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Determination of transient gain lifetime for a 1-ps driven nickellike palladium 14.7 nm x-ray laser

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We present measurements of the gain lifetime for a table-top 14.7 nm nickellike palladium transient collisional x-ray laser irradiated by an 800 ps, 1 TW cm^{-2} formation pulse and a 1.1 ps, 800 TW cm^{-2} pump pulse. In accordance with the transient nature of the obtained inversion, it is observed that the x-ray laser experiences continually decaying amplification conditions with increased target length which implies that the transient gain is short-lived relative to the propagation time along the plasma column. A 1/*e* effective transient gain lifetime of approximately 7 to 8 ps is determined and compared with numerical simulations.

Very recent advances in the transient collisional excitation (TCE) x-ray laser scheme first proposed by Afanasiev and Shlyaptsev, [1] and demonstrated by Nickles *et al.* for the Ne-like Ti $3p\rightarrow3s$ J=0→1 transition at 32.6 nm, [2] indicate one way of achieving a high gain, high efficiency, short pulse x-ray laser. The scheme has been reported to produce saturated output for Ti and Ge at 19.6 nm [3] while lasing has been repeated on the Ne-like $3p\rightarrow3s$ J=0→1 line of V at 30.4 nm [4] and Fe at 25.5 nm. [5] The demonstration of high gain, in excess of 35 cm^{-1}, on the Ni-like analog of the transient scheme for the Pd $4d\rightarrow4p$ J=0→1 line at 14.7 nm has been a further step towards attaining a shorter wavelength x-ray laser pumped by table-top scale lasers. [5, 6] As a result of the fast picosecond driving pulse used to generate the population inversion, it is calculated from numerical simulations that transient collisional excitation can produce very high gains above 100 cm^{-1} on Ne-like and Ni-like ion systems. [1, 6-8] However, a combination of effects including fast collisional redistribution, ionization and plasma cooling produce high gain conditions which are predicted to last a very short period of time from femtoseconds to a few tens of picoseconds. [1, 8]

Experimental characterization of this x-ray laser scheme is necessary to better understand the underlying atomic and plasma processes. A determination of the transient gain lifetime would be important for confirming the atomic kinetics and hydrodynamics simulations as well as determining the optimum laser driver conditions for maximizing the x-ray laser output. In this Letter we report the measurement of the effective gain lifetime for a 1-ps driven table-top 14.7 nm Ni-like Pd transient x-ray laser pumped with less than 10 J of laser energy. This can be determined in the experimental conditions described here because the transient gain timescale is significantly shorter than the laser propagation time along the plasma column. The highest gain, in excess of 35 cm^{-1}, is observed to continually decrease by more than one order of magnitude with increasing target length, L, from 0.1 cm to a maximum of 0.8 cm. The overall gain length product of 12.5 is not in the saturation regime. By using small, 0.05 - 0.1 cm, target length increments corresponding to propagation time steps, L/c, of 1.7 - 3.3 ps, respectively, the evolution of the transient gain can be diagnosed by this self-probing technique. A $1/e$ effective gain lifetime of less than 8 ps is determined and found to be in good agreement with numerical simulations.

The experiments were conducted at the Lawrence Livermore National Laboratory Janus laser facilities. [5, 6] Two stages of laser irradiation were used to achieve the transient collisional excitation x-ray laser. An 800 ps (FWHM) pulse at 1064 nm with up to 6 J energy from Janus was focused to a peak intensity of 1 TW cm^{-2} to produce the long scalelength plasma with the correct ionization. The transient excitation was generated by a 1.1 ps (FWHM) pulse at 1053 nm with a maximum of 6 J energy from the hybrid chirped pulse amplification Janus laser system focused to 800 TW cm^{-2} on target. The two pulses were synchronized and could be fired at a rate of 1 shot/ 3 minutes. The pulseshape and width of the picosecond beam was measured using a single-shot second order autocorrelator while an optical streak camera monitored the synchronization of the two pulses. The line focus was kept fixed at 70 μm wide (FWHM) by 1.25 cm long and the uniformity was monitored on each shot by a crossed slit x-ray charge-coupled device (CCD) camera. The two laser pulses were incident on the target surface with 0° phase along the line focus, shown in Figure 1(a). The target consisted of a 0.1 cm thick polished planar slab of palladium with stepped lengths from 0.1 to 0.8 cm in 0.05 to 0.1 cm increments, Figure 1(b), and was rotated back 10 to 25 mrad to compensate for plasma refraction of the x-rays. A flat-field spectrometer, with a 1200 line mm^{-1} grating, was aligned on axis to the line focus using gold-coated mirror collection optics. The intensity of the Ni-like Pd 14.7 nm x-ray laser line was measured in second diffraction order with a back-thinned 1024×1024 CCD detector. The short pulse was delayed by 1.3 ns relative to the peak of the long pulse to optimize the x-ray laser output. Laser irradiation, focal and pulse synchronization conditions were then held constant for the gain measurements. Figure 2 shows a typical axial spectrum of the 14.7 nm laser line from a 0.6 cm target.

