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Recent results and future prospects of laser fusion research at ILE, Osaka

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Abstract. Reviewed are the present status of the fast ignition researches. Since 1997, the fast ignition experiment and theory researches have been extensively continued at the Institute of Laser Engineering of Osaka University. In particular, the cone-shell target experiments and simulation research have been progressing. In order to demonstrate heating of imploded high density plasma to the ignition temperature, in the April of 2003, the construction of heating laser of 10 kJ/10 ps/1.06 μm (Laser for Fusion Experiment; LFEX), for FIREX-I (Fast Ignition Realization Experiment) has started. The fabrication of DT foam cryogenic cone target is also under development as a collaboration program between Osaka University and NIFS (National Institute for Fusion Science). The LFEX will be completed in 2008. After the completion of LFEX, the foam cryogenic cone shell target experiment will start in 2008. As a new approach toward a compact ignition, an impact fusion has been proposed, where the ablative acceleration to the order of 10^8 cm/s is the key issue. The ablation acceleration related to the impact fusion has been explored by experiments.

PACS. 52.57.-z Laser inertial confinement – 52.57.Fg Implosion symmetry and hydrodynamic instability – 52.57.Kk Fast ignition of compressed fusion fuels

1 Introduction

At the Institute of Laser Engineering, Osaka University, fast ignition, implosion hydrodynamics, laser, target, and reactor technologies and so on have been studied for many years. As for the fast ignition, the cone guide target was invented and the high coupling efficiency of the peta watt laser energy to the core plasma was demonstrated in the Gekko XII laser experiments [1,2]. The fundamental physics of the relativistic laser plasma interactions related to the heating of dense implosion plasmas has also been investigated by experiments and simulations. The critical issues of the fast ignition research are (1) 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, ignition, and burning. The 50–400 J/0.5 ps laser pulses were injected into solid targets or imploded plasmas to study the dense plasma heating [1–3]. The relativistic electron propagation in solid density plasmas has been widely investigated by experiment, simulation and theory [3]. Many experiments and simulations indicate that intense relativistic electron beam in dense plasmas is broken up into filaments and self-organized [3–6]. Recently, it became clear by the experiments and simulations that the filamentation and the self-organization of the relativistic electron beam are sensitive to the target electrical conductivity and thermoelectric processes of dense plasmas [3].

The FIREX project has started in the fiscal year of 2003 to demonstrate the ignition by heating a highly compressed DT fuel with a high energy peta watt laser. In Figure 1, plotted are the fusion plasma parameters achieved by GEKKO XII and PW lasers [1,2] of ILE, Osaka University, NOVA of LLNL, and OMEGA of LLE, University of Rochester and the goals of the fast ignition projects of FIREX-I and -II at ILE and OMEGA-EP at LLE. The goal of NIF and LMJ projects in US and France is also shown in Figure 1. Here, FIREX stands for "Fast Ignition Realization Experiment". The required laser energy for ignition is expected to be 10 times smaller in the fast ignition than that in the central hot spark ignition, although the relativistic laser plasma physics related to fast ignition

