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Theoretical study of Ni-like Ag 13.9 nm TCE x-ray laser driven by two picosecond pulses*

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The Ni-like Ag 13.9 nm x-ray laser has been previously demonstrated that the higher gain near critical surface contributes little to the amplification of the x-ray laser because of severe refraction. In this paper, the transient collision excitation (TCE) Ni-like Ag 13.9 nm x-ray laser is simulated, driven by two 3 ps short pulse preceded by a 330 ps long prepulse, optimization of the peak to peak delay time of the two short pulses is made to get the best results. Simulation indicates that by producing lowly ionized preplasma with smoothly varying electron density, it is possible to decrease electron density gradient in higher density region, and thus higher gains near this region could be utilized, and if the main short pulse is delayed by 900 ps, local gains where electron density larger than $\sim 4 \times 10^{20}\,\mathrm{cm}^{-3}$ could be utilized.

Keywords: x-ray laser, transient collisional excitation (TCE), gain
PACC: 4255V, 5250J, 8220W

1. Introduction

The Ni-like Ag 13.9 nm x-ray laser has high reflectivity (∼64%) on the multi-layer reflector, it can be used to diagnose the plasma status. Using this laser light, the Institute of Laser Plasma in Shanghai has obtained the dynamic interferogram of CH by using a Mach–Zehnder interferometer with the help of the Institute of Applied Physics and Computational Mathematics and other institutes.[1,2] And in 2005, they tried to diagnose the development of R–T instability in plasma which is a key problem in inertial confinement fusion (ICF) research, and better result was obtained. In order to make the diagnosis more believable, the quality of the x-ray laser has to be improved, and thus further research is needed.

Previous simulations show that for the Ni-like Ag 13.9 nm x-ray laser, there exist two gain regions, one is near the critical surface with large electron density gradient ∇n_{e}, the other is near $\sim 2 \times 10^{20}\,\mathrm{cm}^{-3}$ with relatively small ∇n_{e}, and simulations show that the former gain region contributes little to the amplification of the 13.9 nm x-ray laser because of severe refraction, and in this sense, the optimum region lies in the latter region.[3−5] The recently proposed grazing incidence pumping scheme can deposit pumping laser energy in the optimum gain region by selecting a proper grazing incidence angle, it reduces the pumping energy and the efficiency is improved,[6,7] but focusing the grazing incidence pulse to a line on the target surface is very difficult in experiment. The other way is to try to make use of high gain near critical surface, in this paper, we present our simulations aiming at this goal.

Before we start our presentation, we should notice that recent transient collision excitation (TCE) experiments[8−10] pumped by a single ∼ picosecond short pulse with a low-level ns pedestal has also demonstrated strongly amplified x-ray laser suggesting an ionization process during the heating of the ps pulse, and some diagnosis on the preplasma status has also proved this discovery.[11,12] So one would naturally ask whether for Ni-like Ag x-ray laser, if preplasma could be produced, in which the electron density n_{e} varies smoothly at $\sim 2 \times 10^{20}\,\mathrm{cm}^{-3}$ and the ionization z is very low, for example z is less than or equal to 8, with the increase of n_{e} during the process of ionizing preplasma to the Ni-like state, is it possible to decrease the ∇n_{e} at higher n_{e} in the gain region and thus suppresses the refraction effect? In this paper, the Ag slab target is transversely irradiated by a 330 ps Nd-glass laser followed 2.16 ns later by two 3 ps short pulses, producing a ∼50 μm wide and ∼0.6 cm long focus line. The energy of the long pulse is 0.03 J, and the energy of the two 3 ps short pulses is respectively 0.15 J and 3.5 J. The three pumping pulses are all Gaussian pulse at 1.053 μm in wavelength. Travelling wave pumping is adopted and we will show our

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simulations in the following.

2. Simulation results

The 1.5 dimensional hydrodynamic code JB19 was used to calculate the hydrodynamic evolution of the plasma and to provide the temperatures and densities to the atomic physics code which performs the kinetics calculations to determine the gain. The rate equations of level populations are solved for spontaneous emission, collisional excitation and de-excitation, collisional ionization and photo-ionization and the inverse processes. The two-dimensional ray-tracing code XPBA calculates the propagation of x-ray laser to provide output intensity of the x-ray laser.[13−16]

Different delay times between the two short pulses are considered, and Fig.1 shows the small signal gain g in cm^{-1} based on the Linford formula[17] (solid circle) and divergence angle θ in mrad (open pentacle) versus the delay time, the horizontal axis is the peak to peak delay time between the two short pulses. And it indicates that the 900 ps delay time is the optimized one, with g of $76.8\,\mathrm{cm}^{-1}$, and θ of ~ 2.21mrad, in the following text we will study this optimized case. And for the convenience of illustration, we define the 0ps as the peak time of the short main pulse.

