Investigation on the hydrodynamics of slab x-ray laser plasma by nonuiform line focused laser irradiation*

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Based on the two-dimensional model, this paper compares the hydrodynamics of slab x-ray laser plasma produced by different nonuniform line focused irradiations. It finds that the average intensity and the duration of laser pulse and the overall shape of the intensity distribution in the focal line have different influences on the plasma. Calculations show that the evolution of temperature variation is more sensitive to the pulse duration and the electron density variation is more sensitive to the pulse intensity. Pulses with duration of 200 ps to 500 ps and with intensity of 0.2 TW/cm^2 to 1.0 TW/cm^2 are proved acceptable in slab x-ray lasers.

Keywords: plasma, slab x-ray laser, nonuniform line focused laser irradiation, hydrodynamics

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1. Introduction

The x-ray lasers (XRL), which have characteristics such as high spatial coherence and high peak brilliance, have been one of the promising compact x-ray sources in various research fields such as material science, biological science, atomic and molecular physics. Plasma as one of the XRL sources has been intensively studied, especially after 1985 when the XRL was first demonstrated.[1] Since the beginning line focused laser produced plasma has attracted the researchers' interest. The overall shape and character of the line plasma is known to be in most cases of importance to the XRL scheme. The spatial and temporal distributions of the electron and ion densities and the electron temperature critically determine the local conditions for radiative and collisional excitation and de-excitations and ultimately population inversion. Local perturbations in the plasma parameters along the line focus[2,3] can produce spatial and temporal detuning of the gain regions.[4] Characters of the plasma produced by laser line focus on foil target were studied experimentally in early years,[5] in which characterization of the electron density distribution for thin foils and small-diameter solid cylindrical targets has been investigated. Evolution of plasma-jet-like structures in line-focused laser-produced plasma was also studied[6] and it was pointed out that the strong nonuniformities in the plasma may induce hydrodynamic turbulence and other unexpected nonlinear effects, which would reduce the x-ray gain significantly. Later on, using monochromatic imaging diagnostics we observed the large-scale fluctuations of the density along the line focus.[7] Although the results were time-integrated, the observed variations indicated the presence of strong local changes in the plasma hydrodynamics generated by intensity nonuniformities in the driving laser beam. In the development of XRL, slab was introduced in 1987 by Naval Research Laboratory by which power demand of laser was reduced to 10^{12} TW/cm^2.[8] In 1996 multiple irradiating pulses[9] were introduced to the experiment since then the prepulse technique and slabs dominate the XRL plasma experiments.[10−13] In which laser line focus is applied and the deleterious influence of the nonuniformity exists always. In the present work, we will study how the characteristics of the irradiating nonuniform line focused laser pulse affects the slab XRL plasma and the evolution history of the nonuniformity introduced in the plasma.

2. Model equation

In most XRL experiments, plasma is generated by the line focused laser with the geometry adopted

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as Fig. 1 shows. Considering the expansion vertical to the slab (x direction) and evolution along the line focus (z direction), two dimensional (2D) hydrodynamics of the plasma can be described as follows:

$$\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\rho\frac{\partial v_x}{\partial x} - v_x\frac{\partial \rho}{\partial x} - \rho\frac{\partial v_z}{\partial z} - v_z\frac{\partial \rho}{\partial z},\\
\frac{\partial v_x}{\partial t} &= -v_x\frac{\partial v_x}{\partial x} - v_z\frac{\partial v_x}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial x},\\
\frac{\partial v_z}{\partial t} &= -v_x\frac{\partial v_z}{\partial x} - v_z\frac{\partial v_z}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial z},\\
\frac{\partial T}{\partial t} &= -v_x\frac{\partial T}{\partial x} - v_z\frac{\partial T}{\partial z} - \frac{1}{C_{\rm V}}\frac{p}{\rho}\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_z}{\partial z}\right)\\
&\quad + \frac{1}{C_{\rm V}}H + \frac{1}{\rho C_{\rm V}}\frac{\partial}{\partial z}\left(K_0 T^{5/2}\frac{\partial T}{\partial z}\right), \qquad (1)
\end{aligned}$$

where $v_z, v_x, \rho, T, p, K_0, C_{\rm V}, H$ denote the velocity in z direction, velocity in x direction, density of plasma, temperature, pressure, coefficient of heat transport, thermal capacity and energy deposition rate respectively. The 2D model is developed from 1D similarity equation[14] to study the hydrodynamic motion in centimeter scale in z direction. Detailed description of this newly developed 2D model was given in our recent work.[15]

