Weakly ionized cerium plasma radiography

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ABSTRACT

In the plasma flash x-ray generator, high-voltage main condenser of about 200 nF is charged up to 55 kV by a power supply, and electric charges in the condenser are discharged to an x-ray tube after triggering the cathode electrode. The flash x-rays are then produced. The x-ray tube is of a demountable triode that is connected to a turbo molecular pump with a pressure of approximately 1 mPa. As electron flows from the cathode electrode are roughly converged to a rod cerium target of 3.0 mm in diameter by electric field in the x-ray tube, the weakly ionized linear plasma, which consists of cerium ions and electrons, forms by target evaporating. At a charging voltage of 55 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 20 kA. When the charging voltage was increased, weakly ionized cerium plasma formed, and the K-series characteristic x-ray intensities increased. The x-ray pulse widths were about 500 ns, and the time-integrated x-ray intensity had a value of about 40 μC/kg at 1.0 m from x-ray source with a charging voltage of 55 kV. In the angiography, we employed a film-less computed radiography (CR) system and iodine-based microspheres. Because K-series characteristic x-rays are absorbed easily by the microspheres, high-contrast angiography has been performed.

Key words: Plasma x-ray, cerium target, weakly ionized cerium plasma, characteristic x-ray, high contrast angiography

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1. INTRODUCTION

Flash x-rays are useful in order to perform high-speed radiography, and various generators have been developed to correspond to specific radiographic objectives.[1-6] In the cases of multiple-shot and cine radiographies, we have developed several different repetitive-flash[7-11] and stroboscopic x-ray generators.[12-18] Although most flash x-ray generators have cold-cathode tubes, the stroboscopic generators utilize hot-cathode tubes.

In conjunction with single crystals, synchrotrons generate monochromatic x-rays. These rays play important roles in parallel radiography and have been employed to perform high-contrast micro-angiography[19] and x-ray phase imaging.[20,21] However, it is difficult to obtain sufficient machine times for various research projects including medical applications.

As for angiography using iodine-based contrast mediums, K-series characteristic x-rays of cerium are extremely useful, since the rays are absorbed easily by iodine. In particular, since quite intense and sharp characteristic x-rays have been produced from weakly ionized linear plasmas[22-25] of nickel, copper and molybdenum, the development of a cerium-target x-ray tube for angiography is highly desirable.

In this research, we developed a single flash x-ray generator with a cerium-target plasma tube and performed a tentative study on weakly ionized cerium plasma angiography.

2. GENERATOR

2.1 High-voltage circuit

Figure 1 shows block diagram of a 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 about 200 nF, a turbo-molecular 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 55 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode by 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 turbo molecular pump with a pressure of approximately 1 mPa (Fig. 2). This tube consists of the following major parts: a pipe-shaped carbon cathode with a bore diameter of 10.0 mm, a trigger electrode made from a copper wire, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window of 0.25 mm, and a rod-shaped cerium target of 3.0 mm in diameter. The target tip is embedded in the carbon rod in order to absorb the characteristic x-rays of carbon by the window. 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 electric field in the tube, the weakly ionized plasma, which consists of cerium ions and electrons, forms around the target by evaporating.

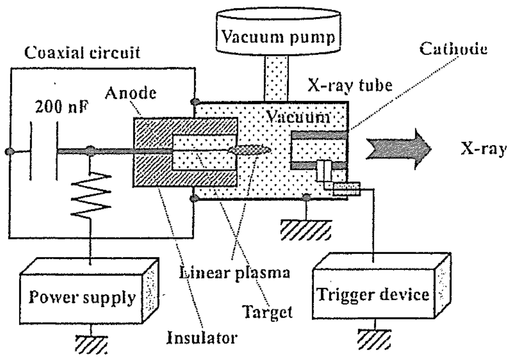


Figure 1: Block diagram of high-intensity plasma flash x-ray generator.

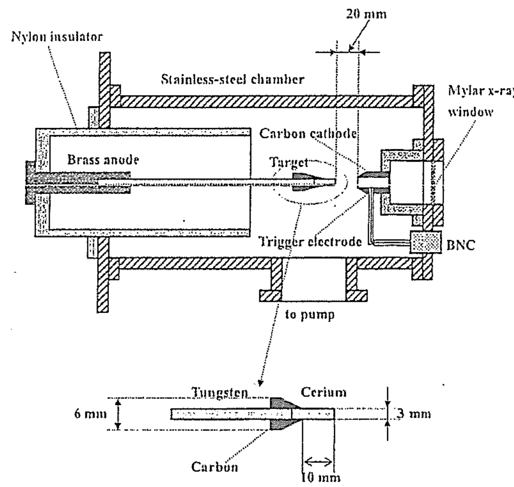


Figure 2: Schematic drawing of flash x-ray tube with a rod target.

3. CHARACTERISTICS

3.1 Tube voltage and current

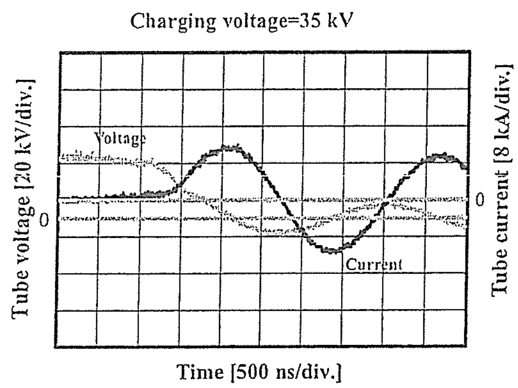
Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. Figure 3 shows time relation between the tube voltage and current. At the indicated charging voltages, they roughly displayed damped oscillations. When the charging voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 55 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was about 20 kA.

