enhanced K-edge angiography using a cerium target X-ray generator. Med. Phys. 31, 3017–3021.
Sato, E., Tanaka, E., Mori, H., Kawai, T., Ichimaru, T., Sato, S., Takayama, Y., Ido, H., 2005a. Compact monochromatic flash X-ray generator utilizing a disk-cathode molybdenum tube. Med. Phys. 32, 49–54.
Sato, E., Tanaka, E., Mori, H., Kawai, T., Sato, S., Takayama, Y., 2005b. High-speed enhanced K-edge angiography utilizing cerium plasma X-ray generator. Opt. Eng. 44, 049001–049016.
Sato, E., Tanaka, E., Mori, H., Kawai, T., Sato, S., Takayama, Y., 2005c. Clean monochromatic X-ray irradiation from weakly ionized linear copper plasma. Opt. Eng. 44, 049002–049016.
Shikoda, A., Sato, E., Sagae, M., Oizumi, T., Tamakawa, Y., Yanagisawa, T., 1994. Repetitive flash X-ray generator having a high-durability diode driven by a two-cable-type line pulser. Rev. Sci. Instrum. 65, 850–856.
Takahashi, K., Sato, E., Sagae, M., Oizumi, T., Tamakawa, Y., Yanagisawa, T., 1994. Fundamental study on a long-duration flash X-ray generator with a surface-discharge triode. Jpn J. Appl. Phys. 33, 4146–4151.
Thompson, A.C., Zeman, H.D., Brown, G.S., Morrison, J., Reiser, P., Padmanabahn, V., Ong, L., Green, S., Giacomini, J., Gordon, H., Rubenstein, E., 1992. First operation of the medical research facility at the NSLS for coronary angiography. Rev. Sci. Instrum. 63, 625–628.

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

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Abstract

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

PACS: 87.59.–e; 87.59.Bh; 87.64.Gb

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

1. Introduction

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

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

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

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

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

2. Experimental setup

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

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

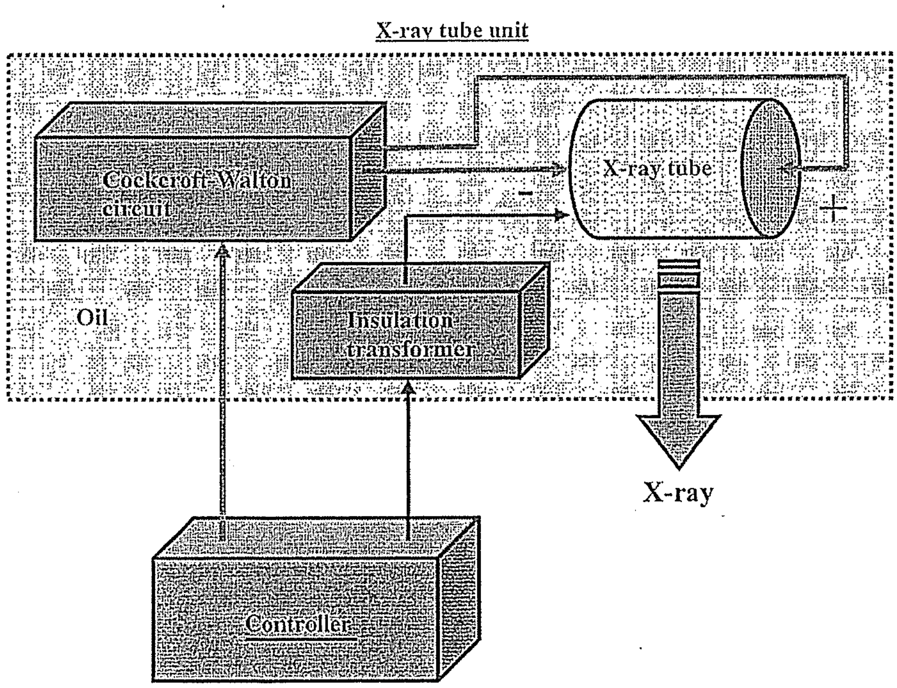

Fig. 1. Block diagram of a compact 100-μm focus X-ray generator with a tungsten-target radiation tube.

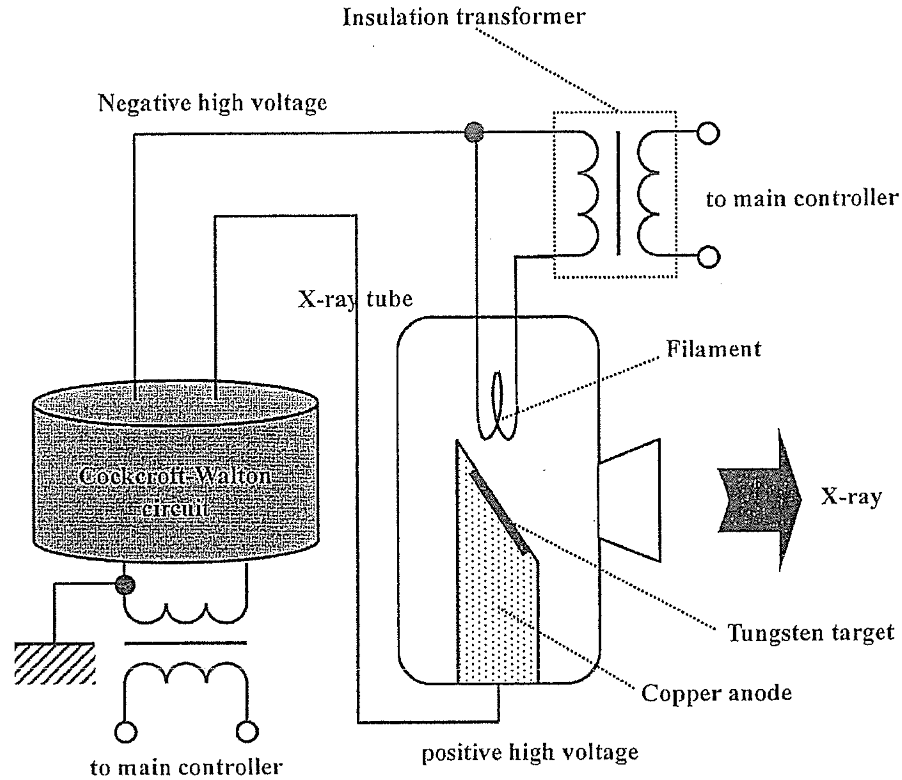

Fig. 2. Main circuit of the X-ray generator.

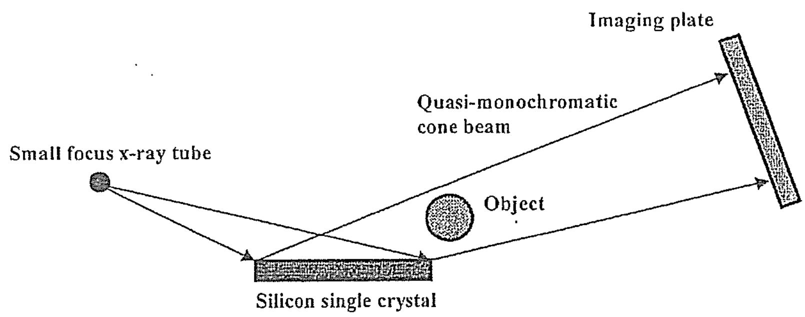

Fig. 3. Experimental setup of the narrow-photon-energy X-ray generator utilizing a single silicon crystal.

