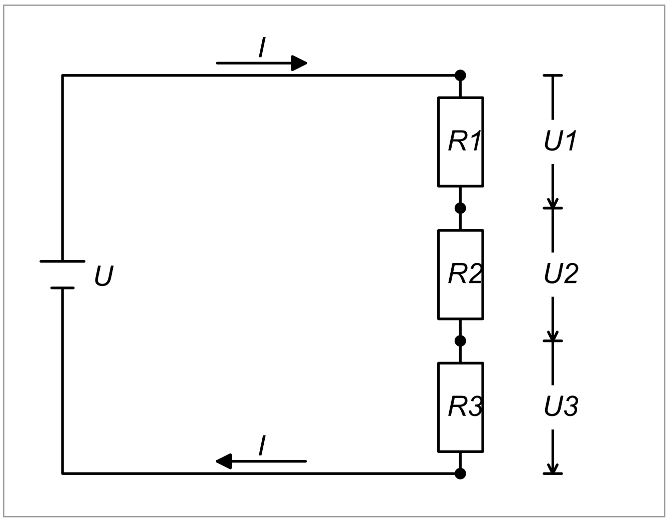


Fig. 1: Schematic for Kirchhoff's laws as applied to a circuit featuring resistors in series

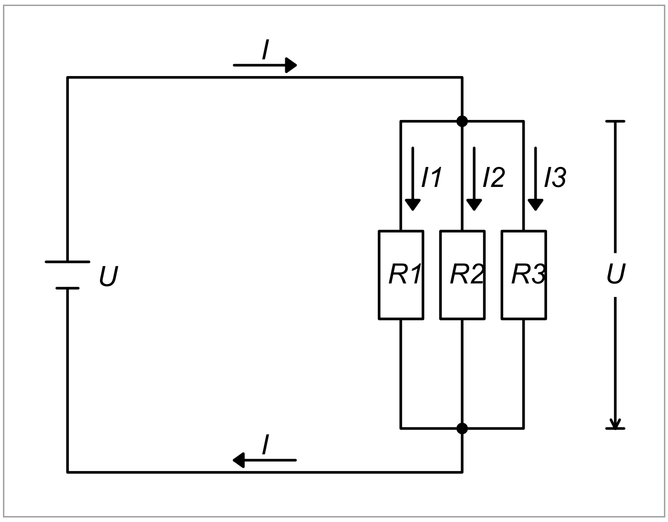


Fig. 2: Circuit diagram for a circuit featuring resistors in parallel

PHYSICS EXPERIMENT

Wheatstone's Bridge (8)

DETERMINE THE VALUE OF CERTAIN RESISTANCES

- Determine resistances using a Wheatstone bridge.
- Estimate the accuracy of the measurements.

