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.

Acknowledgments

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K-edge angiography utilizing a tungsten plasma X-ray generator in conjunction with 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 K-series characteristic X-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 K_α lines increased. The K_α lines were clean, and hardly any bremsstrahlung rays were detected. The X-ray pulse widths were approximately 110 ns, and the time-integrated X-ray intensity had a value of approximately 0.35 mGy at 1.0 m from the X-ray source with a charging voltage of 80 kV. Angiography was performed

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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.

PACS: 52.59.Mv; 52.80.Vp; 87.59.Dj; 87.64.Gb

Keywords: Angiography; Gadolinium-based contrast media; Characteristic X-rays; Quasi-monochromatic X-rays; Tungsten K_α lines

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 (Davis et al., 1995; Momose et al., 1996; Ando et al., 2002) and enhanced K-edge angiography (Thompson et al., 1992; Mori et al., 1996; Hyodo et al., 1998). 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 K_α rays of 34.6 keV (Sato et al., 2004a, b, c).

Gadolinium-based contrast media with a K-edge of 50.2 keV have been employed to perform magnetic resonance angiography (MRA), and the gadolinium density has been increasing. In view of this situation, ytterbium K_α rays (52.0 keV) are useful for enhanced K-edge angiography, because the K_α 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 tends to oxidize in the atmosphere, K_α rays of tantalum (57.1 keV) and tungsten (58.9 keV) are also useful to perform angiography.

To produce high-dose-rate X-rays, several different flash X-ray generators have been developed (Sato et al., 1990, 1994a, b; Shikoda et al., 1994; Takahashi et al., 1994), and plasma flash X-ray generators (Sato et al., 2003a, b, 2004a, b, c, 2005a, b, c) have been developed to perform a preliminary experiment for producing hard X-ray lasers. In the plasma, the bremsstrahlung X-rays are absorbed effectively and are converted into fluorescent rays, and intense and clean K-series characteristic X-rays of nickel and copper have been produced from the axial direction of weakly ionized linear plasma. However, it is difficult to increase the photon energies of characteristic X-rays because the plasma transmits high-photon-energy bremsstrahlung X-rays. In view of this situation, we have developed a compact flash X-ray generator (Sato et al., 2004a, b, c, 2005a, b, c) and have succeeded in producing clean high-photon-energy characteristic X-rays utilizing the angle dependence of bremsstrahlung X-rays, because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory in Sommerfeld's theory.

In this article, we describe an intense quasi-monochromatic plasma flash X-ray generator with a tungsten target tube, and used it to perform a preliminary study on angiography achieved with tungsten K_α rays.

2. Principle of K-edge angiography

Fig. 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 tungsten K_α lines is shown above the gadolinium K-edge. The average photon energy is 58.9 keV, and gadolinium contrast media with a K-absorption edge of 50.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

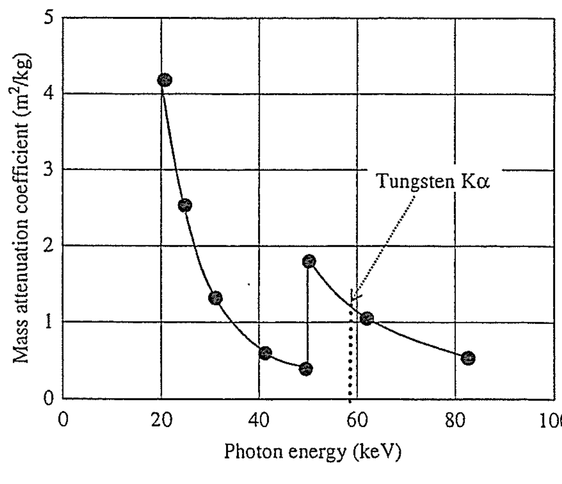

Fig. 1. Mass attenuation coefficients of gadolinium. The average photon energy of tungsten K_α lines is shown above gadolinium K edge.

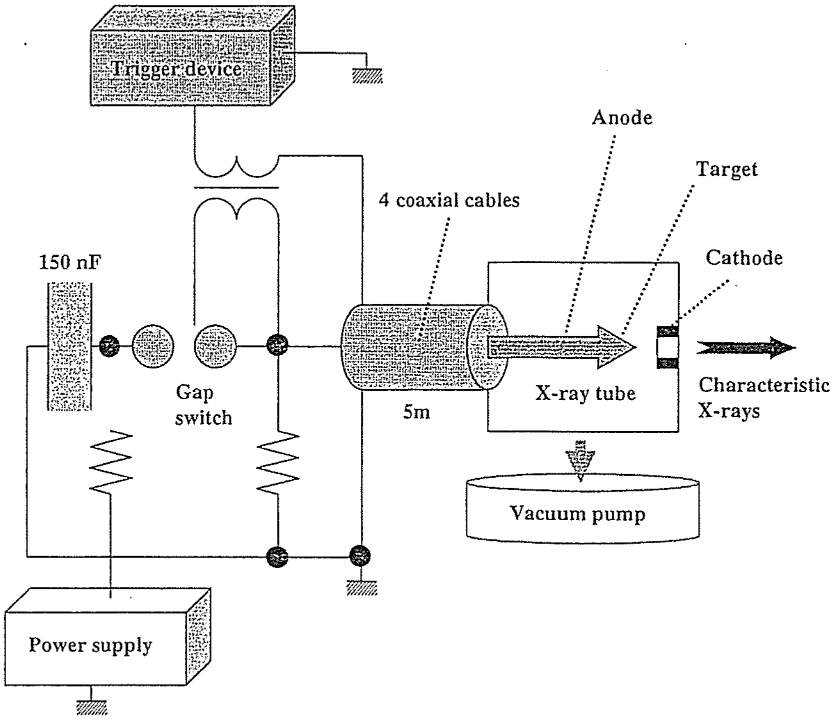

Fig. 2. Block diagram including the high-voltage circuit of the intense quasi-monochromatic plasma flash X-ray generator with a tungsten-target tube.

