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Demonstration of a 2-ps transient x-ray laser

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A time-resolved measurement of the output from the Ni-like Ag transient-collisional-excitation x-ray laser is described. An ultrafast x-ray streak camera was used to diagnose the output of the $J=0\rightarrow1$ $4d$-$4p$ lasing line at 13.9 nm. The full width at half maximum duration of the x-ray pulse is measured to be of 1.9 ± 0.7 ps at optimum conditions of pump laser irradiation. This is the shortest x-ray laser duration directly demonstrated to date and illustrates the great potential of transient x-ray lasers as a high brightness, picosecond x-ray source for applications.

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I. INTRODUCTION

Since the first clear demonstration [1] of laser action in neon-like ions through amplified spontaneous emission at soft x-ray wavelengths there has been determined effort to improve the characteristics of such devices to make them suitable for a range of different potential applications. In particular, effort has been invested to produce very intense and saturated soft x-ray lasers (XRLs) operating at shorter wavelengths and with shorter pulse durations. In this paper, we report on what is, to our knowledge, the first direct experimental measurement indicating that intense, soft XRL pulses shorter than 2 ps in duration can be generated at a wavelength of ≈14 nm. Such sources, delivering ≈90 eV photons, significantly improve the prospects of applications designed to study non-steady-state systems with picosecond transient time scales.

The early XRLs, based on collisional pumping of Ne-like ions in a laser-produced plasma, typically used nanosecond duration drive pulses and time-resolved measurements showed that lasing on the high-gain $J=0\rightarrow1$ $3p$-$3s$ line was relatively short lived (≈100 ps) [2]. Shorter XRL pulse durations were observed when multipulse and prepulse techniques, employing ≈100-ps main pulse drives, were used to enhance the pumping efficiency of these $J=0\rightarrow1$ Ne-like XRLs [3] and this technique was subsequently applied to the Ni-like analogue XRLs operating at relatively shorter wavelengths [4]. Pulse durations as short as ≈35 ps were routinely demonstrated at XRL wavelengths in the range 7–20 nm [5–7]. With the advent of XRL pumping using the transient collisional excitation scheme and chirped pulse amplification (CPA) (≈1-ps main drive duration) pump lasers it was clear that much shorter XRL pulse durations could be generated [8–11]. Initial estimates of the duration relied on modeling, indirect observation through the effect of traveling wave-pump velocity and direct observation with streak cameras of limited temporal resolution [11–14].

In this paper we report the direct pulse-duration measurements of a CPA-driven XRL with a high temporal resolution and find that pulses of ≈2 Ps are attainable. Section II describes the experimental setup used to generate the $J=0\rightarrow1$ $4d$-$4p$ lasing line emitted at 13.9 nm in Ni-like Ag, and to measure its temporal duration. Time-resolved measurements are presented and discussed in Sec. III. Section IV summarizes the results, discusses their potential impact on XRL applications requiring high temporal resolution, and outlines prospects for future work.

II. EXPERIMENTAL SETUP

Figure 1 shows a schematic view of the experimental setup. Two beamlines from the Nd-Glass Vulcan laser at 1.06 μm were used to irradiate a 10-mm-long flat-silver-slab target in a standard line-focus geometry. A 300-ps prepulse, focused into a (21×0.12)-mm line, preformed a plasma at an intensity of $\approx1.2\times10^{12}$ W/cm^2. After a 200 ps peak-to-peak delay, this plasma was strongly heated by a 1.3-ps CPA pulse in a (19×0.08)-mm line focus at an intensity of 1.1×10^{15} W/cm^2. The irradiances and the delay between the long pulse and the short pulse were chosen according to a previous experiment in Ni-like Ag [14]. The duration of the short CPA pulse was set at the minimum value available where the duration of the x-ray laser is expected to be the shortest. The duration of the CPA pulse was monitored shot to shot by a second-order autocorrelator [15].

