研究論文

Fast Ignitor Research with Use of Ultra-Intense Laser System

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Abstract

Several years ago a new concept called "fast ignition" was introduced for inertial confinement fusion (ICF). The concept proposes to use an ultra-intense (Peta watt) short (psec) laser pulse to ignite a highly compressed fuel core within the core disassembly time. Since then, Japan, England, France, Italy, Germany, Spain, Russia, Spain and USA started intensive studies on ultrahigh intensity laser plasma interactions. We report on our most recent experimental and theoretical studies on fast ignitor related research at the Institute of Laser Engineering, Osaka University.

Keywords:

fast ignition, high gain, ultra-intense laser plasma interaction

1. Introduction

Inertial confinement fusion (ICF) using a large laser facility is now about to demonstrate the ignition of the thermonuclear fusion and positive gains [1]. According to the project of "National Ignition Facility" in USA, an ignition experiment will start sometime between 2004 and 2007 and will expect a gain 15 based on their target designs. The laser output energy 1.8 MJ may irradiate a fusion pellet indirectly by converting the laser to x-ray energy producing 27 MJ fusion output per laser shot. There are two types of high density compressed cores proposed for ICF. One is called isobaric and the other is isochoric. Most laser fusion experiments have concentrated on obtaining isobaric type cores, which require a very good driver irradiation uniformity. This is because the isobaric core consists of a hot spark (high temperature) with a relatively low density in the center and a cold, high density fuel surrounding it. For the isobaric compression, it has been studied to have at least a few % laser absorption uniformity on the spherical fuel shell to achieve a finely structured compressed core. On the other hand, the isochoric type core, which may resemble the core demonstrated at ILE [2], has a rather simple core structure, namely a core with a constant density. The core density should be high enough to start the thermonuclear reaction. Once the constant density core is formed, this could be ignited from the outside within a time short enough so that the compressed core stays at a high density. This time is known as an inertial time, which is typically a few hundred pico (= 10^{-12}) seconds for a high gain type target. Mourou *et al.* invented a new

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scheme to compress the laser pulse width making use of the laser light amplified with a large spectral width, which is called chirped pulse amplification [3]. This innovative method to create an ultra-high-intense laser allows a large energy to be delivered to a plasma with a less than pico second pulse width. If a large amount of laser energy is transported to an isochoric core within a time frame much shorter than the core disassembling time and heat the fuel, then the core could be ignited to produce thermonuclear energy. An ultra-intense laser may be relativistically self focused and could possibly penetrate even in overdense plasmas. The interaction processes of the laser with plasmas will create hot electrons of the order of 1 MeV energies, which could be used for the fast ignition. Since all of these processes will be performed at a very high intensity laser field ($>10^{19}$ W/cm^2) in a plasma, the fast ignitor concept raises many new physical issues in order to check the feasibility. It is also of interest to understand these physics mechanisms since they could be applicable to efficient radiography or could be small scale experimental simulations for fields such as astronomy.

2. Possible High Gain for Fast Ignitor

Gains in ICF could be estimated for both isobaric and isochoric schemes and have been calculated in detail by many authors and numerous highly sophisticated computer codes. In principle, laser energy required for compressing the fuel to a high density is obtained with a Fermi degenerate energy which is shown as

$$E_{\mathrm{int.}} = 0.35\ \alpha\, \rho^{2/3}\, M,\ [\mathrm{MJ}], \tag{1}$$

where M is the fuel mass (g), α is the isentrope parameter, and ρ is the compressed fuel density (g/cm^3). Higher α value indicates higher preheat of the fuel. Eq. (1) indicates a minimum internal energy for given fuel density and mass. Since the isochoric core requires only a constant density, the density times radius product should be high enough to absorb high energy electrons for heating. In the fast ignitor scheme, major energy carrier for the ignition is considered to be hot electrons or ions, which could be generated at the stage of the ultra high intense laser energy deposition at close to the compressed core. If hot electrons heat the fuel to a temperature more than the ignition, the entire fuel could be ignited and burned. In the fast ignitor scheme, the required energies are the one for compression and the other for igniting fuel.

In the isobaric scheme, much higher compression energy is required to sustain the fine core structure. Namely, the hot spark central region is surrounded by the cold main fuel region. In this scheme, the compression energy is spent to create the Fermi degenerate fuel state as well as to hold a very high pressure balance created between the central hot spark core and main fuel, resulting in that required laser energy for compression is higher than the one in the isochoric case.

