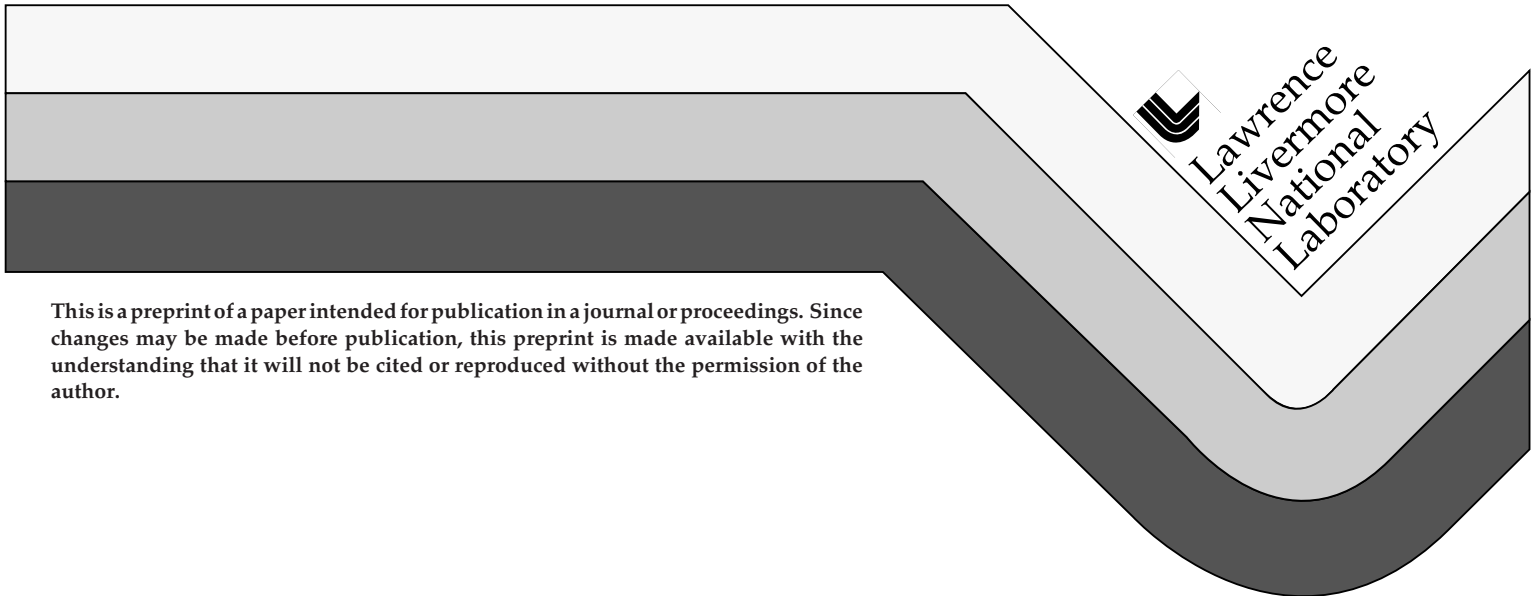


Modeling of psec-laser-driven Ne-like and Ni-like X-ray lasers

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Modeling of psec-laser-driven Ne-like and Ni-like X-ray lasers

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ABSTRACT

This paper models recent experiments in which a solid titanium target was illuminated by several joules of combined energy from a nsec laser pulse to create a preplasma followed by a psec laser pulse to drive the gain. Gains greater than 200 cm^{-1} are predicted for the Ne-like Ti $3p \ ^1S_0 \rightarrow 3s \ ^1P_1$ transition at 32.6 nm which is driven by the monopole collisional excitation. High gain is also predicted for the $3d \ ^1P_1 \rightarrow 3p \ ^1P_1$ transition at 30.1 nm which is driven by a combination of collisional excitation and self photopumping. We also discuss the possibilities for driving a Ne-like Ge laser using this approach. For the Ni-like ions we model a solid molybdenum target under similar conditions used for Ti and predict gains greater than 300 cm^{-1} for the Ni-like Mo $4d \ ^1S_0 \rightarrow 4p \ ^1P_1$ transition at 18.9 nm which is driven by the monopole collisional excitation. High gain is also predicted for a self photopumped $4f \ ^1P_1 \rightarrow 4d \ ^1P_1$ transition at 22.0 nm and several other transitions driven by inner shell collisional ionization.

