Honorable Mention Poster Award

High-speed K-edge angiography achieved with tantalum K-series characteristic x rays

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ABSTRACT

The tantalum plasma flash x-ray generator is useful in order to perform high-speed K-edge angiography using cone beams because Kα rays from the tantalum target are absorbed effectively by gadolinium-based contrast media. 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. When the charging voltage was increased, the K-series characteristic x-ray intensities of tantalum increased. The K lines were clean and intense, and hardly any bremsstrahlung rays were detected. The x-ray pulse widths were approximately 100 ns, and the time-integrated x-ray intensity had a value of approximately 300 μGy at 1.0 m from the x-ray source with a charging voltage of 80 kV. Angiography was performed using a film-less computed radiography (CR) system and gadolinium-based contrast media. In angiography of non-living animals, we observed fine blood vessels of approximately 100 μm with high contrasts.

Keywords: angiography, gadolinium-based contrast media, characteristic x rays, quasi-monochromatic x rays, tantalum Kα photons

1. INTRODUCTION

The successful uses of monochromatic parallel beams from synchrotron orbital radiation in recent years have greatly increased the demand for phase-contrast radiography[1-3] and enhanced K-edge angiography.[4-6] In particular, the parallel beams with photon energies of approximately 35 keV have been employed to perform angiography, because the beams are absorbed effectively by iodine-based contrast media with a K-absorption edge of 33.2 keV. Without using a synchrotron, we have developed an x-ray generator utilizing a cerium-target tube, and have performed cone-beam K-edge angiography achieved with cerium Kα rays of 34.6 keV.[7] However, the x-ray intensity rate was limited because

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the thermal contact between the target and the anode was not good.

Although various flash x-ray generators have been developed,[8] we have developed flash x-ray generators[9-13] with photon energies of less than 150 keV in order to primarily perform high-speed biomedical radiography. Subsequently, we have developed plasma flash x-ray generators[14-16] to perform a preliminary experiment for producing hard x-ray lasers from weakly ionized linear plasma, and have succeeded in producing intense and clean K-series characteristic x rays using copper and nickel targets. In addition, we have confirmed the weak hard x-ray resonation verified from irradiation of weakly higher harmonic x rays. However, it is difficult to produce high-photon-energy characteristic x rays because the plasma transmits high-photon-energy bremsstrahlung x rays. Therefore, we developed a quasi-monochromatic flash x-ray generator[17,18] with a disk-cathode tube to produce high-energy characteristic x rays utilizing the angle dependence of bremsstrahlung x-ray distribution, because the bremsstrahlung rays are not emitted in the apposite direction to that of electron acceleration. Using this generator, we have succeeded in producing clean characteristic x rays from molybdenum, silver and cerium targets.

Gadolinium-based contrast media with a K-edge of 50.2 keV have been employed to perform angiography in MRI, and the gadolinium density has been increasing. In view of this situation, ytterbium Kα rays (52.0 keV) are useful for enhanced K-edge angiography, because the Kα rays are absorbed effectively by gadolinium media. As compared with angiography using iodine media, the absorbed dose can be decreased considerably utilizing angiography achieved with gadolinium media. However, because ytterbium is a lanthanide series element and has a high reactivity, Kα rays of tantalum and tungsten are also useful to perform angiography.

In this article, we describe an intense quasi-monochromatic plasma flash x-ray generator with a tantalum target tube, and used it to perform a preliminary study on angiography achieved with tantalum 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 gadolinium K-edge. The average photon energy of the tantalum Kα lines is shown above the gadolinium K-edge. The average photon energy of tantalum Kα lines is 57.1 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

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 (Fig. 3). 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.

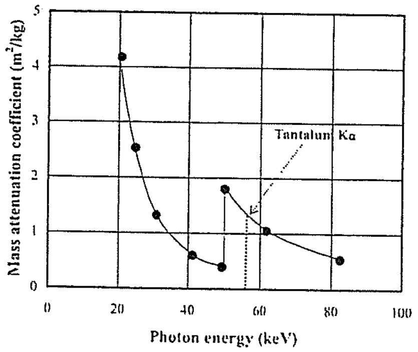

Figure 1: Relation between mass attenuation coefficient of gadolinium and average photon energy of tantalum Kα lines.

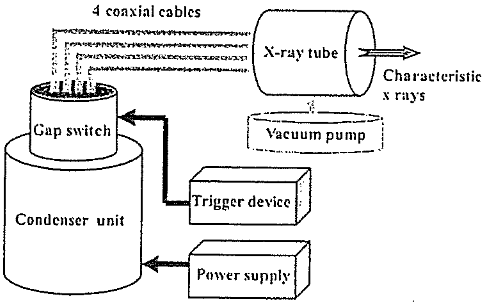

Figure 2: Block diagram of intense quasi-monochromatic flash x-ray generator.