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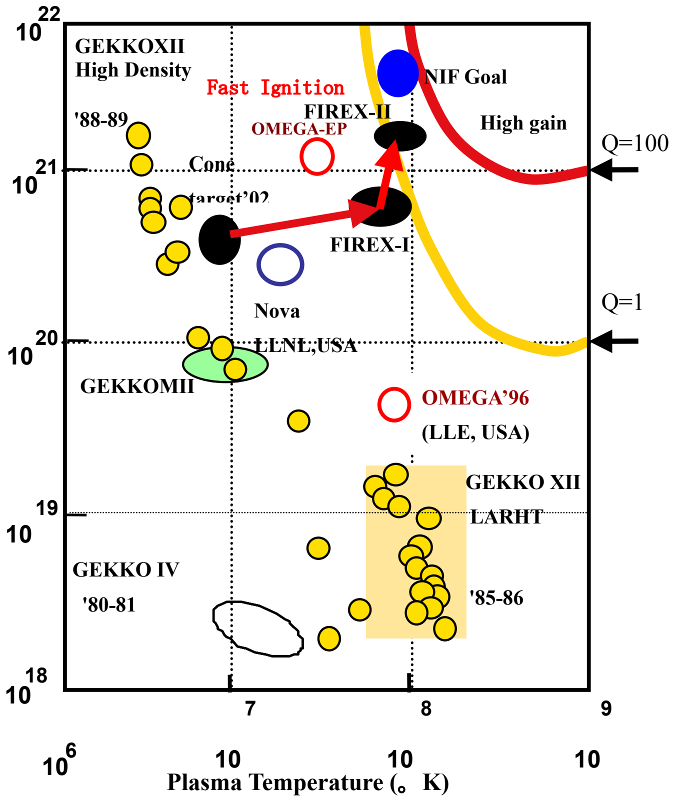
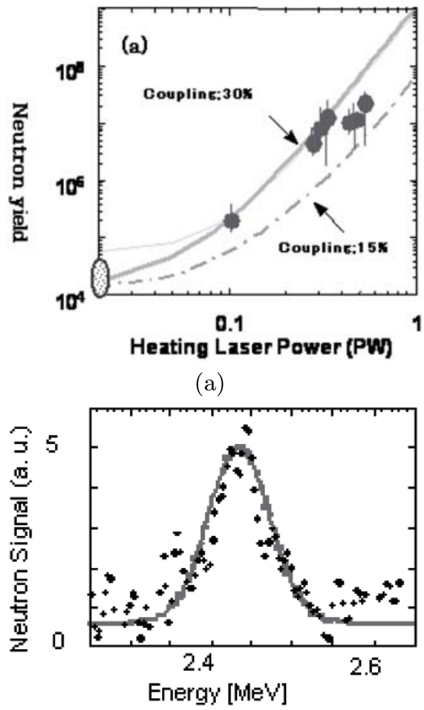


Fig. 1. (Color online) Fusion parameters achieved by Gekko lasers, NOVA, and OMEGA and those expected by FIREX-I and -II, and NIF projects.



(a)

(b)

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

is premature. Heating physics of hot spark formation will be clarified by the FIREX-I project. When the FIREX-I project is successful, the FIREX-II project will follow to demonstrate the fusion ignition and burn. As shown in the Figure 1, the fusion energy gain will be beyond unity in the FIREX-II.

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

2 Fast ignition experiments

2.1 Integrated experiment

We introduced the cone shell target to achieve the higher coupling efficiency of peta watt laser 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 raising the temperature of the core plasma with 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 Figure 2. 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 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 hallow of laser spot is focused by cone guide. In Figure 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 (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).

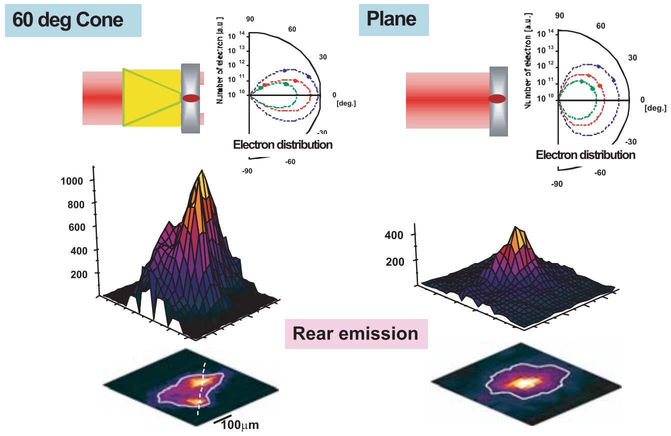


Fig. 3. (Color online) Petawatt laser plasma interactions for cone target and planer target, heating profiles of rear side of the targets are compared for cone and non-cone case (after Yabuuchi et al.).

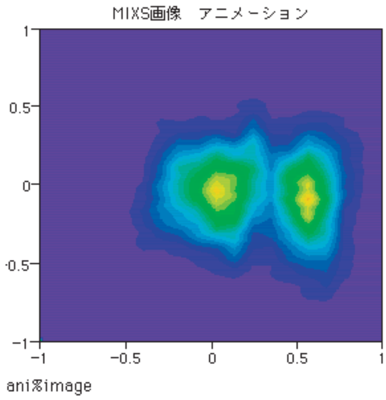
2.2 Heating experiment

Effects of cone on laser plasma interactions and electron energy transport have been explored by Gekko-PW laser experiments [8]. As shown in Figure 3, UV emission of rear side of a Al witness plate attached to a gold cone was measured, which is compared with that without cone. The UV emission intensity is higher by 2–3 in the cone case than in the w/o cone case as shown in Figure 3. This indicates that the absorption and the energy transport to the rear of the witness plate are more efficient in the cone target case. Figure 3 also shows that the electron angular distribution is collimated in forward direction in the cone case.

