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Table-top transient collisional excitation x-ray laser research at LLNL

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ABSTRACT

We describe recent experiments at the Lawrence Livermore National Laboratory (LLNL) to produce a table-top x-ray laser. Using a combination of long 800 ps and short ~ 1 ps high power laser pulses with ~ 6 J in each beam, a transient collisionally excited Ne-like ion x-ray laser scheme has been investigated. We present results of high x-ray laser gain for the Ne-like Ti 3p-3s J=0-1 transition at 326 Å and have achieved gL product of 15 for target lengths up to 1 cm. We have extended the transient collisional scheme to shorter wavelengths using the Ni-like analog, specifically the 4d-4p J=0-1 of Ni-like Pd at 147 Å.

Keywords: x-ray laser, picosecond laser pulse, table-top terawatt laser, transient collisional excitation, Ne-like, Ni-like.

1. INTRODUCTION

There has been significant progress towards the realization of a table-top short wavelength x-ray laser (XRL) in the last few years. This has been achieved by a number of essentially different and novel experimental approaches. The use of a fast capillary discharge has produced x-ray amplification in a Ne-like argon scheme on the 3p-3s J=0-1 transition at 469 Å. ¹ Gain of 0.6 cm^{-1} has been measured for a plasma length up to 12 cm giving a gain-length product of $gL = 7.2$. Saturation has been achieved with $gL > 25$ by using a multilayer mirror to double pass the x-ray laser transition through the plasma column. ² Energies up to 30 μJ have been extracted using this technique. A 10 Hz Pd-like ion x-ray laser scheme has been demonstrated with $gL \sim 11$ at 418 Å for 40 fs irradiation of a xenon gas cell using field-induced tunneling ionization followed by collisional excitation. ³ A shorter wavelength transient collisional excitation (TCE) scheme has produced high gain $g = 19 \text{ cm}^{-1}$ and a gain-length product of 9.5 on a Ne-like titanium 3p-3s J=0-1 transition at 326 Å. ⁴ In addition, there have been a number of notable x-ray laser experimental results below 200 Å with gL products ≤ 6 . These include a 100 ps multiple pulse collisional excitation scheme at 204 Å for Ni-like Nb ⁵, a hydrogenlike carbon recombination scheme at 182 Å using higher laser driver energies of 20 J in a 2 ps pulse ⁶ and a hydrogenlike Li n=2-1 inversion at 135 Å. ⁷ It is important to note that a common theme in many of these recent laser driven x-ray amplifier schemes has been the adoption of high peak power drivers of a few joules available in pulse lengths in the femtosecond to picosecond range.

The TCE scheme first demonstrated at the Max Born Institute in Berlin ^{4,8,9} shows a lot of promise for producing a high gain, inherently short pulse XRL which can be readily scaled to shorter wavelengths. It also takes advantage of the continued development of sub-picosecond, chirped pulse amplification (CPA) multi-terawatt lasers at the table-top size. The combination of these characteristics in both the inherent x-ray laser design and the inversion pumping hardware are essential for a high output XRL with future applications. The TCE scheme relies on the creation of a transient population inversion in a few picoseconds comparable with the collisional excitation timescales. This is in contrast to the quasi-steady state (QSS) collisional excitation x-ray lasers investigated in previous years using kilojoule laser drivers where the heating pulse producing the excitation is 500 ps to 1 ns in duration. ¹⁰⁻¹³ Typically gains of $4 - 9 \text{ cm}^{-1}$ for target lengths of several centimeters have been measured for QSS x-ray lasers. However, the transient population inversion is predicted to produce gains in excess of 100 cm^{-1} which if reproduced experimentally would demonstrate saturated output in a plasma column of a few millimeters. ⁸

The experimental implementation of the scheme is achieved in two stages by using two sequential laser heating pulses. The first long ~ 1 ns pulse at $\sim 10^{12}$ W cm $^{-2}$ preforms a long scale length plasma with the correct ionization stage and electron density but at low electron and ion temperature. The second pulse of ~ 1 ps duration at $\sim 10^{15}$ W cm $^{-2}$ produces a rapid increase in the plasma temperature creating the transient population inversion by collisional excitation from the ground state. The major advantage of the transient scheme is in the efficiency of the excitation process: a few joules of short pulse energy in a line focus of ~ 1 cm is needed to make the x-ray laser work.

