ULTRA-INTENSE LASER PLASMA INTERACTIONS RELATED TO FAST IGNITOR IN INERTIAL CONFINEMENT FUSION

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Abstract. We experimentally studied laser-hole boring with 100 ps /1TW laser light and ultra-intense laser-plasma interactions by using a 0.5-1ps/100TW laser system. Formation of laser-channel into a overdense region was investigated in a long scale-length plasma created on a plane target by measurements of back-scatter light spectra, x-ray image and electron density profiles in under and overdense regions. Taking into account these experimental results, laser-hole boring was tested in implosion plasmas. We also examined generation of high energy particles as well as ultra-intense laser interactions by using 100 TW laser light and a particle-in cell code.

1. Introduction

Demonstration of high density compression up to a six-hundreds times solid density by the GEKKO XII laser at ILE Osaka[1] was a milestone in Inertial Confinement Fusion (ICF) research. The next milestone to be overcome in ICF is formation of a hot spark required to ignite the thermonuclear chain reaction. One of the methods for it is self-generation of the hot spark with an appropriate size at the center of the compressed plasma using a uniform laser irradiation. Another approach to make the hot spark is external heating of the isocoric high density plasma with an ultra-intense short pulse laser, which is called "Fast Ignitor (FI)" [2, 3]. The FI approach will be more attractive since higher pellet gain would be expected with a smaller energy driver. Researches on this concept are now being opened by recent progress on a short pulse laser technology, which enables ultra intense laser-plasma interaction experiments at $>10^{18-21}$W/cm^2 for 1−μm laser light.

The interactions related to the FI are dominated by the enormous photon pressure and relativistic effects in the plasma, which influence the propagation and absorption of the ultra-intense laser light. In the concept, the ultra-intense short pulse laser light as a heating pulse must efficiently penetrate over the long scale-length plasmas into the high density region close to the laser-implosion core. The heating pulse energy must be efficiently absorbed at the high density region and transferred to high energy particles such as hot electrons with an energy of about 1MeV corresponding to the a particle range [3]. Then, the efficient penetration of the heating pulse into an overdense region as a key issue in the concept might require self-channeling of the short pulse and/or predrilling with a moderately long pulse. Predrilling by using an additional pulse with a moderately intense and long pulse [4] may be required for an appropriate approach from the realistic requirement for the laser system.

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From these points of view relevant to the FI concept, we experimentally studied laser-hole boring into the overdense plasma with 100 ps/1TW laser light and short intense laser-plasma interactions using a 0.5 ps/100TW laser system. The channel formation was examined in a long scale-length plasma created on a plastic plane target. Taking account of the experimental results of the channel formation into overdense plasmas using plane targets, laser-hole boring into an implosion plasma was tested with a spherical plastic shell target. Interactions of relativistic short pulse laser light with inhomogeneous plasmas were also studied by using a 100TW / 0.5ps laser system and a particle-in cell (PIC) code to simulate the interaction with a nonuniform plasma.

2. EXPERIMENTS ON LASER-HOLE BORING

2.1. Formation of channel into overdense plasmas

Laser-hole boring experiments were performed by using a 100 ps laser pulse with a wavelength of 1.053 μm of the GEKKO XII laser system at the Institute of Laser Engineering, Osaka University. The 100 mm scale-length plasma was created on a plastic (CH) plane target with a 100 mm thickness by 0.35 μm laser light at 10^{14} W/cm^2. 1.053 μm laser light was focused normally onto the preplasma a peak intensity of 2×10^{17} W/cm^2 with a 30 mm spot diameter. Details of the experimental conditions are presented in Ref. [5]. The pulse shape of the laser light was Gaussian. The laser channel formation in the preformed plasma was measured by using four kinds of diagnostics. Electron density profiles at under densities (10^{19}-10^{20}cm^{-3}) were measured by using a UV (263 nm) interferometer system with a temporal resolution of 10 psec [6]. Properties of the laser turning point close to the critical density were monitored by measurements of a Doppler shift of the back-scattered light spectra and the second harmonic light spectra. The channel formation into the overdense region (~10^{22}cm^{-3}) was directly measured with an X-ray laser (19.6 nm) probe system. A Ne-like germanium X-ray laser [7] was used in the X-ray laser probe system and a grid image refractometry (GIR) technique [8] was applied to obtain two-dimensional density profiles in overdense regions [9]. 1-30 keV X-ray images from the front and side views of the target were obtained with X-ray pinhole cameras coupled to X-ray CCD cameras.

