

## Demonstration of flash K-edge angiography utilizing gadolinium-based contrast medium

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### ABSTRACT

The high-voltage condensers in a polarity-inversion two-stage Marx surge generator are charged from  $-50$  to  $-70$  kV by a power supply, and the electric charges in the condensers are discharged to an x-ray tube after closing gap switches in the surge generator with a trigger device. The x-ray tube is a demountable diode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Tungsten characteristic x rays can be produced, since the tube utilizes a disk cathode and a rod target, and bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration. At a charging voltage of  $-70$  kV, the instantaneous tube voltage and current were 140 kV and 1.0 kA, respectively. The x-ray pulse widths were approximately 90 ns, and the estimated number of K photons was approximately  $5 \times 10^8$  photons/cm<sup>2</sup> per pulse at 0.5 m from the source of 3.0 mm in diameter.

**Keywords:** angiography, gadolinium-based contrast media, characteristic x rays, quasi-monochromatic x rays, tungsten K lines

### 1. INTRODUCTION

So far, several different flash x-ray generators have been developed,<sup>1</sup> and soft generators<sup>2-6</sup> with photon energies of lower than 150 keV can be employed to perform biomedical radiography. In order to produce monochromatic x rays, plasma flash x-ray generators<sup>7-11</sup> are useful, since quite intense and sharp characteristic x rays such as lasers have been produced from weakly ionized linear plasmas of nickel, copper and molybdenum, while bremsstrahlung rays are hardly detected at all. Using these generators, the characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage.

Angiography using iodine-based contrast mediums is the current mainstay for observing blood vessels including coronary arteries. Conventional angiography uses an x-ray tube with a tungsten target, and bremsstrahlung x rays with just above the K-absorption edge (33.2 keV) are applied effectively, since the rays are absorbed easily by the iodine. Subsequently, synchrotrons have been used to form monochromatic parallel beams with photon energies of approximately 35 keV so as to perform enhanced K-edge angiography.<sup>12-15</sup>

Since K-series characteristic x rays from ytterbium, tantalum, and tungsten targets are absorbed effectively by gadolinium-based contrast media, these x rays are very useful for performing enhanced K-edge angiography. As compared with K-edge angiography using iodine-based contrast media with an iodine K-edge of 33.2 keV, the absorbed dose can be decreased easily in cases where the gadolinium media are employed.

In the present research, we developed a quasi-monochromatic flash x-ray generator with a tungsten target tube, and used it to perform a preliminary study on angiography achieved with tungsten K-series characteristic x rays.

## 2. PRINCIPLE OF K-EDGE ANGIOGRAPHY

Figure 1 shows the mass attenuation coefficients of gadolinium at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The average photon energy of the cerium  $K\alpha$  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.

## 3. GENERATOR

### 3.1 High-voltage circuit

Block diagram of a compact monochromatic flash x-ray generator is shown in Fig. 2. This generator consists of the following components: a constant high-voltage power supply, a surge Marx generator with a capacity during main discharge of 425 pF, a thyatron trigger device for the surge generator, a turbomolecular pump, and a flash x-ray tube. Since the electric circuit of the high-voltage pulse generator employs a polarity-inversion two-stage Marx line (Fig. 3), the surge generator produces twice the potential of the condenser charging voltage. When two condensers inside of the surge generator are charged from -50 to -70 kV, the ideal output voltage ranges from 100 to 140 kV.

### 3.2 X-ray tube

The x-ray tube is a demountable diode type, as illustrated in Fig. 4. This tube is connected to the turbomolecular pump with a pressure of about 1 mPa and consists of the following major devices: a rod-shaped tungsten target 3.0 mm in diameter, a disk cathode made of graphite, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a polymethyl methacrylate (PMMA) tube body. The target-cathode space was regulated to 1.25 mm from the outside of the x-ray tube by rotating the anode rod, and the transmission x rays are obtained through a 1.0-mm-thick graphite cathode and an x-ray window. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 5), tungsten characteristic x rays can be produced.

## 4. CHARACTERISTICS

### 4.1 Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 10 k $\Omega$  and a current transformer, respectively (Fig. 6). The voltage and current displayed roughly damped oscillations because the discharge resistance in the tube varied rapidly from infinity to approximately 0  $\Omega$  during the discharge. Thus, at the first quarter cycle of the oscillations, when the voltage decreased, the current increased. The instantaneous voltage and current increased with increases in the charging voltage, and the voltage and current were approximately 140 kV and 1.0 kA, respectively, at a charging voltage of -70 kV.

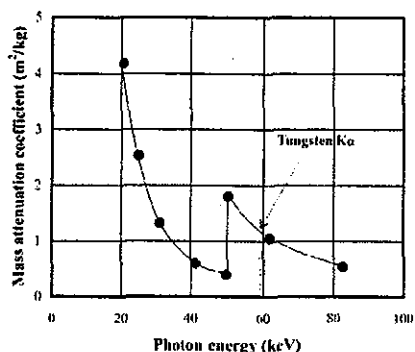


Figure 1: Relation between mass attenuation coefficient of iodine and average photon energy of tungsten K $\alpha$  lines.

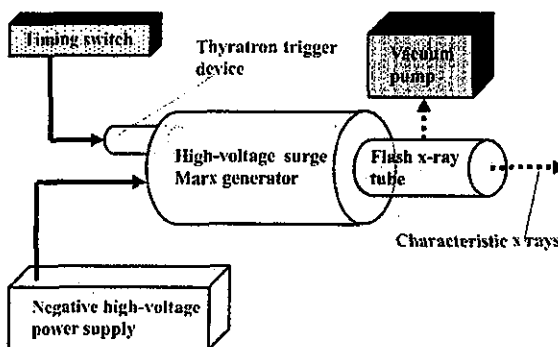


Figure 2: Block diagram of compact quasi-monochromatic flash x-ray generator.

Negative high-voltage input (-50~70 kV)

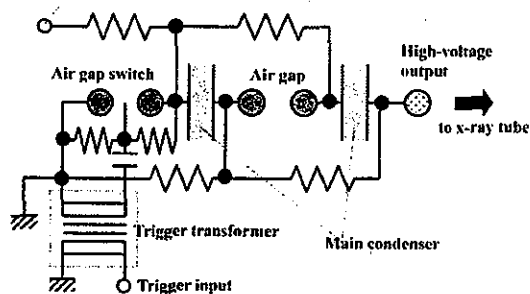


Figure 3: Circuit diagram of two-stage surge Marx generator.

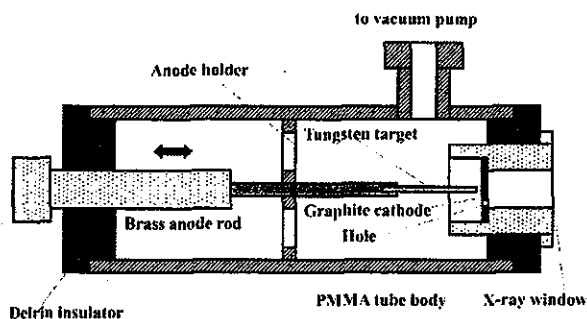


Figure 4: Schematic drawing of flash x-ray tube.

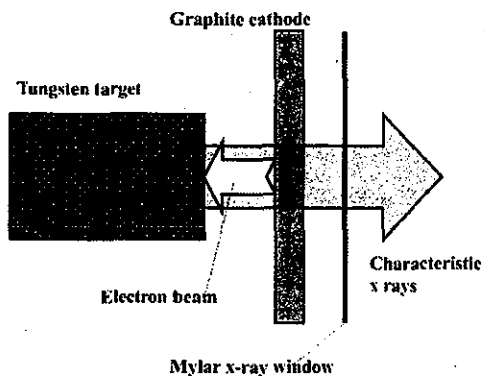


Figure 5: Irradiation of characteristic x rays.

