Pump pulse-width dependence of grazing-incidence pumped transient collisional soft-x-ray lasers

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The output energy dependence of high repetition rate grazing incidence pumped Ni-like Mo, Ni-like Ag, and Ne-like Ti transient collisional soft x-ray lasers on the duration of the pump pulse was studied combining experiments and model simulations. Lasing is observed to occur for a wide range of pump pulse widths (e.g., 2 to 18 ps for Ni-like Ag), with maximum output occurring for pump pulses of 4–6 ps FWHM, corresponding to pump intensities of $1.4–2.0 \times 10^{14}$ W/cm^2. Moderately short pump pulses are observed to be optimum for lasers that make use of preplasmas in which the mean degree of ionization approaches the charge of the lasing ion, while long pump pulses produce over-ionization and weaker lasing. However, long pump pulses are capable of producing gain and lasing in low Z ions even when the preplasma has a very low degree of ionization after expanding for 5 ns. As the duration of the pump pulse shortens the optimum delay respect to the prepulse is observed to decrease. The physics that determines these and other measured trends is discussed.

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INTRODUCTION

Compact high repetition rate soft x-ray lasers are of significant interest for applications. Fast discharge excitation of capillary plasmas has produced very compact 46.9 nm wavelength lasers with repetition rates up to 10 Hz [1]. The generation of population inversions by transient heating of a plasma with picosecond duration optical laser pulses of 3–10 J energy impinging at normal incidence produced gain saturated lasers at wavelengths between 12 and 33 nm [2–4]. These lasers typically operate at a repetition rate of one pulse every several minutes. More recently, plasmas driven by high repetition rate table-top optical lasers have produced gain saturated soft x-ray laser amplification operating at 5–10 Hz repetition rate [5–10]. The more efficient ps laser heating of plasmas by grazing incidence irradiation at angles between 14 and 23° has resulted in gain-saturated transient collisional lasers operating at a repetition rate of 5 Hz at wavelengths as short as 13.2 nm in transitions of Ni-like ions [6,8], and in the observation of amplification for wavelengths as short as 10.9 nm [5]. Lasing in the gain-saturated regime was also obtained at the same repetition rate in Ne-like ions at wavelengths near 30 nm [9]. This plasma heating geometry takes advantage of the refraction of the pump beam in the plasma to increase the path length of the pump laser in the gain region of the plasma, thereby increasing the fraction of the energy absorbed in that region. Refraction allows for a precisely defined electron density n_e at which the beam is reflected based on the grazing incidence angle θ and the pump laser wavelength: $\theta = \sqrt{n_e/n_{cp}}$ [11–13], where n_{cp} is the critical density at the wavelength of the pump. Hence it is possible to select an incidence angle that increases the path length of the pump beam into a preselected region of the plasma with optimum density for soft x-ray laser amplification. The use of pump laser pulses with a duration of several ps and energies up to 1 J impinging at grazing incidence angles between 14 and 23 ° resulted in the demonstration of gain-saturated table-top lasers at 5 Hz repetition rate in Ni-like Mo, Ru, Pd, Ag, and Cd ions at wavelengths of 18.9, 16.5, 14.7, 13.9, and 13.2 nm, respectively. Amplification was also observed for shorter wavelength transitions of the same isoelectronic sequence, with amplification observed for wavelengths as low as 10.9 nm in Ni-like Te. Lasing in the gain-saturated regime was also obtained at the same repetition rate in the 32.6 nm line of Ne-like Ti and in the 30.4 nm line of Ne-like V [9].

Experiments with a Ni-like Pd laser pumped at normal incidence utilizing an echelon mirror determined the optimal pump pulse duration for lasing [18,19]. Here we report measurements of the laser output energy as a function of pump pulse duration and time delay between prepulse and pump pulse for 18.9 and 13.9 nm grazing incidence pumped lasers in Ni-like Mo and Ni-like Ag, respectively, and for the 32.6 nm Ne-like Ti laser. The pump laser energy in these experiments was much lower than that used in the normal incidence experiments, around 1 J, and there is no need for the echelon setup since the pump itself is running almost in the traveling wave excitation regime. The next two sections discuss the experimental layout and the measurements. In the last section the results of model simulations are used to interpret the experimental results.