Figure 1 shows core gain versus core energy [4]. In ICF, the core gain is defined as the ratio of the thermonuclear energy output divided by the value in Eq. (1). In order to compress the initially solid or liquid fuel density shell to this density, typically 10% efficiency (kinetic energy exerted to create a core divided by the laser energy) can be assumed for compression by laser beams. The output energy is given by

$$E_{\mathrm{TN}} = QMf_{\mathrm{B}}\ [\mathrm{GJ}], \tag{2}$$

where Q is 334 [GJ/g], thermonuclear energy and f_{B} is the fuel burning fraction, typically 5%. The pellet gain instead of the core gain is defined as the fusion energy divided by the laser energy. Thus the value on the vertical axis is normally ten times smaller number if the pellet gain is used. The calculated result shows that very high gains are possible for the fast ignitor. The core energy 20 kJ (roughly 200 kJ laser energy) corresponds to the core gain 1,000 (roughly 100 pellet gain). In this calculation additional 13 kJ ignition energy is required for the assumed fuel ρR = 0.5 g/cm^2. The fuel

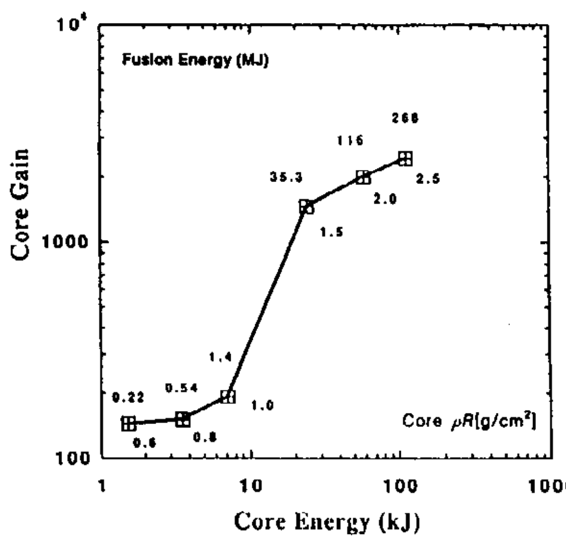

Fig. 1 The core gain vs. core energy. The spark ρR = 0.5 g/cm^2, the spark temperature 10 keV are used. The density of the core is 200 g/cm^3, the isentrope parameter is 2. The numbers below the curve represents the total ρR of the fuel and the ones above the curve represent the fusion output energy in MJ.

compressed density is 200 g/cm^3. The required energy of an ultra-intense laser for ignition needs to divide the ignition energy by the energy transport efficiency through the corona plasma to the core and the production efficiency to hot electrons from the igniting laser. This energy is delivered by an ultra short laser pulse within a very short time scale.

3. Research Issues in Relativistic Parameter Regime for Fast Ignitor

As it is shown in the previous section, the fast ignition scheme may achieve high gains if energetic particles such as hot electrons can heat the compressed core. At the processes of pellet fuel shell compression, there will be a large underdense plasma with a couple hundred micron scale length surrounding the high density compressed core. Ultra-high-intense laser with a short pulse width (less than 10 psec) has to propagate this underdense plasma without too much energy dissipation. One of the scenario is to make use of relativistic self focusing of the fast ignitor laser beam. At above 10^{18} W/cm^2, laser intensities, electrons oscillating in the laser electric field suffer relativistic mass increase, which is given by

$$m_e = \gamma\, m_{\text{still}}, \tag{3}$$

where γ is the Lorenz factor and m_{still} is the electron mass at non relativistic speeds. The refractive index in plasmas is also affected by this mass increase as,

$$n = (1-n_e/\gamma n_c)^{1/2}, \tag{4}$$

where n_e is the plasma density and n_c is the plasma critical density. Since a focused laser beam has a Gaussian focal spot, the central part of the focal spot experiences the relativistic effect most effectively and the whole laser beam is guided to the smaller central region by refraction. This is called relativistic laser light self focus. In addition an ultra-intense laser light can penetrate beyond the critical density. At the critical density the plasma frequency is equal to the laser frequency and the laser light is reflected toward the vacuum side. This relativistic effect induced transparency in overdense plasma otherwise opaque to the laser is also caused by the relativistic mass correction as

$$\omega_p{}^2 = 4\pi n_e\, e^2(\gamma m_{\text{still}})^{-1}, \tag{5}$$

where ω_p is the plasma frequency and e is the electron charge. For higher laser intensity and larger value the apparent plasma frequency becomes smaller and transparent to the laser light, since the plasma frequency can be small compared to the laser frequency at the non-relativistic critical density.

