

# Intense clean characteristic flash x-ray irradiation from an evaporating molybdenum diode

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**Abstract.** In a 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 discharge. 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. Because bremsstrahlung rays are not emitted in the opposite direction of that of electron trajectory, clean molybdenum K-series characteristic x-rays can be produced without using a filter. When the charging voltage is increased, the K-series characteristic x-ray intensities of molybdenum increase. The K lines are clean and intense, and hardly any bremsstrahlung rays are detected. The x-ray pulse widths are approximately 100 ns, and the time-integrated x-ray intensity has a value of approximately 500  $\mu$ Gy per pulse at 1.0 m from the x-ray source, with a charging voltage of 80 kV. © 2007 Society of Photo-Optical Instrumentation Engineers.  
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**Subject terms:** flash x-ray; energy-selective radiography; characteristic x-rays; quasi-monochromatic x-rays; bremsstrahlung x-ray distribution.

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## 1 Introduction

In recent years, there have been several investigations dealing with the production of monochromatic x-rays in radiology and cardiology. Particularly, monochromatic parallel beams using synchrotrons have been employed to perform enhanced K-edge angiography<sup>1,2</sup> and x-ray phase imaging.<sup>3,4</sup> In angiography, parallel beams with photon energies of approximately 35 keV have been employed, since these beams are absorbed effectively by an iodine-based contrast medium. Subsequently, in cases where phase imaging is employed, the spatial resolution can be improved, and the number of tissues that can be observed using x-rays increases.

We have developed several different soft flash x-ray generators<sup>5-11</sup> with photon energy of less than 150 keV corresponding to specific radiographic objectives, and a major goal in our research is the development of an intense and clean monochromatic x-ray generator that can impact applications with medical radiography. Recently, we have succeeded in producing intense K-series characteristic x-rays from the axial direction of linearly evaporating targets.<sup>12-16</sup> In metal vapor, bremsstrahlung spectra with photon energies of higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x-rays. The vapor then transmits the fluorescent rays easily. However, the bremsstrahlung x-rays are produced using a molybdenum target,<sup>12</sup> since high-photon-energy bremsstrahlung x-rays are not absorbed effectively in the linear vapor.

To produce clean characteristic x-rays of molybdenum, silver, cerium, ytterbium, and tungsten, we have developed a compact and weak flash x-ray generator,<sup>17</sup> and succeeded in producing clean molybdenum K-series characteristic x-rays of approximately  $1 \times 10^7$  photons/cm<sup>2</sup> at 1.0 m per pulse using the angle dependence of bremsstrahlung x-rays, since bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory. Therefore, the K photons should be maximized by increasing both the tube voltage and current, and monochromatic K $\alpha$  rays are selected using a zirconium filter.<sup>18</sup> Furthermore, both the bremsstrahlung and characteristic x-rays are produced in a metal vapor, and the vapor transmits K-series characteristic x-rays easily. Thus, we are very interested in the x-ray characteristics of a diode with an evaporating target formed by increasing the electrostatic energy in a high-voltage condenser.

In this work, we developed a new flash x-ray generator utilizing a ring-cathode molybdenum diode, used to perform a preliminary experiment for generating intense and clean K-series characteristic x-rays from an evaporated molybdenum target tip utilizing the angular dependence of the bremsstrahlung x-ray distribution.

## 2 Generator

### 2.1 High-Voltage Circuit

Figure 1 shows a block diagram of an intense 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 thyatron pulse generator as a trigger device, and a flash x-ray tube. In this

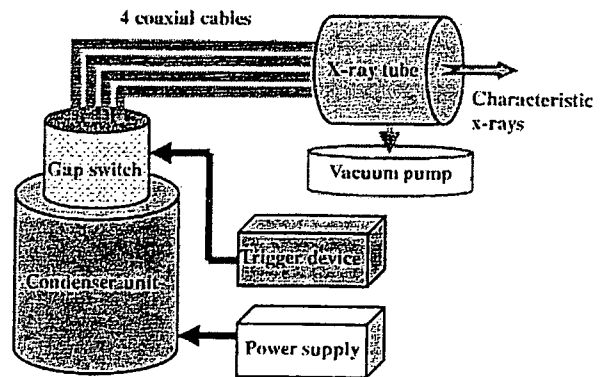


Fig. 1 Block diagram of the intense characteristic flash x-ray generator with a ring-cathode molybdenum diode.

generator, a four-cable transmission line is employed to increase maximum tube voltage using high-voltage reflection and to decrease the impedance of the generator. 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 (Fig. 2).

### 2.2 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 molybdenum 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, the vapor x-ray source forms at the solid target tip. Because bremsstrahlung rays are not emitted in the opposite direction to that of the electron trajectory (Fig. 4), clean molybdenum K-series characteristic x-rays can be produced without using a molybdenum filter.

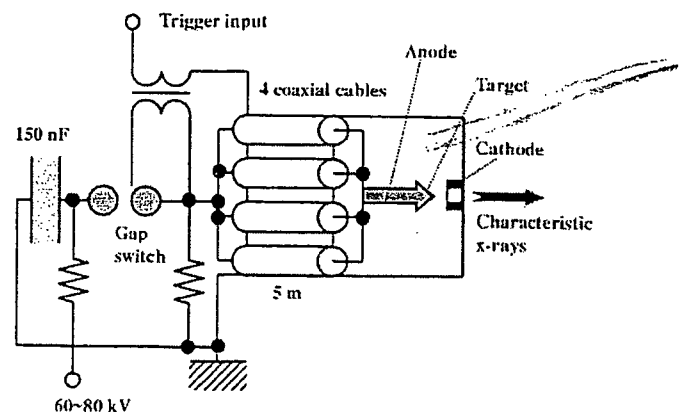


Fig. 2 Circuit diagram of the flash x-ray generator utilizing a coaxial transmission line.

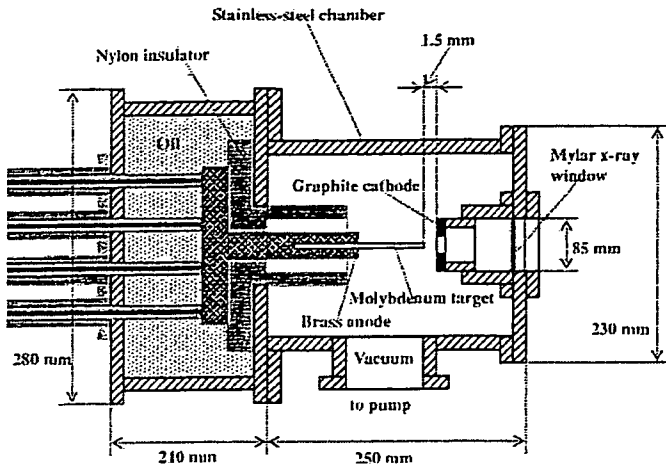


Fig. 3 Schematic drawing of the flash x-ray tube with a rod-shaped molybdenum target and a ring graphite cathode.

### 3 Characteristics

#### 3.1 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. The voltage and current roughly display damped oscillations. When the charging voltage is increased, both the maximum tube voltage and current increase. At a charging voltage of 80 kV, the estimated maximum values of the tube voltage and current are approximately 160 kV (two times the charging voltage) and 40 kA, respectively.

#### 3.2 X-Ray Output

The x-ray output pulse was detected using a combination of a plastic scintillator and photomultiplier (Fig. 5). Due to photoelectric transfer characteristics, the pulse height was not proportional to the x-ray intensity. The x-ray pulse height increased with corresponding increases in the charging

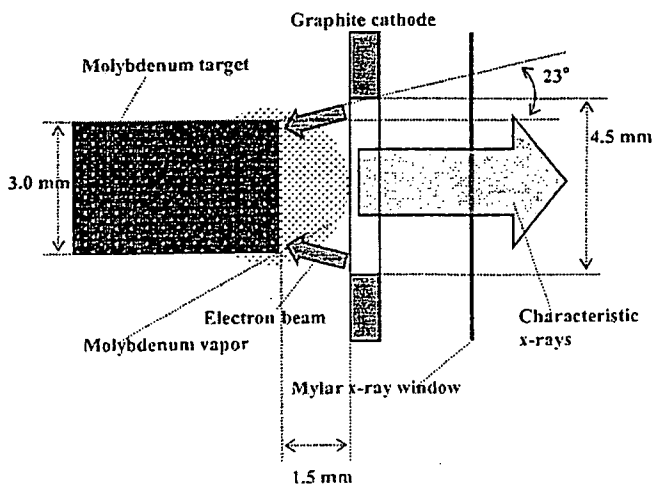


Fig. 4 Irradiation of characteristic x-rays using the angle dependence of bremsstrahlung x-ray intensity distribution. Bremsstrahlung rays are not emitted in the opposite direction of that of electron trajectory.