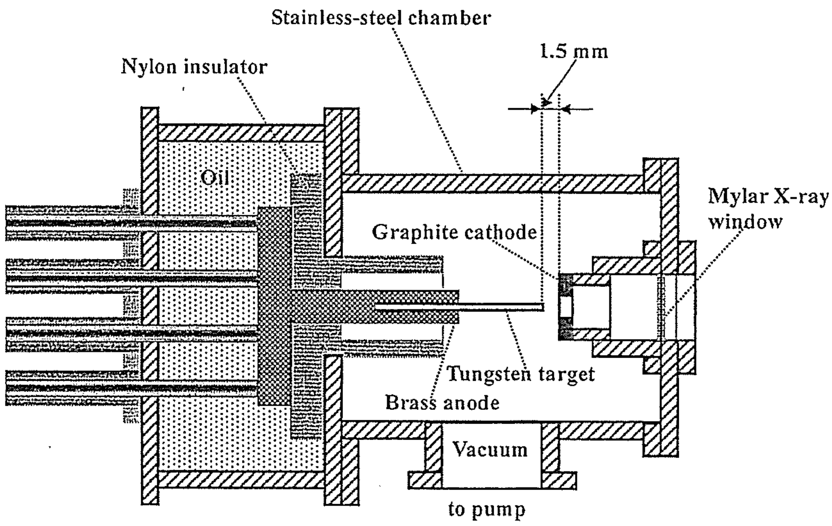

Fig. 3. Schematic drawing of a flash X-ray tube with a rod-shaped tungsten target.

3. Generator

3.1. High-voltage circuit

Fig. 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

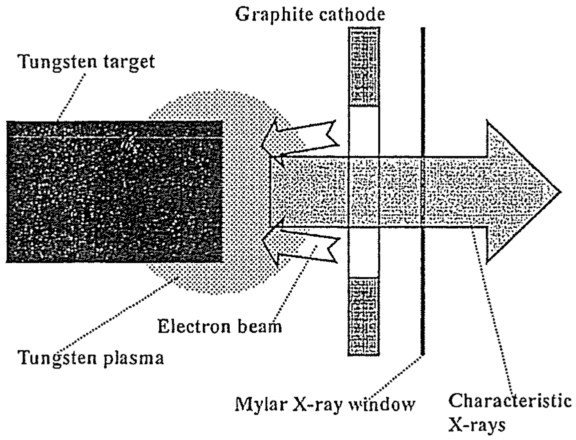

Fig. 4. Irradiation of K-series characteristic X-rays of tungsten.

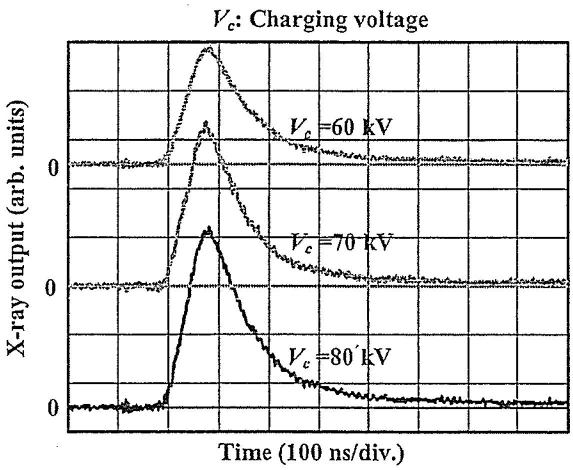

Fig. 5. X-ray outputs detected using a combination of a plastic scintillator and a photomultiplier.

increase maximum tube voltage using high-voltage reflection. The high-voltage main condenser is charged up to 80 kV by the power supply, and electric charges in the condenser are discharged to the tube through the four cables after closing the gap switch with the trigger device.

3.2. X-ray tube

The X-ray tube is a demountable cold-cathode diode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa (Fig. 3). This tube consists of the following major parts: a ring-shaped graphite cathode with an inside diameter of 4.5 mm, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) X-ray window 0.25 mm in thickness and a rod-shaped tungsten 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 tungsten ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory (Fig. 4), tungsten 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

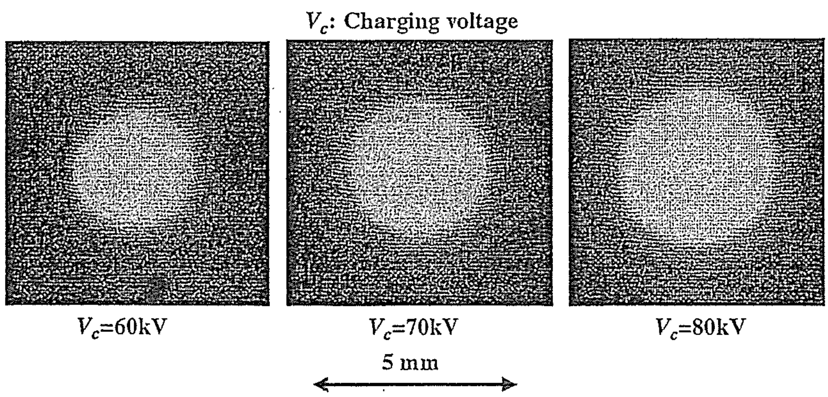

Fig. 6. Images of characteristic X-ray source obtained using a pinhole camera with changes in the charging voltage.

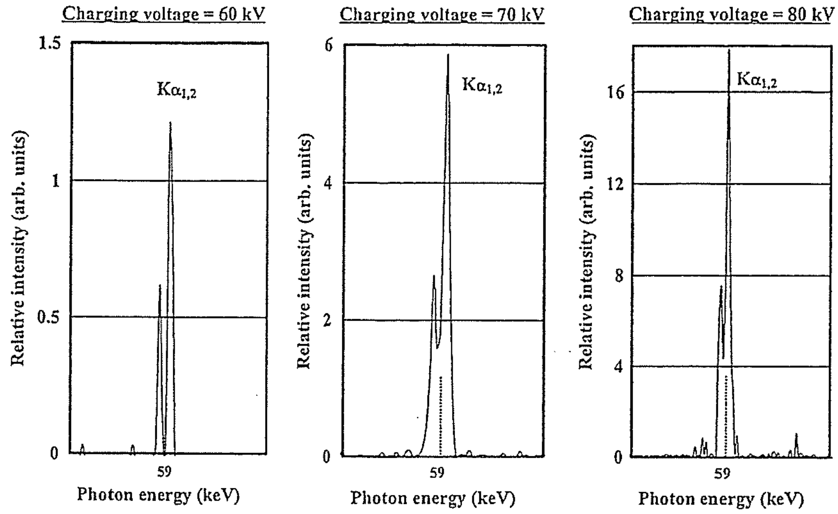

Fig. 7. X-ray spectra from a tungsten target. The spectra were measured using a transmission type spectrometer with a lithium fluoride curved crystal.

