Fast Ignition Experimental and Theoretical Researches toward Fast Ignition Realization Experiment (FIREX)

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Abstract. In 2000, the output energy of the peta watt module (PWM) added to Gekko XII reached a level of 100J in one pico second. In the end of 2001, it was upgraded to a peta watt laser (PW) which delivers 500J/0.8 ps. The PWM and PW laser beams were injected into CD plastic shell pellets with or without cone guide which were imploded by a few kJ / 1ns green beams of the Gekko -XII laser. In the PWM heating, D-D neutron yields are enhanced by one order of magnitude for both spherical implosion and cone guide implosion. In the case of cone-less target, the enhanced neutron yield is due to beam fusion in the edge of the dense plasma. The heating laser energy was not transported to the core plasma efficiently because of strong dumping of the intense laser pulse in coronal plasmas. In the PW heating experiments, the neutron yield increased from 10^5 to 10^7 for cone shell target. The theoretical analysis on cone shell target implosion and heating processes with PIC, hydro code, and Fokker Planck simulations indicates that the relativistic electrons generated in the cone are relatively low energy and the heat flow seems self-focused. From those experimental and theoretical results, it is concluded that the cone guide target can be used for " Fast Ignition Realization Experiment".

1. Introduction

Since 1997, experimental and theoretical studies on the high density plasma heating with ultra-intense lasers have been the main research program of the Institute of Laser Engineering, Osaka University [1]. In 2000, the output energy of the peta watt module (PWM added to Gekko XII) reached a level of 100J in one pico second. CD plastic shell pellets with or without cone guide were imploded by a few kJ / 1ns green beams of the Gekko XII laser, which were heated by the PWM laser. In the experiments, we found that D-D neutron yields are enhanced by one order of magnitude for both cone -less pellets [2] and cone guide pellets [3]. In the cone-less target, the fusion neutron energy spectrum was broad, although the neutron yield increased. This indicates that the neutron enhancement comes from the fast ion driven fusion in the edge of the core plasma. In the cone-shell target experiments, it is indicated that the core plasma is heated efficiently to high temperature[3].

Recently, the PWM laser was upgraded to peta watt level. In PW laser experiments, it is found that the neutron yield increased from 10^5 to 10^7. The neutron yield enhancement, the neutron energy spectrum, and X-ray spectrum of the core plasmas indicate that the temperature increased from 300eV to about

1keV. The experimental results were simulated with the hydrodynamic code “PINOCO”, PIC code ,and Fokker Planck code. The experimental results are well reproduced when the relativistic electron energy spectrum has two components, namely slope temperatures of 0.5MeV and 2MeV. The self-focusing of the relativistic electron heat flow is also found to be effective in the cone shell target by the PIC simulation.

Based upon the recent fast ignition researches at ILE Osaka University in particular on the cone-shell target, we proposed “Fast Ignition Realization Experiment” which will demonstrate α-particle heating of dense plasmas and ignition. In the following sections, discussed are recent experimental and simulation results on cone-less and cone guide shell target.

2. Heating of Spherical Implosion Plasmas

In the case of spherical implosion plasma heating, coupling efficiency of a PWM laser pulse to a core plasma is sensitive to focus position of the heating laser[4]. When the focus position is near the critical surface of corona plasmas, we found that the PWM laser pulse penetrates into over-dense region and the neutron yield is significantly enhanced. However, the neutron energy spectra are broad and not isotropic as shown in Fig.1 (a). The width of the spectral peak around 2.45MeV indicates that reacting ion energy is the order of 100keV. Furthermore, the neutron spectral shape depends upon the direction of the neutron spectrometer. These results can be interpreted by enhancement of fusion reaction in the critical surface. According to PIC simulations, electrons in laser channels are expelled by strong laser heating and ponderomotive force. As the result, ions in the channel expanding by Coulomb repulsion are accelerated to high energy. Since the fusion reaction enhancement by those high energy ions is significant, the thermal neutron enhancement was not observed and the effect of core plasma heating was not clear in the cone-less target. When the short pulse laser energy increases to1kJ level, the laser pulse penetrates to higher density region since nonlinear scattering may be saturated because of the strong plasma heating. It may be possible to heat the core plasma by the PW laser in cone-less target. That is the one of the main objectives of the future PW laser experiment.

