X-ray dosimetry

Related topics

X-rays, absorption inverse-square law, ionizing energy, energy dose, equivalent dose and ion dose and their rates, Q factor, local ion dose rate, dosimeter.

Principle and task

X-rays ionize the molecules of the air within a plate capacitor. The ion dose, ion dose rate and local ion dose rate are calculated from the ionization current and the radiated mass of air.

Equipment

X-ray unit, w. recorder output	09056.97	1
Power supply, 0…600 VD	13672.93	1
DC measuring amplifier	13620.93	1
Digital multimeter	07134.00	2
High-value resistor, 50 megOhms	07159.00	1
Adapter, BNC socket - 4 mm plug	07542.20	1
Screened cable, BNC, l 750 mm	07542.11	1
Connecting cord, 250 mm, red	07360.01	1
Connecting cord, 500 mm, red	07361.01	3
Connecting cord, 500 mm, blue	07361.04	3
Connecting cord, 1000 mm, green-ye	07363.15	1

Problems

1. Measure and graphically record the ion current at maximum anode voltage as a function of the capacitor voltage by using two various beam limiting apertures (d = 0.5 cm and d = 0.2 cm).
2. Determine the ion dose rate from the saturation current values and the radiation-penetrated air masses which are to be calculated.
3. Calculate the energy dose rate and various local ion dose rates.
4. With the aperture of d = 0.5 cm, determine and graphically record the ion current at various anode voltages as a function of the capacitor voltage.
5. Graphically plot of the saturation current as a function of the anode voltage.
6. With the aid of the luminescent screen and by using shadowgraphs, verify the given distance between the aperture and the radiation source at maximal anode voltage.

Fig. 1: Experimental set-up for determination of the ion dose rate.

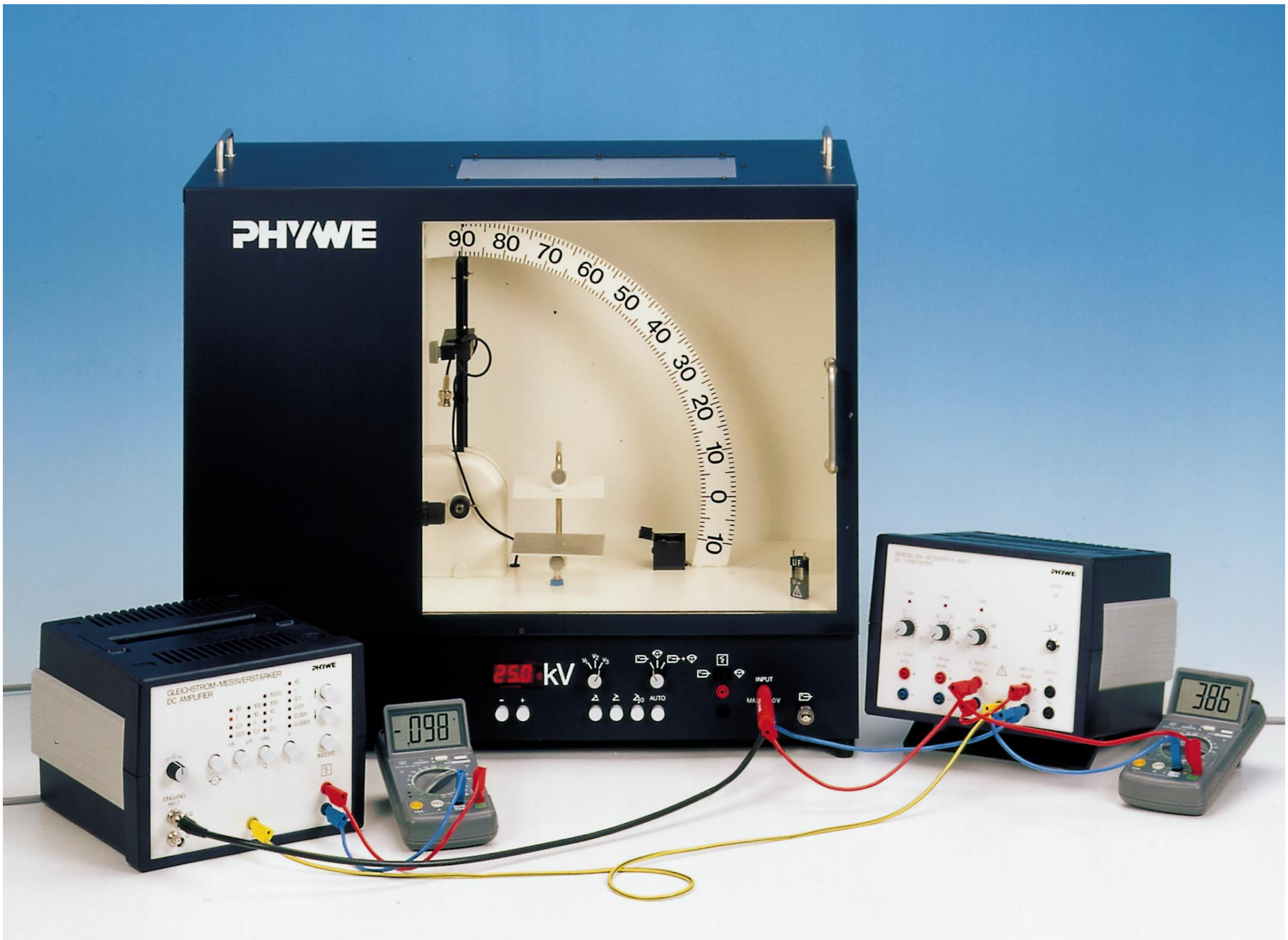
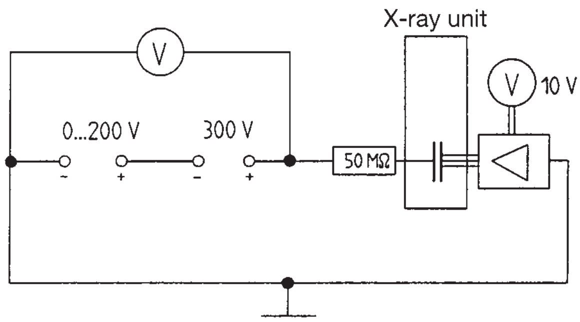