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

3. Results

3.1. X-ray intensity

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

3.2. Radiography

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

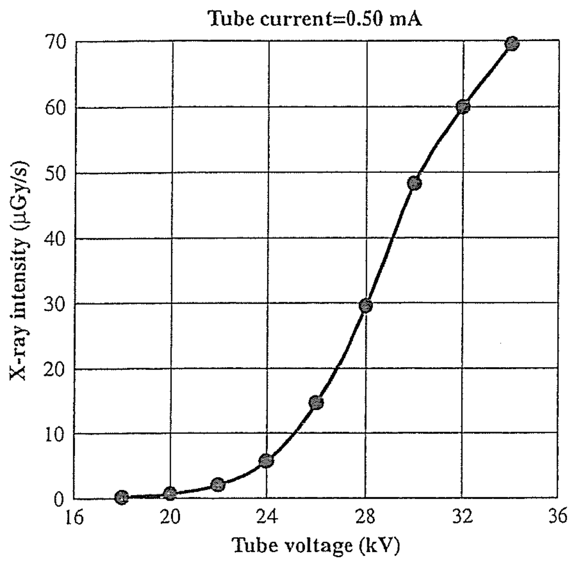

Fig. 4. X-ray intensity (μGy/s) as a function of tube voltage (kV) with a tube current of 0.50 mA.

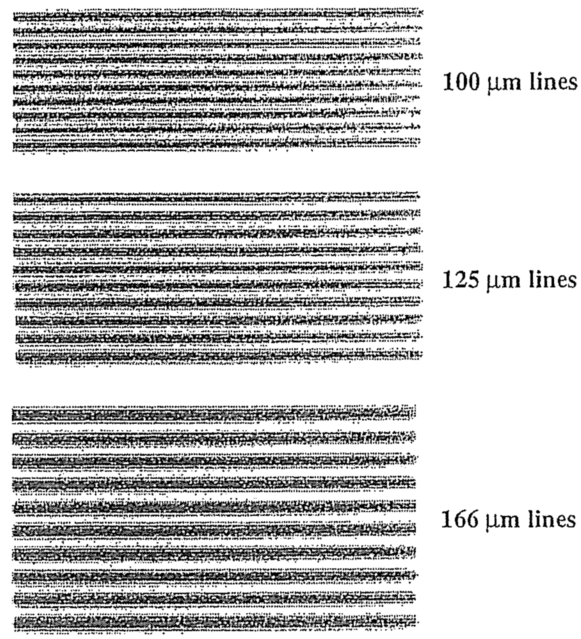

Fig. 6. Radiogram of a lead test chart for measuring the spatial resolution.

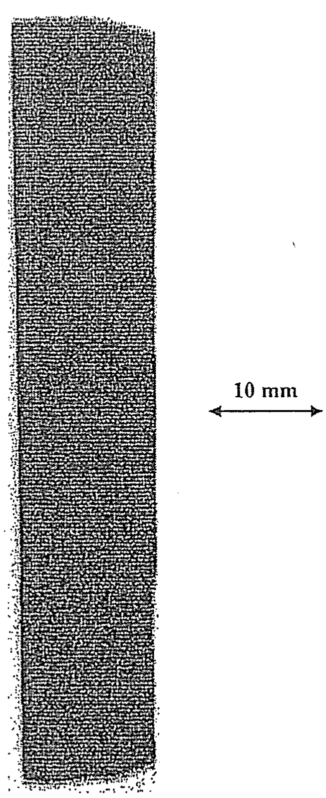

Fig. 5. Irradiation field with photon energies of approximately 17 keV measured using the CR system with a tube voltage of 30 kV.

Because the width of the irradiation field was narrow due to the angle, the distance between the crystal and the imaging plate should be increased. Fig. 6 shows a radiogram of a test chart for determining the spatial resolution. In this radiography, 100-μm-wide lead lines (5 line pair) were observed. Subsequently, fine bone structures were visible in radiograms of a vertebra (Fig. 7), and fine blood vessels were observed in an angiogram of a rabbit heart (Fig. 8).

4. Conclusion and outlook

In summary, we employed a 100-μm-fosus X-ray generator with a tungsten-target tube and succeeded in producing narrow-photon-energy bremsstrahlung X-rays, which are refracted by a silicon single crystal of (1 1 1) plane. The photon energy width is primarily determined by the distance between the X-ray source and the crystal plate, and the irradiation field increases with increases in the distance between the crystal and the imaging plate. Because we employed the microfocus tube, phase-contrast effect was added in the radiography.

The microfocus generator produced maximum X-ray intensity was approximately 50 μGy/s at 1.0 m from the source, but the intensity was decreased substantially after the diffraction. Therefore, a high-current tungsten tube with a large focus should be employed in cases where the phase-contrast radiography is not employed.

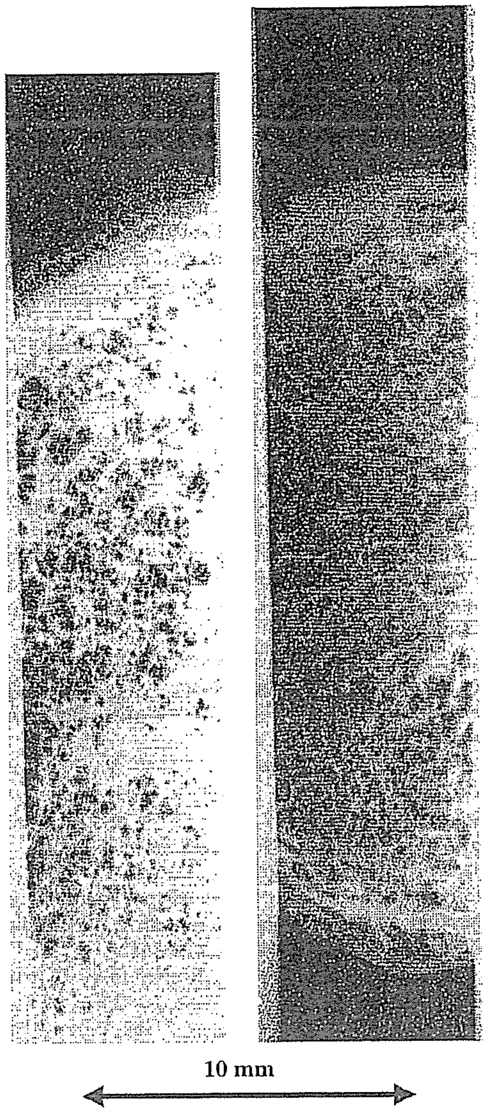

Fig. 7. Radiograms of a vertebra.

The magnification method is needed in phase-contrast radiography, and the method increases the spatial resolution of the digital radiography. Next, in conventional cohesion radiography, the spatial resolution is primarily determined by the sampling pitch of the CR system of 87.5 μm. Therefore, to improve the spatial resolution in cohesion radiography, the resolution of the CR system should be improved to approximately 50 μm (Konica Minolta Regius 190). In addition, the spatial resolution can be improved easily to approximately 50 μm or less in cases where an X-ray film is employed.

