Design and preliminary test of a free-air ionization chamber for low-energy X-ray

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Abstract: A free-air ionization chamber in low-energy X-ray has been designed and manufactured at the National Institute of Metrology (NIM, China) according to the defination of air-kerma. The results of a preliminary test show that the leakage current of ionization chamber is around 2×10^{-15} A, and the correction factor of ion recombination for the ionization chamber is also obtained. The free-air ionization chamber is suitable for the primary standard in low-energy X-rays.

Key words: free-air chamber, air-kerma, low-energy X-ray

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1 Introduction

Free-air ionization chambers (FACs) are widely used as the primary standard for the realization of air kerma in the low- and medium-energy X-ray ranges. Basically, most FACs are of the plane-parallel type. The free-air chamber for medium-energy X-rays between 60 kV to 250 kV was established at the NIM in the 1980s, and the comparison between the Bureau International des Poids et Mesures (BIPM) and the NIM in medium-energy X-rays was made in 2001 [1]. But the FAC for (60–250) kV X-rays is so large that it is not suitable for realizing the air kerma of (10–50) kV X-rays. The BIPM, National Institute of Standards and Technology (NIST, USA), Physikalisch-Technische Bundesanstalt (PTB, Germany), the National Physical Laboratory (NPL, UK) and other standard ionizing radiation laboratories all established a free-air ionization chamber for (10–50) kV X-rays. (10–50) kV X-ray is widely applied in medical diagnosis, radiotherapy and radiation protection, especially in mammography. To establish the air kerma traceability system of low-energy X-rays and participate the key comparison in low-energy X-rays (BIPM.RI(I)-k2), the FAC for (10–50) kV X-rays was designed and established in 2009 at the NIM. This paper describes the characteristics of FAC and irradiation facilities. In addition, the results of the leakage current test and the correction factor of ion recombination for FAC are also reported.

2 Methods

2.1 Irradiation facilities

The X-ray irradiation facilities include an X-ray source, an X-ray tube position adjustment, a diaphragm, a filtration unit and a shutter. Fig. 1 shows a schematic diagram of the setup.

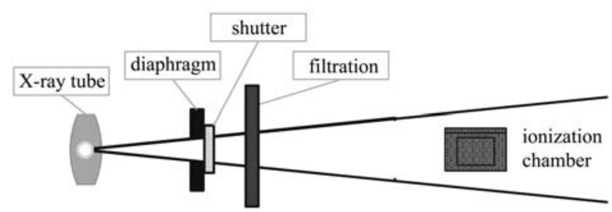

Fig. 1. Schematic diagram of X-ray irradiation facilities.

The low-energy X-ray source was an YXLON MG165 X-ray generator with a metal-ceramic tube Comet MXR-160/22. The main characteristics of the X-ray tube are listed in Table 1. The X-ray tube has a window of 0.8 mm beryllium and a tungsten anode

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at a target angle of 40°. This tube provides two focal spots (1.0 mm × 1.0 mm or 5.5 mm × 5.5 mm). The focal spot-to-FAC distance is 500 mm. At this distance, the diameter of the X-ray beam field is about 50 mm.

Table 1. Characteristics of the X-ray tube.

max. tube voltage	160 kV
focal spot size	1.0 mm/5.5 mm
max. power	0.64 kW/3.0 kW
max. tube current at 160 kV	4.0 mA/19.0 mA
emergent beam angle	40°
inherent filtration	0.8 mm Be
coolant	water

The generator made by YXLON can generate voltages up to 160 kV as well as supplying the filament current for the X-ray tube. The main characteristics are listed in Table 2.

Table 2. Characteristics of the generator.

max. power	2250 W
high voltage adjustment range	7.5–160 kV
high voltage adjustment increments	0.1 kV/ step
tube current adjustment range	0–22.5 mA
tube current adjustment increments	0.05 mA

2.2 Free air ionization chamber

A schematic diagram of the NIM low-energy chamber is shown in Fig. 2. This is a parallel-plate ionization chamber. The plate system is contained in a radiation-shielded box. The measuring volume is determined by the diaphragm, and the length of the collecting region by the length of the collector and by the electric field between the high-voltage and collecting plates.