In this paper we describe recent experimental results at LLNL where we have investigated the transient gain scheme using a long 800 ps and short ~ 1 ps laser pulses at table-top energies, typically 500 mJ/ linear mm. We present preliminary results on Ne-like Ti lasing on the 3p-3s J=0-1 transition at 326 Å and for the Ni-like analog for Pd $18+ 4d-4p$ J=0-1 transition at 147 Å.

Figure 1. Experimental Schematic for target chamber optics to produce line focus.

2. EXPERIMENTAL DESCRIPTION

The TCE experiments at LLNL were conducted on the Janus facilities. An 800 ps (FWHM) laser pulse at 1064 nm wavelength with 6 J energy on target was produced at a repetition rate of 1 shot/ 3 min. by firing the rod amplifiers of one arm of Janus. The short pulse was produced by the Janus-ps laser: this is a hybrid CPA system based on a Ti:Sapphire oscillator and regenerative amplifier front end tuned to 1053 nm wavelength with Nd:phosphate glass power amplifiers. A detailed description of the laser system and optical diagnostics has been given elsewhere for high intensity K- α experiments.¹⁴ The oscillator, pulse stretcher, regenerative amplifier and high power amplifiers with laser diagnostics occupy two 4' $\times$ 12' laser tables. The 7 mm, 16 mm, 25 mm, and 50 mm diameter amplifiers produced 10 J of laser energy prior to compression. Typically, energies on target of 6 J were routinely achieved. After amplification, the beam was enlarged to 8 cm diameter and recompressed in the vacuum grating compressor (dimensions 2.5' $\times$ 4' $\times$ 12') to 500 fs (FWHM) with a *sech*² pulse shape. Also, the short pulse duration could be varied from 0.5 to 10 ps by de-tuning the compressor gratings. For the results obtained in the following sections a 1.1 ps (FWHM) pulse was used. The short pulse beam path was enclosed in vacuum from compressor to target chamber.

Laser parameters including energy, temporal shapes and relative timing, near field image, focal spot and spectrum were monitored on every shot. The regenerative amplifiers of the two laser pulses were synchronized using the 80 MHz radio frequency output from the short pulse oscillator. This resulted in a jitter of 80 ps rms in the

relative timing between the two pulses. A delay of 0 to 3 ns, measured relative to the peak of the 800 ps pulse, could be added so that the short pulse arrived after the long pulse. The Janus long pulse was combined with the short pulse beam after compression in a co-propagating geometry by means of a polarizer. The beams were relayed into the target chamber by steering mirrors, see Figure 1. A line focus 70 μm wide $\times$ 12.5 mm length (variable width but fixed length) was formed using a combination of a concave 400 cm focal length, 10 cm diameter cylindrical lens and a gold-coated 61 cm focal length, 15 cm diameter on-axis paraboloid. A 5 μm thick nitrocellulose debris shield protected the paraboloid from target debris. B-integral effects due to the transmission of the short pulse through the cylindrical lens were not significant for this power density. No traveling wave irradiation was implemented for the experiments described here, though the optics exist for future experiments. The final focus and beam alignment were achieved by lowering the target and using a crossed cylindrical lens microscope on the laser optical axis with different magnification for the length and width. At this stage the final overlap of the two co-propagating beams was adjusted to better than 5 μm . Polished slab targets capable of 40 - 200 laser shots were mounted in a precision target holder. Normal incidence was established at installation with an alignment laser. Target placement was adjusted under vacuum with a numerical readout 4-axis target positioner. A 40 $\times$ telescope mounted transverse to the laser focusing axis was useful for positioning the target relative to the collection optics of the flat-field spectrometer.

The main diagnostic for the x-ray laser lines looking on-axis was a 1200 line mm^{-1} flat-field grating spectrometer with a back-thinned 1024 $\times$ 1024 CCD detector to cover 130 - 350 $\text{\AA}$, shown in Figure 2. A gold-coated mirror collection optic imaged the plasma gain region with 1:1 magnification onto a 100 μm wide entrance slit. This gave the instrument a plasma imaging capability for measuring the spatial position of the gain region. Additional instruments included a CCD x-ray slit camera with 25 μm spatial resolution for line focus uniformity and a CCD flat crystal KAP (001), $2d=26.58 \text{ \AA}$, spectrometer to monitor the ionization in the $n=3-2$, $4-2$ Ne-like resonance lines for wavelengths shorter than 12 $\text{\AA}$. All x-ray instruments used CCD detector systems which were LLNL designed, fabricated and optically calibrated.^{15,16} This allowed real-time data acquisition within 15 seconds of the laser shot.

