X-ray dosimetry (Item No.: P2541801)

Curricular Relevance

Area of Expertise:	Education Level:	Topic:	Subtopic:	Experiment:
Physics	University	Modern Physics	X-ray Physics	X-ray dosimetry

Difficulty	Preparation Time	Execution Time	Recommended Group Size
Difficult	1 Hour	2 Hours	2 Students

Additional Requirements:

Experiment Variations:

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: P2541801

Note

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

Equipment

Position	Material	Order nr.	Quantity
1	XR 4.0 expert unitX-ray unit, 35 kV	09057-99	1
2	XR 4.0 X-ray plug-in unit W tube	09057-80	1
3	DC measuring amplifier	13620-93	1
4	PHYWE Power supply, 0...600 VDC, regulated	13672-93	1
5	XR 4.0 X-ray fluorescent screen	09057-26	1
6	XR 4.0 X-ray optical bench	09057-18	1
7	XR 4.0 X-ray Capacitor plates f.x-ray-unit	09058-05	1
8	XR 4.0 X-ray holder for capacitor plates	09057-05	1
9	High-value resistor, 50 megOhms	07159-00	1
10	Digital multimeter 2005	07129-00	2
11	XR 4.0 X-ray Diaphragm tube d = 2 mm	09057-02	1
12	XR 4.0 X-ray Diaphragm tube d = 5 mm	09057-03	1
13	Slide mount f.opt.profile-bench	08286-00	1
14	Adaptor, BNC socket/4 mm plug	07542-20	1
15	Screened cable, BNC, l 250 mm	07542-10	1
16	Connecting cord, 32 A, 750 mm, red	07362-01	2
17	Connecting cord, 32 A, 500 mm, red	07361-01	2
18	Connecting cord, 32 A, 500 mm, blue	07361-04	2
19	Connecting cord, 32 A, 250 mm, blue	07360-04	1
20	Connecting cord, 32 A, 250 mm, red	07360-01	1
21	Connecting cord, 32 A, 100 mm, blue	07359-04	2

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).

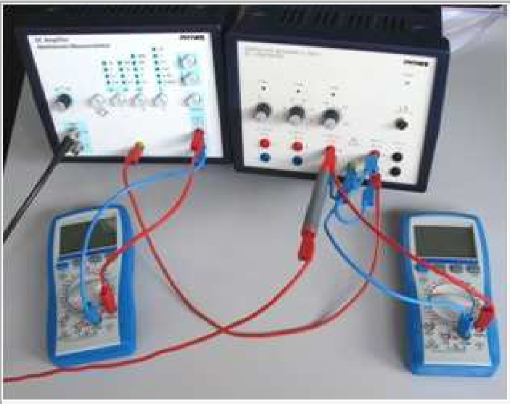

Fig. 2: Wiring of the electrical components

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

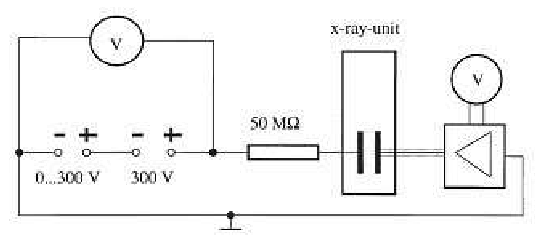

Fig. 6: Schematic wiring diagram for determining the ion currents

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 DC measuring amplifier via the BNC adapter and a BNC cable (see Figures 1 and 3). Set the DC measuring amplifier to “current measurement”. Measuring range: 10 nA (can be adjusted with the arrow buttons; please also refer to the operating instructions of the measuring amplifier).
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).

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

Task 1

In order to determine the irradiated capacitor volume in an approximative manner, the inaccessible distance $x0$ (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 kV and I_A = 1 mA). For this purpose, the experiment chamber must be darkened. The other distances must be determined with the capacitor installed.