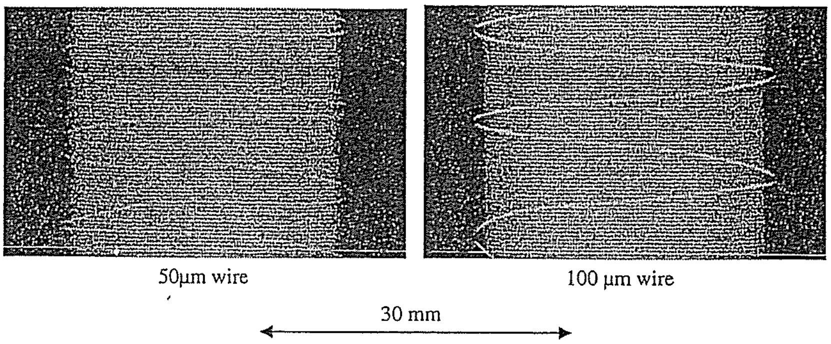

Fig. 8. Radiograms of tungsten wires coiled around rods made of polymethyl methacrylate.

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 (two times the charging voltage) and 40 kA, respectively.

4.2. X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 5). The X-ray pulse height substantially increased with corresponding increases in the charging voltage. The X-ray pulse widths were approximately 110 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 0.35 mGy 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 plasma X-ray source, we employed a 100-μm-diameter pinhole camera and an X-ray film (Polaroid XR-7) (Fig. 6). When the charging voltage was increased, the plasma X-ray source grew, and both spot dimension and intensity increased. Because the X-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing X-rays and decreases in the pinhole diameter.

4.4. X-ray spectra

X-ray spectra were measured 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 (Sato et al., 2000) (Konica Minolta Regius 150) with a wide dynamic range, and

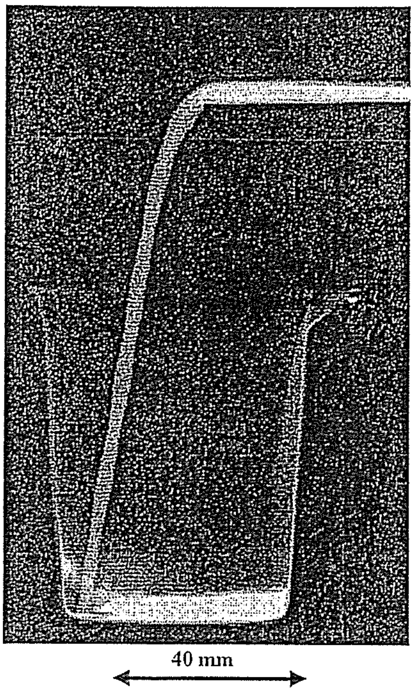

Fig. 9. Radiogram of water falling into polypropylene beaker from a glass test tube.

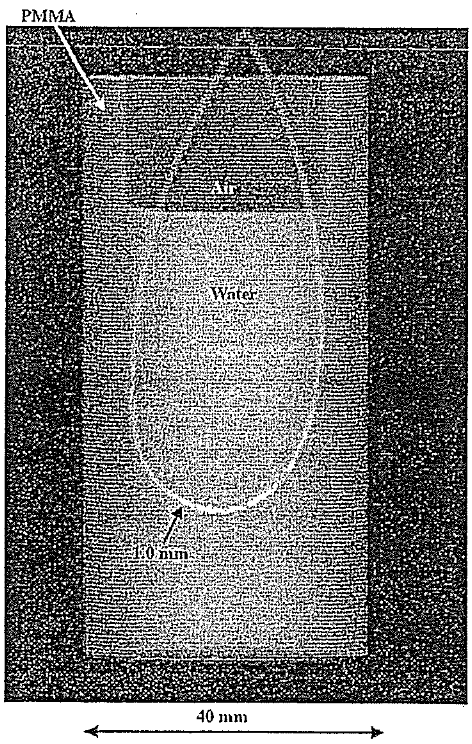

Fig. 10. Angiography of a Teflon tube using a contrast medium which contains approximately 65% gadodiamidehydrate.

Fig. 11. Angiography of a rabbit ear using gadolinium oxide powder.

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. Fig. 7 shows measured spectra from the tungsten target. We observed clean K_α lines, while bremsstrahlung rays were hardly detected. The K_α intensity substantially increased with increases in the charging voltage.

5. Angiography

The flash angiography was performed by the CR system 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. Fig. 8 shows radiograms of tungsten wires coiled around rods 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.

