Advances of Direct Drive Schemes in Laser Fusion Research at ILE Osaka

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Abstract. ILE Osaka is concentrating on the physical elements of fast ignition aiming at the proof of principle for ignition-and-burn of direct-drive laser fusion. A 1PW laser will be introduced to fast ignition experiments by the middle of 2001. A high intensity plasma experimental research system, HIPER, has been in operation for obtaining scientific data base relevant to ignition target. By irradiating a intense short pulse onto a long scale length plasma observed are penetration of a relativistically self-focused laser beam into over-dense region without considerable energy loss in under-dense region, MeV electrons generation with conversion efficiency of 25%, heating of compressed core plasma by irradiating a 100 ps, 10^{17} W/cm^2 pulse and 1 ps, 10^{19} W/cm^2 pulse. In the hydrodynamic instability, the initial imprint of hydrodynamic instability and Rayleigh-Taylor growth rate at wavelength less than 10 μm have been investigated extensively.

1. **Introduction**

After the demonstration of high-density compression [1], the laser fusion research has moved towards the demonstration of ignition-and-burn. The key issues to be studied are how to make a hot spark enough for ignition-and-burn to achieve a high gain. Two methods are investigated for ignition-and-burn. One is the conventional central ignition and the other is the fast ignition [2,3] , which has possibility to achieve higher gain by a smaller laser than the central ignition and has become possible to do experiments recently by the progress of chirped pulse amplification technique of laser pulse [4].

In the fast ignition, the physics related to the energy transfer from the laser beam to the small part of the compressed core plasma of which density is much higher than the cut-off density of the laser beam ; penetration of laser beam into overdense region with relativisitic effects, generation of an intense energetic electron beam, heating a small region of low temperature compressed core plasma with density of > 10^{25}/cm^3 up to ignition temperature of about 10 keV, etc. In the central ignition subjects to be investigated are detailed understanding of Rayleigh-Taylor (R-T) instability at ablation surface with particle and energy flows and development of technologies to reduce the sources of R-T instability such as surface roughness of fuel pellet and laser irradiation non-uniformity which imprints the surface purterbation at very early time of laser irradiation.

The fast ignition is our main program in these ten years and the final goal is the proof of principle of the fast ignition concept. Physics related to the intense short pulse laser propagation into the long scale length plasma and heating of implosion plasma are studying, using a 100 TW laser (Peta Watt Module; PWM) coupled with Gekko XII with synchronization within 100 ps jitter and 50 TW Gekko MII laser. Advances have been found in propagation of short pulse in the plasma, energetic electron beam transport and its energy deposition in the solid and imploded plasma [5, 6]. In the area of hydrodynamic problems investigated are the growth rate of R-T instability at short wavelength, initial perturbation imprint by spatially moving irradiation non-uniformity, mitigation of imprint by x-ray pre-irradiation and direct-and-indirect hybrid scheme [7]. Advancements are also found in laser technology [8, 9], target fabrication technology [10] and physics related to reactor chamber [11].

This paper summarizes the laser facility of our institute, some important experimental results of fast ignitior and hydrodynamic instability.

2. Laser Facility

There have been two advances in laser facility from 1988FY; one is the upgrade of the Peta Watt Module (PWM) laser (0.1 PW, 0.8 ps) [12] to the output power of 1 PW which is used for the formation of ignitor. The other is the new irradiation system of the Gekko XII, named HIPER (High Irradiation Plasma Experimental Research) [8], which is used for accumulation of precise data base for the formation of a low isentrope high density plasma and for the formation of an ignition for the central ignition.

2.1 PW System

The upgraded 1 PW system (PW system) will be assembled by the end of 2000 and introduced to the fast ignition experiments coupling with the Gekko XII by the middle of 2001. The output energy is 800 J in 0.8 ps in wavelength of 1050 nm and in beam diameter of 50 cm. More than 500 J will be delivered to an imploded plasmas. The synchronization with the Gekko XII is less than 10 ps.

