Research on Imploded Plasmas Heating by Short Pulse Laser for Fast Ignition

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Abstract. Since the peta watt module (PWM) laser was constructed in 1995, investigated are heating processes of imploded plasmas by intense short pulse lasers. In order to heat the dense plasma locally, a heating laser pulse should be guided into compressed plasmas as deeply as possible. Since the last IAEA Fusion Conference, the feasibility of fast ignition has been investigated by using the short pulse GEKKO MII glass laser and the PWM laser with GEKKO XII laser. We found that relativistic electrons are generated efficiently in a preformed plasma to heat dense plasmas. The coupling efficiency of short pulse laser energy to a solid density plasma is 40% when no plasmas are pre-formed, and 20% when a large scale plasma is formed by a long pulse laser pre-irradiation. The experimental results are confirmed by numerical simulations using the simulation code “MONET” which stands for the Monte-Calro Electron Transport code developed at Osaka. In the GEKKO XII and PWM laser experiments, intense heating pulses are injected into imploded plasmas. As a result of the injection of heating pulse, it is found that high energy electrons and ions could penetrate into imploded core plasmas to enhance neutron yield by factor 3~5.

1. Introduction

The concept of fast ignition (FI) [1], [2], is to inject an intense short laser pulse into a compressed plasma to heat imploded high density plasmas within core disassembling time. The first step of the fast ignition is the guiding of a short laser pulse to the neighbor of a compressed high density plasma. Then, should be investigated the heating and the ignition processes by relativistic electrons and/or high energy ions generated by intense laser pulses. Recently, by using 10TW~1000TW CPA lasers, relativistic laser plasma interactions, high energy electron generation and transport and high energy ion generation have been widely studied in many laboratories, for examples Rutherford Appleton Laboratory [3], LULI of Ecole polytechnique [4] LLNL [5] and ILE, Osaka University [6].

Since the IAEA Fusion Energy Conference of 1998, the main progresses of the research at ILE, Osaka University are on the energy transport of relativistic electrons and the heating of imploded dense plasmas. As for the relativistic electron transport, LULI and LLNL have found in ultra intense short pulse experiments that an electron stream breaks into many filaments[4] or an annular ring[5]. They were measured by the shadow graph and the X-ray camera. By the PIC simulations of MPQ of Germany and Osaka University it is found that relativistic electron emission breaks up into filaments in dense plasmas. On the other hand, the Paris code[7] developed at LULI, France and the Davis code[8] developed at Imperial College, U.K. have been used to analyze the global behavior of the relativistic electron stream in a cold solid target. They show that the intense electron stream is well confined in a relatively narrow channel by self-generated magnetic fields. The transfer efficiency of the relativistic electrons between laser absorption and solid target interior has been investigated in experiments by making use of $K\alpha$ emission. Those experimental results have been analyzed by the PIC simulation coupled with the Monte-Calro transport code; the MONET code. In the simulations, we found that the coupling efficiency is reduced from 40% to 20 % when a large scale plasma is pre-formed on the solid target surface. We also worked on heating imploded core plasma by short pulse laser. Our PWM laser has been operated in synchronize with the GEKKO XII glass laser. Recently, we studied fast ignition by three types of heating experiments. One of them is the injection of 100psec double pulse into an imploded plasma. Second one is the heating experiments with a picosecond pulse of the PWM laser. The last experiment was a recent collaboration experiments with the Rutherford Appleton group. In this experiment, a heavy metal cone guides a short pulse laser into an imploded dense plasma. In this paper, we show the results of the first and second experiments mainly. The cone target experimental results will be published elsewhere soon.