The overall laser shot rate of 1 shot/ 3 min. was determined by the cooling down period of the laser rod amplifiers. In practice a repetition rate of closer to 1 shot/ 6 min. was dictated by experimental factors. Typically 50 shots on target per day could be achieved with excellent observed repeatability of lasing.¹⁷

Figure 2. Schematic of flat-field spectrometer used for measuring x-ray laser transitions.

3. EXPERIMENTAL RESULTS

X-ray laser action was first observed for polished slab targets of titanium.¹⁷ As reported previously,^{4,18,19} the Ne-like Ti 3p-3s J=0-1 line lases at 326 Å. In this experiment, XRL output was only observed when both pulses were fired. Absence of the short pulse produced no 326 Å line intensity for the target lengths in this study. However, it would be expected to observe QSS gain for longer targets of several centimeters. We observed the x-ray laser output for targets as short as 1 mm and up to 10 mm in length. Figure 3 shows a spectrum for increasing lengths of 2 mm, 3mm and 5 mm slab target. Each spectrum is recorded from a single shot. Strong exponentiating increase in the line output is observed as a function of target length unequivocally identifying laser action. A weaker lasing line is observed at 301.5 Å for the 5 mm target length in Figure 3 and is identified as the 3d-3p J=1-1 transition.^{4,9,20} The upper level of this line is predicted to be partially populated by self photo-pumping of the 3d-2p Ne-like resonance line from the ground state. We note that the output of the 301.5 Å line in this experiment can be significantly enhanced by optimizing the plasma conditions.

Figure. 3 (left) shows the spectrum for Ne-like Ti for 2, 3 and 5 mm target lengths. The Ne-like 3p-3s line is indicated at 326 Å and strongly increases with target length. Note the change in intensity scale on the right hand side for the 5 mm target length. The 3d-3p line at 301 Å is also labeled. Figure. 4 (right) is a plot of the 326 Å XRL output as a function of target length up to 10 mm. A gain of 24 cm^{-1} is established by fitting up to target length 3 mm.

Figure 4 shows the x-ray laser output of the 326 Å transition as a function of target for lengths from 1 to 10 mm. By using the Linford formula²¹ for unsaturated gain we obtain a gain of 24 cm^{-1} for at least the first 3 mm target lengths. We note that the XRL output has significantly rolled over for the 10 mm target length. We believe that this is not as a result of saturated output but in fact due to the transient gain response. For a 10 mm target the propagation time along the line focus is 33 ps while the transient gain timescale is predicted to be 5 - 15 ps.⁸ This means that the optimum gain conditions have decayed after the x-ray laser has propagated a few millimeters. Nonetheless, we observe a 5 orders of magnitude increase in the x-ray laser output from 1 to 10 mm length and estimate the gL product to be in the region of 14 - 15. Saturated gain response for Ne-like Ti is discussed in detail in this proceedings by Shlyaptsev *et al.*⁹

We performed additional characterization of the 326 Å laser output of titanium which we briefly mention here. We found the x-ray laser output to be a strong function of the delay, measured relative to the peak of the long pulse, in the arrival of the short pulse. No XRL output was observed when the short pulse arrived at the peak of the long pulse, i.e. $\Delta t=0 \text{ ns}$. This trend of a null result continued for introduced delays up to $\Delta t=+0.8 \text{ ns}$, where the short pulse arrived after the long pulse. Increasing the delay to larger values resulted in a dramatic onset in the x-ray laser output. The XRL output peaked at +1.6 ns delay and began to drop rapidly for delays above +2 ns. This effect is

most probably explained by steep density gradients within the plasma which refract the XRL ray out of the gain region as it propagates along the plasma column.

Changing the incident laser energy in the long and short pulses is observed to have a significant effect also. Holding the short pulse constant at ~ 5 J, but dropping the long pulse energy indicates a close to linear dependence with energy. XRL intensity is low but measurable for less than 1 J of long pulse energy on target. When the reverse process is repeated, long pulse energy held constant, the laser output is found to drop strongly with decreased short pulse energy.