In this experiment, although we employed the (1 1 1) plane to perform soft radiography, other planes should be employed to perform high-photon-energy radiography. In conjunction with an analyzer crystal, this

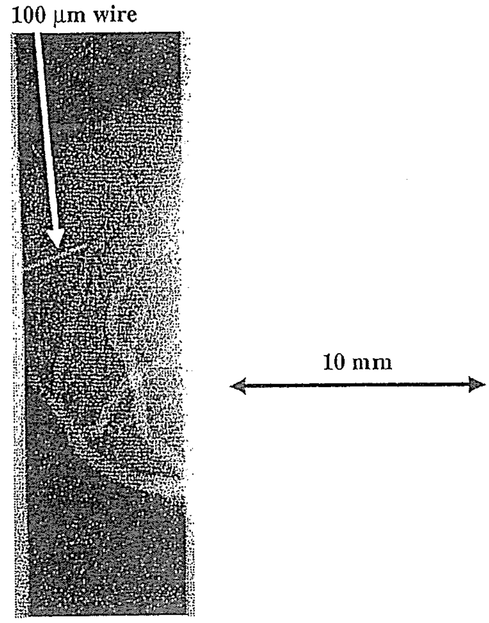

Fig. 8. Angiogram of a rabbit heart.

narrow-photon-energy cone-beam radiography using a microfocus X-ray tube could be useful for phase-contrast radiography as an alternative to radiography using synchrotrons.

Acknowledgments

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References

Ando, M., Maksimenko, M., Sugiyama, H., Pattanasiriwisawa, W., Hyodo, K., Uyama, C., 2002. A simple X-ray dark- and bright- field imaging using achromatic Laue optics. Jpn. J. Appl. Phys. 41, L1016–L1018.

Davis, T.J., Gao, D., Gureyev, T.E., Stevenson, A.W., Wilkins, S.W., 1995. Phase-contrast imagimg of weakly absorbing materials using hard X-rays. Nature 373, 595–597.

Hyodo, K., Ando, M., Oku, Y., Yamamoto, S., Takeda, T., Itai, Y., Ohtsuka, S., Sugishita, Y., Tada, J., 1998. 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 Rad. 5, 1123–1126.

Ishisaka, A., Ohara, H., Honda, C., 2000. A new method of analyzing edge effect in phase contrast imaging with incoherent X-rays. Opt. Rev. 7, 566–572.

Momose, A., Takeda, T., Itai, Y., Hirano, K., 1996. Phase-contrast X-ray computed tomography for observing biological soft tissues. Nature Med 2, 473–475.

Mori, H., Hyodo, K., Tanaka, E., Mohammed, M.U., Yamakawa, A., Shinozaki, Y., Nakazawa, H., Tanaka, Y., Sekka, T., Iwata, Y., Honda, S., Umetani, K., Ueki, H., Yokoyama, T., Tanioka, K., Kubota, M., Hosaka, H., Ishizawa, N., Ando, M., 1996. Small-vessel radiography in situ with monochromatic synchrotoron radiation. Radiology 201, 173–177.

Sato, E., Kimura, S., Kawasaki, S., Isobe, H., Takahashi, K., Tamakawa, Y., Yanagisawa, T., 1990. Repetitive flash X-ray generator utilizing a simple diode with a new type of energy-selective function. 2343–2348. Rev. Sci. Instrum. 61, 2343–2348.

Sato, E., Takahashi, K., Sagae, M., Kimura, S., Oizumi, T., Hayasi, Y., Tamakawa, Y., Yanagisawa, T., 1994a. Sub-kilohertz flash X-ray generator utilizing a glass-enclosed cold-cathode triode. Med. Biol. Eng. Comput. 32, 289–294.

Sato, E., Sagae, M., Takahashi, K., Shikoda, A., Oizumi, T., Hayasi, Y., Tamakawa, Y., Yanagisawa, T., 1994b. 10 kHz microsecond pulsed X-ray generator utilizing a hot-cathode triode with variable durations for biomedical radiography. Med. Biol. Eng. Comput. 32, 295–301.

Sato, E., Sato, K., Tamakawa, Y., 2000. Film-less computed radiography system for high-speed imaging. Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts Sci. vol. 35, pp. 13-23.

Sato, E., Hayasi, Y., Germer, R., Tanaka, E., Mori, H., Kawai, T., Obara, H., Ichimaru, T., Takayama, K., Ido, H., 2003a. Irradiation of intense characteristic X-rays from weakly ionized linear molybdenum plasma. Jpn. J. Med. Phys. 23, 123–131.

Sato, E., Hayasi, Y., Germer, R., Tanaka, E., Mori, H., Kawai, T., Ichimaru, T., Takayama, K., Ido, H., 2003b. Quasi-monochromatic flash X-ray generator utilizing weakly ionized linear copper plasma. Rev. Sci. Instrum. 74, 5236–5240.

Sato, E., Sagae, M., Tanaka, E., Hayasi, Y., Germer, R., Mori, H., Kawai, T., Ichimaru, T., Sato, S., Takayama, Y., Ido, H., 2004a. Quasi-monochromatic flash X-ray generator utilizing a disk-cathode molybdenum tube. Jpn. J. Appl. Phys. 43, 7324–7328.

Sato, E., Hayasi, Y., Germer, R., Tanaka, E., Mori, H., Kawai, T., Ichimaru, T., Sato, S., Takayama, K., Ido, H., 2004b. Sharp characteristic X-ray irradiation from weakly ionized linear plasma. J. Electron Spectrosc. Related Phenom. 137-140, 713–720.

Sato, E., Tanaka, E., Mori, H., Kawai, T., Ichimaru, T., Sato, S., Takayama, K., Ido, H., 2004c. Demonstration of enhanced K-edge angiography using a cerium target X-ray generator. Med. Phys. 31, 3017–3021.

Sato, E., Tanaka, E., Mori, H., Kawai, T., Ichimaru, T., Sato, S., Takayama, Y., Ido, H., 2005a. Compact monochromatic flash X-ray generator utilizing a disk-cathode molybdenum tube. Med. Phys. 32, 49–54.

Sato, E., Tanaka, E., Mori, H., Kawai, T., Sato, S., Takayama, Y., 2005b. High-speed enhanced K-edge angiography utilizing cerium plasma X-ray generator. Opt. Eng. 44, 049001–049016.

Sato, E., Tanaka, E., Mori, H., Kawai, T., Sato, S., Takayama, Y., 2005c. Clean monochromatic X-ray irradiation from weakly ionized linear copper plasma. Opt. Eng. 44, 049002–049016.

Shikoda, A., Sato, E., Sagae, M., Oizumi, T., Tamakawa, Y., Yanagisawa, T., 1994. Repetitive flash X-ray generator having a high-durability diode driven by a two-cable-type line pulser. Rev. Sci. Instrum. 65, 850–856.

