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Quasi-monochromatic x-ray irradiation from weakly ionized linear nickel plasma

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Abstract

In the plasma flash x-ray generator, a high-voltage main condenser of approximately 200 nF is charged up to 50 kV by a power supply, and electric charges in the condenser are discharged to an x-ray tube after triggering the cathode electrode. Flash x rays are then produced. The x-ray tube is a demountable triode connected to a turbo molecular pump with a pressure of approximately 1 mPa. As electrons from the cathode electrode are roughly focused onto a rod nickel target of 3.0 mm in diameter by the electric field in the x-ray tube, a weakly ionized linear plasma consisting of nickel ions and electrons forms by target evaporation. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 17 kA. When the charging voltage was increased, the linear plasma formed, and the intensities of K-series characteristic x rays increased. The K-series lines were quite sharp and intense, and hardly any bremsstrahlung rays were detected. The x-ray pulse widths were approximately 700 ns, and the time-integrated x-ray intensity had a value of approximately 30 μC/kg at 1.0 m from the x-ray source at a charging voltage of 50 kV.

Keywords: flash x-ray, weakly ionized linear plasma, K-series characteristic x rays, quasi-monochromatic x rays

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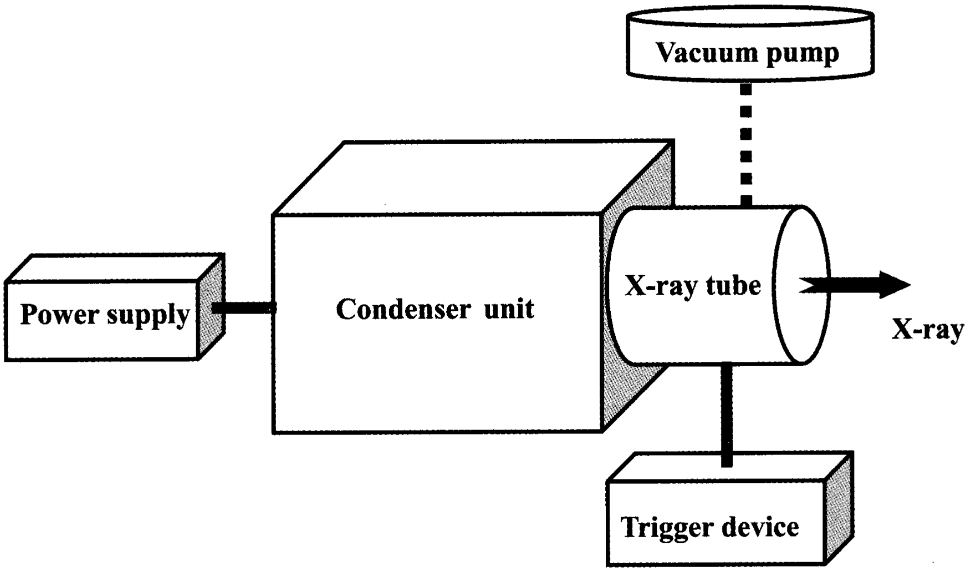


Fig. 1: Block diagram of the high-intensity plasma flash x-ray generator.

1. Introduction

Recently, flash x-ray generators with gas-discharge capillaries have been developed in order to produce soft x-ray laser[1-4] in extremely ultraviolet (XUV) region, and laser energy substantially increased with increases in the capillary length. To be a useful technique for soft biomedical radiography, the photon energy should be increased as much as possible. These kinds of fast discharges can generate hot and dense plasma columns with aspect ratios approaching 1000:1. However, it is difficult to increase the laser photon energy to 10 keV or beyond.

In biomedical radiography, several different flash x-ray generators have been developed corresponding to specific radiographic objectives,[5-7] and high-intensity single generators[8-11] with large capacity condensers were originally developed. Subsequently, repetitive generators[12-16] have been developed, and the repetition rate has been increased to sub-kilohertz using a cold-cathode triode. In addition, the maximum repetition rates were approximately 50 kHz when stroboscopic x-ray generators with hot-cathode tubes is employed.

By forming weakly ionized linear plasma[17-22] using plate and rod targets, we confirmed irradiation of intense K-series characteristic x rays from the plasma axial direction. In these experiments, because we employed a transmission-type x-ray spectrometer utilizing an x-ray film, the relative intensities of the characteristic x rays should be calculated using a digital radiography system.