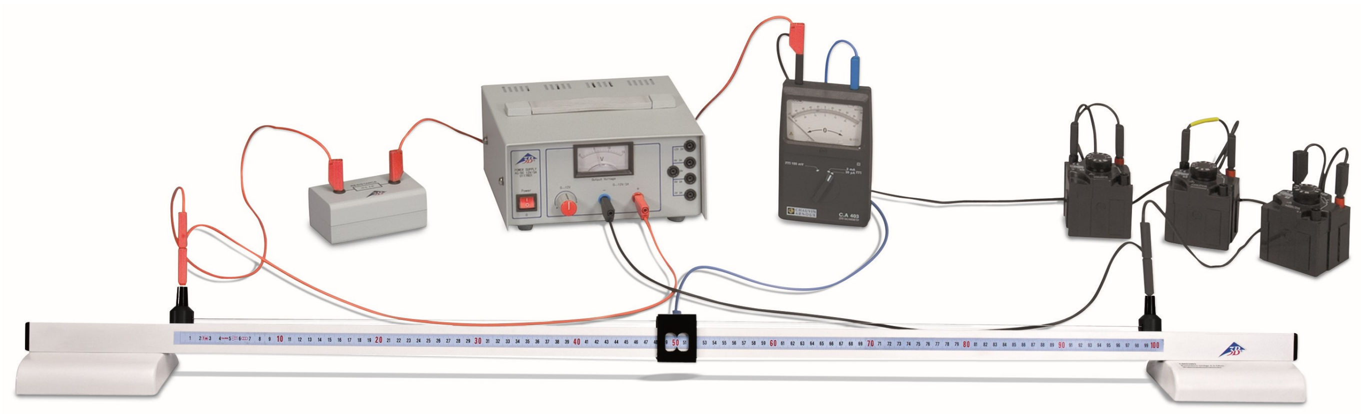


Fig. 1: Experiment set-up.

BASIC PRINCIPLES

A classical method for measuring resistances uses a voltage balancing bridge named after *Charles Wheatstone* to compare the unknown resistance with a reference resistance. This involves setting up a circuit consisting of two voltage dividers in parallel, with a single DC voltage source connected across the whole. The first voltage divider consists of the resistance R_x that is to be measured and a reference resistance R_{ref}, while the second consists of two resistances R_1 and R_2, the sum of which remains constant during the balancing process (see Fig. 2).

The ratio between the resistances R_1 and R_2 and – if necessary – the value of the reference resistance R_{ref} are varied until the current across the diagonal is reduced to zero. This occurs when the ratio between the resistances is the same for both voltage dividers. This balance condition leads to the following expression for the unknown resistance R_x:

(1) $$R_x = R_{ref} \cdot \frac{R_1}{R_2}.$$

In this experiment the second voltage divider consists of a resistance wire 1 metre in length, which is divided into two sections of lengths s_1 and s_2 by a sliding contact.

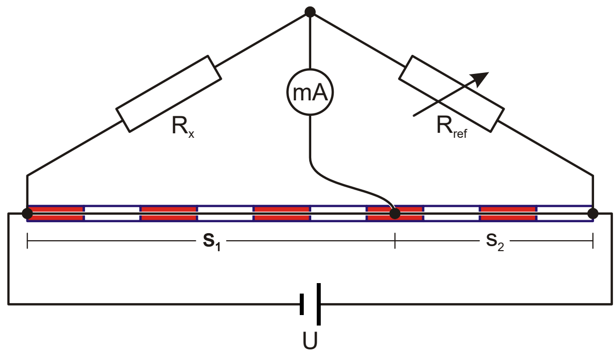


Fig. 2: Schematic diagram of a Wheatstone bridge

The two resistance values R_1 und R_2 are given by the following equation:

$$(2) \quad R_{1,2} = \rho \cdot \frac{s_{1,2}}{A}$$

ρ: Resistivity of wire material
A: Cross sectional area of resistance wire

This is because those two values are represented by the two parts of the resistance wire. Equation (1) can therefore be transformed as follows:

$$(3) \quad R_x = R_{ref} \cdot \frac{s_1}{s_2} = R_{ref} \cdot \frac{s_1}{(1\,\text{m} - s_1)},$$

The accuracy of the result depends on the tolerance of the reference resistance R_{ref}, the accuracy with which it was possible for the ratio of the two lengths of resistance s_1/s_2 to be set up in order to obtain the resistance ratio R_1/R_2 and how accurately it was possible to carry out the balancing of the bridge.

