

## **X-ray Spectra from a Characteristic X-ray Generator with a Molybdenum Tube**

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### **Abstract**

This generator consists of the following components: a constant high-voltage power supply, a filament power supply, a turbomolecular pump, and an x-ray tube. The x-ray tube is a demountable diode which is connected to the turbomolecular pump and consists of the following major devices: a molybdenum rod target, a tungsten hairpin cathode (filament), a focusing electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, and a stainless-steel tube body. In the x-ray tube, the positive high voltage is applied to the anode (target) electrode, and the cathode is connected to the tube body (ground potential). In this experiment, the tube voltage applied was from 22 to 36 kV, and the tube current was regulated to within 100  $\mu$ A by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. The electron beams from the cathode are converged to the target by the focusing electrode, and x-rays are produced through the focusing electrode. Using a lithium fluoride curved crystal, clean K-series characteristic x-rays were observed without using a filter. However, bremsstrahlung x-rays were observed using a cadmium telluride detector.

**Keywords:** demountable x-ray tube, quasi-monochromatic x-rays, K-series characteristic x-rays, Sommerfeld's theory, curved crystal, cadmium telluride detector

### **1. Introduction**

Most flash x-ray generators employ high-voltage condensers and cold-cathode x-ray tubes,<sup>1-5</sup> and the plasma x-ray source has been growing with increases in the electrostatic energy in the condenser. By

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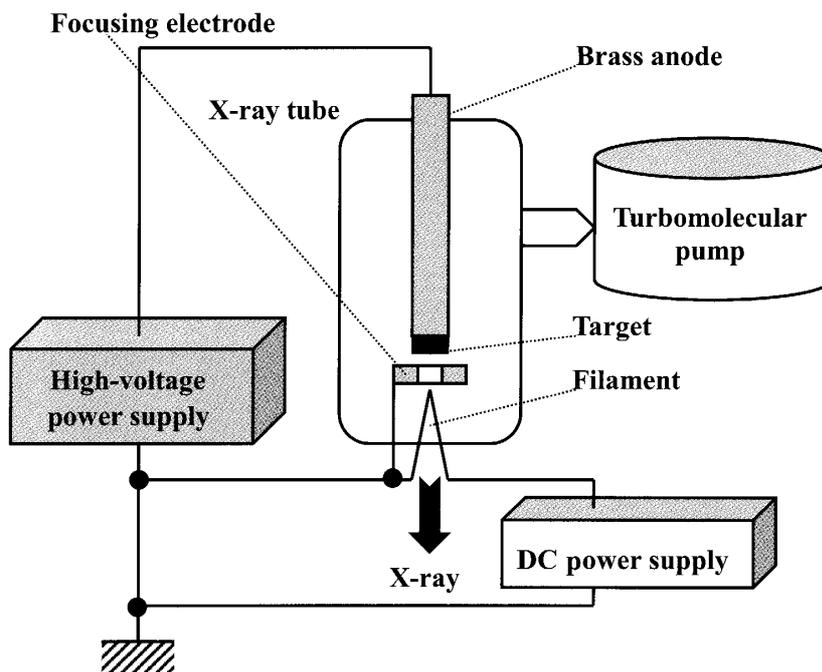


Fig. 1: Block diagram including the main transmission line of the compact x-ray generator with a quasi-monochromatic diode.

forming weakly ionized linear plasma<sup>6-9</sup> using a rod-target triode, we confirmed irradiation of clean K-series characteristic x-rays such as hard x-ray lasers and their higher harmonic hard x-rays from the plasma axial direction. Because the plasma transmits high-photon-energy bremsstrahlung x-rays, it is difficult to produce high-photon-energy characteristic x-rays. In view of this situation, we have developed a super-fluorescent x-ray generator<sup>10-13</sup> by forming weakly ionized plasma at the target tip and have succeeded in producing comparatively clean K-series characteristic x-rays of molybdenum, cerium, tantalum, and tungsten. In particular, the cerium target is useful for performing iodine K-edge angiography, and gadolinium K-edge angiography can be performed using tantalum and tungsten targets.

Steady-state K-series characteristic x-rays left by filters have been employed to perform mammography using a molybdenum target and to perform K-edge angiography<sup>14-17</sup> using a cerium target. In addition, the rays are also useful for performing real-time radiography achieved with a flat panel detector. Because the characteristic x-ray intensity decreases with increases in the filter thickness, the development of a characteristic x-ray generator utilizing the angle dependence of bremsstrahlung x-rays has been wished for.