Takahashi, K., Sato, E., Sagae, M., Oizumi, T., Tamakawa, Y., Yanagisawa, T., 1994. Fundamental study on a long-duration flash X-ray generator with a surface-discharge triode. Jpn. J. Appl. Phys. 33, 4146–4151.

Thompson, A.C., Zeman, H.D., Brown, G.S., Morrison, J., Reiser, P., Padmanabahn, V., Ong, L., Green, S., Giacomini, J., Gordon, H., Rubenstein, E., 1992. First operation of the medical research facility at the NSLS for coronary angiography. Rev. Sci. Instrum. 63, 625–628.

Wilkins, S.W., Gureyev, Gao, T.E., Pogany, D.A., Stevenson, A.W., 1996. Phase-contrast imaging using polychromatic hard X-rays. Nature 384, 335–338.

Enhanced real-time magnification angiography utilizing a 100-μm-focus x-ray generator in conjunction with an image intensifier

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ABSTRACT

A microfocus x-ray tube is useful in order to perform magnification digital radiography including phase-contrast effect. The 100-μm-focus x-ray generator consists of a main controller for regulating the tube voltage and current and a tube unit, with a high-voltage circuit and a fixed anode x-ray tube. The maximum tube voltage, current, and electric power were 105 kV, 0.5 mA, and 50 W, respectively. Using a 3.0-mm-thick aluminum filter, the x-ray intensity was 26.0 μGy/s at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.50 mA. Because the peak photon energy was approximately 35 keV using the filter with a tube voltage of 60 kV, the bremsstrahlung x-rays were absorbed effectively by iodine-based contrast media with an iodine K-edge of 33.2 keV. Real-time magnification radiography was performed by twofold magnification imaging with an image intensifier camera, and angiography was achieved with iodine-based microspheres 15 μm in diameter. In angiography of non-living animals, we observed fine blood vessels of approximately 100 μm with high contrasts.

Keywords: real-time magnification radiography, magnification angiography, 100-μm-focus tube, tungsten target, image intensifier, phase-contrast effect

1. INTRODUCTION

To perform high-speed biomedical radiography, several various flash x-ray generators using cold-cathode tubes have

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been developed.[1-4] In particular, quasi-monochromatic flash x-ray generators[5-10] have been designed to perform preliminary experiments for producing clean K-series x-rays, and higher-harmonic hard x-rays have been observed in a weakly ionized linear plasma of copper and nickel. However, in monochromatic flash radiography, difficulties in increasing x-ray duration and in performing x-ray computed tomography (CT) have been encountered. In view of this situation, we have developed steady-state characteristic x-ray generators to produce clean characteristic x-rays, since bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory.

Monochromatic parallel beams produced from a synchrotron using silicon crystals have been employed in phase-contrast radiography[11,12] and enhanced K-edge angiography.[13,14] In particular, the parallel beams with photon energies of approximately 35 keV have been employed to perform iodine K-edge angiography, because the beams are absorbed effectively by iodine-based contrast media with a K-absorption edge of 33.2 keV.

Without using synchrotrons, phase-contrast radiography for edge enhancement can be performed using a microfocus x-ray tube, and the magnification radiography including the phase-contrast effect[15] has been applied in mammography achieved with a computed radiography (CR) system[16] (Regius 190, Konica Minolta) with a sampling pitch of 43.8 μm using a 100-μm-focus molybdenum tube. Subsequently, we have developed a cerium x-ray generator[17-19] to perform enhanced K-edge angiography using cone beams, and have succeeded in observing fine blood vessels and coronary arteries with high contrasts using cerium Kα rays of 34.6 keV. However, it is difficult to design a small focus cerium tube for angiography.

Magnification radiography 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 to perform high-contrast high-resolution angiography. In magnification radiography, scattering beams from radiographic objects can be reduced without using a grid.

In this research, we employed a 100-μm-focus tungsten tube, used to perform real-time magnification radiography, including angiography, using an image intensifier (II) in conjunction with a CCD camera.

2. X-RAY GENERATOR

Figure 1 shows the block diagram of a microfocus x-ray generator used in this experiment, and the generator consists of a main controller, an x-ray tube unit with a Cockcroft-Walton circuit, an insulation transformer, and a 100-μm-focus x-ray tube. The tube voltage, the current, and the exposure time can be controlled by the controller. The main circuit for producing x-rays employs the Cockcroft-Walton circuit in order to decrease the dimensions of the tube unit. 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.

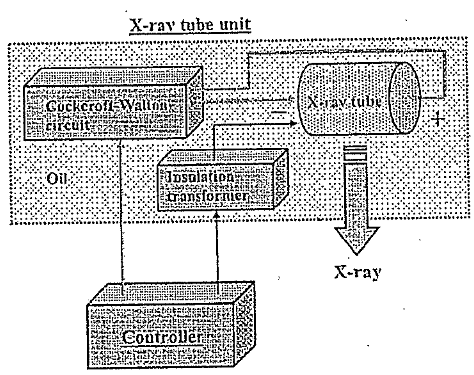

Fig. 1. Block diagram of the x-ray generator.

3. RESULTS AND DISCUSSION

3.1 X-ray intensity

The x-ray intensity was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source using the filter (Fig. 2). 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 μGy/s.

3.2 X-ray Spectra

In order to measure x-ray spectra, we employed a cadmium telluride detector (XR-100T, Amptek) (Fig. 3). When the tube voltage was increased, the bremsstrahlung x-ray intensity increased, and both the maximum photon energy and the spectrum peak energy increased.

In order to perform K-edge angiography, bremsstrahlung x-rays of approximately 35 keV are useful, and the high-energy bremsstrahlung x-rays decrease the image contrast. Using this filter, because bremsstrahlung x-rays with energies higher than 60 keV were not absorbed easily, the tube voltage for angiography was determined as 60 kV by considering the filtering effect of radiographic objects.

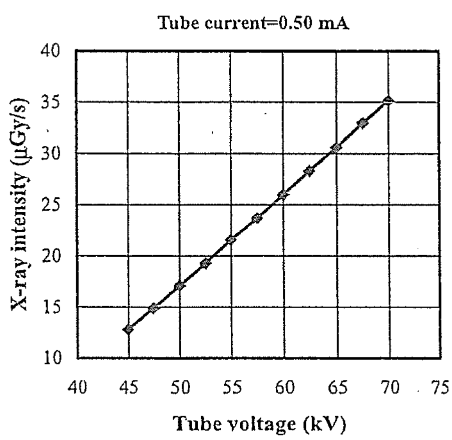

Fig. 2. X-ray intensity (μGy/s) as a function of tube voltage (kV) with a tube current of 0.50 mA.

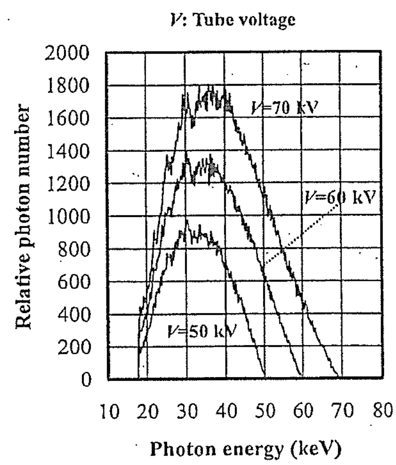

Fig. 3. Bremsstrahlung x-ray spectra measured using a cadmium telluride detector with changes in the tube voltage.