#### 4.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 7). When the charging voltage was increased, the pulse height increased, but the width seldom varied. The widths were about 90 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 an instantaneous value of approximately 5  $\mu\text{C}/\text{kg}$  per pulse at 0.5 m from the x-ray source with a charging voltage of -70 kV.

### 4.3 X-ray source

In order to observe the x-ray source, we employed a 100- $\mu\text{m}$ -diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 8). When the charging voltage was increased, the spot intensity increased, and the intensities corresponded well to the x-ray pulse height. The dimension was almost equal to the target diameter and had a value of about 3.0 mm.

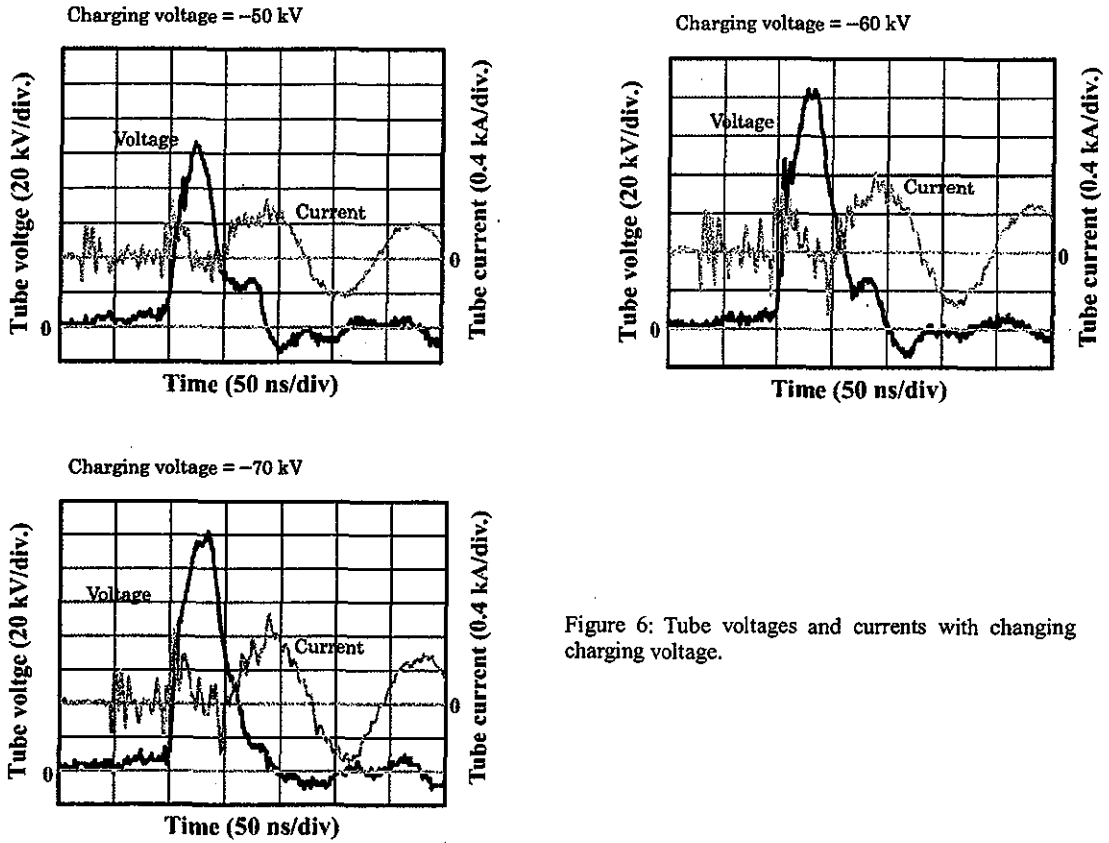


Figure 6: Tube voltages and currents with changing charging voltage.

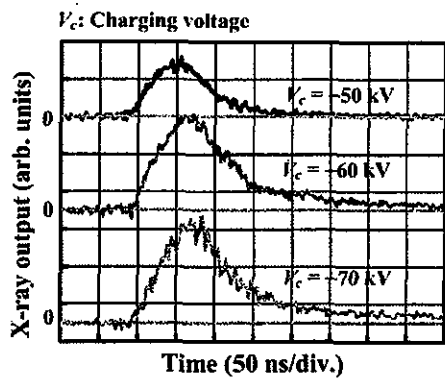


Figure 7: X-ray outputs at indicated conditions.

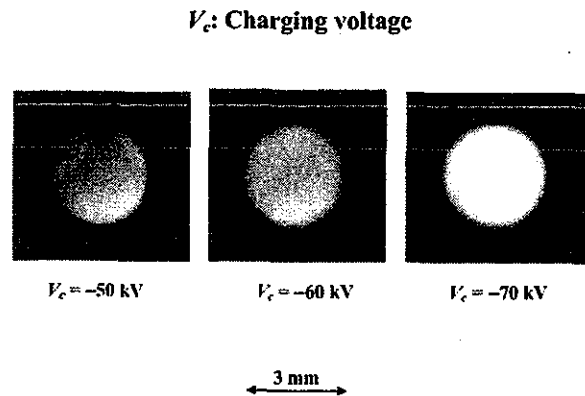


Figure 8: Images of the characteristic x-ray source with changes in charging voltage.

## 5. ANGIOGRAPHY

The flash angiography was performed by a computed radiography (CR) system (Konica Regius 150)<sup>16</sup> at 0.5 m from the x-ray source, and the charging voltage was 70 kV.

Firstly, rough measurements of spatial resolution were made using wires. Figure 9 shows radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate. Although the image contrast increased with increases in the wire diameter, a 50  $\mu\text{m}$ -diameter wire could be observed.

The image of plastic bullets falling into a polypropylene beaker from a glass test tube is shown in Fig. 10. Because the x-ray duration was approximately 100 ns, the stop-motion image of bullets could be obtained.

Angiograms of rabbit hearts are shown in Fig. 11. This image was obtained using iodine microspheres of 15  $\mu\text{m}$ . Because the microspheres transmitted tungsten K-series characteristic x rays easily, the coronary arteries were barely visible. Figure 12 shows an angiogram of a polytetrafluoroethylene (Teflon) tube using a contrast medium which contains 7.5% gadolinium by weight, and a low contrast tube with an inside diameter of 1.0 mm is observed. Subsequently, a radiogram of gadolinium oxide powder in the Teflon tube is shown in Fig. 13, and the gadolinium oxide powder is visible. In cases where a gadolinium oxide suspension of 50% by weight is employed, high-contrast angiography of the tube could be performed (Fig. 14).