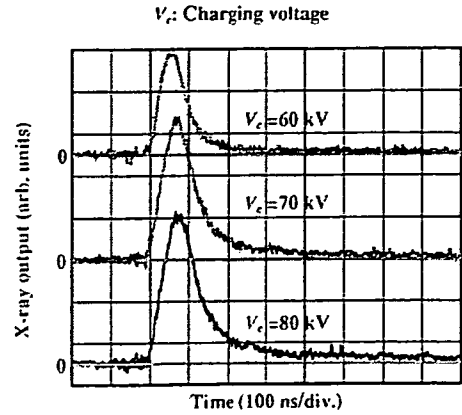


Fig. 5 X-ray outputs detected using a combination of a plastic scintillator and photomultiplier.

ing 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 500  $\mu\text{Gy}$  per pulse at 1.0 m from the x-ray source, with a charging voltage of 80 kV.

#### 3.3 X-Ray Source

To observe the characteristic x-ray source, we employed a 100- $\mu\text{m}$ -diam pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 6). When the charging voltage was increased, both spot dimension and intensity increased. Because the maximum diameter was larger than the target diameter of 3.0 mm, the vapor x-ray source formed at the solid target tip.

#### 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 by a computed radiography (CR) system (Konica Regius 150)<sup>19</sup> with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Using this spectrometer, it is easy to measure low intensity bremsstrahlung x-rays.<sup>12,20</sup> Figure

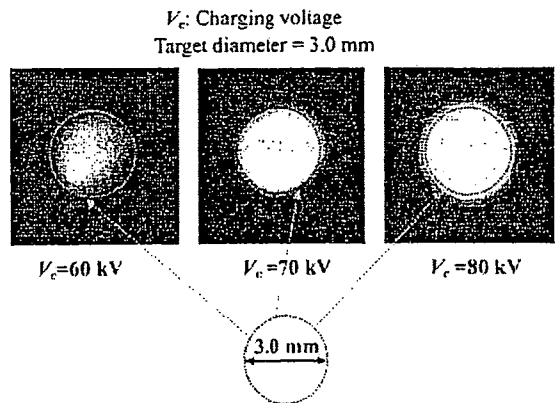


Fig. 6 Images of the characteristic x-ray source measured using a pinhole camera with changes in the charging voltage.

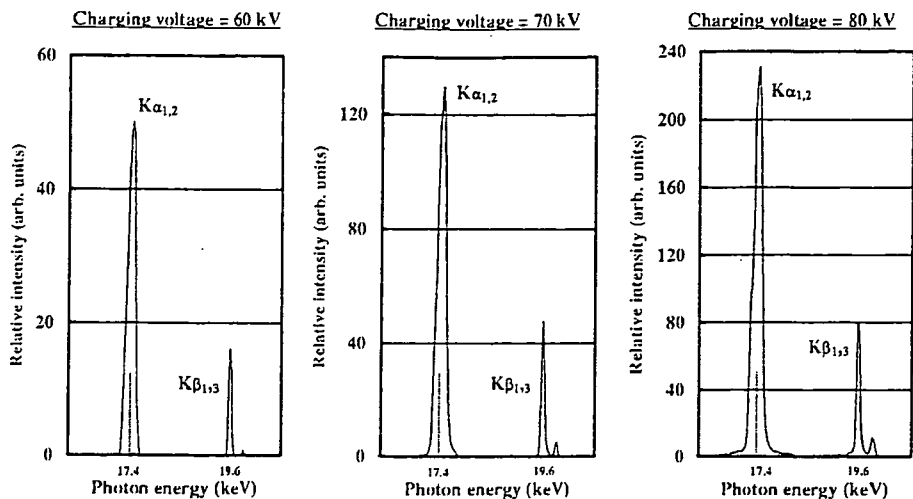


Fig. 7 X-ray spectra from the molybdenum target. The spectra were measured using a transmission-type spectrometer with a lithium fluoride curved crystal.

7 shows measured spectra from the molybdenum target. We observed clean K-series lines, while bremsstrahlung rays were hardly detected at all. The characteristic x-ray intensity substantially increased with increases in the charging voltage.

#### 4 Flash Radiography

The quasi-monochromatic flash radiography was performed by the CR system at 1.2 m from the x-ray source, and the distance between the radiographic object and the imaging plate of the CR was 0 m. First, rough measurements of spatial resolution were made using wires. Figure 8 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate with a charging voltage ( $V_c$ ) of 70 kV. Although the image contrast increased with increases in the wire diameter, a 50- $\mu$ m-diam wire could be observed.

Figure 9 shows a radiogram of a vertebra with a  $V_c$  of 70 kV; fine structures in the vertebra were observed. Next, the image of water spouted from an injector is shown in Fig. 10. This image was taken with the slight addition of an iodine-based contrast medium with a  $V_c$  of 80 kV. Because the x-ray duration was about 100 ns, the stop-motion image of water could be obtained. Figures 11 and 12 show angio-

grams of a rabbit heart ( $V_c=70$  kV) and thigh ( $V_c=80$  kV), respectively. In angiography, iodine-based microspheres 15  $\mu$ m in diameter were used, and fine blood vessels of about 100  $\mu$ m were visible.

#### 5 Discussion and Conclusions

Concerning spectrum measurement, we obtain fairly clean molybdenum  $K\alpha$  (17.4 keV) and  $K\beta$  (19.6 keV) lines without filtering, because the metal vapor at the target tip has a strong monochromatic effect.<sup>21</sup> Therefore, we are very interested in the measurement of the characteristic rays from nickel, copper, silver, cerium, and tungsten targets; the target element should be selected corresponding to the radiographic objectives. In a medical application, K-series characteristic x-rays of cerium are absorbed effec-

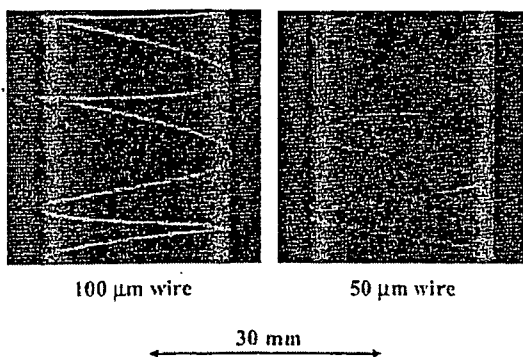


Fig. 8 Radiograms of tungsten wires of 50 and 100  $\mu$ m in diameter coiled around a pipe made of polymethyl methacrylate. A 50- $\mu$ m-diam wire could be observed.

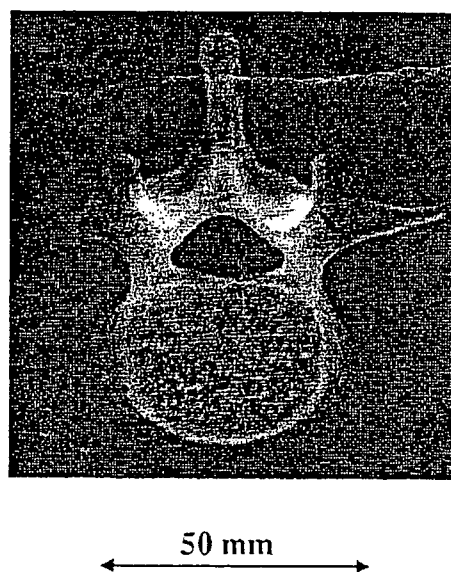


Fig. 9 Radiogram of vertebra. Fine structures of the vertebra were visible.

