ACKNOWLEDGMENTS

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 16591181, 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 the Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and the New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

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Superposition of x-ray spectra using a brass-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 brass target containing 65% copper and 35% zinc by weight, 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 15 kA. When the charging voltage was increased, the linear plasma formed, and the K-series characteristic x-ray intensities of zinc Kα, copper Kα, and copper Kβ lines increased substantially. However hardly any zinc Kβ lines were detected. The x-ray pulse widths were approximately 700 ns, and the time-integrated x-ray intensity was approximately 1.2 mGy 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

Conventional flash x-ray generators[1] utilize high-voltage condensers and cold-cathode x-ray tubes and produce extremely short x-ray pulses with durations of less than 1 μs. Because the high-voltage durability substantially increases 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 utilizing surge Marx generators in conjunction with diodes.

In order to perform biomedical radiography, we have developed several different flash x-ray generators[2-5] corresponding to specific radiographic objectives, and we have succeeded in producing clean K-series characteristic x-rays of nickel and copper from weakly ionized linear plasma using a plasma triode.[6-9] Subsequently, because we have confirmed the irradiations of clean K-series characteristic x-rays of molybdenum using a compact flash x-ray generator with a disk-cathode diode,[10,11] an intense plasma diode have been developed to produce high-photon-energy characteristic x-rays of molybdenum, cerium,[12] tantalum, and tungsten. In particular, the tantalum K rays[13] have been applied to high-speed K-edge angiography using gadolinium-based contrast media.

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: 10.1117/12.620207

On the other hand, we are very interested in the superposition of characteristic x-rays[14] using weakly ionized plasma in order to perform wide-photon-energy or energy subtraction radiography. In particular, the absorption of K rays in the plasma consisting of electrons and two-element metal ions should be investigated. Furthermore, because we have confirmed the irradiation of higher harmonic hard x-rays using nickel and copper targets, the x-ray spectra with photon energies beyond the K edges should be measured.

In this paper, we describe a plasma flash x-ray generator utilizing a brass-target radiation tube, used to perform a preliminary experiment for the superposition of K-series characteristic x-rays in weakly ionized plasma and for producing their higher harmonic hard 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 4.0-mm-diameter rod brass target containing 65% copper and 35% zinc by weight. 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.

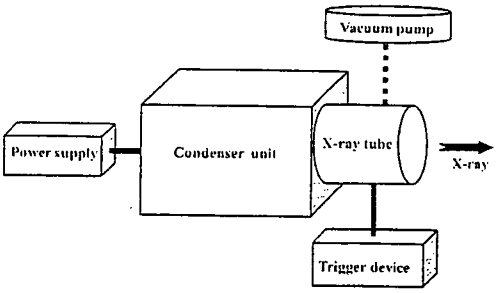


Figure 1: Block diagram of the high-intensity plasma flash x-ray generator.

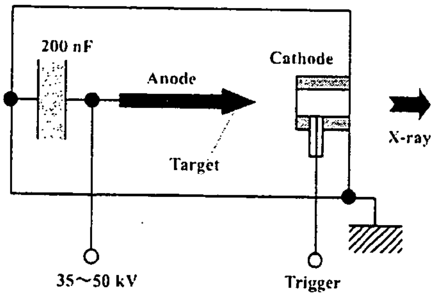


Figure 2: Circuit diagram of the flash x-ray generator.

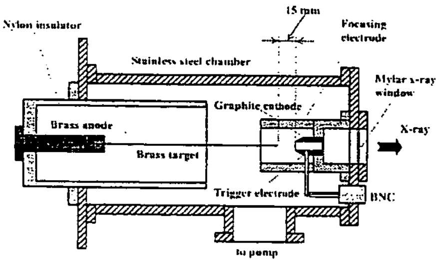


Figure 3: Schematic drawing of the flash x-ray tube with a brass target.

