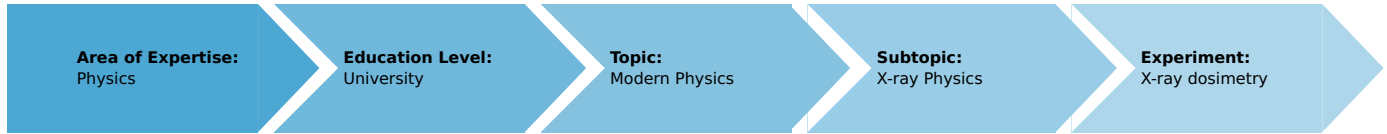


# X-ray dosimetry (Item No.: P2541805)

## Curricular Relevance



**Difficulty**



Difficult

**Preparation Time**



1 Hour

**Execution Time**



2 Hours

**Recommended Group Size**



2 Students

**Additional Requirements:**

**Experiment Variations:**

- As an alternative, this experiment can also be performed with a copper, molybdenum, or iron X-ray tube (09057-50, 09057-60, 09057-70).

**Keywords:**

x-radiation, ionisation energy, absorbed dose, equivalent dose, ion dose, local dose, dose rate, quality factor, inverse-square law, dosimeter

## Overview

### Short description

**Principle**

Dosimetry, as a subspecialty of medical physics, deals with the determination and calculation of dose rates, which is also of great importance in view of the radiation protection directives. This experiment demonstrates the principle of measurement and it explains the various units of absorbed dose, equivalent dose, and absorbed dose rate. Inside a plate capacitor, an air volume is irradiated with X-rays. The resulting ion current is used to determine the dosimetric data.

This experiment is included in the upgrade set "XRD 4.0 X-ray dosimetry and radiation damage".



Fig. 1: Experiment set-up (shows the old DC measuring amplifier instead of universal measuring amplifier)

## Equipment

Position No.	Material	Order No.	Quantity
1	XR 4.0 expert unit, X-ray unit, 35 kV	09057-99	1
2	XR 4.0 X-ray plug-in unit W tube	09057-81	1
3	XR 4.0 X-ray Capacitor plates f.x-ray-unit	09058-05	1
4	PHYWE power supply, regulated DC: 0...12 V, 0,5 A; 0...650 V, 50 mA / AC: 6,3 V, 2 A	13672-93	1
5	PHYWE Universal measuring amplifier	13626-93	1
6	Digital multimeter 2005	07129-00	2
7	High-value resistor, 50 megOhms	07159-00	1
8	Resistor 100 kOhm, 1W, G1	39104-41	1
9	Adapter, BNC-plug/socket 4 mm	07542-26	1
10	Connecting cord, 32 A, 100 mm, blue	07359-04	2
11	Connecting cord, 32 A, 500 mm, red	07361-01	2
12	Connecting cord, 32 A, 500 mm, blue	07361-04	2
13	Connecting cord, 32 A, 750 mm, red	07362-01	2
14	Connecting cord, 32 A, 250 mm, blue	07360-04	2
15	Connecting cord, 32 A, 250 mm, red	07360-01	1
16	XR 4.0 X-ray fluorescent screen	09057-26	1
17	XR 4.0 X-ray holder for capacitor plates	09057-05	1
18	XR 4.0 X-ray optical bench	09057-18	1
19	Slide mount for optical bench expert	08286-00	1
20	XR 4.0 X-ray Diaphragm tube d = 2 mm	09057-02	1
21	XR 4.0 X-ray Diaphragm tube d = 5 mm	09057-03	1

## Tasks

1. Determine the ionised air volume in the capacitor.
2. Determine the ion current as a function of the capacitor voltage and with the aid of two diaphragm tubes with different aperture diameters. Calculate the ion dose and the absorbed dose rate based on the ion saturation current and on the irradiated air volume.
3. Measure the ion currents  $I_c$  for different anode currents  $I_A$  at maximum anode and capacitor voltage.
4. Determine the ion currents  $I_c$  for different anode voltages  $U_A$  at maximum anode current and at maximum capacitor voltage.