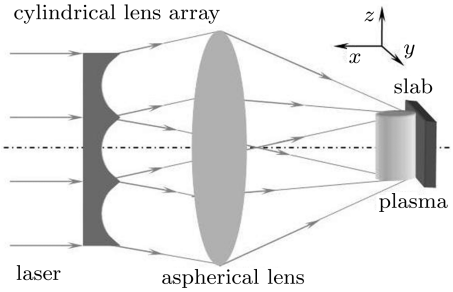


Fig. 1. Experimental setup in slab XRL.

3. Nonuniformity sorts

Nonuniformity in the line focus is inevitable. Figure 2 presents the intensity distribution in part of the line focus detected by a coupled charge device (CCD) measurement system. Two sorts of nonuniformity could be found, one is the compact variation between position 1 and position 2, the average distance between the nearest peak and valley is about one hundred microns. The other is larger scale nonuniformity, shown in Fig. 2 as the contrast between region a and region b, named in this work the large scale variation, mainly with a distance between the peak and valley longer than millimeter. In practical work, both sorts will introduce the nonuniformity to the plasma.

For the modification of XRL experiments, evolution of the plasma in x direction was previously well studied. Recently hydrodynamics of XRL plasma in x and y directions were studied.[16] Under nonuniform irradiation the hydrodynamics in z direction (along the focus line) remains interesting, which has been noticed in our previous work.[15] In the present work, we studied in detail the influence of pulse intensity, pulse duration and non-uniformity sorts on the hydrodynamics of plasma in z direction.

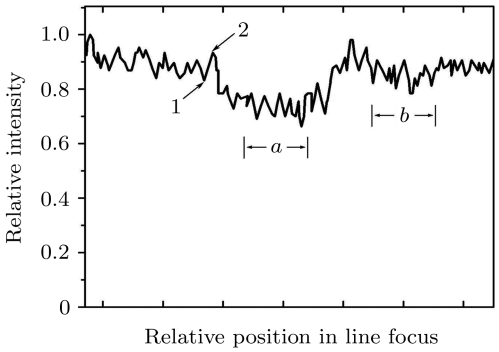


Fig. 2. Intensity distribution in line focus.

4. Nonuniformity in the plasma distribution

Intensity distribution in the line focus in z direction is assumed to be $I_0[1 + C_1\sin(2\pi N_1 z/L) + C_2\sin(2\pi N_2 z/L)]$ in the calculation, where C_1 and C_2 are the variables to determine the amplitude of intensity variation. The N_1 and N_2 are the variables to determine the nonuniformity sorts. The L and I_0 denote the length of focal line and the average intensity respectively.

Referring to practical experiments, variables C_1, C_2, N_1, N_2, L and I_0 are adopted as 0.12, 0.08, 6, 50, 1.0 cm and 1.0 TW/cm^2 in the calculation respectively. The average intensity of incident pulse on Mo slab target is 1.0 TW/cm^2 and duration is 300 ps. Result shows that the spatial distribution of temperature (Fig. 3(a)) and that of electron density (Fig. 3(b)) are notably nonuniform, especially at the end of pulse. The compact intensity variation and large scale variation introduce the corresponding nonuniformity into plasma distribution. After the pulse, the nonuniformity relaxes due to hydrodynamic motion along the focus line. This process is very important to the XRL scheme and in the following we will investigate this process by studying the evolution of temperature variation and electron density variation in the distribution. The variation will be described by the ratio of the discrepancy between maximum and minimum values to the average value.

