Laser Fusion Research with GEKKO XII and PW Laser System at Osaka

Y. Izawa 1), K. Mima1), H. Azechi1), S. Fujioka 1), H. Fujita 1), Y. Fujimoto 1),
T. Jitsuno 1), Y. Johzaki 1),Y. Kitagawa 1), R. Kodama 1), K. Kondo 1), N. Miyanaga 1),
K. Nagai 1), H. Nagatomo 1), M. Nakai 1), Y. Nakao 2), K. Nishihara 1), H. Nishimura 1),
T. Norimatsu 1), P. Norreys 4), H. Sakagami 3), H. Shiraga 1), K. Shigemori 1),
A. Sunahara 1), K. A. Tanaka 1), K. Tsubakimoto 1)

1) Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan
2) Faculty of Engineering, Kyushu University, Fukuoka 812-8581, Japan
3) Faculty of Engineering, Himeji Institute of Technology, Himeji 671-2201, Japan
4) Rutherford Appleton Laboratory, Oxfordshire OX11 0QX, U.K

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

Abstract. Fast heating of the compressed core plasma up to 500eV has been successfully demonstrated by injecting a 400J/0.6ps PW laser into a compressed CD shell through a hollow gold cone. According to this result, we started the FIREX (Fast Ignition Realization Experiment) project toward demonstrating the ignition of the highly compressed DT fuel by the high energy PW laser heating. A new heating laser LFEX (Laser for Fast Ignition Experiment) is under construction. In this paper the progresses in the experimental studies on scientific issues related to fast ignition and the integrated code development toward the FIREX will be reported. Research results on implosion hydrodynamics, Rayleigh-Taylor instability growth and a new stabilization mechanism are also reported.

1. Introduction

Fast ignition is a new scheme of laser fusion, where a fuel shell is compressed with the use of long pulse (1-20 ns) laser beams to more than 1000 times the solid density and is heated to create a hot spot at the edge of the compressed fuel by injecting a highly intense short pulse (~ PW, ~ ps) laser at the moment of maximum compression. In the central ignition scheme, a highly uniform laser irradiation and strict power balance of multi-beam laser system are required to form a hot igniting spot at the center of the compressed fuel. In the fast ignition, such a requirement is relaxed, and all required is to achieve the high-density compression.

On the other hand, for enforced heating of the compressed core plasma, it is important to deliver certain amount of laser energy to heat the core to ignition temperature within an inertial time of the fuel assembly at the maximum density. Since the core is surrounded by a thick low-density corona plasma, it is required for the heating laser pulse to penetrate the surrounding corona plasma to reach the core by the use of nonlinear interaction process like a laser light self-focusing. We have proposed a novel target, cone shell target, in which a gold hollow cone is inserted into a fuel shell to secure a vacuum path for ultra-intense laser heating of the imploded high-density core [1]. The effectiveness of the cone shell target was demonstrated by the experiments with the GEKKO XII and PW lasers. The neutron yield increased from 10^4 without heating to 10^7, when a 400 J/0.6 ps PW laser was injected into a compressed CD shell. This result indicates that the core plasma temperature increases by 500 eV and the energy coupling efficiency between heating laser and core plasma is 20-25% [1]. According to these results, we started the FIREX (Fast Ignition Realization Experiment) project toward demonstrating the fast ignition with a new high energy PW laser, LFEX (Laser for Fast Ignition Experiment).

In this paper, the progresses in the experimental and theoretical researches on scientific and technological issues related to fast ignition toward the FIREX will be described. Research results on implosion hydrodynamics, Rayleigh-Taylor (R-T) instability growth and a new stabilization mechanism are also discussed.

2. FIREX Project

The FIREX project toward demonstrating the ignition and fusion burning has started in the fiscal year of 2003. The project consists of two phases. The goal of the first phase, FIREX-I, is to demonstrate the ignition of the highly compressed DT fuel by a high energy peta watt laser heating. A new heating 10 kJ PW laser, LFEX (Laser for Fast Ignition Experiment), and a cryogenic cone shell target are under development.