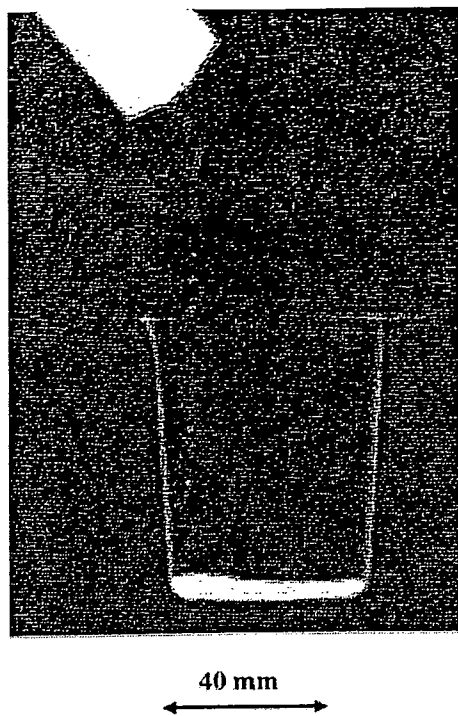


Fig. 10 Radiogram of water spouted from an injector. The stop-motion image of water was obtained by monochromatic flash radiography.

tively by an iodine-based contrast medium with a K-edge of 33.2 keV, and enhanced K-edge angiography can be performed.

In this research, the generator-produced instantaneous number of K photons is approximately  $2 \times 10^8$  photons/cm<sup>2</sup> per pulse at 1.0 m from the source. Subsequently, the intensity can be increased by increasing the electrostatic energy in the condenser, and monochromatic K $\alpha$  lines are selected using a zirconium filter with a K-edge of 17.9 keV.

Compared with a triode, the photon energy of K-series characteristic x-rays can be increased, and the pulse widths are shorter. In addition, because sufficient x-ray intensities for CR radiography have been obtained with high dose rates, we plan to design a high-speed photon-counting radiography system to decrease noise from radiograms.

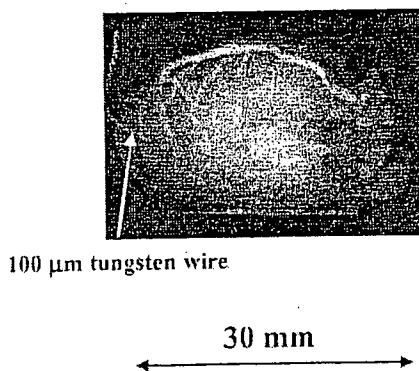


Fig. 11 Angiogram of rabbit heart. Fine blood vessels approximately 100  $\mu$ m in diameter were visible.

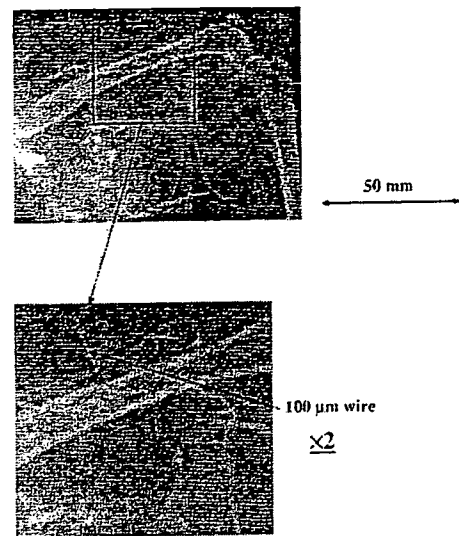


Fig. 12 Angiograms of rabbit thigh. We could see fine blood vessels approximately 100  $\mu$ m.

Using this x-ray generator, demonstrations of various monochromatic high-speed radiography will be accomplished easily, since the target element can be changed easily. In addition, steady-state quasi-monochromatic x-ray generators for medical radiography will be developed soon using angular dependence of the bremsstrahlung x-ray intensity distribution. In cases where monochromatic cone beams are employed (because the irradiation field can be increased easily as compared with monochromatic parallel beams using a synchrotron), high-photon-energy enhanced K-edge angiography using a gadolinium-based contrast medium with a K edge of 50.2 keV can be performed, and the absorbed dose during angiography can be decreased easily.

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#### References

1. H. Mori, K. Hyodo, E. Tanaka, M. U. Mohammed, A. Yamakawa, Y. Shinozaki, H. Nakazawa, Y. Tanaka, T. Sekka, Y. Iwata, S. Honda, K. Umetani, H. Ueki, T. Yokoyama, K. Tanioka, M. Kubota, H. Hosaka, N. Ishizawa, and M. Ando, "Small-vessel radiography in situ with monochromatic synchrotron radiation," *Radiology* 201, 173–177 (1996).
2. K. Hyodo, M. Ando, Y. Oku, S. Yamamoto, T. Takeda, Y. Itai, S. Ohtsuka, Y. Sugishita, and J. Tada, "Development of a two-dimensional imaging system for clinical applications of intravenous coronary angiography using intense synchrotron radiation produced by a multipole wiggler," *J. Synchrotron Radiat.* 5, 1123–1126 (1998).
3. A. Momose, T. Takeda, Y. Itai, and K. Hirano, "Phase-contrast x-ray computed tomography for observing biological soft tissues," *Nat. Med.* 2, 473–475 (1996).
4. M. Ando, A. Maksimenko, H. Sugiyama, W. Pattanasirivisawa, K.

- Hyodo, and C. Uyama, "A simple x-ray dark- and bright- field imaging using achromatic Laue optics," *Jpn. J. Appl. Phys., Part 2* 41, L1016-L1018 (2002).
5. E. Sato, H. Isobe, and F. Hoshino, "High intensity flash x-ray apparatus for biomedical radiography," *Rev. Sci. Instrum.* 57, 1399-1408 (1986).
  6. E. Sato, S. Kimura, S. Kawasaki, H. Isobe, K. Takahashi, Y. Tamakawa, and T. Yanagisawa, "Repetitive flash x-ray generator utilizing a simple diode with a new type of energy-selective function," *Rev. Sci. Instrum.* 61, 2343-2348 (1990).
  7. E. Sato, M. Sagae, K. Takahashi, T. Oizumi, H. Ojima, K. Takayama, Y. Tamakawa, T. Yanagisawa, A. Fujiwara, and K. Mitoya, "High-speed soft x-ray generators in biomedicine," *Proc. SPIE* 2513, 649-667 (1994).
  8. A. Shikoda, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa, and T. Yanagisawa, "Repetitive flash x-ray generator having a high-durability diode driven by a two-cable-type line pulser," *Rev. Sci. Instrum.* 65, 850-856 (1994).
  9. E. Sato, K. Takahashi, M. Sagae, S. Kimura, T. Oizumi, Y. Hayasi, Y. Tamakawa, and T. Yanagisawa, "Sub-kilohertz flash x-ray generator utilizing a glass-enclosed cold-cathode triode," *Med. Biol. Eng. Comput.* 32, 289-294 (1994).
  10. K. Takahashi, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa, and T. Yanagisawa, "Fundamental study on a long-duration flash x-ray generator with a surface-discharge triode," *Jpn. J. Appl. Phys., Part 1* 33, 4146-4151 (1994).
  11. E. Sato, M. Sagae, E. Tanaka, Y. Hayasi, R. Germer, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama, and H. Ido, "Quasi-monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube," *Jpn. J. Appl. Phys., Part 1* 43, 7324-7328 (2004).
  12. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, H. Obara, T. Ichimaru, K. Takayama, and H. Ido, "Irradiation of intense characteristic x-rays from weakly ionized linear molybdenum plasma," *Jpn. J. Med. Phys.* 23, 123-131 (2003).
  13. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, K. Takayama, and H. Ido, "Quasi-monochromatic flash x-ray generator utilizing weakly ionized linear copper plasma," *Rev. Sci. Instrum.* 74, 5236-5240 (2003).
  14. E. Sato, R. Germer, Y. Hayasi, Y. Koorikawa, K. Murakami, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, F. Obara, K. Takahashi, S. Sato, K. Takayama, and H. Ido, "Weakly ionized plasma flash x-ray generator and its distinctive characteristics," *Proc. SPIE* 5196, 383-392 (2003).
  15. E. Sato, Y. Hayasi, R. Germer, H. Obara, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama, and H. Ido, "Sharp characteristic x-ray irradiation from weakly ionized linear plasma," *J. Electron Spectrosc. Relat. Phenom.* 137(40), 713-720 (2004).
  16. E. Sato, E. Tanaka, H. Mori, T. Kawai, S. Sato, and K. Takayama, "Clean monochromatic x-ray irradiation from weakly ionized linear copper plasma," *Opt. Eng.* 44, 049002-1-6, 2005.
  17. E. Sato, M. Sagae, E. Tanaka, Y. Hayasi, R. Germer, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama, and H. Ido, "Quasi-monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube," *Jpn. J. Appl. Phys., Part 1* 43, 7324-7328 (2004).
  18. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama, and H. Ido, "Compact monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube," *Med. Phys.* 32, 49-54 (2005).
  19. E. Sato, K. Sato, and Y. Tamakawa, "Film-less computed radiography system for high-speed imaging," *Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts Sci.* 35, 13-23 (2000).
  20. M. Sagae, E. Sato, E. Tanaka, Y. Hayasi, R. Germer, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama, and H. Ido, "Quasi-monochromatic x-ray generator utilizing graphite cathode diode with transmission-type molybdenum target," *Jpn. J. Appl. Phys., Part 1* 44, 446-449 (2005).
  21. H. Obara, E. Sato, Y. Hayasi, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, T. Ichimaru, K. Takayama, and H. Ido, "Superposition of x-ray spectra using alloy-target plasma triode," *Proc. SPIE* 5920, 59200W-1-8 (2005).

