PROGRESS OF DIRECT DRIVE LASER FUSION RESEARCH AT ILE, OSAKA

K.MIMA, H.AZECHI, H.FUJITA, N.IZUMI, T.JITSUNO, Y.KATO, T.KANABE, Y.KITAGAWA, R.KODAMA, N.MIYANAGA, M.NAKAI, M.NAKATSUKA, S.NAKAI, H.NAGATOMO, T.NORIMATSU, K.NISHIHARA, H.NISHIMURA, H.SHIRAGA, H. TAKABE and T.YAMANAKA

Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan
mima@ile.osaka-u.ac.jp

C. YAMANAKA
Institute of Laser Technology, 1-8-4 Utsubohonmachi, Nishiku, Osaka, 550-0004, Japan

A. NISHIGUCHI
Osaka Institute of Technology, Omiya, Asahi-ku, Osaka 535-0002, Japan

Abstract

Reviewed are the recent achievements of the researches on hydrodynamics, hybrid implosion, fast ignitor and so on. As for hydrodynamics, initial imprint as a seed of the implosion nonuniformity and hydrodynamic instabilities have been investigated. In the hybrid implosion experiments, it is found that the X-ray pre-irradiation and the low density foam layer mitigate the initial imprint. In the research of fast ignitor, investigated are hole boring, high energy electron generation and transport, inward high energy ion generation and related neutron yield and so on. Finally, future prospects of laser fusion research at ILE, Osaka University are also discussed.

1. INTRODUCTION

Since we demonstrated high density compression by laser implosion, the key research issues are how to keep the implosion stability and to generate a hot spark in high density plasmas. In order to solve these research issues, we have worked on very precise experiments and theoretical analysis of initial imprint and hydrodynamic instabilies [1], development of uniform laser irradiation technologies [2], implosion dynamics of hybrid target and ultra-intense laser interactions with dense plasmas by using the peta watt module (PW-M) laser in relation with fast ignitor [3]. In the following, recent research results in the above items are summarized.

2. LASER TECHNOLOGY AND LASER PLASMA PHYSICS RELATED TO FAST IGNITOR

The PW-M was constructed and operated in synchronizing with the GEKKO XII laser. The time zitter is less than 100 psec. The out-put energy reached higher than 50J with a pulse width of sub-picosecond. We also carried out hole boring and heating experiments for imploded CD plasmas by the GEKKO XII laser. In the experiments, a pulse train which consists of two 100J /100ps pulses is used. The hole boring is investigated by x-ray images. Figure.1 shows how a 100ps drilling pulse with 1.06μm wavelength reaches imploding solid density shell. A 500μm diameter CD pellet is imploded by 10 beams of 0.53μm wavelength and a 100psec double pulse with an intensity of 2×10^{17} w/cm^2 irradiates the plasma. Figure. 1 indicates that the 1μm laser light self-focused in the corona plasma to produce a hot spot in the x-ray image.

In the heating pulse train experiments, we also found that DD neutron yields increase by one order of magnitude in comparison with those of non-heating implosions. The shift and spread of neutron energy are large in the forward direction with respect to the heating laser injection direction. From the neutron energy spread and its angular dependence, it is found that energy of reacting deuterons reaches several hundreds keV and collimated in the toward direction. These results indicate that the ions are directly accelerated by very high radiation pressure in a laser channel.

In 100 TW PW-M laser plasma experiments, we observed neutrons together with strong MeV X-ray emission. The neutron yield is the order of 10^6 when a CD foil is irradiated. Energetic deuterons in this case may be produced by the Coulomb explosion of photon bubbles generated by the relativistic modulational instability.

In Fig.2., angular dependence of the neutron spectrum is shown where a short pulse laser irradiate a planar target with an intensity of 5 10×10^{12}ω/cm^2. Neutrons are predominantly emitted in the forward direction and the spectrum is significantly broader in the case of 54.7˚ than in the case of 90˚. These results are compared with the simulation results which are shown in Fig. 3. The neutron spectral shapes of the simulation for the energy higher than 2 MeV agree well with those of the experiments. From this similarity, we can conclude that the neutrons are generated by high energy ion beams which are accelerated by the laser radiation pressure. The ion beams are expected to be well collimated in forward direction according to the simulation results.