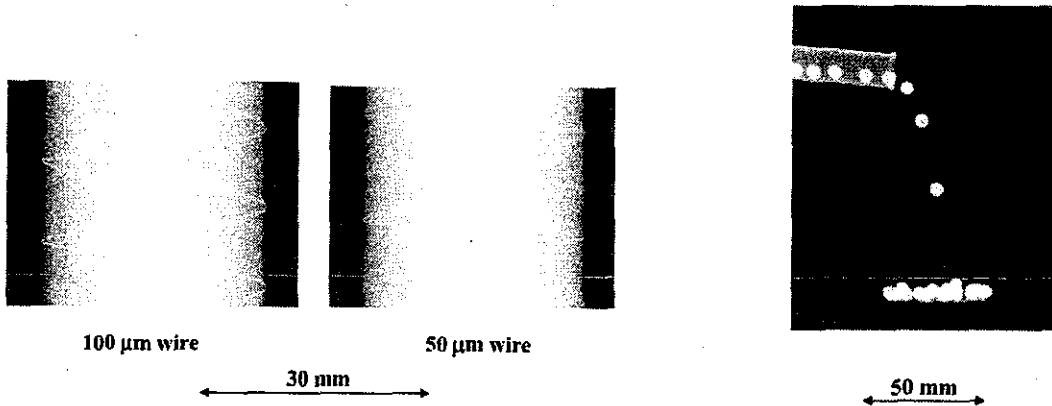


Figure 9: Radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate.

Figure 10: Radiogram of plastic bullets falling into polypropylene beaker from glass test tube.

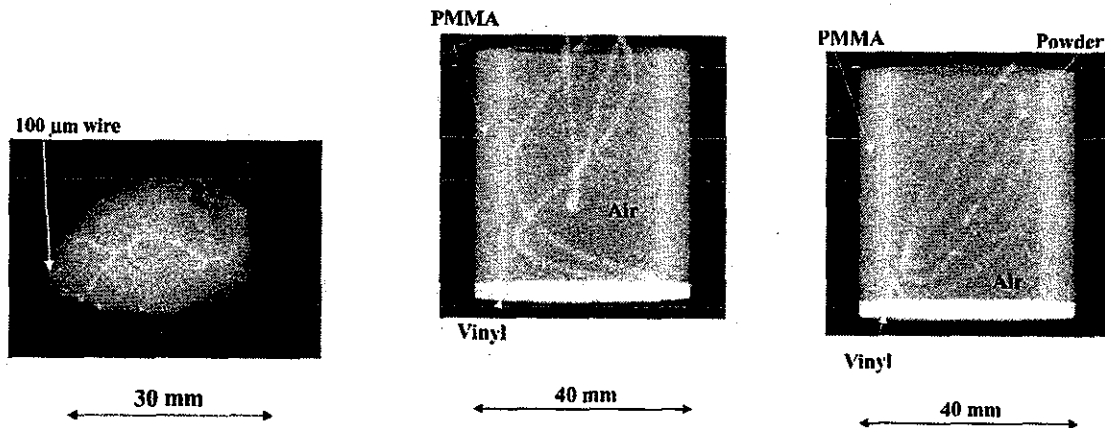


Figure 11: Angiograms of rabbit hearts using iodine microspheres.

Figure 12: Angiograms of Teflon tube using gadolinium contrast medium of 7.5% by weight.

Figure 13: Radiography of gadolinium oxide powder in Teflon tube.

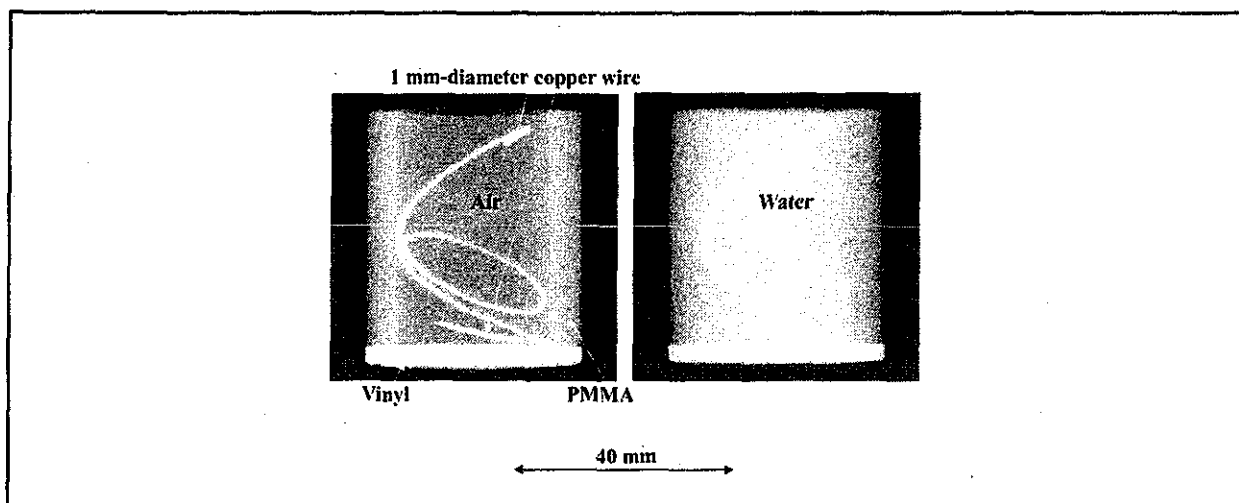


Figure 14: Angiography of Teflon tube using gadolinium oxide suspension of 50 % by weight.

## 6. DISCUSSION

Concerning the spectrum measurement, we have succeeded in measuring K-series characteristic x rays from a cerium target using a curved-crystal spectrometer. However, the tungsten K-series characteristic x rays could not be measured using the spectrometer utilizing a lithium fluoride crystal, because both the diffraction efficiency and the intensity substantially decreased with increases in photon energy. Therefore, optimum single crystal should be selected, and the measurements of the attenuation curve will be a conventional technique to confirm the irradiation of K-series characteristic x rays; the curve of transmittivity (logarithmic scale) vs absorber thickness is almost linear when bremsstrahlung x rays are not produced. In addition, L-series characteristic rays should be absorbed as much as possible before angiography using a tungsten or an ytterbium oxide filter. In these cases, the photon energies of the K-absorption edge of tungsten and ytterbium are 69.5 and 61.3 keV, respectively.

In this research, the generator produced instantaneous number of  $K\alpha$  photons was approximately  $5 \times 10^8$  photons/cm<sup>2</sup> per pulse at 0.5 m from the source. Because the molybdenum plasma generator produced approximately  $2 \times 10^9$  photons/cm<sup>2</sup> per pulse at 0.5 m from the source, the x-ray intensity of  $K\alpha$  lines had a lower value as compared with the plasma x-ray generator described above, which utilizes a large capacity condenser of approximately 200 nF.

Using this flash x-ray generator, the photon energy of characteristic x rays can be selected, and we plan to design a high-speed photon-counting radiography system in order to decrease noise from radiograms. In addition, steady-state monochromatic x rays for fluoroscopy can be produced by a similar tube using a constant high-voltage power supply. In conjunction with the fine focusing, these low-cost monochromatic x-ray generators will be employed to perform K-edge angiography and x-ray phase imaging for edge enhancement.

## ACKNOWLEDGMENT

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## Superposition of x-ray spectra using double-target plasma triode

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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 double target consisting of a copper and a molybdenum rods, 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 metal ions and electrons, around the fine target, and intense characteristic x rays are produced. 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 11 kA. When the charging voltage was increased, the linear plasma formed, and the molybdenum K-series characteristic x-ray intensities increased substantially. Although the intensities of copper K $\alpha$  lines increased with increases in the charging voltage, hardly any clean K $\beta$  lines were detected. The x-ray pulse widths were approximately 1.2  $\mu$ s, and the time-integrated x-ray intensity was approximately 30  $\mu$ C/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

**Keywords:** flash x-ray, plasma x-ray, weakly ionized linear plasma, characteristic x rays, x-ray superposition

### 1. INTRODUCTION

Monochromatic x-ray computed tomography at two different energies has provided information about the electron density of human tissue.<sup>1</sup> In addition, a compact pulsed tunable monochromatic x-ray source has been designed, developed, and tested.<sup>2</sup> From the source, cone x-ray beams from 10 to 50 keV with pulse widths of 8 ps have been produced, and these beams are useful for biomedical imaging and protein crystallography.

