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 5×10^8 photons/cm^2 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,[1] and soft generators[2-6] 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[7-11] 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.

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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.[12-15]

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 an 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 Kα lines is shown just above the gadolinium K-edge. The average photon energy of tungsten Kα 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 thyratron 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 kΩ 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 Ω 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.

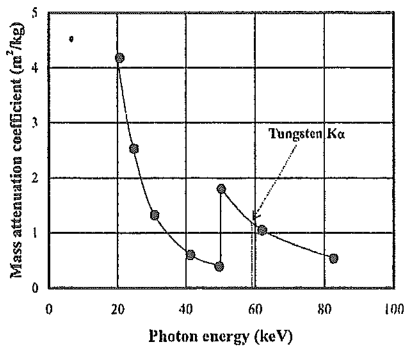


Figure 1: Relation between mass attenuation coefficient of iodine and average photon energy of tungsten Kα lines.

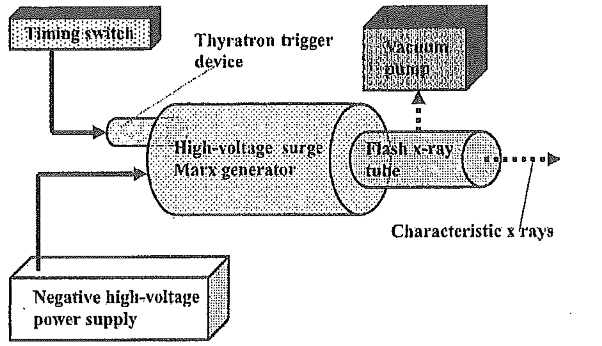


Figure 2: Block diagram of compact quasi-monochromatic flash x-ray generator.

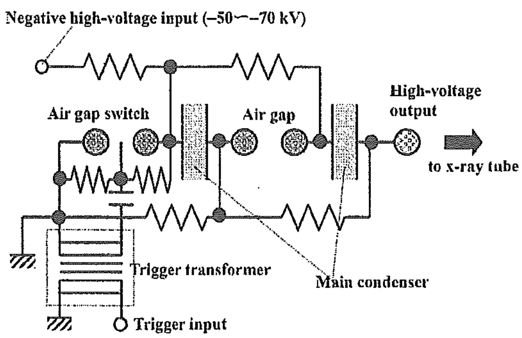


Figure 3: Circuit diagram of two-stage surge Marx generator.

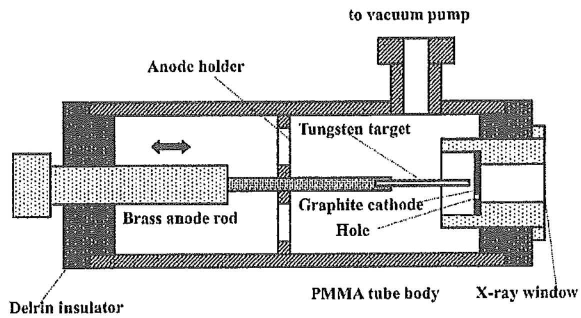


Figure 4: Schematic drawing of flash x-ray tube.

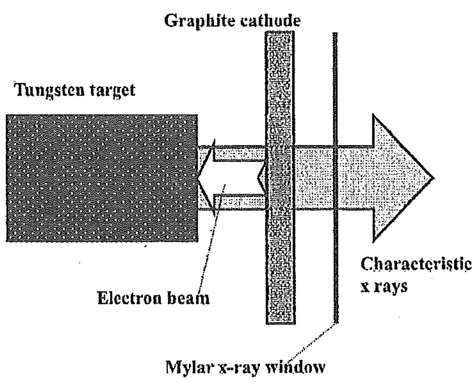


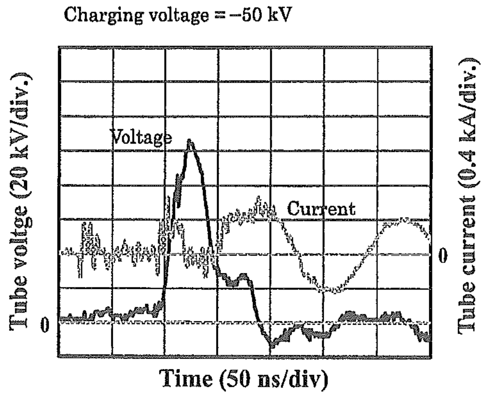
Figure 5: Irradiation of characteristic x rays.

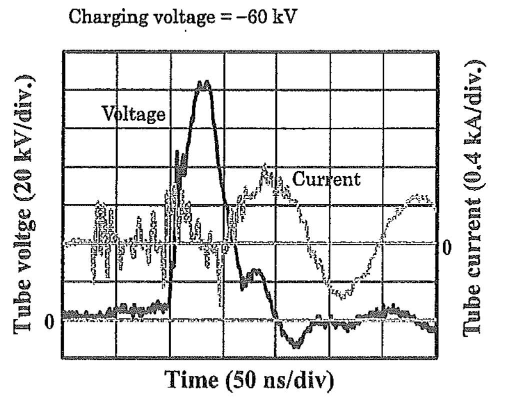
4.2 X-ray output

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 μC/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-μm-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.





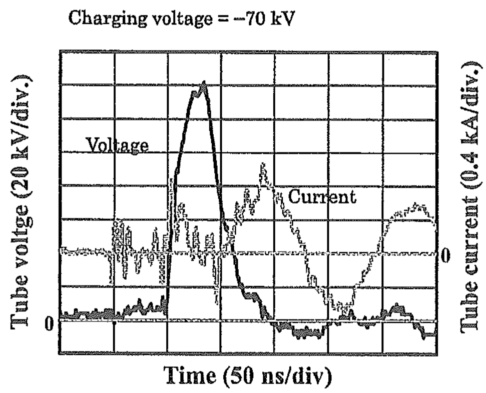


Figure 6: Tube voltages and currents with changing charging voltage.