Keywords: X-ray laser, multiple pulse technique

1. INTRODUCTION

Using the prepulse and multiple pulse techniques[1-9], many low-Z Ne-like ions have lased over the last few years on the $3p \ ^1S_0 \rightarrow 3s \ ^1P_1$ transition. These techniques illuminate solid targets with several pulses, with the first pulse used to create a preplasma which allows the subsequent pulses to be absorbed and create a much larger and more uniform plasma which is at the right densities for gain and laser propagation. Typical pulse durations are 100 ps for the multiple pulse technique and up to 1 ns for the prepulse technique and typically use 100 to 1000 joules of energy. In the above techniques the pulse duration is held constant but the contrast and separation between pulses is varied. A recent variant of these techniques, which uses less than 10 joules of energy, is the use of a nsec prepulse followed by a psec drive pulse to successfully demonstrate lasing in Ne-like Ti at 32.6 nm[10]. In this paper we model the recent Ne-like Ti experiments which use this short pulse/long pulse variant to understand the plasma conditions present and what gain is possible on different transitions. We then look at the analog scheme in Ni-like Mo.

2. LASER SCHEMES

For most Ne-like and Ni-like X-ray lasers the strongest laser line is the $3p \ ^1S_0 \rightarrow 3s \ ^1P_1$ and $4d \ ^1S_0 \rightarrow 4p \ ^1P_1$ transitions, which are driven by the monopole collisional excitation. In the recent Ti experiments, lasing lines were observed at 32.6 nm on the $3p \ ^1S_0 \rightarrow 3s \ ^1P_1$ transition and on a second line near 30.0 nm[10] which we believe is the $3d \ ^1P_1 \rightarrow 3p \ ^1P_1$ transition. The analogous line was observed at 45.0 nm in recent Ar gas puff experiments and lasing was attributed to a self photopumping process in which the intense $3d \rightarrow 2p$ resonance radiation in an optically thick plasma radiatively drives population into the 3d upper laser state[11,12]. Using the experimentally determined energy levels from Ref. [13] we expect the $3d \rightarrow 3p$ line to be at 30.12 nm in Ne-like Ti. Figure 1 shows these two dominant laser lines at 32.6 nm and 30.1 nm. LS coupling notation is used and the $1s^2 2s^2 2p^5$ electrons which are common to all the levels are omitted.

