Ionization capacity, absorption of X-rays: determination of the average ion dose capacity

Ionization of the air between two capacitor plates by X-rays; recording the characteristics of the capacitor; measuring the ionization current in relation to the emission current and the high voltage of the X-ray tube; determination of the ion dose capacity from the ionization current and the mass of the irradiated volume of air between the capacitor plates.

X-rays are electromagnetic radiation rich in energy. In the electromagnetic spectrum, it overlaps the energy range above the UV-radiation from a few keV up to a few hundreds keV. The term X-rays is generally limited to the radiation which occurs through the reciprocal action of fast electrons with materials. The physically identical electromagnetic radiation which occurs through a nuclear reaction is defined as gamma rays.

As with any electromagnetic radiation, X-rays also transport energy. When there is reciprocal action between the X-rays and the material, a part ΔW of the energy of the X-rays is used to ionize the material and energy from the X-rays is then absorbed into the material. If m is the mass of the irradiated substance, then the quotient

$$K = \frac{\Delta W}{m} \qquad (1)$$

is defined as the energy dose and is measured with the unit $J\ kg^{-1}$.

The exact determination of this value requires calorimetric measurements involving much experimental effort. The observation that the physiological effect of X-rays has the same energy dependence as the ionization capacity of the radiation in the air leads to a more practical relationship which also is useful in radiation protection.

The quotient

$$J = \frac{Q}{m} \qquad (2)$$

is defined as ion dose and is measured in the unit $As\ kg^{-1}$. Q is the total charge of all the ions of the same sign generated by the radiation.

The ion dose related to the irradiation time Δt is the ion dose capacity

$$j = \frac{J}{\Delta t}\ . \qquad (3)$$

The definition of the ion dose or ion dose capacity refers to dry air with 0°C at an atmospheric pressure of 1013 mbar.

From the definition (2) of the ion dose J, we can use the following method of measurement: a definite volume of air V of the mass m is ionized by radiation. The number of the occurring charges is measured and is related to the irradiated mass of the air m.

If the irradiated air is located between the plates of a capacitor, the ions can be drawn off as an ionization current I by a voltage on the plates. If the voltage on the capacitor U_K is large enough, then all the ions flow off as the maximum current I_{max}. The resulting charge in the irradiated volume V in the time Δt can be calculated from I_{max}:

$$Q = I_{max} \cdot \Delta t\ . \qquad (4)$$

The mass m of the irradiated air can be calculated with the irradiated volume of air V of the capacitor and the density ρ_{air}:

$$m = V \cdot \rho_{air}$$

For the ion dose we then get

$$J = \frac{I_{max} \cdot \Delta t}{V \cdot \rho_{air}} \qquad (5)$$

and the ion dose capacity

$$j = \frac{I_{max}}{V \cdot \rho_{air}} \qquad (6)$$

Apparatus:

1	X-ray apparatus, 42 kV	554 90/94
1	Plate capacitor	554 91
1	I-amplifier D	532 00
1	Steel tape measure	311 77
1	Low power source, adjustable to 25 V, e.g. 1 transformer, extra-low voltage S	591 09
1	Multimeter, measuring range 30 V∿ and I mA, e.g. demonstration multimeter	531 91
1	Voltmeter, measuring range 1 V-, 3 V-, e.g. 1 moving coil measuring instrument D	531 781
1	Connecting lead, 25 cm, blue	501 21
1	Connecting lead, 25 cm, red	501 20
2	Connecting leads, 50 cm, black	501 28
2	Connecting leads, 50 cm, green	501 27

Setting up:

Refer to the appropriate operating instructions for the X-ray apparatus (554 90) and the I-amplifier D (532 00);
put the capacitor in the X-ray apparatus, and set up the experiment according to Fig. 1;
connect first of all the measuring device (a) (range 30 V-) to the pair of sockets (b) (1 V∿ at the input ≙ 10 V- at the capacitor) in order to measure the input voltage for the internal converter of the capacitor.

