Approach to optimize conversion efficiency of discharge-pumped plasma extreme ultraviolet sources

Majid Masnavi,[a] Mitsuo Nakajima, Akira Sasaki,[b] Eiki Hotta, and Kazuhiko Horioka
Department of Energy Sciences, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226-8502, Japan

(Received 9 February 2005; accepted 27 July 2005; published online 9 September 2005)

The possibility of enhancing the conversion efficiency of a capillary-discharged xenon plasma via a current step is theoretically demonstrated using a simplified model. The current step is shown to exert a significant effect on the plasma dynamics in capillary discharge extreme ultraviolet sources. In particular, the pinching phase can be maintained at a quasi-steady-state by the current control, which prolongs the emission period of radiating plasma. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2048824]

In the past few years, capillary-discharged plasmas became reliable table-top light sources in the soft x-ray and extreme ultraviolet (EUV) spectrum range. They opened the way for laboratory operation of a variety of applications, such as the generation of intense coherent soft x-ray radiation,[1] laser wakefield accelerators,[2] or EUV lithography.[3] The last is of great commercial interest because it is the extension of today's optical lithography toward a shorter wavelength. Currently, a substantial amount of research is focused on three ionic systems (Xe,[4] Sn,[5] and Li[6]) which are believed to produce sufficient flux in the EUV region. Theoretical results revealed, in the discharge-pumped Xe plasma, that the transitions responsible for in-band radiation occur only in ten-times-ionized Xe (Xe XI).[7] Unfortunately, the conversion efficiency (CE) of Xe XI to EUV in-band radiation is small since a large driving power is required to achieve practical exposure intensities. On the other hand, the failure in the heat removal from a capillary tube at the high-power level reminds us that optimization of the CE is of major importance. The CE depends on the conversion of stored electrical energy to the plasma energy (the optimum pinching condition for sinusoidal-like current is at some point after maximum where the current is $\simeq$(20–30)% less)[8] and then to in-band radiation.[9] Previously, we found the limitation on the latter,[10] namely, the plasma CE (PCE) results from the atomic structure of Xe XI and hydrodynamic behavior (primarily, the fast plasma cooling due to a rapid expansion following a high density and temperature at pinching phase) in a capillary-discharged plasmas,[11] and could be overcome if the external parameters (e.g., current pulse, capillary radius, and gas pressure) are controlled in a suitable way. In other words, maintaining the plasma at a quasi-steady-state (QSS) (in the ideal case, Bennett equilibrium[12] where the plasma is in the pressure balance situation) with appropriate conditions which prolong the radiation of Xe XI is an essential requirement to optimize the PCE. So far, all of the experiments with the capillary discharges described in the literature were carried out using sinusoidal-like currents (see, for example, Refs. 4 and 6). Herein, we report the calculation results of a simplified model relevant to the conditions in a capillary-discharged Xe plasma and propose a possible approach to optimize the conversion efficiency using a current step scheme.

We start our analysis using a one-dimensional magnetohydrodynamic (MHD) model with cylindrical geometry,[13] which includes time-dependent ionization of Xe ground states. The populations of the excited levels of Xe XI are calculated at the collisional radiative equilibrium approximation using the necessary atomic data obtained from the Hebrew University-Lawrence Livermore Atomic Code (HULLAC) Package[14] as a postprocessor of the MHD calculation. The PCE (i.e., the quotient of in-band emitted energy and the internal plasma energy) is estimated based on the calculated spectral brightness of in-band transitions integrated over the line profile.[9,10]