EXPERIMENTAL LAYOUT

The soft x-ray lasers were pumped by a table-top Ti:Sapphire chirped pulse amplification laser system ($\lambda = 800$ nm) consisting of a Kerr mode-locked oscillator and three stages of amplification. Pulses from the laser oscillator were stretched to about 180 ps and were subsequently amplified in a three Ti:Sapphire amplifier chain pumped by two Nd:YAG lasers. Gain narrowing reduces the pulse width to ~120 ps. A multilayer coated beam splitter was placed at the output of the third stage amplifier to direct 20% of the laser energy to a prepulse arm. The rest of the third stage amplifier output was sent to a vacuum-grating compressor composed of two

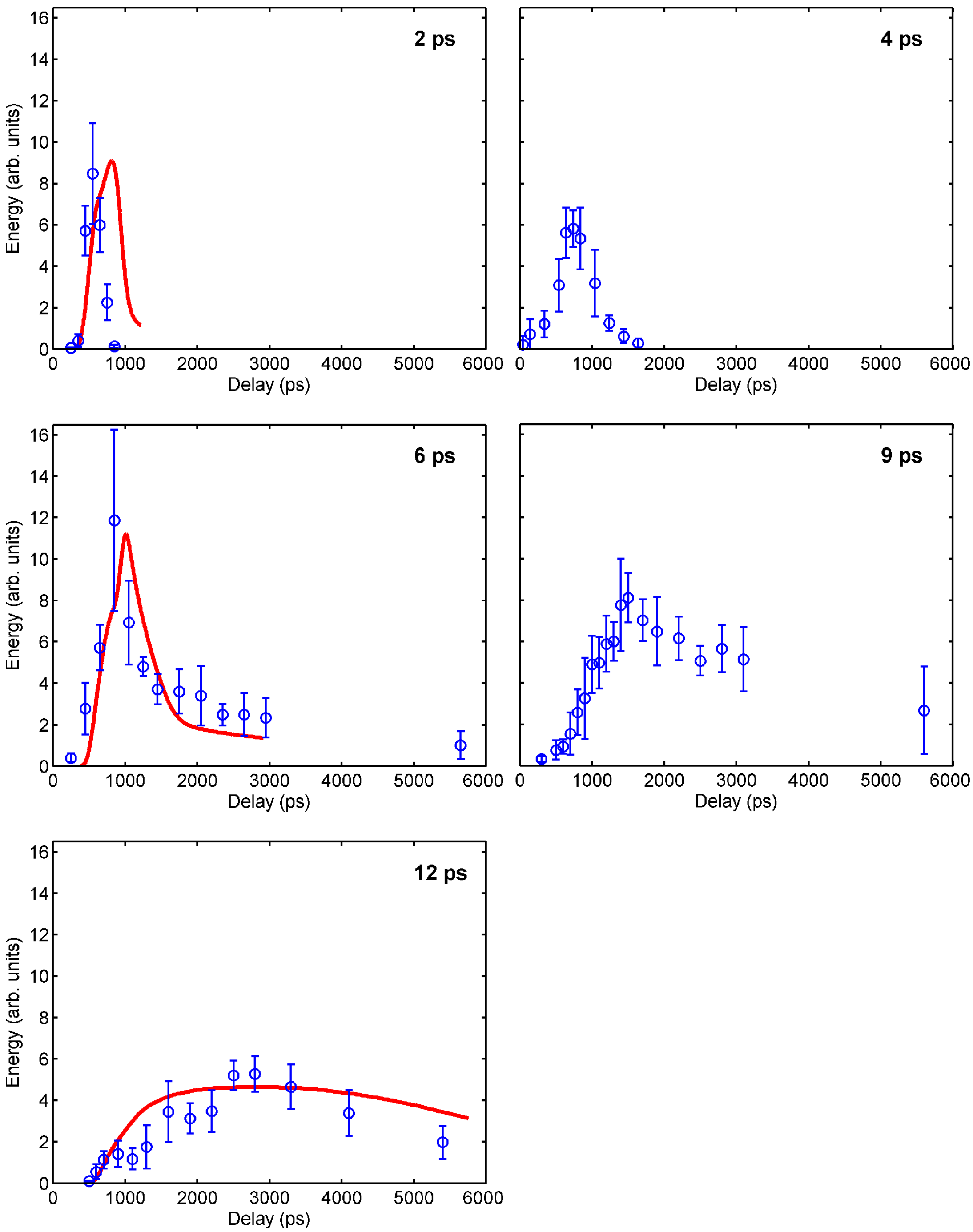

FIG. 1. (Color online) Measured (circles) and simulated (line) laser output pulse energy variation for the 18.9 nm Ni-like Mo laser as a function of time delay between the prepulse and pump pulse for pump pulse durations between 2 ps and 12 ps. Each point in the graphs is an average of about ten laser shots. The energy of the short pump pulse was 1 J.

