

## 1. INTRODUCTION

Flash x-rays have been produced by several different methods, and various generators have been developed corresponding to specific radiographic objectives.<sup>1-3</sup> Currently, the maximum photon energy has been increased to approximately 1 MeV using multiple-stage Marx pulse generators<sup>1,2</sup> in order to produce hard x-rays for military studies. In soft x-ray generators,<sup>4-8</sup> high-intensity single generators with large capacity condensers were originally developed. Subsequently, repetitive generators<sup>9-12</sup> have been developed, and the repetition rate has been increased to sub-kilohertz using a cold-cathode triode.

Recently, soft x-ray lasers have been produced by a gas-discharge capillary,<sup>13-16</sup> and the laser pulse energy substantially increased in proportion to the capillary length. 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. Because there are no x-ray resonators in the high photon energy region, new methods for increasing coherence will be desired in the future.

By forming weakly ionized linear plasma<sup>17-21</sup> 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, it was difficult to determine the relative intensities of the characteristic x-rays. In former experiments, because we have succeeded in producing fairly intense and sharp K-series characteristic x-rays, monochromatic x-rays should be produced using a filter.

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 monochromatic x-rays by forming a linear copper 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 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 with the trigger device. The plasma flash x-rays are then produced.

### 2.2 X-ray tube

The x-ray tube is a demountable cold cathode triode that is connected to the turbo-molecular pump with a pressure of approximately 1 mPa (Fig. 2). This tube consists of the following major parts: a pipe-shaped 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 copper 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. As electron beams from the cathode electrode are roughly converged to the target by the electric field in the tube, evaporation leads to the formation of a weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

the charging voltage of the main condenser, and the maximum tube current was approximately 15 kA.

### 3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier using a 10  $\mu\text{m}$ -thick monochromatic copper filter (Fig. 5). 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 utilizing MSO-S elements without energy compensation) had a value of about 30  $\mu\text{C}/\text{kg}$  at 1.0 m from the x-ray source with a charging voltage of 50 kV.

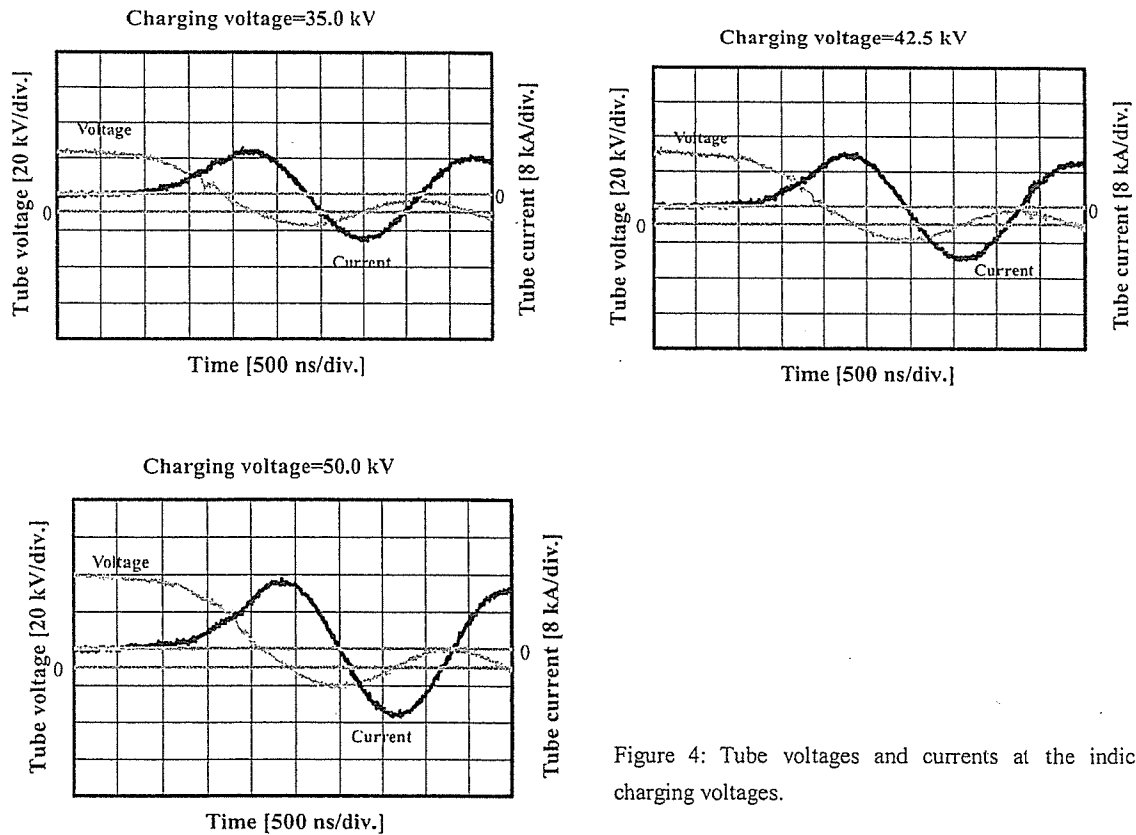


Figure 4: Tube voltages and currents at the indicated charging voltages.

### 3.3 X-ray source

In order to measure images of the plasma x-ray source, we employed a pinhole camera with a hole diameter of 100  $\mu\text{m}$  (Fig. 6). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased.

### 3.4 X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer (Fig. 7) with a lithium

fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system<sup>22</sup> (Konica Regius 150) with a wide dynamic range, using the filter, and relative x-ray intensity was calculated from Dicom digital data. Figure 8 shows measured spectra from the copper target using the filter. In fact, we observed sharp lines of K-series characteristic x-rays such as lasers, while bremsstrahlung rays were hardly detected at all. The characteristic x-ray intensity of the  $K_{\alpha}$  line substantially increased with corresponding increases in the charging voltage, and the  $K_{\beta}$  line was absorbed by the filter.

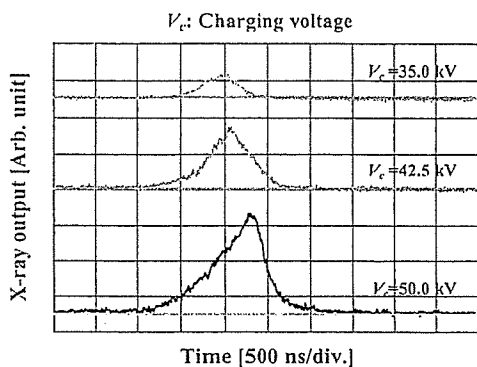


Figure 5: X-ray outputs measured by a plastic scintillator with changes in the charging voltage.

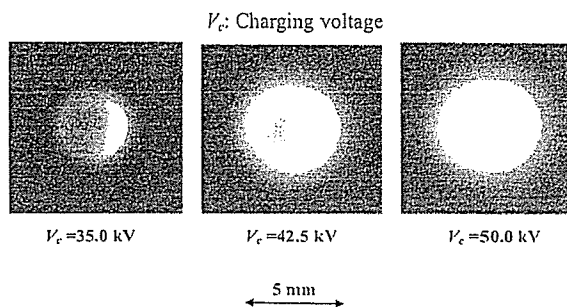


Figure 6: Images of the plasma x-ray source measured by a pinhole of 100  $\mu\text{m}$  from the plasma axial direction.

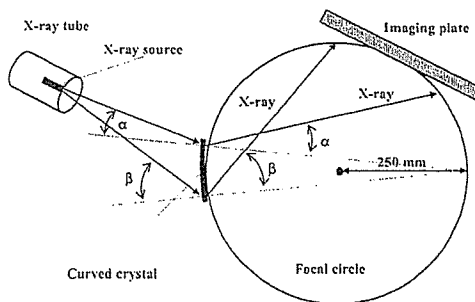


Figure 7: Transmission-type spectrometer with a lithium fluoride curved crystal and an imaging plate.

### 3.5 X-ray divergence by slits

In order to ascertain the difference in characteristics between x-rays from a conventional tube and these from the plasma tube, we employed two lead slits in order to measure the divergence of the x-rays (Fig. 9). As compared with incoherent x-rays from a conventional tube with a tungsten target, the characteristic x-rays from the linear plasma were diffused greatly after passing through the two slits (Fig. 10).