The heated plasma parameters and the gain for the FIREX-I were evaluated to be ρr = 0.15g/cm^2, = 20 m, T = 8 keV, and Q = 0.1 by the integrated simulation with 0.5 MeV slope temperature for the 10 kJ heating pulse energy. When the above expected plasma parameters are achieved, we plan to start the FIREX-II project in which both implosion and heating lasers are up-grated to 50 kJ, and the fusion gain will reach higher than unity.

2.1 New Heating Laser LFEX

The new heating laser LFEX has been designed to deliver 10kJ energy in 10ps with 1ps rise time [2]. It is a four-beam system with a beam size of 40 cm x 40 cm at a booster amplifier in each beam. The major subsystems of the laser are schematically shown in Fig. 1. A front end includes a Nd:glass mode-lock oscillator, a two-stage pulse stretcher and a three-stage OPCPA. A spectral phase modulator is introduced for pulse shaping. The third OPCPA can deliver sub joule output maintaining a broad spectral width and extremely high contrast ratio. A small amount of the output is used to inject into the GEKKO XII amplifier chain for beam synchronization.

The output from the front end system is spatially shaped by a serrated aperture, the image of which is subsequently re-imaged throughout the whole of the amplifier chains, and finally relayed to a pulse compressor. After passing a four-pass preamplifier, the laser beam is divided four beams and injected into a main amplifier chain with a timing error of less than 0.1 ps.

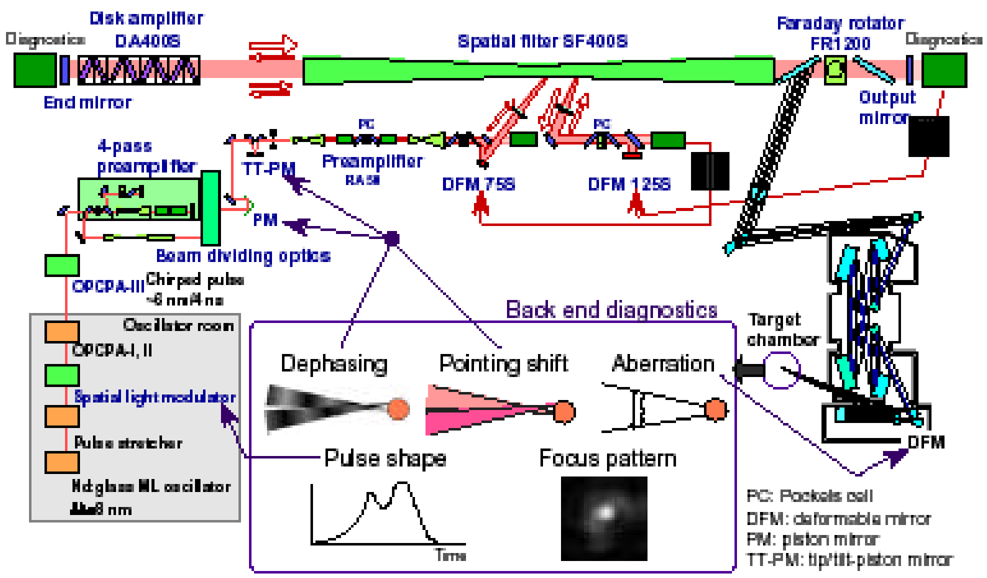


Fig. 1 Schematic layout of LFEX.