1200 lines per millimeter gold coated gratings. The pump laser was operated at 5 Hz repetition rate.

The soft x-ray laser amplifiers consisted of 4 mm long line focus plasmas generated by exciting a 2 mm thick solid polished slab target of the selected lasing material. The plasmas were created and heated with a sequence of a weak prepulse of 120 ps duration and ~10 mJ energy, followed after about 5 ns by a second prepulse of the same duration and ~350 mJ energy. The main prepulse was in turn followed after a variable delay by a short heating pulse of ~1 J energy. In the present study the full width at half maximum (FWHM) duration of the short pump pulse was varied between 2 and 18 ps by adjusting the grating compressor. The width of the compressed pulses was measured using an autocorrelator. The prepulses were focused into a 30 μm wide, 4.1 mm FWHM line focus using the combination of spherical and cylindrical lenses. The short pulse was focused into a similar line focus utilizing a parabolic mirror of focal length 76.2 cm positioned at 7° from normal incidence. The off-axis placement of the paraboloid formed an astigmatic focus that

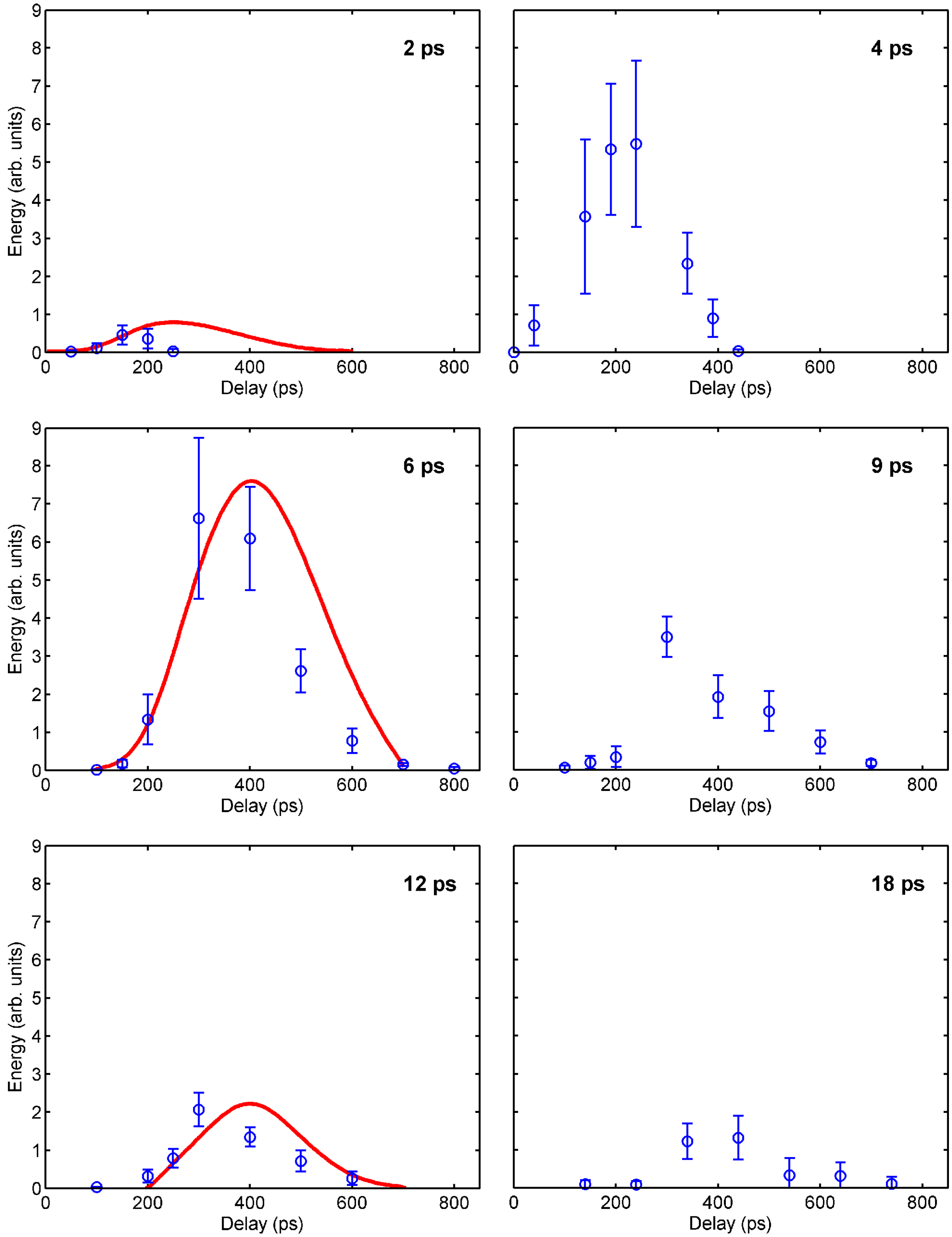

FIG. 2. (Color online) Measured (circles) and simulated (line) laser output pulse energy variation for the 13.9 nm Ni-like Ag laser as a function of time delay between the prepulse and pump pulse for pump pulse durations between 2 ps and 18 ps. Each point in the graphs is an average of about ten laser shots. The energy of the short pump pulse was 1 J.

resulted in a line that was further elongated to 4.1 mm when intercepted at grazing incidence by the target. The target surface was tilted with respect to the axis of the prepulse beam to form grazing incidence angles of 20 or 23° with respect to the axis of the short pulse beam for the Ni-like Mo and Ne-like Ti lasers, and the Ni-like Ag laser, respectively. The output of the x-ray lasers was analyzed using a flat field spectrograph composed of a variably spaced 1200 lines/mm gold-coated spherical grating placed at 3° grazing incidence and a 2048×2048 channel, and a 1 in. square, nongated back-illuminated CCD detector. Spectral filtering was performed using Zr or Al filters and meshes of known transmissivity were placed between the target and the grating to attenuate the beam and avoid saturation of the detector.

EXPERIMENTAL RESULTS

Figure 1 illustrates the dependence of the measured output pulse energy for the 18.9 nm Ni-like Mo (Mo XV) laser on

