Invited Paper

Weakly ionized linear plasma x-ray generator with molybdenum-target triode

Eiichi Sato[a], Yasuomi Hayasi[a], Rudolf Germer[b], Etsuro Tanaka[c], Hidezo Mori[d], Toshiaki Kawai[e], Toshio Ichimaru[f], Shigehiro Sato[g], Hidenori Ojima[h], Kazuyoshi Takayama[h] and Hideaki Ido[i]

[a] Department of Physics, Iwate Medical University, 3-16-1 Honchodori, Morioka 020-0015, Japan
[b] ITP, FHTW FB1 and TU-Berlin, Blankenhainer Str. 9, D 12249 Berlin, Germany
[c] Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
[d] Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565 Japan
[e] Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Toyooka Village, Iwata-gun 438-0193, Japan
[f] Department of Radiological Technology, School of Health Sciences, Hirosaki University, 66-1 Honcho, Hirosaki 036-8564, Japan
[g] Department of Microbiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan
[h] Shock Wave Research Center, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan
[i] Department of Applied Physics and Informatics, Faculty of Engineering, Tohoku Gakuin University, 1-13-1 Chuo, Tagajo 985-8537, Japan,

ABSTRACT

In the plasma flash x-ray generator, a 200 nF condenser is charged up to 50 kV by a power supply, and flash x rays are produced by the discharging. The x-ray tube is a demountable triode with a trigger electrode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Target evaporation leads to the formation of weakly ionized linear plasma, consisting of molybdenum ions and electrons, around the fine target, and intense characteristic x rays are produced. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 16 kA. When the charging voltage was increased, the linear plasma formed, and the K-series characteristic x-ray intensities increased. The K lines were quite sharp and intense. The x-ray pulse widths were approximately 600 ns, and the time-integrated x-ray intensity had a value of approximately 65 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

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

1. INTRODUCTION

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

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

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To apply flash x-ray generators to biomedicine, several different generators[8-11] have been developed, and plasma x-ray generators[12-16] are useful for producing clean characteristic x rays in the low-photon-energy region of less than 20 keV. By forming weakly ionized linear plasma using rod targets, we confirmed irradiation of intense K-series characteristic x rays from the axial direction of the linear plasmas of nickel, copper, and molybdenum, since the bremsstrahlung x rays are absorbed effectively by the linear plasma; monochromatic clean Kα rays were produced using K-edge filters. Subsequently, since high-photon-energy bremsstrahlung x rays are not absorbed effectively by the linear plasma due to attenuation coefficients, high-photon-energy quasi-monochromatic x-ray generators[17] for producing characteristic x rays of molybdenum, silver, cerium, tantalum, and tungsten have been developed utilizing the angle dependence of bremsstrahlung x-ray intensity distribution.

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

2. GENERATOR

2.1 High-voltage circuit

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

2.2 X-ray tube

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

2.3 Principle of characteristic x-ray irradiation

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

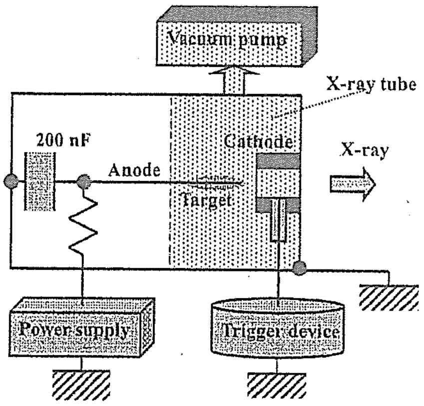


Figure 1: Block diagram of high-intensity plasma flash x-ray generator.

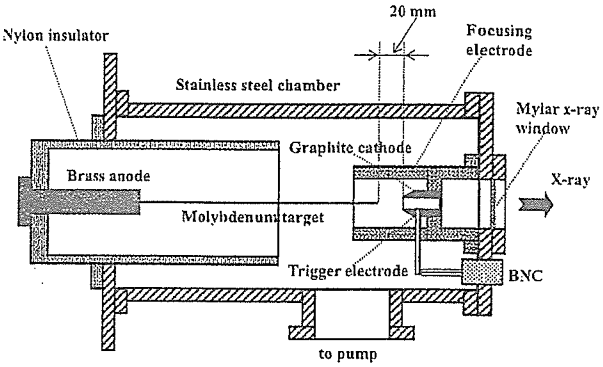


Figure 2: Schematic drawing of flash x-ray tube with rod target.

3. CHARACTERISTICS

3.1 Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. Figure 3 shows the time relation between the tube voltage and current. At the indicated charging voltages, they roughly displayed damped oscillations. When the charging voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was approximately 16 kA.

3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 4). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 600 ns, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 65 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

3.3 X-ray source

In order to roughly observe images of the plasma x-ray source in the detector plane, we employed a pinhole camera with a hole diameter of 100 μm and an x-ray film (Polaroid XR-7) (Fig. 5). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased. Because the x-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing x rays and decreases in the pinhole diameter.

3.4 X-ray spectra

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

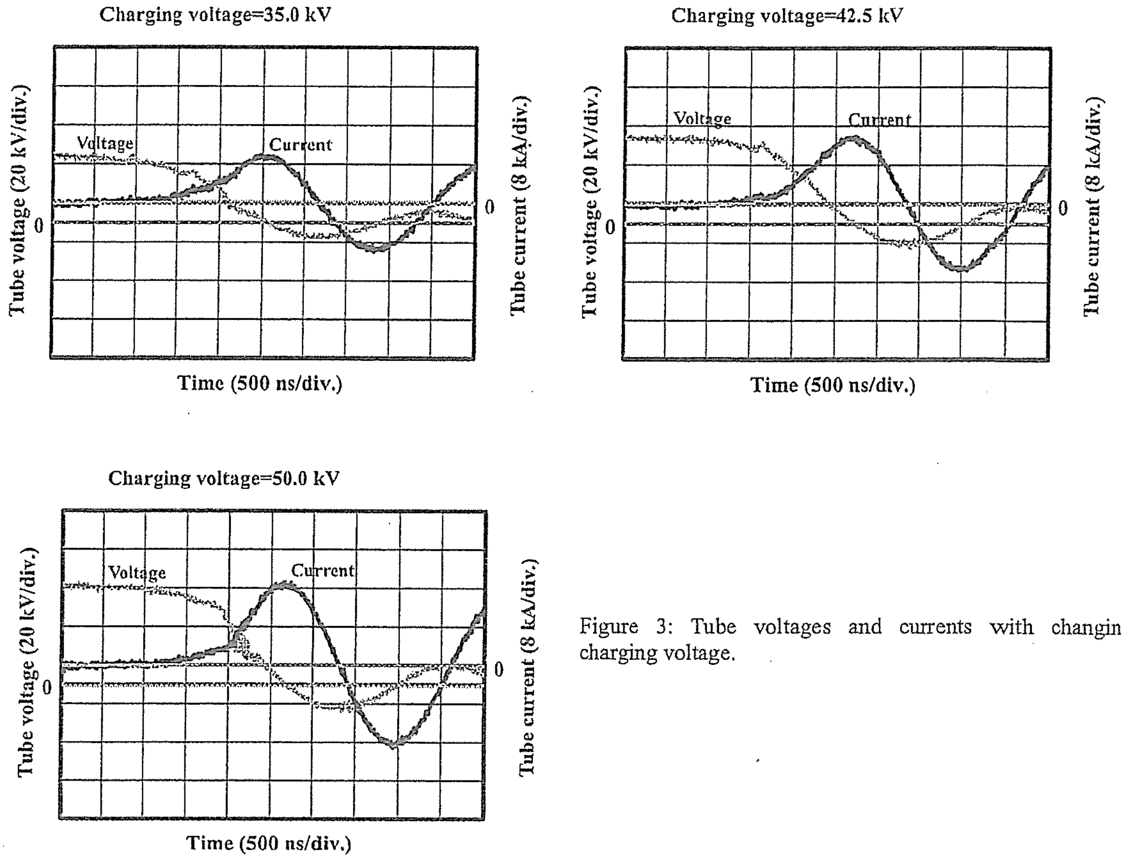


Figure 3: Tube voltages and currents with changing charging voltage.