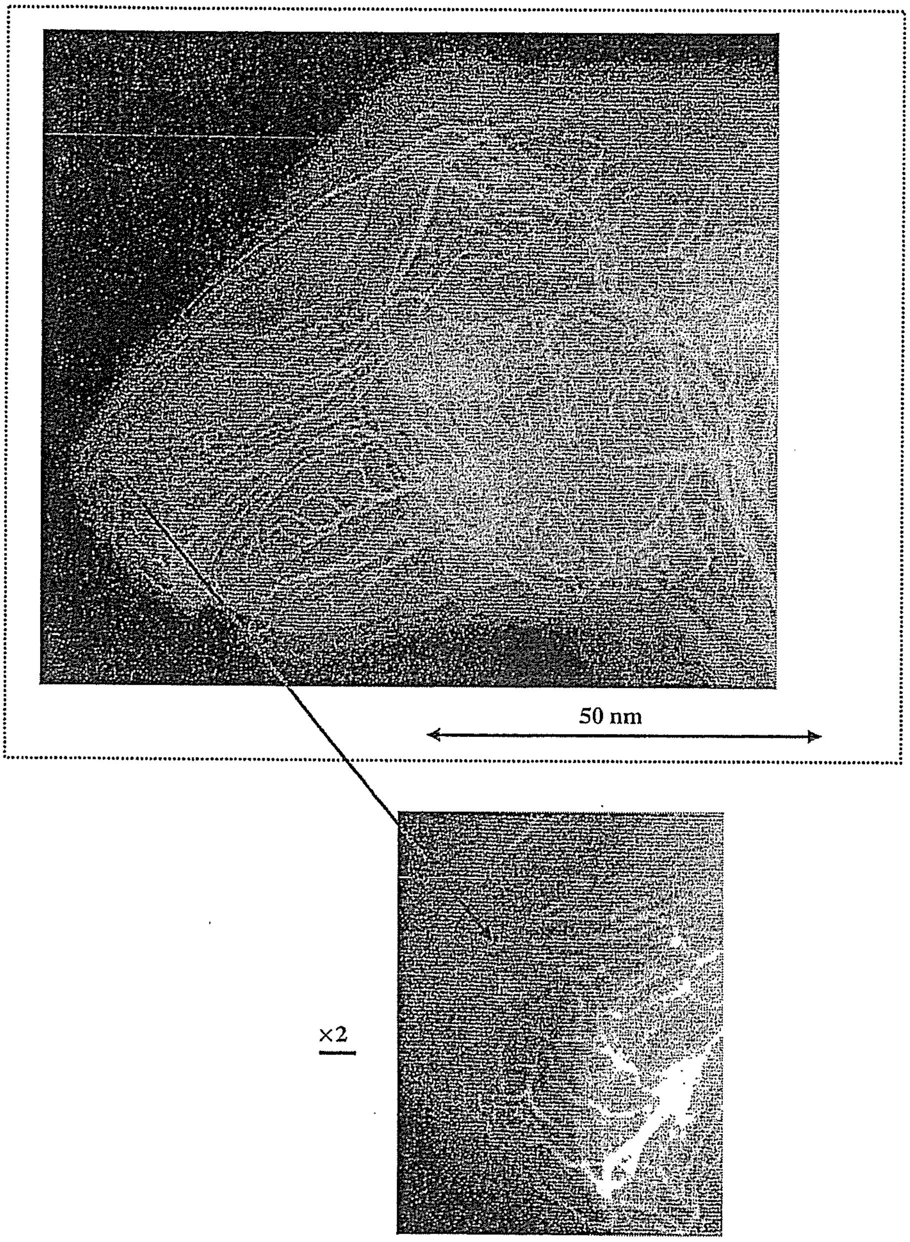

Fig. 12. Angiography of a rabbit head using gadolinium oxide powder.

The image of water (20% gadolinium oxide suspension) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. 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.

Fig. 10 shows an angiogram of a polytetrafluoroethylene (Teflon) tube in a PMMA case using a contrast medium which contains approximately 65% gadodiamidehydrate, and a high-contrast tube with a bore diameter of 1.0 mm is observed. Figs. 11 and 12 show angiograms of a rabbit ear and head using gadolinium oxide powder, and fine blood vessels of approximately 100 μm were visible.

6. Conclusions and outlook

In summary, we succeeded in producing K_{α} rays of tungsten 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 tungsten K_α (58.9 keV) rays, L-series characteristic rays should be absorbed before angiography using a filter.

We obtained sufficient X-ray intensity for CR angiography with X-ray durations of approximately 100 ns, and the intensity can be increased by increasing the charging voltage at a constant target–cathode space. In an empirical equation, because the characteristic X-ray intensity is proportional to approximately 1.5th power of the voltage difference between the tube voltage and the critical excitation voltage, optimum intensity for angiography can be controlled. In this research, 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.

Because the dimensions of the X-ray source are primarily determined by the target diameter, the diameter should be minimized in order to improve the spatial resolution, and can be reduced to approximately 0.5 mm. Subsequently, the sampling pitch can be decreased to 43.8 μm using a CR system (Konica Minolta Regius 190) to observe fine blood vessels of approximately 50 μm diameter.

Using this flash X-ray generator, enhanced K-edge angiography using iodine contrast media can also be performed using a cerium target. In addition, steady-state monochromatic X-rays can be produced by a similar tube utilizing a hot cathode and a constant high-voltage power supply. In addition, fine focusing can be realized using tungsten or molybdenum target, and these X-ray generators could be employed to perform quasi-monochromatic phase-contrast radiography for edge enhancement.

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Preliminary study for producing higher harmonic hard X-rays from weakly ionized nickel 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 nickel ions and electrons, around the fine target, and intense Kα lines are left using a 15-μm-thick cobalt 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 18 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 1.0 mGy at 1.0 m from the X-ray source with a charging voltage of 50 kV.

PACS: 52.80.Vp; 52.90.+z; 87.59.Bh; 87.64.Gb

Keywords: Weakly ionized linear plasma; K-series characteristic X-rays; Clean characteristic X-rays; Higher harmonic hard X-rays

1. Introduction

In conjunction with single crystals, synchrotrons produce monochromatic parallel beams, which are fairly similar to monochromatic parallel laser beams, and the

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beams have been applied to enhanced K-edge angiography (Thompson et al., 1992; Mori et al., 1996; Hyodo et al., 1998), phase-contrast radiography (Davis et al., 1995; Momose et al., 1996; Ando et al., 2002), and crystallography. Therefore, the production of coherent hard X-ray lasers for various research projects, including biomedical applications, has long been wished for.

Recently, soft X-ray lasers have been produced by a gas-discharge capillary (Rocca et al., 1994, 1996; Macchietto et al., 1999), and the laser pulse energy substantially increased in proportion to the capillary length. These kinds of fast discharges can generate hot and dense plasma columns with aspect ratios approaching 1000:1. However, it is difficult to increase the laser photon energy to 10 keV or beyond. Because there are no X-ray resonators in the high-photon-energy region, new methods for increasing coherence will be desired in the future.

