

# Monochromatic x-ray generator utilizing angle dependence of bremsstrahlung x-ray distribution

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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 (Wehnelt) 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 clean  $K\alpha$  rays are produced through the focusing electrode using a 20- $\mu$ m-thick zirconium filter. The x-ray intensity was 12.1  $\mu$ Gy/s at 1.0 m from the x-ray source with a tube voltage of 30 kV and a tube current of 100  $\mu$ A, and monochromatic radiography was performed using a computed radiography system.

**Keywords:** demountable x-ray tube, electron-impact source, monochromatic x-rays,  $K\alpha$  rays, Sommerfeld's theory

## 1. INTRODUCTION

Recently, we have developed several different flash x-ray generators<sup>1-6</sup> corresponding to specific radiographic objectives, and the plasma x-ray source has been growing with increases in the electrostatic energy in the condenser. By forming weakly ionized linear plasma<sup>7-10</sup> using rod targets, we confirmed irradiation of clean K-series characteristic x-rays such as hard x-ray lasers from the plasma axial direction using a table-top flash x-ray generator. This super fluorescence has been employed to perform cone-beam monochromatic radiography such as iodine K-edge angiography.<sup>11</sup> Furthermore, because higher harmonic hard x-rays have been produced from the copper plasma, we have to confirm the irradiations of higher harmonics with charges in the target element.

At present, brilliant monochromatic parallel x-ray beams from synchrotron radiation are used in various fields including medical imaging,<sup>12-15</sup> and large-scale x-ray free electron laser sources are constructing as a new-generation radiation

source for producing monochromatic coherent x-rays. In contrast, small-scale steady-state monochromatic parallel and cone beams can be employed to perform medical imaging including phase-contrast radiography and K-edge angiography<sup>16,17</sup> in hospitals.

In this paper, we developed a monochromatic x-ray generator, used to perform a preliminary experiment for generating clean molybdenum K $\alpha$  rays by angle dependence of the bremsstrahlung x-rays.

## 2. GENERATOR

Figure 1 shows a block diagram of a compact 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 rod target 3.0 mm in diameter, a tungsten hairpin cathode (filament), a focusing (Wehnelt) 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. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory (Fig. 3), clean molybdenum K $\alpha$  rays can be produced using a 20- $\mu$ m-thick zirconium filter.

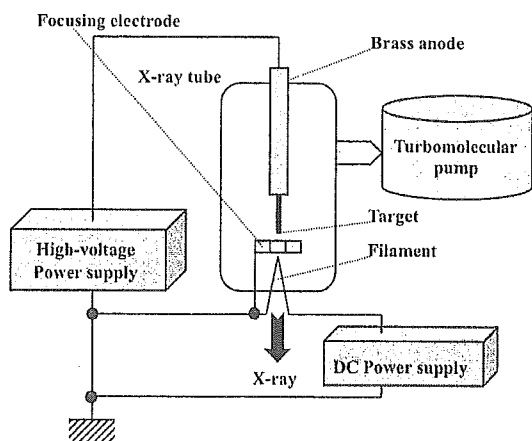


Figure 1: Block diagram including the main transmission line of the compact x-ray generator with a monochromatic diode.

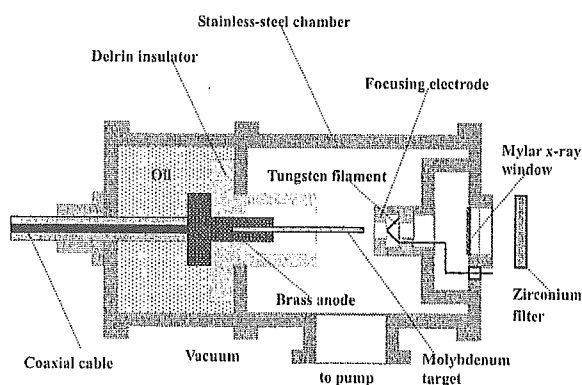


Figure 2: Schematic drawing of the monochromatic x-ray tube.

## 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. 4). At a constant tube current of 100  $\mu$ A, the x-ray intensity increased when the tube voltage was increased. In this measurement, the intensity with a tube voltage of 30 kV and a current of 100  $\mu$ A was 12.1  $\mu$ Gy/s at 1.0 m from the source.

### 3.2 X-ray source

In order to measure images of the x-ray source, we employed a pinhole camera with a hole diameter of 100  $\mu\text{m}$  in conjunction with a computed radiography (CR) system<sup>18</sup> (Fig. 5). When the tube voltage was increased, the spot diameter slightly increased and had a maximum value of approximately 2.3 mm.

### 3.3 X-ray spectra

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 (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; the data was scanned by Dicom viewer in the film-less CR system. Subsequently, the relative x-ray intensity as a function of the data was calibrated using a conventional x-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 6 shows measured spectra from the molybdenum target using the filter. We observed clean  $K\alpha$  lines, while bremsstrahlung rays were hardly detected. The  $K\alpha$  intensity substantially increased with increases in the tube voltage.

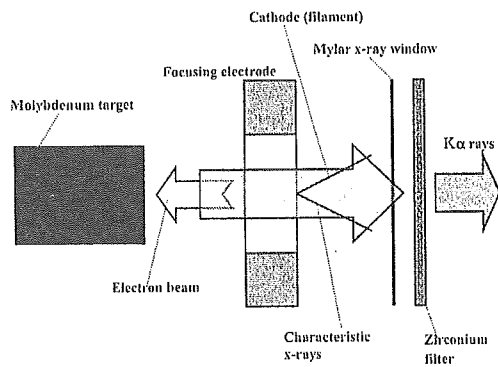


Figure 3: K-photon irradiation from the x-ray tube.

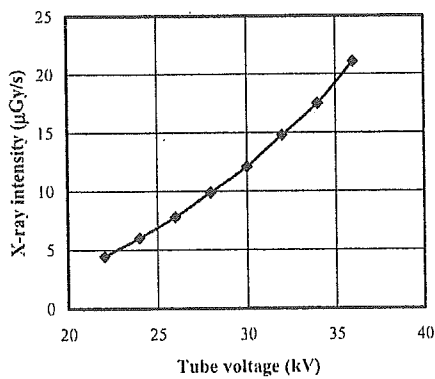


Figure 4: X-ray intensity at 1.0 m from the x-ray source according to changes in the tube voltage.