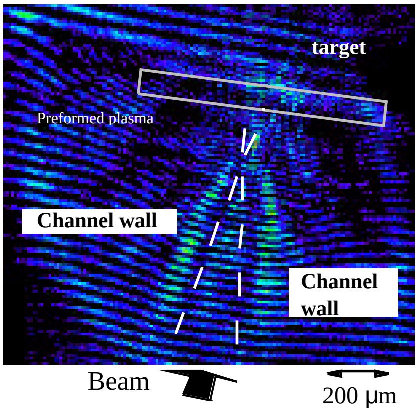

FIG. 1 A typical UV intereferometer image showing a laser channel in the underdense plasma induced by ponderomotive self-focusing. 1μm laser light at an intensity of 2x10^{17}W/cm^{2} with a pulse duration of 100 ps was focused on a 100 μm scale-length plasma. [6]

Laser channeling in underdense plasmas was clearly seen on the image of the UV interferometer as shown in Fig. 1 [6]. The dotted lines show the focused laser geometrical cone in vacuum. There is clearly a high density cylindrical cone formed along the laser focusing geometrical cone in the underdense plasma region. It is estimated from Abel inversion on the data of Fig. 1 that the density well at the center and the maximum wall electron densities are 4x10^{19} cm^{-3} and 5x10^{20} cm^{-3}, respectively at 300 μm from the target surface. The maximum electron density of 5x10^{20} cm^{-3} might have a large error up to a factor of 2, since the UV probe can supply reliable data only up to 1-2x10^{20} cm^{-3} due to the probe laser light refraction through the large scale plasma. We also changed the wavelength of the channeling beam from 1.053 μm to 0.35 μm at an intensity of 10^{17} W/cm^{2}. However, neither channel wall nor density well were observed on the UV interferometer picture for the 0.35-μm laser interaction. As given by $I\lambda^2$, where $I\lambda$ is the laser intensity and λ the wavelength of the laser light, the electron quiver motions for the different wavelength of the laser light must change the channel formation. A larger ponderomotive force is expected in the interaction of laser light with a longer wavelength, resulting in clear formation of the laser channel with the 1.053-μm laser light at a similar intensity.

Properties of the laser turning point were investigated by measurements of a Doppler shift of the back-scattered light with a time-resolved spectrometer [5]. A strong red shift (5-6 nm) from the fundamental wavelength is found on the back-scattered spectrum at the laser peak for the laser focus position of 250 μm from the target surface. We also measured scattered light spectra of the second harmonic light (0.53 μm) generated at the critical density region. The clear red shift was also observed on the second harmonic spectra, which was consistent with the red shift of the back-scattered spectra at the fundamental wavelength. These results indicate that the critical density point penetrates into the overdense region with a speed of at 7-8x10^{7} cm/s the focus condition of about 250 μm. The propagation distance of the critical surface is of the order of 100 μm, close to the distance between the initial critical and the target surfaces. The Doppler shift was evaluated from a simple snow plow model calculation (1-D) with a momentum balance between the photon pressure and mass flow at the critical surface by using a preformed plasma density profile from 1-D simulation and a 100 ps (FWHM) Gaussian profile of the laser pulse. However, a laser intensity of 2x10^{18} W/cm^{2} may be required to yield the Doppler shift as large as 5 nm to move the critical point. Whole beam might be self-focused in underdense region by a strong ponderomotive force and propagated into the overdense region with enhancement of the laser intensity in the channel.

