Overview of Laser Fusion Research at ILE, Osaka

K. Mima 1), H. Azechi 1), Y. Inubushi 1), Y. Fujimoto 1), S. Fujioka 1), A. Hata 1), T. Johzai 1), J. Kawanaka 1), T. Matumoto 1), N. Miyanaga 1), M. Murakami 1), H. Nagatomo 1), K. Nagai 1), M. Nakai 1), T. Nakamura 1), K. Nishihara 1), H. Nishimura 1), T. Norimatsu 1), T. Sakaiya 1), H. Shiraga 1), H. Yoshida 1), T. Jitsuno 1), J. Lu 1), Y. Nakata 1), K. Sueda 1), K. Tsubakimoto 1), G. Xu 1), A. Iwamoto 2), T. Mito 2), H. Sakagami 2), M. Okamoto 2), O. Motojima 2) R. Kodama 3), K. Kondo 3), K.A. Tanaka 3), H.Habara 3), Y. Nakao 4), Y. Sentoku 5), A. Sunahara 6), T. Taguchi 7), T. Kanabe 8)

1) Institute of Laser Engineering, Osaka University, Suita, Osaka, Japan
2) National Institute for Fusion Science, Toki, Gifu
3) Graduate School of Engineering, Osaka University, Suita, Osaka, Japan
4) Graduate School of Engineering, Kyushu University, Fukuoka, Japan
5) Nevada Tera watt Facility, University of Nevada, Reno, Nevada, USA
6) Institute for Laser Technology, Osaka, Japan
7) Setunan University, Neyagawa, Osaka, Japan
8) University of Fukui, Fukui, Japan

E-mail: mima@ile.osaka-u.ac.jp

Abstract. The fast ignition research at Osaka University has been progressing since 2001. In the April of 2003, the construction of heating laser of 10 kJ/10 ps/1.06 μm (Laser for Fusion Experiment; LFEX), for FIREX-I (Fast Ignition Realization Experiment) has started. One beam of LFEX laser will be completed in the end of March, 2007. Then heating experiments with 1~2kJ/10ps will be carried out by the end of 2007.Target fabrication and irradiation system of foam cryogenic target are developed as the collaboration program between Osaka University and NIFS (National Institute for Fusion Science). A foam cryogenic cone target will be imploded and heated as a test experiment in this summer. The target fabrication technology is further developed to reduce the foam density to less than 20mg/cc by the end of 2006. If the heated core plasma temperature reaches higher than 5keV in FIREX-I, we plan to proceed to the FIREX-II as soon as possible. The simulation studies related to FIREX target design is also progressing with the FI3 integrated simulation code. A new laser fusion concept, so called impact fusion has also been explored since 2003. In the recent experiments, a CD plastic foil was accelerated to $6x10^7$ cm/sec and impacted a CD foil. As the result, significant neutron yield was observed.

1. Introduction

Many institutes over the world have started the fast ignition research, since required laser energy for fast ignition will be 10 times smaller than that for the central hot spark ignition, although further researches on relativistic laser plasma science and technology related to heating of high density plasmas are necessary. At ILE, Osaka University, the FIREX project has started in the fiscal year of 2003 toward demonstrating ignition of highly compressed DT fuel by heating with high energy peta watt laser. In the Fig.1, plotted are the fusion plasma parameters achieved by the GEKKO XII and PW lasers of ILE, Osaka University [1][2], NOVA of LLNL, and OMEGA of LLE, University of Rochester and the goals of the fast ignition project of Japan; FIREX-I and FIREX–II and that of the central hot spark ignition project in US; NIF.

