Super-Penetration of Ultra-Intense Laser Light in Long Scale-Length Plasmas Relevant to Fast Ignitor

R. Kodama 1), K. Mima 1), K. A. Tanaka 2), Y. Kitagawa 1), H. Fujita 1), T. Norimatsu 1), H. Yoshida 1), Y. Senoku 1), T. Kawamura 1), H. Habara 1), Y. Toyama 1), M. Tampo 1), T. Miyakoshi 1), Y. Iazawa 1), T. Yamanaka 1)

1) Institute of Laser Engineering, Osaka University, Osaka, Japan
2) The Faculty of Engineering, Osaka University, Osaka, Japan

e-mail contact of main author: ryo@ile.osaka-u.ac.jp

Abstract. The scheme of fast ignition (FI) in inertial fusion energy (IFE) would have the advantage to obtain higher pellet gains with a smaller energy driver as compared with the conventional method or self-ignition scheme making a central hot spark. Ultra-intense laser interactions with long scale length plasmas are especially essential for the FI research. We have studied the interactions with long scale-length plasmas using our 50-100 TW laser systems and particle-in-cell (PIC) simulation codes. We focused on the generation and transport of high energy density particles in the interactions as well as the laser beam behavior in long scale-length plasmas. A super penetration mode of ultra-intense laser light has been observed to penetrate in the long scale plasma to the solid density surface. The penetrated laser pulse has been efficiently converted to energetic electrons and ions. These results arre hopeful for the progress of FI research in IFE.

1. Introduction

The scheme of fast ignition (FI) [1] has been proposed as a new approach to efficiently ignite high-density fusion fuel plasmas in inertial fusion energy (IFE). This concept is to inject an ultra-intense laser light to a highly compressed fuel core plasmas within the core disassembling time. The attractive points of the FI approach would be to obtain higher pellet gains with a smaller energy driver as compared with that of self-ignition scheme making a central hot spark in IFE. The progress of ultra-intense laser systems has realized the research of FI through investigating relativistic plasma interactions with 100 TW to PW peak intensities.

The efficient propagation of ultra-intense short-pulse laser light and the generation of hot electrons in long scale-length plasmas are of critical importance in the FI. Long scale-length plasmas surrounding the imploded core plasma may prevent the heating laser pulse from the efficient coupling into the high-density compressed fuel. Laser hole boring with enormous photon pressures could be one of the candidates to efficiently guide the heating pulse into the over-dense plasma [2]. The other candidate might be a utilization of self-focusing and relativistic transparence [3] of ultra-intense laser light by itself. Measurements of hot-electron generation into the target in short-pulse laser interactions with solid targets or small scale-length plasmas have been reported by using Kα method before [4]. However, no investigation has been reported yet on the hot electron and high-energy ion generation and transport toward the target inside in ultra-intense laser interactions with controlled long scale-length plasmas. This investigation is essential for the FI concept. Among the issues to be studied, we focused on the generation and transport of high-density and high energy particles in the interactions as well as the laser beam behavior in long scale-length plasmas.

2. Experimental Condition

The experiments were conduced using the 50 TW laser system (GMII) [5]and the 100 TW laser (peta watt module: PWM) line [6] coupled with the GEKKO XII laser system. 1.053-μm laser light with a pulse duration of 0.5-1 ps and energies of 20-50 J was focused onto a solid target or a preformed plasma at peak intensities of about $10^{18\text{ -}19}$ W/cm^2. A deuterated-carbon (CD) plasma was preformed on a massive metal solid target by 0.53 μm/100 ps laser light from the three beams of the GEKKO XII long pulse laser system at 750 ps before the short pulse irradiation. The laser intensity was 10^{15}W/cm^2 with a spot diameter of 500 μm. The scale-length of the preformed plasma was estimated from a hydrodynamic simulation checked experimentally with UV and XUV probing [7]. The critical density (n_c) point is located at about 100 μm from the target surface and the scale-length is about 200 μm from the n_c point to the under-dense region. The short pulse laser light was focused onto the preformed plasma at a normal incidence with an f/3.6 on-axis parabola mirror. The spot diameter of the short pulse was measured to be less than 30 μm in vacuum at the best focus position from x-ray pinhole camera images.

3. Super Penetration into Over-Dense Plasmas

Laser propagation experiments were conducted changing the focal position of the 100 TW beam along the laser axis relative to the preformed plasma. The focal position was varied from 50 μm to 1.5 mm from the original target surface. X-ray hot spots as shown in Fig 1(a) appeared on the target surface when the laser focus positions (d) were almost set at 150 μm to 230 μm from the surface corresponding to 0.5nc-0.8nc from hydrodynamic simulation results checked with other experiments [8]. No such strong hot spots were obtained at d = 50 μm -1.5 mm except the window of d=150μm - d=230 μm. This typical image shows the localization of x-ray emission along the laser axis at near solid densities and partially separated from the target surface, indicating energy deposition of laser light with a short absorption length. When the hot spot appeared on the target surface, always observed were jet-like x-ray emission induced by specularly reflected light from the high-density region as shown in Ref. 9. The jet formation will also support the laser light penetration into the high-density region close to the target surface [9]. The short pulse laser light could be self-focused in the long scale-length plasmas to reach the high-density region close to the target surface, named super-penetration. Previous our experimental results of x-ray images, x-ray laser probing and back-scattered spectra on laser self-focusing into overdense plasmas [2, 8] also support that the ultra-intense laser light has penetrated in this long scale preformed plasmas close to the solid target surface. Figure 1 (b) shows the ion density map at 1.1 ps from the 2-D PIC simulation, showing the whole beam self-

