The lasing temporal characteristics of Ni-like Mo x-ray lasers at 18.9 nm driven by a grazing incidence pumping scheme

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Abstract. We numerically investigate the effects of the time delay between prepulse and main pulse on the lasing characteristics of the Ni-like Mo soft x-ray lasers (XRL) at 18.9 nm driven in a grazing incidence pumping (GRIP) geometry by using a modified 1D hydrodynamic code MED103 coupled with an atomic physics data package and a 2D Ray-tracing code. Typical XRL experiments with lasing action in a broad temporal window for the delay are simulated and analyzed. Investigations show a well-performed preplasma together with the proper main pulse is the key to achieve lasing over a broad range of time delay.

1. Introduction

It has been possible to achieve saturated soft x-ray lasers with significant average output powers for various applications [1]. A further advance recently came with the development of the GRazing Incidence Pumping (GRIP) scheme proposed by Dunn et al. [2]. The pumping efficiency and repetition rate of soft x-ray lasers have been significantly improved. The first demonstration of the GRIP is achieved in the 18.9 nm line of Ni-like Mo with total pumping energy of 150 mJ [3]. Lasing was observed in an extremely narrow ~50 ps range of long-pulse-to-short-pulse time delays. Since then, substantial efforts have been devoted to the GRIP scheme and numerous demonstrations of high repetition XRLs have been reported both in Ni- and Ne-like ions. So far many groups have demonstrated the grazing-incidence pumped Ni-like Mo XRL at 18.9 nm using different drive pulse configurations. However, the lasing temporal windows for the delay vary from the short range of ~50ps [3] to the long one of several hundred picoseconds [4,5,6].

In this paper, we numerically study the 18.9 nm XRL driven in GRIP geometry using a modified 1D hydrodynamic code MED103 [7] coupled with an atomic physics data package and a 2D Ray-tracing code. All these codes have been successfully used to analyze the grazing-incidence pumped Ni- and Ne-like XRLs [8]. Herein, we focus mainly on the characteristics of the lasing temporal window for the delay between prepulse and main pulse. Detailed simulations and numerical studies for these experiments are performed to investigate the cause of broad temporal windows and to optimize the XRL pump parameters for applications.
2. Experiments Reproduction
In this section, we show the simulation results of three typical GRIP Ni-like Mo 18.9 nm XRL experiments in which lasing was observed to occur over a broad range of time delays. The modified version of 1D hydrodynamic code MED103 coupled with an atomic data package is used to predict the time evolution of the laser-plasma interactions and gain coefficients; a 2D Ray-tracing code is used to calculate the output intensities of x-ray laser pulses.

In recent demonstration of 18.9 nm line XRLs using GRIP scheme [4] one uncompressed long pre-pulse of 600 mJ in 500 ps was used to form preplasma by irritating the slab target at normal incidence and the intensity was $4.8 \times 10^{11}$ W/cm$^2$. The compressed short pulse with energy around 200 mJ in 200fs was used to rapidly heat the preplasma at a grazing-incidence angle of 14° with the focused intensity about $4.0 \times 10^{14}$ W/cm$^2$. Lasing was observed in a broad range of temporal windows for the prepulse and main pulse delay which is roughly between 200 ps and 800 ps shown by circles in Figure 1(a). Good agreement between the simulation and the experiment results is found.

Numerical study of the preplasma conditions produced by the prepulse(s) can provide detailed information about the plasma, which reveals the critical parameters for getting the broad temporal window. Figure 1(b) shows spatial and temporal evolution of the Ni-like ion abundance together with the electron density distributions in the plasma formed by the 500 ps prepulse. The horizontal axis presents the spatial distance in the direction of plasma expansion and the target surface is located at 100 μm. The peak time of the prepulse is at the zero point of the vertical axis. The abundance of the Ni-like Mo ion is shown by grey scale ranging from over 20% (white) to 80% (black). The electron density is shown by lines, among which the line at the left represents the electron density of $2 \times 10^{20}$ cm$^{-3}$. For the 800nm pumping laser with the 14° incidence angle, the turning point of short pulse is located at electron density of $1 \times 10^{20}$ cm$^{-3}$ where the electron density has a shallow gradient. A little overionization and a higher electron temperature were found, preventing the decrease of the Ni-like ion population via electron-ion recombination. Therefore, high fraction of Ni-like ion can maintain for a long period and in a large space.

Satisfying the requirements of the high abundance of Ni-like Mo ion distribution and the predetermined electron density as shown in Figure 1(b), the x-ray laser output is strongly peaked at the delay between 500 ps and 700 ps as shown.

