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Relativistic Laser Plasma Research for Fast Ignition Laser Fusion

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Abstract

Reviewed are the present status and future prospects of the laser fusion research at the ILE (Institute of Laser Engineering) Osaka. The Gekko XII and Peta Watt laser system have been operated for investigating the fast ignition, the relativistic laser plasma interactions and so on. In particular, the fast ignition experiments with cone shell target have been in progress as the UK and US-Japan collaboration programs. In the experiments, the imploded high density plasmas are heated by irradiating 500 J level peta watt laser pulse. The thermal neutron yield is found to increase by three orders of magnitude by injecting the peta watt laser into the cone shell target.

Transport of relativistic high density electron is the critical issue as the basic physics for understanding the dense plasma heating process. By the theory, simulation and experiment, the collective phenomena in the interactions of intense relativistic electron current with dense plasmas has been investigated to find the formation of self organized flow as the result of filamentation (Weibel) instability.

Through the present understanding, the new project, FIREX-I has started recently to prove the principle of the fast ignition scheme.

Keywords:

fast ignition, peta watt laser, relativistic electron, weibel instability

1. Introduction

At the Institute of Laser Engineering, Osaka University, the fast ignition and the implosion hydrodynamics have been studied by GEKKO-XII and Peta watt laser system since 1996. The 0.1 ~ 1 peta watt short pulse laser has been installed in the GEKKO XII laser system to investigate the fundamental physics of the relativistic laser plasma interactions related to the heating of dense implosion plasmas and the implosion plasma heating at ILE [1,2]. The critical issues of the fast ignition research are 1) the ultra intense laser interactions with high density plasmas, 2) Physics of transport and energy deposition of laser produced relativistic electron and high coupling efficiency of heating laser energy to core plasma thermal energy, and 3) Heating of dense plasmas to 10 keV and hot spark formation, fusion ignition, and burning. The 50 ~ 400 J / 0.5 ps laser pulses were injected into solid targets or imploded plasmas to study the relativistic electron generation and transport, and the dense plasma heating [1,2]. The relativistic electron propagation in solid density plasmas has been widely investigated by experiment, simulation and theory [3]. Many experiments and simulations indicate that the intense relativistic electron energy flow is self-organized. For an example, in the UV (Ultra Violet radiation) image of the solid target rear surface, hot spots generated by relativistic electron heating are observed to indicate that self-generated magnetic fields associating with the relativistic electron current break up the relativistic electron flow into filaments. Furthermore, related simulations show that the cluster of the filaments are merged and self-pinched. Recently, it became clear by the experiments and simulations that the filamentation and the self-pinch of the relativistic electron flow are sensitive to the target electrical conductivity and thermoelectric processes in dense plasmas [4].

As for the propagation of ultra-intense short pulse laser in dense plasmas, the super-penetration and the plasma

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heating have been found by observing the neutron yield enhancement in the direct PW (Peta Watt) laser injection into the imploded plasma [5]. However, the neutron spectra of imploded plasmas directly irradiated by the intense short pulse laser were broad. Therefore, the enhanced D-D fusion reaction is considered to be mainly due to generation of high energy deuterium ion in the coronal plasmas. The recent simulation indicates that the intense relativistic electron flux deposits the energy locally to the back ground plasmas through the anomalous resistivity and the high energy ions of a few hundreds of keV are generated. It was found by the PIC (Particle In Cell) simulations recently [3].

The present status of fast ignition experiment at ILE, Osaka Univ. is presented in the Sec. **2**. In the Sec. **3**, the researches on the simulation code integration for fast ignition and related relativistic laser plasma physics are overviewed. Finally, in the Sec. **4**, the future prospects of the fast ignition research at ILE is described.

2. Fast ignition experiment

We introduced the cone shell target to realize the higher coupling efficiency of peta watt laser pulse to core plasmas. As the results, the neutron yields increased from the order of 10^4 to the order of 10^5 and 10^7 with heating energy of 100 J / 0.5 ps and that of 400 J / 0.5 ps respectively. Namely, they are 10 times and 1000 times higher than that of non-heating case respectively. This indicates that the thermonuclear fusion is enhanced by the temperature increase of the core plasma due to the PW laser heating. The temperature increase was obtained by the neutron energy spectrum and the neutron yield enhancement. In the best shot, the temperature increased by 130 eV with 100 J / 0.5 ps injection and by 800 eV with 400 J / 0.5 ps injection. We found from these results that about 20 % – 25 % of input PW laser pulse energy is deposited in the core plasma which is 100 g/cc (100 times solid density) [1,2].

