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Experiment No. 15

X-RAY DOSIMETRY

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The aim of the experiment

Investigate the phenomenon of ionization of air exposed to X-rays.

1. Tasks

1. Measure dependence of ion current within a plate capacitor on the capacitor voltage using two different beam limiting apertures.
2. Measure dependence of ion current on the X-ray tube anode current using the $d = 5$ mm aperture at the maximum X-ray tube anode voltage.
3. Measure dependence of ion current on the X-ray tube anode voltage using the $d = 5$ mm aperture at the maximum X-ray tube anode current.
4. Using the $d = 5$ mm aperture and the fluorescent screen, verify the given distance between the aperture and the radiation source at the maximum values of the X-ray tube anode voltage and current.
5. Determine the ion dose rate and the energy dose rate from the saturation current values corresponding to the maximum values of the X-ray anode voltage and current.
6. Plot the dependences mentioned in Tasks 1, 2 and 3.
7. Discuss the results.

2. Control questions

1. Define the concept of ionizing radiation, and list its types.
2. The main components and the principle of operation of an X-ray tube.
3. The physical mechanism and spectrum of X-ray radiation.
4. Define the main quantities used in dosimetry and their units.
5. Define the measurement geometry of the experiment and explain the difference between the average and local doses.

3. The types of ionizing radiation

Ionizing radiation is a flux of subatomic particles (e. g. photons, electrons, positrons, protons, neutrons, nuclei, etc.) that cause ionization of atoms of the medium through which the particles pass. ***Ionization*** means the removal of electrons from atoms of the medium. A result of one such event is formation of two ***charge carriers***: free electron and positive ion. Those two opposite charge carriers are called an ***ion pair***. In order to remove an electron from an atom, a certain amount of energy must be transferred to the atom. According to the law of conservation of energy, this amount of energy is equal to the decrease of kinetic energy of the particle that causes ionization. Therefore, ionization becomes possible only when the energy of incident particles (or of the secondary particles that may appear as a result of interactions of incident particles with matter) exceeds a certain threshold value – the ***ionization energy*** of the atom. Ionization energies of isolated atoms are usually of the order of a few electronvolts (eV). 1 eV = $1{,}6022\cdot10^{-19}$ J. The ionization energies of molecules of most gases that are used in radiation detectors are between 10 eV and 25 eV.

Ionizing radiation may be of various nature. The ***directly ionizing radiation*** is composed of high-energy charged particles, which ionize atoms of the material due to Coulomb interaction with their electrons. Such particles are, e. g., high-energy electrons and positrons (beta radiation), high-energy ^{4}He nuclei (alpha radiation), various other nuclei. ***Indirectly ionizing radiation*** is composed of neutral particles which do not directly ionize atoms or do that very infrequently, but due to interactions of those particles with matter high-energy free charged particles are occasionally emitted. The latter particles directly ionize atoms of the medium. Examples of indirectly ionizing radiation are high-energy photons (ultraviolet, X-ray and gamma radiation) and neutrons of any energy. Particle energies of various types of ionizing radiation are given in the two tables below.

Table 1. The scale of wavelengths of electromagnetic radiation

Spectral region	Approximate wavelength range	Approximate range of photon energies
Radio waves	100000 km – 1 mm	$1\cdot10^{-14}$ eV – 0,001 eV
Infrared rays	1 mm – 0,75 μm	0,001 eV – 1,7 eV
Visible light	0,75 μm – 0,4 μm	1,7 eV – 3,1 eV
Ionizing electromagnetic radiation:		
Ultraviolet light	0,4 μm – 10 nm	3,1 eV – 100 eV
X-ray radiation	10 nm – 0,001 nm	100 eV – 1 MeV
Gamma radiation	< 0,1 nm	> 10 keV

Table 2. Particle energies corresponding to ionizing radiation composed of particles of matter

Radiation type	Approximate range of particle energies
Alpha (α) particles (^{4}He nuclei)	4 MeV – 9 MeV
Beta (β) particles (electrons and positrons)	10 keV – 10 MeV
Thermal neutrons	< 0,4 eV
Intermediate neutrons	0,4 eV – 200 keV
Fast neutrons	> 200 keV
Nuclear fragments and recoil nuclei	1 MeV – 100 MeV

The mechanism of interaction of particles with matter depends on the nature of the particles (especially on their mass and electric charge). According to the manner by which particles interact with matter, four distinct groups of particles can be defined:

1) heavy charged particles (such as alpha particles and nuclei),

2) light charged particles (such as electrons and positrons),

3) photons (neutral particles with zero rest mass),

4) neutrons (neutral heavy particles).

This experiment concerns only the third mentioned type of particles (X-ray photons with energy of the order of 3 – 30 keV).

4. Origin of X-ray radiation and its spectrum

The most frequent method of generating X-ray radiation is based on the use of so-called “hot-cathode” ***X-ray tubes***. A simplified diagram of a hot-cathode X-ray tube is shown in Fig. 1. This is a vacuum device containing two electrodes – positive electrode called the anode (1) and negative electrode called the cathode (2). A high voltage is applied between the two electrodes. The cathode (2) is heated. This causes emission of electrons from its surface (emission of electrons from a heated metal is called the ***thermionic effect***). The emitted electrons are accelerated by the mentioned voltage and strike the surface of the anode (1). The interaction of the fast electrons with the material of the anode (usually copper, tungsten or molybdenum) causes emission of X-rays from the anode. X-rays are easily absorbed in solid medium (for example, a 1 mm-thick plate of iron almost completely absorbs X-ray photons with energy of the order of 10 – 30 keV). Therefore, only about 5 % of the total number of X-ray photons escape the anode material (the rest are absorbed in it). For the same reason, the anode is angled in order to maximize the X-ray output in a particular direction, usually perpendicularly to the electron beam (see Fig. 1).