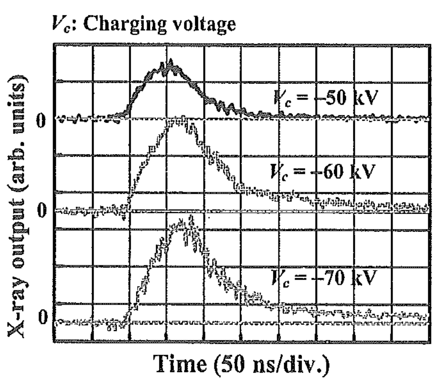


Figure 7: X-ray outputs at indicated conditions.

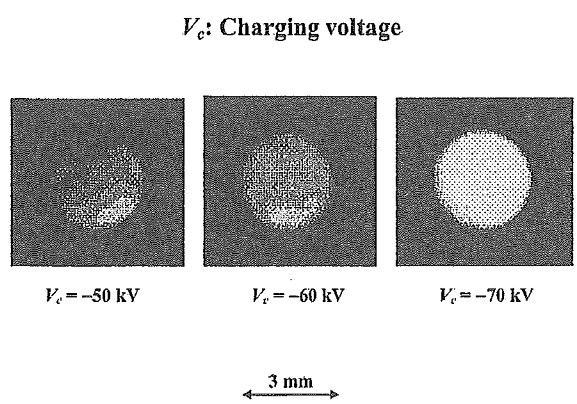


Figure 8: Images of the characteristic x-ray source with changes in charging voltage.

5. ANGIOGRAPHY

The flash angiography was performed by a computed radiography (CR) system (Konica Regius 150) [16] 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 μm-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 μm. 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).

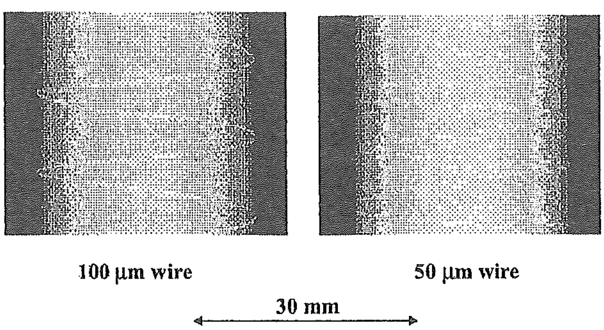


Figure 9: Radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate.

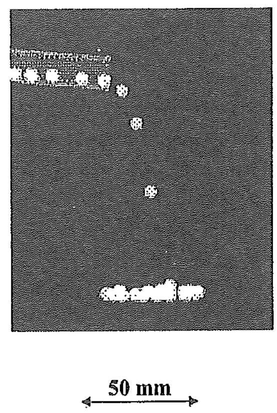


Figure 10: Radiogram of plastic bullets falling into polypropylene beaker from glass test tube.

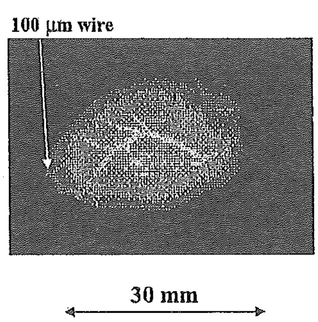


Figure 11: Angiograms of rabbit hearts using iodine microspheres.

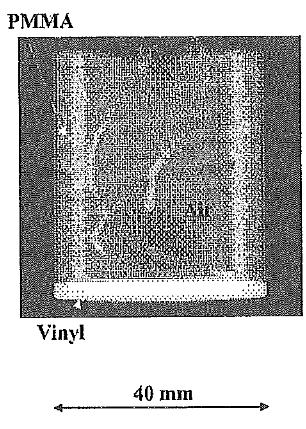


Figure 12: Angiograms of Teflon tube using gadolinium contrast medium of 7.5% by weight.

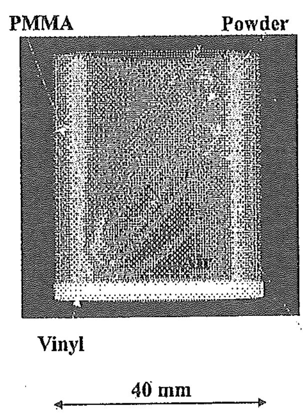


Figure 13: Radiography of gadolinium oxide powder in Teflon tube.

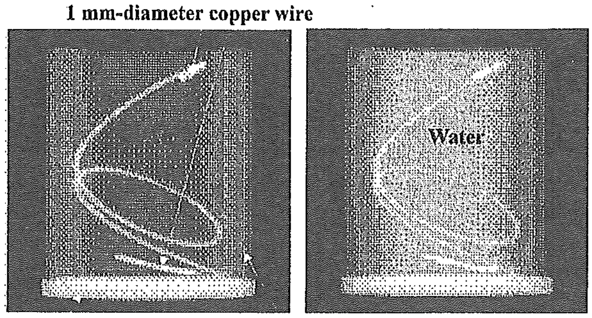


Figure 14: Angiography of Teflon tube using gadolinium oxide suspension of 50 % by weight.

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 Kα photons was approximately 5×10^8 photons/cm^2 per pulse at 0.5 m from the source. Because the molybdenum plasma generator produced approximately 2×10^9 photons/cm^2 per pulse at 0.5 m from the source, the x-ray intensity of Kα 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.

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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 Kα lines increased with increases in the charging voltage, hardly any clean Kβ lines were detected. The x-ray pulse widths were approximately 1.2 μs, and the time-integrated x-ray intensity was approximately 30 μC/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.[1] In addition, a compact pulsed tunable monochromatic x-ray source has been designed, developed, and tested.[2] 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[3,4] in conjunction with cold-cathode diodes and produce extremely short x-ray pulses with durations of less than 1 μs. 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[5-10] corresponding to specific radiographic objectives, and a major goal in our research is the development of an intense and clean

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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.[11-15] 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.

