m from the x-ray source with a charging voltage of 80 kV.

### 4.3 X-ray source

In order to observe the Kα x-ray source, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 6). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased. Because the x-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing x-rays and decreases in the pinhole diameter.

### 4.4 X-ray spectra

X-ray spectra were measured using a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The x-ray intensities of the spectra were detected by an imaging plate of a computed radiography (CR) system[18] (Konica Minolta Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom original digital data corresponding to x-ray intensity; the data was scanned by Dicom viewer in the film-less CR system. Subsequently, the relative x-ray intensity as a function of the data was calibrated using a conventional x-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 7 shows measured spectra from the tungsten target. We observed clean Kα lines, while Kβ lines and bremsstrahlung rays were hardly detected. The Kα intensity increased with increases in the charging voltage.

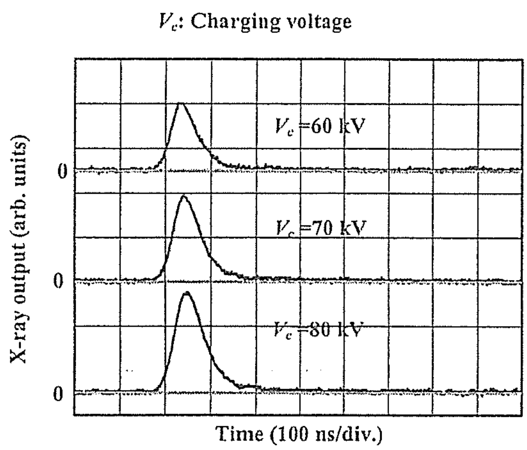


Figure 5: X-ray outputs detected using a combination of a plastic scintillator and a photomultiplier.

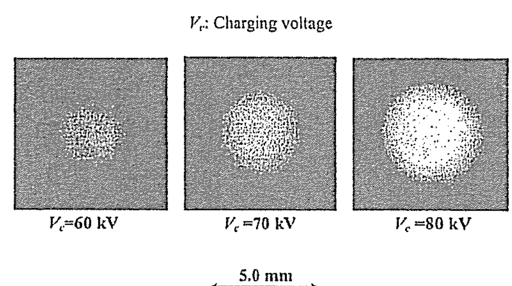


Figure 6: Images of Kα-ray source obtained using a pinhole camera with changes in the charging voltage.

## 5. ANGIOGRAPHY

The flash angiography was performed using the CR system and the filter at 1.2 m from the x-ray source, and the charging voltage was 80 kV.

Firstly, rough measurements of spatial resolution were made using wires. Figure 8 shows radiograms of tungsten wires in a rod made of polymethyl methacrylate (PMMA). 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 μm, a 50 μm-diameter wire could be observed.

The image of water (20% gadolinium oxide suspension) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. The diameter of gadolinium oxide powder ranges from 1 to 10 μm. Because the x-ray duration was about 60 ns, the stop-motion image of water could be obtained.

Figure 10 shows an angiogram of a polytetrafluoroethylene (Teflon) tube in a PMMA case using a contrast medium which contains approximately 65% gadodiamidehydrate, and a high-contrast tube with a bore diameter of 1.0 mm is observed. Figures 11 and 12 show angiograms of a rabbit ear and head using gadolinium oxide powder, and fine blood vessels of approximately 100 μm were visible.

## 6. CONCLUSIONS AND OUTLOOK

We succeeded in producing tungsten Kα rays and in performing K-edge angiography using gadolinium contrast media with a K-edge of 50.2 keV, and this K-edge angiography could be a useful technique to decrease the dose absorbed by patients. In angiography, we employed tungsten Kα (58.9 keV) rays by absorbing Kβ rays (approximately 67 keV) using the ytterbium oxide filter, and L-series characteristic rays were also absorbed.

We obtained sufficient x-ray intensity per pulse for CR angiography with x-ray durations of approximately 60 ns, and the intensity can be increased by increasing the charging voltage at a constant target-cathode space. Currently, the x-ray duration increased with increases in the target-cathode space. In this research, the generator produced instantaneous number of Kα photons was approximately $1.5 \times 10^8$ photons/cm$^2$ per pulse at 1.0 m from the source.

Because the dimensions of the x-ray source are primarily determined by the target diameter, the diameter should be minimized in order to improve the spatial resolution, and can be reduced to approximately 0.5 mm. Because the x-ray intensity is the highest at the center of the spot, the effective focal spot size decreased during x-ray absorption in an object. Subsequently, the sampling pitch can be decreased to 43.8 μm using a CR system (Konica Minolta Regius 190) to observe fine blood vessels of approximately 50 μm in diameter.

Using this flash x-ray generator, enhanced K-edge angiography using iodine contrast media and a cerium target can be also performed. In addition, steady-state monochromatic x-rays can be produced by a similar tube utilizing a hot cathode and a constant high-voltage power supply. Using a tungsten or a molybdenum target, fine focusing can be realized, and these x-ray generators could be employed to perform quasi-monochromatic phase-contrast radiography for edge enhancement.

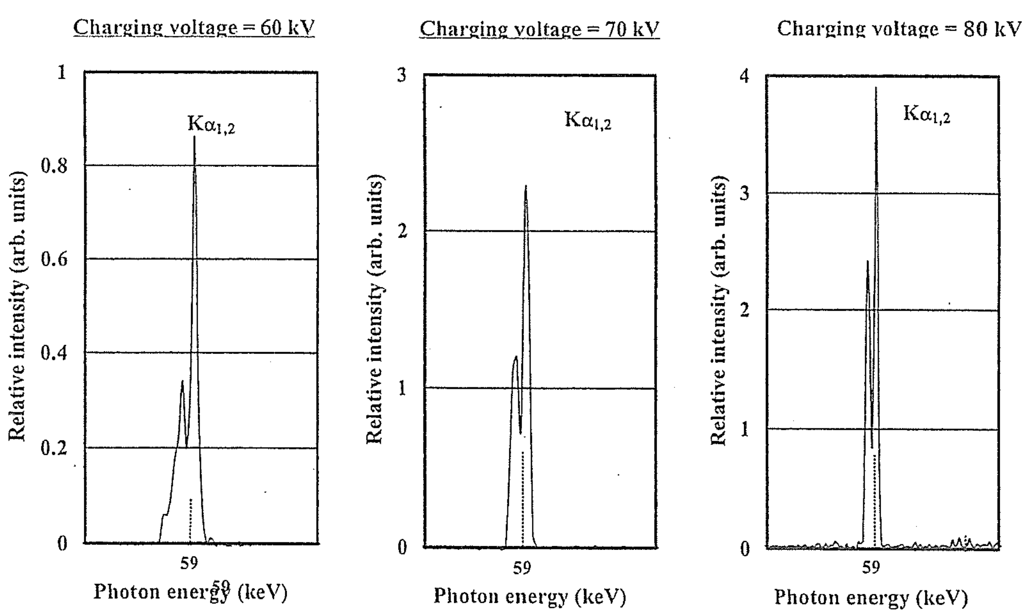


Figure 7: X-ray spectra from a tungsten target. The spectra were measured using a transmission type spectrometer with a lithium fluoride curved crystal.