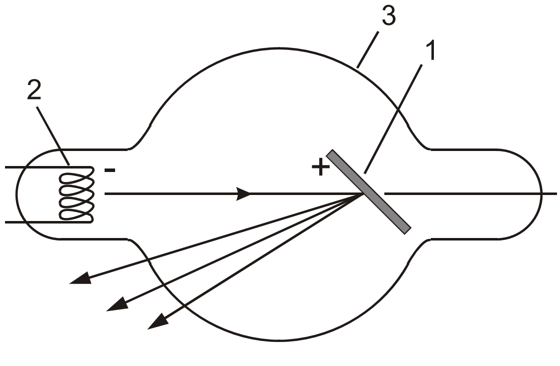

Fig. 1. The simplified diagram of an X-ray tube. 1 – anode, 2 – cathode, 3 – glass vacuum vessel

When fast electrons strike atoms of the anode material, two types of X-ray radiation are generated: the characteristic X-ray radiation (also called “X-ray fluorescence”) and Bremsstrahlung (German pronunciation: [brɛmsʃtra:lʊŋ], from bremsen "to brake" and Strahlung "radiation", i.e. "braking radiation" or "deceleration radiation"). The characteristic X-ray radiation is caused by quantum transitions of electrons of the atoms of the anode material. Therefore, this radiation can be only described in terms of quantum mechanics, which takes into account quantum properties of electromagnetic radiation (and, conversely, wave-like properties of particles of matter). From the point of view of quantum mechanics, electromagnetic radiation can be described as a flux of elementary particles called ***photons***. Each photon moves with a speed of light and carries a certain amount of energy E, which is related to the radiation frequency ν and wavelength λ as follows:

$$E = h\,\nu = h\,c\,/\,\lambda, \tag{4.1}$$

where h is the ***Planck constant***: $h = 6.626 \cdot 10^{-34}$ J·s and c is the speed of light: $c = 2.998 \cdot 10^{8}$ m/s. This energy is usually measured in electronvolts (eV). 1 eV = $1.6022 \cdot 10^{-19}$ J. An approximate range of X-ray photon energies is given in Table 1 in Section 3. The diagram illustrating mechanism of characteristic X-ray radiation is shown in Fig. 2. In order to understand the origin of characteristic radiation, it is necessary to understand the concept of electron shells. Quantum mechanics proves that atomic electrons are arranged in spherical shells around the nucleus (in Fig. 2, those shells are shown as circular “orbits”). The electrons belonging to a specific shell have a specific energy (in other words, those electrons belong to a specific ***energy level***). The shells that are farther from the nucleus have a higher energy. Thus, if all shells are numbered starting from the innermost shell, then shell energy E_i increases with increasing shell number i. If a fast electron hits an atom, that electron can remove an atomic electron from one of the inner shells, creating a “vacancy” in that shell. Since all physical systems (including an atom) tend to occupy the state with a smallest energy, an electron from one of the higher shell will eventually occupy that vacancy (this event is called a “quantum transition”). During this transition, a photon is emitted from the atom.

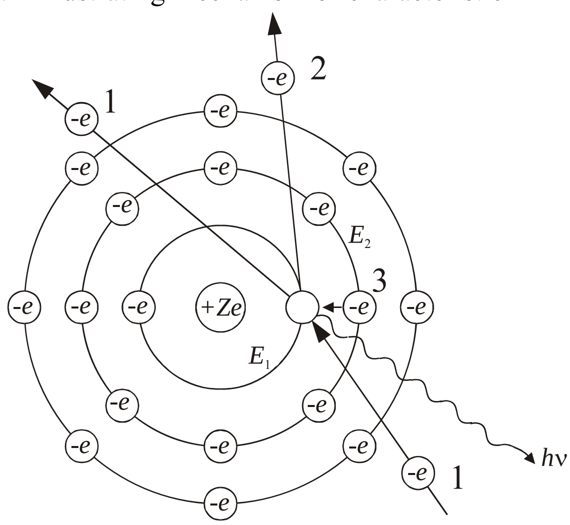

Fig. 2. The mechanism of characteristic X-ray radiation

The energy of that photon follows from the law of conservation of energy: it is equal to the energy difference of the two shells participating in the transition. For example, in the case of Fig. 2 the photon energy would be equal to $E_2 - E_1$. Thus, the energy (and frequency or wavelength) of photons of characteristic X-ray radiation is determined by the differences of energies of the atomic electron shells. Since the electrons are most frequently removed from the innermost (first) shell, the most likely photon energies are $E_2 - E_1$, $E_3 - E_1$, etc. Among those, the most likely transition is from the second shell. The different electron shells are historically marked not by numbers, but by letters K, L, M, etc. Thus, the previous statement can be rephrased as follows: the most likely energy of characteristic X-ray photons is equal to the energy difference of L and K shells. This energy increases with increasing atomic number of the chemical element. For intermediate elements (with atomic numbers between 20 and 50) the energy of K-L transition is between 3 keV and 30 keV (1 keV = 1000 eV). The spectral line corresponding to those transitions is usually called "the K_α line". Since the photons of characteristic X-ray radiation have a well-defined energy, the spectrum of characteristic radiation consists of several sharp peaks as shown in Fig. 3. In this graph, "I_λ" is the so-called "spectral energy density", which in this case is defined as radiation energy per unit area per unit time per unit wavelength (however, the spectral energy density may be also defined per unit frequency or unit photon energy). In order to create a vacancy in a inner shell, the incident electron must have an energy larger than the binding energy of the inner-shell electrons. This energy is slightly larger than the energy of K-L transition, but of the same order of magnitude. Thus, in order to generate characteristic X-ray radiation, the accelerating voltage of the X-ray tube must be of the order of a few kV or a few tens of kV.

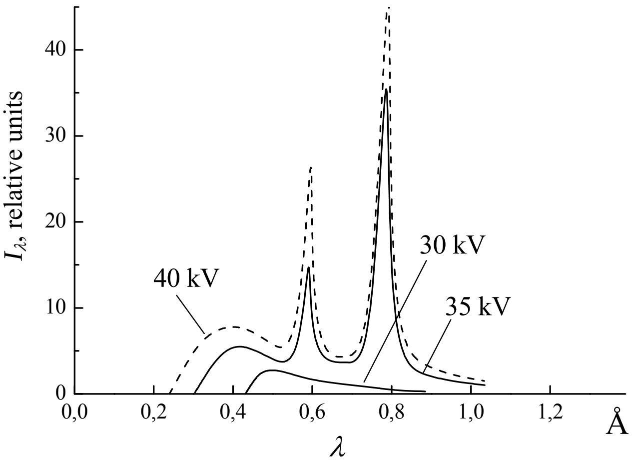

Fig. 3. An example of the spectra of X-ray radiation emitted by an X-ray tube at different values of the X-ray tube voltage. Sharp peaks correspond to characteristic radiation. The narrow peaks correspond to characteristic X-radiation, and the wide continuous spectrum corresponds to bremsstrahlung.