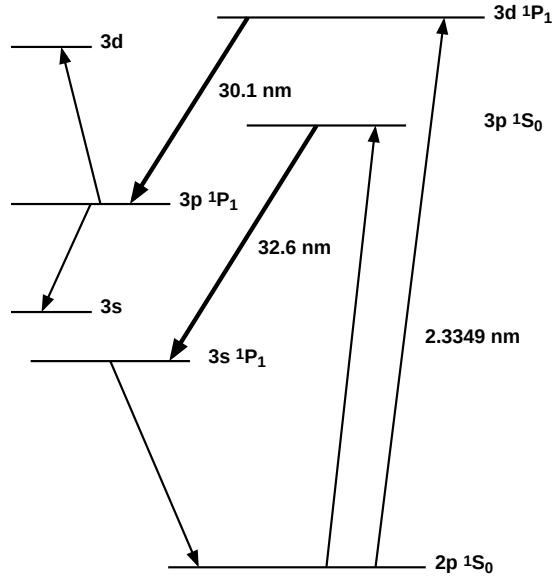


Fig. 1. Energy level diagram showing Ne-like Ti laser lines

For the analog scheme in Ni-like Mo Fig. 2 shows the two dominant laser lines at 18.9 nm and 22.0 nm for a plasma which has been created by a nsec pulse followed by the psec drive pulse. The $4d\ 1S_0 \rightarrow 4p\ 1P_1$ transition at 18.9 nm is driven by the monopole collisional excitation while the $4f\ 1P_1 \rightarrow 4d\ 1P_1$ transition at 22.0 nm is driven by self photopumping by the very strong $4f\ 1P_1 \rightarrow 3d\ 1S_0$ resonance radiation at 3.54 nm . LS coupling notation is used and the $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^9$ electrons which are common to all the levels are omitted.

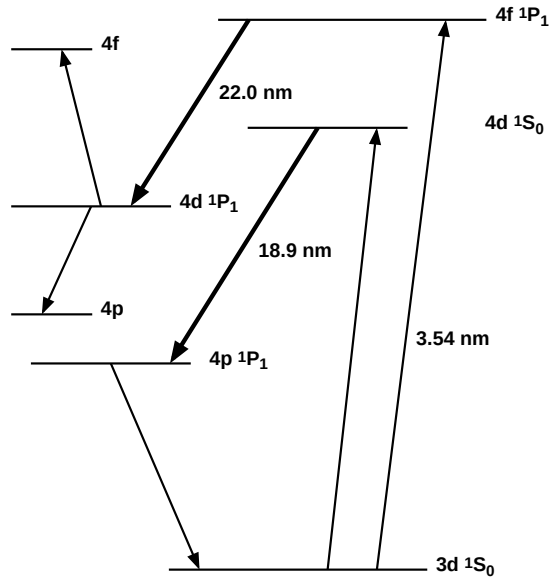


Fig. 2. Energy level diagram showing Ni-like Mo laser lines

3. PLASMA MODELING

To estimate what gain might be achieved on various transitions in Ne-like Ti we did LASNEX one dimensional(1D) computer simulations[14] to model a Ti slab illuminated by a 4 J, 1.5 ns pulse followed by a 3 J, 1 ps pulse from a 1.05 μm Nd laser. The target is assumed to be 0.5 cm long and the laser is focused to a 50 μm width. This is similar to the conditions used to demonstrate lasing in Ne-like Ti[10]. The 1.5 ns pulse rises in 100 ps to a constant intensity of 1.2 TW/cm^2 , which persists for 1.3 ns until the ps pulse is turned on. The ps pulse is triangular shape with a 1 ps full width half maximum and peak intensity of 1200 TW/cm^2 . The nsec pulse then decreases linearly over the next 100 ps. The LASNEX calculations include an expansion angle of 15 degrees in the dimension perpendicular to the primary expansion so as to simulate 2D effects. Figure 3 shows contours of the electron temperature versus space and time during the ps pulse, which turns on at time zero and peaks at 1 ps in this figure. The electron temperature peaks 17 μm from the target with a value of 1450 eV at 1.3 ps. The plasma density is determined by the nsec pulse and does not vary significantly during the ps drive pulse. Figure 4 shows the electron density versus distance from the target surface at 1.3 ps. The temperature is peaking near the critical density surface, which is 10^{21} for the Nd laser.