2. Experimental Facilities

Experiments were conducted using the 100TW laser [peta watt module; PWM] coupled with the GEKKO XII laser system. The PWM laser can deliver a 50~100J with 0.5~1ps pulse width at a 1μm laser wavelength. Twenty percent of the ultra-short pulse energy can be focused to a spot size of 20μm full width at half-maximum (FWHM) using an F/3.5 on-axis parabola mirror at a vacuum intensity of 10^{19}W/cm^2. Preformed plasmas (including imploded plasmas) were created by focusing 100ps~1ns pulses of the GEKKO XII at the wavelength of 0.53μm. In the implosion experiments, the GEKKO XII delivered energy of 1~2kJ with 12 random phase plate (RPP) or partially coherent laser (PCL) beams. Since beginning of this year, we started to upgrade the PWM laser to a petawatt laser. The peta watt laser will be completed before the middle of 2001. The laser will deliver more than 500J in imploded plasmas by that time.

3. Ultra-Intense Laser Behaviors in Preformed Plasmas.

In the planer target experiments, the =1.053μm PWM laser was synchronized with the GEKKO XII laser system within a time jitter of less than 100ps. Thus some of the GEKKO XII laser beams could be used to create coronal plasmas before the PWM laser shot. A relativistic self-focusing experiment has been conducted by changing the focal position of the 100TW beam along the laser axis relative to the preproduced plasma. The focal position vary from 100 to 600μm from the original target surface. The X-ray side-on pictures of those shots are shown in Fig. 1 (a) and 1 (c). There is a large diameter emissions on the target surface, which comes from the preproduced plasma created by GEKKO XII laser beams. In *Fig. 1(b)*, a localized bright X-ray emission of less than 30μm diameter overlapped on the pre-formed plasma X-ray emission. The locally emitted X-ray spot in *Fig. 1(b)* indicates that the ultra-intense laser light has penetrated deeply into the overdense plasmas all the way, close to the solid surface. The Fig. 1(b) also suggests that the relativistic electron beam has a small beam divergence angle to heat a small solid target surface.