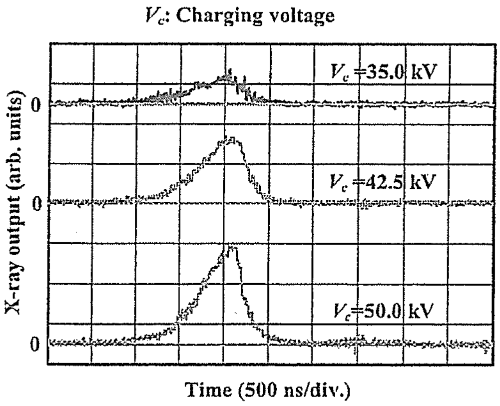


Figure 4: X-ray outputs at indicated conditions.

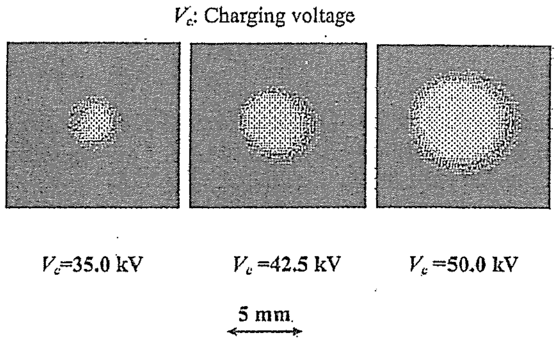


Figure 5: Images of plasma x-ray source.

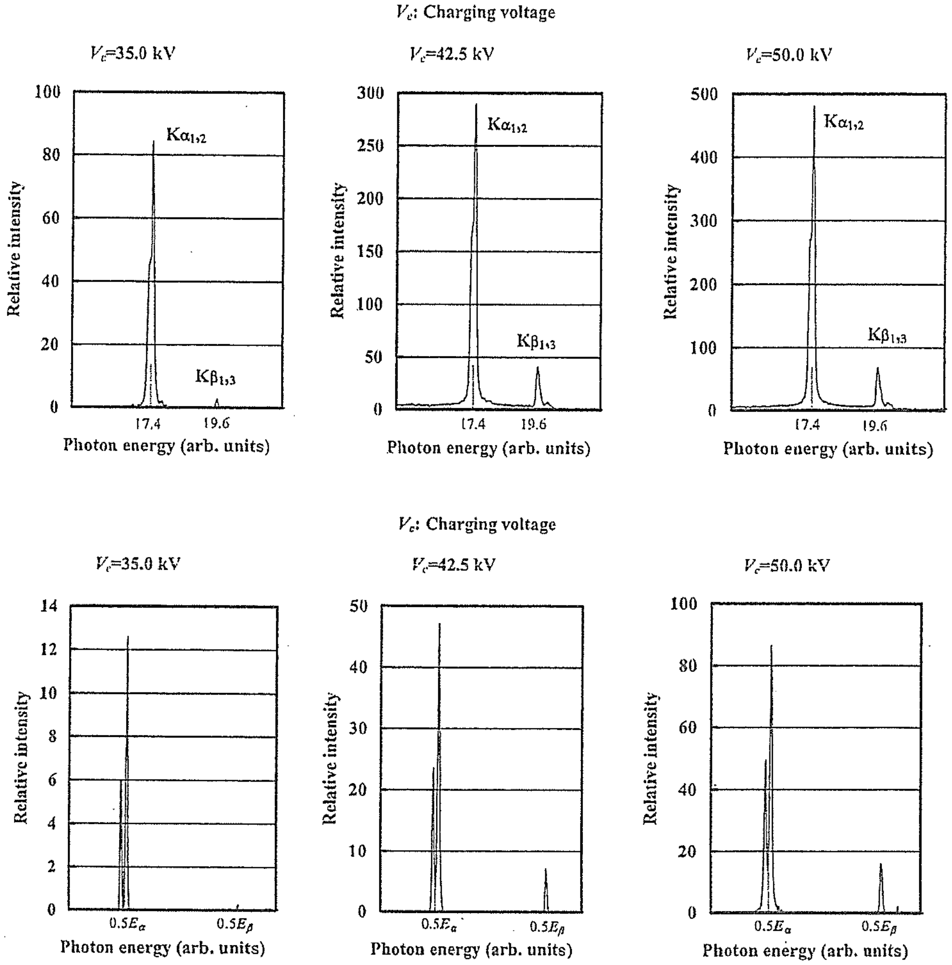


Figure 6: X-ray spectra from molybdenum plasma.

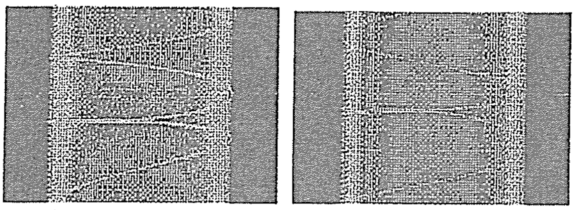
4. RADIOGRAPHY

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

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

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

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


100 µm wire

50 µm wire

Figure 7: Radiograms of tungsten wires in PMMA rod.

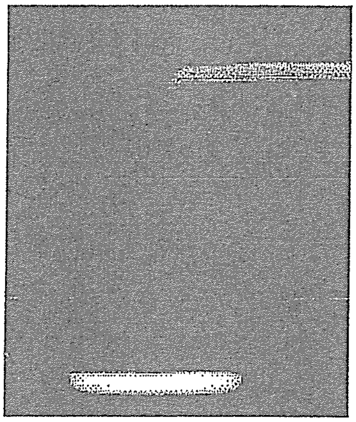


Figure 8: Radiogram of water falling into polypropylene beaker from glass test tube.

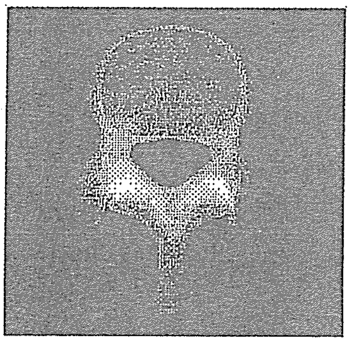


Figure 9: Radiogram of vertebra.

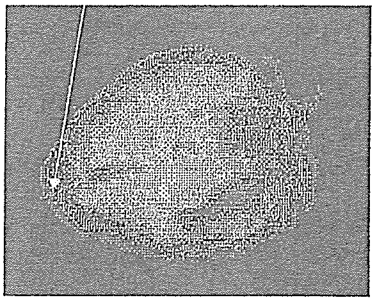


Figure 10: Angiograms of rabbit heart.

5. DISCUSSION

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

In this research, we obtained sufficient x-ray intensity per pulse for CR radiography without using a monochromatic filter, and the generator produced number of characteristic photons was approximately 1×10^9 photons/cm^2 at 1.0 m per pulse. In addition, since the photon energy of characteristic x rays can be controlled by changing target elements, various quasi-monochromatic high-speed radiographies, such as high-contrast micro angiography and dual-energy subtraction radiography, will be possible.