3.3 Magnification radiography

The magnification radiography was performed by twofold magnification imaging using the II camera and the filter at a tube voltage of 60 kV, and the distance between the x-ray source and the II was 1.0 m (Figs. 4 and 5). First, the spatial resolution of magnification radiography was made using a lead test chart (Fig. 6). In the magnification radiography, 109 μm lines (4.6 line pairs/mm) were visible. Subsequently, radiography of tungsten wires coiled around rods made of polymethyl methacrylate (PMMA) was performed (Fig. 7). Although the image contrast decreased somewhat with decreases in the wire diameter, a 50-μm-diameter wire could be observed.

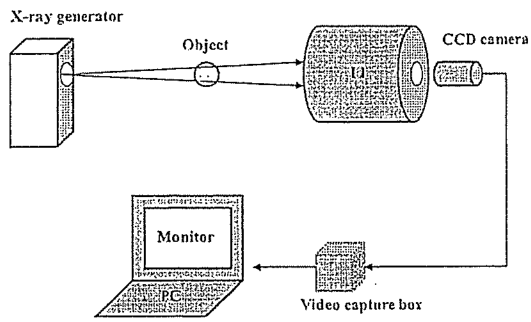

Fig. 4. Real-time magnification imaging using an image intensifier camera (low-resolution mode) in conjunction with a microfocus tube.

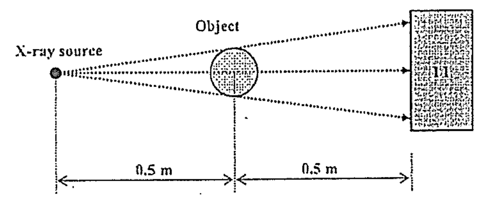

Fig. 5. Twofold magnification imaging.

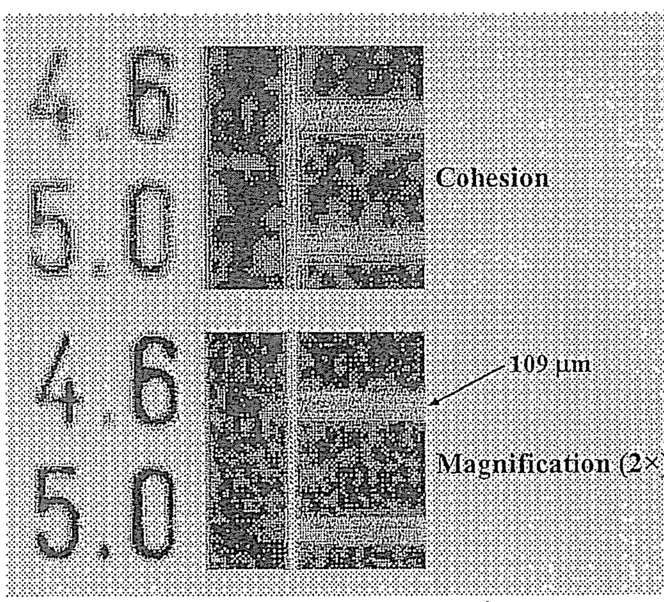

Fig. 6. Radiograms of a test chart for measuring the spatial resolution.

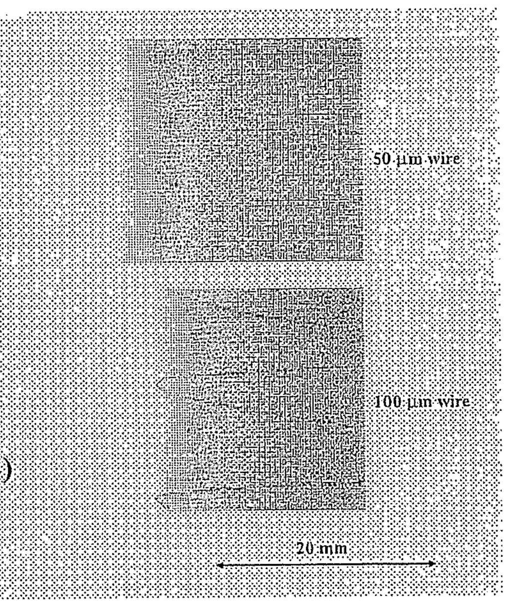

Fig. 7. Radiograms of tungsten wires coiled around PMMA rods.

3.4 Enhanced magnification angiography

Figure 8 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 µm 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 rabbit heart on the turn table is shown in Fig. 9, and the coronary arteries are visible. Figure 10 shows angiograms of a dog heart in an xy table, and blood vessels of approximately 100 µm in diameter were observed.

4. CONCLUSION AND OUTLOOK

We employed an x-ray generator with a 100-μm-focus tungsten tube and performed real-time magnification radiography (fluoroscopy) using the II 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. The bremsstrahlung x-ray intensity substantially increased with increases in the tube voltage, and the tube voltage was determined as 60 kV in order to increase the image contrast by decreasing high-photon-energy bremsstrahlung x-rays with energies beyond 60 keV. In enhanced angiography, low-photon-energy bremsstrahlung rays should be absorbed by an aluminum filter. Although we obtained mostly absorption-contrast images, the phase-contrast effect may be added in cases where low-density media are employed.

We obtained spatial resolutions of approximately 110 μm using twofold magnification imaging using the II even when a 100-μm-focus tube was employed. In order to observe fine blood vessels of less than 100 μm, the spatial resolution of the radiography system should be improved to approximately 50 μm using the II driven in a high-resolution mode, and the iodine density should be increased. At a tube voltage of 60 kV and a current of 0.50 mA, the photon number was approximately 4×10^7 photons/($cm^2 \cdot s$) at 1.0 m from the source, and photon count rate can be increased easily using a rotating anode microfocus tube developed by Hitachi Medical Corporation. Because the focus diameter of the tube has been decreased to 10 μm, a high-resolution real-time magnification radiography system will become possible.

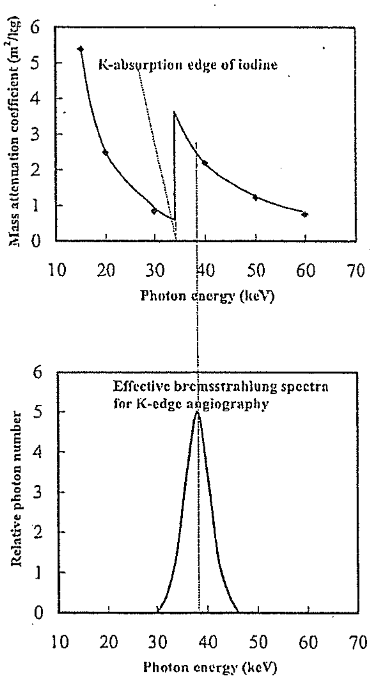

Fig. 8. Mass attenuation coefficients of iodine and effective bremsstrahlung x-rays for enhanced K-edge angiography.