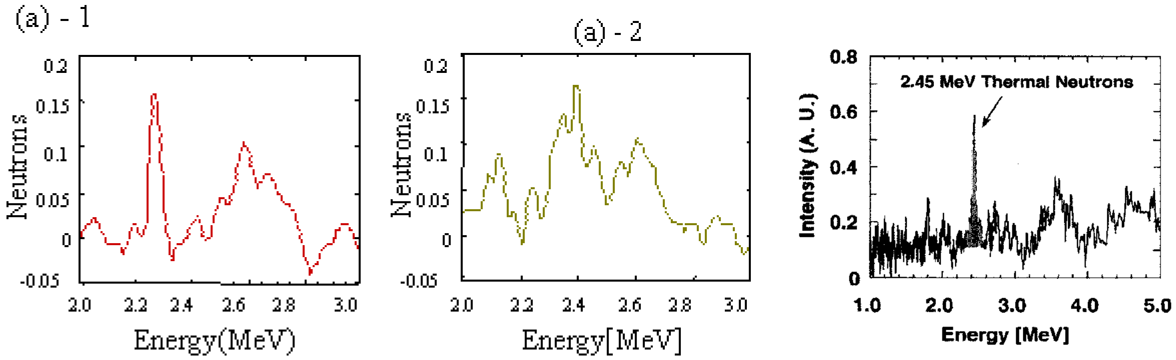


FIG.1 (a) Neutron energy spectra for direct heating of imploded CD pellet. a-1 and a-2 are the spectrum in the difference direction with respect to the incidence laser pulse.

(b) Neutron spectrum from the high density plasma heated by the cone guided short pulse laser.

3. Cone Guide Heating Experiment

On the other hand, in the cone guide target, the neutron spectral peak at 2.45MeV is narrow, as shown in Fig.1 (b). The neutron yield is the order of 10^5 with heating, which is 10 times higher than that of nonheating case. This indicates that the thermonuclear fusion is enhanced by the temperature increase of the core plasma due to the PWM laser heating. The temperature increase is estimated by the neutron yield enhancement and the observed ρ and the burning time. In the best shot, the temperature increased by 130 eV. We found from this results that 25% of input PWM laser pulse energy is transported to the core plasma.

In the peta watt laser experiment, two kinds of cone targets are imploded and heated. The cone angles are 30 and 60 degrees. The heating is more efficient in the 30 degree cone than in the 60 degree cone. When the 300J/0.6ps CPA laser pulse is injected, the neutron yield reaches 10^7 while the neutron yield was 10^5 without heating as shown in FIG2. This indicates that the core plasma temperature increased by 500eV and the energy coupling between heating laser and core plasma is 20-25%. Since the focused laser energy included in 50μm diameter is less than 40%,20-25% coupling efficiency means that actual coupling is higher than 50%. Otherwise, laser energy in the hallo of the spot is collected by the cone guide. In Fig.(2), the simple scaling curve is shown, where the temperature increase is assumed proportional to the input short pulse laser energy and the coupling efficiency is assumed same as the cone guide PWM experimental results. This indicates that the coupling efficiency for 300J case is almost same as for 80J case. This scaling law has been used for planning the fast ignition experiment (FIREX). Further analysis of the experiment has been done by the Fokker Planck simulation and the neutron yield of the simulation agrees well with the experiments. [5]

