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Measurement methods of ionization current and electric charges in radiation dosimetry

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ABSTRACT

This paper deals with the problem of measurement of very low direct currents and electrical charges in dosimetric application. It describes the known and used methods of measurement: the current method, the charge method, and the null method. A new method, which is presented here, is a combination of the two latter methods. The new method is compared with the known methods of measurement and the results of this comparison are summarized and discussed. The new method allows achieving relative standard uncertainty of 0.003% for current measurements around 3 pA and a long term stability of about 0.01%. Apart from this, preliminary measurements by using a built in comparator were also performed. Therefore, the uncertainty budget of the measurements for the system without an external comparator was also taken into account in the paper. The combined measurement uncertainties for current measurements obtained for the above-mentioned two methods (the new method and the method with the comparator built in the 6517A Keithley electrometer used in our experiments) were similar.

1. Introduction

The ionization chamber is the most widely used type of dosimeters for precise measurement. As the primary standards two types of ionization chamber are used, which are fully described in the papers [1–3]. “The typical values of charge or current to be measured by ionization chambers can be estimated from the fact that an exposure of 1 R (Roentgen is now a historical unit of exposure dose) generates a charge of 2.58×10^{-10} C in 1 cm^3 of room temperature air at pressure 1 atm.”

In most practical cases, ionization currents are very small, in the range from 1.0 μA to 0.1 fA, their measurement requires careful technique and appropriate instrumentation. Conducting a measurement with an ionization chamber typically requires a high-voltage power supply and an electrometer. The electrometer used in this work is a sensitive, high input impedance instrument used for specialized measurements of DC voltage, DC, electrical charge, and resistance. The electrometer measures current or charge in the range 200 fA to 1 μA (current mode) and 2 pC to 10 mC (charge mode) with a maximum resolution of 1 fA or 10 fC with accuracy better than 0.5%, features of long term stability of 0.1% per year [4,5]. These parameters are insufficient to measurements in which we use the ionization chambers as the primary standard. There are also problems with calibration of these electrometers performance at a satisfactory level. The solution to these problems might be of use in the null method presented in Section 2. In the same section external feedback used with well known methods of measurements such as current and charges methods is described. Section 2 also describes the theory and basic principles of measurements of low direct currents and electrical charges. Implementation of particular methods of measurement is presented in Section 3. The comparison of the measurement methods with an uncertainty budget is presented and also discussed in Section 3. Section 4 gives the conclusions of the paper.

2. Measurement methods for low direct currents and electrical charges

2.1. The history

Until high-gain negative-feedback amplifiers were introduced, electrometers for ionization current measurements were being used as null detectors [6]. Many years ago, electrical charge or current were measured manually in the most sensitive range of the electrometer. For example, in the null method of measurement, it is necessary to maintain the null such that the collector plate potential is very near the guard-plate potential, but the determination of additional capacitance in the system and the calibration of the electrometer voltage are unnecessary [7]. A difference of potential between the guard and collector plates in a

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free-air ionization chamber distorts the electric field and deforms the defined air volume, causing errors in measurement of exposure [8]. Vibrating-reed electrometers use a variable capacitor formed between a moving electrode (in the form of a vibrating-reed) and a fixed input electrode [9]. As the distance between the two electrodes varies, the capacitance also varies and electric charge is forced in and out of the capacitor. The alternating current signal produced by the flow of this charge is amplified and used as an analogue for the DC voltage applied to the capacitor. The DC input resistance of the electrometer is determined solely by the leakage resistance of the capacitor, and is typically extremely high (although its AC input impedance is lower). The vibrating-reed electrometer was an improvement over direct-current, vacuum-tube electrometers not only because it used negative feedback, but was being an AC amplifier, the problem of zero drift was essentially eliminated. Negative feedback automatically maintains the collector plate of free-air ionization chamber near the guard potential and minimizes field distortion [8]. For many years, the vibrating-reed electrometers have been used at many laboratories as null detectors [10]. Currently, the vibrating reed electrometer is used only in a few laboratories in the World.

The most of modern electrometers consist of a solid state amplifier using one or more field-effect transistors, connections for external measurement devices, and usually a display and/or data-logging connections [11]. On the basis of Keithley Instruments Inc. [12], the typical schema of a digital electrometer is illustrated and presented in Fig. 1. Solid-state electrometers are often multipurpose devices that can measure voltage, charge, resistance and current. The external connections are usually of a coaxial or a triaxial design, and allow attachment of ionization chambers for radiation measurement. Electrometers designed for use with ionization chambers are a high gain, negative feedback, operational amplifiers with a standard resistor or a standard capacitor in the feedback path to measure the chamber current or charge collected over a fixed time interval (see Fig. 1). They may include a high-voltage power supply, which is used to power the ionization chamber. The function of external feedback provides means to extend the capabilities of an electrometer.

2.2. The null method

For precise measurements of small quantities of charge, or of small currents, the Townsend balance circuit, or its modification, are frequently employed [3,7,8,13]. This circuit in its simplest form is illustrated in Fig. 2.