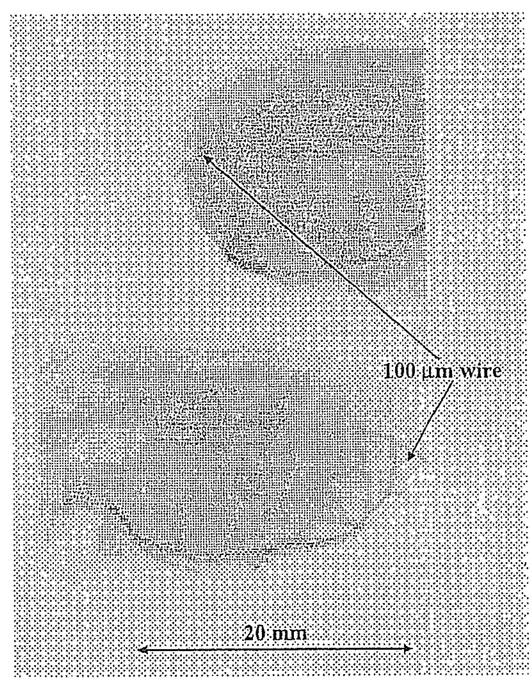

Fig. 9. Angiogram of an extracted rabbit heart using iodine microspheres.

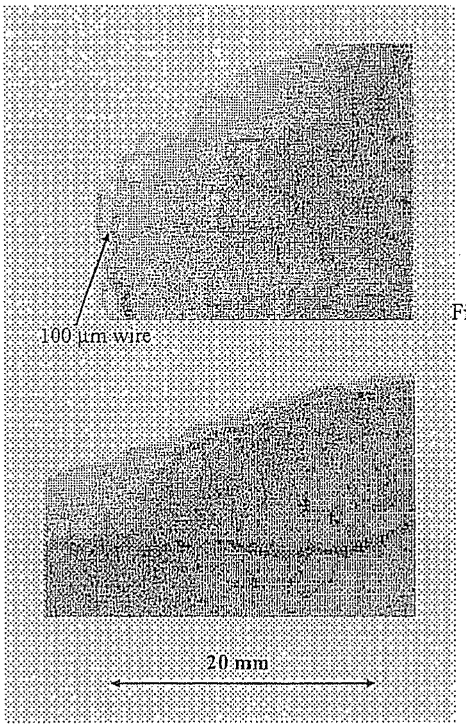

Fig. 10. Angiograms of an extracted dog heart.

ACKNOWLEDGMENT

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REFERENCES

1. 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.
2. 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.
3. 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.
4. 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.
5. 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.
6. 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.
7. 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.
8. 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.
9. 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.
10. 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.
11. T. J. Davis, D. Gao, T. E. Gureyev, A. W. Stevenson and S. W. Wilkins, "Phase-contrast imagimg of weakly absorbing materials using hard x-rays," *Nature*, **373**, 595-597, 1995.
12. A. Momose, T. Takeda, Y. Itai and K. Hirano, "Phase-contrast x-ray computed tomography for observing biological soft tissues," *Nature Medicine*, **2**, 473-475, 1996.
13. 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 synchrotoron radiation," *Radiology*, **201**, 173-177, 1996.
14. 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.
15. A. Ishisaka, H. Ohara and C. Honda, "A new method of analyzing edge effect in phase contrast imaging with incoherent x-rays," *Opt. Rev.*, **7**, 566-572, 2000.
16. 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.
17. 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.
18. 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.
19. 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.

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Super-characteristic x-ray generator utilizing a pipe and rod target

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ABSTRACT

This generator consists of the following components: a constant high-voltage power supply, a filament power supply, a turbomolecular pump, and an x-ray tube. The x-ray tube is a demountable diode which is connected to the turbomolecular pump and consists of the following major devices: a tungsten hairpin cathode (filament), a focusing (Wehnelt) electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, a stainless-steel tube body, a pipe target, and a rod target. The pipe and rod targets are useful for forming linear and cone beams, respectively. In the x-ray tube, the positive high voltage is applied to the anode (target) electrode, and the cathode is connected to the tube body (ground potential). In this experiment, the tube voltage applied was from12 to 20 kV, and the tube current was regulated to within 0.10 mA by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. The electron beams from the cathode are converged to the target by the focusing electrode, and clean K-series characteristic x-rays are produced through the focusing electrode without using a filter. The x-ray intensities of the pipe and rod targets were 1.29 and 4.28 μGy/s at 1.0 m from the x-ray source with a tube voltage of 15 kV and a tube current of 0.10 mA, and quasi-monochromatic radiography was performed using a computed radiography system.

Keywords: demountable x-ray tube, electron-impact source, line beam, cone beam, quasi-monochromatic x-rays, K-series characteristic x-rays, Sommerfeld's theory

1. INTRODUCTION

Gas-discharge capillaries play significant roles in irradiation of soft x-ray lasers,[1-3] and the laser photon energy has been increasing. Subsequently, large-scale x-ray free electron laser sources[4] are constructing as a new-generation radiation source for producing monochromatic coherent x-rays to perform various research projects including biomedical applications. However, it is quite difficult to increase the maximum photon energy to 10 keV or beyond.

Hard X-Ray and Gamma-Ray Detector Physics and Penetrating Radiation Systems VIII,
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To produce short x-ray pulses, several various flash x-ray generators utilizing high-voltage condensers have been developed, and high-speed radiography has been demonstrated. In particular, the importance of forming weakly ionized plasma source[5-8] is well reported to produce clean K-series characteristic x-rays, and the second and fourth harmonic x-rays of the fundamental K-series characteristic x-rays from copper and nickel targets have been confirmed. The x-ray intensities of the harmonics increase with increases in the charging voltage, and the harmonic bremsstrahlung rays survive due to the x-ray resonation in the plasma. However, it is not easy to produce high-photon-energy K-rays using linear plasmas, since the plasmas readily transmit high-photon-energy bremsstrahlung x-rays. In view of this situation, we have developed new flash x-ray generators[9-11] to produce high-photon-energy K-rays of molybdenum, cerium, tantalum, and tungsten.
At present, monochromatic parallel x-ray beams from synchrotrons utilizing silicon crystals are used in various fields including medical imaging. In particular, x-rays with photon energies ranging from 33.3 to 35 keV have been employed to perform enhanced K-edge angiography[12,13] because the rays are absorbed effectively by iodine-based contrast media with an iodine K-edge of 33.2 keV. This imaging plays significant roles in the diagnosis of coronary arteries, fine blood vessels in regenerative medicine, and capillaries in tumors. In contrast, small-scale steady-state monochromatic parallel and cone beams[14-16] can be employed to perform medical imaging in hospitals.

In this research, we developed an x-ray generator used to perform a preliminary experiment for generating clean K-series characteristic x-rays using a pipe and rod target by angle dependence of the bremsstrahlung x-rays.