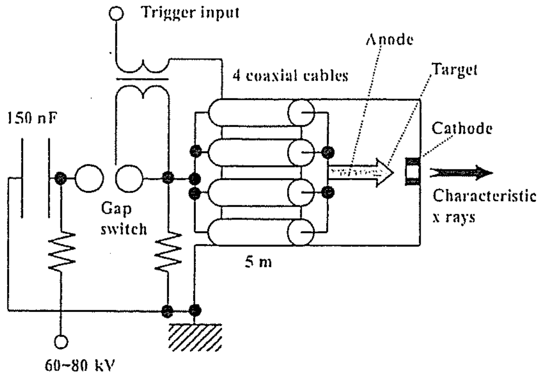

Figure 3: High-voltage circuit of flash x-ray generator.

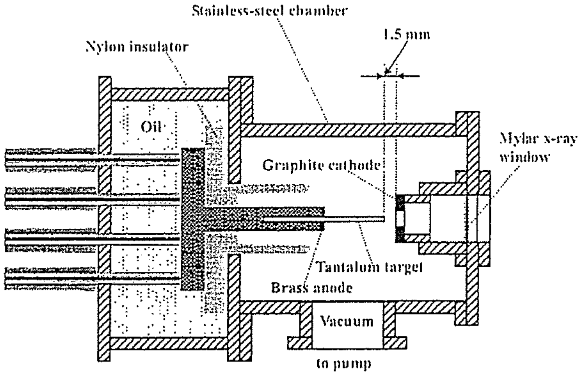

Figure 4: Schematic drawing of flash x-ray tube.

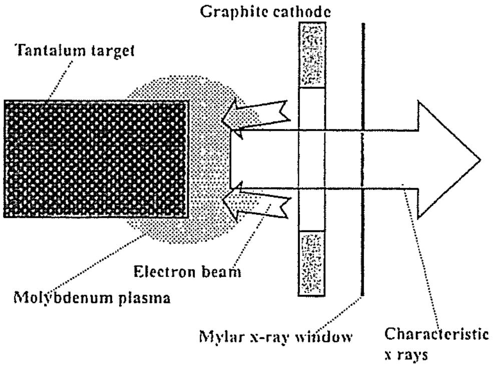

Figure 5: Irradiation of characteristic x rays.

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. 4). This tube consists of the following major parts: a ring-shaped graphite cathode with an bore 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 tantalum 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 tantalum ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 5), tantalum K-series characteristic x rays can be produced without using a filter.

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. 6). 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 300 μGy 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 characteristic x-ray source, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 7). 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 decreases in the pinhole diameter.

4.4 X-ray spectra

X-ray spectra were measured using a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The x-ray intensities of the spectra were detected by an imaging plate of a computed radiography (CR) system[19] (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 tantalum target. We observed clean K-series lines, while bremsstrahlung rays were hardly detected. The characteristic x-ray intensity substantially increased with increases in the charging voltage.

5. ANGIOGRAPHY

The flash angiography was performed by a computed radiography (CR) system (Konica Regius 150)[19] at 1.2 m from the x-ray source, and the charging voltage was 80 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 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. Because the tungsten wires transmitted the characteristic x rays easily, low contrast radiograms were obtained.

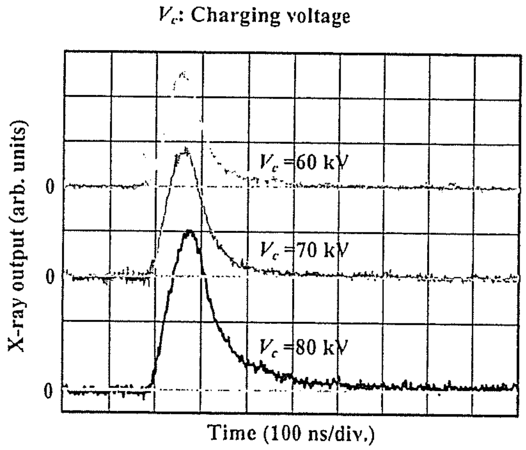

Figure 6: X-ray outputs at indicated conditions.

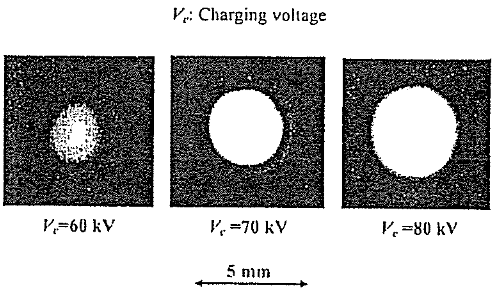

Figure 7: Images of characteristic x-ray source with changes in charging voltage.