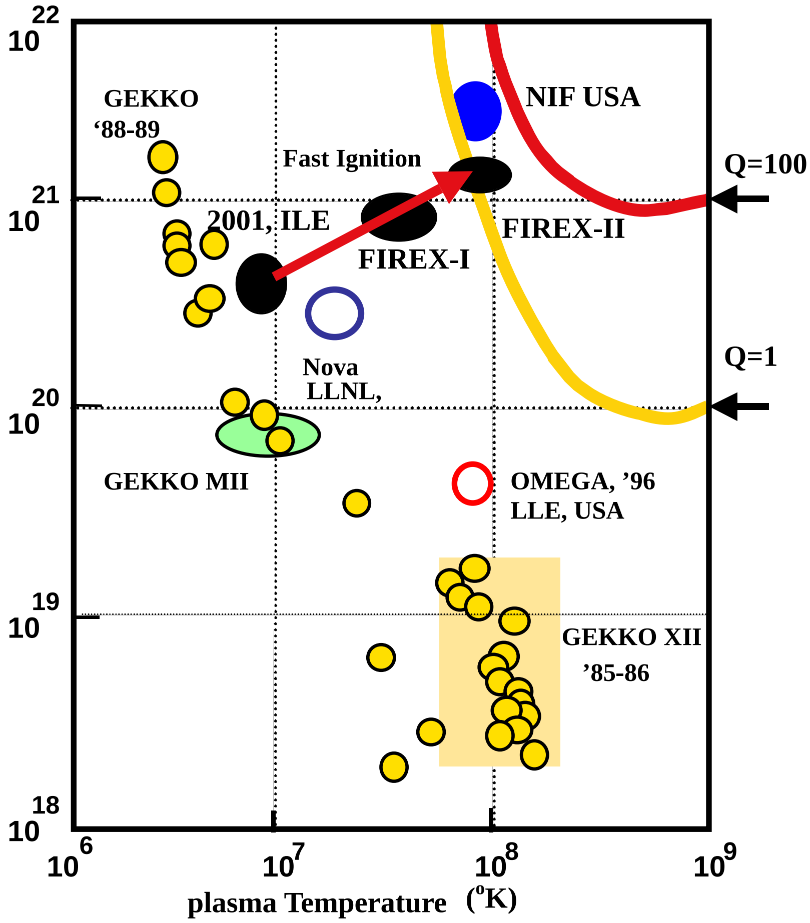


Fig. 1. Fusion parameters achieved by Gekko lasers, NOVA, and OMEGA and those expected by FIREX-I and –II, and NIF project

Here, FIREX stands for "Fast Ignition Realization Experiment". The heating physics of hot spark formation will be clarified by the FIREX-I project. The construction of LFEX, the heating laser for FIREX-I is progressing toward the completion in 2007, March. As another technology R&D for FIREX-I, target fabrication and irradiation system of foam cryogenic target are developed as the collaboration program between Osaka University and NIFS (National Institute for Fusion Science). After the completion of LFEX, we will irradiate a foam cryogenic cone shell target with LFEX in late 2007. In the heating experiments, the foam density is required to be less than 20mg/cc and the technology for fabricating low density foam target will be developed by the end of FY2006. If the heated core plasma temperature reaches higher than 5keV in FIREX-I, we plan to proceed to the FIREX-II as soon as possible. When the FIREX-I project is successful, the FIREX-II project will follow to demonstrate the fusion ignition and burn. The fusion energy gain will be beyond unity in the FIREX-II.

2. Present status of LFEX laser construction

Since April 2003, we started the construction of heating laser of 10kJ/10ps/1.06 μm named LFEX (Laser for Fusion Experiment), for FIREX-I. As shown in the Fig.2, the LFEX will be completed before the end of FY2007. After the completion of LFEX, we will start the foam cryogenic cone shell target experiment in late 2008, and the FIREX-I project will finish in FY.2010 and the FIREX-II is planned to start in FY.2011. The present out look of the LFEX facility is shown in Fig.3. The expected rise time of the short pulse LFEX is less than 1ps and the focus diameter is smaller than 30 mm. As the front end of the laser, OPCPA is introduced to improve the contrast ratio to less than 10^{-8}. For pulse compression, segmented dielectric gratings will be used. The R&D for the coherent combining of the pulse compressed segmented beam has started [3].