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## Novel monochromatic x-ray generators and their applications to high-speed radiography

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### ABSTRACT

Novel monochromatic x-ray generators and their applications to high-speed radiography are described. The five generators are as follows: a weakly ionized linear plasma x-ray generator, a monochromatic compact flash x-ray generator, a super-fluorescent plasma generator, a cerium x-ray generator using a 3.0-mm-thick aluminum filter, and a 100- $\mu\text{m}$ -focus x-ray generator utilizing the filter. Using the linear plasma generator with a copper target, we observed clean K lines and their harmonics, and soft flash radiography was performed with pulse widths of approximately 500 ns. The compact monochromatic flash x-ray generator produced clean molybdenum K lines easily, and high-speed radiography was performed with pulse widths of approximately 100 ns. Using a steady-state cerium x-ray generator, we performed real-time angiography utilizing an image intensifier and a high-sensitive camera (MLX) made by NAC Image Technology Inc. with a capture time of 1 ms. Finally, real-time magnification radiography was performed by twofold magnification imaging using a 100- $\mu\text{m}$ -focus x-ray generator and the high-sensitive camera.

**Keywords:** flash radiography, high-speed radiography, high-speed angiography, real-time radiography, enhanced K-edge angiography, high-sensitive CCD camera, image intensifier



## 1. INTRODUCTION

Conventional flash x-ray generators utilizing high-voltage condensers have been used in high-speed radiography,<sup>1</sup> and single generators have been employed to perform delayed radiography using a trigger delay device. Subsequently, plural flash x-ray generators can be combined to a multi-tube (anode) flash x-ray system to perform extremely high-repetition-rate radiography and multi-direction radiography at desired times. Subsequently, we have developed several different flash x-ray generators<sup>2-5</sup> with photon energies of lower than 150 keV, and these generators have been employed to soft radiography including biomedical applications.

Stroboscopic x-ray generators<sup>6-8</sup> have been developed to primarily perform single and multi-shot radiography using an x-ray film or a computed radiography (CR) system,<sup>9</sup> therefore high-speed real-time radiography can be achieved with a high-speed camera. Although we have developed three stroboscopic generators, major advantages are as follows: maximum repetition rate of approximately 100 kHz, variable x-ray duration, and low noises. Using a special high-voltage pulse generator, the maximum rate can be increased to 1 MHz or beyond.

Recently, we have developed three monochromatic flash x-ray generators<sup>10-18</sup> in order to produce clean K-series characteristic x-rays. The major goal of these developments is to produce slightly coherent clean K lines by x-ray amplification of spontaneous emission of radiation and by increasing the flux of K lines in the plasma. In view of this situation, we have confirmed the irradiation of clean K lines and their harmonics from weakly ionized linear plasmas of nickel and copper.

To perform iodine K-edge angiography using cone beams, we have developed a steady-state cerium x-ray generator<sup>19-21</sup> and have succeeded in observing fine blood vessels and coronary arteries with high contrasts using cerium K lines. Recently, because an extremely high-sensitive CCD camera (MLX) with variable capture times has been developed by NAC Image Technology Inc., stop-motion images can be easily obtained.

Magnification radiography<sup>22</sup> is useful in order to improve the spatial resolution in digital radiography, and narrow-photon-energy bremsstrahlung x-rays with a peak energy of approximately 35 keV from a microfocus tungsten tube are useful for performing high-contrast high-resolution angiography. In magnification radiography, scattering beams from radiographic objects can be reduced without using a grid, and stop-motion images can be taken using the CCD camera.

In this paper, we introduce novel monochromatic x-ray generators, their distinctive radiographic characteristics, and applications to high-speed radiographies including enhanced K-edge angiography.

## 2. WEAKLY IONIZED LINEAR PLASMA X-RAY GENERATOR

### 2.1 Generator

Figure 1 shows a 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 approximately 200 nF, a turbomolecular pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. The high-voltage main condenser is charged to 50 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode with the trigger device. The plasma flash x-rays are then produced.

The x-ray tube is a demountable cold-cathode triode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa. This tube consists of the following major parts: a hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a brass focusing electrode, a trigger electrode made from copper wire, a stainless steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped copper target 3.0 mm in diameter with a tip angle of 60°. The distance between the target and cathode electrodes is approximately 20 mm, and the trigger electrode is set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by the focusing electrode, evaporation leads to the formation of a weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x-rays. 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.

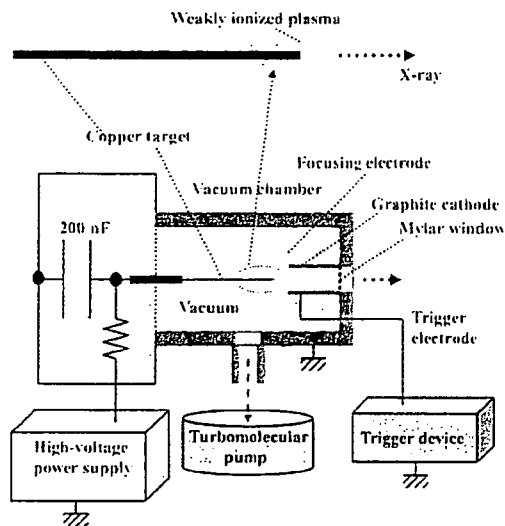


Fig. 1. Block diagram of the weakly ionized linear plasma x-ray generator.

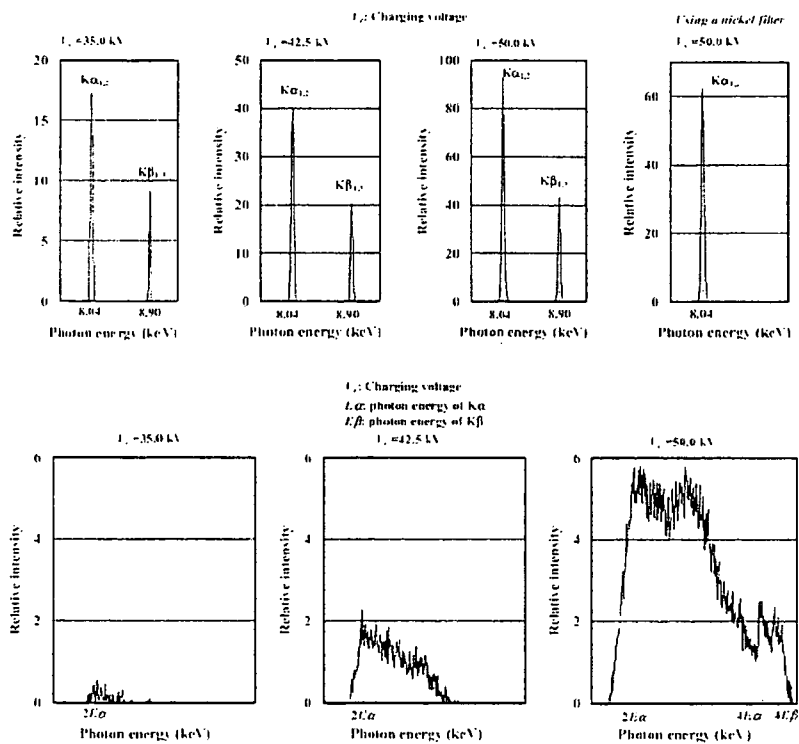


Fig. 2. X-ray spectra from weakly ionized linear copper plasma.

