Effects of delay time on transient Ni-like x-ray lasers

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In transient collisional excitation scheme, a long (nanosecond) prepulse is used to perform and ionize plasmas. After a delay time, a short (sub- or picosecond) intense laser pulse is used to rapidly heat the plasma. This results in transient x-ray lasers with high gain. Effects of delay time on transient collisional excitation *nickel-like* x-ray lasers are investigated analytically using a simple model. The calculations show that the longer delay time can greatly relax the density gradient. This is very critical for the propagation of x-ray lasers. However, a too long delay will reduce the electron temperature of the plasma before the arrival of the short pulse. Increasing the intensity of the long pulse or extending the pulse duration can keep the temperature required to maintain a high percentage of Ni-like ions while the delay time is longer. Similarly, increasing the intensity of the short pulse or extending the duration can also raise the electron temperature, resulting in higher gain coefficient. Our results indicate that extending the pulse duration is more efficient than that of increasing the intensity.

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I. INTRODUCTION

Since high gain transient collisional excitation (TCE) scheme was first demonstrated in 1997 with only a few Joule pump energy [1], great attention was attracted [2–5]. The result of neonlike titanium TCE x-ray laser was reproduced by Dunn in 1998 and extended to nickel-like palladium, and nickel-like molybdenum with a gain coefficient of up to 35 cm^{-1} [2,6–8]. Kalachnikov in 1998 also demonstrated the saturation output of neonlike titanium TCE x-ray laser with only 5-J pump energy [9]. Nilsen modeled the neonlike titanium transient x-ray laser [10] and calculated the hydrodynamic evolution of the plasma under the experimental conditions using LASNEX and XRASER code [4]. In calculations, effects of the delay time between the long pulse and the following short pulse was investigated theoretically for the first time.

A suitable delay time between the long pulse and the short pulse is beneficial for relaxing the plasma density gradient, and thus is very critical for the propagation of x-ray lasers [11].

One of the main objectives to enhance the efficiency of x-ray lasers is to develop a ''table-top'' x-ray laser for applications [12,13,9]. In the ''traditional'' quasi-steady state scheme, the prepulse is only to create a preplasma. The delay is used to make a longer scale length. The main pulse is then not only required to heat plasma to reach the electron temperature required by population inversion, but also needed to ionize the plasma to a correct ionization state of Ni-like (or Ne-like). By comparison, the prepluses and main pulses serve different functions in the TCE scheme. The long (pre) pulse is not only required to create a preplasma, but also needed to prepare an optimized preplasma with a rich Ni-like (or Ne-like) ionization stage. Then the short (main) pulse heats the plasma rapidly to reach required conditions with high electron temperature while keeping the ion temperature low. This is beneficial for forming a high gain transient population inversion. For the TCE scheme, a longer delay can make a longer scale length. But a too long delay will also reduce the temperature in the plasma [14]. Thus, if we would like to use the delay to relax the plasma density gradient, the delay and the pulse duration between the long pulse and the short pulse should be optimized.

In this paper, we investigate the effects of the delay time on hydrodynamics of transient Ni-like Pd x-ray lasers using the formulas of Ref. [14]. In order to understand the optimization conditions of plasmas, we calculate the electron temperature, scale length, electron density for different delay time. The results show that extending the pulse duration is more efficient than that of increasing the intensity to generate transient x-ray lasers with high gain.

II. ANALYTIC FORMULAS FOR TCE NI-LIKE X-RAY LASERS

According to the formula of Ref. [14], useful scaling laws for plasma variables are used to describe the hydrodynamic process of TCE Ni-like x-ray lasers. The convenient units listed in Table I are employed, which scale the variable with underline in the whole derivation, to simplify the calculation.

TABLE I. Normalized values for scaled variables.

Physical variable	Symbol	Normalized value
Time	t	1 ns
Laser intensity	I	10^{14} W cm^{-2}
Laser wavelength	λ	1.053 μm
Ablation mass	m	10^{-4} g cm^{-2}
Ion charge	Z	65
Atomic mass	A	240
Coulomb logarithm	Λ	5

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The processes of laser pulses interacting with plasmas are divided into four distinct periods. They are $t \leqslant t_{1L}$, $t_{1L} \leqslant t \leqslant t_m$, $t_m \leqslant t \leqslant t_{2L}$, and $t_{2L} \leqslant t$, respectively, where $t_{1L} = \Delta t_{1L}$ is the long pulse duration, Δt_m is the delay time, $t_m = \Delta t_{1L} + \Delta t_m$ is the time when the short pulse arrives, Δt_{2L} is the short pulse duration, $t_{2L} = t_m + \Delta t_{2L}$ is the turning off time of the short pulse.