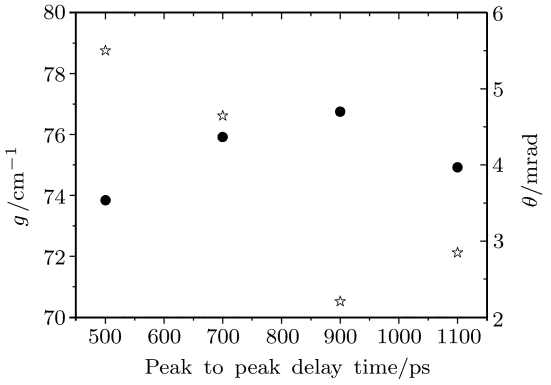


Fig.1. Small signal gain g in cm^{-1} (solid circle) and divergence angle θ in mrad (open pentacle) versus the peak to peak delay time of the two short pulses in ps.

Figure 2 shows the preplasma status at $t = -14$ ps, the n_e in $10^{21}\,\mathrm{cm}^{-3}$ (open circles), z in 10 in unit (solid line), electron temperature T_e (dot line) and ion temperature T_i (dashed line) in 100 eV in unit as a function of distance from target surface x. One can see that the n_e varies very smoothly near $\sim 2\times10^{20}\,\mathrm{cm}^{-3}$, with the average gradient of $\sim -6.6\times10^{22}\mathrm{cm}^{-4}$, and z is less than ~ 7. The T_e and T_i are nearly equal in the most region with average value of ~ 20 eV except for a sharp peak on the T_i. And a peak also appears on the curves for ionization at almost the same place. The reason for it can be attributed to the influence of the shock wave, and it has little influence on gain.

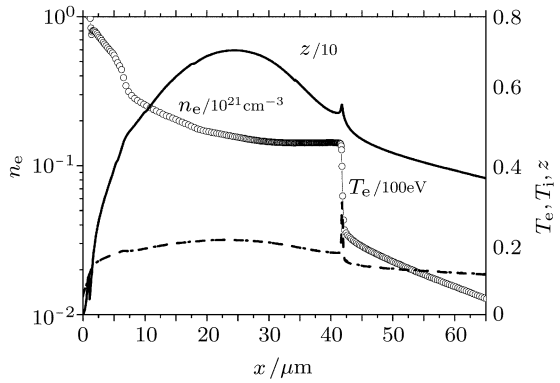


Fig.2. n_e in $10^{21}\,\mathrm{cm}^{-3}$(open circle), T_e (dot line) and T_i (dash line) in 100 eV, and ionization z in 10 (solid line) as function of distance from the target surface x (μm) at $t = -14$ ps, the position of the initial target surface is at 0 μm on the horizontal axis.

Figure 3 shows n_e (open circle) in $10^{21}\,\mathrm{cm}^{-3}$, fraction of Ni-like ions η in 1% in unit (dash-dot line), Te (dotted line) and $10\times T_\mathrm{i}$ (dash line) in 20 eV, z (dash-dot line) and local gain G (solid line) in cm^{-1} as function of x at $t = 0.5$ ps when the output intensity peaks. One can see that the G peaks at $\sim 84.8\,\mathrm{cm}^{-1}$, where the n_e is $\sim 5.2\times10^{20}\,\mathrm{cm}^{-3}$, the T_e and T_i is respectively ∼940 eV and ~ 22.6 eV, and with only 12% of Ni-like ions, and the z of ~ 18.8. The full width at half maximum (FWHM) of the gain region is $\sim 26\,\mu$m, which is quite large.

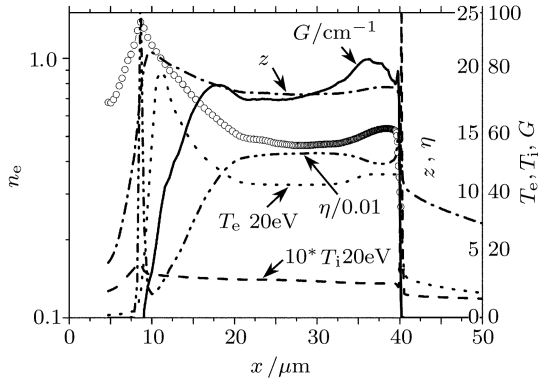


Fig.3. Plasma status at $t = 0.5$ ps, n_e (open circle) in $10^{21}\,\mathrm{cm}^{-3}$, z (dash dot line), η in 1% in unit (dash-dot-dot line), T_e (dotted line) and $10\times T_\mathrm{i}$ (dash line) in 20 eV and G (solid line) in cm^{-1}.