In most general terms, the above-described mechanism of characteristic X-ray radiation is similar to the mechanism of gamma radiation (as shown in Table 1, gamma radiation is also electromagnetic radiation, but with higher photon energies than X-ray radiation). The main difference is that in the case of gamma radiation the system that undergoes quantum transitions is not the system of atomic electrons, but the nucleus. The main similarities are the following:

1) Energy values of the system (atom or nucleus) are discrete (not continuous as in classical physics). In energy diagrams those values are usually shown as horizontal lines and called "energy levels" (see Fig. 4).

2) The system has an excess internal energy (using terminology of quantum mechanics, the system is in ***excited state***). Because of the quantum transition, the system eventually occupies the state with the lowest energy.

A generic energy diagram showing such quantum transition is presented in Fig. 4. The typical differences of nuclear energy levels are larger than the typical differences of atomic energy levels by several orders of magnitude. Therefore, the photon energies of gamma radiation are usually higher than the photon energies of X-ray radiation. The excitation methods are also different: a nucleus can not be excited by fast electrons with energy of the order of few tens of keV (much higher energies would be needed). The most common method of obtaining gamma radiation is radioactive decay. During radioactive decay, a nucleus ("the primary nucleus") transforms into a different nucleus ("the secondary nucleus"). The secondary nucleus is frequently in an excited state. Usually it emits the excess energy in the form of gamma photons (however, other mechanisms of energy loss are possible, too).

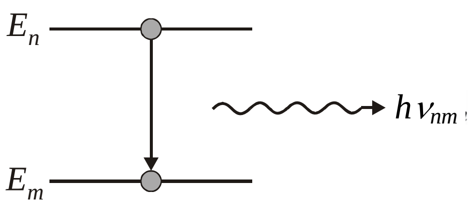

Fig. 4. An energy diagram illustrating a quantum transition from a higher energy level E_n to a lower energy level E_m. As a result of this transition, a photon with energy $h\nu_{nm} = E_n - E_m$ is emitted.

Unlike the characteristic X-ray radiation, the other mentioned type of X-ray radiation (bremsstrahlung) can be described in terms of classical physics. The fast incident electron interacts with charged particles of the anode material (atomic electrons and atomic nuclei) by Coulomb forces. Those interactions are random and they tend to slow down the incident electron and change direction of its motion. Thus, the incident electron does not move with constant velocity. In other words, it moves with *acceleration*. In classical electrodynamics, it is proved that when a charged particle moves with acceleration, it emits electromagnetic radiation. Intensity of this radiation is directly proportional to the square of the particle's charge and to the square of its acceleration (it does not matter if acceleration is positive or negative, i. e. if the particle's velocity increases or decreases). Historically, this type of radiation emitted by charged particles as they slow down in matter is referred to by a German term "bremsstrahlung" (even in English texts). The acceleration is larger when the incident electron's velocity is higher. Therefore, intensity of bremsstrahlung increases with increasing voltage of X-ray tube. The bremsstrahlung spectrum is continuous (see Fig. 3). As we see in Fig. 3, the spectrum of bremsstrahlung has a short-wavelength limit, which decreases with increasing X-ray tube voltage. The existence of this limit and its dependence on accelerating voltage can be explained as follows. The minimum wavelength corresponds to the maximum photon energy (see Eq. 4.1). The maximum energy of bremsstrahlung photons is obtained when the incident electron emits its entire kinetic energy in a single photon. Thus, the maximum energy of bremsstrahlung photons is equal to the energy of incident electrons. From definition of voltage it follows that this kinetic energy is equal to eU, where e is the elementary charge and U is the accelerating voltage. Thus, from (4.1) it follows that the minimum wavelength of X-ray radiation emitted by an X-ray tube is equal to

$$\lambda_{\min} = \frac{hc}{eU}. \tag{4.2}$$

5. Measuring the ionizing effect of radiation

When ionizing radiation impinges with matter of amount Δm, a portion of the energy ΔW is absorbed. The ratio of the absorbed energy to the amount of absorbing matter is defined as the ***energy dose*** D:

$$D = \mathrm{d}W / \mathrm{d}m \tag{5.1}$$

The "Gray" (Gy) must be introduced here as the unit of radiation dose, whereby [1 Gy] = 1 J/kg. The biological effects, for example somatic or genetic radiation damage, caused by different types of radiation with the same energy dose, are not always the same. On taking this difference into account by a ***quality factor*** Q (gained through experience), the following ***equivalent dose*** H is given:

$$H = D \cdot Q \tag{5.2}$$

The unit of the equivalent dose is the "Sievert" (Sv): [1 Sv] = 1 J/kg. The values of the quality factors for different types of ionizing radiation are given in Table 3.

Table 3. Quality factors for different types of ionizing radiation

The type of radiation	Q	The type of radiation	Q
Gamma radiation	1	Thermal neutrons	3
X-ray radiation	1	5 keV neutrons	2.5
Beta radiation	1	20 keV neutrons	5
Alpha radiation (≤ 10 MeV)	10	100 keV neutrons	8
Protons (10 MeV)	10	1 MeV neutrons	10.5
Heavy recoil nuclei	20	10 MeV neutrons	6.5

The actuation time of the ionizing radiation plays an important part in the evaluation of its effect. For this reason, the additional term "***dose rate***" P has been introduced. One must therefore differentiate between equivalent dose rate and energy dose rate. The energy dose rate is defined as

$$P = \mathrm{d}D / \mathrm{d}t \tag{5.3}$$

with unit 1 Gy/s = 1 J/(kg·s).