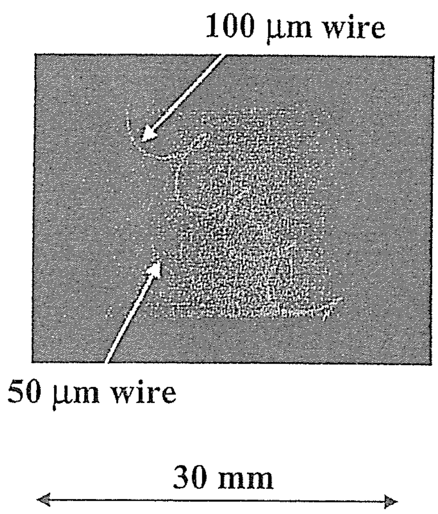


Figure 8: Radiograms of tungsten wires in a PMMA rod. gadodiamidehydrate.

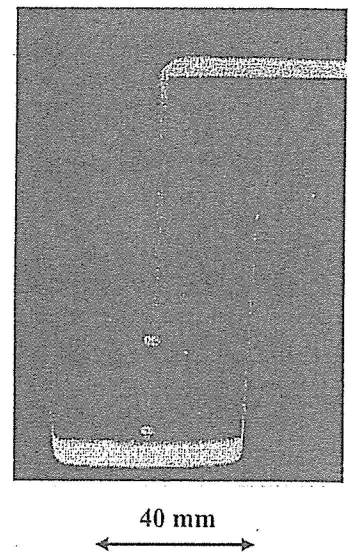


Figure 9: Radiogram of water falling into a polypropylene beaker from a glass test tube.

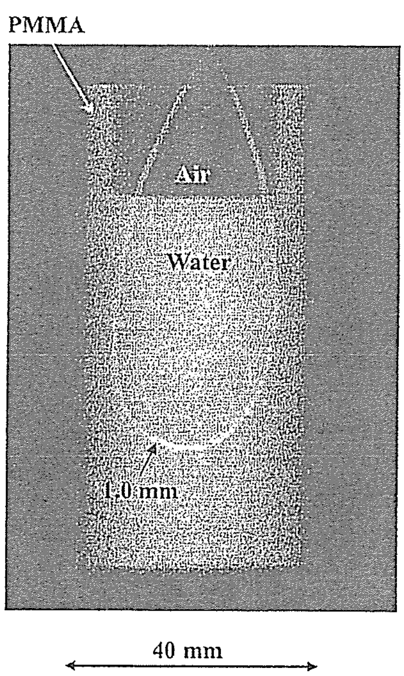


Figure 10: Angiography of a Teflon tube using a contrast medium which contains approximately 65% gadodiamidehydrate.

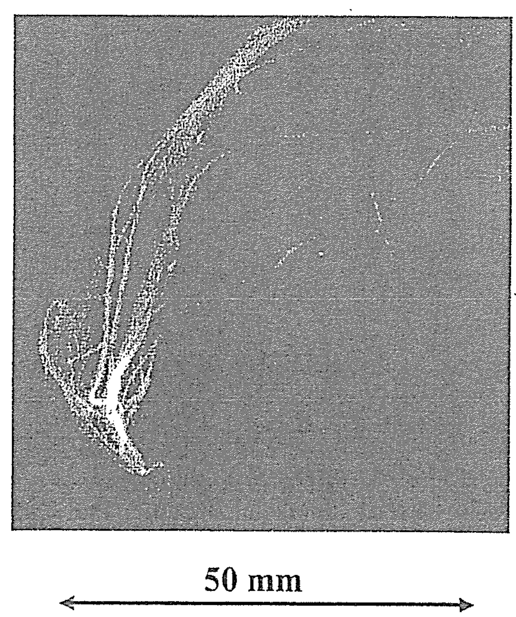


Figure 11: Angiography of a rabbit ear using gadolinium oxide powder.

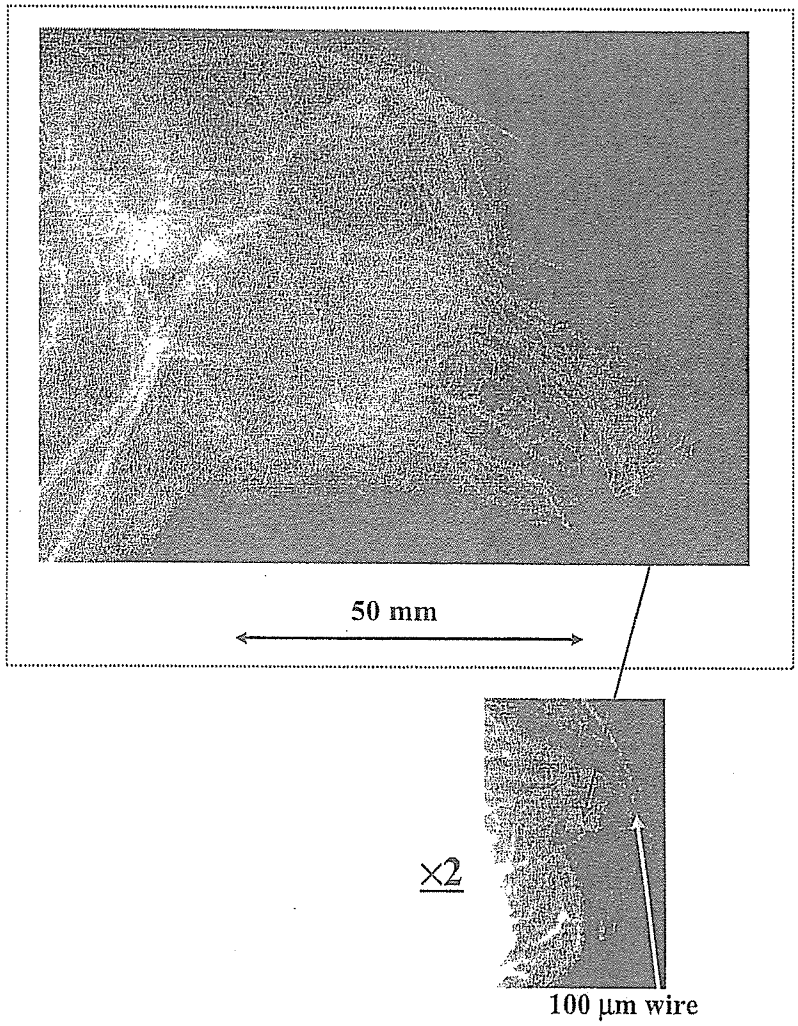


Figure 12: Angiography of a rabbit head using gadolinium oxide powder.