2. GENERATOR

Figure 1 shows a block diagram of a compact characteristic (quasi-monochromatic) x-ray generator. This generator consists of the following components: a constant high-voltage power supply (SL150, Spellman), a DC filament power supply, a turbomolecular pump, and an x-ray tube. The structures of the x-ray tube are illustrated in Figs. 2 and 3. The x-ray tube is a demountable diode which is connected to the turbomolecular pump with a pressure of approximately 0.5 mPa and consists of the following major devices: a tungsten hairpin cathode (filament), a focusing (Wehnelt) electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, a stainless-steel tube body, a rod copper target of 3.0 mm in diameter, and a pipe copper target with an outside and a bore diameters of 5.0 and 4.0, respectively. In the x-ray tube, the positive high voltage is applied to the anode (target) electrode, and the cathode is connected to the tube body (ground potential). In this experiment, the tube voltage applied was from 12 to 20 kV, and the tube current was regulated to within 0.10 mA by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. The electron beams from the cathode are converged to the target by the focusing electrode, and x-rays are produced through the focusing electrode. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory in Sommerfeld's theory[20] (Figs. 4 and 5), clean molybdenum K-series x-rays can be produced without using a filter.

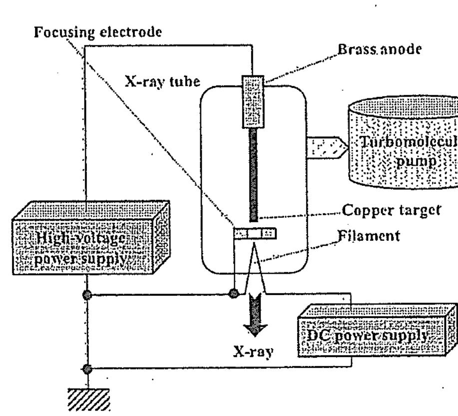

Fig. 1. Block diagram including the main transmission line of the compact x-ray generator with a quasi-monochromatic diode.

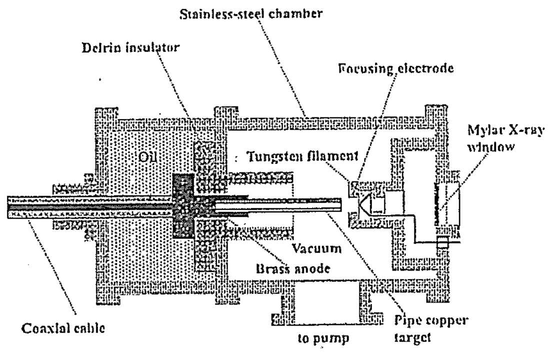

Fig. 2. Schematic drawing of the characteristic x-ray tube with a pipe copper target

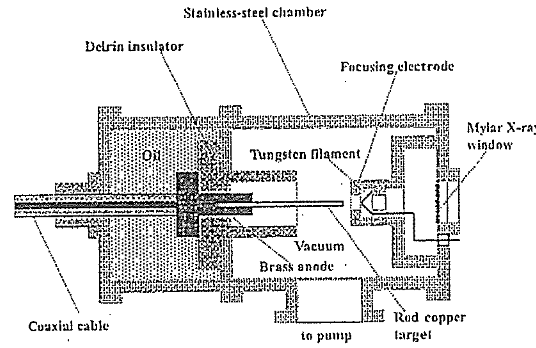

Fig. 3. Structure of the characteristic x-ray tube with a rod copper target.

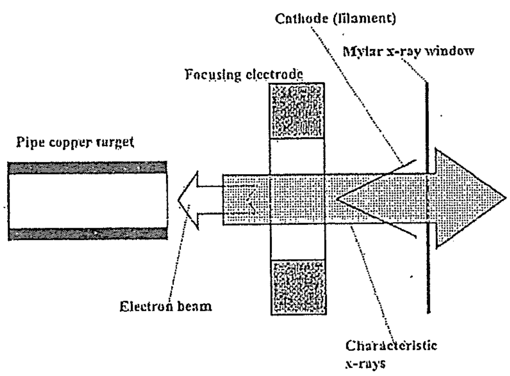

Fig. 4. K-photon irradiation from the pipe-target x-ray tube.

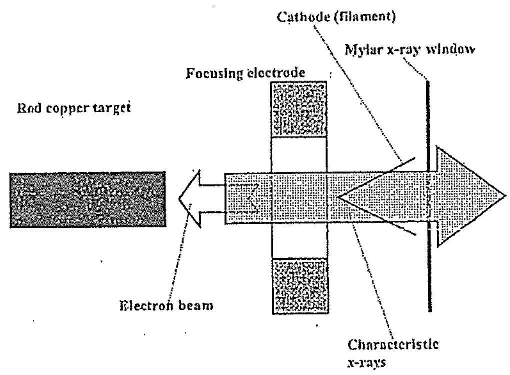

Fig. 5. K-photon irradiation from the rod-target x-ray tube.

3. CHARACTERISTICS

3.1 X-ray intensity

X-ray intensities from the pipe and rod targets were measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source (Figs. 6 and 7). At a constant tube current of 0.10 mA, the x-ray intensity increased when the tube voltage was increased. In this measurement, the intensities of the pipe and rod targets were 1.29 and 4.28 μGy/s, respectively, at 1.0 m from the source with a tube voltage of 15 kV.

3.2 X-ray source

In order to measure images of the x-ray sources, we employed a pinhole camera with a hole diameter of 100 μm in conjunction with a computed radiography (CR) system (Figs. 8 and 9). When the tube voltage was increased using the pipe target, the spot intensities increased, and the maximum diameter was equal to the bore diameter. On the other hand, both the intensity and diameter increased with increases in the tube voltage, and the maximum diameter was approximately 2.2 mm.

3.3 X-ray spectra

X-ray spectra were measured using a silicon detector (XR-100CR, Amptek). We observed sharp K lines, and the characteristic x-ray intensities substantially increased with increases in the tube voltage (Figs, 10 and 12). Clean K lines were left by a 10-μm-thick copper filter, and the Kα lines were selected out by absorbing Kβ lines using a 10-μm-thick nickel filter (Figs. 11 and 13).

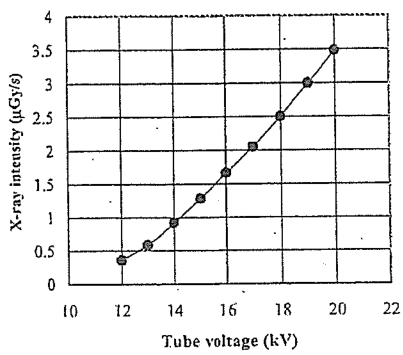

Fig. 6. X-ray intensity at 1.0 m from the pipe target according to changes in the tube voltage with a tube current of 0.10 mA.

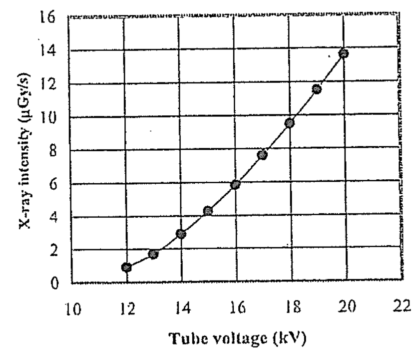

Fig. 7. X-ray intensity at 1.0 m from the rod target with changing the tube voltage with a tube current of 0.10 mA.