When the 300 J / 0.6 ps CPA (Chirp Pulse Amplification) laser pulse is injected, the neutron yield reaches 10^7 while the neutron yield was$10^4 - 10^5$ without heating as shown in Fig. 1. This indicates that the core plasma temperature increased by 500 eV and the energy coupling between heating laser and core plasma is 20 – 25 %. Since the focused laser energy included in 30 μm diameter is less than 30 %, the 20 – 25 % coupling efficiency means that actual coupling is higher than 70 %. Instead of such high coupling efficiency, it is more likely that the energy in the hallo of laser spot is focused by cone guide. In Fig. 1, 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 (Peta Watt Module) laser experimental results. This indicates that the coupling efficiency for 300 J case is almost same as for 80 J case as far as neutron yields are concerned. This scaling law has been used for planning the fast ignition experiment (FIREX). Further analysis of the cone target experiments are going with PIC simulation and 2D (2 Dimensional) hydro simulation including the Fokker Planck simulation as discussed in Sec. **2** and **3** [6].

3. Simulations related to fast ignition and FIREX project

Recent 3D (3 Dimensional) PIC simulation results show that the relativistic electron current is well organized and confined in a small radius in the over-dense plasma [3]. This indicates that a hot spot could be generated by the relativistic electron heating. In the PIC simulations, we found that small scale magnetic field fluctuations generated by the Weibel instability are inversely cascaded to longer wavelength fluctuations and subsequently self-organization of the relativistic electron flow occurs as shown in Fig. 2.

The spatial evolutions of mean square average of magnetic field fluctuations and transverse spatial average longitudinal DC electric field are indicated in Fig. 3. The DC electric field intensity is proportional to $<B^2>$ near the surface on which a laser is irradiated. This is explained as follows. When the electron inertia is neglected for the averaged motion of back ground electrons, we can assume,

$$< \boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} > = 0, \tag{1}$$

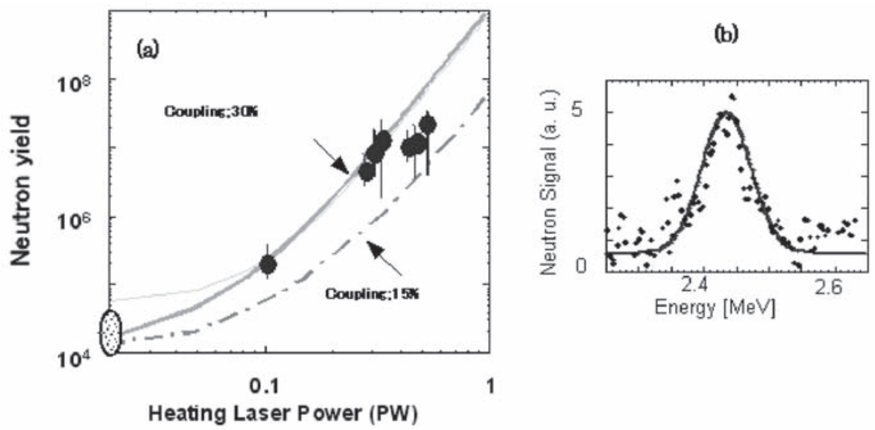

Fig. 1 DD fusion neutron yield enhancement (a) and neutron energy spectrum (b) from ref. [2].

