The image of water (20% gadolinium oxide suspension) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. Because the x-ray duration was 1.0 ms, the stop-motion image of water could be obtained.
Figure 10 shows an angiogram of a polytetrafluoroethylene (Teflon) tube in a PMMA case using a contrast medium which contains approximately 65% gadodiamidehydrate with a duration of 1.0 ms, and a high-contrast tube with a bore diameter of 1.0 mm is observed. Figures 11 and 12 show angiograms of a rabbit ear and head using gadolinium oxide powder with a duration of 1.0 ms, and fine blood vessels of approximately 100 μm were visible.

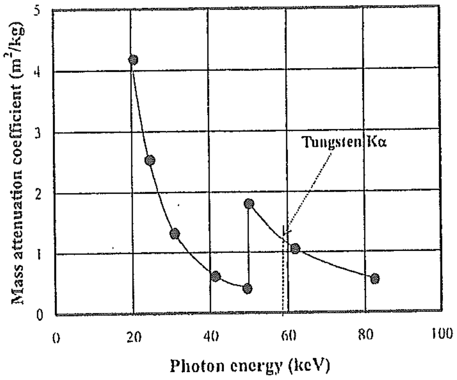
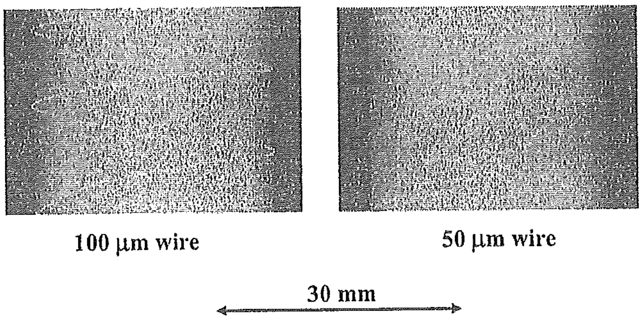
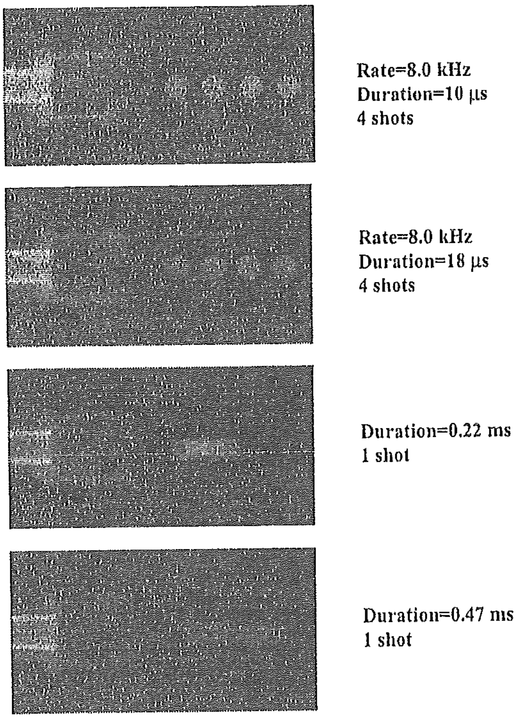


Figure 6: Mass attenuation coefficient of gadolinium and the average photon energy of tungsten Kα lines is shown above gadolinium K edge.



100 μm wire **50 μm wire**

Figure 7: Radiograms of tungsten wires coiled around PMMA rods.



Rate=8.0 kHz
Duration=10 μs
4 shots

Rate=8.0 kHz
Duration=18 μs
4 shots

Duration=0.22 ms
1 shot

Duration=0.47 ms
1 shot

Figure 8: Radiograms of plastic bullets from an air gun at the indicated conditions.

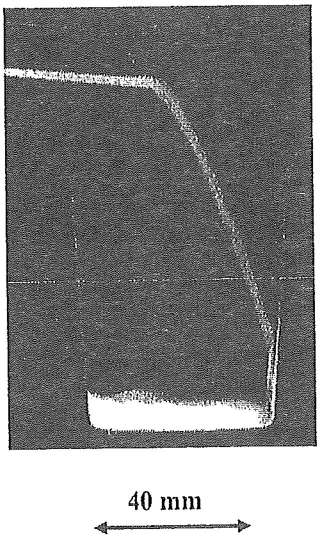


Figure 9: Radiogram of water falling into a polypropylene beaker from a glass test tube.