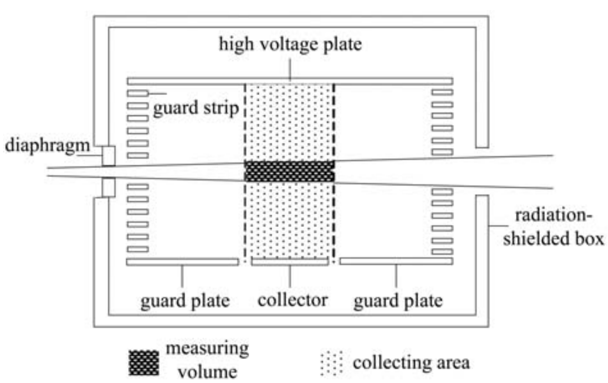

Fig. 2. A schematic diagram of the NIM low-energy X-ray FAC.

The grounded lead box tends to distort the electric field in the collecting region. A system of guard strips is designed to eliminate the electric field distortion. Twelve guard strips are uniformly spaced between the collecting and high voltage plates. The potentials of the strips are fixed by resistors to give a linear potential gradient between the plates. The important dimensions and the measuring volume of this chamber are shown in Table 3.

Table 3. The main dimensions of the free-air chamber.

characteristics	dimensions
aperture diameter/mm	8.0
air path length/mm	100.0
collecting length/mm	40.5
electrode separation/mm	79.2
collector width/mm	100.0
guard plate length/mm	59.5
measuring volume/mm^3	2034.4

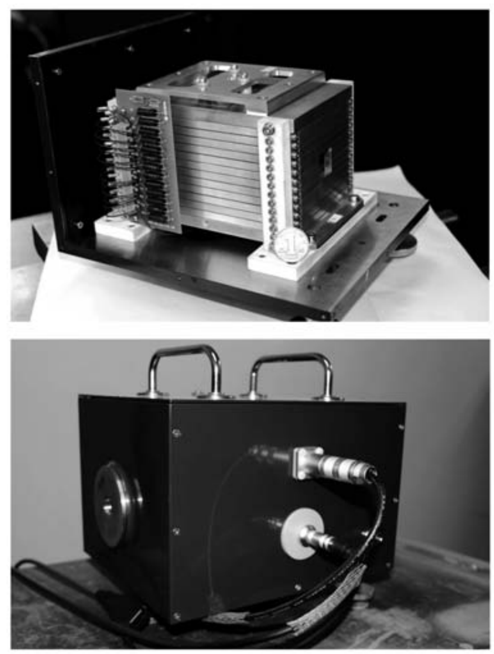

Fig. 3. A picture of the free air chamber for low-energy X-rays.

3 Results

3.1 Leakage current

The leakage current from the free-air chamber was measured by the Townsend method, which consists of charging a capacitor with the ionization current, and measuring the time Δt necessary to accumulate a given charge $C\Delta V$. Fig. 4 shows the changes in leakage current of the free-air chamber under 1500 V. After one hour, the leakage current becomes nearly stable. It is about 2×10^{-15} A.

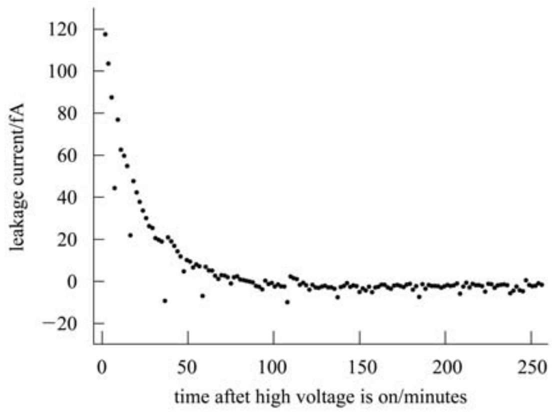

Fig. 4. Leakage current versus time.

3.2 High voltage characteristics

The current versus applied high voltage characteristics of the free-air chamber are illustrated in Fig. 5. This curve is divided into two regions: a low voltage region between 0 and 400 volts and a saturated current region above 400 V. In the low voltage region, the current increases almost linearly with the applied voltage. The saturated current region is the operating region of this free-air chamber. If the polarizing voltage is set at 1500 V, the electric field intensity is around 190 V·cm^{-1}.