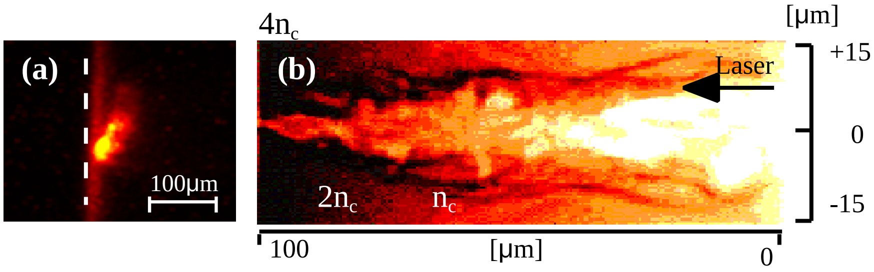


FIG. 1. (a) X-ray image and (b) ion density map from the 2-D PIC simulation indicating that the laser light has penetrated in the long scale preformed plasmas close to the solid target surface.

focusing into $2n_c$ close to the target surface at this density profile. The PIC shows that filamentation is induced by hot electrons and magnetic fields created in the underdense plasmas at the beginning. Later several filaments are combined to be one single hole as shown in Fig 1(b). Although more detailed discussions should follow to explain the difference and the mechanism of these propagation modes, clearly seen in both cases is that the laser beam can relativistically self-focus in the plasma and can propagate into the overdense plasmas. These results are fully consistent with the x-ray images indicating super-penetration of laser light into high-density regions.

4. Generation of High-Density Relativistic Electrons

At the super penetration mode, energetic electrons and their transport were measured both inside and outside the target. The energetic electron spectra were measured with an electron spectrometer. The eneregetic electron temperature with the preformed plasma was 2.5 MeV to 3.8 MeV whereas 1.8 MeV - 2.2 MeV without the preformed plasma. The interaction with the long scale-length plasma creates higher energy electrons. Beam self-focusing in the plasma can create higher energy electrons due to the increase in the local intensity of laser light. The simulation indicates that magnetic fields in the channel in underdense plasmas (acceleration at betatron resonance [6]) could also generates higher energy electrons in the laser direction with >10 MeV. Generation of eneregetic electrons toward the target inside with energies of less than a few MeV was also measured at the super-penetration mode with the Kα method. Figure 2 shows the target areal mass-density dependence of the Ag Kα yields and Kα spectra with the pre-formed plasmas. To interpret the coupling efficiency of hot electrons to the target inside from the Kα data, we used a 3-D Montecalo hot electron transport code. Even with the long scale-length plasmas, the coupling efficiency of the laser energy to the electrons in the laser direction was 25% at the super penetration mode from Kα x-ray as shown in Fig. 2 (cf. the efficiency without the preformed plasma was 40%).

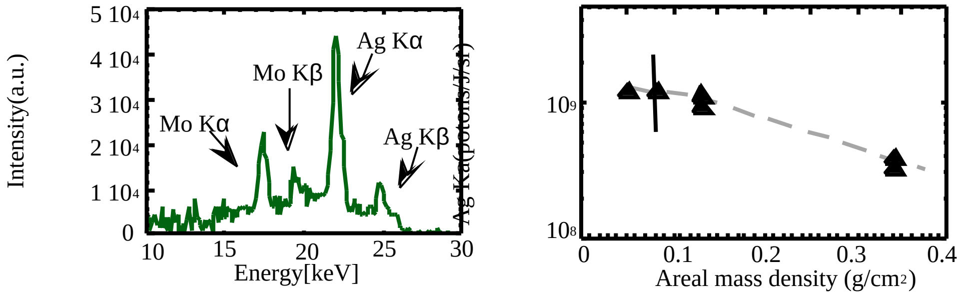
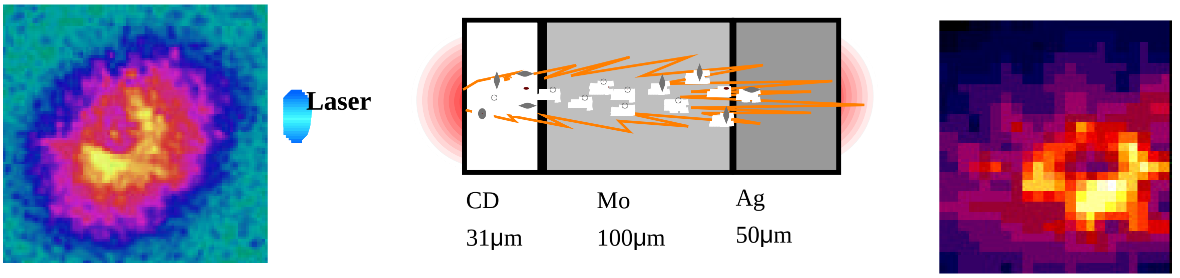


FIG. 2. Left: Ka spectra from the target rear side. Right: The Ka yields vs. target areal-mass density. The dependence indicates 2-3MeV electrons with an efficiency of about 25%.

