High Intensity Laser Propagation through Overdense Plasmas

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High intensity laser propagation in plasmas is one of the key issues in fast ignition scheme of laser fusion energy. We have investigated experimentally and computationally the laser propagation in dense plasmas. The experiment demonstrates plasma channel formation and indicates laser propagation through overdense plasmas with relativistic self-focusing. The channel direction coincides with the laser axis. Two and three-dimensional particle-in-cell simulation reproduces the plasma channel and reveals that the laser propagation is dependent on the laser focus position in plasmas.

Key Words: Inertial fusion energy, Fast ignition, Laser plasma interaction, Particle acceleration, X-ray radiation

1. Introduction

The dream of energy generation by laser fusion has been pursued since the invention of the laser with continuous innovation in laser and target design. The recent invention of chirped pulse amplification has given birth to reasonably compact relativistic intensity laser systems and has opened many new frontiers such as fast ignition (FI) of laser fusion.1,2 In the FI scheme, a fuel shell is imploded by high energy, nanosecond laser beams, as in conventional fusion experiments, forming a high-density core plasma. At its maximum compression a high intensity laser is focused into the coronal plasma for rapid heating of the core plasma. This scheme requires the high intensity laser pulse to channel into the dense fuel through over dense plasmas. Relativistic laser channelling in plasmas has been explored for FI both computationally and experimentally,2-12 where different plasma density profiles, laser powers, and timings between the laser pulses for preplasma (or preformed plasma) creation and channelling have been considered. Complex nonlinear processes are involved in the relativistic laser-plasma interactions, such as laser beam breakup and propagation instabilities. Technically, the laser channelling phenomenon in an over dense plasma makes the measurement difficult. Hence, relativistic laser channelling in a dense plasma has not been yet observed. We here report relativistic laser channelling in dense plasmas. On-axis propagation of the laser in the plasma is demonstrated and we find the relativistic laser channelling in the plasma is dependent on the laser focus position.

2. Experimental setup and results

A long GXII laser pulse (λ = 0.527 μm, τFWHM = 1.3 ns with Gaussian temporal profile, Elong = 40-48 J) was focused onto a 1 μm thick CD target with 0.1 μm thick Al coating on the front surface to generate the preformed plasma. At 0.15 ns after the peak of the GXII laser, the short pulse PW laser (λ = 1.053 μm, τ = 0.6 ps, Eshort = 150-250 J) was focused into the preformed plasma from the same side as the GXII laser. The focus spot sizes of the GXII and PW lasers were about 500 and 70 μm (FWHM), respectively. The time-integrated keV x-ray images were obtained with a charge coupled device (CCD) backed x-ray pinhole camera (XPHC), placed in front of the target at 21° to the PW laser axis. The transmitted PW laser energy through the plasma was measured via the imaging system consisting of an optical diffuser placed behind the target. Figure 1 shows the experiment setup.
Time-integrated XPHC images from the preformed plasmas with and without the PW laser interactions are shown in Fig. 2 (a) and Fig. 2 (b), respectively, as indicated by the energy values of the GXII laser $E_{\text{long}}$ and the PW laser $E_{\text{short}}$. The x-ray intensity profiles along the vertical dashed red lines in the images were added at the left side of the images. The preformed plasma shown in Fig. 2 (a) had about 500 $\mu$m thick under dense region (from $0.1n_i$ to $n_i$) and about 80 $\mu$m thick over dense region with peak density of about $10n_i$ at the timing of the PW laser interaction, based on the simulation by the 1D hydrodynamic code ILESTA_1D. Here $n_i$ is the plasma critical density. The large ellipse in Fig. 2 (a) is due to the GXII laser irradiation on the target, corresponding to the preformed plasma. The most striking feature in Fig. 2 (a) is that there is an elongated region at the centre of the ellipse from where the x-ray emission is considerably weaker than in the surrounding region, as indicated in the x-ray intensity profile of Fig. 2 (a). This elongated region can be interpreted as due to the presence of a plasma channel. There was no such channel formation observed when only GXII laser irradiated the target, as shown in Fig. 2 (b). These two observations indicate the PW laser channelling in the preformed plasma.

