Plasma Physics and Controlled
Fusion

Fast ignition integrated experiments with Gekko and LFEX lasers

To cite this article: H Shiraga *et al* 2011 *Plasma Phys. Control. Fusion* **53** 124029

View the article online for updates and enhancements.

You may also like

- Hot electron spectra in hole-cone shell targets and a new proposal of the target for fast ignition in laser fusion
T Ozaki, A Sunahara, H Shiraga et al.

- Measurement of heating laser injection time in a fast-ignition experiment
M Koga, Y Ishii, K Shigemori et al.

- Hot electron and ion spectra on blow-off plasma free target in GXII-LFEX direct fast ignition experiment
T. Ozaki, Y. Abe, Y. Arikawa et al.

This content was downloaded from IP address 18.117.183.150 on 23/04/2024 at 19:35

Plasma Phys. Control. Fusion **53** (2011) 124029 (6pp) doi:10.1088/0741-3335/53/12/124029

Fast ignition integrated experiments with Gekko and LFEX lasers

H Shiraga[1], S Fujioka[1], M Nakai[1], T Watari[1], H Nakamura[1], Y Arikawa[1], H Hosoda[1], T Nagai[1], M Koga[1], H Kikuchi[1], Y Ishii[1], T Sogo[1], K Shigemori[1], H Nishimura[1], Z Zhang[1], M Tanabe[1], S Ohira[1], Y Fujii[1], T Namimoto[1], Y Sakawa[1], O Maegawa[1], T Ozaki[2], K Tanaka[3], H Habara[3], T Iwawaki[3], K Shimada[3], H Nagatomo[1], T Johzaki[1], A Sunahara[4], M Murakami[1], H Sakagami[2], T Taguchi[5], T Norimatsu[1], H Homma[1], Y Fujimoto[1], A Iwamoto[2], N Miyanaga[1], J Kawanaka[1], T Jitsuno[1], Y Nakata[1], K Tsubakimoto[1], N Morio[1], T Kawasaki[1], K Sawai[1], K Tsuji[1], H Murakami[1], T Kanabe[6], K Kondo[7], N Sarukura[1], T Shimizu[1], K Mima[1] and H Azechi[1]

[1] Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan
[2] National Institute for Fusion Science, Toki, Gifu, 509-5292, Japan
[3] Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan
[4] Institute for Laser Technology, Suita, Osaka 565-0871, Japan
[5] Faculty of Science and Engineering, Setsunan University, Neyagawa, Osaka 572-8508, Japan
[6] Graduate School of Engineering, University of Fukui, Fukui, Fukui 910-8507, Japan
[7] Kansai Photon Science Institute, Japan Atomic Energy Agency, Kizu, Kyoto 619-0215, Japan

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

Received 25 June 2011, in final form 31 August 2011
Published 14 November 2011
Online at stacks.iop.org/PPCF/53/124029

Abstract
Based on the successful result of fast heating of a shell target with a cone for heating beam injection at Osaka University in 2002 using the PW laser (Kodama *et al* 2002 *Nature* **418** 933), the FIREX-1 project was started in 2004. Its goal is to demonstrate fuel heating up to 5 keV using an upgraded heating laser beam. For this purpose, the LFEX laser, which can deliver an energy up to10 kJ in a 0.5–20 ps pulse at its full spec, has been constructed in addition to the Gekko-XII laser system at the Institute of Laser Engineering, Osaka University. It has been activated and became operational since 2009. Following the previous experiment with the PW laser, upgraded integrated experiments of fast ignition have been started using the LFEX laser with an energy up to 1 kJ in 2009 and 2 kJ in 2010 in a 1–5 ps 1.053 μm pulse. Experimental results including implosion of the shell target by Gekko-XII, heating of the imploded fuel core by LFEX laser injection, and increase of the neutron yield due to fast heating compared with no heating have been achieved. Results in the 2009 experiment indicated that the heating efficiency was 3–5%, much lower than the 20–30% expected from the previous 2002 data. It was attributed to the very hot electrons generated in a long scale length plasma in the cone preformed with a

prepulse in the LFEX beam. The prepulse level was significantly reduced in the 2010 experiment to improve the heating efficiency. Also we have improved the plasma diagnostics significantly which enabled us to observe the plasma even in the hard x-ray harsh environment. In the 2010 experiment, we have observed neutron enhancement up to 3.5×10^7 with total heating energy of 300 J on the target, which is higher than the yield obtained in the 2009 experiment and the previous data in 2002. We found the estimated heating efficiency to be at a level of 10–20%. 5 keV heating is expected at the full output of the LFEX laser by controlling the heating efficiency.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Fast ignition (FI) is a new scheme for inertial confinement fusion, in which a high-power short-pulse laser is injected into the imploded core for heating the fuel core plasma [1–3]. A shell target with a cone for guiding the heating beam has been proposed for the FI scheme [4]. Based on the successful result of fast heating of an imploded shell target with a cone [4], the FIREX-1 project [5] was started in 2004. Its goal is to demonstrate fuel heating up to 5 keV using an upgraded heating laser beam. For this purpose, the LFEX laser, which is a Nd : glass laser and can deliver, at the full spec, an energy up to10 kJ in a 0.5–20 ps pulse, has been constructed in addition to the Gekko-XII laser system at the Institute of Laser Engineering (ILE), Osaka University (figure 1). It has been activated and became operational since 2009. Following the previous experiment with the PW laser, upgraded integrated experiments of FI have been started using the LFEX laser with an energy up to 2 kJ in a 1–5 ps 1.053 μm pulse. The initial experiment with the LFEX laser was performed in June–September 2009, and the second one in September–December 2010 to demonstrate implosion of the shell target by the Gekko-XII laser and its heating by the LFEX laser.