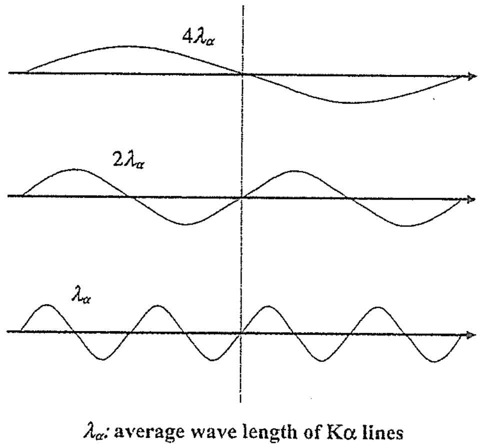


Figure 11: Assumption of hard x-ray resonation without using resonator.

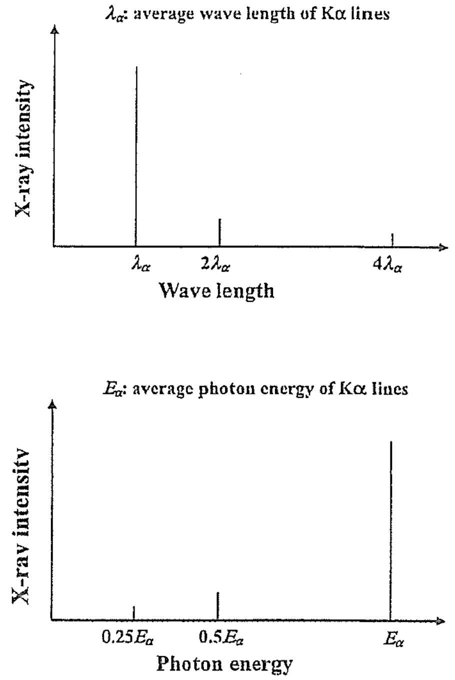


Figure 12: Estimated x-ray spectra under resonation.

ACKNOWLEDGMENT

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*dresato@iwate-med.ac.jp; phone, phone +81-19-651-5111; fax +81-19-654-9282

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Enhanced K-edge Angiography Utilizing Tantalum Plasma X-ray Generator in Conjunction with Gadolinium-Based Contrast Media

Eiichi SATO, Yasuomi HAYASI, Koji KIMURA[1], Etsuro TANAKA[2], Hidezo MORI[3], Toshiaki KAWAI[4], Takashi INOUE[5], Akira OGAWA[5], Shigehiro SATO[6], Kazuyoshi TAKAYAMA[7], Jun ONAGAWA[8] and Hideaki IDO[8]

Department of Physics, Iwate Medical University, 3-16-1 Honchodori, Morioka 020-0015, Japan
[1]*Department of Physiology, Tokai University School of Medicine, Boseidai, Isehara, Kanagawa 259-1193, Japan*
[2]*Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku, Tokyo 156-8502, Japan*
[3]*Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565, Japan*
[4]*Electron Tube Division #2, Hamamatsu Photonics K.K., 314-5 Shimokanzo, Toyooka Village, Iwata, Shizuoka 438-0193, Japan*
[5]*Department of Neurosurgery, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan*
[6]*Department of Microbiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan*
[7]*Shock Wave Research Center, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan*
[8]*Department of Applied Physics and Informatics, Faculty of Engineering, Tohoku Gakuin University, 1-13-1 Chuo, Tagajo, Miyagi 985-8537, Japan*

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The tantalum plasma flash X-ray generator is useful for performing high-speed enhanced K-edge angiography using cone beams because K-series characteristic X-rays from the tantalum target are absorbed effectively by gadolinium-based contrast media. In the flash X-ray generator, a 150 nF condenser is charged up to 80 kV by a power supply, and flash X-rays are produced by the discharging. The X-ray tube is a demountable cold-cathode diode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Since the electric circuit of the high-voltage pulse generator employs a cable transmission line, the high-voltage pulse generator produces twice the potential of the condenser charging voltage. At a charging voltage of 80 kV, the estimated maximum tube voltage and current were approximately 160 kV and 40 kA, respectively. When the charging voltage was increased, the K-series characteristic X-ray intensities of cerium increased. The K lines were clean and intense, and hardly any bremsstrahlung rays were detected. The X-ray pulse widths were approximately 100 ns, and the time-integrated X-ray intensity had a value of approximately 300 μGy at 1.0 m from the X-ray source with a charging voltage of 80 kV. Angiography was performed using a filmless computed radiography (CR) system and gadolinium-based contrast media. In the angiography of nonliving animals, we observed fine blood vessels of approximately 100 μm with high contrasts. [DOI: 10.1143/JJAP.44.8716]

KEYWORDS: angiography, gadolinium-based contrast media, characteristic X-rays, quasi-monochromatic X-rays, tantalum K lines

1. Introduction

Enhanced K-edge angiography[1–4] has been performed utilizing monochromatic parallel X-ray beams produced from synchrotron orbital radiation using a monochrocollimator. The photon energies of the beams are approximately 35 keV, and are absorbed effectively by iodine-based contrast media with a K-absorption edge of 33.2 keV. Nowadays, an X-ray generator with a cerium-target tube[5] can be used in order to perform the K-edge angiography because K-series characteristic X-rays with photon energies just beyond the K-edge are absorbed effectively by iodine.

To perform high-speed biomedical radiography, we have developed several different high-dose-rate X-ray generators corresponding to specific objectives. For example, flash X-ray generators[6–9] with cold-cathode tubes produce extremely short X-ray pulses with durations of less than 1 μs, and the X-ray duration can be controlled accurately from 10 μs to 1.0 ms in cases where stroboscopic X-ray generators[10,11] utilizing hot-cathode triodes are employed.

Recently, although clean K-series characteristic X-rays of copper[12] and nickel[13] have been produced using plasma flash X-ray generators, low-intensity bremsstrahlung X-rays have been observed using a molybdenum target.[14] Therefore, we have performed preliminary experiments for producing clean high-photon-energy characteristic X-rays from molybdenum, silver and cerium targets using a compact flash X-ray generator with a disk-cathode tube,[15] and have succeeded in producing clean characteristic X-rays using the angle dependence of bremsstrahlung X-ray distributions. However, the X-ray intensity should be increased to a sufficient level for iodine angiography by increasing the electrostatic energies in the generator.

Since K-series characteristic X-rays from ytterbium, tantalum, and tungsten targets are absorbed effectively by gadolinium-based contrast media used in MRA, these X-rays are very useful for performing enhanced K-edge angiography. As compared with K-edge angiography using an iodine medium with an X-ray photon energy of 35 keV, the absorbed dose can be decreased easily in cases where the gadolinium medium is employed.

In the present research, we developed an intense quasi-monochromatic plasma flash X-ray generator with a tantalum target tube, and used it to perform a preliminary study on angiography achieved with tantalum K-series characteristic X-rays.