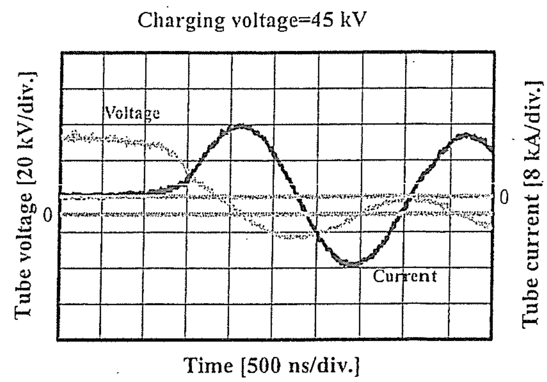
3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier. The x-ray pulse height substantially increased with corresponding increases in the charging voltage (Fig. 4). The x-ray pulse widths were about 500 ns, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 utilizing MSO-S elements without energy compensation) had a value of about 40 μC/kg at 1.0 m from the x-ray source with a charging voltage of 55 kV.

3.3 X-ray source

In order to measure images of the plasma x-ray source, 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. In contrast, both the dimension and intensity decreased according to insertion of the monochromatic filter.





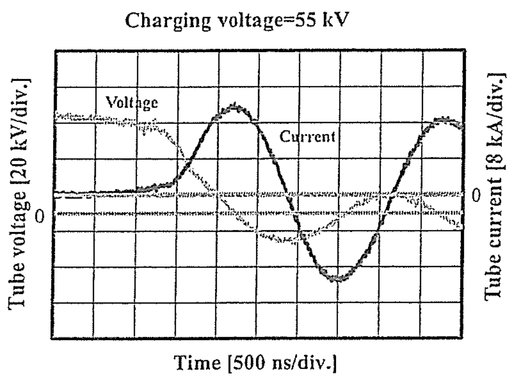


Figure 3: Tube voltages and currents at the indicated charging voltages.

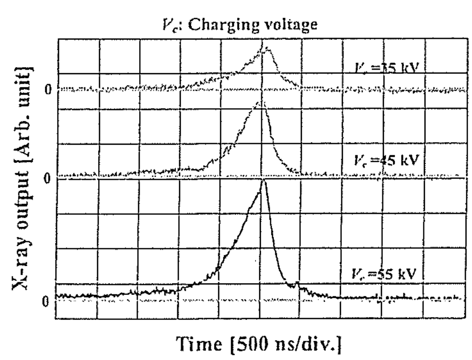


Figure 4: X-ray outputs at the indicated conditions.

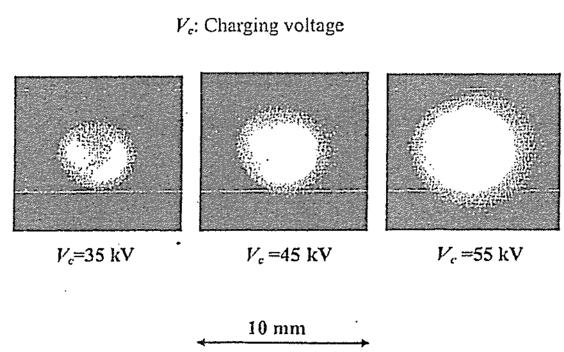


Figure 5: Images of plasma x-ray source.

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 of 0.5 mm in thickness (Fig. 6). The spectra were taken by a computed radiography (CR) system[26] (Konica Regius 150) having a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 7 shows measured spectra from the cerium target. In this experiment, although we observed both the bremsstrahlung and characteristic x-rays, we could not observe characteristic x-rays with a charging voltage of 35 kV because the critical excitation energy is 40.3 keV. Both the intensities increased substantially with increases in the charging voltage.

3.5 X-ray divergence by slits

In order to ascertain difference of characteristics between x-rays from a conventional tube and these from the plasma tube, we employed two lead slits in order to measure the divergence of the x-rays (Fig. 8). As compared with x-rays from a conventional tube having a tungsten target, the characteristic x-rays from the plasma were diffused greatly after passing through two slits (Fig. 9).

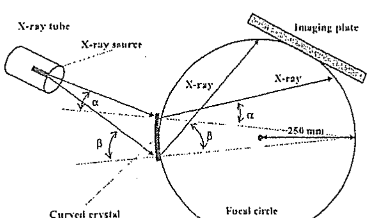


Figure 6: Transmission-type spectrometer with a lithium fluoride curved crystal and an imaging plate.

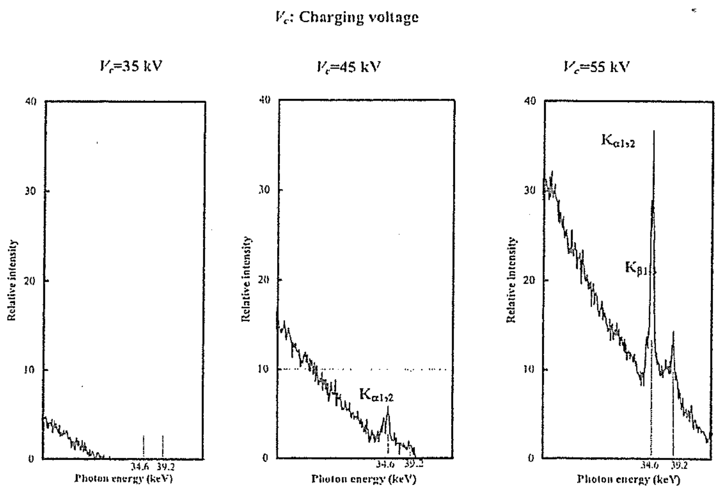


Figure 7: X-ray spectra from weakly ionized cerium plasma.

