Soft X-Ray Spectroscopic Study of a Gas-Puff Z-Pinch Argon Plasma

Seong Ho Kim, Dong-Eon Kim, and Tong Nyong Lee

***Abstract*— X-ray radiation characteristics of argon plasma produced by a gas-puff Z-pinch device were investigated using an X-ray crystal spectrometer, an X-ray diode, and an extreme ultraviolet (XUV) spectrometer. Using a germanium crystal we have observed spectral emission from Ar XVII produced by hot spots at the pinched stage. With the help of a 2-m grazing incidence XUV spectrometer, the spectrum of 30 to 250 Å were obtained. Strong lines from Ar VIII to Ar XIII were observed with a continuum whose peak is around 120 Å. The radiation energy in the spectral range is estimated to be about 23 joule which is about 0.6% of the electrical energy stored in capacitors.**

***Index Terms*—Gas-puff Z-pinch, spectroscopy, X-ray.**

I. Introduction

Z-PINCH plasma has been widely studied as an intense pulsed light source in the soft X-ray region for various X-ray applications such as microscopy, lithography [1], and X-ray lasers [2], [3]. Its dynamics have been known to be complicated, and particularly the origin and dynamics of hot spots have attracted many researchers [4]. We have constructed a gas-puff Z-pinch device to study its radiation characteristics. The experiments for the study of hot spots and the estimation of radiation energy in the XUV spectral region were conducted. The dI/dt signal of the discharge was recorded to monitor the reproducibility of pinches. The spectroscopic study of small-scale gas-puff Z-pinch has been done by many researchers [5]–[7], and the energy estimation using vacuum X-ray diode (XRD) arrays was done by Bailey [9], where the spectral profile was deconvoluted from the simultaneous signals of the XRD arrays with different filters.

In this paper, we present the basic diagnostic results obtained using a crystal and an XUV spectrometer, and the estimation of energy radiated in the spectral region of 44 to 110 Å using an XRD where the spectral profile obtained with an XUV spectrometer is used to estimate the energy.

II. Experimental and Diagnostic Apparatus

The gas-puff Z-pinch device has four capacitors in parallel. The schematic drawing of the discharge chamber of the gas-puff Z-pinch device is shown in Fig. 1. The diameter of the inner wall of the chamber is 13.5 cm. The anode is made of copper, the cathode brass, and the other parts stainless steel. The device is pumped down to the pressure of 10^{-6} torr by a diffusion pump. A hollow gas shell is puffed through an annular nozzle into the vacuum chamber by opening the fast valve. The diameter of the annular nozzle is 2.8 cm and the separation of the electrodes is 8 mm. The mass of gas shell can be controlled mainly by changing the time delay between the gas puff and the discharge. The mass load is carefully adjusted so that a pinch occurs when the current reaches its maximum. Argon is used as a working gas.