## Setup and Procedure

### Setup

The wiring of the electrical components is shown in Figures 2-4. Figure 6 shows a schematic wiring diagram. One digital voltmeter is used to determine the capacitor voltage  $U_c$ , while the other one is connected to the measuring output of the amplifier. For capacitor voltages  $U_c > 300$  V, the corresponding outputs of the power supply unit are connected in series (see Figures 4a and 4b).

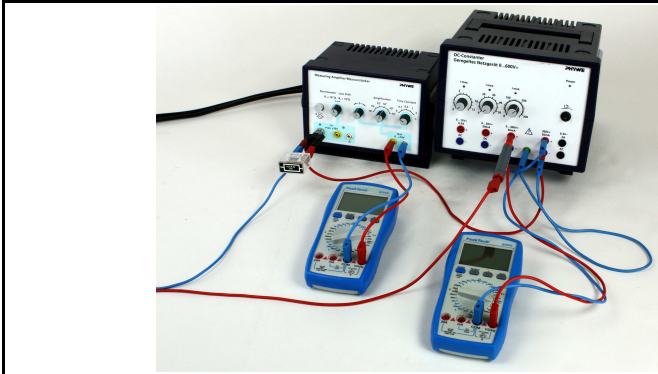


Fig. 2: Wiring of the electrical components



Fig. 3: Connection of the X-ray unit

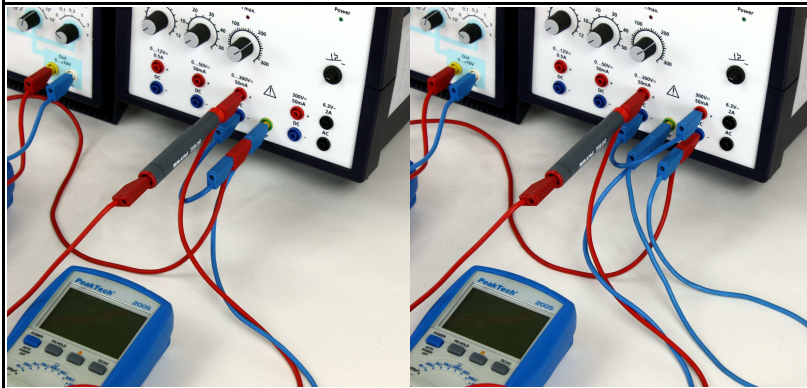


Fig. 4a: Detailed wiring at the power supply unit for measurements up to 300 V; Fig. 4b: Series connection for measurement up to 600 V



Fig. 5: Set-up and wiring of the capacitor plates inside the experiment chamber

Connect the capacitor plates to the corresponding sockets of the adapter. Then, connect the latter to the sockets in the experiment chamber with the aid of two 25 cm long cables. Ensure that the cables do not come into contact with each other (Fig. 5)! For safety reasons, the positive (red) output of the external connection block must be connected to the positive voltage output of the power supply unit via the 50-M $\Omega$ -resistor. The other one must be connected to the measuring amplifier via the BNC adapter, to which the 100 k $\Omega$  measuring resistor is connected in parallel (see Figures 1 and 3).

Set the measuring amplifier to "Electrometer", select an amplification of  $10^3$ , and a time constant of 0 s. Set the multimeter to DC mode and select a measuring range of 2 V.