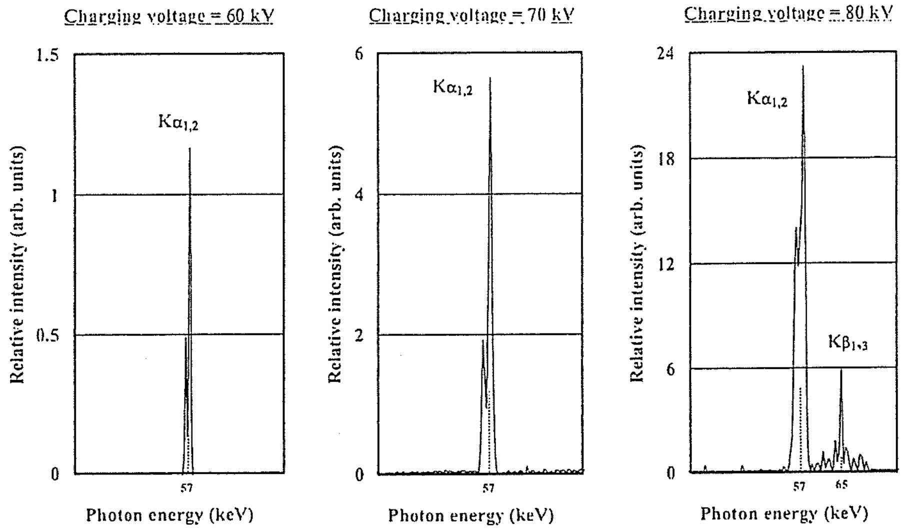

Figure 8: X-ray spectra from tantalum target.

The image of water (gadolinium oxide suspension of 20%) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 10. The diameter of gadolinium oxide powder ranges from 1 to 10 µm. Because the x-ray duration was about 100 ns, the stop-motion image of water could be obtained.

Figure 11 shows an angiogram of a silicone rubber tube in a polymethyl methacrylate (PMMA) case using a contrast medium which contains 32.3% gadodiamidehydrate, and a low contrast tube with a bore diameter of 1.0 mm is observed. In cases where a gadolinium oxide suspension of 50% is employed, high-contrast angiography of the tubes (1.0 mm and 0.5 mm in bore diameter) could be performed (Fig. 12). Figure 13 shows an angiogram of a rabbit head using gadolinium oxide powder, and fine blood vessels of approximately 100 µm were visible.

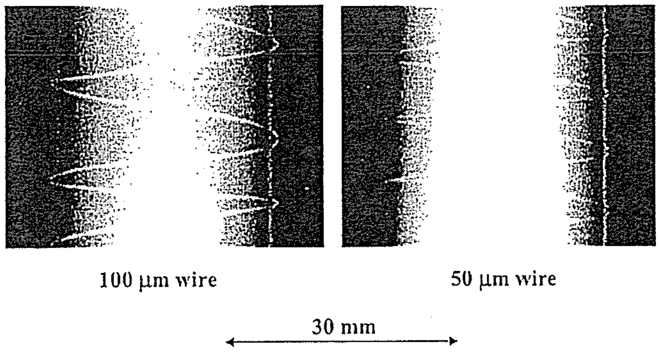

Figure 9: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate.

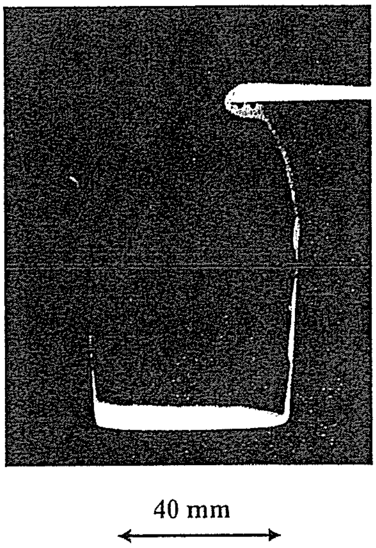

Figure 10: Radiogram of water falling into polypropylene beaker from plastic test tube.

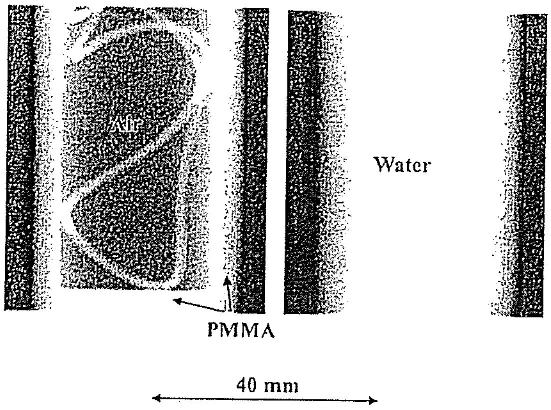

Figure 11: Angiograms of silicon tube using contrast medium of 32.3% gadodiamidehydrate.

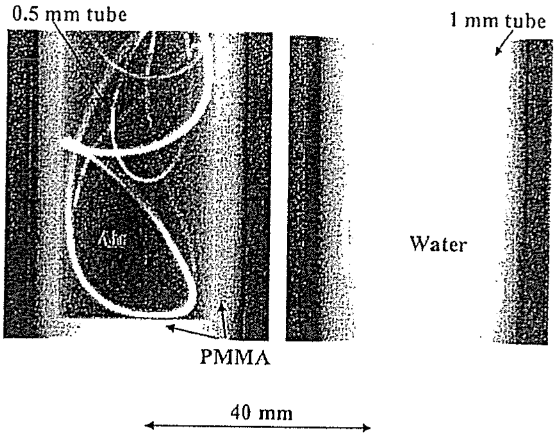

Figure 12: Angiography of silicon tube using gadolinium oxide suspension of 50%.