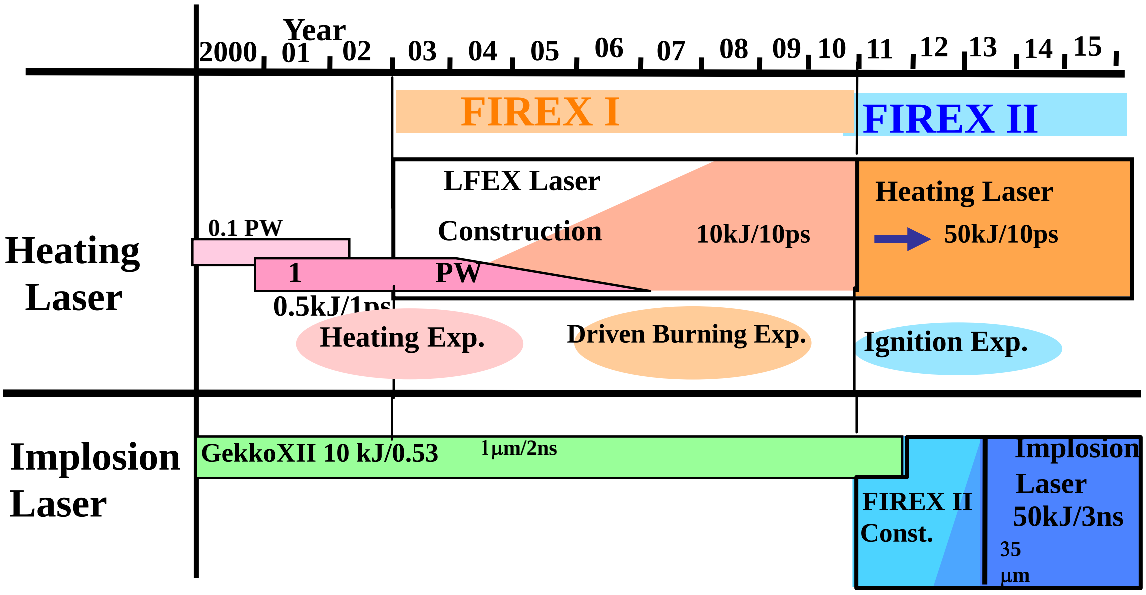


Fig. 2. Time schedule for FIREX-I project and expected plan for FIREX-II project Plasma experiment of FIREX-I will start in 2007.

In 2006 May, LFEX laser was tested as for the amplification. The out-put energy of a narrow band pulse reaches 3.6kJ/pulse which corresponds to 14.4 kJ for 4 beams. Although the broad band pulse energy may be smaller than this value, the designed pulse energy of total energy, 12kJ/4 beams is expected to be achieved. Recently, a compressor chamber for 40cmx40cm x 4 beams was installed in the implosion target chamber room as shown in Fig. 3. In the end of FY.2006, one beam compression test and a plasma experiment will be carried out to demonstrate 2.5kJ/10ps pulse generation. In FY.2007, compression optics for remaining 3 beams will be installed and full beam compression test will start. After the completion of LFEX, we will start the foam cryogenic cone shell target experiment in late 2007.

(a) (b)

Fig. 3. Present outlook of LFEX (a); main amplifier and (b) compressor chamber

3. Fabrication of foam cryogenic cone-shell target

The target fabrication and irradiation system with characterization of DT cryogenic foam layer are also under development as the collaboration program between Osaka University and NIFS (National Institute for Fusion Science). The DT fuel will be fed to the foam shell layer through a capillary and then, frozen to a solid layer as shown in Fig. 4[4]. The calibration of uniformity of cryogenic layer just before target shot is important for high density implosion. So, we are trying to make a cryogenic target transparent for visible light. Recently, we developed a target which meets this condition as shown in Fig.8. It is also important to reduce the foam density to less than 20mg/cc. The task to develop a technology fabricating an ultra light foam layer should be finished until the end of FY.2007.

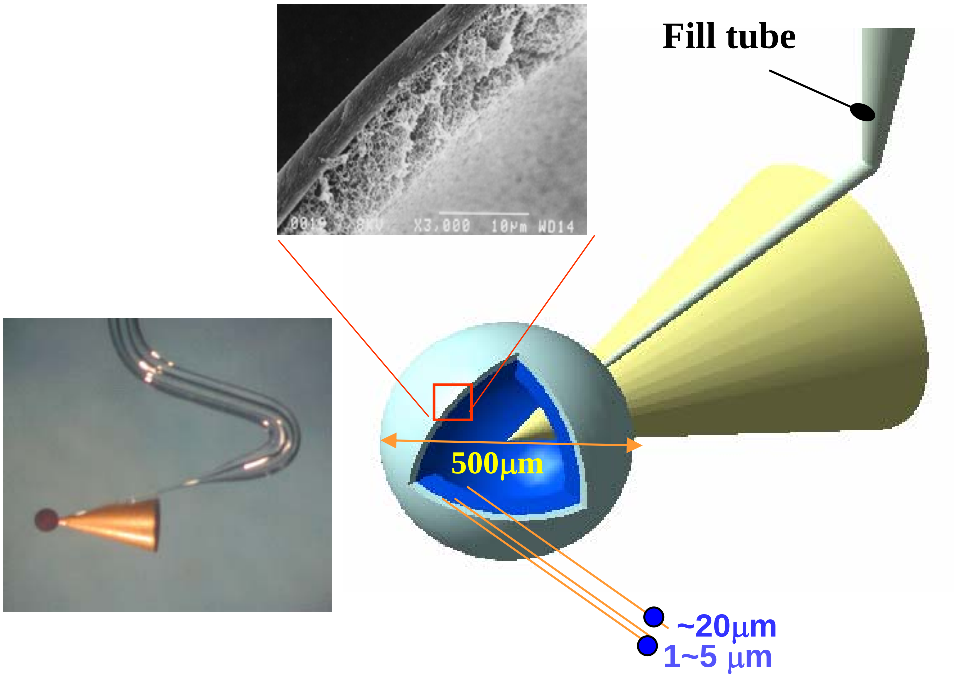


Fig. 4. Fabrication and Fueling of cryogenic foam shell target with cone target.