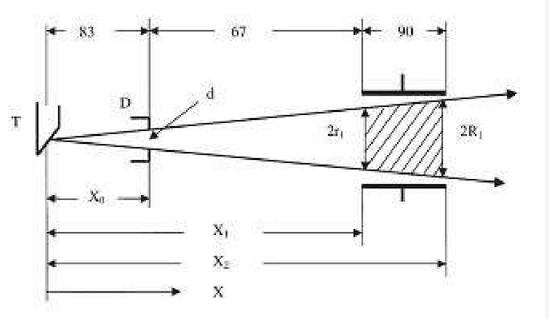

Fig. 7: Schematic representation of the beam geometry for the determination of the irradiated air volume (values in mm)

Task 2

Measure the ion currents I_c with the diaphragm tubes with d = 2 mm and d = 5 mm as a function of the capacitor voltage U_c. For this purpose, the anode voltage U_A = 35 kV and the anode current I_A = 1 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 mm. For this purpose, the anode voltage U_A = 35 kV and the capacitor voltage U_c = 500 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 mm. For this purpose, the anode current I_A = 1 mA and the capacitor voltage U_c = 500 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 Δm, a portion of the radiation energy ΔE is absorbed. The ratio of the absorbed energy to the absorbing mass is defined as the absorbed dose D.

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

The SI unit of the absorbed dose is “Gray” (Gy) [1 Gy = 1 Jkg^{-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.

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

The unit of the equivalent dose is “Sievert” (Sv): [1 Sv = 1 Jkg^{-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:

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

The corresponding Si unit is: 1 Gys^{-1} = 1 $Jkg^{-1}s^{-1}$
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 ΔQ of like sign and of the mass Δm of an air volume element ΔV under normal conditions.

$$I = dQ/dm [Askg^{-1}] \qquad (4)$$

The following applies to the corresponding ion dose rate j:

$$j = \frac{dI}{dt} = \frac{d}{dt}\left(\frac{dQ}{dm}\right) = \frac{di}{dm}[Akg^{-1}] \qquad (5)$$

Measuring principle:

The X-radiation generates a current in the capacitor when voltage is applied. The DC measuring amplifier detects this current and produces a voltage signal U_{Sig} that is proportional to the current. This signal is then displayed by the connected digital measuring instrument. The conversion is as follows:

$$I_c = \frac{U_{sig}}{1G\Omega}$$

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:

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

with the radii

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

$x0$ 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:

$x0$ = 6.65 cm
$x1$ = 12.95 cm
$x2$ = 20.85 cm

For d = 2 mm (2-mm-diaphragm-tube), the following results:

r = 0.39 cm
R = 0.63
$V = 6.57cm^3$

For d = 5 mm (5-mm-diaphragm-tube), the following results:

r = 0.97 cm
R = 1.57 cm
V = 40.76

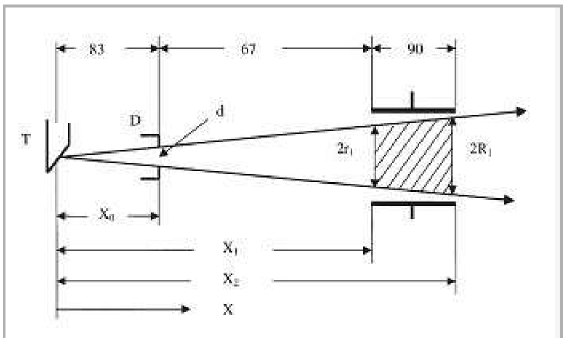

Fig. 7: Schematic representation of the beam geometry for the determination of the irradiated air volume (values in mm)

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.

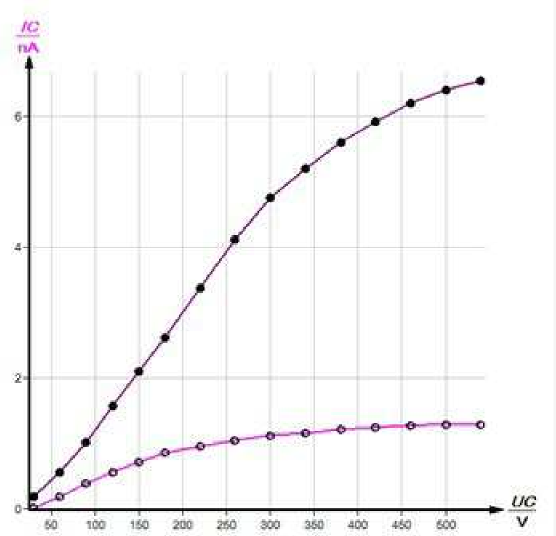

Fig. 8: Ionisation current Ic as a function of the capaci-tor voltage Uc X-ray tube: UA = 35 kV; IA = 1 mA Curve A: diaphragm tube d = 5 mm Curve B: diaphragm tube d = 2 mm