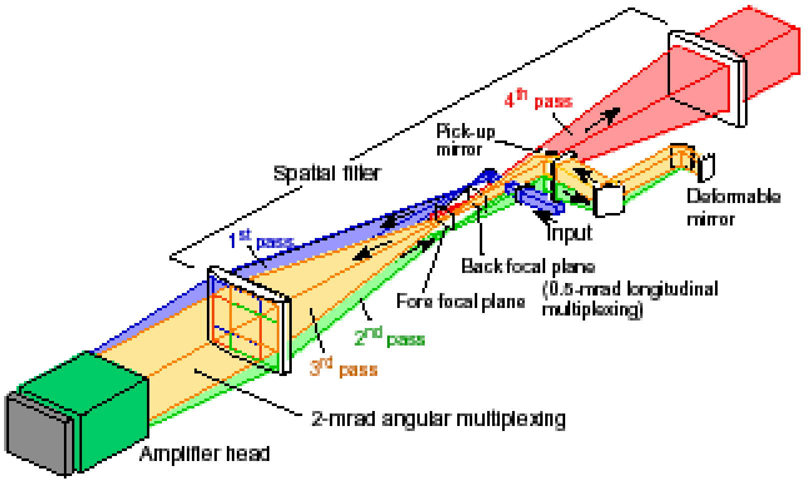


Fig. 2 Beam path arrangement of the four-pass booster amplifier utilizing angular-longitudinal multiplexing.

Each main amplifier chain consists of the rod amplifiers and a four-pass disk booster amplifier. The arrangement of beam path in the booster amplifier is schematically shown in Fig. 2. A laser pulse from the rod amplifier is injected into the first path with a focal position shift of ~ 1.5 m prior to the nominal far-field position of a spatial filter SF400S. This focal shift corresponds to a 0.5-mrad beam divergence which causes a reverse focal shift in the second beam path. Using this angular-longitudinal multiplexing technique, the beam size on a pick-up mirror can be enlarged without intersecting other beam path, thus a mirror coating with an extremely high damage threshold is not needed. The output energy from each amplifier chain will be 3 kJ in 3 ns at CPA mode.

The amplified laser pulse enters into the pulse compressor. A double-pass two-grating arrangement was newly designed for pulse compression. The segmented gratings will be used because of the limited size of the multilayered dielectric grating with high damage threshold.

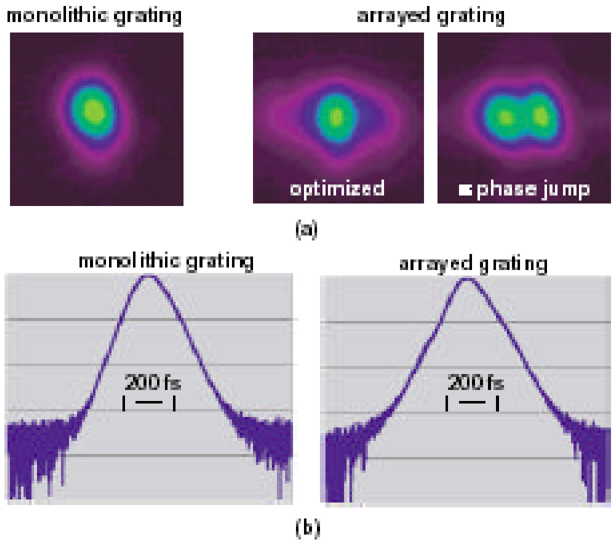


Fig. 3 Far-field pattern (a) and autocorrelation trace of the compressed pulse obtained for the monolithic grating and the arrayed grating.

We have performed a preliminary experiment by using a Ti:sapphire laser of 6 cm beam diameter and a round-trip compressor, where the second grating was composed of two pieces arrayed along the direction of dispersion. Figure 3 shows far-field patterns and an autocorrelation traces of compressed pulse obtained for the arrayed and the monolithic gratings. No significant changes in compressed pulse width and far-field pattern were observed between the segmented gratings and a monolithic grating.

After pulse compression, four laser beams are combined into one beam for obtaining a single focal spot without reducing the encircled energy. Finally the laser beam is focused to the target by a parabolic mirror. One of the critical technical issues of the LFEX is the coherent combining of 4 segmented beams. The sensitivity of the focused beam profile on phase error between each beam suggests that the required accuracy of the phase control is less than $\lambda/4$. A precise phase control system in beam and among beams is introduced.