Figure 1(b) presents the radius-time trajectories of the Lagrangian cells which are calculated based on the driving current (I_1: Solid line) as shown in Fig. 1(a). We assumed that Xe ions and electrons initially have uniform distributions with equal densities 0.6×10^{16} cm^{-3} in a capillary of radius 0.2 cm. The current is treated as an external source; $I_1(t)=I_0 \sin(\pi t/2t_r)\exp(-t/t_f)$ with $I_0=18$ kA, $t_r=75$ ns, and $t_f=340$ ns. When the plasma is compressed by the azimuthal magnetic field as shown in Fig. 1(b), it is also heated and finally producing a high density and temperature at the time of maximum compression called pinch. The temporal variations of the electron density (N_e) and the electron temperature (T_e) on the axis are shown in Fig. 1(c). At the pinch moment, the plasma thermal energy exceeds the magnetic energy containing the plasma temporarily. As a result, the plasma expands and in doing so reduces the temperature and becomes less dense. Figure 1(d) shows the time evolutions of average ionic charge state ($Z_{\rm ave}$), and population of Xe XI ground state (N_Z) on the axis. In addition, the total PCE calculated using the radial optical depths (at static approximation)[15] for all cells with the assumption that the plasma length equals to 0.15 cm (approximately according to étendue limit)[16] is shown. A comparison of Figs. 1(c) and 1(d) indicates that the occurrence of a low electron density and temperature in the expansion phase limits the integrated PCE due to a reduction in the in-band intensity. The plasma velocities against radius at times of 126 and 144 ns are shown in Fig. 1(e). Comparing Figs. 1(b) and 1(e) shows the expansion time is $\simeq$20 ns, which has agreement with the

[a]Electronic mail: majid@es.titech.ac.jp
[b]Also at: Advanced Photon Research Center, Japan Atomic Energy Research Institute, 8-1 Umemidai Kizu-cho, Souraku-gun, Kyoto 619-0215, Japan.

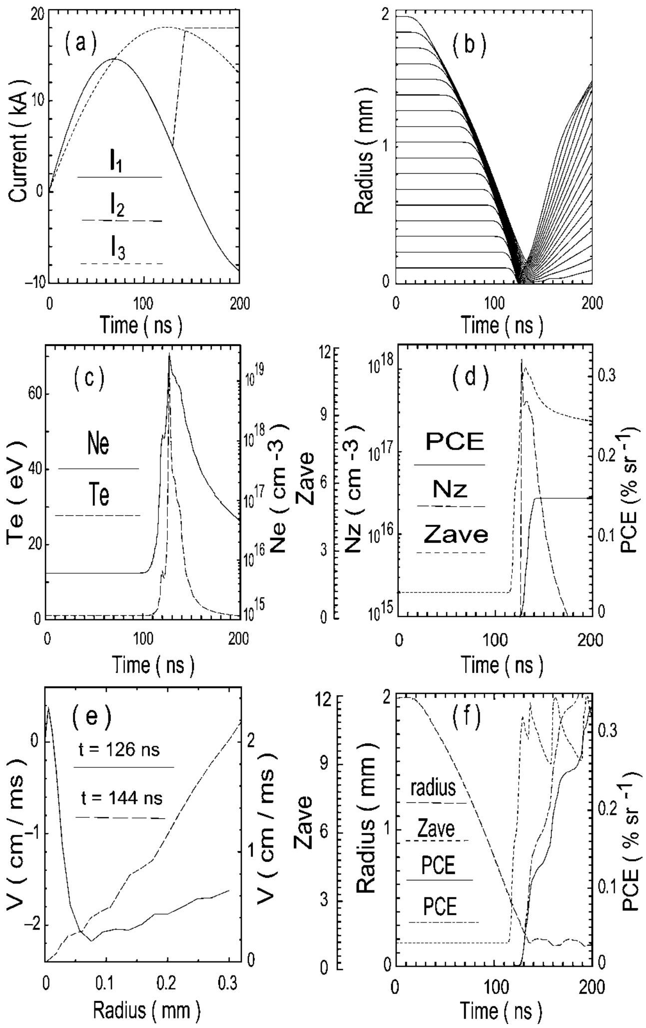

FIG. 1. (a) The currents assumed in the calculations. (b) The plasma radii against time. (c) Time evolutions of N_e and T_e on the axis. (d) Time evolutions of Z_{ave} and N_Z on the axis, and the total integrated PCE. (e) Velocities of plasma vs radius at different times of 126 and 144 ns. (f) The radius of the plasma boundary, Z_{ave} on the axis, and the total integrated PCE (solid line), and without taking the ionization potentials into account after time $\simeq$135 ns for estimating of the plasma energy (dotted-dashed line), where the driving current is assumed to be I_2.

