Preplasma conditions for collisional Mo soft x-ray lasers with the grazing incidence pumping scheme

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By comparing soft x-ray spectra from experiments with numerical calculation results, the preformed plasma medium was characterized for Mo 18.9 nm x-ray lasers with the grazing incidence pumping scheme. The effects of prepulse intensities and durations on the charge state distributions as well as other parameters of preformed plasmas were investigated for previously demonstrated soft x-ray lasers. Experiments with small total energy were conducted to check the understanding of reasons why Mo 18.9 nm soft x-ray lasers were realized on laser facility platforms with parameters varying so much. © 2010 Optical Society of America

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1. INTRODUCTION

The grazing incidence pumping scheme, in which the main pulse at a specific grazing angle preferentially heats the selected optimum medium region for x-ray amplification [1,2], has significantly reduced the necessary energy down to sub-Joule for gain-saturated soft x-ray lasers (SXRLs) operating at a 5–10 Hz repetition rate with average output powers exceeding one microwatt in systems of nickel-like ions [3–5] and neon-like ions [6]. Besides the studies of the laser's performance itself, the bright SXRLs with high system stability and good beam quality [7–10] are also promising to boost their applications in university-scale laboratories [11]. It is noted that, however, those saturated Mo SXRLs operated in regimes different from each other, and the lasing properties vary much, such as the pulse energy, the optimum delay time between prepulses and main pulses, and the width of the lasing windows [1,5,12,13]. The significant difference is mostly caused by different pumping conditions applicable on laser facilities at different laboratories. It is therefore important to establish directly what kind of plasma conditions obtained when different pumping laser configurations are utilized. With plenty of energy available in prepulse, which produced plasmas with the mean degree of ionization approaching the charge of the lasing ion, studies of the dependence of the SXRL's energy and the lasing window width on the main pumping pulse duration with similar energy indicated that moderately short pump pulses (~6 ps) were preferable over long pump pulses (>10 ps) for the later produced overionization and weaker lasing [14]. Another important factor that is expected to determine the SXRL's lasing properties is the preplasma conditions. It was found that there exists a lasing threshold in the pump parameters in specific experiments [4,15]. We present here the quantitative experimental characterization of x-ray laser plasmas created with prepulses. We studied the charge state distributions of Mo ions in plasmas produced by laser pulses with different intensities but in fixed duration of 200 ps. The prepulse duration effects on the temporal evolution of the charge state distributions when the energy was fixed were also investigated by comparing with previous experimental results. We then present the lasing observation when small total pumping energy is available.

2. EXPERIMENTAL SETUP

The experiments were performed in the XL-II laser facility of the Institute of Physics in Beijing, China [16]. Figure 1 shows the schematic illustration of the experiment setup. The laser pulse of 200 ps and 450 ± 30 mJ after the main amplifier was divided by a splitter into two beams, one of which was directed to the prepulse arm with a timing slide providing a delay of 0–1 ns, and focused normally on a slab Mo target by combining a spherical lens of $f = 800$ mm and a cylindrical lens of $f = 1000$ mm. Both lenses were moved along the laser propagation direction so that line foci of different lengths were produced at average intensities between 1.0×10^{11} and 2.0×10^{13} W/cm^2 in Gaussian profiles. The other beam was directed to a vacuum compressor to produce the main pulse, measured as $\sim 200 \pm 15$ fs, which was focused by an on-axis parabola of $f = 609.6$ mm on the preformed plasma at a grazing incidence angle of $\phi = 14°$, with $\sin^2\phi = n_e/n_c$ giving the expected gain region between 5×10^{19} and 10^{20} cm^{-3}. In experiments for lasing observation, line foci of 2.6 mm were produced with the prepulse of ~120 mJ at 2.5×10^{11} W/cm^2 and the main-pulse of ~140 mJ at 2.8×10^{14} W/cm^2. A cross-slit camera was set at the top-front of the target to monitor the overlap of the two line foci with a magnification ratio of 10.5 and 1 in the perpendicular and parallel direction, respectively. The main diagnostic was an on-axis 1200 grooves/mm aberration-corrected concave grating flat-field spectrometer

(FFS), coupled with a charge-coupled device (CCD). The FFS recorded soft x-ray emissions between 8 and 22 nm with a spectral resolution of 0.005 nm.