A. During the time of $t \leqslant t_{1L}$

The long pulse creates an optimized preplasma. The analytic solutions after the influence of the initial conditions are

$$T = 3.90 \ \ \mathrm{keV}\, I^{5/9} A^{2/9} \Lambda^{2/9} \lambda^{2/3} t^{2/9}, \tag{1a}$$

$$L = 2.87 \times 10^{-2} \ \ \mathrm{cm}\, I^{10/27} A^{-2/27} \lambda^{4/9} \Lambda^{4/27} t^{31/27}, \tag{1b}$$

$$n_0 = 20.82 \times 10^{20} \ \ \mathrm{cm}^{-3}\, I^{11/54} A^{4/27} \lambda^{-5/9} \Lambda^{-2/54} t^{-14/27}, \tag{1c}$$

where I is the laser intensity, λ is the laser wavelength, Λ is the Coulomb logarithm, A is the atomic mass. T is the electron temperature, L is the scale length, n_0 is the maximum value of the electron density.

B. During the time of $t_{1L} \leqslant t \leqslant t_m$

After the time t_{1L}, the long laser pulse is turned off and the plasma continues to expand adiabatically. The exact analytical solutions can be obtained for this period using the condition before t_{1L},

$$T = T_{1L} t_{1L}^{2/3} t^{-2/3}, \tag{2a}$$

$$L = L_{1L} t_{1L}^{-5/9} t^{5/9}, \tag{2b}$$

$$n_o = n_{1L} t_{1L}^{7/9} t^{-7/9}, \tag{2c}$$

where T_{1L}, L_{1L}, and n_{1L} are the electron temperature, scale length, and electron density at t_{1L}.

C. During the time of $t_m \leqslant t \leqslant t_{2L}$

At time t_m, when the short pulse has switched on, the solutions can be obtained by considering the initial conditions before t_m:

$$T = 23.12 \ \ \mathrm{keV}\, I_2 m^{-1} A Z^{-1} t \left(1 - t_m^{5/3} t^{-5/3} + \frac{T_m t_m^{2/3}}{T_2} t^{-5/3} \right), \tag{3a}$$

$$L = 5.16 \times 10^{-2} \ \ \mathrm{cm}\, I_2^{1/2} m^{-1/2} t^{3/2} \times \left(1 - t_m^{5/3} t^{-5/3} + \frac{L_m^2}{L_2^2 t_m^{4/3}} t^{-5/3} \right)^{1/2}, \tag{3b}$$

$$n_0 = 3.16 \times 10^{20} \ \ \mathrm{cm}^{-3}\, I_2^{-1/2} m^{3/2} A^{-1} Z t^{-3/2} \times \left(1 - t_m^{-5/3} t^{-5/3} + \frac{n_2^2 t_m^{1/6}}{n_m^2} t^{-5/3} \right)^{-1/2}, \tag{3c}$$

where T_m is the electron temperature at t_m, $T_2 = 23.12$ keV $I_2 m^{-1} A Z^{-1}$. L_m is the scale length at t_m, $L_2 = 5.16 \times 10^{-2}$ cm $I_2^{1/2} m^{-1/2}$. n_m is the electron density at t_m, $n_2 = 3.16 \times 10^{20}$ cm^{-3} $I_2^{-1/2} m^{3/2} A^{-1} Z$.