The η in the gain region is less than 20%, because the Ni-like ions are easily ionized to Co-like ion as the T_e rises, and this sets a key limit to obtaining high G, which is also indicated by the similar shape of the curves for G and η as presented in Fig.3. As preplasma is ionized by the main short pulse, the n_e greatly increases to larger than $\sim 4 \times 10^{20}\,\mathrm{cm}^{-3}$ in the gain region compared with that at $t = -14\,\mathrm{ps}$ as shown by the open circle in Fig.2. With the increase of the x, the n_e first slowly decreases to $\sim 4.61 \times 10^{20}\,\mathrm{cm}^{-3}$ at $\sim$27.8 μm from the target surface, and then slightly increases to $\sim 5.34 \times 10^{20}\,\mathrm{cm}^{-3}$ at $\sim$39.80 μm from the target surface.

Figure 4 shows G in cm^{-1} (a), T_e in eV (b) and z (c) as a function of x at several times near $t = 0$ps. The life time within which G is larger than $\sim 40\,\mathrm{cm}^{-1}$ is $\sim$2 ps, and the peak G value is found to move away from the target surface as time goes on, which means that plasma with higher n_e is first ionized to Ni-like ions and G appear earlier, while plasma with lower n_e produces G later. No obvious expansion of the gain region is found in this time period, which can be explained by the evolution of T_e and z in Fig.4(b) and Fig.4(c).

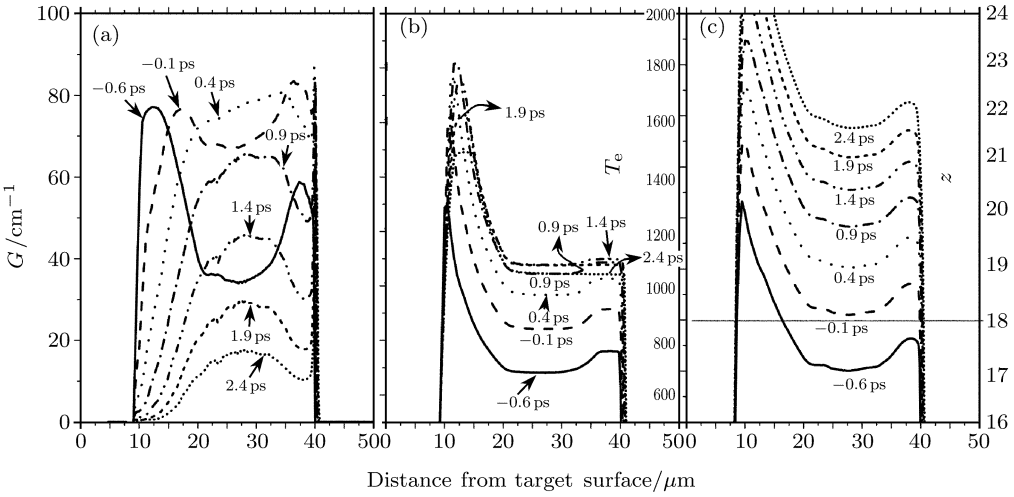


Fig.4. G (a) in cm^{-1}, T_e in eV (b) and z as function of x for several times near the peak time of the short pulse. The 0 ps is the peak time of the short pulse.

3. Discussion

Ni-like Ag 13.9 nm x-ray laser driven by two 3 ps short pulses preceded by a 330 ps long pulse is simulated by our code series. Different delay times are considered to optimize the pumping condition and the simulation shows that 900 ps delay time works better with g of $\sim 76.8\,\mathrm{cm}^{-1}$ and θ of $\sim$ 2.21mrad. For the 0.6 cm length target, the gain–length product is $\sim$45, suggesting saturation. By producing lowly ionized preplasma and the short pulse not only heating but ionizing the plasma, high electron density of larger than $\sim 4 \times 10^{20}\,\mathrm{cm}^{-3}$ in the gain region is obtained and the width of the gain region is $\sim$26 μm. And the simulation shows that the low fraction of Ni-like ions is the key factor limiting obtaining higher gain.

Acknowledgments

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