At maximum capacitor voltage and without a running X-ray tube, there should be no current (if necessary, readjust this with the aid of the zero controller of the amplifier). With the above settings, a measured voltage of 0.1 V corresponds to a current of 1 nA (with measuring resistance 100 k $\Omega$ ):

$$I_c = \frac{U_{\text{sig}}}{V \cdot R}$$

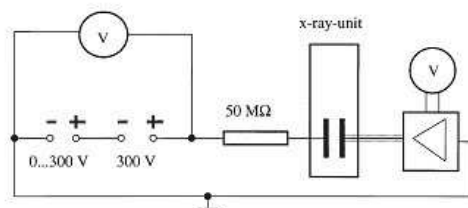


Fig. 6: Schematic wiring diagram for determining the ion currents

### Task 1

In order to determine the irradiated capacitor volume in an approximative manner, the inaccessible distance  $x_0$  (see Fig. 7) must be determined indirectly. For this purpose, the capacitor must be removed and the various diaphragm tubes must be used in order to measure the diameters of the corresponding luminous patterns on the fluorescent screen ( $U_A = 35 \text{ kV}$  and  $I_A = 1 \text{ mA}$ ). For this purpose, the experiment chamber must be darkened. The other distances must be determined with the capacitor installed.

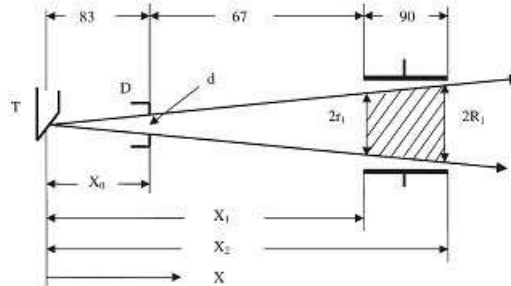


Fig. 7: Schematic representation of the beam geometry for the determination of the irradiated air volume (values in mm)

### Task 2

Measure the ion currents  $I_c$  with the diaphragm tubes with  $d = 2 \text{ mm}$  and  $d = 5 \text{ mm}$  as a function of the capacitor voltage  $U_c$ . For this purpose, the anode voltage  $U_A = 35 \text{ kV}$  and the anode current  $I_A = 1 \text{ mA}$  are kept constant and the capacitor voltage is increased in steps of 30 to 40 V. Measurements that are performed without any limiting diaphragm tubes lead to false results, since, in this case, X-rays also hit the capacitor plates where they release secondary electrons.

### Task 3

Measure the ionisation current  $I_c$  as a function of the anode current  $I_A$  with the aid of the diaphragm tube with  $d = 5 \text{ mm}$ . For this purpose, the anode voltage  $U_A = 35 \text{ kV}$  and the capacitor voltage  $U_c = 500 \text{ V}$  are kept constant and the anode current  $I_A$  is increased from 0.1-1 mA in steps of 0.1 mA.

### Task 4

Measure the ionisation current  $I_c$  as a function of the anode voltage  $U_A$  with the aid of the diaphragm tube with  $d = 5 \text{ mm}$ . For this purpose, the anode current  $I_A = 1 \text{ mA}$  and the capacitor voltage  $U_c = 500 \text{ V}$  are kept constant and the anode voltage  $U_A$  is increased from 10-35 kV in steps of 5 kV.

## Theory and Evaluation

### Theory

When ionising radiation impinges on a mass element  $\Delta m$ , a portion of the radiation energy  $\Delta E$  is absorbed. The ratio of the absorbed energy to the absorbing mass is defined as the absorbed dose  $D$ .

$$D = \Delta E / \Delta m \quad (1)$$

The SI unit of the absorbed dose is "Gray" (Gy) [ $1 \text{ Gy} = 1 \text{ J kg}^{-1}$ ]. Different types of radiation with the same absorbed dose have identical physical, but different biological effects. In order to ensure comparability, the equivalent dose  $H$  has been introduced while taking into account a so-called quality factor  $Q$ .

$$H = D \cdot Q \quad (2)$$

The unit of the equivalent dose is "Sievert" (Sv): [ $1 \text{ Sv} = 1 \text{ J kg}^{-1}$ ].