According to Gauss's theory on the propagation of uncertainty, the absolute error in the measurement is as follows:

$$(4) \quad \Delta R_x = \sqrt{\left(\frac{s_1}{(1\,m - s_1)} \cdot \Delta R_{ref}\right)^2 + \left(R_{ref} \cdot \frac{1\,m \cdot \Delta s_1}{(1\,m - s_1)^2}\right)^2}$$

This results in the following relative uncertainty:

$$(5) \quad \frac{\Delta R_x}{R_x} = \sqrt{\left(\frac{\Delta R_{ref}}{R_{ref}}\right)^2 + \left(\frac{\Delta s_1}{s_1} \cdot \frac{1\,m}{(1\,m - s_1)}\right)^2}.$$

The relative uncertainty in the measurement $\Delta R_x/R_x$ is shown in Figure 3 for the range $0\text{ m} < s_1 < 1\text{ m}$, $\Delta R_{ref}/R_{ref} = 0.005$ (0.5%) and a reading error of $\Delta s_1 = \pm 0.5$ mm. It is symmetrical with reference to $s_1 = 0.5$ m, where it is at a minimum and tends to infinity for $s_1 \to 0$ m and $s_1 \to 1$ m.

The accuracy of a Wheatstone bridge in this slider and wire configuration is therefore greatest when the sliding contact is positioned in the centre at $s_1 = s_2 = 0.5$ m. According to equation (3) it will then also be the case that $R_x = R_{ref}$. The reference resistance should therefore be sought out in such a way that the two sections of the wire s_1 and s_2 are the same length, i.e. $s_1/s_2 = 1$.

The accuracy with which the balancing of the bridge can be determined is described by the uncertainty in the balancing, which is inversely proportional to the sensitivity of the bridge, i.e. the more sensitive the bridge is, the more accurate the balance will be.

The sensitivity is given by the ratio between the full scale of the zero point galvanometer measuring the balance and the change in position of the sliding contact which causes the needle to deflect by the full scale. This increases with the sensitivity of the galvanometer and the supply voltage U for the measuring bridge. It also depends on the resistance values of the resistors in the bridge and the resistance of the zero point galvanometer. It is at a maximum when the sliding contact is at the centre of the resistance wire. This means that not only is the ratio s_1/s_2 as good as it can be but so is the accuracy of the balancing.

Since the resistance of the wire used in the bridge is only about one order of magnitude greater than that of the conductors leading to it, resistors of value $R_x \geq 100\ \Omega$ are used for the measurement.

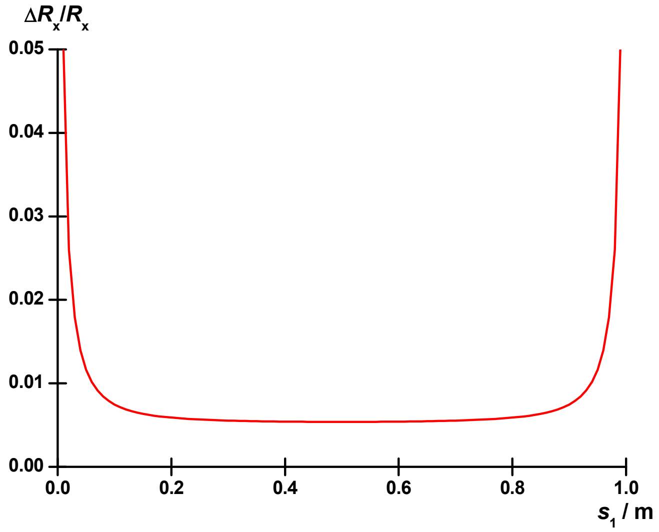


Fig. 3: Relative error $\Delta R_x/R_x$ as a function of s_1 according to equation (5) where $\Delta R_{ref}/R_{ref} = 0.005$ (0.5%) and $\Delta s_1 = \pm 0.5$ mm

LIST OF EQUIPMENT

1 Resistance Bridge	1009885 (U8551002)
1 AC/DC Power Supply 0…12 V/ 3 A @230V	1002776 (U117601-230)
or	
1 AC/DC Power Supply 0…12 V/ 3 A @115V	1002775 (U117601-115)
1 Zero Point Galvanometer	1023786
1 Resistance Decade 100 Ω	1002732 (U11182)
1 Resistance Decade 1 kΩ	1002733 (U11180)
1 Resistance Decade 10 kΩ	1002734 (U11181)
1 Precision Resistor 100 Ω	1009886 (U51004)
1 Precision Resistor 1 kΩ	1009887 (U51005)
1 Set of 15 Safety Experiment Leads, 75 cm	1002843 (U138021)

SET UP AND PROCEDURE

Safety instructions:

Do not exceed the maximum permissible voltage of 8 V or the maximum permissible current of 1.5 A.