Carrying out the experiment:

1. Recording the characteristics of the capacitor (ionization current I as a function of the capacitor voltage U_K).

Turn the X-ray apparatus on with switch (c); choose an operating duration of >30 min on the clock (f); switch on the high voltage U_A with key (h) and with stepped switch (g) set to I; adjust with switch (g) and the lever (i) the maximum values of the high voltage U_A (level (8) ≙ approx. 42 kV_s) and the emission current I_{EM} (1 mA).
Increase the voltage U_K between the capacitor plates from 0 to 250 V-. Read the ionization current I (measuring instrument (j)) for every capacitor voltage U_K.

2.1 Ionization current I as a function of the emission current I_{EM}.

Connect the measuring instrument (a) with a measuring range of 1 mA to the pair of sockets (e) to measure the emission current I_{EM}; measuring range of the amplifier: 10^{-9} A, at indicating instrument 3 V-;
Choose a capacitor voltage U_K > 100 V-;
keeping the high voltage U_A (level 8) constant, increase the emission current I_{EM} with the lever (i) step by step from 0.1 mA up to 1 mA and measure the values for the ionization current I.

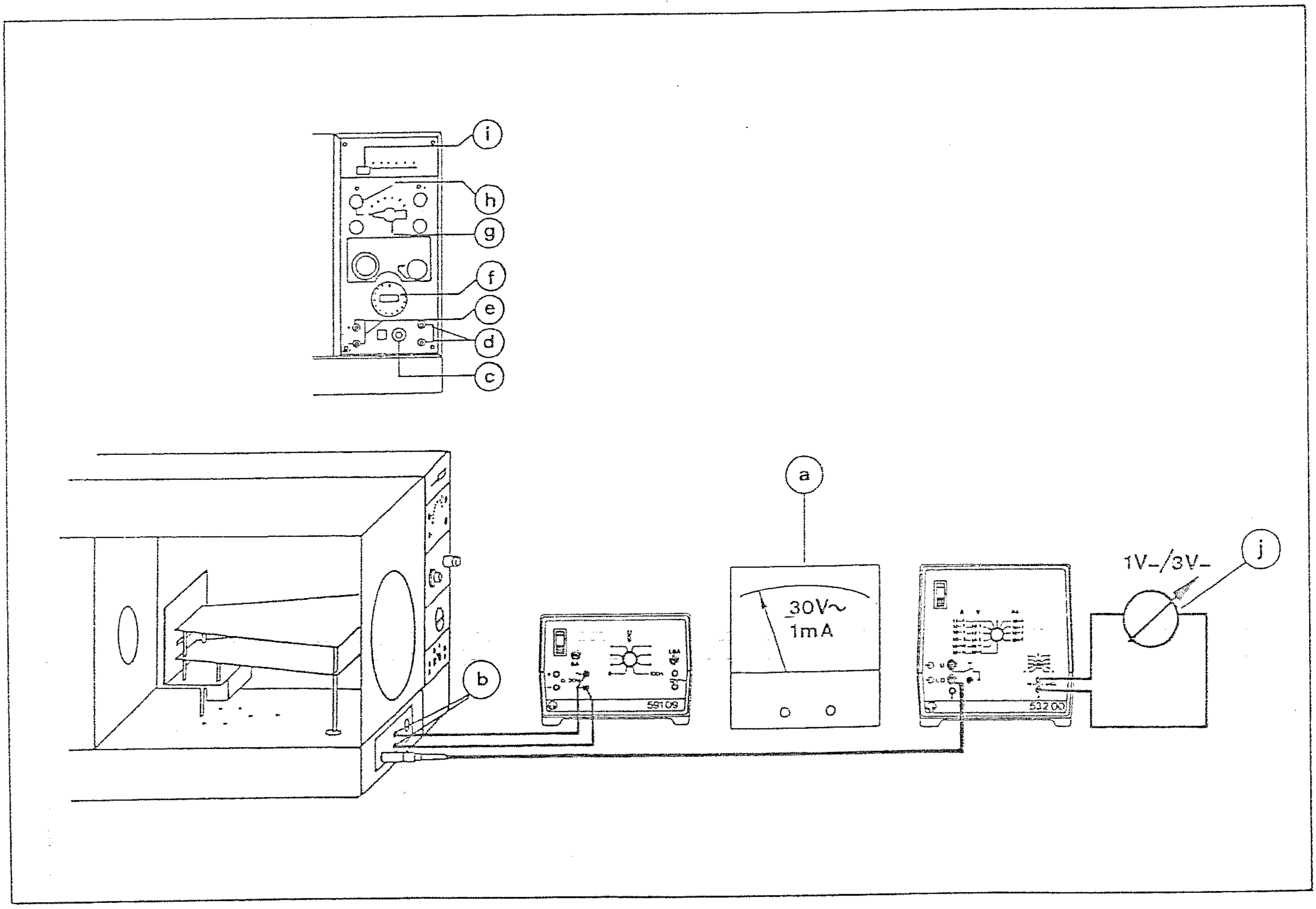

Fig. 1: Experiment setup: ionization capacity of X-rays; ion dose capacity.