The intensity of the 14.7 nm laser line was observed to increase by 4 orders of magnitude when the target length was changed from 0.1 to 0.8 cm. [6] The intensity as a function of length could not be fitted by a function with a single exponential gain value. Instead the gain was extracted by averaging the intensity of typically two to three shots at a particular length and then applying the Linford formula for small signal gain [9] over the adjacent target lengths. The complete gain profile was determined up to the maximum 0.8 cm with the available target length increments of 0.05 to

0.1 cm. Figure 3 shows gain as a function of time, where the measured effective gain (full circles) is plotted for a particular length converted into the equivalent propagation time, *L*/*c*. The inferred gain starts high in excess of 35 cm^{-1} at 3 - 7 ps, corresponding to the shortest Pd lengths of 0.1 - 0.2 cm, but smoothly decreases to a minimum of 3 cm^{-1} by about 27 ps. This behavior is a consequence of the entire target length being pumped simultaneously by the short pulse and the transient gain conditions rapidly decaying in time as the x-ray laser beam propagates along the plasma column. The target increments chosen here are sufficiently short to give a snapshot of the effective gain with a few picoseconds resolution. The error bars in gain represent the values from the fit of the Linford formula to the data points. Overall, the decay in the measured gain values can be well represented empirically by an exponential function (dashed line) with a 1/*e* transient gain lifetime of 8.1 ± 1.0 ps.

The 1-dimensional numerical code RADEX [1, 2] with self-consistent transient hydrodynamics, atomic kinetics and radiation transport is used to model the experiment. An additional ray-tracing package calculates the x-ray laser intensity. It is important that not only the hydrodynamics and atomic kinetics but also the ray-tracing have to be made in the transient approximation. The main reason lies in the short gain rise-time of 1 to 3 ps and life-time of 5 to 15 ps (at $n_e \sim 1 - 3 \times 10^{20}$ cm^{-3}) compared to the propagation time along the amplified medium $L/c \sim 30$ ps. For a direct comparison with the experimental measurements of effective gain, the simulations model the target length over a larger range of values with finer steps. The experimental dependence of x-ray laser intensity versus plasma length is well reproduced by RADEX modeling. [6] The theoretical effective gain versus length is then obtained by applying the Linford equation to the calculated x-ray laser intensity emitted from each plasma length. In a similar manner to the experimental data, the target length is converted into an equivalent propagation time. It should be noted that the theoretical effective gain is distinguished from the plasma gain in space and time, since it includes gain decreasing effects such as plasma inhomogeneity, propagation in a refractive medium and gain decay during amplification. Also, it should be noted that the simulations take into account the full evolution of the gain in the plasma medium from transient to quasi-steady state (QSS). Both have long-lasting tails, with the QSS substituting TCE inversion later in time up to 100ps until the plasma overionizes and cools. The RADEX simulations are shown (full curve) on Fig. 3. The overall agreement with the measured effective gain data points lie within the error bars of the experiment. The high effective gain at early time and the rapid fall with increasing time is expected from the nature of the transient inversion before the x-ray laser intensity reaches saturation. The simulations from RADEX also suggest that two characteristic timescales can be inferred and this is explained by the crossover between the transient to the quasi-steady state regime with increasing time. The faster 1/*e* effective gain decay of 7 ps occurs early in time and corresponds to the high gain transient regime. The second has a slower effective gain decay with 1/*e* time of 18 - 20 ps at about 25 - 30 ps after the short pulse deposition when the gain is already close to quasi-steady state [6] value of 4 cm^{-1}. The inferred maximal values of the gain and its duration correspond to the optimal electron densities of $1 - 1.5 \times 10^{20}$ cm^{-3}. More detailed values can be obtained by observation of the x-ray laser near and far-field exit beam patterns as reported with QSS schemes in laser plasmas [10] and capillary x-ray lasers [11].

In summary, we have determined the 1/*e* effective gain lifetime to be 7 to 8 ps for a 14.7 nm Ni-like Pd x-ray laser driven by a 1 ps optical laser pump. This is in good agreement with modeling simulations of the experimental conditions. The equivalent propagation time would correspond to a target length of approximately 0.2 cm. It is clear that one consequence of the effective gain lifetime is significant reduction of the maximum gain observed in this system for these pulse durations. Higher effective gains are expected by using traveling wave irradiation geometry, see for example Barty *et al.*, [12] to synchronize the phase of the pump pulse with the propagation of the x-ray laser along the plasma column. With this technique at more dense and homogeneous plasma profiles, gains exceeding 100 cm^{-1} are anticipated.