The LFEX is under construction and the FIREX-I experiment will start before 2007 [2].

2.2 Foam Cyogenic Target

A cryogenic foam shell target with cone guiding, as shown in Fig. 4, will be used in the FIREX-I [3]. A low density foam layer supports the liquid DT fuel and the foam shell is covered with a thin plastic layer. A conical light guide made of gold is attached to the foam shell. Mixture of deuterium and tritium gas is fed into the foam layer through a glass capillary tube, which is attached on the outer surface of the guiding cone and cooled down to fill up the foam layer in a liquid or solid state.

A new foam layer made by poly(4-methyl-1-pentene) (PMP) is under development in addition to acrylic and resorcinol/formalin (RF) foams. The mass density of acrylic resin or RF foams is limited to be 40~50 mg/cm^3, but for PMP foam ultra-low density of ~ 10 mg/cm^3 is possible. In the FIREX-I a PMP foam shell will be used.

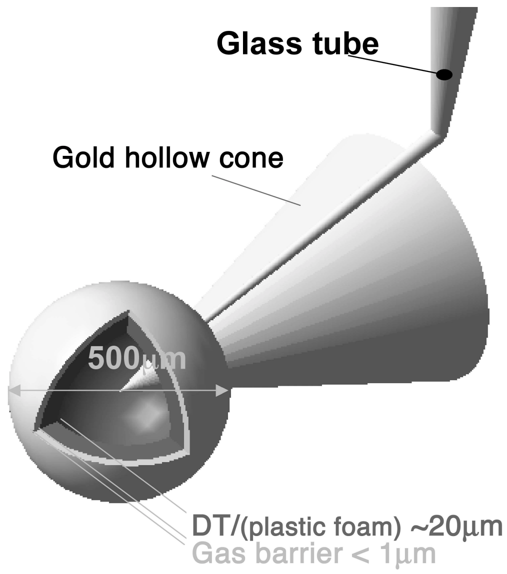


Fig. 4 Schematic view of a cryogenic foam shell target with gold cone.

3. Fast Ignition Experiment and Simulation

In the fast ignition scheme using cone-shell target, it is important to understand the physics of ultra-intense laser absorption, relativistic electron generation and transport in the cone and the compressed plasma, as well as non-spherical cone-shell target implosion. As interpretation of the cone-shell-target experiment, the relativistic electron propagation in dense plasmas has been widely investigated by experiment, simulation and theory.

3.1 Fundamental experiments for fast ignition

In order to heat the compressed core plasma, hot electron of the order of 1 MeV is necessary for a density radius product of ρr ~ 0.3 g/cm^2. Hot electron temperature is higher than that estimated by simple JxB heating, and 1 MeV electrons are obtained at laser intensity above 10^{18} W/cm^2, as shown in Fig. 5. The energy transport of hot electron was measured by observing the UV to visible emission at the rear side of 200 mm thick Al planar target with a special framing camera [4]. At low laser intensity region of ~ 10 TW, a filamentary structure in rear side emission was observed. A number of filament rapidly decreased with increasing the laser intensity, while the peak brightness increases rapidly, as shown in Fig. 6. Finally the filamentary structure disappeared at the laser power of a few 10 TW. It is suggested that the filament could merge due to magnetic field generated by inhomogeneous conductivity, which depends on the heating power. These behaviors indicate that the hot electrons can be transported not breaking into filaments at the laser intensity of ~PW, and be maintained in a flux to heat the compressed core plasma.

When electrons pass through a clear boundary such as from a solid to a vacuum, coherent transition radiation is emitted. We have measured such radiation to estimate the hot electron temperature inside targets [5]. A model calculation shows that the spectral intensity of coherent radiation at the fundamental and the second harmonics is much higher compared to the incoherent and blackbody radiation, as shown in Fig. 7(a). The intensity of coherent radiation from the rear surface of the planar target at the fundamental frequency is plotted in Fig. 7(b) as a function of target thickness for different hot electron temperatures. Experimental results suggests two components of hot electron temperature, ~ 1 MeV and ~ 5 MeV, from the fitting with the model calculation [6] .