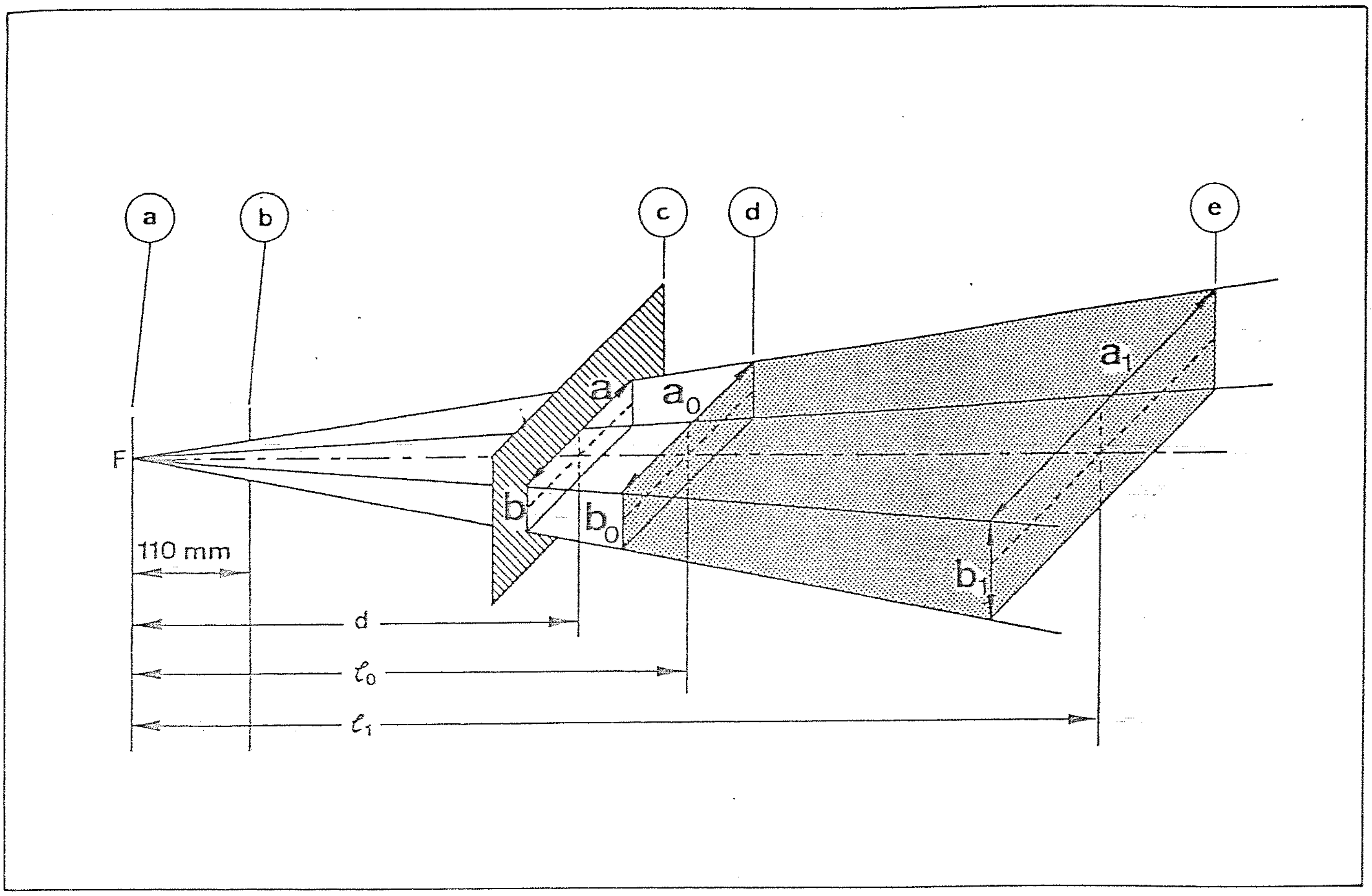

Fig. 2: Schematic representation of the course taken by the radiation when determining the volume of irradiated air in the capacitor (identified by the dotted area).

(a) Focal point F
(b) Ray outlet opening
(c) Rectangular diaphragm
(d) Beginning) of the capacitor
(e) End)

2.2 Ionization current I as a function of high voltage U_A.

Connect the measuring instrument (a) (measuring range 30 V∿) to the pair of sockets (d), to which a voltage U proportional to U_A is applied, in order to determine U_A ($U_A = \sqrt{2} \cdot 10^3 \cdot U$); set the high voltage levels 1 to 8 with switch (g) and read the "proportional voltage" U and the ionization current I each time.

3. Measurements to determine the irradiated volume of air V.

