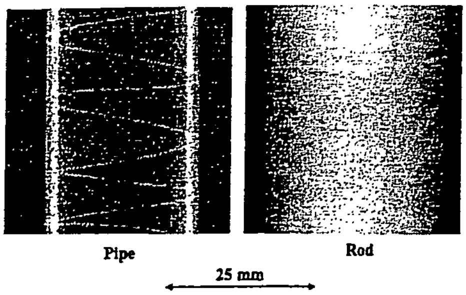

Fig. 8 Radiograms of tungsten wires of 50 μm in diameter coiled around pipe and rod made of PMMA.

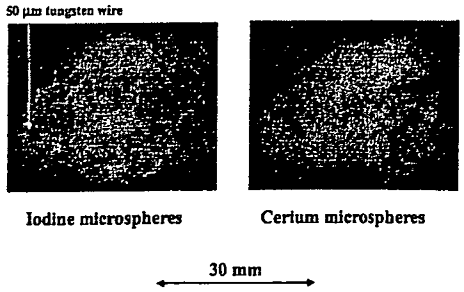

Fig. 10 Angiograms of rabbit hearts using iodine and cerium microspheres.

4.4 *X-Ray Spectra*

X-ray spectra from the plasma source were measured by a transmission-type spectrometer with a lithium fluoride curved crystal of 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[25] (Konica Regius 150) having a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 7 shows measured spectra from the cerium target. In this experiment, although we observed both the bremsstrahlung and characteristic x-rays, we could not observe characteristic x-rays with a charging voltage of 35 kV, because the critical excitation energy is 40.3 keV. Both intensities increased substantially with increases in the charging voltage.

5 Angiography

The plasma angiography was performed by the CR system without using a monochromatic filter, and the distance between the x-ray source and the imaging plate was 1.2 m. Subsequently, in angiography testing, we usually employ nonliving animal phantoms using microspheres.

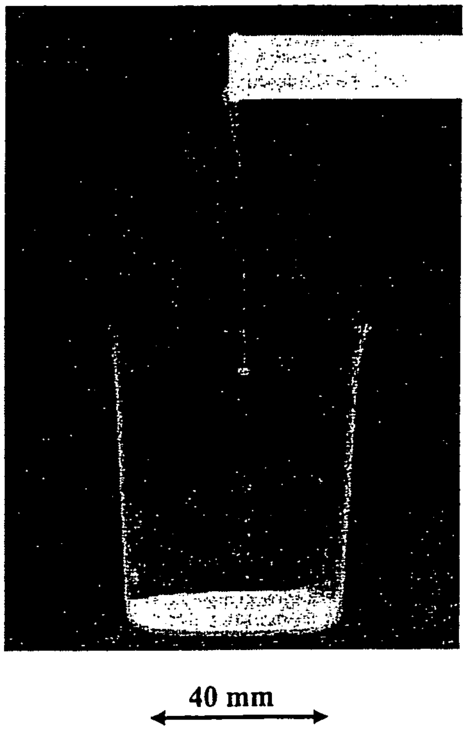

Fig. 9 Radiogram of water falling into a polypropylene beaker from a glass test tube.

First, rough measurements of image resolution were made using wires. Figure 8 shows radiograms of 50-μm-diam tungsten wires coiled around a pipe, and a rod made of polymethyl methacrylate (PMMA) with a charging voltage of 55 kV. Although the image contrast increased using the pipe, 50-μm-diam wires could be observed.

The image of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 9. This image was taken with a charging voltage of 55 kV, with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 1 μs, the stop-motion image of water could be obtained.

Angiograms of rabbit hearts are shown in Fig. 10. These two images were obtained using iodine and cerium microspheres of 15 μm, respectively, with a charging voltage of 55 kV. In cases where the cerium spheres were employed, the coronary arteries were barely visible. Figure 11 shows an angiogram of the external ear of a rabbit using iodine spheres with a charging voltage of 55 kV, and fine blood vessels of about 50 μm are visible. In angiography of a larger heart extracted from a dog, using iodine spheres, a PMMA plate was set in front of a heart facing x-ray source, and image contrast of coronary arteries improved with increases in the plate thickness (Fig. 12).

6 Discussion

In an earlier experiment using a copper target,[24] bremsstrahlung x-rays were hardly observed at all, and we confirmed the irradiation of fairly clean K-series characteristic x-rays such as lasers. In the present work, although we confirmed intense characteristic x-rays with a higher charging voltage, bremsstrahlung x-rays were detected, since the bremsstrahlung intensity is proportional to the atomic num-

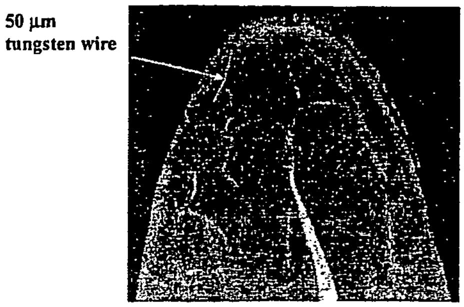

Fig. 11 Angiograms of external ear of rabbit.

