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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 multi-purpose 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.

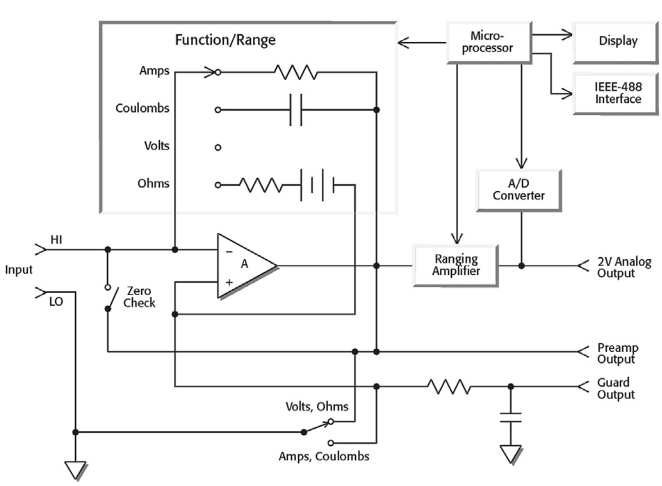

Fig. 1. The typical scheme of a digital electrometer (illustrated on the basis of Kethley Instruments Inc., 2004).

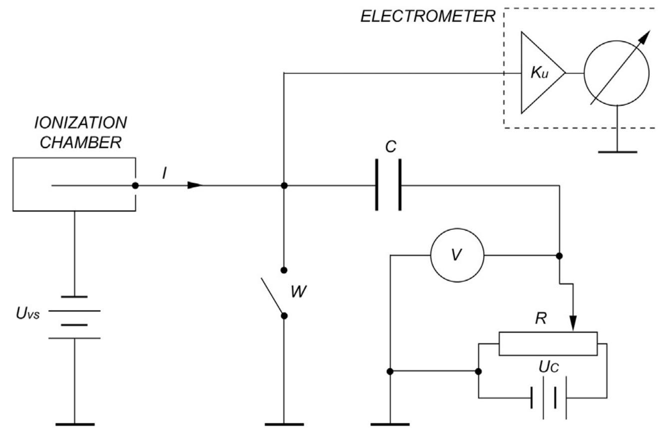

Fig. 2. The Townsend balance circuit (the null method).

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].

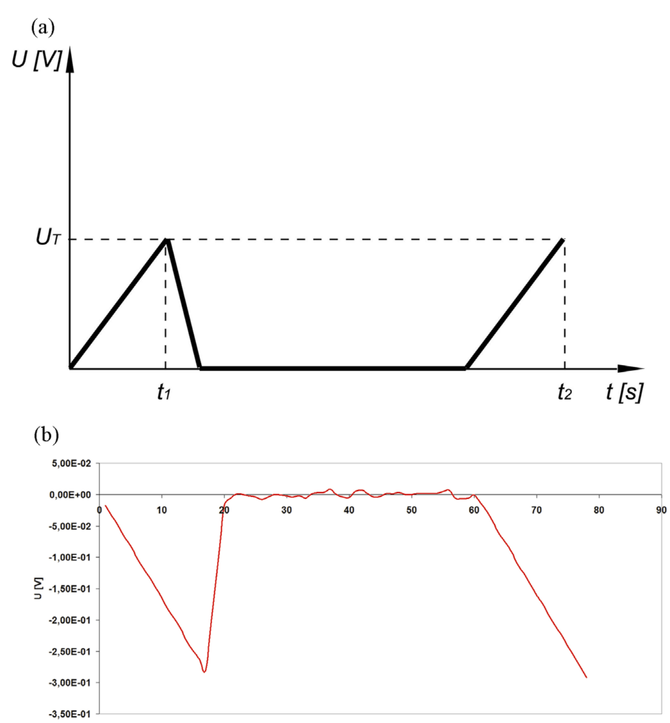

Fig. 3. Graph of the change in voltage at the output of the amplifier as a function of time during measuring the ionization current in the null method: (a) theoretical curve and (b) experimental curve.