If there is appreciable energy dissipation during the relativistic self focus, it may be necessary to guide the fast ignitor pulse close enough to the core boring the long underdense plasma right before the intense pulse. We call this predrilling. Once the fast ignitor pulse energy is released at a very high density compressed plasma, the energy partition into hot electrons, energetic ions should be studied in detail. About 1 MeV hot electrons are required to heat the core to a temperature needed for the ignition for a ρR = 0.3 g/cm^2 core.

We list up the following as necessary issues to be studied.

(A) Laser beam behaviors
1. Predrilling or hole boring
2. Relativistic self focusing

(B) Heating
1. Hot electron production efficiency, spectrum, and energy transport
2. Energetic ion production efficiency, spectrum, and energy transport
3. Neutron production, spectrum and production mechanisms
4. Heating of imploded core with externally applied ultra-intense laser pulse

4. Fast Ignitor Related Experiments at Osaka

4.1 Making hole with laser light self focusing

We have started experiments related to the fast ignitor scheme, including the above list of the issues. In Fig. 2, we show an experimental set up for the predrilling (or hole boring) experiment. To test the predrilling or ponderomotive self focusing with a 100 psec pulse width laser beam at a laser intensity 10^{17} W/cm^2, a preformed plasma with a density scale length 50−100 μm is created on a massive plastic target within a diameter of 300 μm. After 1 nsec delay, the drilling laser beam with a wavelength 1 μm was focused at 250 μm from the original solid surface.

Under this condition, we have observed the drilling laser behavior from 90° direction with an x-ray laser beam (λ_L = 19.6 nm, τ_L = 80 psec). Figure 3 shows typical such shot taken as a grid image refractrometry [5]. In Fig. 3, the details of drilling channel created in both overdense and underdense plasma region is shown. The drilling laser comes from the right side, which is focused at around 200 μm from the target surface into the preformed plasma of 40 μm plasma density scale length. Arrows indicated as "S" and "D" show the ridge of plasma channels and the shock Mach