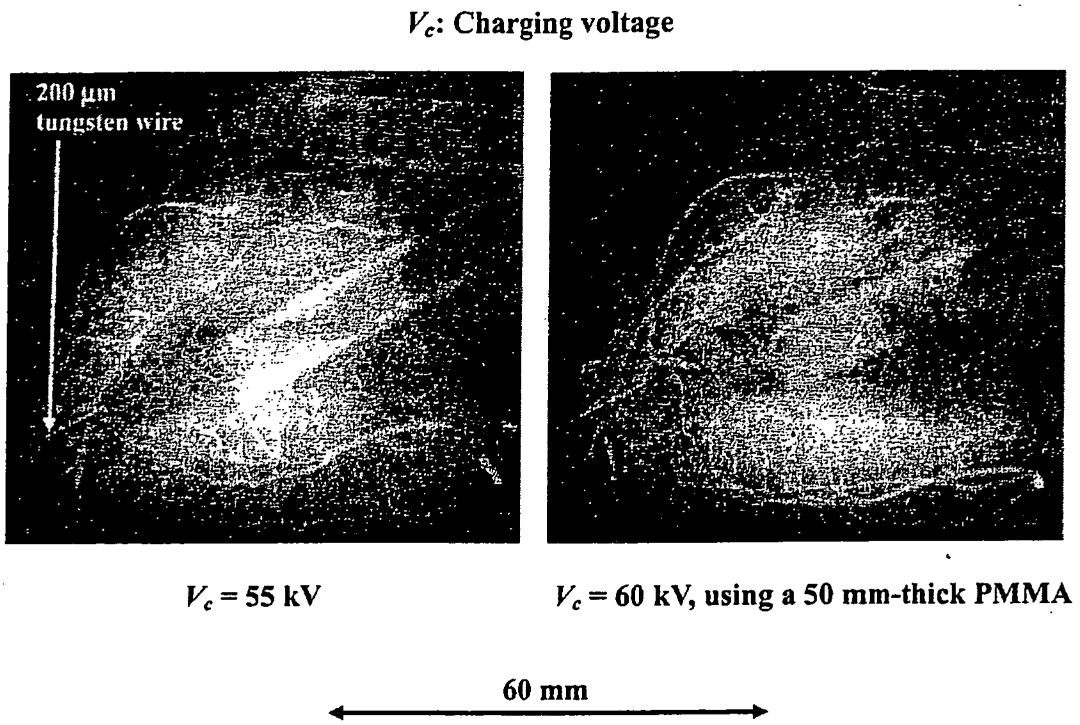

Fig. 12 Angiograms of extracted heart of dog.

ber of the target element, and high-photon-energy bremsstrahlung x-rays are not absorbed effectively in the plasma. Therefore, the condenser charging voltage should be raised as high as possible to increase the characteristic x-ray intensity. To decrease emission of bremsstrahlung x-rays from the carbon target holder, the target length should also be set as long as possible. Next, since the spheres easily transmit bremsstrahlung x-rays with energies lower than the edge, it is important that the rays be absorbed as much as possible before angiography to increase the image contrast.

In this research, we obtained sufficient x-ray intensity per pulse for CR radiography, and the generator produced high-dose-rate plasma x-rays of approximately 80 C/kg·s at 1.0 m with a charging voltage of 55 kV. In addition, because the x-ray intensity increases with increases in the electrostatic energy in the main discharge condenser, the flash x-rays from weakly ionized linear cerium plasma can be employed to perform high-speed angiography for cardiovascular disease.

Acknowledgments

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, and 16591222) and Advanced Medical Scientific Research from MECSST; Health and Labor Sciences Research Grants (RAMT-nano-001, RHGTEFB-genome-005, and RHGTEFB-saisei-003); and 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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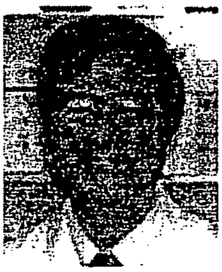

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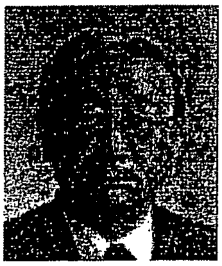

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Quasi-monochromatic cerium flash angiography

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ABSTRACT

The cerium target plasma flash x-ray generator is useful in order to perform high-speed enhanced K-edge angiography using cone beams because K-series characteristic x rays from the cerium target are absorbed effectively by iodine-based contrast mediums. 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 cerium 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 10 µC/kg at 1.0 m from the x-ray source with a charging voltage of 80 kV. In the angiography, we employed a film-less computed radiography (CR) system and iodine-based microspheres.

Keywords: flash x-ray, cerium target, characteristic x rays, bremsstrahlung x-ray distribution, K-edge angiography

1. INTRODUCTION

The potential of monochromatic parallel x-ray beams using a synchrotron and a monochrometor poses a major challenge to competing image acquisition technology, for example, x-ray phase imaging[1,2] and enhanced K-edge angiography.[3,4] Recently, cone-beam phase imaging[5] for the edge enhancement technique has been employed using a mini-focus x-ray tube. Subsequently, K-edge angiography has also been performed using cone beams of cerium Kα rays[6] of 34.6 keV, since K-series characteristic x rays from the cerium target are absorbed effectively by iodine-based contrast media.

Currently, most flash x-ray generators utilize cold-cathode x-ray tubes and produce extremely high-dose-rate pulse x rays with durations of less than 1 µs.[7] A number of flash x-ray generators have been developed in order to perform high-speed radiography, and the generators with maximum photon energies of less than 150 keV can be employed to

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perform soft radiography including biomedical applications.[8-12]
In a former experiment, we performed a preliminary experiment of high-speed K-edge angiography using a cerium plasma x-ray generator,[13] which produced both characteristic and bremsstrahlung x rays. As compared with a steady state x-ray generator with a constant tube voltage, the effective x-ray photon energies are lower, since both the tube voltage and current display damped oscillations; the tube current increases with decreasing tube voltage. Therefore, the condenser charging voltage should be increased as much as possible to increase the cerium characteristic x-ray intensity.
In the present research, we improved a plasma x-ray generator[14-18] with a cerium-target tube, and used it to perform a preliminary study on angiography achieved with cerium K-series characteristic x rays.