2. Principle of Angiography

Figure 1 shows the mass attenuation coefficients of gadolinium at the selected energies; the coefficient curve is discontinuous at the gadolinium K-edge. The average photon energy of the tantalum $K\alpha$ lines is shown above the gadolinium K-edge. The average photon energy of tantalum $K\alpha$ lines is 57.1 keV, and gadolinium contrast media with a K-absorption edge of 50.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

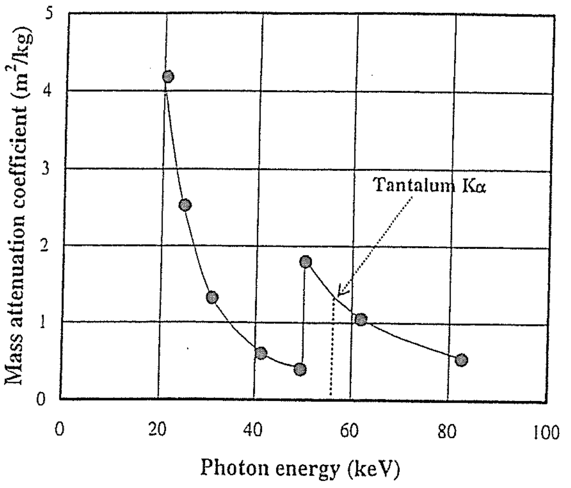

Fig. 1. Mass attenuation coefficient of gadolinium. The average photon energy of tantalum Kα lines is shown above the gadolinium K-edge.

3. Generator

3.1 *High-voltage circuit*

Figure 2 shows a block diagram including the electric circuit of a high-intensity plasma flash X-ray generator. The generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 150 nF, an air gap switch, a turbomolecular pump, a thyratron pulse generator as a trigger device, and a flash X-ray tube. In this generator, a coaxial cable transmission line is employed in order to increase maximum tube voltage using high-voltage reflection. The high-voltage main condenser is charged up to 80 kV by the power supply, and electric charges in the condenser are discharged to the tube through the four cables after closing the gap switch with the trigger device.

3.2 *X-ray tube*

The X-ray tube is a demountable cold-cathode diode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa (Fig. 3). This tube consists of the following major parts: a ring-shaped graphite cathode with an inside diameter of 4.5 mm, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) X-ray window 0.25 mm in thickness, and a rod-shaped tantalum target 3.0 mm in diameter. The distance between the target and cathode electrodes can be regulated from the outside of the tube, and is set to 1.5 mm. As electron beams from the cathode electrode are roughly converged to the target by the electric field in the tube, evaporation leads to the formation of weakly ionized plasma, consisting of tantalum ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of the electron trajectory in Sommerfeld's theory[16] (Fig. 4), tantalum K-series characteristic X-rays can be produced without using a filter.

4. Characteristics

4.1 *Tube voltage and current*

In this generator, it was difficult to measure the tube voltage and current since the tube voltages were high, and there was no space to set a current transformer for measuring the tube current. Currently, the voltage and current roughly display damped oscillations. When the charging voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 80 kV, the estimated maximum values of the tube voltage and current were approximately 160 kV (two times the charging voltage) and 40 kA, respectively.

4.2 *X-ray output*

The 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 charging

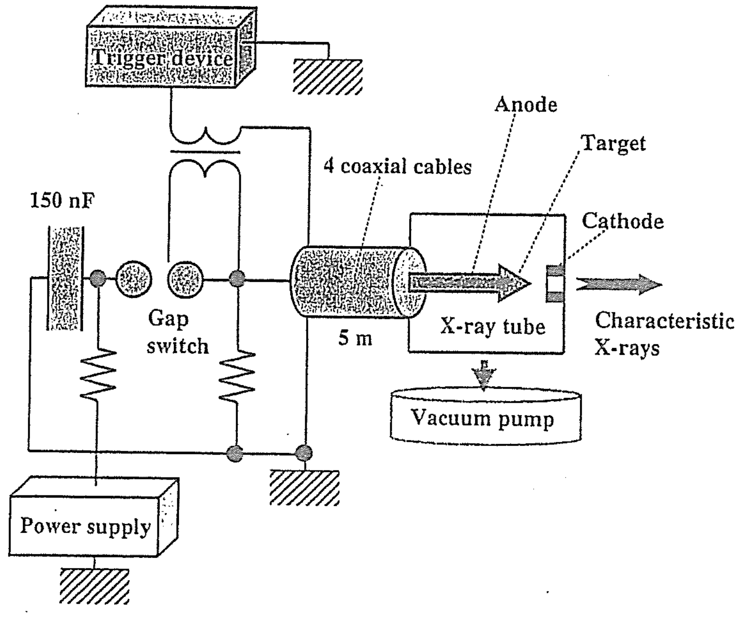

Fig. 2. Block diagram including high-voltage circuit of intense quasi-monochromatic plasma flash X-ray generator with tantalum-target tube.

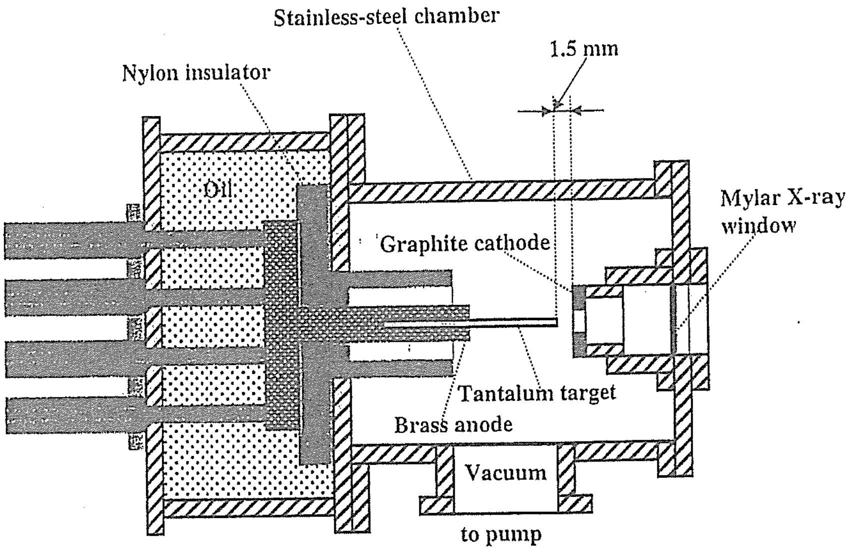

Fig. 3. Schematic drawing of flash X-ray tube with rod-shaped tantalum target.

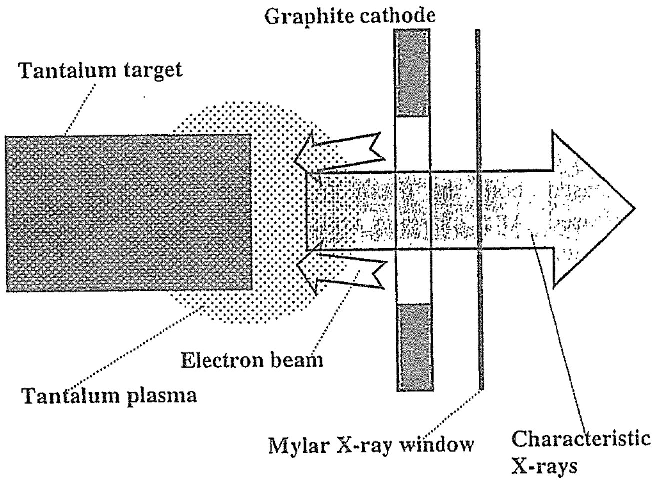

Fig. 4. Irradiation of K-series characteristic X-rays of tantalum.