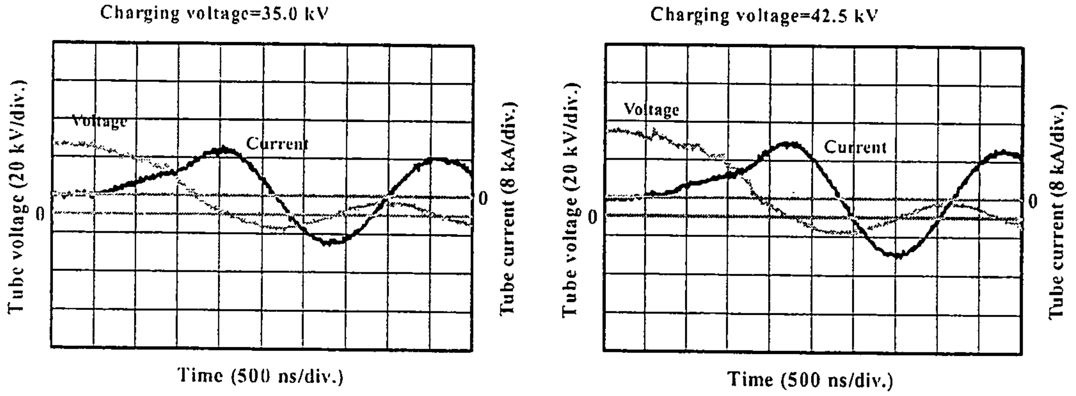
3. CHARACTERISTICS

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 15 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 700 ns, 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 1.2 mGy at 1.0 m from the x-ray source with a charging voltage of 50 kV.



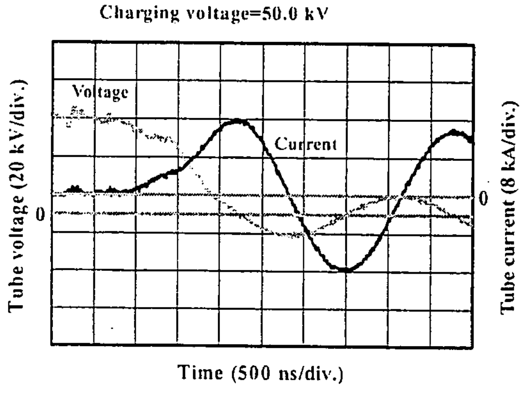


Figure 4: Tube voltages and currents with changes in the charging voltage.

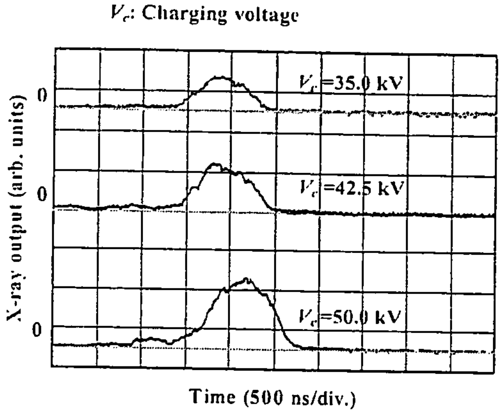


Figure 5: X-ray outputs at the indicated conditions.