Disconnect the power if the zero point galvanometer used for reading the balance is overloaded.

- Set up the experiment as shown in Fig. 1. Connect the black terminal on the right of the measuring bridge via one wire to the negative of the power supply and by another to the "COM" socket of the zero point galvanometer via the resistor decades connected in series. The red terminal on the left of the bridge should be connected via one wire to the positive terminal of the power supply and by another to the "COM" socket of the zero point galvanometer via precision resistors of value 100 Ω or 1 kΩ. The second socket of the zero point galvanometer should be connected to the sliding contact on the measuring bridge. Do not turn on the power supply yet.
- Select a 50 μA range on the zero point galvanometer and check that the needle is correctly pointing to zero. If necessary, calibrate the zero point by turning the adjustment screw on the front panel.

The precision resistors act as the resistance R_x to be measured. The resistor decades are used for generating various fixed reference values R_{ref}.

The resistance R_x = 100 Ω is measured with the help of reference resistors R_{ref} = 10 Ω, 50 Ω, 100 Ω, 500 Ω and 1 kΩ (Table 1), while resistance is measured R_x = 1 kΩ with R_{ref} = 100 Ω, 500 Ω, 1 kΩ, 5 kΩ and 10 kΩ (Table 2). The procedure is described in the following section

At the beginning of a set of measurements:

- Select a range of 5 mA on the zero point galvanometer.
- Set up the smallest reference resistor.
- Position the sliding contact at about $s_1 \approx 90$ cm.
- Turn on the power supply and set the voltage to 5 V.

Recording measurements:

- Move the sliding contact to the position where the zero point galvanometer can no longer detect any current across it (balancing of the resistance bridge).
- Select a 50 μA range on the zero point galvanometer and carry out the balancing procedure as accurately as possible.
- Read off the length of the first part of the resistance wire s_1 from the scale on the rail with the help of the pointer on the sliding contact. Enter the value into tables 1 and 2.
- Select the 50 mA range on the zero point galvanometer.
- Step by step, set up the next highest reference resistance and balance the bridge to zero for each one as described above. In each step, make sure that the galvanometer is not overloaded. You may need to move the sliding contact to roughly the right place in advance.

SAMPLE MEASUREMENT AND EVALUATION

Table 1: Measurement of resistance for R_x = 100 Ω. Set resistance values R_{ref}, lengths measured s_1 and calculated resistance values with measurement errors determined in accordance with equation (4).

$R_x \pm \Delta R_x$ / Ω Nominal value	$R_{ref} \pm \Delta R_{ref}$ / Ω	$s_1 \pm \Delta s_1$ / cm	$R_x \pm \Delta R_x$ / Ω Result
100±1			

Table 2: Measurement of resistance for R_x = 1 kΩ. Set resistance values R_{ref}, lengths measured s_1 and calculated resistance values with measurement errors determined in accordance with equation (4).

$R_x \pm \Delta R_x$ / Ω Nominal value	$R_{ref} \pm \Delta R_{ref}$ / Ω	$s_1 \pm \Delta s_1$ / cm	$R_x \pm \Delta R_x$ / Ω Result
1000±10			

- From the lengths s_1 (Table 1, Table 2) measured, use equation (3) to determine the values R_x using various different reference resistances R_{ref} and use equation (4) to calculate the measurement error ΔR_x. For each measurement, enter the results into Table 1.
- Taking into account the measurement error calculated for the values of R_x determined by experiment with the various reference resistances R_{ref} and lengths s_1, compare the values determined with the nominal values.