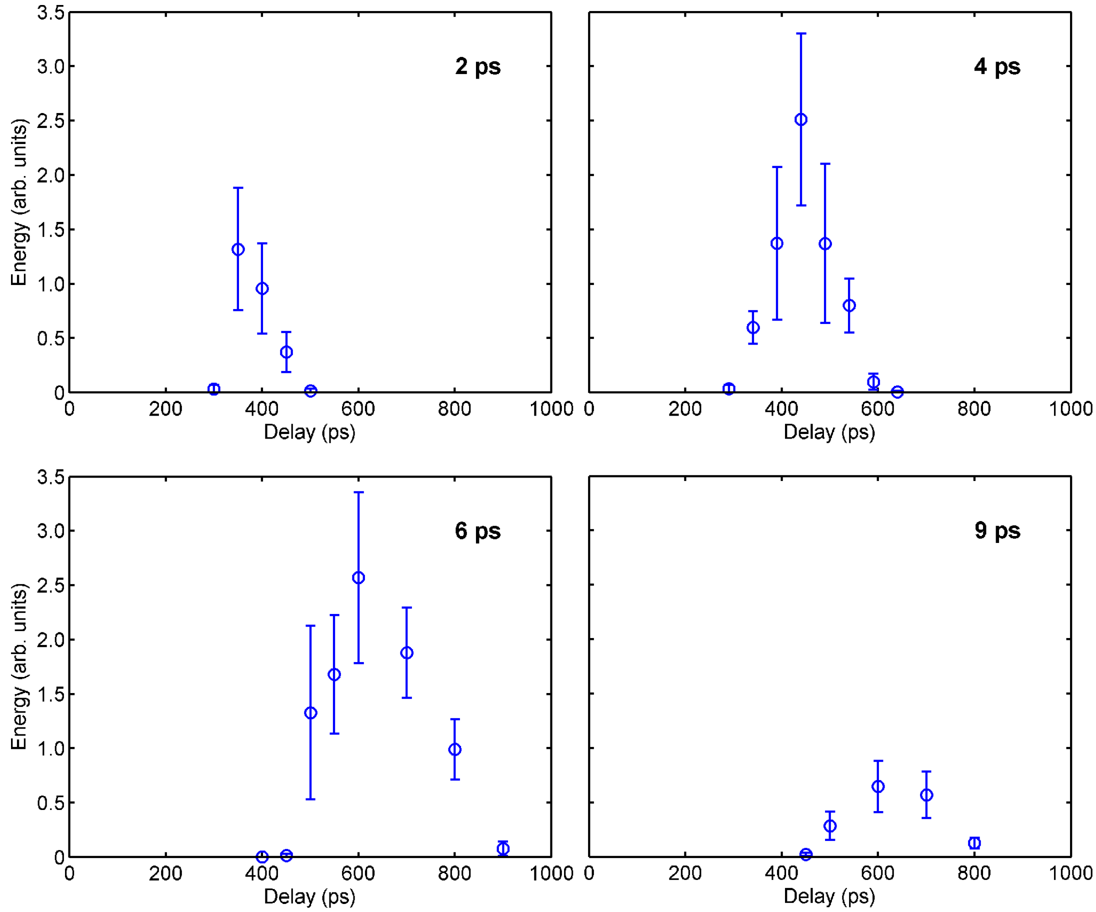

FIG. 3. (Color online) Measured laser output pulse energy variation of the 32.6 nm Ne-like Ti laser as a function of time delay between the pre-pulse and pump pulse for pump pulse durations between 2 ps and 9 ps. The energy of the peak intensity of the pump pulse was 1 J.

the duration of the pump pulse, as a function of the time delay between the prepulse and the short pulse for a given width of the pump pulse. Pulse widths of 2–9 ps duration are observed to produce similar maximum soft x-ray laser output energy, with a maximum pulse energy of about 1.4 μJ, corresponding to an efficiency of $\sim 10^{-6}$. However, the optimum time delay between the prepulse and the pump pulse is seen to increase from 0.7 ns to about 3 ns as the duration of the pump pulse increases from 2 to 12 ps. This increase in the optimum time delay is also accompanied by a large increase in the range of time delays for which strong lasing is observed. While for a pump pulse of 2 ps strong lasing is achieved for delays between about 300 and 700 ps, for the 9 and 12 ps pump pulse the range of time delays for which strong lasing is observed expands over several nanoseconds. For 9 and 12 ps pump pulses strong lasing is observed at time delays of more than 5 ns from the 350 mJ prepulse.

The measured dependence of the laser output energy of the 13.9 nm Ni-like Ag (Ag XX) on the pump laser pulse width is illustrated in Fig. 2. Lasing is observed over nearly an order of magnitude variation of the pump pulse width, from 2 ps to 