An output pulse from the oscillator is stretched from 150 fs to 3 ns with a 2 stage pulse stretcher in order to avoid beam breakup and damage of optical components in the amplifier chain. The stretched pulse is divided into two beams. One beam is supplied to the amplifier chain of the PW system and the other is used as a master pulse of the Gekko XII. By this way high performance of synchronization can be achieved. The main amplifier is a Cassegranian 3-pass amplifier consisting of 8 disc glass plates with an ability to deliver up to 4 kJ in 3ns. The output pulse is transferred to the pulse compressor with a 94-cm grating pair in a 2.6m$^{\varphi}$ × 11.4m^{l} vacuum chamber through a 1:1 image relaying spatial filter, a deformable mirror and a beam expander from 35 cm to 50 cm in diameter. The deformable mirror corrects the wave front of the laser beam for energy concentration at the focal point. High performance of the deformable mirror to the beam quality is proved with PWM laser. A removable 20-cm Faraday rotator is set in the spatial filter to protect the front-end agent the reflected light from the target. The focusing optics is an off-axial parabolic mirror with focal length of 3.5 m and incident angle of 20 degree as shown in Fig.1. The beam is injected to the imploded high density plasma in the equator plane of the target chamber.

2.2 HIPER System

The target chamber II of the Gekko XII has been converted from two-side irradiation