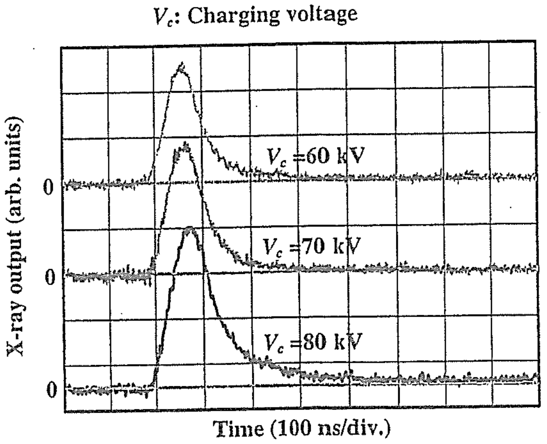

Fig. 5. X-ray outputs detected using combination of plastic scintillator and photomultiplier.

voltage. The X-ray pulse widths were approximately 100 ns, and the time-integrated X-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 300 μGy per pulse at 1.0 m from the X-ray source with a charging voltage of 80 kV.

4.3 *X-ray source*

In order to observe the characteristic X-ray source, we employed a 100-μm-diameter pinhole camera and an X-ray film (Polaroid XR-7) (Fig. 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 as the thickness of a filter for absorbing X-rays increased and as the pinhole diameter decreased.

4.4 *X-ray spectra*

X-ray spectra were measured using a transmission-type spectrometer[14] 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 CR system[17] (Konica Regius 150) with a wide dynamic range, and relative X-ray intensity was calculated from Dicom original digital data corresponding to X-ray intensity; the data was scanned by a

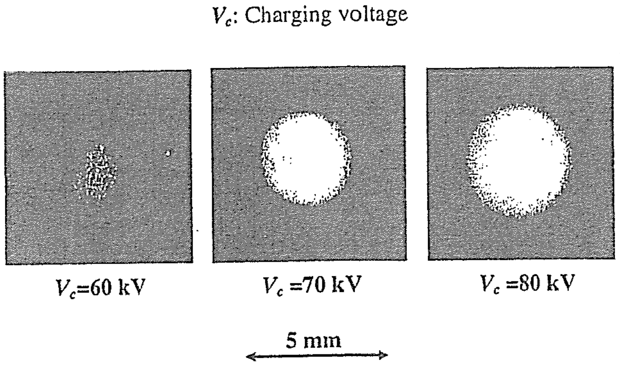

Fig. 6. Images of characteristic X-ray source obtained using pinhole camera with changes in charging voltage.

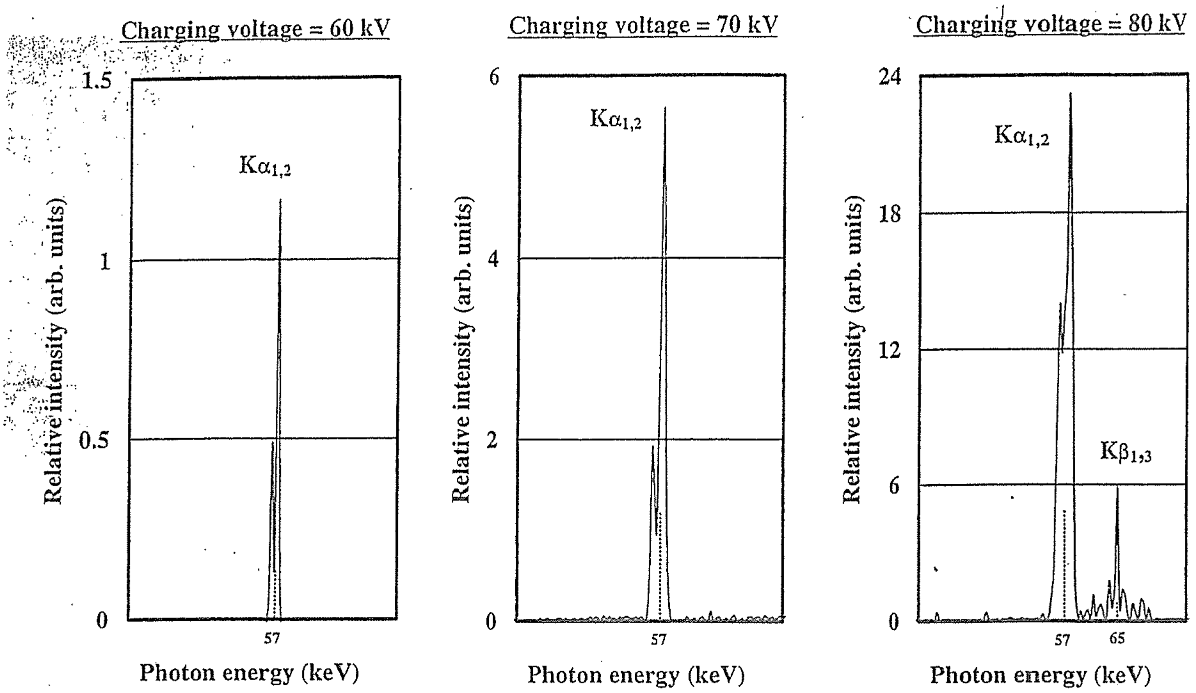

Fig. 7. X-ray spectra from tantalum target. Spectra were measured using a transmission-type spectrometer with a lithium fluoride curved crystal.

Dicom viewer in the filmless CR system. Subsequently, the relative X-ray intensity as a function of the data was calibrated using a conventional X-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 7 shows measured spectra from the tantalum target. We observed clean K-series lines, while bremsstrahlung rays were hardly detected. The characteristic X-ray intensity substantially increased with charging voltage.

5. Angiography

Flash angiography was performed using the CR system at 1.2 m from the X-ray source, and the charging voltage was 80 kV. First, rough measurements of spatial resolution were made using wires. Figure 8 shows radiograms of tungsten wires in a rod made of poly(methyl methacrylate) (PMMA). Although the image contrast decreased slightly with wire diameter, due to blurring of the image caused by the sampling pitch of 87.5 µm, a 50-µm-diameter wire could be observed. Because the tungsten wires transmitted the characteristic X-rays easily, low-contrast radiograms were obtained.

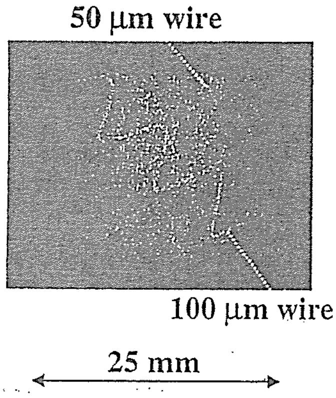

Fig. 8. Radiograms of tungsten wires in PMMA rod.

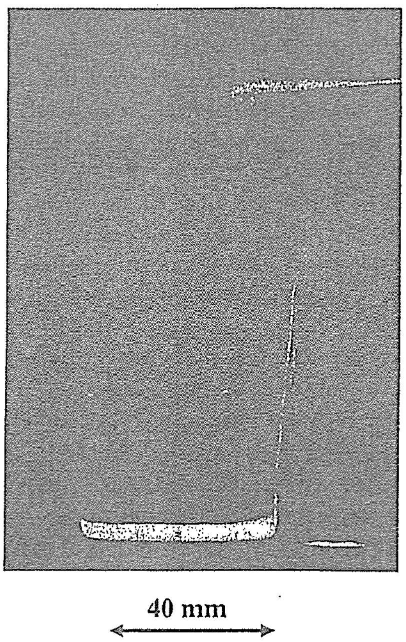

Fig. 9. Radiogram of water (20% gadolinium oxide suspension) falling into polypropylene beaker from glass test tube.

The image of water (gadolinium oxide suspension of 20%) 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.

