Irradiation of Intense Characteristic X-rays from Weakly Ionized Linear Plasma

Eiichi Sato[a], Yasuomi Hayasi[b], Etsuro Tanaka[c], Hidezo Mori[d], Toshiaki Kawai[e], Kazuyoshi Takayama[f] and Hideaki Ido[g]

[a] Department of Physics, Iwate Medical University, 3-16-1 Honcho-dori, Morioka 020-0015, Japan
[b] Electrical Engineering, Hachinohe National College of Technology, 16-1 Tamonoki Uwanotai, Hachinohe 039-1104, Japan
[c] Department of Physiology, School of Medicine, Tokai University, Boseidai, Isehara 259-1193, 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 Inc., 314-5 Shimokanzo, Toyooka-village, Iwata-gun 438-0193, Japan
[f] Shock Wave Research Center, Institute of Fluid Science, Tohoku University, 1-1 Katahira, Sendai 980-8577, Japan
[g] Department of Applied Physics, Faculty of Engineering, Tohoku Gakuin University, 1-13-1 Tagajo 985-0873, Japan
e-mail: dresato@iwate-med.ac.jp

ABSTRACT

Intense quasi-monochromatic x-ray irradiation from the linear plasma target is described. The plasma x-ray generator employs a high-voltage power supply, a low-impedance coaxial transmission line, a high-voltage condenser with a capacity of about 200 nF, a turbo-molecular pump, a thyristor pulse generator as a trigger device, and a flash x-ray tube. The high-voltage main condenser is charged up to 55 kV by the power supply, and the electric charges in the condenser are discharged to the tube after triggering the cathode electrode. The x-ray tube is of a demountable triode that is connected to the turbo molecular pump with a pressure of approximately 1 mPa. As electron flows from the cathode electrode are roughly converged to the molybdenum target by the electric field in the tube, the weakly ionized plasma, which consists of metal ions and electrons, forms by the target evaporating. In the present work, the peak tube voltage was almost equal to the initial charging voltage of the main condenser, and the peak current was about 20 kA with a charging voltage of 55 kV. When the charging voltage was increased, the linear plasma x-ray source grew, and the characteristic x-ray intensities of K-series lines increased. The quite sharp lines such as hard x-ray lasers were clearly observed. The quasi-monochromatic radiography was performed by a new film-less computed radiography system.

Keywords: X-ray amplification, spontaneous emission, quasi-monochromatic x-ray, quasi-x-ray laser

1. INTRODUCTION

Recently, we have developed several different plasma flash x-ray generators[1-5] in order to increase the conversion efficiency of the electrostatic energies into x-rays and to generate higher-intensity x-rays. Using these generators, we have found irradiation of higher-intensity characteristic x-rays by forming the plasma x-ray source using rod and plate targets, because the bremsstrahlung x-rays with energies of higher than K-absorption edge are absorbed by the plasma and are converted into fluorescent and characteristic x-rays. In 2001, we have developed a plasma flash x-ray generator having a new radiation tube[6-8] for forming linear plasma and have performed tentative study on quasi-monochromatic parallel radiography. In the linear plasma, the characteristic x-ray amplification may be performed when the bremsstrahlung rays are absorbed effectively by the linear plasma. In addition, the K-fluorescent yield increases and becomes to one according to increases in atomic number of target. For this research, we introduce a flash x-ray generator utilizing a molybdenum-target radiation tube and have performed tentative experiment for generating higher-intensity quasi-monochromatic x-rays such as hard x-ray lasers by the new amplification method in characteristic x-rays.

2. GENERATOR

Figure 1 shows block diagram of a high-intensity plasma flash x-ray generator. This generator employs a high-voltage power supply, a high-voltage condenser with a capacity of about 200 nF, a turbo-molecular pump, a thyristor pulse generator as a trigger device, and a flash x-ray tube. The high-voltage main condenser is charged up to 55 kV by the power supply, and the electric charges in the condenser are discharged to the tube after triggering cathode electrode. The x-ray tube is of a demountable cold-cathode triode that is connected to the turbo molecular pump with a pressure of approximately 1 mPa. This tube consists of the following major parts: a pipe-shaped carbon cathode with a hole diameter of 10.0 mm, a trigger electrode made from a copper wire, a stainless-steel vacuum chamber, insulators, a polyethylene terephthalate x-ray window of 0.25 mm, and a rod molybdenum target of 3.0 mm in diameter. The space between the anode and cathode electrodes has a value of approximately 15 mm, and the trigger electrode is set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by electric field in the tube, the plasma x-ray source, which consists of metal ions and electrons, forms by the target evaporating. If we assume that the weakly ionized plasma thickness has a small value, the spectra from the transverse direction have a standard distribution. Next, the bremsstrahlung spectra with photon energies of higher than K-absorption edge are effectively absorbed and are converted into the fluorescent x-rays, and the high-intensity characteristic x-rays are generated from the plasma-axial direction (refer to Fig. 1).

