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Development of an extremely soft x-ray generator

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Abstract

The development of an extremely soft x-ray generator with a tungsten-target tube and its applications including radiography are described. This generator consists of a high-voltage transformer, a filament power supply, and an x-ray tube. Negative high voltages are applied to the cathode electrode in the x-ray tube, and the tube voltage and current are regulated by the input voltage of the transformer and the filament voltage, respectively. The x-ray tube is a glass-enclosed double-focus diode with a tungsten target and a 0.2 mm-thick beryllium window. The maximum tube voltage and the electric power were 60 kV and 400 W, respectively. The focal-spot sizes were 4 × 4 (large) and 1 × 1 mm (small), respectively. Radiography was performed with a computed radiography system. In angiography using iodine-based microspheres, we observed fine blood vessels of about 50 μm or less with high contrasts. Using this generator, we designed an experimental setup for disinfection achieved with extremely soft x rays.

Keywords: extremely soft x-ray, beryllium window, disinfection, soft radiography

1. Introduction

Synchrotrons generate high-dose-rate bremsstrahlung x rays with wide photon energy latitudes, and monochromatic x rays have been produced using single crystals. These monochromatic rays play an important role in parallel radiography and have been employed to perform high-contrast micro-angiography[1] and phase imaging.[2-4]

So far, several different flash x-ray generators have been developed, and soft generators[5-12] with photon

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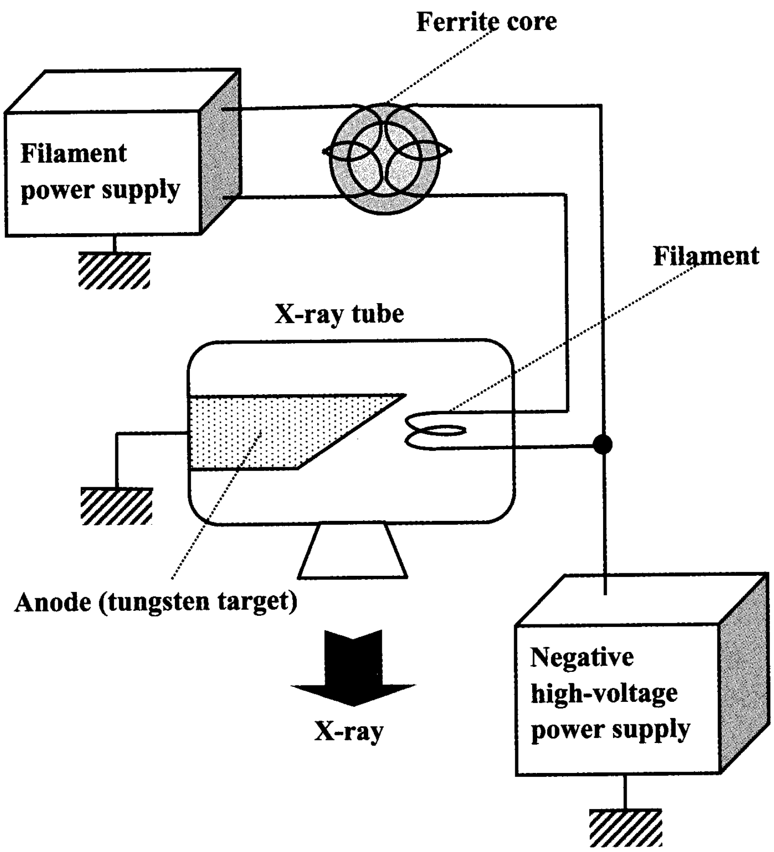


Fig. 1: Block diagram of the extremely soft x-ray generator.

energies of lower than 150 keV can be employed to perform biomedical radiography. In order to produce monochromatic x rays, plasma flash x-ray generators[13-18] are useful, since quite intense and sharp characteristic x rays such as lasers have been produced from weakly ionized linear plasmas of nickel, copper and molybdenum, while bremsstrahlung rays are hardly detected at all.

