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Numerical study of the Ne-like Cr x-ray laser at 28.6 nm*

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We investigate the Ne-like Cr x-ray laser at 28.6 nm by using a modified 1D lagrangian hydrodynamic code MED103 coupled with an atomic physics data package and a 2D ray tracing code as a post-processor. The laser pumping configuration includes two prepulses and one main pulse. The first prepulse normally irradiates the target, while the second prepulse and the main pulse irradiate the target at grazing-incident angles. We predict that saturation can be achieved for the Ne-like Cr x-ray lasers with a total pumping energy of 125 mJ. Good beam qualities with no deflecting angle and a small divergence angle of 5 mrad are observed.

Keywords: x-ray lasers, grazing incidence, laser plasma
PACC: 4255V, 9870Q, 5250J

1. Introduction

Over the last two decades great efforts have been made to improve the pumping efficiency of collisionally excited soft x-ray lasers. A multi-pulse pumping scheme was developed to generate a smooth electron density, enhance the absorption of pumping lasers, minimize the deflection of the x-ray laser away from the effective gain region and improve the x-ray laser beam quality.[1−3] The application of chirped-pulse-amplified (CPA) laser pulses to the transient collisional excitation (TCE) scheme reduced dramatically the pumping energy.[4,5] The pumping efficiency has been further improved by using the grazing-incidence pumping (GRIP) scheme.[6,7] In this scheme, a prepulse (or multi-prepulses) first normally irradiates a slab target to generate a plasma column. After an appropriate delay time, a short main pulse irradiates the preformed plasma at a predetermined grazing-incident angle to generate the population inversion. By controlling the incidence angle, most of pumping energy is absorbed via the inverse bremsstrahlung (IB) absorption into a selected plasma region, i.e. the gain region for an x-ray laser at a specific wavelength. This GRIP arrangement also brings other advantages, like the lengthened propagation path in the gain region, and the inherent travelling wave pumping. With this scheme, several high repetition rate operations of saturated collisionally excited soft x-ray lasers have been demonstrated in the $2p^5 3p\,{}^1S_0 \rightarrow 2p^5 3s\,{}^1P_1$ transitions of Ne-like ions Ti (Z=22), V (Z=23) at 32.6 and 30.4 nm, and also in the $4d\,{}^1S_0 \rightarrow 4p\,{}^1P_1$ transitions of Ni-like ions Mo (Z=42), Ru (Z=44), Pd (Z=46), Ag (Z=47), Cd (Z=48).[6,8−12]

Theoretically, we have simulated and reproduced the GRIP experimental results of the Ne-like Ti soft x-ray lasers, where double normally incident prepulses were used to generate the plasma before the grazing-incident main pulse.[13] In this work, we further optimize the grazing-incident angles of the main pumping pulses used in that experiments.[9] Then we introduce a new pumping scheme with two prepulses: one normally irradiates the target, the other is incident at a grazing-incident angle. This scheme helps to generate an appropriate plasma condition with a smooth gradient of electron density in the gain region. Following this pumping configuration, as an example, we numerically investigate a transient collisionally pumped Ne-like Cr x-ray laser at 28.6 nm. Compared with the double normally incident prepulse experiments,[9]

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where strong lasing in Ne-like Cr at 28.6 nm was observed with a pump energy of 1.5 J, our scheme can achieve saturation under a small pumping energy. The modified version of the 1D Lagrangian hydrodynamic code Med103 coupled with an atomic physics data package is used to predict the time evolution of the laser–plasma interactions and gain coefficients. A 2D ray-tracing code is developed to calculate the near-field and the far-field distributions of the output intensities of x-ray lasers.

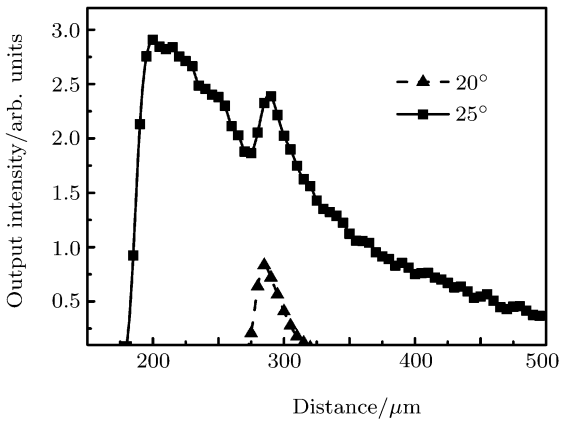


Fig.1. Simulation results of the output intensities of the 32.6 nm Ne-like Ti x-ray lasers versus source position in two cases of incidence angles: 20° and 25°, at the end of a 4.1 mm long target, with the initial front surface of the target located at 100 μm away from the back side of the 100 μm thick target.