In Fig. 2 (a), one sees that the direction of the plasma channel coincides with the PW laser axis, indicating the pointing of the PW laser channelling in the preformed plasmas is along the laser axis. The PW laser beam pointing is a crucial issue for FI. One of the necessary conditions for FI is the generation of collimated hot electron beam along the PW laser axis towards the compressed tiny core plasma for efficient heating. If the PW laser and the generated hot electrons miss the core plasma, then the electron beam cannot initiate a hot spark and thermonuclear burn propagation. The PW laser must propagate in the plasma along its axis in an integrated FI experiment.

The value of transmitted PW laser energy through the diffuser images was estimated to be 3.8%, indicating successful channelling of the PW laser pulse into the high density plasma. The PW laser focus size in vacuum was about 70 $\mu$m. Taking into account of both relativistic induced transparency and laser hole-boring for the simulated plasma density profile, we consider that the PW laser self-focused down to at least 20 $\mu$m to penetrate through the preformed plasma. This transmission together with the keV x-ray measurement shown in Fig. 2 (a) indicate the PW laser channelling through the over dense plasma along its axis with relativistic self-focusing.

### 3. Simulations and Discussions

The observed channel region shown in Fig. 2 (a) is created by the strong ponderomotive force of the PW laser pulse. This force pushes the electrons and subsequently ions out of the channel, leading to the depletion of electrons and ions in the channel region. First, although the PW laser energy is locally converted into the multi-MeV hot electrons in the channel region, the hot electrons may not be responsible to heat locally the channel wall and background plasma, but rather responsible to heat the whole plasma due to their long mean free path, consistent with the higher background x-ray level in Fig. 2 (a) than in Fig. 2 (b). Second, the GXII laser heating causes relatively weaker x-ray emission from the plasma channel region. The electrons and ions in the plasma channel are expelled into the surrounding plasma region by the PW laser and the radialy expanding plasma channel will be depleted of electrons and ions. After the PW laser passage and the plasma channel formation, the GXII laser still irradiated the whole plasma for several 100 ps. The plasma channel with depleted electrons and ions therefore has less x-ray emission than other plasma regions, leading to the contrast of x-ray intensity on the XPHC images shown as the elongated region with weaker x-ray emission.

We performed 3D Virtual Laser Plasma Laboratory PIC simulation\(^\text{(3)}\) to reproduce the channel structure in the over dense plasma. The plasma has the density profile similar to the experimental one for the shot shown in Fig. 2 (a). The channelling laser pulse has both spatial and temporal Gaussian profiles with peak power of 0.3 petawatt. Figure 3 shows the channel formation at different times. One sees that the laser pulse filaments first, as shown in Fig. 3 (a), and then the filaments coalesce into a single conic channel and the channel continuously drills through the plasma layer up to $10n_i$, as shown in Fig. 3 (b) and Fig. 3 (c).

We also performed 2D PIC simulation\(^\text{(4)}\) to examine the laser focus position effect on the intense laser propagation in the dense plasma. The simulation box is 30 $\mu$m long along the $x$-axis and 20 $\mu$m wide along the $y$-axis. Inside the simulation box, a 20 $\mu$m long plasma layer with uniform density $4n_i$ is
located at the middle, connecting to two 5 μm long vacuum regions on the right and left side, respectively. A linearly polarized spatially Gaussian laser beam is incident from the left vacuum region into the plasma layer. The laser pulse duration is 133.3 fs at FWHM. Figure 4 shows the evolution of the normalized vector potential $a$ at time $t/T = 90$, for the laser focus positions at $x=5$ μm (i.e., vacuum-plasma boundary) and $x=20$ μm (i.e., inside the plasma layer), respectively. One sees that when the laser is focused at the vacuum-plasma boundary (shown in Fig.4 (a)), the filamentation instability develops, and 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. However, when the laser focus position is inside the plasma layer the filamentation instability is greatly suppressed and the laser can propagate deeper into the plasma layer. The intense laser propagation in the dense plasma is strongly dependent on the laser focus positions.

4. Conclusion

In summary, we experimentally and computationally investigated high intensity laser propagation in dense plasmas. Our keV x-ray and laser light transmittance measurements indicates laser channelling through over dense plasmas with relativistic self-focusing. 3D PIC simulation reproduces the channel formation and 2D PIC simulation indicates that the laser channelling is strongly dependent on the laser focus position in plasmas.

References