## 2.2 Characteristics

In the flash x-ray generators, the tube voltage and current were measured by a high-voltage divider and a current

transformer, respectively. The tube voltage and current displayed damped oscillations. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 16 kA.

The x-ray pulse widths were approximately 300 ns, and the time-integrated x-ray intensity had a value of approximately 1.5 mGy per pulse at 1.0 m from the x-ray source with a charging voltage of 50 kV.

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 the CR system (Konica Regius 150), and relative x-ray intensity was calculated from Dicom digital data. Figure 2 shows measured spectra from the copper target at the indicated conditions. In fact, we observed clean K lines, and  $K\alpha$  lines were left by absorbing  $K\beta$  lines using a 10- $\mu\text{m}$ -thick nickel filter. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage, and higher harmonic hard x-rays were observed.

### 2.3 High-speed radiography

The plasma radiography was performed by the CR system using the filter. The charging voltage and the distance between the x-ray source and imaging plate were 50 kV and 1.2 m, respectively.

First, rough measurements of spatial resolution were made using wires. Radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate (PMMA) are shown in Fig. 3. 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  $\mu\text{m}$ , a 50- $\mu\text{m}$ -diameter wire could be observed. Figure 4 shows a radiogram of plastic bullets falling into a polypropylene beaker from a plastic test tube. Because the x-ray duration was about 500 ns, the stop-motion image of bullets could be obtained.

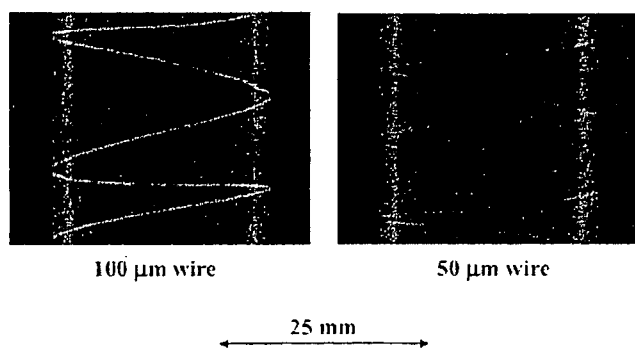


Fig. 3. Radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate (PMMA).

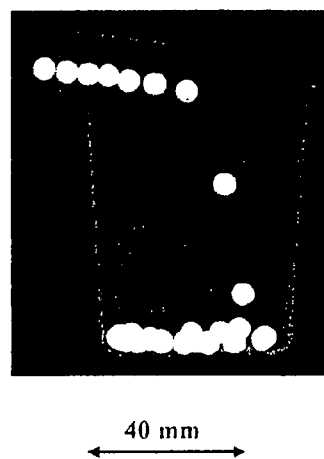


Fig. 4. Radiogram of plastic bullets falling into a polypropylene beaker from a plastic test tube.

## 3. COMPACT MONOCHROMATIC FLASH X-RAY GENERATOR

### 3.1 Generator

Figure 5 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 surge Marx generator with a capacity during main discharge of 425 pF, a thyatron trigger device of the surge generator, a turbomolecular pump, and a flash x-ray tube. Since the electric circuit of the high-voltage pulse generator employs a polarity-inversion two-stage Marx line, 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.

The x-ray tube is a demountable diode type, as illustrated in Fig. 6. This tube is connected to the turbomolecular pump with a pressure of about 1 mPa and consists of the following major devices: a rod-shaped molybdenum 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 1.0 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 trajectory, molybdenum  $K\alpha$  rays can be produced using a 20- $\mu\text{m}$ -thick zirconium K-edge filter.

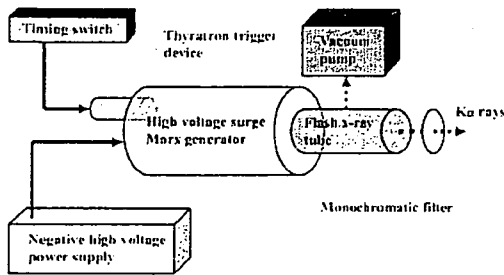


Fig. 5. Block diagram of the compact monochromatic flash x-ray generator.

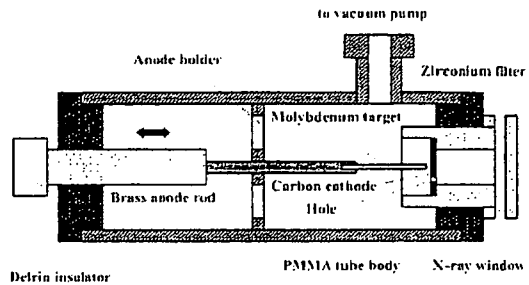


Fig. 6. Structure of the monochromatic flash x-ray tube with a PMMA tube body.

### 3.2 Characteristics

At a charging voltage of  $-70$  kV, the maximum tube voltage and current were 120 kV and 1.0 kA, respectively. The x-ray pulse widths were approximately 70 ns, and the  $K\alpha$  intensity was approximately  $70 \mu\text{Gy}$  per pulse at 0.5 m from the source of 3.0 mm in diameter. In the spectrum measurement, clean molybdenum  $K\alpha$  lines were left using the zirconium filter, and the K-ray intensity substantially increased with increasing the charging voltage (Fig. 7).

### 3.3 High-speed radiography

The monochromatic flash radiography was performed by the CR system at 0.5 m from the x-ray source with the filter, and the charging voltage was  $-70$  kV. The radiogram of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 8. This image was taken with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 100 ns, the stop-motion image of water could be obtained.

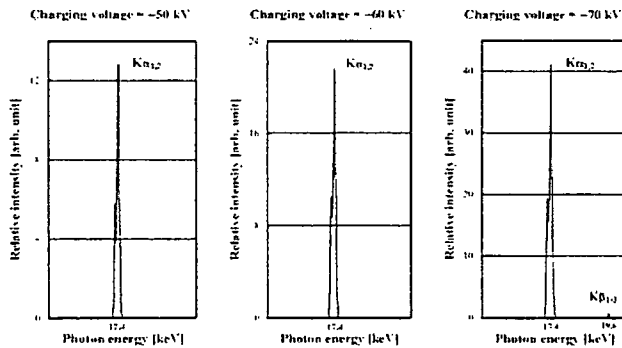


Fig. 7. X-ray spectra from the monochromatic flash x-ray tube with a molybdenum target.

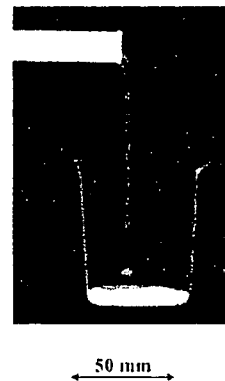


Fig. 8. Radiogram of water falling into a polypropylene beaker from a glass test tube.

## 4. SUPER-FLUORESCENT PLASMA X-RAY GENERATOR

### 4.1 Generator

Figure 9 shows a block diagram of a high-intensity super-fluorescent 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.

The x-ray tube is a demountable cold-cathode diode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa. 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, at the target tip. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory, tungsten  $K\alpha$  lines are left by absorbing  $K\beta$  lines using an ytterbium oxide filter.

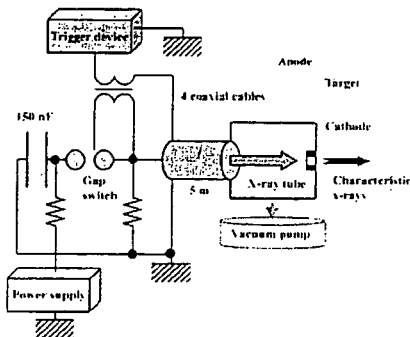


Fig. 9. Block diagram of the high-intensity super-fluorescent plasma flash x-ray generator

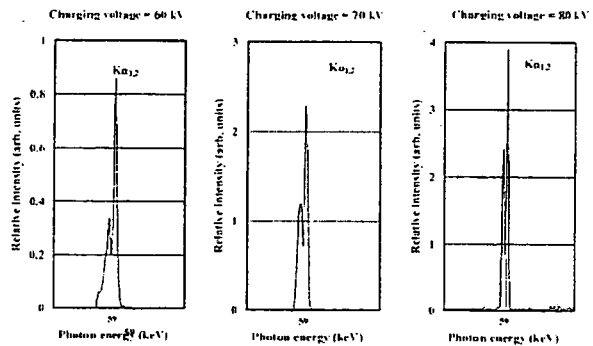


Fig. 10. X-ray spectra from the super-fluorescent plasma x-ray tube with a tungsten target.