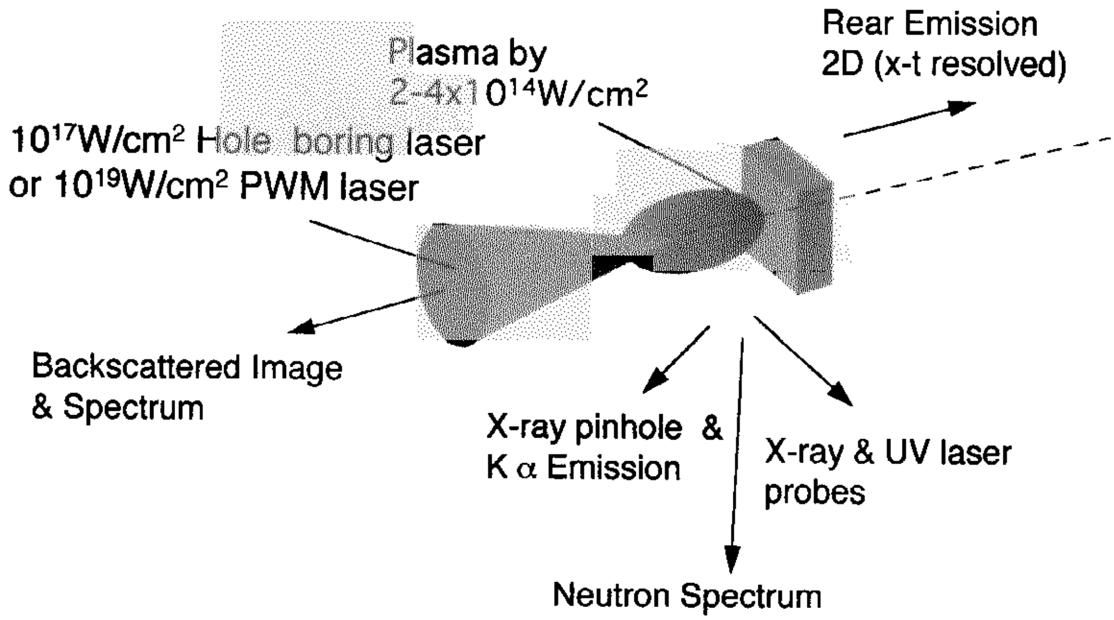

Fig. 2 Experimental set up of ultra-inetense laser plasma interactions. A plasma is created first using two or three beams of GEKKO XII laser system. The plasma typically has its cut off density at 70 μm from the original target surface when the interaction laser is injected after 1 nsec. At normal to the plasma, either 2×10^{17} W/cm^2 (100 psec pulse width) or 10^{19} W/cm^2 (1 psec pulse width) laser is injected to study the various interactions. Diagnostics are (1) x-ray laser probe, (2) ultraviolet laser probe (at 263 nm), (3) backscattered laser light imaging and spectroscopy, (4) x-ray self emission imaging, (5) neutron spectroscopy, and (6) blackbody emission measurement on the target rear side with time, space resolution.

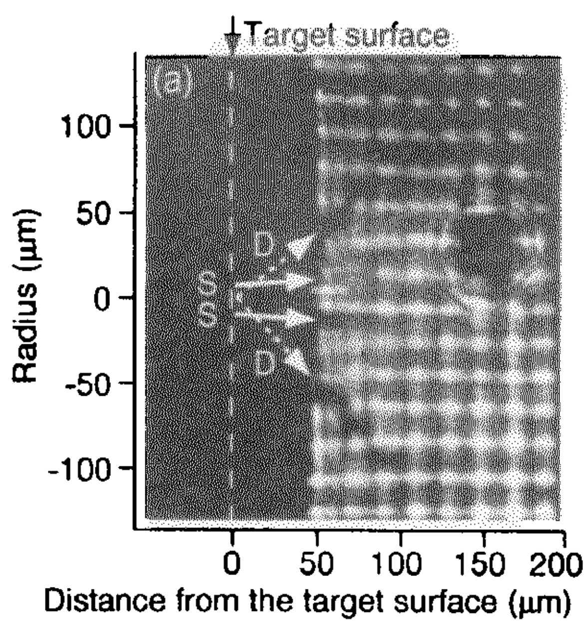

Fig. 3 X-ray laser probed image of bored hole in a plasma. X-ray laser probe is used to study the details of channeling into overdense plasmas at 19.6 nm with a 80 psec pulse width for the first time. In order to obtain the channeling informations, we used a grid image refractometry in the probe system. A fine mesh is inserted in the x-ray probe beam, resulting in that each mesh address each part of the x-ray laser beam cross section. When the x-ray laser probes through the plasma, each addressed part of the beam experiences different degree of refraction, resulting in distorted mesh image at the detection plane. After proper ray tracing undecoding, we were able to recreate the detailed shape of the hole bored by the 100 psec laser driling.

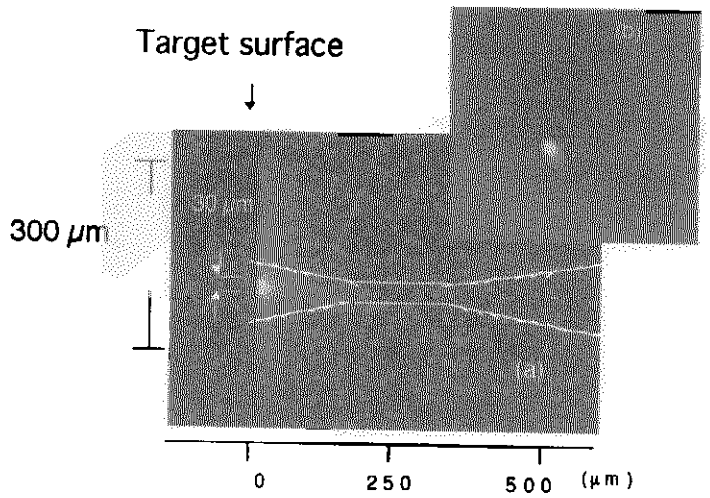

Fig. 4 X-ray self emitted image of (a) front and (b) side views for predrilling laser shot. X-ray pinhole picture shows that there is a bright small spot (30 μm dia.) appearing at the surface of the target, while the white lines indicate the focusing cone of f/3 lens used in the experiement. The emitted region is well in the overdense plasmas. Data of backscattered light spectrum shows a clear Doppler shift corresponding to the plasma receding speed 10^8 cm/sec, coming back from the self focused channel. Considering these data, the bright spot is due to the self focusing laser light actually reached almost the original target surface and heated there locally.

cones. After proper data reduction, the channel formation is confirmed to have a 30 μm channel diameter and to have propagated into overdense plasma very close to the original target surface.