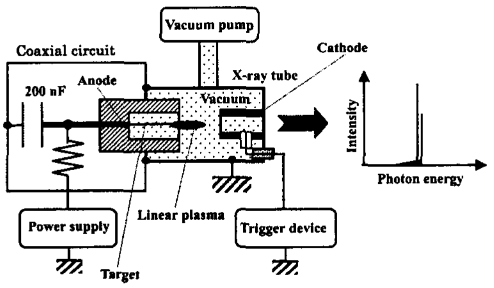


Fig. 1: Block diagram of the high-intensity plasma flash x-ray generator.

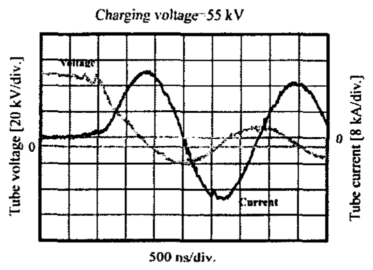


Fig. 2: Tube voltage and current.

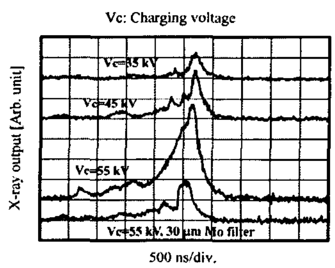


Fig. 3: X-ray outputs at the indicated conditions

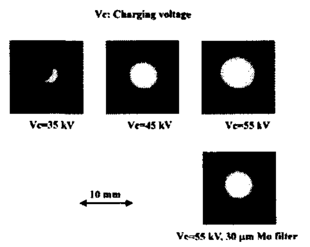


Fig. 4: Images of the x-ray source.

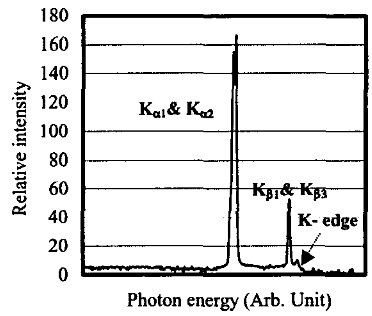


Fig. 5: X-ray spectra from the molybdenum-plasma target with a charging voltage of 45 kV.

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 2 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 by using a combination of a plastic scintillator and a photomultiplier (Fig. 3). The x-ray pulse height substantially increased with corresponding increases in the charging voltage and decreased in the case where a monochromatic molybdenum filter of 30 μm was inserted. The x-ray pulse widths were about 700 ns, and sufficient x-ray intensities for computed radiography (CR) system[9] were obtained.

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. 4). 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 molybdenum filter.

3.4. X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer[6] having a lithium fluoride curved crystal of 0.5 mm in thickness. The spectra were taken by the CR system having a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage and decreased according to insertion of molybdenum filter. In the digital analysis, intense molybdenum K-series characteristic x-rays such as hard x-ray lasers and K-absorption edge were clearly observed (Fig. 5).

3.5. X-ray diffraction by slits

Although coherence is the most important factor in x-ray amplification, it is quite difficult to measure the coherence, because the x-rays for biomedical radiography can penetrate various objects easily. Currently, since the coherent rays are diffracted greatly by a knife edge and a knife slit, we employed two lead slits in order to measure the diffraction power of characteristic x-rays (Fig. 6). Compared with incoherent x-rays from a hot-cathode x-ray tube, the characteristic x-rays from the linear plasma are diffracted and diffused greatly after passing through two slits (Fig. 7).

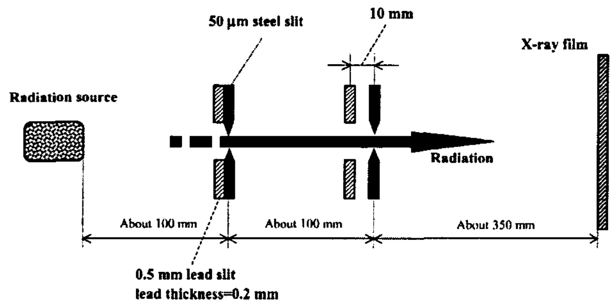


Fig. 6: Setup for x-ray diffraction using four slits.

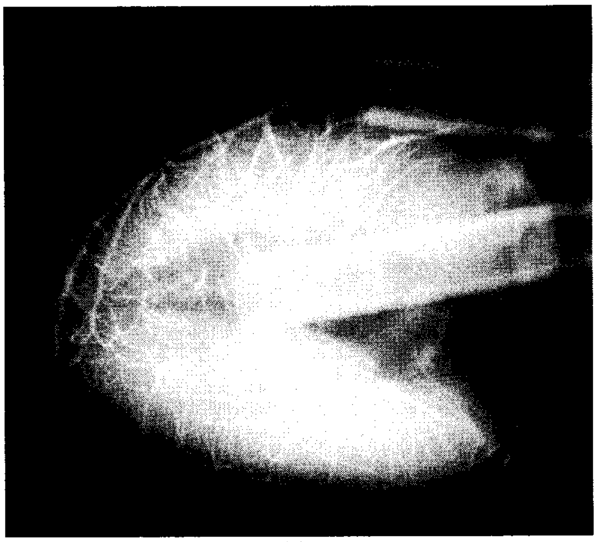
Fig. 7: Diffraction patterns.