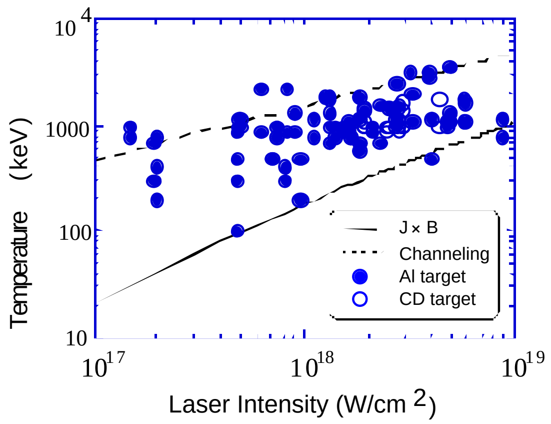


Fig. 5 Hot electron temperature as a function of laser intensity.

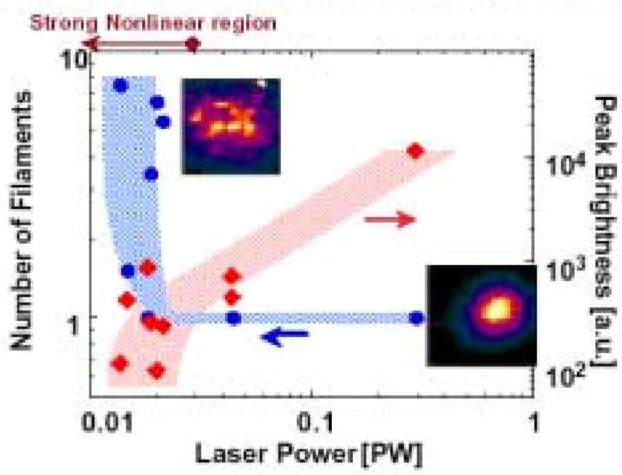
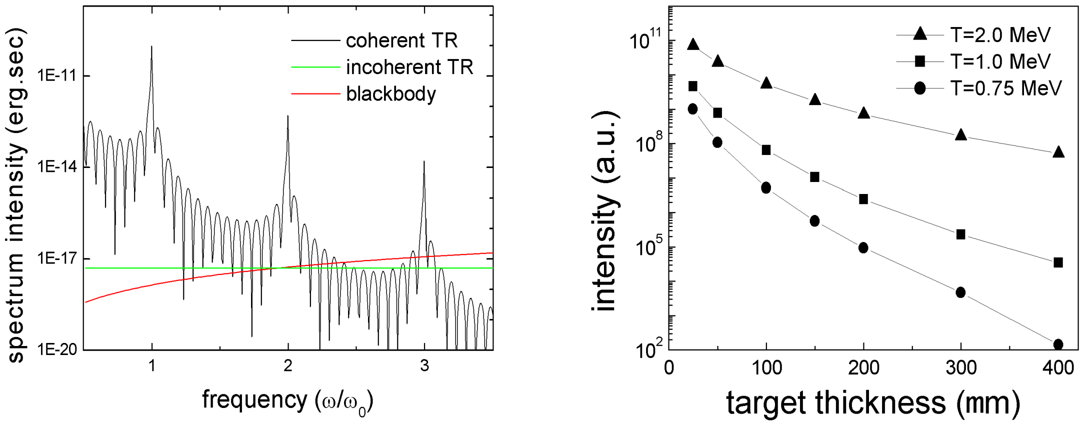


Fig. 6 Filamentation of hot electrons and peak brightness in the rear side emission of Al target.



(a) (b)

Fig. 7 Model calculation of coherent transition radiation spectrum (a), and radiation intensity at the fundamental frequency (b).