Conclusion:

The values measured are in good agreement with the nominal values within the measurement errors determined for all reference resistance values and positions of the sliding contact. The error in the measurement is at its minimum when $s_1 = s_2 = 50$ cm but does not vary significantly within the range 10 cm ≤ s_1 ≤ 90 cm (cf. Fig. 3).

OTHER MEASURING METHODS

Balancing by adapting the reference resistances

- Position the sliding contact in the centre of the resistance wire such that $s_1 = s_2 = 50$ cm.
- Set up the resistor decades in such a way that their reference resistance causes the needle of the zero point galvanometer to be as close as possible to the zero point.
- Move the sliding contact to the position where the needle of the galvanometer is exactly at the zero point and determine the resistance to be measured from the result.

Fixed reference resistance for various resistances to be measured

- Swap over the precision resistors and the resistor decades so that the precision resistors now act as a fixed reference resistance R_{ref} and the resistor decades can be used to measure a variety of different resistance values R_x.

PHYSICS EXPERIMENT

Electric Field in a Plate Capacitor (9)

MEASURE THE ELECTRIC FIELD IN A PLATE CAPACITOR USING THE ELECTRIC FIELD METER.

- **Measuring the electric field within a plate capacitor as a function of the distance between the plates.**
- **Measuring the electric field within a plate capacitor as a function of the applied voltage**

Fig. 1: Measurement set-up

BASIC PRINCIPLES

The electric field meter can be used to measure electric fields directly. In front of an induction plate with four sectors in a star-shaped arrangement, a fan-like disc of similar shape is rotated. It continually interrupts the electrostatic flux, and thereby causes periodic induced charges, which are allowed to dissipate through a large resistance. The voltage pulses that are thereby generated are amplified to give an output voltage, which is then rectified to give a DC voltage that is proportional to the electric field *E* acting on the induction plate.

In the experiment, the electric field strength

$$(1) \quad E = \frac{U}{d}$$

in a plate capacitor is measured using the electric field meter. The applied voltage U and the distance d between the plates are varied in separate experimental runs.

In applying Equation 1, one must take into account the fact that the induction plate is about 1 mm below the lower capacitor plate. Therefore, Equation 1 must be replaced by:

$$(2) \quad E = \frac{U}{d_{\mathrm{eff}}} = \frac{U}{d + 1\,\mathrm{mm}}.$$

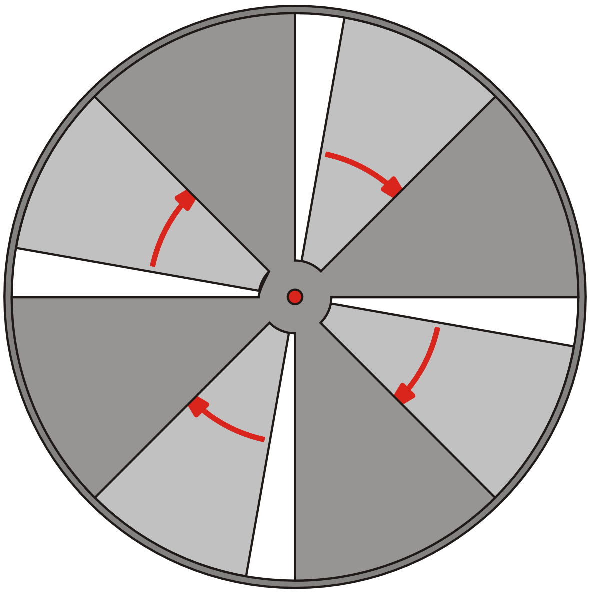


Fig. 2: Rotating disc of electric field meter.