2. PRINCIPLE OF K-EDGE ANGIOGRAPHY

Figure 1 shows the mass attenuation coefficients of iodine at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The average photon energies of the cerium Kα and Kβ lines are shown above the iodine K-edge. Cerium is a rare earth element and has a high reactivity; however, the average photon energy of Kα and Kβ lines are 34.6 and 39.2 keV, respectively, and iodine contrast media with a K-absorption edge of 33.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

3. GENERATOR

3.1 High-voltage circuit

Figure 2 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 thyratron 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.

3.2 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 cerium 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), cerium K-series characteristic x rays can be produced without using a filter.

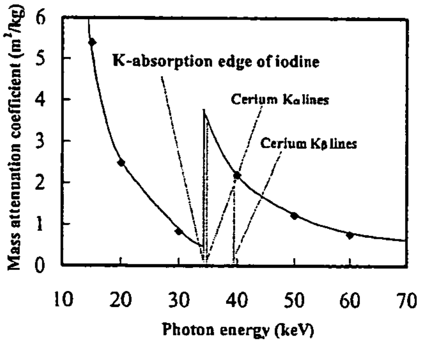

Figure 1: Relation between mass attenuation coefficient of iodine and average photon energies of cerium Kα and Kβ lines.

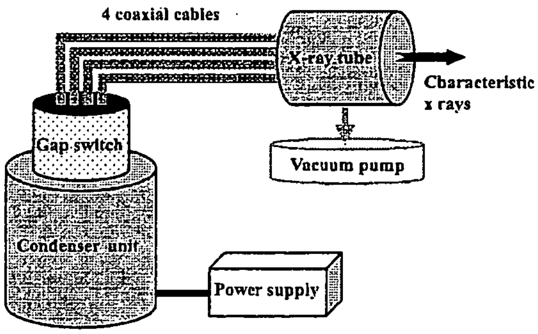

Figure 2: Block diagram of intense quasi-monochromatic flash x-ray generator.

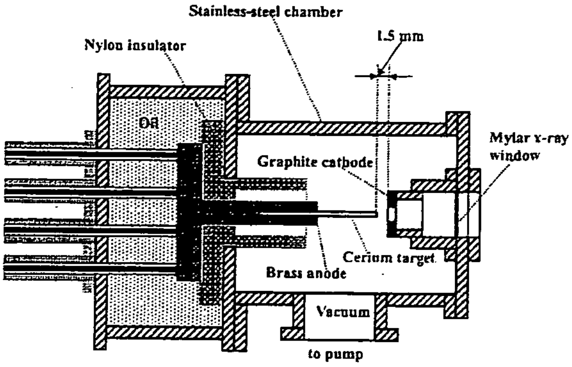

Figure 3: Schematic drawing of flash x-ray tube.

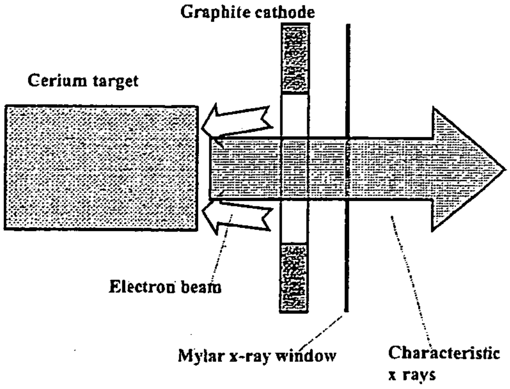

Figure 4: Irradiation of characteristic x rays.

4. CHARACTERISTICS

4.1 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 display 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.

4.2 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 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 10 μC/kg at 1.0 m from the x-ray source with a charging voltage of 80 kV.

4.3 X-ray source

In order to observe the Kα x-ray source, we employed a 100-μm-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.

4.4 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[19] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 7 shows measured spectra from the cerium 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.

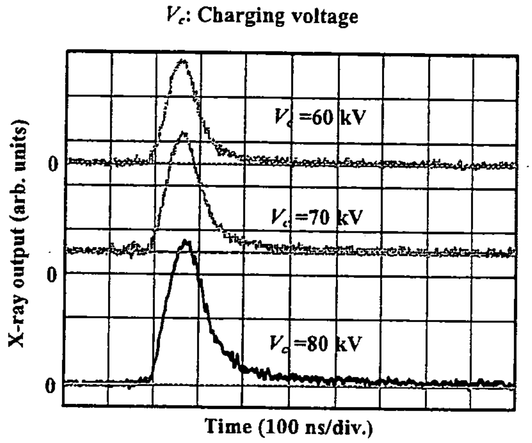

Figure 5: X-ray outputs at indicated conditions.

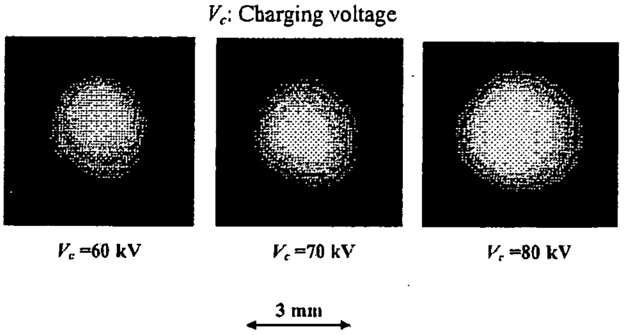

Figure 6: Images of characteristic x-ray source with changes in charging voltage.