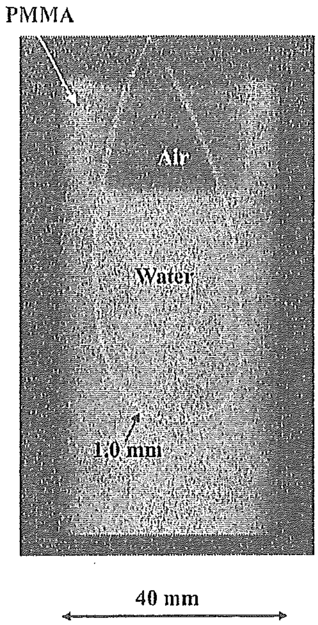


Figure 10: Angiography of a Teflon tube using a contrast medium which contains approximately 65% gadodiamidehydrate.

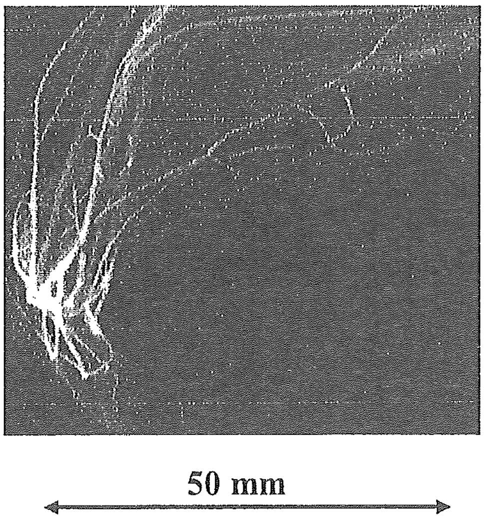


Figure 11: Angiography of a rabbit ear using gadolinium oxide powder.

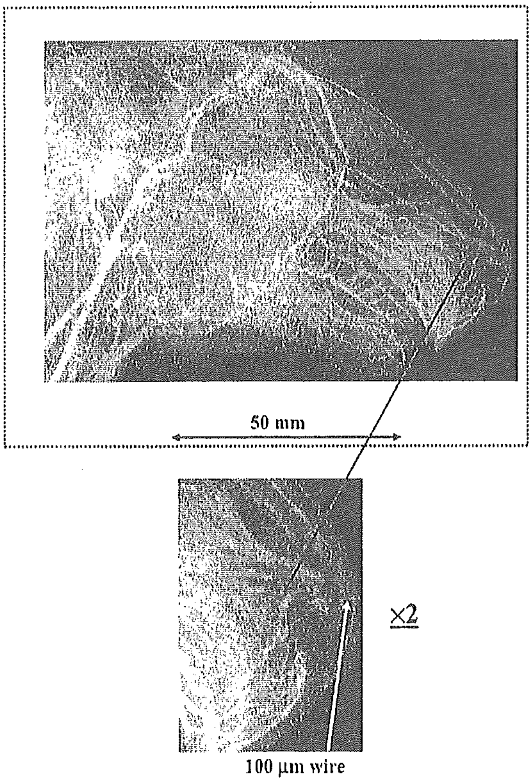


Figure 12: Angiography of a rabbit head using gadolinium oxide powder.

5. DISCUSSION

In summary, we succeeded in performing high-speed enhanced angiography utilizing tungsten K-series characteristic x-rays and gadolinium contrast media. As compared with angiography using iodine media, the absorbed dose could be decreased utilizing angiography achieved with gadolinium media.

Concerning the spectrum measurement, we obtained K-series characteristic x-rays using the tungsten filter. When the filter was employed with a charging voltage of 100 kV, the peak photon energy of the spectra was approximately 50 kV. Therefore, the filter thickness should be increased in order to decrease bremsstrahlung x-rays with energies lower than the K-absorption edge of tungsten. In the imaging, we have to consider the filtering effect of human body. Subsequently, Kβ rays should be absorbed using an ytterbium oxide filter in order to improve the image contrast of blood vessels.

Using this filter with a charging voltage of 100 kV and a pulse width (exposure time) of 1.0 ms, although we obtained the x-ray intensities of approximately 10 μGy at 1.0 m per pulse, the intensity should be maximized by increasing the tube current in order to improve the image quality using the CR system.

Nowadays, because flat panel detectors are very useful in order to perform real-time dynamic imaging with high spatial resolutions of 100 μm or less, stop-motion images of blood flows can be obtained using gadolinium media.

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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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.

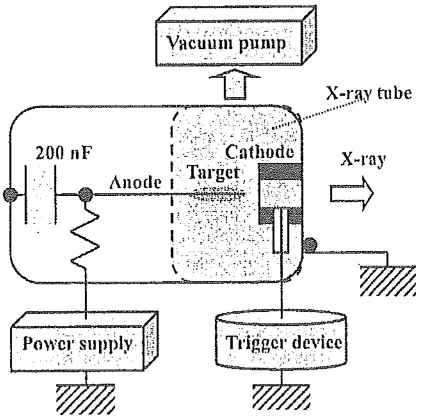


Figure 1: Block diagram including the electric circuit of the plasma flash x-ray generator.