Fig. 2: Schematic diagram for determination of the ionization currents.



Set-up and procedure

The experiment is set up as shown in Fig. 1. Crystal holder and counter tube holder without counter tube are to be turned to 90°. The capaciter plates are inserted after this step has been completed. For safety reasons, the controlling devices for counter tube and crystal holder are disconnected when inserting the capacitor plates.

The circuit-diagram is as indicated in Fig. 2. Please observe that, due to safety reasons, the positive pole of the voltage can only be connected to the capacitor plate by the 50 MΩ protective resistor. The digital multimeter serves to determine the capacitor voltage and the other multimeter is connected to the measuring amplifier output whose input lies on the second capacitor plate by means of the screened cable and an adapter. The constant voltage output is to be connected in series with the variable source for capacitor voltages above 300 V. After a time of app. 5 min at maximal capacitor voltage, there should be no current. (Measuring amplifier set to zero).

Measure the ionization current with apertures of d = 0.2 cm and d = 0.5 cm at maximal anode voltage as a function of the capacitor voltage (Fig. 3). Repeat the measurement with the aperture of d = 0.5 cm at various anode voltages (Fig. 5). In order to verify the distance x_0 between the aperture and the radiation source shown in Fig. 4, remove the capacitor plates and the aperture. Then set the counter tube holder to position zero.

The shadeowgraph of the holder can be recognized on the luminescent screen at maximal anode voltage and at dampened light. The intervals necessary to the approximate determination of the distance x_0 can be measured with a ruler.

Theory and evaluation

When ionizing radiation impinges with matter, a portion of the energy is absorbed. The ratio of the absorbed energy and the absorbing matter is defined as *energy dose D.*

$$D = \frac{dW}{dm} \qquad (1)$$

As unit the "Gray" (*Gy*) is introduced.

$$[1\ Gy] = 1\ \mathrm{Jkg}^{-1}$$

(former unit:
1 rad [radiation absorbed dose] = $10^{-2} \cdot Gy = 10^{-2}$ Jkg^{-1})

The biological effects, for example, of somatic or genetic radiation damages caused by different types of radiation with the same energy dose are not always alike.