18 ps. This shows that these are very robust soft x-ray amplifier systems. Optimum soft x-ray laser operation is obtained for pump pulses of 4–6 ps. In a separate set of measurements we have determined that under these optimum pumping conditions the soft x-ray laser pulse duration is ~5 ps [7] and the peak laser pulse energy is about 0.85 μJ [5]. As in the case of Ni-like Mo, the optimum delay is observed to increase as a function of pump pulse width, but it always remains below 500 ps, significantly shorter than the optimum time delays observed for the Ni-like Mo laser. Figure 3 shows the measured variation of the laser output energy for the 32.6 nm line of Ne-like Ti for pump pulse widths between 2 and 9 ps. Optimum output, of about 0.8 μJ, is again observed for pump pulse widths in the range of 4–6 ps. The optimum time delay is observed to increase as a function of the pump pulse width, in this case from about 350 ps for the 2 ps pump pulse to slightly more than 600 ps for the 9 ps pump pulse.

MODELING AND DISCUSSION

To allow a better understanding of the measurements we used two hydrodynamic/atomic physics models [15,16] that produced similar results. The comparison of experimental results for different laser materials obtained in a systematic way under similar experimental conditions also serves to benchmark the codes. The simulations solve the magnetohydrodynamic equations for the plasma in a Lagrangian grid. The gain coefficients are computed from the excited state populations of the Ni-like or Ne-like ions. The plasma den-

