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Demonstration of Mo Soft X-Ray Lasers with a Grazing Incidence Pumping Scheme in the XL-Ⅱ Facility *

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A Ni-like Mo soft x-ray laser (SXRLs) operating at 18.9 nm has been demonstrated by employing a grazing incidence pumping scheme with 120 mJ in the 200 ps pre-pulse and 140 mJ in the 200 fs main pulse. The SXRL gain is estimated to be 1.5–3 cm^{-1} when a grazing incidence angle of 14° is applied. Numerical simulations are also performed to investigate the dynamics of the ion distribution. It is found that a high intensity at 2.4×10^{14} W/cm^2 of the 200 fs main pulse could heat the pre-plasma rapidly to an appropriate temperature for population inversion, and could compensate for the shortage of the total pump energy to a certain extent.

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The development of plasma-based soft x-ray lasers (SXRLs) has made major advances by applying the grazing incidence pumping (GRIP) scheme, in which the pumping efficiency is increased by irradiating the pre-plasma with the main pulse at a specific grazing angle so that its energy deposition in the selected medium region is significantly enhanced and the travelling-wave pumping geometry is inherently realized.[1−3] Saturated tabletop SXRLs have been demonstrated at 5–10 Hz repetition rate in university-scale laboratories with sub-joule laser pumping energies and average output powers exceeding 1 microwatt in lasers with Ni-like ions[4−6] and Ne-like ions.[7] With an average brightness of 6×10^{17} photons s^{-1}mm^{-2}mrad^{-2} and a peak brightness of about 10^{28} photons s^{-1}mm^{-2}mrad^{-2} [6] in ps pulses[8] with high spatial coherence,[9,10] compact continuous high-repetition-rate plasma-based SXRLs[11] can provide alternatives for some specific applications.[12] However, in obtaining the saturated SXRLs, the pumping condition varies greatly due to the different parameters of optical laser facilities at different laboratories. Keenan *et al.*[13] reported an nearly saturated Mo laser with total pumping energy around 150 mJ and a lasing window determined as 50 ps with the optimum time delay to the peak of the pre-pulse centered at 450 ps. With the pre-pulse energy applied as much as 600 mJ, however, the lasing window was extended to 800 ps as demonstrated by researchers at RAL, and the optimum time delay appeared at 630 ps.[14] Other experiments on Mo soft x-ray lasers have also demonstrated different widths of lasing windows.[5,15−18] It was shown in theory that the lasing window width is determined by the condition of the plasma medium produced by pre-pulses applicable with different characteristics, such as energy and temporal durations, in different laboratories.[19] The electron density and the electron temperature, together with their profile smoothness, determine the abundance of the Ni-like ions and the refraction of the amplified x-ray pulse. By introducing a second grazing incidence long pulse, the plasma density can be modulated to form a flat plateau with shallow-gradient electron density. The quality of the saturated soft x-ray laser pulse was predicted to be significantly improved.[20] However, theory development requires more experimental results for possible intercomparison and detailed analysis of the optimum pump parameters for the saturated operation of SXRLs in different atom systems.

In this Letter, we report the demonstration of Mo SXRLs with the XL-Ⅱ laser facility. A Kerr mode-locked Ti-sapphire laser oscillator produces ∼ 6 nano-joule pulses of about 25 fs duration that are stretched to about 200 ps by a grating expansor. The stretched pulses are subsequently passed through the first stage amplifier, a regeneration one, and the second stage smplifier, a six-pass one, and finally obtain energy around 450 mJ. In experiments, a beam splitter was then used to direct 30% of the laser energy to the pre-pulse arm with a timing slide providing a delay of 0–1 ns between pumping pulses. The rest of the energy was directed to the vacuum compressor to produce the main pulse with the duration measured to be about 200 ± 15 fs. Figure 1 shows the basic experimental setup. A 3-mm-long polished molybdenum slab target was used in the whole experiment as a survey of Mo SXRLs indicates that saturation operations can take place at this tar-