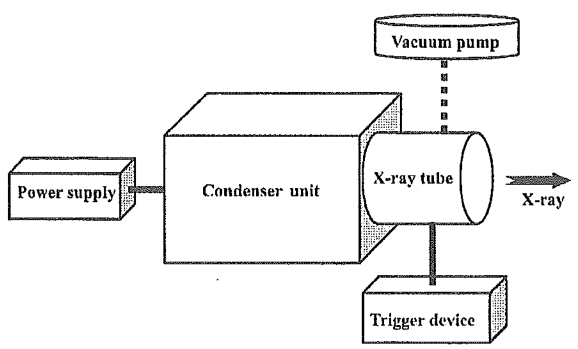


Figure 1: Block diagram of high-intensity plasma flash x-ray generator.

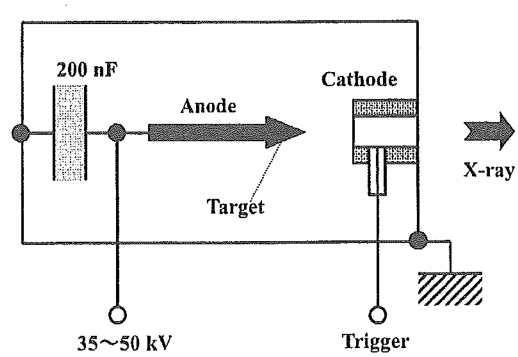


Figure 2: Circuit diagram of flash x-ray generator.

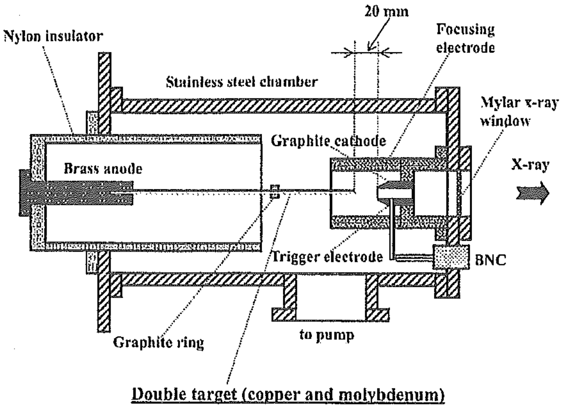


Figure 3: Schematic drawing of flash x-ray tube with double target.

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.

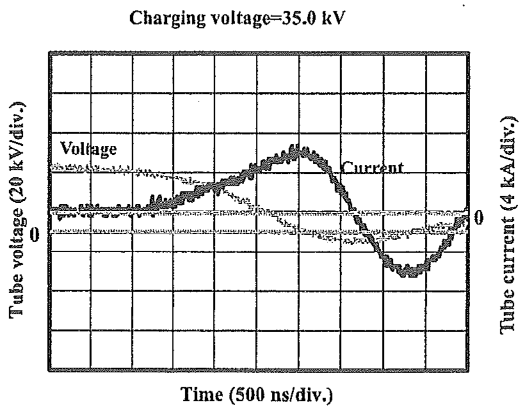
3.3 X-ray source

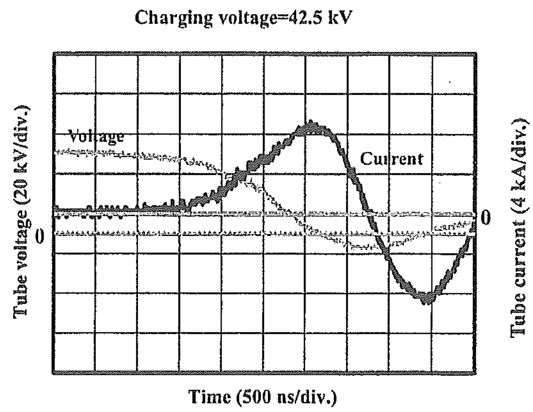
In order to roughly observe images of the plasma x-ray source in the detector plane, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 6). At a charging voltage of 35 kV, we observed two spots of the double target. When the charging voltage was increased, the plasma 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[16] 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 $0.5E_\alpha$, but $0.5E_\beta$ lines were not detected. Here, E_α and E_β are the average photon energies of molybdenum Kα and Kβ lines, respectively.





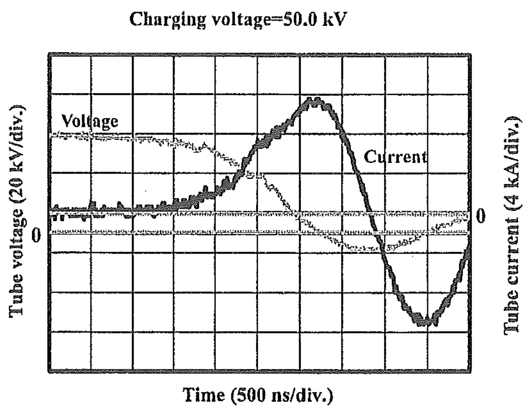


Figure 4: Tube voltages and currents with changing charging voltage.

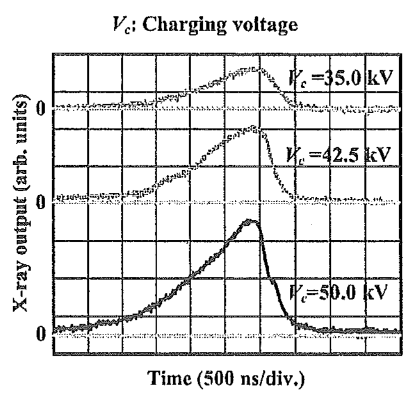


Figure 5: X-ray outputs at indicated conditions.

