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Multi-concentric-ring open-air ionization chamber for high-intensity X-ray beams

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A B S T R A C T

An ionization chamber with four concentric ring electrodes was used to measure doses of white, 10, 15 and 20 keV synchrotron X-ray beams. The ring-shaped electrodes, which had diameters less than 11.8 mm, collected charges independently only around the beam, excluding strong in-beam charges when the beams passed through a small hole in the electrode centers. As a result, under low saturation voltages, the measured dose rates were confirmed to correlate with the beam intensity when conversion factors calculated with a Monte Carlo code were employed. The influence of the assumed beam sizes and incident positions on the current was almost negligible, with the exception of the incident position dependence at 10 keV.

1. Introduction

Ionization chambers are widely employed as intensity monitors for X-rays. The intensity of radiation generated by synchrotron radiation and X-ray free-electron laser facilities is continuously increasing [1] and has reached a level where ion recombination is no longer avoidable when conventional ionization chambers receive a beam directly. Ionization chambers, however, provide an unparalleled advantage in that they enable absolute measurements without disturbing the beam, which is desirable for monitoring the beam intensity.

When an X-ray beam travels through air, the emitted electrons induce ionization even around the beam at the photon interaction. The degree of ionization is considerably smaller in this case than that in the beam but increases with increasing beam intensity; as a result, the degree of ionization can reach a measurable level even in an ionization chamber. Because of the lower ionizing density, current saturation is expected to occur at a lower voltage.

The method of measuring the charge only around the beam is intended for electrons alone; therefore, a cavity ionization chamber such as a thimble-type chamber cannot be used for the measurements because electrons are blocked by the chamber wall surrounding the cavity gas. Only free-air and open-air ionization chambers can be used for the measurements. In the present study, a distinctive ionization chamber is designed using four concentric ring electrodes positioned vertically to the beam. The electrodes have a hole in their center through which the beam passes, preserving the non-destructive nature of the beam. The four electrodes with different radii measure the radial dose distribution within each defined collection volume. The relative distribution reflects the beam energies. As expected, however, the readings can be influenced by the beam size and the injection position, depending on the electrode size and X-ray energy.

This study aims to confirm that beam intensity can be derived from the current of the ring electrodes. Therefore, radial dose distribution was measured with the multi-concentric-ring ionization chamber around white and monochromatic synchrotron X-ray beams from an 8 GeV storage ring. The results are compared with those calculated using a Monte Carlo code based on the monitored beam intensity. Furthermore, the influence of beam size and injection position is examined.

2. Materials and methods

The experiments were conducted at the BL09XU and 28B2 beamlines of SPring-8 in Japan. The storage ring was operated in top-up mode, so that the current was stable at 95 mA. At BL09XU, monochromatic X-rays of 10, 15 and 20 keV were provided through monochromators from the undulator source. The beam was a square with each side measuring 0.5 mm, the experimental slit size was 0.1 mm $\times$ 0.1 mm, and the intensity was of the order of 10^{11}–10^{12} photons/s. Because the intensity varied according to the monochromator condition within a range from time to time, the magnitude was monitored with a 4.2-mm-gap free-air ionization chamber for reference [2]. The photon attenuation in the 14-cm-long air path between the reference and open-air chambers was considered at the monitoring. At BL28B2, white X-rays from the bending magnet were used after being filtered through 3-mm-thick copper set in the hutch; the effective energy was 90 keV, and

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the air kerma rate was 150 Gy/s [3]. The beam was also collimated into a square having sides of 0.5 mm with a variable gap slit in the hutch.

The cross section and front of the collecting electrodes of the open-air ionization chamber are shown in Figs. 1 and 2. Starting from the inner electrode, the electrodes were labeled as ch1–ch4. To determine the radius of each electrode in the design, Monte Carlo calculations were executed in advance using the PENCYL program in the PENELOPE2011 code [4] under assumed X-ray energies of 10–20 keV. From the results of the energy deposition in air, the inner and outer radii were determined as shown in Table 1. Because the electron ranges in air are 2.39, 4.88 and 8.12 mm at 10, 15 and 20 keV, respectively, the electrons lose all their energy at least in ch1, ch2 and ch3. In the gap between each collecting ring, the collection volume was considered to be equally shared by the neighboring rings. The sizes of these assumed collection regions are also indicated in the table. The current at each electrode was collected independently for 60 s with electrometers, and the average was converted into the absorbed dose rates multiplied by the W value in air and divided by the air mass of collecting regions corrected for by the atmospheric pressure and temperature. The conversion factors were 1.0×10^8, 5.7×10^7, 4.7×10^7 and 3.7×10^7 Gy/s/A for ch1, ch2, ch3 and ch4, respectively.

Next to the collecting rings, guard rings were positioned at the inner and outer sides. The hole in the center of the inner guard ring was 1.2 mm in diameter. The 5-mm-thick stainless-steel collecting electrodes and high-voltage electrode face each other at an interval of 5 mm as shown in Fig. 1. The maximum applicable voltage was 2.5 kV. The high-voltage electrode also has a 1.2-mm-diameter hole for the beam path behind a 1.6-mm-diameter opening at the diaphragm. For the alignment of the beam injection, GafChromic films were set at the diaphragm to check the beam positions. The stainless-steel case was 10 mm thick except for the left and right sides which were 5 mm thick.