Although the experiments on the fast ion generation are preliminary, the results suggest that imploded core plasmas could be heated by intense ion beams collectively accelerated by the laser radiation pressure. In the short pulse laser plasma experiments, long-scale jet like x-ray emission was observed. The jet-like emission appeared from the target surface into the underdense region for distances of >3mm to the direction of the specular reflected laser light. Figure.4. shows a typical jet-like emission from the target rear side. The divergence of the jet is estimated to be 10~20 mrad for 3mm distance. The experimental results are compared with two dimensional particle simulations. In the simulations, a few MeV high energy electrons are ejected from the laser spot to the direction of the specular reflected light and to the inward direction which is normal to the target surface. The generation of those MeV electrons are explained by the relativistic resonance absorption and the wake field acceleration in the underdense plasma. The inward jet as shown in Fig.5 is useful for the core plasma heating. The present simulation results show that the inward jet contains about 20% of incident laser energy.

In summary for the fast ignition research, both inward ion and electron-jets with energies of MeV will be useful for heating the core plasmas. The coupling efficiency to the inward beams can be higher than 30%. If the heating efficiency is higher than 30%, the additional heating concept and/or fast ignition concept will work for high gain fusion burning.

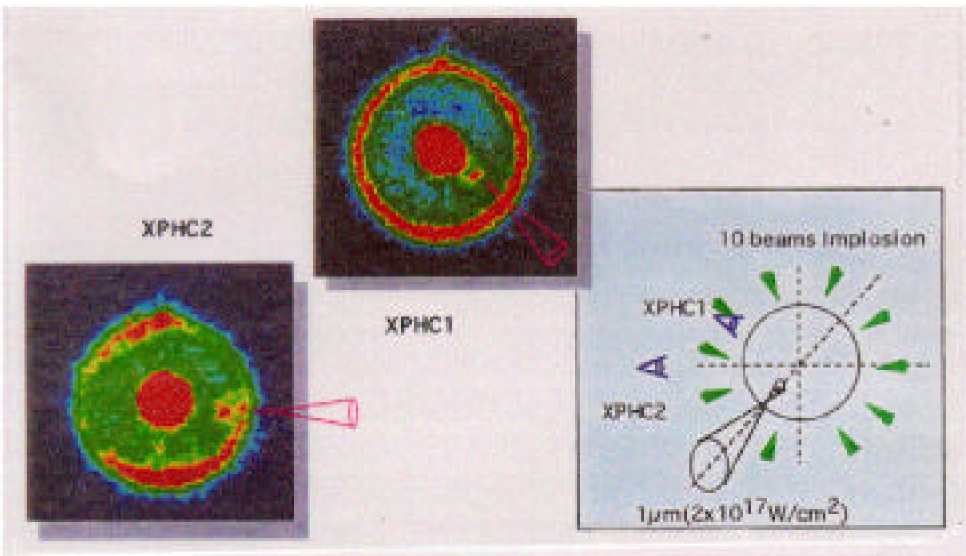

FIG.1. X-ray Images indicate additio nal heating of the shell 1 μm laser light self focused when a CD shell target was imploded by 10 beams of 0.53μm laser light.

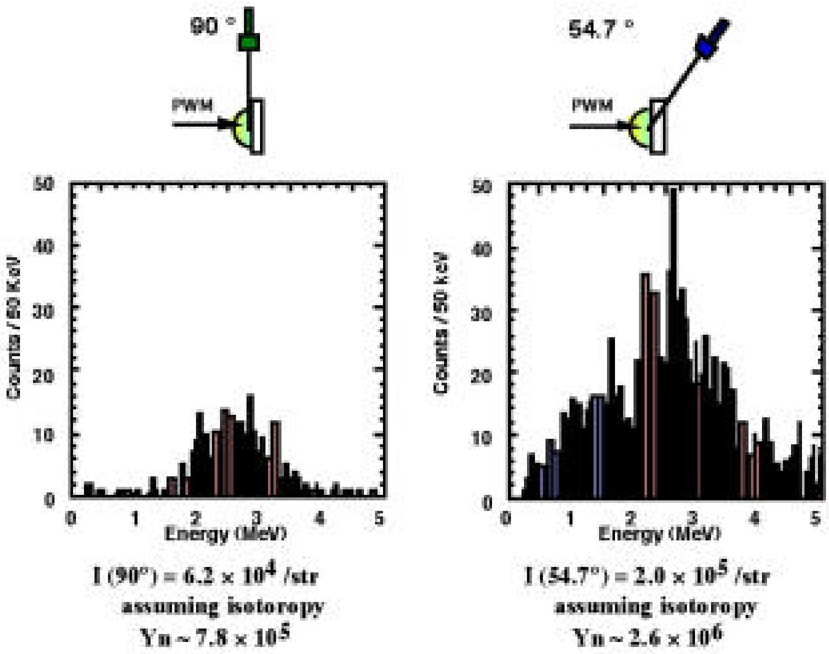

FIG.2. D-D neutron spectrum measured by a multi-channel neutron spectromete "Mandala" Neutrons are generated by 100TW laser beam interaction with a solid CD target. The energy spread is the order of MeV