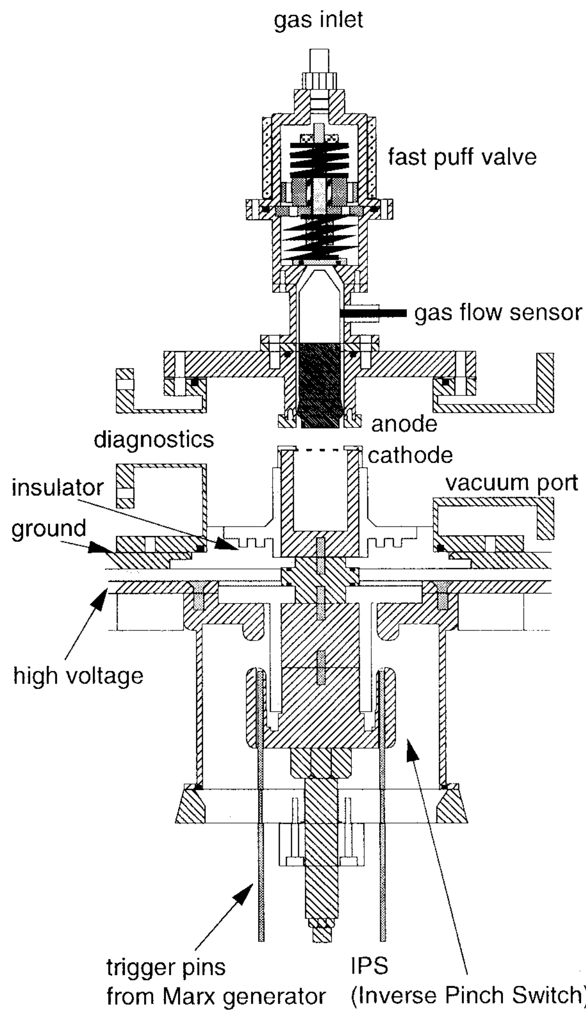

Fig. 1. Schematic drawing of gas-puff Z-pinch device.

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For the study of pinched stage with a crystal spectrometer and a pin-hole camera, 8 μF capacitors were used, and these were replaced with 11.5 μF capacitors for the measurements with an XRD and an XUV spectrometer to increase energy storage. An inverse pinch switch (IPS) was adopted as a main switch of discharge which has many advantages over a conventional spark gap switch [10]. IPS accommodates a large current since its current spreads out due to inverse pinch dynamics and shows small erosion of electrode materials compared with a conventional spark gap switch. Since it is adopted as a single unit, a requirement of simultaneous triggering arising when several spark gaps are used may be avoided. The basic electrical parameters of the gas-puff Z-pinch device were obtained by short-circuit discharge. With 8 μF capacitors its inductance is measured to be 51 nH and the rise time of the current is 1.0 μsec. With 11.5 μF capacitors, the inductance of 57 nH is obtained with the rise time of 1.27 μsec.

In order to monitor the pinch time and the reproducibility of pinches a B-dot probe was placed inside the chamber through a chamber port. The probe is a small acrylic rod of 4 mm diameter wound with copper wires of 0.3 mm diameter. The distance of the probe from the central axis of the two electrodes is 59 mm. The calibration of B-dot probe was done through a short-circuit discharge whose result agrees with a calculation using the probe parameters of fabrication. In a cylindrical geometry the induced voltage at this probe is proportional to the change rate of magnetic flux so that we can measure the change of the plasma current dI/dt.

An X-ray pin-hole camera was used to image the high-temperature, high-density region of plasma radiating X-rays. A stainless steel pin-hole of 100 μm diameter was used and a 5 μm-thick aluminum foil was placed in front of the pin-hole as a filter which transmits an X-ray whose photon energy is above 0.8 keV (10% cutoff). Kodak DEF-392 film was used to record the images. The distance from plasma source to the pin-hole is 7.7 cm and from the pin-hole to the film 6.6 cm.

X-rays emitted from hot spots of pinch stage were recorded using a flat germanium crystal ($2d = 6.5$ Å) spectrometer. The spatial resolution along the axis was obtained by placing a horizontal slit of 1 mm width in the midpoint between source and the crystal. The distance from plasma source to the crystal is 18 cm. The film, Kodak DEF-392, was covered with 4 μm-thick aluminized Kimfol foil to prevent the exposure by visible lights.

Soft X-ray spectra of gas-puff Z-pinch plasmas were obtained with a 2 m grazing incidence XUV spectrometer [11]. A 600 lines/mm grating was set at a grazing angle of 1.5° with the entrance slit of 22 μm width. A toroidal mirror was placed between the plasma source and the spectrometer to collect and focus the light into the entrance slit and also to correct the astigmatism of the grazing incidence spectrometer. A glass capillary array of 2 mm thickness was placed in front of the toroidal mirror to protect the optical elements from plasma debris.

The spectrometer was oriented so that the plane of dispersion was perpendicular to the axis of plasma column to spatially resolve the spectra in the axial direction. The distance from plasma source to the center of the toroidal mirror is 54.5 cm and from the mirror to the grating 60.7 cm. Time-integrated soft X-ray emissions were recorded on the Kodak 101-05 photographic plates.