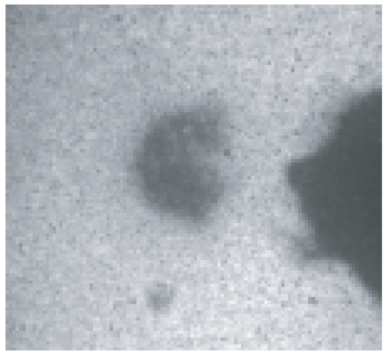
2.3 Implosion experiment and simulation for cone shell target

The implosion of the cone target has been investigated by the US-Japan joint experiment with OMEGA laser at the LLE of the University of Rochester [7]. The implosion images of the imploded shell and the cone target are obtained as shown in Figures 4a and 4b. Those imaged have been compared with the simulations with the LASNEX code (Ref. [9] Hachett et al.). The implosion hydrodynamics of the cone target has been also explored with a new implosion code PINOCO developed by Nagatomo [8]. The density and temperature profiles of the simulation related to the experiment are shown in Figure 4c. It is found that the shape of the core plasma of the experiment is well reproduced in the simulation. Namely, the top of the cone is damaged by the jet produced by the stagnation of imploding fuel shell.

The PINOCO simulation results also show that the plasma density is as high as the maximum density of spherical implosion and the area density can be higher than the spherical implosion. From the present understanding on the heating physics and the cone shell implosion hydrodynamics, we believe that the ρR will reach



(a)



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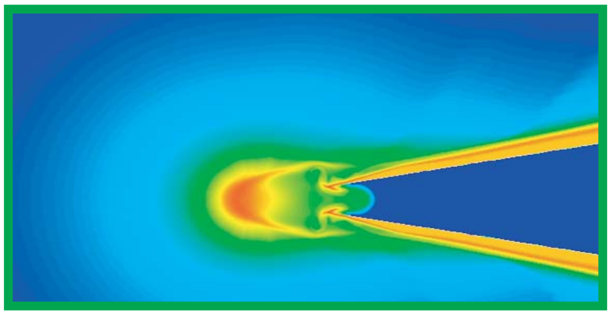


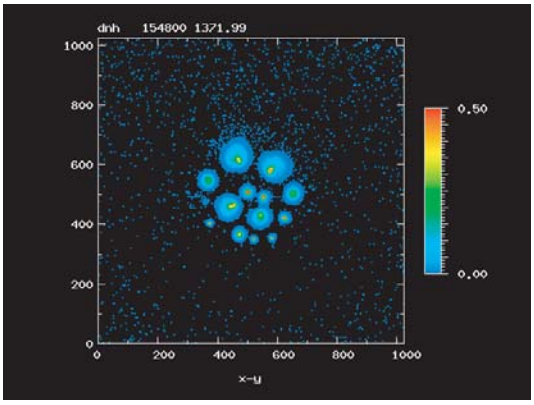
(c)

Fig. 4. (Color online) X-ray self emission time resolved image and X-ray back lighting image of cone shell target implosion experiments [7] (a, b).

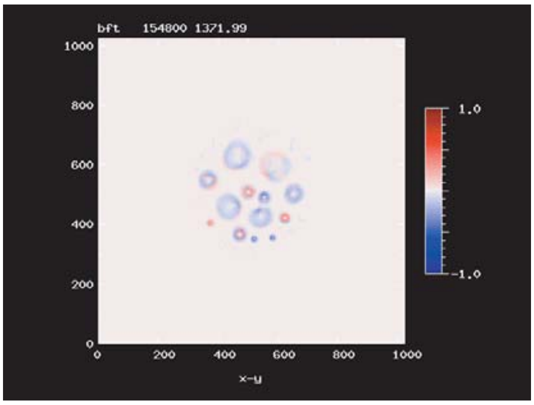
0.45 g/cm^2 and 1.2 g/cm^2 respectively in the FIREX-I, and -II.