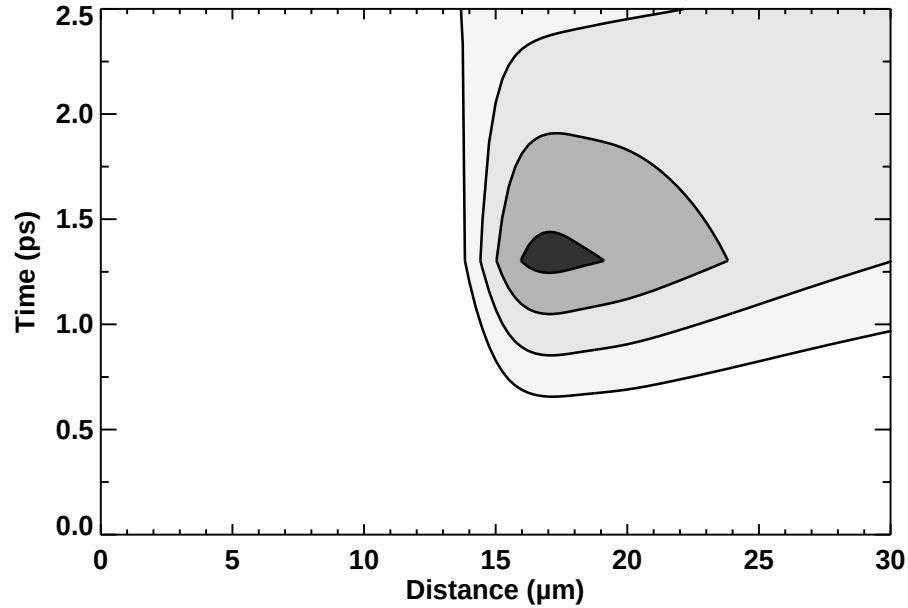


Fig. 3. Contours of electron temperature. The darkest region represents temperatures greater than 1400 eV while the other contours are set at 1190, 980, and 770 eV.

Using the LASNEX calculated densities and temperatures as input to the XRASER code[15], the gains of the laser lines were calculated including radiation trapping effects for all seven $n = 3 \rightarrow n = 2$ resonance lines in Ne-like Ti. Bulk Doppler effects due to the expansion of the plasmas were also included. The XRASER atomic model includes all 89 detailed levels for levels up to $n = 4$ in Ne-like Ti. Figure 5 shows contours of the gain versus space and time for the 32.6 nm laser lines. Comparing this with Fig. 3 we can see that the gain is strongly driven by the rising temperature pulse which is driving both the collisional excitation processes and the strong $3d \rightarrow 2p$ line radiation. The gain contour for the 30.1 nm laser line is very similar to that of the 32.6 nm line. More detail is available in Ref. [16]. The Ne-like population is also quite transient as the plasma tend to overionize quickly at these high temperatures and densities. Figure 6 shows contours of the fraction of the ions in the Ne-like isoelectronic sequence versus space and time. The gain tends to follow the Ne-like

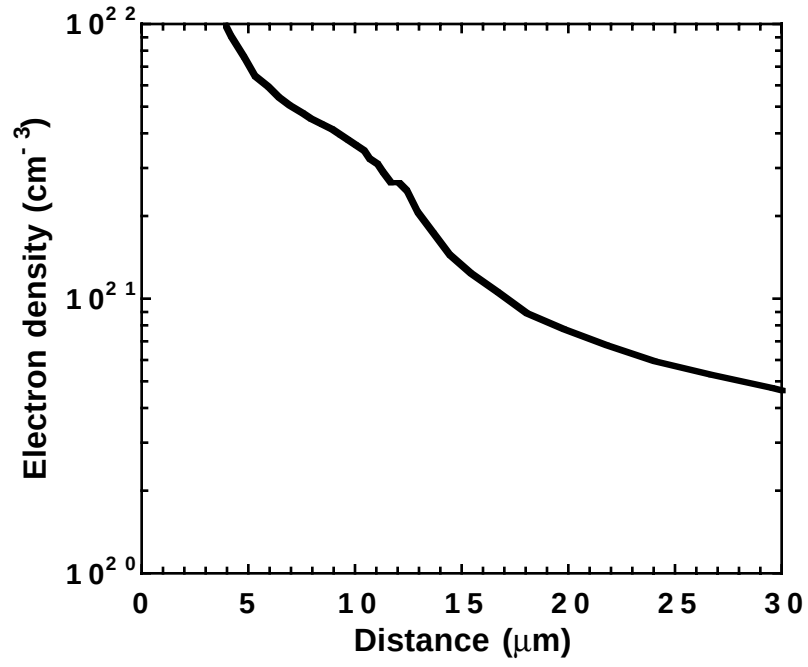


Fig. 4. Electron temperature vs distance from target surface in hydrodynamic expansion direction at 1.3 ps for Ti plasma.