Turn off the capacitor voltage and determine the distance d, l_0 and l_1 as well as the length a and b of the rectangular diaphragm (see Fig. 2).

Evaluation and results

1. Air in the capacitor is ionized by the X-rays (see Fig. 3): When capacitor voltages are low, ions are only partly drawn to the plates. When the voltage is increased, the number of the ions generated by this capacitor current I first increases proportionally to the capacitor voltage, up to approx. 100 V when all the ions are then drawn off. Any further increase in the capacitor voltage does not increase the capacitor current (saturation).

This maximum capacitor current I_{max} is a measure of the number of ions generated by the X-rays.

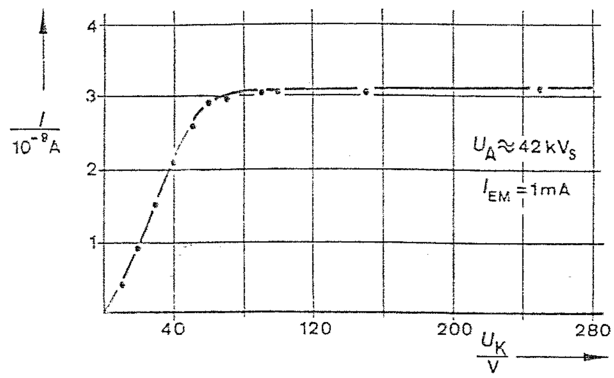

Fig. 3: Ionization current as a function of the capacitor voltage: $I = f(U_K)$;

(characteristics of the plate capacitor serving as an ionization chamber).