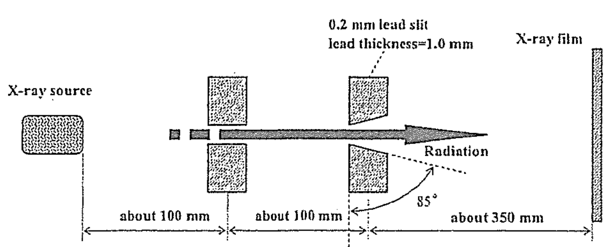


Figure 8: Experimental setup for measuring x-ray divergence using two lead slits.

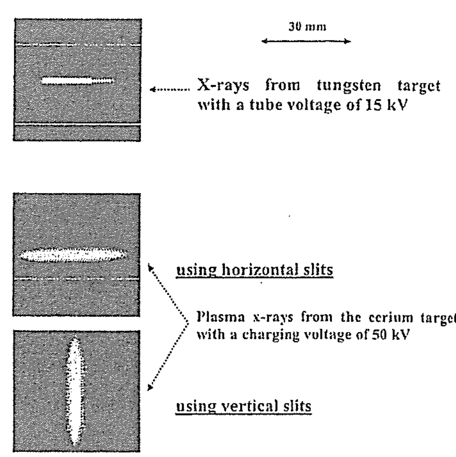


Figure 9: X-ray divergence by two lead slits.

4. ANGIOGRAPHY

The plasma angiography was performed by the CR system without using a monochromatic filter, and the distance between the x-ray source and the imaging plate was 1.2 m.

Firstly, rough measurements of image resolution were made using wires. Figure 10 shows radiograms of 50 μm-diameter tungsten wires coiled around a pipe and a rod made of polymethyl methacrylate (PMMA) with a charging voltage of 55 kV. Although the image contrast increased using the pipe, 50 μm-diameter wires could be observed.

The image of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 11. This image was taken with a charging voltage of 55 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.

Angiograms of rabbit hearts are shown in Fig. 12. These two images were obtained using iodine and cerium microspheres of 20 μm, respectively, with a charging voltage of 55 kV. In case where the cerium spheres were employed, the coronary arteries were barely visible. Figure 13 shows an angiogram of the external ear of a rabbit using iodine spheres with a charging voltage of 55 kV, and fine blood vessels of about 50 μm are clearly visible. In angiography of a larger heart extracted from a dog, using iodine spheres, a PMMA plate was set in front of heart facing x-ray source, and image contrast of coronary arteries increased with increases in the plate thickness (Fig. 14).

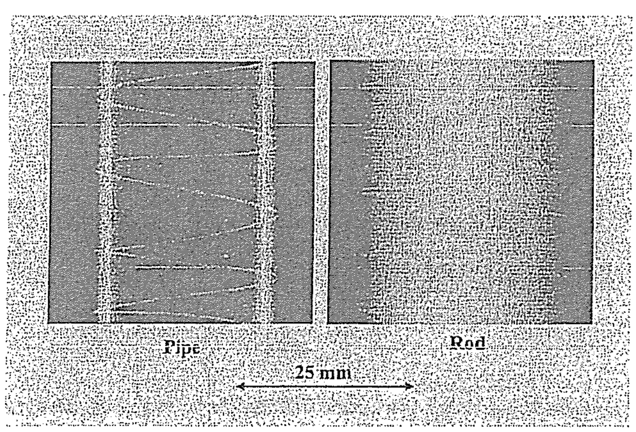


Figure 10: Radiograms of tungsten wires of 50 μm in diameter coiled around pie and a rod made of PMMA.

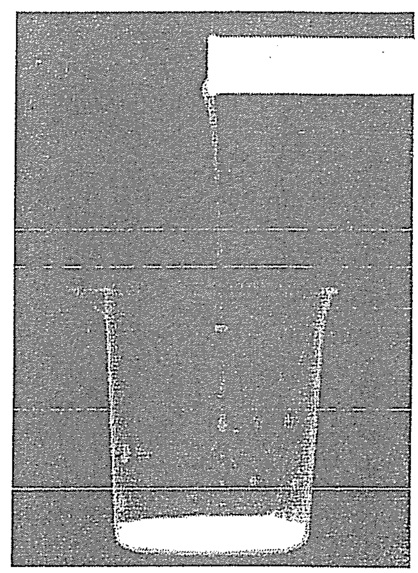


Figure 11: Radiogram of water falling into a polypropylene beaker from a glass test tube.

