Direct Heating and Basic Experiments for Fast Ignition

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Abstract. Fast ignition study has been extensively conducted at the ILE, Osaka University. The fundamental study shows that hot electron characteristics are obtained using coherent transition radiation. Relativistic transparency has been also observed through an over-dense plasmas, which may be extended to be an attractive tool for the direct illumination of ultra-intense laser pulse to a highly compressed core. A model experimental results are also reported of direct illumination of a PW laser onto a compressed core.

1. Introduction

Fast ignition is a newly proposed scheme to separate the laser systems for implosion and heating. For implosion the requirement is that a fuel shell should be compressed with the use of long (<20 nsec) laser pulse beams to more than 1000 times the solid density. Compared to the central ignition scheme which requires forming a hot igniting spot in the center of the compressed fuel, all required is to achieve the high density for fast ignition. This relaxes the requirements such as laser irradiation uniformity and power balance: strictly required for the central ignition scheme. For enforced heating the requirement is to deliver certain amount of energy to heat the core to ignition temperature within an inertial time of the fuel assembly at the maximum density.

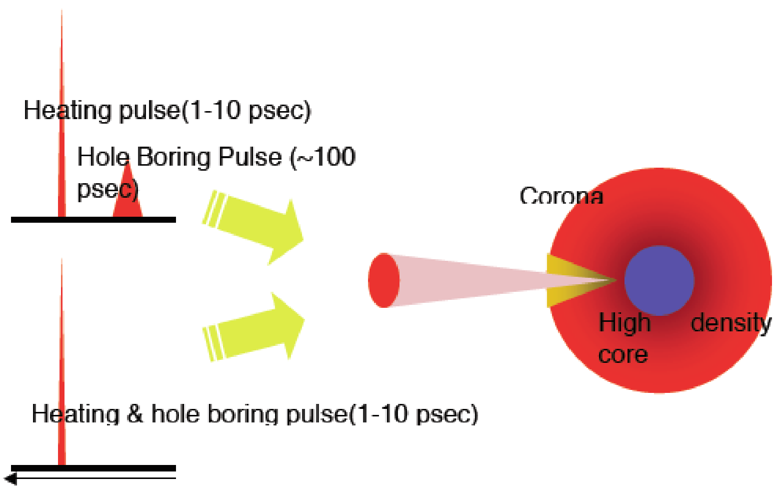

Figure 1.Modeling experiments for Fast ignition. The upper scheme with double pulses is to use the first to hole bore the corona plasma and the second to heat the high-density core. The lower scheme is to inject the heating pulse directly into the core. Both schemes may interact nonlinearly with the surrounding corona plasmas.

There are several experimental types possible for modeling fast ignition. One is to inject an ultra intense laser pulse into a plasma channel created by a preceding hole boring pulse to heat highly compressed core as shown in Fig. 1. This is to inject an ultra-intense laser pulse directly into the imploded core also shown in Fig. 1. Laser pulses in both types may interact with surrounding corona plasmas before reaching the core. The interactions may include stimulated Raman scattering [1], filametations [2], and absorptions in the corona plasma regions, all-resulting in possible energy loss.

Unique idea has been proposed to use a gold hollow cone inserted in a fuel shell under the international collaboration with the Institute of Laser Engineering, Osaka University and Rutherford Appleton Laboratory [3,4] as shown in Fig. 2.

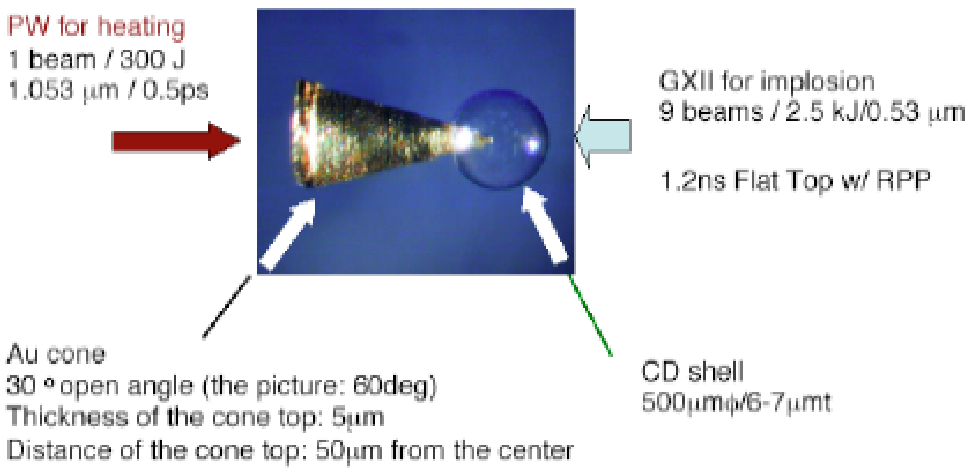

Figure 2. Au cone shell for modeling fast ignition.

