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Measurement of temporal durations of transient collisional excitation X-ray lasers

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ABSTRACT We have measured temporal durations of Ni-like transient collisional excitation X-ray lasers ($4d \rightarrow 4p$, $J = 0 \rightarrow 1$) using a high-speed X-ray streak camera coupled with a flat field grating spectrometer. The pumping laser pulse consisted of a 400-ps prepulse and a 4.8-ps main pulse derived from a Nd:glass laser system with chirped pulse amplification. A quasi-traveling-wave pumping using a six-step mirror was adopted to synchronize the X-ray laser pulse and the onset of gain in a plasma medium. The X-ray laser outputs from three different materials, silver ($Z = 47$), palladium ($Z = 46$) and molybdenum ($Z = 42$), showed that the X-ray laser duration became shorter as the atomic number decreased.

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1 Introduction

Since the first lasing of the X-ray laser (XRL) was demonstrated [1], there has been much progress in improving the energy efficiency and beam quality. The transient collisional excitation (TCE) scheme proposed by Afanasiev and Shlyaptsev [2] enabled gain to be achieved with table-top lasers. The first experimental TCE gain was demonstrated with Ne-like titanium at the wavelength of 32.6 nm [3] at the Max Born Institute, and saturated gain was reported subsequently [4]. Gain-saturated XRLs have also been reported with Ni-like ions at wavelengths ranging from 13.9 nm to 20.3 nm [5].

At the Advanced Photon Research Center, we have demonstrated gain saturation with Ni-like silver and tin at the wavelengths of 13.9 nm and 12.0 nm respectively [6] and also substantial gain with Ni-like lanthanum at the shorter wavelength of 8.8 nm [7]. In addition, we have achieved a spatially full-coherent and diffraction-limited XRL beam with a beam divergence of 0.2 mrad for the Ni-like silver XRL using a double-target scheme [8]. These high-quality and table-top XRL beams have potential to be used in new research fields such as coherent X-ray science. Consequently, it becomes important to characterize temporal features of the TCE XRL, e.g. time coherence and temporal duration. The temporal duration of the Ni-like silver XRL pumped by a 1.3-ps chirped pulse amplification (CPA) pulse was directly measured to be 1.9 ± 0.7 ps using a high-speed streak camera by Klisnick et al. [9]. Kawachi et al. [6] constructed a one-dimensional ray-tracing code including X-ray amplification and calculated XRL output intensities as a function of gain duration. An intensity ratio for the cases with and without traveling pumping was compared with the experimental one, resulting in a gain duration of 8 ps for the Ni-like silver XRL.

In the present paper, we measured TCE XRL durations for Ni-like silver, palladium and molybdenum directly using a fast X-ray steak camera attached to a flat-field spectrometer. The pumping laser pulse consisted of a 4.8-ps main pulse and a 400-ps prepulse derived from the CPA laser system. A quasi-traveling-wave pumping using a six-step mirror was adopted, since the TCE gain duration is shorter than the traveling time through the plasma medium. We discuss the mechanism dominating the TCE XRL duration through the atomic number dependence.

2 Experiments

The experiment was performed with a Nd:glass laser system with chirped pulse amplification at the wavelength of 1.053 μm at the Advanced Photon Research Center, JAERI [10]. The laser system produced a low-intensity prepulse and a high-intensity main pulse: the prepulse was attached to produce preformed plasma in a Ni-like ionizing stage and the main pulse to generate population inversions. The pulse durations were 400 ps and 4.8 ps for the prepulse and the main pulse respectively. The time separation between the pulses was set to be 500 ps. The irradiation laser energy on the target was 5–12 J. The energy ratio of the main pulse to the prepulse was set to be 8:1. A six-step mirror was employed before an off-axis parabolic focusing mirror in order to generate a quasi-traveling wave [6]. The temporal and spatial distribution of the laser light at the target position was measured by use of a femtosecond streak camera (Hamamatsu Photonics model C6138) with a time resolution of 2.15 ps. The obtained streak image is shown in Fig. 1 together with temporal profiles. The main pulses coming from two neighboring blocks of the six-step mirror are seen. The traveling-wave velocity is determined from the time separation between the two pulses,

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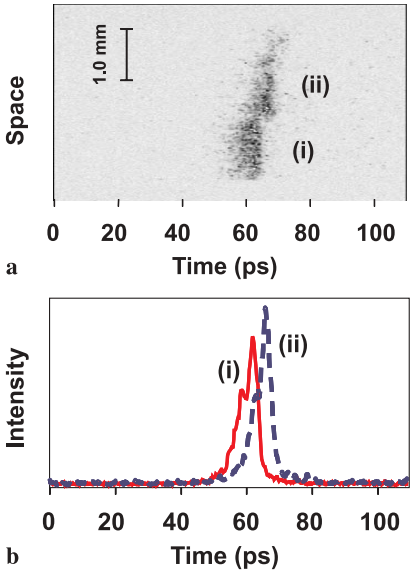