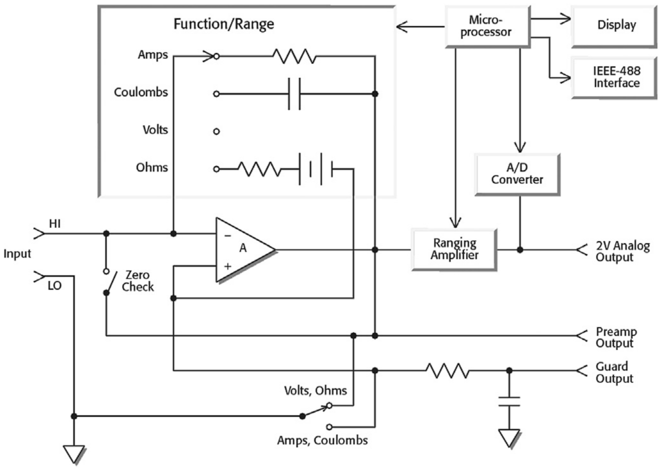

Fig. 1. The typical scheme of a digital electrometer (illustrated on the basis of Kethley Instruments Inc., 2004).

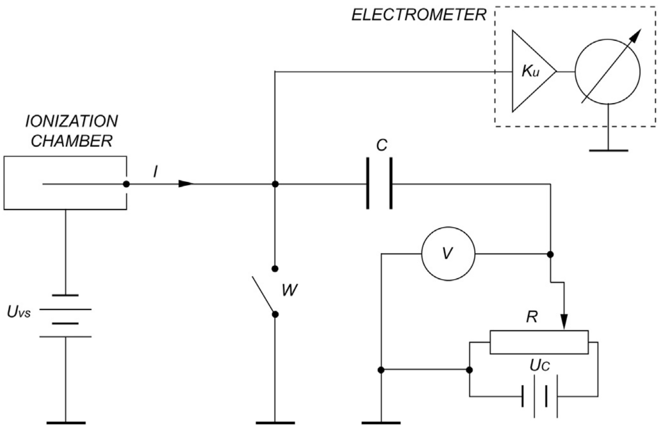

Fig. 2. The Townsend balance circuit (the null method).

The null indicating instrument can be any electrometer of adequate sensitivity and low input capacitance, and its calibration voltage can be unknown. Initially, the switch, *W*, is closed, bringing the electrometer to ground potential. At the commencement of a measurement the potentiometer, *R*, is set at zero volts and the grounding switch, *W*, is opened and the ionization current from the chamber proceeds to charge the capacitor, *C*. The electrometer is maintained at ground potential by varying the voltage, *U*. As charge collects on *C*, the potentiometer tapping is increased so as to keep the electrometer needle constantly at zero (see Fig. 3). At the end of exposure the voltage, *U*, is noted on an accurate voltmeter. The total charge, *Q*, collected at time *t* is then equal to *CU* [7,13]. Ionization current is described by the equation:

$$I = C\frac{U}{t} \tag{1}$$

Thus, an accuracy of the measurement depends only on quantities which can readily be measured with high precision [7,8,13].

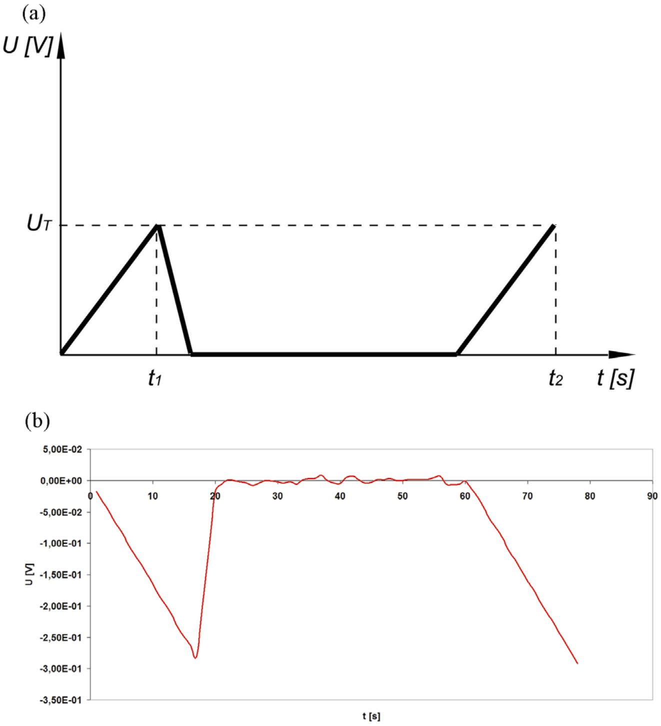

Fig. 3. Graph of the change in voltage at the output of the amplifier as a function of time during measuring the ionization current in the null method: (a) theoretical curve and (b) experimental curve.

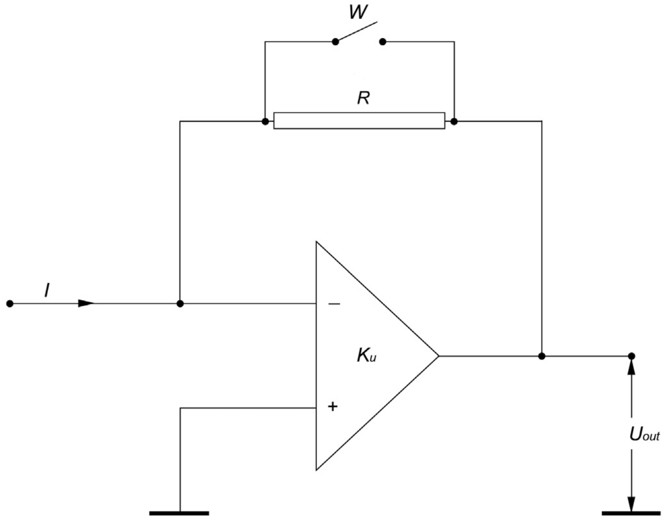

Fig. 4. Circuit of negative-feedback amplifier with feedback resistor (the current method).