### 3.6 Rectilinear power

Figure 11 shows the experimental setup for measuring the rectilinear power of the  $K_{\alpha}$  lines from a conventional tube and that from the plasma tube using the spectrometer previously described. In this experiment, we measured the coefficient  $(I_k/I_t)$  of peak diffraction intensity of  $K_{\alpha}$  ( $I_k$ ) to transmission intensity ( $I_t$ ). In the case where the

conventional tube was used, we employed the filter with a tube voltage of 17 kV. When the charging voltage was increased, the linear plasma grew, and the  $I_p/I_s$  decreased to approximately 0.004. As compared with a value of 0.009 obtained by the conventional tube, the rectilinear power may be increased, because the values from the plasma were approximately halved.

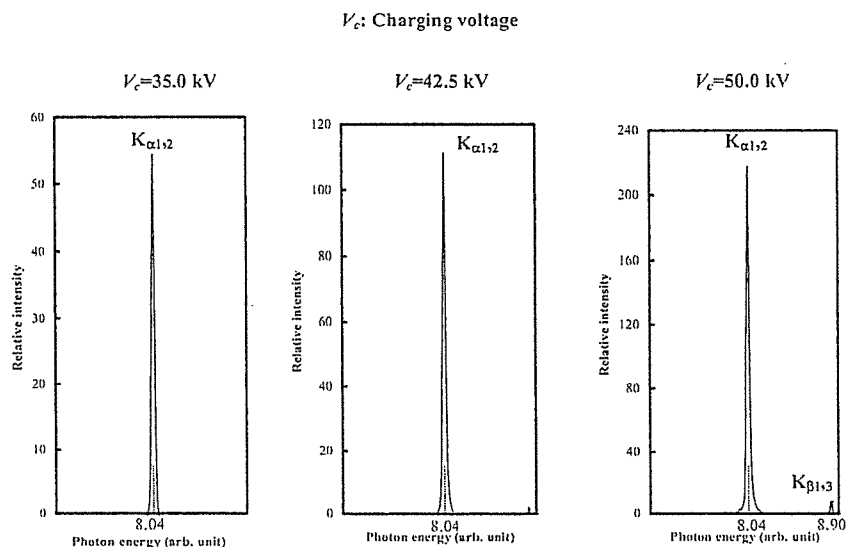


Figure 8: X-ray spectra from weakly ionized copper plasma according to changes in the charging voltage and to insertion of a nickel monochromatic filter.

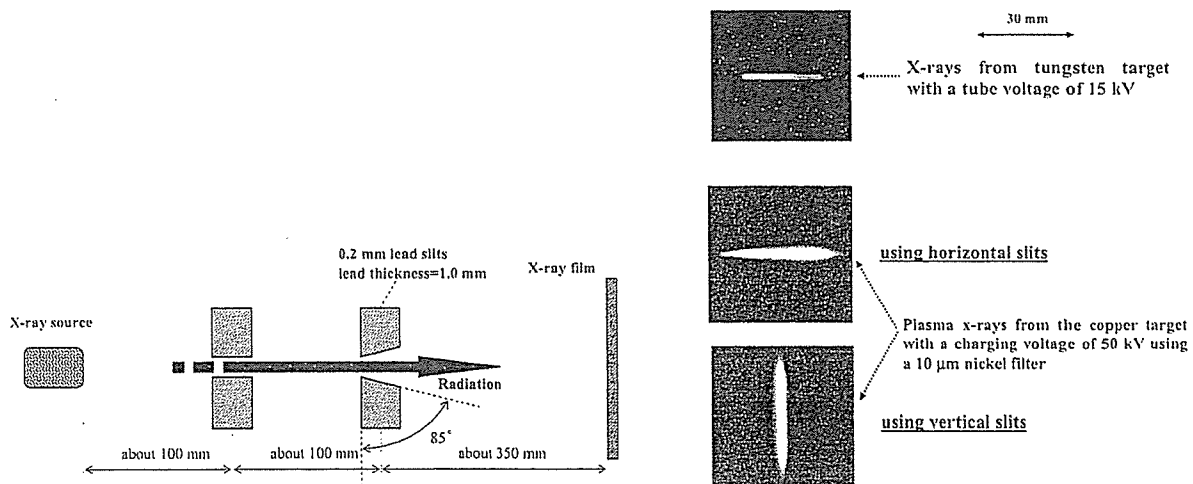


Figure 9: Experimental setup for measuring x-ray divergence using two lead slits.

Figure 10: X-ray divergence with two lead slits.

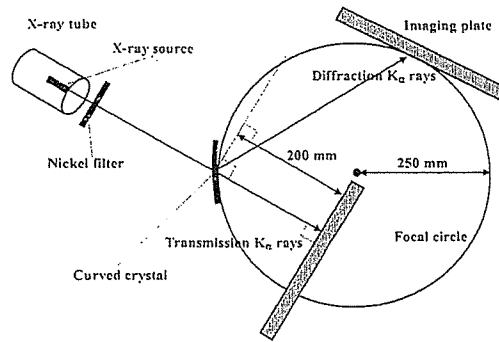


Figure 11: Experimental setup for roughly determining the rectilinear power of the characteristic  $K_{\alpha}$  lines.

#### 4. RADIOGRAPHY

The plasma radiography was performed by the CR system without using the filter, and the distance between the x-ray source and imaging plate was 1.2 m.

Firstly, rough measurements of image resolution were made using wires. Figure 12 shows radiograms of 50  $\mu\text{m}$ -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  $\mu\text{m}$ -diameter wires could be observed.

The image of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 13. This image was taken with a charging voltage of 45 kV, with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 1  $\mu\text{s}$ , the stop-motion image of water could be obtained.

Figure 14 shows an angiogram of a rabbit heart; iodine-based microspheres of 20  $\mu\text{m}$  in diameter were used with a charging voltage of 50 kV, and fine blood vessels of about 100  $\mu\text{m}$  were visible.

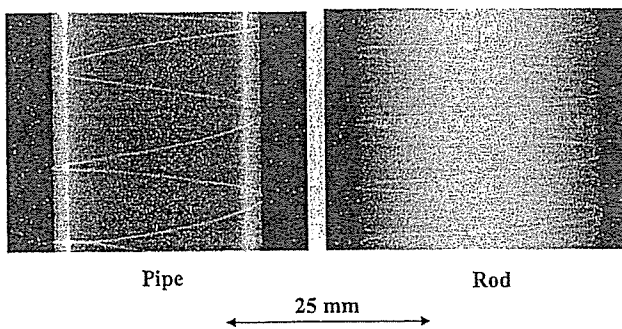


Figure 12: Radiograms of tungsten wires of 50  $\mu\text{m}$  in diameter coiled around a pipe and a rod made of polymethyl methacrylate.

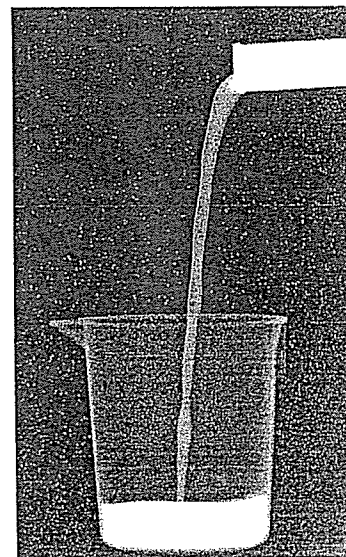


Figure 13: Radiogram of water falling into a polypropylene beaker from a glass test tube.