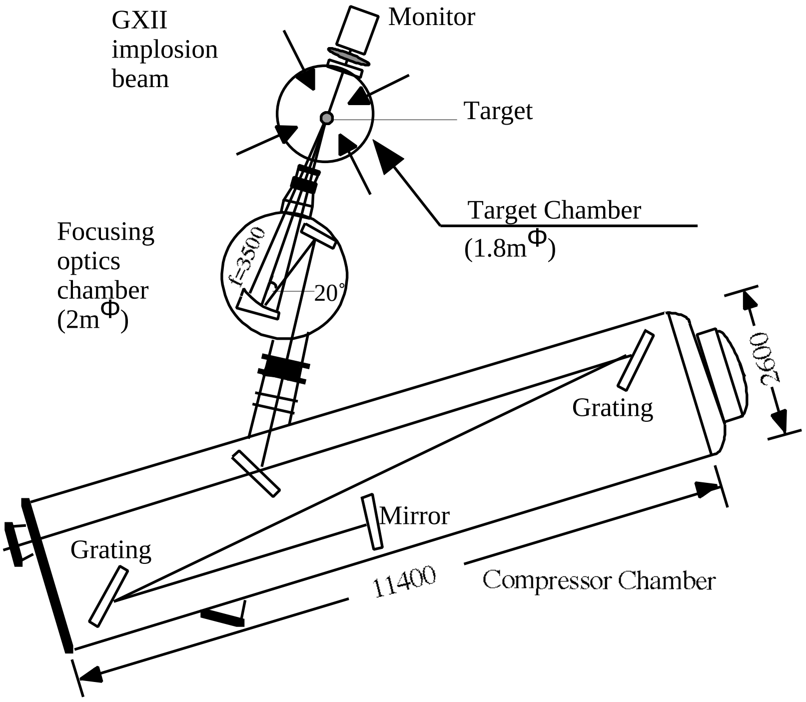


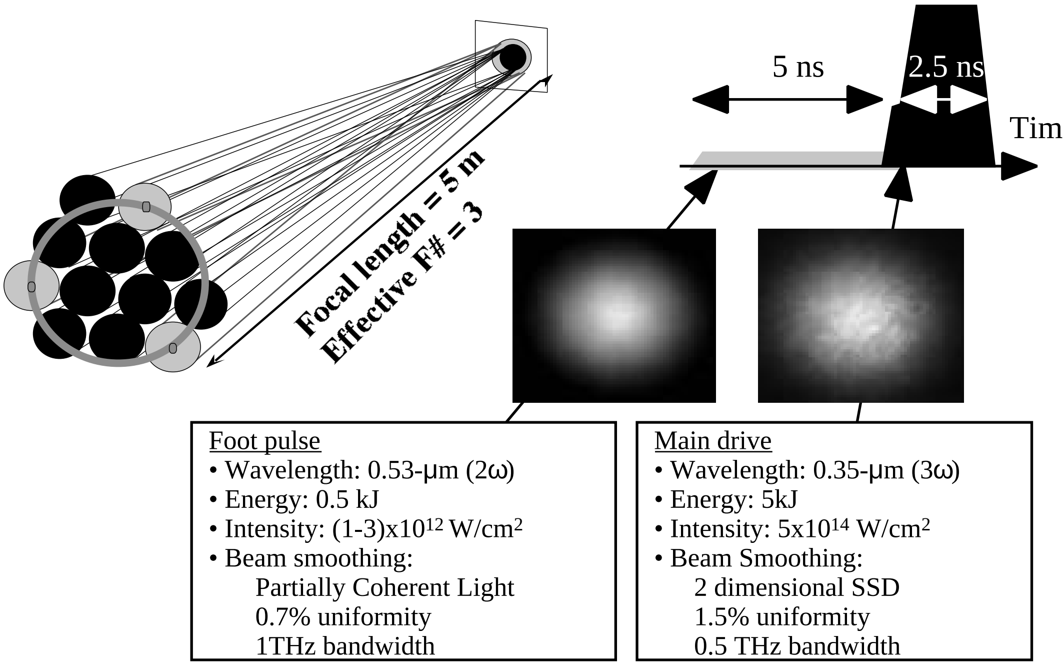
FIG.1 Schematic arrrangement of compressor and focusing system of Peta Watt laser.

arrangement to one-side irradiation arrangement in order to obtain scientific data base relevant to ignition targets, and that is named HIPER irradiation system. Twelve beams of the Gekko XII are bundled to irradiate a target from one side. The F number is 3 and focal length is 5 m. Three beams are 530 nm spectrum-dispersed partially coherent light (PCL)[13] with band width of 1 THz to deliver a highly uniform foot pulse of implosion. Remaining 9 beams are 2D or 3D spatially-spectral-dispersed (SSD) light [14] with wavelength of 350 nm and are used for main drive pulses for implosion. The total energy and intensity of the foot pulse are 500 J and (1-3) × 10^{12} W/cm^2 in 1 mm spot, respectively. Typical pulse shape is rectangular with rise time of 50 ps and pulse width is able to change up to 5 ns. The irradiation non-uniformity is 0.7% rms with 2D angular spectral dispersion mode [15]. The required averaging time for irradiation non-uniformity 0.7% rms is 500 ps. The performances of the main pulse are 5 kJ in energy, 5 × 10^{14} W/cm^2 in intensity in 0.7 μm spot, 1.5% rms in irradiation non-uniformity with spectral band width of 0.5 THz. The required time to reach 1.5% rms non-uniformity is 1 ns for 2D-SSD light. The output pulse from the main amplifier of PW laser is used for the beam to produce an x-ray source for diagnostics of plasma. Beam arrangement and typical pulse shapes are shown in Fig.2 with intensity patterns. Detail is described in Ref. [8].

3 Fast Ignition Experiments

Following experiments have been conducted for the study of the fast ignition. First three categories are performed with PWM laser at intensity of 10^{19} W/cm^2. The last one is done both with a short pulse (100 ps) from the Gekko XII at 10^{17} W/cm^2 and an ultra-short pulse from PWM. Those are

(1) Ultra-intense laser behavior in plasmas on planar targets,
(2) High energy electron generation and its heating of solid target,
(3) Energetic ion generation and the subsequent fusion process, and



Foot pulse
- Wavelength: 0.53-μm (2ω)
- Energy: 0.5 kJ
- Intensity: (1-3)x10^{12} W/cm^2
- Beam smoothing:
  Partially Coherent Light
  0.7% uniformity
  1THz bandwidth

Main drive
- Wavelength: 0.35-μm (3ω)
- Energy: 5kJ
- Intensity: 5x10^{14} W/cm^2
- Beam Smoothing:
  2 dimensional SSD
  1.5% uniformity
  0.5 THz bandwidth

FIG.2 Schematic illustration of HIPER system with beam pattern and specification for laser beams: Three green beams are used for foot pulse of implosion. Nine blue beams for main drive pulse pf implosion.