We used X-ray laser grid image refractometry (XRL-GIR) to investigate the channel formation in the overdense region. Figure 2(a) shows a typical XRL-GIR image and (b) an electron density profile in the transverse direction to the axis of the channeling beam(2×10^{17}W/cm^{2}). The channel beam was focused on the preplasma at 210-250 μm distance from the target surface. Clear grid distortions are seen on the GIR image except for the distortion due to the plasma expansion. One kind of distortion appeared along the beam direction indicating ridges of density humps such as the plasma wall of the laser-channel. Assuming the refractive index is given by only free electrons, density well and walls are obtained at overcritical regions on the electron densityprofiles from the grid images. The channel width was less than 30 μm at 50-60 μm distance from the target surface. A width of the laser profile less than 26 μm could be required to explain the density profile from a simple estimation given by an equilibrium condition between the the ponderomotive force and thermal pressure for 1-10 keV. This result indicates laser self focusing and channeling into overdense plasmas. Another ridge of the density humps, diverging along the channel in the opposite direction to the laser beam, appeared at outer regions from the channel walls. Extrapolated lines of this ridge of the density hump cross at the target surface on the beam axis corresponding to the channel axis. These density humps may indicate a Mach cone of the shock waves created by supersonic propagation of the channel front. From a Doppler shift of the back scattered light spectra showing a front speed of 7x10^{7} cm/s, the angle of the Mach cone is estimated to be 43 deg. for a plasma temperature of 3keV. This Mach cone angle from the front speed is consistent with the experimental observation (45 deg.) [10].

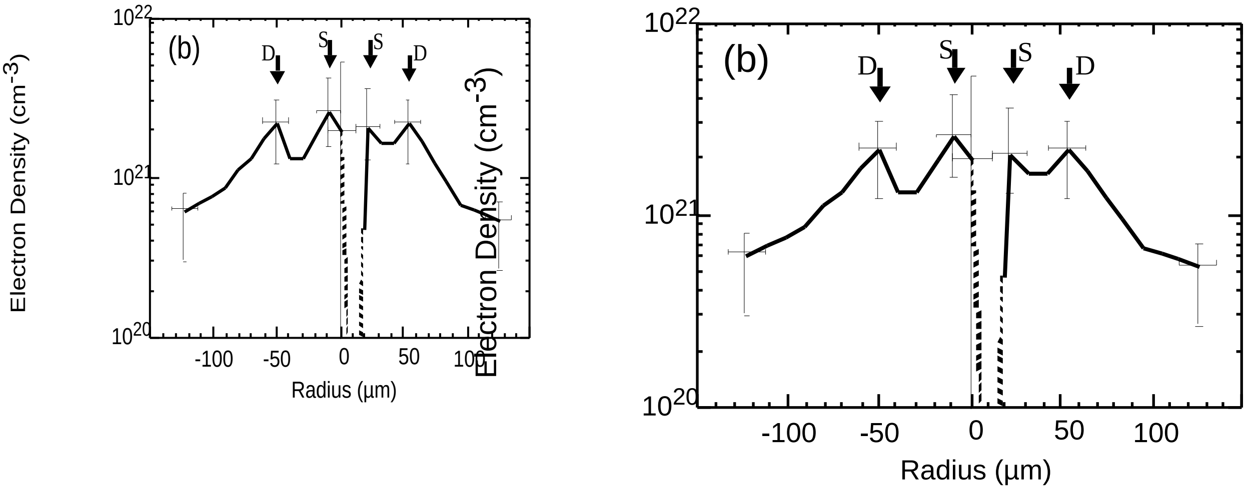

FIG. 2 (a)A typical XRL-GIR image and (b) an electron density profile in the transverse direction to the axis of the the channeling beam (2x10^{17}W/cm^{2}). The white dotted lines show two kinds of a serial density humps (channel wall and Mach cone).