2. Further study of the GRIP experiments using double normally incident prepulses

As shown in our previous paper, using a modified 1D MED103 and 2D raytracing codes, we could theoretically reproduce the double-prepulse experimental results of the saturated output of GRIP Ne-like Ti x-ray lasers, given in Refs.[9, 13]. The wavelength of the pump laser was 800 nm. The pumping geometry was a standard line focus on a 100 μm thick slab target. All pulses were of a Gaussian profile. In the experiments, pre-plasmas for Ne-like Ti, V and Cr x-ray lasers were generated by double 120 ps normally incident pulses with an interval of 5 ns. An 8 ps main pulse then irradiated the pre-plasma at a grazing-incident angle, which was modulated to maximize the output of Ne-like x-ray lasers. For the Ne-like Ti x-ray lasers, three incident angles of 17°, 20° and 23° were used. An optimum angle was shown to be 20°. This could be explained by the effective energy coupling of the main pulse into the gain region with an electron density of $2 \times 10^{20}\mathrm{cm}^{-3}$ of the Ne-like Ti x-ray lasers. Most energy of the main pulse with an incidence angle of $\theta = 20°$ was dumped at the turning point, where the electron density was deduced from $n_\mathrm{e} = n_\mathrm{c}\sin^2(\theta)$ to be $2 \times 10^{20}\mathrm{cm}^{-3}$.

However, when we increase the incidence angle of the main pulse to 25° but keep all the other pumping conditions unchanged, the output of Ne-like Ti x-ray laser beams at the end of the 4.1 mm long target splits into two parts with much high intensities as compared with the case of an incidence angle of 20° (see Fig.1). The surface of the slab target is located at 100 μm away from the back side of the 100 μm thick target. Further study indicates that it is due to the step-like distribution of electron density resulting from the double prepulse-heating as shown in Fig.2. A flat stage

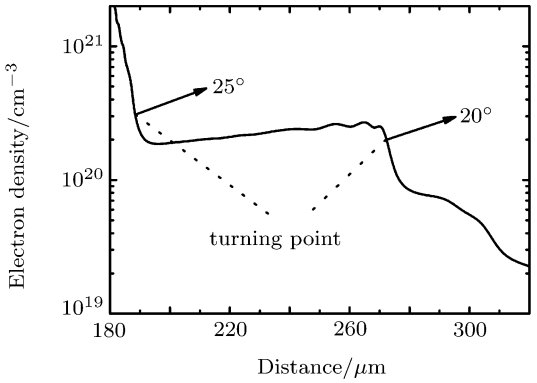


Fig.2. The simulated electron density in the plasma before the onset of the main pulse in the experiment.[9] versus distance from the back side of the 100 μm thick slab target.

of electron density profile ranges from 190 to 270 μm. The values of electron density n_e at turning points of main pulses with incidence angles of 20° and 25° can be deduced from $n_\mathrm{e} = n_\mathrm{c}\sin^2(\theta)$, where $n_\mathrm{c} \simeq 1.1 \times 10^{21}/\lambda^2\,(\mathrm{cm}^{-3})$ is the critical density of the pumping laser wavelength. The turning points are before the flat stage for 20° and after the flat stage for 25° separately as marked in Fig.2. We can find a very steep electron density gradient at the turning point for the incidence angle of 20°. The refraction effect, when the refraction wave propagates in this steep region, reduces the effective absorption of the main pulse and stops the amplification of x-ray laser beams in this gain region, while the energy of the main pulse with a deeper incidence angle of 25° is efficiently absorbed in the flat stage with a smooth electron density profile,

which is helpful for the propagation of both the main pulse and amplified x-ray laser beams. Even though the electron density in the flat stage is a little higher than the required optimum density in the gain region, a much higher output of soft x-ray lasers is produced.