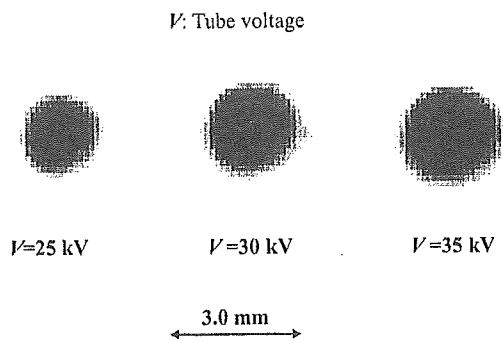


Figure 5: Images of the characteristic x-ray source obtained using a pinhole camera with changes in the tube voltage.

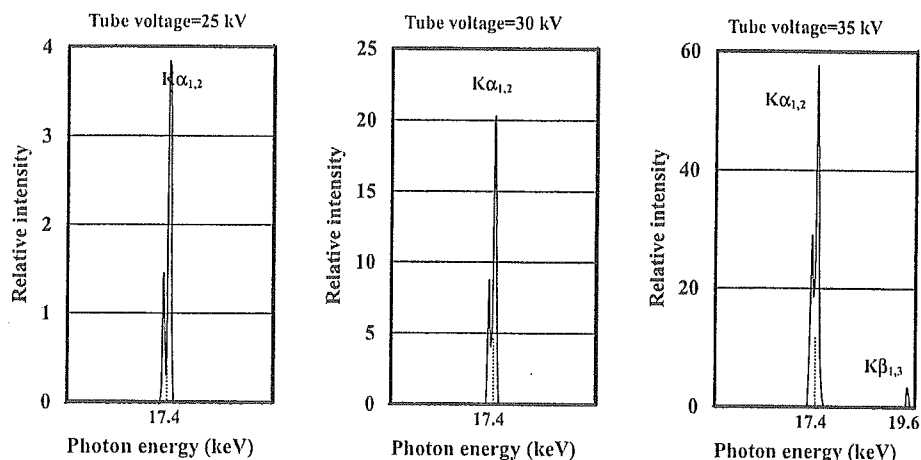


Figure 6: X-ray spectra from the molybdenum target. The spectra were measured using a transmission type spectrometer with a lithium fluoride curved crystal.

#### 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.

Firstly, rough measurements of image resolution were made using wires. Figure 7 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. 8, and the fine structure of the vertebra was observed. Next, angiography was performed using iodine microspheres of 15  $\mu\text{m}$  in diameter. Figures 9 and 10 show angiograms of a rabbit heart and thigh, respectively, and we could obtain high contrast images of coronary arteries and fine blood vessels.

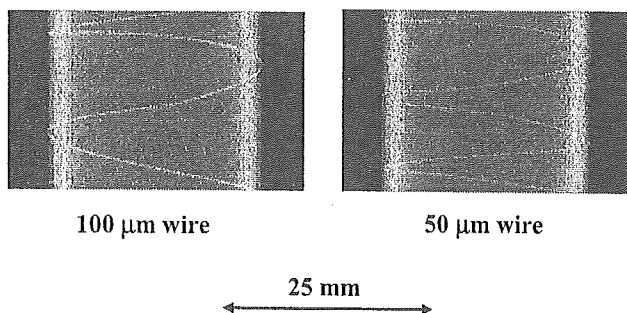


Figure 7: Radiograms of tungsten wires of 50 and 100  $\mu\text{m}$  in diameter coiled around pipes made of polymethyl methacrylate. A 50  $\mu\text{m}$ -diameter wire could be observed.

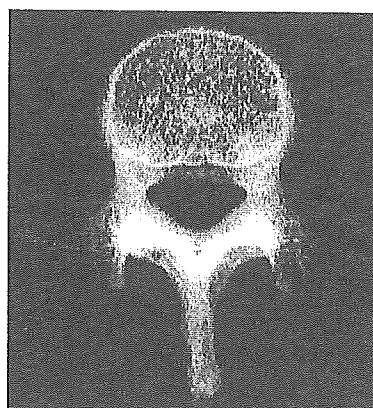


Figure 8: Radiogram of a vertebra. Fine structure of the vertebra were visible.

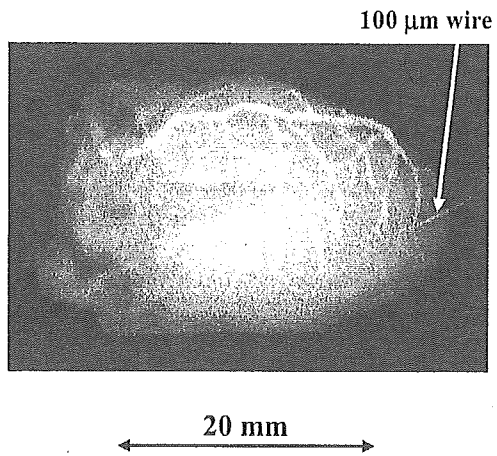


Figure 9: Angiograms of a rabbit heart. Coronary arteries were visible.

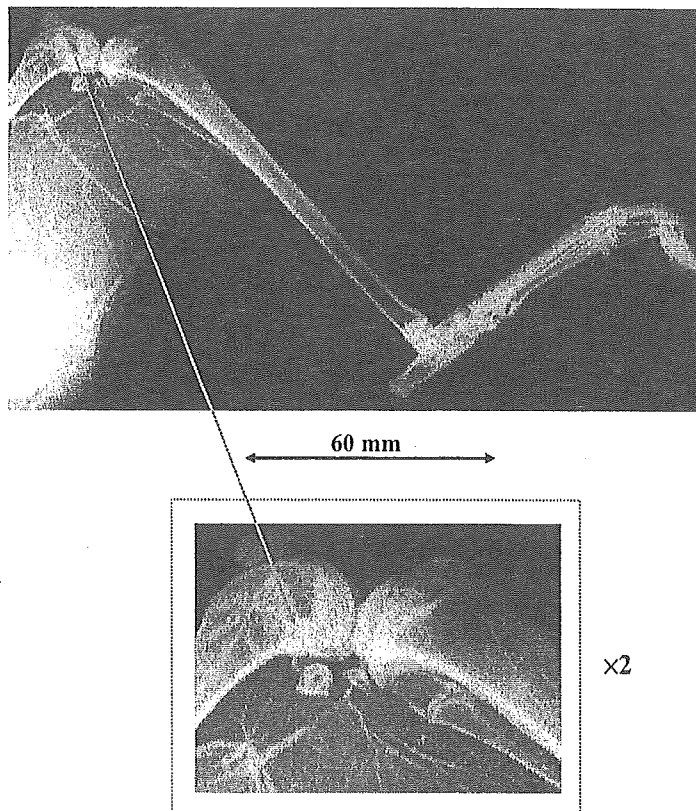


Figure 10: Angiogram of a rabbit thigh. Fine blood vessels of approximately 100  $\mu\text{m}$  in diameter were visible.

