Progress in Direct-Drive Laser Fusion Using GEKKO-XII/PW Facility

T. Yamanaka 1), H. Azechi 1), Y. Fujimoto 1), H. Fujita 1), A. Hall 1, 7), H. Habara 5), Y. Izawa 1), T. Jitsuno 1), T. Johzaki 1), T. Kanabe 2, 1), Y, Kitagawa 1), R. Kodama 1), M. Krushelnick 6), K. L. Lancaster 5, 6), K. Mima 1), N. Miyanaga 1), M. Murakami 1), H. Nagatomo 1), K. Nagai 1), M. Nakai 1), S. Nakai 3), M. Nakatsuka 1), K. Nishihara 1), H. Nishimura 1), T. Norimatsu 1), P. A. Norreys 5), S. Sakabe 2, 1), Y. Sentoku 1), K. Shiraga 1), K. Shigemori 1), H. Takabe 1), K. A. Tanaka 2, 1), K. Tsubakimoto 1), S. Yamada 1), C. Yamanaka 4), M. Yamanaka 1) and M. Zepf 8)

1) Institute of Laser engineering, Osaka University, Suita, Osaka, Japan
2) Faculty of Engineering, Osaka University, Suita, Osaka, Japan
3) Kochi National college of Technology, Nangoku, Kochi, Japan
4) Institute for Laser Technology, Nishiku, Osaka, Japan
5) Rutherford Appleton Laboratory, Didcot Oxon, UK
6) Blacket Labolatory, Imperial College, London, UK
7) University of Essex, Essex, UK
8) Queens University of Belfast, Belfast, UK

e-mail contact of main author: tyama@ile.osaka-u.ac.jp

Abstract: ILE Osaka University is pursuing the fast ignition experiments in direct drive scheme. In order to advance the experiments a peta watt laser has been constructed and successfully introduced to the fast ignition experiments. The imploded core plasma is heated up to 1 keV with high efficiency of energy transfer from the laser to the compressed high density core plasma. The results suggest that heating for ignition could be achieved using a few peta watt heating laser pulses of which width is close to the duration of stagnation of imploded plasma. Some of the theoretical researches, Rayleigh-Taylor instability experiments and future plans towards proof of principle of ignition are also described.

1. Introduction

In inertial fusion energy research two approaches are under investigation to achieve an ignition-and-burn. One is the central ignition scheme in which a hot spark enough to ignite thermonuclear burn is produced at the center of the implosion plasma. This method requires both precise implosion symmetry and a large energy driver. The other is the new fast ignition in which a hot spark is created by irradiating an intense-short pulse laser to the imploded core plasma [1]. This fast ignition scheme may relax both implosion symmetry and driver energy to generate fusion gain required for a fusion reactor. This indicates a possibility of a relatively small output power plant.

ILE Osaka University has pursued the fast ignition research since 1994, and has investigated the intense laser plasma interactions, the generation and transport of high energy electrons and the heating of compressed fuel plasma [2~4]. We demonstrated heating of imploded core plasmas produced using a novel target by irradiating a 100 TW pulse showing the enhanced yield of thermonuclear neutrons in 2000 [5]. The experimental results were consistent with the knowledge obtained by researches on intense laser plasma interaction and transport of energetic electrons in that power/intensity regime.

Based on those results we have upgraded the output power of the heating laser up to 1 PW, which is estimated to be enough for heating 1000 times solid density plasma. Heating of the compressed core plasma up to 1 keV has been achieved using the Peta Watt (PW) laser [6]. Detailed researches on implosion physics such as hydrodynamic instability, which are important for high density implosion for the central ignition, R&Ds for high repetition-rate laser for a future energy driver [7], developments of fuel pellet technologies [8], and reactor designs [9] are pursued with fast ignition experiments. This report summarizes recent advancements in direct drive laser fusion researches which can be extended to ignition-and-burn experiments at ILE, Osaka University.

2. Peta-Watt Laser for Fast Ignition

The PW laser is an upgraded system of the Peta Watt Module (PWM) laser with output power of 100 TW and is successfully introduced to the fast ignition experiments coupled with the GEKKO-XII implosion laser in August 2001. Three new technologies have been employed; optical parametric chirp pulse amplifiers (OPCPA) for suppression of prepulse energy, an adaptive mirror for correction of wave front distortion of the laser beam, and usage of the chirped pulse of PW system for the GEKKO-XII source pulse. The output energy from the amplifier chain is 1.1 kJ in pulse width of 1.8 ns with spectral width of 3.7 nm. The power at the compressor output is suppressed so far to be 0.9 PW (420 J in 0.47 ps) to avoid any damage of compressor gratings. The GEKKO-XII is synchronized within 10 ps with the PW laser system. Figure 1 shows the schematic layout of the PW laser.