In this paper, we describe a plasma flash x-ray generator utilizing a rod-target radiation tube, used to perform a preliminary experiment for generating intense and sharp quasi-monochromatic x rays by forming a linear nickel plasma cloud around a fine target.

2. Generator

2.1. High-voltage circuit

Figure 1 shows a block diagram of the high-intensity plasma flash x-ray generator. This generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser

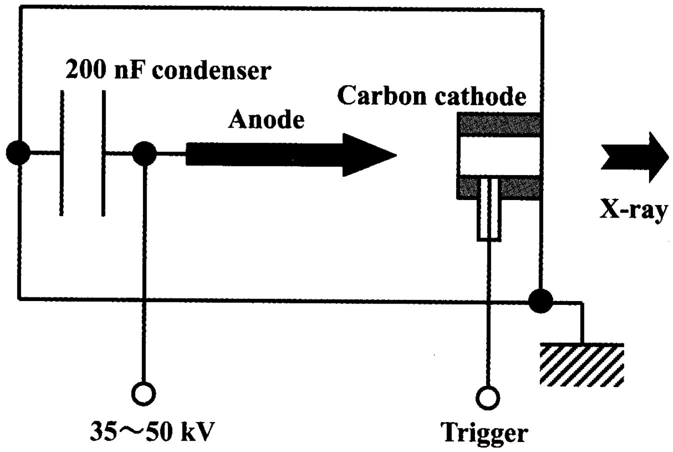


Fig. 2: Circuit diagram of the plasma x-ray generator.

with a capacity of approximately 200 nF, a turbo-molecular vacuum pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. In this generator, a low-impedance transmission line is employed in order to increase maximum tube current. The high-voltage main condenser is charged to 50 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode (Fig. 2). The plasma flash x rays are then produced.

2.2. X-ray tube

The x-ray tube is a demountable cold cathode triode connected to a turbo-molecular pump. The pressure in the tube is approximately 1 mPa (Fig. 3). The tube consists of the following major parts: a hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a trigger electrode made from copper wire, a stainless steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped nickel target 3.0 mm in diameter with a tip angle of 60°. The distance between the target and cathode electrodes is approximately 20 mm, and the trigger electrode is set in the cathode electrode. The electron beam from the cathode electrode is roughly focused onto the target by the electric field in the tube, and evaporation leads to the formation of a weakly ionized linear plasma of nickel ions and electrons around the fine target.

2.3. Principle of characteristic x-ray irradiation

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x rays (Fig. 4). The plasma then transmits the fluorescent rays easily, and bremsstrahlung rays with energies lower than the K-edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the direction opposite that of electron acceleration (Fig. 5), intense characteristic x rays are generated along axial direction of the plasma.

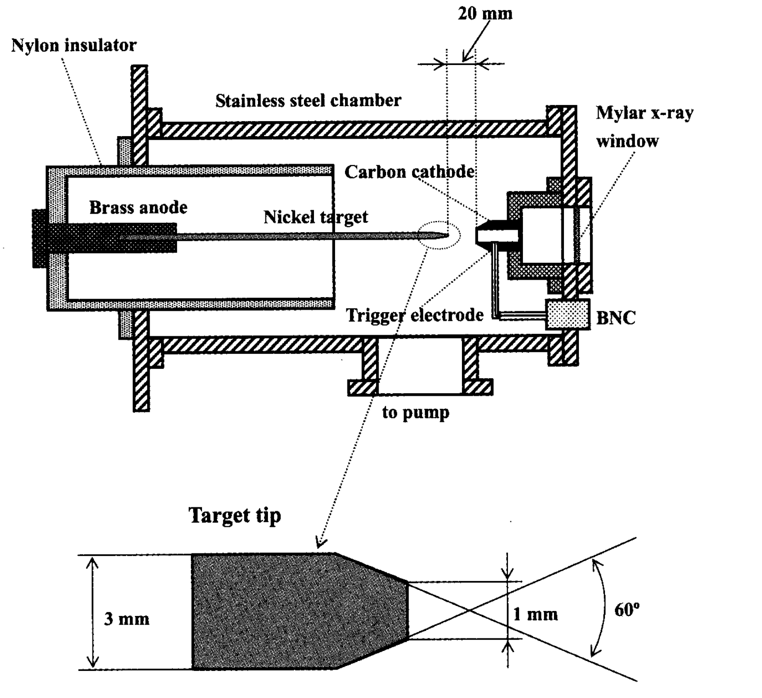


Fig. 3: Schematic drawing of the flash x-ray tube with a rod target.