## 5. CONCLUSIONS AND OUTLOOK

We developed a new monochromatic x-ray generator with a molybdenum-target tube and succeeded in producing clean

molybdenum  $K\alpha$  lines. The  $K\alpha$  intensity increased with increases in the tube voltage, and monochromatic  $K\alpha$  rays were left by the zirconium filter. Without using the filter, bremsstrahlung x-rays were hardly observed.

In this experiment, although the maximum tube voltage and current were 36 kV and 0.10 mA, the voltage and current could be increased to 100 kV and 1.0 mA, respectively. Under the pulsed operation, the current can be increased to approximately 1 A without considering the target evaporation. Subsequently, the maximum number of characteristic photons was approximately  $5 \times 10^6$  photons/cm<sup>2</sup>·s at 1.0 m from the source, and the photon count rate can be increased easily by increasing the current.

The molybdenum K-series characteristic x-rays are useful for mammography, and the photon energies of characteristic x-rays can be selected by the target element. In particular, enhanced K-edge angiography can be performed using a cerium target because cerium  $K\alpha$  rays (34.6 keV) are absorbed easily by iodine-based contrast media with an iodine K-edge of 33.2 keV. Furthermore, low-dose enhanced K-edge angiography can be performed utilizing a tungsten target in conjunction with gadolinium media.

Using these angiographies, coronary arteries and fine blood vessels formed in regenerative medicine may be observed with high contrasts. Furthermore, a flat panel detector is useful to observe blood flows for cases of cardiovascular disease.

### ACKNOWLEDGMENTS

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# Energy-selective gadolinium angiography utilizing a stroboscopic x-ray generator

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## ABSTRACT

Energy-selective high-speed radiography utilizing a kilohertz-range stroboscopic x-ray generator and its application to high-speed angiography are described. This generator consists of the following major components: a main controller, a condenser unit with a Cockcroft-Walton circuit, and an x-ray tube unit in conjunction with a grid controller. The main condenser of about 500 nF in the unit is charged up to 120 kV by the circuit, and the electric charges in the condenser are discharged to the triode by the grid control circuit. Although the tube voltage decreased during the discharging for generating x-rays, the maximum value was equal to the initial charging voltage of the main condenser. The maximum tube current and the repetition rate were approximately 0.5 A and 50 kHz, respectively. The x-ray pulse width ranged from 0.01 to 1.0 ms, and the maximum shot number had a value of 32. At a charging voltage of 100 kV and a width of 1.0 ms, the x-ray intensity obtained using a 50- $\mu$ m-thick tungsten filter was 9.88  $\mu$ Gy at 1.0 m, and the dimensions of the focal spot had values of approximately  $1 \times 1$  mm. Angiography was performed using the filter at a charging voltage of 100 kV.

**Keywords:** energy-selective radiography, bremsstrahlung x-rays, filtering, stroboscopic x-ray, pulse x-ray, enhanced angiography

## 1. INTRODUCTION

Flash x-ray generators are capable of producing high-dose rate short x-ray pulses, and have been applied to high-speed radiography in various fields.<sup>1</sup> To produce hard flash x-rays with maximum photon energies of approximately 1 MeV, multistage Marx surge generators have been developed. Furthermore, induction linear accelerators have been developed

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Proc. of SPIE 59200V-1



and improved to produce 10-MeV-order flash x-rays.<sup>2</sup> In contrast, 100-kV-order flash x-ray generators have been developed and applied to biomedicine. Subsequently, soft x-ray lasers have been produced using a gas-discharge capillary,<sup>3-5</sup> and clean K-series characteristic x-rays<sup>6-9</sup> and their higher harmonic hard x-rays have been produced from weakly ionized linear plasma.

In high-speed medical radiography, the repetition rate is one of the technical key parameters in real-time dynamic radiography. In view of this situation, we have developed two stroboscopic x-ray generators<sup>10</sup> and have succeeded in producing repetitive x-rays with a maximum repetition rate of approximately 50 kHz. These generators employ 500 nF condensers and hot-cathode tungsten tubes, and the duration can be controlled from 10  $\mu$ s to 1.0 ms

Recently synchrotrons generate monochromatic parallel x-ray beams using a monochromator, and these beams have been employed to perform enhanced K-edge angiography.<sup>11-13</sup> To perform angiography, the beams with photon energies of approximately 35 keV have been used, because iodine contrast media with a K-absorption edge of 33.2 keV absorb the beams effectively. In view of this situation, we have developed x-ray generators with cerium-target tubes<sup>14,15</sup> which can produce K $\alpha$  rays (34.6 keV). Subsequently, we have performed energy-selective high-speed angiography<sup>16</sup> using quasi-monochromatic x-rays produced by the aluminum filtering.

Gadolinium-based contrast media with a K-edge of 50.2 keV have been employed to perform angiography in MRI, and the gadolinium density has been increasing. In view of this situation, K $\alpha$  rays of tantalum (57.1 keV)<sup>17</sup> and tungsten (58.9 keV) are also useful to perform angiography, because the K $\alpha$  rays are absorbed effectively by gadolinium media. As compared with angiography using iodine media, the absorbed dose can be decreased considerably utilizing angiography achieved with gadolinium media.

In this research, we employed a tungsten-target x-ray tube and performed a preliminary study on high-speed gadolinium angiography achieved with quasi-monochromatic x-rays produced by the tungsten filtering in conjunction with a computed radiography system.

## 2. GENERATOR

Figure 1 shows the block diagram of the kilohertz-range stroboscopic x-ray generator. This generator consists of the following major components: a main controller, a condenser unit with a Cockcroft-Walton circuit, and an x-ray tube unit in conjunction with a grid controller (Fig. 2). The main condenser of approximately 500 nF in the unit is charged up to 120 kV by the circuit, and the electric charges in the condenser are discharged to the triode by the grid control circuit. Although the tube voltage decreased during the discharging for generating x-rays, the maximum value was equal to the initial charging voltage of the main condenser. In this generator, positive and negative high voltages are applied to the anode and cathode electrodes, respectively.

The x-ray tube is a glass-enclosed hot-cathode triode and is composed of the following major parts: a rotating anode tube with a tungsten target, a focusing electrode, a hot cathode (filament), a grid, and a glass tube body. The electron beams from the cathode are accelerated between the anode and cathode electrodes and are converged to the target by the focusing electrode. The tube is set in the metal case filled with insulation oil, and the diaphragm regulates the irradiation field.