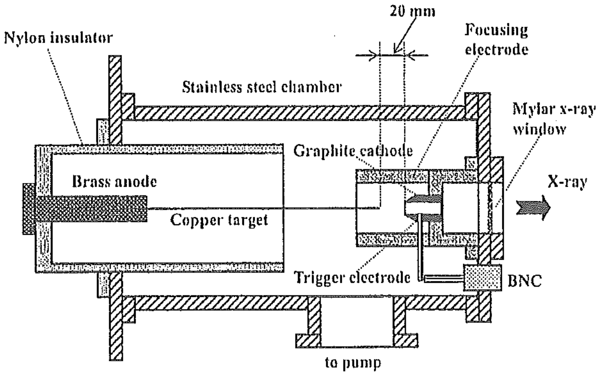


Figure 2: Schematic drawing of the flash x-ray tube with a rod copper target.

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.

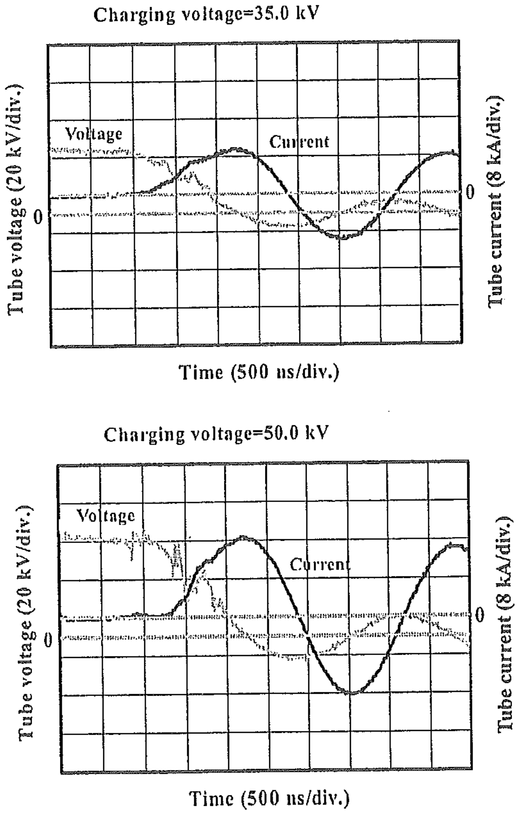
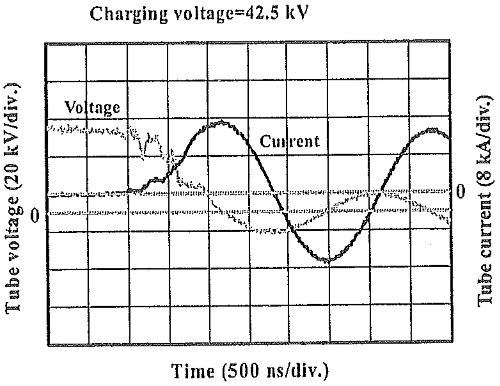


Figure 3: Tube voltages and currents with changes in the charging voltage.



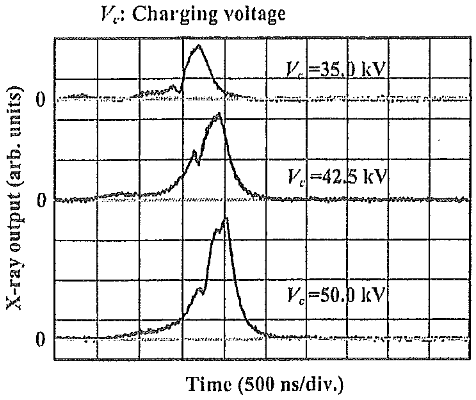


Figure 4: X-ray outputs at the indicated conditions.

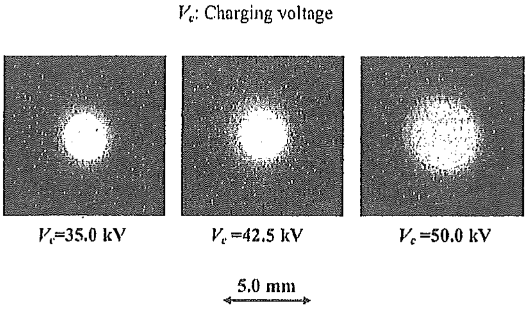


Figure 5: Images of the plasma x-ray source.