Figure 10 shows an angiogram of poly(tetrafluoroethylene) (Teflon) tubes of 0.5 and 1.0 mm bore diameter in a

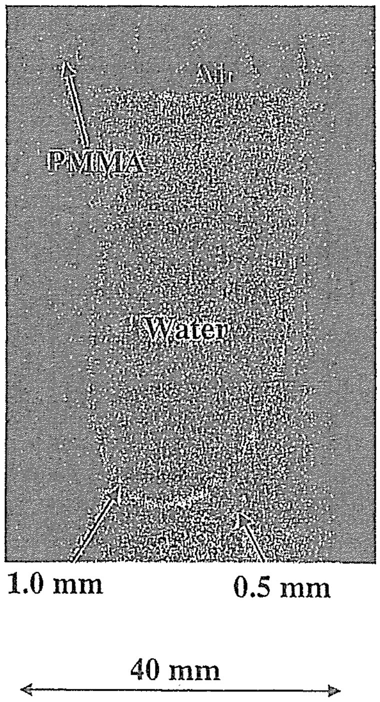

Fig. 10. Angiography of Teflon tube using contrast medium which contains approximately 65% gadodiamidehydrate.

PMMA case using a contrast medium which contains approximately 65% gadodiamidehydrate; the 0.5 mm tube can be observed easily. Figure 11 shows an angiogram of a rabbit head using gadolinium oxide powder, and fine blood vessels of approximately 100 μm were visible.

6. Discussion

In summary, we succeeded in producing K-series characteristic X-rays of tantalum and in performing K-edge angiography using gadolinium contrast media with a K-edge of 50.2 keV; this K-edge angiography could be a useful technique for reducing the dose absorbed by patients. Although we employed tantalum Kα (57.1 keV) and Kβ (approximately 65 keV) rays, Kβ rays should be absorbed using an ytterbium oxide filter in order to increase the image contrast of blood vessels. In addition, L-series characteristic rays should be absorbed before angiography using a tungsten or an ytterbium oxide filter. In these cases, the photon energies of the K-absorption edges of tungsten and ytterbium are 69.5 and 61.3 keV, respectively.

In cases where a high tube voltage beyond the critical excitation potential is applied, the optimum intensity for angiography can be controlled because the K-series characteristic intensity substantially increases with charging voltage. 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.

Using this flash X-ray generator, because the photon energy of characteristic X-rays can be selected, quasi-monochromatic imaging, such as enhanced K-edge angiography using iodine contrast media and mammography, can be performed. 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 conjunction with the fine focusing technique, these monochromatic X-ray generators could be employed to perform K-edge angiography and X-ray phase-contrast radiography for edge enhancement.

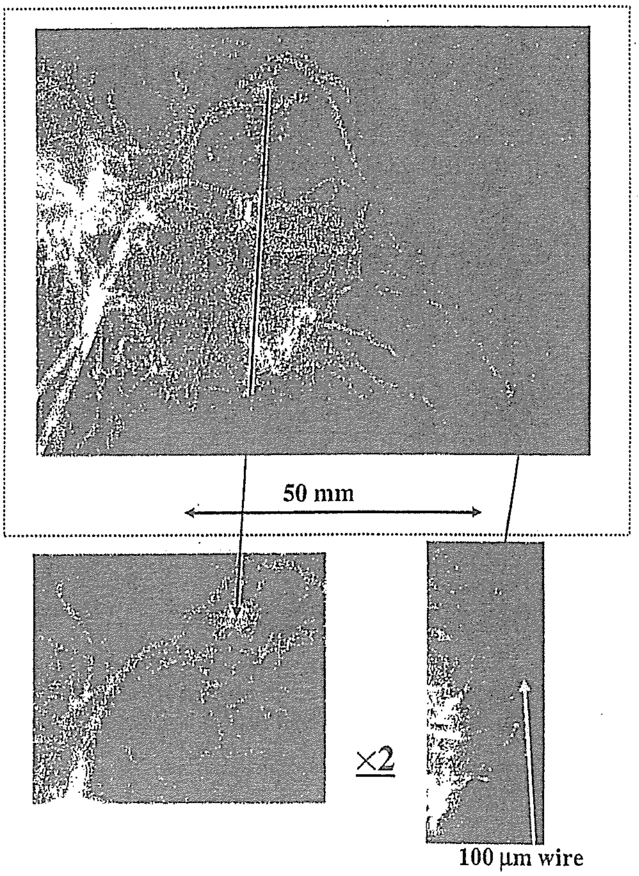

Fig. 11. Angiography of rabbit head using gadolinium oxide powder.

Acknowledgment

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Monochromatic flash x-ray generator utilizing copper-target diode

Eiichi Sato*[a], Michiaki Sagae[a], Makoto Komatsu[a], Rudolf Germer[b], Etsuro Tanaka[c], Hidezo Mori[d],
Toshiaki Kawai[e], Toshio Ichimaru[f], Shigehiro Sato[g], Hidenori Ojima[h],
Kazuyoshi Takayama[h] and Hideaki Ido[i]

[a] Department of Physics, Iwate Medical University, 3-16-1 Honchodori, Morioka 020-0015, Japan
[b] ITP, FHTW FB1 and TU-Berlin, Blankenhainer Str. 9, D 12249 Berlin, Germany
[c] Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
[d] Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565 Japan
[e] Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Toyooka Village, Iwata-gun 438-0193, Japan
[f] Department of Radiological Technology, School of Health Sciences, Hirosaki University, 66-1 Honcho, Hirosaki 036-8564, Japan
[g] Department of Microbiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan
[h] Shock Wave Research Center, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan
[i] Department of Applied Physics and Informatics, Faculty of Engineering, Tohoku Gakuin University, 1-13-1 Chuo, Tagajo 985-8537, Japan

ABSTRACT

High-voltage condensers in a polarity-inversion two-stage Marx surge generator are charged from −50 to −70 kV using a power supply, and the electric charges in the condensers are discharged to an x-ray tube after closing the gap switches in the surge generator using a trigger device. The x-ray tube is a demountable diode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Clean copper Kα lines are produced using a 10-μm-thick nickel filter, since the tube utilizes a disk cathode and a rod target, and bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration. The peak tube voltage increased with increasing charging voltage. At a charging voltage of −70 kV, the peak tube voltage and current were 140 kV and 0.8 kA, respectively. The pulse widths were approximately 30 ns, and the maximum dimension of the x-ray source was 3.0 mm in diameter. The number of generator-produced Kα photons was approximately 2.5×10^6 photons/cm^2 at 0.5 m per pulse.

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

1. INTRODUCTION

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

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

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direction. Without forming the linear plasma, because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, characteristic x rays can be produced by considering the angle dependence of bremsstrahlung x rays.[16] As compared with the plasma generator, the photon energy of the characteristic x rays can be increased by increasing the maximum output voltage, since a multistage Marx generator can be employed.

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

2. GENERATOR

2.1 High-voltage circuit

Figure 1 shows a block diagram of a compact monochromatic flash x-ray generator. This generator consists of the following components: a constant high-voltage power supply, a polarity-inversion two-stage surge Marx generator with a capacity during main discharge of 425 pF, a trigger device for the surge generator, a turbomolecular pump, and a flash x-ray tube. Since the electric circuit of the surge generator employs a polarity-inversion two-stage Marx line (Fig. 2), the surge generator produces twice the potential of the condenser charging voltage. When two condensers inside of the surge generator are charged from −50 to −70 kV, the ideal output voltage ranges from 100 to 140 kV.