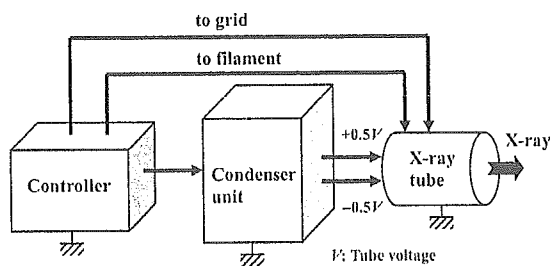


Figure 1: Block diagram of the kilohertz-range stroboscopic x-ray generator.

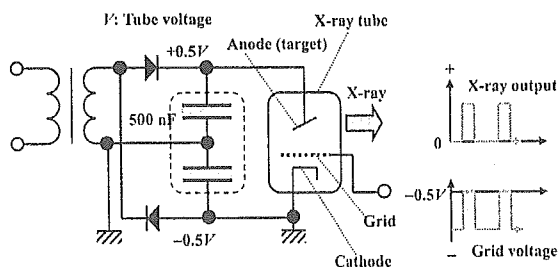


Figure 2: Main circuit of the kilohertz-range stroboscopic x-ray generator.

### 3. CHARACTERISTICS

#### 3.1 X-ray output

The x-ray output signal was measured by a digital storage scope (Fig. 3) at the indicated conditions. Using this generator, the pulse width could be controlled correctly and ranged from 10  $\mu$ s to 1.0 ms. The maximum repetition rate was approximately 50 kHz, and stable repetitive x-ray pulses were obtained.

#### 3.2 Time-integrated x-ray intensity

Figure 4 shows the time-integrated (absolute) value of the x-ray intensity at 1.0 m per pulse measured by a Victoreen 660 ionization chamber. The intensity was proportional to the driving pulse width. At a constant pulse width of 1.0 ms, the intensity increased with increases in the charging voltage. At a charging voltage of 100 kV and a width of 1.0 ms, the x-ray intensity obtained using a 50- $\mu$ m-thick tungsten filter was 9.88  $\mu$ Gy per pulse at 1.0 m from the source.

#### 3.3 X-ray source

The image of the x-ray source was measured using a pinhole camera with a hole diameter of 50  $\mu$ m and a computed radiography (CR) system (Konica Regius 150)<sup>18</sup> with a sampling pitch of 87.5  $\mu$ m. When the charging voltage was increased, the dimensions hardly varied, and were approximately 1  $\times$  1 mm.

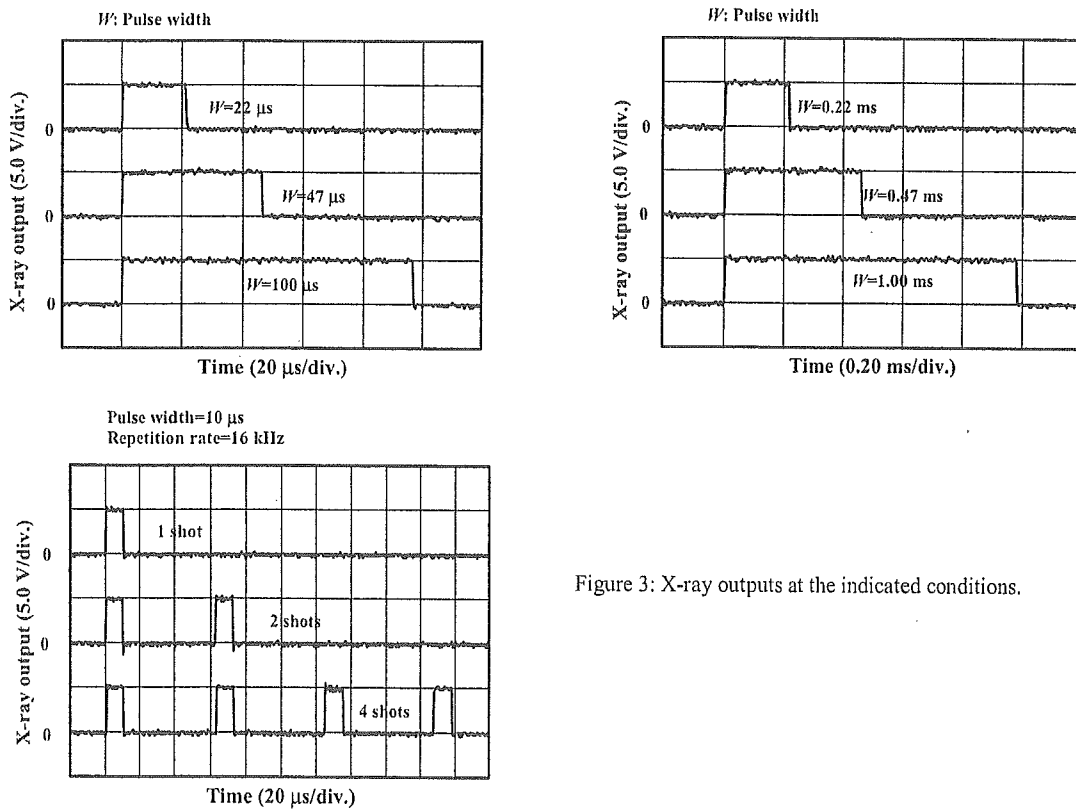


Figure 3: X-ray outputs at the indicated conditions.

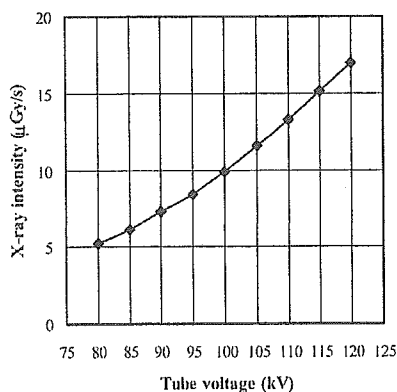


Figure 4: X-ray intensities at 1.0 m per pulse with changes in the charging voltage with an exposure time of 1.0 ms.