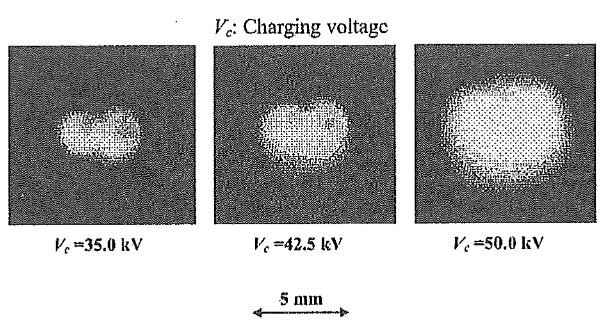


Figure 6: Images of plasma x-ray source of double target.

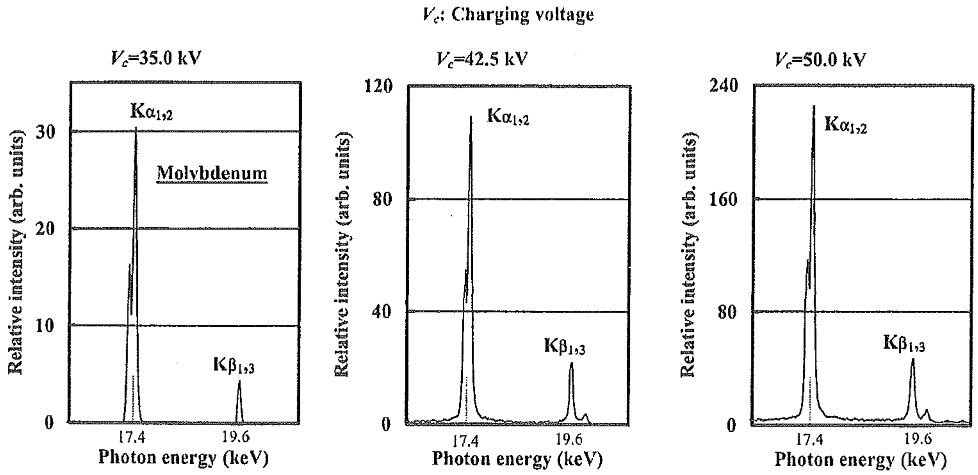


Figure 7: X-ray spectra near molybdenum K-series characteristic x rays.

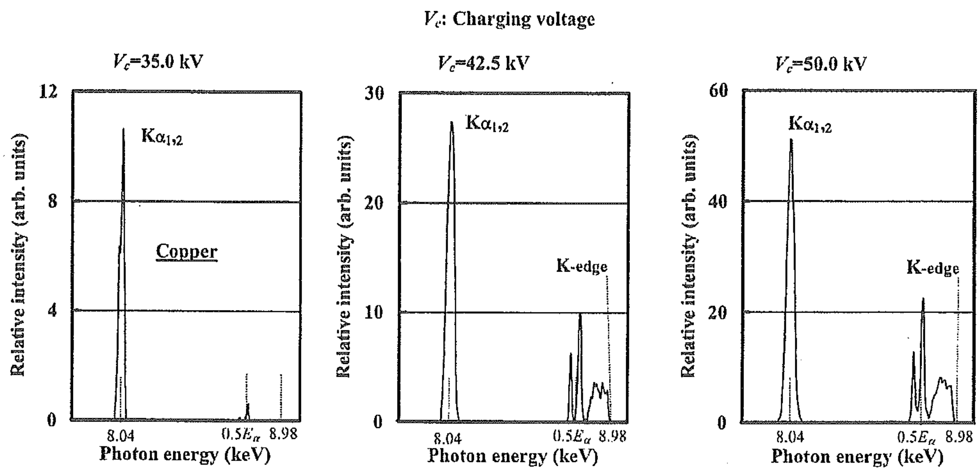


Figure 8: X-ray spectra near copper K-series characteristic x rays.

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-μm-diameter wire could be observed. Next, the image of water falling into a polypropylene beaker from an 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 μs, 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 μm in diameter were used, and fine blood vessels of about 100 μm 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.

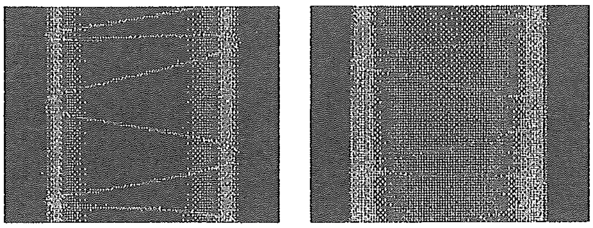


Figure 9: Radiograms of tungsten wires coiled around pipe made of polymethyl methacrylate.

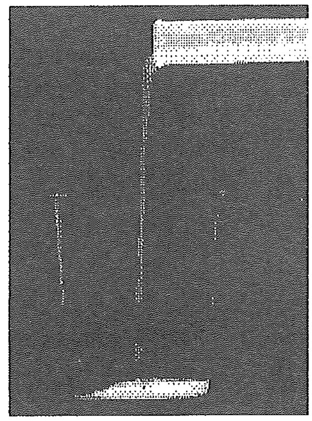


Figure 10: Radiogram of water from glass test tube.

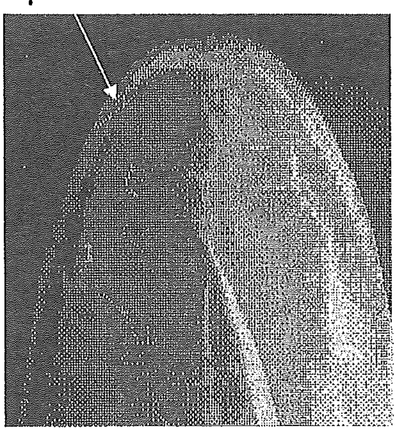


Figure 11: Angiogram of external ear.

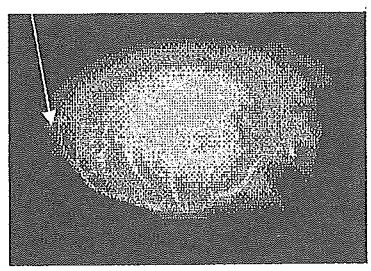


Figure 12: Angiogram of rabbit heart.