3. Target Design by simulations and Analysis of Fast Ignition Experiments with Integrated Code FI3

Many works [5-7] have investigated the ignition conditions for a given heat deposition model with 2-D burning simulations. The figure 5 shows the burning simulation results for (a) FIREX-I, (b) FIREX-II, and (c) a high gain target [5], where the heating and implosion laser energies are (a) 10kJ (1PW/10ps)+10kJ, (b) 50kJ (5PW/10ps)+50kJ and (c) 100kJ (5PW/20ps) +1MJ respectively. Here, it is assumed that the core plasma density is 300g/cm^3 and the initial area mass densities; ρR are 0.7g/cm^2, 1.2g/cm^2, and 2.7g/cm^2, when the implosion efficiency is 5% and the isentrope is 2. The core plasma heating by peta watt laser is assumed uniform with a fixed range of ρL = 1.0 g/cm^2, where the heating spot radii are assumed 15µm, 15µm and 30µm, respectively. According to these results, the gain reaches 0.2 in the FIREX-I, and the ignition and the gain of 10 will be achieved in the FIREX-II, as shown in Fig.5. The gain of 150 will be achieved with 1MJ laser input energy, where 100kJ short pulse laser and 900kJ/0.35 μm wavelength implosion laser are assumed. In summary, the above investigation clarifies the heating parameters; laser to high energy electron coupling efficiency of 30% and the electron stopping range of 1.0 g/cm^2 will achieve the goals of the FIREX-I and -II.

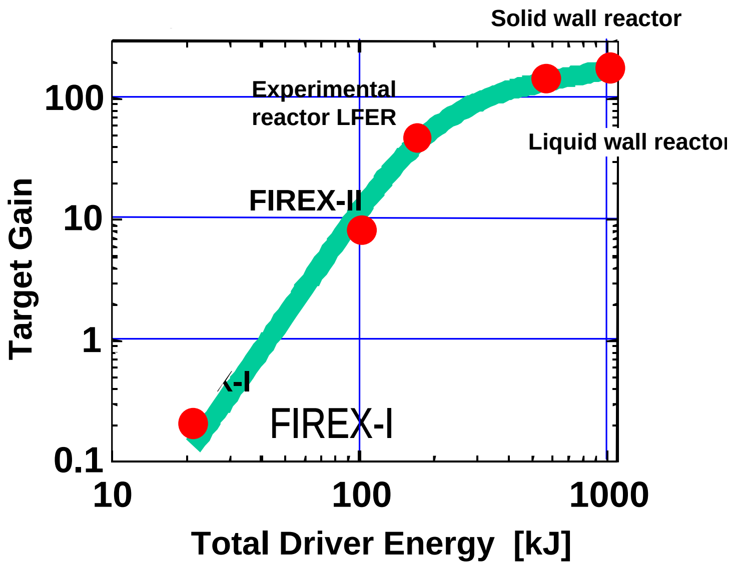
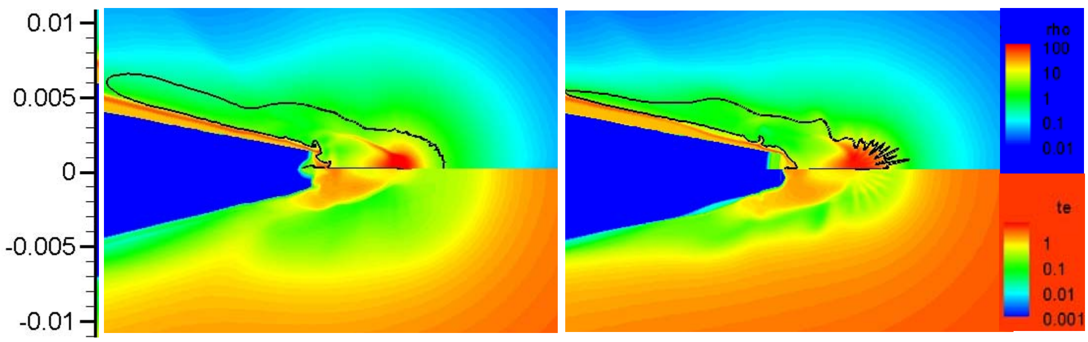


Fig. 5. Gain curve for the fast ignition.