D. During the time of $t_{2L} \leqslant t$

After the time t_{2L}, the short laser pulse is turned off and the plasma continues to expand adiabatically. The analytical solutions can be obtained for this period using the condition before t_{2L}:

$$T = 23.12 \ \ \mathrm{keV}\, I_2 m^{-1} A Z^{-1} t_{2L}^{5/3} t^{-2/3} \times \left(1 - t_m^{5/3} t_{2L}^{-5/3} + \frac{T_m t_m^{2/3} t_{2L}^{-5/3}}{T_2} \right), \tag{4a}$$

$$L = L_2 t_{2L}^{5/6} t^{2/3} \left(1 - t_m^{5/3} t_{2L}^{-5/3} + \frac{L_m^2}{L_2^2} t_m^{2/3} t_{2L}^{-5/3} \right)^{1/2}, \tag{4b}$$

$$n_0 = n_2 t_{2L}^{-5/6} t^{-2/3} \left(1 - t_m^{-5/3} t_{2L}^{-5/3} + \frac{n_2^2 t_{2L}^{-5/3}}{n_m^2 t_m^{2/3}} \right)^{-1/2}. \tag{4c}$$

III. RESULTS AND DISCUSSION

In order to understand the effects of the delay time on hydrodynamics of the transient collisional x-ray laser under different conditions, we calculate the hydrodynamics of the transient collisional Ni-like Pd x-ray laser for different intensity and duration for the long pulse and the short pulse, respectively. First, we discuss why the transient x-ray laser is *sensitive* to the delay time. Second, we investigate the effects of the delay time by changing the intensity and the duration for long pulse. Finally, we discuss how to effectively enhance the electron temperature in the preplasma before the short pulse comes.

A. The effects of sensitivity of x-ray laser gain to the delay time

Experimental results and numerical simulations have shown that the x-ray laser output is quite sensitive to the delay time between the long- and the short-pulse drive lasers [15,4]. In order to understand the dependence of the x-ray laser on the delay time, we calculate hydrodynamics of the transient collisional Ni-like Pd x-ray laser with three different values of delay time of 1.1, 1.9, and 2.6 ns. The conditions in the calculations are as almost the same as in Ref. [2], except the intensity of the long pulse of $I_1 = 3.0 \times 10^{12}$ W/cm^2.

The calculations show that the densities are 5.79×10^{20}, 4.41×10^{20}, and 3.68×10^{20} cm^{-3} for the three different delay times, respectively, as shown in Fig. 1(a). The difference among the three densities will not much affect the gain of the x-ray lasers. In the calculations, 152.7 μm is the longest scale length for the 2.6 ns delay time, as shown in Fig. 1(b). For this delay time, the electron temperature is 160.9 eV, as shown in Fig. 1(c). This results in an average ionization of

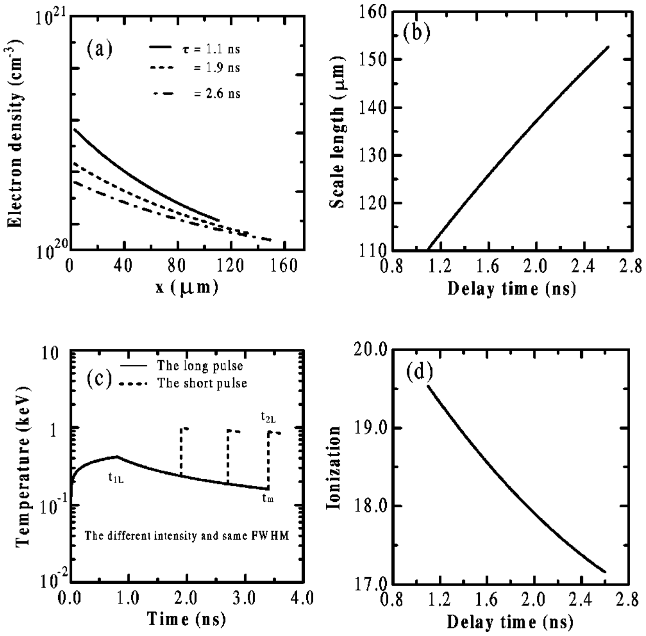

FIG. 1. (a) Electron density versus x with deferent delay, (b) temperature versus delay, (c) temperature history, (d) ionization versus delay. The conditions are $I_1 = 0.7\times 10^{12}$ W/cm^2, $t_{1L} = 0.8$ ns, $\lambda = 1.053$ μm, $I_2 = 5.2\times 10^{14}$ W/cm^2, $t_{2L} = 1.1$ ps, the delay time τ is from 1.1 to 2.6 ns.