The line foci were superimposed to an accuracy within 10% of the focus linewidth. A CCD x-ray cross-slit camera monitored the line-focus plasma uniformity and overlap of the laser pulses. Due to the previously inferred [14] short-

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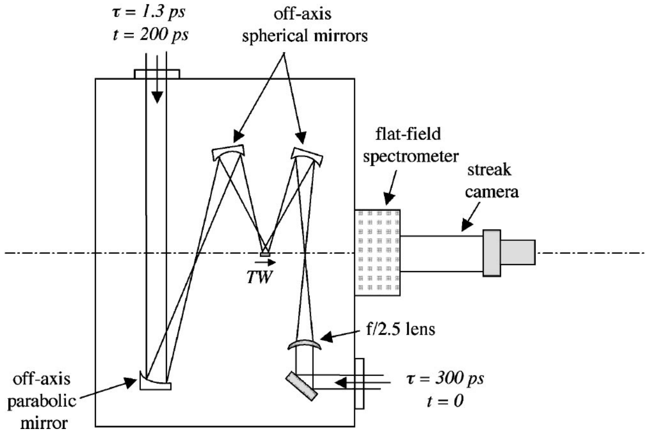

FIG. 1. Schematic view of the experimental setup showing the pump laser beamlines and the diagnostics used in the target-interaction chamber.

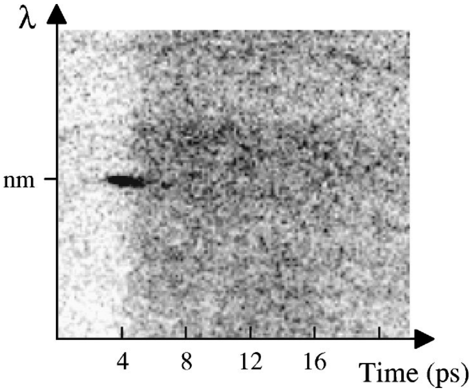

FIG. 2. Portion of the CCD image showing the time-resolved emission of the 13.9-nm lasing line and of the continuum emission. Irradiation conditions: 4.3 J/cm (1.2×10^{12} W/cm^2) in the 300-ps preforming pulse and 11.8 J/cm (1.1×10^{15} W/cm^2) in the 1.3-ps CPA pulse with a temporal peak-to-peak delay of 200 ps between both pump laser pulses.

gain duration (≈10 ps) at 13.9 nm, relative to the transit time of the x-ray photons along the gain medium (≈33 ps for 1 cm), it was necessary to implement traveling-wave pumping. A combination of three effects was used to generate an optimum traveling-wave velocity at the speed of light c in the direction towards the primary x-ray laser diagnostic: (i) intrinsic traveling-wave introduced by the off-axis focusing geometry, (ii) an additional 600-lines/mm grating was inserted into the CPA beamline to introduce an extra shear in the energy front of the beam [16], and (iii) for a fine tuning, the technique of slightly tilting the second compressor grating was employed [17]. These techniques were previously used independently to create a traveling wave that allowed an efficient extraction of the x-ray laser photons and led to a significant enhancement of the transient x-ray laser output [11,18].

An on-axis flat-field spectrometer (FFS) was used to diagnose the output of the x-ray laser both spectrally and angularly (in the direction normal to the target surface). For the time-resolved shots an AXIS-Photonique x-ray streak camera [19] equipped with a KBr photocathode was positioned at the focal plane of the FFS. In our setup the 1×15 mm slit supporting the photocathode was placed parallel to the direction of spectral dispersion, at an angular position of 5 m rad off axis, corresponding to the peak of the x-ray laser output. The streak camera thus gave wavelength resolution within an integrated horizontal angle of 1.1 m rad around the angular peak of the XRL emission. The output from the streak camera was amplified and recorded by the combination of a 50/40 Kentech intensifier butt coupled to an optical CCD camera.