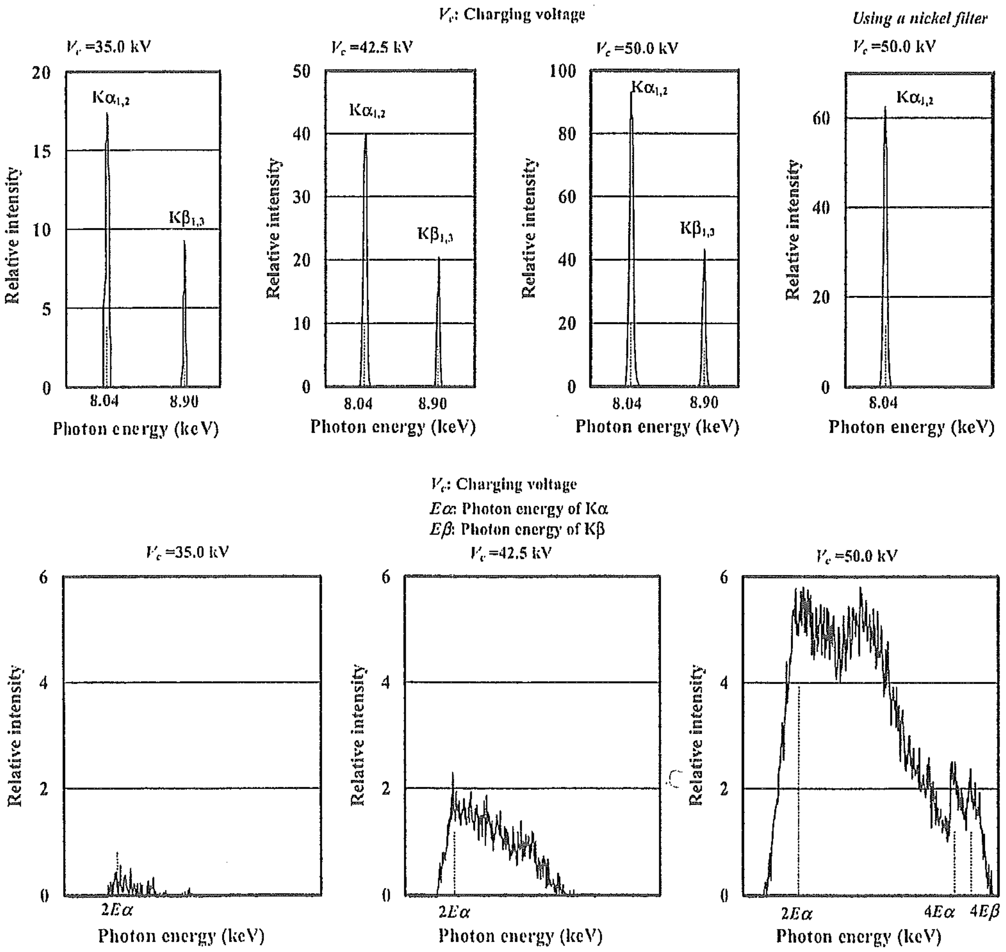


Figure 6: X-ray spectra from weakly ionized copper plasma at the indicated conditions.

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

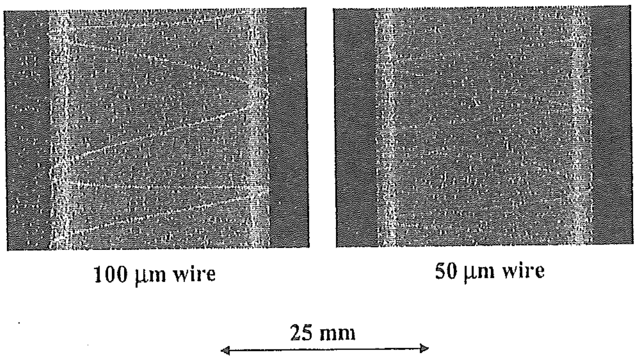
X-ray spectra from the plasma source were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[18] (Konica Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated 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.

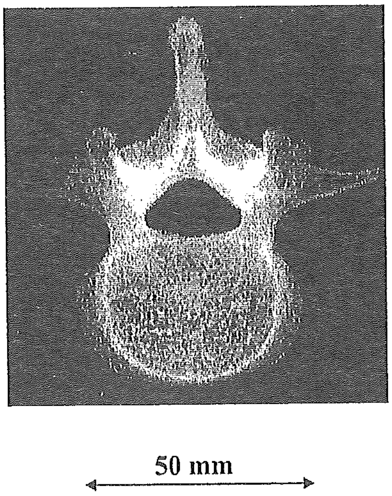


Figure 8: Radiogram of a vertebra.