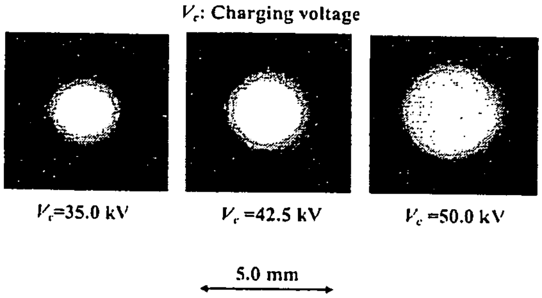
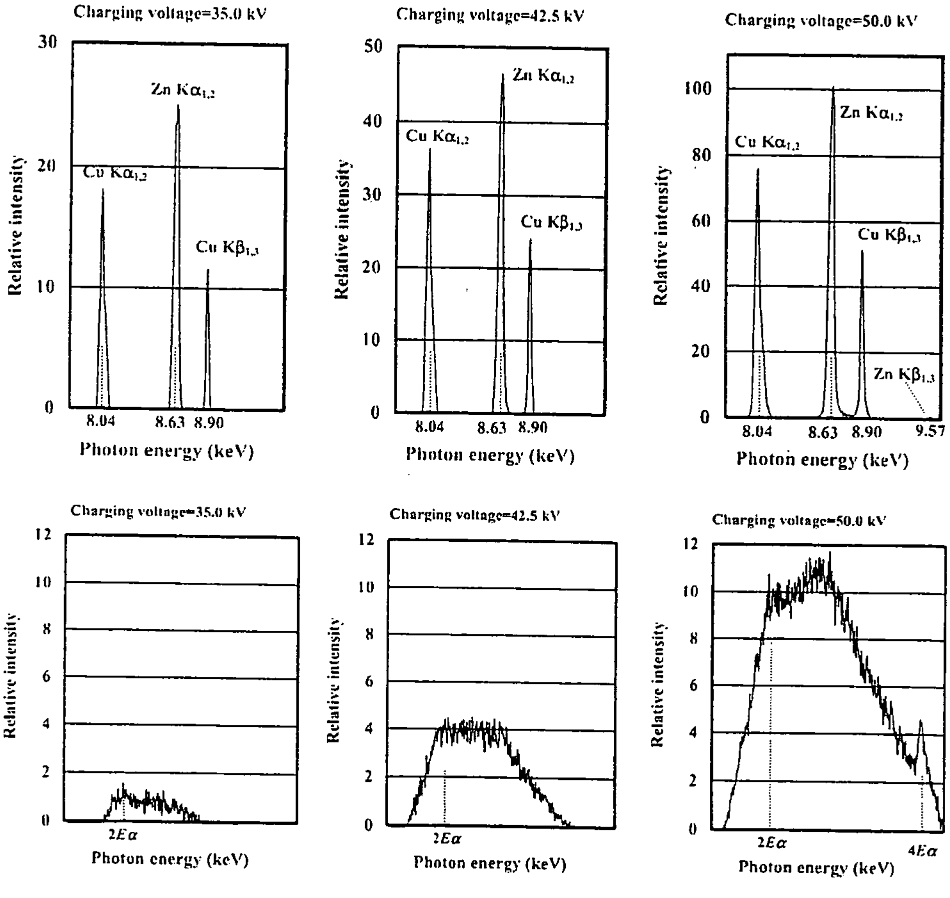


Figure 6: Images of plasma x-ray source.



Eα: Photon energy of copper Kα

Figure 7: X-ray spectra 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 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 target, 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[15] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data.

Figure 7 shows measured spectra from weakly ionized metal plasma. We observed sharp lines of K-series characteristic x- rays of copper Kα, copper Kβ and zinc Kα lines. However, zinc Kβ and bremsstrahlung rays were hardly detected. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage. In the high-photon-energy region, higher harmonic hard x-rays with photon energies of approximately $2E_\alpha$ and $4E_\alpha$ were observed. Here, E_α is the average photon energies of copper Kα lines.

4. RADIOGRAPHY

The plasma radiography was performed by the CR system (Konica Regius 150) without using a filter, and the charging voltage and the distance (between the x-ray source and imaging plate) were 501 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. Next, the image of aluminum grains falling into a polypropylene beaker from a glass test tube is shown in Fig. 9. Because the x-ray duration was approximately 700 ns, the stop-motion image of grains could be obtained.

Figures 10 and 11 show angiograms of a rabbit heart and a thigh, respectively. In angiography, iodine-based microspheres of 15 µm in diameter were used, and fine blood vessels of about 100 µm are clearly visible.

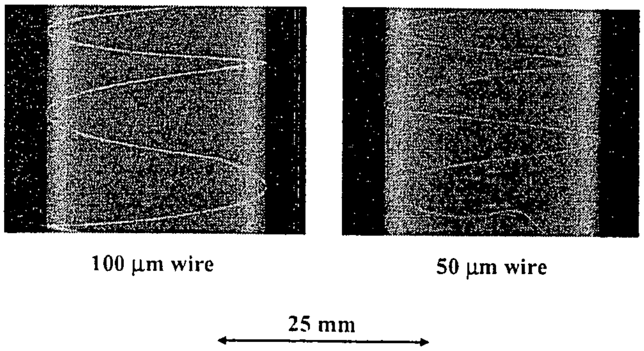

100 µm wire
50 µm wire

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

Figure 9: Radiogram of aluminum grains from a glass test tube.