TAB. I: EXPERIMENTAL CONDITION OF FAST IGNITION

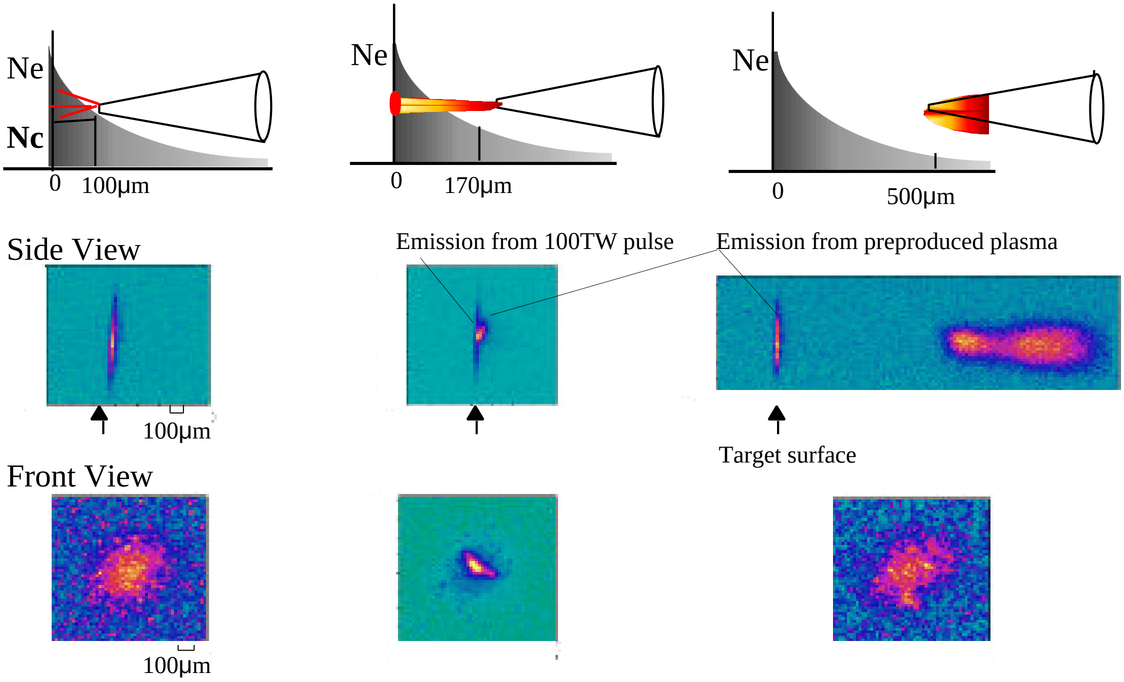
Intense short pulse		Related to target plasma production	
PWM		Gekko XII	530 nm
Wavelength	1050 nm	Wavelength	
Pulse width	0.5 - 1 ps	Energy/Pulse width/No.beam	
Energy	40 - 50 J	for planar target	
Beam diam.	annular	300 J / 100 ps / 3 beams	
	20 out. diam.	for implosion	
	10 in. diam.	1 - 21 kJ / 1 ns / 12 beams	
Intensity at focal point	$10^{18} \sim 10^{19}$ W/cm^2	Size of Plasma/Scale length/Temp.	
Focusing optics	F/3.5 on - axis	Planar	
	Palaboric Mirror	500 μm / 100 μm - 200 μm at < n_c / a few KeV	
		Implosion	
		in corona	
GXII	1050 nm, 100 ps	> 500 μm / 100 μm - 200 μm at < n_c / Te = a few KeV	
GMII	1050 nm, 0.5 ps	core plasma	
	50 TW	30 μm - 5 μm / / Ti = 300 - 400 eV	

(4) Heating of compressed core plasmas by self-focusing and high energy electrons.
Obtained are promising experimental results for the fast ignition and useful data to understandthe physics of intense laser interaction with plasmas. The typical experimental conditions are
shown in Table I.