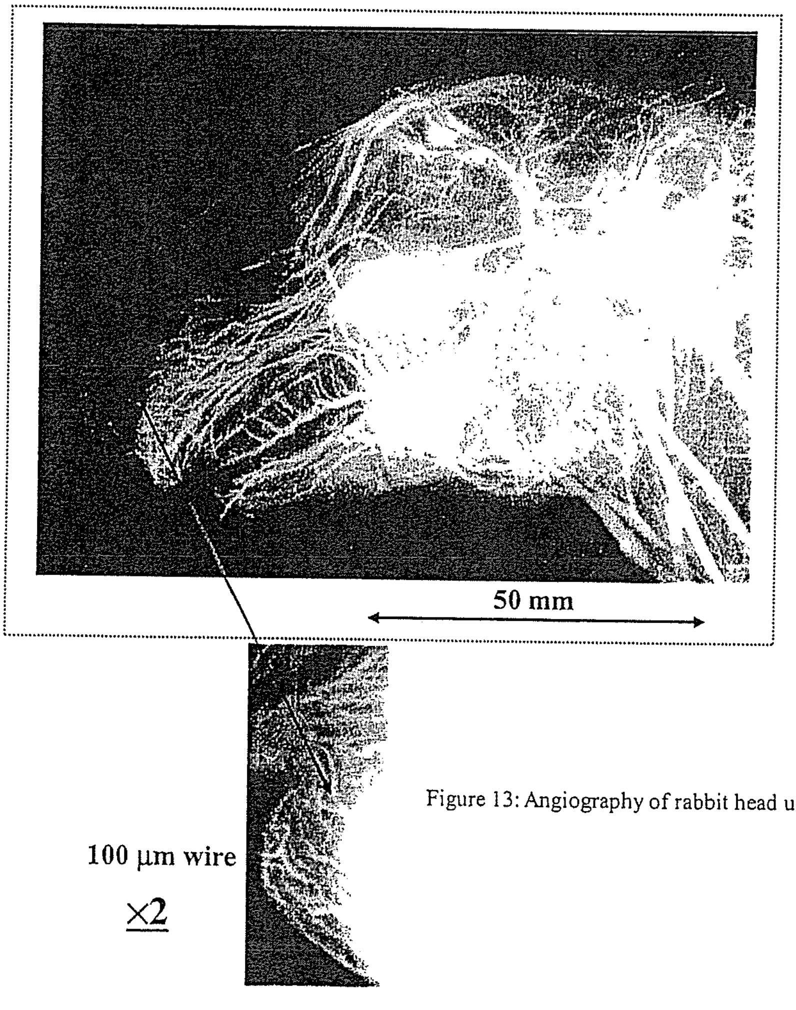

Figure 13: Angiography of rabbit head using gadolinium oxide powder.

6. DISCUSSION AND CONCLUSIONS

In summary, we succeeded in producing K-series characteristic x rays of tantalum and in performing K-edge angiography using gadolinium contrast media with a K-edge of 50.2 keV, and this K-edge angiography could be a useful technique to decrease the dose absorbed by patients. Although we employed tantalum Kα (57.1 keV) and Kβ (approximately 65 keV) rays, Kβ rays should be absorbed using an ytterbium oxide filter with an ytterbium K edge of 61.3 keV in order to increase the image contrast of blood vessels.

To perform K-edge angiography using gadolinium media, although an ytterbium target with a Kα energy of 52.0 keV is useful, the ytterbium has a high reactivity. If we assume that the ytterbium is employed, an alloy target should be developed. In this research, we obtained sufficient x-ray intensity per pulse for angiography, and the intensity can be increased by increasing the electrostatic energies in the high-voltage condenser. At a condenser capacity of 150 nF, the generator produced instantaneous number of K photons was approximately 1×10^9 photons/cm^2 per pulse at 1.0 m from the source.

In the flash x-ray tube, bremsstrahlung x rays with energies higher than the K-edge are absorbed effectively by the weakly ionized plasma and are converted into fluorescent (characteristic) x rays. In conjunction with this property, because the bremsstrahlung x rays are not emitted in the opposite direction to that of electron acceleration, clean characteristic x rays are produced. Using this flash x-ray generator, with which the photon energy of characteristic x rays can be selected, quasi-monochromatic imaging such as enhanced K-edge angiography using iodine contrast media and mammography can be performed.

ACKNOWLEDGMENT

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Preliminary experiment for producing higher harmonic x rays utilizing copper 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 trigger electrode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Target evaporation leads to the formation of weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target, and intense Kα lines are left using a 10-μm-thick nickel filter. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 15 kA. The K-series characteristic x

rays were clean and intense, and higher harmonic x rays were observed. The x-ray pulse widths were approximately 700 ns, and the time-integrated x-ray intensity had a value of approximately 20 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

1. Introduction

Recently, soft x-ray lasers have been produced by a gas-discharge capillary,[1-4] and the laser pulse energy substantially increased in proportion to the capillary length. 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.

To perform high-speed soft radiography, several different flash x-ray generators[5-10] have been developed corresponding to specific objectives. Subsequently, we have developed a compact flash x-ray generator utilizing a disk-cathode demountable diode,[11,12] and have performed a preliminary experiment for producing clean characteristic x rays utilizing angle dependence of bremsstrahlung x rays.