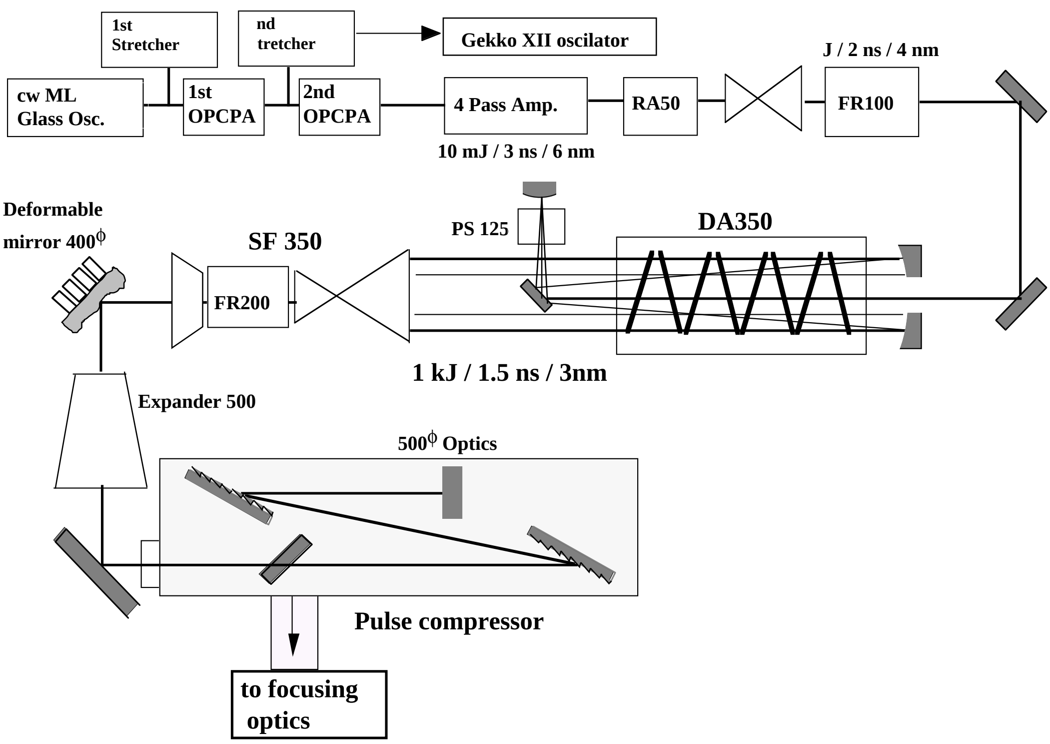


FIG. 1 Schematic diagram of the PW laser system. Three new technologies are employed.

The oscillator is Nd:glass mode locked laser. The wavelength, spectral width and pulse width are 1053 nm, 8 nm, 150 fs, respectively. An output pulse from the oscillator is stretched and amplified by two-stage stretcher-OPCPA system. Each OPCPA consists of two type-1 BBO crystals with 15 mm long and 8x8 mm^2 pumped longitudinally by the single longitudinal mode second harmonics of Nd:YAG laser with 9.5 ns pulse width. Both sides of the crystal are coated with Teflon to suppress the reflection and deliquescence of the surface. The output energy is 10 mJ in3 ns at the output point of the stretcher-OPCPA system. The prepulse energy is 1.5×10^{-8} of the main pulse. The pump-to-signal conversion efficiency is 23 % reaching almost theoretical limit. The output pulse is sent to the main amplifier through a serrated aperture, 2 glass preamplifiers and a spatial filter. The source pulse to GEKKO-XII is split out after the second pulse stretcher. The pulse width of the GEKKO-XII source pulse is adjusted by limiting the spectral width of chirped pulse by a slit.

The main amplifier is a Cacegranian 3-pass disc type with diameter of 35 cm. It consists of directly coupled 4 amplifier boxes with 2 discs of laser glass. In order to suppress amplified spontaneous emission (ASE), a Pokels cell shutter (PS) is installed in front of the beam-expanding mirror. The output energy of 1.1 kJ in spectral width of 2 nm is obtained when the incident energy to the main amplifier (DA350) is 3 J in 2 ns. The intensity profile of output beam is flat top doughnut shape with outer diameter of 31.5 cm and inner diameter of 13.5 cm. The output beam is transferred to the pulse compressor chamber through a 35 cm spatial filter with magnification 1, an adaptive mirror and a beam expander from 32 cm to 50 cm in diameter. The spatial filter includes a Faraday rotator with 20 cm in diameter, which is set on a sliding table so that it can be retracted when the non-chirped pulse with higher energy is supplied to Target chamber II of the Gekko-XII. The adaptive mirror is 40 cm in diameter and 7 mm thick, and is driven by 37 actuators connected to a computer. It is confirmed that low mode wave front distortions are corrected as low as 0.36 λ in rms.