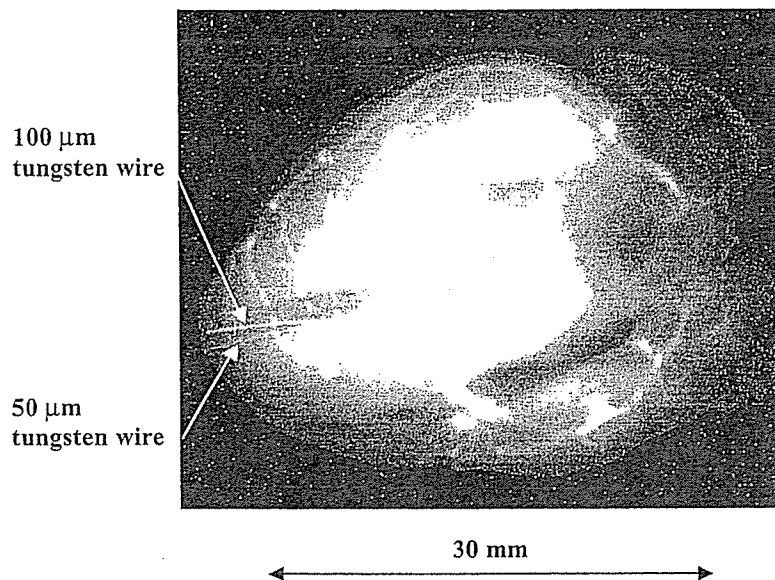


Figure 14: Angiograms of a rabbit heart.

## 5. DISCUSSION

Concerning the spectrum measurement, we obtained fairly intense and sharp  $K_{\alpha}$  lines from a weakly ionized linear plasma x-ray source by absorbing  $K_{\beta}$  lines using the monochromatic filter. In fact, these rays were diffused after passing through slits, and this x-ray divergence mechanism has to be solved clearly. Because the diffracting intensity rate decreases with increases in the charging voltage, the rectilinear power may be increased.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography using a monochromatic filter, and the generator produced high-count-rate monochromatic photons as compared with the synchrotron monochromatic photons. 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<sup>23</sup> and parallel radiography<sup>24,25</sup> using an x-ray lens, will be possible.

## ACKNOWLEDGMENT

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## Sharp characteristic X-ray irradiation from weakly ionized linear 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  $\mu\text{C}/\text{kg}$  at 1.0 m from the X-ray source at a charging voltage of 50 kV.  
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**Keywords:** Flash X-ray; Weakly ionized linear plasma; K-series characteristic X-rays; Quasi-monochromatic X-rays; Monochromatic X-rays

### 1. Introduction

Flash X-ray generators utilizing condensers are of great technological importance due to their extremely short X-ray durations, and several different types of generators have been developed for specific radiographic applications [1,2]. In particular, flash X-ray generators with energies lower than 150 keV have been developed in order to perform soft radiographies with biomedical applications [3–8], and these generators have large capacity condensers in order to increase the X-ray intensity by increasing electrostatic energy.

Using a gas-discharge capillary [9–12], soft X-ray lasers have been produced to form a linear plasma, in which the laser intensity increases proportionally to the capillary length. However, it is quite difficult to increase the laser photon energy beyond 10 keV. Because there are no X-ray resonators in the high photon energy region, new methods for increasing coherence will be desired in the future.

By forming a weakly ionized linear plasma [13–16] using plate and rod targets, we confirmed the production of intense K-series characteristic X-rays along the plasma axial direction. In these experiments, because we employed a transmission-type X-ray spectrometer utilizing an X-ray film, it was difficult to determine the relative intensities of the characteristic X-rays.

In this paper, we describe a flash X-ray generator utilizing a large capacity condenser of 200 nF and a rod-target

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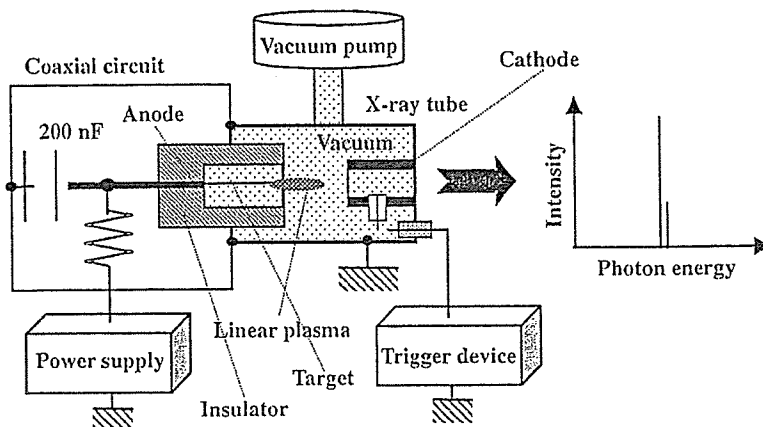


Fig. 1. Block diagram of the high-intensity plasma flash X-ray generator. This generator employs a large capacity condenser in order to increase the characteristic X-ray intensities in a low photon energy region by increasing the electrostatic energy in the condenser.

radiation tube, used to perform a preliminary experiment for generating intense and sharp monochromatic X-rays by forming a linear nickel plasma cloud around a fine target.

## 2. Generator

### 2.1. High-voltage circuit

Fig. 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 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. The plasma flash X-rays are then produced.

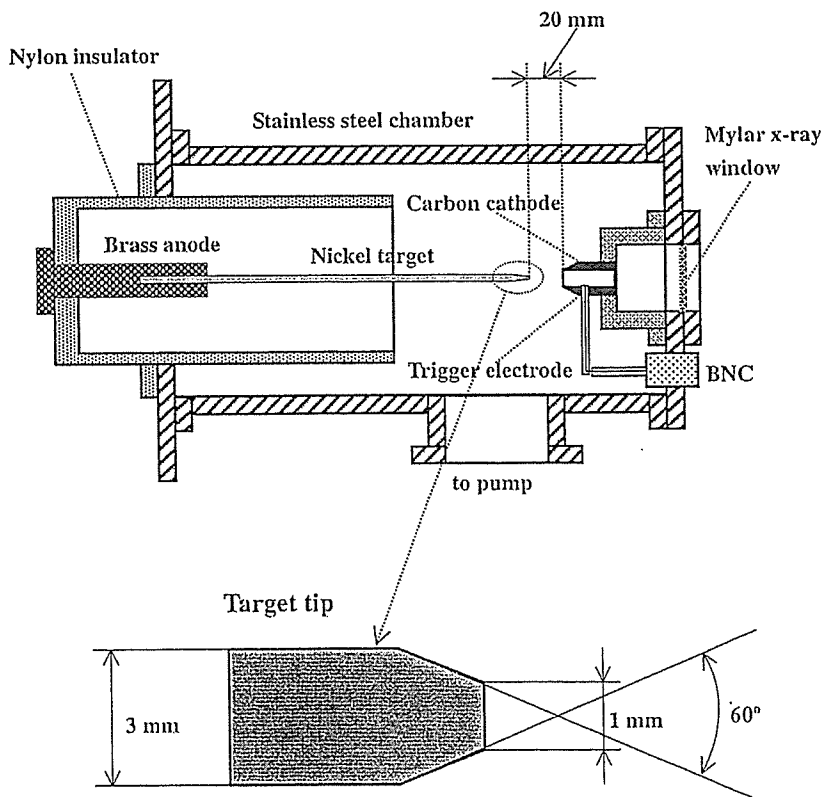


Fig. 2. Schematic drawing of the flash X-ray tube with a rod target. The tube utilizes a long target to form a weakly ionized linear plasma to absorb bremsstrahlung X-rays produced in the plasma, which transmits the characteristic X-rays easily due to the absorption coefficient.

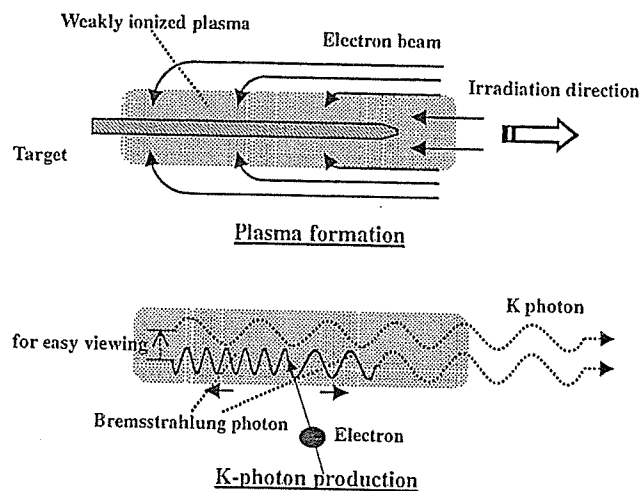


Fig. 3. K-photon irradiation from the plasma. The bremsstrahlung X-rays are absorbed and are converted into fluorescent (characteristic) X-rays in the weakly ionized linear plasma.