## ACKNOWLEDGEMENTS

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 16591181, and 16591222) and Advanced Medical Scientific Research from MECSST, Health and Labor Sciences Research Grants (RAMT-nano-001, RHGTEFB-genome-005 and RHGTEFB-saisei-003), Grants from the Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and the New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

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# Preliminary study for producing higher harmonic hard x-rays from weakly ionized copper plasma

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## ABSTRACT

In the plasma flash x-ray generator, a 200 nF condenser is charged up to 50 kV by a power supply, and flash x-rays are produced by the discharging. The x-ray tube is a demountable triode with a trigger electrode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Target evaporation leads to the formation of weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target, and intense Kα lines are left using a 10-μm-thick nickel filter. 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 K-series characteristic x-rays were clean and intense, and higher harmonic x-rays were observed. 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.

**Keywords:** weakly ionized linear plasma, K-series characteristic x-rays, clean characteristic x-rays, higher harmonic hard x-rays

## 1. INTRODUCTION

In order to produce soft x-ray lasers, several different methods have been developed, and a discharge capillary[1-3] is very useful to increase the laser pulse energy with increases in the capillary length. However, it is difficult to increase the laser photon energy to 10 keV or beyond.

Using monochrocollimators, synchrotrons produce monochromatic parallel beams, which are fairly similar to monochromatic parallel laser beams, and the beams have been applied to various research project including

Ultrafast X-Ray Detectors, High-Speed Imaging, and Applications, edited by Stuart Kleinfelder, Dennis L. Paisley, Zenghu Chang, Jean-Claude Kieffer, Jerome B. Hastings, Proc. of SPIE Vol. 5920 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.620216

phase-contrast radiography[4,5] and enhanced K-edge angiography.[6,7] Because there are no x-ray resonators in the high-photon-energy region, new methods for increasing coherence will be desired in the future.

To apply flash x-ray generators to biomedicine, several different generators[8-13] have been developed, and plasma x-ray generators[14-17] are useful for producing clean characteristic x-rays in the low-photon-energy region of less than 20 keV. By forming weakly ionized linear plasma using rod targets, we confirmed irradiation of intense K-series characteristic x-rays from the axial direction of the linear plasmas of nickel, copper, and molybdenum, since the bremsstrahlung x-rays are absorbed effectively by the linear plasma; monochromatic clean K$\alpha$ rays were produced using K-edge filters. In this paper, we describe a recent plasma flash x-ray generator utilizing a rod target triode, used to perform a preliminary experiment for generating clean K-series characteristic x-rays and their higher harmonic hard x-rays by forming a plasma cloud around a fine target.

## 2. GENERATOR

Figure 1 shows a block diagram of the high-intensity plasma flash x-ray generator. This generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 200 nF, a 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 schematic drawing of the plasma x-ray tube is illustrated in Fig. 2. 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.

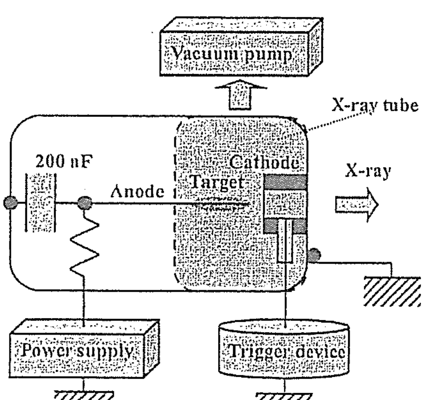



Figure 1: Block diagram including the electric circuit of the plasma flash x-ray generator.

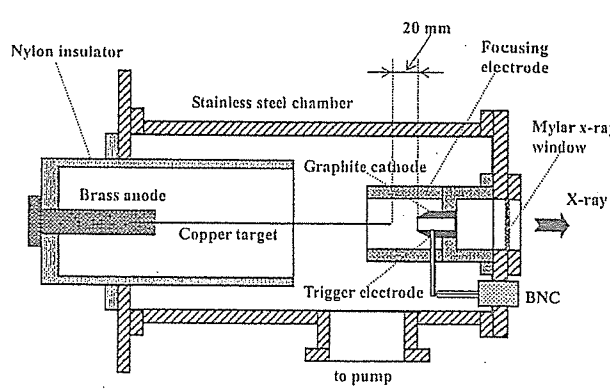



Figure 2: Schematic drawing of the flash x-ray tube with a rod copper target.

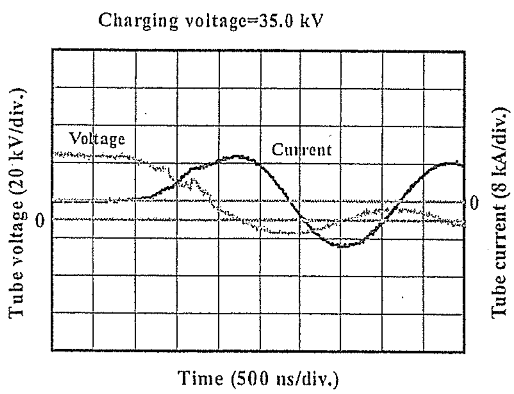
# 3. CHARACTERISTICS

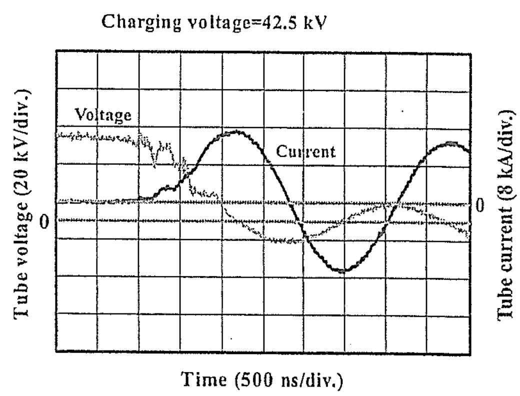
### 3.1 Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. Figure 3 shows the 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 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was approximately 16 kA.