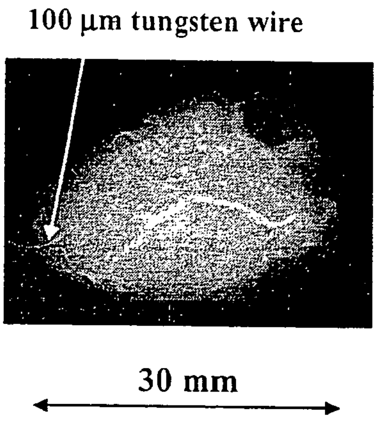


Figure 10: Angiogram of a rabbit heart.

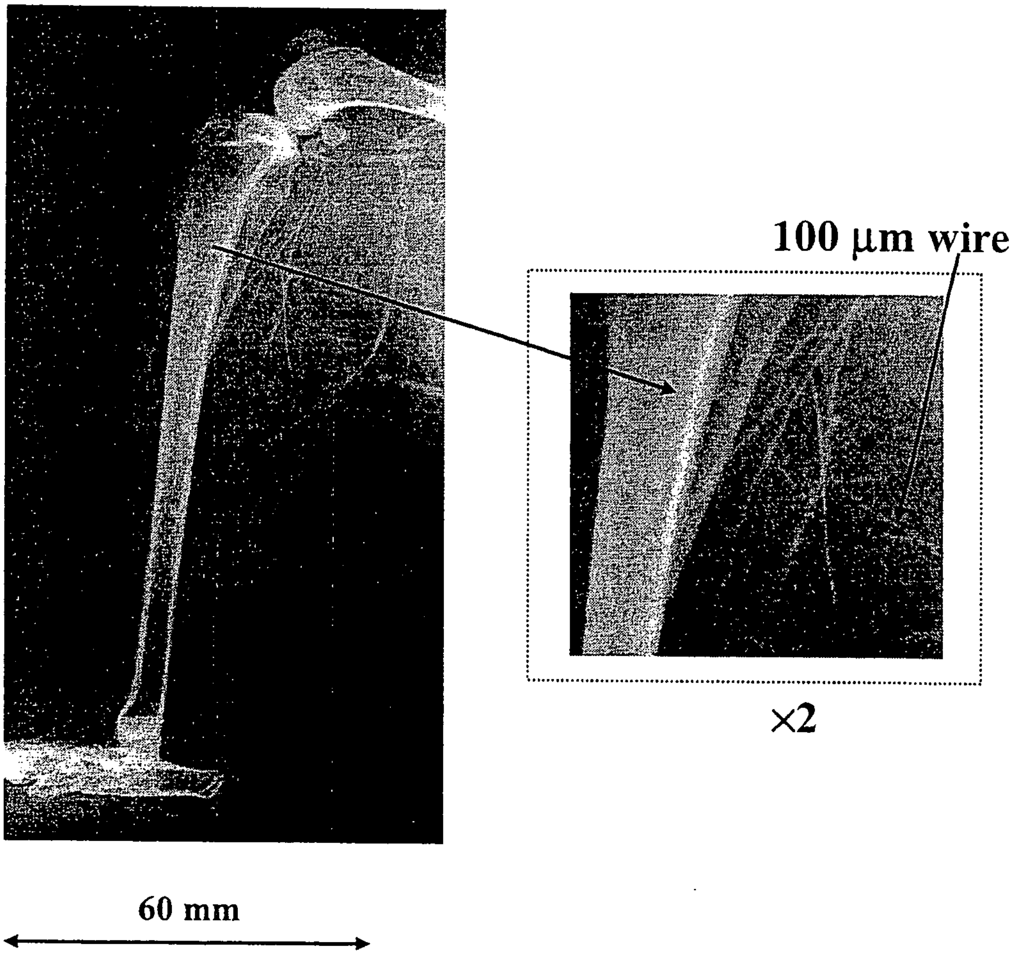


Figure 11: Angiogram of a rabbit thigh.