3.1 Ultra-Intense Laser Behavior in Plasma

It is an important subject for the fast ignition concept to know if an ultra-short laser pulse with an intensity exceeding 10^{19} W/cm^2 can propagate into over-dense region with minimum energy loss through a thick corona plasma with relativistic self-focusing, since nonlinear interactions such as a parametric instability takes place in under-dense region and laser energy is dissipated. Therefore it is considered that a vacuum or low-density channel (plasma channel) would be required for sending an intense short pulse into over-dense region without energy loss. In the previous works [16, 17], we succeeded in forming a plasma channel (hole boring) in the corona plasma, reaching to the over-dense region by the self-focusing of laser beam with a 100 ps pulse width and intensity of 10^{17} W/cm^2 at focal point. That self-focusing was due to the Ponderomotive force. Now we have studied the propagation behavior of ultra-intense short pulse laser in the long scale length plasma with the critical density for 1050 nm laser light at 100 μm from the original target surface. The plasma is created on deuterated polystyrene (CD_2) planar targets. The focal position of the short pulse in the corona plasma is changed along the laser axis parallel to the density gradient of the plasma from 50 μm to 1.5 mm from the original target surface.

Typical x-ray side-on images for these shots are shown in Fig.3, where (a), (b) and (c) correspond to the focal position of 100, 170 and 500 μm, respectively. In Fig. 3 (a) and 3 (c), large diameter emissions are observed from the original target surface, which come from the preformed plasma by the Gekko XII laser with an intensity of 10^{15} W/cm^2 within a 500 μm spot. While a focal position is at 150 – 230 μm, an intense local emission with less than 30 μm diameter is observed at 50 μm from the original target surface overlapped with the emission from the preformed plasma both in the side-on and the face-on images as seen in Fig. 3 (b) . This intense emission is considered due to the whole beam self-focusing of the intense short pulse and resultant penetration deeply into the over-dense region. This type of penetration is simulated with the 3D particle simulation [18]. The previous hole boring experiments [16, 17], resemble side- and face-on images shown here were observed. The



(a) (b) (c)

FIG.3 X-ray side-on and face-on images which correspond to three different focusing positions of intense short pulse (100 TW, 10^{19} W/cm^2) in long scale lwngth plasma. (a) 100 μm from initial target surface, (b) 170 μm , (c) 500 μm. Cut-off density nc is at 100 μm from the target surface.

formation of the channel in an over-dense region was confirmed by the measurement of density profile along the laser pass with UV- and x-ray-laser probes. The mechanism of self-focusing and penetration into over-dense region is due to the relativistic self-focusing and self-transparency of the laser beam since at laser intensity of > 5 × 10^{18} W/cm^2 a relativistic

effect takes place by increases of quivering electron mass. The relativistic effect decreases plasma frequency or increases refractive index proportional to laser intensity. The observed local x-ray emission is due to the laser energy deposition at the end of the penetration [19]. This laser penetration into over-dense region is very promising for fast ignition and we call it "super-penetration" mode. The x-ray emission in under-dense region in Fig. 3 (c) is due to the high energy electrons produced by stimulated Raman scattering. No such a x-ray emission in under-dense region in case of Fig. 3 (a) and 3 (b) means an intense laser beam can propagate at least to the cut-off region without considerable energy loss.

3.2 Generation of Energetic Electrons and Ions and Energy Deposition

Under intense laser fields electrons can be accelerated via $\mathbf{J} \times \mathbf{B}$ force (**J** ; electron current in laser field, **B**; laser magnetic field), vacuum heating and stimulated Raman scattering etc. Once energetic electrons are generated, an electrostatic field by charge separation takes place resulting in ion acceleration. The spectrum and direction of energetic electrons, and the conversion efficiency from laser are investigated by the intense short pulse irradiation on the target with and without a plasma. The electron energy spectrum is measured using a magnetic type spectrometer with an imaging plate [20] as a detector since a strong electromagnetic noise from the intense laser shot screens, the most of electrical detectors. Measured direction is 19˚ in the horizontal plane and 45˚ in the longitude to the target normal. The electron spectrum to the vacuum side has a peak at around 1 MeV and reaches up to 10 MeV or beyond for the super penetration mode at 10^{19} W/cm^2 [18].

The energy conversion efficiency from laser to energetic electrons going to the target interior is measured using a Kα emission method. Targets used consist of CD^2, Mo and Ag layers of which thickness is 30, 50 – 300 and 50 μm, respectively. Laser is irradiated onto the CD^2 surface. Mo layer acts as an energy absorber of electrons and Ag as Kα emitter. The Kα yield is dependent upon the electron energy and flux coming into the emitter. Therefore one can decide the conversion efficiency by finding the electron energy spectrum which reproduces the Kα emission dependence on the absorber thickness with help of 3D Monte-Carlo simulation. From the experimental results, the coupling efficiency from the laser to energetic electrons toward the target interior are estimated to be about 25% and 40% with and without plasma on targets, respectively [5].