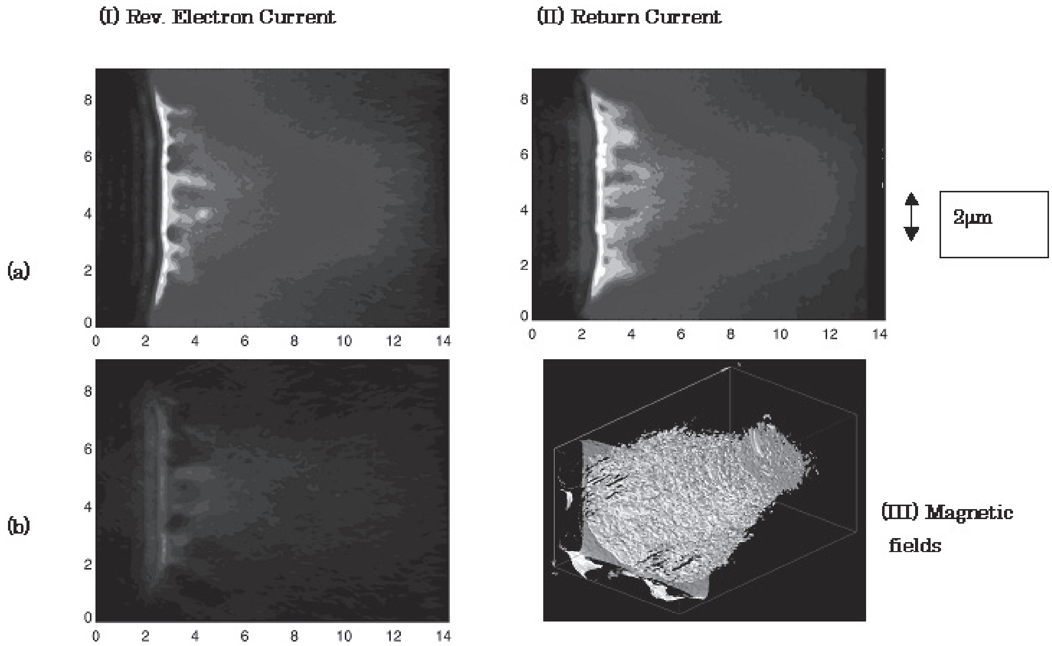

Fig. 2 Relativistic electron current self-organization (self-pinch); (B); (I)–(a); the current profile of hot electron with energy lower than 1.0 MeV, (I)–(b); current profile of hot electron of the energy higher than 1 MeV, (II); return current profile, and (III); magnetic field iso-intensity contour [3].

namely,

$$<\boldsymbol{E}> = -<[e\boldsymbol{v}_0 \times \boldsymbol{B}/mk_{surf}v_e] \times \boldsymbol{B}> \sim v_0<B^2>, \quad (2)$$

where v_0 is the electron flow velocity of back ground electron, k_{surf} is the inverse of the surface layer thickness and v_e is the electron thermal velocity. The potential drop in this region reaches 100 keV. Note that $1/k_{surf}v_e$ is an effective acceleration time. So the back ground electron temperature near the surface is heated up to the order of 100 keV. On the other hand, far inside the over-dense plasma, the DC electric field is proportional to $[<B^2>]^{1/2}$ as indicated in Fig. 3. Since the spatial scale of the magnetic field fluctuation in this region is longer than the electron gyro-radius, the fluctuation velocity in eq. (1) should be replaced by $(e\boldsymbol{v}_0 \times \boldsymbol{B}/m)/\Omega$, where Ω is the average cyclotron frequency given by $e[<B^2>]^{1/2}/m$. Therefore,

$$<\boldsymbol{E}> = -<[e\boldsymbol{v}_0 \times \boldsymbol{B}/m\Omega] \times \boldsymbol{B}> \sim \boldsymbol{v}_0\ [<B^2>]^{1/2} \quad (3)$$

Note that the DC electric field given by eq. (3) is proportional to $\boldsymbol{v}_0$, namely the current. The relation of eq. (3) is also indicated in Fig. 3 and the corresponding potential drop is about 50 keV. When the simulation time is longer than the present case, the back ground electrons are further heated due to this anomalous resistivity and ions may be accelerated and contribute to the energy transport.

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

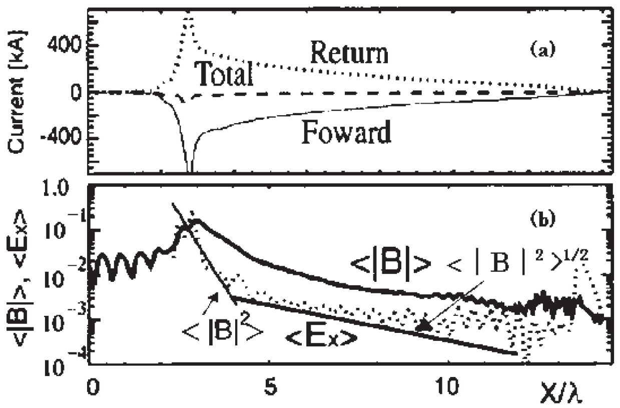

Fig. 3 (a) The spatial profiles of the high energy electron current (Forward) and cold back ground electron current (Return) (b) *B* and *E* field profiles and phenomenological relation of *E* field to *B* field.