5. CONCLUSIONS AND OUTLOOK

Regarding the spectrum measurement, although we confirmed clean copper Kα, copper Kβ and zinc Kα lines, zinc Kβ lines were hardly observed. Because weakly ionized zinc plasma (ion) transmits zinc Kβ lines easily, the lines were absorbed by copper plasma. In high-photon-energy region, although we could not observe clean higher harmonics, bremsstrahlung x-rays with photon energies approximately $2E_\alpha$ and $4E_\alpha$ were left in cases where a high charging voltage of approximately 50 kV was applied.

From the experimental results, because the x-ray spectra with photon energies just beyond copper K edge are absorbed effectively by the copper plasma, zinc Kβ rays are useful to produce copper fluorescent rays. In addition, we are very interested in the results using a capillary-type target for forming weakly ionized linear plasma.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography, and the generator produced number of characteristic photons was approximately 1×10^8 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-photon-energy radiography, will be possible.

ACKNOWLEDGMENT

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 16591181, 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 the Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and the New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

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原子核研究
Vol. 49 No. 5
研究会報告

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.

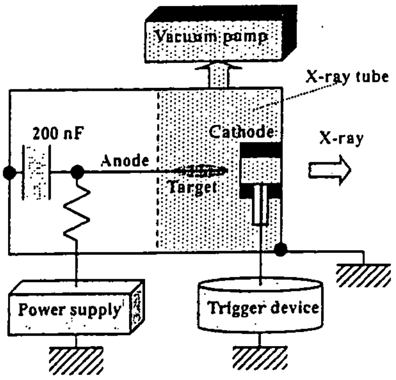

Fig. 1: Block diagram including electric circuit of plasma flash x-ray generator.

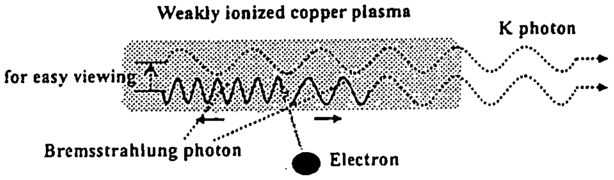

Fig. 2: K-photon irradiation from plasma.

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.

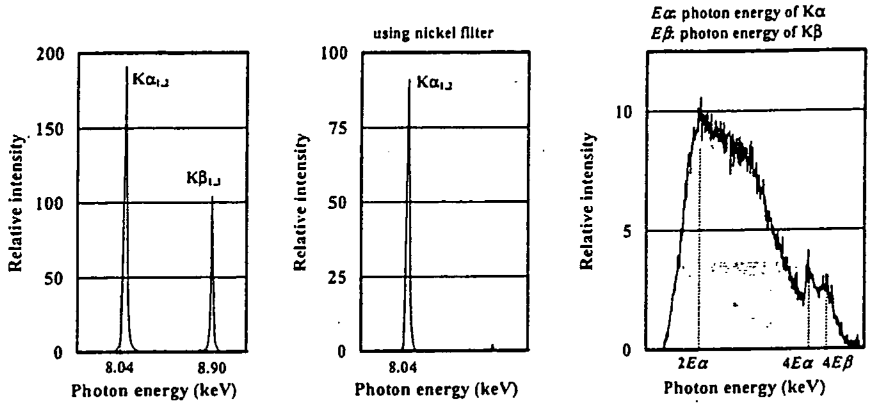

Fig. 3: X-ray spectra from weakly ionized copper plasma at indicated conditions.

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.

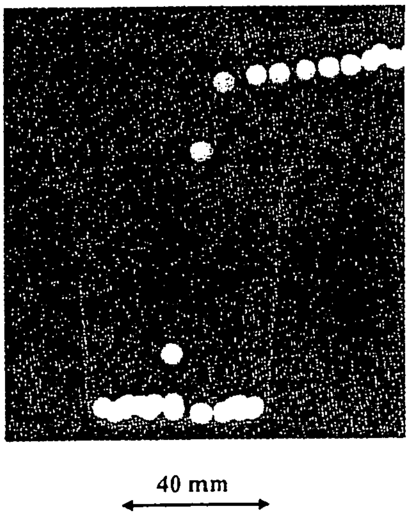

Fig. 4: Radiogram of water falling into polypropylene beaker from plastic test tube.