Currently, soft x rays are employed in order to perform soft radiographies with biomedical applications, and are fairly useful to image soft-tissue biomedical objects. Hereafter, the thickness of the x-ray window of the tube should be decreased as much as possible to produce soft bremsstrahlung x rays of lower than 5 keV. In addition, soft x rays may be used to perform disinfection of various fungi including anthrax, because the x rays are absorbed easily by fungi.

In the present research, we developed an extremely soft x-ray generator with a tungsten-target tube, and used it to perform preliminary studies on disinfection and extremely soft radiography.

2. Generator

Figure 1 shows the block diagram of the x-ray generator, which consists of a high voltage power supply (Figs. 2 and 3), an x-ray tube unit (Fig. 4), and a filament power supply (Fig. 5). The negative high-voltage is applied to the cathode electrode, and the anode (target) is connected to the ground potential. In this experiment, the peak tube voltage was regulated from 10 to 15 kV, and the peak tube current was regulated within 15 mA by the filament voltage (temperature). The exposure time is controlled in

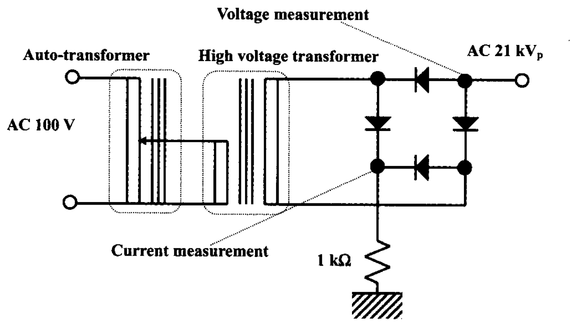


Fig. 2: Circuit diagram of the high voltage power supply.

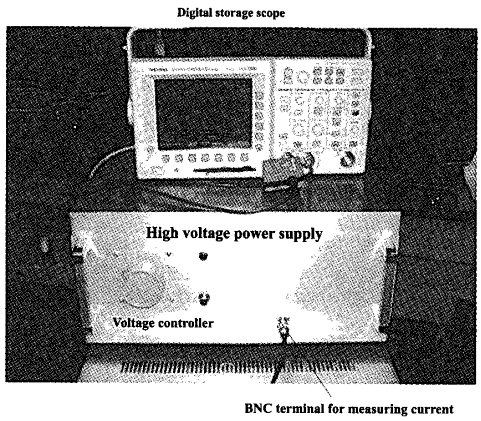


Fig. 3: High-voltage power supply.

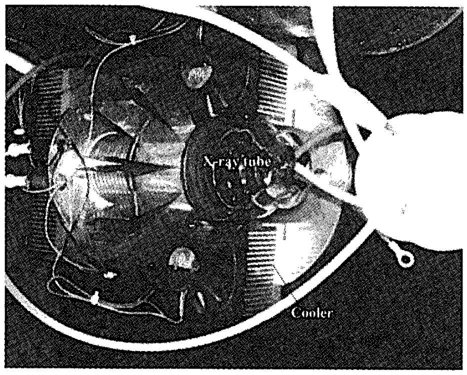


Fig. 4: X-ray tube unit with coolers.

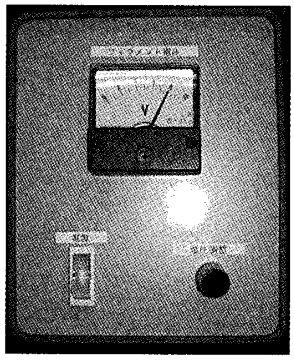


Fig. 5: Filament power supply.

order to obtain optimum x-ray intensity, and the x-ray tube is a double-focus type with focal-spot dimensions of approximately 4 × 4 (large spot) and 1 × 1 mm (small spot), respectively.