We carried out F.P. (Fokker Planck) simulations related to the cone target experiment for predicting the neutron yield. In the F.P. simulations, the relativistic electron energy spectrum was taken from the cone target PIC simulation, where the spectrum has two kinds of slope temperature which are 0.5 MeV and 2.0 MeV as shown in Fig. 4 (b). The 0.5

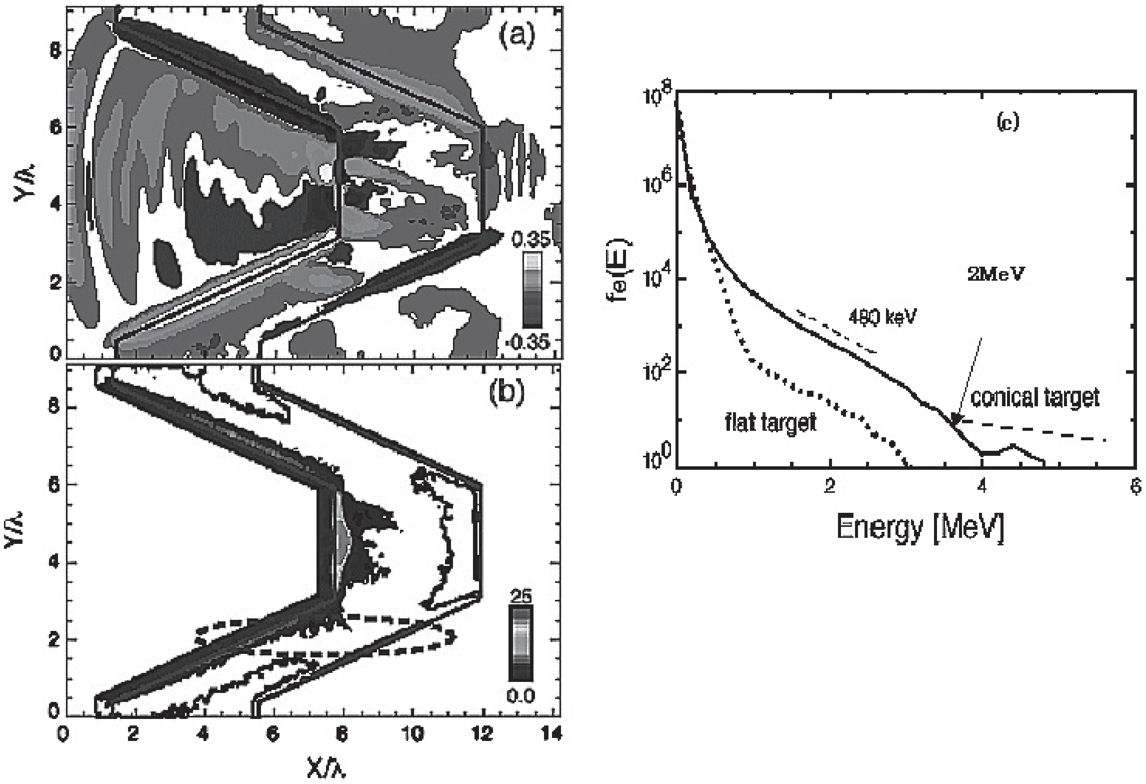

Fig. 4 3D PIC simulation of cone target plasma interactions, (a) contour of magnetic field associated with hot electron flow, (b) contour of hot electron energy density; $(\gamma-1)n_e/n_c$, (c) hot electron energy spectrum for cone target and flat target. 480 keV slope temperature electron component is significantly enhanced in the cone.

MeV slope temperature is related to the Brunel absorption on the cone sidewall [7], where the laser intensity is lower than that of the top of the cone, since the laser beam diameter shrinks toward the top of the cone. The total absorbed laser energy included in the 0.5 MeV component is about 80 %. The F.P. simulation shows that the plasma heating and the neutron yield depend on the 0.5 MeV electron heating. This softening of the electron spectrum is also one of the advantages of the cone guide.

The fusion gain has been evaluated by the F.P. simulation which is coupled with the hydro-burning code. The results are shown in Fig. 5, which indicate that the gain expected in the FIREX I is 0.1 according to the Fokker Planck simulations with 0.5 MeV slope temperature for the 10 kJ heating pulse energy, where the fuel areal mass density; $\rho r = 0.7$ g/cm^2. If the energy fraction of 0.5 MeV component is 50 % and the other component has 2.0 MeV slope temperature and the stopping is classical (no magnetic field effects), more than 15 kJ heating energy is necessary to achieve the gain of 0.1. However, the recent 2D F.P. simulation shows that the effective stopping power is enhanced by the self-generated magnetic fields. So, the requirement on the heating laser may be relaxed. In the FIREX II, the both implosion and heating lasers are up-grated to 50 kJ. In this case, the ρr reaches 1.2 g/cm^2 and the hot spark ρr will be greater than 0.5 g/cm^2. So, the gain will reach higher than unity and the ignition will be achieved.

