UCRL-CONF-204359

LAWRENCE LIVERMORE NATIONAL LABORATORY

Pulse duration measurements of a picosecond laser-pumped 14.7 nm x-ray laser

J. Dunn, R. F. Smith, R. Shepherd, R. Booth, J. Nilsen, J. R. Hunter, V. N. Shlyaptsev

August 23, 2004

9th International Conference on X-ray Lasers
Beijing, China
May 24, 2004 through May 28, 2004

Pulse duration measurements of a picosecond laser-pumped 14.7 nm x-ray laser

J. Dunn, R.F. Smith, R. Shepherd, R. Booth, J. Nilsen, J.R. Hunter
Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

V.N. Shlyaptsev
University of California, Davis, Livermore, CA 94551, USA

Abstract. The temporal dependence of the 14.7 nm Ni-like Pd ion x-ray laser is measured as a function of the laser drive conditions with a fast sub-picosecond x-ray streak camera. The chirped pulse amplification laser beam that pumps the inversion process is varied from 0.5 – 27 ps (FWHM) to determine the effect on the x-ray laser pulse duration. The average x-ray laser pulse duration varies by a relatively small factor of 2.5 times from 3.6 ps to 8.1 ps with travelling wave (TW) irradiation conditions. Slightly shorter pulse durations approaching 2 ps are observed with the x-ray laser operating below saturation. The x-ray laser is found to be 4 – 5 times transform-limited for 6 – 13 ps laser pumping conditions.

1. Introduction

We report results of the Ni-like Pd 4d – 4p x-ray laser pulse duration as a function of the short pumping pulse duration at a fixed delay of 700 ps peak-to-peak between the two laser pulses. These experiments in common with many transient x-ray lasers use a combination of two laser pulses where a long pulse (0.2 – 1 ns) forms a pre-plasma that is further heated by a second, shorter picosecond, high intensity pulse [1]. The precise laser pumping conditions can dramatically affect the x-ray laser characteristics. For example, the x-ray laser intensity can be optimized as a function of the short pulse duration with a maximum achieved for 6 – 13 ps pumping [2]. Recent temporal measurements of Ni-like Ag 4d – 4p 13.9 nm x-ray laser pumped by 1.3 ps laser pulses have demonstrated that the x-ray laser pulse duration can be as short as 2 – 3 ps (FWHM) [3, 4]. The objective of this work is to determine the sensitivity of the x-ray laser duration to the short pulse pumping duration when the laser pulse is varied from 0.5 ps to 27 ps.

2. Experimental Description and Results

The Ni-like Pd 14.7 nm x-ray laser was generated using two 1054 nm wavelength laser beams from the Compact Multipulse Terawatt (COMET) facility at LLNL This laser can be fired at a repetition rate of 1 shot every 4 minutes [5]. A 600 ps (FWHM) pulse forms the pre-plasma and is followed by a short pulse after a delay of 700 ps peak-to-peak. The long pulse was focused to 1.6 cm × 150 μm (FWHM) (L × W) with 1.25 ± 0.25 J energy on target (EOT). The short pulse beam was focused to 1.6 cm × 100 μm (FWHM) and contained 3.75 ± 0.25 J EOT. Travelling wave (TW) line focus geometry was implemented before the focusing optics by using a high-reflectivity, 0° dielectric-coated reflection echelon consisting of seven flat vertical mirror segments. The TW line focus irradiation geometry is stepped and set for c along the target. The picosecond beam was set by adjusting the compressor gratings to give a duration of 0.5, 1.75, 3.4, 6.7, 13.4, and 26.8 ps (FWHM). Polished Pd slab targets up to a maximum of 1.25 cm were irradiated.