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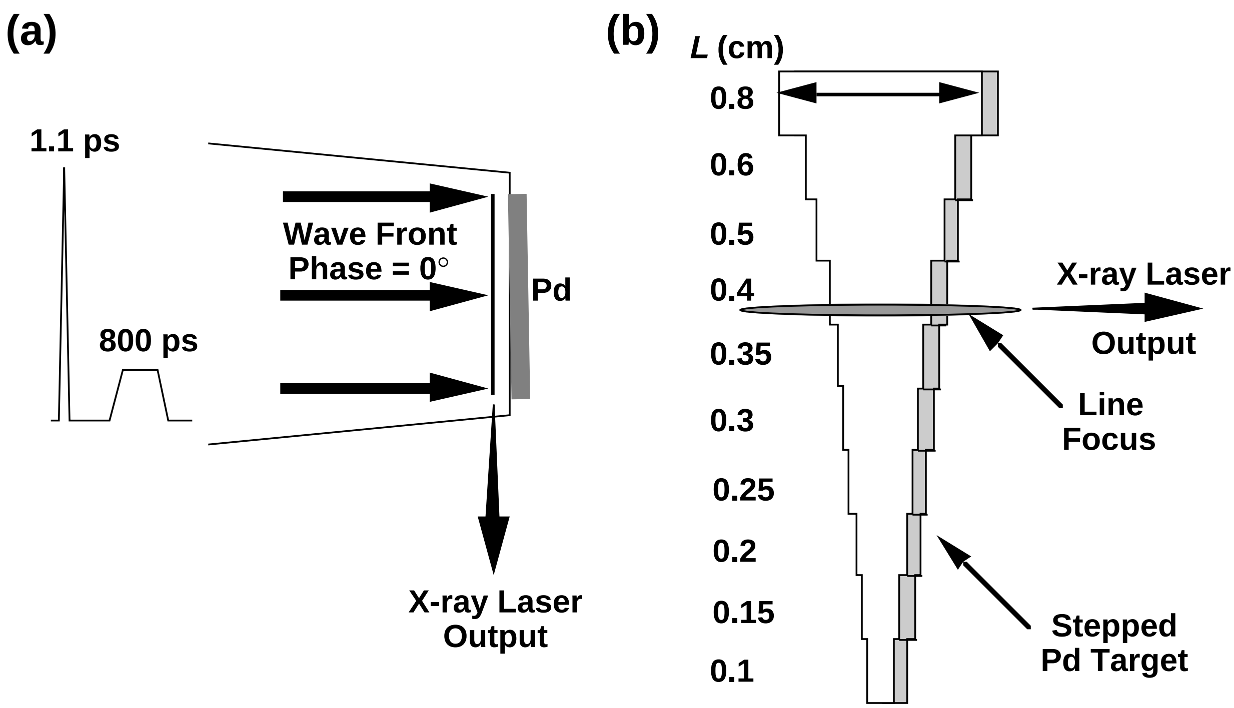
Figure Captions

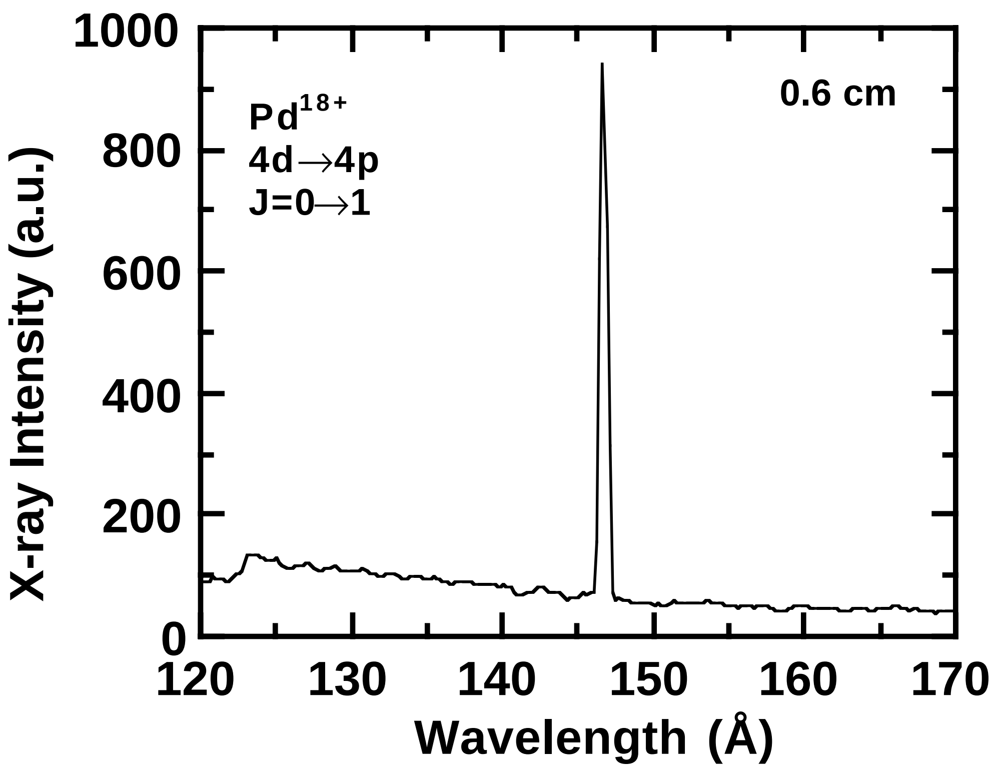
Figure 1 (a) Plan view shows double pulse incident on target with 0° phase on the wave front relative to the target surface, i.e. each laser pulse irradiates full target length simultaneously. (b) Schematic showing one piece stepped Pd target with step lengths, *L* in cm, indicated on left hand side. Line focus irradiates target tranversely with x-ray laser output observed by spectrometer from the end of the line focus axis.