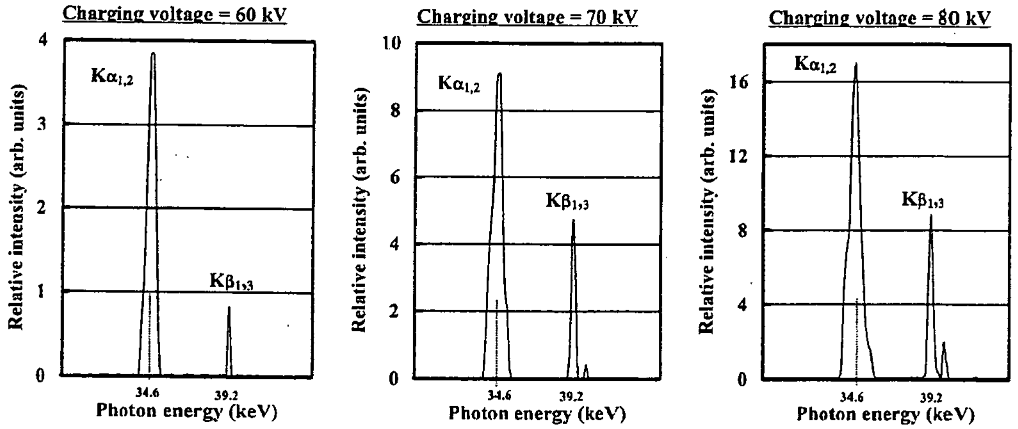

Figure 7: X-ray spectra from cerium target.

5. ANGIOGRAPHY

The plasma angiography was performed by the CR system (Konica Regius 150) without using a monochromatic filter, and the charging voltage and the distance between the x-ray source and the imaging plate were 70 kV and 1.2 m, respectively.

Figure 8 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.

The image of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 9. This image was taken with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 100 ns, the stop-motion image of water could be obtained.

Angiograms of rabbit hearts are shown in Fig. 10. These two images were obtained using iodine and cerium microspheres of 15 μm, respectively. In case where the cerium spheres were employed, the coronary arteries were barely visible. In angiography of a larger heart extracted from a dog using iodine spheres, fine blood vessels of approximately 100 μm were visible (Fig. 11).

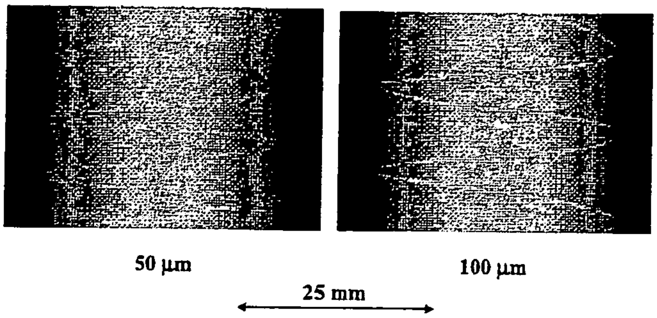

Figure 8: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate.

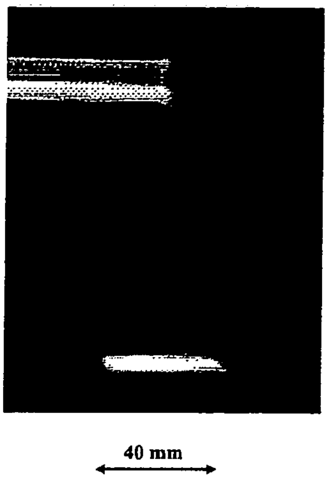

Figure 9: Radiogram of water falling into polypropylene beaker from glass test tube.

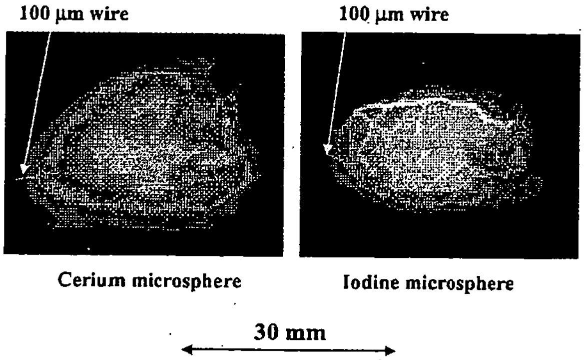

Figure 10: Angiograms of rabbit hearts using iodine and cerium microspheres.

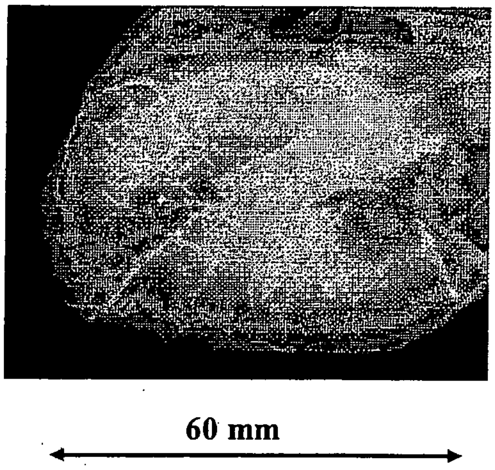

Fig. 11 Angiograms of extracted heart of dog.

6. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean cerium Kα and Kβ lines. Therefore, we are very interested in the measurement the characteristic rays from nickel, copper, molybdenum, silver, and tungsten targets; the target element should be selected corresponding to the radiographic objectives.

In this research, the generator produced instantaneous number of K photons was approximately 5×10^8 photons/cm^2 per pulse at 1.0 m from the source. Subsequently, the intensity can be increased by increasing the electrostatic energy in condenser, and monochromatic Kα lines are produced using a barium oxide filter with a barium K-edge of 37.4 keV.

Using this flash x-ray generator, as high output voltages can be produced using cables, high-photon-energy K-series characteristic x rays can be produced by increasing the atomic number of the target element. With recent advances in angiography using MRI, if the density of gadolinium-based contrast media increases, enhanced K-edge angiography utilizing monochromatic x-ray generators, which produce Kα rays from ytterbium, tantalum, and tungsten targets, will be a useful technique to decrease the absorbed dose during angiography.