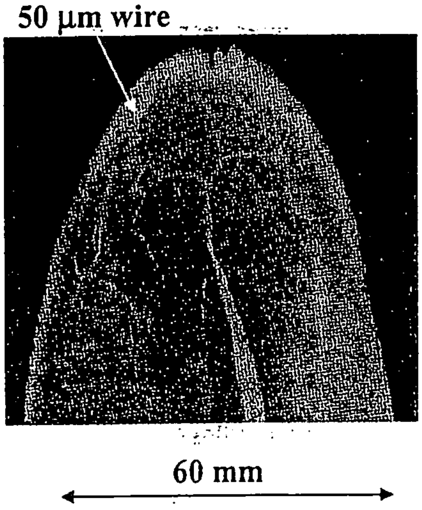

Fig. 5: Angiograms of rabbit ear.

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 $K\alpha$ lines were left by absorbing $K\beta$ 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 $K\alpha$ 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.

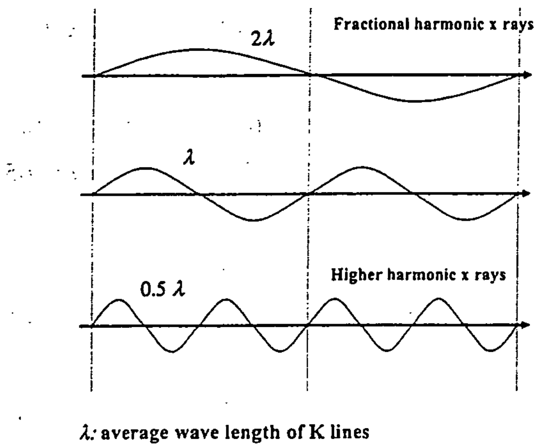

Fig. 6: X-ray resonation without using resonator.

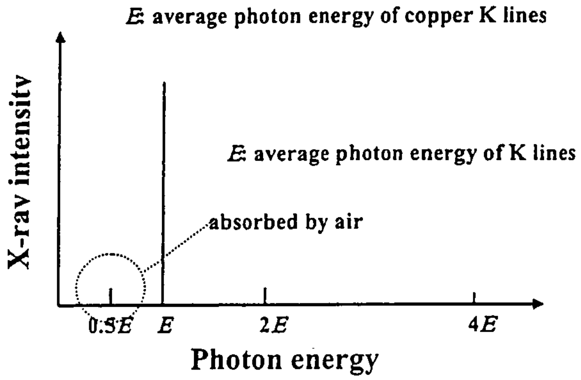

Fig. 7: Estimated x-ray spectra under resonation.

Acknowledgment

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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原子核研究
Vol. 49 No. 5
研究会報告

Conventional enhanced K-edge angiography utilizing cerium x-ray generator

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Abstract

The cerium-target x-ray tube is useful in order to perform cone-beam K-edge angiography because Kα rays from the cerium target are absorbed effectively by iodine-based contrast media. The maximum tube voltage and current were 65 kV and 0.40 mA, respectively, and the focal-spot sizes were approximately 1×1 mm. Sharp cerium Kα lines were left using a barium sulfate filter, and the x-ray

intensity was 16.8 μGy/s at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.40 mA. Angiography was performed using iodine-based microspheres 15 μm in diameter. In angiography of non-living animals, we observed fine blood vessels of 100 μm or less.

1. Introduction

Synchrotrons generate monochromatic parallel x-ray beams using single crystals. These beams with photon energies of approximately 35 keV have been employed to perform enhanced K-edge angiography,[1-3] since the beams are absorbed effectively by iodine-based contrast media.

In order to perform high-speed medical radiography, although several different flash x-ray generators[4-9] utilizing cold-cathode tubes have been developed, plasma flash x-ray generators[10-13] are useful to produce quasi-monochromatic x rays without using a K-edge filter. Therefore, we have performed a demonstration of cone-beam K-edge angiography[14] utilizing a cerium plasma generator, since K-series characteristic x rays from the cerium target are absorbed effectively by iodine. Recently, we have developed a steady-state x-ray generator utilizing a cerium-target tube, and have demonstrated enhanced K-edge angiography utilizing a barium sulfate filter.[15] In this research, Kα lines (34.6 keV) were left by absorbing Kβ lines (39.2 keV).