2.3. The current method

The current method is implemented by a negative-feedback electrometer with the feedback resistor and is shown in Fig. 4.

The input current, I, from an ionization chamber flows through the feedback resistor, R. Low offset current of the amplifier, K_u, changes the current, I, by a negligible amount (under 3 fA). The amplifier output voltage, U_{out}, is calculated as

$$U_{out} = -IR \tag{2}$$

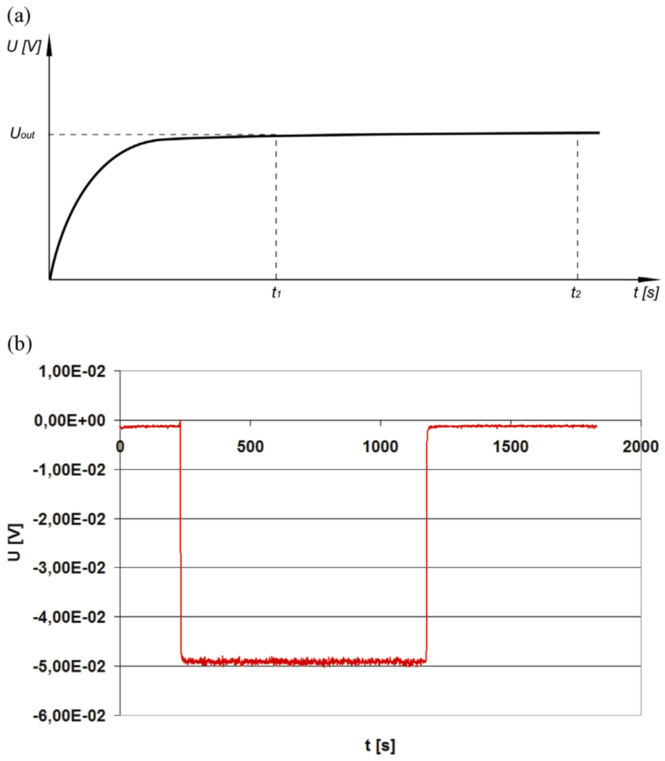

Fig. 5. Graph of the change in voltage at the output of the amplifier as a function of time during measuring the ionization current in the current method: (a) theoretical curve and (b) experimental curve.

Thus, the output voltage, U_{out}, is a measure of the input current, and overall sensitivity is determined by the feedback resistor, R. In Fig. 5, changes in voltage at the output of the amplifier as a function of time during measuring the ionization current in the current method: theoretical and experimental are shown.

For low current measurements, resistors with values in the high megaohm range are required. For example, a feedback resistor of 20 MΩ is required to develop a feedback voltage of 1 V for the exceptionally large ionization current of 50 nA. Typical high-megaohm resistors show resistance changes of about 1% over a period of six months [8]. The low input voltage burden and the corresponding fast rise time are achieved by the high gain operational amplifier, which forces input voltage to be nearly zero. The measured current, I, is calculated as

$$I = -\frac{U_{out}}{R} \tag{3}$$

This current method is implemented in an electrometer as current mode (see Fig. 1). This method can be implemented in an external feedback with standard resistor, what simplifies calibration and improves the metrological properties of the measurement system [7].

2.4. The charges method

The charges method is implemented by a negative-feedback electrometer with the feedback capacitor and is shown in Fig. 6.

Using the relation for Q mentioned in Section 2.2, the basic charge measuring scheme is to transfer the electrical charge to be measured to a capacitor of known value and then measure the voltage across the known capacitor. That case is presented in (Fig. 6) Q=-$C\cdot U_{out}$. In practice, the current I is determined from the measurement of output voltage, U_{out}, using accurate digital voltmeters which can be commanded to sample-and-hold readings of U_{out} at preset time intervals. The inverting operational amplifier has other advantages. Since, they affect the application of these devices to low direct current measurements from ionization chambers [8].

These features are the inherent linearity of the change in U_{out} with time (see Fig. 7), giving, $\Delta U_{out}/\Delta t$ = const. and the ability of the device to transfer essentially all of the electrical charge produced in the ionization chamber to the measurement system [8].