3. RESULTS AND DISCUSSION

Figure 2(a) shows two typical spectra measured with laser intensities at 2.3×10^{11} W/cm^2 and 2.5×10^{12} W/cm^2, respectively. Although the spectra were time and space integrated, these emissions were representative of the conditions that the plasma had reached. For all the prepulse intensities explored, Cu-like Mo ions were produced as indicated by the clear line emissions related to transitions between $3d^{10}4p$–$3d^{10}5s$. For higher energy or intensities applied, the absence or significant weakening of the emission lines of Mo VIII and IX indicates the mean charge state of Mo ions in the plasma should be higher than Mo X.

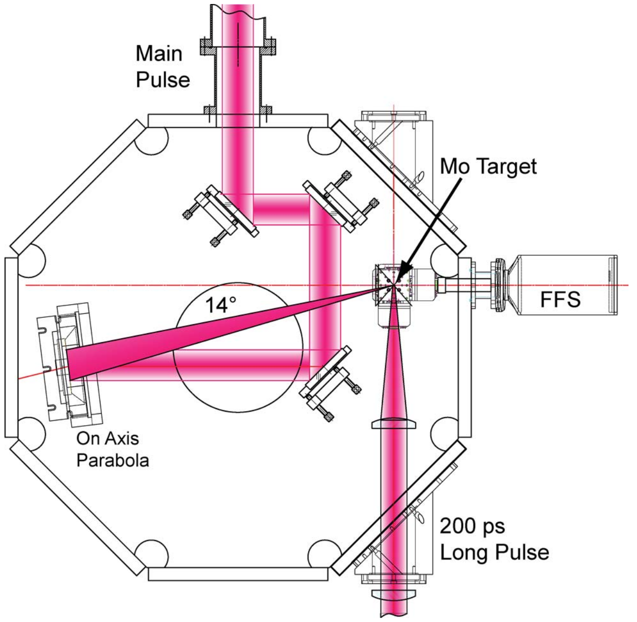

Fig. 1. (Color online) Experimental setup showing the pump laser beam lines and diagnostics. A crossed slit camera was installed at the top-front of the target which is not shown in the sketch.

From the soft x-ray spectra, the charge state distribution of Mo ions was extracted by comparing to those from theoretical calculations with a collisional-radiative model applying fine atomic data, mostly calculated from the flexible atomic code (FAC) [17], in all important atomic processes. The whole set of time-dependent rate equations was resolved and coupled with MEDUSA [18], a modified one-dimensional hydrodynamic code, for the hydro variables required. One spectrum obtained at a prepulse intensity of 2.5×10^{12} W/cm^2 is presented in Fig. 2(b) as an example, with the continuum from the recombination and the bremsstrahlung radiation considered. Figure 2(c) shows charge state distributions produced by prepulses with different intensities. For the lowest intensity explored, although the average ionization was far below the