Taking this difference into account by a *quality factor Q* (gained through experience) the following *equivalent dose* is achieved:

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

The unit of the equivalent dose is the "Sievert" (*Sv*):

$$[1\ Sv] = 1\ \mathrm{Jkg}^{-1}$$

(Former element unit:
1 rem [radiation equivalent man] = 10^{-2} Jkg^{-1})

The following Q values are valid for the various types of radiation:

Q = 1	for X-rays, gamma-rays, beta-particles
Q = 3	for thermal neutrons
Q = 10	for fast neutrons and protons
Q = 10−20	for alpha particles

Thus, at the same energy absorption, the biological effect of the alpha particles is 10−20 times greater than that of X-rays. For the latter, the energy dose and equivalent dose correspond.

The actuation time of the ionizing radiation plays an important role in the evaluation of its effect. For this reason, the additional term "*dose rate*" has been introduced.

Accordingly, one must differentiate between *equivalent dose rate* and *energy dose rate*.

$$P = \frac{dD}{dt} \qquad (3)$$

with the unit 1 Gys^{-1} = 1 Jkg^{-1}s^{-1} = 1 Wkg^{-1}

Since the determination of the absorbed energy is not easy, the ionizing radiation effect is used to ascertain its *ion dose* I as ratio of the charge Q of ions of the same sig (produced under normal conditions by air ionization) and the radiation-penetrated air mass m.

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

(Former unit: 1*R* [Roentgen] = $2.58 \cdot 10^{-4}$ Askg^{-1})

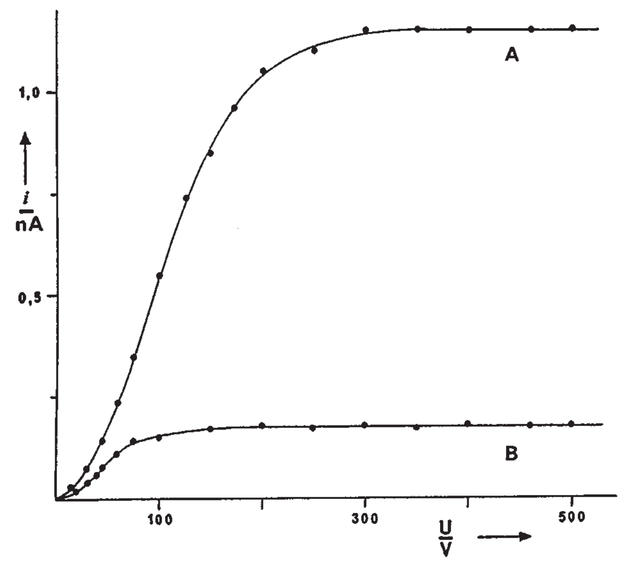
The effective intensity is expressed through the *ion dose rate*.

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

In order to determine the ion dose rate of X-rays, a defined air volume is radiated between the plates of a capacitor. The electrons and positive ions created through ionization produce an ionization current for an applied voltage. At first, this current grows almost linearly at increasing capacitor voltage and then eventually takes on a constant value despite increasing voltage.

Within this saturation range, a recombination of the charge carriers is prevented so that all of these reach the capacitor

Fig. 3: Ionization current i as s function of capacitor voltage U
Anode voltage of the X-ray tube U_A = 25 kV
Aperture: d = 5 mm, curve A
d = 2 mm, curve B



plates. Fig. 3 indicates the ion current i as a function of the capacitor voltage U at maximum anode voltage U_A = 25 kV of the X-ray tube; in this case, curve A was taken with the aperture of d = 5 mm and curve B with the aperture of d = 2 mm.

The corresponding air volumes can be ascertained from the schematically plotted geometry in Fig. 4.

The radiation emitted from anode T of the X-ray tube is limited by the diaphragm D with aperture d and penetrates the truncated cone shaped air volume V in cpacitor C.

$$V = \frac{\pi\,(x_2 - x_1)}{3}\,(R^2 + r^2 + rR) \qquad (6)$$

with the radii

$$r = \frac{x_1 \cdot d}{2x_0} \quad \text{and} \quad R = \frac{x_2 \cdot d}{2x_0} \qquad (7)$$

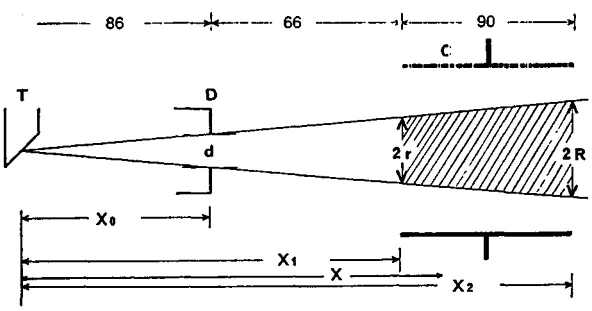


Fig. 4: Schematic representtation of the experiment geometry for determination of the radiated air volume.