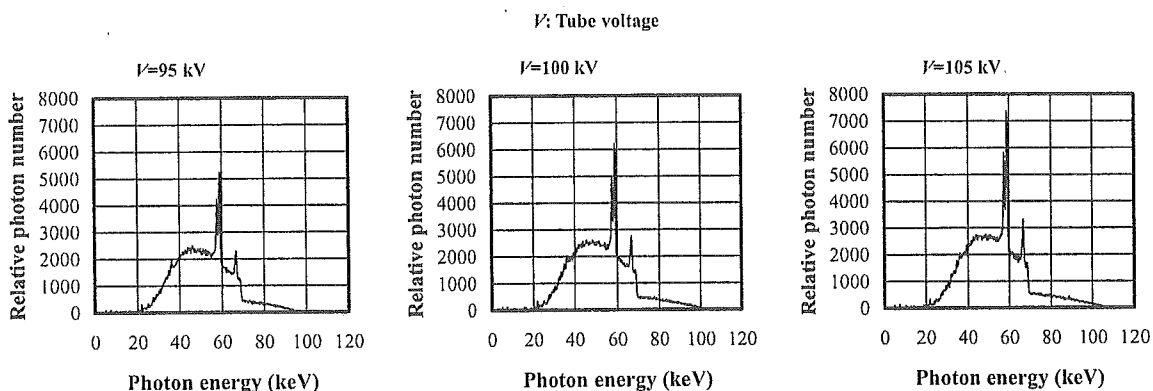


Figure 5: X-ray spectra at the indicated conditions.

### 3.4 X-ray spectra

In order to measure x-ray spectra with the filter, we employed a cadmium telluride detector (XR-100T, Amptek Inc.) (Fig. 5). When the charging voltage was increased, both the maximum photon energy and the intensities of bremsstrahlung x-rays increased, and the photon energy of the spectrum peak also increased. The areas under the spectral curves correlate closely to the total x-ray intensities shown in Fig. 4.

## 4. ANGIOGRAPHY

Figure 6 shows the mass attenuation coefficients of gadolinium at the selected energies; the coefficient curve is discontinuous at the gadolinium K-edge. The average photon energy of the tungsten  $K\alpha$  lines is shown just above the gadolinium K-edge. The average photon energy of tungsten  $K\alpha$  lines is 58.9 keV, and gadolinium contrast media with a K-absorption edge of 50.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts. The radiography was performed by the CR system using the filter with a charging voltage of 100 kV, and the distance between the x-ray source and the imaging plate was 1.0 m. The image contrast hardly varied even when the filter was changed.

Firstly, rough measurements of spatial resolution were made using wires. Figure 7 shows radiograms of tungsten wires coiled around rods 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. Next, the time resolutions were roughly observed using a plastic bullet from an air gun. Although we obtained completely stop-motion images of a bullet utilizing multi-shot radiography with a duration of 10  $\mu\text{s}$ , the average velocity could be measured with durations of sub-milliseconds (Fig. 8).

The image of water (20% gadolinium oxide suspension) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. Because the x-ray duration was 1.0 ms, the stop-motion image of water could be obtained. Figure 10 shows an angiogram of a polytetrafluoroethylene (Teflon) tube in a PMMA case using a contrast medium which contains approximately 65% gadodiamidehydrate with a duration of 1.0 ms, and a high-contrast tube with a bore diameter of 1.0 mm is observed. Figures 11 and 12 show angiograms of a rabbit ear and head using gadolinium oxide powder with a duration of 1.0 ms, and fine blood vessels of approximately 100  $\mu\text{m}$  were visible.

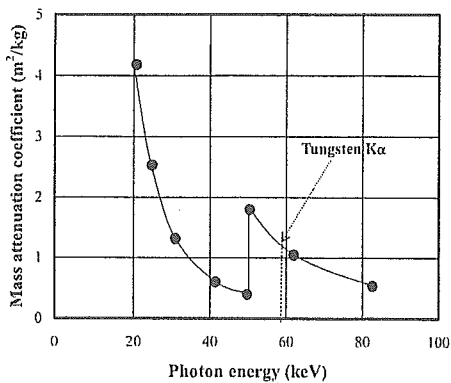


Figure 6: Mass attenuation coefficient of gadolinium and the average photon energy of tungsten  $K\alpha$  lines is shown above gadolinium K edge.

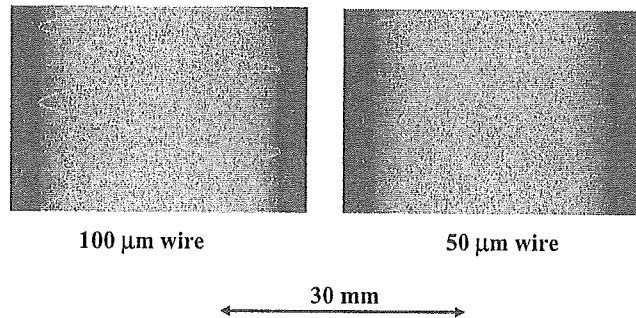
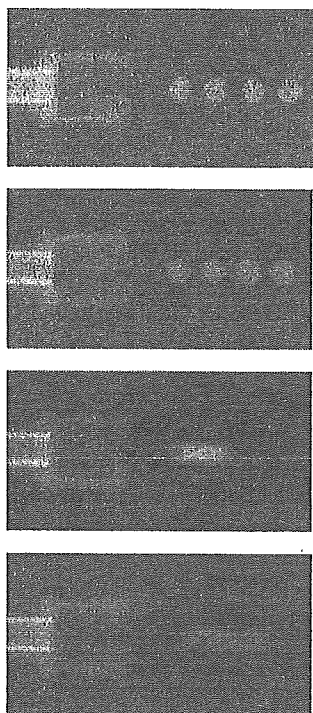


Figure 7: Radiograms of tungsten wires coiled around PMMA rods.



Rate=8.0 kHz  
Duration=10  $\mu\text{s}$   
4 shots

Rate=8.0 kHz  
Duration=18  $\mu\text{s}$   
4 shots

Duration=0.22 ms  
1 shot

Duration=0.47 ms  
1 shot

Figure 8: Radiograms of plastic bullets from an air gun at the indicated conditions.

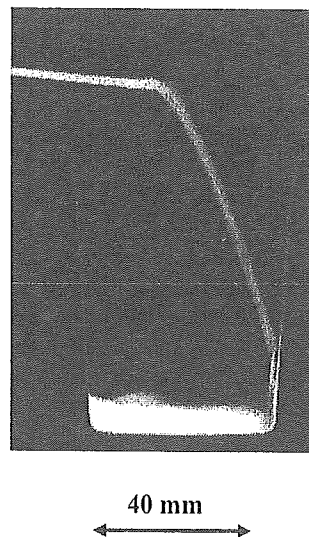


Figure 9: Radiogram of water falling into a polypropylene beaker from a glass test tube.

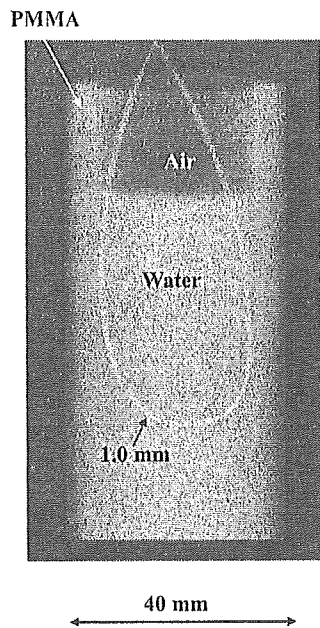


Figure 10: Angiography of a Teflon tube using a contrast medium which contains approximately 65% gadodiamidehydrate.