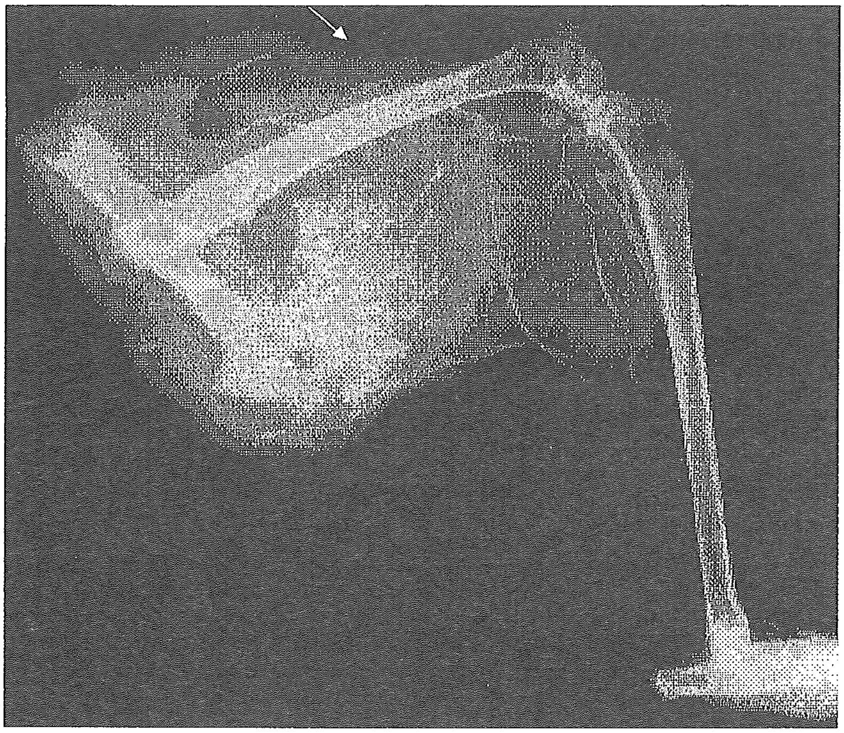


Figure 13: Angiogram of rabbit thigh.

5. DISCUSSION

Regarding the spectrum measurement, although we obtained intense and sharp molybdenum K-series lines, we could not observe copper Kβ lines. In addition, we observed $0.5E_\alpha$ lines and the copper K-absorption edge. If we assume that the $0.5E_\alpha$ lines are molybdenum Kα lines detected by the high order diffraction, the molybdenum Kβ lines, the copper Kβ 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 4×10^8 photons/cm^2 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

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

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Compact monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube

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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 turbo molecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Clean molybdenum $K\alpha$ lines are produced using a 20 μm-thick zirconium filter, 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 120 kV and 1.0 kA, respectively. The x-ray pulse widths were approximately 70 ns, and the generator produced instantaneous number of $K\alpha$ photons was approximately 3×10^7 photons/cm^2 per pulse at 0.5 m from the source of 3.0 mm in diameter. © *2005 American Association of Physicists in Medicine.* [DOI: 10.1118/1.1829247]

Key words: x-ray source, x-ray tube, x-ray spectra, rapid imaging, x-ray beam filtration, monochromatic x ray

I. INTRODUCTION

In recent years, many valuable discoveries have been made in laser technology, and soft x-ray lasers of neonlike argon (46.9 nm, 26.4 eV) have been produced using a gas-discharge capillary.[1–3] In these experiments, the laser energy increased with increases in the capillary length, and these kinds of first discharges can generate hot and dense plasma columns with aspect ratios of 1000:1. However, it is difficult to increase the laser photon energy to 10 keV or beyond.

We have developed several different soft flash x-ray generators[4–8] 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 medical radiography. 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.[9–12] In the plasma, bremsstrahlung spectra with photon energies of higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x rays, and the plasma then transmits the fluorescent rays easily. However, the bremsstrahlung x rays are produced using a molybdenum target,[11] since high photon energy bremsstrahlung x rays are not absorbed effectively in the linear plasma.

Without forming the linear plasma, because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, characteristic x rays can be produced by considering the angle dependence of bremsstrahlung x rays. As compared with the plasma generator, the photon

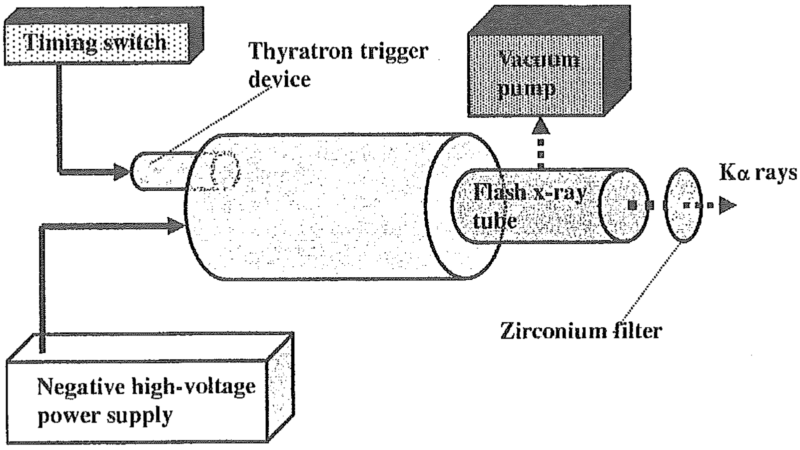

FIG. 1. Block diagram of the compact quasimonochromatic flash x-ray generator with a cold-cathode monochromatic diode.

energy of the characteristic x rays can be increased by increasing the maximum output voltage of the pulse generator, since a multistage Marx generator[13,14] can be employed. In this case, the output voltage is equal to the value of the condenser charging voltage multiplied by the stage number.