FIGURE 1 **a** Streak image of the main pumping laser at the target position. Two light components reflected by neighboring blocks of the six-step mirror are seen at spatially separated positions. **b** Spatially integrated profiles of the pulses

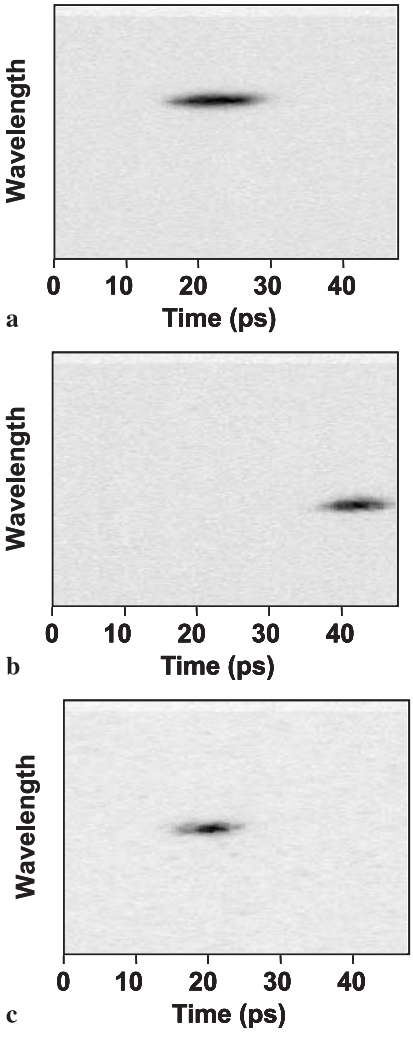

FIGURE 2 Streak images of XRL with **a** Ag, **b** Pd and **c** Mo. The bremsstrahlung emissions were less than the detectable level. There is no correspondence between the time coordinates in Figs. 1 and 2

resulting in $1.03c$, where c represents the light speed. A line-focusing system consists of an off-axis parabolic mirror with a focal length of 772 mm and a spherical mirror with a curvature of 1000 mm. The line-focus size was 4.0 mm in length and 20 μm in width at the target position. Consequently, the irradiation intensities were $(1.3–2.7) \times 10^{15}$ W/cm^2 and $(1.9–4.1) \times 10^{12}$ W/cm^2 for the main pulse and the prepulse respectively.

Three different materials, silver (Ag; $Z = 47$), palladium (Pd; $Z = 46$) and molybdenum (Mo; $Z = 42$), coated on flat glass plates were irradiated. The wavelengths of the Ni-like XRL transition ($4d \rightarrow 4p$, $J = 0 \rightarrow 1$) are 13.9 nm, 14.7 nm and 18.9 nm for Ag, Pd and Mo respectively. The XRL outputs were recorded using an X-ray streak camera (XSC: Hamamatsu Photonics model C4575) coupled with a flat field grating spectrometer (FSS). The time resolution of the XSC with a 50-μm photocathode slit (τ_{xsc}) was 1.68 ps. The FSS consisted of a toroidally bent gold mirror, an entrance slit of 200-μm width and a holographic laminar grating with the average groove number of 1200 lines/mm. The temporal smearing on the XRL (τ_{ffs}) produced by the grating was calculated to be 2.58 ps, 2.73 ps and 3.51 ps for Ag, Pd and Mo respectively. The total instrumental time resolution (τ_R) was represented by the root mean square of τ_{xsc} and τ_{ffs}, i.e. $\tau_R = (\tau_{xsc}^2 + \tau_{ffs}^2)^{1/2}$ assuming Gaussian temporal shapes.

Shown in Fig. 2 are the obtained streak images of the XRLs. It should be noted that the time coordinates in Fig. 2 do not correspond to each other and to those in Fig. 1. The bremsstrahlung emissions were not measured because of the instrumental detection limit.