In the spectrum measurements, we employ a cadmium telluride detector and a lithium fluoride curved crystal. The detector is useful to measure the total spectra including scattering beams. On the other hand, the spectra from only the x-ray source can be measured using the crystal by selecting Bragg's angle.

In this paper, we describe an x-ray generator developed and used to perform a preliminary experiment for generating clean K-series characteristic x-rays by angle dependence of the bremsstrahlung x-rays and measurement of the x-ray spectra using two methods.

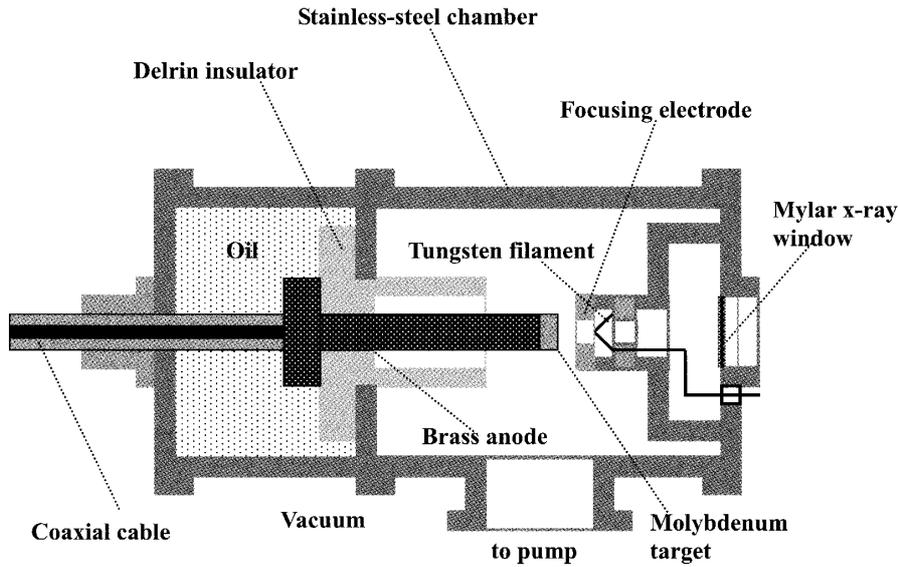


Fig. 2: Schematic drawing of the quasi-monochromatic x-ray tube.

## 2. Generator

Figure 1 shows a block diagram of a compact characteristic (quasi-monochromatic) x-ray generator. This generator consists of the following components: a constant high-voltage power supply (SL150, Spellman Inc.), a DC filament power supply, a turbomolecular pump, and an x-ray tube. The structure of the x-ray tube is illustrated in Fig. 2. The x-ray tube is a demountable diode which is connected to the turbomolecular pump with a pressure of approximately 0.5 mPa and consists of the following major devices: a molybdenum plate target, a tungsten hairpin cathode (filament), a focusing electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, and a stainless-steel tube body. In the x-ray tube, the positive high voltage is applied to the anode (target) electrode, and the cathode is connected to the tube body (ground potential). In this experiment, the tube voltage applied was from 22 to 36 kV, and the tube current was regulated to within  $100 \mu\text{A}$  by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. The electron beams from the cathode are converged to the target by the focusing electrode, and x-rays are produced through the focusing electrode. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory, clean molybdenum K-series x-rays can be produced without using a filter.

## 3. Characteristics

### 3.1 X-ray intensity

X-ray intensity was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source (Fig. 3). At a constant tube current of  $100 \mu\text{A}$ , the x-ray intensity increased when the tube voltage was

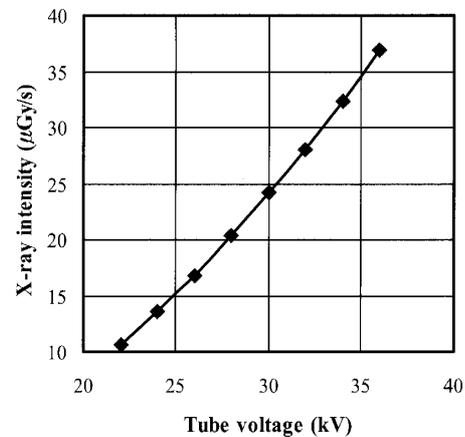


Fig. 3: X-ray intensity at 1.0 m from the x-ray source according to changes in the tube voltage.