3.2 Integrated Code Development

The fast ignition includes two processes, implosion of cone-shell target by ns laser and heating of core plasma by ps laser. The numerical simulation plays an important role in designing the target, estimating the performance of the scheme, and optimizing the laser pulse shape. It is desired that all the physics from the initial laser irradiation to the final fusion burning are self-consistently described in numerical simulation. However it is difficult to simulate laser plasma interaction and radiation hydrodynamics in a single code, without numerical dissipation, special assumption or conditional treatment. We have developed the Fast Ignition Integrated Interconnecting code (FI^3) [7], which consists of collective Particle-in-Cell code (FISCOF1), relativistic Fokker-Planck (RFP) code [8], and 2-dimensional radiation hydrodynamics code (PINOCO) [9]. Figure 8 shows the radial profiles of plasma density at implosion (right) and at heating (left), respectively, and the corresponding code. For cone-shell implosion, radiation hydrodynamics is dominant, and 2-D ALE (Arbitrary Lagrangian Eulerian) PINOCO can simulate the implosion dynamics accurately. In the relativistic laser plasma interaction, the collective PIC code can evaluate the time-dependent energy distribution of fast electron. The core heating process can be simulated by the RFP code.

We have performed an integrated fast ignition simulation, which was the first numerical

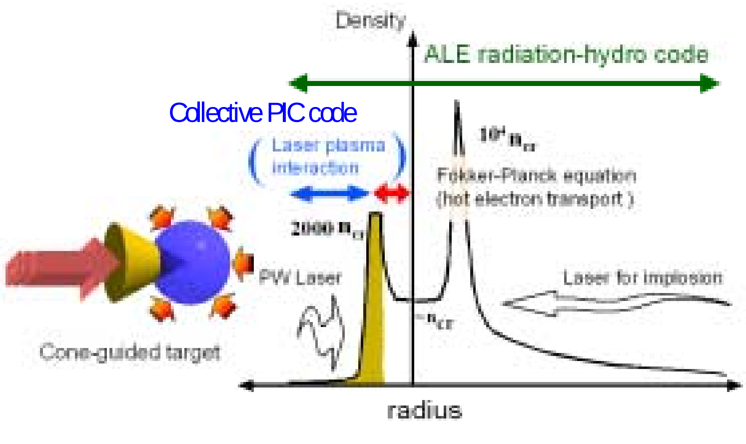


Fig.8 Fast Ignition Integrated Interconnecting code and related physics.

example of FI[3] project to show the capability of the codes. At first, cone-guided implosion was simulated by PINOCO. The density (up) and the temperature profiles near the tip of the cone simulated by PINOCO are shown in Fig. 9. The vertical red bar indicates the hot electron generation region and the purple region indicates the high energy electron injection position. Because of the effect of cone the position of hot spot shifts to right-hand side of the mass center along the cone axis. The compressed shell collides on the axis and creates the high density jet flow toward the cone tip. Finally, the jet penetrates into the cone. Such features were also observed in the implosion experiments by cone-shell target.

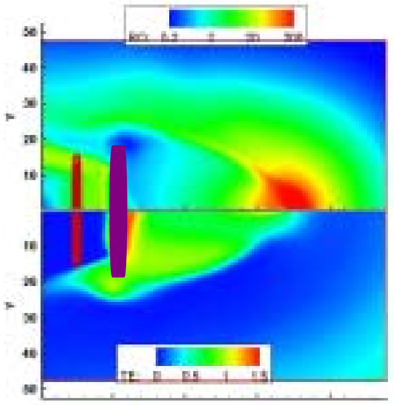


Fig. 9. Density (up) and temperature (down) profiles of cone-guided implosion by PINOCO. A vertical red bar indicates petawatt laser plasma interaction region and .a purple region is the injection place of high energy electron.