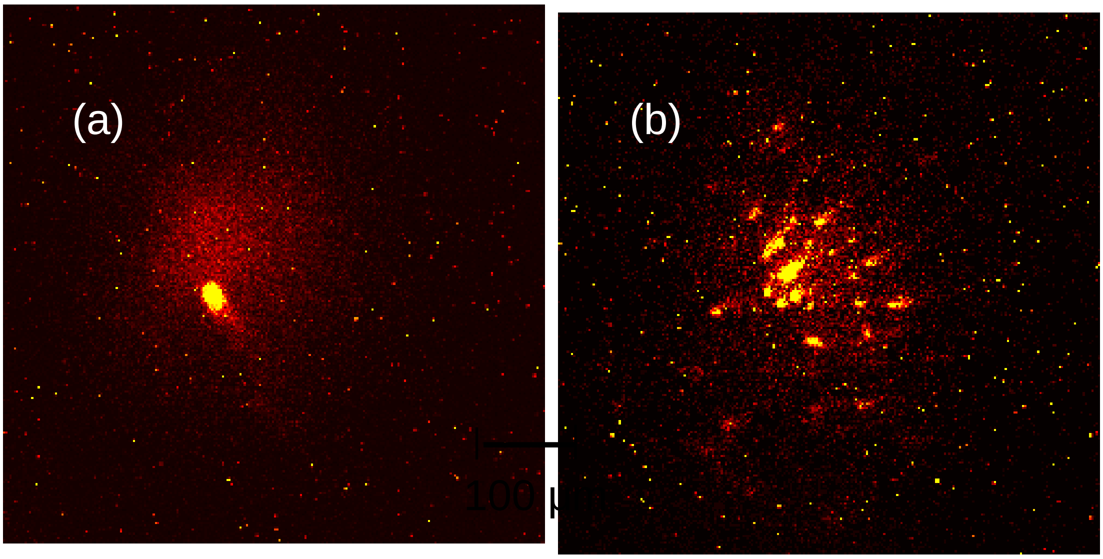

FIG. 3 X-ray images from the target front side at laser focus positions of (a)250 µm and (b)400 µm from the target surface, indicating whole beam laser self-focusing and filamentation into overdense region, respectively

X-ray images were obtained to investigate the laser energy deposition into high density regions from the target tangential and front side. Figure 3 shows X-ray images from the target front side at laser focus positions of (a)250 µm and (b)400 µm from the target surface[5]. The spot size on the target surface geometrically determined by the focus cone would be >80 µm. Weak emission with a 300 µm dia. was due to the preformed plasmas. A single strong hot spot of <30 µm φ on the target surface as shown on Fig. 3(a) was observed only when the strong red shift (5-6 nm) of the back-scattered light and the clear evidence of the channel formation on the XRL-GIR image were obtained. This result indicates whole beam self-focusing of laser light into overdense plasmas. Many hot spots as shown on Fig. 3(b) was obtained when the laser was focused at >300 µm from the target surface and modulations were observed on the back scatter spectra and on the transverse electron density profile. Many hot spots and the spectral modulation may be due to beam filamentation. No such tight hot spot was obtained at laser focus positions of 100 µm from the target surface when we observed no strong Doppler shift.

By changing laser focus positions from 100 µm to 400 µm, three different propagation modes of the laser light were cleared from the X-ray images, density profiles and Doppler shifts. All of the data presented above are consistent with each other indicating whole beam self-focusing of laser light into overdense region at an appropriate focus condition. The focus position of the laser light will affect the ponderomotive self-focusing in underdense region, which may change the intensity of the laser light in the channel and the spatial profile of the beam at the critical density. This effect in the underdense region might influence the laser propagation into overdense region.

2.2. Laser-hole boring into implosion plasmas

We have tested laser hole boring into an implosion plasma using a spherical plastic shell target. 0.53-µm laser light from 10 beams of the GEKKO XII laser system uniformly irradiated the shell target at an average intensity of $5x10^{14}$ W/cm^2. The target thickness and the radius were 5-10

