Prepulse technique for producing low-Z Ne-like x-ray lasers

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We report an application of the prepulse technique which uses a low-intensity prepulse before the main optical drive pulse to prepare the plasma prior to lasing in low-Z, Ne-like ions. Ne-like x-ray lasers are now available over a previously inaccessible range of wavelengths. As an illustration of this technique we report an observation of lasing in Cr^{14+} and Fe^{16+} on the Ne-like $J=0\rightarrow1$, $3p\rightarrow3s$ transitions at 285 and 255 Å as well as gain measurements for Ti^{12+}.

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I. INTRODUCTION

Since the first demonstration of soft-x-ray lasing using the collisional-excitation mechanism in Ne-like Se, many other Ne-like ions ranging from Cu ($Z=29$) to Ag ($Z=47$) have been made to lase [1,2]. At lower Z's only Ne-like Ti ($Z=22$) has lased [3] and there was some evidence which suggested Ti was unique and may be resonantly photopumped. This belief was supported by the inability to make Sc ($Z=21$) and V ($Z=23$) lase. This paper presents evidence for lasing in Ne-like Cr ($Z=24$) and Fe ($Z=26$) using a prepulse technique to prepare the plasma amplifier. The $J=0\rightarrow1$, $3p\rightarrow3s$ transition, which is at 285.5 Å in Cr and 254.9 Å in Fe, dominates the spectra as it did for Ti and as was originally predicted, but never observed, for other Ne-like lasers [1]. We also observe lasing on other $J=0\rightarrow1$ and $2\rightarrow1$ transitions of Cr and Fe. Based on the experimental results described in this paper, we believe that resonant photopumping is not a dominant pumping mechanism for the Ti laser.

II. EXPERIMENTS

Experiments were conducted at Lawrence Livermore National Laboratory on the Nova laser using $\lambda=0.53$ μm. The Nova laser illuminated a 500-μm-thick, 4.5-cm-long Cr slab. The above length of the target was reduced by a 16% gap in the center which results in an actual length of 3.8 cm. The pump-laser beam was a 600-ps-FWHM (full width at half maximum) Gaussian pulse with 1100 J of energy in a 120-μm-wide (FWHM) by 5.4-cm-long line focus, resulting in a peak intensity of 3.4×10^{13} W/cm^2. A 6-J prepulse (also 600 ps FWHM) preceded the main pulse by 7 ns.

The principal instruments were a time-gated, microchannel plate intensified grazing-incidence grating spectrograph (MCPIGS) and a streaked flat-field spectrograph (SFFS); both of these instruments observed the axial output of the x-ray laser. The MCPIGS provided angular resolution over 10 mrad near the x-ray laser axis, while the SFFS integrated over an angular acceptance of 10 mrad. The angular resolution of both instruments was perpendicular to the target surface. The MCPIGS used a 600-line/mm grating and had spectral coverage of approximately 150–680 Å. A second MCPIGS spectrometer with a 1200-line/mm grating and spectral coverage of 75–340 Å was located 45° off axis to observe the strong $2p\rightarrow2s$ emission lines from the plasma and provide information about the ionization balance.

Lasing was determined by observing the high spectral brightness of the lasing lines relative to the strong emission lines on axis, the absence of the lasing lines off axis, the short time duration of the lasing relative to the optical drive pules, and the exponential growth of the laser output as the length was increased [4].

A spectrum from the MCPIGS, Fig. 1, shows quite clearly the strong $J=0\rightarrow1$ laser line at 285.5 Å and the weaker $J=2\rightarrow1$ laser line at 402.2 Å in Ne-like Cr. Identification of the 285.5 Å line as being the $2p_{1/2}3p_{1/2}(J=0)\rightarrow2p_{1/2}3s_{1/2}(J=1)$ line is based on laser plasma experiments [5] which give a value of 285.38