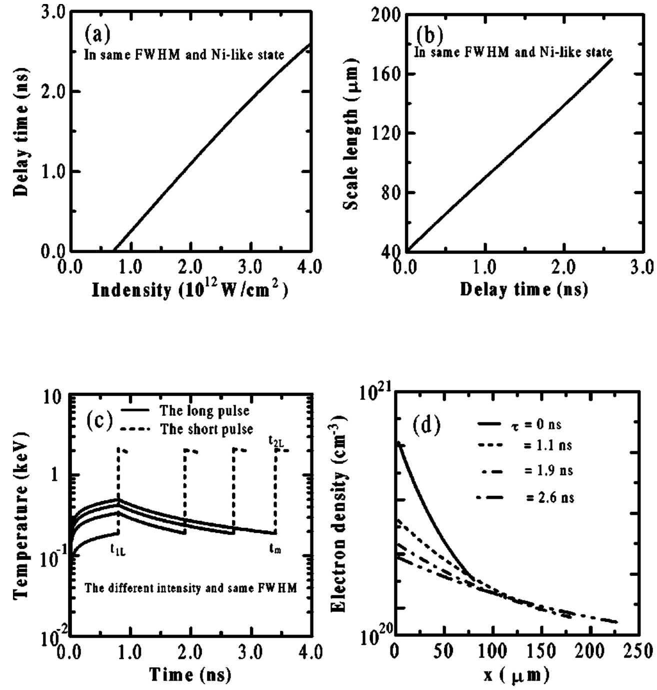

FIG. 2. (a) Delay time versus long-pulse intensity, (b) scale length vs delay time, (c) temperature history, (d) electron density vs x with deferent delay for the same long-pulse duration and Ni-like ionization. The conditions are I_1 from 0.7×10^{12} to 4×10^{12} W/cm^2, $\lambda = 1.053$ μm, $t_{1L} = 0.8$ ns, $I_2 = 5.2\times 10^{14}$ W/cm^2, $t_{2L} = 1.1$ ps, the delay time τ is from 0 to 2.6 ns.

only 17.16, as shown in Fig. 1(d). This is lower than the requirement for rich Ni-like Pd ionization population. For the 1.9 ns of the delay time, the scale length is 134.3 μm, which is middle among the three scale lengths. But the temperature is 187.6 eV, corresponding to an ionization of about 18.06. This is almost the Ni-like Pd ionization population. For the 1.1 ns of the delay time, the scale length is 110.5 μm, which is the shortest one. The temperature is 237.1 eV, corresponding to an ionization of about 19.5. This is obviously over-ionized. In nanosecond process, the ionization is sensitively dependent on the temperature. The temperature depends sensitively on the delay time, as seen in the Fig. 1(c). Thus the different delay time cause ionization difference sensitively. From the comparison between the sensitivity of the ionization to delay time and the x-ray laser output to delay time, it is clear that the sensitivity of the x-ray laser output to the delay time is finally due to the different ionization population. The scale length also depends sensitively on the delay time. However, This will not sensitively affect the gain of the x-ray lasers.

We know that the main function of the long pulse is to prepare a preplasma with a rich Ni-like (or Ne-like) ionization population and a low ion temperature before the arrival of the short pulse. And the main function of the delay time is to relax the density gradient, that is critical for the x-ray laser propagation [14]. Of course, a longer delay time can make the scale length longer. However, a rich Ni-like (or Ne-like) ionization population is the most important condition. Thus in the design of the x-ray laser experiment, we not only need to optimize the scale length, but also need to optimize the ionization, which is more important than the scale length.

B. The efficiency of the long pulse heat under the delay time

From the calculations above, we know that a delay time will decrease the Ni-like (or Ne-like) ionization population while it relaxes the density gradient. Thus we have to increase the temperature so that the average ionization is kept in the Ni-like (or Ne-like) ionization state before the arrival of the short pulse. There are two ways to increase the temperature. The first one is to enhance the intensity of the long pulse. The another one is to extend the duration of the longer pulse. Here what we want to know is which one is more efficient.

We calculate the change of the intensity, scale length, density, and temperature while extending the delay time from 0 to 2.6 ns and keeping the duration to be a constant of 0.8 ns. The results show that the intensity has to be increased from 0.7×10^{12} to 4.0×10^{12} W/cm^2 so that the most Pd ions are kept in Ni-like ionization stage, as shown in Fig. 2(a). The scale lengths are prolonged from 40 to 169.8 μm with the extension of the delay, as shown in Fig. 2(b). And the electron density range is from 3.90×10^{20} to 8.44×10^{20} cm^{-3}, as shown in Fig. 2(d). However, the highest temperature during the short pulse laser is dropped from 1.84 keV to 800 eV with the extension of the delay, as shown in Fig. 2(c).