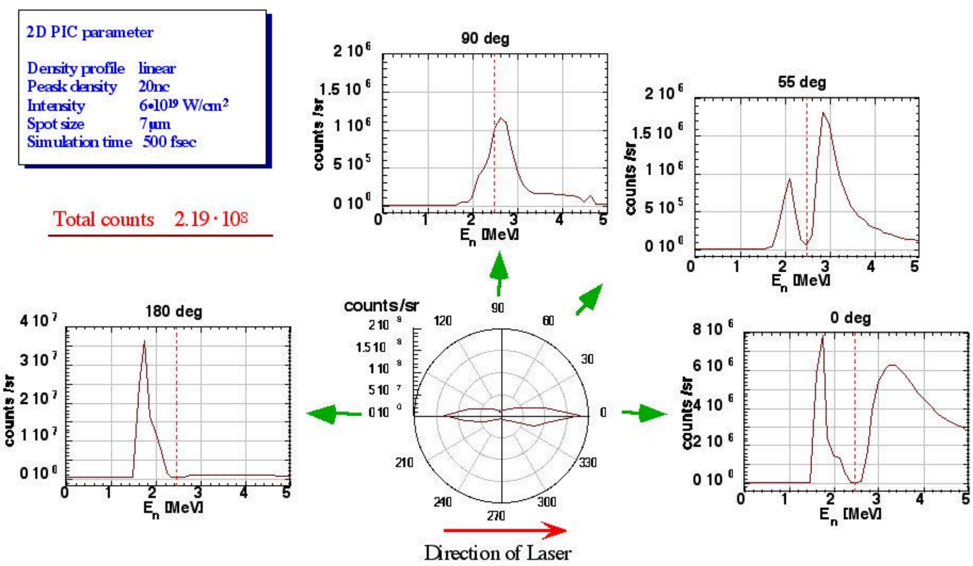

FIG.3. Simulation results for ion angular distribution and neutron energy spectrum. The 4 neutron spectrum are for the directions 0˚, 55˚, 90˚ and 180˚ with respect to the inward target normal. The central circule shows the ion angular distribution.

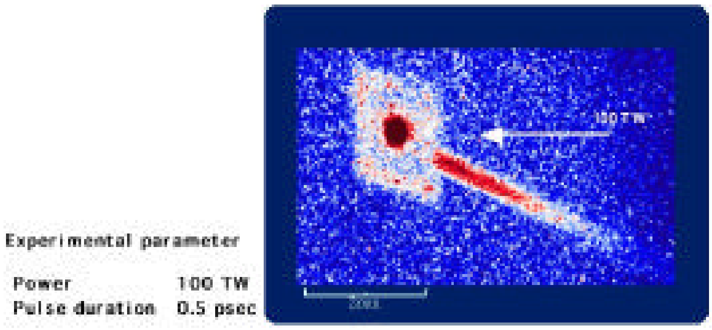

FIG.4. X-ray image with the large aperture pinhole camera showing a mm-scale jet-like emission.

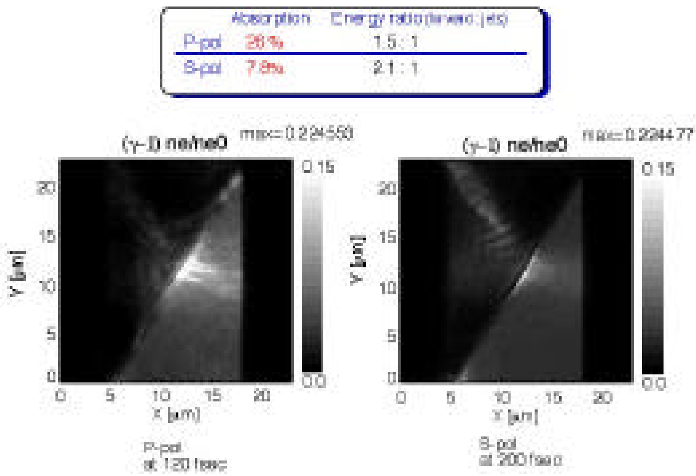

FIG.5. Absorption efficiency and energy ratio of forward electron jet to specular jet
In the overdense plasma, electrons are emitted toward target normal direction for P-polarized laser and toward the laser incident direction for S-polarized laser.