In this article, we describe a compact flash x-ray generator utilizing a molybdenum-target radiation tube, used to perform a preliminary experiment for producing clean monochromatic x rays.

II. GENERATOR

A. High-voltage circuit

Figure 1 shows a block diagram of a compact monochromatic flash x-ray generator. 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 thyratron trigger device of the surge generator, a turbo molecular 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[13,14] (Fig. 2), 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.

B. X-ray tube

The x-ray tube is a demountable diode type, as illustrated in Fig. 3. This tube is connected to the turbo molecular pump with a pressure of about 1 mPa and consists of the following major devices: a rod-shaped molybdenum 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 tube body. The target-cathode space was regulated to 1.0 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. 4), molybdenum $K\alpha$ rays can be produced using a 20 μm-thick zirconium K-edge filter.

III. CHARACTERISTICS

A. Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 10 kΩ and a current transformer, respectively (Fig. 5). The voltage and current displayed roughly damped oscillations because the discharge resistance in the tube varied rapidly from infinity

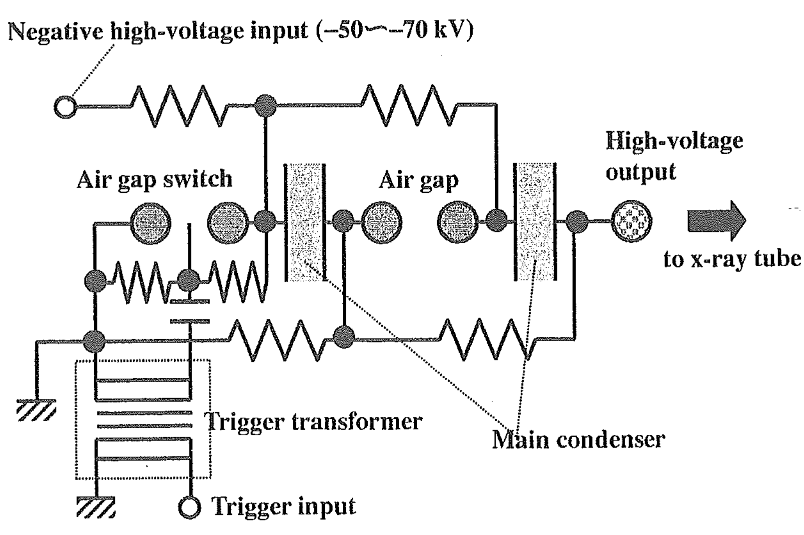

FIG. 2. Circuit diagram of the two-stage surge Marx generator. The generator produces twice the potential of the condenser charging voltage.

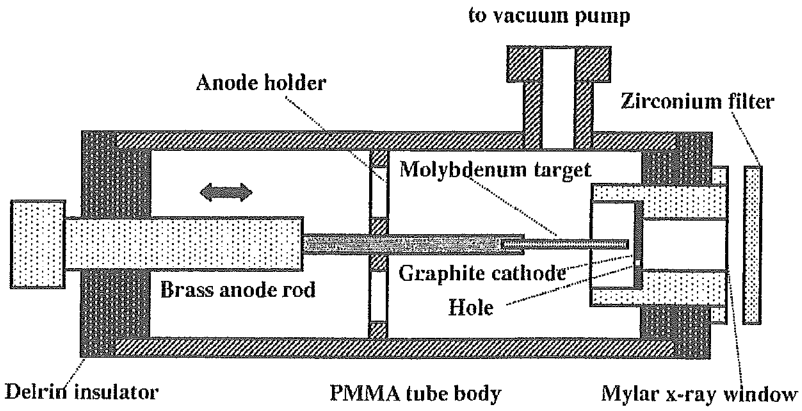

FIG. 3. Schematic drawing of the flash x-ray tube with a rod-shaped molybdenum target and a disk graphite cathode.

to approximately 0 Ω 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 120 kV and 1.0 kA, respectively, at a charging voltage of −70 kV.

B. X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator, a photomultiplier, and the filter (Fig. 6). When the charging voltage was increased, the pulse height increased, but the width seldom varied. The widths were about 70 ns, and the time-integrated x-ray dose measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had an instantaneous value of approximately 70 μGy per pulse at 0.5 m from the x-ray source with a charging voltage of −70 kV.

C. X-ray source

In order to observe the Kα x-ray source, we employed a 100 μm-diameter pinhole camera, an x-ray film (Polaroid XR-7), and the filter (Fig. 7). 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.

D. X-ray spectra

X-ray spectra were measured using a transmission-type spectrometer[11] 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 a computed radiography (CR) system[15] (Konica 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 8 shows measured spectra from the molybdenum target with the filter. In fact, we observed clean Kα lines, while bremsstrahlung rays were hardly detected at all. The Kα intensity substantially increased with increases in the charging voltage.

IV. RADIOGRAPHY

The monochromatic flash radiography was performed by the CR system at 0.5 m from the x-ray source with the filter, and the charging voltage was −70 kV.

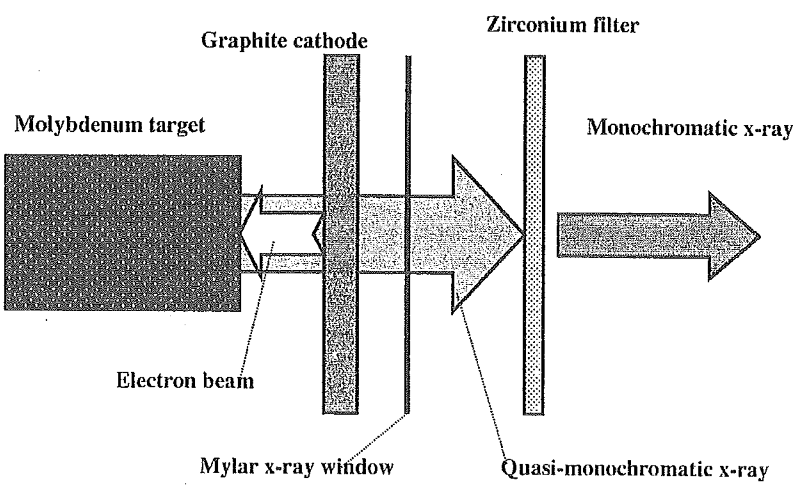

FIG. 4. Irradiation of Kα rays using a monochromatic zirconium filter. Bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, and molybdenum Kα rays are left using a zirconium filter.