### 4.2 Characteristics

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 are approximately 160 kV and 40 kA, respectively. The x-ray pulse widths were approximately 110 ns, and the time-integrated x-ray intensity had a value of approximately 50  $\mu\text{Gy}$  at 1.0 m from the x-ray source with a charging voltage of 80 kV using the filter. When the charging voltage was increased using the filter, the characteristic x-ray intensities of tungsten  $K\alpha$  lines increased. The  $K\alpha$  lines were clean, and hardly any  $K\beta$  lines and bremsstrahlung rays were detected (Fig. 10).

### 4.3 High-speed gadolinium K-edge angiography

Figure 11 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  $K\alpha$  lines is shown just above the gadolinium K-edge. The average photon energy of tungsten  $K\alpha$  lines 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. The flash angiography was performed by the CR system at 1.2 m from the x-ray source, and the charging voltage was 70 kV. Figure 12 shows angiogram of a rabbit head using gadolinium oxide powder, and fine blood vessels of approximately 100  $\mu\text{m}$  were visible.

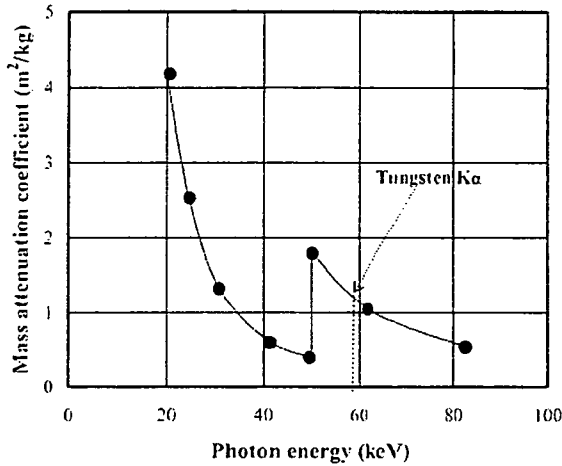


Fig. 11. Mass attenuation coefficients of gadolinium and the average photon energy of the tungsten Kα lines.

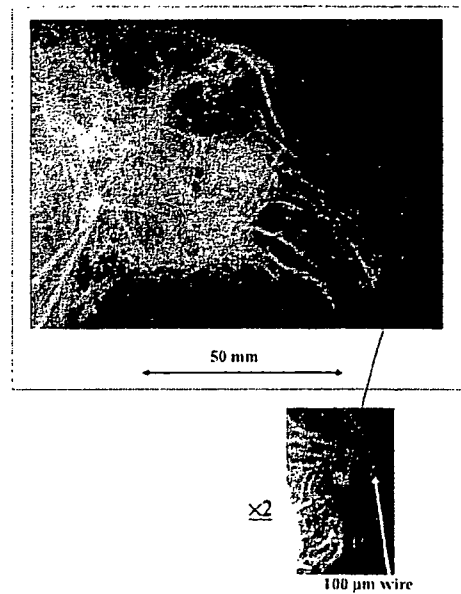


Fig. 12. Angiogram of a rabbit head using gadolinium oxide powder.

## 5. CERIUM X-RAY GENERATOR

### 5.1 Generator

The main circuit for producing x-rays is illustrated in Fig. 13, and employed the Cockcroft-Walton circuit in order to decrease the dimensions of the tube unit. In the x-ray tube, the negative high voltage is applied to the cathode electrode, and the anode (target) is connected to the tube unit case (ground potential) to cool the anode and the target effectively. The filament heating current is supplied by an AC power supply in the controller in conjunction with an insulation transformer. In this experiment, the tube voltage applied was from 45 to 65 kV, and the tube current was regulated to within 0.40 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. Quasi-monochromatic x-rays are produced using a 3.0-mm-thick aluminum filter for absorbing soft bremsstrahlung rays.

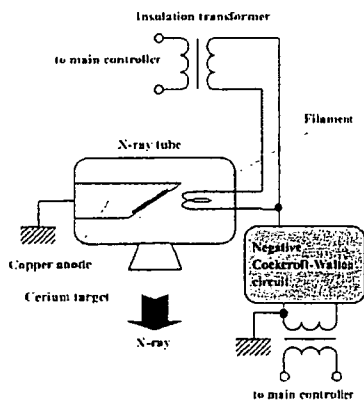


Fig. 13. Main high-voltage transmission line of the cerium x-ray generator.

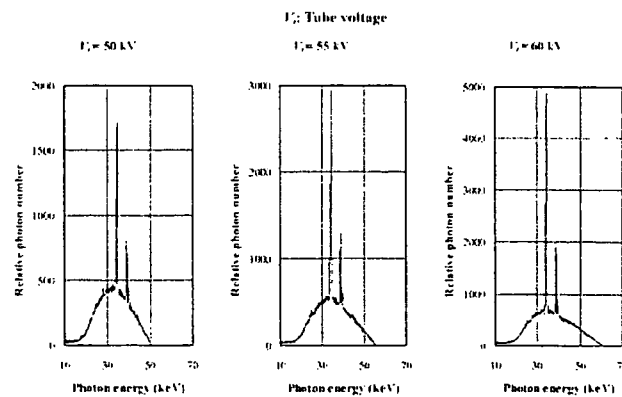


Fig. 14. X-ray spectra using a 3.0-mm-thick aluminum filter with changing the tube voltage.

### 5.2 Characteristics

The maximum tube voltage and current were 65 kV and 0.4 mA, respectively, and the focal-spot sizes were 1.3×0.9 mm. Cerium K-series characteristic x-rays were left using a 3.0 mm-thick aluminum filter (Fig. 14), and the x-ray intensity was 19.9 μGy/s at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.40 mA.

### 5.3 High-speed radiography

Real-time cohesion radiography was performed using an image intensifier (I I) and a high-sensitive CCD camera (MLX) made by NAC Image Technology at a frame speed of 30 Hz and an image capture time (shutter speed) of 1 ms (Fig. 15). Radiograms from the I I are taken by the CCD camera, and digital video files are recorded by a personal computer through a video capture box.

Figure 16 shows the mass attenuation coefficients of iodine at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The average photon energy of the cerium Kα lines is shown just above the iodine K-edge. The average photon energy of Kα lines is 34.6 keV, and iodine contrast media with a K-absorption edge of 33.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

Figure 17 shows two frames (angiograms) of water falling into polypropylene beaker from a plastic test tube. These images were taken with a tube voltage of 60 kV, and an iodine-based contrast medium was added a little. Because the capture time was about 1 ms, the stop-motion images of water were obtained. Therefore, blood vessels can be seen with high contrasts.

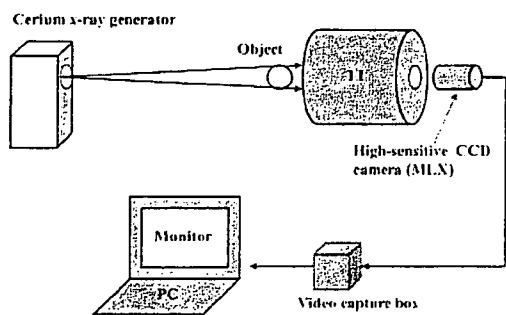


Fig. 15. Experimental setup for performing real-time radiography with a short capture time utilizing an image intensifier and the MLX camera.

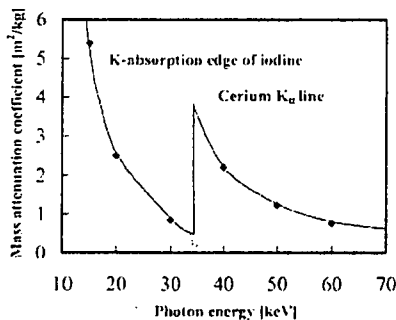


Fig. 16. Mass attenuation coefficients of iodine at the selected energies and the average photon energy of the cerium Kα lines.