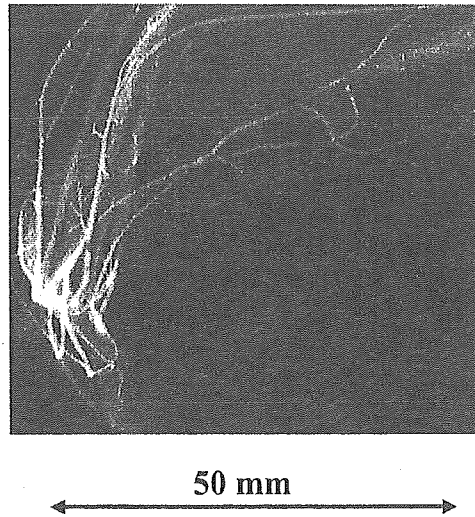


Figure 11: Angiography of a rabbit ear using gadolinium oxide powder.

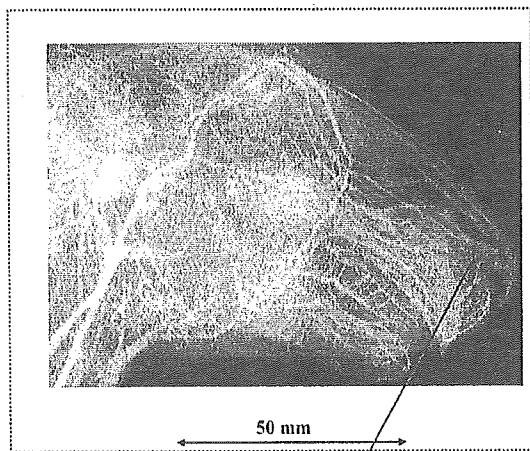
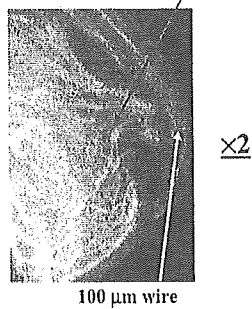


Figure 12: Angiography of a rabbit head using gadolinium oxide powder.



## 5. DISCUSSION

In summary, we succeeded in performing high-speed enhanced angiography utilizing tungsten K-series characteristic x-rays and gadolinium contrast media. As compared with angiography using iodine media, the absorbed dose could be decreased utilizing angiography achieved with gadolinium media.

Concerning the spectrum measurement, we obtained K-series characteristic x-rays using the tungsten filter. When the filter was employed with a charging voltage of 100 kV, the peak photon energy of the spectra was approximately 50 keV. Therefore, the filter thickness should be increased in order to decrease bremsstrahlung x-rays with energies lower than the K-absorption edge of tungsten. In the imaging, we have to consider the filtering effect of human body. Subsequently, K $\beta$  rays should be absorbed using an ytterbium oxide filter in order to improve the image contrast of blood vessels.

Using this filter with a charging voltage of 100 kV and a pulse width (exposure time) of 1.0 ms, although we obtained the x-ray intensities of approximately 10  $\mu$ Gy at 1.0 m per pulse, the intensity should be maximized by increasing the tube current in order to improve the image quality using the CR system.

Nowadays, because flat panel detectors are very useful in order to perform real-time dynamic imaging with high spatial resolutions of 100  $\mu$ m or less, stop-motion images of blood flows can be obtained using gadolinium media.

## ACKNOWLEDGMENT

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 16591181, and 16591222) and Advanced Medical Scientific Research from MECSS, Health and Labor Sciences Research Grants (RAMT-nano-001, RHGTEFB-genome-005 and RHGTEFB-saisei-003), Grants from the Keiryō Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and the New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

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# Preliminary study for producing higher harmonic hard x-rays from weakly ionized copper plasma

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## ABSTRACT

In the plasma flash x-ray generator, a 200 nF condenser is charged up to 50 kV by a power supply, and flash x-rays are produced by the discharging. The x-ray tube is a demountable triode with a trigger electrode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Target evaporation leads to the formation of weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target, and intense  $K\alpha$  lines are left using a 10- $\mu\text{m}$ -thick nickel filter. 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 16 kA. The K-series characteristic x-rays were clean and intense, and higher harmonic x-rays were observed. The x-ray pulse widths were approximately 300 ns, and the time-integrated x-ray intensity had a value of approximately 1.5 mGy per pulse at 1.0 m from the x-ray source with a charging voltage of 50 kV.

**Keywords:** weakly ionized linear plasma, K-series characteristic x-rays, clean characteristic x-rays, higher harmonic hard x-rays

## 1. INTRODUCTION

In order to produce soft x-ray lasers, several different methods have been developed, and a discharge capillary<sup>1-3</sup> is very useful to increase the laser pulse energy with increases in the capillary length. However, it is difficult to increase the laser photon energy to 10 keV or beyond.

Using monochromators, synchrotrons produce monochromatic parallel beams, which are fairly similar to monochromatic parallel laser beams, and the beams have been applied to various research project including

Ultrafast X-Ray Detectors, High-Speed Imaging, and Applications, edited by Stuart Kleinfelder, Dennis L. Paisley, Zenghu Chang, Jean-Claude Kleffer, Jerome B. Hastings, Proc. of SPIE Vol. 5920 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/\$15 · doi: 10.1117/12.620216

Proc. of SPIE 59200U-1



phase-contrast radiography<sup>4,5</sup> and enhanced K-edge angiography.<sup>6,7</sup> Because there are no x-ray resonators in the high-photon-energy region, new methods for increasing coherence will be desired in the future.

To apply flash x-ray generators to biomedicine, several different generators<sup>8-13</sup> have been developed, and plasma x-ray generators<sup>14-17</sup> are useful for producing clean characteristic x-rays in the low-photon-energy region of less than 20 keV. By forming weakly ionized linear plasma using rod targets, we confirmed irradiation of intense K-series characteristic x-rays from the axial direction of the linear plasmas of nickel, copper, and molybdenum, since the bremsstrahlung x-rays are absorbed effectively by the linear plasma; monochromatic clean K $\alpha$  rays were produced using K-edge filters. In this paper, we describe a recent plasma flash x-ray generator utilizing a rod target triode, used to perform a preliminary experiment for generating clean K-series characteristic x-rays and their higher harmonic hard x-rays by forming a plasma cloud around a fine target.