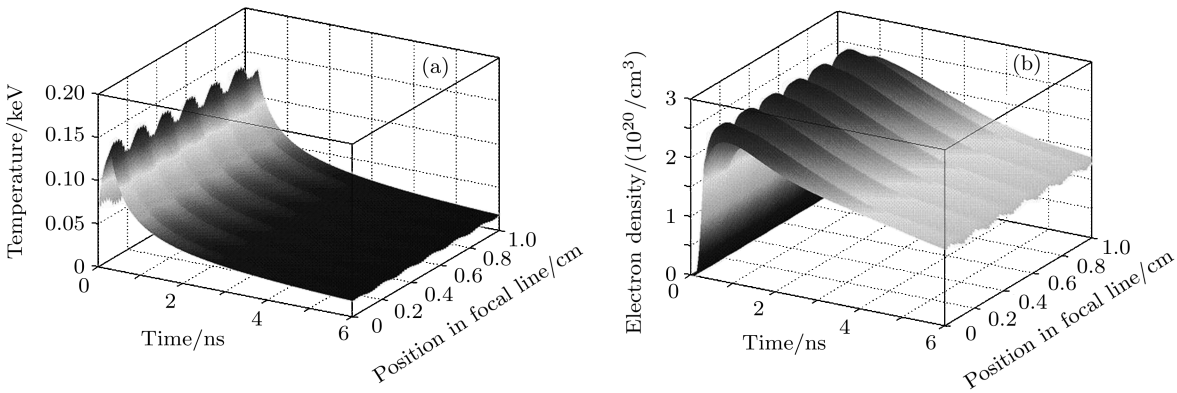


Fig. 3. Nonuniform distribution of temperature and electron: (a) the history of temperature; b) the history of electron density.

4.1. Influence of the nonuniformity sorts on the plasma

Intensity variation is assumed as ±12% for both sorts of nonuniformity for comparing the influence of nonuniformity sorts on the evolution of plasma.

In Fig. 4 the average irradiance intensity is 1.0 TW/cm^2, the pulse duration is 300 ps, the Mo target is used. Dot line and dash–dot line present the history of temperature variation with large scale and compact intensity nonuniformity respectively. With large scale intensity nonuniformity, variation drops slowly as dot line shows. In the case of compact intensity nonuniformity, dash-dot line shows a rapid drop.

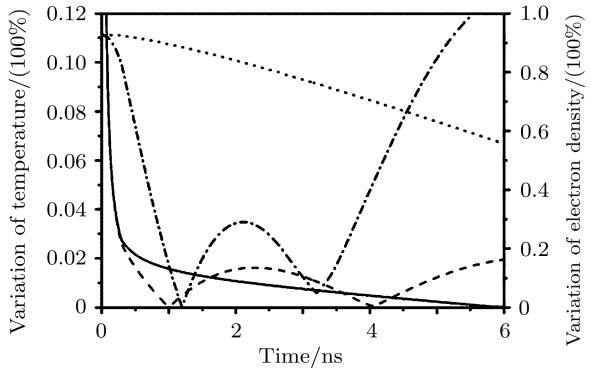


Fig. 4. History of the variation.

Solid line and dash line show the history of electron density variation with large scale and compact intensity nonuniformity respectively. The former drops much slower than the latter, which is similar to the temperature. It implies that the large scale intensity variation introduces a durable nonuniformity into the plasma. With compact intensity variation, the nonuniformity in the plasma decays rapidly.

Considering that durable nonuniformity is harmful to the XRL, we should refrain the laser line focus used in XRL experiments from the large scale intensity variation. For making sense to practical XRL experiments, our work considers only the compact intensity variation in studying the influence of pulse character.

4.2. Variation in the temperature distribution

Lines in Fig. 5 present the history of temperature variation with pulse duration of 200 ps (solid line), 500 ps (dash line), 800 ps (dot line) and 1.2 ns (dash–dot line) respectively. The intensity is 1.0 TW/cm^2. Every line shows that the temperature variation approaches to a minimum value after certain time. But the delay needed is different from each other. With 200 ps irradiation, the time is 1.25 ns after the end of pulse. In contrast it is 0.5 ns for condition with 500 ps pulse and 0.2 ns delay for 800 ps pulse. For the condition with 1.2 ns irradiance, the variation approaches to minimum in less than 100 ps after the end of pulse.

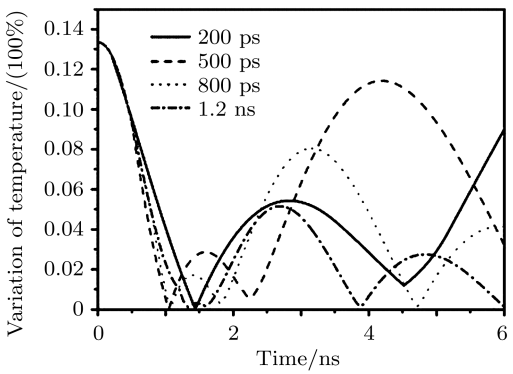


Fig. 5. Temperature variation history versus pulse duration.