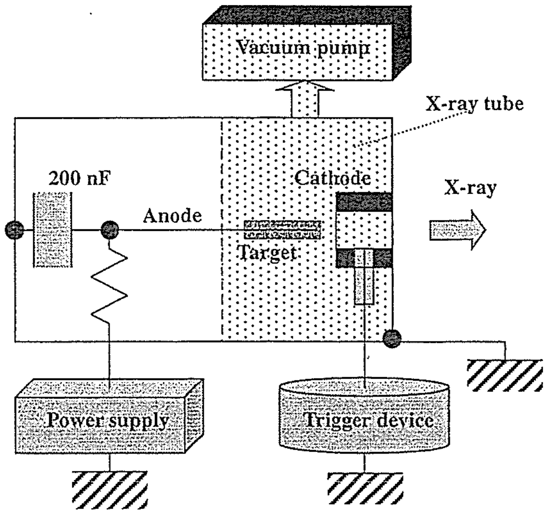

Fig. 1. Block diagram including electric circuit of the plasma flash X-ray generator.

To apply flash X-ray generators to biomedicine, several different generators have been developed (Germer, 1979; Sato et al., 1990, 1994a, b; Shikoda et al., 1994; Takahashi et al., 1994), and plasma X-ray generators (Sato et al., 2003a, b, 2004a–c, 2005a–c) 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, 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

Fig. 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

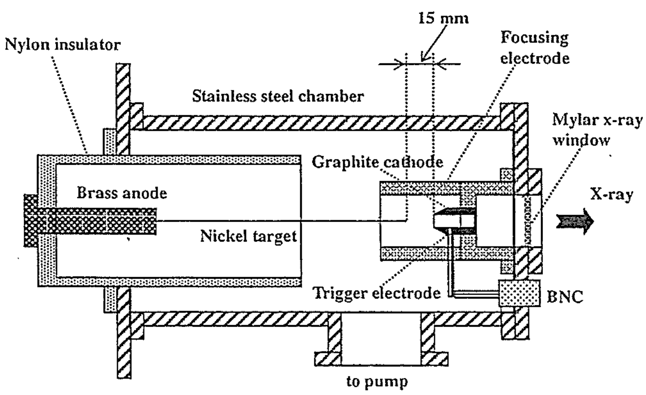

Fig. 2. Schematic drawing of the flash X-ray tube with a rod nickel target.

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 nickel target 3.0 mm in diameter with a tip angle of 60°. The distance between the target and cathode electrodes is approximately 15 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 nickel 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.

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. Fig. 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 18 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 about 1.0 mGy at 1.0 m from the X-ray source with a charging voltage of 50 kV.

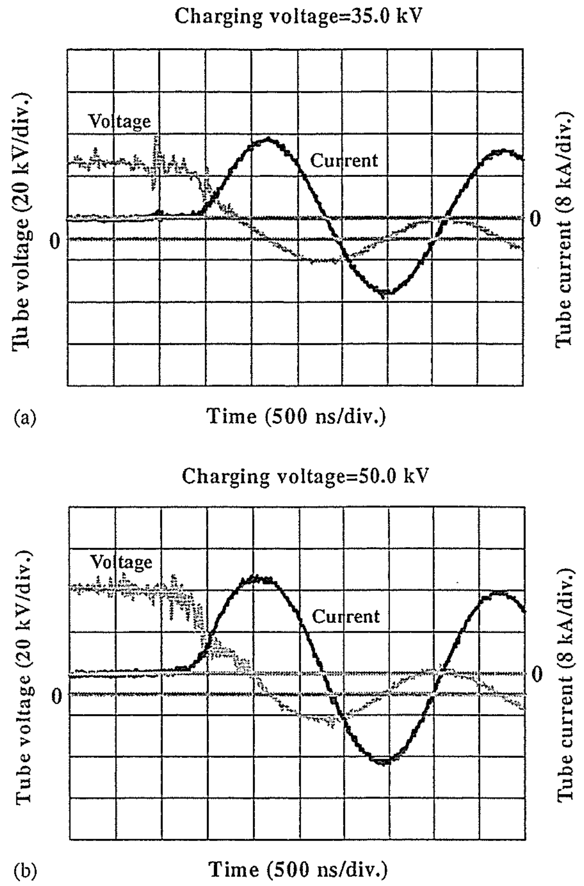

Fig. 3. Tube voltages and currents with a charging voltage of (a) 35.0 kV and (b) 50.0 kV.

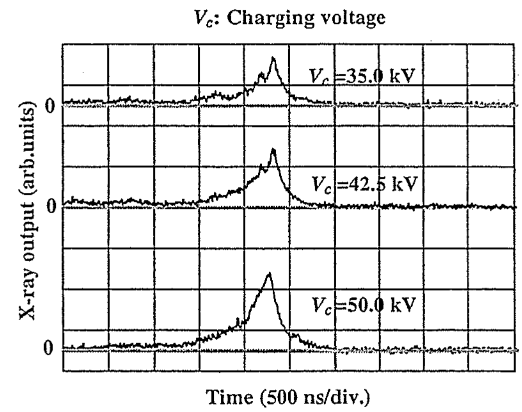

Fig. 4. X-ray outputs at the indicated conditions.

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.

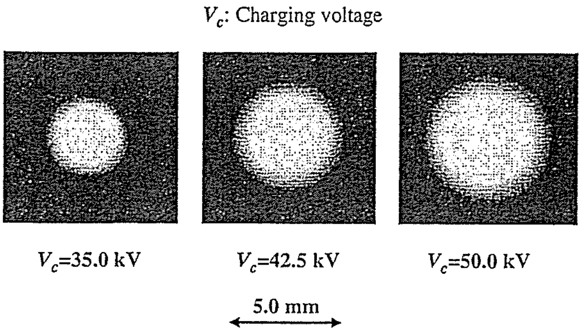

Fig. 5. Images of plasma X-ray source.