Since the duration of action of the ionising radiation plays an important role in the evaluation of radiation damage, for example, the ion dose rate  $P$  has been introduced. For the absorbed dose rate, which must be distinguished from the equivalent dose rate, the following applies:

$$P = dD/dt \quad (3)$$

The corresponding SI unit is:  $1 \text{ Gy s}^{-1} = 1 \text{ J kg}^{-1} \text{ s}^{-1}$

As it is not easy to measure the absorbed energy, one measures the ions that are generated in an air volume due to radiation. For this purpose, the ion dose  $I$  is defined as the quotient of the generated charge  $\Delta Q$  of like sign and of the mass  $\Delta m$  of an air volume element  $\Delta V$  under normal conditions.

$$I = dQ/dm [\text{As kg}^{-1}] \quad (4)$$

The following applies to the corresponding ion dose rate  $j$ :

$$j = \frac{dI}{dt} = \frac{d}{dt} \left( \frac{dQ}{dm} \right) = \frac{di}{dm} [\text{A kg}^{-1}] \quad (5)$$

#### Measuring principle:

The X-radiation generates a current in the capacitor when voltage is applied. The measuring amplifier measures the voltage drop across the input resistance and produces a voltage signal  $U_{sig}$  that is proportional. This signal is then displayed by the connected digital measuring instrument. The conversion, depending on the input resistance in use, is as follows:

$$I_c = \frac{U_{sig}}{V \cdot R} = \frac{U_{sig}}{10^3 \cdot 100 \text{ k}\Omega} = \frac{U_{sig}}{10^8 \Omega}$$

### Task 1

**Determine the ionised air volume in the capacitor.**

The radiation that is emitted by the anode  $T$  of the X-ray tube (see Fig. 7) is limited by the diaphragm tube with the aperture diameter  $d$ . It irradiates an air volume of the plate capacitor in a cone-shaped manner. The irradiated air volume results from Figure 7:

$$V = \frac{\pi(X_2 - X_1)}{3} (R^2 + rR + r^2) \quad (6)$$

with the radii

$$r = \frac{X_1 \cdot d}{X_0}; R = X^2 \cdot dX_0 \quad (7)$$

$x_0$  can be determined with the aid of the theorem of intersecting lines based on the diameters of the luminous patterns that were measured in task 1.

In our case, the mean value is:

- $x_0 = 6.65 \text{ cm}$
- $x_1 = 12.95 \text{ cm}$
- $x_2 = 20.85 \text{ cm}$

For  $d = 2 \text{ mm}$  (2-mm-diaphragm-tube), the following results:

- $r = 0.39 \text{ cm}$
- $R = 0.63$
- $V = 6.57 \text{ cm}^3$

For  $d = 5 \text{ mm}$  (5-mm-diaphragm-tube), the following results:

- $r = 0.97 \text{ cm}$
- $R = 1.57 \text{ cm}$
- $V = 40.76$

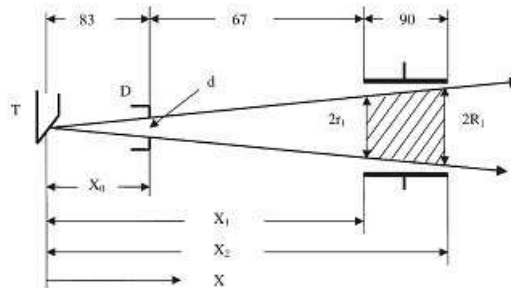


Fig. 7: Schematic representation of the beam geometry for the determination of the irradiated air volume (values in mm)

## Task 2

Determine the ion current as a function of the capacitor voltage at maximum anode voltage and current. Perform the measurement series with two diaphragm tubes with different aperture diameters.

Figure 8 shows the capacitor current  $I_c$  as a function of the capacitor voltage  $U_c$  for two different irradiated volumes.