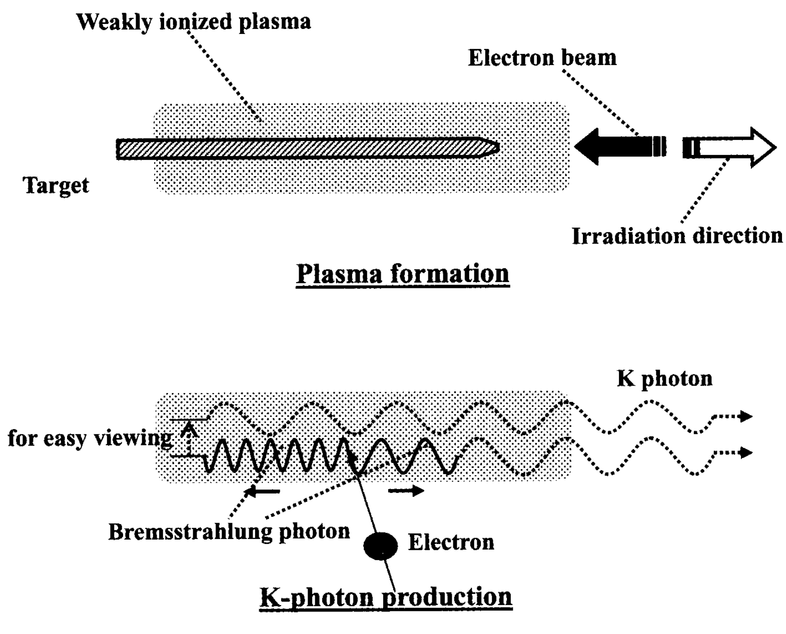


Fig. 4: K-photon irradiation from the plasma.

3. Characteristics

3.1. Tube voltage and current

The tube voltage and current were measured by a high-voltage divider with an input impedance of 1 G Ω and a current transformer, respectively. Figure 6 shows the time relation for the tube voltage and current. At the indicated charging voltages, they displayed damped oscillations. When the charging

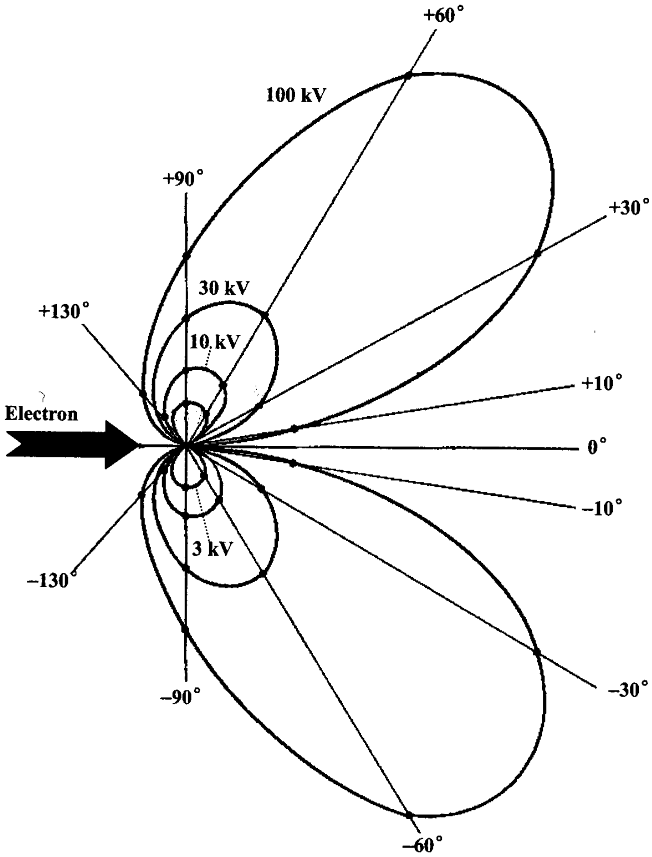


Fig. 5: Bremsstrahlung x-ray distribution with the angle.