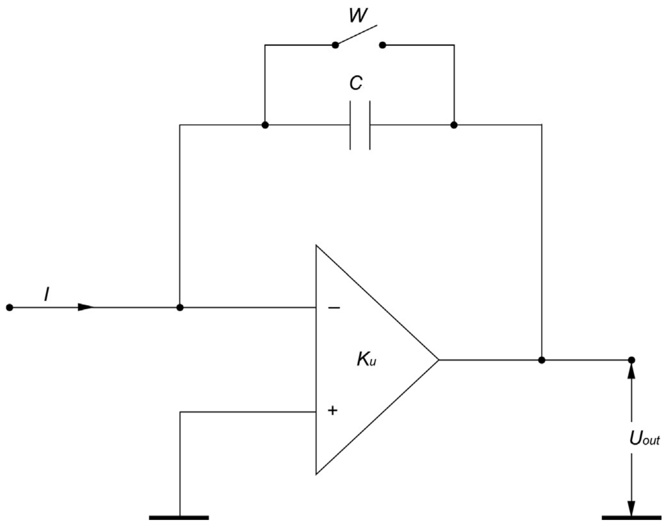

Fig. 6. Circuit of negative-feedback amplifier with feedback capacitor (the charges method).

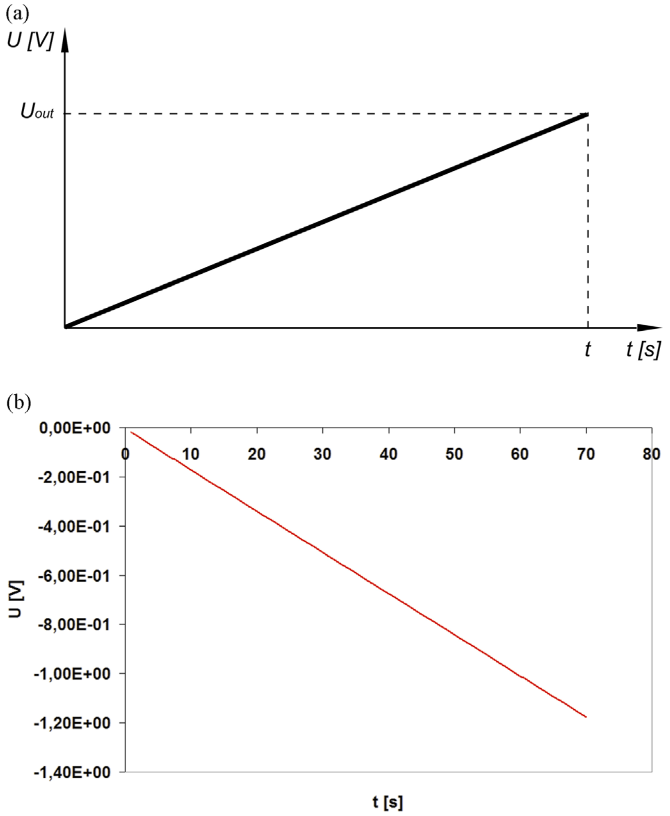

Fig. 7. Graph of the change voltage at the output of the amplifier as a function of time during measuring the ionization current by the charges method: (a) theoretical curve and (b) experimental curve.

In this case the measured current, I, is calculated as

$$I = -C\frac{\Delta U_{out}}{\Delta t} \tag{4}$$

This charges method is implemented in an electrometer as charge mode (see Fig. 1). Typical values, for this measurement system are: $C=2$ nF, $dV/dt=50$ mV/s, i.e. $I=100$ pA, of statistical relative standard uncertainty typically below 0.02% over a period of 3 months and the long-term reproducibility is 0.06% over a period of 15 years [13–15].

3. Setup implementation for high precision ionization current measurements

Implementations in performance measurement were done with digital electrometer Keithley model 6517A using an external feedback function [12]. These implementations are shown in Figs. 8–10. In null and charge methods, standard air-dielectric capacitors, in range from 100 pF to 10 nF, were used. In the current method standard resistors, in the range from 0.1 GΩ to 100 GΩ, in negative external feedback were used.

3.1. *The null method*

In the null method the digital multimeter Keithley model 2100, the battery of accumulators and a potentiometer were used. For measuring time, the digital counter Hameg model 8123 at the interval time function (timer) was applied. In the null method, the counter was connected to a comparator with triggers and an analog output of electrometer. This case is shown in Fig. 8. Instead of an external comparator with triggers, we can also use triggers built in an electrometer with using “limit” function. When the voltage reaches a fixed value on the comparator or “limit” function of electrometer TTL signal is sent from trigger to the counter, what starts a time of compensation in the null method. After the end of compensation the ionization current makes the voltage increase and in the result TTL signal is sent from trigger to counter, what stops a timer. We receive compensatory time that is equal to the collection time of electrical charges on known capacitance.

3.2. *Current and charge measurements methods*

The other way of measuring time is to apply electrometer built-in timer where a good description of this one can be found in user's manual of an electrometer [12]. The result of measurement consists of measurand value (in this case – voltage), time stamp and reading number, etc. In this format it is written to data storage of electrometer. Setting the number of readings and the time between readings can make the measurement of time. This is very simple, comfortable and accurate solution. It is used by the author