For the fast ignition, an energetic electron beam with narrow divergence angle is required to heat up a high density compressed core plasma to the ignition temperature since larger heating region, bigger ignition laser. The emission angle of energetic electron beam is investigated by irradiating 40 TW, 0.5 ps laser on the Al solid target without a performed plasma. If the energetic electron beam reaches to the rear surface of the solid target the surface is heated up or ionized. Therefore the beam diameter or profile are obtained by measuring the UV image of the rear side. The UV images are measured by changing the target thickness from 5 μm (ρl = 1.5 × 10^{-3} g/cm^2) to 1mm (0.3 g/cm^2) with UV framing camera. The experimental results say that the electron beam propagates as a single narrow beam more than 200 μm and the electron beam is broke up to filaments at 500 μm. The divergence angle of the beam before the break-up is 20˚ - 30˚ FWHM.

The temperature heated by electron beam is also measured from neutron yields and x-ray spectrum by changing Al target to CD^2 targets with 10 mm Al layer at laser irradiation side which can prevent beam fusion in the CD^2 layer. The thickness of CD^2 layer is 0.68 g/cm^2. The observed D-D neutrons consist of 2.45 MeV thermal neutron peak. The estimated plasma temperature from thermal neutron is about 300 - 400 eV. The current could be over Alfven limit but the electron beam could propagate in long distance in solid target. This long propagation would be due to the return current in the material and/or self-generated magnetic field from the temperature dependent conductivity.

Irradiation of an intense laser beam onto the CD^2 target creates also beam fusion neutrons in the produced plasma and/or interior of solid target. From the analysis of the neutron spectra measured at different directions, the energetic ions characteristics can be evaluated. The momentum distributions of energetic ions are decided by finding ones which meet to neutron spectra measured at different direction with help of 3D Monte-Carlo simulation. Results say that the direction of the ion acceleration is rear normal of the target front surface and has no dependence on polarization of oblique incident laser or direction of the electron beam. Note the direction of electron beam is normal to target surface for the p-polarization laser and is towards laser propagation direction for the s-polarization, which are confirmed by the experiments for the absorption mechanism of intense laser with different polarization. The ion acceleration mechanism could be due to the electrostatic field by the charge separation, taking place at very narrow region just behind the laser absorption region.

3.3 Heating of Implosion Plasma

Based on the knowledge obtained in basic physics experiments and theoretical works, heating experiments of implosion plasma have been performed with three different ways shown in Fig.4; channel guiding mode, super-penetration mode and cone guiding mode.

In the channel guiding mode, successive two 1053 nm, 100 ps pulses from one beam of the Gekko XII are injected, using same focusing lens with F/3 to the implosion plasma; The implosion plasmas are created, using 10 or 12 beams of the Gekko XII with wavelength of 530 nm. The imploded targets are CD^2 shell with 500 μm diameter. First 100 ps pulse is to form the plasma channel to guide the second pulse to the compressed core plasma. A

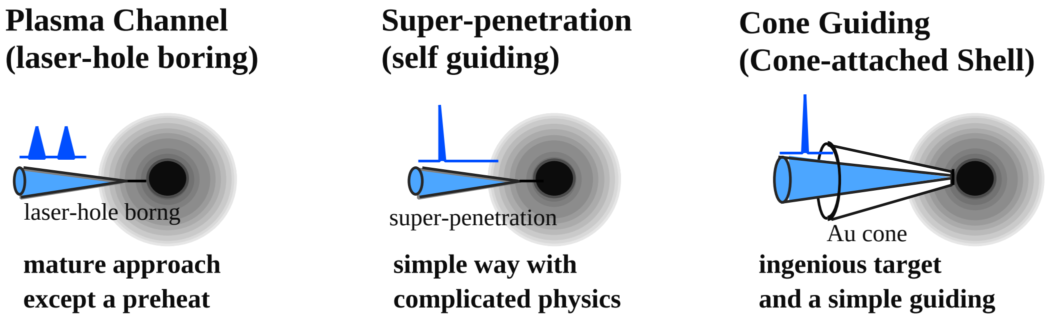


FIG.4 Schematic illustration of 3 types heating of implosion plasma. (a): heating by 100 ps 10^{17} W/cm^2 , (b): heating by super-penetration mode of 100 TW laser, (c): heating by 100 TW laser through a vacuum cone touvhed to compressed high density plasma directly. The end of cone has a plate to prevent flowing -out of the plasma.