The gold cone keeps the vacuum path for the heating pulse until the max compression timing. With this guide, the ultra-intense laser could avoid any nonlinear laser plasma interactions and could reach very close to the core, damping its energy at the tip of the cone. Model experiments with this idea has been proven to be promising for reaching the ignition or even higher gain.

It has been required to know the hot electron temperature and the number within the target or at the vicinity of the highly compressed core. The use of coherent transition is proposed for this purpose. In addition for the feasibility study of fast ignition it is of importance to survey the other possibilities such as the direct irradiation of ultra-intense laser pulse into a highly compressed core. For the direct irradiation it is necessary to study the characteristics of the ultra-intense laser focusing in plasmas. The TW focused laser light has been studied for the penetration into an over-dense plasmas with a peak density as high as 10 x critical density. Finally a first attempt is shown with use of the PW laser direct injection to an imploded core as a fast ignition model experiment.

2. Fundamental Experiments.

Using relatively large laser facilities at 10- 100 TW peak power, we have measured the hot electron spectral dependence on the laser intensity as shown in Fig. 3. In order to fast heat the core, hot electron of the order of 1 MeV is necessary for a density radius product of $\rho R \sim 0.3$ g/cm^2. Figure 3 shows typical hot electron spectra taken at laser intensities from 10^{18}-10^{19} W/cm^2. Figure 3 shows that hot electron can be about 1MeV at laser intensities above 10^{18} W/cm^2. The laser intensity was varied from 10^{18} to 10^{19} W/cm^2.

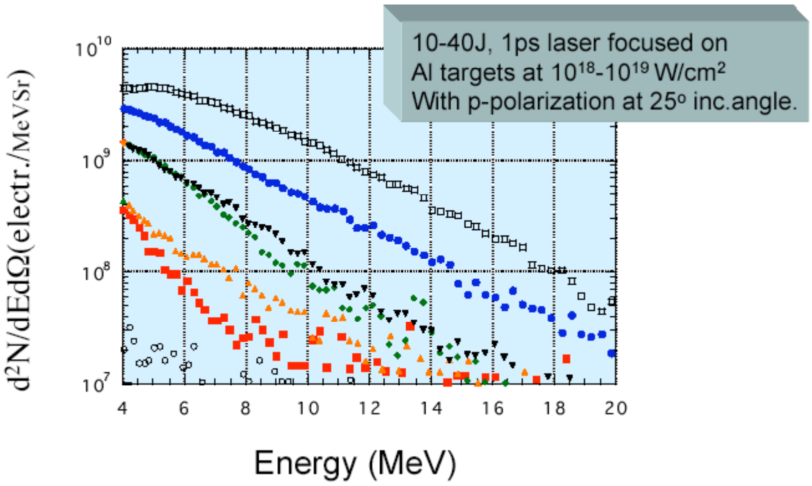

Figure 3. Hot electron temperature dependence on the laser intensity. More than 1 MeV hot electrons are readily obtained.

The hot electron energy transport was measured with a special framing camera to observe the rear of plane targets irradiated with an ultra-intense laser pulse at 10^{19} W/cm^2. [5] The hot electrons inside the target may propagate and heat the target. By looking at the rear of the target in a UV to visible region, the behaviors of the hot electrons could be recorded. The rear of Al plates (200 and 500 micron) were observed to show that the hot electrons tend to break into filaments at 15 TW while the hot electron stayed in a flux at 30 TW. The number of filaments reduces quickly at the laser intensity above 0.02 PW while the peak brightness increases rapidly at above this laser intensity. These behaviors indicate that the hot electrons may be transported not breaking into filaments at a higher laser irradiance and may be maintained in a flux to heat the core.

Coherent transition radiation was utilized to estimate the hot electron temperature inside targets. The transition radiation is known to emit when electrons pass through a clear boundary such as from a solid to a vacuum. We have made a model to estimate the hot electron temperature [6]. The coherent type transition radiation is expected to dominate in our experimental condition over the incoherent type and black body emissions. By changing the target thickness it is predicted that the intensity of the coherent emission from the rear of plane targets decreases. Then an experiment was conducted to show that the hot electron temperatures inside the target fit well with 1.3 and 5.5 MeV as shown in Fig. 4[7]. We know that the electron spectrum measured at some distance (0.5 – 1m) by a spectrometer may not reflect the spectrum inside the target since the electro-static potential and strong B field affects the electron escaping from the target. This method gives an important way to estimate the temperature inside the target.