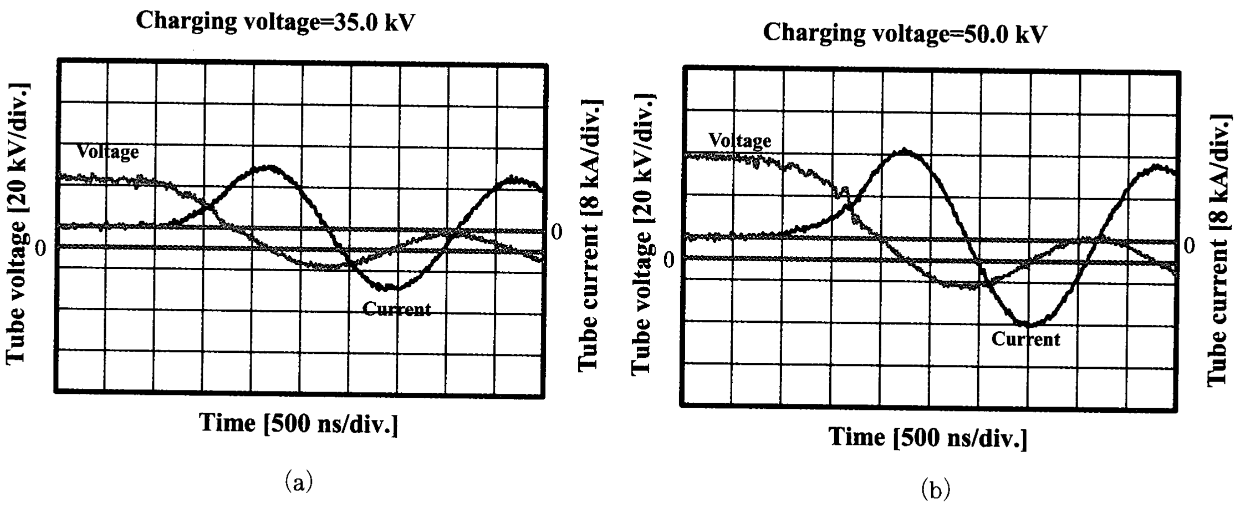


Fig. 6: Tube voltages and currents with a charging voltage of (a) 35.0 kV and (b) 50.0 kV.

voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was approximately 17 kA.

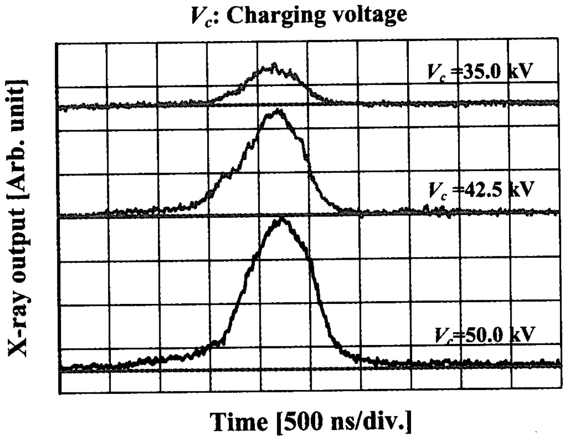


Fig. 7: X-ray outputs measured by a plastic scintillator with changes in the charging voltage.