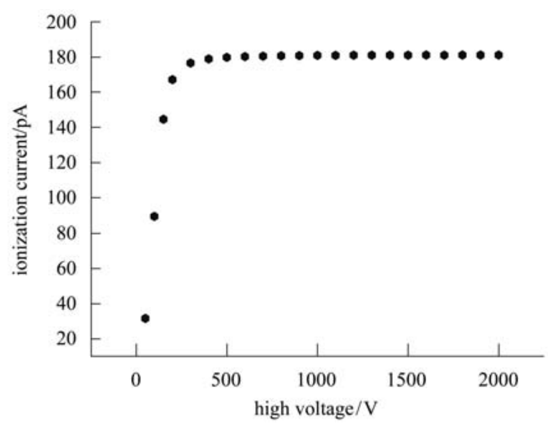

Fig. 5. Current versus high voltage.

3.3 Correction factor of ion recombination

All of the ionization produced in the measuring volume is not collected completely due to the ion recombination and diffusion. Hence, it is necessary to get the correction factor for ion recombination k_s. The saturation correction was determined using the method proposed by De Almeida and Niatel [2], as implemented by Boutillon and Burns [3, 4]. This methold involves ionization current measurement at two polarizing voltages set at the FAC, V and V/n, where V is the normal polarizing potential and n is typically between 2 and 4. Here, n=3 is chosen. The current I_V and $I_{V/n}$ are measured without correction for temperature and pressure of air for different air-kerma rates. A plot of the current ratio of I_V and $I_{V/n}$ against I_V should be linear.

Figure 6 shows the measured current ratios $I_{1500\mathrm{V}}/I_{500\mathrm{V}}$ plotted as a function of the current $I_{1500\mathrm{V}}$ measured at the polarizing potential 1500 V. For a linear fit with intercept $(1{+}a_0)$ and gradient a_1, the total recombination correction k_s is evaluated as

$$k_{\mathrm{s}}=1+k_{\mathrm{int}}+k_{\mathrm{vol}}I_V, \tag{1}$$

where

$$k_{\mathrm{init}}=\frac{a_0}{n-1},\ k_{\mathrm{vol}}=\frac{a_1}{n^2-1},$$

and I_V is the ionization current when the high voltage is 1500 V.

The correction factor is given by

$$k_{\mathrm{s}}=1+6.1\times10^{-4}+4.51\times10^{-6}\times I_V. \tag{2}$$

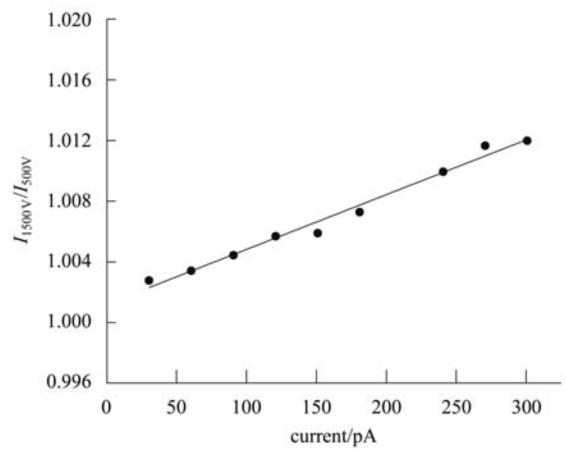

Fig. 6. Ratio of the ionization currents $I_{1500\mathrm{V}}$ and $I_{500\mathrm{V}}$ as a function of $I_{1500\mathrm{V}}$.

4 Conclusion

The NIM has established reference low-energy X-ray radiation facilities and designed and manufactured a free-air ionization chamber for air-kerma in the continuous X-ray radiation of low-energy. The preliminary test results show that the leakage current of the free-air chamber is around 2×10^{-15} A. The ionization current is around 3.5×10^{-11} A when the air kerma rate measured is set to 0.5 mGy/s. The leakage current was less than 0.006% of the ionization current. For the BIPM, NIST, NPL and PTB standards, the leakage current did not exceed 0.05% [5–7]. So the leakage current of our FAC is satisfied and would not affect the air-kerma measurement.

According to the test result of high voltage characteristics, the polarizing voltage is set at 1500 V, the FAC can get a saturated current and the effect of high voltage ripple can be neglected. According to the method implemented by Boutillon and Burns, the formula for the correction factor of ion recombination is also obtained. It would be used to correct the air kerma, and the relative standard uncertainty of 0.02% is evaluated for this correction. The preliminary test results show that the FAC designed is suitable for the primary standard in low-energy X-rays.

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