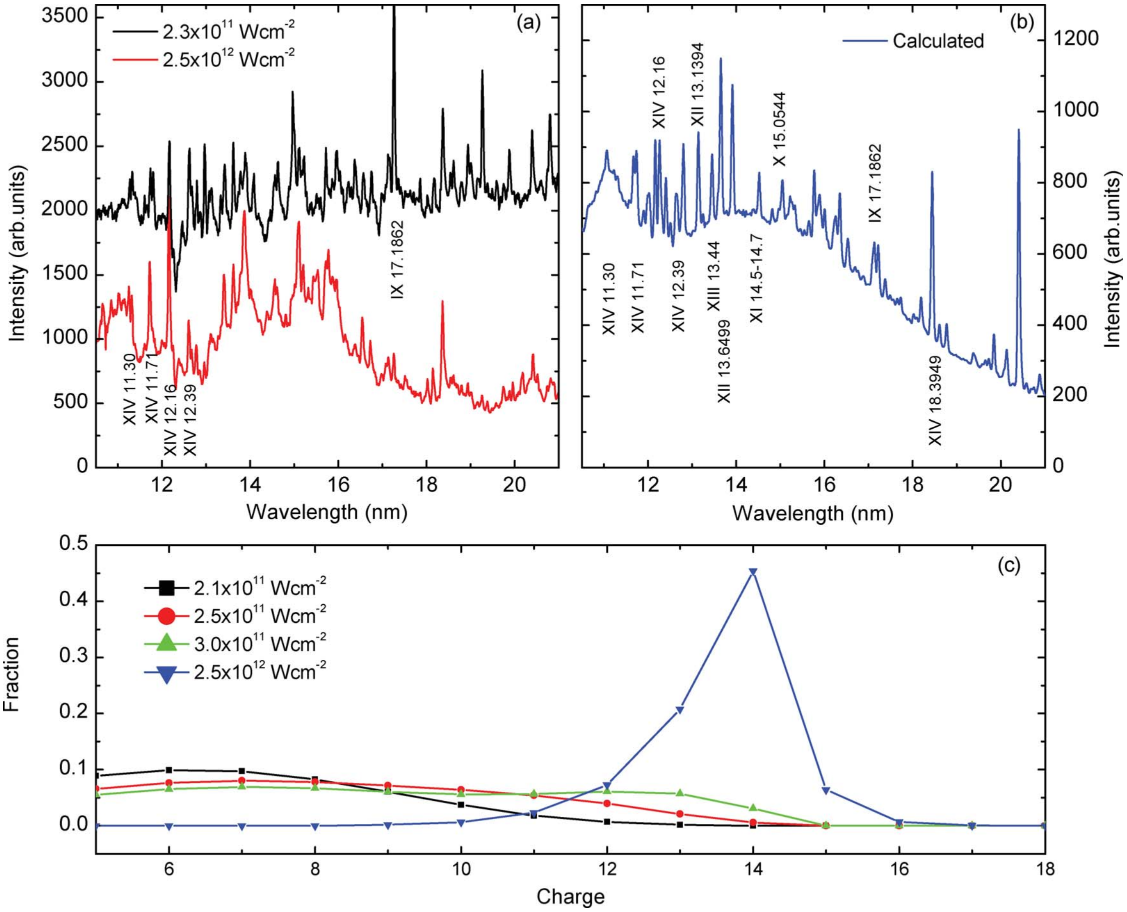

Fig. 2. (Color online) Comparison between (a) the experimental spectra with different irradiation intensities and (b) the calculated one for intensity of 2.5×10^{12} W/cm^2. (c) Charge state distributions produced by prepulses with different intensities.

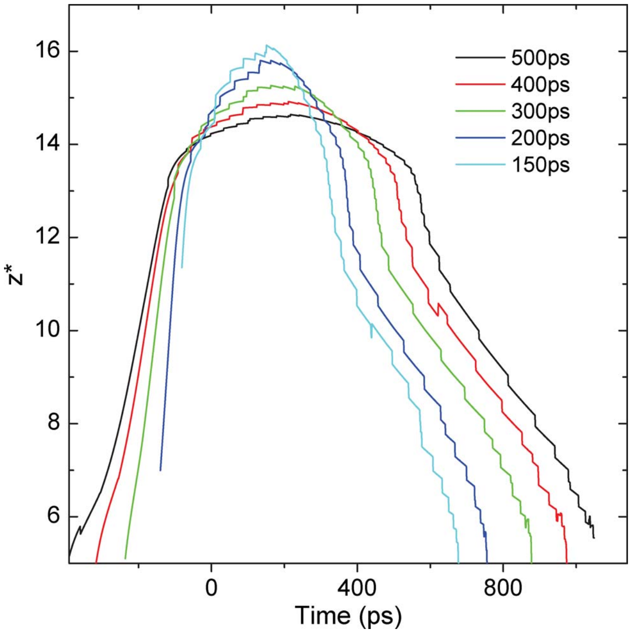

Fig. 3. (Color online) Time evolutions of the average charge state of Mo plasmas obtained with fixed energy in different pulse durations.

expected lasing ions, the Cu-like ions really occupied a minor fraction of the whole population as indicated by its emission lines. It was expected that such a fraction was produced at the intensity peak of the laser spot. To obtain plasmas dominated by Cu-like Mo ions or even the lasing ions, the required peak intensity in pulse duration less than 200 ps was around 2.5×10^{12} W/cm^2. Experiments by Luther *et al.* utilized laser prepulses with an average intensity of 2.4×10^{12} W/cm^{2}and obtained preplasma dominated by Cu-like Mo ions [4].

