Soft Plasma Flash X-ray Generator Utilizing a 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 were primarily performed in order to generate line spectra such as x-ray lasers. The generator consists of a high-voltage power supply, a polarity-inversion ignitron pulse generator, a turbo-molecular 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 –10.8 kV and 4.7 kA, respectively. The x-ray durations observed by a 1.6 μm aluminum filter were less than 30 μs, and we detected the aluminum characteristic x-ray intensity using a 6.8 μm aluminum filter. In the spectrum measurement, two sets of aluminum and titanium electrodes were employed, and we observed multi-line spectra. The line photon energies seldom varied according to changes in the condenser charging voltage and to changes in the electrode element. In the case where the titanium electrode was employed, the line number decreased with corresponding decreases in the capillary length. Compared with incoherent visible light, these rays from the capillary were diffracted and diffused greatly after passing through two slits.

Keywords: Plasma x-ray, flash x-ray, linear plasma, capillary discharge, vacuum discharge

1. INTRODUCTION

Without considering coherence, we have performed tentative experiments for generating higher-intensity K-series characteristic x-rays from weakly ionized linear metal plasma.[1-3] In these experiments, we have confirmed the irradiation of intense characteristic x-rays from the plasma axial direction, because the bremsstrahlung x-rays with energies of higher than K-absorption edge are absorbed effectively and are converted into fluorescent (characteristic) x-rays. Now, we are confirming the coherence of these rays obtained by x-ray amplification by spontaneous emission, and the rays are diffracted greatly after passing through two thick lead slits. Although high brightness x-ray lasers have been generated by optical lasers,[4] the lasers can be generated using a gas-discharge capillary.[5] In the capillary discharge, the laser intensity increases according to increases in the capillary length. However, using x-ray amplification by stimulated emission, it is very difficult to increase the x-ray photon energy and the duration. Therefore, for the first time, we have performed some experiments for generating incoherent K-series characteristic x-rays using a vacuum discharge capillary[6] by forming weakly ionized linear plasma. In the present work, we have developed a low-photon-energy flash x-ray tube having a new capillary with aluminum and titanium electrodes and have measured the radiographic characteristics including x-ray spectra.

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 turbo-molecular 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.

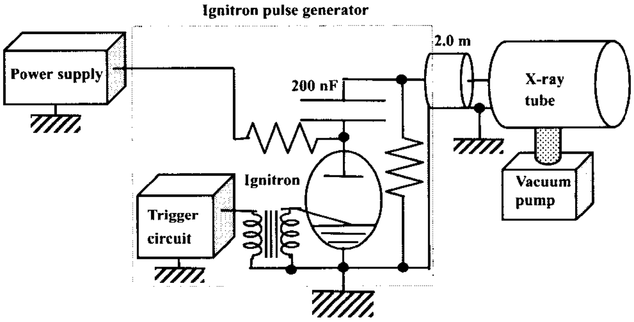

Fig. 1: Block diagram including the main transmission line of the low photon energy flash x-ray generator.

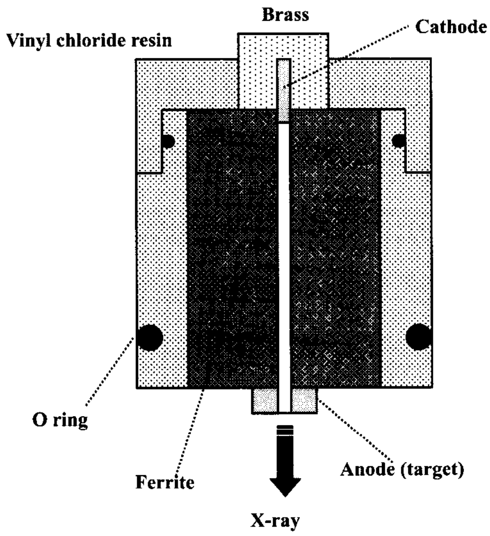

Fig. 2: Schematic drawing of the capillary.

2.2. Low photon energy flash x-ray tube

The x-ray tube is composed of the following major parts: a ferrite capillary, 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 (Fig. 2) 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.

3. RADIOGRAPHIC CHARACTERISTICS

3.1. Voltage, current and x-ray output

The cathode voltage (−1 times the tube voltage), the discharge current, and the x-ray output were measured by a high-voltage divider, a current transformer, and a plastic scintillator, respectively. 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 −10.8 kV and 4.7 kA, respectively. The x-ray durations observed by a 1.6 μm aluminum filter were less than 30 μs, and we detected the aluminum characteristic x-ray intensity using a 6.8 μm aluminum filter. Figure 3 shows time relations among the cathode voltage, the discharge current, and the soft x-ray output. In summary concerning the x-ray generation, when the plasma source forms by the capillary discharge, soft x-rays are produced by decreasing the effective electron accelerating voltage by the surface discharging.

3.2. Spectra

The x-ray spectra were measured by using a holographic plate grating of 1,200 lines per 1 mm. In this setup, the spectra are diffracted and taken by an x-ray glass plate (Ilford Q Plate). Figure 4 shows the measured spectra obtained by aluminum electrodes at the indicated conditions. Because aluminum $K_{\alpha 1}$ and $K_{\alpha 2}$ 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 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 corresponding decreases in the capillary length.

3.3. Diffraction by two slits

In the x-ray region, the determination of coherence is very difficult, because x-rays have short wavelengths. In view of this situation, the measurement of diffracting power using two slits is a conventional method for determining the coherence degree (Fig. 5). Compared with incoherent visible light, these rays from the capillary were diffracted and diffused greatly after passing through two slits (Fig. 6).