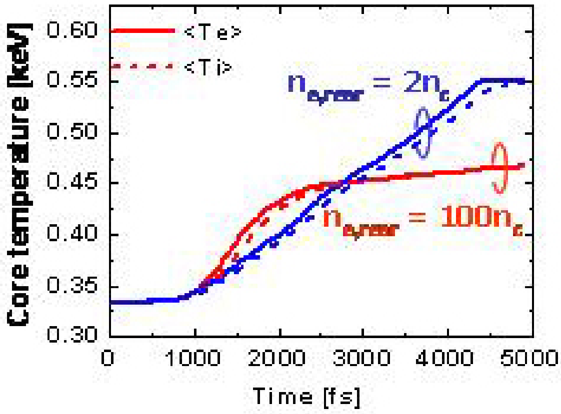


Fig. 10. The temporal evolutions of temperature of ion (broken line) and electron (solid line) which are averaged over the dense core region ($\rho > 50$ g/cc).

The mass density, temperatures, and other profiles calculated by a PINOCO simulation are used as initial and boundary conditions for collective PIC and RFP-hydro simulations. The relativistic laser plasma interaction inside the cone target is simulated by the collective PIC code. The PIC simulation provides the time-dependent energy distribution of fast electron which is used in a RFP-hydro simulation. Through these combined simulations, the core heating process was investigated. As a result of the simulation, the temporal profiles of ion and electron temperatures averaged over the dense core region ($\rho > 50$ g/cc) are obtained as shown in Fig.10. The blue line shows the result for the case that a density jump effect is important behind the cone tip, while the red line represents the case that the plasma density jump behind the cone tip does not exist. Here, the time t was set to be 0 at the beginning of the injected high energy electron pulse. When the plasma density behind the cone tip is comparable to the high energy electron density, strong two stream instabilities occur to moderate the high energy electron spectrum and reserve the energy for a while after the petawatt laser. Therefore, the heated plasma temperature is higher in the case of a blue curve in Fig.10.

4. Hydrodynamic Instability

One of the most crucial issues for the spherical implosion is the hydrodynamic instability such as the Rayleigh-Taylor (RT) instability on the ablatively accelerated target. We established the experimental techniques to obtain a full set of required data to analyze the growth rate of RT

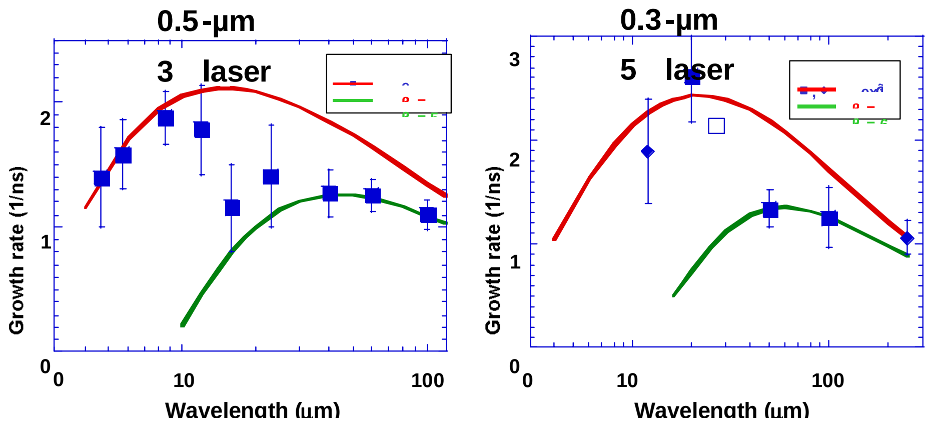


Fig. 11 Growth rates of the ablative Rayleigh-Taylor instability
for 0.53 µm and 0.35 µm laser.

instability for the ablatively accelerated planar target. The experimentally observed RT growth rates for 0.53 µm and 0.35 µm laser wavelengths are shown in Fig. 11 as a function of the perturbation wavelength [10]. The growth rate for the relatively shorter wavelength is well fitted to the Takabe formula for a reasonable value of β = 1.7, where β is a coefficient of ablative stabilization in the Takabe formula. However, for the modes with longer wavelength relative to the stand-off-distance, the growth rate is lower than that given by β = 1.7. The experimental results can be fitted with β = 5 and 7 for 0.53 µm and 0.35 µm laser, respectively.