Figure 2 Axial spectrum from 0.6 cm long palladium target showing strong lasing on Ni-like Pd $4d \rightarrow 4p$ $J=0 \rightarrow 1$ line at 14.7 nm.

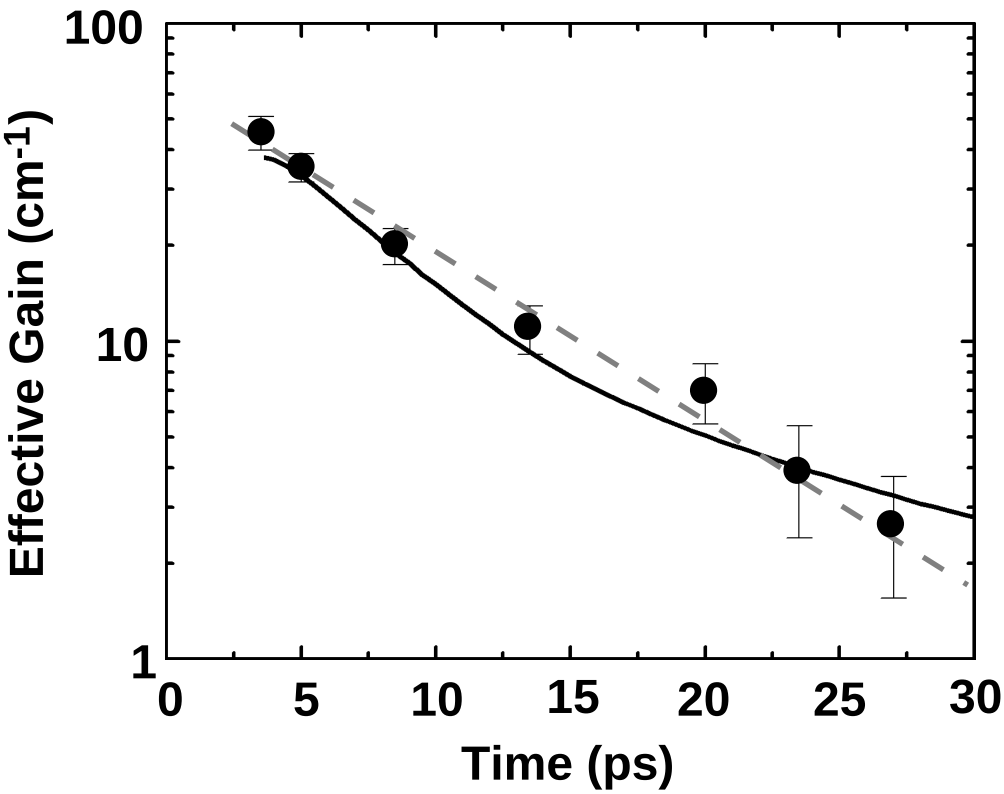
Figure 3 Plot of experimental gain (full circles) as a function of propagation time. Error bars in the gain measurement are from the local Linford fit to the intensity data. An exponential fit to the experimental data points is shown (dashed line) indicating a transient gain lifetime of 8.1 ± 1.0 ps. Simulations of the effective gain from the RADEX code (full curve) infer two slopes of 7 ps and 18 - 20 ps corresponding to TCE and QSS inversion, respectively.



J. Dunn et al Fig. 1



J. Dunn et al Fig. 2



J. Dunn et al Fig. 3

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