As it is not easy to determine the absorbed energy, the effect of the ionizing radiation is used to ascertain its ***ion dose*** I as ratio of the charge Q of ions of the same sign (produced under normal conditions by ionization of air) and the air mass penetrated by the radiation m:

$$I = \mathrm{d}Q / \mathrm{d}m \ [\mathrm{A{\cdot}s/kg}] \tag{5.4}$$

The effective intensity is expressed by the ***ion dose rate***:

$$j = \frac{\mathrm{d}I}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}Q}{\mathrm{d}m}\right) = \frac{\mathrm{d}i}{\mathrm{d}m} \quad [\mathrm{A/kg}]. \tag{5.5}$$

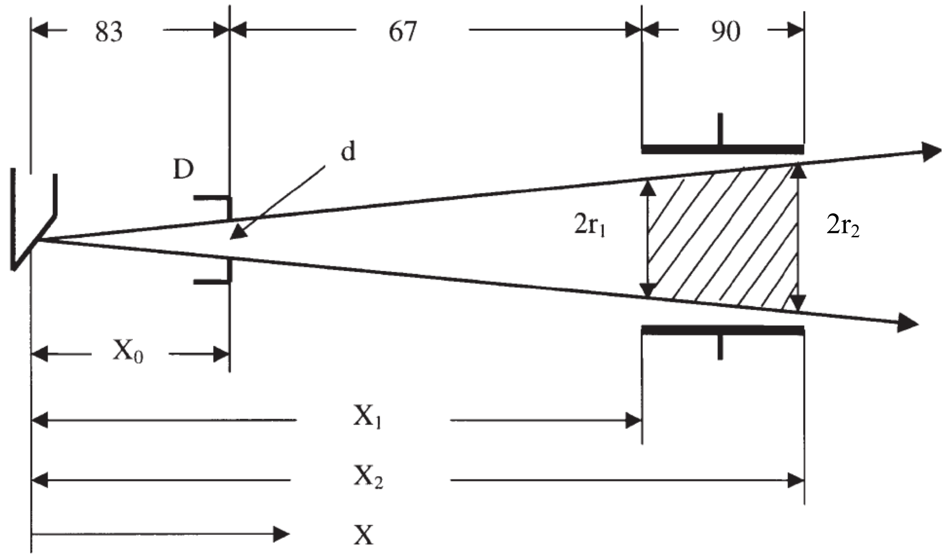

Fig. 5. Measurement geometry and distances needed for calculating the air volume where the charge carriers are created (all distances are given in millimeters)

In this experiment, in order to determine the ion dose rate of X-rays, a defined air volume between the plates of a capacitor is irradiated. The electrons and positive ions released by ionization produce ionization current when a voltage is applied. This current first increases almost linearly with increasing capacitor voltage, but eventually takes on a constant value despite further increase in the capacitor voltage. In this region of saturation, the charge carriers are prevented from recombining and so all of them reach the capacitor plates. The corresponding air volumes can be determined from the geometry of the radiation beam and the capacitor (see Fig. 5). In this experiment, the incident beam is conical in shape. The irradiated volume is defined by the intersection of that beam and the area between the capacitor plates. The radiation emitted from the anode of the X-ray tube is limited by the diaphragm tube D with aperture *d* and penetrates the truncated cone shaped air volume *V* in the capacitor. That volume is equal to

$$V = \frac{\pi(x_2 - x_1)}{3}(r_1^2 + r_1 r_2 + r_2^2)\,. \tag{5.6}$$

The radii r_1 and r_2 are equal to

$$r_1 = \frac{x_1 d}{2x_0}\,, \qquad r_2 = \frac{x_2 d}{2x_0}\,, \tag{5.7}$$

where x_0 is the distance between the radiation source (anode of the X-ray tube) and the limiting diaphragm (see Fig. 5). The air mass in the volume *V* is equal to

$$m = V\rho\,, \tag{5.8}$$

where ρ is the air density. Density of dry air at normal atmospheric pressure ($1.013 \cdot 10^5$ Pa) at a temperature of 20°C is 1.2 kg/m^3.

Energy dose and ion dose defined by (5.1) and (5.4) are *local*, i. e. they are defined for a specific point in space (that is why their definitions involve the ratio of infinitesimal quantities). Since the electric current *i* is caused by *all* carriers created in the irradiated volume, we can only measure the *average* ion dose rate, which is equal to

$$\bar{j} = \frac{i}{m}\,. \tag{5.9}$$

Here, *i* is the measured current and *m* is the total irradiated mass of air (defined by (5.8)). It can be shown that in the case of such measurement geometry as in Fig. 5 the average dose rate (5.9) is approximately equal to the local dose rate (5.5) measured halfway between the left and right edges of the irradiated volume, i. e. at the point $x = (x_1 + x_2) / 2$ (see Fig. 5).

Once the ion dose rate has been measured, the energy dose rate can be determined, if the average absorbed energy *W* per one charge carrier (i. e. per one electron liberated during ionization of an atom or molecule) is known. In order to do that, the ion dose rate must be divided by the elementary charge *e* and multiplied by *W*:

$$P = j\frac{W}{e}. \tag{5.6}$$

The average value of energy lost in air by an X-ray photon per one created ion pair (i. e. per one ionized molecule of air) is $W = 33$ eV. ***Note***: this energy is not the same as the ionization energy defined in Section 3 (ionization energy is the *smallest* energy needed for the ionization to become possible), because not all energy lost by the incident photons is lost due to ionization. Some of the interactions that decrease photon energy are not accompanied by ionization. Therefore, the average energy loss per one ion pair W is always larger than the ionization energy.

6. Experimental setup and procedure

6.1. The circuit diagram

In this experiment, the ionization current i is measured. The circuit diagram is shown in Fig. 6. The capacitor voltage is supplied by a power supply with two independent outputs. One of those outputs has an adjustable voltage (from 0 to 300 V), whereas the other one has constant voltage (about 300 V). During the experiment, the capacitor voltage must be varied from 0 to 500 V. When the required voltage is less than 300 V, only one output (with adjustable voltage) is needed. When the required voltage is between 300 V and 500 V, the two outputs must be connected in series as shown in Fig. 6.