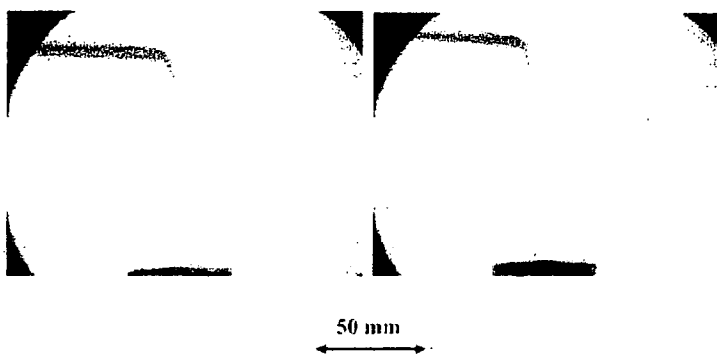


Fig. 17. Two angiograms (frames) of water falling into a polypropylene beaker from a plastic test tube using an iodine medium.

## 6. MICROFOCUS X-RAY GENERATOR

### 6.1 Generator and experimental setup

The microfocus x-ray generator consists of a main controller, an x-ray tube unit with a Cockcroft-Walton circuit, an insulation transformer, and a 100- $\mu\text{m}$ -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 employs the Cockcroft-Walton circuit in order to decrease the dimensions of the tube unit (Fig. 18). In the x-ray tube, the 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 which is used for isolation from the high voltage from the Cockcroft-Walton circuit. In this experiment, the tube voltage applied was from 45 to 70 kV, and the tube current was regulated to within 0.50 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity, and narrow-photon-energy bremsstrahlung x-rays are produced using a 3.0-mm-thick aluminum filter for absorbing soft x-rays.

### 6.2 Characteristics

At a constant tube current of 0.50 mA, the x-ray intensity increased when the tube voltage was increased. At a tube voltage of 60 kV, the intensity with the filter was 26.0  $\mu\text{Gy/s}$ . Subsequently, in order to measure x-ray spectra, we employed a cadmium telluride detector (XR-100T, Amptek). When the tube voltage was increased, the bremsstrahlung x-ray intensity increased, and both the maximum photon energy and the spectrum peak energy increased.

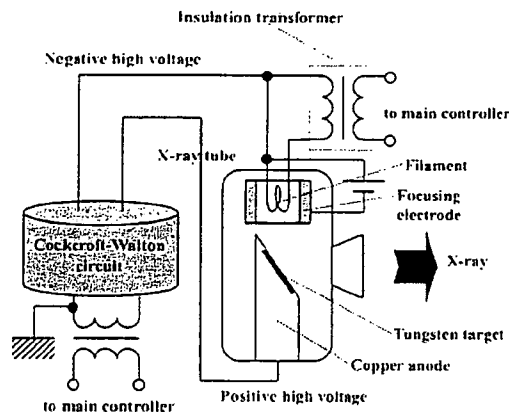


Fig. 18. Circuit diagram of the microfocus x-ray generator.

### 6.3 High-speed radiography

Real-time magnification radiography was performed by twofold magnification imaging using the I I, the camera, and the filter. The tube voltage, the capture time, and the distance between the x-ray source and the I I were 60 kV, 1 ms, and 1.0 m, respectively. Figure 19 shows radiograms of a metronome, and stop-motion images of a pendulum were observed.

### 6.4 High-speed enhanced magnification angiography

Figure 20 shows the mass attenuation coefficients of iodine at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The effective bremsstrahlung x-ray spectra for K-edge angiography are shown above the iodine K-edge. Because iodine contrast media with a K-absorption edge of 33.2 keV absorb the rays easily, blood vessels were observed with high contrasts.

The magnification angiography was performed at the same conditions using iodine microspheres of 15  $\mu\text{m}$  in diameter, and the microspheres (containing 37% iodine by weight) are very useful for making phantoms of non-living animals used for angiography. Angiograms of a dog heart on a turn table is shown in Fig. 21, and the fine coronary arteries are not visible due to the spatial resolution of I I. In addition, neo-capillaries in a rabbit cancer are clearly visible using a high-resolution I I (Fig. 22).



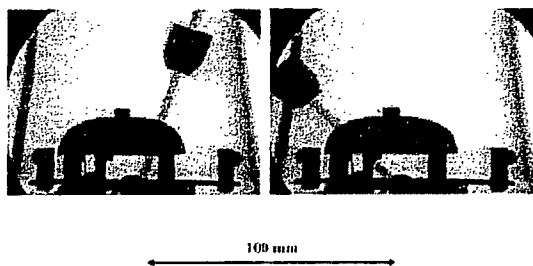


Fig. 19. Radiograms of a metronome.

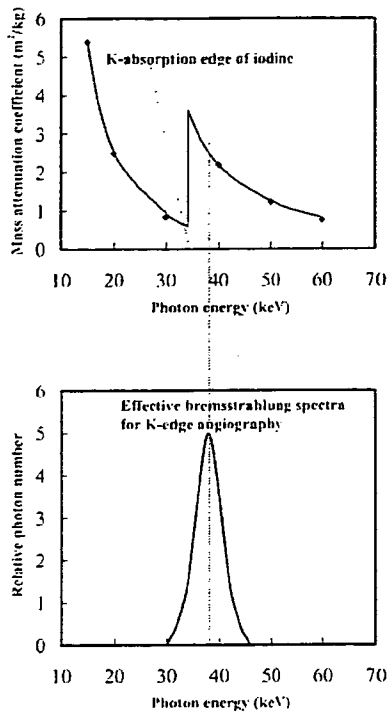


Fig. 20. Mass attenuation coefficients of iodine and effective bremsstrahlung x-rays for enhanced K-edge angiography.

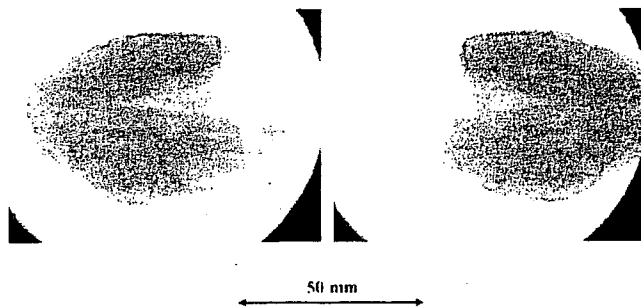


Fig. 21. Angiogram of an extracted dog heart using iodine microspheres on a turn table.

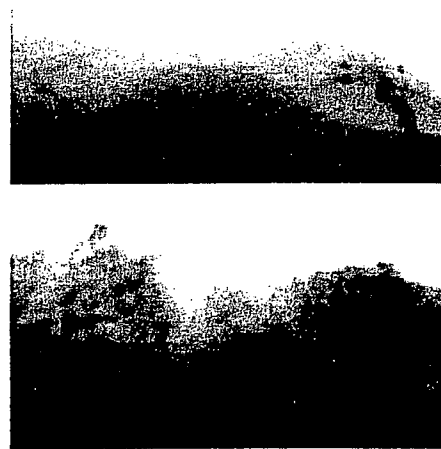


Fig. 22. Angiograms of a rabbit cancer using a high-resolution II.

## 7. CONCLUSION AND OUTLOOK

We have developed various x-ray generators corresponding to specific radiographic objectives, and the x-ray duration ranges from approximately 100 ns to continuous exposure. In the weakly ionized plasma formation, extremely clean and intense K lines were produced, since the bremsstrahlung x-rays were absorbed effectively by the plasma. In particular, the harmonic bremsstrahlung rays survived and waved due to the x-ray resonance in the plasma.

Although most flash x-ray generators utilize Marx surge generators and produce hard bremsstrahlung x-rays, monochromatic flash x-ray generators have been employed to observe aluminum grains in studies on space debris on the earth. In addition, because the monochromatic tubes realize uniform monochromatic x-ray intensity distributions, the absorber thickness can be calculated easily.