2.2 X-ray tube

The x-ray tube is a demountable diode type, as illustrated in Fig. 3. This tube is connected to the turbomolecular pump with a pressure of approximately 1 mPa and consists of the following major devices: a rod-shaped copper target 3.0 mm in diameter, a disk cathode made of graphite, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a polymethyl methacrylate (PMMA) tube body. The target-cathode space was regulated to 1.25 mm from the outside of the x-ray tube by rotating the anode rod, and the transmission x rays are obtained through a 1.0-mm-thick graphite cathode and an x-ray window. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Figs. 4 and 5), copper Kα rays can be produced using a 10-μm-thick nickel K-edge filter.

3. CHARACTERISTICS

3.1 Tube voltage and current

Tube voltage and current were measured using a high-voltage divider with an input impedance of 10 kΩ and a current transformer, respectively (Fig. 6). The voltage and current displayed roughly damped oscillations because the discharge resistance in the tube varied rapidly from infinity to approximately 0 Ω during the discharge. Thus, at the first quarter cycle of the oscillations, when the voltage decreased, the current increased. The instantaneous voltage and current increased with increases in the charging voltage, and the voltage and current were approximately 140 kV and 0.8 kA, respectively, at a charging voltage of −70 kV.

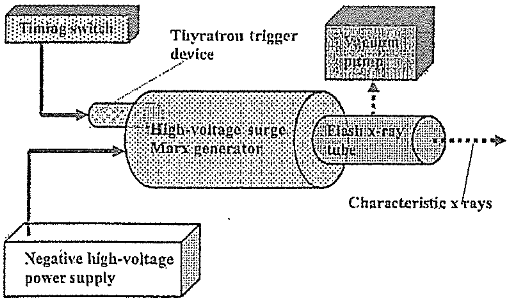


Figure 1: Block diagram of compact monochromatic flash x-ray generator.

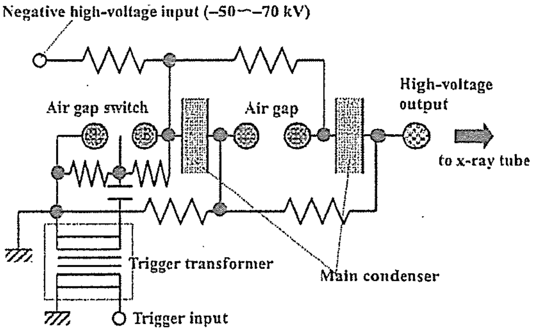


Figure 2: Circuit diagram of flash x-ray generator.

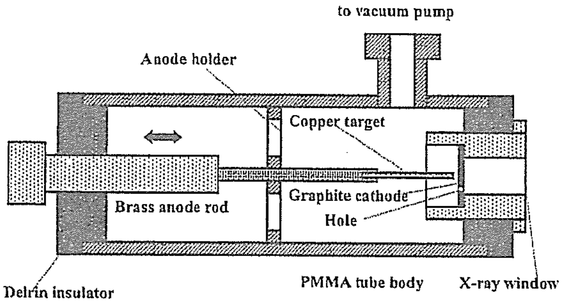


Figure 3: Schematic drawing of flash x-ray tube.

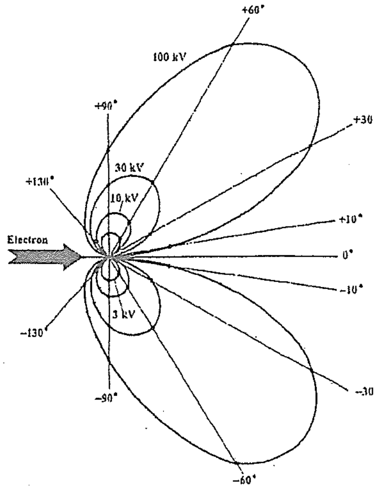


Figure 4: Bremsstrahlung x-ray intensity distribution vs angle.

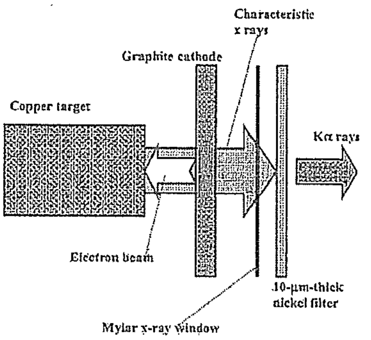


Figure 5: Characteristic x-ray irradiation.

3.2 X-ray output

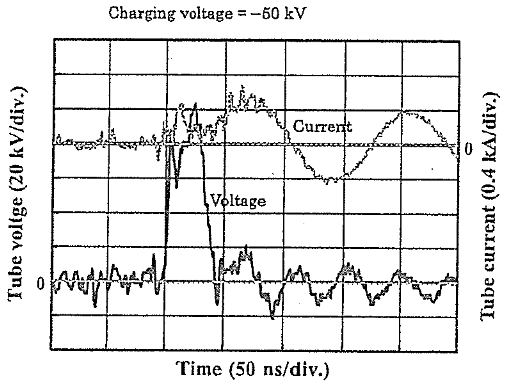
X-ray output pulse was detected using a combination of a plastic scintillator, a photomultiplier, and the filter (Fig. 7). When the charging voltage was increased, the pulse height increased, but the width seldom varied. The widths were approximately 30 ns, and the time-integrated x-ray intensity measured using a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 1.0 μC/kg per pulse at 0.5 m from the x-ray source with a charging voltage of −70 kV.

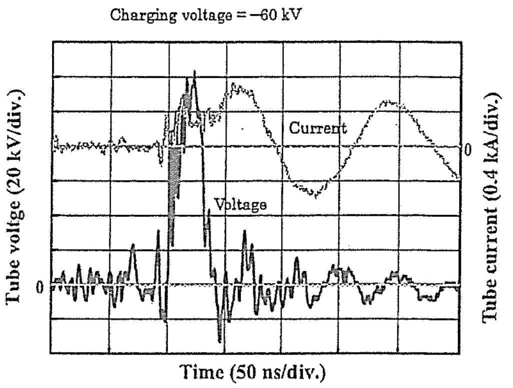
3.3 X-ray source

In order to observe the x-ray source, we employed a 100-μm-diameter pinhole camera, an x-ray film (Polaroid XR-7), and the filter (Fig. 8). When the charging voltage was increased, the spot intensity increased, and the intensities corresponded well to the x-ray pulse height. The dimension was almost equal to the target diameter and had a value of approximately 3.0 mm.

3.4 X-ray spectra

X-ray spectra were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken using a computed radiography (CR) system[17] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 9 shows the measured spectra from the copper target with the filter. We observed clean copper Kα lines, while bremsstrahlung rays were hardly detected at all. The Kα intensity increased with increases in the charging voltage.





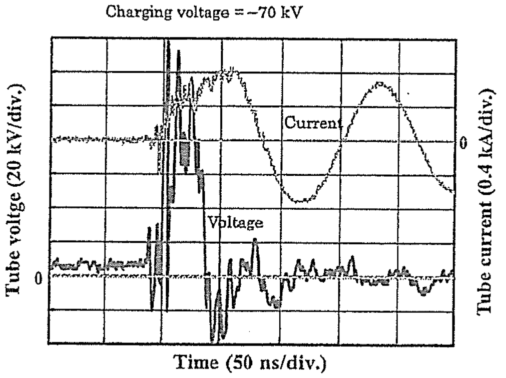


Figure 6: Variations in tube voltage and current with charges in charging voltage.