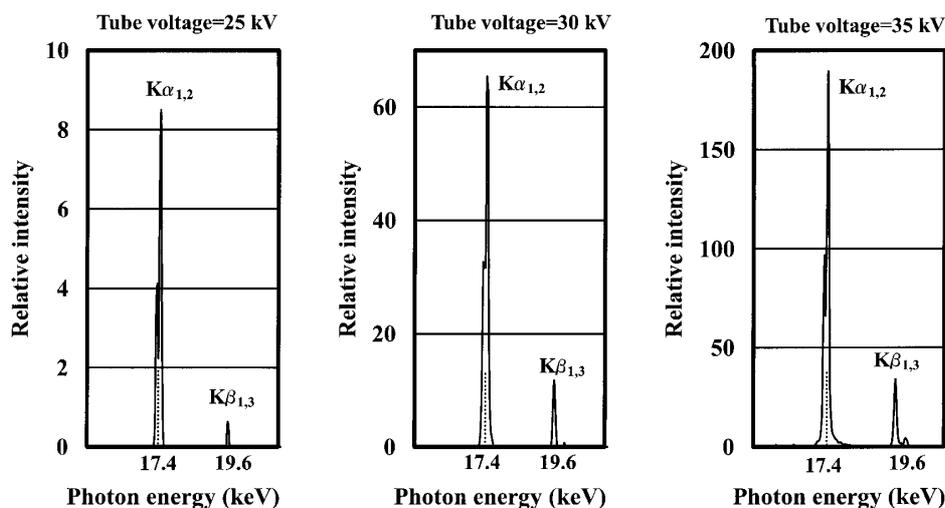


Fig. 4: X-ray spectra from the molybdenum target measured using a transmission type spectrometer with a lithium fluoride curved crystal.

increased. In this measurement, the intensity with a tube voltage of 30 kV and a current of  $100 \mu\text{A}$  was  $24.2 \mu\text{Gy/s}$  at 1.0 m from the source.

### 3.2 X-ray spectra

First, x-ray spectra were measured using a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The x-ray intensities of the spectra were detected by an imaging plate of the CR system<sup>18</sup> (Konica Minolta Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom original digital data corresponding to x-ray intensity. Figure 4 shows measured spectra from the molybdenum target. We observed clean K lines, while bremsstrahlung

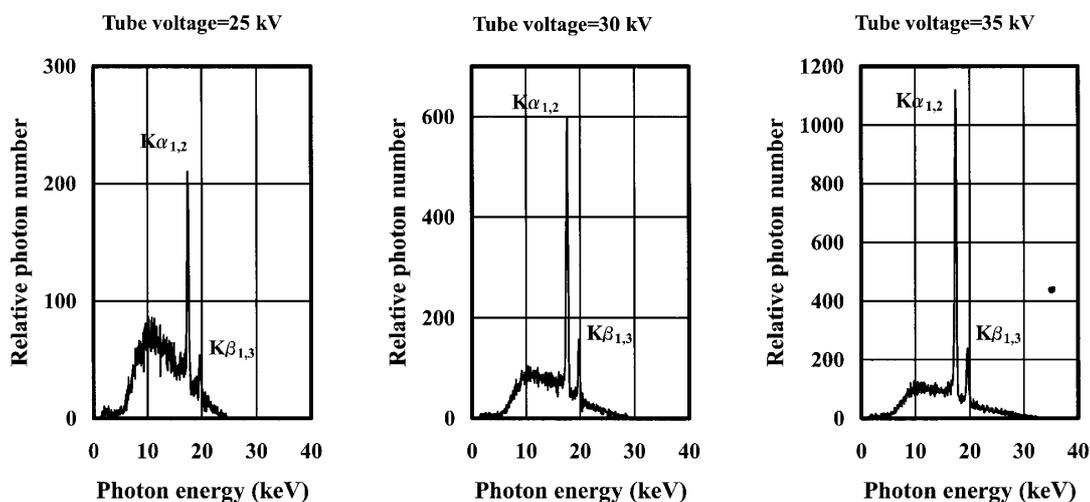


Fig. 5: X-ray spectra from the molybdenum target measured using a cadmium telluride detector.