3 Discussion

Figure 3 shows temporal durations of the XRLs as a function of the effective Ni-like charge of the target materials. The durations (τ) were obtained from the wavelength-integrated profile of the streak data shown in Fig. 2. The substantial durations were obtained after deconvolving the instrumental time resolution τ_R using the relationship $\tau_{XRL} = (\tau^2 - \tau_R^2)^{1/2}$. In this experiment, a discontinuous six-step mirror was used for generating the traveling wave. The reflection from each block corresponded to a length of

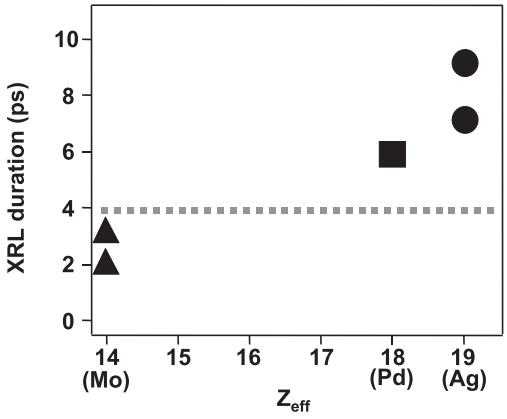

FIGURE 3 X-ray laser durations for the effective Ni-like charge. *Dotted line* represents the time step of the quasi-traveling wave which corresponds to the minimum duration to be measured

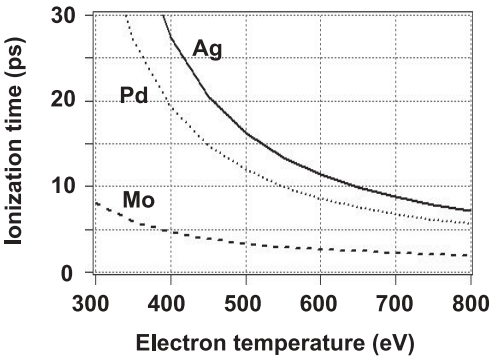

FIGURE 4 Collisional ionization time from the Ni-like ground state 3d for Ag (*solid*), Pd (*dotted*) and Mo (*dashed*). The collisional ionization coefficients are calculated from (1) and a typical electron density of the gain region, 5×10^{20} cm^{-3}, is assumed

1.2 mm, i.e. to a time of 4 ps, in the line focus on the target. The minimum XRL duration to be observed is determined by this time step, which is shown in Fig. 3 by a dotted line. Since the measured XRL durations for the Mo case are shorter than the time step, we can only say that they are shorter than 4 ps. However, it is clearly seen that the XRL duration becomes shorter as the atomic number decreases. The durations of Ag and Pd XRLs are longer than the main-pulse duration. It should be noted that the obtained duration of an Ag XRL is consistent with values estimated in our previous work, in which the gain duration is investigated using an intensity ratio of XRL output without and with traveling-wave pumping [6].

The spontaneous decay time from the lower level of the Ni-like XRL transition (4p) to the Ni-like ground state (3d) is faster than 1 ps and it does not depend on electron temperature. Therefore, we consider the collisional ionization from the Ni-like ground state as the main process to decrease the gain in the plasma medium. The collisional ionization coefficient (I^{c}) is given by Landshoff and Perez as the following empirical formula [11]:

$$I^{\mathrm{c}} = 1.24 \times 10^{-6} \hat{\imath} {T_{\mathrm{e}}}^{-3/2} \frac{\exp(-E/T_{\mathrm{e}})}{(-E/T_{\mathrm{e}})^2} \times \left[\frac{0.915}{\left(1+0.064\frac{T_{\mathrm{e}}}{E}\right)^2} + \frac{0.42}{\left(1+0.5\frac{T_{\mathrm{e}}}{E}\right)^2} \right] [\mathrm{cm}^3/\mathrm{s}], \quad (1)$$

where $\hat{\imath}$ is the number of bound electrons, T_{e} is the electron temperature in eV and E is the ionization energy in eV. Figure 4 shows the collisional ionization time calculated by assuming the electron density of 5×10^{20} cm^{-3} [6]. Since the irradiation parameters and atomic numbers of the target materials were not so different, generated plasmas on each target should be similar. In Fig. 4, it is obvious that the collisional ionization time becomes shorter as the atomic number decreases at the same electron temperature. The collisional ionization times at 500 eV, which is the typical electron temperature of the gain region [6], are comparable with the obtained XRL durations. This suggests that the collisional ionization from the Ni-like ground state could be the main cause to determine the XRL duration in the TCE scheme. In addition, the plasma heating time corresponding to the main laser duration may have an influence on the XRL duration. This will be investigated by changing the main-pulse duration in a future experiment.

4 Summary

We have investigated the temporal duration of a Ni-like transient collisional excitation XRL pumped by a CPA laser. The temporal durations of three different materials, Ag ($Z = 47$), Pd ($Z = 46$) and Mo ($Z = 42$), were measured using a fast X-ray streak camera coupled with a flat field grating spectrometer. The obtained durations, 7.3–9.3 ps for Ag, 6.2 ps for Pd and less than 4.0 ps for Mo, showed shortening as the atomic number decreased. This atomic number dependence suggested that the collisional ionization from the Ni-like ground state (3d) could be the important process to determine the XRL duration in the transient collisional excitation scheme.

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