Effect of focus position on a high intensity laser propagation in a dense plasma

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Abstract. A tightly focused laser pulse with relativistic intensity propagating in a dense plasma is studied by means of 2D particle-in-cell simulation. The results demonstrate that the laser propagation in the plasma is strongly dependent on the laser focus position. It is found that the laser can penetrate deeper in the plasma and create an on-axis plasma channel at certain focus positions, which is due to the suppression of the filamentation instability in the laser plasma interactions. The results are of interest for understanding of the fast ignition related experiments.

1. Introduction
Fast ignition [1] in laser fusion [2] relies on successful channeling of a relativistic laser pulse in the plasma. Relativistic laser channeling in plasmas has been explored extensively both computationally and experimentally [3-15]. The FI scheme requires deep penetration of the relativistic laser pulse into the high density plasma region as close as to the compressed core plasma. This will minimize the distance of the generated fast electron beam transport into the core plasma. The penetration must be along the laser axis towards the core plasma so that the fast electron beam having a small divergence can efficiently heat the core plasma. Recent experiments showed that the intense laser propagation in the plasma is sensitive to the laser focus position [13-15]. It was demonstrated that the laser could propagate into the over dense plasma along its axis and the values of intense laser light transmittance through over dense plasmas varied with the laser focus position [13]. It was found that a strong x-ray emission along the laser axis at the near solid densities appeared only when an intense laser was focused at certain positions in the preformed plasmas [14, 15]. This indicated that the laser could penetrate deeper into the plasma when only focused at these certain positions. Here we studied the effect of the focus position on the relativistic laser channeling in the plasma by means of PIC simulation. The results clearly show the effect of the focus position on the stability of the laser channeling in the dense plasma. On-axis propagation and deeper penetration of the laser in the plasma are demonstrated when the laser is focused at certain positions compared to other positions.
2. Simulation result and discussion

The propagation of a relativistic laser pulse in plasmas is investigated using a 2D3V particle-in-cell code (PIC) [16]. In the code, the focus spot of the laser beam can be set at an arbitrary position, e.g., the laser beam can be focused at the vacuum-plasma boundary or inside the plasma, as shown in Fig.1. The simulation box is $30\lambda_\text{p}$ long along the $x$-axis and $15\lambda_\text{p}$ wide along the $y$-axis, where $\lambda_\text{p} = 1$ µm is the laser wavelength. Inside the simulation box, a $20\lambda_\text{p}$ long plasma layer with uniform density $2n_\text{i}$ ($n_\text{i}$ is the plasma critical density) is located at the middle, connecting to two $5\lambda_\text{p}$ long vacuum regions on the right and left side, respectively. The simulation grid is $900 \times 450$ in size, with 40 particles per cell. The time step considered is $0.052T_\text{i}$, where $T_\text{i} \approx 3.3$ fs is the laser period. Both of the initial electron and ion temperatures are assumed to be 1 keV, and the electron-ion mass ratio and charge ratio are 1/1836 and $Z = -1$, respectively. A linearly polarized spatially Gaussian laser beam is incident from the left vacuum region into the plasma layer. The normalized laser strength is $a_0 = 10$, the laser pulse width is $20\lambda_\text{p}$ (66.6fs at FWHM) and the focus spot radius is $b_\text{e} = 2\lambda_\text{p}$.

Fig.1. A schematic view of the 2D3V particle-in-cell simulation model. A tightly focused linearly polarized Gaussian laser beam is incident from the left vacuum region to interact with a plasma layer with uniform density $2n_\text{i}$. (a) The laser focus point is set at $x = 5\lambda_\text{p}$, which is the vacuum-plasma interface. (b) The laser focus point is moved inside the plasma layer at $x = 20\lambda_\text{p}$, by moving the focusing lens towards plasma layer.

Fig.2. (a-c) show the ion density distributions at times $t/T_\text{i} = 10, 20, \text{ and } 30$, respectively. The laser focus point is set at the vacuum-plasma interface $x = 5\lambda_\text{p}$.

We first set the incident laser focus position at $x = 5\lambda_\text{p}$, i.e., at the vacuum-plasma interface on the left side. Figure 1a shows the configuration with Gaussian laser beam curvature representing the spot radius of size $b_\text{e}$ at the vacuum-plasma interface. The solid curve represents the laser beam curvature towards the vacuum side and dashed curve inside the plasma. Due to nonlinear laser plasma interaction processes, such as self-focusing, the actual laser beam radius inside the plasma is
somewhat different than depicted by the dashed curve. Since the laser beam is tightly focused, we have at the vacuum-plasma boundary $b_0 = b_n$.