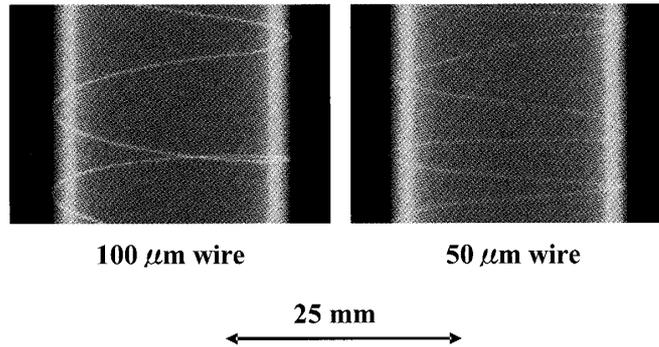


Fig. 6: Radiograms of tungsten wires of 50 and 100  $\mu\text{m}$  in diameter coiled around pipes made of polymethyl methacrylate. A 50- $\mu\text{m}$ -diameter wire could be observed.

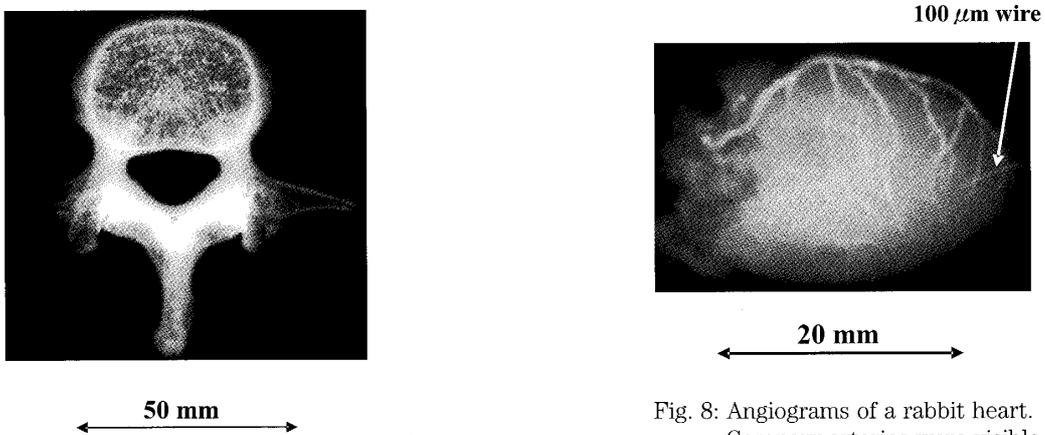


Fig. 7: Radiogram of a vertebra. Fine structure of the vertebra were visible.

Fig. 8: Angiograms of a rabbit heart. Coronary arteries were visible.

rays were hardly detected. The characteristic x-ray intensity substantially increased with increases in the tube voltage.

The measured spectra using a cadmium telluride detector are shown in Fig. 5. Using the detector, we observed low intensity continuous x-rays. When the tube voltage was increased, both the characteristic x-ray intensity and the maximum photon energy increased.

#### 4. Radiography

The monochromatic radiography was performed by the CR system at 1.0 m from the x-ray source with the filter, and the tube voltage was 30 kV.

First, rough measurements of image resolution were made using wires. Figure 6 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate (PMMA). Although the image contrast increased with increases in the wire diameter, a 50- $\mu\text{m}$ -diameter wire could be observed.

A radiogram of a vertebra is shown in Fig. 7, and the fine structure of the vertebra was observed. Next, angiography was performed using iodine microspheres of 15  $\mu\text{m}$  in diameter. Figure 8 shows an angiogram of a rabbit heart, and we obtained high contrast images of coronary arteries and fine blood vessels.

## 5. Conclusions and Outlook

In summary, we developed a new characteristic x-ray generator with a molybdenum-target tube and measured clean molybdenum K lines using the crystal spectrometer. However, continuous x-rays were detected using the detector. In both measurements, the characteristic x-ray intensity increased with increases in the tube voltage, and monochromatic  $K\alpha$  lines were left by a zirconium filter. Because we could measure bremsstrahlung x-rays<sup>19</sup> from a transmission-type molybdenum target using the crystal, the bremsstrahlung intensity was low as compared with that obtained using conventional molybdenum tubes.

In this preliminary experiment, although the maximum tube voltage and current were 36kV and 100 $\mu$ A, the voltage and current could be increased to 100kV and 1.0mA, respectively. Under the pulsed operation, the current can be increased to approximately 1A without considering the target evaporation. Subsequently, the generator produced maximum number of characteristic photons was approximately  $1 \times 10^8$  photons/(cm<sup>2</sup>·s) at 1.0m from the source, and the photon count rate can be increased easily by increasing the current.

Using this x-ray generator, because it is not easy to produce high-photon-energy K-series characteristic x-rays, we are very interested in increasing the energy by changing the electrode configuration between the target, cathode, and focusing electrodes.

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