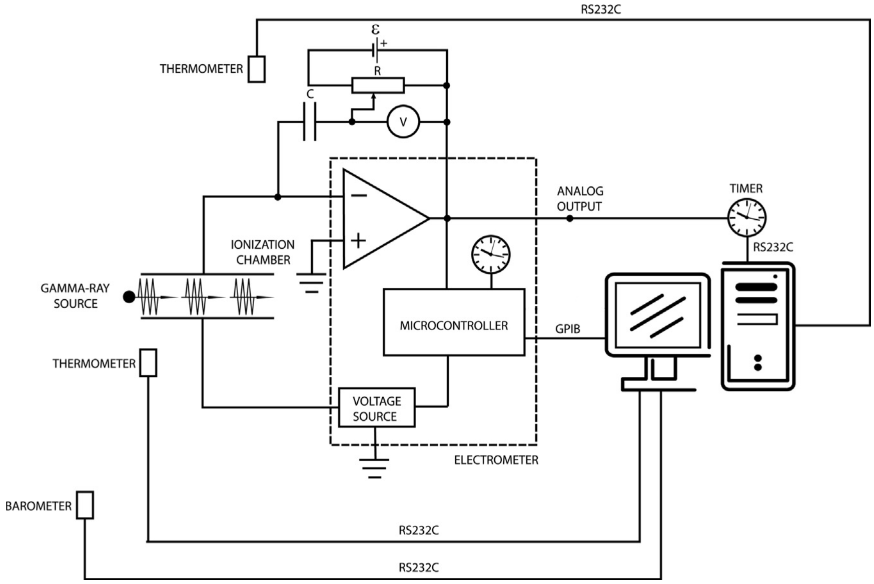

Fig. 8. Implementation of the null method.

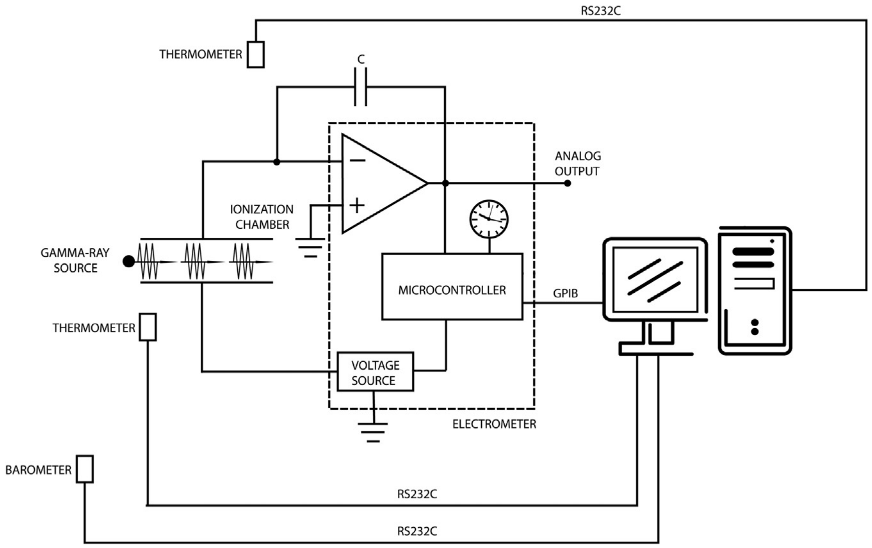

Fig. 9. Implementation of the charges method.

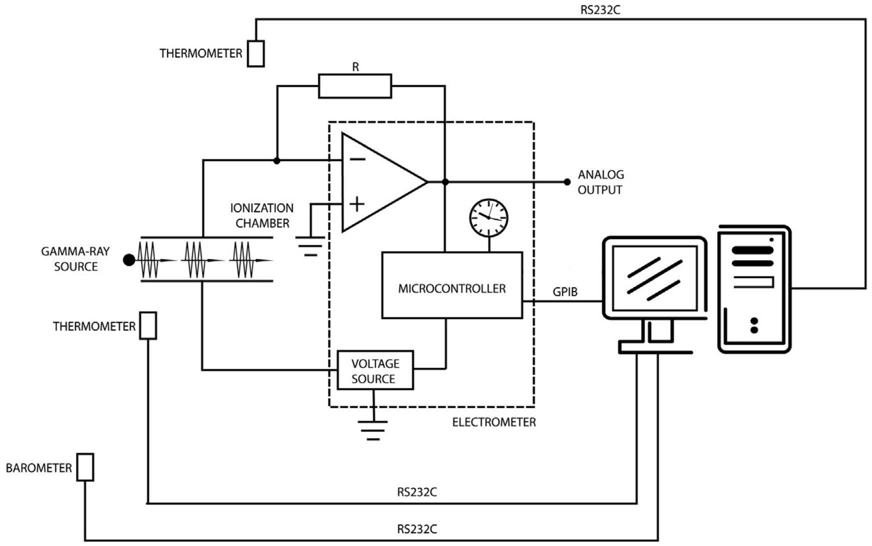

Fig. 10. Implementation of the current method.