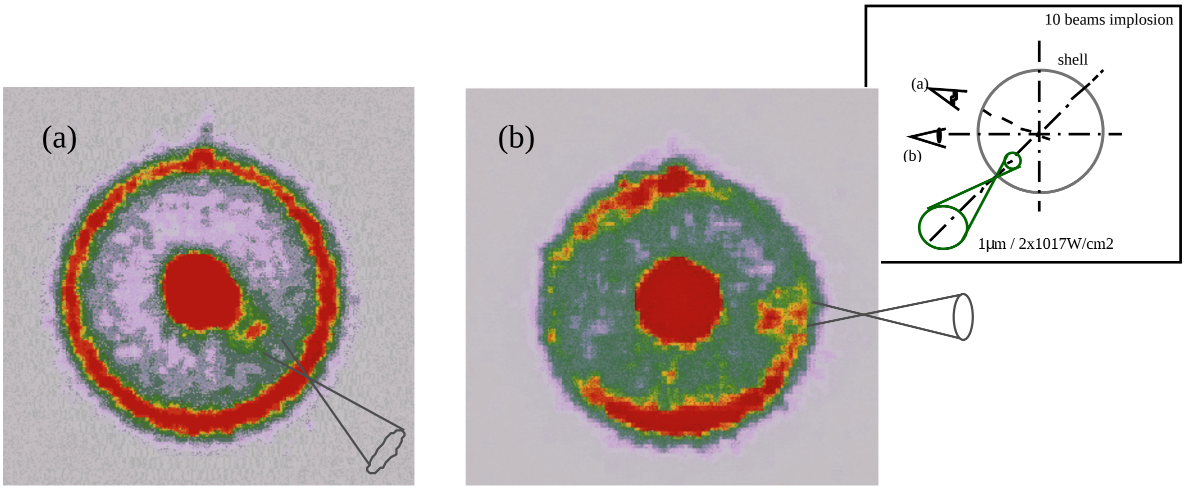

FIG. 4 X-ray images indicating laser-hole boring into the implosion plasmas from different angles. 1.053-μm laser light was focused at +100 μm far from the initial target surface at a peak intensity of 2x10^{17} W/cm^{2} when the shell was imploded at the center of the target .

μm and 250 μm, respectively. X-ray images of the implosion plasmas were monitored with two x-ray pinhole camera systems (time-integrated images) from different angles. The dynamics of the implosion was also monitored with an x-ray streak cameras. 1.053-μm laser light from one beam of the GEKKO XII laser system was focused in the underdense plasma at a peak intensity of 2x10^{17} W/cm^{2} with a pulse duration of 100 ps. The laser pulse had a double peak in time and the time separation of the each pulse was 400 ps. The focus position of the channeling beam was changed i.e., -100 μm, 0, +100μm from the initial target surface. The laser light was interacted with the long scale-length plasma when the shell was imploded at the center of the target from the implosion dynamics.

Figure 4 shows typical x-ray images when the channeling beam was focused at +100 μm far from the initial target surface. Intense hot spots are clearly seen along the axis of the channeling beam as well we the emission from the imploded core plasmas at the center of the target. The hot spot is located at the position close to the center core plasmas. The hot spot was observed on the beam axis only when the channeling beam was focused at +100 μm far from the initial target surface. The focus condition significantly influences the creation of the hot spot. Comparing with the experimental results on laser hole boring into over dense plasmas using a plane target as mentioned before, laser light might be self focused in the plasma and channeled into over dense plasmas. More details must be studied to investigate a possibility of additional heating with self-focused laser beam as well as laser hole boring into implosion plasmas.

3. ULTRA-INTENSE LASER PLASMA INTERACTIONS

Short pulse ultra-intense laser plasma interactions were investigated by using a 100 TW laser system (PWM laser) [11]. The 100 TW laser system was synchronized with the GEKKO XII laser system within a time jitter of less than 100 psec delivering an energy of 50 J with a 0.5-1 psec pulse at a 1.053-μm wavelength. The short pulse was focused with an f/3.3 on-axis aspherical mirror and the peak intensity on the target was 10$^{18-19}$ W/cm^{2}. The intensity ratio of the prepulse to the main pulse was less than 10^{-4}-10^{-5}.