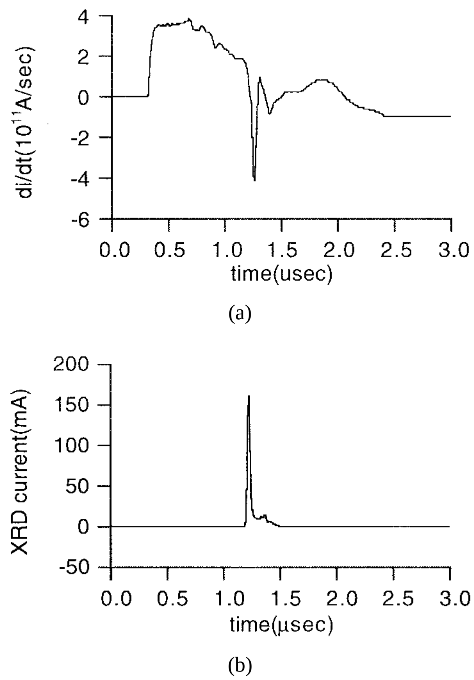

Fig. 2. dI/dt of gas-puff Z-pinch and current of XRD. (a) dI/dt is measured by B-dot probe for discharge of argon gas-puff Z-pinch with 11.5 μF capacitance and 25 kV charging voltage. The pinch time is 0.95 μsec after breakdown. (b) Current signal of XRD is measured with an XRD made of aluminum cathode and filtered by 1.5 μm thick mylar. It reaches peak about 50 ns earlier than that of dI/dt dip signal.

An XRD was used to acquire the time-evolution of soft X-ray emissions. It consists of a filter, a nickel mesh anode of 75% transmittance, and an aluminum photocathode which is biased to −400 V. The cathode material was prepared similarly to R. H. Day *et al.* [12]. Thus we used the quantum efficiency data measured by them. The entrance hole of XRD is 17.9 cm distant apart from plasma source and 6 mm in diameter, and a stainless steel mesh of 28% transmittance was inserted to reduce the intensity of the incident light. A 1.5 μm-thick mylar ($C_{10}H_8O_4$) sheet was used as a filter with which the photocathode sensitively responds to soft X-rays in the spectral region of 44 to 110 Å. XRD yields a photoelectric current responding to incident radiation. The integration of this current provides us with the total charge of electrons ejected.

III. Hot Spots of Pinch Plasma

In this experiment we charged the capacitors of 8 μF up to the voltages of −25 kV to −30 kV. The current rose within 1.0 μsec to about 300 kA at pinch. After puffing argon gas, we adjusted the delay time between gas puffing and the main discharge in order to obtain a pinch at current maximum. The pinch appears as an abrupt dip of about 100 ns width in the B-dot probe signal as shown in Fig. 2(a). Shot-to-shot variation of the pinch time is within 10%. Hot spots are formed in the pinch stage. This is shown by the X-ray pin-hole photography (Fig. 3). In Fig. 3(b), four to five spots with the size of about 400 μm diameter appeared accompanying plasma

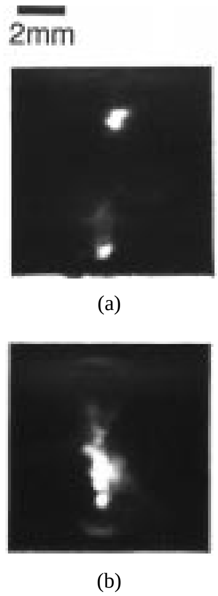

Fig. 3. X-ray pin-hole pictures (×3 enlarged) of hot spots. Top side of the picture corresponds to anode and it is taken through 5 μm-thick aluminum filter. (a) Two spots emitting X-rays and (b) shows more complicated shapes. Discharges were done with 8 μF capacitance and charging voltages −25 kV in (a) and −30 kV in (b).

clouds. These spots have been considered to be initiated by sausage instabilities in a cylindrical Z-pinch type plasma. In our experiment the number of spots and their positions were not regular, but they were localized within a radius less than 1 mm from the central axis of the electrodes and their sizes were a few-hundred μm in diameter. The pin-hole picture also shows that a plasma is more broadly distributed around the anode than near cathode. He-like resonance lines and Li-like dielectronic satellite lines from the hot spots were recorded with crystal spectrometer.