Another experiment of 18.9 nm lasers with a broad temporal window for the delay from approximately 500 to 1200 ps was reported by B. M. Luther et al. [5]. The normal incidence prepulse (120 ps FWHM, 350 mJ) was focused into a line of 30 μm × 4.1 mm. The preplasma was rapidly
heated by the short pulse (8.1ps FWHM, ~1 J) impinging at a grazing-incidence angle of 14° to generate the XRL. Figure 2(a) shows the lasing observed in the experiment with a broad range of time delays. The solid line is the result of the simulation in which the peak intensity 2.4×10^{12}W/cm^2 for prepulse and 9.0×10^{13}W/cm^2 for short pulse were used.

Figure 2. (a) Variation of the intensity of the 18.9 nm line as a function of time delay between the prepulse and short pulse. Circles from Luther’s experiments [5] and solid line from the simulation. (b) Spatiotemporal profile of the Ni-like Mo ion abundance and the electron density generated by a 120 ps prepulse with peak intensity of 2.4×10^{12}W/cm^2. Scales are the same as in Figure1.

The spatiotemporal profile of the Ni-like ions fraction and the electron density distributions in the plasma are shown in Figure 2(b). It is obvious that the high intensity of 2.4×10^{12}W/cm^2 for the prepulse induced much overionization in the preformed plasma with high electron temperature. Allowing large time delay, the preformed plasma can expend to a uniform states with low electron density due to the electron-ion recombination at lower temperature. Such plasma needs a main pulse with large energy and a little longer duration to re-ionize, heat and pump the XRLs. Experiment with main pulse of ~1J and ~8.1ps has proven this idea.

Figure 3. (a) Delay temporal window for lasing by using two pre-pulses and a 19° grazing-incidence short pulse. Circles from Cassou’s experiments [6] and solid line from the simulation. (b) Spatiotemporal profile of the Ni-like Mo ion abundance and the electron density generated by two pre-pulses with an interval of 1.3 ns. The scale of electron density is the same as previous two figures.

Recently, K. Cassou et al. reported their experiment result of 18.9 nm XRL pumped in GRIP geometry [6]. Two uncompressed laser pulses (300 ps duration) with an interval about 1.3 ns are used to form a plasma by irradiating the target at normal incidence. A 5 ps short pulse with an intensity of
3.6×10^{13}\text{W/cm}^2 is used to heat the plasma at a selected grazing incidence angle of 19°. Figure 3(a) is the x-ray intensities as a function of the delay between the second prepulse and the main pulse in both the experiment and the simulation. In the simulation we choose the intensities of three pulses slightly higher than that in the experiment, which are 7×10^{10}\text{W/cm}^2 for the first prepulse, 5.7×10^{11}\text{W/cm}^2 for the second and 4.68×10^{13}\text{W/cm}^2 for the main pulse.

Figure 3(b) shows the information of the preformed plasma. The second prepulse reaches its peak intensity at time of 1300 ps. For main pulse at a incidence angle of 19°, the turning point is located at electron density of ~1.8×10^{20}\text{cm}^{-3}. It is obviously that the two prepulses form a electron density of shallow gradient, but the fraction of Ni-like ions is not very high and do not have long spatiotemporal maintenance. We tried to understand the functions of the first prepulse. The first prepulse might be used to produce plasma as gain medium, which after proper delay was heated and prepared by the second prepulse into the right conditions for the main pulse to pump. Another function of the first prepulse might be used to produce a tenuous plasma (Part I) to tamp the newly performed plasma (Part II) by the second prepulse with larger energy. This arrangement allows generating a uniform gain medium from plasma of Part II with a higher Ni-like ion density. From our simulations, it seems that the first prepulse produces the gain medium, while the high intense output 3 μJ in the experiment [6] indicates the plasma of Part I as the tamper.

3. Conclusion
The lasing temporal characteristics of three Ni-like Mo XRLs are analyzed by numerical method. We find that the lasing temporal characteristics is determined by the balance between the fraction of Ni-like ions, the electron density and the adequate electron temperature overlapped in the spatial-temporal ranges. The large temporal window for delay in Edwards’s experiment is mainly decided by the good plasma conditions generated by a suitable prepulse, while in Luther’s experiment it benefits from the main pulse of ~1J and ~8.1ps. A considerable broad XRL output temporal window for time delay can be achieved under a properly overionized preplasma, in which the smooth electron density profile of interest and the high Ni-like ion abundance match each other in large spatiotemporal ranges.

Acknowledgments
This work is jointly supported by the National Natural Science Foundation of China (under grants 10474137, 60478047, 60321003, 10374114, 10374116, 60678007), the National Hitech ICF (Inertial Confinement Fusion) Program and National Basic Research Program of China (973 Program) (grant No. 2007CB815101).

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