localized x-ray emission is observed at the compressed core plasma with neutron yield when the double pulses are focused at 100 μm far from the initial target surface. X-ray emission and neutron yield are significantly influenced by the focusing condition and no bright x-ray spot and neutrons are observed when focusing points are ~100 μm far from that point. These results implies that the core plasma is additionally heated by the second pulse guided by the plasma channel produced by the first pulse. Heating mechanism is, however, not clear whether shock heating or energetic electron heating. It is required further study by changing the timing of heating pulse, etc.

In the second mode, a 100 TW short pulse is launched onto the imploded plasma with super-penetration mode described at §3.1. The energy of the heating pulse is 50 – 80 J. We limit the implosion laser energy up to 2 kJ in order to minimize the internal energy of the core plasma and to keep the core sensitive enough to the additional heating. Only at the super-penetration mode or focusing the intense short pulse at (0.5 – 0.8) times critical density, neutron emission increased. The neutron yield is a few times of 10^5 whereas the yield is less than 10^4 at neither injection of heating pulse nor super-penetration mode. The observed neutrons could be generated by both beam fusion reactions due to the high-energy deuterons and thermalreactions from the plasma heated by the layer. Clear observation of thermal neutrons above the beam fusion neutrons could be achieved at the super-penetration mode with the 1 PW laser. As the third approach, we have imploded CD shells attached with Au cones and injected an intense short pulse into the cone (see Fig. 4 (c)). This approach has advantages of avoiding the energy loss during the propagation in plasmas and a high conversion efficiency from the intense short pulse laser energy to energetic electrons in the Au foil at interface of compressed plasma.

4 Dynamic Property of Initial Imprint and Rayleigh-Taylor Growth

Even if the foot pulse intensity of the implosion pulse is as low as 10^{12} W/cm^2 , an irradiation non-uniformity imprints a perturbation on the target surface, resulting in the source of Rayleigh-Taylor instability. In order to reduce the initial imprint induced by the irradiation non-uniformity produced by finite beam numbers, interference fringe due to the coherence of laser beams, etc, smoothing techniques such as PCL with spectral dispersion and SSD light are developing which can average the irradiation non-uniformity in time. Investigated are the imprint behavior of a beam with spatial intensity profile, changing temporally on the target (dynamic imprint) [22]. An interference pattern produced by two wavelength, Young‘s interference technique is used to make a temporally changing non-uniform pattern. The moving speed of the pattern on target is decided by the wavelength difference between two beams, and the spatial wavelength of interference pattern is dependent upon the crossing angle of two beams. The moving speed is changed up to 2 × 10^7 cm/s with a fixed wavelength of 40 mm. The wavelength of laser is 530 nm and the average intensity is (0.5 – 0.1) × 10^{13} W/cm^2 with 100% modulation. Targets are flat plastic foil of PTFMA ($C_6H_7F_3O_2$). Imprinted perturbations are amplified by the subsequent R-T instability to be observed with the face-on x-ray backlight technique. A clear reduction of the initial imprint is observed, comparing with the static imprint [22]. The amount of the imprint is decreased with increasing the moving speed of the non-uniformity. In this experimental conditions, no clear growth of R-T instability by acceleration is observed at the moving speed of 1 × 107 cm/s for non-uniformity wavelength of 40 μm. The experimental results suggests that the modulation frequency of 1D SSD light with instantaneous non-uniformity wavelength of 40 μm has to be higher than 2.5 GHz.