Most flash x-ray generators utilize surge Marx generators<sup>3,4</sup> in conjunction with cold-cathode diodes and produce extremely short x-ray pulses with durations of less than 1  $\mu$ s. In the surge generator, the output voltage is equal to the value of the condenser charging voltage multiplied by the stage number. Because the high-voltage durability substantially increased under the pulsed operation, the maximum photon energy of flash x rays has been increased to 1 MeV or beyond so as to perform military applications.

To perform biomedical radiography, we have developed several different soft flash x-ray generators<sup>5-10</sup> corresponding to specific radiographic objectives, and a major goal in our research is the development of an intense and clean



monochromatic x-ray generator that can impact applications with biomedical radiography with photon energies of approximately 10 keV or beyond. In view of this situation, we confirmed irradiation of intense K-series characteristic x rays from the plasma axial direction by forming weakly ionized linear plasma.<sup>11-15</sup> On the other hand, we are very interested in the superposition of characteristic x rays in order to perform wide latitude radiography or energy subtraction radiography.

In this paper, we describe a plasma flash x-ray generator utilizing a double-target radiation tube, used to perform a preliminary experiment for the superposition of characteristic x rays

## 2. GENERATOR

### 2.1 High-voltage circuit

Figure 1 shows a block diagram of a high-intensity plasma flash x-ray generator. The 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. In this generator, a low-impedance transmission line is employed in order to increase maximum tube current (Fig. 2). The high-voltage main condenser is charged up 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 turbomolecular pump with a pressure of approximately 1 mPa (Fig. 3). This tube consists of the following major parts: a pipe-shaped graphite cathode with a bore diameter of 10.0 mm, a trigger electrode made from copper wire, a brass focusing electrode, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a double-rod target. The target is composed of a copper rod and a molybdenum rod each 2.0 mm in diameter, and the plasma length is primarily determined by the distance between the target tip and the graphite ring. 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 weakly ionized linear plasma, consisting of metal ions and electrons, around the fine target.

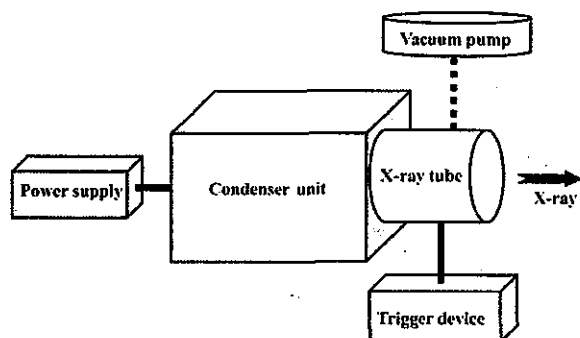


Figure 1: Block diagram of high-intensity plasma flash x-ray generator.

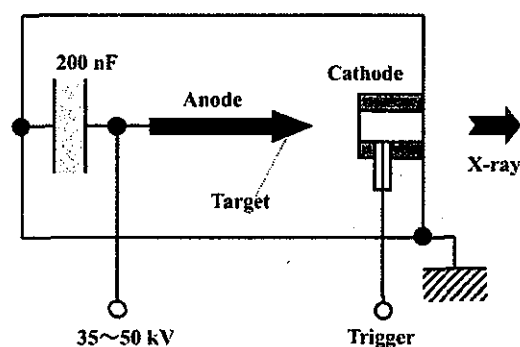


Figure 2: Circuit diagram of flash x-ray generator.

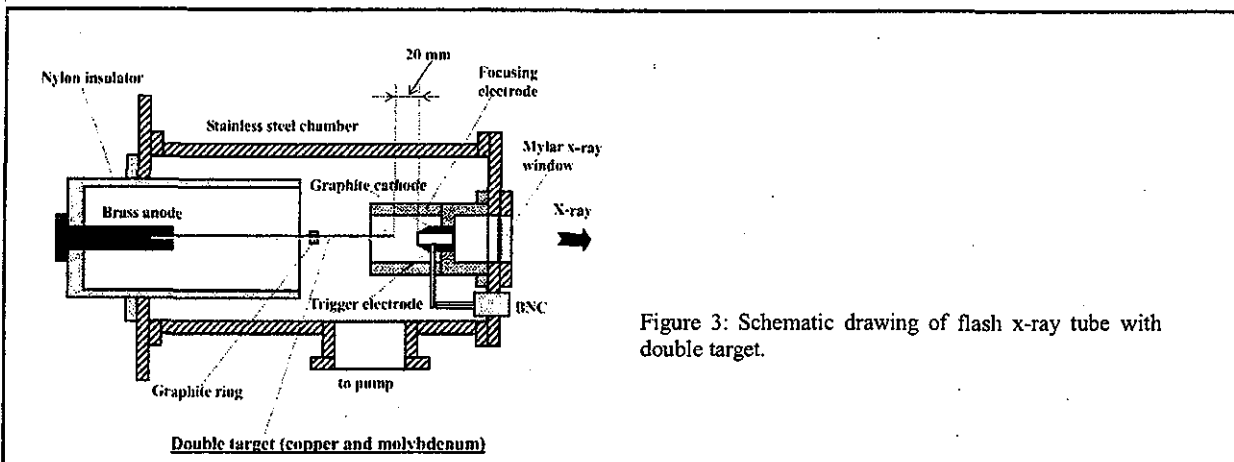


Figure 3: Schematic drawing of flash x-ray tube with double target.

### 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 GΩ and a current transformer, respectively. Figure 4 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 11 kA.

#### 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 1.2 μs, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 with MSO-S elements without energy compensation) had a value of approximately 30 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

#### 3.3 X-ray source

In order to roughly observe images of the plasma x-ray source in the detector plane, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 6). At a charging voltage of 35 kV, we observed two spots of the double target. 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 two targets, 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 mm in thickness. The spectra were taken by a computed radiography (CR) system<sup>16</sup> with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data.

Figure 7 shows measured spectra near molybdenum K-series characteristic x rays. We observed sharp lines of K-series characteristic x rays of molybdenum. However bremsstrahlung rays were only detected slightly. The molybdenum characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage. In the measurement of copper spectra (Fig. 8), although fairly clean Kα lines were observed, any sharp Kβ lines were hardly detected. In addition, we found lines of 0.5E<sub>α</sub> but 0.5E<sub>β</sub> lines were not detected. Here, E<sub>α</sub> and E<sub>β</sub> are the average photon energies of molybdenum Kα and Kβ lines, respectively.