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 (Sato et al., 2000) (Konica Minolta 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

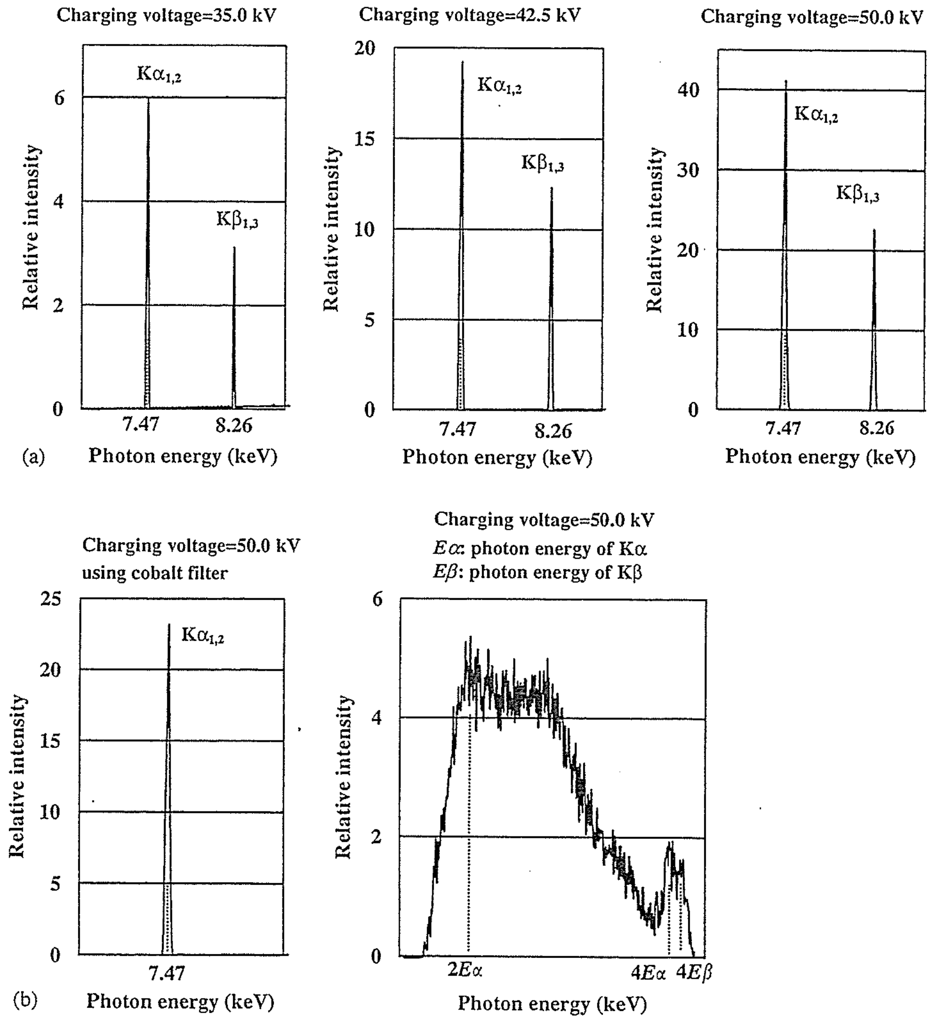

Fig. 6. X-ray spectra from weakly ionized nickel plasma at the indicated conditions. (a) $K\alpha$ and $K\beta$ rays and (b) $K\alpha$ and higher harmonic rays.

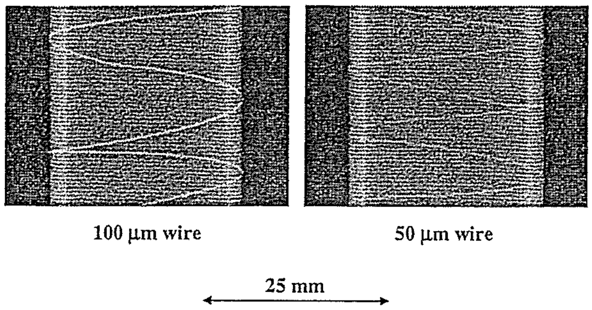

Fig. 7. Radiograms of tungsten wires coiled around PMMA pipes.

exposure time. Fig. 6 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 a 15-μm-thick cobalt filter. The characteristic X-ray intensity substantially increased with corresponding increases in the charging voltage, and higher harmonic hard X-rays were observed.

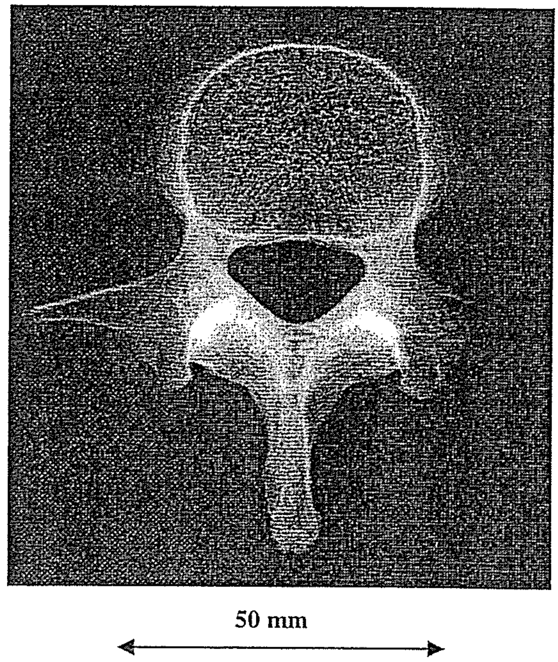

Fig. 8. Radiogram of a vertebra.

4. Radiography

The plasma radiography was performed by the CR system without 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. Fig. 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.

Fig. 8 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. Next, an image 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 500 ns, the stop-motion image of bullets could be obtained.