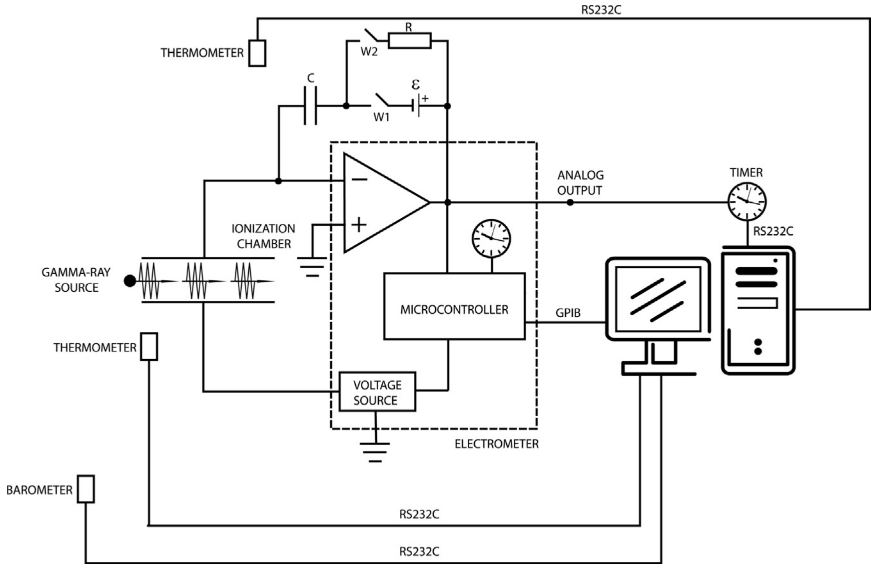

Fig. 11. Circuit of the new method and its implementation.

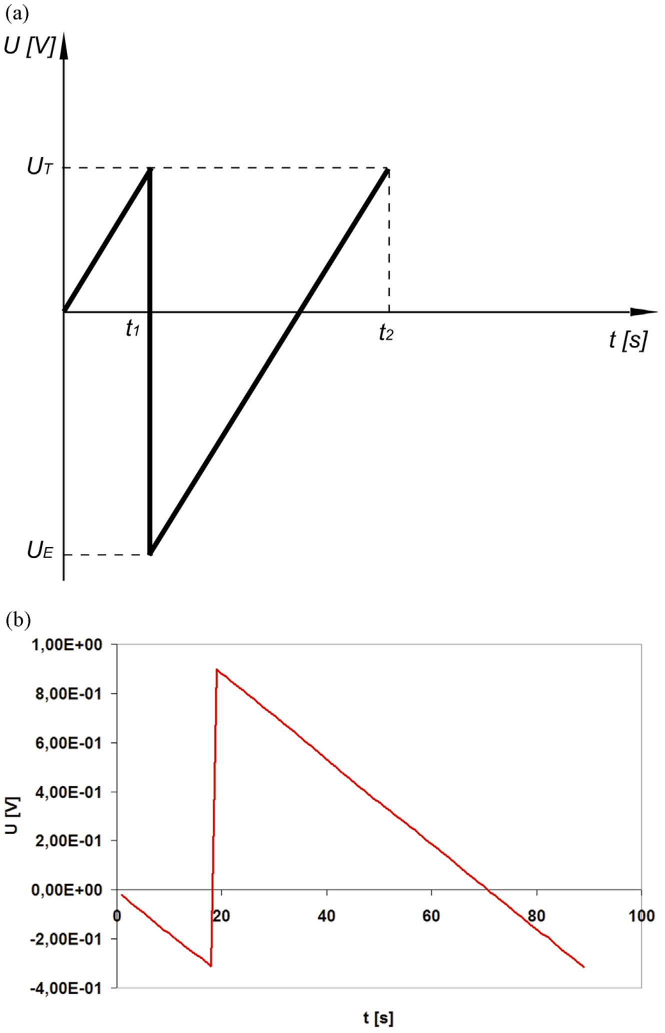

Fig. 12. Graph of the voltage change at the output of the amplifier as a function of time during measuring the ionization current by the new method: (a) theoretical curve and (b) experimental curve.

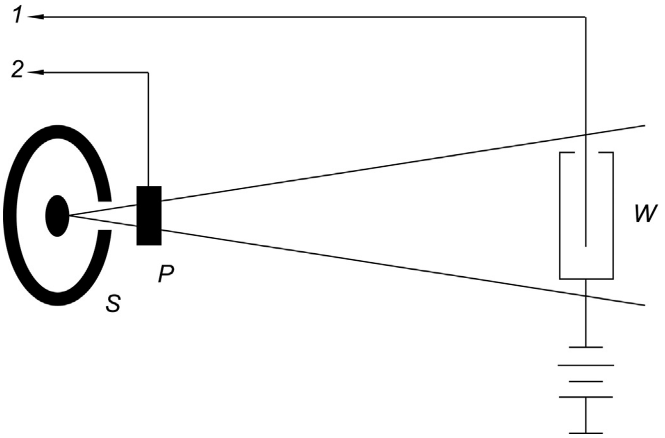

Fig. 13. The diagram of a current source is used for comparison: *W*—ionization chamber, *P*—shutter, *S*—gamma radiation source in lead sheath with collimator, *1*—system of measurement of low DC current and 2—system of control shutter.

in current and charge methods [14,15]. Implementation in performance measurement by the charges method is shown in Fig. 9.

In the current method (which is shown in Fig. 10) a given number of measurements, for example, the sixty measurements of voltage at intervals of one second is used to calculate the averaged value which is the result of the final value of current or electrical charges.

Measurement systems are consisted of auxiliary devices serving to determine the correction factor to correct ionizing current of chamber to reference values. It is described in the papers [1,2]. Resistance, *R*, and capacitance, *C*, vary with temperature, *T*. If the temperature, *T*, does not vary too much, a linear approximation is typically used:

$$R(T) = R_0[1 + \alpha(T - T_0)] \tag{5}$$

$$C(T) = C_0[1 + \alpha(T - T_0)] \tag{6}$$

where α is called the temperature coefficient of resistance or capacitance, T_0 is a fixed reference temperature, and R_0 is the resistance or C_0 is the capacitance at temperature T_0. For measurements of these quantities, digital thermometers, barometer and hygrometer are used. All measurements are controlled by dedicated programs installed on a PC. Their tasks are also data acquisition and calculations.