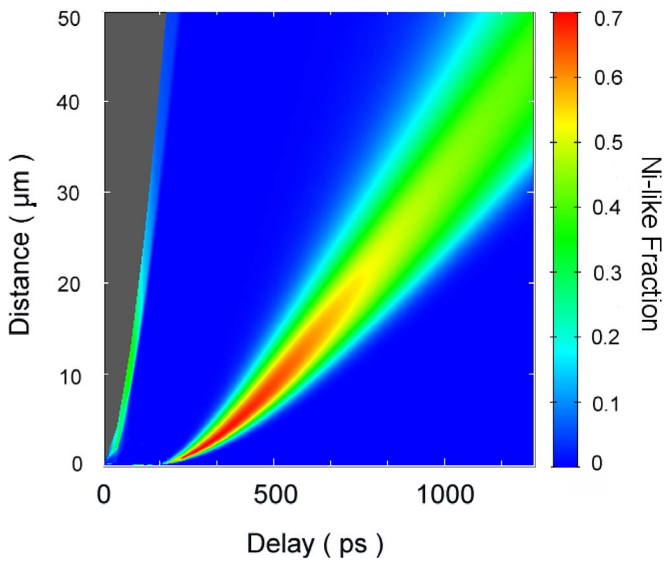

FIG. 4. (Color online) Computed relative abundance of Ni-like Mo as a function of distance to the target and time as calculated by the code. Maximum abundance in color scale is 70% and includes the region from the target surface at 200 ps to 10 μm from the target at 500 ps. For an accurate color map please see the online version.

sity distribution and population densities are used in a three-dimensional (3D) ray-trace post processor code to simulate the characteristics of the soft x-ray laser beam by solving the atomic rate equations including stimulated emission in a self-consistent manner. The results presented here are those obtained with the code RADEX [15].

The observed lasing behavior of both low-Z (Mo) and mid-Z (Ag) plasmas in Figs. 1 and 2 have clear similarities but also reveal substantial differences. In analyzing the observed lasing behavior it is important to notice that there exist two distinct plasma regions which expand into vacuum and define the lasing medium. One is the hotter laser subcritical region where absorption of the pump pulse takes place, and the other is the dense supercritical region that is heated by electron heat conduction and plasma radiation. At the conditions of the experiment analyzed here the first region is substantially overheated in the low-Z case of Mo, with a degree of ionization that surpasses the Ni-like stage. Due to the high temperature this plasma rapidly expands into vacuum. The dense supercritical plasma, which has an initial thickness of less than 1 micron positioned on the slope of the heat wave, always contains the region with maximum abundance of Ni-like ions. After being heated by the prepulse, this layer also expands and the zone containing Ni-like ions stretches into a region >10 micrometers wide that when heated by the pump pulse becomes the active medium region (Fig. 4). For the fixed selected prepulse parameters used in the experiment the time delay between the prepulse and the pump pulse governs the initial degree of ionization and plasma density gradients. The arrival of the pump pulse rapidly heats the plasma, leading to the creation of a transient population inversion and gain.

The case of Mo is a good example to illustrate the strong influence of the degree of ionization of the prepulse plasma in the observed laser behavior. The line plots in Fig. 1 show modeling results for the laser output energy of the 18.9 nm line of Ni-like Mo superposed on the experimental measurements for representative cases of a short (2 ps), medium (6 ps), and long (12 ps) pump pulse. Observation of the results corresponding to short time delays of less than 1 ns show that for the highly ionized preplasmas with a dominant population of Ni-like and Cu-like ions present at this time, optimum lasing is obtained for pump pulses of moderately short duration (2–6 ps). In contrast, for these short delays, long pump pulses (e.g., 12 ps) rapidly over ionize the plasma, destroying the lasing ions by electron impact ionization at a substantially earlier time than that at which the plasma reaches its maximum temperature. As a result the gain and temperature maxima do not coincide, leading to smaller gain values, as illustrated by the simulation results shown in Figs. 5(a) and 5(b). Instead, as shown in Figs. 5(c) and 5(d), with short pulse excitation (2 ps) the temperature and gain peaks coincide, resulting in almost twice the gain. With long prepulse to pump pulse delays of 2–5 ns we observe the opposite situation: lasing is only obtained with long pulse excitation, while no lasing is observed for short pulse pumping. The observation of lasing at such long delays might look surprising at first glance, since according to the simulations the degree of ionization is $Z=2-6$. Nevertheless, since the ionization rate for low Z ions is large, the 9–12 ps pulses succeeds in ionizing the plasma to the Ni-like stage and produces strong lasing. At the relatively small laser pump energy used in these experiments this happens only for low-Z materials such as Mo, since due to the Z^{-3} dependence of the ionization rate for mid-Z materials, such as Ag, is nearly 2 times smaller [17]. Additionally, for long time delays the shorter 2 ps pulses heat the plasma to a lower electron temperature due to the Z^2 dependence of the absorption coefficient. As a result, the fraction of Ni-like ions only reaches its maximum when the temperature has already decayed. Again we encounter a case in which the temperature and gain maxima are separated in time, for which the gain is drastically reduced. Also, as the duration of the pump pulse is shortened, the optimum delay with respect to the prepulse is observed to decrease. This is again due to the decreased ability of the pump pulse to quickly ionize the plasma.