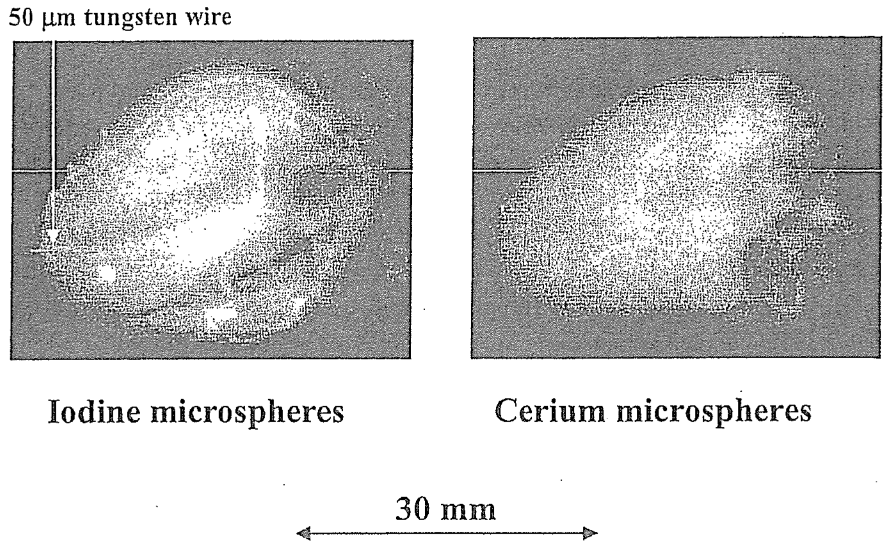


Figure 12: Angiograms of rabbit hearts using iodine and cerium microspheres.

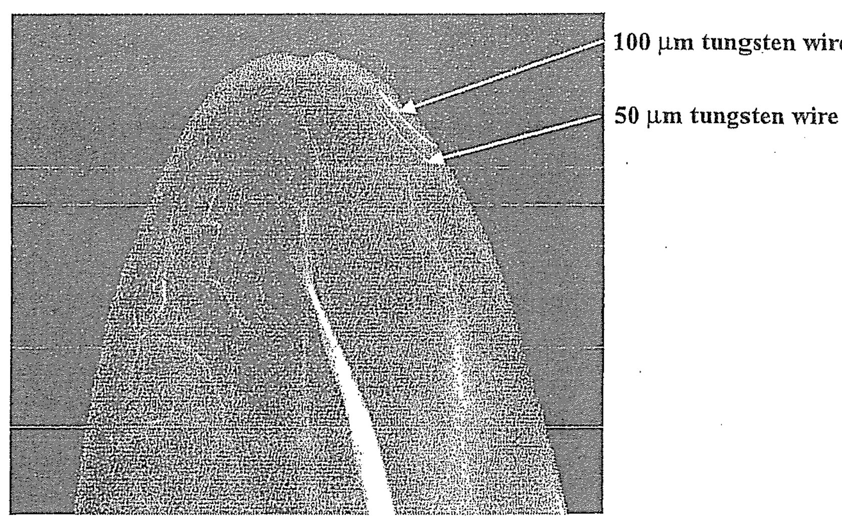


Figure 13: Angiograms of the external ear of a rabbit.

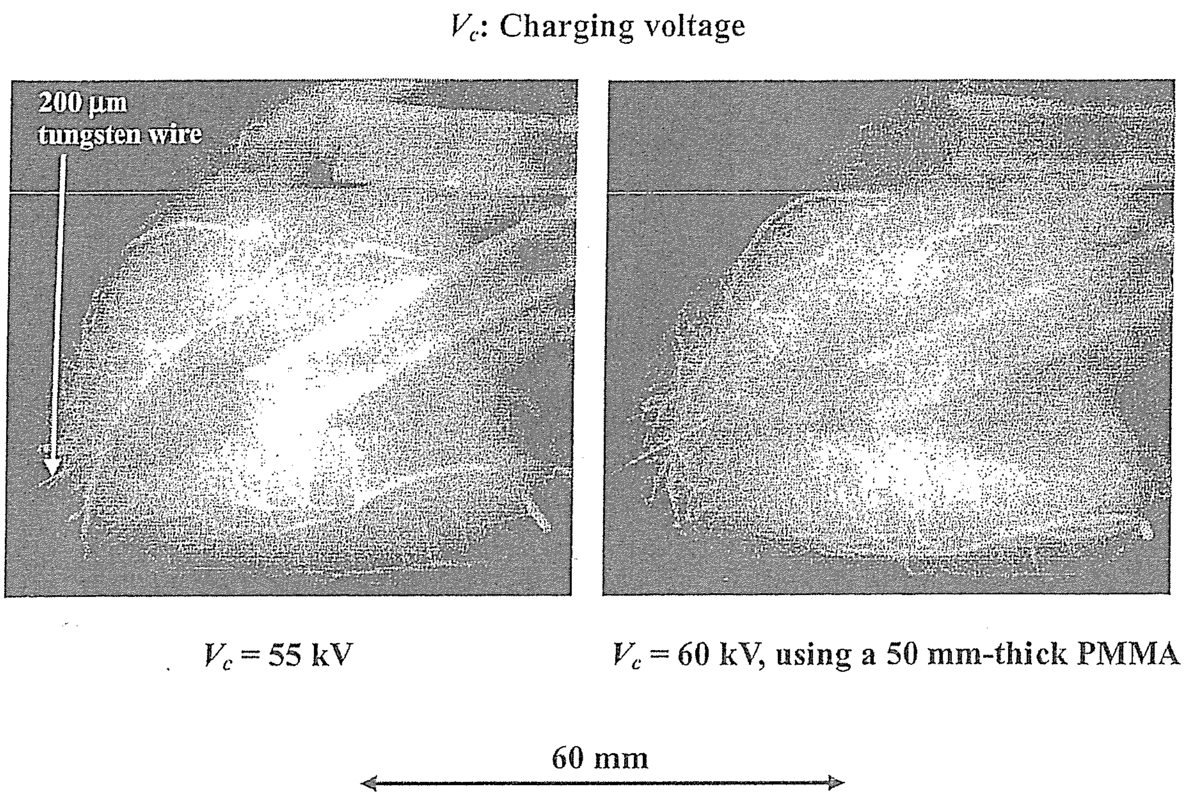


Figure 14: Angiograms of an extracted heart of a dog.