(a) (b)

FIG. 6. Mass density contours in g/cm^3 (above) and electron temperature contours in keV (below), non-perturbed shell target (a) and a perturbed shell of mode ℓ =24 (b). The black lines are contact surface between CH pusher and DT fuel.

The numerical simulation plays an important role in studying detail mechanism of fast ignition, demonstrating the performance, designing the targets and laser pulse shapes. In the previous IAEA/FEC, we have presented the feature of "Fast Ignition Integrated Interconnecting code" (FI^3) [8, 9] and a representative numerical result. In FI^3, radiation hydrodynamic code, PINOCO [10] simulates implosion. Particle-in-Cell code, FISCOF [11] calculates relativistic laser plasma interaction. And relativistic Fokker-Planck hydrodynamic code, FIBMET simulates the hot electron transport and depositing electron energy in the core plasma as the meso-scale region [12]. Here, we describe the latest result of the integrated simulation, and discuss these element physics which relate to the FI.

The formation of high density core plasma is key issue for FI scheme, as well as heating core pl (a) problem. For the preliminary study, we have performed the non-spherical implosion with initial perturbation on the target surface to estimate the effect of RT instability. The target (CH-DT shell with gold cone, radius=250 mm) and laser condition (4.5 kJ, Gaussian pulse) are similar to the FIREX-I experiment. Figure 6 shows the mass density contours and electron temperature contours at the maximum compression time of the implosions with non-perturbed shell, and perturbed shell of mode ℓ=24. Even though there is RT instability, a high core plasma is formed as well as the non-perturbed case. These results give the evidence of the robustness of non-spherical implosion, which is a favorable fact for FI. These latest results will be reflected to the FI^3 system and the design for FIREX-I experiment.

Heating processes have been investigated for reproducing the GEKKO XII and peta watt laser experiments (Kodama et al. [1, 2]) by using Fokker Planck simulation and 1 and 2D-PIC simulations. The heating of highly compressed DT plasmas by the peta watt laser is investigated by Fokker Planck simulations with a probable relativistic electron spectrum predicted by the PIC simulations. The recent results are show in Fig. 7 and Table1 that the heating efficiency is sensitive to the preformed plasma scale length and it is maximum and about 15% when the scale length is 1 μm.

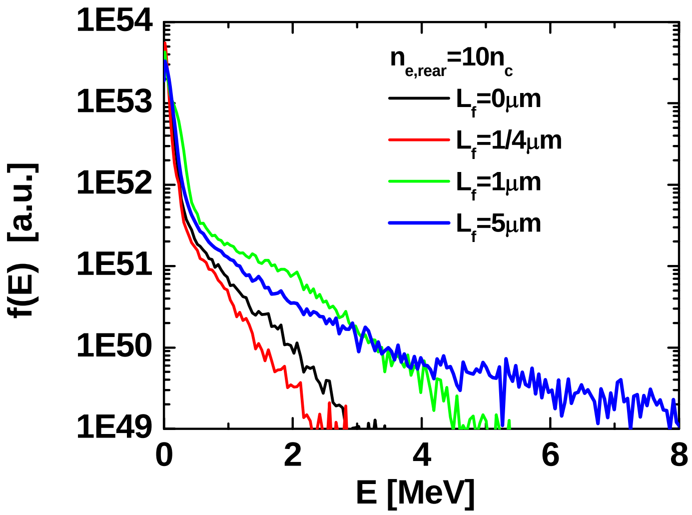


Fig. 7. Electron energy spectrum depending on pre formed plasma density scale.

Table 1: Fractions of absorbed laser energy, total transferred energy, and low energy (less then 2MeV) component, and stored energy

Cone angle	Flux ratio 1* (%)	Flux ratio 2 * (%)	Absorption rate (stored at tip) (%)
15deg	**21.5**	**2.2**	**52 (25)**
30deg	**18.0**	**3.6**	**55 (25)**
40deg	**16.9**	**4.0**	**49 (26)**

Note that the high efficiency at 1 μm scale is due to the higher electron population in the energy range of 1-2 MeV. In this case, the average ion temperature obtained by the simulation reaches 800 keV in the core plasma region as shown in Fig.8. This is approximately consistent with the experimental results.