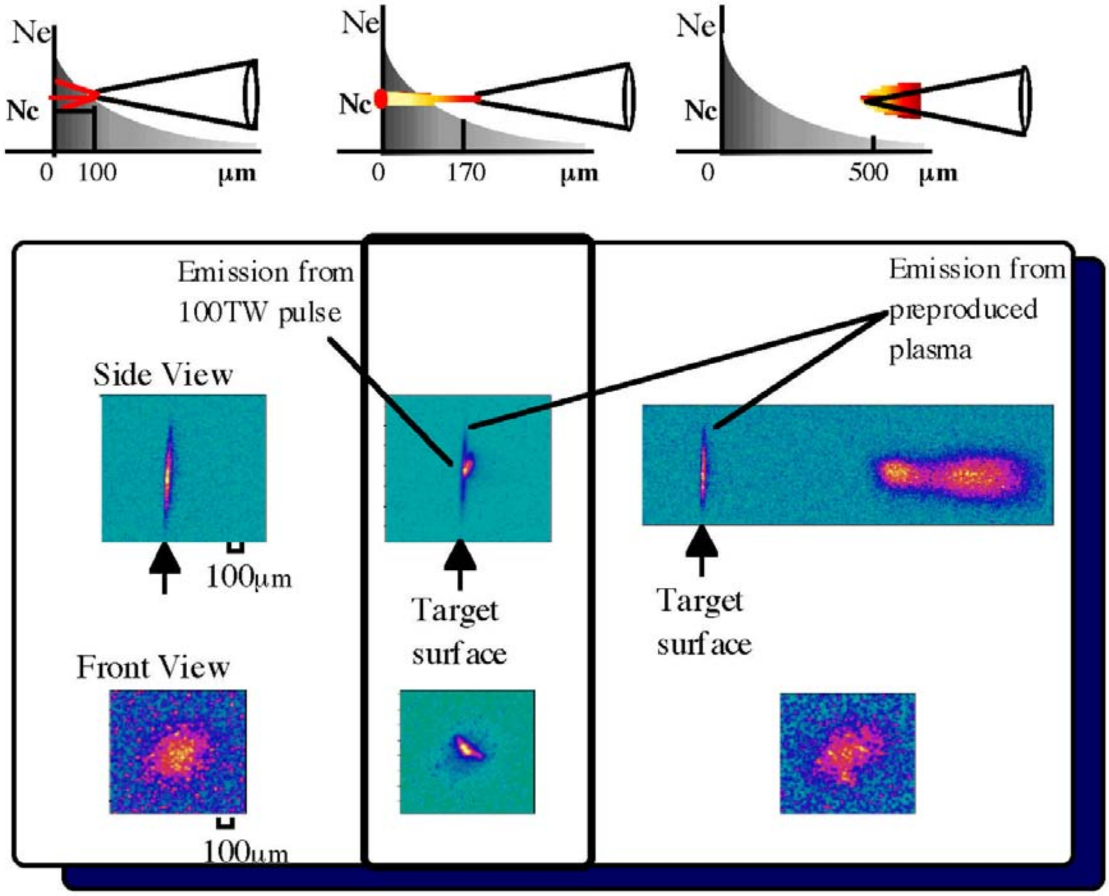

Fig.1 X-ray images indicating that a 100TW pulse penetrates into large scale plasma over 100μm

As for the solid target heating by the short pulse laser, we irradiate a thick CD_2 target with a 20J/0.5psec short laser pulse. In the experiments, the CD_2 target was overcoated with a 10μm Al layer. As shown in *Fig. 2*, the observed neutron spectrum has a narrow peak at 2.45MeV. Since the laser is absorbed on the Al surface, high energy ions were not generated by the radiation pressure of the short laser pulse. Instead, the neutrons are generated in the solid density CD plasma heated by an intense relativistic electron stream. The neutron yield reaches 4×10^4 which means the solid CD_2 target is heated up to 400eV. The narrow neutron energy spectrum indicates that only thermonuclear reactions are relevant to the observed neutron signal. The evidence of the local heating was also obtained in the UV emission on the rear side Al layer. The details of the analysis of the UV emission and the Kα emission experiments are presented in the other paper of this conference. As the result, the yields of Kα indicate the transfer efficiency and the energy spectrum of high energy electron. The suggested temperature is about 1MeV both for with and without pre-formed plasma and the transferred energy is about 20% of incident laser energy with preformed plasma and 40% without preformed plasma.

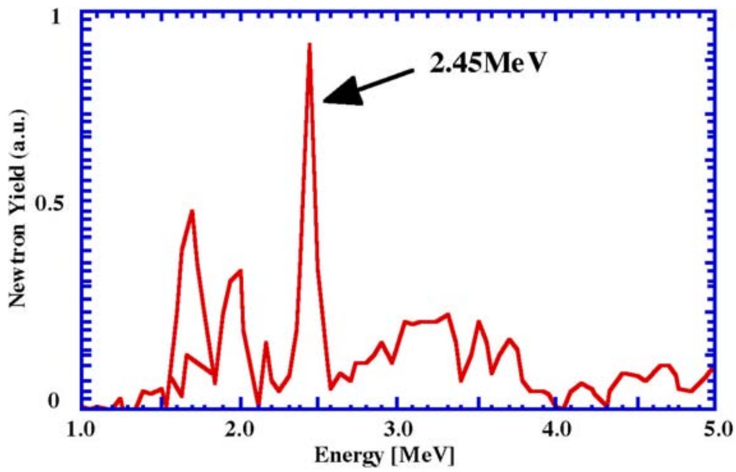

Fig. 2 Neutron energy spectrum from a solid CD_2 target irradiated by 20J/1psec laser pulse.

4. PIC Simulations on Electron Transport

The electron currents generated near the vacuum plasma interface exceed the Alfvén critical current which should produce intense self-consistent B fields bending the electron trajectories backwards and prevending their penetration into the overdense plasma. While a dense plasma tends to shield itself from injected electro magnetic fields and the high energy electron current is neutralized by a cold electron return current. This allows the high energy electrons to propagate into the overdense plasmas. However, the system is unstable to a relativistic electro-magnetic two stream instability (the so called Weibel instability) which breaks up the fast elctron current into filaments.