5. DISCUSSION

Cerium is a rare earth element and has a high reactivity. However, the average photon energy of K_{α} lines is 34.566 keV, and iodine spheres with a K-absorption edge of 33.155 keV absorb the lines easily (Fig. 15). Next, since the spheres easily transmit bremsstrahlung x-rays with energies of lower than the edge, it is important that the rays be absorbed as much as possible before angiography in order to increase the image contrast.

In an earlier experiment using a copper target,[23] bremsstrahlung x-rays were hardly observed at all, and we confirmed the irradiation of quite sharp and intense K-series characteristic x-rays such as lasers. In the present work, although we confirmed intense characteristic x-rays with a higher charging voltage, bremsstrahlung x-rays were detected, since the bremsstrahlung intensity is proportional to the atomic number of the target element. Therefore, the condenser charging voltage should be raised as high as possible to increase the characteristic x-ray intensity. In order to decrease emission of bremsstrahlung x-rays from the carbon target holder, the target length should also be set as long as possible.

In this research, we obtained sufficient x-ray intensity per pulse for CR radiography, and the generator produced high-dose-rate plasma x-rays of approximately 80 C/kg·s at 1.0 m with a charging voltage of 55 kV. In addition, because the x-ray intensity increases with increases in the electrostatic energy in the main discharge condenser, the flash x-rays from weakly ionized linear cerium plasma can be employed to perform high-speed angiography for cardiovascular disease.

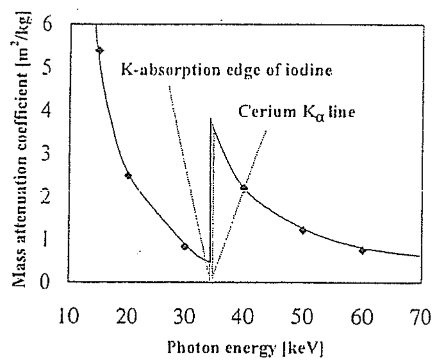


Figure 15: Relation between the mass attenuation coefficient of iodine and the average photon energy of cerium K_α lines.

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Weakly ionized plasma flash x-ray generator and its distinctive characteristics

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ABSTRACT

In the plasma flash x-ray generator, a high-voltage main condenser of approximately 200 nF is charged up to 50 kV by a power supply, and electric charges in the condenser are discharged to an x-ray tube after triggering the cathode electrode. The flash x-rays are then produced. The x-ray tube is a demountable triode that is connected to a turbo molecular pump with a pressure of approximately 1 mPa. As electron flows from the cathode electrode are roughly converged to a rod copper target of 3.0 mm in diameter by the electric field in the x-ray tube, weakly ionized linear plasma, which consists of copper ions and electrons, forms by target evaporation. 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 increased. The K-series lines were quite sharp and intense, and hardly any bremsstrahlung rays were detected. The x-ray pulse widths were approximately 700 ns, and the time-integrated x-ray intensity had a value of approximately 30 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, K-series characteristic x-rays, monochromatic x-rays, x-ray divergence, rectilinear power

1. INTRODUCTION

Flash x-rays have been produced by several different methods, and various generators have been developed corresponding to specific radiographic objectives.[1-3] Currently, the maximum photon energy has been increased to approximately 1 MeV using multiple-stage Marx pulse generators[1,2] in order to produce hard x-rays for military studies. In soft x-ray generators,[4-8] high-intensity single generators with large capacity condensers were originally developed. Subsequently, repetitive generators[9-12] have been developed, and the repetition rate has been increased to sub-kilohertz using a cold-cathode triode.

Recently, soft x-ray lasers have been produced by a gas-discharge capillary,[13-16] 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.

By forming weakly ionized linear plasma[17-21] using plate and rod targets, we confirmed irradiation of intense K-series characteristic x-rays from the plasma axial direction. In these experiments, because we employed a transmission-type x-ray spectrometer utilizing an x-ray film, it was difficult to determine the relative intensities of the characteristic x-rays. In former experiments, because we have succeeded in producing fairly intense and sharp K-series characteristic x-rays, monochromatic x-rays should be produced using a filter.

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

2. GENERATOR

2.1 High-voltage circuit

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 turbo-molecular vacuum 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 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 turbo-molecular pump with a pressure of approximately 1 mPa (Fig. 2). This tube consists of the following major parts: a pipe-shaped carbon 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 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 electric field in the tube, evaporation leads to the formation of a weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

2.3 Principle of characteristic x-ray irradiation

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x-rays (Fig. 3). 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 direction opposite that of electron acceleration, intense characteristic x-rays are generated from the plasma-axial direction.

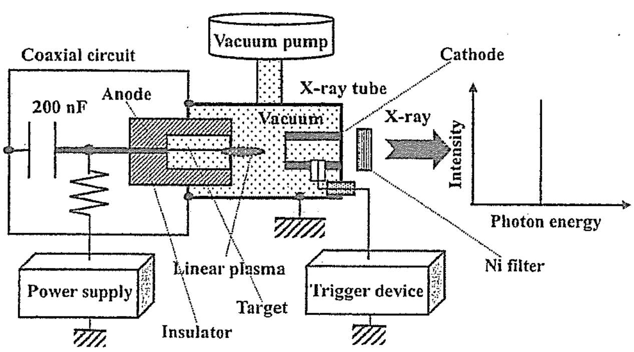

Figure 1: Block diagram of the high-intensity plasma flash x-ray generator.