Figure 2 is the photo of the compressor and focusing mirror chambers installed next to the GEKKO-XII target chamber. The pulse compressor is a double-pass configuration consisting of two gold gratings with 90 cm in diameter and 1480 lines/mm set in a vacuum chamber with 2.6 m in diameter and 11.4 m long. The spacing between two gratings is 970 cm so that 1.5 ns chirped pulse can be compressed to 0.5 ps or less. Output-energy, pulse-width, signal-to-noise ratio, and both far- and near-field patterns are monitored using a partially

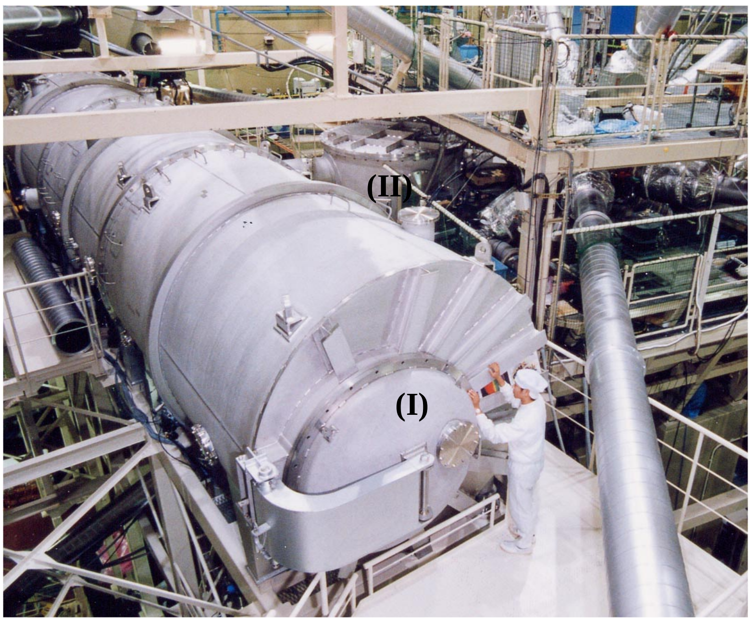
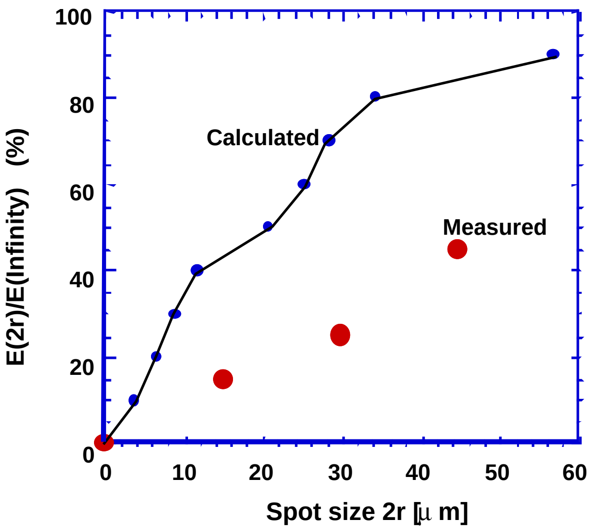
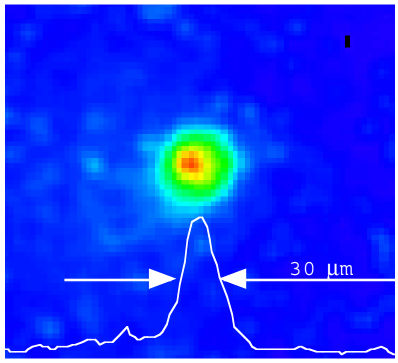


FIG. 2 Compressor (I) and focusing mirror chambers (II) installed by GEKKO-XII target chamber.





(a) *(b)*

FIG. 3 Focusing performance of PW laser. (a): Encircled energy. (b): X-ray emission pattern as irradiated on the planar target. FWHM is 30 μm

transmitted light through the kicking out mirror of the compressed pulse to the focusing mirror. Energy transfer efficiency of the compressor is measured to be 60 %. The output beam with 50 cm in diameter is focused using an off-axis parabolic mirror onto the target. The focusing length and F number are 3.8 m and 7.6, respectively. A blast shield plate with 1.5 mm thick and 60 cm in diameter is set on the parabolic mirror to protect from target debris. Both surfaces of the plate are over-coated with porous silica for antireflection. The blast shield plate has a spherical asymmetry of 27 λ so that it is easily compensated the focusing quality by changing the position of focusing mirror without the degradation of energy concentration. Spot size of focused beam (FWHM) is 30 μm in which 30% of the energy is so far concentrated. The x-ray emission pattern irradiated on a planar target is shown in Fig. 3 with encircled energy. The maximum intensity is $1x10^{20}$ W/cm^2. That value will be improved by further adjustment of the adaptive mirror. Details of the PW laser is described in the paper IF/P-04 of this Proceedings [10].