## 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. 2). 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. 3). 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, intense characteristic X-rays are generated along axial direction of 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 $\Omega$  and a

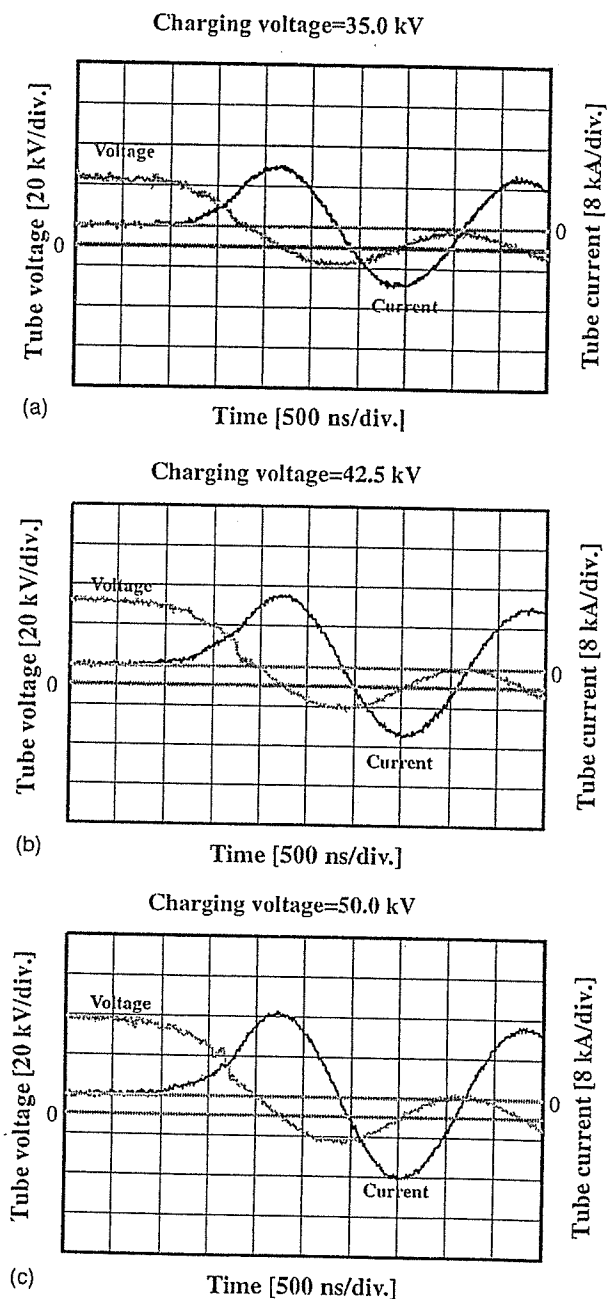


Fig. 4. Tube voltages and currents with a charging voltage of (a) 35.0, (b) 42.5, and (c) 50.0 kV.

current transformer, respectively. Fig. 4 shows the time relation for the tube voltage and current. At the indicated charging voltages, they displayed damped oscillations. When the charging 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.

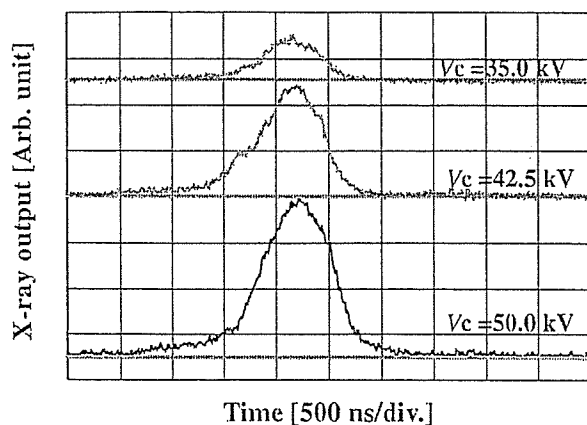


Fig. 5. X-ray outputs measured by a plastic scintillator with changes in the charging voltage.

### 3.2. X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 5). 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  $30 \mu\text{C}/\text{kg}$  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  $100 \mu\text{m}$  (Fig. 6). When the charging voltage was increased, the plasma X-ray source grew, and both the beam dimension and the intensity increased.

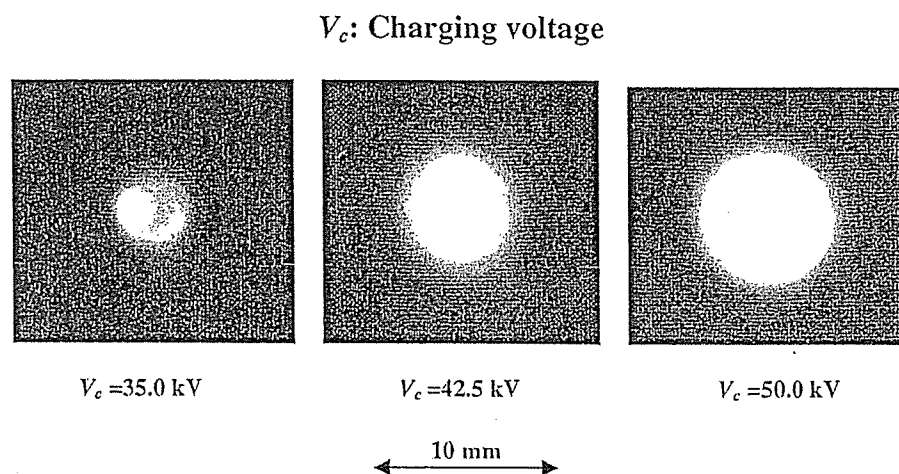


Fig. 6. Images of the plasma X-ray source measured by a pinhole of  $100 \mu\text{m}$  from the plasma axial direction.

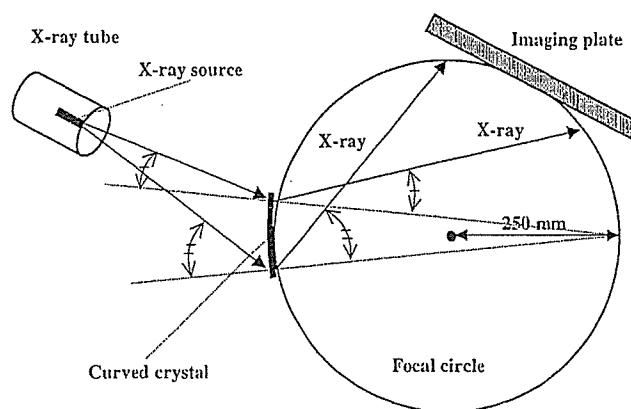


Fig. 7. Transmission-type spectrometer with a lithium fluoride curved crystal and an imaging plate. The X-rays from the source are diffracted by the crystal and are imaged by the imaging plate.

### 3.4. X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer (Fig. 7) 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) [17] with a wide dynamic range, and the relative X-ray intensity was calculated from Dicom digital data. Fig. 8 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  $K_\alpha$  and  $K_\beta$  lines substantially increased with corresponding increases in the charging voltage, and the  $K_\beta$  line was absorbed by a monochromatic cobalt filter of  $15 \mu\text{m}$  thickness.