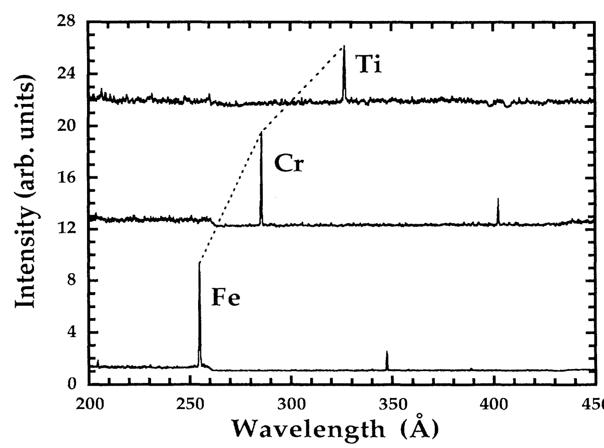

FIG. 1. MCPIGS on-axis spectra obtained in the Nova experiments from 3.8 cm long targets of Ti, Cr, and Fe. For Cr, the Ne-like $J=0\rightarrow1$ laser line at 285.5 Å dominates the spectrum. The $J=2\rightarrow1$ line at 402.2 Å is quite visible while the other $J=2\rightarrow1$ line which would be expected at 392.8 Å is missing. The dotted line connects the three Ne-like $J=0\rightarrow1$ lines, which are seen at 326 and 255 Å in Ti and Fe, respectively.

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Å. The bar over the $2p$ state indicates a vacancy in the closed L shell. By comparing the existing experimental data for nearby elements with the theoretical values calculated from the atomic physics code of Grant *et al.* [6] we estimate a value of 285.46 Å for this line, consistent with the experiments. Our results for Ti, Cr, and Fe are summarized in Table I along with the uncertainties in the measured values. The theoretical values have an uncertainty of 0.2 Å.

The 402.2 Å line of Cr is the analog to the strong $J=2\rightarrow1$ Ne-like Se laser line at 209.8 Å. The other $J=2\rightarrow1$ line, the analog to the 206.4 Å Se line, which would be at 392.81 Å, is not seen [5]. These two lines are the $\overline{2p}_{1/2}3p_{3/2}(J=2)\rightarrow\overline{2p}_{1/2}3s_{1/2}(J=1)$ and $\overline{2p}_{3/2}3p_{3/2}(J=2)\rightarrow\overline{2p}_{3/2}3s_{1/2}(J=1)$ transitions, respectively. Thus Cr is the lowest-Z Ne-like ion in which the $J=2\rightarrow1$ line has been observed to lase. We also observe very weak Ne-like Cr lines at 240.2 Å and 440.7 Å which we identify as the $\overline{2p}_{1/2}3p_{1/2}(J=0)\rightarrow\overline{2p}_{3/2}3s_{1/2}(J=1)$ and $\overline{2p}_{3/2}3p_{1/2}(J=2)\rightarrow\overline{2p}_{3/2}3s_{1/2}(J=1)$ lines, respectively [5,7]. The 240 Å line has the same upper state as the 285 Å line but a different lower state. This line has been observed to lase weakly in selenium [4] but has not been seen in other Ne-like ions. The 440 Å line is the analog of the very long wavelength $J=2\rightarrow1$ line seen in many other Ne-like ions; in selenium it is the analog of the 262.9 Å line.

The angular distribution of the 285 Å Cr line on the MCPIGS shows the intensity peaking on the laser axis and falling to one half peak intensity 4 mrad off axis. This is evidence that lasing occurs in a region far off the target surface where the plasma has small gradients in the electron density. By comparisons, the 236 Å laser output for a typical slab target of Ge peaks 13 mrad off axis with a FWHM divergence of 10 mrad [8].

To estimate the gain for the 285 Å Cr laser line we compared the observed power seen in the SFFS for targets of different lengths. Temporally, the 285 Å line lases near the peak of the main optical laser pulse with a FWHM duration of 120 ps. The power was integrated over the duration of the lasing to provide better signal to noise. Comparing targets of length 1.7 and 3.8 cm we observe a 140 times increase in the 285 Å signal. Using the standard formula [1] we estimate a gain of 2.6 cm^{-1} for the 285 Å line. We did a similar gain length study for Ti using the MCPIGS data and estimate a gain of 2.6 cm^{-1} for the 326 Å line, which is consistent with the previously published estimate [3].