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get length. The long pre-pulse was focused at normal incidence on the target by combining a spherical lens of $f = 800$ mm and a cylindrical lens of $f = 1000$ mm. The obtained line foci have full width at half maximum (FWHM) of 0.08 mm at an intensity of about 2×10^{11} W/cm^2. The main short pulse was launched a few hundred picoseconds after the long pulse, and 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}. The main pulse energy arriving at the target surface was measured to be about 140 mJ, producing an intensity of about 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 on the perpendicular and parallel directions to the line foci, respectively. The primary diagnostic to record the x-ray laser emission was a flat field spectrometer (FFS) installed on the axis. Another FFS with spatial resolution ability was also installed to measure the self-emission of the plasma medium. Spectral filtering was performed with aluminum foils of various thicknesses placed before the entrance slit of the spectrometer. The CCD detector had an angular view of about 77.5 mrad in the horizontal direction and about 8 mrad in the vertical direction as determined by the effective size of the grating.

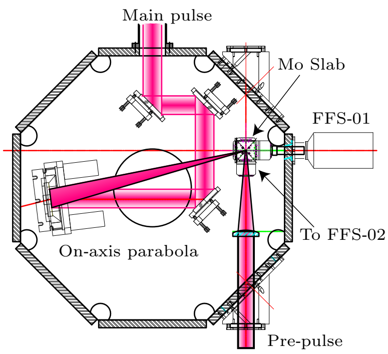

Fig. 1. A diagram of the basic experimental setup. A crossed slit camera was installed at the top-front of the target. Another flat field spectrometer with space imaging ability was used to measure the self emission of the plasma medium. Neither of the latter two instruments is shown on the diagram.

Figure 2(a) gives the time-integrated flat-field image at the first order of on-axis FFS. The fiducial wire indicates the expected x-ray lasing direction according to the numerical simulation. The abrupt drop of intensity at the left of the image marks the Al L-shell absorption edge at 17.05 nm. Strong emission was observed at the 18.9 nm $4d\ ^1S_0$–$4p\ ^1P_1$ line of the Ni-like Mo ions, showing a very directional output (10-mrad FWHM) in the direction perpendicular to the target surface. The spatially integrated spectra on the axis is shown in Fig. 2(b). A spectral analysis indicates that the Mo line at 18.9 nm is far brighter than any other line in the spectrum. The spectral brightness and the narrow divergence of the beam are clear indications of lasing. Another characteristic showing the lasing behavior is the gain narrowing of the Mo 18.9 nm line. Figure 2(b) also plots one spectrum from the shot with only pre-pulse launched, and one of the off-axis emission in lasing situations. When only the pre-pulse is launched, several strong lines corresponding to Cu-like Mo were observed, indicating that the plasma was likely to contain a significant concentration of Ni-like ions. Those Cu-like ion lines were measured to be 0.08 nm in width as the same as Mo 18.9 nm measured off axis, while the lasing line shows an FWHM as narrow as 0.03 nm, indicating that the lasing gain was far from saturation. Because 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 a part of the CCD. This allowed that it is possible to observe the x-ray laser signal as well as the off-axis emission, with both of which we estimated the time-integrated gain of the Mo 18.9 nm laser to be 1.5–3 cm^{-1}. This value was likely the lower bound to the actual gain as some refraction of the laser beam contributes to off-axis emission near the target surface.

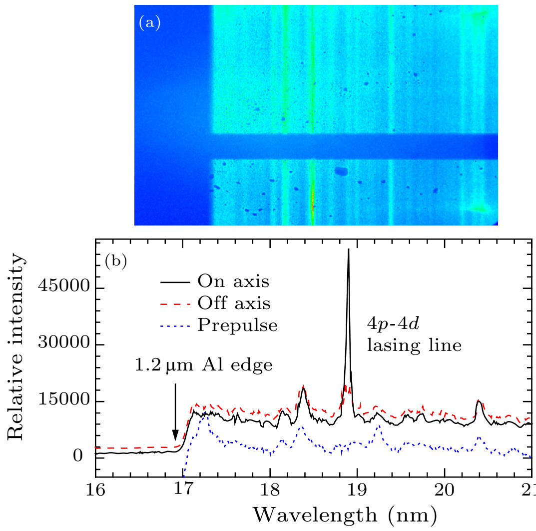

Fig. 2. (a) A time integrated image from the flat field spectrometer on the axis. The $4d - 4p$ Ni-like Mo lasing line at 18.9 nm is clearly seen. (b) A spatially integrated spectrum near the 18.9 nm lasing line (solid line). A plot of the spectra of the off-axis emission (dashed line) when lasing and a plot of the spectra with only pre-pulse launched (dotted line) are also shown.