With recent advances in high-voltage pulse technology, several different plasma flash x-ray generators have been developed 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.

In this paper, we describe a plasma flash x-ray generator[13-15] utilizing a rod-target radiation tube, used to perform a preliminary experiment for generating intense and clean K-series characteristic x rays and their higher harmonic x rays by forming a linear copper plasma cloud around a fine target.

2. Generator

Figure 1 shows a block diagram of the high-intensity plasma flash x-ray generator. This generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 200 nF, a turbomolecular pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. The high-voltage main condenser is charged to 50 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode with the trigger device. The plasma flash x rays are then produced.

The x-ray tube is a demountable cold-cathode triode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa. This tube consists of the following major parts: a hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a brass focusing electrode, a trigger electrode made from copper wire, a stainless steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped copper target 3.0 mm in diameter with a tip angle of 60°. The distance between the target and cathode electrodes is approximately 20 mm, and the trigger electrode is set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by the focusing electrode, evaporation leads to the formation of a weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x rays (Fig. 2). The plasma then transmits the fluorescent rays easily, and bremsstrahlung rays with energies lower than the K-edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, intense characteristic x rays are generated from the plasma-axial direction.

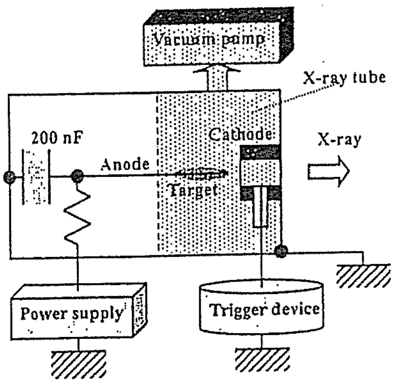

Fig. 1: Block diagram including electric circuit of plasma flash x-ray generator.

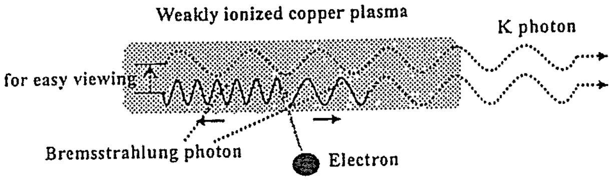

Fig. 2: K-photon irradiation from plasma.

3. Characteristics

Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. 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 15 kA.

X-ray output pulse was detected by a combination of a plastic scintillator and a photomultiplier using a 10-μm-thick nickel filter. The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 700 ns, and the time-integrated x-ray intensity per pulse measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 utilizing MSO-S elements without energy compensation) had a value of about 20 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

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] (Konica Regius 150) with a wide dynamic range, using the filter, and relative x-ray intensity was calculated from Dicom digital data. Figure 3 shows measured spectra from the copper target with a charging voltage of 50 kV. In fact, we observed clean K lines such as lasers, and Kα lines were left by absorbing Kβ lines using the filter. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage, and higher harmonic x rays were observed.

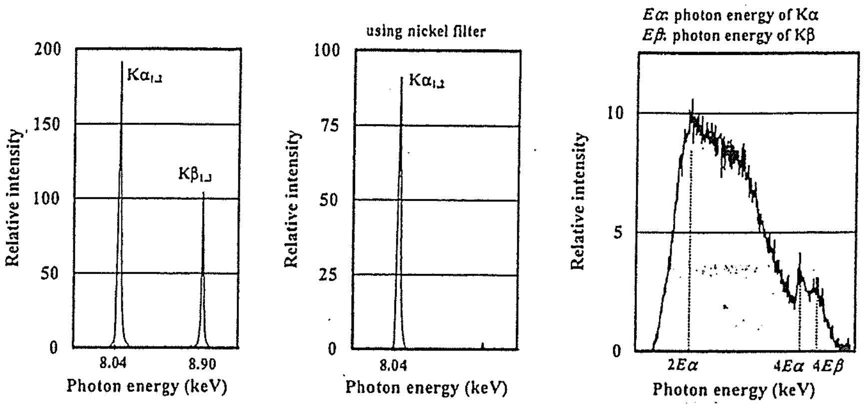

Fig. 3: X-ray spectra from weakly ionized copper plasma at indicated conditions.

4. Radiography

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

Firstly, an image of plastic bullets falling into a polypropylene beaker from a plastic test tube is shown in Fig. 4. Because the x-ray duration was about 1 μs, the stop-motion image of bullets could be obtained. Figure 5 shows an angiogram of a rabbit ear; iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 50 μm were visible.

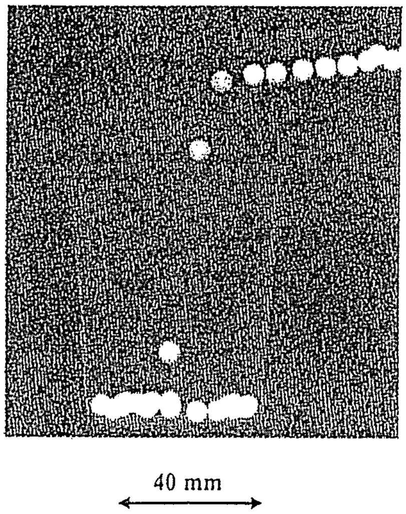

Fig. 4: Radiogram of water falling into polypropylene beaker from plastic test tube.