Lines in Fig. 6 present the temperature variation under conditions with irradiances of different intensities. The pulse duration is 300 ps. Solid line, dash line, dot line and dash–dot line refer to the case with average intensity of 0.2 TW/cm^2, 0.5 TW/cm^2, 1.0 TW/cm^2 and 2.0 TW/cm^2 respectively. With the increase of intensity, the delay time needed for variation to arrive at the minimum decreases.

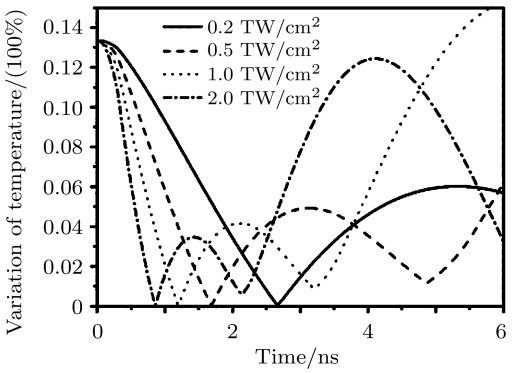


Fig. 6. Temperature variation history versus average intensity.

One similar phenomenon under all conditions in Figs. 5 and 6 is that the variation will get large again after keeping lower for a certain period. During such period, the plasma possesses a relative uniform distribution with lower variation, which is known to benefit the XRL gain. When changing the pulse duration or pulse intensity, such period varies. From Fig. 5 we can find that under the condition with 200 ps pulse, the variation keeps lower than 6% till to 5.5 ns. With 500 ps and 800 ps irradiances the variation keeps lower than 6% before 3.0 ns and 2.5 ns respectively. When enlarging the pulse duration up to 1.2 ns, dash–dot line shows the variation keeping lower than 5% for longer time. It can be concluded that the evolution of temperature distribution in z direction is sensitive to the pulse duration.

From Fig. 6, we can find that with 300 ps duration, the lower intensity is more helpful in obtaining plasma which keeps low variation for long time. For instance, with the average intensity as 0.5 TW/cm^2, the temperature variation could keep lower than 5% longer than 4.5 ns.

From Figs. 5 and 6, we know that the pulses with duration shorter than 500 ps or longer than 1.2 ns are both suitable for supporting relatively low variation for a long period. Short pulse becomes favourite in recent years, in the case of using short pulse to produce the pre-plasma, pulses with intensity from 0.2 TW/cm^2 to 1.0 TW/cm^2 are more helpful.

4.3. Variation in the electron density distribution

Lines in Fig. 7 present the electron density variation history under conditions with irradiances of different durations, which are 300 ps (solid line), 400 ps (dash line), 500 ps (dot line) and 1.0 ns (dash–dot line). The average intensity is 1.0 TW/cm^2.

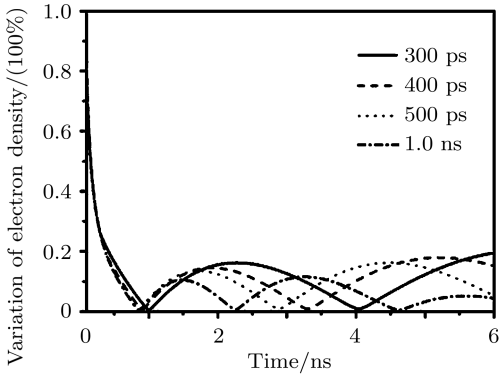


Fig. 7. Density variation history versus pulses duration.

Solid line, dash line, dot line and dash–dot line in Fig. 8 refer to the case with average intensity as 0.2 TW/cm^2, 0.5 TW/cm^2, 1.0 TW/cm^2 and 1.2 TW/cm^2 respectively. Pulse duration is 300 ps.