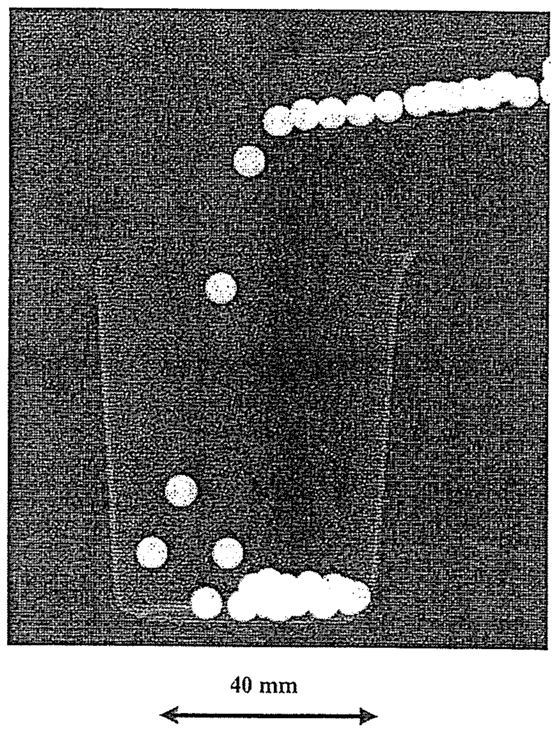

Fig. 9. Radiogram of plastic bullets falling into polypropylene beaker from a plastic test tube.

5. Conclusions and outlook

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 cobalt filter. In particular, the higher harmonic X-rays were produced from the plasma. Because the X-ray intensities of the harmonics increased with increases in the charging voltage, the harmonic bremsstrahlung rays survived due to the X-ray resonation.

To perform monochromatic radiography, the higher harmonics are not necessary. Therefore, the condenser charging voltage should be minimized in order to decrease the intensities of higher harmonics, and the condenser capacity should be maximized to increase the characteristic X-ray intensity. On the other hand, because the intensities of harmonics increase with increases in the charging voltage, high-photon-energy monochromatic radiography may be realized.

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, 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.

Acknowledgments

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Tunable narrow-photon-energy X-ray generator utilizing a tungsten-target tube

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Abstract

A preliminary experiment for producing narrow-photon-energy cone-beam X-rays using a silicon single crystal is described. In order to produce low-photon-energy X-rays, a 100-μm-focus X-ray generator in conjunction with a (1 1 1) plane silicon crystal is employed. The X-ray generator consists of a main controller and a unit with a high-voltage circuit and a microfocus X-ray tube. The maximum tube voltage and current were 35 kV and 0.50 mA, respectively, and the X-ray intensity of the microfocus generator was 48.3 μGy/s at 1.0 m from the source with a tube voltage of 30 kV and a current of 0.50 mA. The effective photon energy is determined by Bragg's angle, and the photon-energy width is regulated by the angle delta. Using this generator in conjunction with a computed radiography system, quasi-monochromatic radiography was performed using a cone beam with an effective energy of approximately 17 keV.

PACS: 87.59.–e; 87.59.Bh; 87.64.Gb

Keywords: Narrow-photon-energy X-rays; Tunable photon energy; Silicon single crystal; Cone beam

1. Introduction

Since the birth of the synchrotron, monochromatic parallel X-ray beams have been applied to X-ray phase-contrast radiography (Davis et al., 1995; Momose et al.,

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1996; Ando et al., 2002) and enhanced K-edge angiography (Thompson et al., 1992; Mori et al., 1996; Hyodo et al., 1998). The phase imaging is primarily based on the X-ray refraction, and the angiography is performed using X-rays with a photon energy of just beyond the K-absorption edge of iodine.

In order to perform high-speed medical radiography, although several different flash X-ray generators utilizing cold-cathode tubes have been developed (Sato et al., 1990, 1994a, b; Shikoda et al., 1994; Takahashi et al., 1994), quasi-monochromatic flash X-ray generators (Sato et al., 2003a, b, 2004a,b, 2005a–c) are useful to produce clean K-series characteristic X-rays without using a filter. Therefore, we have performed a demonstration of cone-beam K-edge angiography utilizing a cerium plasma generator, since K-series characteristic X-rays from the cerium target are absorbed effectively by iodine. In view of this situation, we have developed a steady state X-ray generator utilizing a cerium-target tube (Sato et al., 2004c), and have demonstrated enhanced K-edge angiography utilizing cerium Kα lines.

Without using synchrotrons, X-ray phase-contrast radiography for edge enhancement has been performed using a microfocus X-ray tube (Wilkins et al., 1996), and the digital imaging achieved with a 100-μm-focus molybdenum tube has been applied effectively to perform mammography (Ishisaka et al., 2000).

In this paper, we present a tunable narrow-photon-energy X-ray generator utilizing a single silicon crystal, and examine its suitability for energy-selective cone-beam radiography.

2. Experimental setup

Fig. 1 shows the block diagram of the X-ray generator, which consists of a main controller and an X-ray tube unit with a Cockcroft–Walton circuit and a 100-μm-focus X-ray tube. The tube voltage, the current, and the exposure time can be controlled by the controller. The main circuit for producing X-rays is illustrated in Fig. 2, and employed the Cockcroft–Walton circuit in order to decrease the dimensions of the tube unit. In the X-ray tube, positive and negative high voltages are applied to the anode and cathode electrodes, respectively. The filament heating current is supplied by an AC power supply in the controller in conjunction with an insulation transformer. The maximum tube voltage and current of the generator are 105 kV and 0.50 mA, respectively. In this experiment, the tube voltage applied was from 18 to 34 kV, and the tube current was 0.50 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum X-ray intensity.