As a comparison with the case of changing the pulse intensity, we calculate the same parameters' change by extending the delay time from 0 to 1.0 ns and keep the intensity as a constant of 0.7×10^{12} W/cm^2. The results show that the durations are increased from 0.8 to 2.4 ns with the extension of the delay time while keeping the Pd ions as Ni-like ions,

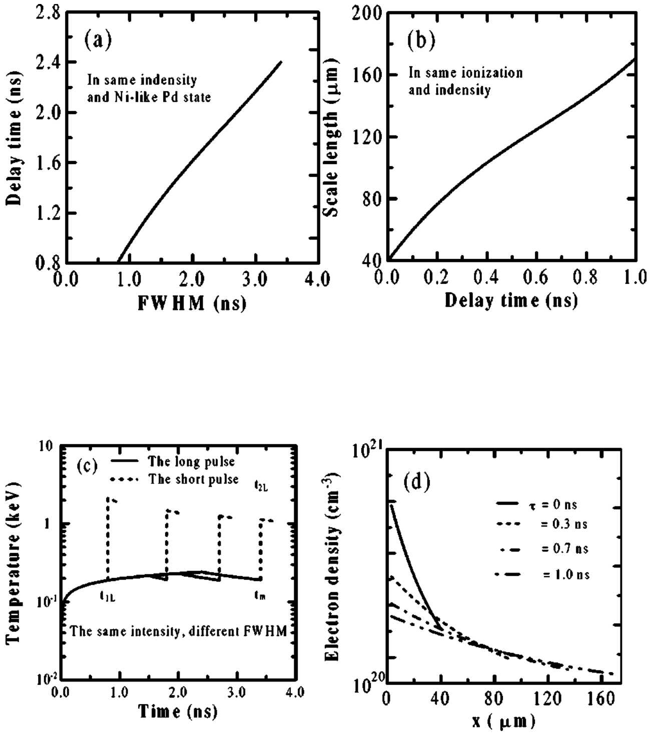

FIG. 3. (a) Delay time versus full width at half maximum (long-pulse duration), (b) scale length versus delay time, (c) temperature history, (d) electron density vs x for deferent delay for the same intensity and Ni-like ionization. The conditions are $I_1=0.7\times10^{12}$ W/cm^2, the long-pulse duration t_{1L} are from 0.8 to 2.4 ns, $\lambda=1.053$ μm, $I_2=5.2\times10^{14}$ W/cm^2, $t_{2L}=1.1$ ps, the delay time τ is from 0 to 1.0 ns.

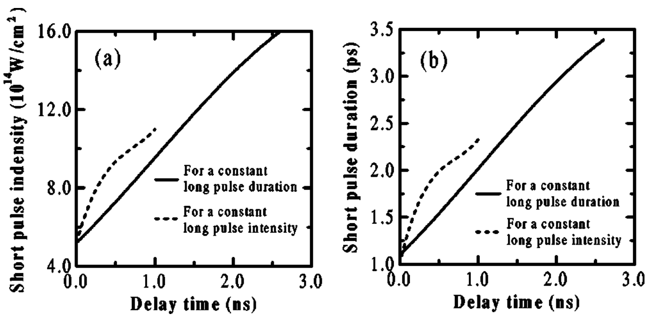

FIG. 4. (a) The short-pulse intensity versus delay time for a constant long-pulse duration, the ionization is Ni-like and the electron temperature is optimized temperature of 1.84 keV during the short pulse. The conditions are I_1 from 0.7×10^{12} to 4×10^{12} W/cm^2, $\lambda=1.053$ μm, $t_{1L}=0.8$ ns, I_2 are from 5.2×10^{14} to 1.6×10^{15} W/cm^2 or t_{2L} are from 1.1 to 3.4 ps, the delay time τ is from 0 to 2.6 ns. (b) The short-pulse duration versus delay for a constant long-pulse intensity, the ionization is Ni-like and the electron temperature is optimized temperature of 1.84 keV during the short-pulse. The conditions are $I_1=0.7\times10^{12}$ W/cm^2, $\lambda=1.053$ μm, t_{1L} are from 0.8 ns to 2.4 ns, I_2 are from 5.2×10^{14} to 1.2×10^{15} W/cm^2 or t_{2L} are from 1.1 ps to 2.3 ps, the delay time τ is from 0 to 1.0 ns.

as shown in Fig. 3(a). The scale lengths are prolonged from 40 to 170.8 μm with the extension of the delay, as shown in Fig. 3(b). And the highest temperature is only dropped from 1.84 to 1.1 keV during the short pulse with the extension of the delay time, as shown in Fig. 3(c). The electron density range is from 3.64×10^{20} to 8.44×10^{20} cm^{-3}, which is almost the same as the case above, as shown in Fig. 3(d).