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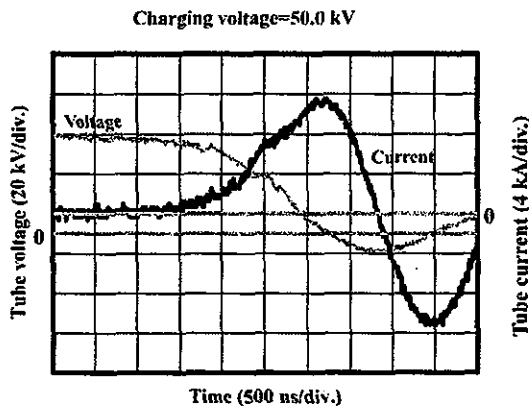
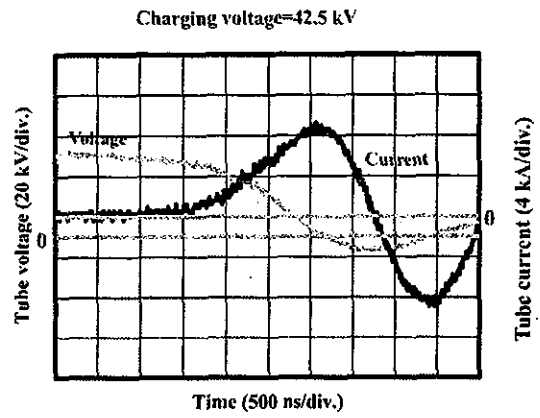
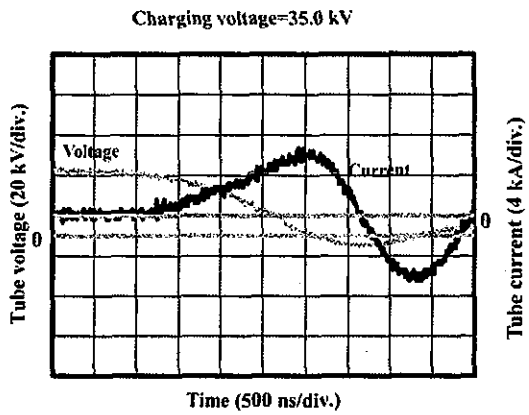


Figure 4: Tube voltages and currents with changing charging voltage.

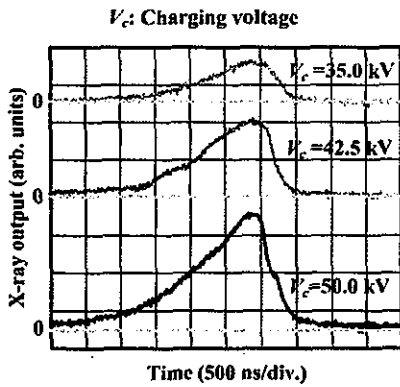


Figure 5: X-ray outputs at indicated conditions.

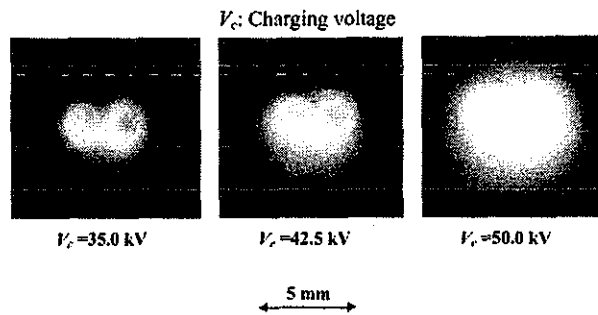


Figure 6: Images of plasma x-ray source of double target.

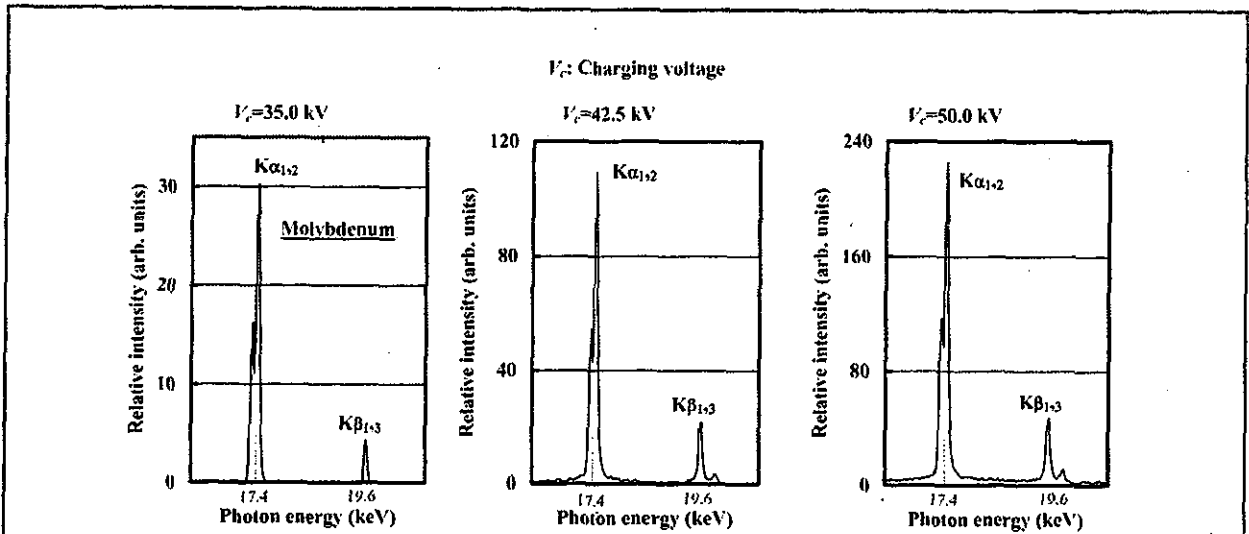


Figure 7: X-ray spectra near molybdenum K-series characteristic x rays.

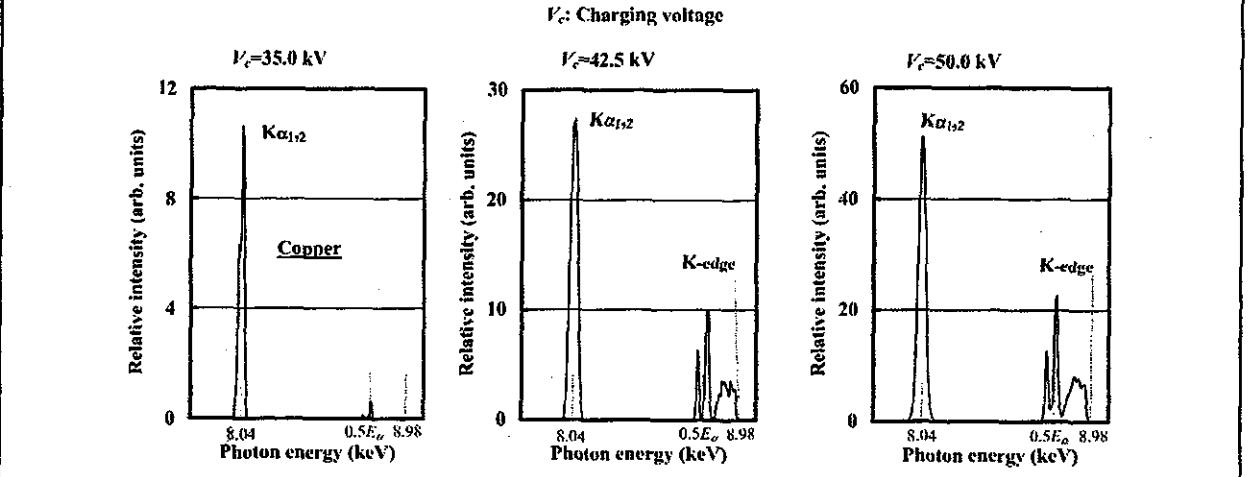


Figure 8: X-ray spectra near copper K-series characteristic x rays.