In this section, we extend the previous works to the three dimensional case with the help of 3D particle simulation. *Figure.3* shows the build-up of the coalescent filament or channels, penetrating stably into the overdense plasma at t=28 laser periods (approximately 100psec). *Figire 3(a)* is the iso-surface <lBl>=24MG. Frames(b) and (c) are transverse cuts of the forward and backward electron flows at 6μm from the target surface. In the channel, as shown in *Fig. 3(d)*, at 40 laser periods, 20% of ions are evacuated from the channels by the electro-stalic fields

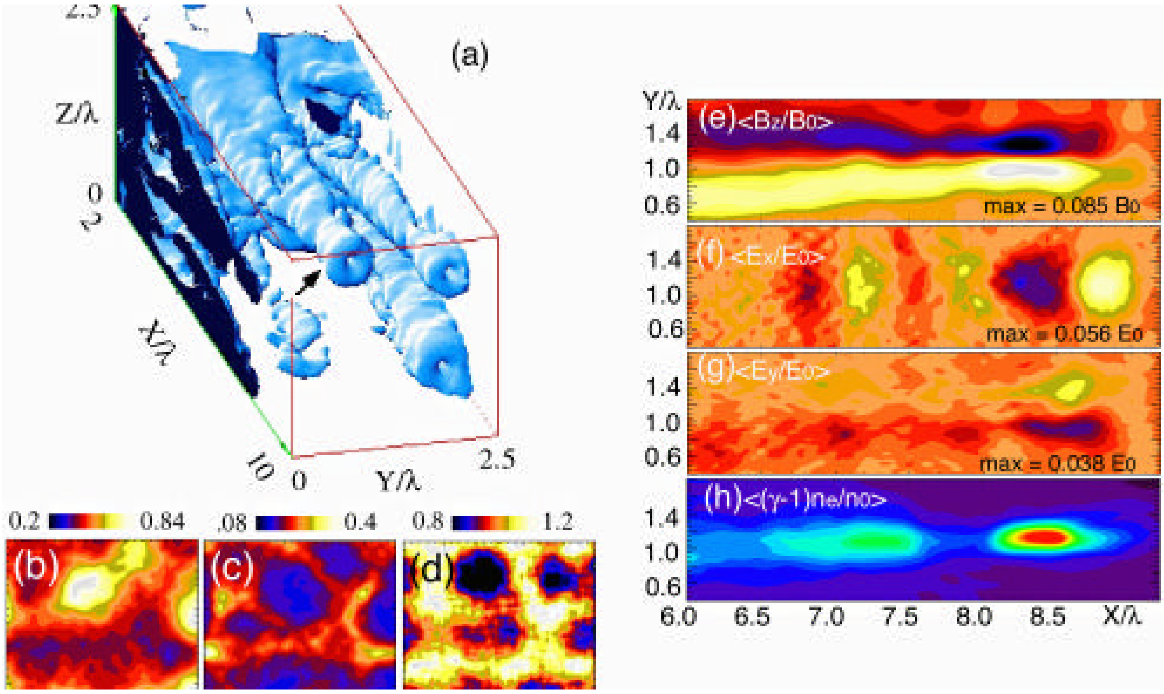

Fig. 3 (a) I Structure of magnetic channels; iso-surfaces for B=24MG are shown ,(b), (c) and (d) forward and backward electron energy density and ion density distribution respectively. (e) longitudinal cross section of profiles of magnetic field, (f) i longitudinal E-field (g) I transverse E-field, and (h) electron energy density.

Figure 3(e),(f),(g) and (h) display the longitudinal cuts at the center of a magnetic channel for B−field and electron energy density. Those figures show that the intense relativistic electron stream breaks up into many electron filaments which marge into lager scale filaments and penetrate with a velocity of 0.4c. In long time simulations, we found that three channels observed in Fig. 3(a) are merged into one after 160fs. In this final stage, the simulation system is occupied by one filament which extends to 2.5μm×2.5 μm in transverse dimension. This large sclae filament may corresponds to the UV pattern on a rear side surface of a laser head target. In summary for the PIC simulation on the electron transport, the relativistic electron energy is carried into overdense plasmas through electron filaments guided by magnetic field channels which prevent divergence of electron flux.