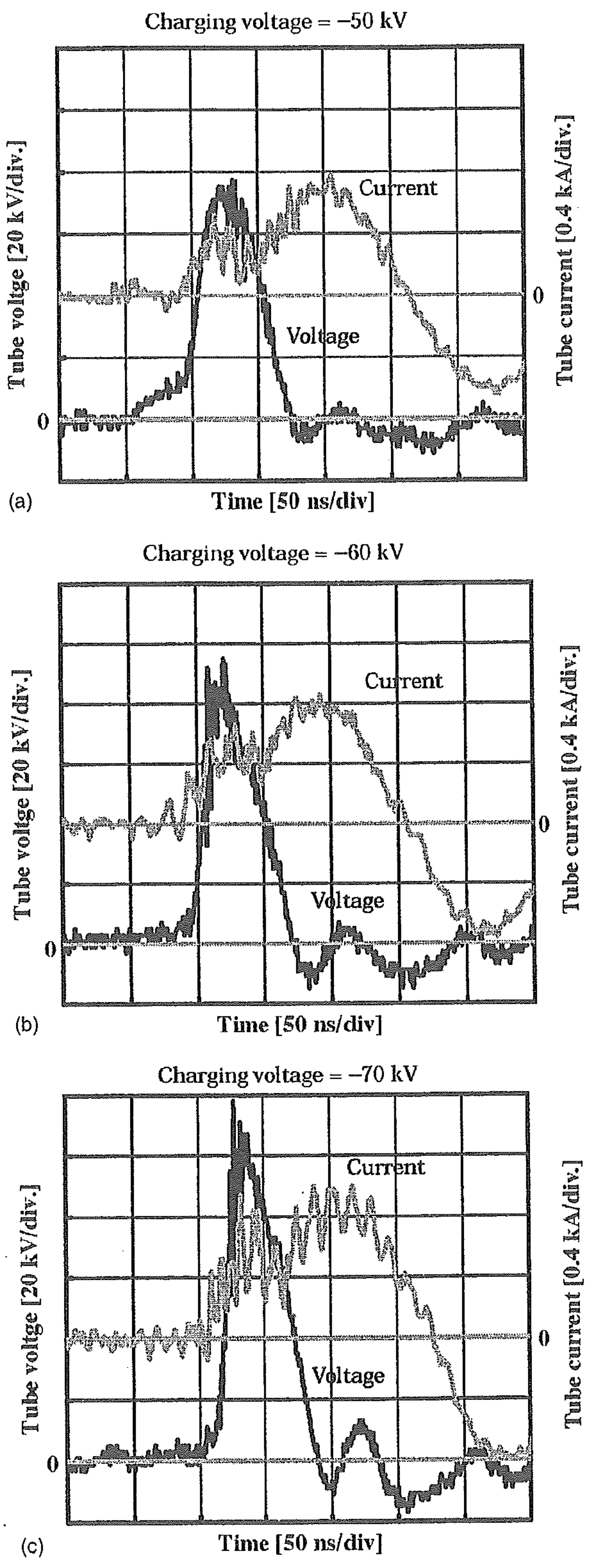

FIG. 5. Variations in the tube voltage and current with a charging voltage of (a) −50 kV, (b) −60 kV, and (c) −70 kV.

First, rough measurements of spatial resolution were made using wires. Figure 9 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate. Although the image contrast increased with increases in the wire diameter, a 50 μm-diameter wire could be observed.

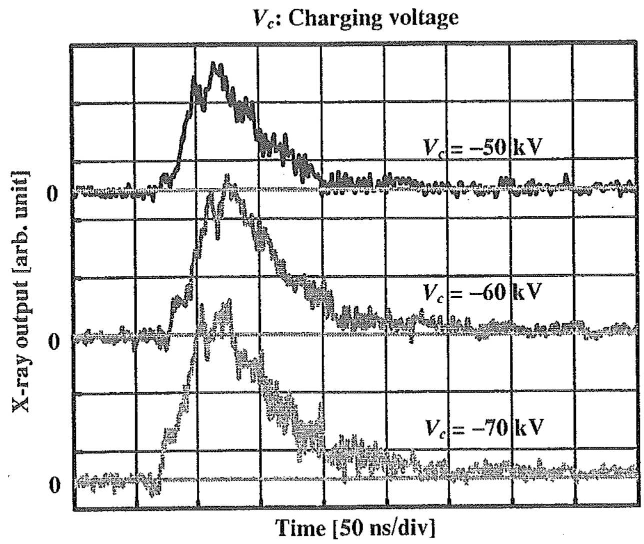

FIG. 6. X-ray outputs detected using a combination of a plastic scintillator, a photomultiplier, and the zirconium filter.

Figure 10 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. Next, the image of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 11. This image was taken with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 70 ns, the stop-motion image of water could be obtained. Figure 12 shows an angiogram of a rabbit heart; iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm were visible.

V. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean molybdenum Kα rays (17.4 keV). Therefore, we are very interested in the measurement the Kα rays from nickel (7.47 keV), copper (8.04 keV), silver (22.1 keV), cerium (34.6 keV), and tungsten (58.9 keV) targets; the target element should be selected corresponding to the radiographic objectives. In a medical application, K-series characteristic x rays of cerium are absorbed effectively by an iodine-based contrast medium with a K-edge of 33.2 keV, and high contrast microangiography can be performed.