3. Fast Ignitor Research

In the fast ignition one expects that high energy electrons produced in over-dense region of the imploded plasma by an intense focused laser beam penetrate into the compressed core plasma to heat up to ignition temperature. The conversion efficiency from laser to high energy electrons and the propagation of high-energy electrons in solid targets (such as aluminum targets) have been studied using the Gekko MII short pulse laser of 50 TW and PWM laser in the Gekko XII facilities. It is found that the conversion efficiencies from laser to high energy electrons are 30-40% on solid targets and 15-25 % in plasma, and the generated electrons propagate in solid targets with beam divergence of 20-30 degrees. The efficient heating of implosion plasma (coupling efficiency from laser to compressed dense plasma is 30 %) by 100 TW laser was demonstrated in 2000 in the experiments with deuterated polystyrene shell targets with a hollow gold cone (cone-shell target) as shown in Fig. 4 [5]. Where the imploded core plasma is produced at the tip of the gold corn and is heated by high energy electrons generated at the thin gold plate set at the tip of the cone by irradiation of the intense short pulse laser (heating laser).

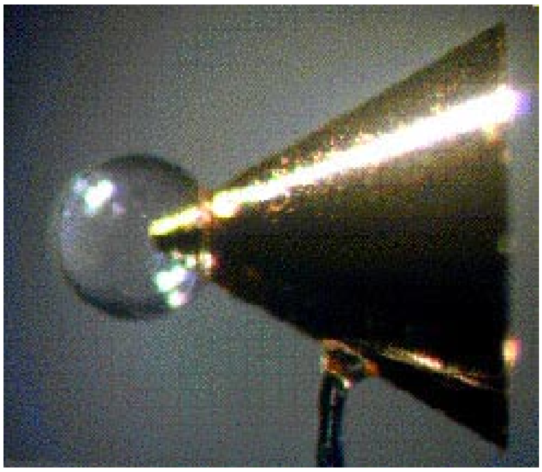


FIG. 4 Cone-shell target for fast ignition experiments.

We have performed fast ignition experiments using the PW laser to further confirm the enforced heating of the imploded core plasma with laser energy of 300 J at a peta watt level [6]. Targets are same as used at previous experiments [5]. Those are deuterated polystyrene shells with 500 μm in diameter and 7 μm thick with a hollow gold cone with a 5 μm plate at the tip. The tip of the corn is set to be at 50 μm from center of the shell. Shells are imploded with 9 green (λ=530 nm) laser beams of the Gekko-XII with an energy of 2.5 kJ for 1.2 ns flat-top pulses. The imploded core plasma is created at the target center and ismeasured to be 40-50 μm in diameter by X-ray back-lighting technique which has a temporal resolution of 100 ps. The average density is estimated to be 50-100 g/cm^3 from the opacity data of the x-ray back-lighting with the support of 2D simulation. The neutron yield by D-D reaction is 2-5x10^4 without heating pulse. The heating laser power is changed up to 0.5 TW.

Neutron yields are measured as a function of the injection timing of the heating pulse to the time of peak compression. The timing of heating is checked with x-ray streak images as well as the injection timing of the pulse to maximum compression, from hydrodynamic simulations of the shell implosion. Results are shown in Fig. 5. Enhancement is clearly appeared during $\pm$ 40 ps, at the maximum compression. The 80 ps correspond to the stagnation time of the imploded plasma and is two orders of magnitude longer than the heating pulse duration of 60 ps. The results suggest that heating for ignition could be possible

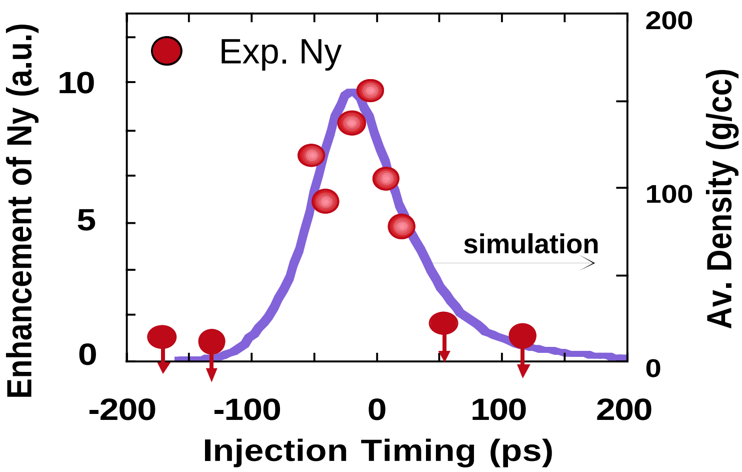


FIG. 5 Neutron yield dependence on injection timing of the heating pulse to imploded plasma.