3.3. *A new method of the measurement of low direct currents*

A new method of the measurement of low currents and electrical charges is a combination of two methods of measurements: the null method and the charges method. A current and electrical charge measuring system has been built using the principle from Allisy [16] in a modernized version and provided with automatic features. In principle, the time required to accumulate a given electrical charge on a capacitor is measured. The simplified circuit diagram is given in Fig. 11.

The measurement system implemented for this method comprises the same elements used for the null method. The difference is in the elements of external feedback. The potentiometer, voltmeter and battery of accumulators were replaced by two switches, resistor in the range from 10 kΩ to 100 kΩ, and voltage source. The principle of the time measurement is identical in both of the methods and is described in Section 3. At the beginning of the measurement the switch, W1, is closed and switch, W2, is opened. Opening electrometer starts the measurement.The current, from the ionization chamber, makes the output voltage increase linearly with time. When the output voltage is equal to the voltage of comparator U_T (see Fig. 12) signal TTL is sent to timer. Switch, W2, is closed and switch, W1, is opened. The potential ε from the voltage source is applied to the electrode of standard capacitor, C. At this moment the voltage output, U_ε, is equal to ε-U_T and increases linearly with time. When the output voltage reaches the voltage of comparator, U_T, signal TTL is sent to timer. It ends measuring time, *t*. The total electrical charge stored at time *t* is then $\mathrm{C}\cdot\varepsilon$. Ionization current is described by the equation:

$$I = -C\frac{\varepsilon}{t} \tag{7}$$

Switch, W2, is closed and switch, W1, is opened. The electrometer is closed and the measurement is over. For automatic control of the measuring system W1 and W2 switches were replaced by relays. The voltage change at the output of the amplifier as a function of time during measuring the ionization current by the new method are shown in Fig. 12.

The advantage of the new method and the null method is to eliminate the phenomenon of dielectric absorption capacitor. This phenomenon consists in a capacitor that has been charged for a long time then briefly discharged, so discharge can be incomplete because of short time of discharge. Although, an ideal capacitor would remain at zero volts after being discharged, real capacitors will develop a small voltage coming from time-delayed dipole

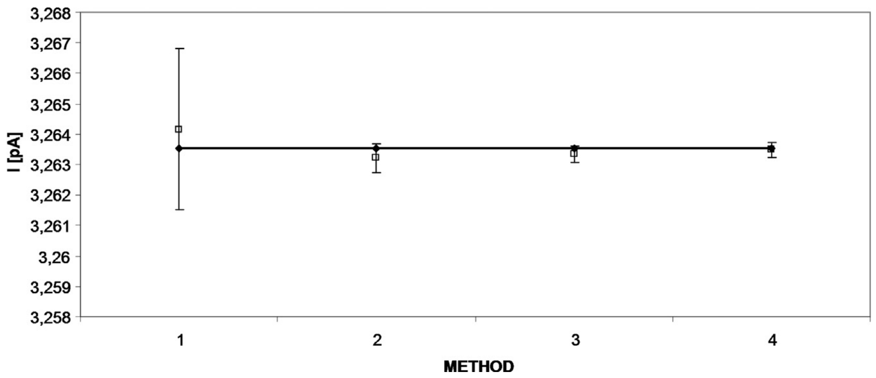

Fig. 14. The graphical presentation of result of comparison of the measuring methods: 1—the current method, 2—the charge method, 3—the null method and 4—null method with modification.

Table 1
The result of comparison of the measuring methods: I—mean value of current, σ_I—standard deviation, σ_I/I—relative standard uncertainty. In the measurements methods, the external comparator was used.

No.	Methods			
	Current method	Charge method	Null method	New method
	I (pA)			
1	3.26189	3.26382	3.26334	3.26312
2	3.26707	3.26260	3.26311	3.26355
3	3.26095	3.26330	3.26322	3.26362
4	3.26053	3.26324	3.26314	3.26345
5	3.26624	3.26324	3.26327	3.26373
6	3.26573	3.26260	3.26312	3.26312
7	3.26562	3.26371	3.26321	3.26364
8	3.26773	3.26264	3.26361	3.26371
9	3.26388	3.26384	3.26390	3.26376
10	3.26191	3.26315	3.26362	3.26322
$\langle I \rangle$	3.26416	3.26321	3.26335	3.26349
σ_I	0.00266	0.00048	0.00027	0.00025
σ_I/I (%)	0.082	0.015	0.008	0.008
I_{ref}/I (%)	0.002	−0.010	−0.006	−0.002

discharging, a phenomenon that is also called dielectric relaxation. This phenomenon contributes to the formation of non-linear accumulation of charge at the time of charging the capacitor. In both methods, the initial electrical charge is eliminated to neutralize this effect.