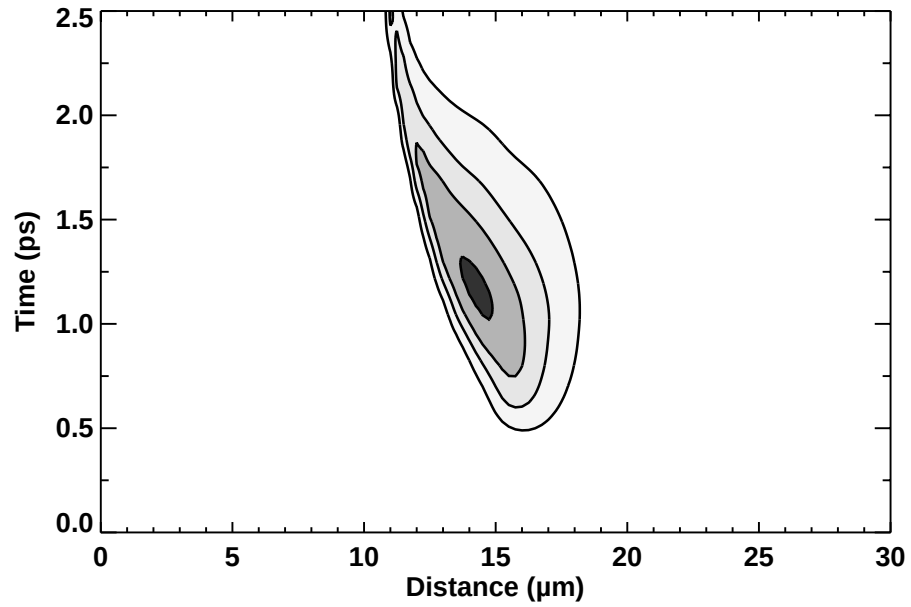


Fig. 5. Contours of gain for the Ne-like Ti 32.6 nm laser line. The darkest region is gain greater than 200 cm^{-1} and the other contours are set at 150, 100, and 50 cm^{-1} . The drive pulse peaks at 1 ps.

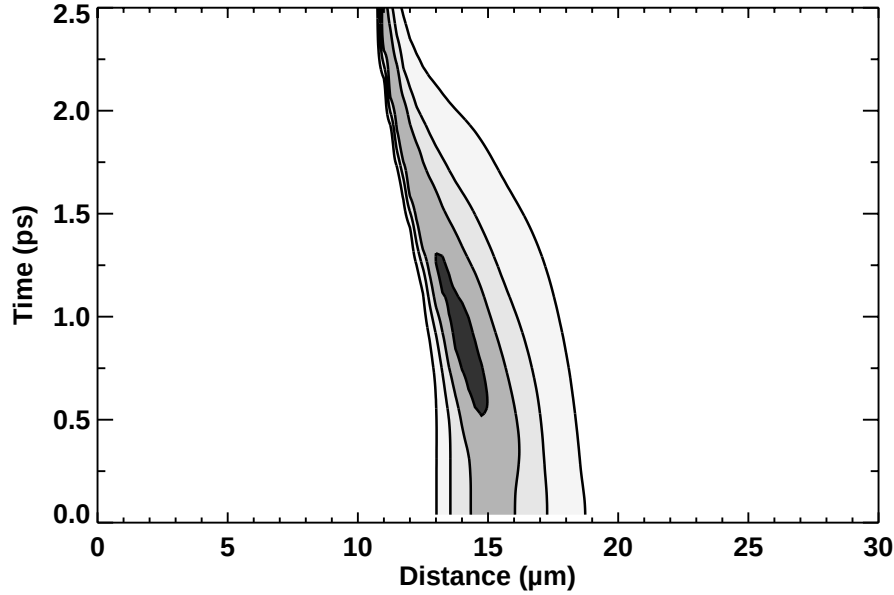


Fig. 6. Contours of the Ne-like Ti fraction. The darkest region has fractions greater than 72% while the other contours are set at 54%, 36%, and 18%. The drive pulse peaks at 1 ps.