The heating of the solid target by the energetic electrons at the super-penetration mode was also investigated by time-resolved 2-dimensional UV images [10] from the target rear. Figure 3 shows the x-ray image of the laser irradiation on the target surface at the super-penetration. At the same shot, the target-rear-side heating by energetic electrons from the target front side through the areal density of about 0.1 g/cm^2. The energetic electron heating area at the target-rear side follows well the heating area at the front side. The divergence of the hot electron beam could be 20-30deg. (FWHM) from the images. The electrons must transport through the large areal density as a beam. From the conversion efficiency of the energetic electrons, the current might be over the Alfven limit but the electron beam could propagated in the long distance. This would be due to return current in the material and/or self-generated magnetic fields from the temperature dependent conductivity. More details must be studied on the propagation of the high-density relativistic electrons in high-density plasmas.



X-ray front Image

UV target rear Image

FIG. 3. X-ray image and rear side UV image showing the relativistic electron heating of the solid targets with an aeral-densityof 0.1 g/cm2at the super penetration modes.

5. High-Energy Ion Generation

In a long scale-length plasmas, ion acceleration with ultra-intense laser light will be different from that at the interaction with solid material. The ion acceleration at the interaction regions is mainly due to the potential created by the charge displacement with the strong ponderomotive force of the light. Then, the ions would be more isotropicaly accelerated in the long scale-length plasmas because the photon pressure of the light could create a channel into overdense regions. If the laser channel penetrated into high-density regions of deuteron plasmas, the deuteron ions accelerated in the direction perpendicular to the laser propagation will interact with the surrounding high-density deuteron ions, resulting in the observation of neutrons from the DD reactions. From the neutron spectra, ion momentum distribution is estimated as shown in Fig. 4. In longer scale-length plasmas such as a 100 μm scale length, the neutron yields from the beam fusion could depend on the laser propagation. The ion acceleration in the underdense plasma must be inefficient and neutron yield will be less than the detection because of the low density of

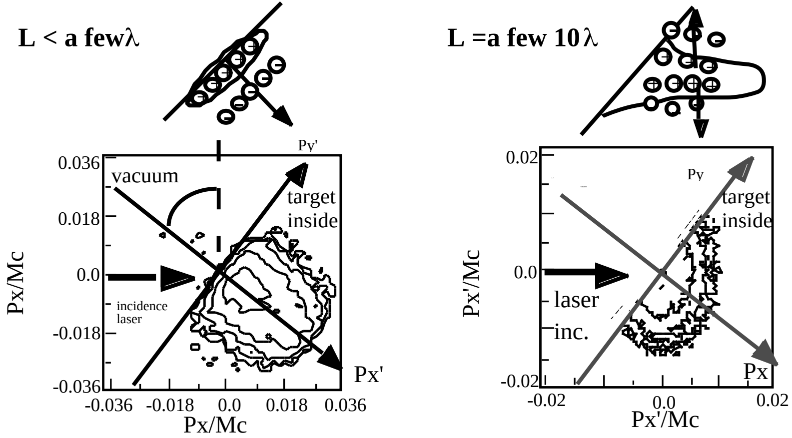


FIG. 4. Ion momentum distributions at different scale-length preformed plasmas from the energy spectra of beam fusion neutrons. Left: scale-length is less than a few μm ; Right: more than a few 10 μm.

the accelerated ions and surrounding ones. We have measured the beam fusion neutrons from implosion plasma surrounded by 100-μm scale-length plasmas. Only at the super penetration mode, we observed the beam fusion neutrons from the core plasmas, indicating the penetration of the laser light into high-density regions.

6. Summary

We have studied the ultra-intense laser plasma interactions including the high-density relativistic electron transport and high energy ion generation relevant to the FI concept in ICF. In the interactions with long scale-length plasmas, we found the propagation mode of ultra-intense short pulse laser light into over dense regions as a super penetration mode. The penetrated laser pulse has been efficiently converted to reletivistic electrons in the laser direction with a coupling efficiency of 14-25%. These electrons propagate in the target to be collimated and efficiently heat the solid target. At the super penetration mode, we also observed beam fusion neutrons from implosion plasmas, indicating the ion acceleration with the laser light at high density regions. These results on the energetic particles generation and transport with super-penetration of ultra-intense laser light in long scale-length plasmas will be promising for the progress of FI research in IFE.

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