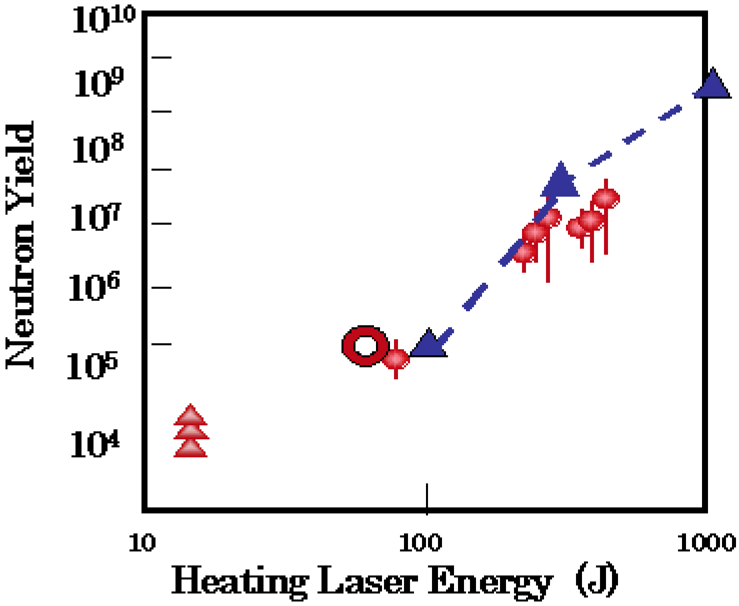


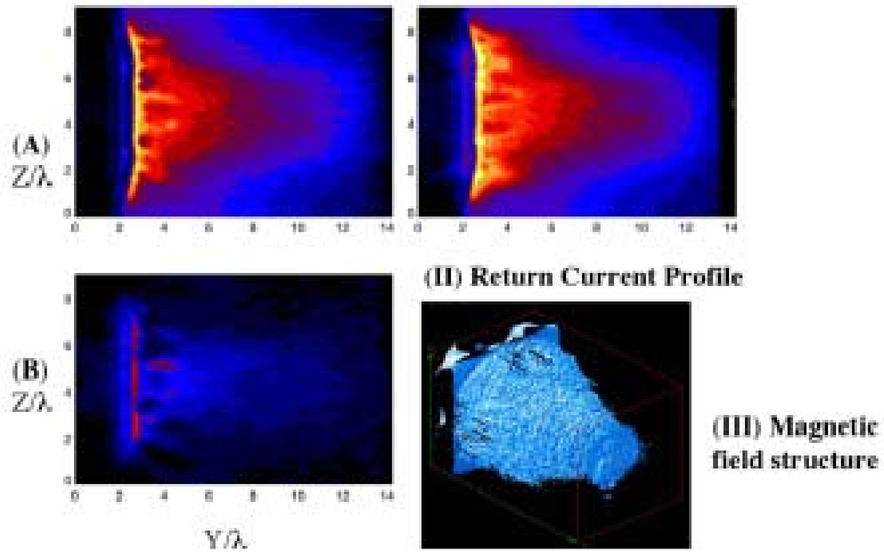
Fig. 2 Neutron yield V.S. heating laser energy in the recent experiments (solid circle), the scaling law based upon simulations and experiments (Triangle),and the direct heating experiment(double circle)

4. Simulation Studies

Recent 3D PIC simulation results show that the relativistic electron current profile in a dense plasmas is well organized and confined in a small radius as shown in the figure 3. This indicates that the localized hot spot could be generated by the relativistic electron generated by ultra-intense lasers.

In the cone target, a ultra-intense laser light is partially reflected on the cone surface wall and focused to the top of the cone while the relativistic electrons are generated on the side wall of the cone and the top wall. Since the electrons are accelerated along the laser propagation direction, strong current is driven along the cone axis and the relativistic electron flows are pinched to the top of the cone as shown in Fig.4. The guiding of the relativistic electron is due to the strong magnetic field generated by the electron acceleration along the surface of the cone. These characters of the laser interaction with cone contribute to enhance the coupling efficiency of short pulse laser to the core plasmas. However, since the PIC simulations are limited to the small scale and short time duration, it is necessary to see longer space and time scale simulation for quantitative comparison between experiment and simulation.

We also carried out Fokker Planck simulations on the cone target experiment for predicting the neutron yield. In the simulation, the relativistic electron energy spectrum was taken from the cone target PIC simulation (Fig.5), when the spectrum has two slope temperatures which are 0.5Me V and 2.0Me V. The 0.5MeV slope temperature is related to the cone side wall Brunnel absorption [6], where the laser intensity is lower than the top of the cone, since the laser is focused toward the top of the cone. The Fokker Planck simulation shows that the plasma heating and the neutron yield depend on the 0.5MeV electron heating. This softening of the electron spectrum is also one of the advantages of the cone guide target.



(II) Return Current Profile

(III) Magnetic field structure

(I) Forward current profile

FIG3. Relativistic electron current self-organization(self-pinch)
(A); the current profile of hot electron with energy lower than 1.0 MeV
(B); current profile of hot electron of the energy higher than 1 MeV