The ultimate temporal resolution that can be reached by the camera is 700 fs, when it is operated in a one-dimensional mode involving a 60-μm wide photocathode slit. However, this operation mode could not be used in our setup, for which the overall temporal resolution was limited by (i) the finite width of the photocathode slit and by (ii) the temporal stretch of the x-ray pulse introduced after reflection via the grazing incidence grating of the spectrometer . The photocathode slit yields an instrumental resolution of 1.9 ±0.2 ps. This figure accounts for a sweep speed of 4.8 ±0.4 ps (previously calibrated [20]) and a slit width of 0.4 mm that includes the demagnification factor given by the streak-electron optics. The contribution of the grating to the stretch of the x-ray laser pulse was calculated to be of 1.6 ±0.2 ps, as 30±3 mm of the 1200 grooves/mm grating was illuminated by the 13.9 nm emission.

An optical trigger system including an air-pulse compressor and a Ge-Auston switch [21] was specifically designed for this experiment to allow a stable triggering of the high-voltage streak ramp, with a jitter better than 10 ps. Finally parylene-E ($C_{18}H_{20}$) filters (2.1 μm thick) were used to attenuate the x-ray laser emission by $\approx10^{-3}$ to ensure that space-charge effects in the camera and saturation of the detector, which would artificially broaden the pulse duration, were avoided.

III. RESULTS AND DISCUSSION

Figure 2 shows the time-resolved spectral output from the Ni-like Ag plasma emitted in the traveling-wave geometry, as recorded at the output of the streak camera. One can see that the cutoff of the x-ray laser output coincides with the onset of the continuum emission, visible on both sides of the 13.9-nm Ni-like Ag line. Assuming that bremsstrahlung emission dominates, the increased continuum emission corresponds to the rise of electron temperature induced by the short CPA pulse heating. The fact that the x-ray laser-emission peaks before the temperature has reached its maximum suggests that overionization could be the main cause for quenching the population inversion, through destruction of Ni-like species. This observation has to be confirmed by detailed numerical simulations. We note, however, that similar conclusions have been inferred recently [22] from simulations performed for an x-ray laser based on Ne-like titanium. The effect of overionization on the x-ray laser lifetime is likely to be even more critical for Ni-like ions, because they are less stable than Ne-like ions. We thus anticipate that transient x-ray lasers based on Ne-like ions may show a

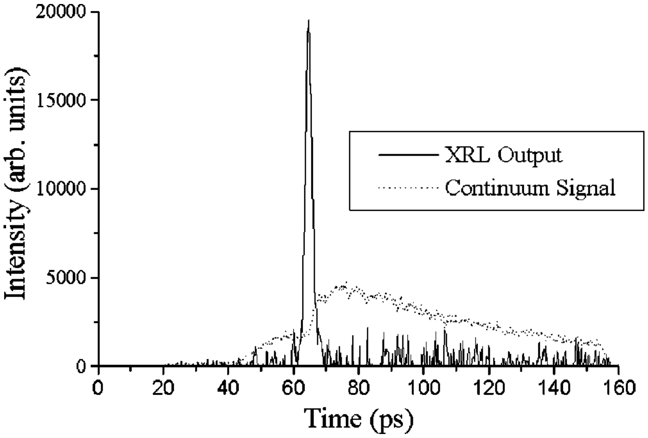

FIG. 3. Plots of intensity versus time taken from the time-resolved image, for the lasing line (integrated over linewidth and background substracted) and for the continuum emission (averaged over a 0.8-nm interval).

slightly different temporal history and in particular they may last longer.

Figure 3 shows the output of the x-ray laser as a function of time, after subtraction of the continuum emission and integration over linewidth. The full width at half maximum (FWHM) duration of the x-ray laser was measured to be 3.1 ± 0.2 ps. If we assume effective Gaussian temporal shapes for the true x-ray laser-pulse duration (τ' FWHM) and also for the instrument smearing functions due to the photocathode slit (T_s FWHM) and the grating (T_g FWHM) we can deconvolve from the measured x-ray laser duration (τ FWHM), using the quadrature relationship $\tau'=(\tau^2-T_s^2-T_g^2)^{1/2}$, to make an estimate of the true pulse duration. The deconvolved duration of the X-ray laser pulse is then calculated to be of 1.9 ± 0.7 ps. Only small differences in this value are found when different shapes (i.e., square, Lorentzian, etc.) for the instrumental functions and x-ray laser pulse are considered. The quoted error bar accounts for the uncertainties in τ, T_s, and T_g. The measured duration is hence about four times shorter than was estimated in previous experiments [14] and is a direct confirmation that the transient pumping scheme extends the range of durations of x-ray lasers available for applications to the picosecond range.