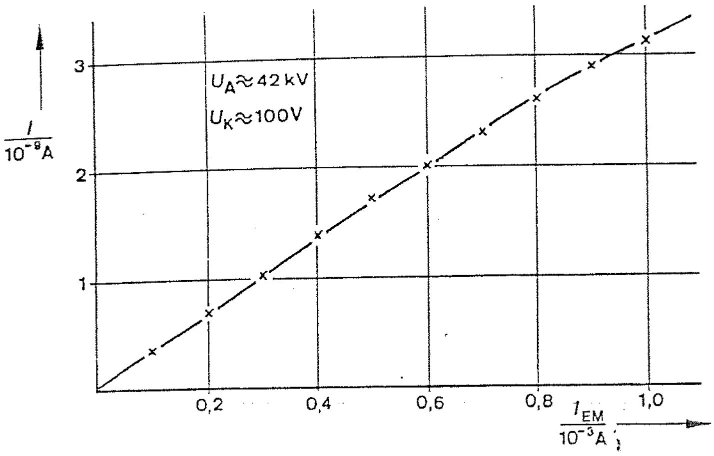

Fig. 4: Ionization current as a function of the emission current: $I = f(I_{EM})$.

2.1 The ionization current is proportional to the emission current of the X-ray tube (see Fig. 4): $I \sim I_{EM}$

2.2 The ionization current I increases superproportionallly with the high voltage U_A at the X-ray tube.

The general shape of the curve (Fig. 5) presupposes a lower limit value; below 15 kV_s no radiation worth mentioning is emitted.

3. The volume of irradiated air corresponds to a truncated cylinder (see Fig. 2). To calculate the volume:

$$V = \frac{h}{3} \cdot (G_0 + \sqrt{G_0 \cdot G_1} + G_1) \qquad (7)$$

with base surface $G_1 = a_1 \cdot b_1$
with top surface $G_0 = a_0 \cdot b_0$
height $h = l_1 - l_0$.

By applying the second radiation law from diagram 2, it follows that from (7) we obtain

$$V = \frac{l_1 - l_0}{3\ d^2} \cdot a \cdot b\ (l_0{}^2 + l_0 \cdot l_1 + l_1{}^2) \qquad (8)$$

With the measured values:
$d = 153$ mm $a = 45$ mm
$l_0 = 173$ mm $b = 6$ mm
$l_1 = 333$ mm
the irradiated volume of air is calculated with (8) as
$V = 122{,}1\ cm^3$.

4. From the measured values

$I_{max} = 3.1 \cdot 10^{-9}$ A (from Fig. 3-5)
$V = 122.1\ cm^3$
and the table value

$\rho_{air} = 1.205 \cdot 10^{-6}\ kg\ cm^{-3}$ (based on a temperature of 20°C and a pressure of 1013 mbar)

we can calculate the ion dose capacity from (6)

$$j = \frac{I_{max}}{V \cdot \rho_{air}} = 2.11 \cdot 10^{-5}\ a\ kg^{-1}.$$

Note:

- The ion dose capacity is dependent upon the region where it is measured. When determining the regional ion dose capacity, the generally present non-uniformities of the energy flow in the ray cross-section with increasing capacitor depth must be taken into consideration. This is done by a differential approach to the equations (2) and (3). Usually though, it is enough to know the average dose and the dose capacity determined from the experiment according to (2) and (3), in order to undertake physically relevant interpretations (for an examination of the regional ion dose capacity, see "X-ray. apparatus 42 kV", 554 991).

- Differences from the values of the ionization current can be attributed to the tolerances spreads of the X-ray tubes, the condition of used tube (age, hardness) as well as the height adjustment inside of the X-ray apparatus.