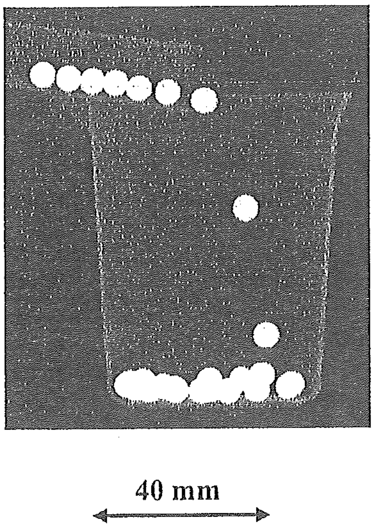


Figure 9: Radiogram of plastic bullets falling into polypropylene beaker from a plastic test tube.

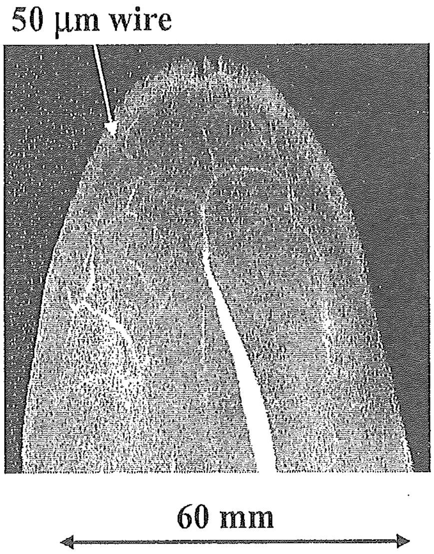


Figure 10: Angiogram of a rabbit ear.

5. CONCLUSIONS AND OUTLOOK

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. 11), the estimated spectra are shown in Fig. 12. In cases where a nickel target is employed, fractional harmonic x-rays are absorbed by the x-ray window and the air. In cases where weakly ionized linear plasma is employed, intense and clean K-series characteristic x-rays can be obtained. However, it is not easy to produce high-photon-energy K-series characteristic x-rays because the plasma transmits high-photon energy bremsstrahlung x-rays. Therefore, high-photon-energy plasma flash x-ray generator utilizing angle dependence of bremsstrahlung x-rays are very useful to produce K photons of molybdenum, silver, cerium, tantalum, and tungsten.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography, and the generator produced number of characteristic K photons was approximately 1×10^8 photons/cm^2 at 1.0 m per pulse. In addition, we are very interested in producing steady-state clean K rays and their higher harmonic hard x-rays using a similar tube in near future.

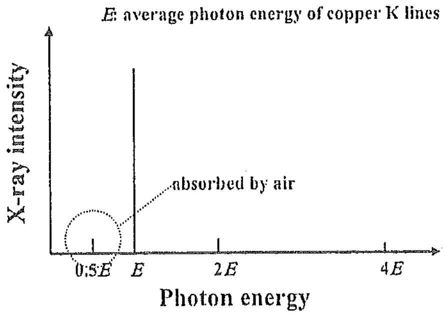


Figure 11: X-ray resonation without using a resonator.

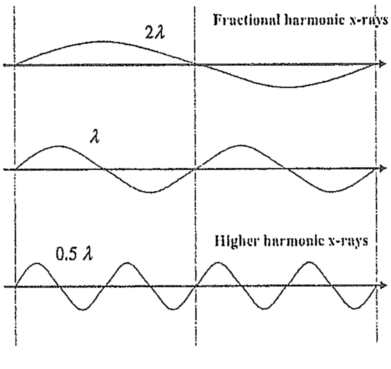


Figure 12: Estimated x-ray spectra under resonation.

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.

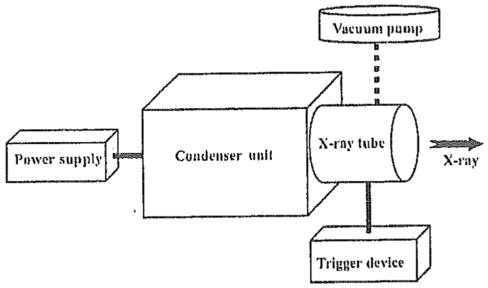


Figure 1: Block diagram of the high-intensity plasma flash x-ray generator.

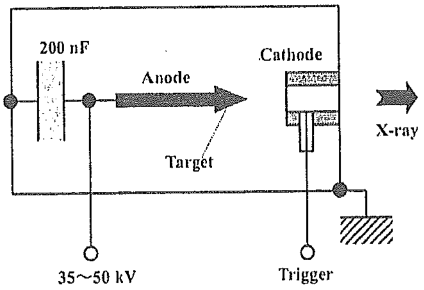


Figure 2: Circuit diagram of the flash x-ray generator.