population. One also observe that the plasma is ionized significantly by the nsec pulse which heats the plasma to 100 - 200 eV in the regions below critical density. The gain of the 32.6 nm and 30.1 nm lines are very similar in the calculation but the saturation intensity of the 30.1 nm line is about 4 times larger than the 32.6 nm line so it has the potential for higher laser output. For the 32.6 nm line, the gain peaks 14 μm from the target surface at 1.2 ps with a value of 201 cm^{-1} . The electron density is $1.5 \times 10^{21}\text{ cm}^{-3}$, the gradient in the electron density is $-2.9 \times 10^{24}\text{ cm}^{-4}$, the electron temperature is 890 eV, and the ion temperature is 78 eV. At this temporal and spatial position, the 30.1 nm line has a gain of 205 cm^{-1} . The plasma conditions predicted for lasing in this plasma are much different than those predicted for the case of the prepulse technique[1] where the gain region peaks almost 400 μm from the surface at an electron temperature of 200 eV and an electron density of 10^{19} cm^{-3} .

To understand the role of the self photopumping process on the gain of the Ne-like Ti laser lines, XRASER calculations were done with the line transfer package turned off so that all the $n = 2 \rightarrow n = 3$ resonance lines are optically thin and the self photopumping process is absent. For the 32.6 nm lines the peak gain is reduced by 12%, which indicates that the self photopumping process plays a small role in pumping this line. However, for the 30.1 nm line the gain is reduced by 40%, which shows that the photopumping by the strong $3d \rightarrow 2p$ radiation plays an important role in the gain process. Direct collisional excitation from the ground state is the other main process. Comparing the two processes driving population from the ground state into the 3d upper laser level, the direct collisional excitation rate is 0.47 ps^{-1} while the radiative excitation rate due to photopumping by the $3d \rightarrow 2p$ resonance line is 0.46 ps^{-1} . In contrast, the monopole collisional excitation rate driving the gain of the 32.6 nm line is 0.13 ps^{-1} .

Two major limitations to propagating the gain through the plasma are refraction and transit time effects. In the region of peak gain, assuming a constant gradient in the electron density mentioned above, a 32.6 nm X-ray is refracted by 17 μm after traveling only 0.05 cm. For a 2 ps gain duration the laser photons propagate only 0.06 cm. Both these effects severely limit the laser propagation through the gain region and can explain why the experimentally measured gain is much smaller than the predicted gain. The small spatial extent of the gain region suggests that target preparation is important and that using curved targets may be useful.