## 2. GENERATOR

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 turbomolecular pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. 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.

The schematic drawing of the plasma x-ray tube is illustrated in Fig. 2. The x-ray tube is a demountable cold-cathode triode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa. This tube consists of the following major parts: a hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a brass focusing electrode, 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 focusing electrode, evaporation leads to the formation of a weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x-rays. 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 opposite direction to that of electron trajectory, intense characteristic x-rays are generated from the plasma-axial direction.

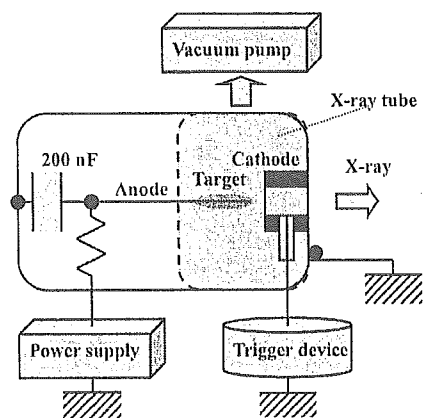


Figure 1: Block diagram including the electric circuit of the plasma flash x-ray generator.

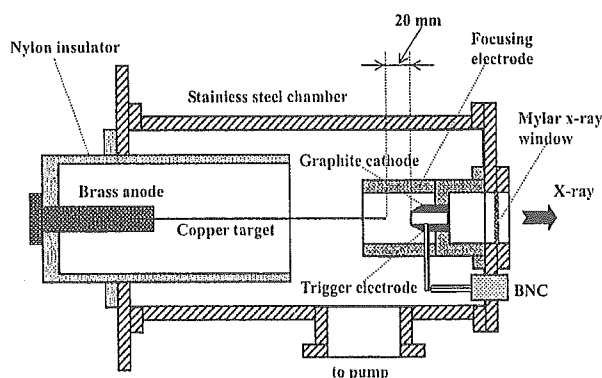


Figure 2: Schematic drawing of the flash x-ray tube with a rod copper target.

### 3. CHARACTERISTICS

#### 3.1 Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of  $1\text{ G}\Omega$  and a current transformer, respectively. Figure 3 shows the time relation between the tube voltage and current. At the indicated charging voltages, they roughly 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 16 kA.

#### 3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 4). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 300 ns, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 1.5 mGy at 1.0 m from the x-ray source with a charging voltage of 50 kV.

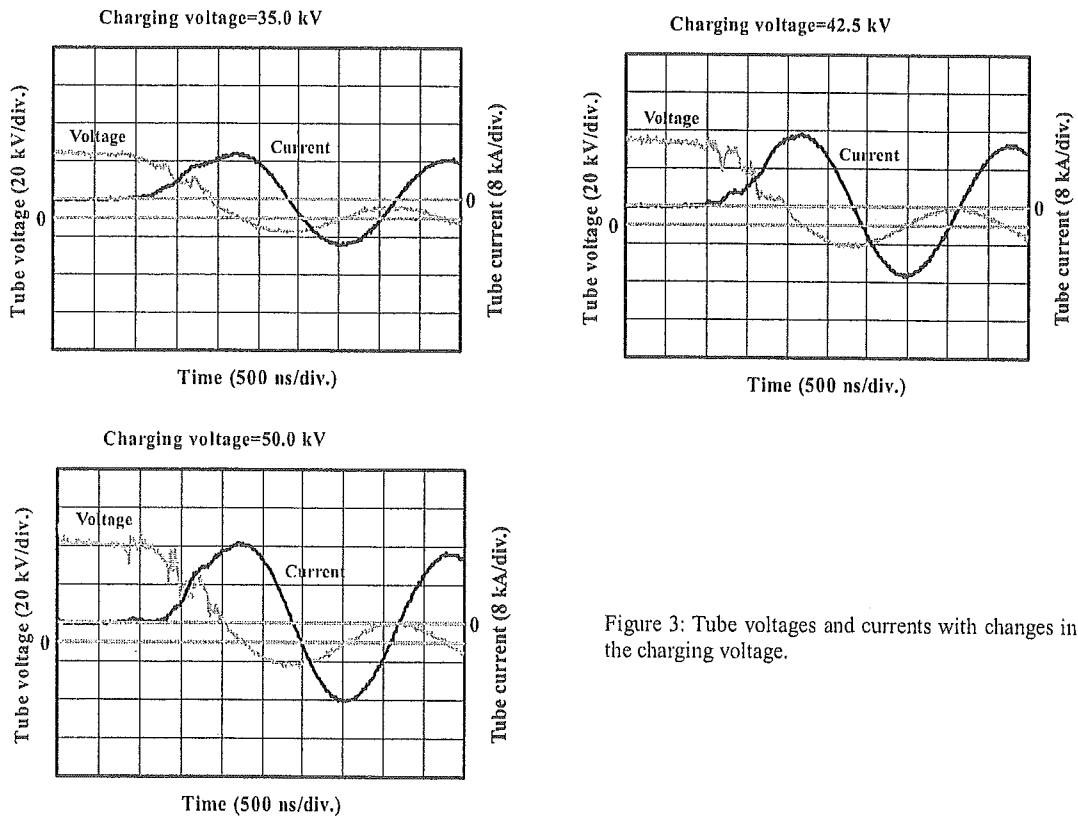


Figure 3: Tube voltages and currents with changes in the charging voltage.

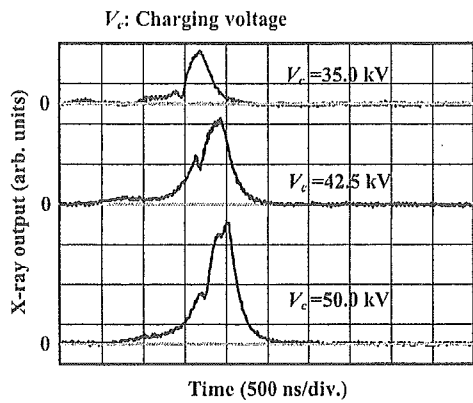


Figure 4: X-ray outputs at the indicated conditions.

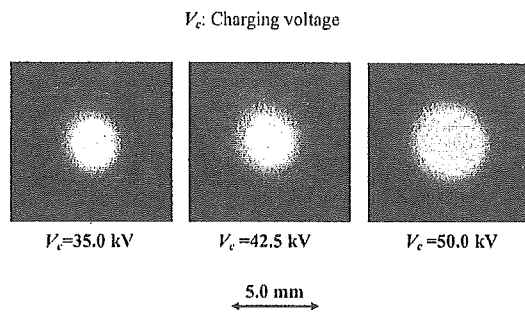


Figure 5: Images of the plasma x-ray source.