2. Integrated experiments of FI with Gekko-XII and LFEX lasers

LFEX has been constructed, and then, fine tuning of the amplification, pulse compression, and focusing of the laser output beam have recently been successfully performed. The full system has four $37 \times 37\,cm^2$ square beams, although only one or two of those were used in the present experiment. A pulse from the oscillator was spectrally chirped and was amplified with rod and disk amplifiers. Then the pulse was compressed with a large grating compression optical system down to 1 ps in the present experiment. The beams were focused with an off-axis parabola mirror down to a focal spot size of 30–60 μm in diameter as shown in figure 2, which was nearly twice the diffraction limit, resulting in an irradiation intensity of order of $1 \times 10^{19}\,W\,cm^{-2}$. Beam synchronization of LFEX to Gekko-XII was performed optically using the common oscillator pulse for both lasers.

Implosion and heating experiments of FI targets for FIREX-1 have been performed by operating both Gekko-XII and LFEX lasers. Typical laser and target parameters were as follows. The Gekko-XII laser for implosion: 0.53 μm light with an energy of 1.5–4.5 kJ in total in a 1.5 ns nearly Gaussian pulse in 2002 and 2009, and a nearly flat-top pulse in the 2010 experiment, nine beams among twelve. The LFEX laser for heating: 1.053 μm light with an energy up to 1–2 kJ in 1–5 ps. The LFEX beam(s) were focused and injected into a cone attached to a shell target. Shell targets (CD: deuterated polystyrene): 500 μm in diameter and

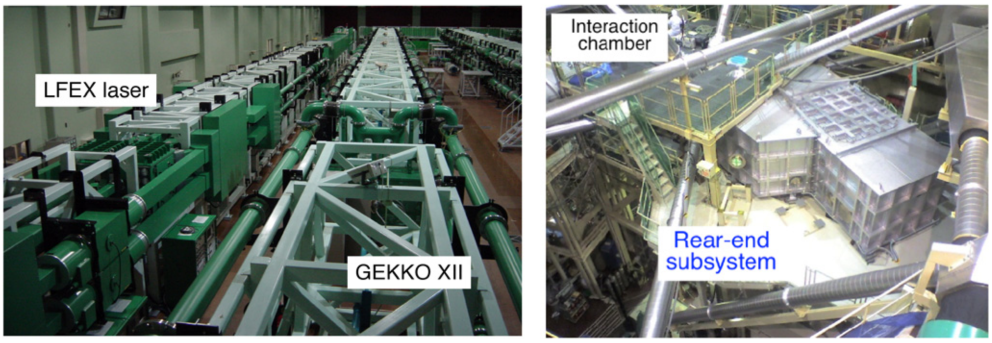

Figure 1. Left: Gekko-XII laser system for implosion of the fuel target, and the LFEX laser beam line for FI heating. Right: rear-end subsystem including pulse compressor and focusing optics inside the vacuum chamber and the interaction chamber.

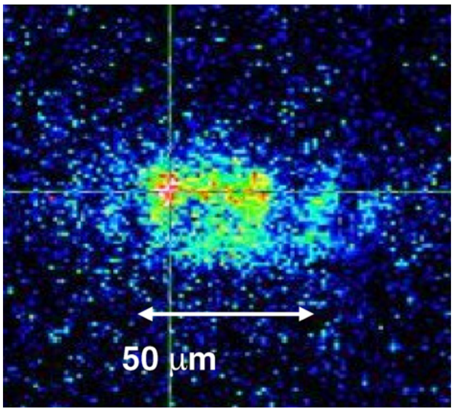

Figure 2. X-ray emission image of a Au plane target irradiated with the LFEX beam, showing the LFEX focal spot size.

7 μm in thickness. A 10–20 μm wall-thickness Au cone with an opening angle of 30° or 45°. The outer surface of the Au cone was coated with a 10 μm thick CH layer. The distance from the center of the shell to the cone tip was 50 μm.