3. Characteristics

3.1. Cathode voltage and current

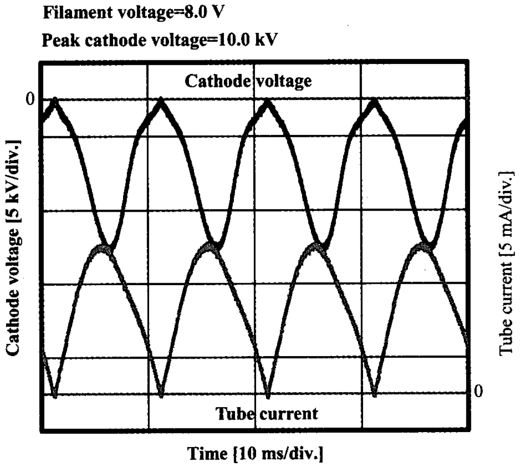
The tube voltage and current were measured by a high-voltage divider and a resistor, respectively, and the tube voltage was −1 times the cathode voltage. Figure 6 shows variations in the voltage and current. At a constant filament voltage of 8 V, the peak tube current increased with increases in the voltage. Next, at a constant tube voltage, the peak current increased when the filament voltage was increased.

3.2. X-ray source

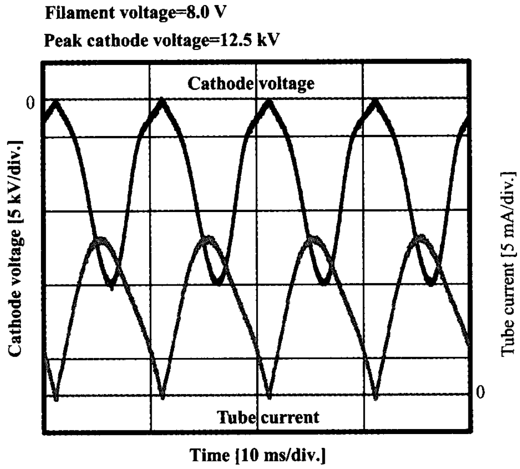
In order to measure images of the x-ray source, we employed a pinhole camera with a hole diameter of 50 μm in conjunction with a Computed Radiography (CR) system.[19] The dimensions of small and large spots seldom varied and had values of approximately 1 × 1 and 4 × 4 mm, respectively.

3.3. X-ray spectra

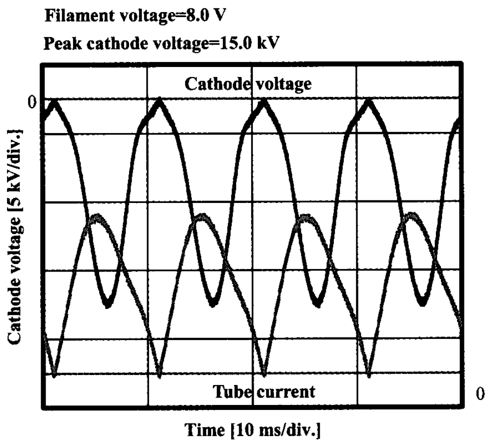
Figure 7 shows transmittivities of beryllium and dry air with changes in the photon energy. When a 0.2 mm-thick beryllium window is employed, x-ray spectra with energies of lower than 2 keV are absorbed



(a)



(b)



(c)

Fig. 6: Cathode voltages and tube currents at the indicated conditions.

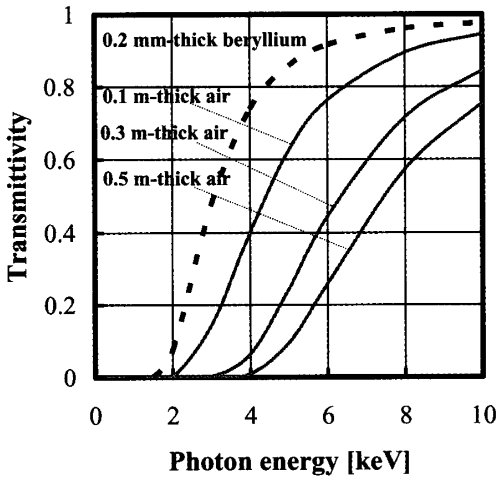


Fig. 7: Transmittivities of x rays with the photon energy.