### 3.5. X-ray divergence

In order to ascertain the difference in characteristics between X-rays from a conventional tube and these from the

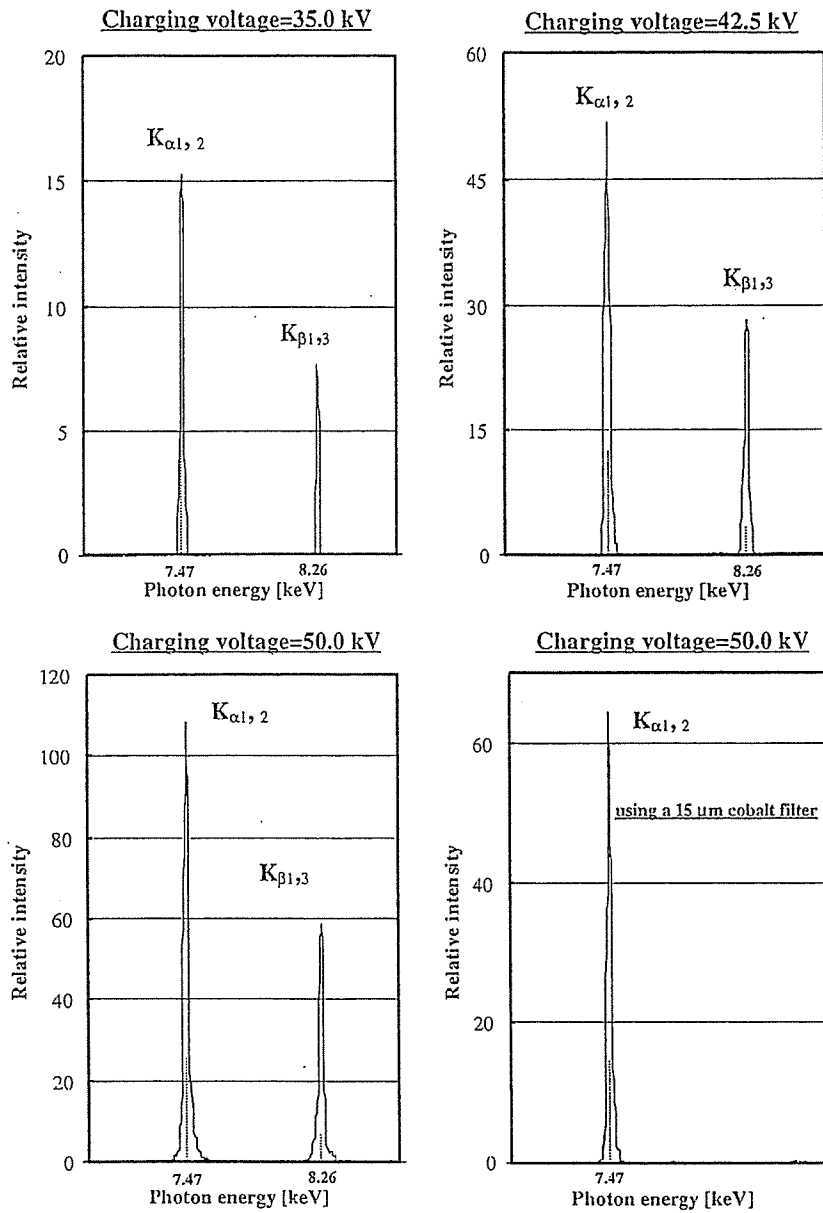


Fig. 8. X-ray spectra from weakly ionized nickel plasma according to changes in the charging voltage and to insertion of a cobalt monochromatic filter. In the measurement, we observed very sharp and intense characteristic X-rays such as lasers, while bremsstrahlung X-rays were hardly detected at all.

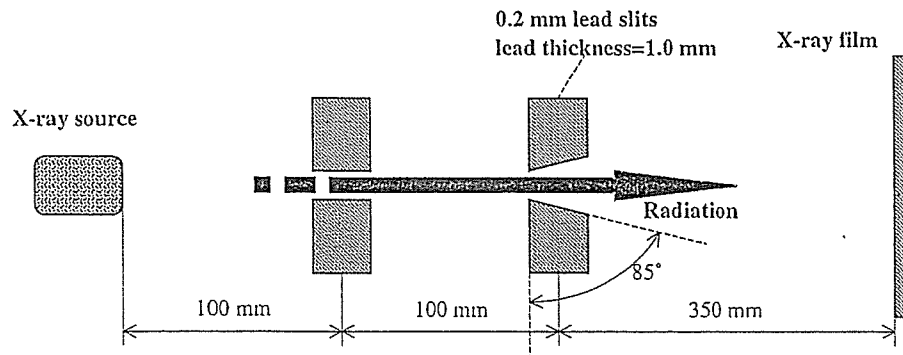


Fig. 9. Experimental setup for measuring X-ray divergence using two lead slits.

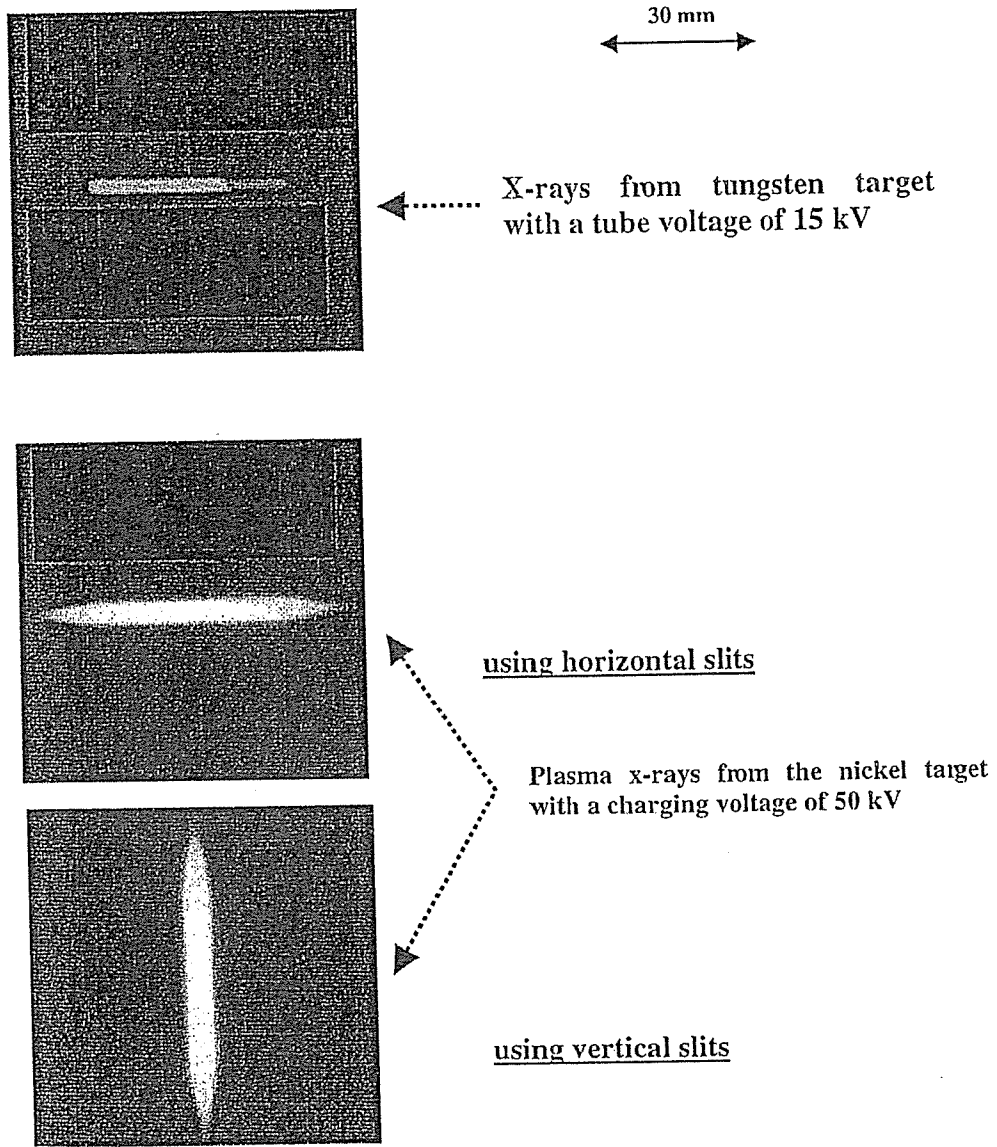


Fig. 10. X-ray divergence with two lead slits. The characteristic X-rays from the plasma were diffused greatly after passing through two lead slits.