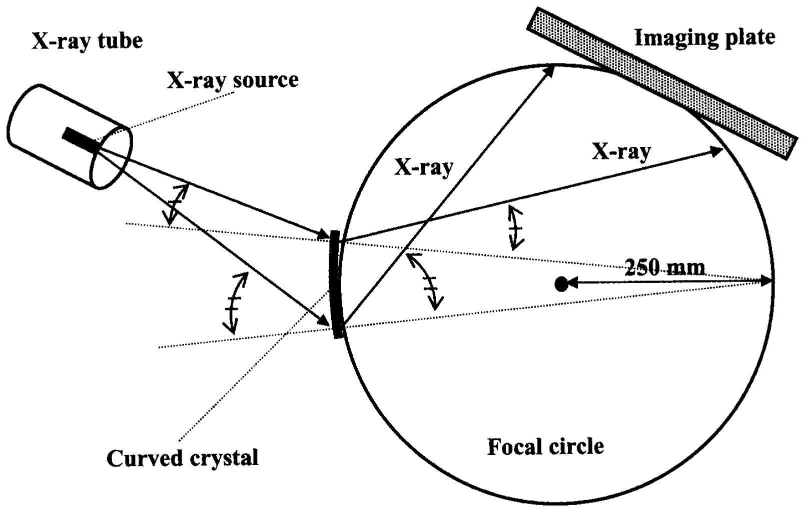


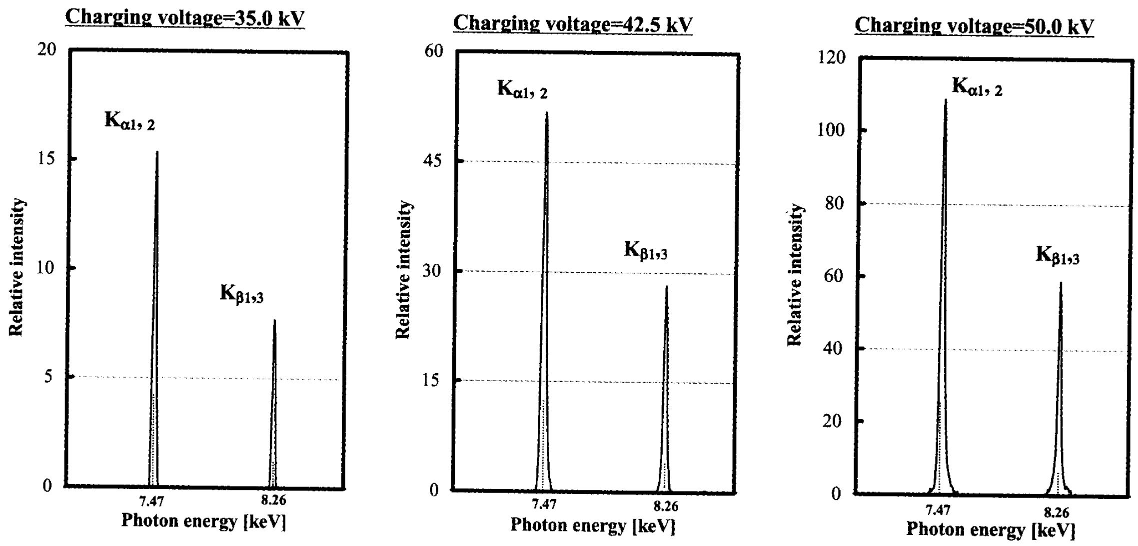
Fig. 8: Transmission-type spectrometer with a lithium fluoride curved crystal and an imaging plate.

3.2. X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 7). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 700 ns, and the time-integrated x-ray intensity per pulse, measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation), had a value of about 30 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

3.3. X-ray source

The images of the plasma x - ray source were taken using a pinhole camera with a hole diameter of 100 μm. When the charging voltage was increased, the plasma x-ray source grew, and both the beam dimension and the intensity increased.



Charging voltage=50.0 kV

Fig. 9: X-ray spectra from weakly ionized nickel plasma according to changes in the charging voltage.

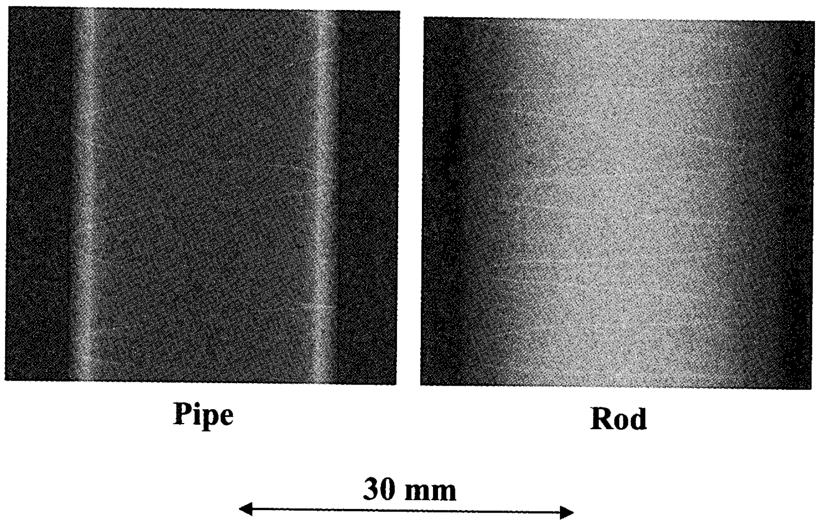


Fig. 10: Radiograms of 50 μm-diameter tungsten wires coiled around a pipe and a rod made of polymethyl methacrylate.