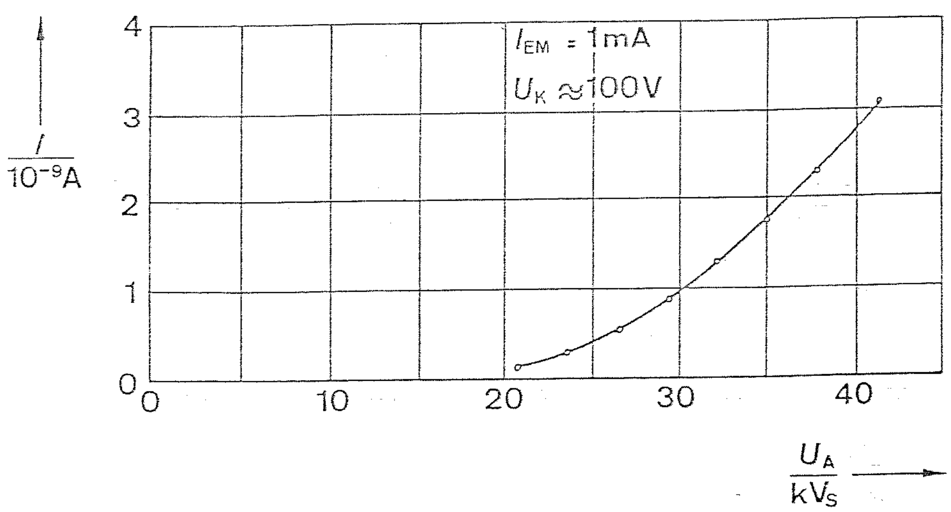

Fig. 5: Ionization current as a function of the high voltage U_A: $I = f(U_A)$.

- The ion dose capacity outside of the X-ray apparatus 42 kV is, at a distance of 10 cm and maximum operating data, $2.15 \cdot 10^{-11}$ A kg^{-1}; it is also smaller than in the inner chamber by a factor of 10^6.

Measurements from experiment 2.2 (see Fig. 5) confirm the theory of the relationship between the ionization current I and the high voltage U_A (see Fig. 6).

$$I \sim \sqrt{U_A^3}$$

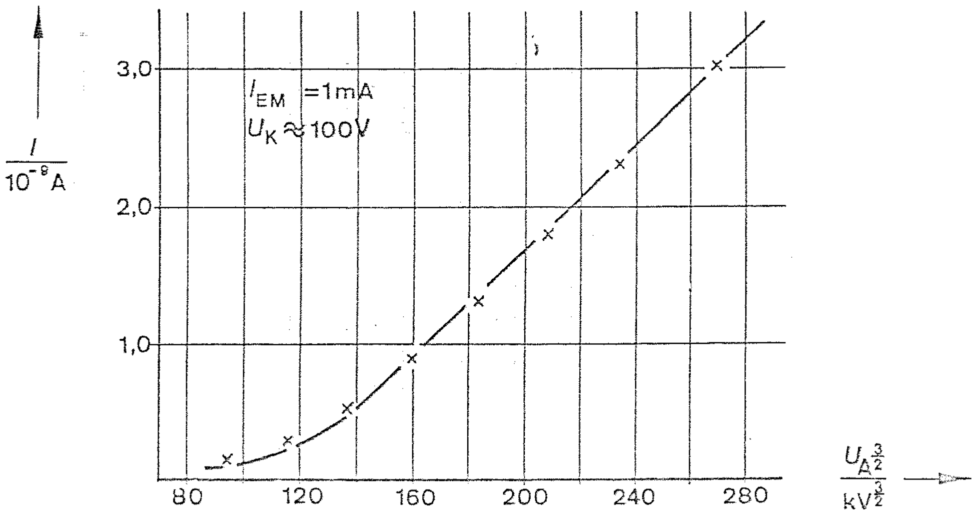

Fig. 6: Linearization of the relationship between ionization current and high voltage U_A: $I = f(U_A^{3/2})$

- The described method to determine the ion dose capacity presupposes an insulated capacitor. In order to verify the insulation, the capacitor current I is measured as a function of the capacitor voltage U_K, when no radiation is present (do not turn on the high voltage U_A;

  measuring instrument (a) - measuring range 30 V ∿ - attached to the pair of sockets (b);

  measuring amplification range: 10^{-10} A; do not move the measuring cables! The charge is shifted, which disturbs the display in the highly sensitive measuring range .

  The current should not exceed 10^{-10} A at maximum voltage (if necessary, carefully clean the insulators on the capacitor; reduce the humidity with a warm air fan - e.g. 545 20).