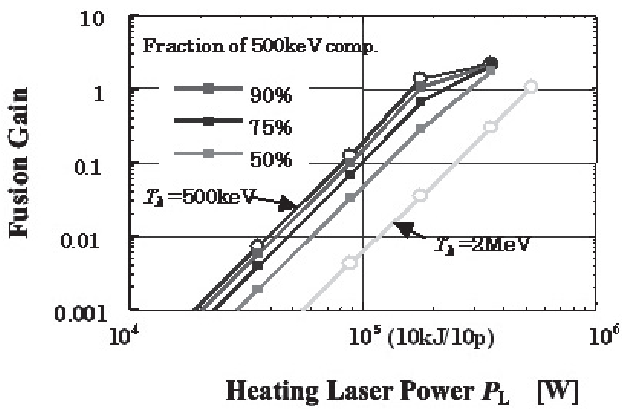

Fig. 5 Fast ignition burning simulation with Fokker Planck transport model. Gain curves for FIREX-I (ρR = 0.7 g/cm^2). For the small ρR, the fusion gain during the laser heating is significant without ignition. The gain is sensitive to the fraction of low energy relativistic electron component.

4. Future prospects

The plasma physics related to the fast ignition laser fusion is the new physics so called high field physics which is opened up by ultra intense laser technology. One of the critical issues of fast ignition is the transport physics of extremely intense electron and ion beams in dense plasmas. Since the relevant electrons are relativistic and the momentum distribution is non–equilibrium and non-isotropic, effects of electromagnetic instabilities and turbulences on the energy

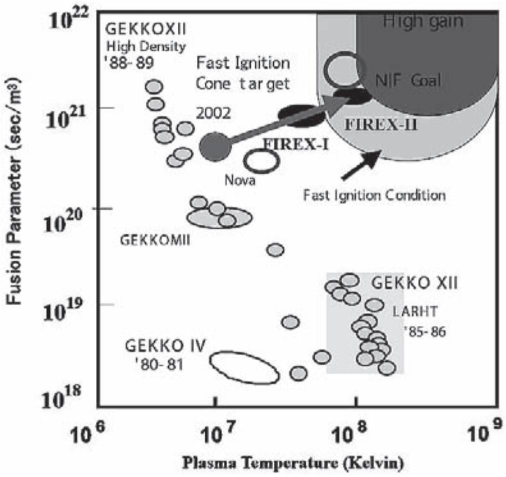

Fig. 6 Fusion parameter achievement by Gekko lasers and NOVA. Ignition condition for fast ignition, FIREX-I and -II, and NIF goals are indicated.

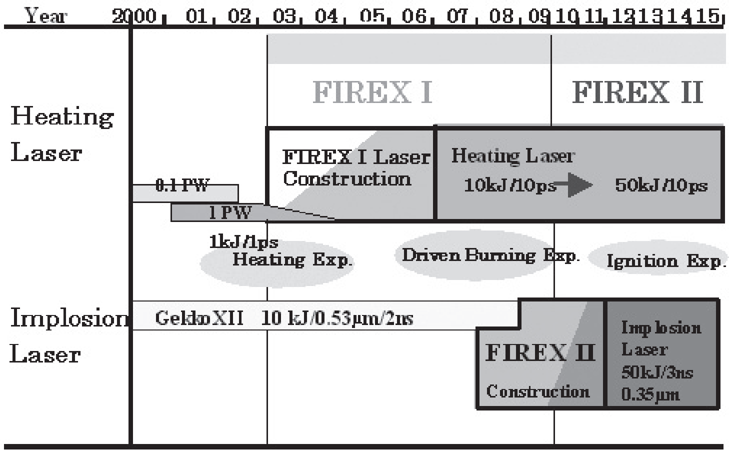

Fig. 7 Time schedule for FIREX-I project and expected plan for FIREX-II project. Plasma experiment of FIREX-I will start in 2007.

transport are essential in the fast ignition. Peta watt laser heating processes should be further explored by theory, simulations, and experiments carried out by present ultra-intense laser facilities and future larger scale lasers.

In the Fig. 6, the fusion plasma parameters achieved by the GEKKO XII and PW lasers and the NOVA are plotted together with the goals of the FIREX-I and -II and NIF (National Ignition Facility). The fast ignition condition will be clarified by the FIREX-I experiment and the following FIREX-II will demonstrate fusion burning in the fast ignition scheme.

Heating laser of 10 kJ / 10 ps / 1.06 μm for FIREX-I is under development and will be completed before 2007. The expected rise time of the pulse is shorter than 1 ps and the focus diameter is smaller than 20 μm. If the gain of higher than 0.1 is achieved in FIREX-I, we plan to proceed to the FIREX-II as shown in Fig. 7.

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