LIST OF EQUIPMENT

1 Electric Field Meter @230V 1001030 (U8533015-230)
or
1 Electric Field Meter @115V 1001029 (U8533015-115)

1 DC Power Supply 450 V@230V 1008535 (U8521400-230)
or
1 DC Power Supply 450 V@115V 1008534 (U8521400-115)

1 Digital Multimeter E 1018832 (U8531051)

1 Analogue Multimeter Escola 30 1013526 (U8557330)

1 Set of 15 Safety Experiment Leads, 75 cm 1002843 (U138021)

SET UP AND PROCEDURE

General instructions

- Whenever possible, conduct the experiments using voltages that are not dangerous to the touch.
- When using mains-connected instruments that generate a voltage that would be dangerous to touch, use a 300 kΩ resistor (1000690) to limit the current.
- For all measurements, connect the contact rod to the earth socket on the screening cylinder and hold it in your hand, so that you are also at the same potential.
- Before each set of measurements, the zero-point of the electric field meter should be calibrated for all the measurement ranges.
- After plugging into the mains, wait a few minutes for the instrument to reach normal working temperature.
- To avoid damage to the electric field meter, do not touch the rotating vaned wheel.
- The insulating parts of the instrument and the measurement plates must be kept clean and dry (avoid touching them). When the air is very humid, it may be necessary to dry them in a current of warm air (use a hair-dryer).

Zero-point calibration

- Set up the experiment as shown in Fig. 1. Do not turn on the DC power supply yet.
- Put the voltage measurement plate for measuring range 1x (with 4-mm socket) on the screening cylinder, secure it with the help of the knurled screw and connect it to the earth socket of the screening cylinder.
- First calibrate the zero-point for the indicating instrument (Analogue Multimeter Escola 30) (see relevant instruction sheet).
- Turn the measurement range switch to the “U” position and set to the highest range.
- Switch on the electric field meter and set the zero point using offset adjustment.
- Calibrate the zero-point for the two lower measurement ranges by the same procedure.

Tab. 1: Adjustment of plate separations *d* = 1 – 15 mm by combinations of spacers.

	d / mm														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Knurled screw from below		X	X	X	X	X	X	X	X	X	X	X	X	X	X
Spacer, 2 mm with thread		X	X	X	X	X	X								
Spacer, 8 mm with thread								X	X	X	X	X	X	X	X
Spacer, 1 mm	X		X		X		X		X		X		X		X
Spacer, 2 mm				X	X					X	X			X	X
Spacer, 4 mm						X	X					X	X	X	X

- Replace the voltage measurement plate, putting the capacitance measuring plate on the screening cylinder instead. Secure it in place with its fastening screw.

Adjustment of plate separation

- To adjust plate separation to d = 1 mm, place the three 1 mm spacer discs about 120° apart on the edge of the capacitance measuring disc and then put the capacitor plate on top of them.
- To adjust plate separation to d = 2 – 7 mm, screw the three 2 mm spacers with internal thread about 120° apart on the edge of the capacitance measuring disc by means of the knurled screws. Then also slot the three 1, 2 and 4 mm spacers onto the knurled screws as shown in Table 1 and place the capacitor plate on top of these spacers.
- To adjust plate separation to d = 8 – 15 mm, use the three 8 mm spacers with internal thread instead of the 2 mm ones.

Electric field as a function of plate separation

- Set the plate separation to d = 2 mm and enter the corresponding effective plate separation d_{eff} = 3 mm into Table 2.
- Turn on the DC power supply and set the voltage to U = 100 V.
- Select a measuring range of 100 V/cm on the electric field meter.

A voltage of 1 V read off from the analogue multimeter corresponds to an electric field of 100 V/cm = 1 V/m.

- Enter the voltage reading from the analogue multimeter as the value of the electric field in units of V/m into Table 2.
- Turn the voltage down all the way on the DC power supply then turn off the power supply and discharge the capacitor plate by briefly connecting it to the screening cylinder.
- Repeat the measurement with the same applied voltage U = 100 V for plate separations of d = 4, 6, 8, 10 and 12 mm (Table 1) and enter the field strengths you measure next to the corresponding effective separations d_{eff} in Table 2.