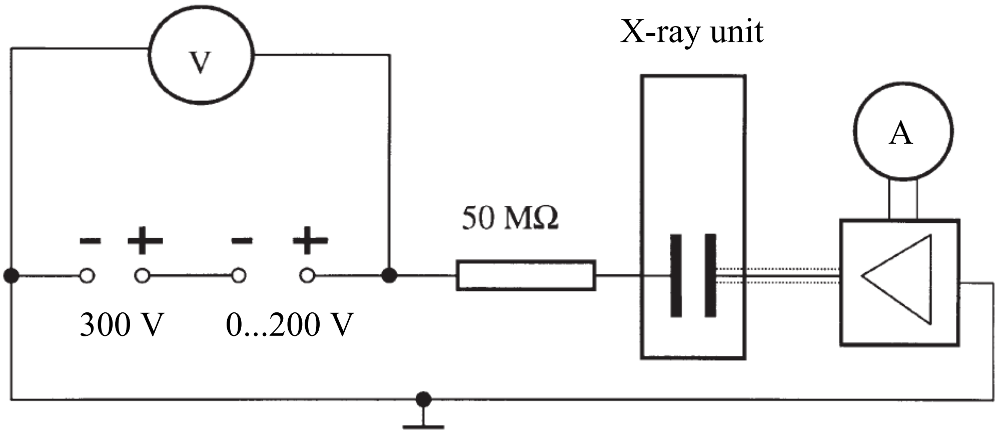

Fig. 6. The circuit diagram for determination of ionization currents

6.2. The equipment

For this experiment, a set of educational equipment manufactured by a German company “Phywe Systeme” is used. The equipment consists of the following devices:

1) an X-ray unit with a plug-in module with an X-ray tube (any one of three X-ray tubes with copper, molybdenum or iron anode may be used);
2) a parallel-plate capacitor;
3) an adjustable direct-current power supply;
4) a direct-current (DC) amplifier, which is used for measuring weak currents (several nanoamperes);
5) two digital multimeters;
6) a 50 MΩ resistor.

The general view of the equipment is shown in Fig. 7. The bottom part of the front panel of the X-ray unit is shown in Fig. 8. Figures 9 and 10 show the front panels of the direct-current amplifier and the power supply, respectively.

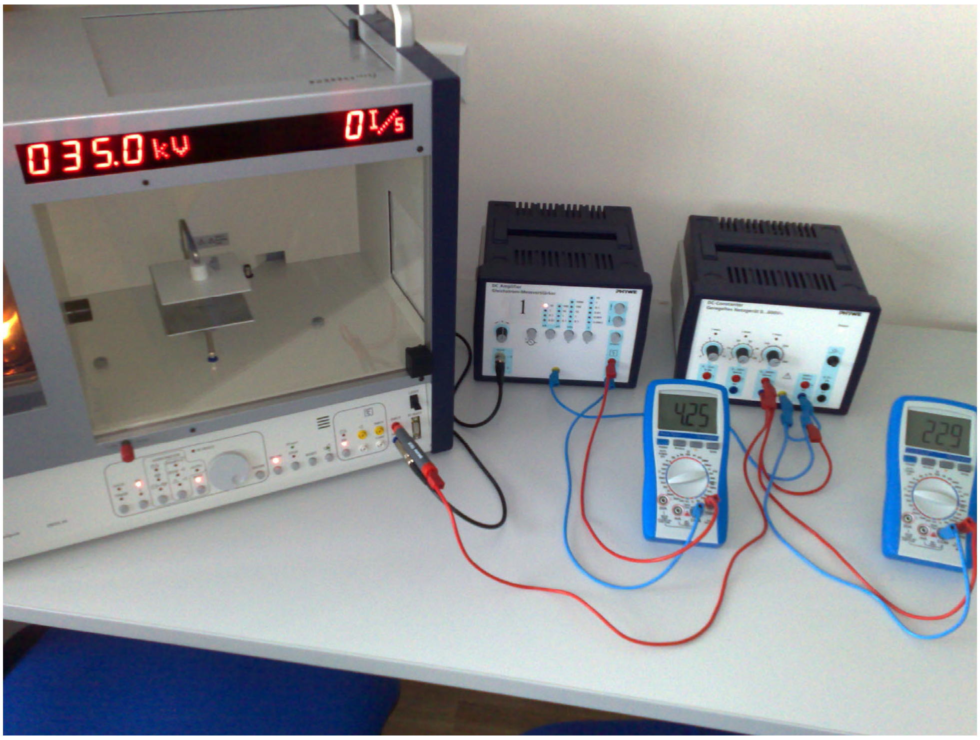

Fig. 7. The general view of the equipment

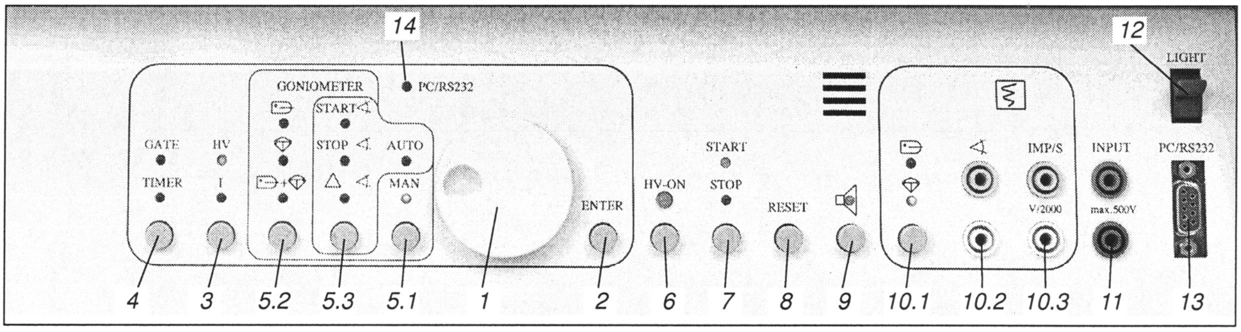

Fig. 8. The manual operation controls of the X-ray unit

The controls of the X-ray unit that are needed for this experiment are listed below (the numbering is the same as in Fig. 8):

1. The anode voltage and anode current manual adjustment wheel (in order to set the adjusted quantity, the button “Enter” must be pressed);

2. The button „Enter“. It is used in order to set the value selected with the wheel (1).

3. The button „HV-I“. This button is used for selecting one of the two quantities defining operation of the X-ray tube (anode voltage or anode current) for adjustment with the wheel (1). The selected quantity is indicated by one of two light-emitting diodes (LED) that are above the button “Enter”. The LED “HV” corresponds to anode voltage, and “I” corresponds to anode current. The value of the selected quantity is shown at the top of the front panel of the X-ray unit (see Fig. 7).