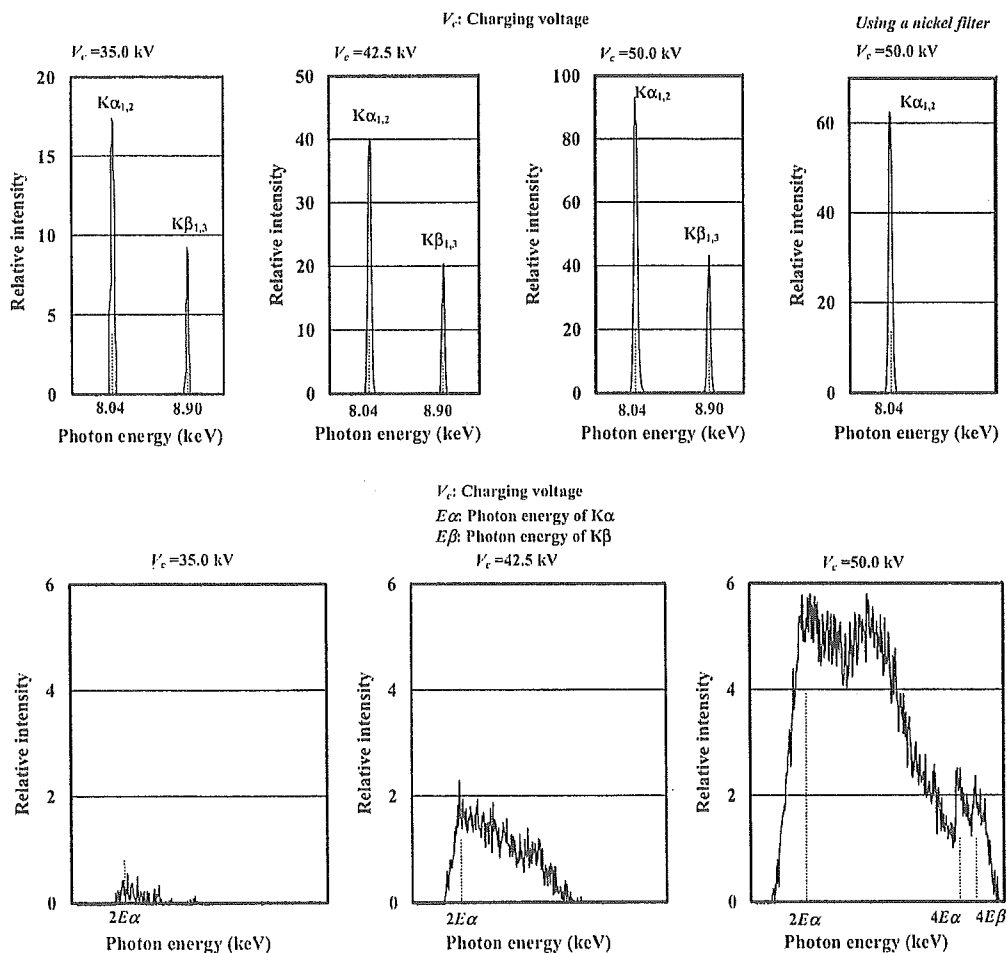


Figure 6: X-ray spectra from weakly ionized copper plasma at the indicated conditions.

### 3.3 X-ray source

In order to roughly observe images of the plasma x-ray source in the detector plane, we employed a pinhole camera with a hole diameter of  $100\ \mu\text{m}$  (Fig. 5). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased. Because the x-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing x-rays and decreases in the pinhole diameter.

### 3.4 X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer with a lithium fluoride curved crystal  $0.5\ \text{mm}$  in thickness. The spectra were taken by a computed radiography (CR) system<sup>18</sup> (Konica Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Subsequently, the relative x-ray intensity as a function of the data was calibrated using a conventional x-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 6 shows measured spectra from the copper target at the indicated conditions. In fact, we observed clean K lines such as  $K\alpha$  lines were left by absorbing  $K\beta$  lines using a  $10\text{-}\mu\text{m}$ -thick nickel filter. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage, and higher harmonic hard x-rays were observed.

## 4. RADIOGRAPHY

The plasma radiography was performed by the CR system using the filter. The charging voltage and the distance between the x-ray source and imaging plate were  $50\ \text{kV}$  and  $1.2\ \text{m}$ , respectively.

Firstly, rough measurements of spatial resolution were made using wires. Figure 7 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate (PMMA). Although the image contrast decreased somewhat with decreases in the wire diameter, due to blurring of the image caused by the sampling pitch of  $87.5\ \mu\text{m}$ , a  $50\text{-}\mu\text{m}$ -diameter wire could be observed.

Figure 8 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. Next, a radiogram of plastic bullets falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. Because the x-ray duration was about  $0.5\ \mu\text{s}$ , the stop-motion image of bullets could be obtained. Figure 10 shows an angiogram of a rabbit ear; iodine-based microspheres of  $15\ \mu\text{m}$  in diameter were used, and fine blood vessels of about  $100\ \mu\text{m}$  were visible.

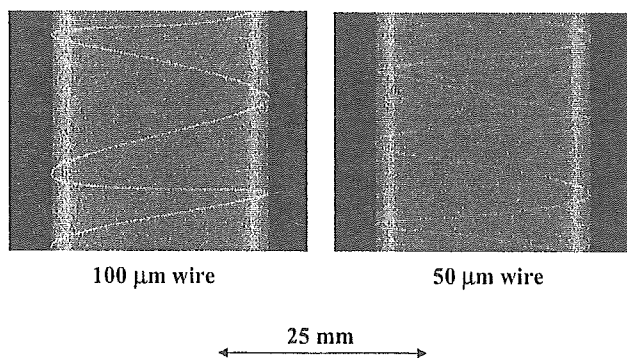


Figure 7: Radiograms of tungsten wires coiled around PMMA pipes.

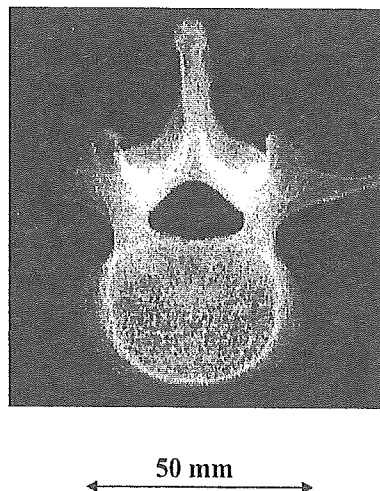


Figure 8: Radiogram of a vertebra.