4. RADIOGRAPHY

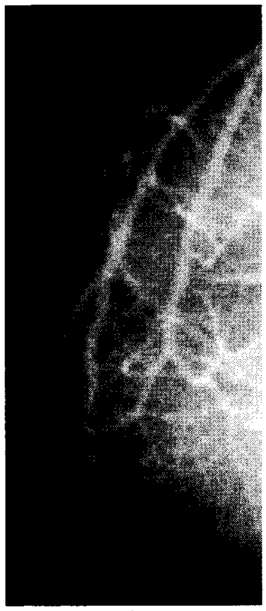
The radiography was performed by the CR system utilizing imaging plates, and the charging voltage and the distance between the x-ray source and imaging plate were 50 kV and 1.2 m, respectively. Figure 8 shows angiograms of a heart extracted from a dog using iodine-based microspheres of 20 μm, and the fine blood vessel are clearly visible in the enlarged angiogram.

5. DISCUSSION

In the present work, we have succeeded in generating intense characteristic x-rays such as hard x-ray lasers using the plasma flash x-ray generator with a new radiation tube and have performed high-intensity soft radiography. In fact, we observed quite sharp K-series lines and K-absorption edge clearly, and bremsstrahlung x-rays were not so detected in the region of higher than K-edge.



(a)



(b)

Fig. 8: Angiogram of a heart extracted from a dog. (a) Normal image. (b) Enlarged image.

Compared with the target such as silver with a lower melting temperature, it is difficult to form molybdenum plasma at a lower charging voltage of about 40 kV or less. In view of this situation, the current density at the target tip should be increased as large as possible by increasing the condenser capacity and by decreasing the target diameter.

ACKOWLEDGEMENTS

This work was supported by Grants-in-Aid for Scientific Research (12670902, 13470154 and 13877114) from MECSST, Japan Science and Technology Corporation, Scientific Research from New Energy and Industrial Technology Development Organization, and Cardiovascular Disease (H13C-1) from MHLW.

REFERENCES

1. E. Sato, M. Sagae, K. Takahashi, T. Ichimaru, A. Wataru, S. Kumagai, H. Ido, K. Sakamaki, K. Takayama and Y. Tamakawa, "Monochromatic plasma x-ray generator and its applications," *SPIE*, **3336**, pp. 75-86, 1998.

2. K. Takahashi, E. Sato, M. Sagae and Y. Tsukahara, "Semi-monochromatic plasma flash radiography and its application to biomedical image simulation," *Jpn. J. Appl. Phys.*, **37**, pp. 4222-4227, 1998.

3. E. Sato, M. Sagae, T. Ichimaru, Y. Hayasi, H. Ojima, K. Takayama, H. Ido, K. Sakamaki and Y. Tamakawa, "Tentative study on x-ray enhancement by fluorescent emission of radiation by plasma x-ray source," *SPIE*, **3771**, pp. 51-60, 1999.

4. E. Sato, Y. Hayasi, H. Mori, E. Tanaka, K. Takayama, H. Ido, K. Sakamaki and Y. Tamakawa, "Quasi-monochromatic x-ray production from the cerium target," *SPIE*, **4142**, pp. 17-28, 2000.

5. E. Sato, Y. Hayasi, T. Ichimaru, H. Mori, E. Tanaka, H. Ojima, K. Takayama, T. Usuki, K. Sato, K. Sakamaki and Y. Tamakawa, "Tentative study on high-photon-energy quasi-x-ray laser generator by forming plasma x-ray source," *SPIE*, **4183**, pp. 326-338, 2000.

6. E. Sato, Y. Suzuki, Y. Hayashi, E. Tanaka, H. Mori, T. Kawai, K. Takayama, H. Ido and Y. Tamakawa, "High-intensity quasi-monochromatic x-ray irradiation from the linear plasma target," *SPIE*, **4505**, pp. 154-164, 2001.

7. E. Sato, Y. Hayasi, E. Tanaka, H. Mori, T. Kawai, H. Obara, T. Ichimaru, K. Takayama, H. Ido, T. Usuki, K. Sato and Y. Tamakawa, "Polycapillary radiography using a quasi-x-ray laser generator," *SPIE*, **4508**, pp. 176-187. 2001.

8. E. Sato, Y. Hayasi, H. Ojima, K. Takayama and Y. Tamakawa, "High photon energy quasi-x-ray laser generator for shock wave research," *Proc. 23rd Symp. on Shock Waves, Fort Worth*, 2001, to be published.

9. E. Sato , Y. Hayasi and Y. Tamakawa, "Film-less computed radiography system for high-speed Imaging," *Ann. Rep. Iwate Med. Univ. Lib. Arts and Sci.*, **35**, pp. 13-23, 2000.