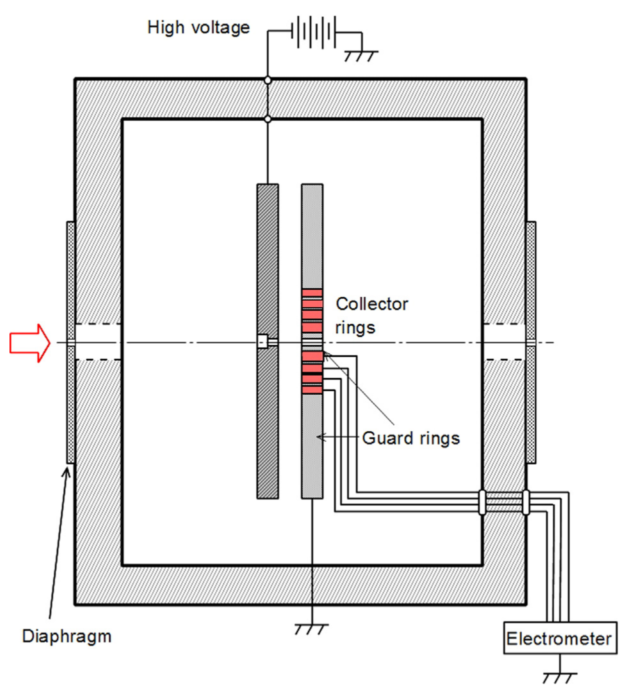

Fig. 1. Interior of the ionization chamber. The circular parallel-plate electrodes are supported in air. The beam was incident from the left. The upstream electrode was a high voltage electrode, and the downstream electrodes were the collecting electrodes. No solid materials exist in the beam path.

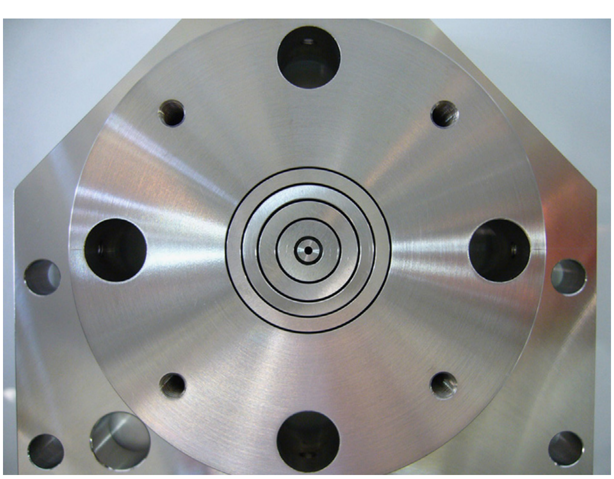

Fig. 2. Four collector rings and two guard rings. The inner radii of collector rings were 2.1, 4.8, 7.5 and 9.8 mm.

3. Results and discussions

3.1. Saturation voltages

Fig. 3 shows the current saturation curves of each channel for white X-rays. The saturation voltages were 200, 150, 60 and 60 V; these potentials decreased with increasing distance from the beam and decreasing saturation current. When an ionization chamber with an 85-mm gap was used, a voltage of 10 kV was necessary [3]. In this context, a voltage of 600 V would be required for a 5-mm-gap free-air ionization chamber; hence, when the ring collectors were used, the saturation voltages decreased to less than one-third of their original values.

Table 1
Radii of collecting rings and regions corrected for the gap between the rings.

		ch1	ch2	ch3	ch4
Ring radius (mm)	Inner	2.1	4.8	7.5	9.8
	Outer	4.5	7.2	9.5	11.8
Collecting region (mm)	Inner	1.85	4.65	7.35	9.65
	Outer	4.65	7.35	9.65	11.95

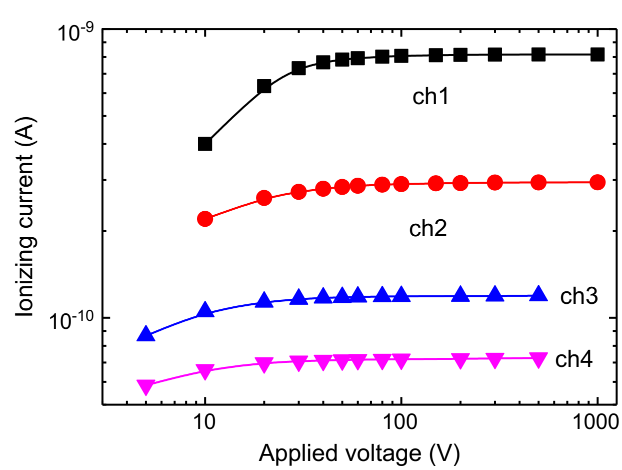

Fig. 3. Saturation curves obtained at each electrode for white X-rays. The saturation voltages were 200, 150, 60 and 60 V for ch1, ch2, ch3 and ch4, respectively.