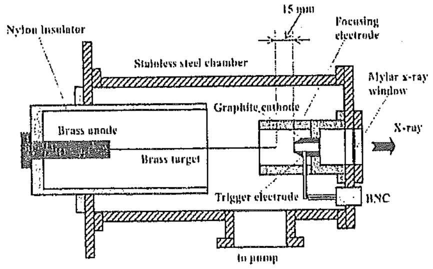


Figure 3: Schematic drawing of the flash x-ray tube with a brass target.

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.

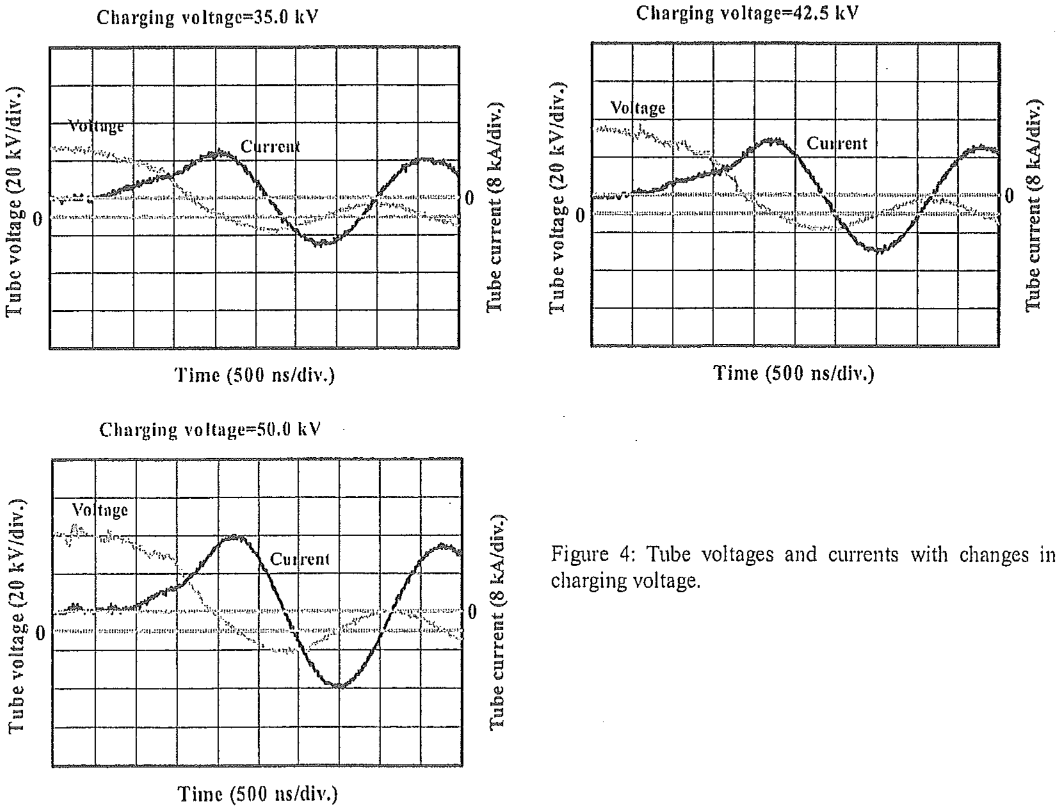


Figure 4: Tube voltages and currents with changes in the charging voltage.

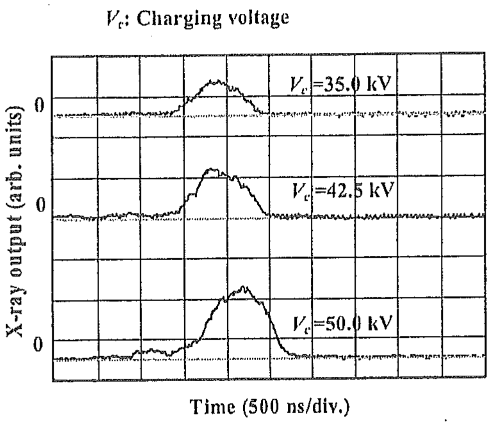


Figure 5: X-ray outputs at the indicated conditions.