### 3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 4). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 300 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 1.5 mGy at 1.0 m from the x-ray source with a charging voltage of 50 kV.



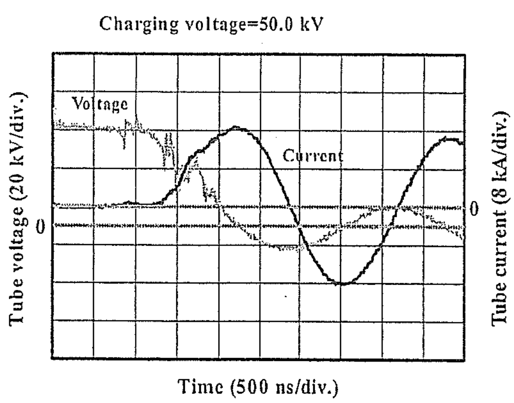




Figure 3: Tube voltages and currents with changes in the charging voltage.

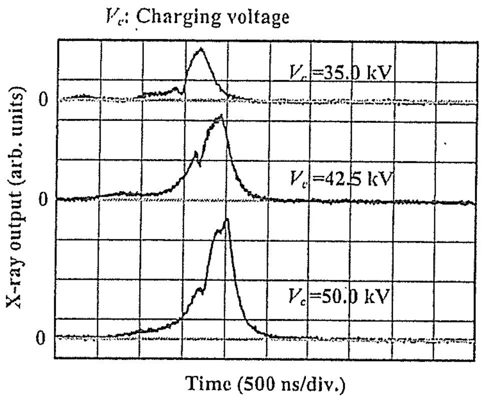



Figure 4: X-ray outputs at the indicated conditions.

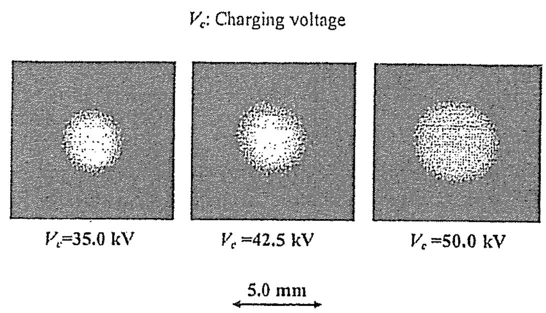



Figure 5: Images of the plasma x-ray source.

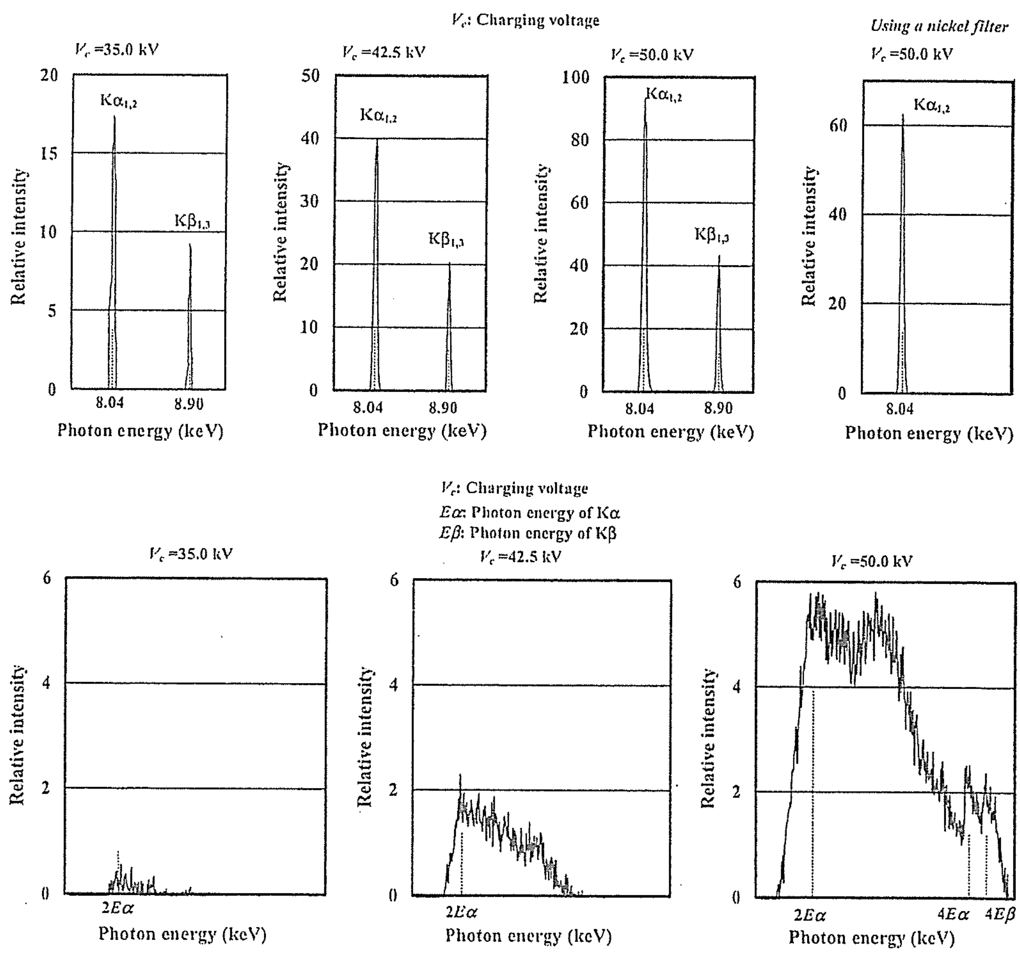



Figure 6: X-ray spectra from weakly ionized copper plasma at the indicated conditions.

## 3.3 X-ray source

In order to roughly observe images of the plasma x-ray source in the detector plane, we employed a pinhole camera with a hole diameter of 100 µm (Fig. 5). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased. Because the x-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing x-rays and decreases in the pinhole diameter.