Analysis of experimental results in Figs. 1–3 reveals several interesting aspects. The physics of the dependence of the lasing on the pump pulse width for the Ni-like Ag and Ne-like Ti lasers is similar to that discussed above for the Ni-like Mo laser, but some differences exist. For example, the decrease of delay with shortening of the pump pulse also takes place for Ag, though the delays are quantitatively shorter. Higher Z elements require a higher initial degree of ionization (+19 times ionized for lasing in Ag at 13.9 nm), and therefore the significant initial fraction of Ni-like ions required can only be encountered at time delays below 500 ps, when the electron density, the density gradients, and refraction are very high. This is consistent with our previous observation of continuously decreasing optimum time delays for lasing in Ni-like ions ranging from Mo ($Z=14$) to Te ($Z=24$) [8].

Another difference is the behavior for short pump pulses. While the decrease of the laser signal for the longer pump

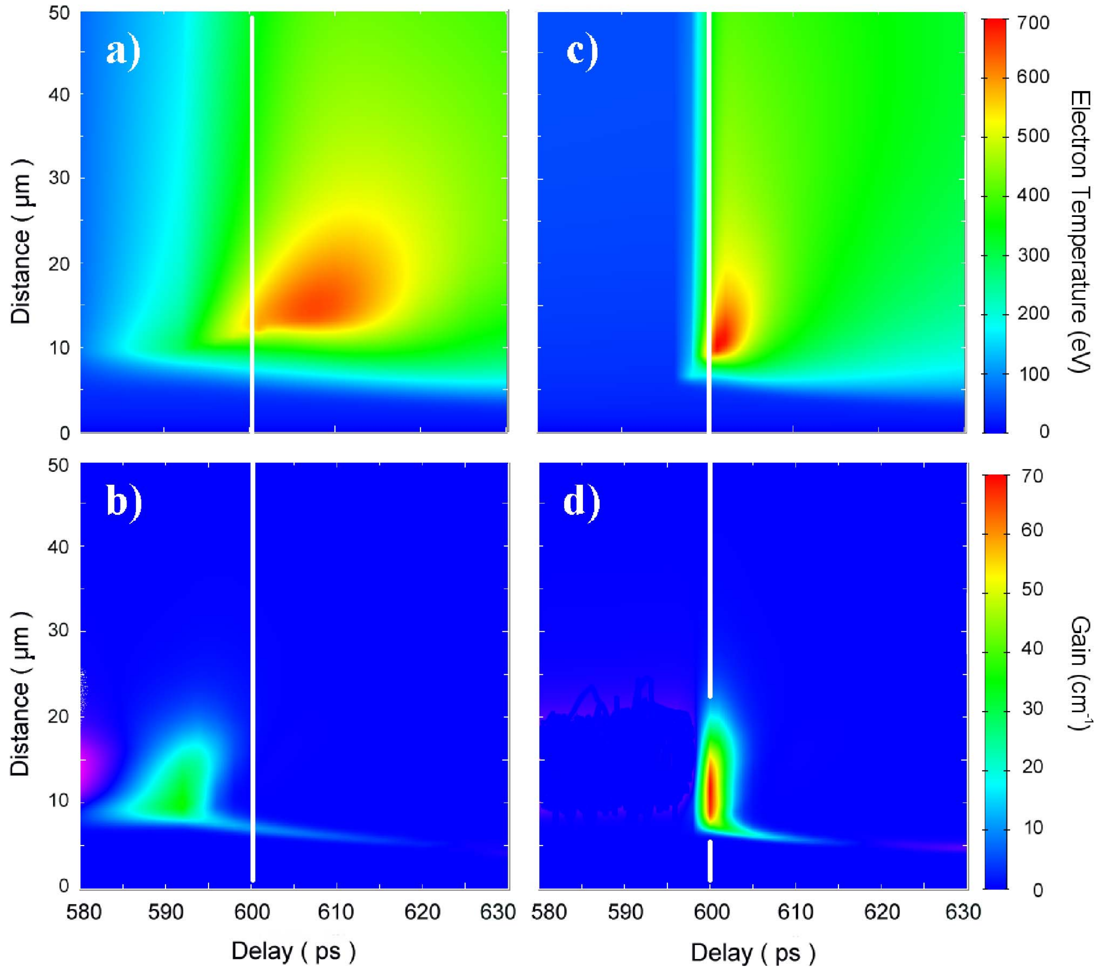

FIG. 5. (Color online) Calculated spatiotemporal distribution of the temperature and gain in Ni-like Mo for pump pulse durations of 12 ps [left pictures (a) and (b), respectively] and 2 ps [right pictures (c) and (d), respectively]. The delay between the 120 ps prepulse and the pump pulse is 600 ps. The vertical white line shows the time of the peak intensity of the pump pulse.