5. Imploded Plasma Heated by Intense Short Pulse Laser

In order to study the short pulse laser heating of imploded plasma, we irradiate a 50~100J/1psec PWM laser pulse on an imploded CD shell target. The evidences of significant heating were observed. *Figure.4* shows (a) the X-ray pinhole images and (b) X-ray streak image of X-ray emission from PWM laser heated plasmas. In these experiments, we found than an intense short pulse laser heats both coronal plasma and core plasma. The neutrons are generated both by high energy ion interaction with core plasmas and heating high density imploded plasma. When a heating pulse was not injected, the neutron yield was less than 10^4. On the other hand, the neutron yields with heating were higher than 10^5. In *Fig. 5*, we show backward reflectivity depending on the focus position relatively to the critical surface and neutron energy spectra for two cases. It is found that when the focus position is far from the critical surface by 60μm ~100μm, neutron yield is enhanced. Although the detail analysis has not been done sufficiently, the neutron yield cold be related to the backscattering reflectivity. As shown in *Fig. 5(b)*, thermal neutrons near the 2.45 MeV energy and non-thermal neutron separated from the 2.45 MeV region are observed. This indicated that high energy deuterium ions generated near the critical surface penetrate into dense plasma region to cause D-D fusion reactions.

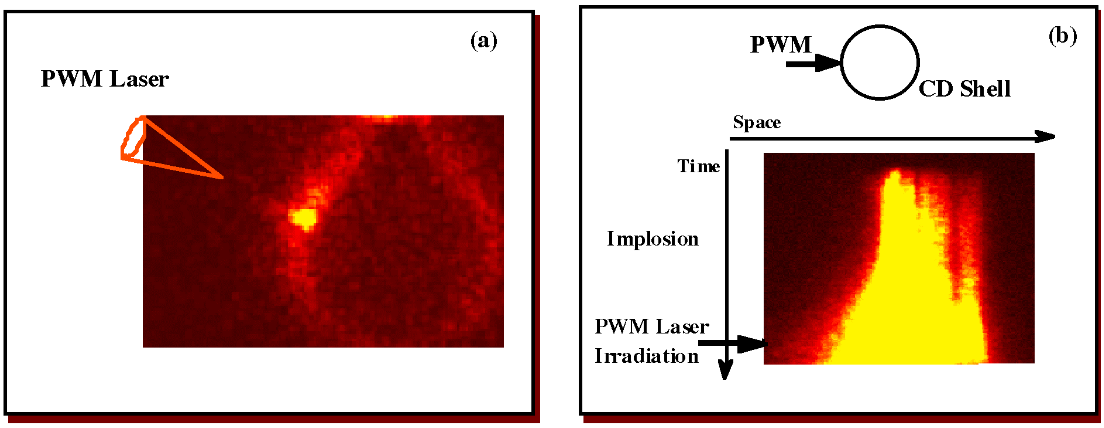

Fig.4 (a) X-ray pinhole image (b) X-ray streak image

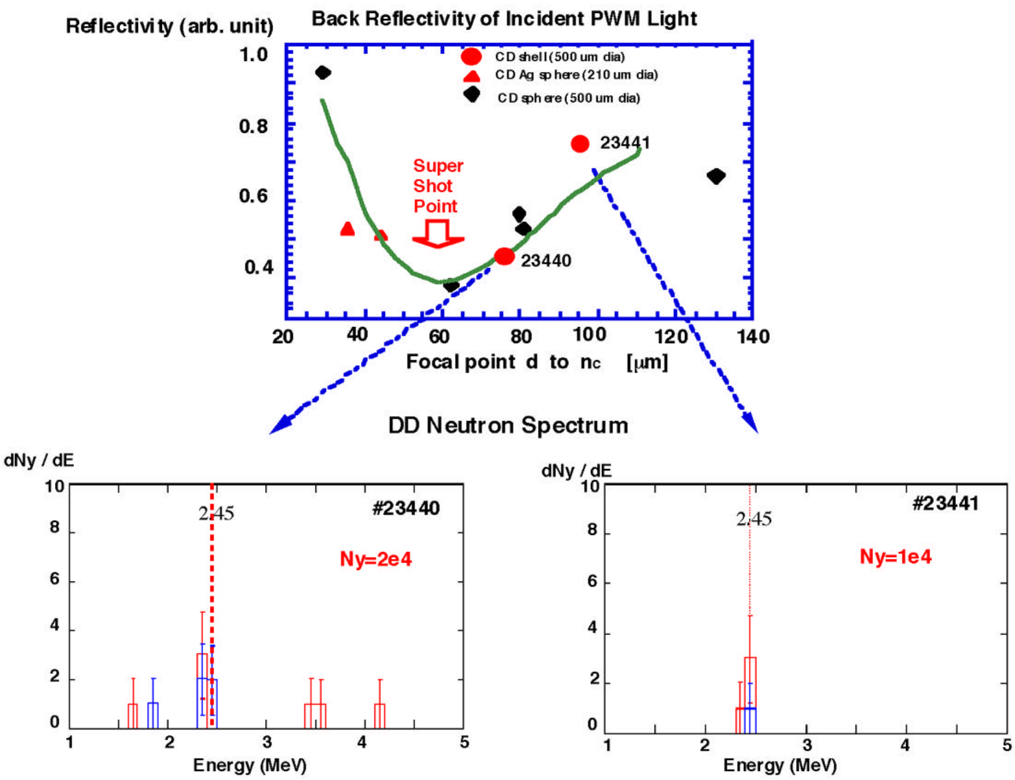

Fig. 5 Focus point dependence of the backscattered light reflectivity and neutron energy spectrum.