6. The button „HV-ON“. When this button is pressed, the high voltage is applied to the X-ray tube and current begins to flow between the cathode and the anode of the X-ray tube. Then the LED that is above the button „HV-ON“ lights up. After pressing this button again, anode voltage and cathode heating are switched off.

11. The capacitor voltage leads. The bottom (blue) lead is for grounding and connecting the direct-current amplifier. The top (red) lead is for connecting positive direct-current voltage (up to 500 V). For safety reasons, the positive pole of the voltage must be connected to the capacitor plate via the 50 MΩ protective resistor (see the circuit diagram in Fig. 6).

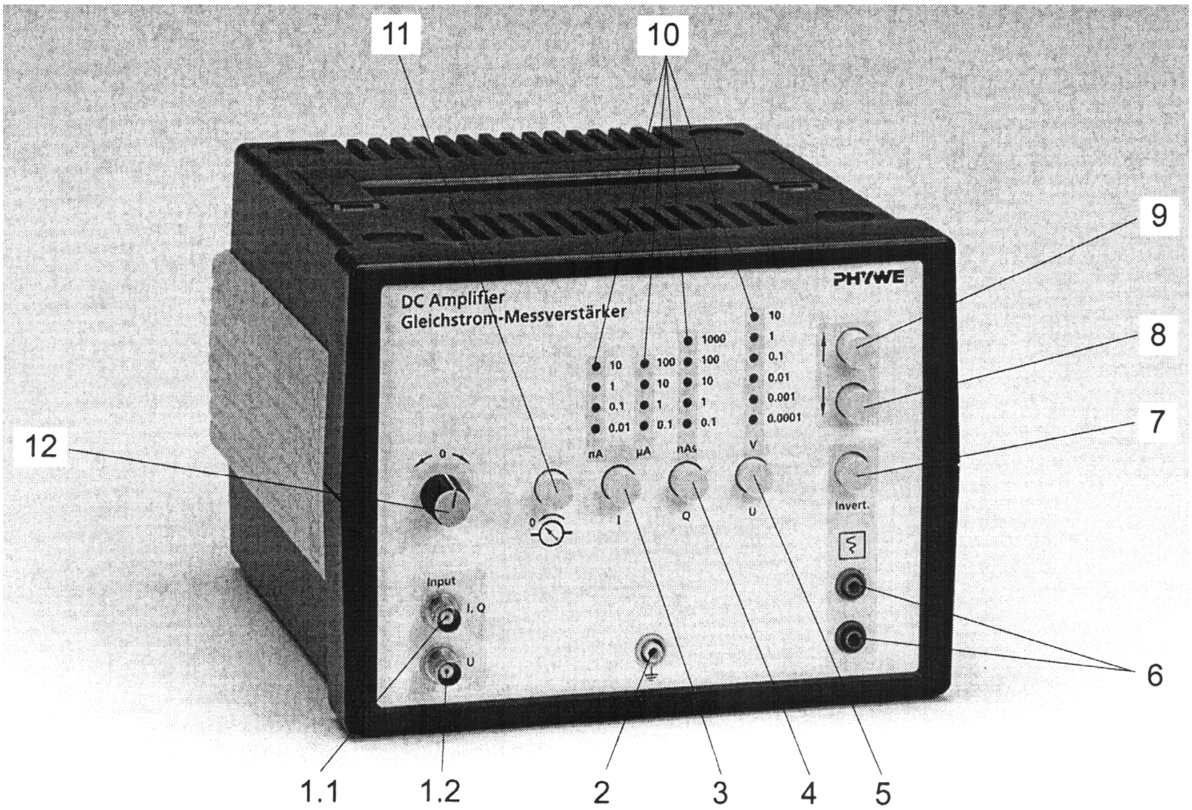

Fig. 9. The front panel of the direct-current amplifier

The controls of the direct-current amplifier that are needed for this experiment are listed below (the numbering is the same as in Fig. 9):

1.1. The BNC socket for connecting the measured signal in direct current or charge measurement mode.

2. The ground connection lead.

3. The button for selecting the electric current measurement mode. During this experiment, this button must be in the depressed position.

6. The output leads for connecting a direct-current voltage measurement device with the measurement range 0 to 10 V. The output voltage is proportional to the measured quantity, which may be electric current, electric charge or voltage depending on selected mode (as mentioned above, in this experiment the measured quantity is electric current). The maximum output voltage is about 10,5 V. When this value is exceeded, the output voltage is not longer proportional to the measured input signal (due to the internal voltage limiter). Therefore, the measurement range must be chosen so that this voltage never exceeds 10 V (selection of the measurement range is explained below).

7. The button „Invert“. When this button is pressed, the sign of the output voltage is inverted. In this experiment, this button must not be pressed.

8. The button „↓“. When this button is pressed, the maximum allowable value of the input signal (e. g., electric current) decreases. The maximum allowable value of the input signal corresponds to the value 10 V of the output voltage. Thus, this button increases the sensitivity of the amplifier (i. e. the ratio between the output and input signals).

9. The button „↑“. When this button is pressed, the maximum allowable value of the input signal (e. g., electric current) increases. The maximum allowable value of the input signal corresponds to the value 10 V of the output voltage. Thus, this button decreases the sensitivity of the amplifier (i. e. the ratio between the output and input signals).

10. Light-emitting diodes (LED) indicating the selected mode (electric current, charge or voltage measurement) and the maximum allowable value of the measured quantity, i. e. the value corresponding to the output voltage 10 V. For example, the LED “10 nA” indicates that output voltage of 10 V corresponds to input current 10 nA. Thus, in this case 1 V of output voltage corresponds to 1 nA of input current. The LED “1 nA” indicates that output voltage of 10 V corresponds to input current 1 nA. Thus, in this case 1 V of output voltage corresponds to 0.1 nA of input current.