From the comparison, we know that the prolonged ranges of the scale lengths and density ranges are almost the same for both cases. However, the intensity is increased from 0.7×10^{12} to 4.0×10^{12} W/cm^2 when the duration is a constant of 0.8 ns, and the duration is only increased from 0.8 to 2.4 ns when the intensity is a constant of 0.7×10^{12} W/cm^2. While keeping the Pd ionization stage in Ni-like, the efficiency of the heating pulse for prolonging the long-pulse duration while keeping the constant intensity is greater than that for increasing the intensity while keeping the constant duration. It is significant because prolonging the pulse duration is much easier than increasing the pulse intensity in the x-ray laser experiment.

C. The influence of the delay time on the short-pulse conditions

For the TCE scheme, the change of the ionization state and ablation mass can be neglected during the short pulse [14]. To help understand the influence of the delay time, we calculate only the temperature changed with different delay time, which is very important for the gain, and find out the optimized intensity or duration of the short pulse while keeping the electron temperature as 1.84 keV and the Pd ions as Ni-like.

The temperature during the short pulse goes down with the extension of the delay time from Fig. 1(c) and Fig. 2(c). It is not beneficial for the output of the x-ray laser because the gain coefficient is proportional to the electron temperature and inversely proportional to the square root of the ion temperature. The ways to enhance the temperature are also to increase the intensity or the duration of the short pulse.

We first calculate the case of changing short-pulse intensity while keeping the pulses duration the same for different long-pulse intensity or duration and delay time. The calculations show that the short-pulse intensity needs to increase from 5.2×10^{14} to 1.6×10^{15} W/cm^2 with the delay extension from 0 to 2.6 ns for a constant long-pulse *duration*, as shown as the solid line in Fig. 4(a). And the intensity only needs to increase from 5.2×10^{14} to 1.2×10^{15} W/cm^2 with the delay extension from 0 to 1.0 ns for a constant long-pulse intensity, as shown as the dashed line in Fig. 4(a). The efficiency for keeping the long-pulse intensity constant is greater than that for keeping the long-pulse duration constant.

Then we calculate the case of changing short-pulse duration while keeping the pulses intensity the same for different long-pulse intensity or duration and delay. The calculations show that the short-pulse durations need to increase from 1.1 to 3.4 ps with the delay extension from 0 to 2.6 ns for a constant long-pulse duration, as shown as the solid line in Fig. 4(b). And the duration only need to increase from 1.1 to 2.3 ps with the delay extension from 0 to 1.0 ns for a constant long-pulse intensity, as shown as the dashed line in Fig. 4(b). The efficiency for keeping the long-pulse intensity constant is also greater than that for keeping the long-pulse duration constant.

From the calculations above, the conclusion we get here is that increasing the duration of the short laser pulse will be more beneficial to enhance the temperature than that of increasing the intensity. However, it should be noted that the duration for the short pulse could also not be too long because of the requirements of TEC limit.

IV. CONCLUSIONS

We investigate analytically the effects of delay time on nickel-like Pd TCE x-ray lasers using an analytical model. The calculations show that a longer delay time can greatly relax the density gradient. This is very critical for the propagation of x-ray lasers. However, a too long delay will reduce the electron temperature before the arrival of the short pulse. Increasing the long-pulse intensity or extending the pulse duration can keep the temperature required, and therefore high percentage of Ni-like Pd ions. Extending the long-pulse duration is more efficient than that of increasing the intensity. Similarly, increasing the short-pulse intensity or extending the duration can also raise the temperature that is important for enhancing gain coefficient because it is proportional to the electron temperature and inversely proportional to the square root of the ion temperature. As a result, extending the short-pulse duration is also more efficient than that of increasing the intensity.

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