We also worked on the imploded plasma heating with tightly focused 100J/100ps pulses. In the experiments, four beams of GEKKO XII laser system are divided into a center part and an outer part which are arranged co-axially. The central parts are RPP beams of wavelength 0.53μm, and the ourter parts of beams are used for heating after the implosion with central beams. Each heating beam deliver two or three 100J/100psec, 1.06μm wavelength pulses which are tightly focused on the critical surface. In these experiments, the neutron yield is enhanced significantly and the X-ray pinhole images indicate that the plasmas are heated significantly.

6. Summary

The experiments and theory on intense laser plasma interactions show that MeV electrons are efficiently generated and they penetrate into overdense plasmas in a form of electron filaments. The electron filaments seem to be guided well by self-generated magnetic channels.

In the imploded plasma heating experiments, we demonstrated the enhancement of neutron yield. The neutrons are generated by high energy D-ion interaction with core plasma and core plasma heating with MeV electron stream. Since we did not inject a hole boring beam before the short laser pulse, significant amount of energy is converted into high energy ions. In the next step, we will introduce a hole for guiding heating pulses by making use of heavy metal cone or injection of hole boring beams.

References

[1] TABAK, M., Hammer, J. et.al., Phys. Plasmas 1 (1994) 1626.
[2] MAHDY, A.I., TAKAB, H., and K.MIMA, Nuclear Fusion to be published
[3] NORREYS, P.A., et.al., Phys.Plasmas 6 (1999) 2150.
[4] MALKA, LEFEVRE, E., and MIQUEL, J.L., Phys.Rev.Lett. 78 (1997) 3314.
[5] KET, M.H., et.al., Phys.Plasmas, 5(1998) 1966.
[6] TANAKA, K.A., et.al., Phys.Plasmas, 7 (2000) 2014.
[7] TOUPIN, C.et.al., Proceedings of the 25th European Phys.Soc. on Contr.Fusion and Plasma Physics Conference, Vol.22c Praha, Czech Rep., 1998, ECA (1998) 914-917.
[8] DAVIES, J.R., BELL, A.R., HAINES, M.G., and GUERIN, S.M., Phys.Rev.E 56 (1997) 7193.