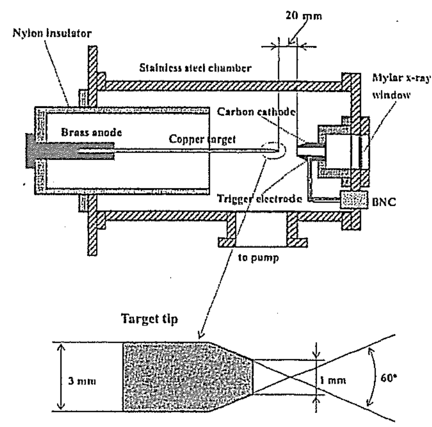

Figure 2: Schematic drawing of the flash x-ray tube with a rod target.

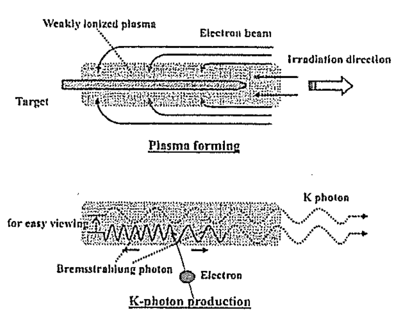

Figure 3: K-photon irradiation from the plasma.

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 for 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 using a 10 μm-thick monochromatic copper filter (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 per pulse measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 utilizing MSO-S elements without energy compensation) had a value of about 30 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

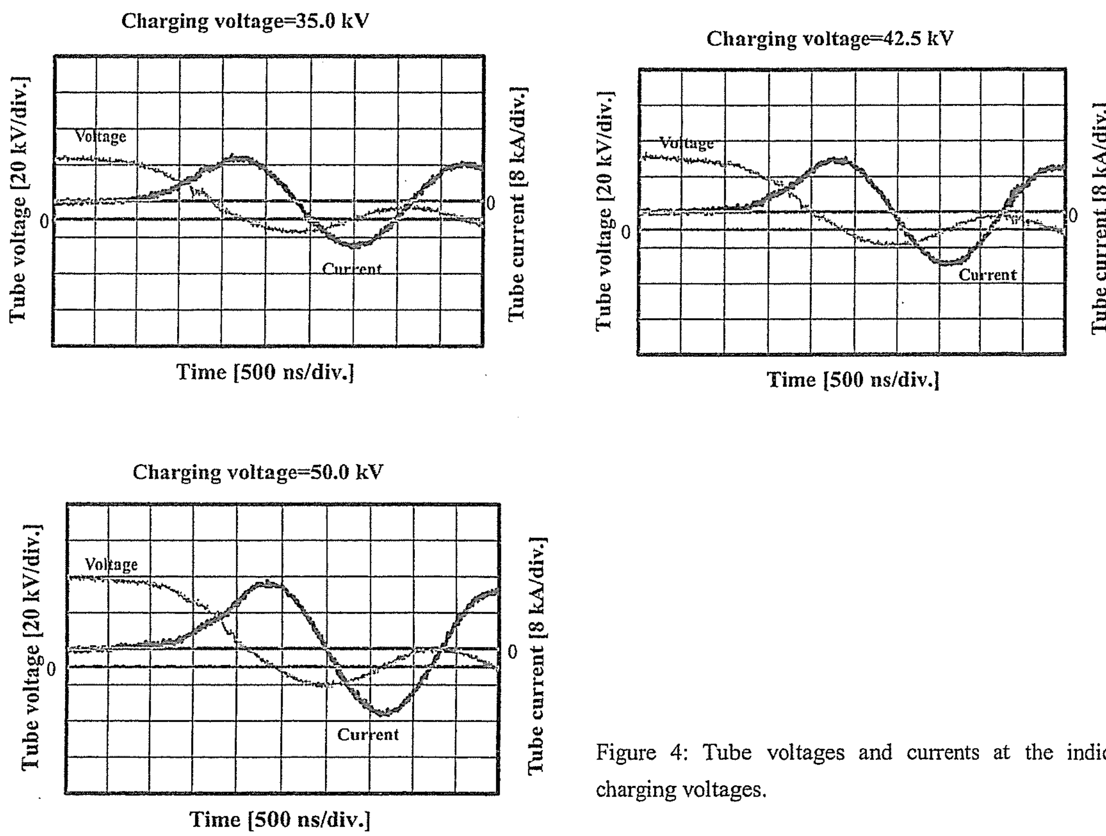

Figure 4: Tube voltages and currents at the indicated charging voltages.

3.3 X-ray source

In order to measure images of the plasma x-ray source, we employed a pinhole camera with a hole diameter of 100 μm (Fig. 6). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased.

3.4 X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer (Fig. 7) with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[22] (Konica Regius 150) with a wide dynamic range, using the filter, and relative x-ray intensity was calculated from Dicom digital data. Figure 8 shows measured spectra from the copper target using the filter. In fact, we observed sharp lines of K-series characteristic x-rays such as lasers, while bremsstrahlung rays were hardly detected at all. The characteristic x-ray intensity of the K_α line substantially increased with corresponding increases in the charging voltage, and the K_β line was absorbed by the filter.