2.4 Electron transport simulations related to fast ignition

Recent 2D (two dimensional) hybrid simulation results show that the relativistic electron current is well organized and confined in a small radius in the over-dense plasma [4]. This indicates that a hot spot could be generated by the relativistic electron heating. In the hybrid 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



(a)



(b)

Fig. 5. (Color online) 2D hybrid simulation of relativistic electron beam propagation in dense plasmas. (a) Self-organized state of relativistic electron beam after Weibel instability or transverse two stream instability, (b) structure of magnetic fields in θ-direction of each filament. The color bar indicates strength of B_θ and sign of B_z.

occurs as shown in Figure 5. The quasi-DC electric field is produced during the merging processes. It is proportional to $-\partial A/\partial t$ which becomes effective during the merging processes since the vector potential $A_\|$ increases in the merging. This is one of the anomalous softening of relativistic electron spectrum in over dense plasmas. This process may contribute to the enhanced stopping of electron beam.

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. These characters of the laser interaction with the cone contribute to enhance the coupling efficiency of short pulse laser to core plasmas as it is measured in experiments (see Fig. 3).

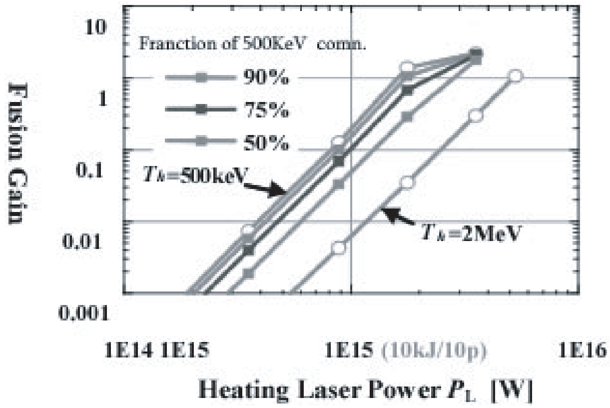


Fig. 6. Fast ignition burning simulation with Fokker Planck transport model. Gain curves for (1) FIREX-I $\rho r = 0.7$ g/cm^2) For the small ρr, the fusion gain during the laser heating is significant without ignition. The gain is sensitive to the fraction of low energy relativistic electron component.

2.5 Fokker Planck simulation on the heating and goals of FIREX projects

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 Figure 4b. The 0.5 MeV slope temperature is related to the Brunel absorption on the cone sidewall, 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 [9].

The fusion gain has been evaluated by the F.P. simulation which is coupled with the hydro-burning code. The results are shown in Figure 6, 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 area mass density; $\rho r = 0.7$ g/cm^2. However, 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.

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.

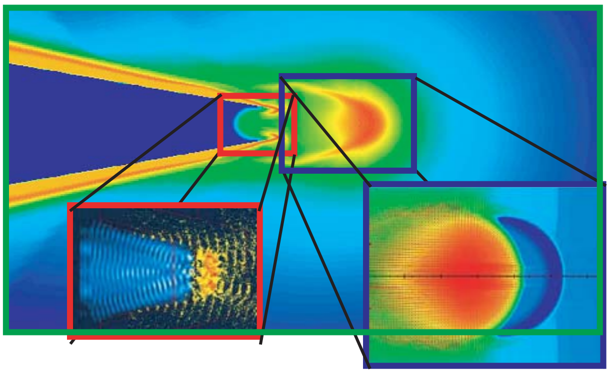


Fig. 7. (Color online) Scheme of fast ignition interconnected integrated code (FI3). Density profile of imploded cone shell target is given by PINOCO simulation. The density profile of PINOCO simulation is used for 2-D PIC simulation result as shown in the left hand side bottom. The PINOCO and PIC simulation results are used for simulations of heating and burning processes with Fokker Planck code as shown in the right hand side corner.

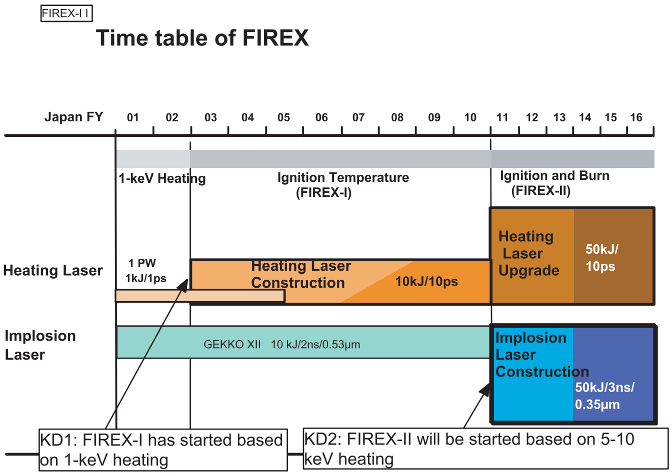


Fig. 8. (Color online) Time schedule for FIREX-I project and expected plan for FIREX-II project. Plasma experiment of FIREX-I will start in FY2007.