ACKNOWLEDGMENT

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, and 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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Invited Paper

Weakly ionized linear plasma x-ray generator with molybdenum-target 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 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 molybdenum 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 16 kA. When the charging voltage was increased, the linear plasma formed, and the K-series characteristic x-ray intensities increased. The K lines were quite sharp and intense. The x-ray pulse widths were approximately 600 ns, and the time-integrated x-ray intensity had a value of approximately 65 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

Keywords: flash x-ray, weakly ionized linear plasma, molybdenum characteristic x rays, quasi-monochromatic x rays, x-ray resonation

1. INTRODUCTION

In conjunction with monochromators, synchrotrons produce monochromatic parallel beams, which are fairly similar to monochromatic parallel laser beams, and the beams have been applied to enhanced K-edge angiography,[1,2] phase imaging,[3,4] and crystallography. Therefore, the production of coherent hard x-ray lasers for various research projects, including biomedical applications, has long been wished for.

Recently, soft x-ray lasers[5-7] have been produced by a gas-discharge capillary, and the laser pulse energy substantially increased in proportion to the capillary length. These kinds of fast discharges can generate hot and dense plasma columns with aspect ratios approaching 1000:1. However, it is difficult to increase the laser photon energy to 10 keV or beyond. Because there are no x-ray resonators in the high-photon-energy region, new methods for increasing coherence will be desired in the future.

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To apply flash x-ray generators to biomedicine, several different generators[8-11] have been developed, and plasma x-ray generators[12-16] 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 Kα rays were produced using K-edge filters. Subsequently, since high-photon-energy bremsstrahlung x rays are not absorbed effectively by the linear plasma due to attenuation coefficients, high-photon-energy quasi-monochromatic x-ray generators[17] for producing characteristic x rays of molybdenum, silver, cerium, tantalum, and tungsten have been developed utilizing the angle dependence of bremsstrahlung x-ray intensity distribution.

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

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. 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. 2). 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 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 is approximately 20 mm, and the trigger electrode is set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by the electric field in the tube, evaporation leads to the formation of weakly ionized linear plasma, consisting of molybdenum ions and electrons, around the fine target.

2.3 Principle of characteristic x-ray irradiation

In weakly ionized linear plasma, bremsstrahlung spectra with photon energies of 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 of lower than the K-edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the direction opposite to electron acceleration, intense characteristic x rays are generated from the plasma-axial direction.

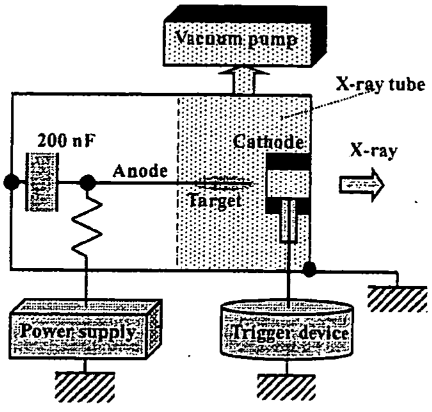

Figure 1: Block diagram of high-intensity plasma flash x-ray generator.

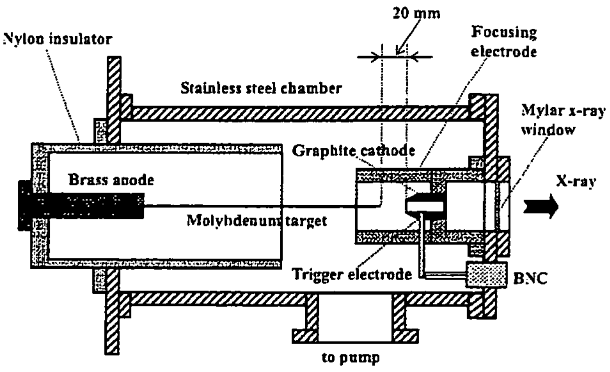

Figure 2: Schematic drawing of flash x-ray tube with rod target.

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 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 600 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 65 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 pinhole camera with a hole diameter of 100 μm and an x-ray film (Polaroid XR-7) (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 mm in thickness. The spectra were taken by a computed radiography (CR) system[18] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 6 shows measured spectra from the molybdenum target. In fact, we observed quite sharp lines of K-series characteristic x rays, and bremsstrahlung rays were detected slightly at a high charging voltage of approximately 50 kV. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage. We found high-intensity lines with a photon energy of $0.5E_\alpha$ corresponding to Kα lines with an average photon energy of E_α. Although lines of $0.5E_\beta$, corresponding to Kβ lines with an average photon energy of E_β, were also detected, hardly any bremsstrahlung x rays were detected at all.