There are experiments demonstrating the saturated SXRLs with prepulses of higher energy but in longer durations [5,12]. The intensities used there in the preplasma production were around 4×10^{11} W/cm^2. The effects of the pulse duration, or the implanting energy when the intensity was fixed, were studied by numerical simulations, as the access of such various instrument parameters was limited. We took laser parameters used in Rutherford Appleton Laboratory (RAL) experiments [12] as simulation targets. Figure 3 shows time evolutions of the average charge state of Mo plasmas obtained with fixed energy of about 600 mJ in different pulse durations from 150 ps to 500 ps. For shorter prepulse with higher intensity, the plasma was quickly overionized, while at later time, after the prepulse, the average charge state decreased rapidly to under Ni-like Mo ions due to the plasma expansion. For longer prepulse with relatively lower intensity, the target was slowly ionized into plasmas with abundant Ni-like Mo ions. Such conditions lasted for 500 ps before the average charge state began to decrease. These long-life span plasmas abound with of the Ni-like Mo ions, which might explain the near ~800 ps lasing windows obtained in the experiments. In the explored parameter range, neither the electron temperature, around 80 eV, nor the density profile changes greatly.

Limited by the total pumping energy, we made use of our laser system to check the above understandings. In the experiments, the prepulses had an energy of 120 mJ in 200 ps, and the main pulses had an energy of 130 mJ in 200 fs. The lasing was observed at the optimal time delay of 500 ps, with a lasing window of ±25 ps. Figure 4(a) gives the time-integrated flat-field image at the first order of on-axis FFS. The fiducial wire indicated the expected x-ray lasing direction according to the numerical simulation. The abrupt drop of intensity at the left of the image marked the Al L-shell absorption edge at 17.05 nm. Clear lines corresponding to Cu-like Mo were observed. Strong emission at the 18.9 nm $4d^1S_0 - 4p^1P_1$ line of the Ni-like Mo ions showed a very directional output (10 mrad FWHM) in the direction perpendicular to the target surface. The spatially integrated spectra on axis are shown in Fig. 4(b). A spectral analysis indicated that the Mo line at 18.9 nm was far brighter than any other line in the spectrum. The spectral brightness and the narrow divergence of the beam were clear indications of lasing. Another characteristic showing the lasing behavior was the gain narrowing of the Mo 18.9 nm line. Those Cu-like ion lines were measured to be 0.08 nm in width, the same as the off-axis measurement of Mo 18.9 nm, while the lasing line showed an FWHM as narrow as 0.03 nm [see the inset of Fig. 4(b)]. This indicates that the lasing gain was far from saturation. Because