pulse durations are obviously related to the mismatch between the pump pulse duration, the ionization time, and the transient characteristic of the gain, the reason of decreased laser signal of the Ni-like Ag for very short pump pulses (see Fig. 2) is not as obvious and can look surprising. The combination of different physical effects is responsible for this behavior. As a general tendency, obtaining soft x-ray lasing in higher Z ions requires hotter and denser plasmas due to the steep gain dependence with Z, $g \sim 1/Z^{3.5}$ [15]. In principle, for short pulses the temperature should only depend on the pump fluence, or pulse energy $\int q dt$ (where q is the laser power density), which is constant for all pulse durations. However, at high flux densities and short pulse durations the high-field effects start to influence the electron collision frequency and modify the electron distribution function, decreasing the absorption of the pump laser light and lowering temperature by 30% or more in the case of 2 ps pump pulses. As a result, for these short pump pulses the laser signal substantially drops for the Ag laser amplifier, which requires a larger temperature than Mo to achieve high gain. Also contributing to the decreased laser signal for short pump pulses is an increased mismatch between the excitation traveling wave velocity and the group velocity of the amplified signal. The optimum plasma density is ~1.3 times larger for Ag than for Mo, which increases the grazing angle by ~15%. The larger grazing incidence angle increases the excitation traveling wave velocity. With angles of $\theta = 20° - 23°$ the pump wave front speed $v_p = c\cos(\theta)$ is 6–9 % faster than the speed of light. In addition, the group velocity v_g that can be obtained from the relation $1/v_g = 1/c + g/\Delta\omega$ (here g is gain, and $\Delta\omega$ is the linewidth) [14], may be smaller than the speed of light by 10% or more as a result of the high transient gain and narrow linewidth. For a target length $L = 4$ mm, if the signal is not saturated, the total mismatch $\tau = L(1/v_g - 1/v_p)$ can exceed 2–3 ps and is larger for Ag than for Mo. Laser amplification at shorter pulses is more sensitive to this mismatch because, in general, the gain duration decreases with shortening of pump pulse [18]. Therefore in contrast with the Ni-like Mo laser case, lasing in Ni-like Ag is weak for the short pump pulses.

Optimum laser output at 13.9 nm in Ni-like Ag is obtained for pump pulses of 6 ps at time delays of about 300 ps, where the initial mean degree of ionization is computed to be $Z = 18 - 19$, and the electron temperature after irradiation by the short pulse is calculated to reach Te ~500 eV. However, lasing is also observed for pump pulse widths of 18 ps for an optimum delay of about 400 ps, a situation where the pump pulse is able to ionize a slightly under-ionized plasma to create a significant density of Ni-like ions. Nevertheless at these conditions the laser output energy is measured to be several times smaller than for the 6 ps pump pulse width.

CONCLUSIONS

In summary, we have measured the dependence of grazing incidence pumped collisional lasers on pump pulse duration. The analysis of the experimental results reveals several interesting tendencies that highlight aspects of the physics of these collisional soft x-ray lasers. One is the unusual and somewhat unexpected observation of lasing in Mo at large delays of 5 ns for long pump pulses, that results from the fact that long pump pulses are capable of ionizing an initially very low Z plasma to the Ni-like ionization stage. Another is the decrease of the soft x-ray laser signal at the smallest pump pulse durations in Ag, caused by a combination of effects that include the plasma kinetic effects, and the mismatch of the excitation traveling wave speed and soft x-ray pulse group velocity. In all three lasers studied the maximum output pulse energy was observed for 6 ps pump pulses. A third tendency is the shortening of the optimal delay between the prepulse and the heating pulse as the duration of the heating pulse shortens and its ability to ionize decreases. The optimum time delay also decreases as a function of the charge Z of the lasing ion. Overall, grazing incidence heated plasmas are shown to be robust and efficient soft x-ray laser amplifier systems in which large gain is obtained over a broad range of pump pulses.

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