## 3.4 X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[18] (Konica Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Subsequently, the relative x-ray intensity as a function of the data was calibrated using a conventional x-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 6 shows measured spectra from the copper target at the indicated conditions. In fact, we observed clean K lines such as lasers, and Kα lines were left by absorbing Kβ lines using a 10-µm-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.

# 4. 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.

Firstly, rough measurements of spatial resolution were made using wires. Figure 7 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate (PMMA). 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 µm, a 50-µm-diameter wire could be observed.

Figure 8 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. Next, a radiogram of plastic bullets falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. Because the x-ray duration was about 0.5 µs, the stop-motion image of bullets could be obtained. Figure 10 shows an angiogram of a rabbit ear; iodine-based microspheres of 15 µm in diameter were used, and fine blood vessels of about 100 µm were visible.

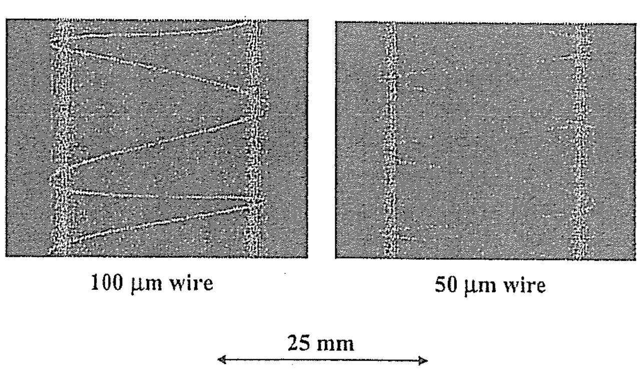



Figure 7: Radiograms of tungsten wires coiled around PMMA pipes.

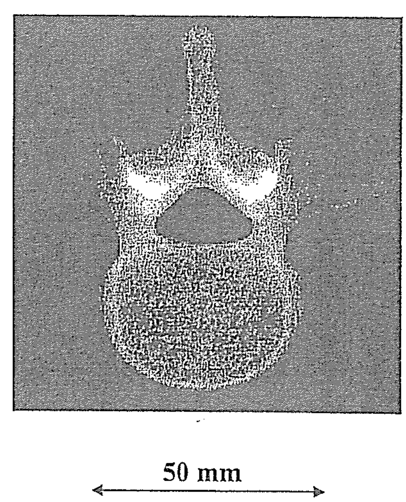



Figure 8: Radiogram of a vertebra.

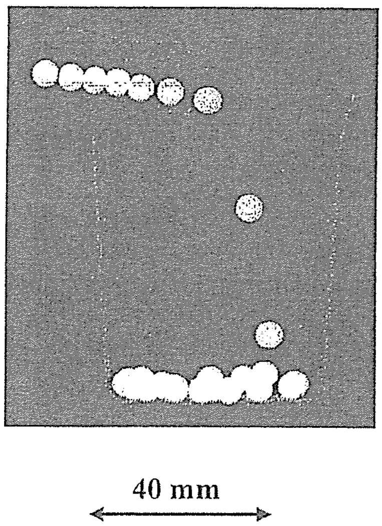



Figure 9: Radiogram of plastic bullets falling into polypropylene beaker from a plastic test tube.

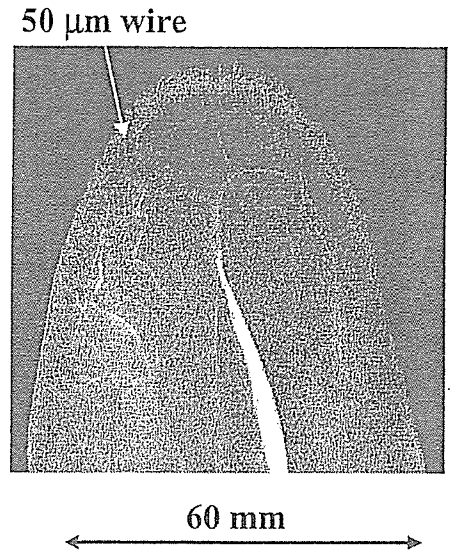



Figure 10: Angiogram of a rabbit ear.

## 5. CONCLUSIONS AND OUTLOOK

We obtained fairly intense and clean K lines from a weakly ionized linear plasma x-ray source, and Kα lines were left by absorbing Kβ lines using the nickel filter. In particular, the higher harmonic x-rays were produced from the plasma. Assuming that the harmonic rays are produced by the x-ray resonation (Fig. 11), the estimated spectra are shown in Fig. 12. In cases where a nickel target is employed, fractional harmonic x-rays are absorbed by the x-ray window and the air. In cases where weakly ionized linear plasma is employed, intense and clean K-series characteristic x-rays can be obtained. However, it is not easy to produce high-photon-energy K-series characteristic x-rays because the plasma transmits high-photon energy bremsstrahlung x-rays. Therefore, high-photon-energy plasma flash x-ray generator utilizing angle dependence of bremsstrahlung x-rays are very useful to produce K photons of molybdenum, silver, cerium, tantalum, and tungsten.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography, and the generator produced number of characteristic K photons was approximately $1\times10^8$ photons/cm$^2$ at 1.0 m per pulse. In addition, we are very interested in producing steady-state clean K rays and their higher harmonic hard x-rays using a similar tube in near future.

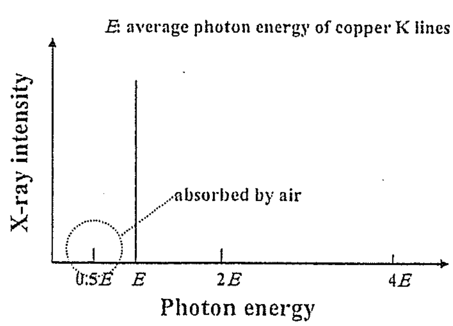



Figure 11: X-ray resonation without using a resonator.

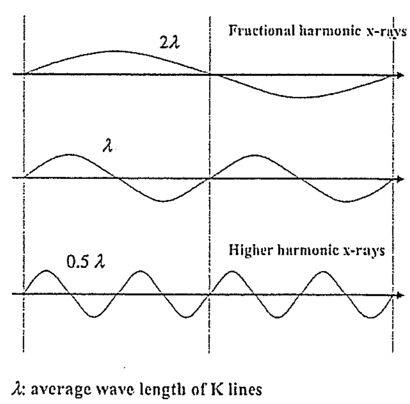



Figure 12: Estimated x-ray spectra under resonation.