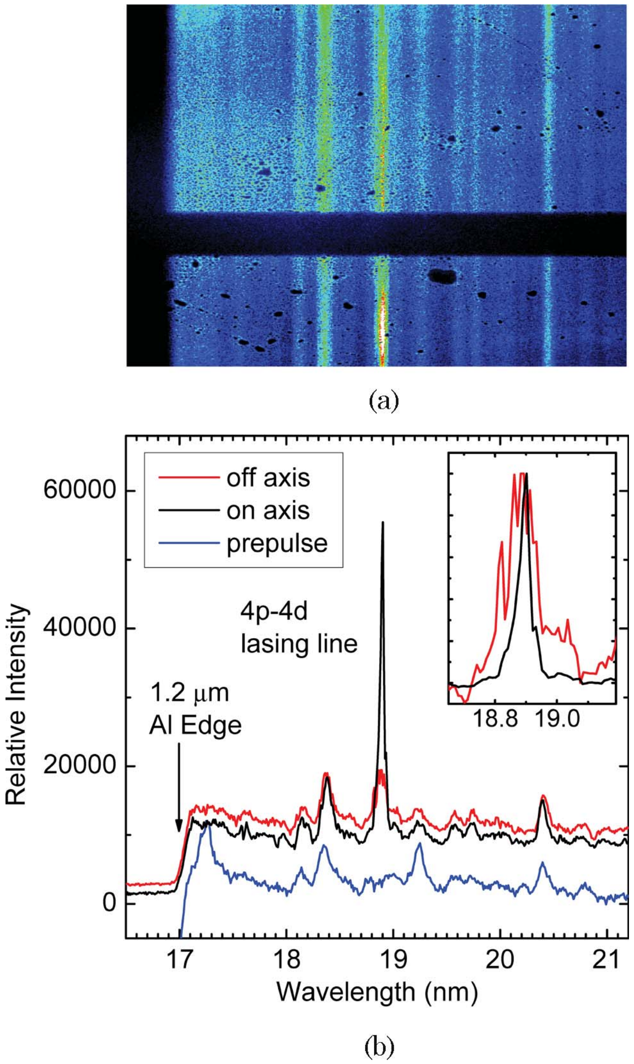

Fig. 4. (Color online) (a) Time-integrated image from the FFS on the axis. (b) Spatially integrated spectrum near the 18.9 nm lasing line (black). A plot of the spectra of the off-axis emission (red) when lasing and a plot of the spectra with only prepulse launched (blue) are also shown (inset, FWHM comparison between lasing line emissions on axis and off axis. The intensities are normalized).

the angular output distribution of the x-ray laser was narrower than the acceptance angle of the spectrograph in the slit direction, the laser beam irradiated only part of the CCD. This allowed us to observe the x-ray laser signal as well as the off-axis emission, for both of which the time-integrated gain of the Mo 18.9 nm laser was estimated to be 1.5–3 cm^{-1}. This value was likely the lower bound to the actual gain as some of refraction of the laser beam contributed to the off-axis emission near the target surface.

The observations confirmed our understandings of the situation with small total pump energy that there were two crucial factors leading to the lasing behavior. One was the higher intensity of the short main pulse in a good line foci well overlapped with the prepulse. The electron was heated to a proper temperature in a short time, which compensated the energy shortage in the experiments. The other was the expansion-produced uniform plasma density profile, which helped to enhance the laser absorption and reduced the refraction of lasing line emission during its propagation. The SXRLs with small total pumping energy operated in the regime far different from those with pumping energy around one Joule [4,5], but similar to those with gas targets, in which the main pumping laser pulse ionized atoms to proper charge state and heated the electrons to excite the expected lasing ions to the state of the population inversion as well.

4. CONCLUSION

In summary, we have systematically studied the charge state distributions in plasmas produced by prepulses of different intensities. The results presented above shed some light on the reasons why it is possible to achieve nearly saturated Mo 18.9 nm SXRLs with pumping parameters varying so much. It is shown that, in the situation with the prepulse of small energy and average intensity as low as $2 \times 10^{11}\ \text{W/cm}^2$, a main pulse as short as hundreds of femtoseconds but with higher intensity can compensate the energy shortage by rapidly heating plasma electrons to proper temperature, producing and exciting the lasing ions. However, the lasing behavior can only be observed when a proper long time delay is introduced to produce a uniform plasma for the enhancement of the laser absorption, the generation of a wide gain region, and avoidance of the refraction of the lasing emission in its propagation path. As to the situation with higher pumping energy available, a longer prepulse can produce a relatively uniform plasma medium with abundant Ni-like Mo ions, while a relatively shorter prepulse with higher intensities will produce a rather overionized medium, which can cool down into proper conditions for lasing by expansion after the pumping pulses. In both cases of the second situation, the main-pulse heated electrons first excite the Ni-like ions to lasing and then continue to overionize the plasma medium and end the lasing process.

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