To modulate the electron density in the flat stage to the density required by soft x-ray lasers with a specific wavelength, we propose to modify the incidence angle of the second prepulse. In the next sections, we theoretically investigate the Ne-like Cr x-ray laser by using this pumping configuration. In the double-prepulse experiments, strong lasing is observed in Ne-like Cr at 28.6 nm with a total pumping energy of 1.5 J. Optimizations should be performed to generate an optimum plasma condition for the transient pumped x-ray lasers.

3. Optimizing Ne-like Cr x-ray lasers with new GRIP scheme

Plasma conditions including the distribution of ground-state Ne-like ions and the electron density profile at the onset of the main short pulse, are essential to collisionally pumped soft x-ray lasers. Unlike the GRIP experiment,[9] our proposal requires that for the pumping arrangement, a normally incident 300 ps pulse be followed by a grazing-incident second 300 ps pulse to generate an optimum plasma for the Ne-like Cr x-ray lasers. In the numerical simulations, the wavelength of the pumping laser is 800 nm. The pumping geometry is a standard line focus on a 100 μm thick slab target. The first weak 300 ps pulse with an intensity of 1×10^{11} W/cm^2 irradiates the target to generate an initial plasma with no Ne-like ions. The production of abundant ground-state Ne-like ions and the modulation of electron density profile are mainly operated by the grazing-incident second 300 ps pulse. Optimum plasma conditions are established by adjusting the delay time, peak intensity and incidence angle of the grazing-incident second pulse.

The interval between the two 300 ps pulses is optimized to be about 5 ns. The second pulses irradiate the initial plasma at different incidence angles (16°, 18°, 20°). Plasmas with rich ground-state neon-like Cr ions are generated by laser pulses with optimized peak intensities of 5.0×10^{11}, 5.2×10^{11} and 5.4×10^{11} W/cm^2, respectively. Laser pulse with deeper incidence angle needs a higher peak intensity, because of the shorter absorption path in the plasma. The electron density and the spatial distribution of the ground-state Ne-like ions, at the onset time (optimized in the next section) of the main pulse, are modulated by second pulses with different incidence angles as shown in Fig.3. A shallower incidence angle results in a smoother stage of electrons and a lower electron density n_e in the stage, corresponding to the turning point of the grazing-incident second 300 ps pulse, deduced from $n_e = n_c \sin^2(\theta)$ with an incidence angle θ. A more extended distribution of Ne-like ions is also formed and located in the smooth stage of electrons. The electron density at the highest abundance of Ne-like ions is also determined by the turning back point of the second 300 ps pulse in the plasma, where the laser dumps most of its energy.

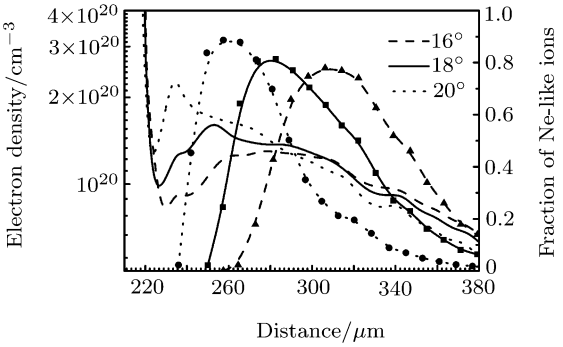


Fig.3. Spatial distributions of electron density and ground-state Ne-like ion density for the second pulse with three different incidence angles at the onset of the main pulse.

The plasmas generated by different second 300 ps pulses are transiently heated by a main short pulse with a grazing-incident 300 fs FWHM (which stands for full width at half maximum). to collisionally excite the population inversions of Ne-like Cr x-ray laser at 28.6 nm. The main pulse irradiates the plasma at the same incidence angle as the second pulse. This configuration ensures that most energy of the main pulse is absorbed at the same position where there exists a high fraction of ground-state Ne-like ions. The delay times between the second prepulse and main pulse are optimized to be 160, 160 and 120 ps, for incidence angles of 16°, 18° and 20°, respectively. The peak intensity of the main pulse is optimized to be 3×10^{14} W/cm^2. Figure 4 gives the simulated gain coefficient profiles 1 ps after the onset of the 300 fs main pulse. We can find that most of pumping energy is dumped at the turning point of the main pulse, which corresponds to the inner peak gain, close to the target initial front surface at 100 μm. Many small peaks of