#### 4. RADIOGRAPHY

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

Figure 9 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate with a charging voltage of 45 kV. Although the image contrast increased with increases in the wire diameter, a 50- $\mu$ m-diameter wire could be observed. Next, the image of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 10. This image was taken with a charging voltage of 50 kV, and an iodine-based contrast medium was added a little. Because the x-ray duration was about 1  $\mu$ s, the stop-motion image of water was obtained. Figure 11 shows an angiogram of the external ear of a rabbit with a charging voltage ( $V_c$ ) of 45 kV. In angiography, iodine-based microspheres of 15  $\mu$ m in diameter were used, and fine blood vessels of about 100  $\mu$ m are clearly visible. Figures 12 and 13 show angiograms of a rabbit heart ( $V_c=45$  kV) and a thigh ( $V_c=50$  kV), respectively, and fine blood vessels were visible.

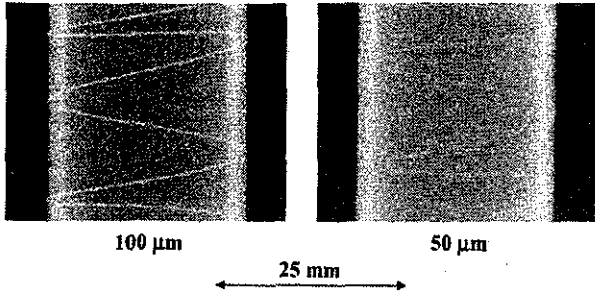


Figure 9: Radiograms of tungsten wires coiled around pipe made of polymethyl methacrylate.

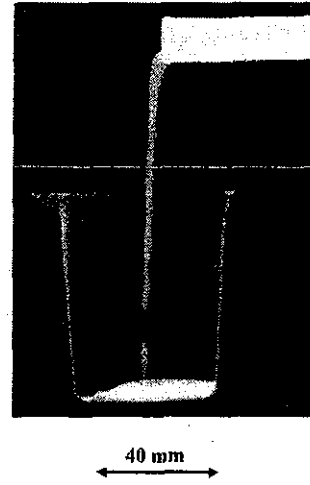


Figure 10: Radiogram of water from glass test tube.

**50  $\mu\text{m}$  wire**

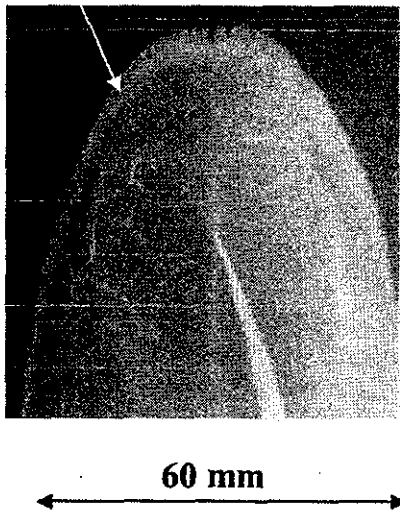


Figure 11: Angiogram of external ear.

**100  $\mu\text{m}$  tungsten wire**

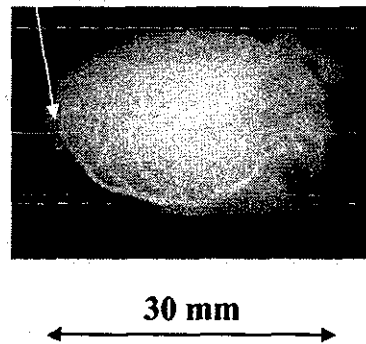


Figure 12: Angiogram of rabbit heart.

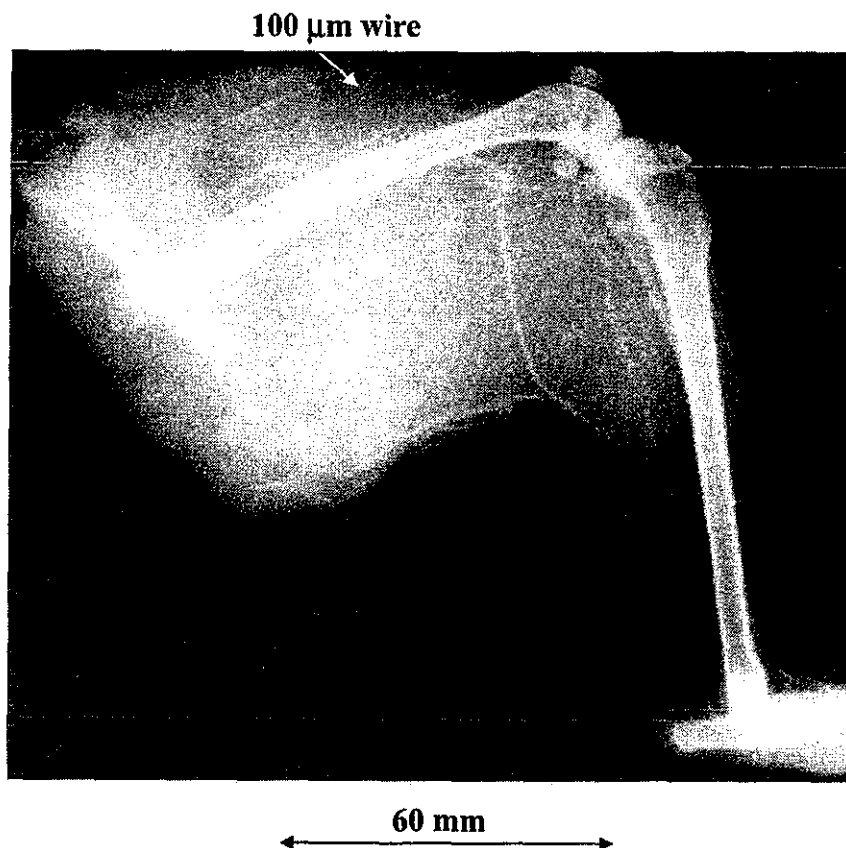


Figure 13: Angiogram of rabbit thigh.

## 5. DISCUSSION

Regarding the spectrum measurement, although we obtained intense and sharp molybdenum K-series lines, we could not observe copper  $K\beta$  lines. In addition, we observed  $0.5E_c$  lines and the copper K-absorption edge. If we assume that the  $0.5E_c$  lines are molybdenum  $K\alpha$  lines detected by the high order diffraction, the molybdenum  $K\beta$  lines, the copper  $K\beta$  lines, and the bremsstrahlung rays should be observed.

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  $4 \times 10^8$  photons/cm<sup>2</sup> at 1.0 m per pulse. 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 flash energy subtraction radiography using a metal filter and wide latitude radiography, will be possible.

## ACKNOWLEDGMENT

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## Intense quasi-monochromatic flash x-ray generator utilizing molybdenum-target diode

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### ABSTRACT

In the flash x-ray generator, a 150 nF condenser is charged up to 80 kV by a power supply, and flash x rays are produced by the discharging. The x-ray tube is a demountable diode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Since the electric circuit of the high-voltage pulse generator employs a cable transmission line, the high-voltage pulse generator produces twice the potential of the condenser charging voltage. At a charging voltage of 80 kV, the estimated maximum tube voltage and current were approximately 160 kV and 40 kA, respectively. When the charging voltage was increased, the K-series characteristic x-ray intensities of molybdenum increased. The K lines were clean and intense, and hardly any bremsstrahlung rays were detected at all. The x-ray pulse widths were approximately 100 ns, and the time-integrated x-ray intensity had a value of approximately 15  $\mu\text{C}/\text{kg}$  at 1.0 m from the x-ray source with a charging voltage of 80 kV.