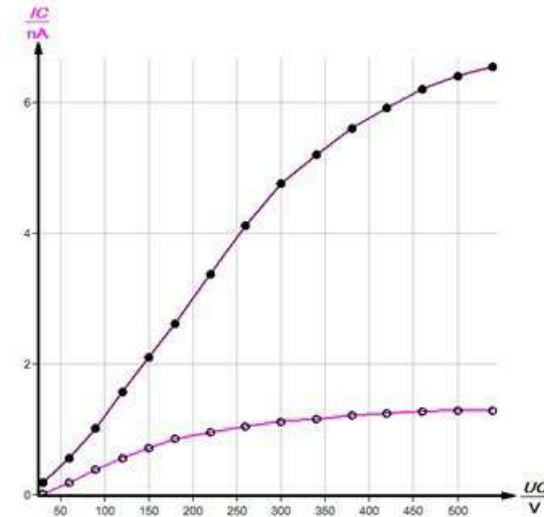


Fig. 8: Ionisation current  $I_c$  as a function of the capacitor voltage  $U_c$  X-ray tube:  $U_A = 35$  kV;  $I_A = 1$  mA Curve A: diaphragm tube  $d = 5$  mm Curve B: diaphragm tube  $d = 2$  mm

### Calculation of the ion dose

In order to be able to determine the ion dose rate of X-rays, the air volume that is enclosed in a plate capacitor is irradiated. The generated electrons and the positive ions generate a current at the capacitor. This current increases with an increasing voltage before it reaches a zone of saturation where all of the generated charge carriers contribute to the current.

Based on the saturation current values from Fig. 8 (for curve A, a saturation current of 6.7 nA is found by extrapolation) as well as on the values from task 1, one obtains the following values for the ion dose rate in accordance with (5):

$$d = 0.5\text{cm} : j_m = \frac{I_{Csaturation}}{m_{air}} = \frac{I_{Csaturation}}{\rho_{air} \cdot V} = \frac{6.7 \cdot 10^{-9} \text{ A}}{1.2 \cdot 10^{-6} \frac{\text{kg}}{\text{cm}^3} \cdot 40.76 \text{ cm}^3} = 1.4 \cdot 10^{-5} \text{ Akg}^{-1} \quad (8)$$

$$d = 0.2\text{cm} : j_m = \frac{1.29 \cdot 10^{-9}}{1.2 \cdot 10^{-6} \cdot 6.57} \text{ Akg}^{-1} = 1.6 \cdot 10^{-5} \text{ Akg}^{-1}$$

(Density of air at 20°C and 1,013 hPa:  $\rho = 1.2 \cdot 10^{-6} \text{ kgcm}^{-3}$ )

### Calculation of the absorbed dose rate

Dividing the mean value of the ion dose rates (determined above) by the elementary charge  $e$  gives the number of ions  $n$  generated per time and mass unit. The ionisation energy  $\Phi$  of an air molecule amounts to approximately  $\Phi \approx 33\text{eV} = 52.8 \cdot 10^{-19} \text{ J}$ . In accordance with (1) and (3) and based on the mean value of the values for  $j$  that were calculated above, the mean absorbed dose rate per time and mass unit results as follows:

$$P_m = \frac{D}{t} = \frac{W}{m \cdot t} = n \cdot \Phi = \frac{1.5 \cdot 10^{-5} \cdot 52.8 \cdot 10^{-19}}{1.6 \cdot 10^{-19}} \text{ Jkg}^{-1} \text{ s}^{-1} = 4.95 \cdot 10^{-4} \text{ Jkg}^{-1} \text{ s}^{-1} \quad (9)$$

### Task 3

Measure the ion currents  $I_c$  for different anode currents  $I_A$  at maximum anode and capacitor voltage. Plot the function  $I_c = f(I_A)$ .

Figure 9 shows the linear course of the ionisation current as a function of the anode current ( $U_A = \text{const.}$  and  $U_C = \text{const.}$ ).