These drilling has been also observed to reach actually almost to the original target surface with the side on x-ray pinhole picture. Such a shot of the x-ray picture is shown in Fig. 4, where the drilling laser beam was focused in a preformed plasma at 250 μm from the original target surface. If there is no preformed plasma the laser beam should be defocused with a 80 μm diameter focal spot on the plastic target and the x-ray emitted diameter should be 80 μm or larger, considering the laser focus F number. However the observed x-ray emission, which is obviously caused by the drilling laser beam penetrating through the preformed plasma and reaching the solid surface, shows only a 30 μm spot diameter. The backscattered light spectrum of the drilling laser pulse has been measured at the fundamental and second harmonic wavelengths [6]. The spectra showed a clear Doppler shift from the receding edge of the self focusing, indicating that the self focusing occurred at a drilling speed 10^8 cm/sec. All of these results supports that a whole beam self focus is created by the 100 psec laser pulse over a distance 100 μm well into an overdense plasma.

4.2 Energetic particle generation by ultra-intense laser

The GEKKO XII, 12 laser beam system has been added recently with a 0.1 PW (Peta = 10^{15}) laser beam. The 100 TW (= 0.1 PW) laser can deliver an energy 50 J with a 0.5 psec pulse width within a 30 μm focal spot at a 1,054 nm laser wavelength. Thus the GEKKO XII system stands as a unique facility to study the ultra intense laser plasma interactions, relativistic laser self focus, and energetic particle generation for fast ignitor, possibly with a substantial plasma created by the GEKKO XII laser beams. In order to study the ultra-intense laser plasma interactions, the 100 TW (= 0.1 PW) beam is injected into the plasma shown as Fig. 2. Focused laser intensity is 10^{19} W/cm^2. For such a shot, x-ray (> 1 keV) self emission image taken with a 250 μm pinhole camera is shown in Fig. 5. On this shot, the 100 TW laser propagated through the preformed plasma and reached close to the edge of the plasma. Then the laser was reflected specularly. A long (4 mm) jet formation is observed toward the specular direction of this laser. This type of jet formation has been seen never before for laser plasma interaction experiments using less than 10^{17} W/cm^2 laser intensities. 2D PIC code simulation indicates that the jet is due to the electron accelerated by the laser light photon pressure, which could exceed 1 Gbar at a laser intensity 10^{19} W/cm^2.

Hot electron generation is studied by monitoring the Kα x-ray emission spectrum from specially designed layered metal target irradiated by the 100 TW laser pulse at a 10^{19} W/cm^2 laser intensity. The target consists of a CH (10 μm thickness), Sn (50 μm) Pd (50 μm), and Mo (20 μm) layers and the laser irradiates from the plastic side. When hot electrons are created in ultra-intense laser plasma interactions, they penetrate into the layered target and emit the characteristic x-ray emissions. When we see Kα x-ray emission from the Pd layer, the energy range of hot electrons is 700 keV ($\pm$250 keV). We have estimated that about 6% of total laser energy is converted to ~700 keV hot electrons.