Hot electron generation and transport were preliminary studied by monitoring KαX-ray emission spectra from layered metal targets. The target consists of a CH (10μm thickness), Sn (50 μm), Pd (50 μm) and Mo (20 μm) layers and the laser irradiated the plastic side. Hot electrons generated at ultra-intense laser interactions penetrate into the layered metal and emit the characteristic X-ray emission from each layer. The Kα X-ray emission spectra photon numbers were absolutely monitored with calibrated x-ray CCD cameras as single photon detectors for 15 keV-30 keV. Spatial information of the energy deposition of the hot electrons is estimated from the spectra which depended on the layer of the target. From the Kα X-ray measurements, estimated were generation of hot electrons with an energy of 700 keV+/-250 keV. More detail of the hot electron generation and transport must be experimentally studied taking into account the conductivity and the return current of the electrons in the target.

Ion acceleration in the short pulse laser interactions was studied by measurements of the neutrons via deuterium-fusion reactions in the CD target. Neutron spectra were measured by using 2 sets of the multi-channel (842ch) photo-multiplier detector systems, which were called MANDALA. The MANDALA was installed 15 m away from the target chamber. A single channel photo multiplier detector (GPU) was also set at 2 m from the target to monitor the time of flight of the neutrons. Figure 5 shows a typical time-of-flight signal showing the D-D neutron products and energy spectra from the 100 TW (50J) laser interaction with a CD target at an intensity of 10^{19} W/cm^2. 10^6 DD neutrons and the significant broadening was obtained on the spectra, indicating beam-like fusion reaction in the target with accelerated ions. More precise spectra of the neutrons was obtained with the MANDALA. Using momentum and energy conservation relations at the given observation angles, the temperature of accelerated deuteron ions is estimated to be about a few 100 keV as a Maxwell distribution. The ion acceleration could be performed by a strong electrical static field created by energetic electrons and/or explosion of ion bubbles. Another interesting point in the time-of-flight signal is a significant intensity level of g rays from the ultra-intense laser interaction plasma. A lot of energetic electrons created in the ultra-intense laser interactions could generate the intense γ rays. The production of large amount of the γ rays might be consistent with the hot electron generation (MeV electrons) measured by Kα spectroscopy.

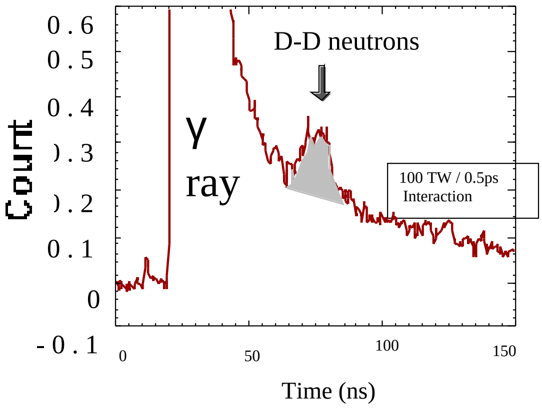

FIG. 5 A signal of the time-of-flight from a 100 TW laser interaction with a CD target , showing strong γ-ray emission, D-D fusion neutrons of 10^6 *and broadening of the spectra..*

4. Summary

We studied intense laser-plasma interactions related to the Fast Ignition concept in Inertial Confinement Fusion (ICF). Laser-hole boring as one of the important issues in the concept was investigated by using 100 ps laser light interacted with 100−μm scale plasmas at an intensity of 2×10^{17} W/cm^2. Back-scatter light spectra, x-ray image and electron density profiles in under and over dense regions were measured, indicating laser self-focusing of the laser beam into overdense region. Laser-hole boring into an implosion plasma was tested with a spherical plastic shell target taking account of these experimental results on the channel formation into overdense plasmas. We also examined ultra-intense short pulse laser interactions by using the 100TW / 0.5 psec laser system. Neutron yield of 10^6 and its spectrum were obtained from a CD target irradiated by the 100 TW laser light at intensity of about 10^{19} W/cm^2, indicating the acceleration of high energy ions with about MeV energy in the plasma. High energy electrons (MeV) was also measured by a K- α method. In the future, we will have to examine the ultra-intense laser propagation in the channel created by laser light as well as the laser propagation in implosion plasmas.

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