Using the saturation current values from Fig. 3 and the corresponding penetrated air masses, the following mean values for the ion dose rate are found in accordance with (5):

$$d = 0.5\ \text{cm}: j_m = \frac{1.15 \cdot 10^{-9}}{1.2 \cdot 10^{-6} \cdot 9.434}\ \text{Akg}^{-1}$$

$$= 1.01 \cdot 10^{-4}\ \text{Akg}^{-1}$$

$$d = 0.2\ \text{cm}: j_m = \frac{0.18 \cdot 10^{-9}}{1.2 \cdot 10^{-6} \cdot 1.509}\ \text{Akg}^{-1}$$

$$= 0.99 \cdot 10^{-4}\ \text{Akg}^{-1}$$

(Density of air at 20 °C and
$1.013 \cdot 10^4$ Pa : $\rho = 1.2 \cdot 10^{-6}$ kgcm^{-3})

Measurements taken without an aperture lead to erroneous results because, in this case, the X-rays impinge on the capacitor plates and trigger perturbing secondary electrons there.

Dividing the mean value of the ion dose rate (determined above) by the elementary charge e results in the number n of the ionizations per time and mass unit. By taking into account that the ionizing energy Φ of one air molecule amounts to approximately 33 eV = $52.8 \cdot 10^{-19}$ J, it is possible to calculate the mean energy dose rate per time and mass unit according to (1) and (3):

$$P_m = \frac{D}{t} = \frac{W}{m \cdot t} = n \cdot \Phi = \frac{j\Phi}{e} \qquad (9)$$

$$= \frac{1 \cdot 10^{-4} \cdot 52.8 \cdot 10^{-19}}{1.6 \cdot 10^{-19}}\ \text{Jkg}^{-1}\text{s}^{-1} = 3.3 \cdot 10^{-3}\ \text{Jkg}^{-1}\text{s}^{-1}$$

In order to determine the *local ion dose rate* at any point x from the radiation source, it is most effective to start with definition (5)

$$i(x) = \int j(x)\, dm \qquad (10)$$

and to take into account that the decline in the ion dose rate at increasing distance is determined by the law of absorption as well as by the inverse-square law.

$$j(x) = j_0 \cdot \frac{x_1^2}{x_2^2} \cdot e^{-\mu\,(x - x_1)} \qquad (11)$$

Here, μ is the wavelenght-dependent attenuation coefficient for air.
For a mass element at distance x, the following holds:

$$dm = \rho \cdot F(x) \cdot dx = \pi \cdot \rho \cdot R^2(x) \cdot dx \qquad (12)$$

Using the radiation theorem and according to Fig. 4, the following results for $R^2(x)$:

$$\frac{d}{x_0} = \frac{2R(x)}{x} \rightarrow R^2(x) = \frac{x^2 \cdot d^2}{4 \cdot x_0^2} \qquad (13)$$

(11) – (13) inserted into (5) results in:

$$i = j_0 \pi \cdot \rho\, \frac{x_1^2 \cdot d^2}{4 \cdot x_0^2} \cdot e^{\mu x_1} \cdot \int_{x_1}^{x_2} e^{-\mu x_1} dx \qquad (14)$$

Integration and transformation yield:

$$j_0 = \frac{4x_0^2 \cdot \mu \cdot i}{\pi \rho x_1^2 d^2}\ (1 - e^{-\mu(x_2 - x_1)})^{-1} \qquad (15)$$

Inserting (15) into (11) yields the final form to determine the local ion dose rate for all distances $x \geq x_1$.

$$j(x) = \left[\frac{4 \cdot x_0^2 \cdot \mu \cdot i \cdot (e^{-\mu \cdot x_1} - e^{-\mu \cdot x_2})^{-1}}{\pi \cdot \rho \cdot d^2}\right] \frac{1}{x^2 e^{\mu x}} \qquad (16)$$