The energetic ion generation has been studied by

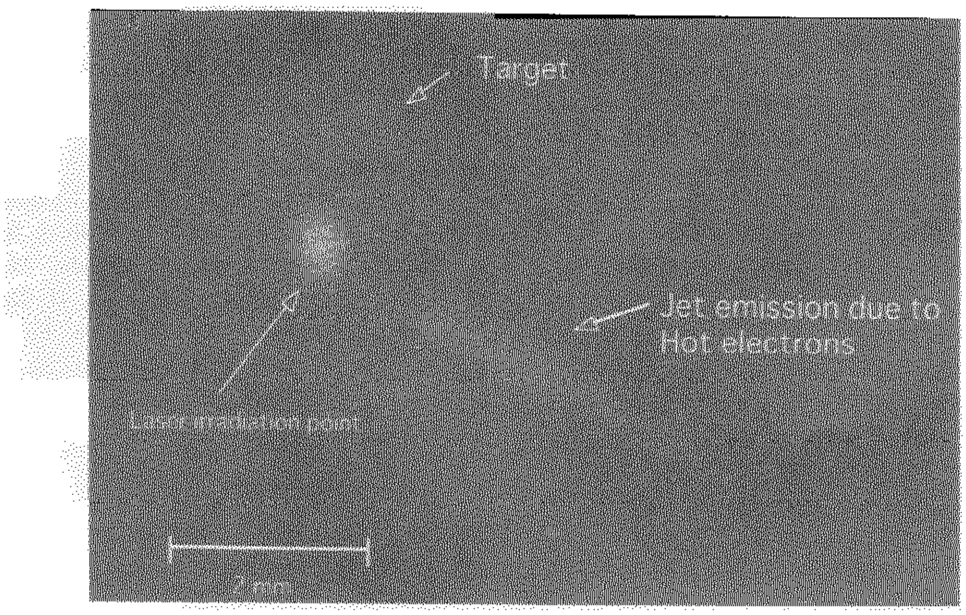

Fig. 5 X-ray self emitted image taken for 100 TW laser illumination onto plasma. The image was taken for x-ray energy above 1 keV and was viewed from the rear side of the illumnated target at an oblique angle. The laser irradiation point indicates that the zeroth order emission on the rear side of the target. The jet strucutre is seen to have about 4 mm length. It is indicated that the jet is caused by the laser photon pressure acceleration of electrons.

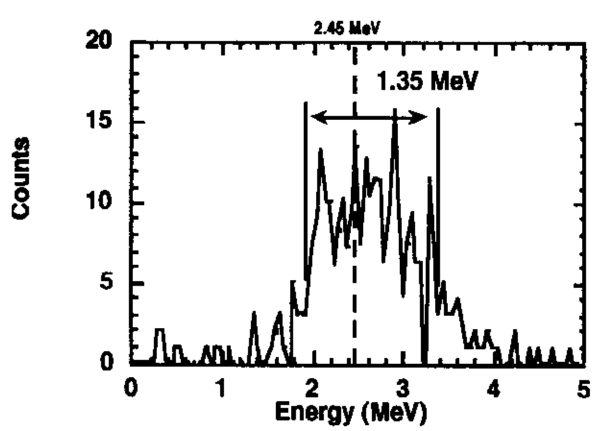

Fig. 6 Neutron spectrum observed by Mandala 421 channel scintillation counter. Two sets of Mandala were installed 15 m away from the target chamber. One looks at the target at 90 degrees normal to the laser, while the other looks at the target 55 degrees from the laser. Neutron spectrum is observed via "photon counting" mode. The spctrum reflects the history of how deuteron ions are accelerated by ultrastrong static field caused by the electron acceleration.

irradiating the 100 TW laser pulse directly on a plane target. Neutron spectrum was measured to estimate the energetic ion generations, especially deuterium ions via nuclear reactions. Two sets of 421 channel scintillation detector array "Mandala" were installed 13.5 m away from either the target vacuum chamber at 90° or at 55° to the 100 TW laser beam axis. This large number of scintillation counters are used as "photon counting" mode for neutrons. In order to measure the neutron production only from the laser irradiated spot, not from somewhere else, a 15 mm thick plastic housing was placed surrounding the target. Opening holes are only made for the laser entrance and neutron observations. The 100 TW laser beam has been focused on a CD (deuterated plastic) plane target at a laser intensity 10^{19} W/cm^2. Measured neutron spectrum is shown in Fig. 6. On the shot 10^6 DD neutrons have been observed. The observed spectral width is 1.35 MeV, which could be caused by highly accelerated deuteron ions colliding with deuterons in the target. The broadened spectrum implies that the deuteron ions are accelerated both toward and away from the detector, causing red and blue side broadening. The ion acceleration could be performed by the strong electrostatic field created by energetic electrons and/or Coulomb explosion. Using the momentum and energy conservation relations at the given observation angles, accelerated deuteron energy is estimated to be about several hundred keV.

5. Conclusion

We have shown the current research at the Institute of Laser Engineering dedicated to fast ignition. Using a 100 psec, 10^{17} W/cm^2 laser pulse, a whole beam self focusing has been demonstrated over a 100 μm distance well into an overdense plasma. The plasma column created by this self focusing could be used as a guide for a fast ignitor laser pulse to reach a high density compressed core. When our 100 TW laser pulse (E_L = 50 J, τ_L = 0.5 psec, λ_L = 1,054 nm) is focused on a CD planet target, a considerable energy shift in the neutron spectrum is observed. It is estimated that deuteron ions are accelerated up to several hundred keV. Hot electron generation is also studied with layered metal targets irradiated by the 100 TW laser pulse. 700 keV hot electrons are observed with a coupling efficiency 6%. Consequently we have shown a possible beam guiding in a dense plasma and energetic particles production for fast ignitor studies.

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