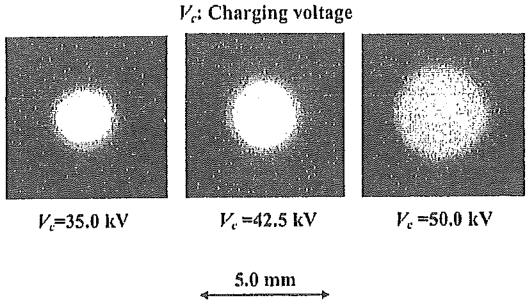
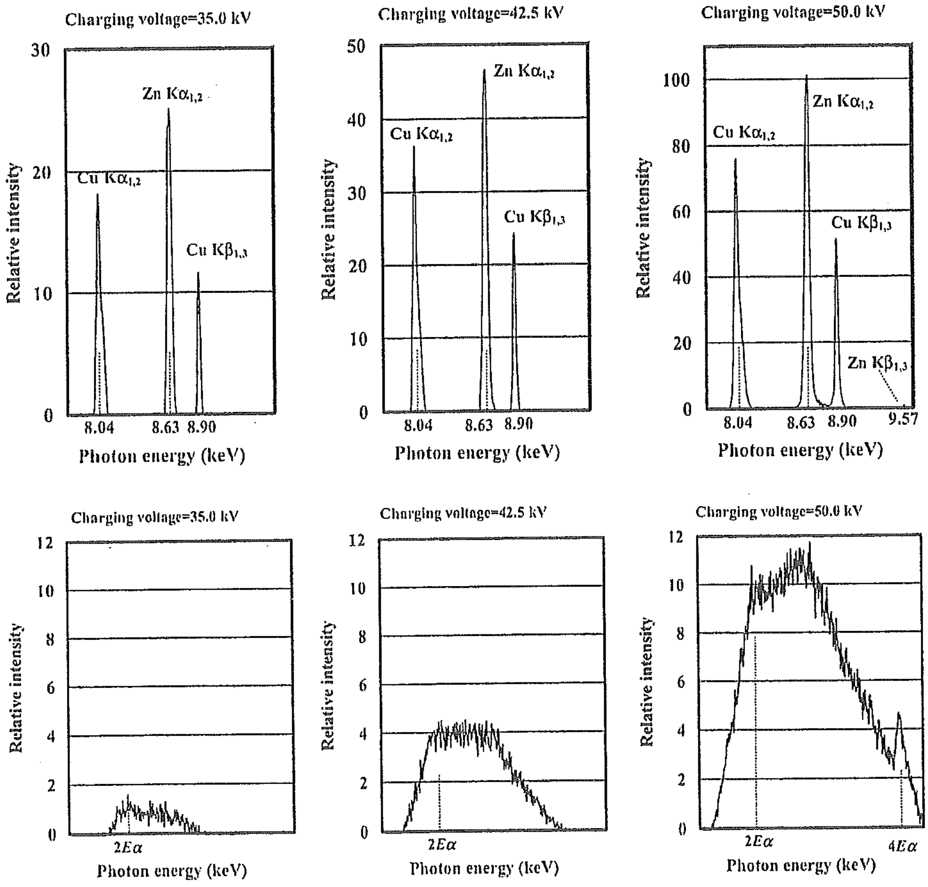


Figure 6: Images of plasma x-ray source.



$E\alpha$: 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.

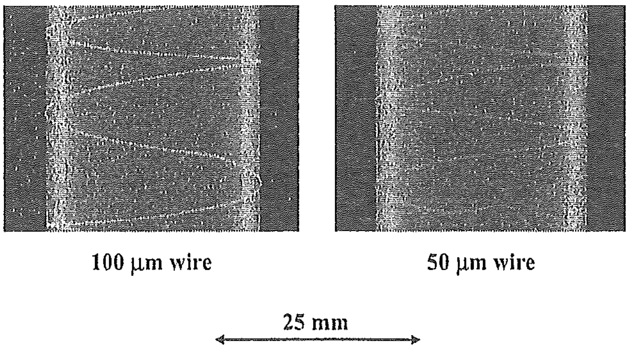
Figure 7 shows measured spectra from weakly ionized metal plasma. We observed sharp lines of K-series characteristic x- rays of copper Kα, copper Kβ and zinc Kα lines. However, zinc Kβ and bremsstrahlung rays were hardly detected. The characteristic x-ray intensity substantially increased with corresponding 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.

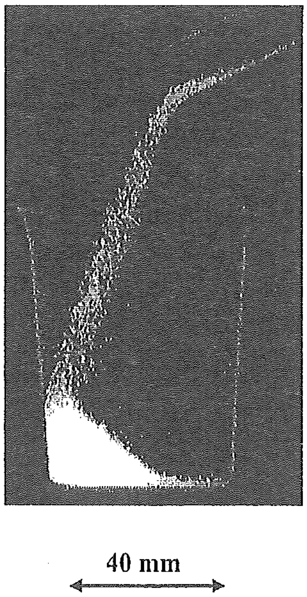


Figure 9: Radiogram of aluminum grains from a glass test tube.