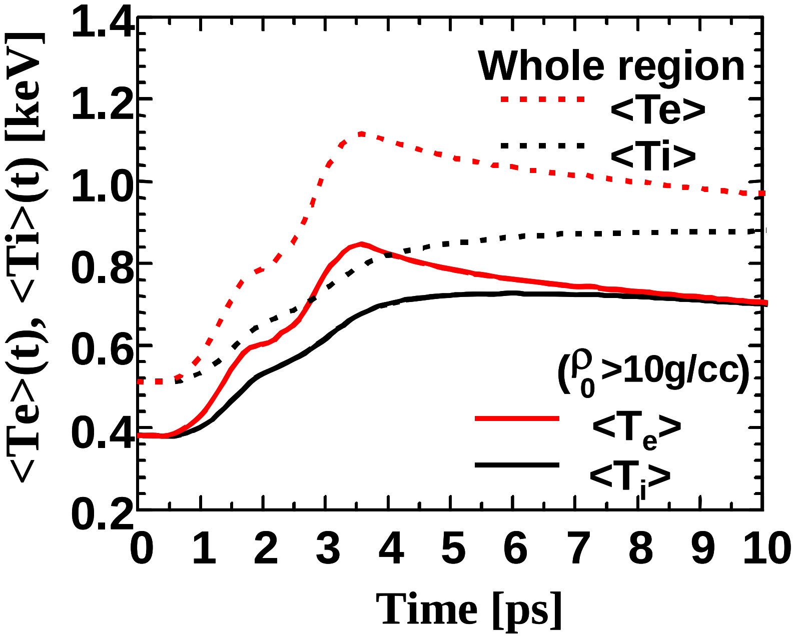
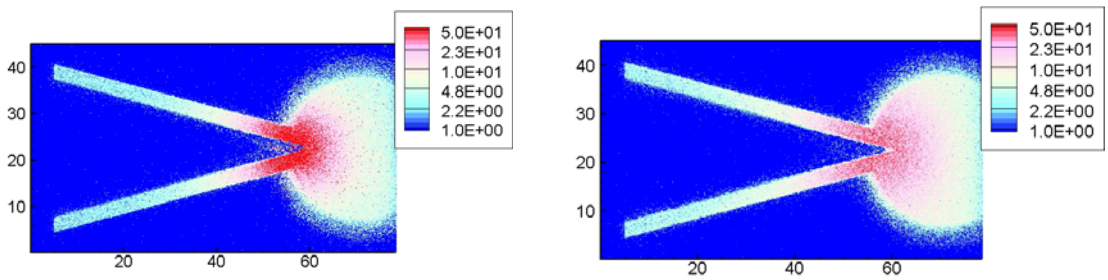


Fig. 8. Temporal evolution of heated plasma electron and ion temperature.

An electron energy density spatial distribution after the laser pulse is shown in the Fig. 9. The significant amount of absorbed laser energy (50% of absorbed laser energy) remains in the cone region as shown in table 1. This may be related to electrostatic confinement of MeV electron near the tip of the cone. The long time scale transport of those electrons is very important for determining the heating efficiency of the fast ignition. Further investigations are required.



(a) (b)

Fig.9 MeV electron energy spatial distributions at (a) 0.45ps (at the end of the laser pulse) and (b) 0.6ps (0.15 ps after the laser pulse)

5. Cryogenic target compression and heating experiments

The elementary processes of cryogenic cone shell target implosion have been explored by experiments with a foam layer cryogenic target. As shown in Fig 10, the preheating level on rear surface is measured. The preheating is found to be significant in a plastic and foam cryogenic layer target and has to be reduced for high density compression. We put a thin gold layer between plastic and the foam layer to reduce the preheating. As the result, the preheating level is reduced to the reasonable level.