3.INDIRECT-DIRECT HYBRID IMPLOSION EXPERIMENTS

In order to reduce small scale non-uniformities generated by irradiation intensity fluctuation, indirect-direct hybrid scheme targets are proposed. This concept combines smoothing by x-ray heating in the start-up phase and acceleration by the direct drive. We have investigated two types of hybrid implosion. One is called external x-ray hybrid implosion in which a fuel pellet is covered with a gold cavity which has 12 holes for direct drive laser beams as shown in Fig.6.(a). Pre-pulse beams which are off-axis of main beams irradiate the cavity inner surface to emit x-ray, and the main beams directly irradiate the fuel pellet. The other is the foam hybrid target which has been fabricated as reported in the last IAEA conference in Montreal [2]. The fuel pellet is covered by a thick foam layer with a thickness of 20μm and density of 80mg/cc (see Fig.6.(b)). In the experiments, it is found that effects of irradiation non-uniformities on an accelerated foil are significantly reduced.

Implosion experiments for the two types of hybrid target shown in Fig.6 have been carried out recently. Although small scale irradiation nonuniformities might be mitigated, the neutron yeilds normalized by 1D simulation yeilds and the x-ray framing images are not improved, as we expected. This may be attributed to large scale nonuniformities which depend upon the irradiation geometry. In order to reduce the large scale nonuniformities, we are introducing the kino phologram plate (KPP) to optimize beam envelop shape.

FIG.6.(a)

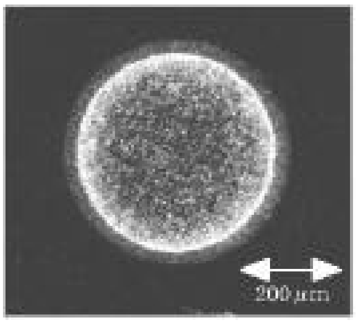

FIG.6.(b)

FIG.6. External x-ray hybrid target and foam hybrid target
This is a proposed new target design for the indirect-direct hybrid implosion. 12 beams of GEKKO XII laser are separated into two part. The central small parts of the beams are deflected by optical wedges to irradiate the gold cavity inner wall. The main parts of the beams directly irradiate the fuel pellet.

4. HYDRODYNAMIC INSTABILITY

A series of experiments has been conducted on the GEKKO XII laser facility to measure hydrodynamics of planar targets accelerated by 0.53μm wavelength PCL beams. Since the last IAEA conference, we accumulated data base on the laser imprint efficiency for various spatial modes and time dependent laser intensity modulation. Parametric study of Rayleigh-Taylor instability is also continued to clarify the growth rate reduction by nonlocal heat transport process. Using the implosion stability data base which is available at present, we checked the stability of a high gain implosion where the gain is 100. It is found that the R-T growth rate reduction stabilizes the high gain implosion significantly.

The spherical asymmetry is introduced by pellet nonuniformities and laser irradiation nonuniformity. The pellet fabrication techniques have been developed substantially in this decade to supply high quality pellets for the coming ignition experiment. However, the laser irradiation uniformity is not sufficient to keep turbulent mixing low enough on the interface between hot spark and main fuel.

In these two years, imprints of laser irradiation nonuniformities on ablatively accelerated target and the following hydrodynamic instabilities are investigation by theory and experiments. Figure.7(a)-7(c) show the x-ray streak images for the case of (a) 40%, (b) 10% imposed Nonuniformity of the laser beam, and (c) without nonuniformity. We irradiated an unperturbed polystyrene target of a 16μm thickness with a two stepwise PCL pulse. The pulse consists of a pre-pulse at an intensity of 4×10^{12}W/cm^2, 1.8ns long and a subsequent main drive at an intensity of 7×10^{13}W/cm^2, 1.8ns or 2.2ns long. The nonuniformity is imposed only on the foot pulse. In the case (a) and (b), the x-ray contrast increases with increasing nonuniformity. No perturbation on the x-ray image of the case (c) is not observed. Figure.7(d) shows the areal-mass perturbation devided by the imposed irradiation nonuniformity $\delta I/Io$ versus time. The data for the 40% and

10% intensity modulations are in good agreement with each other indicating that the imprint process is essentially linear. The interference fringe is nearly averaged out in the time-integrated image as shown in Fig.7(c).

The equivalent initial surface perturbation is defined by $\delta(\rho l)=\delta(\rho l)_o G(t)$, where $\delta(\rho l)_o$ is the equivalent initial areal mass perturbation and G(t) is the measured growth factor. The $(\rho l)_o/\delta I/I_o)$ is found to be 0.8μm g/cm^3 in the present case where the perturbation wave length is 60μm. The experimental data for $\delta(\rho l)_o$ are accumulated for various wavelengths and a typical laser pulse shape. The results will make the requirements of laser irradiation uniformity to be clear for achieving high gain implosion.