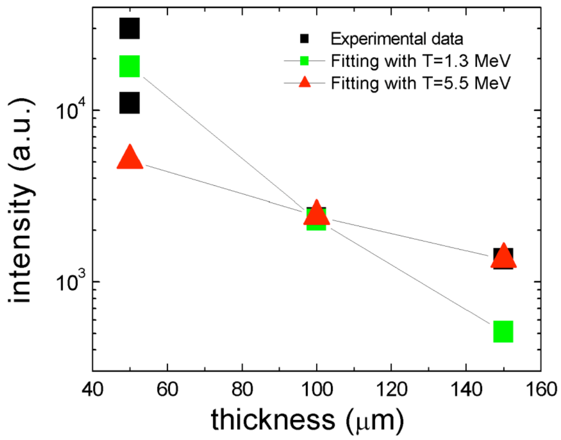

Figure 4. Coherent transition radiation is measured at the fundamental laser wavelength. As predicted in the modeling (Fig. 5), the CTR decreased the intensity for increasing the target thickness. The fitting with the model indicates that the hot electron temperatures are separated in two parts: one at 1.3 MeV and the other at 5.5 MeV.

As basic studies for fast ignition we have studied relativistic transparency of ultra-intense laser light through over-dense plasmas. Plasmas with 20-50 times critical density have been created with the overdense thickness 50 micron. Using both 20TW and PW laser systems the transmission properties have been studied. The transmission could be as high as 10 % through such a plasma. In the PW laser experiment clear evidence of super-penetration has been obtained.

3. Modeling Experiment for Fast Ignition

An idea of fast ignition is to implode a fuel shell with a number of laser beams and then to ignite the compressed core with directly injected ultra-intense laser pulse. In order to study this, we conducted an integrated model experiment with direct heating by the PW laser pulse. The implosion only yielded neutrons as high as 10^6. The net increase of neutrons due to the enforced heating is within an order of magnitude.
Fast ignition model experiment was conducted using an implosion of CD shell directly illuminated with the PW laser pulse [8]. In this case the PW laser might suffer non-linear interactions with the long density scale plasma, our initial study showed that stimulated Raman scattering is well suppressed [1].

Energy of 190 J at 1.053 μm is transported to the target with 0.6 - 0.7 ps pulse length as a fast heating pulse. The beam size is 50 cm. An off-axial parabola(OAP), 21 degree off axial and 3.8 m in focal length (F/7.6) focuses the beam at the critical point in 15μm spot radius, r_0, providing I~10^{19} Wcm^{-2} of the peak intensity I_L on target. CD shell target of 500-micron diameter was imploded with 12 beams of GEKKO system at 2.3 kJ with 1.3 nsec pulses at 531 nm. The predicted critical density point of the imploded plasma is typically 200 μm from the target center.

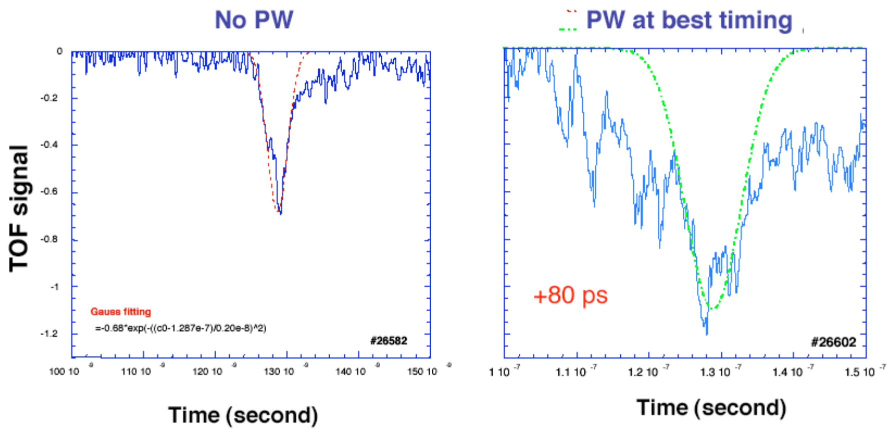

Figure 5. Neutron signal is enhanced at PW direct heating an imploded core.

D-D neutrons are detected by a fast plastic (BC-422) scintillator (NS) of 10 cm in diameter and 5 cm in length, set at 3.0 m from the target and 43 degree back to the PW laser axis. Compared to the neutron yield at the implosion only the yield increased by a factor 4 when the PW laser is injected to the imploded core plasma.

4. Summary

Ultra-intense laser plasma interactions related to fast ignition have been summarized. Hot electron temperature enough to heat a highly compressed core is experimentally confirmed. Optical coherent transition radiation has been used to estimate the hot electron characteristics inside the target. Super-penetration has been studied to inject TW to PW laser pulses into overdense plasmas to study a plasma channel formation. 10TW laser experiment indicated a 10 % transmission through the pre-plasma with 10 times critical density. Modeling experiment was conducted using both GEKKO and PW laser systems, injecting the PW laser pulse into imploded core plasma. Factor 4 enhancements of neutrons were observed.

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