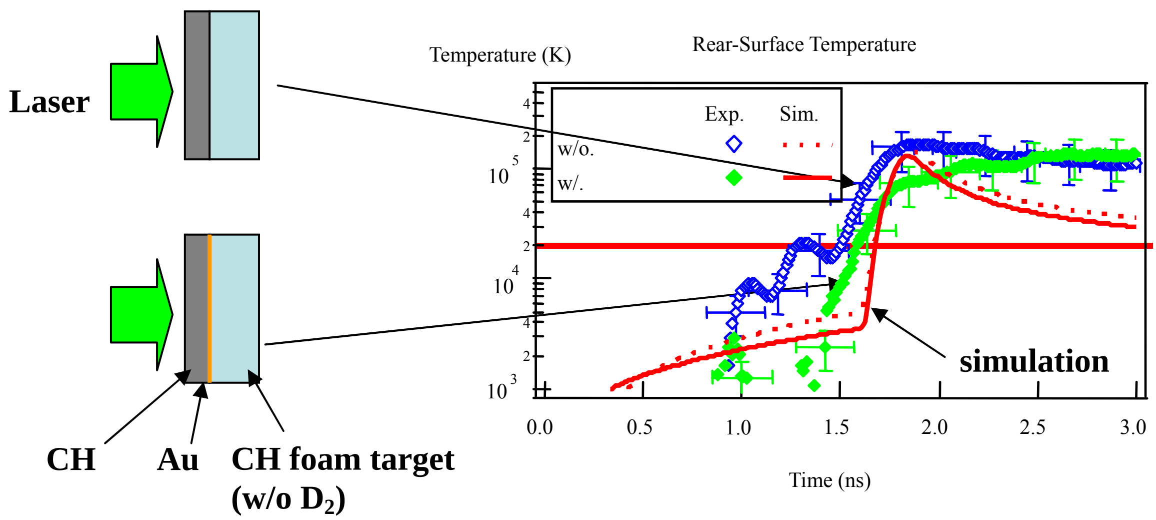


Fig. 10. Pre-heat level of rear surface of an ablative acceleration of cryogenic layer.

The experiments for the relativistic electron transport have been explored with GEKKO XII and Peta Watt lasers at ILE, Osaka University. In order to increase the hot electron production and its subsequent heating, gold foam target was shown very effective in our PW laser experiment. The foam coated target shows 3 times more efficient heating than a plane solid observed at the rear side of the target when 20 μm Mo plane coated either with 2 μm gold or 2 μm gold foam was irradiated with a PW laser at Inst. Laser Eng., Osaka University at 100J enegy with 0.6 psec pulse width [14].

Figure 11 shows the keV x-ray pinhole camera (XPHC) images taken from both front and rear of the targets irradiated by the GXII PW laser. The targets used were 20 μm thick molybdenum with front surface (i.e., laser interaction side) coated by either 2 μm solid gold or 2 μm gold foam. The density and porous cell size of the gold foam were 20% of the solid gold and about 0.3 μm. The front XPHC monitored the laser interaction dynamics and had a 18 μm small pinhole with 40 μm thick beryllium filter. The rear XPHC monitored the heating of the rear surface of the target and had a 200 μm large pinhole with 40 μm thick beryllium filter. Thus both XPHCs had the x-ray spectral sensitivity in the range 1-30 keV, with an effective peak of the spectral response at about 5 keV. The front x-ray emission from the gold foam coating target is weaker than the solid gold coating target. However, the rear x-ray emission from the gold foam coating target is much stronger than the solid gold coating target. The total count of the rear x-ray emission intensity from the gold foam coating target is about *3 times* of the solid gold coating target. The rear x-ray emission intensity reflects the deposited energy density located at the rear surface of the target and the heating of rear surface of the target. Higher x-ray emission count implies larger energy deposited. The deposited energy and heating are mainly from the hot electrons generated at the front of the target during the laser interaction. These hot electrons transport through the bulk target to heat the rear surface, resulting in the rear x-ray emission. Note the x-rays generated from the laser interactions at front surfaces cannot be responsible for the enhancement of the rear x-ray emission from the gold foam coating target. The target is too thick for keV x-rays to transmit from the front to the rear of the target. Moreover, with gold foam coating target the x-ray emission from the target front is weaker, thus one would expect a weaker rear x-ray emission, contrary to the experimental result, due to the x-ray transmission from the target front. We thus conclude that with the gold foam coating on the front surface, more laser energy is absorbed and coupled into hot electrons, resulting in the enhancement of both heating of the rear surface of the target and rear x-ray emission.