## ACKNOWLEDGMENTS

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循環器疾患等生活習慣病対策総合研究事業

# 心筋微小血管造影装置の開発による
# 糖尿病性心筋微小循環障害の可視化

(H18-循環器等（生習）- 一般 -018)

平成16-18年度　総合研究報告書

Vol.2

主任研究者　盛　英三

平成19年（2007年）3月

# Irradiation of orderly multi-line spectra from linear plasma formed by vacuum discharge capillary

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## ABSTRACT

The fundamental experiments for measuring soft x-ray characteristics from the vacuum capillary are described. These experiments are primarily performed in order to generate intense soft x rays. The generator consists of a high-voltage power supply, a polarity-inversion ignitron pulse generator, a turbomolecular pump, and a radiation tube with a capillary. A high-voltage condenser of 200 nF in the pulse generator is charged up to 20 kV by the power supply, and the electric charges in the condenser are discharged to the capillary in the tube after closing the ignitron. During the discharge, weakly ionized plasma forms on the inner and outer sides of a capillary. In the present work, the pump evacuates air from the tube with a pressure of about 1 mPa, and a demountable capillary was developed in order to measure x-ray spectra according to changes in the capillary length. In this capillary, the anode (target) and cathode elements can be changed corresponding to the objectives. The capillary diameter is 2.0 mm, and the length is adjusted from 1 to 50 mm. When a capillary with aluminum anode and cathode electrodes was employed, both the cathode voltage and the discharge current almost displayed damped oscillations. The peak values of the voltage and current increased when the charging voltage was increased, and their maximum values were –11.5 kV and 4.7 kA, respectively. The x-ray durations observed by a 1.6 μm aluminum filter were less than 30 μs. In the spectrum measurement, we observed orderly multi-line spectra. The line photon energies seldom varied according to changes in the condenser charging voltage and to changes in the electrode element. The line number decreased with corresponding decreases in the capillary length.

**Keywords:** flash x-ray, capillary discharge, vacuum discharge, orderly multi-line spectra, x-ray resonation

## 1. INTRODUCTION

A number of flash x-ray generators have been developed in order to perform high-speed radiography,[1] and the generators with maximum photon energies of less than 150 keV can be employed to perform soft radiography including biomedical applications.[2-7] Without considering the coherence, we performed preliminary experiments for generating high-intensity K-series characteristic x rays from weakly ionized linear metal plasma.[8-11] In these experiments, we confirmed the irradiation of intense characteristic x rays from the plasma axial direction, because the bremsstrahlung x rays with energies of higher than the K-absorption edge are absorbed effectively and are converted into fluorescen x rays.

In recent years, many valuable discoveries have been made in laser technology, and high brightness x-ray lasers have been generated by optical lasers.[12] Subsequently, the lasers have been produced using a gas-discharge capillary.[13,14] In these experiments, the laser energy increased with increases in the capillary length, and these kinds of first discharges can generate hot and dense plasma columns with aspect ratios of 1000:1. However, using x-ray amplification by stimulated emission, it is very difficult to increase the x-ray photon energy and the duration.

We performed some experiments for generating K-series characteristic x rays using a vacuum discharge capillary by forming weakly ionized linear plasma. When a capillary with aluminum anode and cathode electrodes was employed, we observed multi-line spectra. These rays could penetrate a 2.4 μm aluminum filter easily, and we found an ordinality in the wave length.

In this paper, we present the experimental results for the low-photon-energy flash x-ray generator with an x-ray tube



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utilizing a vacuum-discharge ferrite capillary, and derive a hypothesis concerning soft x-ray resonation without using a resonator.

## 2. GENERATOR

### 2.1 High-voltage transmission line

The block diagram including the high-voltage transmission line of a low-photon-energy flash x-ray generator is illustrated in Fig. 1. This generator consists of the following essential components: a high-voltage power supply, a polarity-inversion ignitron-driven pulse generator, a turbomolecular pump, and a radiation tube with a new capillary. A high-voltage condenser of 200 nF in the high-voltage pulse generator is charged up to 20 kV by the power supply, and the electric charges in the condenser are discharged to the capillary in the tube through a 2.0 m coaxial cable after closing the ignitron. The plasma flash x-ray source formed on the inner and outer sides of a capillary, and soft x rays are then produced.

### 2.2 Low-photon-energy flash x-ray tube

Figure 2 shows schematic drawing of the low-photon-energy flash x-ray tube. This tube is composed of the following major parts: a ferrite capillary (Fig. 3), insulators, and a polymethyl methacrylate chamber. In the present work, the pump evacuates air from the tube with a pressure of about 1 mPa, and a demountable capillary was developed in order to measure x-ray spectra according to changes of the capillary length. In this capillary, the anode (target) and cathode elements can be changed corresponding to the objectives. The capillary diameter is 2.0 mm, and the length is adjusted from 1 to 50 mm.

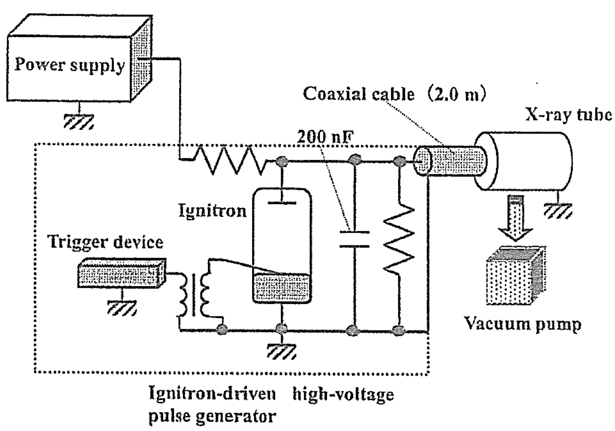



Figure 1: Block diagram including main transmission line of low photon energy flash x-ray generator.

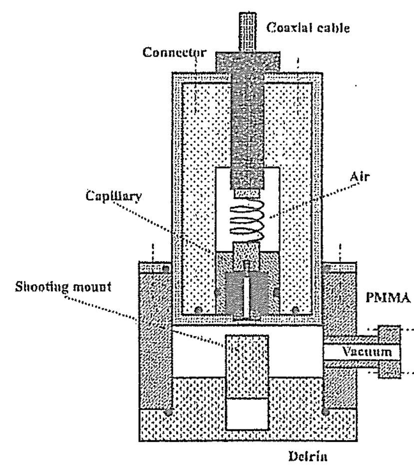



Figure 2: Low-photon-energy flash x-ray tube.