**Keywords:** flash x-ray, energy-selective radiography, characteristic x rays, quasi-monochromatic x rays, bremsstrahlung x-ray distribution

### 1. INTRODUCTION

In recent years, there have been several investigations dealing with the production of monochromatic x rays in radiology and cardiology. Particularly, monochromatic parallel beams using synchrotrons have been employed to perform enhanced K-edge angiography<sup>1,2</sup> and x-ray phase imaging.<sup>3,4</sup> In angiography, parallel beams with photon energies of approximately 35 keV have been employed, since these beams are absorbed effectively by an iodine-based contrast medium. Subsequently, in cases where phase imaging is employed, the spatial resolution can be improved, and the number of tissues which can be observed using x rays increases.

In order to perform biomedical radiography, we have developed several different soft flash x-ray generators<sup>5-10</sup> corresponding to specific radiographic objectives. Subsequently, electron impact flash x-ray sources can produce quasi-monochromatic x rays, because bremsstrahlung rays are not emitted in the opposite direction to that of electron



acceleration.<sup>11</sup> Therefore, the sources will be conventional x-ray tubes for producing cone-beam K-series characteristic x rays, and monochromatic  $K\alpha$  rays are obtained using a K-edge filter.

We have developed several different plasma flash x-ray generators<sup>12-16</sup> corresponding to specific radiographic objectives, and a major goal in our research is the development of an intense and sharp monochromatic x-ray generator that can impact applications with biomedical radiography. By forming weakly ionized linear plasma, because we have succeeded in producing fairly intense and clean K-series characteristic x rays. Without forming the linear plasma, characteristic x rays can be produced by considering the angle dependence of bremsstrahlung x rays. On the other hand, the electrostatic energy in the main discharge condenser should be increased as much as possible to increase the characteristic x-ray intensity.

In this paper, we describe an intense single flash x-ray generator utilizing a rod-target radiation tube, used to perform a preliminary experiment for generating intense and clean molybdenum K-series characteristic x rays.

## 2. GENERATOR

### 2.1 High-voltage circuit

Figure 1 shows a block diagram of a high-intensity plasma flash x-ray generator. The generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 150 nF, an air gap switch, a turbomolecular pump, a thyatron pulse generator as a trigger device, and a flash x-ray tube. In this generator, a coaxial cable transmission line is employed in order to increase maximum tube voltage using high-voltage reflection. The high-voltage main condenser is charged up to 80 kV by the power supply, and electric charges in the condenser are discharged to the tube through the four cables after closing the gap switch with the trigger device (Fig. 2).

### 2.2 X-ray tube

The x-ray tube is a demountable cold-cathode diode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa (Fig. 3). This tube consists of the following major parts: a ring-shaped graphite cathode with an inside diameter of 4.5 mm, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped molybdenum target 3.0 mm in diameter. The distance between the target and cathode electrodes can be regulated from the outside of the tube, and is set to 1.5 mm. 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 weakly ionized plasma, consisting of molybdenum ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 4), molybdenum K-series characteristic x rays can be produced without using a filter.

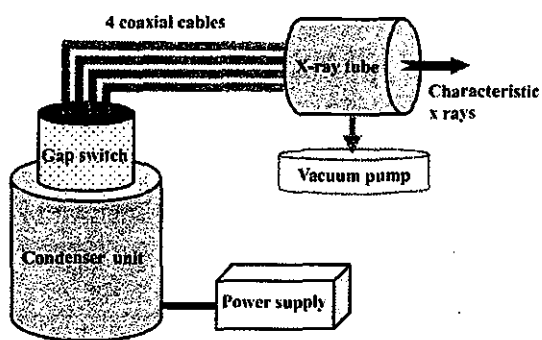


Figure 1: Block diagram of intense quasi-monochromatic flash x-ray generator.

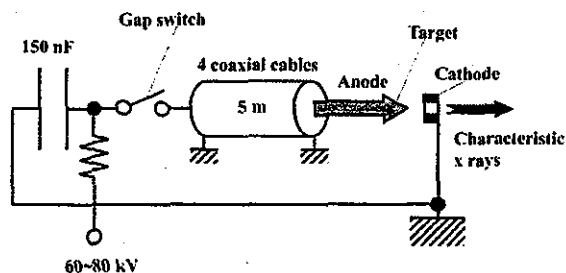


Figure 2: Circuit diagram of flash x-ray generator.

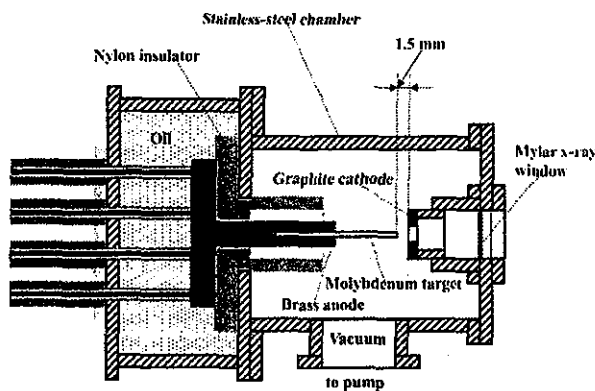


Figure 3: Schematic drawing of flash x-ray tube.

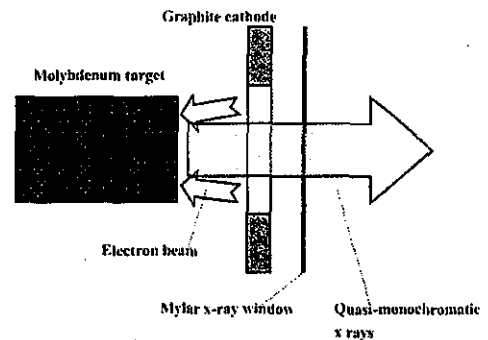


Figure 4: Irradiation of characteristic x rays.

### 3. CHARACTERISTICS

#### 3.1 Tube voltage and current

In this generator, it was difficult to measure the tube voltage and current since the tube voltages were high, and there was no space to set a current transformer for measuring the tube current. Currently, the voltage and current roughly displayed damped oscillations. When the charging voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 80 kV, the estimated maximum values of the tube voltage and current were approximately 160 kV (2 times the charging voltage) and 40 kA, respectively.

#### 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 increased with corresponding increases in the charging voltage. The x-ray pulse widths were approximately 100 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 15  $\mu\text{C}/\text{kg}$  at 1.0 m from the x-ray source with a charging voltage of 80 kV.

#### 3.3 X-ray source

In order to observe the characteristic x-ray source, we employed a 100- $\mu\text{m}$ -diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 6). 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 were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system (Konica Regius 150)<sup>17</sup> with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 7 shows measured spectra from the molybdenum target. We observed clean K-series lines, while bremsstrahlung rays were hardly detected at all. The characteristic x-ray intensity substantially increased with increases in the charging voltage.

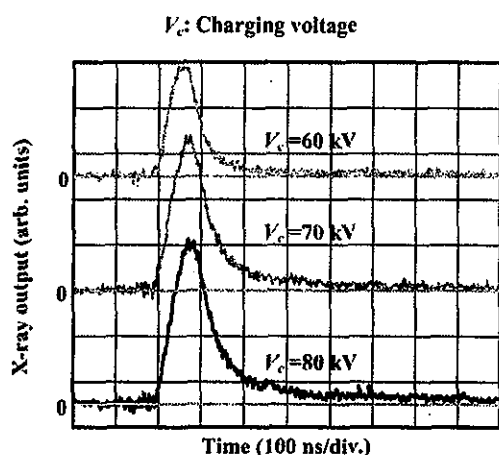


Figure 5: X-ray outputs at indicated conditions.