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):

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

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

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

Calculation of the absorbed dose rate

Dividing the mean value of the ion dose rates (determined above) by the elementary charge ε gives the number of ions n generated per time and mass unit. The ionisation energy Φ of an air molecule amounts to approximately $\Phi \approx 33eV = 52.8 \cdot 10^{-19} J$. 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:

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

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 = const. and U_C = const.).

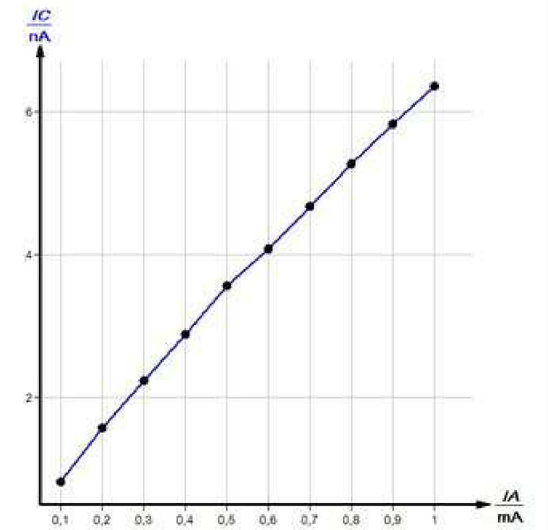

Fig. 9: Ionisation current Ic as a function of the anode current IA Anode voltage UA = 35 kV Capacitor voltage Uc = 500 V Diaphragm tube d = 5 mm

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 < 8 kV no X-rays are generated.

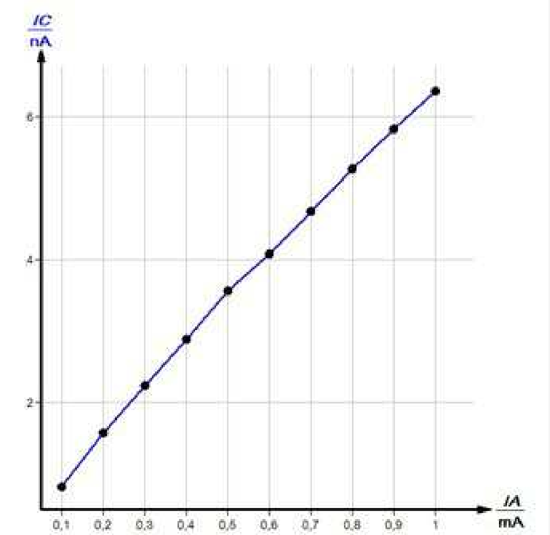

Fig. 9: Ionisation current Ic as a function of the anode current IA Anode voltage UA = 35 kV Capacitor voltage Uc = 500 V Diaphragm tube d = 5 mm

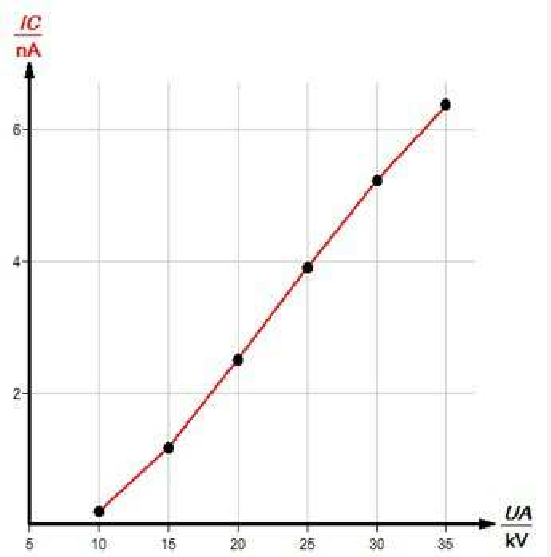

Fig. 10: Ionisation current Ic as a function of the anode voltage UA ; Anode current IA = 1 mA ; Capacitor voltage Uc = 500 V ; Diaphragm tube d = 5 mm