The time-integrated signal recorded by the FFS was used to estimate the energy contained in the 13.9 nm, 2-ps laser pulse, by taking into account the filter transmission, the overall efficiency of the spectrometer grating and the CCD quantum efficiency. The major source of inaccuracy in this estimate comes from the grating efficiency, which is considered to be within $(5-19)\times10^{-2}$. Within this interval the energy of the x-ray laser is estimated between ≈2 and 6 μJ per pulse. If we assume a 50 μm$\times$75 μm output size, as predicted by numerical simulations, the above measured energy corresponds to a peak power of 0.9–3 MW, and an intensity in the order of $(2-8.5)\times10^{10}$ W/cm^2. This level of intensity is consistent with the XRL being operated in the saturation regime. Recent detailed calculations [23] have shown that the duration of the x-ray pulse is shortened due to gain narrowing arising from exponential amplification, until saturation tends to rebroaden it. In our experiment the limited number of useful shots did not allow investigation of the dependence of the pulse duration with target length and the possible effect of saturation. However, it can be expected that pulses even shorter than 2 ps can be obtained from smaller plasma lengths where saturation does not dominate the x-ray laser signal. This will be investigated in a future experiment.

IV. CONCLUSION

In conclusion, the FWHM duration of the Ni-like transient pumping Ag x-ray laser at 13.9 nm pumped in a traveling wave irradiation was measured to be 1.9 ± 0.7 ps. This is to our knowledge the shortest pulse duration measured to date for an x-ray laser and we point out that this will have important implications for applications requiring high-temporal resolution.

To date several applications have been successfully demonstrated using XRL pulses of duration 100–200 ps from laser-pumped XRLs and also with longer XRL pulses (600–800 ps) from capillary discharge pumped XRLs. These applications include investigations of small scale, transient phenomena occurring in plasmas or on perturbed surfaces and were based on soft x-ray interferometry, making use of the high brightness, monochromaticity, and spatial coherence of existing soft x-ray lasers. For example, a Fresnel interferometer illuminated by a 21.2-nm saturated soft x-ray laser enabled *in situ* characterization of nanometric perturbations of a metal surface on which a strong dc electric field was applied [24]. A Mach-Zehnder interferometer combined with a 15.5-nm soft x-ray laser was used to study the collision of counterstreaming high-density plasmas that are of particular interest to inertial confinement fusion [25]. More recently, a 46.9-nm capillary-discharge laser was used with a Lloyd's mirror wave-division interferometer to map the electron density of the cathode region of a pinch discharge [26]. In all these experiments the temporal resolution provided by the snapshot interferograms is limited by the duration of the x-ray laser pulse. Shorter XRL durations, of the order of a picosecond, will extend the options for applying such techniques to more transient phenomena, such as plasmas produced by short, picosecond driving pulses.

Our estimate of the intensity emitted by the 13.9-nm x-ray laser is consistent with strong saturation of the amplification. According to recent calculations [23], the measured duration might hence be broadened by saturation and even shorter pulses could be obtained by reducing the plasma length. Finally we observe that the x-ray laser-pulse peaks in the rising edge of the continuum emission. This suggests that the duration of the x-ray laser is limited by overionization of the plasma, in agreement with recent theoretical predictions [22]. This behavior could be more pronounced for x-ray lasers based on Ni-like ions, that are less stable relative to overionization than Ne-like ions. This would lead to longer pulse duration with Ne-like based x-ray lasers.

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