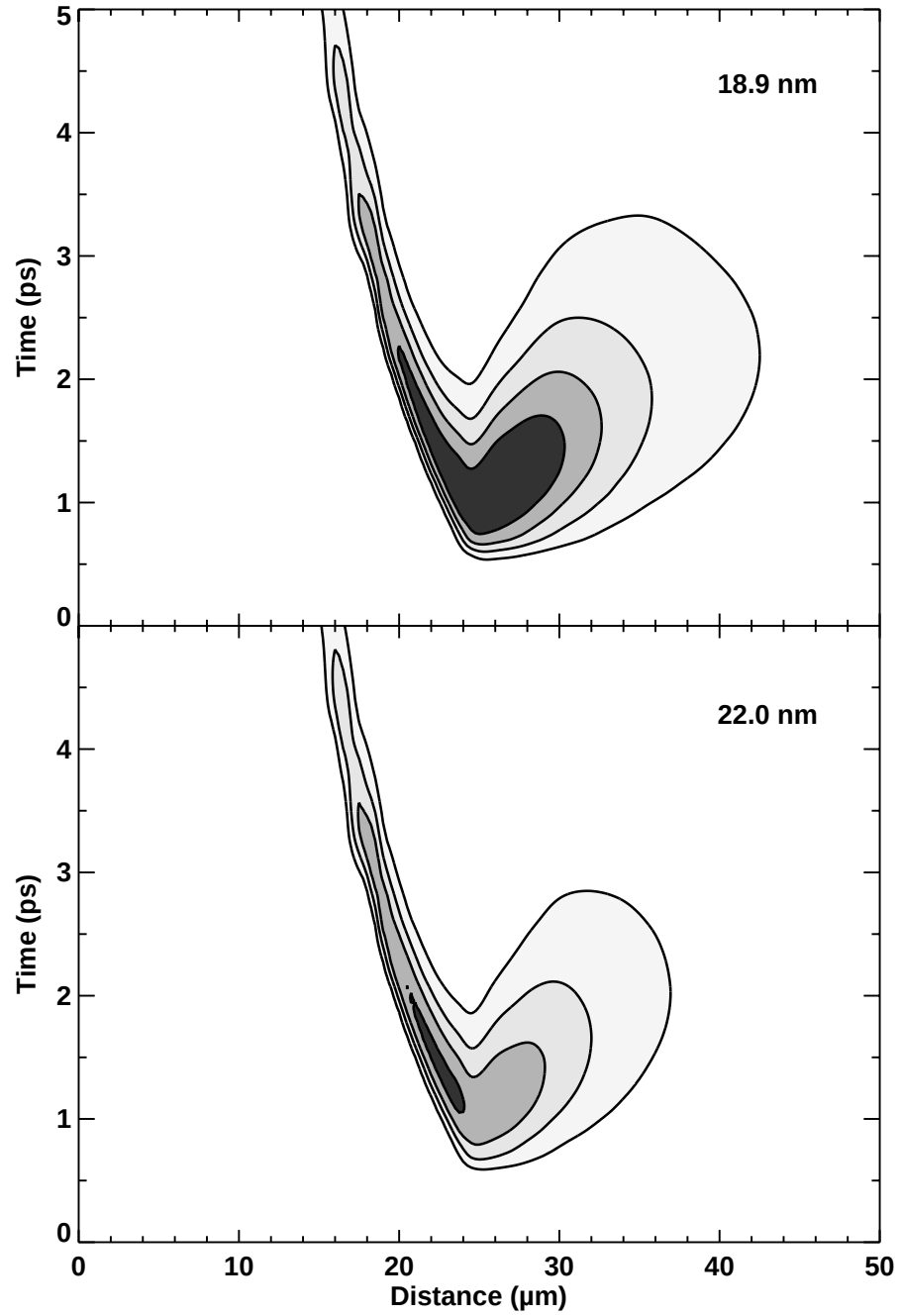


Fig. 7. Contours of gain for the Ni-like Mo 18.9 and 22.0 nm laser lines. The darkest region is gain greater than 300 cm^{-1} and the other contours are set at 225 , 150 , and 75 cm^{-1} . The drive pulse peaks at 1 ps.

At higher-Z we modeled a Ge slab target illuminated under the conditions used for Ti. The gain of the dominant 19.6 nm laser line is only 54 cm^{-1} while gain of only 15 cm^{-1} is predicted on the $3d \rightarrow 3p$ line near 16.0 nm. The other $3p \rightarrow 3s$ line at 13.1 nm has a gain of 25 cm^{-1} and is predicted to be second strongest. The gain also peaks 3 - 4 ps after the peak of the drive pulse. If we increase the intensity of the ps pulse by a factor of ten, the gain of the 19.6 nm line increases to 184 cm^{-1} and the gain of the $3d \rightarrow 3p$ line is 68 cm^{-1} . We also see gain of 30 cm^{-1} on a $2p \rightarrow 2s$ transition near 6.4 nm. Redoing this calculation without line transfer, the gain of the $3d \rightarrow 3p$ line disappears. This does suggest that lasing on the $3d \rightarrow 3p$ transitions favors lower-Z ions where the $3d \rightarrow 2p$ resonance line can be made very intense.