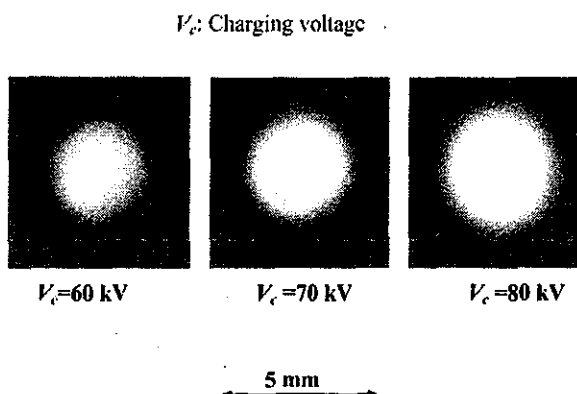


Figure 6: Images of characteristic x-ray source.

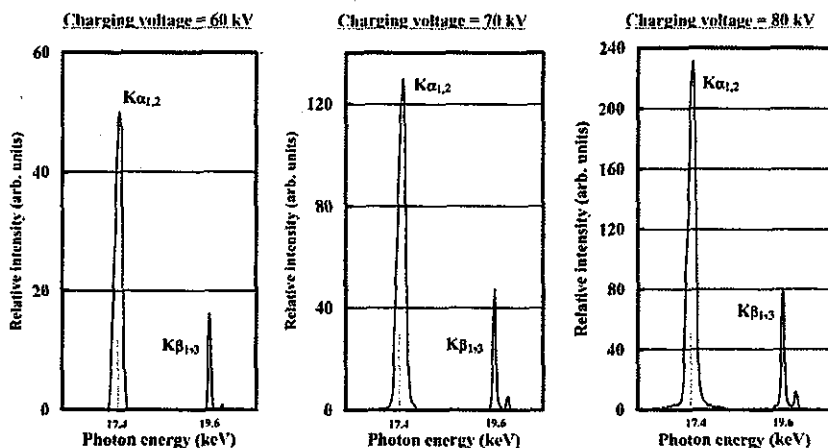


Figure 7: X-ray spectra from molybdenum target.

#### 4. RADIOGRAPHY

The quasi-monochromatic flash radiography was performed by the CR system at 1.2 m from the x-ray source. Firstly, rough measurements of spatial resolution were made using wires. Figure 8 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate with a charging voltage ( $V_c$ ) of 70 kV. Although the image contrast increased with increases in the wire diameter, a 50- $\mu\text{m}$ -diameter wire could be observed.

Figure 9 shows a radiogram of a vertebra with a  $V_c$  of 70 kV, and fine structures in the vertebra were observed. Figures 10 and 11 shows an angiogram of a rabbit heart ( $V_c=70$  kV) and thigh ( $V_c=80$  kV), respectively. In angiography, iodine-based microspheres of 15  $\mu\text{m}$  in diameter were used, and fine blood vessels of about 100  $\mu\text{m}$  were visible. Next, the image of aluminum grains falling into a polypropylene beaker from a glass test tube with a  $V_c$  of 80 kV is shown in Fig. 12. Because the x-ray duration was approximately 100 ns, the stop-motion image of grains could be obtained.

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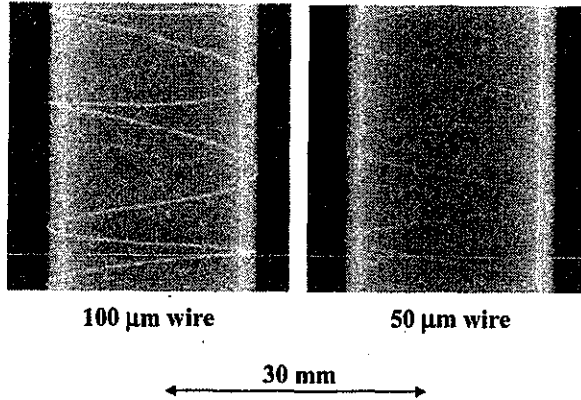


Figure 8: Radiograms of tungsten wires coiled around pipe made of polymethyl methacrylate.

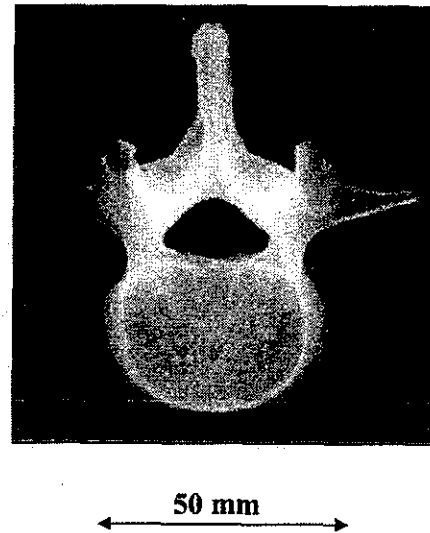


Figure 9: Radiogram of vertebra.

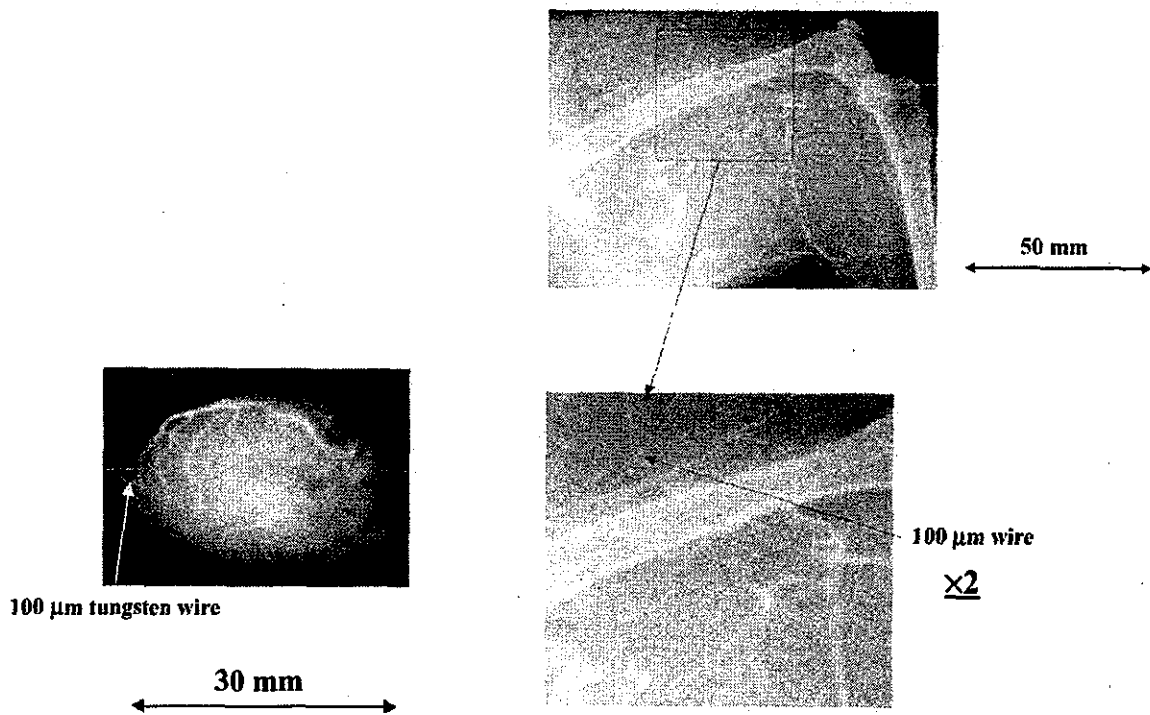


Figure 10: Angiograms of rabbit heart.

Figure 11: Angiograms of rabbit thigh.