The narrow-photon-energy X-ray generator utilizing a single silicon crystal of (1 1 1) plane is shown in Fig. 3. The effective photon energy is determined by Bragg's angle, and the photon-energy width is regulated by the

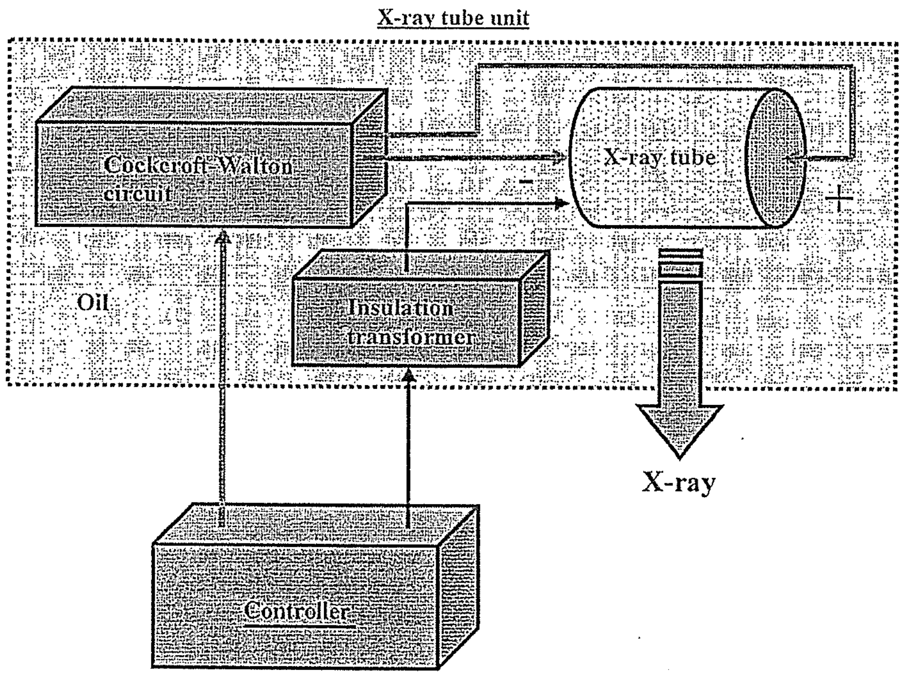

Fig. 1. Block diagram of a compact 100-μm focus X-ray generator with a tungsten-target radiation tube.

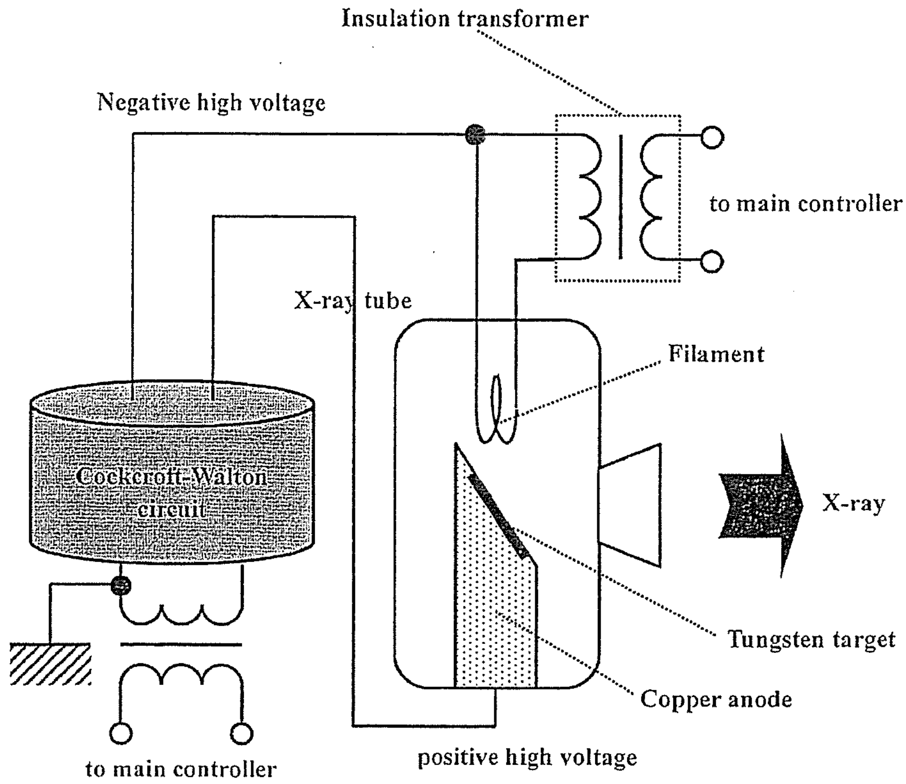

Fig. 2. Main circuit of the X-ray generator.

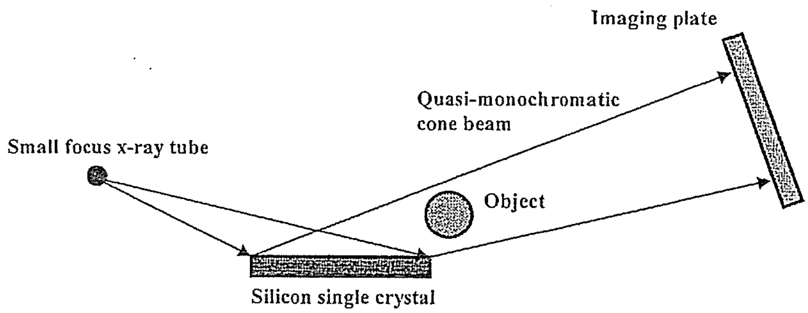

Fig. 3. Experimental setup of the narrow-photon-energy X-ray generator utilizing a single silicon crystal.

angle delta. Using this generator in conjunction with a computed radiography (CR) system (Sato et al., 2000), quasi-monochromatic radiography was performed using a cone beam with an effective energy of approximately 17 keV.

3. Results

3.1. X-ray intensity

X-ray intensity was measured by a Victoreen 660 ionization chamber at 1.0 m from the X-ray source (Fig. 4). At a constant tube current of 0.50 mA, the X-ray intensity increased when the tube voltage was increased. In this measurement, the intensity with a tube voltage of 30 kV was 48.3 μGy/s at 1.0 m from the source.

3.2. Radiography

The radiography was performed by the CR system (Konica Minolta Regius 150) with a sampling pitch of 87.5 μm, and the conditions for radiography were as in Fig. 3. Fig. 5 shows the irradiation field diffracted by the crystal with photon energies of approximately 17 keV.