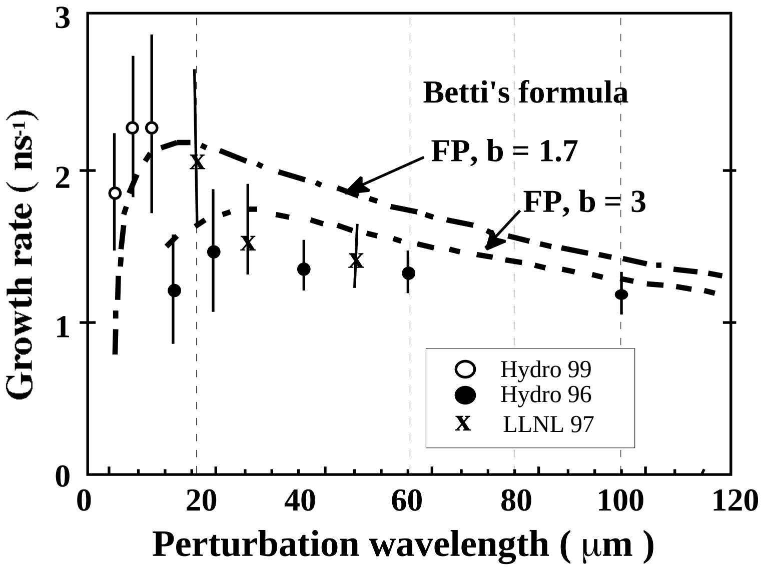


FIG.5 Growth rate of Rayleigh-Taylor instability in the target irradiated by 530 nm laser with intensity of 0.7× 10^{13} *W/cm*^{2} *. Newly measured data for wavelength of < 10 μm shows different tendency from the previous data for long wavelengrh.*

In the previous experiments of R-T instability in ablation plasma, the growth rate was measured by a laser of 530 nm for the plastic target with spatial modulation wavelength from 15 µm to 100 µm. It was found that 1) the growth rate measured is lower than the values expected by the Takabe formula [23], 2) it has maximum at wavelength around 20 µm and decreases to zero as wavelength decreases taking the cut-off at about 5 µm. Note the existing of the cut-off wavelength is expected by the Takabe formula.

The growth rate for shorter wavelength, which is not measured so far due to the poor diagnostic resolution, has been measured to know the cut-off wavelength. The used diagnostics is newly developed x-ray backlighting Moir6 interferometry [2l]. Measured are for wavelength of 8.5, 5.7 and 4.7 µm. The experimental conditions are adjusted to be same as the previous experiments except the treatment of corrugated surface which is irradiated by laser. This time a very thin Al layer is coated at the corrugated surface to prevent a shine-through. The experimental results are shown in Fig.5 with the previous ones. The experimental results show the higher growih rate than the expected ones from extrapolation of the previous results. The new experimental results fit with the Betti formula [24] coupled with I D hydro-code simulation. The explanation of the discrepancy between two experiments is still in controversy.

Surnmary

ILE Osaka university concentrates so far on the research of elements physics of the fast ignition. The followings are obtained in the intense laser plasma experiments.

[l] 100 TW beam with 10^{19} W/cm^2 focused in the long scale length plasma can penetrate into the over-dense region (super-penetration) when focusing points are at 50 - 130 µm far from he critical density point.

[2] The energy conversion efficiencies from the short pulse to energetic electrons are up to 20% and 40% for the irradiation on to the targets with and without long scale length plasmas. respectively.

[3] The generated energetic electron beam effectively propagates into a solid target with divergence angles of 20 - 30 degree.
[4] At the super-penetration mode, beam fusion D-D neutrons are observed from the 100 TW Iaser interactions with implosion plasmas, indicating the ion acceleration in high-density regions.
[5] Hydrodynamic instabilities related to the pellet implosion and beam smoothing techniques have been studied intensively on the conventional GEKKO XII facility. The extended series of experiment has just started to investigate the element physics for high density compression under the conditions similar to the high gain design.

These results on energetic particle generation and beam propagation in long scale-length plasmas with ultra-intense laser light could be promising the realization of fast ignition concept. The hydrodynamic instability studies provide a required data base to achieve high density compression of fuel for a fast ignition as well as for the center ignition. A peta watt laser system will be completed by the middle of 2001 and will contribute to accumulate a data base for a future demonstration of proof of principle of fast ignition.

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