12. Zero adjustment knob.

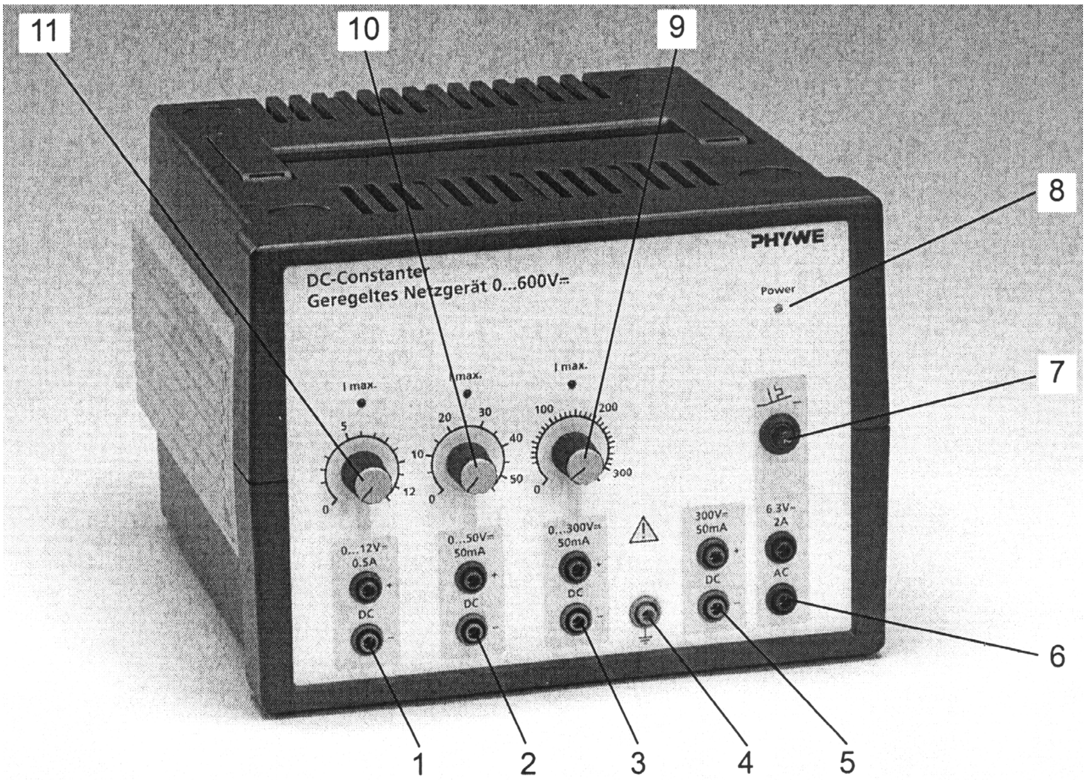

Fig. 10. The front panel of the adjustable direct-current power supply

The controls of the power supply that are needed for this experiment are listed below (the numbering is the same as in Fig. 10):

3. The leads of adjustable direct-current voltage (0 – 300 V). The positive pole is red, and the negative pole is blue.

4. The ground connection lead.

5. The leads of constant (non-adjustable) direct-current voltage (about 330 V). The positive pole is red, and the negative pole is blue.

9. Output voltage adjustment knob (0 – 300 V).

6.3. The measurement procedure

1. Connect the wires according to the circuit diagram (Fig. 6) and according to descriptions of equipment given in Section 6.2. The ground leads of the direct-current (DC) amplifier and the power supply must be connected with each other. The negative (blue) pole of the non-adjustable 330 V output (No. 5 in Fig. 10) must be also connected to the ground at all times, whereas the positive (red) pole of the adjustable voltage output (No. 3 in Fig. 10) must be at all times connected to the X-ray unit's "INPUT" red lead (No. 11 in Fig. 8) via the 50 MΩ resistor. If the needed capacitor voltage is less than 300 V, the non-adjustable voltage output is not used, i. e., the negative (blue) pole of adjustable voltage must be connected to the ground. If the needed capacitor voltage is larger, then the negative pole of the adjustable voltage output must be connected to the positive (red) pole of the non-adjustable voltage output. After connecting all wires, the equipment should look as shown in Fig. 7.

2. Switch on the X-ray unit (its mains switch is on its back panel). Write down the anode material (it is indicated on the left side of the X-ray unit). ***Note***: Although this information is not used during this experiment, the knowledge of the anode material may be useful when comparing the results obtained with different anodes (the ionization current depends on anode material).

3. Open the experimenting area of the X-ray unit. In order to do this, press the red knob at the lower-left corner of the experimenting area and, while keeping it pressed, turn it to the right (clockwise). Then slide the glass door to the left.

4. Fix a 2 mm diaphragm tube in the X-ray outlet tube. The diaphragm tube compartment is at the top of the X-ray unit. In total, there are three diaphragm tubes: 1 mm, 2 mm and 5 mm. Only the 2 mm and 5 mm diaphragms are needed for this experiment.

5. Close the experimenting area of the X-ray unit, i. e., slide the glass door to the right, then turn the red knob to the left (counterclockwise). Then press that knob once again (this is needed in order to be able to apply high voltage to the X-ray tube).

6. Switch on both multimeters. The multimeter that is connected to the DC amplifier must be in DC voltage measurement mode (multimeter knob position "20 V"). The multimeter that is connected to the power supply must be in high DC voltage measurement mode (multimeter knob position "1000 V").

7. Turn the capacitor voltage adjustment knob (No. 9 in Fig. 10) all the way to the left (counterclockwise). Switch on the DC amplifier and the power supply.

8. Press the DC amplifier button "I" (i. e. select the electric current measurement mode), then select the measurement limit "1 nA" (in this case, the DC amplifier output voltage, which is shown by a multimeter, is 10 times larger than the measured current expressed in nanoamperes).

9. Check that the X-ray tube high-voltage LED "HV-ON" is off (see No. 6 in Fig. 8). If that LED is on, press the button below it.

10. Select the X-ray tube anode voltage adjustment mode. The X-ray unit LED "HV" must on and the LED "I" must be off. This is achieved by pressing the button that is below those two LEDs (No. 3 in Fig. 8). Then set the maximum X-ray tube anode voltage 35 kV by turning the X-ray unit adjustment wheel (No. 1 in Fig. 8). The value of the X-ray tube voltage is shown on the display that is at the top of the front panel of the X-ray unit (see Fig. 7). When the required voltage is shown, press the button "ENTER" (No. 2 in Fig. 8).

11. Select the X-ray tube anode current adjustment mode. Press the button "HV-I", so that the LED "HV" is off and the LED "I" is on. In the same way as setting the X-ray tube voltage, set the X-ray tube current to the maximum value 1 mA. When the required value is shown, press the button "ENTER" (No. 2 in Fig. 8).