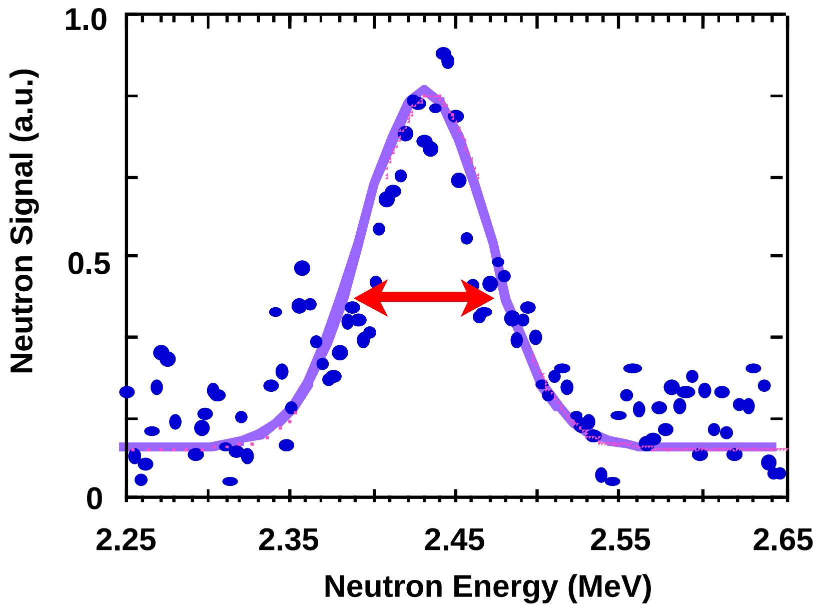


*FIG . 6 Neutron spectrum at the heating power of 0.5 PW. Ion temperature is*0.8 Il keV.

using a few peta watt laser of which pulse width is close to the duration of stagnation of compressed plasma.

Energy spectra of neutrons are measured using time-of flight scintillator-photomultiplier detectors at different distances and angles. The resolution of neutron energy is ~50-60 keV which corresponds to ion temperature of 0.3-0.4 keV. Figure 6 is the obtained neutron spectrum at the heating power of 0.5 PW. The spectrum fits well with a Gaussian profile which is the indication that the origin of neutrons is thermonuclear fusion. The spectral peak is at 2.45 keV within the resolution of diagnostics. The spectral width of this case is 90±5 keV, which corresponds to ion temperature of 0.86±0.1 keV. While the ion temperature was 0.3-0.4 keV for no heating pulse, which is less than or close to the spectral resolution. This means that temperature increase of core plasma is 400 eV at heating by the laser pulse with 0.5 PW in 0.6 ps, total energy of 300 J. This result is consistent with the enhancement of neutron yield by three orders of magnitude. The temperature is also estimated from the measurements of the change of intensity and spectra of x-rays from the heated core plasma using an x-ray streak camera. The electron temperature of 1±0.1 keV is obtained for the 0.5 PW heating from the intensity increase by a factor of 1.5-2.0 and slope of the continuum in the range of 3-4 keV.

Neutron yields dependence on the heating power is summarized in Fig. 7 for 0.6 ps heating pulses. Simple predictions of the neutron yield estimated based on the yield without heating are also shown as a function of the heating laser energy for the coupling from laser to the core plasma of 15% (dashed line) and 30% (solid line). The yield increases with almost constant coupling efficiency of 30% with increase of the laser power.

Energy transport of energetic electrons has been investigated by measurements of the rear side emission of solid plane targets. Al solid targets are irradiated with 20 to 500 TW laser. 2D images of the target rear side emission, indicating the energetic electron propagation, are measured with a 2-dimensional spatial-resolved UV high-speed sampling camera [11]. The images in 200 μm Al targets show a filamentary structure at lower power irradiation

(20TW/12J) and a single structure at a higher power (0.33PW/200J) with a beam divergence of about 20°. We have also investigated such filamentary propagation in different target material and for target thickness. All the data shows the number of filaments decreases with increasing the irradiation power, eventually to be single beam propagation at higher irradiation power. These results would promise efficient heating of imploded plasmas with jet-like relativistic electrons at a high current density close to the ignition condition such as peta watt laser. From all of these experimental results, it is suggested that heating to the ignition temperature 10 keV could be achieved with a few peta watt laser of which pulse width is close to the stagnation duration of imploded plasma.

4. Hydrodynamic Instability Research

Detailed understanding of the Rayleigh-Taylor (R-T) instability is essentially important both for the target and implosion lasers designs. The growth rate of the R-T instability is theoretically predicted by Takabe formula [12], and it is approved widely. However, to determine the reduction term of the growth rate appeared in the formula, which is given by $\beta k v_a$, as the ablation effect, one has to determine an unknown factor β. Here k and $v_a = m/\rho_a$ (m: mass ablation rate, ρ_a: density at the ablation front) are the wave number of perturbations and the ablation velocity of plasma. A lot of experimental and theoretical works have been done world wide to determine the growth rate and β. Betti *et al*. predict the value of β is 1.7 for CH targets [13]. However, no one has succeeded to determine β directly from experiments because of the difficulty of the measurement of ablation velocity v_a or density ρ_a, so that the value of β is usually discussed with help of numerical simulation.