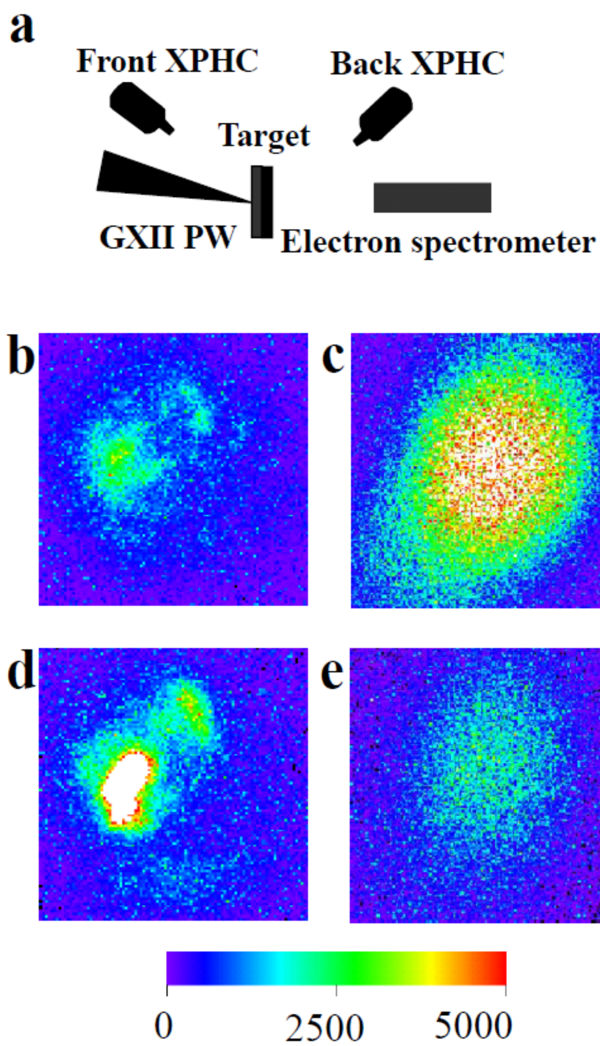


Figure 11 (Color) x-ray pinhole camera (XPHC) images taken from the front and rear of the targets. (a) is the experimental setup. (b) and (c) are the front and rear XPHC images from the solid gold coating target, (d) and (e) are the front and rear XPHC images from the gold foam coating target, respectively. The front x-ray emission is weaker while the rear x-ray emission is stronger from the gold foam coating target in comparison with the solid gold coating target. The rear x-ray emission is due to the heating of rear surface of the target by hot electrons generated in the GXII PW laser interactions. The GXII PW laser energies were 113 J and 98 J for gold foam and solid gold coating targets, respectively.

We should point out that the GXII PW laser energy was only 15% larger but the rear x-ray emission was about 2 times stronger in the gold foam coating target case. We consider that the enhanced rear x-ray emission is not due to larger laser energy but to enhanced laser energy absorption and hot electron production in the laser-foam interaction.

The relativistic electron energy transport has been shown that the hot electrons can be guided along the cone wall when the laser intensity is high enough such as at 10^{19} W/cm^2, resulting in strong B field. The strong B field appears to be responsible to bind the hot electrons toward the tip of the cone. [15]

6. Summary and Planning

The heating laser construction, target fabrication, implosion and heating experiments, target design have progressed in the FIREX-I projects. In 2007, a one beam experiment with the LFEX will be carried out. In 2008, the full beam experiments are expected.

The implosion and heating experiment with LFEX laser will be done before the end of 2010. If the temperature of dense imploded plasma is higher than 5keV in this FIREX-I experiment, we plan to proceed to the FIREX-II in 2010. Then, the ignition will be demonstrated until 2015 with FIREX-II.

References

[1] R. Kodama, P. Norreys, K.Mima, etal, Nature, 412, 798 (2001)
[2] R. Kodama, et al., Nature, 418, 933 (2002)
[3] N. Miyanaga, et al., Proceedings of IFSA2002, Monterey, Ca., US.
[4] T. Niromatsu, et al., Proceedings of IFSA2003, Monterey, Ca., US
[5] T. Johzaki, et al., Annual Progress Report, ILE, Osaka University, p. 95, (2002), and Fusion Science and Technology, 43,3,428 (2003)
[6] S. Atzeni, et al., Physics of Plasmas vol. 7, 3316 (1999)
[7] A.I. Mahady, H.Takabe, and K.Mima , Nucl. Fusion vol. 39,467 (1999)
[8] H. Nagatomo, Proceedings of the IFSA2003, Monterey, Ca., US
[9] H. Nagatomo, et al., IAEA-CN-116/IFP/07-29, (2004).
[10] H. Nagatomo et al., IAEA-CN-94/IFP/07, (2002).
[11] H. Sakagami, Proc. of IFSA '05, *to be published*
[12] T. Johzaki, Proc. of IFSA '05, *to be published.*
[13] T. Nakamura, Proc. of IFSA '05, *to be published.*
[14] A.L. Lei, K.A. Tanaka et al., Phys. Rev. Lett., **96**, 255006 (2006).
[15] H. Habara, K. Adumi, K. A. Tanaka et al. To appear in Phys. Rev. Lett. (2006).