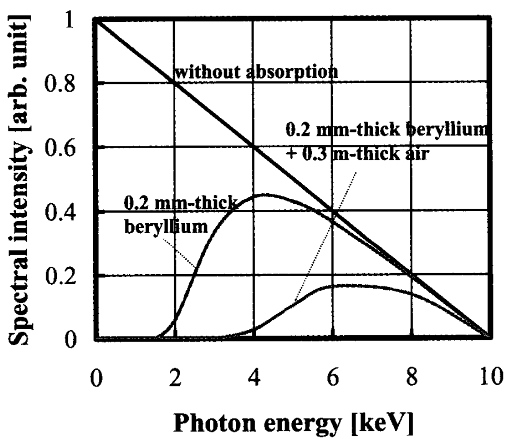


Fig. 8: Calculated bremsstrahlung spectra at the indicated conditions.

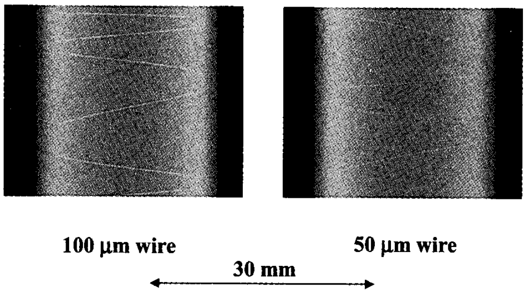


Fig. 9: Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around pipes made of polymethyl methacrylate.

Fig. 10: Radiogram of cigarettes.

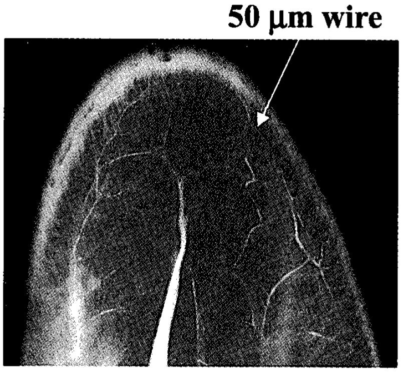


Fig. 11: Angiograms of the external ear of a rabbit using iodine-based microspheres.

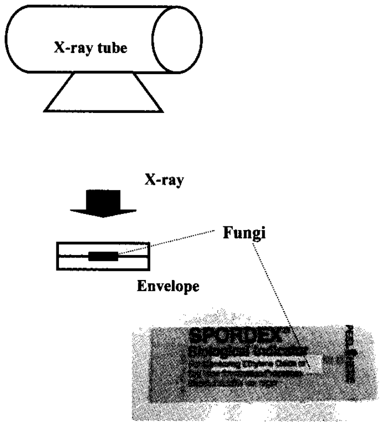


Fig. 12: Experimental setup for disinfection.

effectively. Subsequently, 0.5 m-thick air transmits x rays with energies of higher than 4 keV.
The x-ray spectra were calculated by the mass attenuation coefficients of the beryllium and the dry air (Fig. 8). As shown in this figure, the soft x rays of lower than 2 keV were primarily absorbed by the beryllium x-ray window, and the rays were also absorbed by the air. Therefore, the distance should be decreased as much as possible in order to obtain soft x rays.

4. Radiography

The radiography was performed by the CR system (Konica Regius 150), and the distance between the x-ray source and imaging plate was 0.35 m. Next, the peak tube voltage, the peak current, and the exposure time were 10 kV, 10 mA, and 10 s, respectively. Figure 9 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate. Although the image contrast increased with increases in the wire diameter, a 50 μm-diameter wire could be observed.
A radiogram of cigarettes is shown in Fig. 10. In this radiography, we obtained an extremely soft radiogram, and the contents of cigarettes were hardly observed at all.
Figure 11 shows an angiogram of the external ear of a rabbit; iodine-based microspheres of 15 μm diameter were used, and fine blood vessels of about 50 μm were clearly visible.

5. Design of experimental setup for disinfection

Figure 12 shows the experimental setup for disinfection using soft x rays. Fungi were enclosed in an envelope and were exposed to soft x rays. After measuring all the radiographic characteristics, we plan to perform disinfection of various fungi with changes in the radiographic conditions.