In the present research, we describe a preliminary study on cone-beam K-edge angiography achieved with cerium Kα rays using a barium sulfate filter.

2. Generator

Figure 1 shows the block diagram of the x-ray generator, which consists of a main controller, a cerium-target x-ray tube unit with a Cockcroft-Walton circuit and an insulation transformer, and a personal computer. The tube voltage, the current, and the exposure time can be controlled by both the controller and the computer. The main circuit for producing x rays is illustrated in Fig. 2, and employs the Cockcroft-Walton circuit in order to decrease the dimensions of the tube unit. In the x-ray tube, the negative high-voltage is applied to the cathode electrode, and the anode (target) is connected to the tube unit case (ground potential) to cool the anode and the target effectively. The filament heating current is supplied by an AC power supply in the controller in conjunction with an insulation transformer. In this experiment, the tube voltage applied was from 45 to 65 kV, and the tube current was regulated to within 0.40 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. Monochromatic Kα lines were left using a 5-mm-thick barium sulfate filter in which barium sulfate powder was mixed with polymethyl methacrylate (PMMA) resin, since both the bremsstrahlung and the Kβ rays were absorbed effectively by the filter. In designing the filter, the surface density of the barium sulfate powder is important, since the x rays are absorbed effectively by the powder as compared with the PMMA resin. In this case, the density was approximately 10 mg/cm^2.

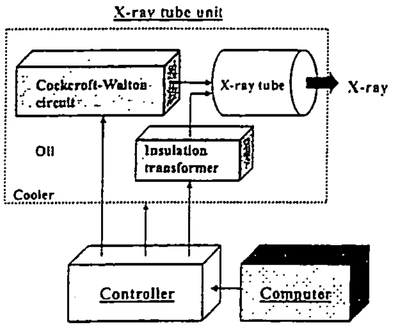

Fig. 1: Block diagram of compact x-ray generator with cerium-target tube.

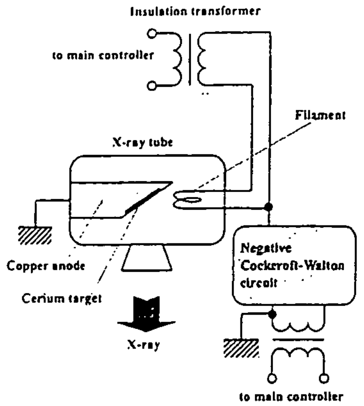

Fig. 2: Main circuit of x-ray generator.

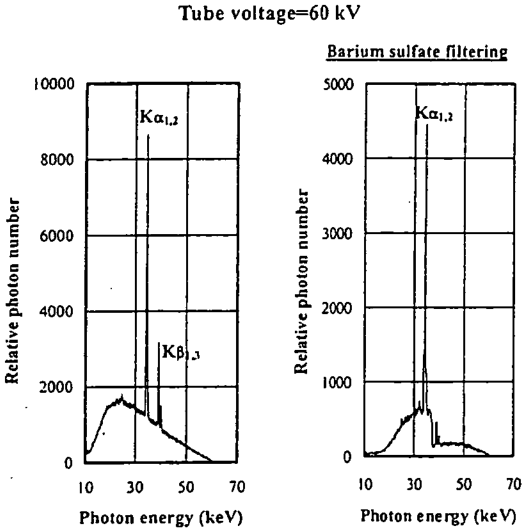

Fig. 3: X-ray spectra measured using germanium detector and filter.

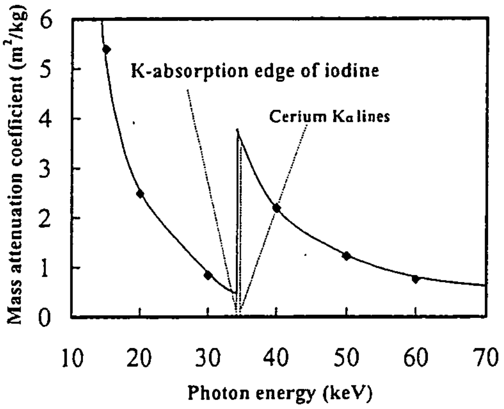

Fig. 4: Mass attenuation coefficients of iodine, and average photon energy of cerium Kα lines.