3.4. X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer (Fig. 8) with a lithium fluoride curved crystal of 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system (Konica Regius 150)[23] with a wide dynamic range, and the relative x-ray intensity was calculated from Dicom digital data. Figure 9 shows measured spectra from the nickel target. We observed quite sharp lines of K-series characteristic x rays such as lasers, while bremsstrahlung rays were hardly detected. The characteristic x-ray intensities of K_α and K_β lines substantially increased with corresponding increases in the charging voltage.

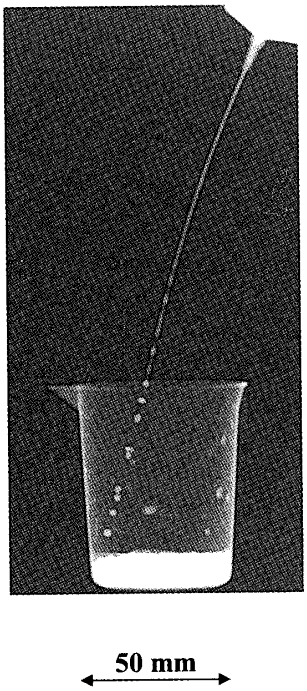


Fig. 11: Radiogram of water droplets falling into a polypropylene beaker from an injector.

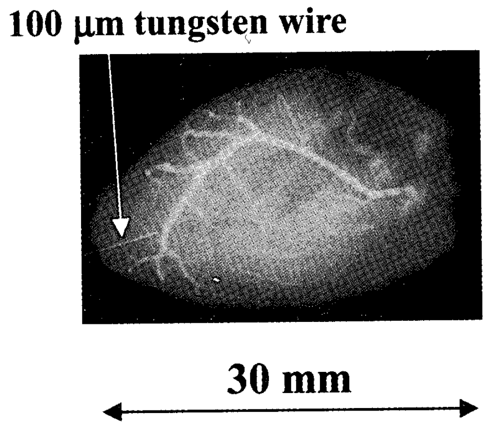


Fig. 12: Angiograms of a rabbit heart.

4. Radiography

Firstly, rough measurements of image resolution were made using wires. Figure 10 shows radiograms of 50 μm-diameter tungsten wires coiled around a pipe and a rod made of polymethyl methacrylate with a charging voltage of 50 kV. Although the image contrast increased using the pipe, 50 μm-diameter wires could be observed.

The image of water droplets falling into a polypropylene beaker from an injector is shown in Fig. 11. This image was taken at a charging voltage of 45 kV, with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 1 μs, the stop-motion image of water could be obtained. Figure 12 shows an angiogram of a rabbit heart; iodine-based microspheres of 15 μm in diameter were used with a charging voltage of 50 kV, and fine blood vessels of about 100 μm were visible.

5. Discussion

Concerning the spectrum measurement, we obtained fairly intense and sharp K_α and K_β lines from a weakly ionized linear plasma x-ray source without using the monochromatic filter. Subsequently, the K_β lines can be absorbed easily by a monochromatic cobalt filter.

In medical radiography, because a photon-counting radiography system will be employed, a quasi-monochromatic or monochromatic x-ray generator will be useful to obtain noise-less digital radiograms. In addition, we are designing quasi-monochromatic flash x-ray generator with microsecond x-ray durations utilizing angle dependence of bremsstrahlung x rays.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography without using a monochromatic filter, and the generator produced number of characteristic photons was approximately 1×10^{14} photons/cm$^2 \cdot$ s at 1.0 m from the source.

In addition, since the photon energy of characteristic x rays can be controlled by changing the target elements, various quasi-monochromatic high-speed radiographies, such as high-contrast micro angiography[23] and parallel radiography[24,25] using an x-ray lens, will be possible.

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