We have studied extensively dependence of the growth rate of R-T instability on perturbation

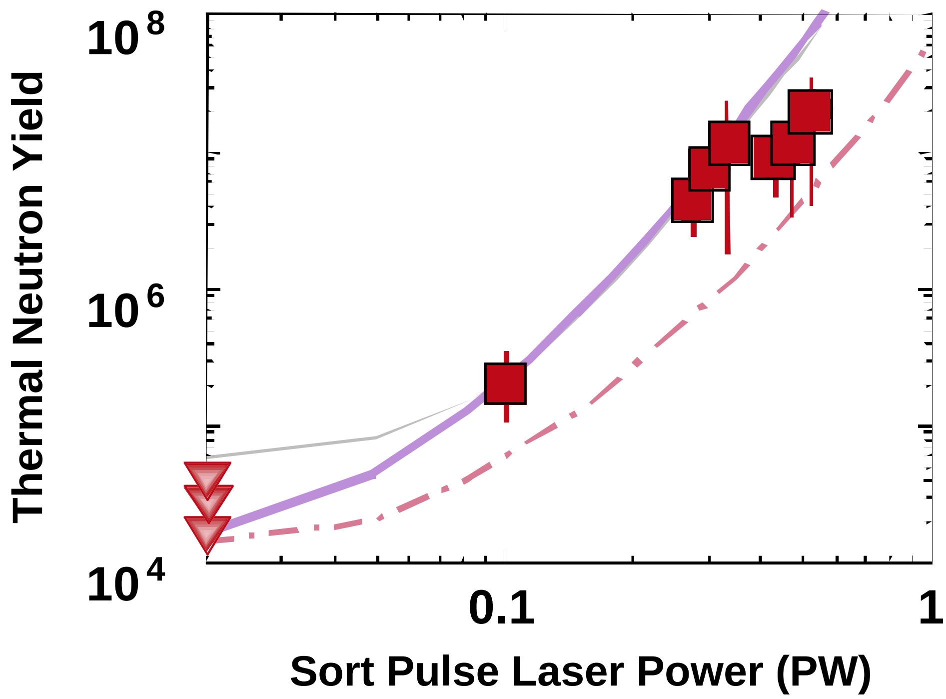


FIG. 7 Dependence of neutron yields on the heating power.
Solid and dashed lines correspond to energy Conversion efficiency from laser to plasma, 30% and 15%, respective.

wavelength using 530 nm wavelength laser, and have found that the growth rate for the case of 530 nm laser is suppressed significantly by the non-local heat transport of high energy electrons of the Maxwellian distribution tail. This time we have succeeded to measure the density profile of the plasma including ablation surface with spatial resolution of 3 μm using two methods; the penumbral imaging and the Fresnel phase zone plate methods. In the experiments, side-on x-ray backlighting technique with 4.8 keV Titanium line emission is employed for the measurements. These methods are applied for the determination of the R-T growth rate for the 350 nm laser ablation and will contribute to detailed understanding of the R-T instability. More informations are described in IF/P-15 in this Proceedings [14].

5. Theoretical Researches

Numerical simulation plays an important role in laser fusion research for understanding of implosion, spark formation and future planning. We have developed a new 2-D ALE (Arbitrary Lagrangian Eulerian) code, and also studied extensively high energy electrons transport for fast ignition with PIC codes and relativistic Fokker-Planck codes.

The hydrodynamic solver is the base line of the integration code of implosion. Because of the large scale-ratio of the expanded plasma to the target shell thickness, the implosion has to be solved on Lagrangian coordinate to save the computational resources and to capture the large gradient values in the phase space clearly. Therefore ALE codes based on Lagrangian method are used usually. However, computational grids are destroyed in general when applying the Lagrangian method, so that it is required a sophisticated and expensive rezoning/remapping algorithm to continue the calculation. In order to avoid such problems a simple hydrodynamic solver has been developed using CIP (Constrained Interpolation Profile) method [15]. The developed ALE-CIP method enables the code to execute accurate calculation and to capture the detail phenomena in the very wide dynamic range. The developed 2-D code is named PINOCO (Precision Integrated Implosion Numerical Observation COde) [16]. We have extended the Code for the simulation of non-spherical target such as a cone-shell target where accurate rezoning and material tracking systems are required. Figure 8 shows one of the simulation results of the corn-shell target implosion. The results agree well qualitatively with the fast ignition experiments showing that a high density core plasma is formed as well as the spherical implosion and it stays longer than in the spherical implosion. Experimental results with detailed density and temperature profiles are expecting for the quantitative check of accuracy of the code. Detailed is shown in the paper of IF/P-07 this Proceedings.