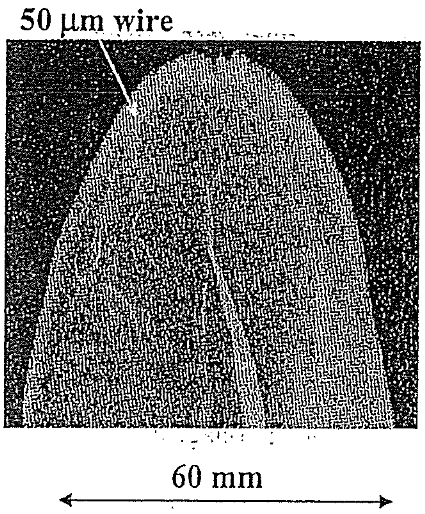

Fig. 5: Angiograms of rabbit ear.

5. Discussion and Conclusions

Concerning the spectrum measurement, we obtained fairly intense and clean K lines from a weakly ionized linear plasma x-ray source, and Kα lines were left by absorbing Kβ lines using the nickel filter. In particular, the higher harmonic x rays were produced from the plasma. Assuming that the harmonic rays are produced by the x-ray resonation (Fig. 6), the estimated spectra are shown in Fig. 7. In cases where a copper target is employed, fractional harmonic x rays are absorbed by an x-ray window and air.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography, and the generator produced number of characteristic Kα photons was approximately 5×10^7 photons/cm^2 at 1.0 m per pulse. In addition, since the photon energy of characteristic x rays can be controlled by changing the target elements, various quasi-monochromatic high-speed radiographies, such as high-contrast angiography and mammography, will be possible.

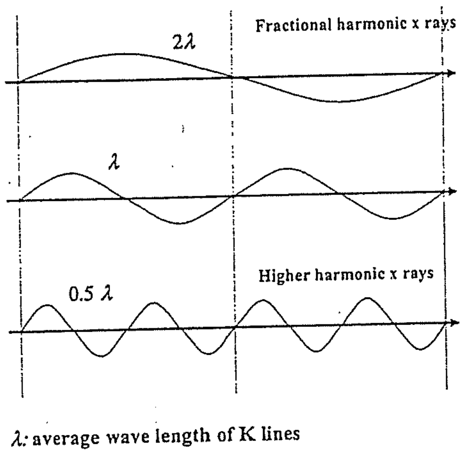

Fig. 6: X-ray resonation without using resonator.

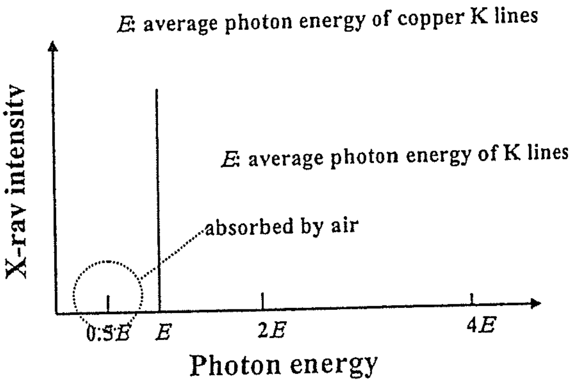

Fig. 7: Estimated x-ray spectra under resonation.

Acknowledgment

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

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ABSTRACT

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

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

1. INTRODUCTION

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

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

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

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

To apply flash x-ray generators to biomedicine, several different generators[8-13] have been developed, and plasma x-ray generators[14-17] 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.

In this paper, we describe a recent plasma flash x-ray generator utilizing a rod target triode, used to perform a preliminary experiment for generating clean K-series characteristic x-rays and their higher harmonic hard x-rays by forming a plasma cloud around a fine target.

2. GENERATOR

Figure 1 shows a block diagram of the high-intensity plasma flash x-ray generator. This generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 200 nF, a turbomolecular pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. The high-voltage main condenser is charged to 50 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode with the trigger device. The plasma flash x-rays are then produced.

The schematic drawing of the plasma x-ray tube is illustrated in Fig. 2. The x-ray tube is a demountable cold-cathode triode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa. This tube consists of the following major parts: a hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a brass focusing electrode, a trigger electrode made from copper wire, a stainless steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped copper target 3.0 mm in diameter with a tip angle of 60°. The distance between the target and cathode electrodes is approximately 20 mm, and the trigger electrode is set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by the focusing electrode, evaporation leads to the formation of a weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x-rays. The plasma then transmits the fluorescent rays easily, and bremsstrahlung rays with energies lower than the K-edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory, intense characteristic x-rays are generated from the plasma-axial direction.

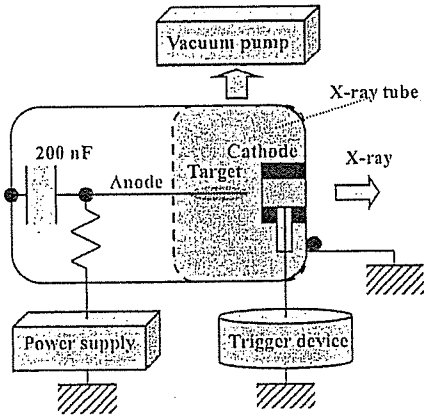


Figure 1: Block diagram including the electric circuit of the plasma flash x-ray generator.