When amplification at 326 Å was first observed in Ne-like Ti [3], its behavior was considered anomalous as compared with known Ne-like lasers. The absence of lasing in neighboring elements suggested that the lasing was enhanced by resonant photopumping of the Ne-like Ti by strong emission lines from C-like and N-like Ti [3]. These resonances are unique to Ti and this mechanism explained the requirement for overionizing the Ti so as to produce the pump lines. In the previous experiments, Sc and V had failed to lase and Ti produced evidence for lasing in only 60% of the experiments. Ti is now lasing reliably on every shot as the prepulse energy is now more reproducible. We attempted to observe lasing in Sc and V, without success. Recent calculations and experiments [9] suggest that the hyperfine effect plays a major role in the nonlasing of Sc and V. Since elements with odd Z have a nuclear spin and a nuclear moment and those with even Z tend to have no nuclear spin, the hyperfine effect tends to adversely impact the gain of ions with odd Z. The Cr meanwhile has lased in all seven experiments which used the 0.5% prepulse 7 ns before the main pulse. We tried Fe under the same conditions used for Cr and it lased on the $J=0\rightarrow1$ line at 254.9 Å, as shown in Fig. 1, as well as several weaker lines listed in Table I. When the Cr was tried without a prepulse it did not lase. The Cr did lase when a prepulse was used 4 ns early instead of 7

TABLE I. Wavelengths of observed laser lines for Ne-like Ti, Cr, and Fe and the range of conditions under which lasing has occurred. The Nova pulses were 600 ps Gaussian pulses of 0.53-μm light with intensity I and delay Δt between the prepulse and main pulse. For previously measured wavelengths, see footnotes (a)–(d).

Ion	Lines observed	Gain (cm^{-1})	λ_{obs}(Å)	$\lambda_{\text{prev exp}}$(Å)	λ_{calc}(Å)	I_{prepulse} (TW/cm^2)	Δt(ns)	$I_{\text{main pulse}}$ (TW/cm^2)
Ti^{12+}	$J=0\rightarrow1$	2.6	326.3±0.5	326.29±0.05[b]	326.24	0.1	7	8–30
Cr^{14+}	$J=0\rightarrow1$	2.6	285.5±0.5	285.375±0.02[a]	285.46	0.2	4–7	34
	$J=2\rightarrow1$		402.2±0.5	402.346±0.02[a]	402.32			
	$J=0\rightarrow1$		240.2±0.5		240.17			
	$J=2\rightarrow1$		440.7±0.5	440.772±0.02[a]	440.78			
Fe^{16+}	$J=0\rightarrow1$		254.9±0.5	254.87±0.03[c]	254.92	0.2	7	34
	$J=2\rightarrow1$		347.6±0.5	347.96±0.05[d]	347.84			
	$J=0\rightarrow1$		204.2±0.5	204.65±0.03[c]	204.80			
	$J=2\rightarrow1$		388.9±0.5	389.25±0.05[d]	389.15			

[a]Ref. [5].
[b]Ref. [7].
[c]Ref. [13].
[d]Ref. [14].

ns, however, the lasing was weaker. The uniqueness of the Ti was the strongest argument for the resonant photopumping hypothesis and it is now clear that Ti is not unique and that this hypothesis is less likely. Calculations suggest that direct collisional excitations of the upper laser state by monopole collisions is the main mechanism driving the $J=0\rightarrow 1$ line with other mechanisms such as recombination playing an important role in the other laser lines. Radiative transport processes are also important for all the lines and mechanisms such as self-pumping need to be studied more to understand their importance [10,11].

III. PLASMA MODELING

Based on our calculations, we believe the prepulse is playing a key role in creating a larger, more uniform density plasma, at the low densities required for lasing at these wavelengths. Previous calculations showed that single-pulse illumination of slab targets produce density gradients which are very steep and are therefore limited in their effective lasing length by refraction [8]. To understand the effect of the prepulse we did LASNEX 1D computer simulations [12] of the Ti laser with and without the prepulse. The calculations with the prepulse use a 550-J main pulse with a 3-J prepulse 7 ns early while the calculations without the prepulse use an 160-J main pulse. Both calculations assume a 4.5 cm long slab target driven by a 600 ps FWHM Gaussian pulse of 0.53 μm light. The prepulse calculations correspond to experimental conditions in which lasing was observed, as shown in Fig. 1, while the calculations without the prepulse use an intensity chosen by scaling from successful experiments in Ne-like Ge.