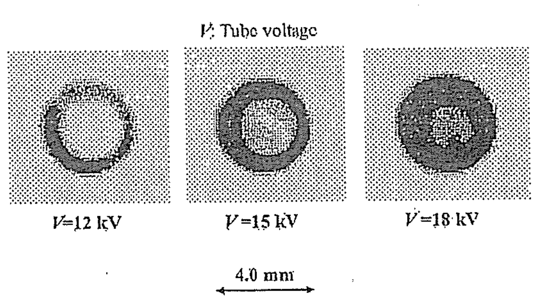

Fig. 8. Images of the characteristic x-ray source from the pipe target with changes in the tube voltage.

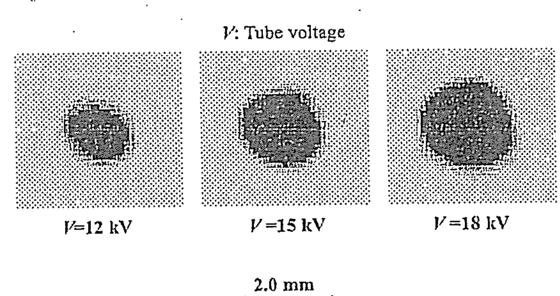

Fig. 9. Images of the characteristic x-ray source from the rod target.

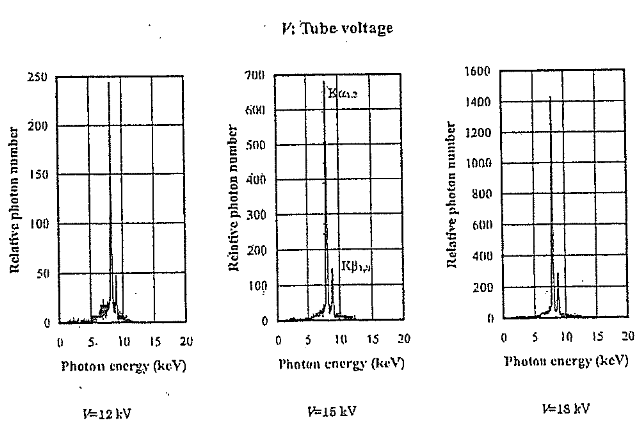

Fig. 10. X-ray spectra from the pipe target with changes in the tube voltage.

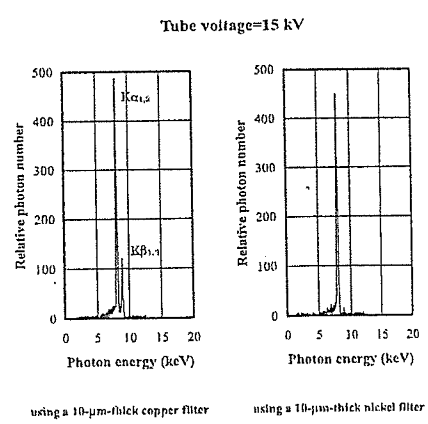

Fig. 11. X-ray spectra from the pipe target according to insertion of filters.

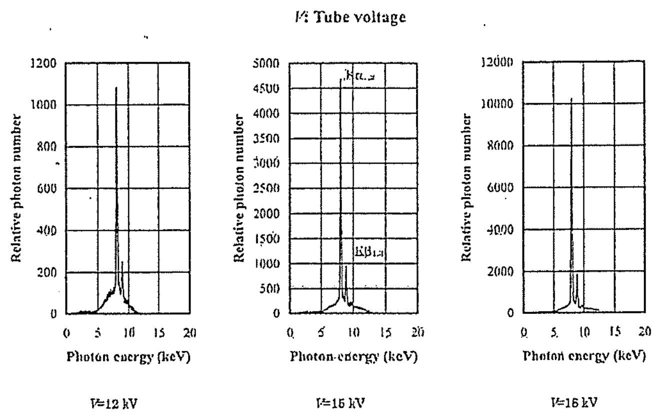

Fig. 12. X-ray spectra from the rod target with changing the tube voltage

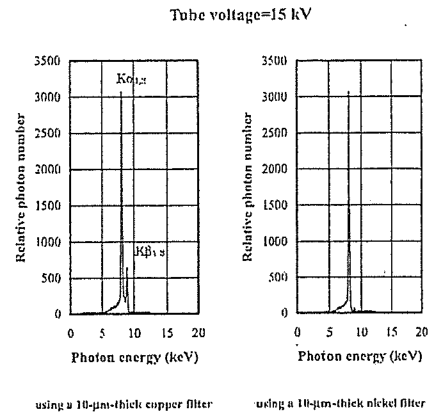

Fig. 13. X-ray spectra from the rod target according to insertion of filters.

4. CONCLUSIONS AND OUTLOOK

We developed a super-characteristic x-ray generator with the pipe and rod targets and succeeded in producing copper K lines. The characteristic x-ray intensity increased with increases in the tube voltage, and monochromatic Kα lines were left by the nickel filter.

In the spectrum measurements, we usually employ a silicon detector and a lithium fluoride curved crystal. The detector is useful for measuring the total spectra, including scattering beams. On the other hand, the spectra from only the x-ray source can be measured using the crystal by selecting Bragg's angle. Using the crystal in conjunction with a computed radiography system, we observed clean copper K lines.

In this preliminary experiment, although the maximum tube voltage and current were 20 kV and 0.10 mA, the voltage and current could be increased to 100 kV and 1.0 mA, respectively. Using the rod target, the generator produced maximum number of characteristic photons from the rod target was approximately 1×10^6 photons/(cm$^2\cdot$ s) at 1.0 m from the source, and the photon count rate can be increased easily by increasing the current.

Currently, the copper K-series characteristic x-rays are useful for extremely soft radiography, and the photon energies of characteristic x-rays can be selected by the target element. In particular, the pipe target is useful for forming monochromatic line beams by decreasing the bore diameter.

ACKNOWLEDGMENT

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REFERENCES

1. J.J. Rocca, V. Shlyaptsev, F.G. Tomasel, O.D.Cortazar, D. Hartshorn and J.L.A. Chilla, "Demonstration of a discharge pumped table-top soft x-ray laser," *Phys. Lev. Lett.*, 73, 2192-2195, 1994.

2. J.J.G. Rocca, J.L.A. Chilla, S. Sakadzic, A. Rahman, J. Filevich, E. Jankowska, E.C. Hammarsten, B.M. Luther, H.C. Kapteyn, M. Murnane and V.N. Shlyapsev, "Advances in capillary discharge soft x-ray laser research," *SPIE*, 4505, 1-6, 2001.

3. S. Le Pape, Ph. Zeitoun, J.J.G. Rocca, A. Carillon, P. Dhez, M. Francois, S. Hubert, M. Idir and D. Ros, "Characterisation of an x-ray laser beam," *SPIE*, **4505**, 23-34, 2001.

4. C. Gerth, "Free-electron laser at the TESLA test facility at DESY: toward a tunable short-pulsed soft x-ray source," *SPIE*, **4505**, 131-145, 2001.

5. 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.

6. 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.

7. 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.

8. 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.

9. 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.

10. 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.

11. 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 gadolium-based contrast media," *Jpn. J. Appl. Phys.*, **44**, 8716-8721, 2005.

12. 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 synchrotoron radiation," *Radiology*, **201**, 173-177, 1996.

13. 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.

14. 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.

15. 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.

16. 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.

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