Figure 2a-c show the ion density profiles (normalized by the initial plasma density $n_0 = 2n_e$) at $t/T_w = 10$, 20 and 30, respectively. With the laser beam focused at the vacuum-plasma boundary, the laser intensity at that position is as high as $I = 1.38 \times 10^{20}$ Wcm$^{-2}$. The light pressure punches a $\Delta$-shape crater into the plasma layer, as shown by the plots for $t/T_w = 10$ in Fig.2. Meanwhile, filamentation instability develops and a number of fine filaments appear in the crater region. Later, as the intense laser propagates into the plasma layer, the laser ponderomotive force pushes away the plasma electrons and creates an electrostatic field of charge separation which in turn drags the ions as well, leading to the formation of plasma channels. The process of laser propagation in the plasma is accompanied by the decay of strong laser field. As the laser intensity decreases to a certain extent, the laser propagation finally stops. The filamentation instability quickly develop as the laser propagates in the plasma. This results in the formation of several plasma channels, as clearly shown in Fig.2c. The direction of laser propagation becomes somewhat tilted with respect to the $x$-axis. This tilt changes with time and its direction varies statistically from shot to shot, which is undesirable in FI.

We changed the laser focus position from the vacuum-plasma interface $x = 5\lambda_0$ to $x = 20\lambda_0$, which is inside the plasma layer. This can be realized in an experiment via moving the laser focusing lens back or forth to adjust the laser focus position [13]. Figure 1b shows the laser focus configuration, in which the laser parameters and plasma layer are the same as given in Fig.1a, except the laser focus position changing to $x = 20\lambda_0$. Thus, we have $b_0 > b_n$, and a larger spot size or lower laser intensity at the vacuum-plasma boundary.

![Figure 1b](image1.png)

Fig.3. (a-c) show the ion density distributions at times $t/T_w = 10$, 20, and 30, respectively. The laser focus point is set inside the plasma layer at $x = 20\lambda_0$.

Figure 3a-c show the ion density profiles (normalized by the initial plasma density $n_0 = 2n_e$) at $t/T_w = 10$, 20 and 30, respectively. At the vacuum-plasma boundary $x = 5\lambda_0$, the incident laser intensity is now reduced to $I = 1.13 \times 10^{19}$ Wcm$^{-2}$ In this case, the incident light can still punch a $\Delta$-shape crater into the dense plasma, as shown in Fig.3a, but the growth rate of the filamentation instability is greatly suppressed due to the significantly reduced laser intensity. In particular, the fine filaments that appeared in Fig.2a do not emerge here. As the laser propagates into the plasma the laser power start decreasing, but due to the combined effect of lens focusing and self-focusing in the plasma it leads to a decreasing laser spot size, which to some extent can prevent the laser intensity from quick decay. As a result, the laser can propagate to a longer distance in the plasma. This is good for FI since the FI scheme requires that the relativistic laser propagate into the dense plasma as deep as possible for the efficient heating of the compressed core plasma. One can also see that the filamentation instability are confined to a lower level and their growth is inhibited, reflected by the profile of ion density shown in Fig.3c, where only one single plasma channel is formed, which is contrary to the case when the laser was focused at the vacuum-plasma boundary. Importantly, Fig.3 shows that the
direction of laser propagation and plasma channel is maintained along the straight path without any tilt, much different from the case in which the laser was focused at the vacuum-plasma boundary. This stable and on-axis behavior of laser propagation in the plasma is crucial to generate a highly directional fast electron beam to heat the compressed core plasma in a FI experiment. The suppression of the filamentation instability and subsequent stable and on-axis propagation might also contribute to the deeper penetration of the laser in the plasma.

Our simulation results presented here could explain the experiment data obtained in Ref. 13-15. When a relativistic laser is focused at optimum positions, the laser plasma interaction instabilities could be well suppressed and the laser can propagate stably maintaining its on-axis direction in the plasma, leading to deep penetration of the laser in the plasma. This can explain the experimental results of strong x-ray emission at near solid density regions [14, 15] and the higher value of laser light transmittance through over dense plasmas [13]. Thus, the on-axis propagation and x-ray emission evidenced experimentally during the plasma channel formation is intimately related to the focus position of the laser in the dense plasma.

Varying the relativistic laser focus position so as to find its optimum focus point for it to penetrate into the over dense plasma applies to a real integrated FI experiment. In a real integrated FI experiment, the relativistic channeling laser pulse should be injected into the coronal plasma at the time when the maximum compression of the core plasma is achieved. This means that the plasma density profile and the timing for the channeling laser pulse injection will be fixed and determined by the implosion process. Varying the relativistic laser focus position does not change the laser and plasma parameters, which satisfies the requirement of the integrated FI experiment.

3. Conclusion
In summary, we have investigated relativistic laser channeling in the dense plasma using 2D PIC simulations. The results show that the relativistic laser pulse propagation in the dense plasma is closely related to the laser focus position and the laser could create a stable and on-axis plasma channel when focused at certain positions, which is desirable in FI application.

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