time-scale characteristic of the Bennett equilibrium,[17] i.e., the mean Alfvén transit time [$\bar{\tau}_A = a/\bar{V}_A$ where a is the plasma radius, $\bar{V}_A(\text{m/s}) = (1/4)\sqrt{\mu_0/\pi M_i N I}$ is the mean Alfvén velocity, I is the plasma current, M_i is the ionic mass, μ_0 is the permeability of free space, and $N = \int 2\pi n(r) r dr$ is the line density of ion]. The expansion velocity shown in Fig. 1(e) may also be estimated using the ion sound velocity relation as $V_{\text{ion}}(\text{m/s}) \simeq 8.9 \times 10^3 \sqrt{Z_{\text{ave}} T_e(\text{eV})/Z_a}$ where Z_a is the atomic number. The $Z_{\text{ave}} \simeq 10$ is approximately related to $T_e \simeq 50$ eV, thus $V_{\text{ion}} \simeq 2.7 \times 10^6$ cm/s. Previous results in capillary discharge x-ray laser[11] revealed the occurrence of rapid plasma expansion due to the reflection of the shock wave that reaches the axis, expands, and heats the plasma. The plasma thermalization time (τ_{th}) can be estimated by the time taken for a reflected shock wave to pass through the collapsing plasma shell as $\tau_{\text{th}} \simeq 2a/(V_s + W)$. Here, V_s is the shock velocity and W is the velocity of reflected shock wave. For $V_s \simeq W \simeq 3 \times 10^6$ cm/s and $a \simeq 0.02$ cm, the thermalization time is $\simeq$7 ns.