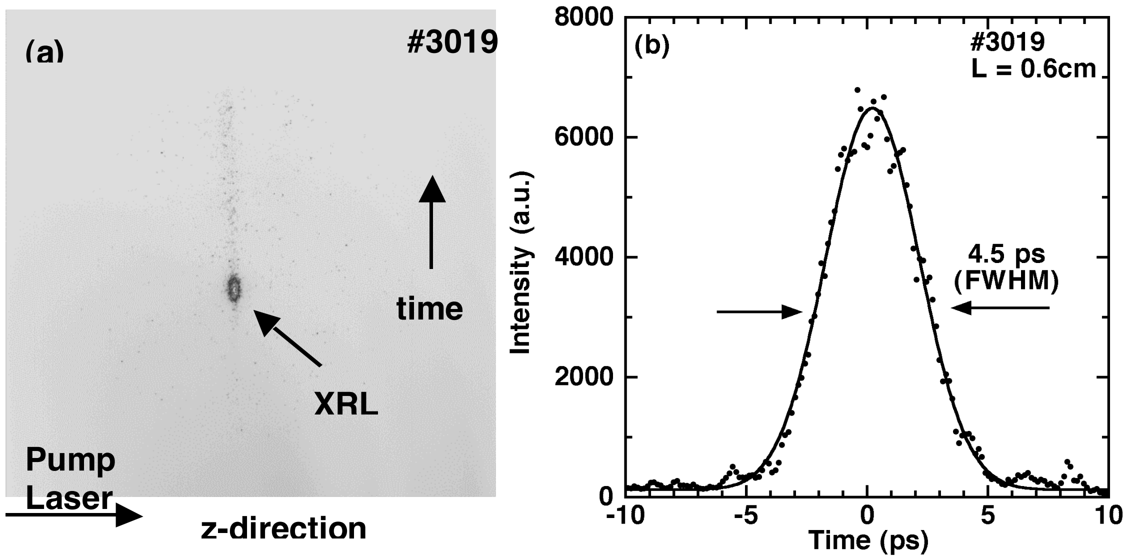

Figure 1. (a) X-ray laser streak image for 6.7 ps (FWHM) short pulse pumping incident on a 0.6 cm target. Laser pump is incident from left and time is increasing up. (b) Intensity lineout through X-ray laser image. Experimental data (solid circles) fit by Gaussian shape (solid line) with 4.5 ps (FWHM).

The experimental geometry was chosen to spatially and temporally resolve the x-ray laser emission relative to the target. The x-ray laser beam leaving the plasma column was imaged by a Mo:Si multilayer-coated, high reflectivity spherical mirror with 11.75 cm focal length. This was relayed by a 45° Mo:Si multilayer-coated flat mirror onto either a streak camera or back-thinned CCD camera with 22× magnification. Both detectors were at normal incidence to the x-ray laser beam and equidistant to the Pd target to within ±0.05 cm. A second Mo:Si flat motorized mirror could intercept the x-ray laser beam and direct it to either detector. A time-integrated 2-D near-field image or a 1-D time-resolved image of the x-ray laser beam was recorded. The streak camera entrance slit 100 μm × 2.5 cm (W × L) was orientated in the horizontal direction, with the long axis aligned along the z-axis of the near-field image perpendicular to the Pd target. This is swept in time as shown in Fig. 1(a). The streak camera has been used previously with a measured temporal response of 500 fs [6]. In this experiment the photocathode consisted of 120 nm CsI/75 nm Al coated on a thin, etched 40 nm Si_3N_4 window in a 250 μm Si wafer substrate. A combination of three filters was used to attenuate the x-ray laser fluence up to a maximum of 10^4 to keep the x-ray signal within the linear range of the detectors. This was particularly important for the x-ray streak camera where instrumental space charge saturation effects can produce pulse broadening and loss of temporal resolution. The streak camera characteristics were measured during the experiment with the instrumental temporal resolution determined to be 1.1 ± 0.3 ps (FWHM) [7]. More experimental details can be found elsewhere [7]. Figure 1(a) shows the 14.7 nm x-ray laser from a 0.6 cm Pd target pumped with a 6.7 ps short pulse where the output is operating in the gain saturation regime. The x-ray laser emission is short-lived, less than 5 ps, with a low intensity continuum lasting for many tens of picoseconds and beyond the streak camera window. An intensity lineout, Fig. 1(b), shows the x-ray laser pulse shape is symmetrical and is well-fitted by a Gaussian. Some variation in the pulse shape is observed from shot-to-shot.

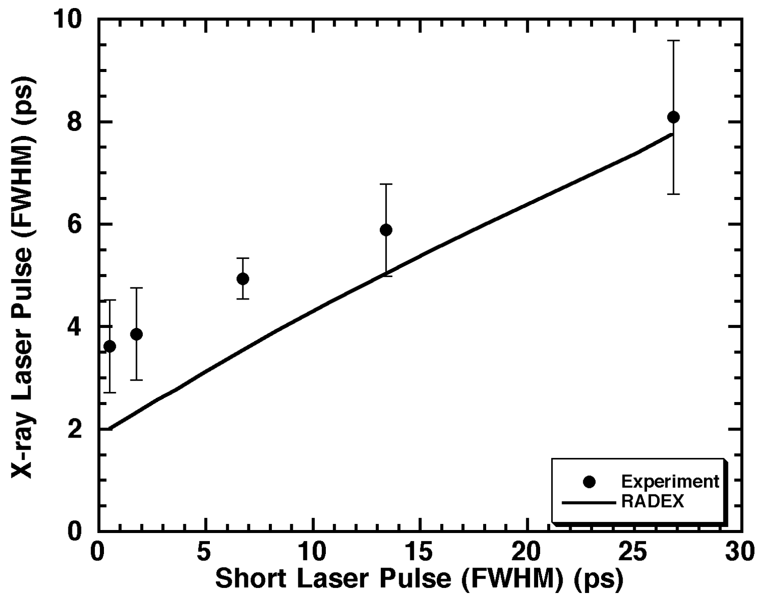

Figure 2. X-ray laser duration plotted as a function of short pulse laser drive from 0.5 to 27 ps. The mean value, of 4 – 6 experimental data points, (closed circles) is shown with error bars of 1σ. RADEX simulations are shown for the experimental pumping conditions.