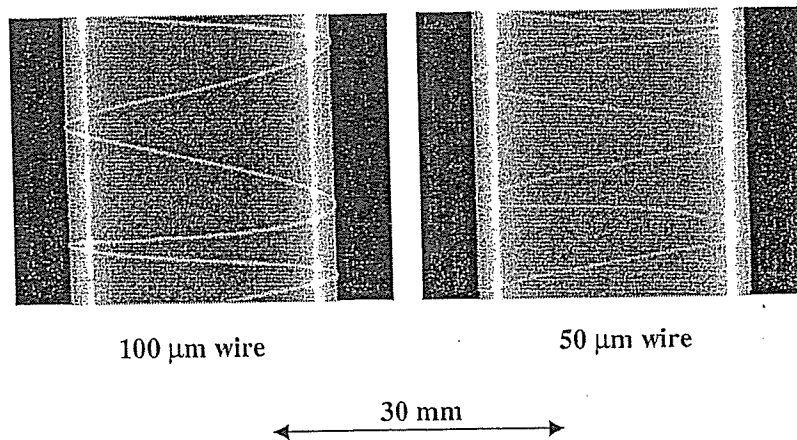


Fig. 11. Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around pipes made of polymethyl methacrylate.

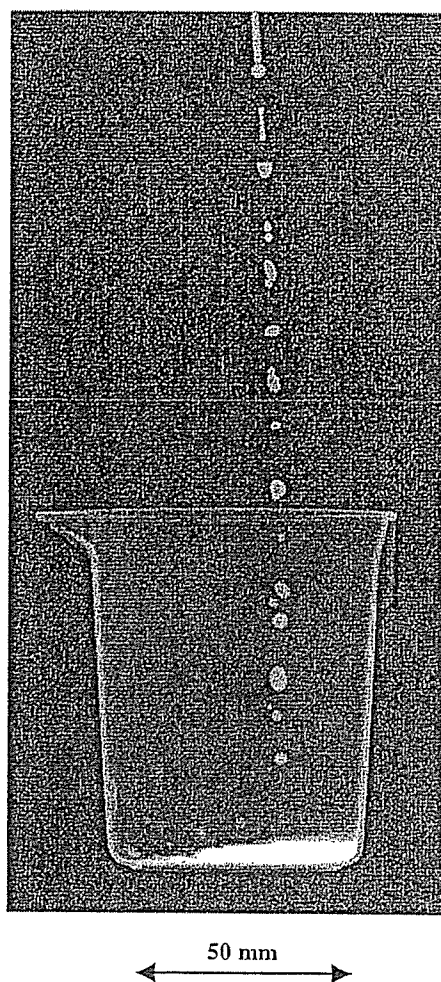


Fig. 12. Radiogram of water droplets falling into a polypropylene beaker from an injector.

plasma tube, we employed two lead slits in order to measure the divergence of the X-rays (Fig. 9). As compared with X-rays from a conventional tube with a tungsten target, the characteristic X-rays from the linear plasma were diffused greatly after passing through the two slits (Fig. 10).

#### 4. Radiography

The plasma radiography was performed by the CR system (Konica Regius 150) without using a monochromatic filter, and the distance between the X-ray source and imaging plate was 1.2 m.

Firstly, the image resolution was measured using wires. Fig. 11 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate at a charging voltage of 50 kV. Although the image contrast increased with increases in the wire diameter, a 50  $\mu\text{m}$ -diameter wire could be observed.

The image of water droplets falling into a polypropylene beaker from an injector is shown in Fig. 12. This image

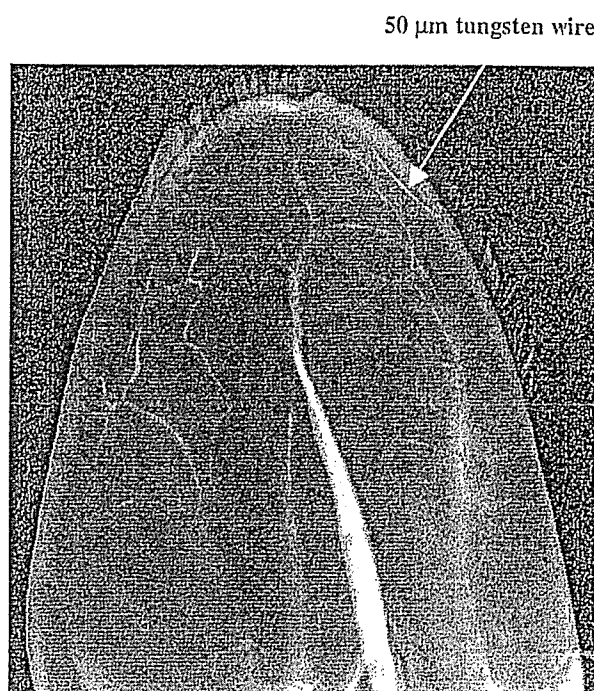


Fig. 13. Angiograms of the external ear of a rabbit.

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  $\mu\text{s}$ , the stop-motion image of water could be obtained.

Fig. 13 shows an angiogram of the external ear of a rabbit; iodine-based microspheres of 15  $\mu\text{m}$  diameter were used at a charging voltage of 45 kV, and fine blood vessels of about 50  $\mu\text{m}$  were clearly visible.

#### 5. Discussion

Regarding the spectrum measurement, although we obtained quite intense and sharp K-series lines without bremsstrahlung X-rays by forming a linear plasma X-ray source, we could not observe the difference between the  $K\alpha_1$  and  $K\alpha_2$  lines. In addition, we confirmed the divergence of K-series characteristic X-rays using two lead slits, and the maximum divergence angle was approximately  $0.5^\circ$ .

If we assume that the characteristic and bremsstrahlung X-rays are signal and noise, respectively, the signal to noise ratio is higher than 1000:1, and this value is almost equal to those of soft X-ray lasers produced by the gas-discharge capillary.

In this research, we obtained sufficient characteristic X-ray intensity per pulse for CR radiography, and the generator produced number of characteristic photons of approximately  $1 \times 10^{14}$  photons/cm<sup>2</sup>s at 1.0 m from the source. In addition, since the photon energy of characteristic X-rays can be controlled by changing target elements, various quasi-monochromatic high-speed radiographies,

such as high-contrast micro angiography<sup>22</sup> and parallel radiography<sup>23</sup> using an X-ray lens, will be possible.

### Acknowledgements

This work was supported by Grants-in-Aid for Scientific Research and Advanced Medical Scientific Research from MECSST (12670902, 13470154, and 13877114), Grants from Keiryō Research Foundation, JST (Test of Fostering Potential), NEDO, and MHLW (HLSRG, RAMT-nano-001, RHGTEFB-genome-005, and RGCD13C-1).

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## Quasi-monochromatic parallel radiography utilizing a computed radiography system

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### Abstract

A fundamental study on quasi-monochromatic parallel radiography using a polycapillary plate and a copper-target X-ray tube is described. The X-ray generator consists of a negative high-voltage power supply, a filament (hot cathode) power supply, and an X-ray tube. The negative high-voltage is applied to the cathode electrode, and the anode electrode is connected to the ground. In this experiment, the tube voltage was regulated from 12–25 kV, and the tube current was regulated within 3.0 mA by the filament temperature. The exposure time was controlled in order to obtain optimum X-ray intensity, and the maximum focal spot dimensions were approximately 2 mm × 1.5 mm. The polycapillary plate was J5022-21 (Hamamatsu Photonics Inc.), and the plate thickness was 1.0 mm. The outer, effective, and hole diameters were 87 mm, 77 mm, and 25 μm, respectively. Quasi-monochromatic X-rays were produced using a 10 μm-thick copper filter, and these rays were formed into parallel beams by the polycapillary, and the radiogram was taken using a computed radiography system utilizing imaging plates. In the measurement of image resolution, the resolution fell according to increases in the distance between the chart and imaging plate using a polycapillary. We could observe a 50 μm tungsten wire clearly, and fine blood vessels of approximately 100 μm were visible in angiography. © 2004 Elsevier B.V. All rights reserved.