12. Turn slowly the capacitor voltage adjustment knob on the power supply (No. 9 in Fig. 10) until a required value is shown by the multimeter that is connected to the power supply. The initial value of that voltage should be about 20 V.

13. Turn the zero adjustment knob of the DC amplifier (No. 12 in Fig. 9) until the multimeter that is connected to that amplifier shows approximately zero. If the zero value can not be achieved, memorize the average value of the voltage that is shown (later on, that value will have to be subtracted from the measured value). ***Note***: The output voltage of the amplifier is sensitive to various small electric charges in the environment. Therefore large fluctuations of the measured voltage are possible. In order to minimize those undesirable effects, one should avoid movement in the vicinity of the DC amplifier.

14. Press the button "HV-ON" that switches on the X-ray tube voltage and cathode heating (No. 6 in Fig. 8). Then the LED above it lights up.

15. Wait for a few seconds until the DC amplifier output voltage stops increasing, then write down the corresponding value of the capacitor current. ***Note***: If the output voltage of the DC amplifier exceeds 10 V, then, as mentioned in Section 6.2, the measurement limit of the DC amplifier must be increased, i. e. the LED "10 nA" must be lit instead of the LED "1 nA" (when "10 nA" is lit, the DC amplifier output voltage shown by the multimeter is equal to the capacitor current in nanoamperes).

16. Switch off the X-ray tube anode voltage and cathode heating, i. e. press the button "HV-ON" (No. 6 in Fig. 8), so that the LED that above it is no longer lit. Wait for a few seconds until the output voltage of the DC amplifier (i. e. the capacitor current) drops to zero.

17. Repeat Steps 12 to 16 while changing the capacitor voltage from 20 V to 300 V in increments of approximately 20 V.

18. In order to use capacitor voltage values that are larger than 300 V, connect the two outputs of the power supply (No. 3 and No. 5 in Fig. 10) in series. This is done by switching off the power supply, turning the voltage adjustment knob (No. 9 in Fig. 10) all the way to the left (counterclockwise) and connecting the negative (blue) pole of the adjustable voltage output (No. 3 in Fig. 10) to the positive (red) pole of the non-adjustable voltage output (No. 5 in Fig. 10). Then the power supply must be switched on. ***Warning***: any manipulations with the wires connected to the power supply are only allowed when the power supply is switched off.

19. Repeat Steps 12 to 16 while changing the capacitor voltage from 330 V to 500 V in increments of approximately 20 V.

20. Switch off the power supply. Turn the capacitor voltage adjustment knob (No. 9 in Fig. 10) all the way to the left (counterclockwise).

21. Replace the 2 mm diaphragm by the 5 mm diaphragm (see Steps 3 to 5). Connect the negative (blue) pole of the adjustable voltage output (No. 3 in Fig. 10) to the ground lead again. Switch on the power supply again.

22. Repeat Steps 12 to 20.

In the remainder of this experiment, two dependences are measured: dependence of the capacitor current on the X-ray tube anode current (at the maximum anode voltage 35 kV) and dependence of the capacitor current on the X-ray tube anode voltage (at the maximum anode current 1 mA). Both dependences must be measured using the 5 mm diaphragm and at a constant value of the capacitor voltage (500 V).

23. By turning the adjustment wheel on the X-ray unit (No. 1 in Fig. 8) set the required value of the anode current (the anode voltage must be 35 kV). The initial value of the anode current must be 0. Press the button “ENTER” (No. 2 in Fig. 8).
24. Turn the zero adjustment knob of the DC amplifier (No. 12 in Fig. 9) until the multimeter that is connected to that amplifier shows approximately zero. If the zero value can not be achieved, memorize the average value of the voltage that is shown (later on, that value will have to be subtracted from the measured value).
25. Press the button “HV-ON” that switches on the X-ray tube voltage and cathode heating (No. 6 in Fig. 8). Then the LED above it lights up.
26. Wait for a few seconds until the DC amplifier output voltage stops increasing, then write down the corresponding value of the capacitor current.
27. Switch off the X-ray tube anode voltage and cathode heating, i. e. press the button “HV-ON” (No. 6 in Fig. 8), so that the LED that above it is no longer lit. Wait for a few seconds until the output voltage of the DC amplifier (i. e. the capacitor current) drops to zero.
28. Repeat Steps 23 to 27 while changing the X-ray tube anode current from 0 to 1 mA in increments of approximately 0.05 mA.

29. By turning the adjustment wheel on the X-ray unit (No. 1 in Fig. 8) set the required value of the anode voltage (the anode current must be 1 mA). The initial value of the anode voltage must be approximately 6 kV. Press the button “ENTER” (No. 2 in Fig. 8).
30. Turn the zero adjustment knob of the DC amplifier (No. 12 in Fig. 9) until the multimeter that is connected to that amplifier shows approximately zero. If the zero value can not be achieved, memorize the average value of the voltage that is shown (later on, that value will have to be subtracted from the measured value).
31. Press the button “HV-ON” that switches on the X-ray tube voltage and cathode heating (No. 6 in Fig. 8). Then the LED above it lights up.
32. Wait for a few seconds until the DC amplifier output voltage stops increasing, then write down the corresponding value of the capacitor current.
33. Switch off the X-ray tube anode voltage and cathode heating, i. e. press the button “HV-ON” (No. 6 in Fig. 8), so that the LED that above it is no longer lit. Wait for a few seconds until the output voltage of the DC amplifier (i. e. the capacitor current) drops to zero.
34. Repeat Steps 29 to 33 while changing the X-ray tube anode voltage from 6 kV to 35 kV in increments of approximately 2 kV.

35. Measure the diameter of the X-ray pattern on the fluorescent screen (on the right-hand side of the X-ray unit). The pattern is visible at maximum values of anode voltage and current under subdued light (it must be observed from the outside). ***Note***: The distance between the diaphragm and the fluorescent screen is 35 cm. The distance x_0 between the X-ray tube anode and diaphragm can be calculated using elementary trigonometric relations (see Fig. 5 and Eq. 5.7).

36. Switch off the X-ray unit, DC amplifier and the capacitor power supply.

37. Show the measurement results (in table format) to the laboratory supervisor for signing.