Fig. 4 shows a resonance line and an intercombination line of He-like Ar XVII and dielectronic satellite (jkl) lines of Li-like Ar XVI for the pinched hot plasmas, whose pin-hole images are shown in Fig. 3. The relative intensities between these lines are similar to others' results [7]. Though several spots were produced as shown in the pin-hole image, the spatially-resolved spectra indicated that noticeable intensities were contributed mainly from one hot spot. Electron temperature and density can be diagnosed from the intensity ratios of these lines [13], [14]. Even though the dependence of the ratio of the resonance line intensity (I_R) to the intercombination line intensity (I_I) on the temperature and the dependence of the ratio of the satellite line (jkl) intensity (I_S) to I_R are weak, the electron density and temperature were determined to satisfy both of the ratios that were experimentally observed. Fig. 5 is the contour plot of the intensity ratios of I_R/I_I and I_S/I_R calculated using RATION code [15]. It shows the weak dependence of I_R/I_I on the temperature and the weak dependence of I_S/I_R on the density. The electron density and temperature satisfying both ratios are 8×10^{20} cm^{-3} and 850 eV for Fig. 4(a) and 5×10^{20} cm^{-3} and 800 eV for Fig. 4(b), as shown in Fig. 5. A little higher density and temperature were obtained for 25 kV-discharge. In the 25 kV-discharge, a pinch occurred at the time of maximum current while in the 30 kV-discharge 150

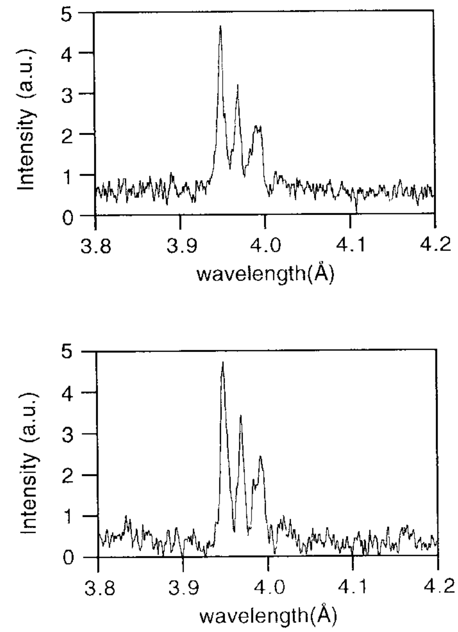

Fig. 4. Lines from Ar XVI and XVII. The left two lines are $1s2p^1P - 1s^{21}S_0$ (resonance line) and $1s2p^3P - 1s^{21}S_0$ (intercombination line) of Ar XVII, respectively. The third is dielectronic satellite line (jkl) of Ar XVI. Corresponding pin-hole pictures of each spectrum are shown in Fig. 3.

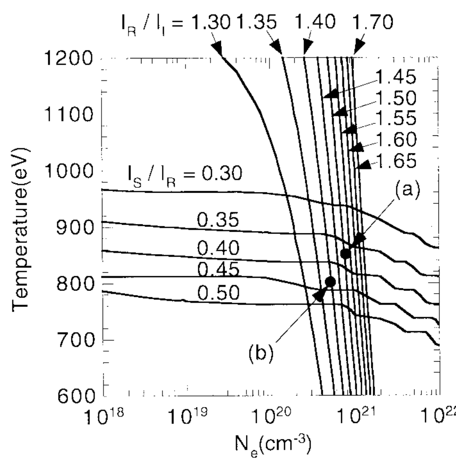

Fig. 5. The contour plot of the intensity ratios of I_R/I_I and I_S/I_R of He-like argon. The points marked as (a) and (b) represent the ratios corresponding to the spectra (a) and (b) of Fig. 4, respectively.

ns earlier before pinch. A large discharge voltage or current would not always correspond to a higher temperature. Though the condition where a pinch occurs at the time of maximum current is certainly important, however, a more significant factor may be the pinch-spot state such as the number and sizes of hot spots. In case a lot of spots are generated, spectral intensities radiated from each spot would be smaller.