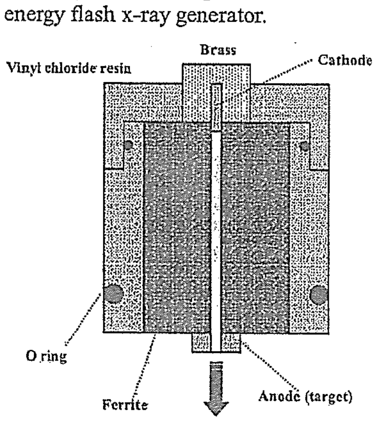



Figure 3: Ferrite capillary.

## 3. RADIOGRAPHIC CHARACTERISTICS

The cathode voltage, the discharge current, and the x-ray output were measured with a capillary length of 25 mm and a time scale of 5 μs/div.

### 3.1 Cathode voltage

The cathode voltages (−1 times the tube voltage) measured by a divider are shown in Fig. 4. The voltages almost displayed damped oscillations, and the peak cathode voltage roughly increased in proportion to the charging voltage. The maximum voltage had a value of −11.5 kV with a charging voltage of 20 kV. In the present work, since the surface-discharge capillary was employed, the electron accelerating voltage was much lower than the tube voltage.

### 3.2 Discharge current

In order to measure the discharge current, we employed a current transformer (Fig. 5). The discharge currents also displayed damped oscillations. When the charging voltage was increased, both the peak current and the current duration increased. The maximum tube current had a value of 4.7 kA, and the current duration was less than 30 μs.

### 3.3 X-ray output

In order to measure soft x rays, a plastic scintillator was employed to decrease electromagnetic noises caused by the vacuum discharge. The fluorescent outputs from the scintillator were lead to a photomultiplier through a plastic fiber, and the output voltages from the photomultiplier were measured by a digital storage scope.

Figures 6 and 7 show the soft x-ray outputs from the capillary according to changes in the charging voltage. Although this flash x-ray generator is primarily designed to produce characteristic x rays of aluminum Kα, the generator also produces ultraviolet rays and visible lights. When we employed an aluminum filter of 1.6 μm, extremely soft x rays were detected. Both the pulse height and duration substantially increased with corresponding increases in the charging voltage (Fig. 6). The soft x-ray outputs obtained using an aluminum filter of 6.8 μm are shown in Fig. 7. When this filter is employed, we can detect K-series characteristic x rays effectively, and the x-ray intensity increased substantially with corresponding increases in the charging voltage.

### 3.4 Spectra

The x-ray spectra were measured using a holographic plate grating of 1,200 lines per 1 mm (Fig. 8). In this setup, the spectra are diffracted and taken by an x-ray glass plate (Ilford Q Plate). Figures 9 show the measured spectra obtained by aluminum electrodes, respectively, at the indicated conditions. Because aluminum Kα lines with photon energies of 1.486 keV is as near as the total internal reflecting rays, it was very difficult to distinguish the lines from the reflecting rays. However, we observed high-intensity multiple lines in the lower photon energy region, and the 2.4 μm aluminum filter transmitted the x rays easily. These lines are not high order diffraction lines because some lines are absorbed easily by the filter.

In the measurement using titanium electrodes, the photon energies (wave lengths) of the lines seldom varied according to changes in the condenser charging voltage, but the line number decreased with decreases in the capillary length.

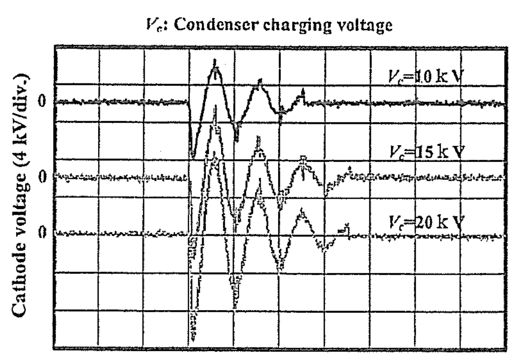



Figure 4: Cathode voltages at the indicated conditions.

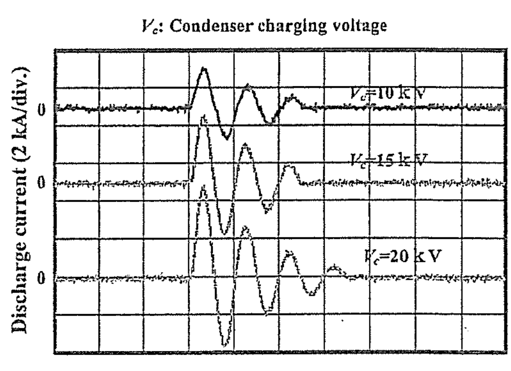



Figure 5: Discharge currents.

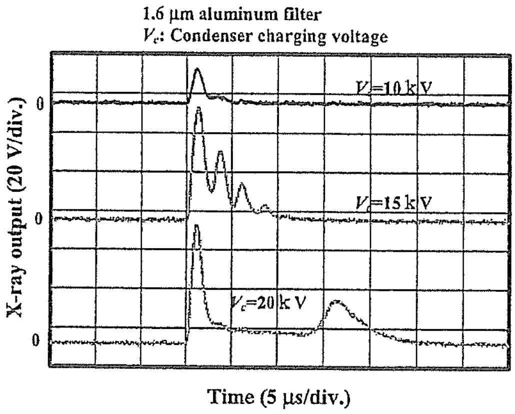



Figure 6: Soft x-ray outputs detected by using 1.6 μm aluminum filter.

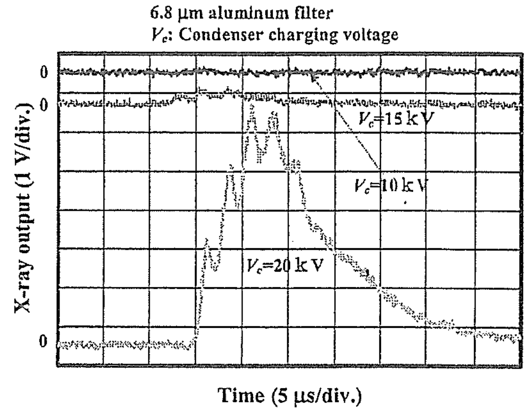



Figure 7: Soft x-ray outputs detected by 6.8 μm aluminum filter.