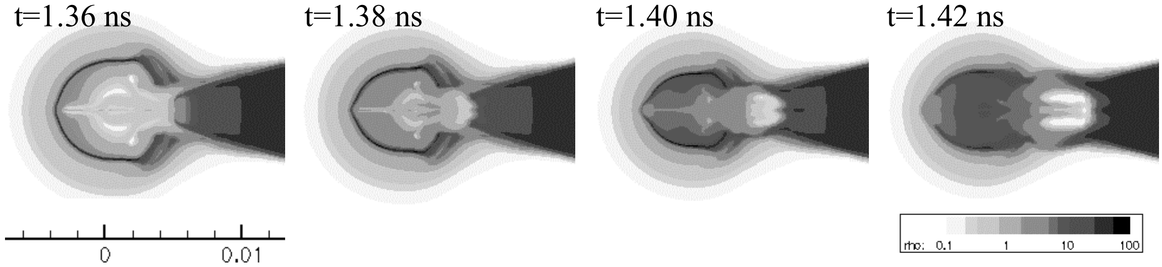


FIG.8 The time history of the density contours in the implosion with conical target case.

An integrated code for describing the fast ignition dynamics is under development. It consists of 2D hydro-code (PINOCO), a relativistic Fokker-Planck (F-P) code and a 2D-PIC code. In this code the relativistic electron generation and the transport in the corona plasma are described by 2D-PIC code. The output of the PIC simulation is used in the F-P code to simulate the heating process in the implosion plasma. A PIC simulation result on the relativistic electron transport is shown in Fig. 8. It is found that an intense relativistic electron flow breaks up to many filaments near the surface by the Weibel instability, and then they are merged into a few filaments as shown in the cross-sectional view of the magnetic field distribution. And finally as seen in the figure, the filaments are merged into one and self-pinched on the rear surface of the plasma.

6. FIREX Program for Demonstration of Proof-of-Principle of Ignition

On the basis obtained through experimental and theoretical researches and technological developments, we have proposed the FIREX (Fast Ignition Realization Experiment) program for demonstrating the proof-of-principle of ignition by the fast ignition scheme. This program consists of two phases, FIREX-I and FIREX-II. Each phase is planned in 6 years for including construction of the required installation. In FIREX-I we will construct a heating laser with output energy of 10 kJ in 2-10 ps which is estimated to be enough for heating a thousand times solid density DT plasma to the temperature at which α-particle heating overcomes the radiation loss. Four beams are planned for delivering 10 kJ at peta watt level. Each beam of which can deliver 2.5 kJ in 10 ps. With this heating laser and GEKKO-XII implosion laser which can deliver 10 kJ in wavelength of 530 nm, we are planning to achieve the heating up to 10 keV and the fusion gain of unity. In the second phase, FIREX-II, the implosion laser