**Keywords:** Parallel radiography; Quasi-monochromatic X-ray; Characteristic X-ray; X-ray lens; Polycapillary plate

### 1. Introduction

Thus far, we have developed several different soft flash X-ray generators [1–8] in order to perform soft radiographies with biomedical applications. In particular, plasma flash X-ray generators [9–11] are very useful to produce fairly high-dose-rate monochromatic X-rays as compared with a synchrotron. When a weakly ionized linear plasma formed using a rod target evaporation, irradiation of quite intense and sharp characteristic X-rays from the plasma axial direction was confirmed.

Monochromatic parallel radiography using synchrotrons plays important roles in microangiography [12] and X-ray phase imaging, [13–15] and further applications have long been wished for. In view of this situation, several different X-ray lenses have been developed [16,17], and a polycapillary plate [18–20] has been shown to be useful to realize a low-priced X-ray system and to perform parallel radiography. Therefore, we performed parallel radiography using a tungsten-target X-ray tube [19] and an X-ray film, and an image resolution of approximately 50 μm or less was obtained.

The tungsten target produced L-series characteristic and bremsstrahlung X-rays with tube voltages of 20–30 kV, and these rays were formed into parallel beams to perform radiography. Thereafter, K-series characteristic X-rays could

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be employed for quasi-monochromatic and monochromatic radiographies using filters. In these cases, the photon energies of characteristic X-rays were determined by the target element.

In this research, we performed preliminary study on quasi-monochromatic parallel radiography utilizing a polycapillary plate, a Computed Radiography (CR) system [21], and a copper-target radiation tube in order to create a new X-ray system to be used instead of the synchrotron.

## 2. Experimental set-up

Fig. 1 shows the circuit diagram of the X-ray generator, which consists of a negative high-voltage power supply, a filament (hot cathode) power supply, and a copper-target X-ray tube. The negative high-voltage is applied to the cathode electrode, and the anode (target) is connected to the ground. In this experiment, the tube voltage was regulated from 15–25 kV, and the tube current was regulated by the filament temperature and ranged from 1.0–3.0 mA. The exposure time was controlled in order to obtain optimum X-ray intensity.

The experimental set-up for performing parallel radiography is shown in Fig. 2. Quasi-monochromatic X-rays are produced using a 10  $\mu\text{m}$ -thick copper filter, and these rays are formed into parallel beams by a polycapillary plate. The polycapillary is J5022-21 (Hamamatsu Photonics Inc.), and the thickness and the hole diameter of the polycapillary are

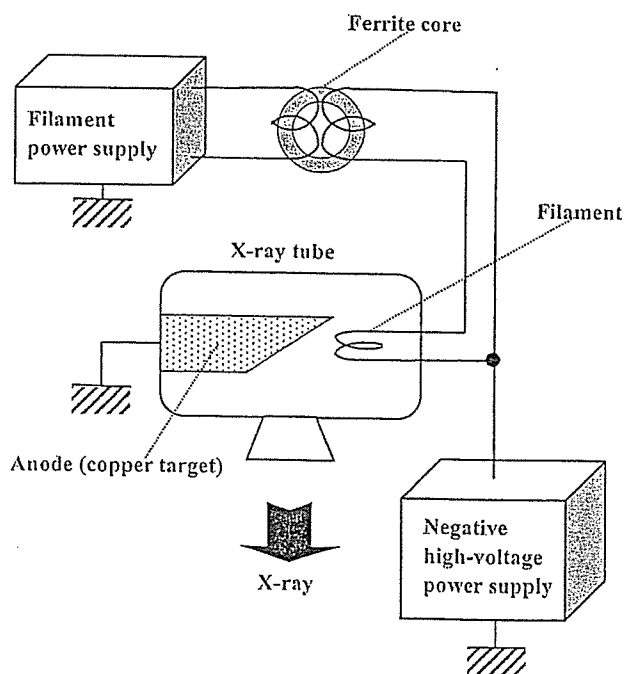


Fig. 1. Circuit diagram of the X-ray generator. Because the negative high voltage is applied to the cathode electrode, the tube voltage is  $-1$  times the cathode voltage. The X-ray tube employs a 0.5 mm-thick beryllium window in order to produce soft X-rays effectively.

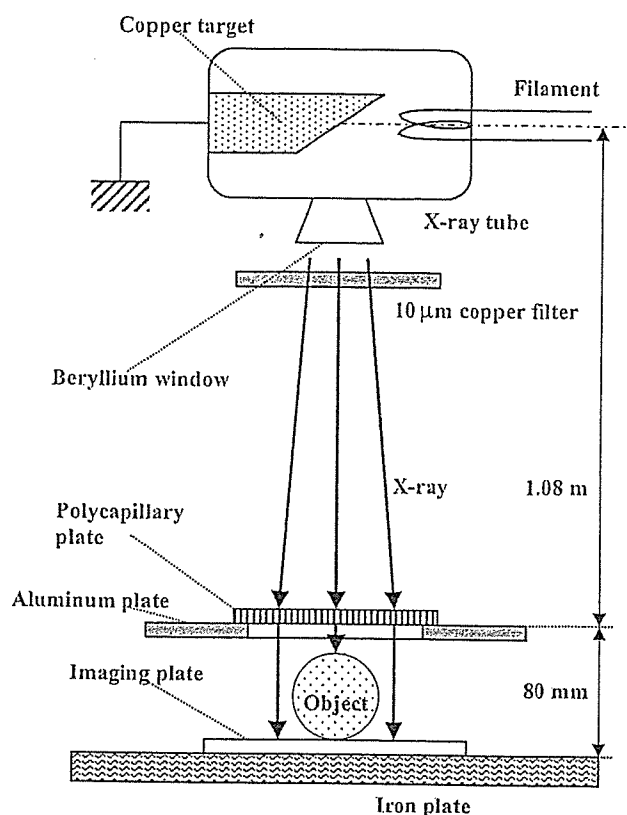


Fig. 2. Experimental set-up for parallel radiography utilizing a polycapillary plate and a CR system. Quasi-monochromatic X-rays are formed into parallel beam by a polycapillary, and the image is taken by a CR system.

1.0 mm and 25  $\mu\text{m}$ , respectively (Fig. 3). Radiography was performed by a CR system (Konica Regius 150) utilizing imaging plates.

The distance between the X-ray source and the polycapillary was 1.08 m, and the polycapillary plate was placed on the aluminum plate, and the distance between the aluminum and imaging plates was regulated by the height of polymethyl methacrylate (PMMA) spacers of 30 mm in height.

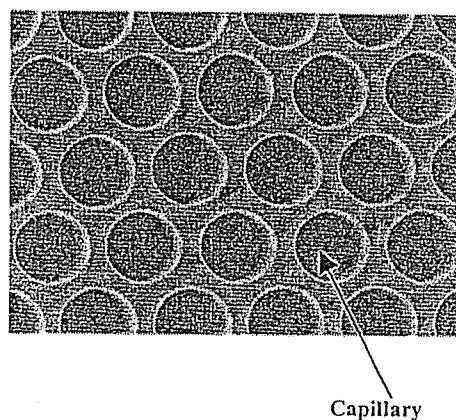


Fig. 3. Magnification of a polycapillary plate with a thickness of 1.0 mm and a hole diameter of 25  $\mu\text{m}$ , respectively.

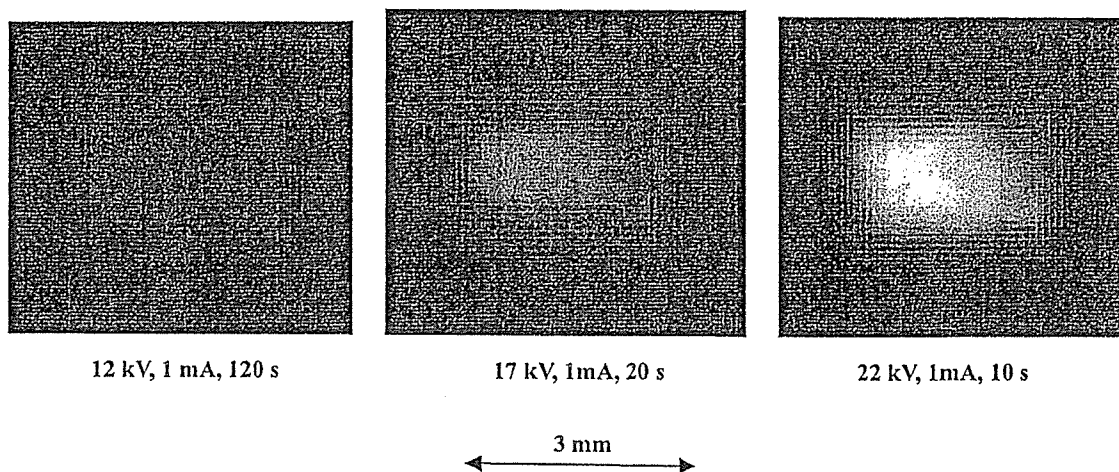


Fig. 4. Images of the X-ray source measured by a 50  $\mu\text{m}$ -diameter pinhole with changes in the tube voltage.