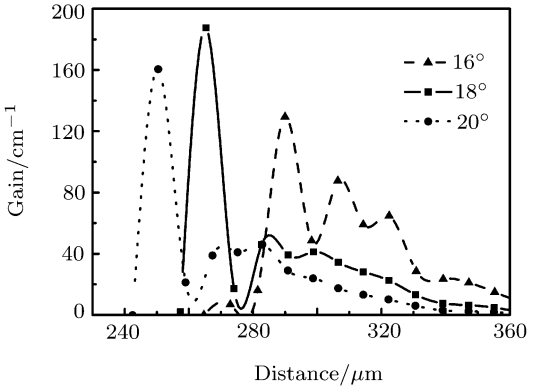


Fig.4. Gain profiles pumped by main pulses with different incidence angles.

gain coefficient appear at outward positions. They result from an oscillating electron density profile generated by the second 300 ps pulse. Maximum gain coefficient happens at an incidence angle of 18°, in which situation the refraction helps to couple the pumping beam into the gain region with an optimum electron density of $1.5 \times 10^{20}\,\mathrm{cm}^{-3}$ for Ne-like Cr x-ray lasers.

Using our 2D ray-tracing code, the characteristics of the output soft x-ray laser beam are investigated. Figure 5 gives the results of output intensities of the soft x-ray laser versus the plasma length (a) and the far field angular distribution (b). The optimized pumping configuration is shown to have an incidence angle of 18°. Saturation is achieved at a plasma length of 0.15 cm. If the focal spot width is assumed to be 30 μm, the necessary pumping energies are 13.5, 70.2 and 40.5 mJ for each laser pulse, separately, which makes a total energy of 125 mJ. Especially, the output of x-ray laser has been shown to have excellent beam qualities: no deflecting angle and a small horizontal divergence of ~ 5 mrad.

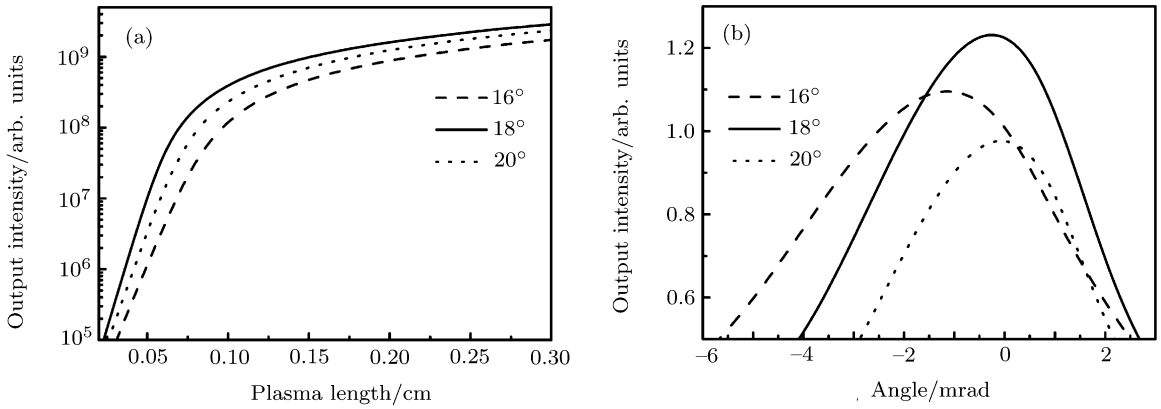


Fig.5. Ray-tracing results of the output of x-ray laser intensity versus the plasma length (a) and the far field angle distribution (b), respectively.

4. Conclusions

Experimental studies have shown that the normally incident double prepulse scheme cannot generate an optimum plasma with a smooth electron density profile in the gain region for soft x-ray lasers with a specific wavelength. Numerical simulations are presented to investigate the Ne-like Cr x-ray laser at 28.6 nm, in which a preplasma is generated by a normally incident prepulse followed by a grazing-incident second prepulse. The main 300 fs pulse irradiates the plasma at the same grazing-incident angle as the second prepulse. Optimizations are performed through the terms of the peak intensities of the pumping pulses, delay times among the three pulses, and incidence angle of the second prepulse. We predict that saturation can be achieved for Ne-like Cr x-ray lasers by using the optimized drive configuration with a total pumping energy of about 125 mJ.

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