A study covering the Pd pre-formed plasma density profile, x-ray laser near-field imaging, temporal duration and output intensity was reported for a large range of pumping conditions [8]. Here, the measurements were taken for a delay of 700 ps between the two laser pulses with all other laser pumping conditions, including the laser energy, kept constant. The measured x-ray laser pulse duration is plotted versus the short pulse drive of 0.5 to 27 ps, Fig. 2. The short pulse irradiance varies by 50 times. The x-ray laser output intensity is also changing for the optical pump drives: The 6.7 ps and 13 ps pumping pulses typically operated in the gain saturation range with highest output while the shorter pumping pulses had lower output. The plotted experimental measurements are the mean value for several data points corrected for the instrumental response of 1.1 ± 0.3 ps by subtracting in quadrature. From Fig. 2 the trend is clear that the x-ray laser pulse duration decreases with the laser drive, but only by a factor of 2.2× compared with the 50× decrease in the laser drive duration. The longer laser drives generate x-ray pulses of 8.1 ps while the shortest drive gives 3.6 ps. The shortest x-ray laser pulse durations observed (not plotted) are 2.4 ± 0.1 ps for drives below 1.75 ps. It is also noted that in some cases when the laser pump energy is lowered close to the threshold for lasing, sub-3 ps x-ray laser durations are measured for a 6.7 ps laser drive. The x-ray laser is operating below the gain saturation regime in both cases. These shorter x-ray laser pulse durations are within ~0.5 ps of the results reported recently for the Ni-like Ag laser for different pumping conditions [3, 4].

The experimental values shown in Fig. 2 are slightly higher than RADEX simulations modelled with a perfect travelling wave [9]. These simulations do not include ray-tracing but assume from earlier beam deflection measurements [5] that the optimum propagation for the x-ray laser beam is at a maximum electron density of 1.3 – 1.9 × 10^{20} cm^{-3}. There is good agreement at the longer pulse drive with some deviation at the shorter durations. Part of this difference is from the decoupling of the different gain regions along the line focus from the stepped mirror TW irradiation that results in a lengthening of the pulse.

The longitudinal coherence of the Pd x-ray laser was measured for the 6 ps and 13 ps drives using a Michelson interferometer. It was found to have a 1/e half width (HW) of 342 μm ± 24 μm and 400 μm ± 35 μm corresponding to a spectral line width of 0.34 pm and 0.29 pm (FWHM) respectively [10]. The fringe visibility measurements around the spectral line center had a Gaussian shape primarily explained by gain-narrowing of a low temperature thermally-broadened line. As previously discussed [10] this did not give a complete explanation and other contributions to the line shape would have to be taken into account. Nonetheless, the time-bandwidth product $\Delta\nu\ \Delta t = 0.441$ for Gaussian shapes, e.g. Fig. 1(b), suggests the transform limit is 0.93 – 1.09 ps for the above spectral line widths. Therefore, the Pd x-ray laser is 4 – 5× transform limited for these pumping conditions. Recent measurements of the longitudinal coherence for the Ag x-ray laser have better dynamic range that indicate more Lorentzian profile in the wings [11]. It should be possible to make a more complete study that includes full analysis of all of the spectral line-broadening (and narrowing) contributions. When combined with the temporal pulse shape data a better understanding of the conditions determining the transform limit may be achieved.

3. Conclusions

We have reported measurements of the Pd 14.7 nm x-ray laser duration as a function of the short pulse laser drive. The 14.7 nm pulse duration is largely determined by the gain lifetime influenced by collisional and ionization times within the plasma. The trend shows that ps-driven x-ray lasers are limited to ~1 ps operation by the transform limit.

Acknowledgments

The continued support and encouragement of Al Osterheld is greatly appreciated. This work was performed under the auspices of the U.S. Dept. of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

References

[1] P.V. Nickles *et al.*, *Phys. Rev. Lett.* **78**(14), 2748-2751 (1997).

[2] J. Dunn, *et al.*, *X-ray Lasers 2000*, ed. G. Jamelot, C. Möller, and A. Klisnick, J. Phys. IV **11**, Pr2-19 (2001).

[3] A. Klisnick *et al.*, *Phys. Rev. A.* **65**, 033810 (2002).

[4] Y. Abou-Ali *et al.*, *Opt. Comm.* **215**, 397 (2003).

[5] J. Dunn *et al.*, *Phys. Rev. Lett.* **84**, 4834 - 4837 (2000).

[6] P. Audebert, R. Shepherd, *et al.*, *Phys. Rev. Lett.* **89**, 265001-1 - 4 (2002); R. Shepherd, R. Booth, private communication (2002).

[7] J. Dunn *et al.*, *Soft x-ray lasers and Applications V*, SPIE Int. Soc. Opt. Eng. Proc, vol. **5197**, ed. E.E. Fill and S. Suckewer, 51-59 (2003).

[8] R.F. Smith *et al.*, *Soft x-ray lasers and Applications V*, *ibid.*, 155-167 (2003).

[9] V.N. Shlyaptsev *et al.*, *Soft x-ray lasers and Applications V*, *ibid.*, 221-228 (2003).

[10] R. F. Smith *et al.*, *Opt. Lett.* **28**(22), 2261 (2003); J. Dunn *et al.*, *Soft x-ray lasers and Applications V*, *ibid.*, 43-50 (2003).

[11] A. Klisnick *et al.*, these proceedings (2004).