IV. Estimation of Radiation Energy

In this experiment we increased the capacitance to 11.5 μF with a voltage of −25 kV in order to increase energy storage. A typical dI/dt signal and the soft X-ray output are shown in Fig. 2, where the dI/dt signal is measured by the

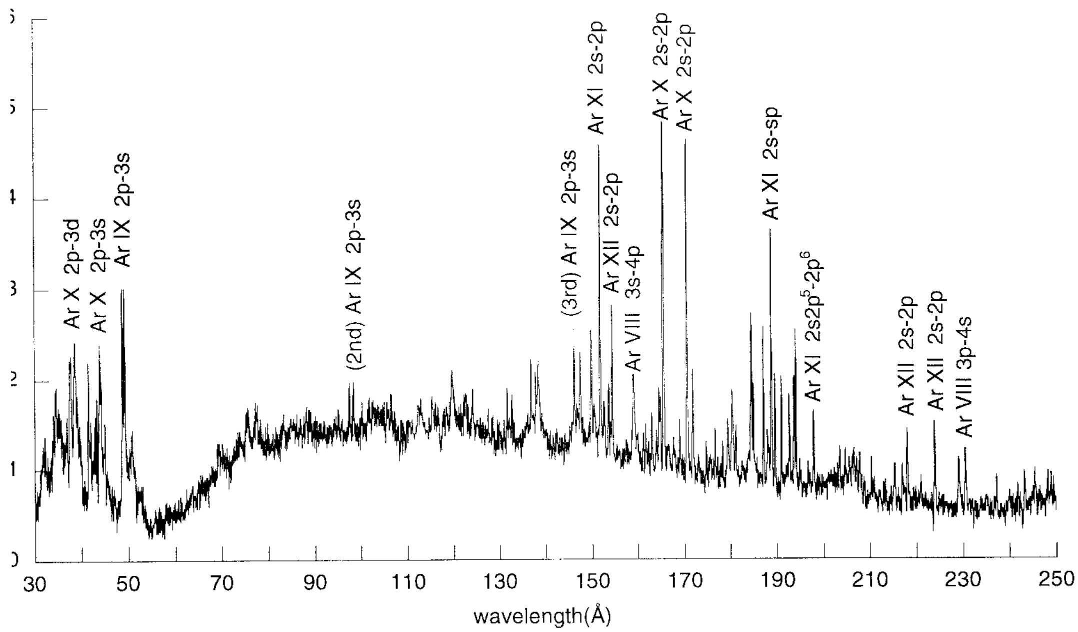

Fig. 6. Spectra of argon gas-puff Z-pinch plasma. The corresponding dI/dt and XRD current are shown in Fig. 2.

B-dot probe and the soft X-ray radiation with XRD. A pinch occurred at 0.95 μsec after initial breakdown, which is 0.32 μsec before the quarter period, i.e., 1.27 μsec. The current at pinch is 260 kA. The XRD signal was sensitive to the pinch formation. When the dip in the dI/dt signal was not strong, no XRD output was obtained. The outputs, however, were not much varied when the dip sizes in the dI/dt signals were of the same magnitudes. In Fig. 2, the full-width half-maximum (FWHM) of the soft X-ray pulse is about 40 ns and the signal peaks about 50 ns earlier than the time of dI/dt dip, i.e., the maximum compression time. On the contrary, the hard X-ray signal detected by XUV Si-semiconductor photodiode detecting photon energy range above 4.6 keV (10% cutoff with 36 μm-thick aluminum filter) reached its peak about 20 ns later than the peak of XRD signal. This implies that soft X-rays are emitted from the beginning of compression and the power reaches its maximum before stagnation, and as the plasma is further compressed and attains higher temperature and density, more intense hard X-rays are emitted.