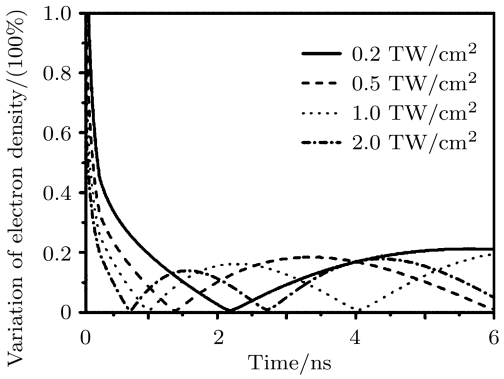


Fig. 8. Density variation history versus average intensity.

From Figs. 7 and 8, one can find that the delay time reduces with the increase of pulse duration and the intensity. One interesting phenomenon in Fig. 7 is that lines give almost the same history before the variation getting to the minimum. This is because when the duration of pulse exceeded the time for which the electron density needed to get uniform, the conditions with longer pulse duration make no difference in the hydrodynamic motion. This suggests that the pulses with duration less than 500 ps is more acceptable, which offer the same character but with lower energy demandable.

Furthermore under different conditions in Figs. 7 and 8, we can find that the period with lower variation differs from each other. In Fig. 7, when changing the pulse duration only, such period changes a little. In Fig. 8 such period decreases greatly with the increase of intensity. It implies that the electron density variation is much more sensitive to the pulse intensity.

From the above investigation, we found that pulses with duration between 200 ps to 500 ps and intensity between 0.2 TW/cm^2 to 1.0 TW/cm^2 benefit the uniformity of both electron density and temperature.

4.4. Oscillation along the line focus

In nonuniform plasma, hydrodynamic motion will result in the oscillation. In our calculation such perturbation is obtained.

Solid line and dash line in Figs. 9 and 10 present the history of temperature or electron density on two different positions in z direction. In Fig. 9 the average intensity of irradiances is different. In Fig. 10 the pulse duration is different. From the two lines in Figs. 9 and 10, we find that alternation exists in both electron density and temperature distribution. When enlarging the intensity from 0.5 TW/cm^2 to 2.0 TW/cm^2, the alternation occurs more rapidly. Also in the case of longer pulse duration, the alternation is more rapid.

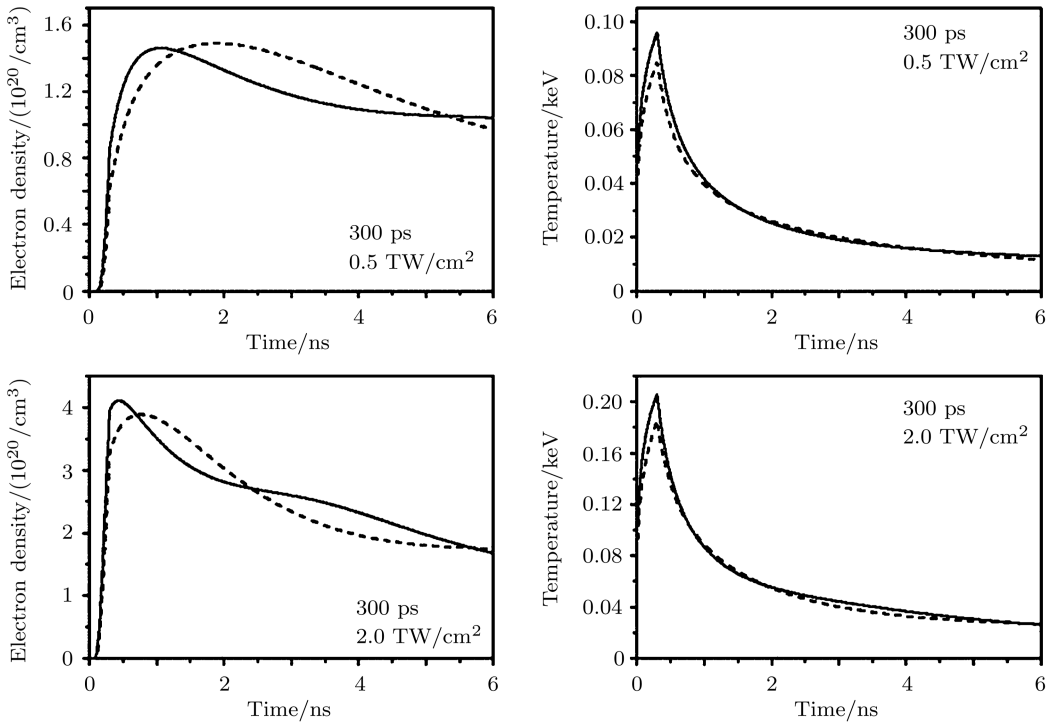
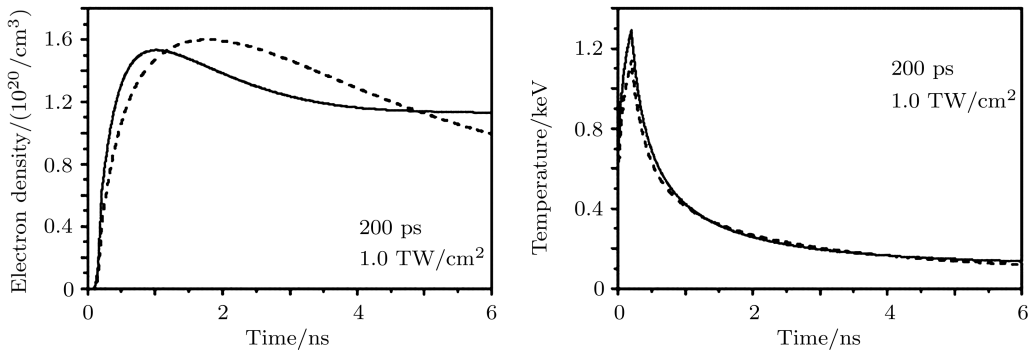