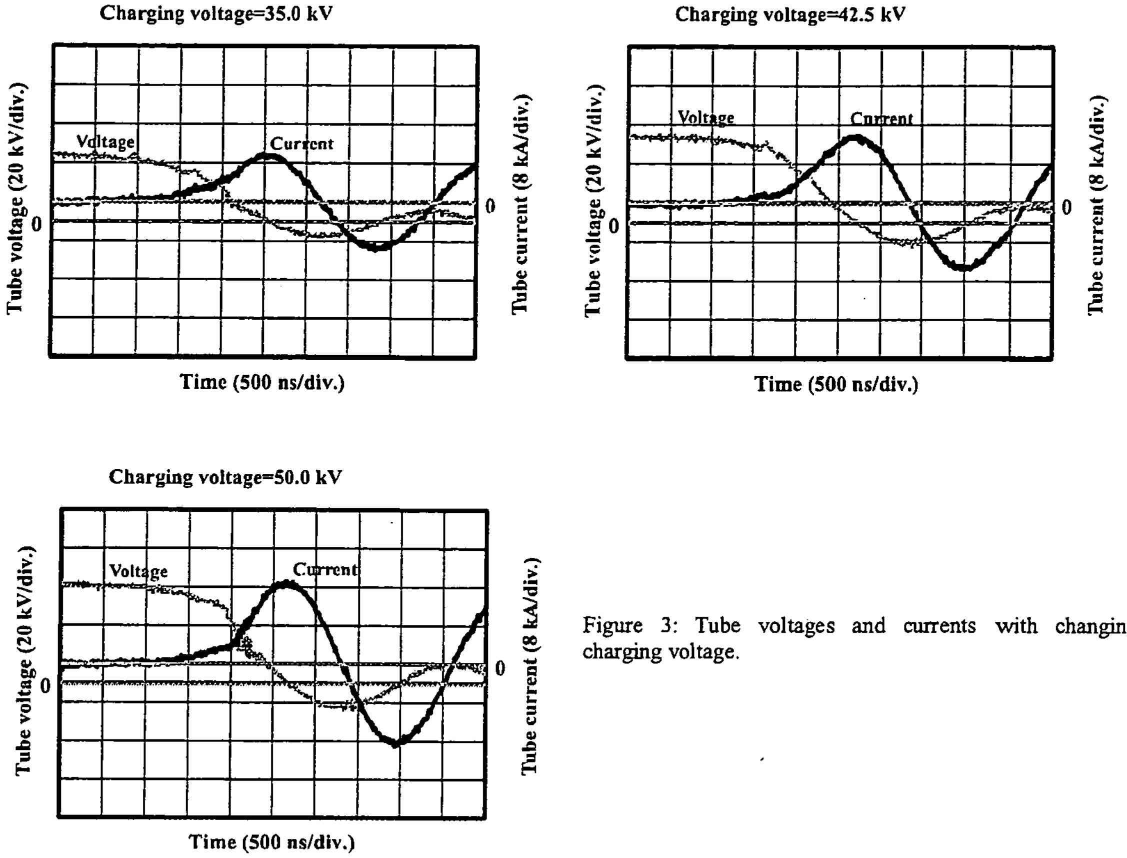

Figure 3: Tube voltages and currents with changing charging voltage.

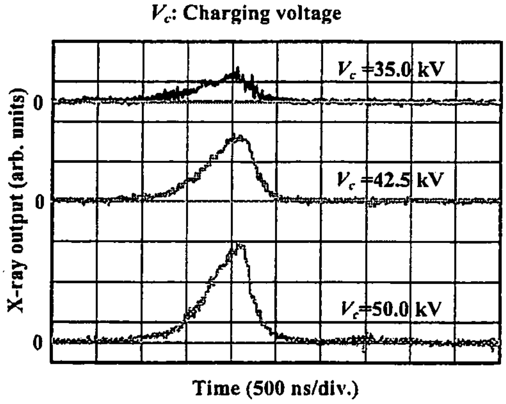

Figure 4: X-ray outputs at indicated conditions.

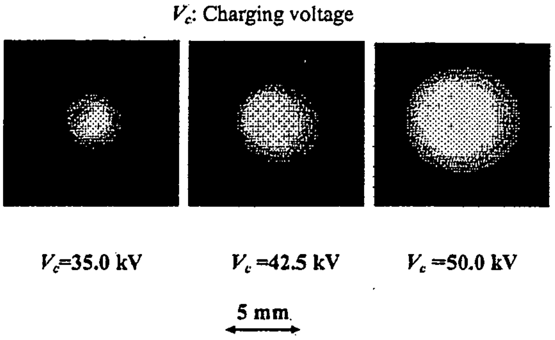

Figure 5: Images of plasma x-ray source.