If we consider a pinching phase already formed, it is clear that to enhance the PCE, we cannot rely on inertial confinement time but must preserve radial confining by the azimuthal magnetic field. If the current is smoothly controlled, the available magnetic pressure is also smooth. One can estimate using the snowplow model,[8] the necessary current that should be used to maintain plasma at QSS in pinching phase. Imaging the current increases to I_s, instantaneously. Then, this model gives a solution for the compression velocity as $V_{\text{com}} = \sqrt{\mu_0/8\rho I_s/\pi a}$, where ρ is density. We may put $\rho = \bar{\rho}$, namely, the mean density $\bar{\rho} = NM_i/\pi a^2$. The compression velocity can now be written as $V_{\text{com}}(\text{m/s}) = \sqrt{\mu_0/8\pi M_i N I_s}$. This formula for line density related to our condition, and $I_s = 18$ kA gives $V_{\text{com}} \simeq 3 \times 10^6$ cm/s [note that here, the current required to maintain plasma at pressure balance is $I(\text{kA}) \simeq 1.8 \times 10^{-9}\sqrt{N(1+Z_{\text{ave}})T(\text{eV})} \simeq 13$ kA for $Z_{\text{ave}} \simeq 10$ and $T \simeq 60$ eV]. If the current is suddenly increased, it must flow at the plasma surface. An estimation for the classical diffusion time of the magnetic field into plasma is determined by a binary collision formula given by Spitzer, with a correction for cylindrical geometry as[18] $\tau_D = 1.3 \times 10^{-2} a^2 T_e^{1.5}(\text{eV})/Z_{\text{ave}} \ln \Lambda$. For the Coulomb logarithm $(\ln \Lambda) = 10$, $a = 0.02$ cm, $Z_{\text{ave}} = 10$, and $T_e = 50$ eV, it gives $\tau_D \simeq 2$ ns. This discussion agrees with our numerical calculations. Figure 1(f) illustrates the radius of plasma boundary, Z_{ave} on the axis, and the total PCE. The initial conditions are the same as Fig. 1(b). But, we assumed that the current I_1 increases linearly to $I_s = 18$ kA between the time of 130 and 142 ns (in fact, the current step can be switched on the pinching phase within inertial confinement time $\tau_c = 2a/V_{\text{ion}}$), namely, $dI/dt = 1.5 \times 10^{12}$ A/s, and then it remains constant (I_2) as shown in Fig. 1(a). The Z_{ave} and the radius of plasma boundary as shown in Fig. 1(f), indicate that the plasma after pinch reaches QSS. Figure 1(f) shows that the current stepping can exert a significant effect on the plasma expansion, consequently, enhancing the PCE (solid line). It should be noticed that to calculate the PCE (solid line) in Figs. 1(d) and 1(f), the required plasma energy estimated based on the sum of thermal energy of ions and electrons, and ionization potentials of different charge states. Suppose the kinetic energy of the imploding plasma due to first current (I_1) makes the required temperature and Xe XI charge state. In the current step regime, we expect the PCE enhancement due to the approximately constant average ionic charge state. Figure 1(f) also shows the PCE (dotted-dashed line) which the plasma energy after time $\simeq$135 ns is calculated based on only the thermal energy. It is difficult to sustain a pinch plasma column for long time interval owing to growth of the MHD instabilities. However, the Lundquist number [$Lu \simeq 4.52 \times 10^{21}(I^4 a/N^2)$ for a Xe plasma and $Z_{\text{ave}} \simeq 10$] in Fig. 1(f) is $\simeq$2.5 at time $\simeq$140 ns, which is substantially lower than the critical Lundquist number (namely, $Lu \lesssim 100$, in which the plasma is in a resistive regime and should be stable during some $\bar{\tau}_A$, at least against sausage mode) for a Z pinch stability.[19] Therefore, the total PCE in Fig. 1(f) is calculated for a time interval $\simeq Lu \times \bar{\tau}_A$ of the pinching phase. Since Lu depends strongly on I and N, the calculation results for different sets of parameters and shape of current step (for instance, $I_2(t) \propto t^{1/3}$) will be reported elsewhere. Using the power balance equation,[17] $1.5(1+Z_{\text{ave}})NdT/dt = P_j - P_r - (I^2/c^2 a)(da/dt)$ and with assumption $da/dt \simeq 0$ (namely, the magnetic pressure does not approximately perform work by compressing the pinch column in current step region), the only mechanism that can couple more energy into the pinch seems to be the Joule heating. The Joule power per unit length of the pinch is $P_j(\mathrm{W/m}) = 1.03 \times 10^{-4} \ln \Lambda Z_{\mathrm{ave}} I^2 / \pi a^2 T_e^{1.5}(\mathrm{eV})$. On the other hand, the optically thin radiated power density (P_r) can be written as[20] $P_r(\mathrm{W/m}) \simeq \pi a^2 (1 + 0.3T(\mathrm{keV})) \times 10^{-37} Z_a^{(3.7-0.33 \ln T)} N_Z N_e$. Substituting $a = 0.02$ cm, $N_e = 10^{18}$ cm^{-3}, $N_Z = 10^{17}$ cm^{-3}, $I = 18$ kA, $T_e = T = 50$ eV, $\ln \Lambda = 10$, and $Z_{\mathrm{ave}} = 10$, into those equations yields $P_j(\mathrm{W/m}) \simeq 7.5 \times 10^{10}$ and $P_r(\mathrm{W/m}) \simeq 10^{11}$, which shows the Joule heating has a significant contribution.

To better characterize the effect of the current shape, we calculated the total PCE ($\simeq 0.05\%$ sr^{-1}) using current I_3 as shown in Fig. 1(a), in which has the same maximum current value with I_2. As the higher current before pinch produces much larger shock wave [the shock velocity[21] scales as $V_s \propto I(t)/a(t)$], I_3 leads to a shorter confinement time and ionization time of Xe XI. The present results demonstrate the importance of the current profiles on the conversion efficiency of discharge-pumped plasma EUV sources. In fact, a more sophisticated two-dimensional MHD model,[22] self-consistently coupled to the ionization dynamics, and radiative transfer equation is necessary to predicts quantitatively the conversion efficiency of Xe plasma. However, the calculated results clearly reveal the possibility to enhance the plasma conversion efficiency of discharge-pumped plasma EUV sources by the control of the plasma current shape.

This work is partly supported by New Energy and Industrial Technology Development Organization (NEDO) and Extreme Ultraviolet Lithography System Development Association (EUVA) of Japan.

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