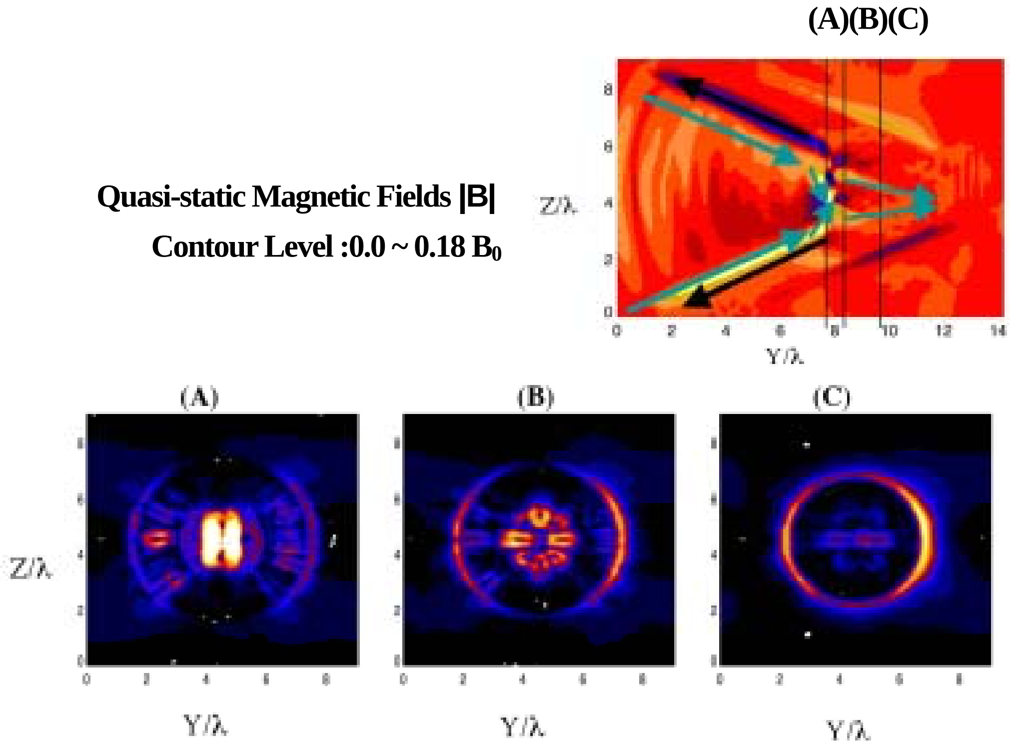
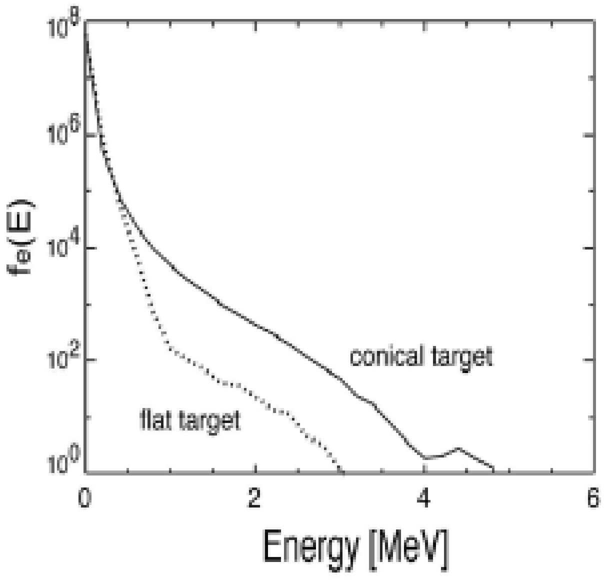


Fig. 4 Magnetic field structures in intense laser interaction with gold cone target



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5. Peta Watt Laser and Future Fast Ignition Facility

The peta watt laser was recently completed to deliver 500J / 0.5ps [2]. By the PW laser, imploded plasmas have been heated up to about 1keV. The present and future PW laser heating experiments will clarify the heating scaling law which determines the relation between heating pulse energy and hot spot temperature. If the coupling efficiency is higher than 25%, the required heating laser energy for break even experiment (Fast Ignition realization Experiment I; FIREX-I) is estimated to be 10kJ for 1500 times solid density DT plasmas and 30μm spot diameter.

Toward the ignition, the most critical parameter is the hot spot diameter which strongly depends upon the relativistic electron transport. According to the simulation and fundamental experiment results, the relativistic electron heat flow is well confined by self-generated magnetic field. From the present understanding on the heating processes, the ignition will be achieved with pulse energy less than 50kJ / 10psec for the imploded plasma ρR higher than 0.5 g / cm^2 (FIREX-II). We planned to construct the FIREX-I before 2005, and the FIREX-II before 2010.

6. Summary

1. An ultra intense laser pulse penetrates into the over-dense region and dissipates strongly to accelerate ions which produce non-thermal neutron.
2. In a cone guide target, compressed plasmas are heated efficiently to enhance thermo-nuclear reactions. The coupling efficiency of the heating laser pulse to the core plasma is found to be about 0.25 in the experiment.
3. The 0.5kJ peta watt laser has become available for fast ignition experiment to heat dense plasmas up to 1keV.
4. For the future, we propose to construct the 10kJ/10ps laser for few tens of kJ / 10ps laser and 50kJ / a few nsec implosion laser for ignition experiment..

Acknowledgement

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