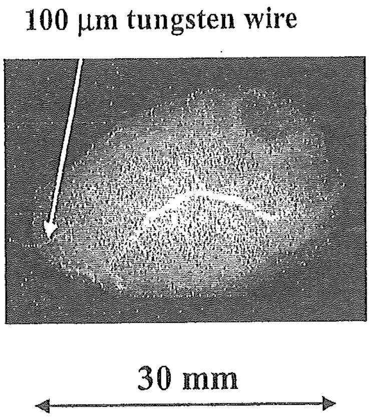


Figure 10: Angiogram of a rabbit heart.

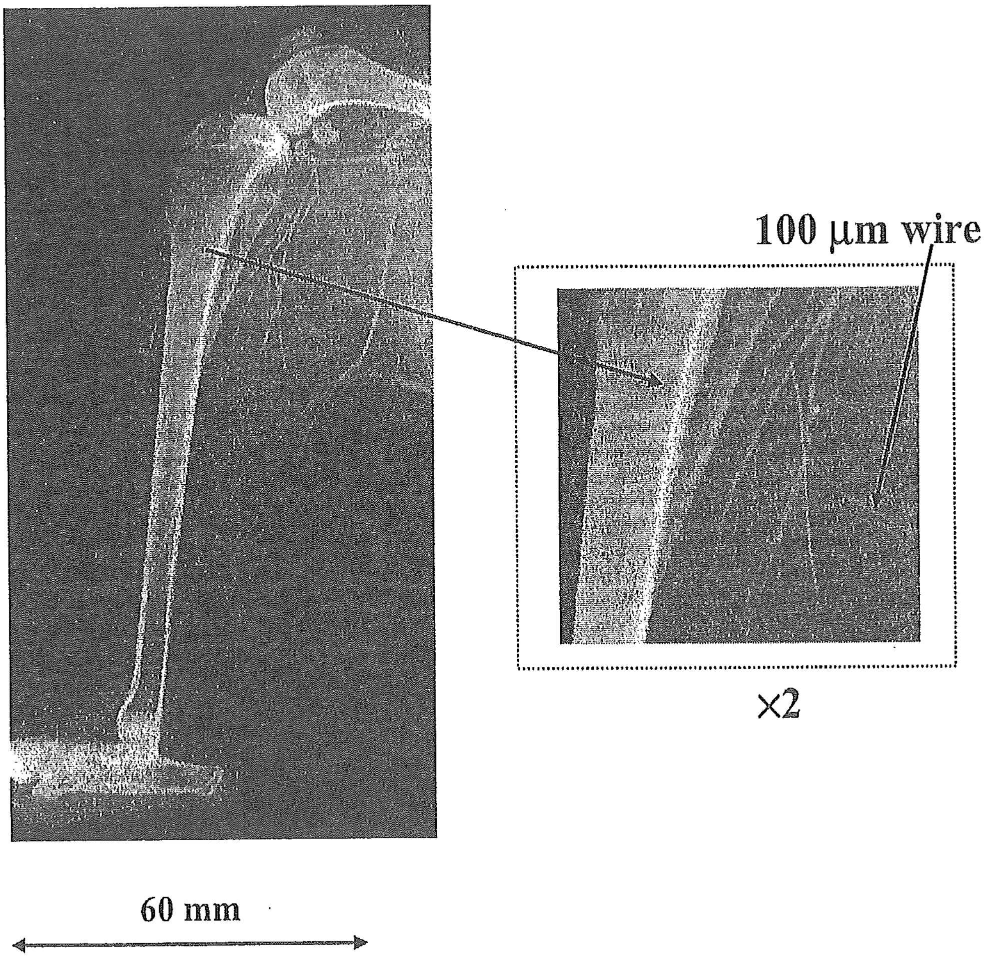


Figure 11: Angiogram of a rabbit thigh.

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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Enhanced K-edge plasma angiography achieved with tungsten Kα rays utilizing gadolinium-based contrast media

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ABSTRACT

The tungsten plasma flash x-ray generator is useful in order to perform high-speed enhanced K-edge angiography using cone beams because Kα rays from the tungsten 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. 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 characteristic x-ray intensities of tungsten Kα lines increased. Using an ytterbium oxide filter, the Kα lines were clean, and hardly any Kβ lines and bremsstrahlung rays were detected. The x-ray pulse widths were approximately 60 ns, and the time-integrated x-ray intensity had a value of approximately 50 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 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, monochromatic x-rays, tungsten Kα rays

1. INTRODUCTION

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