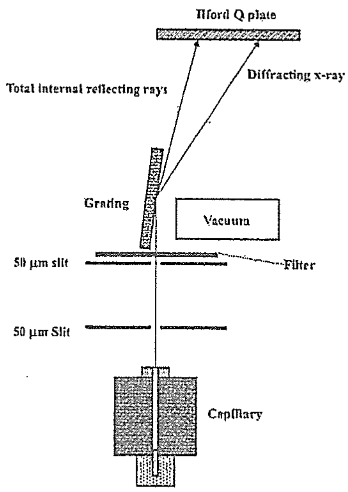
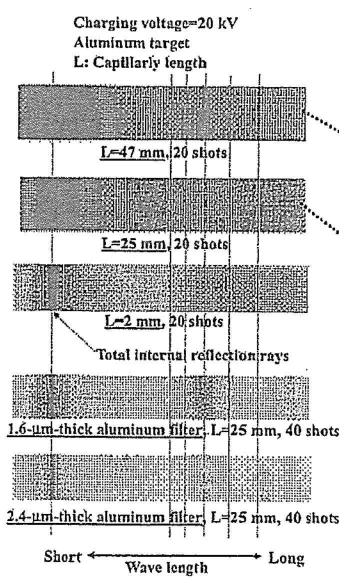



Figure 8: Experimental setup for measuring spectra.



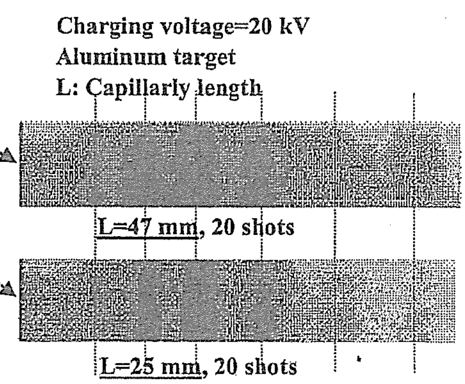




Figure 9: Soft x-ray spectra using aluminum-electrode capillary.

# 4. DISCUSSION

This flash x-ray generator utilizing a new capillary was primarily designed in order to produce high-intensity characteristic x rays with low photon energies, and we confirmed the multi-line spectra. However, the line photon energies seldom varied according to changes in the electrode element.

In summary concerning the x-ray generation (refer to Fig. 10), when the plasma source forms by the capillary discharge, soft x rays are produced by decreases in the effective electron accelerating voltage caused due to surface discharging.

In the spectrum measurement by a diffraction grating, soft x rays are diffracted based on the following equation:

$$m\lambda = d(\sin\alpha - \sin\beta), \qquad m = 1,2,3,4\cdots, \qquad (1)$$

where $\lambda$ is the wave length, $d$ is the space between grating lines, $\alpha$ is the incident angle, and $\beta$ is the diffraction angle. Because the width between lines increases at a low photon energy region, the wavelength may be represented by:

$$\lambda \cong \lambda_0 n^2, \qquad n = 1,2,3,4\cdots. \qquad (2)$$

In the measurement, it is difficult to determine the wave length of $\lambda_0$ due to the diffraction efficiency as a function of wave length.

Using this generator utilizing a capillary-type radiation tube, we observed unknown multi-line spectra. Because these lines disappeared following increases in the capillary diameter, clearly the rays are not characteristic x rays.

If we assume that the x-ray resonation without using a resonator is caused by the matching of wave articulation (Fig. 11), the wave length is given by Eq. (2), and x-ray spectra are written as in Fig. 12. In the spectrum measurement, because the incident angle is approximately 2°, the wave length vs the relative distance (90°–$\beta$) on a Q-plate with $m$=1 is represented in Fig. 13.

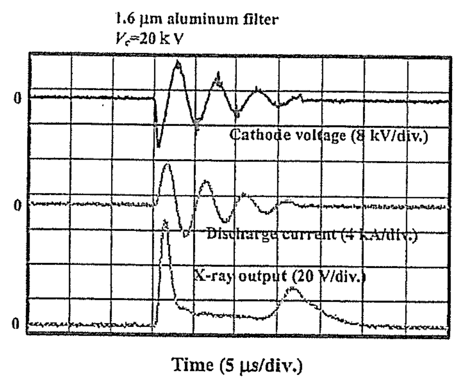



Figure 10: Time relation among cathode voltage, tube current, and x-ray output.

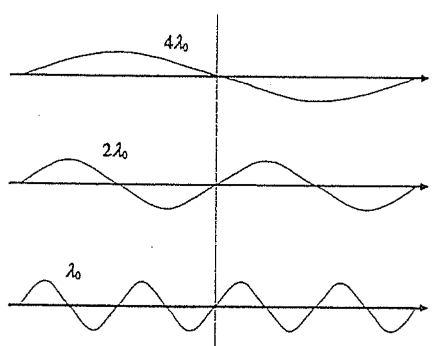



Figure 11: Assumption of hard x-ray resonation without using resonator.

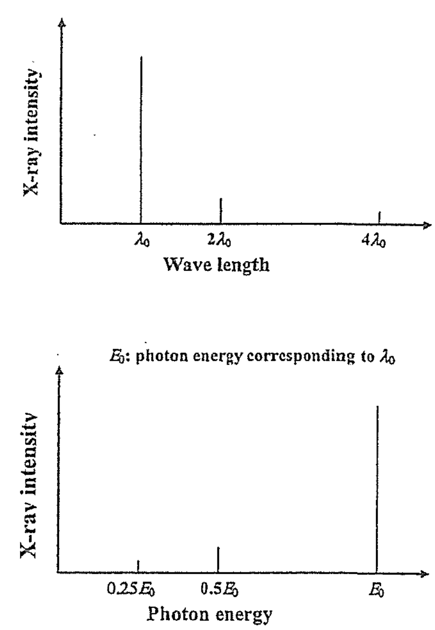



Figure 12: Estimated x-ray spectra under resonation.

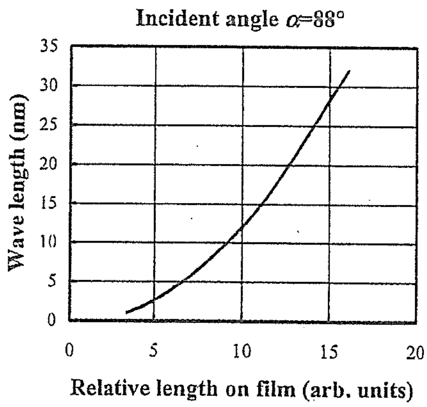


Figure 13: Wave length vs relative length on film.

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