### 3. Characteristics

#### 3.1. Focal spot

In order to measure images of the X-ray source, we employed a pinhole camera with a hole diameter of 50  $\mu\text{m}$  (Fig. 4). When the tube voltage was increased, the spot intensity increased, and spot dimensions increased slightly and had values of approximately 2 mm  $\times$  1.5 mm.

#### 3.2. X-ray spectra

X-ray spectra from the copper-target tube were measured by a transmission-type spectrometer (Fig. 5) with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by the CR system with a wide dynamic range, and relative X-ray intensity was calculated from Dicom digital data. Fig. 6 shows measured spectra from the copper target. When the tube voltage was increased, the bremsstrahlung

X-ray intensity increased, and the characteristic X-ray intensity of  $K_{\alpha}$  and  $K_{\beta}$  lines also increased. Following insertion of the copper filter, since the bremsstrahlung X-rays with energies higher than the  $K$ -absorption edge were absorbed effectively, we observed the edge.

### 4. Radiography

The quasi-monochromatic radiography was performed with a tube voltage of 20 kV using the filter. Fig. 7 shows radiography for imaging a polycapillary plate, and the radiograms of the polycapillary are shown in Fig. 8. The center of the black spot in the polycapillary radiogram was mainly imaged by direct transmission beams through capillary holes. As shown in this figure, both the spot density and the dimensions hardly varied according to decreases in the polymethyl methacrylate (PMMA) spacer height.

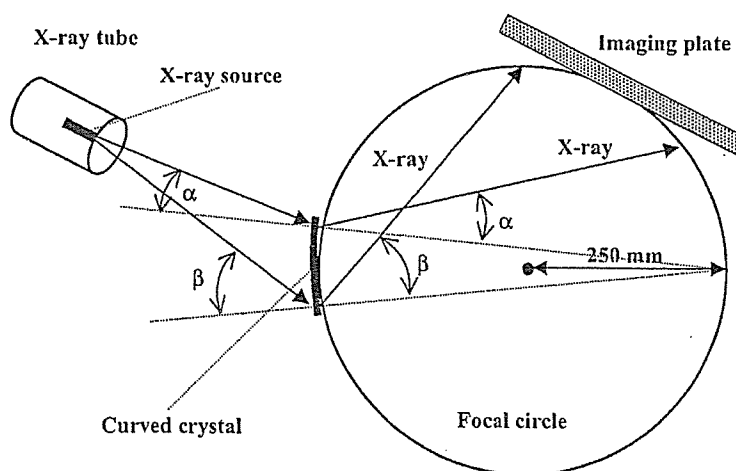


Fig. 5. Transmission-type spectrometer with a lithium fluoride curved crystal and an imaging plate. The X-rays from the source are diffracted by the crystal and are imaged on the imaging plate.

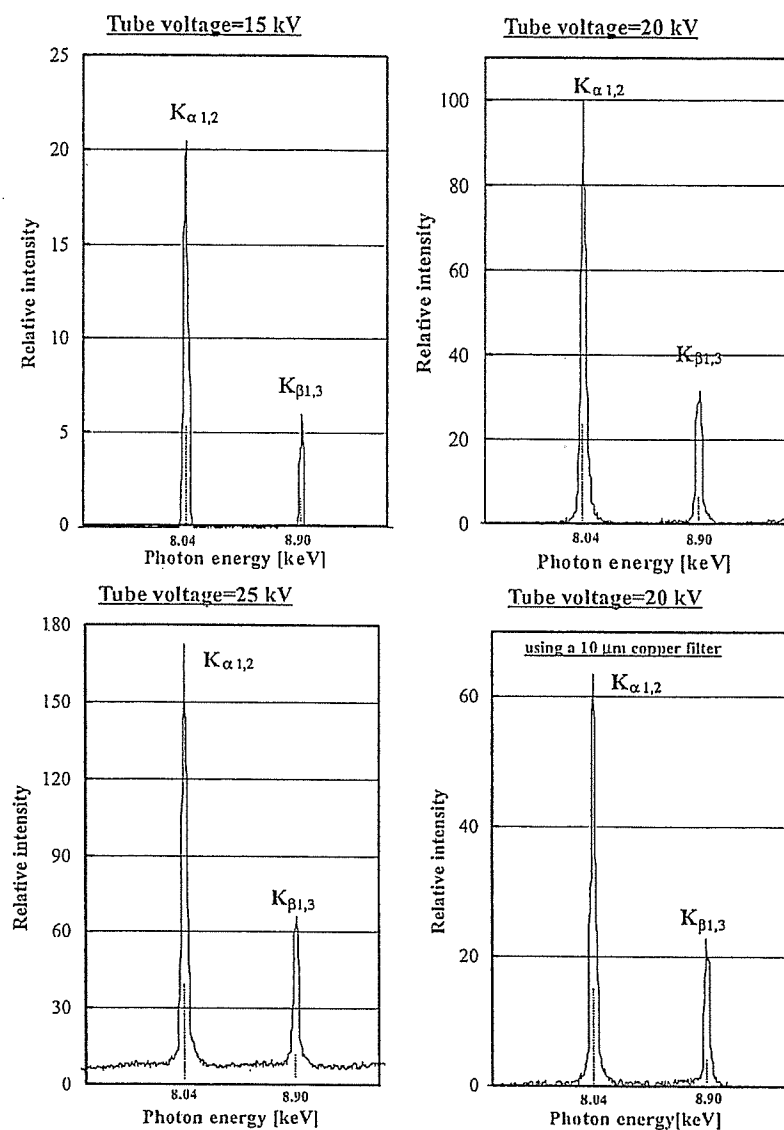


Fig. 6. Measured X-ray spectra according to changes in the tube voltage. Both the bremsstrahlung and characteristic X-ray intensities increased with corresponding increases in the tube voltage, and we determined the conditions for radiography as follows: a tube voltage of 20 kV and a filter thickness of 10  $\mu\text{m}$ .

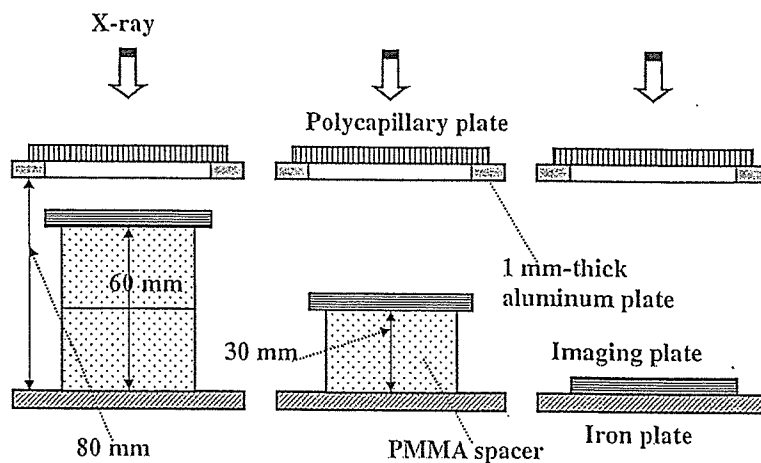


Fig. 7. Radiography for imaging a polycapillary plate according to changes in the distance between the polycapillary and imaging plates. Because the distance was regulated by the spacer thickness, the distance decreased according to increases in the spacer height.