The imprint model is also tested for the experiment where the nonuniformity is temporally changed. The nonuniformity was constructed by Young's interference but with two different laser wavelengths, as shown in Fig. 8(a). Due to the frequency deference $\delta\omega$, the interference fringes move in the direction of modulation. The time scale of the motion of interference fringe on the target plane recorded by a streak camera.

The effective reduction of the imprint can be expected when the cycle of the oscillation of the irradiation nonuniformity is comparable to or less than the time interval during which the momentum perturbation is imprinted. This time interval would be about the time required to establish corona plasmas cloud so that the thermal smoothing sufficiently reduces the pressure perturbation after this time interval. The ILESTA-1D predicts that large enough corona plasmas are established by the time of about 100 ps after the onset of the foot pulse. Since this time interval is long compared to the cycle of the laser nonuniformity, the imprint is expected to be reduced significantly, as observed.

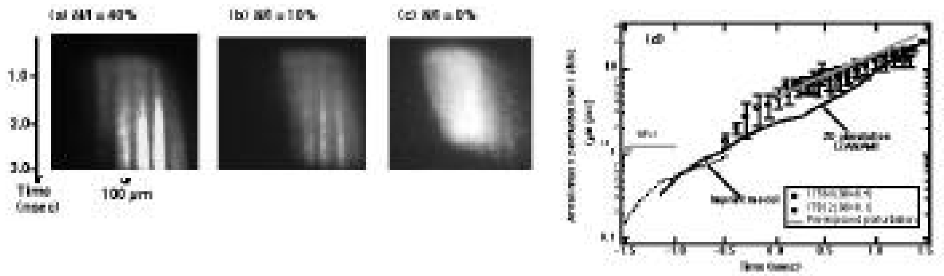

FIG.7. Results for static imprint experiments. (a)-(c):Streak x-ray backlighting images of the accelerated plastic planar targets irradiated with a sinusoidally modulated laser beam of 40%, 10% modulation depth, and no modulation respectively. The imprinted areal-mass perturbatios are amplified by the subsequent R-T instability driven by uniform laser irradiation. No significant perturbation is observed for the case of no modulation(c). The timing of the vertical axis is arbitrarily offset. (d):Areal-mass perturbation divided by the laser irradiation nonuniformity $\delta I/I_o$ versus time for the 40% and 10% modulation cases. Two solid curves are the corresponding data of the growth from the preimposed perturbation, and the result of the two-dimensional hydrodynamic simulation IZANAMI.

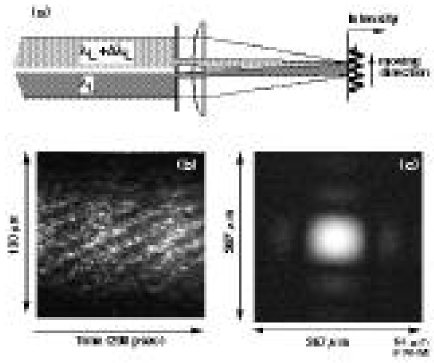

FIG.8. (a) Set up Young's interferometer with two different laser wavelengths, constructing the moving interference fringe. (b) A streak record of the focal pattern on the target plane. Titled lines are the moving fringe. (c) A time-integrated focal pattern.

5. SUMMARY

In these two years, we concentrated our effort on investigating two innovative implosion concepts which are fast ignition and direct-indirect hybrid implosion. New findings are listed below;

(1) A 100 J / 100 ps pulse injected into an imploding pellet penetrates deeply into the overdense region to produce a hot dense spot and enhances the neutron yield.
(2) The PW-M laser is operated at 50 J / 0.5 ps and used for target experiments. High neutron yield with strong X-ray emission is observed.
(3) A new type hybrid target is designed and will be used for experiments.
(4) Experimental and theoretical data basis for implosion hydrodynamics are accumulated. By using the data base, we found that the hydrodynamic stability of high gain implosion can be retained.

REFERENCES

[1] AZECHI. H., et al., "Direct-drive hydrodynamic instability experiments on the GEKKO XII laser", Phys. Plasmas 4 (1997) 4079-4089
[2] MIMA. K, et al., " Recent progress of laser fusion research with the GEKKO lasers at ILE, Osaka", in Fusion Energy 1996, vol.3, IAEA-CN-64 / B1-2, 13
[3] KATO, Y, etal, "Approaches to fast ignition in inertial confinement fusion at ILE, Osaka" ibid., vol.3, IAEA-CN-64/B2-6, 85 (1996)