6. Discussion

In the present work, we succeeded in generating extremely soft x rays using a 0.2 mm-thick beryllium window in conjunction with a tungsten target. Therefore, L-series characteristic x rays are produced with tube voltage of higher than 12.1 kV. In radiography, the image quality became hard according to increases in the thickness of the aluminum filter, because the low photon energy x rays were absorbed easily by the filter. Using this x-ray generator, although K-series characteristic x rays of tungsten are not produced due to the tube voltage, the photon energies of the characteristic x rays can be selected by the target element.

In disinfection, the distance between the x-ray source and fungi should be decreased as much as possible to decrease the absorbed x-ray intensity by air. Subsequently, because the air is dissociated greatly, ion beams will also be a useful technique for disinfection and the excluding of static electricity from semiconductor devices.

Because it is possible to produce low photon energy x rays and to perform extremely soft radiography and x-ray disinfection, and to exclude electricity, this system can be applied in various fields.

Acknowledgments

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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 synchrotoron radiation," *Radiology*, **201**, pp. 173-177, 1996.
2. T.J. Davis, D. Gao, T.E. Gureyev, A.W. Stevenson and S.W. Wilkims, "Phase-contrast imagimg of weakly absorbing materials using hard x-rays," *Nature*, **373**, pp. 595-597, 1995.
3. A. Momose, T. Takeda, Y. Itai and K. Hirano, "Phase-contrast x-ray computed tomography for observing biological soft tissues," *Nature Medicine*, **2(4)**, pp. 473-475, 1996.
4. 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**, pp. 566-572, 2000.
5. 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**, pp. 2343-2348, 1990.
6. S. Kimura, E. Sato, M. Sagae, A. Shikoda, T. Oizumi, K. Takahashi, Y. Tamakawa and T. Yanagisawa,

"Disk-cathode flash x-ray tube driven by a repetitive two-stage Marx pulser," *Med. & Biol. Eng. & Comput.*, **31**, pp. S37-S43, 1993.

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," *SPIE*, **2513**, pp. 649-667, 1994.
8. E. Sato, M. Sagae, K. Takahashi, A. Shikoda, T. Oizumi, H. Ojima, K. Takayama, Y. Tamakawa, T. Yanagisawa, A. Fujiwara and K. Mitoya, "Dual energy flash x-ray generator," *SPIE*, **2513**, pp. 723-735, 1994.
9. 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**, pp. 850-856, 1994.
10. 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**, pp. 289-294, 1994.
11. 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**, pp. 4146-4151, 1994.
12. E. Sato, M. Sagae, A. Shikoda, K. Takahashi, T. Oizumi, M. Yamamoto, A. Takabe, K. Sakamaki, Y. Hayasi, H. Ojima, K. Takayama and Y. Tamakawa, "High-speed soft x-ray techniques," *SPIE*, **2869**, pp. 937-955, 1996.
13. E. Sato, Y. Suzuki, Y. Hayasi, 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.
14. 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.
15. E. Sato, Y. Hayasi, E. Tanaka, H. Mori, T. Kawai, T. Usuki, K. Sato, H. Obara, T. Ichimaru, K. Takayama, H. Ido and Y. Tamakawa, "Quasi-monochromatic radiography using a high-intensity quasi-x-ray laser generator," *SPIE*, **4682**, pp. 538-548, 2002.
16. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, H. Obara, T. Ichimaru, K. Takayama and H. Ido, "Intense characteristic x-ray irradiation from weakly ionized linear plasma and applications," *Jpn. J. Med. Imag. Inform. Sci.*, **20**, pp. 148-155, 2003.
17. 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.*, **20**, pp. 123-131, 2003.
18. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, K. Takayama and Hideaki Ido, "Quasi-monochromatic flash x-ray generator utilizing weakly ionized linear copper plasma," *Rev. Sci. Instrum.*, **74**, pp. 5236-5240, 2003.
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 and Sci.*, **35**, pp. 13-23, 2000.