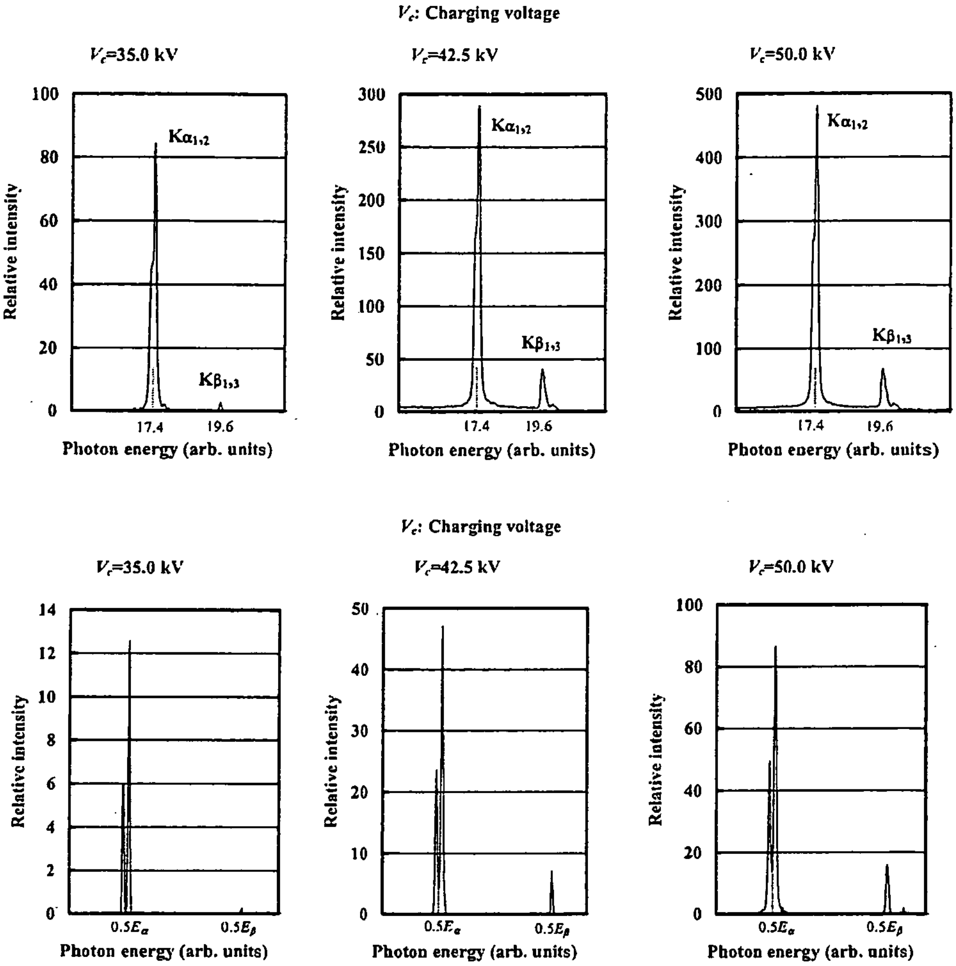

Figure 6: X-ray spectra from molybdenum plasma.

4. RADIOGRAPHY

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

Firstly, rough measurements of image resolution were made using wires. Figure 7 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate with a tube voltage of 50 kV. 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 μm, a 50-μm-diameter wire could be observed.

The image of water falling into a polypropylene beaker from a plastic test tube is shown in Fig. 8. This image was taken with a charging voltage of 50 kV, with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 1 μs, the stop-motion image of water could be obtained.

Figure 9 shows a radiogram of a vertebra with a charging voltage of 45 kV, and fine structures in the vertebra were observed. Figure 10 shows an angiogram of a rabbit heart with a charging voltage of 50 kV. In angiography, iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm were visible.

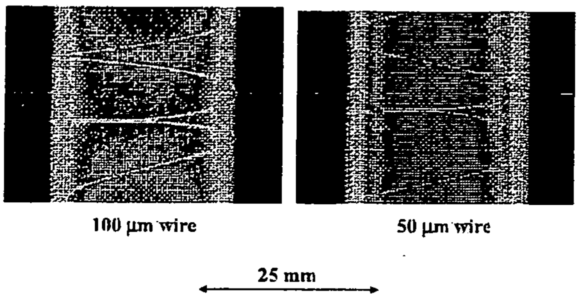
100 μm wire   50 μm wire

Figure 7: Radiograms of tungsten wires in PMMA rod.

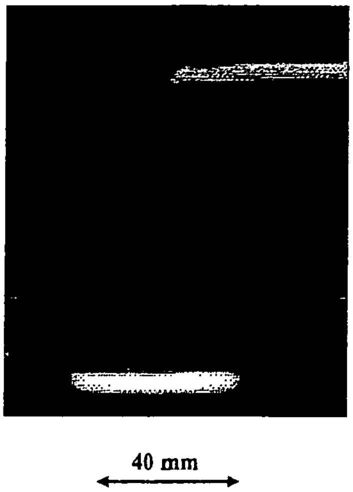

Figure 8: Radiogram of water falling into polypropylene beaker from glass test tube.

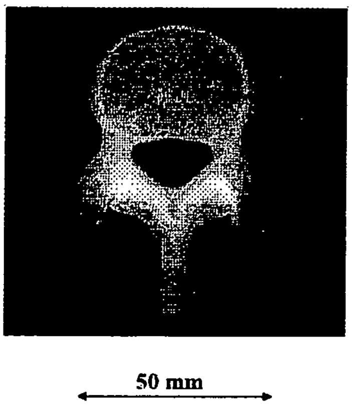

Figure 9: Radiogram of vertebra.

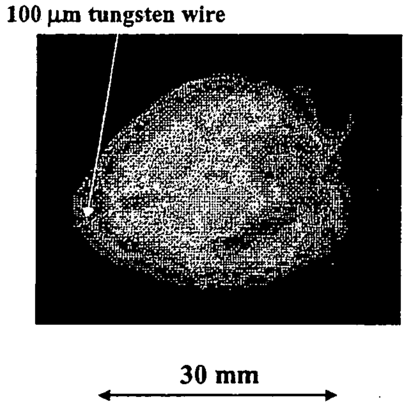

Figure 10: Angiograms of rabbit heart.

5. DISCUSSION

Regarding the spectrum measurement, although we obtained quite intense and sharp K-series lines by forming a linear plasma x-ray source, bremsstrahlung x rays were observed slightly at charging voltages of approximately 50 kV. In addition, we observed fairly intense and clean lines with photon energies of $0.5E_\alpha$. Because bremsstrahlung x rays were hardly observed, we thought that the $0.5E_\alpha$ and $0.5E_\beta$lines were not characteristic x rays reflected by the high order diffraction and were produced by the hard x-ray resonation (oscillation) without using a resonator (Figs. 11 and 12). If we assume that x-ray intensities of the two lines and bremsstrahlung rays are signal and noise, respectively, the signal to noise ratio is higher than 1000:1, and this value is almost equal to those of soft x-ray lasers produced by the gas-discharge capillary.

In this research, we obtained sufficient x-ray intensity per pulse for CR radiography without using a monochromatic filter, and the generator produced number of characteristic photons was approximately 1×10^9 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 high-contrast micro angiography and dual-energy subtraction radiography, will be possible.