For the case of Ni-like Mo we used the same conditions as described for Ti above to illuminate a Mo target. Using the LASNEX calculated densities and temperatures as input to the XRASER code[15], the gains of the laser lines were calculated including radiation trapping effects on the $3d \rightarrow 4p$ and $4f$ transitions in Ni-like Mo. Bulk Doppler effects due to the expansion of the plasmas were also included. The XRASER atomic model includes all 107 detailed levels for levels up to $n = 4$ in Ni-like Mo. The gain of the 18.9 nm line is stronger and has a larger spatial and temporal duration than the 22.0 nm line. For the 18.9 nm, $4d \rightarrow 4p$, line the gain peaks $26 \mu\text{m}$ from the target surface at 1.15 ps with a value of 387 cm^{-1} . The electron density is $8.5 \times 10^{20} \text{ cm}^{-3}$, the gradient in the electron density is $-1.4 \times 10^{24} \text{ cm}^{-4}$, the electron temperature is 1460 eV, and the ion temperature is 70 eV. At this temporal and spatial position, the 22.0 nm line has a gain of 291 cm^{-1} . The next strongest line is a $4f \rightarrow 4d$ line at 24.8 nm with gain of 271 cm^{-1} . This line is driven by $3d$ inner shell collisional ionization of the Cu-like ground state. Given the simplicity of our model with regard to this process a more detailed atomic model is needed to better understand the gain on this line. More details on these and other laser lines are given in Ref. [17].

To understand the role of the self photopumping process on the gain of the Ni-like Mo laser lines, XRASER calculations were done with the line transfer package turned off so that all the $3d \rightarrow 4p$ and $4f$ resonance lines are optically thin and the self photopumping process is absent. For the 18.9 nm line the peak gain is reduced by 26%, which indicates that the self photopumping process plays a small role in pumping this line. However, for the 22.0 nm line the gain is reduced by 88%, which shows that this line is primarily driven by the photopumping by the strong $4f \rightarrow 3d$ radiation. The 24.8 nm line which is driven by the inner shell collisional ionization process is not significantly affected by the photopumping process.

4. CONCLUSIONS

In conclusion, calculations show that strong gain can be produced in Ne-like Ti by illuminating a Ti slab with a nsec pulse to create a preplasma followed by a psec pulse to drive the temperature in the plasma and create gain by two processes: collisional excitation and self photopumping. The strongest observed laser line at 32.6 nm has peak gain of 201 cm^{-1} and is driven by the monopole collisional excitation process. The line at 30.1 nm which is driven by a combination of collisional excitation and self photopumping has peak gain of 205 cm^{-1} . This analysis suggests that psec laser drivers can be used to create very high gain in Ne-like systems on the standard $3p \rightarrow 3s$ transition as well as the new $3d \rightarrow 3p$ transition and produce psec X-ray laser pulses which can be used for applications such as imaging other plasmas.

Calculations also show that strong gain can be produced in Ni-like Mo under the same conditions used in the Ti experiments by three processes: monopole collisional excitation, self photopumping process, and inner shell collisional ionization. The strongest line at 18.9 nm has peak gain of 387 cm^{-1} and is driven by the monopole collisional excitation process. The self photopumped line at 22.0 nm has peak gain of 291 cm^{-1} while the 24.8 nm line driven by inner shell collisional ionization has peak gain of 271 cm^{-1} . The low energy requirements of the psec laser drivers suggest that this may be the route towards making practical, high repetition rate X-ray lasers in the future with both Ne-like and Ni-like systems.

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