Fig. 9. Temporal evolution of temperature and electron density under irradiance of 300 ps.



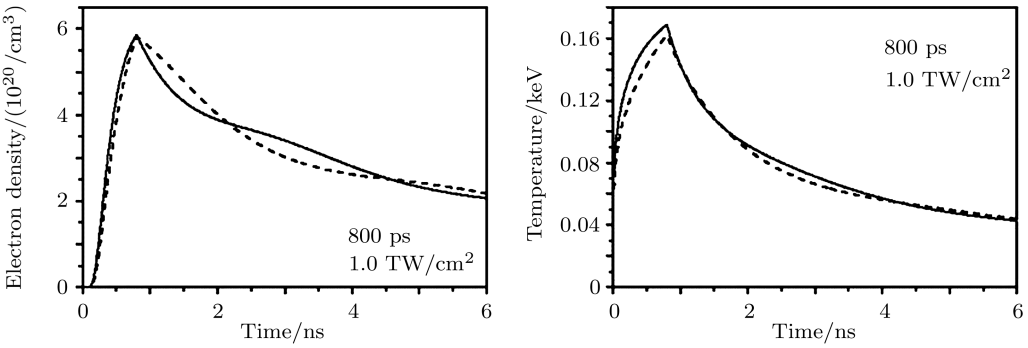


Fig. 10. Temporal evolution of temperature and electron density under irradiance of 1.0 TW/cm^2.

The above phenomena can be explained by the hydrodynamic evolution of plasma along the focal line. The nonuniformity drives the hydrodynamic motion in z direction which could reduce the variation. However when the plasma distribution gets uniform, hydrodynamic moment still remains which results in the oscillation and the re-growth of variation again. With long pulse duration or larger intensity, more energy is deposited in the plasma, the high temperature and electron density variation can drive rapid oscillation, this could explain why the alternation in Figs. 9 and 10 gets fast with the increase of pulse duration and pulse intensity.

The oscillation could explain why the variations get larger in later time in Figs. 5 and 6. In the expansion of plasma, the decrease of temperature and electron density reduces the pressure inside. Therefore it will take longer time and larger variation to force backing.

5. Conclusions

In summary we have studied the influence of pulse character on the hydrodynamic motion of plasma along the focal line. Oscillation and variation in the plasma distribution depend on the character of pulse, e.g. the pulse duration, pulse intensity and the sorts of intensity variation. Large scale intensity variation in the focal line results in a durable nonuniformity. Therefore it should be avoided in the experiment. Long pulse duration can offer enough time for plasma to get uniform. Temperature variation is found to be sensitive to the pulse duration and the electron density variation is found to be sensitive to the pulse intensity. Considering the lower energy requirement, pulses with duration of 200 ps to 500 ps and with intensity of 0.2 TW/cm^2 to 1.0 TW/cm^2 are more acceptable in supporting lower variation in plasma distribution for a long time, which could be utilized in XRL experiments.

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