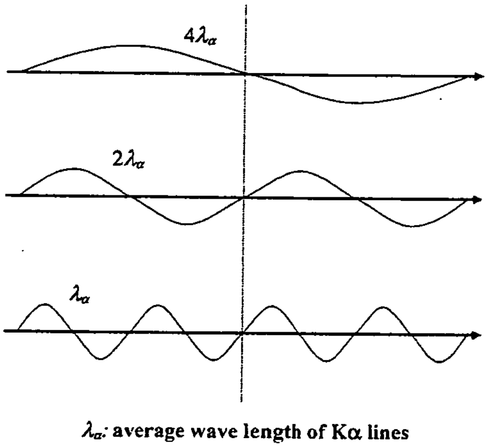

Figure 11: Assumption of hard x-ray resonation without using resonator.

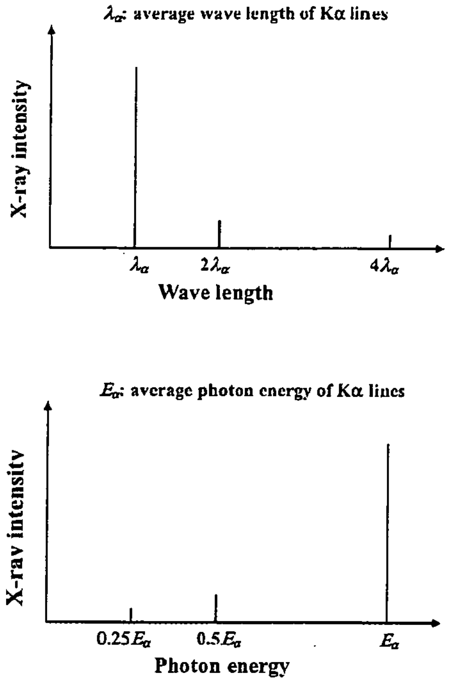

Figure 12: Estimated x-ray spectra under resonation.

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Monochromatic flash x-ray generator utilizing copper-target diode

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ABSTRACT

High-voltage condensers in a polarity-inversion two-stage Marx surge generator are charged from −50 to −70 kV using a power supply, and the electric charges in the condensers are discharged to an x-ray tube after closing the gap switches in the surge generator using 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. Clean copper Kα lines are produced using a 10-μm-thick nickel 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. The peak tube voltage increased with increasing charging voltage. At a charging voltage of −70 kV, the peak tube voltage and current were 140 kV and 0.8 kA, respectively. The pulse widths were approximately 30 ns, and the maximum dimension of the x-ray source was 3.0 mm in diameter. The number of generator-produced Kα photons was approximately 2.5×10^6 photons/cm^2 at 0.5 m per pulse.

Keywords: flash x-ray, characteristic x rays, bremsstrahlung x-ray distribution, copper Kα lines, monochromatic radiography

1. INTRODUCTION

Flash radiography[1] is a major technique that uses high-voltage vacuum discharges to produce short x-ray pulses of less than 1 μs. Basically, although there are several different types of generators, the generator with a multistage Marx surge generator in conjunction with a cold-cathode x-ray tube is popular.[1,2] To apply the generator to biomedicine, several different flash x-ray generators[3-8] have been developed, and monochromatic or quasi-monochromatic generators are useful to perform energy-selective imaging, for example, enhanced K-edge angiography[9-11] using iodine-based contrast media; the angiography is specially performed using a synchrotron in conjunction with a monochromator.

In order to produce clean characteristic x rays with photon energies of less than 20 keV, weakly ionized linear plasma x-ray generators[12-15] are very useful, and intense quasi-monochromatic x rays are produced from the plasma axial

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direction. 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.[16] As compared with the plasma generator, the photon energy of the characteristic x rays can be increased by increasing the maximum output voltage, since a multistage Marx generator can be employed.

In this paper, we describe a compact flash x-ray generator utilizing a cold-cathode radiation tube, used to perform a preliminary experiment for generating clean copper Kα lines.

2. GENERATOR

2.1 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 polarity-inversion two-stage surge Marx generator with a capacity during main discharge of 425 pF, a trigger device for the surge generator, a turbomolecular pump, and a flash x-ray tube. Since the electric circuit of the surge generator employs a polarity-inversion two-stage Marx line (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.

2.2 X-ray tube

The x-ray tube is a demountable diode type, as illustrated in Fig. 3. This tube is connected to the turbomolecular pump with a pressure of approximately 1 mPa and consists of the following major devices: a rod-shaped copper 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 (Figs. 4 and 5), copper Kα rays can be produced using a 10-μm-thick nickel K-edge filter.

3. CHARACTERISTICS

3.1 Tube voltage and current

Tube voltage and current were measured using 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 0.8 kA, respectively, at a charging voltage of −70 kV.

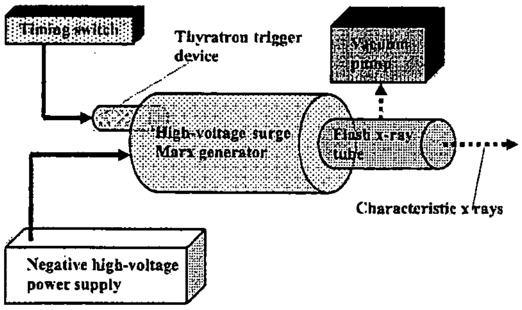

Figure 1: Block diagram of compact monochromatic flash x-ray generator.

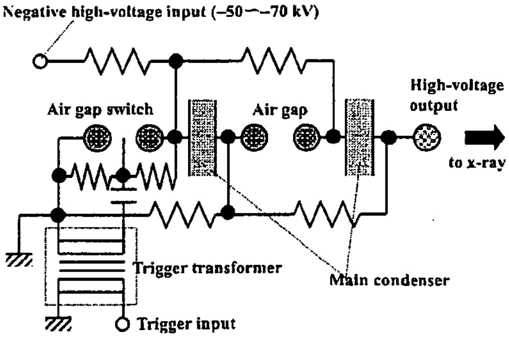

Figure 2: Circuit diagram of flash x-ray generator.