Electric field as a function of applied voltage

- Set the plate separation to d = 9 mm (d_{eff} = 10 mm).
- Turn on the DC power supply and set the voltage to U = 50 V.
- Select a measuring range of 100 V/cm on the electric field meter.

A voltage of 1 V read off from the analogue multimeter corresponds to an electric field of 100 V/cm = 1 V/m.

- Enter the voltage reading from the analogue multimeter as the value of the electric field in units of V/m into Table 3.
- Turn the voltage down all the way on the DC power supply then turn off the power supply and discharge the capacitor plate by briefly connecting it to the screening cylinder.
- Repeat the measurement with the same plate separation d = 9 mm for voltages of U = 100, 150, 200, 250, 300, 350, 400 and 450 V and enter the field strengths you measure next to the corresponding effective separations d_{eff} in Table 3.

SAMPLE MEASUREMENT

Tab. 2: Electric field strength as a function of plate separation for U = 100 V.

d_{eff} / mm	E / V/m
3	
5	
7	
9	
11	
13	

Tab. 3: Electric field strength as a function of applied voltage U for d_{eff} = 10 mm.

U / V	E / V/m
50	
100	
150	
200	
250	
300	
350	
400	
450	

EVALUATION

- Plot the electric field strengths E you have measured against the effective plate separations d_{eff} (Table 2) and the applied voltage U (Table 3) (see Figs. 3, 4).
- The hyperbolic relationship between field strength and effective plate separation (Fig. 3) and the linear dependence on applied voltage (Fig. 4) as predicted by equation (2) are verified by these graphs.

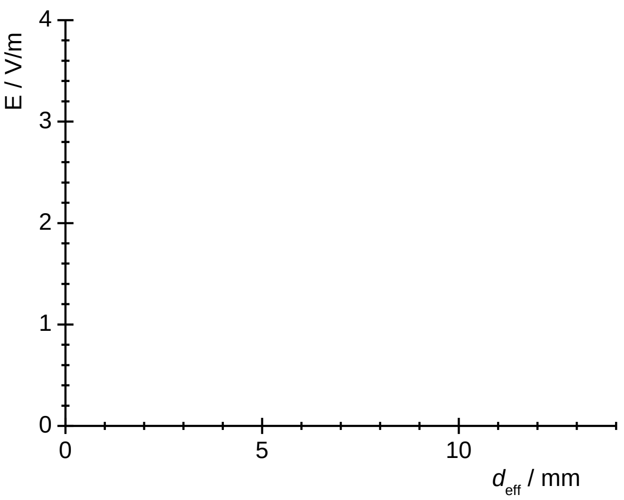


Fig. 3: Electric field within plate capacitor as a function of plate separation for U = 100 V.

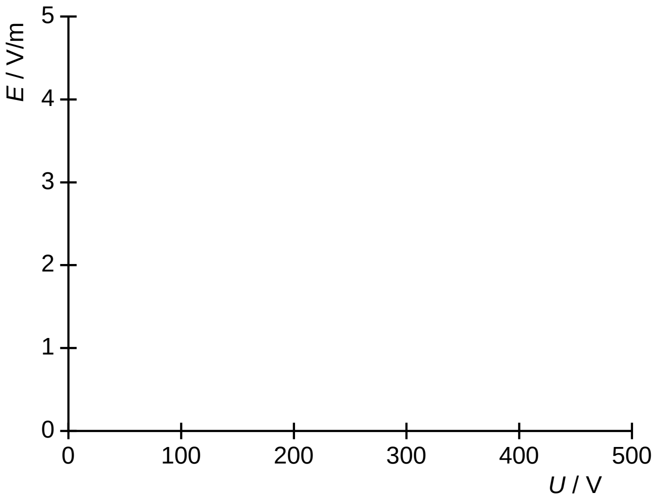


Fig. 4: Electric field within plate capacitor as a function of applied voltage U for d_{eff} = 10 mm.