Fig. 9. (Color online) Present outlook of laser for FIREX-I (LFEX; 10 kJ/10 ps).

3 Integrated simulation with the FI3 simulation code

More details of cone target ignition process are studied by using the Fast Ignition Integrated Interconnected code (FI3 code) which connects a radiation hydro code (PINOCO), a collective PIC code where the weight of the simulation particle are varied according to the plasma density, and the Fokker Planck simulation. The temperature and the gain of highly compressed DT plasmas heated by the short pulse laser have been predicted by the FI3 simulations. The Fokker Planck simulation of heat deposition is coupled with the hydro-burning code to see the temporal evolution of the heated plasma and the fusion reactions as shown in Figure 7. The FI3 has been applied to analyze the cone shell target experimental results. It is found in the simulation that the significant amount of relativistic electron is confined inside the cone and the delayed heating of the imploded core plasma contributes to the enhancement of core heating. The heated core plasma temperature reaches about 550 eV in the present FI3 simulation. This is lower than the experimental results. The ion heating, magnetic field generation during the implosion, 3-D electron transport effects, and so on may be important and the evaluation of those effects will be investigated in future.

4 Present status and planning

Since April, 2003, we started the construction of heating laser of 10 kJ/10 ps/1.06 μm; named LFEX (Laser for Fusion Experiment), for FIREX-I. As shown in Figure 8, the LFEX will be completed before the end of 2007. The expected rise time of the short pulse LFEX is less than 1 ps and the focus diameter is smaller than 30 μm. As the front end of the laser, OPCPA is introduced to improve the contrast ratio to less than 10^{-8}. For pulse compression, segmented dielectric gratings will be used. The R&D for the coherent combining of the pulse compressed segmented beam has started [10]. The present status of the FIREX-I laser is shown in Figure 9. The first light of kJ level was obtained in May, 2005. In 2006, the infra structure of the compressor will be completed.

After the completion of LFEX, we will start the foam cryogenic cone shell target experiment in late 2007. The target fabrication and irradiation system with characterization of DT cryogenic foam layer are also under development as the collaboration program between Osaka University and NIFS (National Institute for Fusion Science). The DT fuel will be fed to the foam shell layer through a capillary and then, frozen to a solid layer as shown in Figure 11. We are reducing the foam density to less than 20 mg/cc and testing the uniformity of the frozen layer until the end of FY2005. Then, the implosion experiment will be done in 2006. If the gain of the order of 0.1 and the temperature higher than 5 keV are achieved in FIREX-I before the end of 2008, we plan to proceed to the FIREX-II in 2009. Then, the ignition will be demonstrated until 2015 as shown in Figure 8.

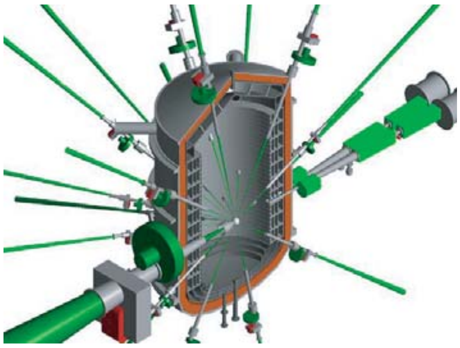


Fig. 10. (Color online) Wet wall reactor for fast ignition. A cone target is injected from the right hand side and 100 kJ heating laser irradiates the target from the left.

5 Summary and 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 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 Figure 1, 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.

Finally, the Figure 10 shows a conceptual design for cone target fast ignition. The reactor surface is protected by liquid LiPb. The cone shell target is imploded with 1 MJ blue laser and then heated with 100 kJ short pulse laser which is injected from the left hand side of the Figure 10. The gain of 160 is expected in this power plant. The detail of the design is presented in the proceedings of IFSA2005 [10].

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