3. Characteristics

The x-ray intensity rate was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source. At a constant tube current of 0.40 mA, the x-ray intensity increased when the tube voltage was increased. In this measurement, the intensity with a tube voltage of 60 kV and a current of 0.40 mA was 16.8 μGy/s with errors of less than 0.2%.

In order to measure images of the x-ray source, we employed a pinhole camera with a hole diameter of 50 μm in conjunction with a Computed Radiography (CR) system[16] with a sampling pitch of 87.5 μm. When the tube voltage was increased, spot dimensions increased slightly and had values of approximately 1×1 mm.

In order to measure x-ray spectra, we employed a germanium detector (GLP-10180/07-P, Ortec Inc.) (Fig. 3). When the tube voltage was increased, the Kα intensity substantially increased, and both the maximum photon energy and the intensities of bremsstrahlung x rays increased.

4. Angiography

Figure 4 shows the mass attenuation coefficients of iodine 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 iodine K-edge. Cerium is a rare earth element and has a high reactivity; however, the average photon energies of Kα is 34.6 keV, and iodine contrast mediums with a K-absorption edge of 33.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

The angiography was performed using the CR system (Konica Regius 150), iodine microspheres of 15 μm in diameter, and the filter. The distance (between the x-ray source and the imaging plate) was 1.5 m, and the tube voltage was 60 kV. Figure 5 shows angiograms of an extracted dog heart. Because the size of the dog heart is almost the same as human heart, human coronary arteries can be observed.

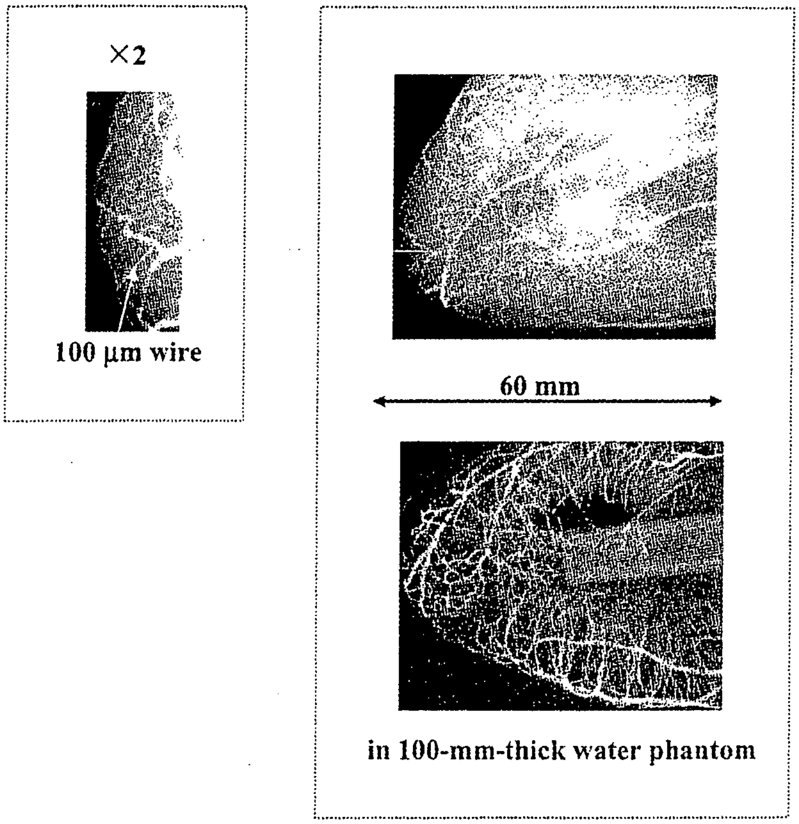

Fig. 5: Angiogram of extracted dog heart using iodine microspheres.