At the time of peak illumination by the optical drive pulse, Fig. 2(b) shows the gain of the 326 Å Ne-like Ti laser line versus distance from the surface of the foil in the direction of the hydrodynamic expansion for the two cases. Both cases show similar gain, however, the spatial FWHM of the gain is 180 μ with the prepulse as compared to 50 μ without the prepulse. At the region of peak gain, the electron temperature varies between 210 and 240 eV, the ion temperature between 44 and 47 eV, the Ne-like fraction between 26% and 38%, and the electron density between 2 and 1×10^{19} cm^{-3} for the cases with and without the prepulse, respectively. The plasma conditions are very similar in the two cases; the difference is the gradient in electron density and the size scale.

Figure 2(a) shows the electron density versus distance from the surface for the two cases at the time of peak illumination by the optical drive pulse. The larger density gradient for the case without the prepulse is quite apparent. At the peak of the lasing, the prepulse case has an electron density gradient of 1.3×10^{21} cm^{-4} while the gradient is 5.2×10^{21} cm^{-4} for the case without the prepulse. If one assumes a constant gradient, a lasing photon propagating down the lasing axis would travel 1.4 cm before it was refracted from the middle to the edge of the gain region for the case without the prepulse. For the case with the prepulse, the same photon would travel 5.4 cm before reaching the edge of the gain region, defined as

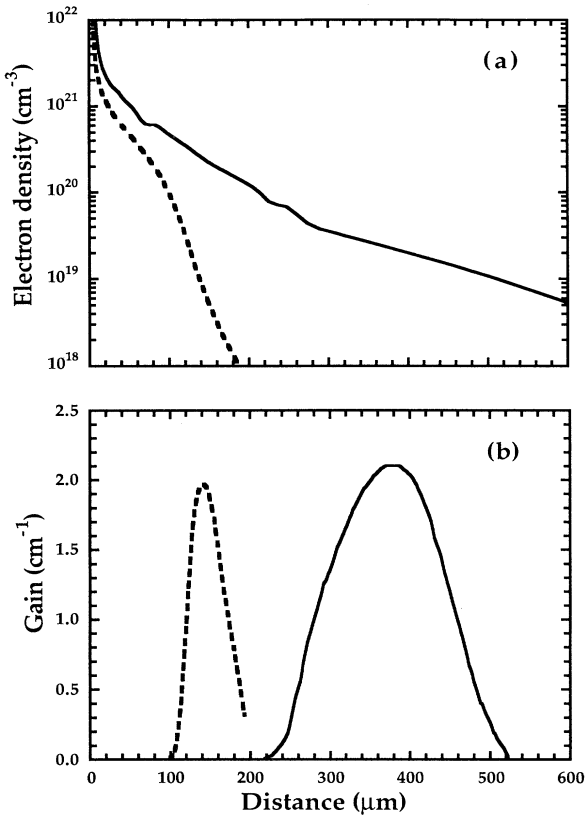

FIG. 2. (a) Electron density and (b) gain of the 326 Å Ne-like Ti line versus distance from the surface of the slab in the direction of the hydrodynamic expansion. Two cases are shown: with (solid) and without (dashed) the prepulse. The LASNEX calculations are at the time of peak illumination from the optical drive laser.

the position where the gain is one-half its peak value. Therefore, the prepulse is creating a larger gain region with a lower density gradient which allows most of the photons to be amplified by the entire length of the laser. The combination of the small gain region with the inability to propagate the length of the laser is no doubt the reason these lasers have not worked without the prepulse.

IV. CONCLUSIONS

We have observed lasing in Ne-like Cr at 285.5 and 402.2 Å which has narrow divergence and requires a prepulse in order to lase. In addition we see lasing in Ne-like Fe as well as the previously observed Ne-like Ti. The $J=0\rightarrow 1$, $3p\rightarrow 3s$ transition dominates the spectra as was originally predicted, but never observed, in other Ne-like ions. These experiments show that Ti is not unique and it is therefore unlikely that resonant photopumping is playing a dominant role in the gain of the Ne-like Ti laser. The use of this prepulse technique has opened up another class of Ne-like x-ray lasers for investigation.

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