Using a 2-m grazing incidence XUV spectrometer, a spectrum corresponding to the Fig. 2 was recorded. The developed plate was read by a densitometer. The calibrated optical density was obtained by the use of standard diffuse density wedge and Henke's formula [16]. The intensities of the spectrum varied along the axial direction. The spectrum in the region of 30 to 250 Å is shown in Fig. 6. An intense continuum is present around 120 Å, and most of spectral lines are emitted from the ions of Ar VIII to Ar XIII ionization stages. The electron temperature of a plasma radiating lines from these ionization stages is about 150 eV [6]. The electron density estimated from the ratio of the line Ar XI $2s2p^5 - 2p^6$ (197.95 Å) to Ar XI $2s^2 2p^4 - 2s^2 p^5$ (171.86 Å) is about 8 $\times$ 10^{18} cm^{-3} [17].

The radiation output energy can be estimated with the known filter transmission [18], cathode response [12], and the relative spectral intensity profile obtained with the XUV spectrometer. The spectral profile dW/dE in the photon energy range $[E, E + dE]$ incident on a spectrometer results in a modified spectral intensity dW'/dE

$$\frac{dW'}{dE} = A(E)\frac{dW}{dE} \tag{1}$$

where $A(E)$ is a sensitivity factor including a grating efficiency. Charge Q collected by an XRD is expressed as

$$Q = \int \left(\frac{dW}{dE}\right) \cdot S(E) \cdot dE \tag{2}$$

where $S(E)$ is a response sensitivity of an XRD with a filter. For a relatively narrow region of photon energy, $A(E)$ can be set as a constant. We estimate the radiation energy in the region where the sensitivity of the XRD is high. The absolute radiation energy W can be rewritten as

$$W = Q \cdot \frac{\int \frac{dW'}{dE} \cdot dE}{\int \frac{dW'}{dE} \cdot S(E) \cdot dE} \tag{3}$$

where the integration is done over the energy region where the response of XRD is sensitive. Fig. 7 shows the spectra (Fig. 6) in the energy scale with the response sensitivity of XRD filtered by a 1.5 μm-thick mylar. The XRD is sensitive in the wavelength range of 44 to 110 Å or in the energy region of 110 to 280 eV. Considering transmittance of meshes, and assuming the uniform radiation through 4π steradian, we estimated the total radiation energy from Z-pinch source to be 11 Joule in the wavelength range of 44 to 110 Å into 4π steradian for the measurement of XRD in Fig. 2(b). Assuming uniform efficiency in the wavelength range of 30 to 250 Å for a rough estimation, the above result implies that the output energy in the range would be 23 Joule which is about 0.6% of the stored electric energy (3.6 kJoule). In another experiment done after some modifications on the device (nozzle shape and switch), the radiated energy of up to 206 Joule was estimated

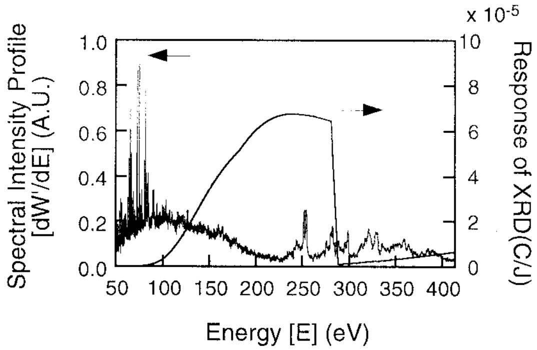

Fig. 7. Spectral intensity profile and response sensitivity of XRD. The spectra in Fig. 6 are shown in the energy scale with the response sensitivity of aluminum XRD filtered by 1.5 μm-thick mylar.

in the spectral range of 30 to 250 Å, for which a separate paper is under preparation.

V. Conclusion

The radiation characteristics of a gas-puff Z-pinch argon plasma has been studied. Diagnostics of hot spots at pinch using a crystal spectrometer shows that its electron temperature and density are about 1 keV and 10^{21} cm^{-3}, respectively. The XUV spectra show that the device can be a good source for the spectroscopy and X-ray applications since it emits spectra of highly-ionized ions and its radiation output is efficient to produce copious soft X-rays. We estimated the radiation output of 11 Joule in the wavelength range of 44 to 110 Å into 4π steradian.

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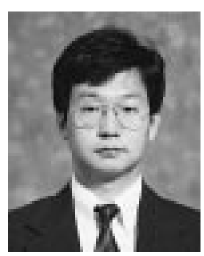

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