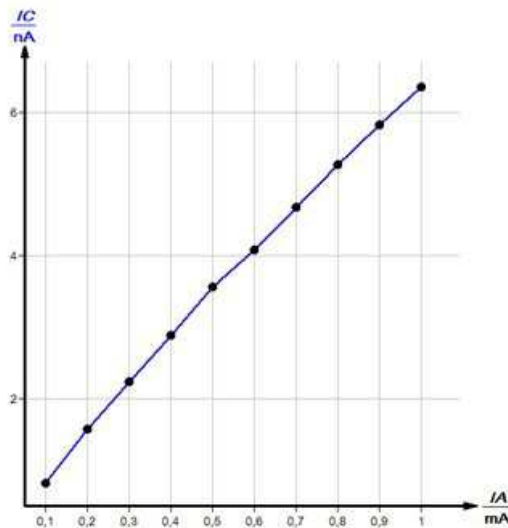


Fig. 9: Ionisation current  $I_c$  as a function of the anode current  $I_A$ . Anode voltage  $U_A = 35 \text{ kV}$ . Capacitor voltage  $U_c = 500 \text{ V}$ . Diaphragm tube  $d = 5 \text{ mm}$ .

### Task 4

Determine the ion saturation current as a function of the anode voltage.

Figure 10 shows the function course  $I_c = f(U_c)$  for various anode voltages  $U_A$ . The extrapolation of the curve  $I_c = f(U_A)$  towards smaller  $U_A$  values (Fig. 9) shows that for  $U_A$

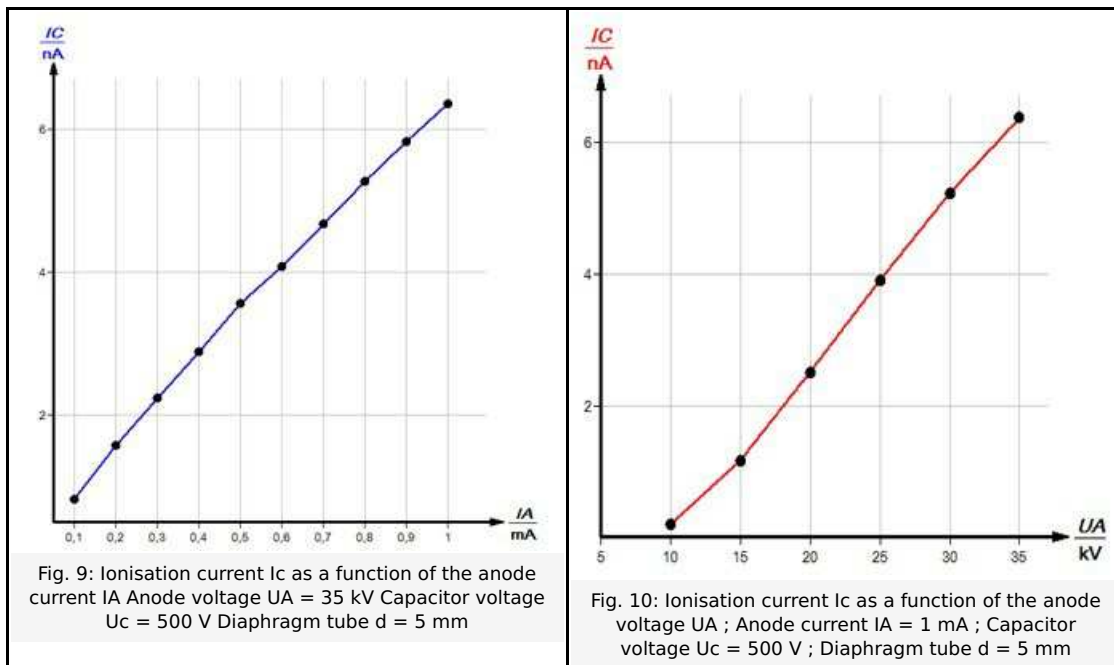


Fig. 9: Ionisation current  $I_c$  as a function of the anode current  $I_A$ . Anode voltage  $U_A = 35 \text{ kV}$ . Capacitor voltage  $U_c = 500 \text{ V}$ . Diaphragm tube  $d = 5 \text{ mm}$ .

Fig. 10: Ionisation current  $I_c$  as a function of the anode voltage  $U_A$ ; Anode current  $I_A = 1 \text{ mA}$ ; Capacitor voltage  $U_c = 500 \text{ V}$ ; Diaphragm tube  $d = 5 \text{ mm}$ .