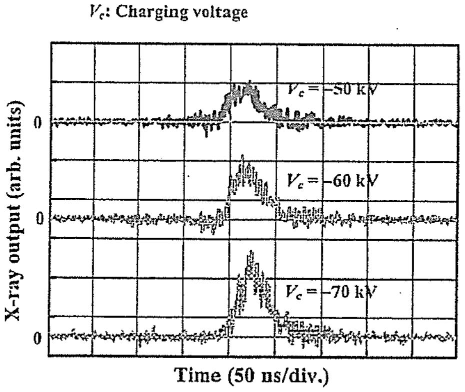


Figure 7: X-ray outputs according to changes charging voltage.

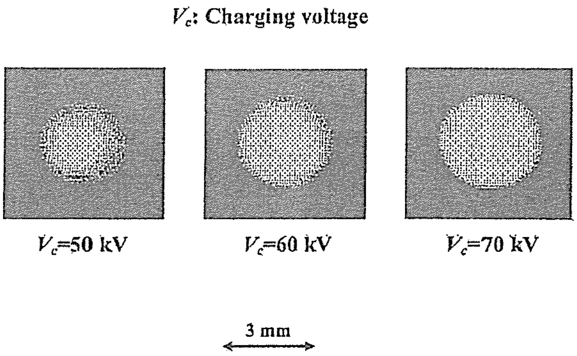


Figure 8: Images of x-ray source with changes in charging voltage.

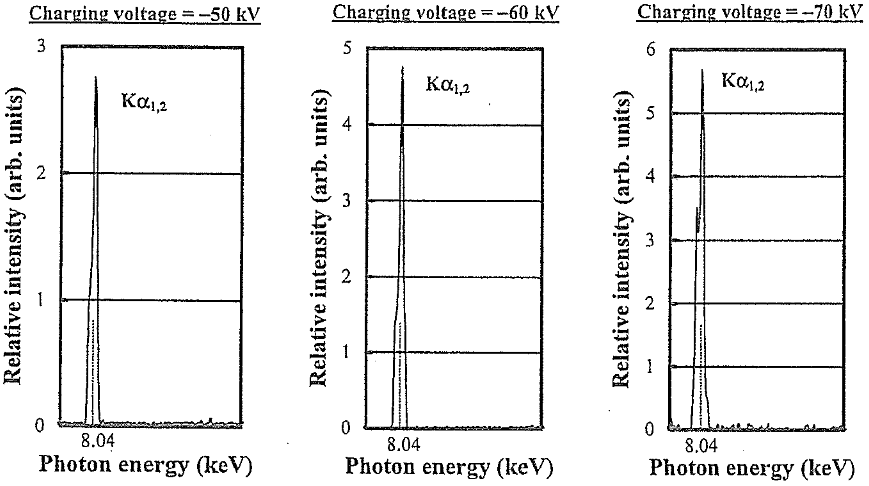


Figure 9: X-ray spectra from copper target according to changes in charging voltage.

4. RADIOGRAPHY

Flash radiography was performed using the CR system (Konica Regius 150) at 0.5 m from the x-ray source, and the charging voltage was −70 kV.

Firstly, rough measurements of spatial resolution were made using wires. Figure 10 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate. Although the image contrast increased with increasing wire diameter, a 50-µm-diameter wire could be observed.

Figure 11 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. The image of water falling into a polypropylene beaker from a plastic test tube is shown in Fig. 12. This image was taken with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 50 ns, the stop-motion image of water could be obtained. Figure 13 shows an angiogram of a rabbit heart; iodine-based microspheres of 15 µm in diameter were used, and fine blood vessels of approximately 100 µm were visible.

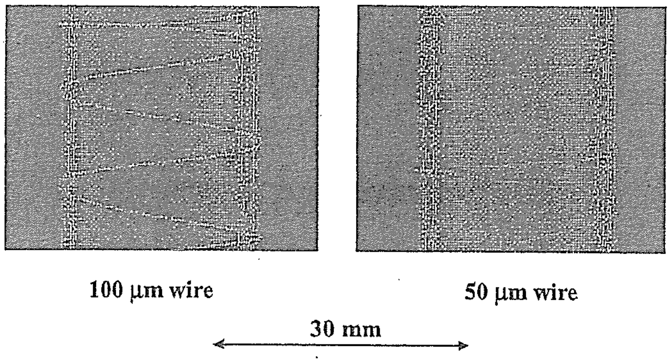


Figure 10: Radiograms of tungsten wires of 50 and 100 µm in diameter coiled around pipe made of polymethyl methacrylate.

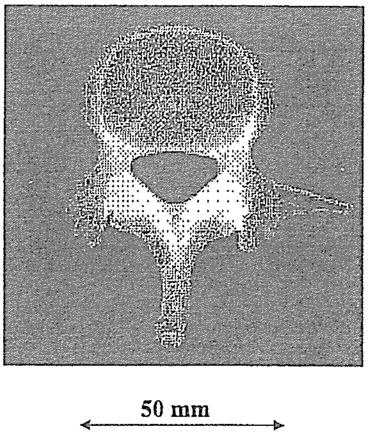


Figure 11: Radiogram of vertebra.

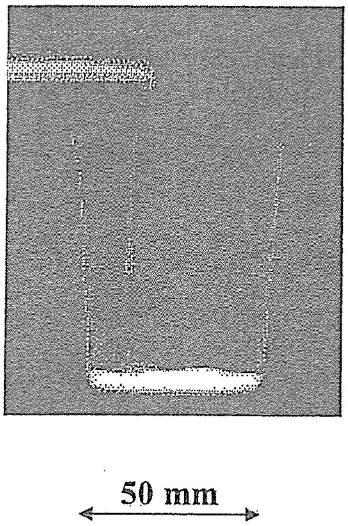


Figure 12: Radiogram of water falling into polypropylene beaker from plastic test tube.

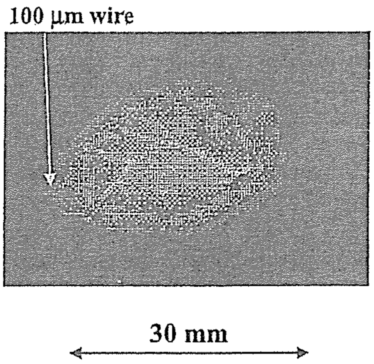


Figure 13: Angiograms of rabbit heart.

5. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean copper $K\alpha$ rays (8.04 keV). Therefore, we are very interested in the measurement the $K\alpha$ rays from cerium (34.6 keV), ytterbium (52.0 keV), tantalum (57.1 keV), and tungsten (58.9 keV) targets; the target element should be selected corresponding to the radiographic objectives. In medical applications, $K\alpha$ rays of cerium are absorbed effectively by an iodine-based contrast medium with a K-edge of 33.2 keV, and K-edge angiography can be performed. In addition, since $K\alpha$ rays from ytterbium, tantalum, and tungsten targets are absorbed effectively by gadolinium-based contrast media with a K-edge of 50.2 keV, these x rays are very useful for performing enhanced K-edge angiography.

In this research, the instantaneous number of generator-produced $K\alpha$ photons was approximately 2.5×10^6 photons/cm^2 per pulse at 0.5 m from the source. However, the intensity can be increased by increasing the electrostatic energy in condensers in the surge generator, and quasi-monochromatic x rays of both $K\alpha$ and $K\beta$ (8.90 keV) lines are produced without using the nickel filter with a K-edge of 8.33 keV.

Using this flash x-ray generator, because the photon energy of characteristic x rays can be selected, a high-speed photon-counting radiography can be performed in order to decrease noise from radiograms. As compared with a steady-state x-ray generator, since the target element can be changed easily using this demountable PMMA tube, demonstrations of monochromatic radiography will be accomplished.

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