4. DISCUSSION

This low photon energy flash x-ray generator utilizing a new capillary was primarily designed in order to produce higher-intensity characteristic x-rays, and we have confirmed the multi-line spectra such as characteristic x-rays. In particular, the line photon energies seldom varied according to changes in the electrode element. If we assume that the multi-line spectra are detected by first order diffraction, because the width between lines increases at a low photon energy region, the wavelength may be represented by:

$$\lambda \cong n\lambda_0, \qquad n = 1,2,4,8\cdots. \tag{1}$$

In this case, it is very difficult to measure the constant wavelength λ_0.

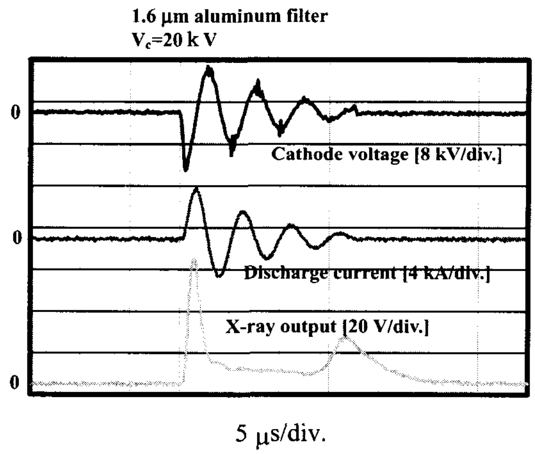

Fig. 3: Time relations among the cathode voltage, the discharge current, and the soft x-ray output.

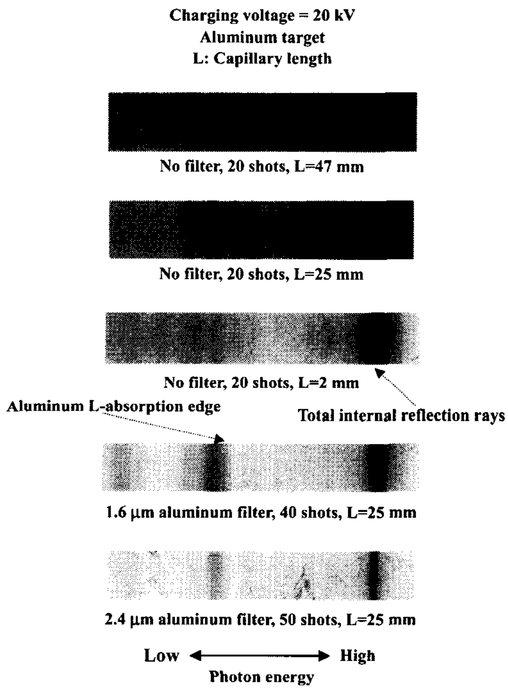

Fig. 4: Soft x-ray spectra using an aluminum-electrode capillary.

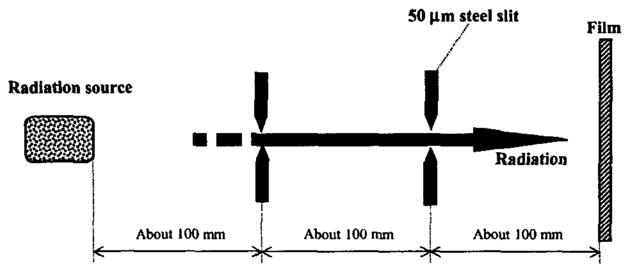

Fig. 5: Setup for diffraction using two slits.

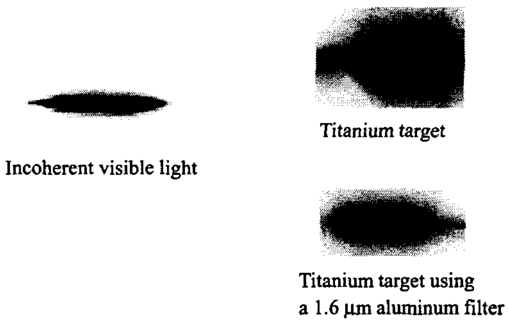

Fig. 6: Diffraction patterns.

In this capillary discharge, the electron accelerating voltage is much lower than the tube voltage. In order to calculate the number of K_i photons N_{ki} from the transmission-type thick plasma target, if we assume that the maximum photon energy E_0 corresponding to electron accelerating voltage has a constant value in order to simplify an equation, the photon number[7] N_{ki} is represented by:

$$N_{kip} \cong K\,\omega_k \int_0^{x_p} \int_{E_k}^{E_0} N'_e(E,\ x)\ \sigma'_K(E)\ \exp\{-\mu_{pki}\ (x_p - x)\}\ \mathrm{d}E\ \ \mathrm{d}x,$$
$$\mu_{pki} = \mu(E_i)\ \rho_e\ , \qquad \rho_e = m\ /\ \pi r^2 x_p\ , \qquad (2)$$

where ω_k is the K-fluorescent yield, x_p is the plasma length, E_k is the critical excitation potential of K-photon radiation, μ_{pki} is the linear absorption coefficient of the target, $\sigma'_K(E)$ is the cross section for K-photon radiation in plasma as a function of photon energy E, $N'_e(E,\ x)$ is the electron distribution at the depth x in the plasma, $\mu(E_i)$ is the mass absorption coefficient, ρ_e is the effective density, m is the evaporated mass of electrodes, r is the capillary radius, and K is a constant. Using this generator utilizing a capillary-type radiation tube, we observed unknown multi-line spectra such as laser. Because these lines disappeared according to increases in the capillary diameter, the rays are not characteristic x-rays. Thus we have to explain these strange phenomena such as x-ray resonance by changing various experimental conditions.

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