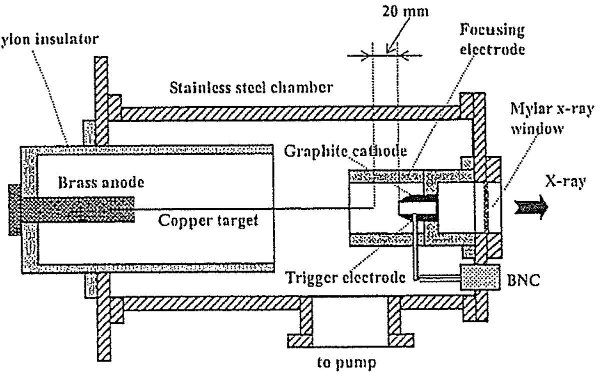


Figure 2: Schematic drawing of the flash x-ray tube with a rod copper target.

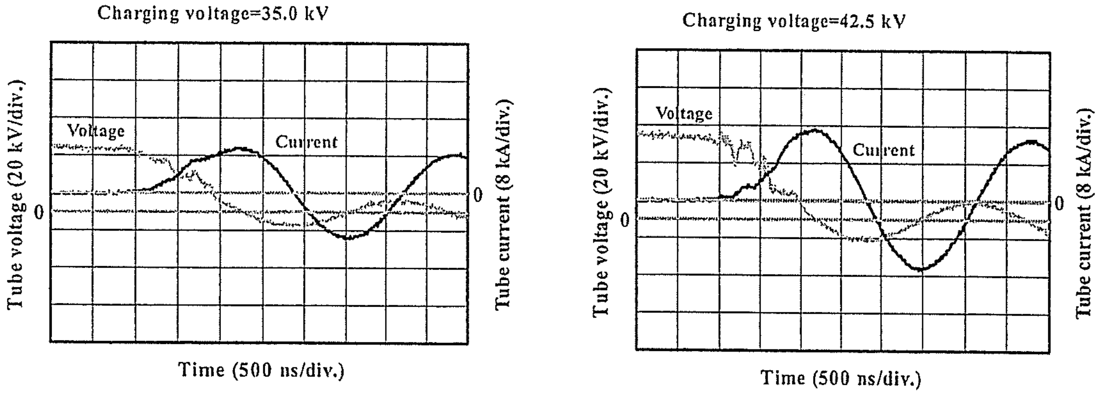
3. CHARACTERISTICS

3.1 Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 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 300 ns, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 1.5 mGy at 1.0 m from the x-ray source with a charging voltage of 50 kV.


Charging voltage=35.0 kV

Charging voltage=42.5 kV

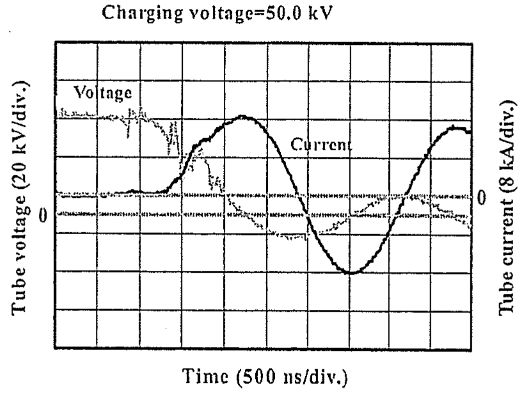

Charging voltage=50.0 kV

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

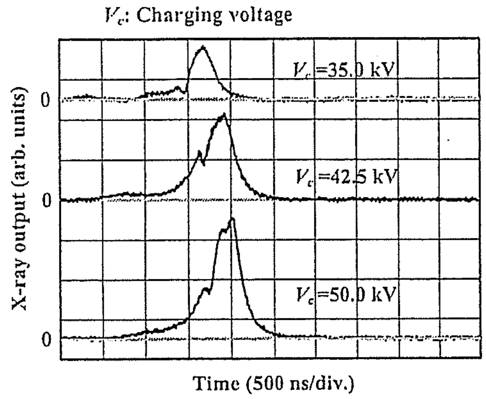


Figure 4: X-ray outputs at the indicated conditions.

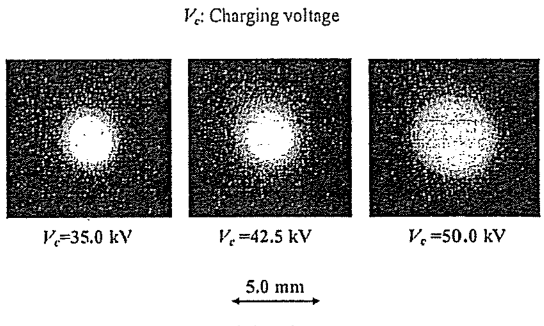


Figure 5: Images of the plasma x-ray source.