In this research, the generator produced instantaneous number of Kα photons was approximately 3×10^7

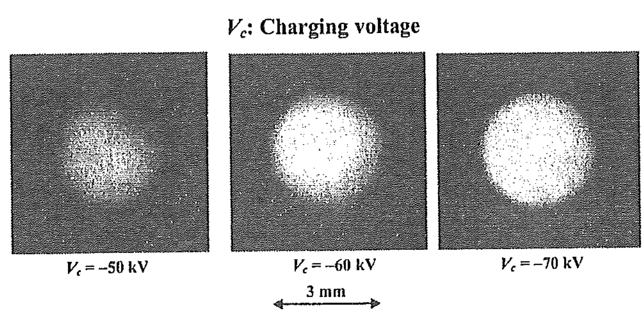

FIG. 7. Images of the x-ray source of Kα lines obtained using a pinhole camera with changes in the charging voltage.

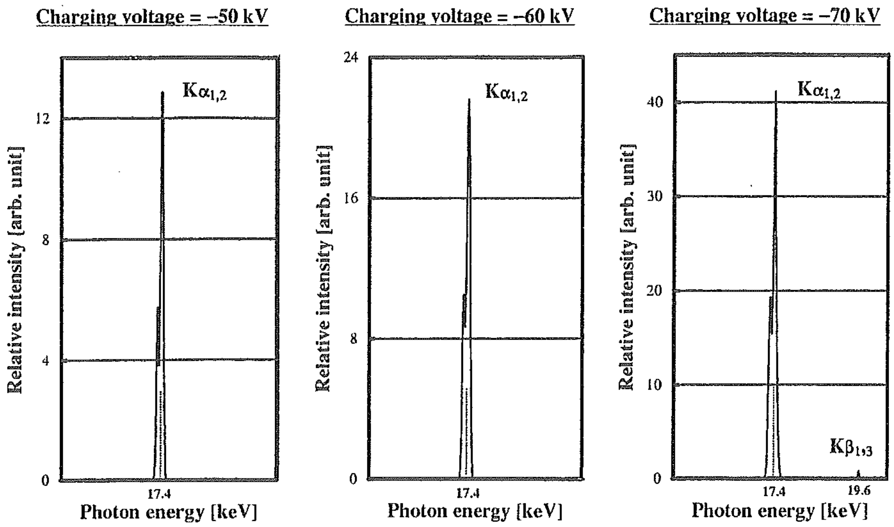

FIG. 8. X-ray spectra from the molybdenum target with the filter. The spectra were measured using a transmission type spectrometer with a lithium fluoride curved crystal.

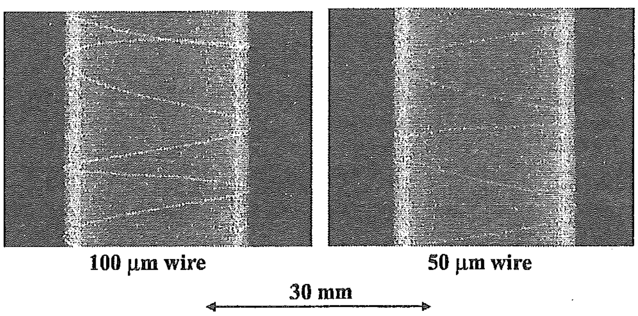

FIG. 9. Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around a pipe made of polymethyl methacrylate. A 50 μm-diameter wire could be observed.

photons/cm^2 per pulse at 0.5 m from the source. Because the molybdenum plasma generator produced approximately 5 $\times 10^8$ photons/cm^2 per pulse at 1.0 m from the source, the x-ray intensity of Kα lines had a lower value as compared with the plasma x-ray generator[11] described above, which utilizes a large capacity condenser of approximately 200 nF. However, the intensity can be increased by increasing the electrostatic energy in condensers in the surge generator, and quasi-monochromatic x rays of both Kα and Kβ (19.6 keV) lines are produced without using the zirconium filter with a K-edge of 17.9 keV.

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

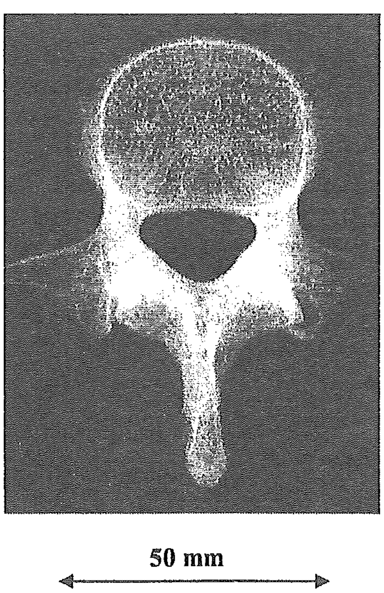

FIG. 10. Radiogram of a vertebra. Fine structure of the vertebra were visible.

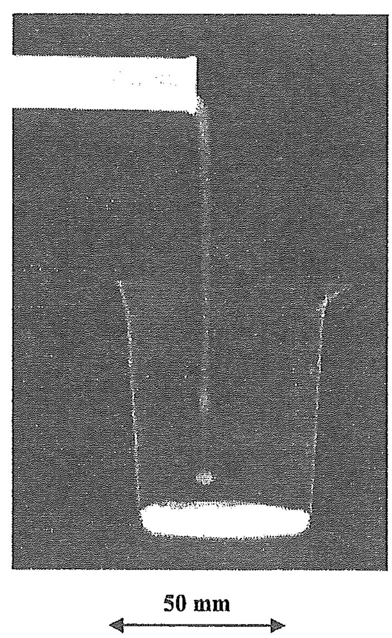

FIG. 11. Radiogram of water falling into a polypropylene beaker from a glass test tube. The stop-motion image of water was obtained by monochromatic flash radiography.