The growth rate is strongly dependent on the ablation structure, and hence, there is a possibility to reduce RT growth by controlling the energy transport in the laser-driven target.We proposed two schemes to mitigate the RT instability growth [11]. One is to enhance the non-locality of the electron heat transport by illuminating the target with the additional laser light of the longer wavelength than the main drive laser simultaneously [12]. In the second scheme, radiation has a dominant role in the energy transport [13].

Nonlocal electron transport was found to be effective in observed RT growth rate reduction [6]. Such electrons with mean free path longer than the temperature scale length modify the density structure at the ablation front, i.e., reduce the density and/or enlarge the density scale length. The effect can be enhanced by using laser irradiation of longer wavelengths. We tested this idea at the GEKKO-HIPER system [1] using not only the main driving beams of the third harmonics (3ω) of the glass laser but also the second harmonic (2ω) beams or fundamental (1ω) beams. Additional to the standard 3ω main drive pulse of the GEKKO-HIPER, 25-µm thick polystyrene targets were irradiated also with 1ω or 2ω heating pulse overlapped to the main drive. It was found that additional 1ω or 2ω irradiation significantly reduces in the RT instability growth.

When a small amount of high-Z material is doped in the ablator material, x-rays are generated in the laser-irradiated high-temperature region. Then, the generated x rays are transported to the inner region of the target and deposit their energy to dopant ions there, causing heating and hence radiation-driven ablation, if the dopant material and its density are properly chosen. We doped CH target with 3 atom% Br. According to 2D simulations, it is found that the radiative ablation front is RT unstable, while the conventional electron driven ablation front is RT stable because the pressure is almost constant around the front. However, the RT growth rate in the radiation-driven ablation is expected to be much smaller than the electron-driven ablation because mass ablation velocity in the radiation-driven ablation is much larger. Growth of RT instability was experimentally measured for such Br doped CH target by face-on x-ray backlighting. Initially imposed perturbation with a wavelength of 20 μm was found to be dramatically reduced compared from the value for pure CH targets as shown in Fig.12.

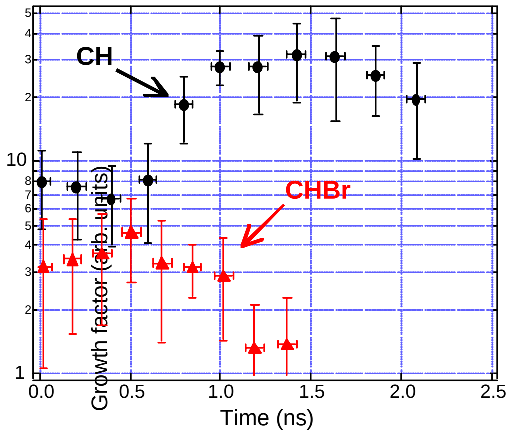


Fig. 12 RT growth of CH and CHBr targets with initial surface perturbations with the wavelength of 20~25 μm.

5. Summary

We have started the FIREX-I program toward demonstrating the ignition of the highly compressed DT fuel by fast ignition with the use of high energy PW laser. A new heating laser LFEX is under construction, which can deliver 10 kJ energy in 10 ps. Toward the FIREX-I experiment, we also started research and development for fabricating cryogenic foam shell cone target and the Fast Ignition Integrated Interconnecting code for designing the target. The cone-guided implosion and hot electron transport have been studied by the experiment and simulation. It was found that the higher fuel ρr can be expected by the cone-guided implosion compared with that by spherical implosion and hot electrons can propagate in dense plasma as a single beam. For high-density compression, new stabilization schemes of Rayleigh-Taylor instability were proposed and the significant suppressions of instability growth were demonstrated by the experiments. The FIREX-I experiment will start before 2007.

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