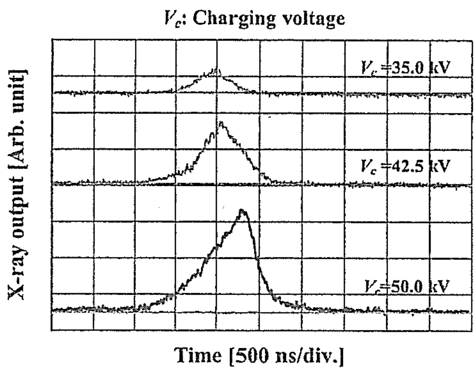

Figure 5: X-ray outputs measured by a plastic scintillator with changes in the charging voltage.

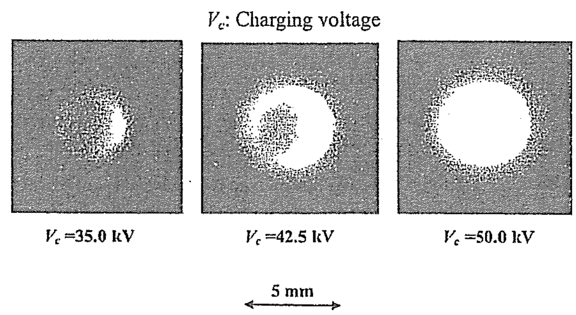

Figure 6: Images of the plasma x-ray source measured by a pinhole of 100 μm from the plasma axial direction.

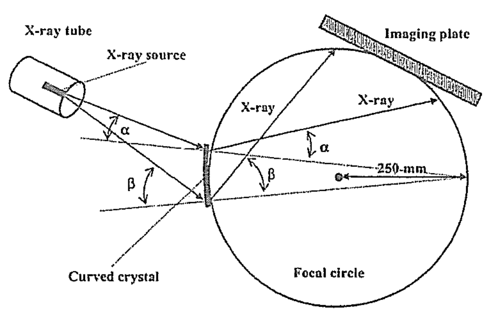

Figure 7: Transmission-type spectrometer with a lithium fluoride curved crystal and an imaging plate.

3.5 X-ray divergence by slits

In order to ascertain the difference in characteristics between x-rays from a conventional tube and these from the plasma tube, we employed two lead slits in order to measure the divergence of the x-rays (Fig. 9). As compared with incoherent x-rays from a conventional tube with a tungsten target, the characteristic x-rays from the linear plasma were diffused greatly after passing through the two slits (Fig. 10).

3.6 Rectilinear power

Figure 11 shows the experimental setup for measuring the rectilinear power of the K_α lines from a conventional tube and that from the plasma tube using the spectrometer previously described. In this experiment, we measured the coefficient (I_k/I_t) of peak diffraction intensity of K_α (I_k) to transmission intensity (I_t). In the case where the conventional tube was used, we employed the filter with a tube voltage of 17 kV. When the charging voltage was increased, the linear plasma grew, and the I_k/I_t decreased to approximately 0.004. As compared with a value of 0.009 obtained by the conventional tube, the rectilinear power may be increased, because the values from the plasma were approximately halved.

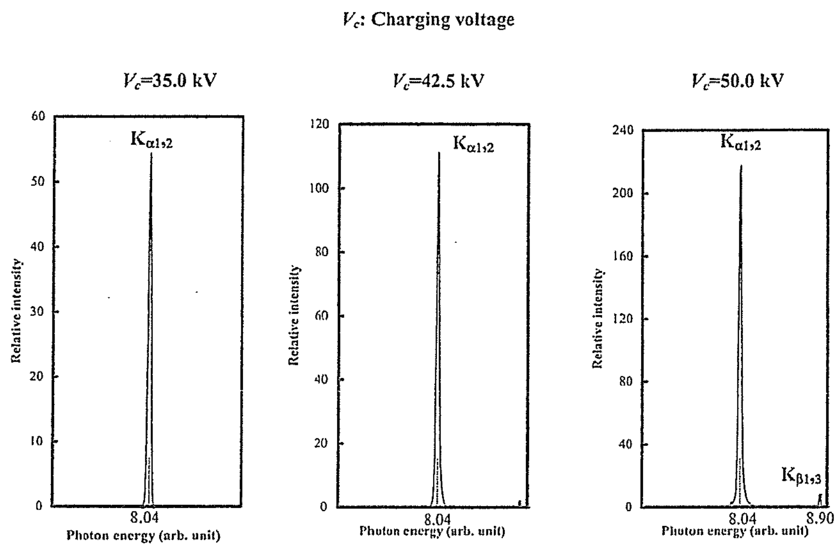

Figure 8: X-ray spectra from weakly ionized copper plasma according to changes in the charging voltage and to insertion of a nickel monochromatic filter.

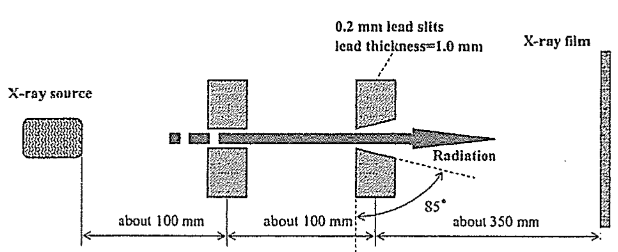

Figure 9: Experimental setup for measuring x-ray divergence using two lead slits.

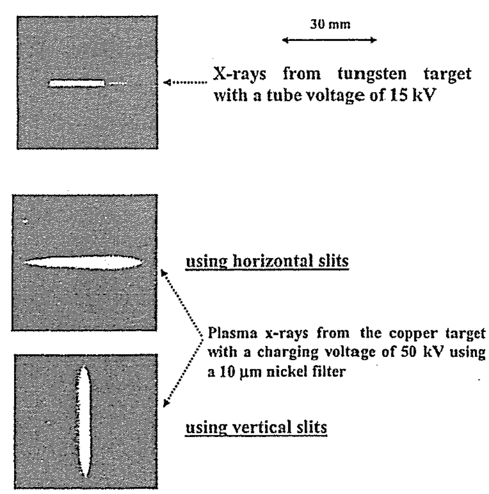

Figure 10: X-ray divergence with two lead slits.