3.4. Comparison of methods and uncertainty budget

3.4.1. Comparison of methods

For the comparison of the methods, a measuring system for the calibration of dosimeters in the field of gamma radiation was used. The measuring system consisted of two main elements: direct current source and circuit of current measurement. The direct current source was system: gamma radiation source of nuclide ^{137}Cs and ionization chamber OMH model ND10005/A. This system is shown in Fig. 13.

The distance between gamma radiation source and the ionization chamber was equal to 1 m. In this distance value of air-kerma rate was about 1 μGy/s. The current reference value, I_{ref}=3.2635, was determined with the use of the null method. This value was compared with the mean value derived from measurements over 5 years. Standard uncertainty of the current reference value was 0.06%. The comparison between implementations in performance measurement was taken in 5 days – one method in one day. The current reference value is derived from the first day measurement. The measurements were made in 10 series with 15 measurements in each series. The time for single measurement was about 60 s. The results of this comparison are presented in Fig. 14 and Table 1.

In 3 years of measurements, for the new method, similar results were being repeated several times. The standard deviation was less than 0.02%. The results of the uncertainty budget for the measurements performed without the external comparator are described in Section 3.4.2.

3.4.2. Uncertainty budget

A very important thing is to ensure the reproducibility of the setting of the distance between gamma radiation source and ionization chamber. The setting of the distance is the main source of error in this case. Preliminary measurements by using the built-in comparator (without the external comparator) were performed. On the basis of the measurements, the uncertainty budget was calculated.

The current measured is expressed by the following equation:

$$I = \frac{C_0}{t} \cdot (1 + \alpha \cdot \Delta t) \cdot U \tag{8}$$

where C_0 is the capacitance at temperature T_0; t is the time of single measurement; ΔT stands for the temperature difference between fixed reference temperature and temperature during measurement; U is the bias voltage; α is called the temperature coefficient of capacitance.

Therefore, the equation for combined standard measurement uncertainty of the current, u_c (I) will have the following formula:

Table 2
Uncertainty budget.

Quantity	Value, x_i	u	c_i	u_c
U	10.000000 V	0.000015 V	2.71×10^{-12} V	0.41×10^{-16}
C_0	165.77×10^{-12} F	0.01×10^{-12} F	0.16399447	1.64×10^{-16}
α	$63.1 \times 10^{-6} \frac{1}{°C}$	$2.87 \times 10^{-6} \frac{1}{°C}$	1.08442×10^{-10}	3.11×10^{-16}
t	60.9930 s	0.0021 s	-4.45713×10^{-13}	-9.15×10^{-16}
I	27.185 pA		u_c(I)	0.002 pA

$$u_c(I) = ([c_1 \cdot u(U)]^2 + [c_2 \cdot u(C_0)]^2) + [c_3 \cdot u(\alpha)]^2 + [c_4 \cdot u(t)]^2 + [c_5 \cdot u(\Delta T)]^2)^{\frac{1}{2}} \tag{9}$$

where c_i (i from 1 to 5) are sensitivity coefficients, u (variables) standard measurement uncertainties for the corresponding variable: U, C_0, α, t, ΔT. The sensitivity coefficients were calculated as follows:

$$c_1 = \frac{\partial I}{\partial U} = \frac{C_0}{t}(1 + \alpha \cdot \Delta T) \tag{10}$$

$$c_2 = \frac{\partial I}{\partial C_0} = \frac{U}{t}(1 + \alpha \cdot \Delta T) \tag{11}$$

$$c_3 = \frac{\partial I}{\partial \alpha} = \frac{C_0}{t} \cdot U \cdot \Delta T \tag{12}$$

$$c_4 = \frac{\partial I}{\partial t} = \frac{C_0}{t^2} \cdot U \cdot (1 + \alpha \cdot \Delta T) \tag{13}$$

$$c_5 = \frac{\partial I}{\partial \Delta T} = \frac{C_0}{t} \cdot \alpha \cdot U \tag{14}$$

The results for the uncertainty budget of measurements are presented in Table 2.

For coverage factor $k = 2$ and 95% confidence interval expanded measurement uncertainty, u was equal to 0.004 pA. The relative standard uncertainty for current ca. 27.2 pA was 0.007%.

4. Conclusions

The comparison result and a lot of the results of measurements showed excellent metrological properties for the null method and the new developed method (Fig. 14). These results also show that the null method hardly used today is still the best way to measure low direct currents and electrical charges. This null method eliminates the leakage current and the capacitor dielectric absorption phenomenon. The new method eliminates only the capacitor dielectric absorption phenomenon. However, comparison of the results leads to the conclusion that the phenomenon of dielectric absorption capacitor has a much greater impact on the result of measurement than the leakage current. The advantage of measuring using the new method is certainly the possibility of full automated control of the measurement process as in the current method and the charge method.

New method allows to achieve relative standard uncertainty of 0.003% for current around 3 pA and long term stability around 0.01%. The results of these research are used at the Central Office of Measures in the Laboratory of Ionizing Radiation and Colour Standards. Based on these studies new measurement systems are being built at the Central Office of Measures for example: measuring system for the primary standards of absorbed dose to water and air kerma.

Additionally, preliminary measurements by using built-in comparator (without external comparator) were also performed. On the basis of the measurement, the relative standard uncertainty of 0.007% for current ca. 27.2 pA has been achieved. These results are satisfactory and investigations in this direction will be preformed in the future.

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