We have measured x-ray lasing for a polished iron slab target on the Ne-like 3p-3s J=0-1 transition at 255 Å. This has been studied in long pulse collisional excitation experiments with a pre-pulse^{19,22} but this is the first time that it has been observed in a table-top transient collisional excitation scheme. We observed strong output up to target lengths of 8.5 mm with 6 J and 5 J in the long and short pulses, respectively.

4. NI-LIKE SCHEME RESULTS

The Ne-like 3p-3s XRL scheme can be readily scaled to shorter wavelengths by choosing a higher Z target. For example, to produce an x-ray laser to operate at ~ 100 Å would require a target of atomic number $Z=47$, silver. Experiments conducted previously on Nova with 500 ps pulses have shown that intensities considerably higher than 5×10^{14} W cm⁻² are required to achieve Ne-like ionization of Ag.¹³ This irradiance is several orders of magnitude higher than the output of most table-top laser systems for line focus geometry experiments. The solution to shorter wavelength XRLs is to utilize the Ni-like 4d-4p analog of the Ne-like 3p-3s XRL, as described in MacGowan *et al*¹¹ and references therein.

Figure. 5 (left) shows a simplified energy level diagram for Ni-like Pd. Figure. 6 (right) shows a Ni-like Pd spectrum for a 6 mm target with the 147 Å XRL line observed in first and second order.

We chose to study palladium $Z=46$ as a possible medium Z nickellike ion. A simplified energy level diagram is shown in Figure 5. The upper 4d J=0 level is pumped directly from the ground state by transient collisional excitation thus producing the transient population inversion between the 4d and 4p levels. We observe the Ni-like Pd 4d-4p J=0-1 transition to lase at 147 Å as shown in Figure 6 for a 6 mm polished slab target irradiated with 5.7 J of 800 ps and 5.2 J of 1.1 ps duration pulses.²³ The line is measured in first and second order; no other lasing lines are visible in the spectrum. The structure observed to the short wavelength side of 250 Å in Figure 6 is identified as the Si L-edge at ~ 123 Å in second order from surface layers on the back-thinned CCD detector.

Figure 7 shows the spectrum and lineout for 1 mm, 2 mm and 3mm palladium slabs. Very strong output is observed over short target lengths with an increase of more than 2 orders of magnitude from 1 to 3 mm. Above 3 mm or so it is the brightest line in the spectrum. We measure 4 orders of magnitude overall increase in the x-ray laser line for up to 8 mm target lengths. The gain is observed to fall with increasing target lengths as a result of the transient gain: the highest value of 35 cm^{-1} is measured in the first few millimeters. This requires target increments of 0.5 mm in order to measure the gain accurately. ²³ A gL product of >11 is obtained which potentially can be extended to saturated output with traveling wave irradiation. We would summarize that the TCE nickellike scheme is an excellent candidate for scaling to shorter wavelengths at table-top energies.

Figure. 7 Spectral image and lineout for 1 mm, 2 mm and 3 mm slabs of palladium measured in second order. Horizontal direction is wavelength dispersive axis. Vertical direction of image is vertical divergence. Ni-like Pd 4d-4p J=0-1 line at 147 Å, arrowed, is weak but visible for 1 mm target length. Intensity increases by two orders of magnitude for 3 mm target length.

5. CONCLUSIONS

In conclusion we have demonstrated high gain on the transient collisional excitation scheme at table-top energies, defined here as ~ 500 mJ/ linear mm in each of a long and short pulse beams. We have studied Ne-like 3p-3s J=0-1 x-ray laser lines at 326 Å and 255 Å for Ti and Fe slab targets, respectively. We observe gain on the Ti target of 24 cm^{-1} with an overall gL product of 14 - 15. The Ni-like analog has also been investigated at similar irradiances. The Ni-like Pd 4d-4p J=0-1 line at 147 Å has been observed with gain of 35 cm^{-1} and $gL > 11$: this is the first time the nickellike scheme has been observed to lase using transient collisional excitation.²³ It should be possible to produce gain saturation in a shorter wavelength XRL with a traveling wave irradiation geometry at table-top driver energies.

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