To perform enhanced K-edge angiography using iodine-based contrast media, the cerium, samarium and gadolinium targets are very useful because K lines from these targets are absorbed effectively by iodine media. Therefore, using the x-ray II in conjunction with the MLX camera with short capture times of approximately 1 ms, stop-motion images of fine blood vessels can be almost seen. Using this image intensifying system, the image quality slightly fell with decreases in the capture time. However, stop-motion image can be obtained when the capture time is decreased.

We employed an x-ray generator with a 100- $\mu\text{m}$ -focus tungsten tube and performed real-time twofold magnification radiography (fluoroscopy) using the II and the MLX camera. To perform angiography, we employed narrow-photon-energy bremsstrahlung x-rays with a peak photon energy of approximately 35 keV, which can be absorbed easily by iodine-based contrast media. Although we obtained mostly absorption-contrast images, the phase-contrast effect may be added in cases where low-density media are employed.

Because the focus diameter of the tube has been decreased to 10  $\mu\text{m}$  using a rotating anode microfocus tube developed by Hitachi Medical Corporation, a high-resolution and high-speed magnification radiography system will become possible.

## ACKNOWLEDGMENTS

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## REFERENCES

1. R. Germer, "X-ray flash techniques," *J. Phys. E: Sci. Instrum.*, **12**, 336-350, 1979.
2. E. Sato, S. Kimura, S. Kawasaki, H. Isobe, K. Takahashi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator utilizing a simple diode with a new type of energy-selective function," *Rev. Sci. Instrum.*, **61**, 2343-2348, 1990.
3. A. Shikoda, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator having a high-durability diode driven by a two-cable-type line pulser," *Rev. Sci. Instrum.*, **65**, 850-856, 1994.
4. E. Sato, K. Takahashi, M. Sagae, S. Kimura, T. Oizumi, Y. Hayasi, Y. Tamakawa and T. Yanagisawa, "Sub-kilohertz flash x-ray generator utilizing a glass-enclosed cold-cathode triode," *Med. & Biol. Eng. & Comput.*, **32**, 289-294, 1994.
5. K. Takahashi, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa, "Fundamental study on a long-duration flash x-ray generator with a surface-discharge triode," *Jpn. J. Appl. Phys.*, **33**, 4146-4151, 1994.
6. E. Sato, Y. Hayasi and Y. Tamakawa, "Recent stroboscopic x-ray generators and their applications to high-speed radiography," *Ann. Rep. Iwate Med. Univ. Lib. Arts and Sci.*, **35**, 1-11, 2000.
7. E. Sato, E. Tanaka, H. Mori, T. Kawai, S. Sato, H. Ojima, K. Takayama and H. Ido, "Energy selective high-speed radiography utilizing stroboscopic x-ray generator," *SPIE*, **5580**, 765-771, 2005.
8. E. Sato, Y. Hayasi, R. Germer, K. Kimura, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama and H. Ido, "Energy-selective gadolinium angiography utilizing a stroboscopic x-ray generator," *SPIE*, **5920**, 5920V-1-8, 2005.

9. E. Sato, K. Sato and Y. Tamakawa, "Film-less computed radiography system for high-speed imaging," *Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts and Sci.*, **35**, 13-23, 2000.
  10. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, K. Takayama and H. Ido, "Quasi-monochromatic flash x-ray generator utilizing weakly ionized linear copper plasma," *Rev. Sci. Instrum.*, **74**, 5236-5240, 2003.
  11. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Sharp characteristic x-ray irradiation from weakly ionized linear plasma," *J. Electron Spectrosc. Related Phenom.*, **137-140**, 713-720, 2004.
  12. E. Sato, M. Sagae, E. Tanaka, Y. Hayasi, R. Germer, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Quasi-monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube," *Jpn. J. Appl. Phys.*, **43**, 7324-7328, 2004.
  13. E. Sato, E. Tanaka, H. Mori, T. Kawai, S. Sato and K. Takayama, "Clean monochromatic x-ray irradiation from weakly ionized linear copper plasma," *Opt. Eng.*, **44**, 049002-1-6, 2005.
  14. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Compact monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube," *Med. Phys.*, **32**, 49-54, 2005.
  15. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, T. Ichimaru, K. Takayama, J. Onagawa and H. Ido, "Monochromatic flash x-ray generator utilizing a disk-cathode silver tube," *Opt. Eng.*, **44**, 096501-1-6, 2005.
  16. E. Sato, Y. Hayasi, K. Kimura, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama, J. Onagawa and H. Ido, "Enhanced K-edge angiography utilizing tantalum plasma x-ray generator in conjunction with gadolinium-based contrast media," *Jpn. J. Appl. Phys.*, **44**, 8716-8721, 2005.
  17. E. Sato, Y. Hayasi, R. Germer, K. Kimura, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama and H. Ido, "Enhanced K-edge plasma angiography achieved with tungsten K $\alpha$  rays utilizing gadolinium-based contrast media," *SPIE*, **5920**, 592012-1-8, 2005.
  18. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama, J. Onagawa, "X-ray spectra from weakly ionized linear copper plasma," *Jpn. J. Appl. Phys.*, **45**, 5301-5306, 2006.
  19. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Demonstration of enhanced K-edge angiography using a cerium target x-ray generator," *Med. Phys.*, **31**, 3017-3021, 2004.
  20. E. Sato, A. Yamadera, E. Tanaka, H. Mori, T. Kawai, F. Ito, T. Inoue, A. Ogawa, S. Sato, K. Takayama, J. Onagawa and H. Ido, "X-ray spectra from a cerium target and their application to cone beam K-edge angiography," *Opt. Eng.*, **44**, 096502-1-6, 2005.
  21. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, A. Yamadera, S. Sato, F. Ito, K. Takayama, J. Onagawa and H. Ido, "Variations in cerium x-ray spectra and enhanced K-edge angiography," *Jpn. J. Appl. Phys.*, **44**, 8204-8209, 2005.
  22. E. Sato, E. Tanaka, H. Mori, H. Kawakami, T. Kawai, T. Inoue, A. Ogawa, S. Sato, T. Ichimaru, K. Takayama and H. Ido, "Enhanced magnification angiography including phase-contrast effect using a 100- $\mu$ m focus x-ray tube," *SPIE*, **5918**, 591811-1-9, 2005.
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# High-sensitive radiography system utilizing a pulse x-ray generator and a night-vision CCD camera (MLX)

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## ABSTRACT

High-sensitive radiography system utilizing a kilohertz-range stroboscopic x-ray generator and a night-vision CCD camera (MLX) is described. The x-ray generator consists of the following major components: a main controller, a condenser unit with a Cockcroft-Walton circuit, and an x-ray tube unit in conjunction with a grid controller. The main condenser of about 500 nF in the unit is charged up to 100 kV by the circuit, and the electric charges in the condenser are discharged to the triode by the grid control circuit. The maximum tube current and the repetition rate are approximately 0.5 A and 50 kHz, respectively. The x-ray pulse width ranges from 0.01 to 1.0 ms, and the maximum shot number has a value of 32. At a charging voltage of 60 kV and a width of 1.0 ms, the x-ray intensity obtained without filtering was 6.04  $\mu$ Gy at 1.0 m per pulse. In radiography, an object is exposed by the pulse x-ray generator, and a radiogram is taken by an image intensifier. The image is intensified by the CCD camera, and a stop-motion image is stored by a flash memory device using a trigger delay device. The image quality was improved with increases in the x-ray duration, and a single-shot radiography was performed with durations of less than 1.0 ms.

**Keywords:** high-sensitive radiography, image intensification, high-sensitive CCD camera, pulse x-ray generator

## 1. INTRODUCTION

With advances in high-voltage pulse technology, high-photon-energy flash x-ray generators<sup>1,2</sup> have been developed utilizing multi-stage Marx generators, and the maximum photon energy has been increased up to approximately 1 MeV for military applications. In contrast, we have developed low-photon-energy flash x-ray generators<sup>3-6</sup> with photon energies of lower than 150 keV, and have performed high-speed soft radiographies including biomedical applications.

To produce extremely clean K-series characteristic x-rays such as lasers, we have developed three characteristic flash x-ray generators<sup>7-15</sup> and have succeeded in producing clean K lines. In particular, bremsstrahlung x-rays are absorbed effectively by weakly ionized metal plasmas. Subsequently, we have developed steady-state characteristic x-ray