It is also found that in our experiments the lasing behavior is very sensitive to the time delay between the pre-pulse and the main pulse. In our optimum lasing shots, we delayed the main pulse by 500 ps with respect to the pre-pulse. When the time delay was varied by ±25 ps, however, the lasing behavior disappeared. However, with the same total energy, the ionization distributions after the main pulse should be similar and both contain abundant Ni-like Mo ions, as indicated by strong Cu-like Mo lines and the significantly reduced line intensity of Mo IX located at 17.26 nm compared to the situation with only prepulse launched. It is obvious that the conditions of the pre-plasmas is the critical factor for the present experiment with a small amount of energy available in the main pulse.

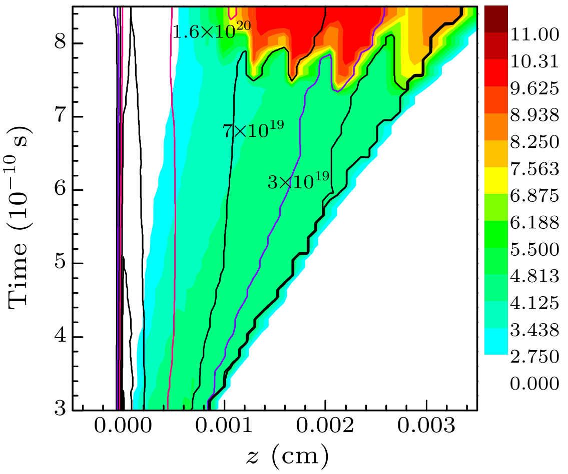

Fig. 3. Calculated spatial and temporal distribution of the average ionization stage (color patches) and the electron density (lines).

To investigate the physical process in the laser-plasma interaction, we performed numerical simulations by using laser pulses with parameters similar to those used in experiments. Figure 3 shows the spatial and temporal distributions of the average ionization stage and the electron density. It is suggested that properly over ionized pre-plasma is preferred to high pumping efficiency and lasing beam quality.[3] However, with limited energy in the two pumping arms, the pre-pulse is only required to prepare the plasma with proper abundance of Ni-like Mo ions, so that the main pulse can hold more energy and sufficient intensity to produce high electron temperatures for excitation of the population inversion. In fact, during the main pulse, the plasma medium continues to be ionized. A pure transient collision excitation (TCE) conception might be realized with only main pulses of tens of femtosecond.[21] For our pre-pulse intensity of 2.4×10^{11} W/cm^2, the Ni-like Mo ions attributed little of the whole distributions with the average ionization under $\bar{Z} = 5$ in the electron density region between 5×10^{19} and 1×10^{20} cm^{20}. Shortly after the main pulse, plasma average ionization was increased to $\bar{Z} = 10$, more Ni-like Mo ions were produced and excited to the population inversion. Luther *et al.* indicated that in experiments with 140 mJ energy in 120 ps laser pulse as the pre-pulse, and 310 mJ in 8.1 ps laser pulse as the main pulse, the Mo 18.9 nm lasing line was observable.[5] We have similar energies in the pre-pulses of 200 ps, but a much shorter main pulse of 200 fs with 140 mJ, less than half of the previous one. By using a well focused short main pulse with higher intensity, the electron could be heated to a proper temperature in a short time. This could be used to compensate for the energy shortage in some experiments.

In summary, we have observed soft x-ray lasing at 18.9 nm in experiments on the XL-Ⅱ facility with total energy of 260 mJ. The gain was measured to be 1.5–3 cm^{-1} in a lasing window less than 50 ps. Numerical simulations were performed with similar parameters used in the experiments. With 120 mJ at 2.4×10^{11} W/cm^2 in the pre-pulse, few Ni-like Mo ions were produced in the plasma medium. However, with the main pulse duration reduced from several ps, as usually used in previous experiments, to 200 fs in the present experiments, the main pulse laser intensity of 2.8×10^{14} W/cm^2 continued to ionize the plasma and produced more Ni-like ions, and also heated the plasma to a proper state with electron temperature high enough to excite lasing. With non-sufficiently ionized pre-plasma, a main pulse with higher intensity was demonstrated to be more effective in producing lasing.

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