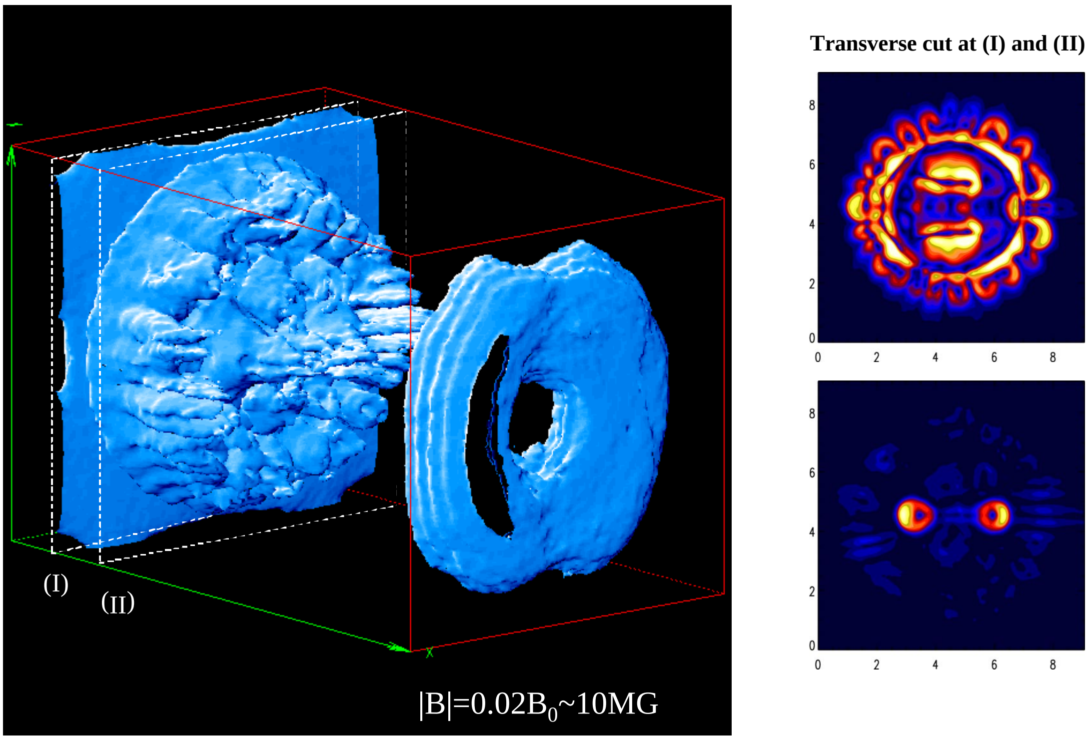


Fig. 8 PIC simulation results of relativistic electron transport. (I) and (II) show the isosurface of the quasi-static magnetic field $<|B|>$ *which is the reflection of electron beam currents.*

will be upgraded to 50 kJ in wavelength of 350 nm to increase the mass of the imploded plasma (density-times-radius ρR to 0.7 g/cm^2)which is able to maintain α-burn propagation and release an energy gain of ~10.

We are planning to perform two types of experiments in the first phase. One is the experiment using the cone-shell targets. The most important issue to be studied is the cone physics. Relatively long pulse irradiation into the inside of the cone generates a plasma which may affect to the generation of high energy electrons, especially the conversion efficiency from laser to energetic electrons. The other is the experiments where the high density plasma is produced using the conventional spherical shell targets and is heated by irradiating a heating pulse through peripheral corona plasma. The physics of intense laser beam propagation in peripheral corona plasma should be studied although we have some experimental data for intense beam (0.1 PW beam) propagating into an over-dense region without energy loss and a vacuum channel formation in the corona plasma with non-relativistic intensity region [3].

7. Summary

We have upgraded Peta Watt Module (PWM) laser to Peta Watt (PW) laser, which can deliver 1 PW, and have introduced to the fast ignition experiments. Three new technologies are introduced; 1) OPCPA amplifier in front end, 2) adaptive mirror in front of the final pulse compressor and 3) use of chirped pulse for the source pulse of the Gekko XII implosion laser. By these techniques, a very high signal-to-noise ratio, high focusability and accurate synchronization between the Gekko XII and the PW lasers are achieved.

In the experiments of the fast ignition using PW laser, enforced heating of the imploded core plasma up to 1 keV has been achieved with high conversion efficiency from laser to thermal energy of plasma. The D-D neutron yields are enhanced 3 orders of magnitude. It is also found by the experiments and simulations that the relativistic electron beam can propagate in dense plasma as a single beam. These results suggest that heating to ignition temperature of 10 keV could be achieved with a few peta watt heating lasers of which pulse width is close to the duration of stagnation of imploded plasma. Based on these results we have proposed the FIREX (Fast Ignition Realization Experiment) program in order to demonstrate the proof of principle of ignition by the fast ignition scheme.

References

[1] TABAK, M., et al, Phys. Plasma **1** (1994) 1626. YAMANAKA. T, Internal Rep. ILE Osaka Univ. (1983) 4 (in Japanese. unpublished).

[2] KODAMA. R., et al, Phys. Rev. Lett. **77** (1996) 4906.

[3] TANAKA, K. A., et al, Phys. Plasma **7** (2000) 2014.

[4] KODAMA, R., et al, Phys. Plasma 8 (2001) 2268.

[5] KODAMA, R., et al, Nature **412** (2001) 798.

[6] KODAMA, R., et al, Nature **418** (2002) 933.

[7] KAWASHIMA, T., et al, *Inertial Fusion Sciences and Applications 2001* (TANAKA, K.

A., et al, Ed) Elsevier, (2002) 505.

[8] NORIMATSU, T., et al, 19th IAEA Fusion energy Conference, Lyon (2002) IAEA-CN-94/FT/1-3Ra.

[9] KOZAKI, Y., et al, 19th IAEA Fusion energy Conference, Lyon (2002) IAEA-CN-94/FT/P1-25.

[10] IZAWA, Y., et al, 19th IAEA Fusion energy Conference, Lyon (2002) IAEA-CN-94/IF/P-04.

[11] KODAMA, R., et al, Rrv. Sci. Instrum. **70** (1999) 625.

[12] TAKABE, H., et al, Phys. Fluids **28** (1985) 3676.

[13] BETTI, R ., et al, Phys. Plasma 5 (1998) 1446.

[14] SHIGEMORI, T., et al, 19th IAEA Fusion energy Conference, Lyon (2002) IAEA-CN-94/IF/P-15.

[15] YABE, T., et al, J. Comput. Phys. **169** (2001) 556.

[16] NAGATOMO, H, et al, *Inertial Fusion Sciences and Applications 2001* (TANAKA, K. A., et al, Ed) Elsevier, (2002) 140.