The bracket contains known values only. For the measurement with d = 0.5 cm according to Fig. 3, a saturation current $i = 1.15 \cdot 10^{-9}$ A must be observed. Taking into further account that the total intensity of the X-rays is given by the characteristic copper radiation with wave length $\lambda \sim 1.45 \cdot 10^{-10}$ m, it is appropriate to hold valid $\mu \sim 10^{-2}$ cm^{-1}.
Using the geometrical representation from Gif, 4 results in:

$$j(x) = 48.85 \cdot 10^{-3} \frac{1}{x^2 e^{\mu x}} \text{ [Akg}^{-1}\text{]} \qquad (17)$$

This results in the following values:

Capacitor start	$x = x_1$	; $j(x_1) = 1.8 \cdot 10^{-4}$ Akg^{-1}
Capacitor middle	$x = x_m = x_1 + \frac{1}{2}\ (x_2 - x_1)$	; $j(x_m) = 1.03 \cdot 10^{-4}$ Akg^{-1}
Capacitor end	$x = x_2$	; $j(x_2) = 6.5 \cdot 10^{-5}$ Akg^{-1}
Luminescent screen	$x = x_L = x_0 + 40$ cm	; $j(x_L) = 1.3 \cdot 10^{-5}$ Akg^{-1}

The local ion dose rate for the capacitor middle calculated according to (17) corresponds acceptably well with the previously determined total ion dose rate (8).

Fig. 5 shows the ion current dependence upon the capacitor voltage for the various anode voltages.

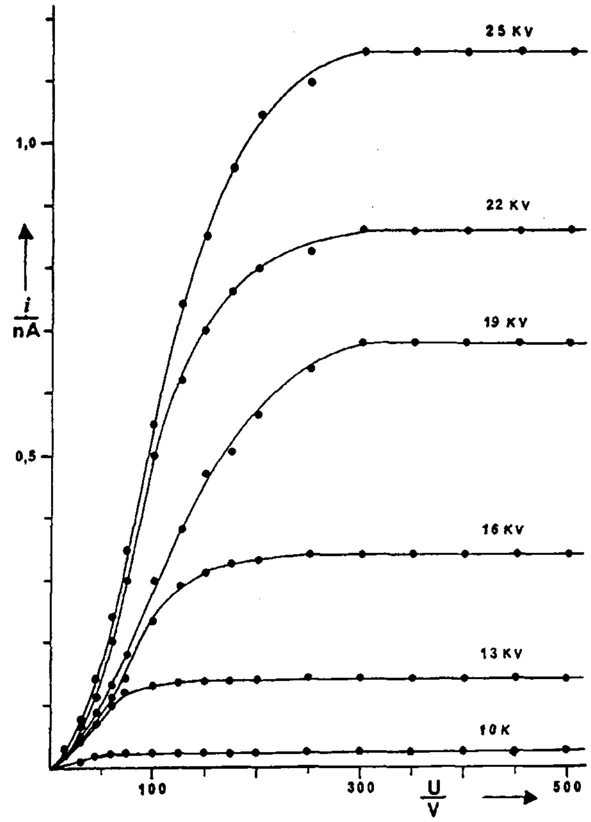
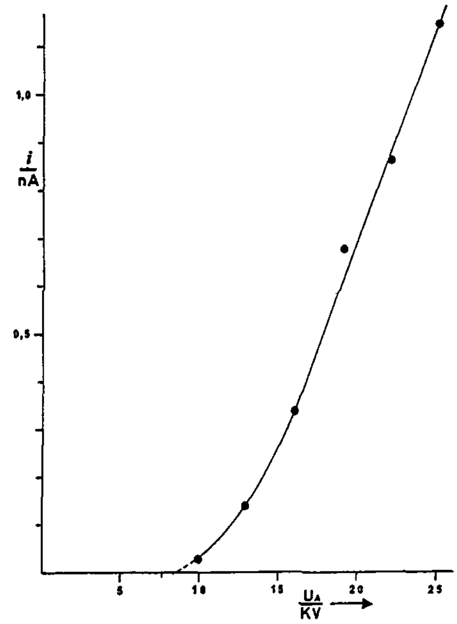


Fig. 5: Ion current is as a function of the capacitor voltage U for various anode voltages U_A.

Fig. 6: Saturation current i as a function of the anode voltage U_A.



The saturation currents taken from these measurements are recorded as a function of the anode voltage in Fig. 6. The curve extrapolated to low U_A values indicates that no X-ray created for U_A < 8 kV is worth mentioning.