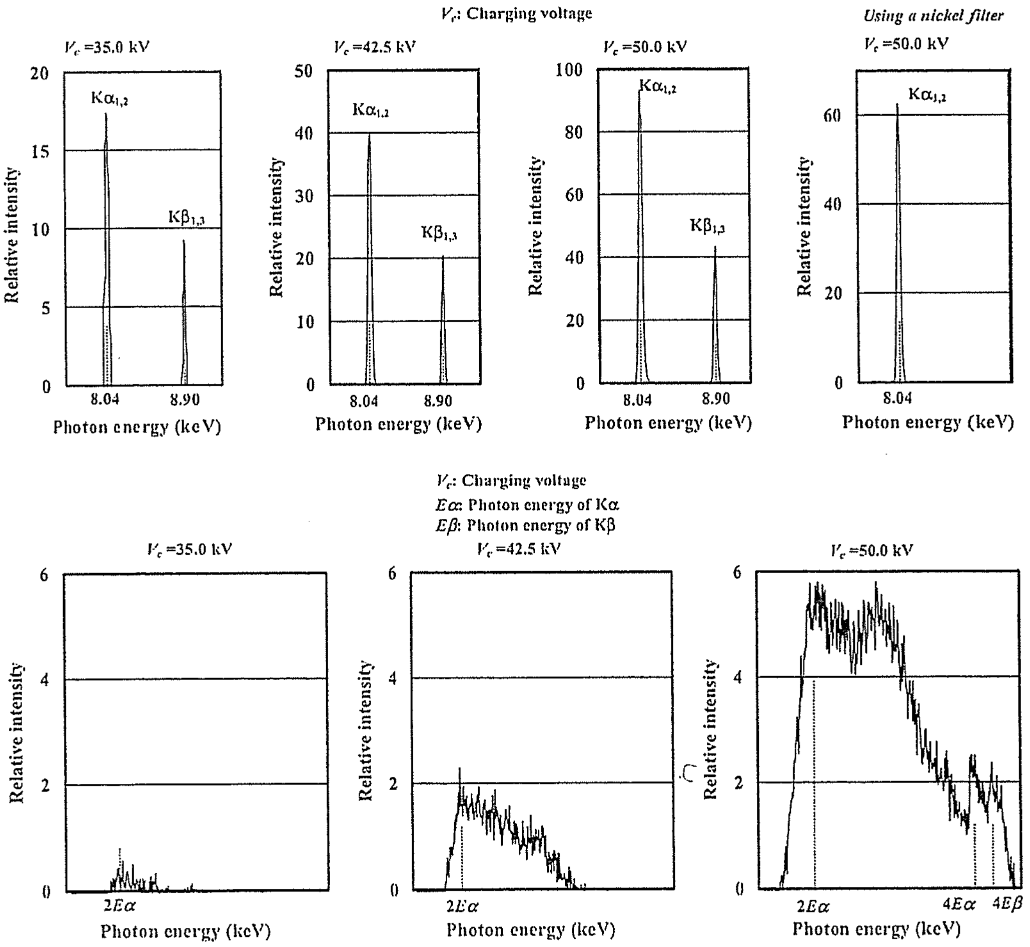


Figure 6: X-ray spectra from weakly ionized copper plasma at the indicated conditions.

3.3 X-ray source

In order to roughly observe images of the plasma x-ray source in the detector plane, we employed a pinhole camera with a hole diameter of 100 µm (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

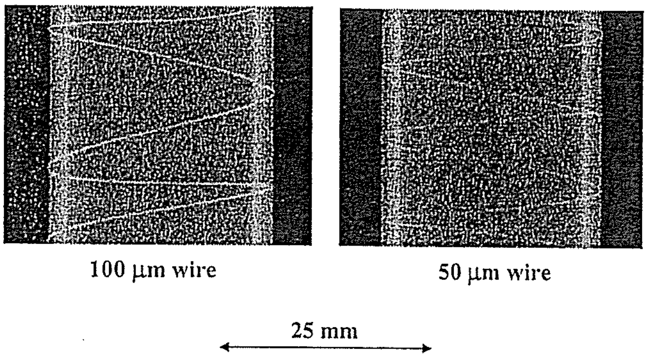
X-ray spectra from the plasma source were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[18] (Konica Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated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

4. RADIOGRAPHY

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

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

Figure 8 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. Next, a radiogram of plastic bullets falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. Because the x-ray duration was about 0.5 µs, the stop-motion image of bullets could be obtained. Figure 10 shows an angiogram of a rabbit ear; 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 coiled around PMMA pipes.

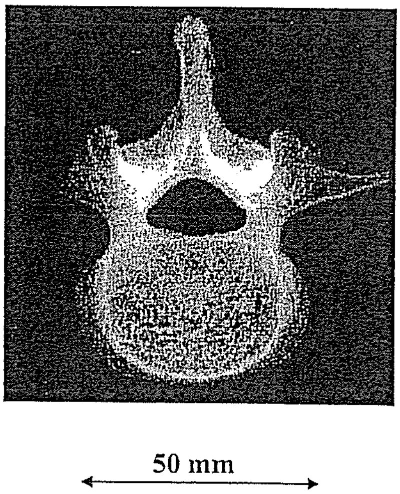


Figure 8: Radiogram of a vertebra.