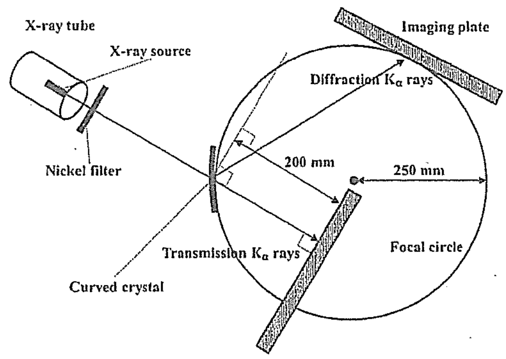

Figure 11: Experimental setup for roughly determining the rectilinear power of the characteristic K_α lines.

4. RADIOGRAPHY

The plasma radiography was performed by the CR system without using the 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 12 shows radiograms of 50 μm-diameter tungsten wires coiled around a pipe and a rod made of polymethyl methacrylate with a charging voltage of 50 kV. Although the image contrast increased using the pipe, 50 μm-diameter wires could be observed.

The image of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 13. This image was taken with a charging voltage of 45 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 14 shows an angiogram of a rabbit heart; iodine-based microspheres of 20 μm in diameter were used with a charging voltage of 50 kV, and fine blood vessels of about 100 μm were visible.

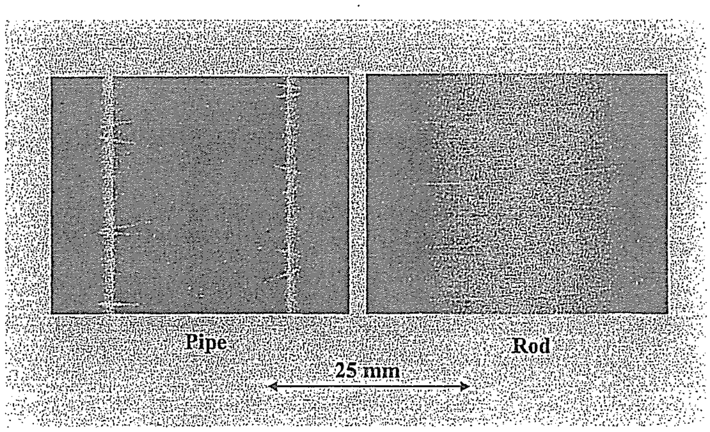

Figure 12: Radiograms of tungsten wires of 50 μm in diameter coiled around a pipe and a rod made of polymethyl methacrylate.

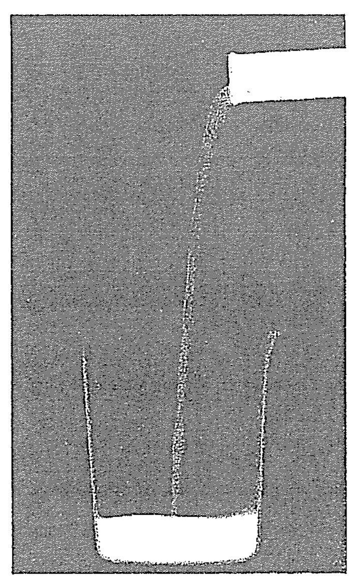

Figure 13: Radiogram of water falling into a polypropylene beaker from a glass test tube.

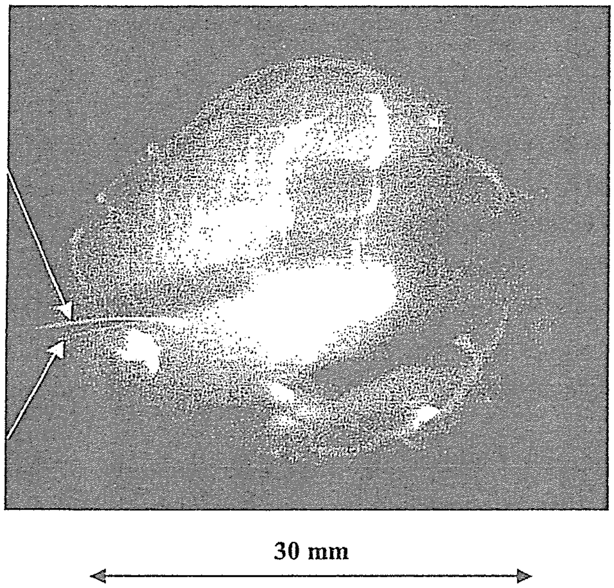

Figure 14: Angiograms of a rabbit heart.

5. DISCUSSION

Concerning the spectrum measurement, we obtained fairly intense and sharp K_{α} lines from a weakly ionized linear plasma x-ray source by absorbing K_{β} lines using the monochromatic filter. In fact, these rays were diffused after passing through slits, and this x-ray divergence mechanism has to be solved clearly. Because the diffracting intensity rate decreases with increases in the charging voltage, the rectilinear power may be increased.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography using a monochromatic filter, and the generator produced high-count-rate monochromatic photons as compared with the synchrotron monochromatic photons. 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 micro angiography[23] and parallel radiography[24,25] using an x-ray lens, will be possible.

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