Characteristics of the imploded and heated fuel plasma were observed using a variety of plasma diagnostics. Dynamics of the imploded fuel plasma was observed with ultrafast x-ray spectroscopic imaging utilizing x-ray streak cameras [6–8] and x-ray framing cameras [9]. Fusion products were observed with detectors including a multi-channel single-hit neutron spectrometer, ultrafast liquid scintillator neutron detectors [10], filtered CR-39 detectors, etc. Hot electrons generated with LFEX beam irradiation were observed with electron spectrometers. In the 2009 experiment, we had serious problems in plasma diagnostics when we used the LFEX laser. The laser intensity on the target was so high and the amount of laser energy was so large that tremendous amounts of hard x-rays and electro-magnetic pulse (EMP) were generated, and the plasma diagnostics were in a very serious condition. In the 2010 experiment, we improved these plasma diagnostic instruments to be compatible even with such a serious hard x-ray and EMP harsh environment. The injection time of the heating beam relative to the implosion was measured with an x-ray streak camera with accuracy better than $\pm$10 ps.

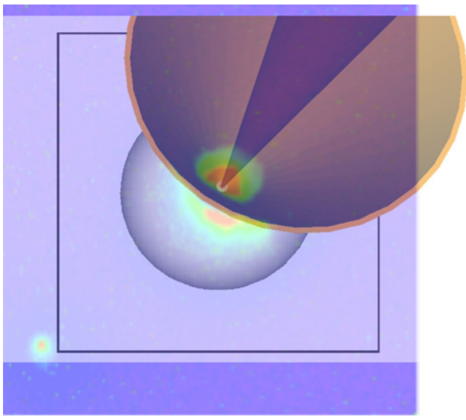

Figure 3. Time-integrated x-ray image of shell target with cone irradiated with Gekko-XII and LFEX lasers. A cartoon of the initial target is overlaid. The initial diameter of the shell is 500 μm. The left bottom spot is noise.

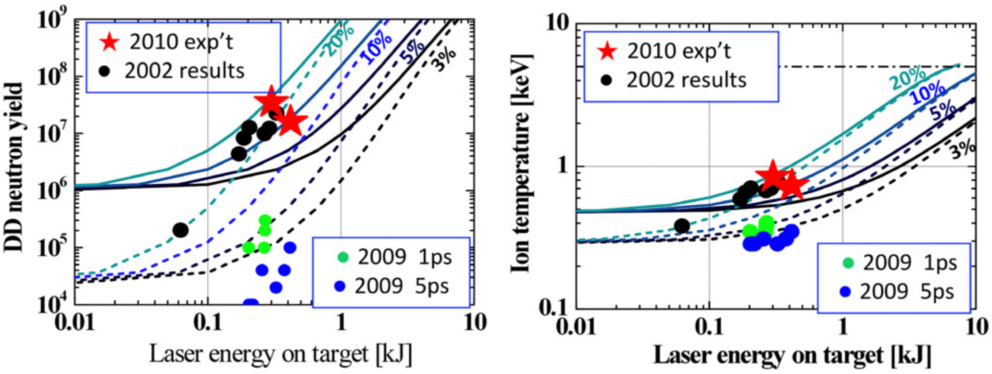

Figure 4. Left: neutron yield obtained in the 2010, 2009 and 2002 experiments. Curves are from simulations with assumed heating efficiencies. Right: estimated ion temperature for the same data.

3. Fast heating of the fuel plasma

Figure 3 shows a typical time-integrated x-ray image of a shell target with a cone. The camera observed from the opening side of the cone. A cartoon is overlaid to show the configuration. It is shown that the LFEX beam, injected and focused into the cone, generated plasma right at the interior of the tip of the cone. This plasma is expected to create hot electrons to heat the core plasma, a part of which can be seen beyond the cone tip.

Figure 4 shows neutron yield obtained from imploded and heated fuel plasma with heating by a 1 ps PW laser in 2002 [4], a 1 ps and 5 ps LFEX beam in 2009, and a 1 ps LFEX in 2010. Curves are from hydro-simulations assuming the initial condition of the imploded fuel plasma as well as the heating efficiencies as indicated. Although the actual density of the core plasma was not yet experimentally measured, here in the simulations, the density profile before the fast heating was assumed as a typical one of the implosion at this level to be a Gaussian distribution with a central peak density of 100 g cm^{-3}, and a half density radius of 20 μm, resulting in $\rho R = 0.2$ g cm^{-2}. The distance from the cone tip to the core was 50 μm. The initial temperature of the core plasma in the simulation was set to explain the experimentally observed neutron yield without fast heating with this assumed density profile. Rise in the ion temperature (figure 4, right) and the resulting neutron yield (figure 4, left) were calculated from the thermal energy increase in the core plasma with the assumed heating efficiencies. Dashed curves are for 2002 and 2009 data, and solid curves are for 2010 data. The neutron yield without heating beam was 1×10^4 in the 2002 and 2009 experiments, and 1×10^6 in the 2010 experiment. The difference is due to different pulse shapes of the driving Gekko-XII laser for implosion.

In the 2009 experiment, enhancement of the neutron yield compared with no heating case has been achieved by 1 ps heating. Note that the 30° cone was used for the 5 ps data, and the 45° one for 1 ps. Although the result looks as if there is a strong dependence on the pulse width, it is not clear because other experimental conditions were not the same. The ion temperature estimated from the 1 and 5 ps data in 2009 indicated that the heating efficiency was only 3–5%, which is much lower than 20–30% in the previous 2002 data. Observed hot electrons had a higher energy spectrum of about 10 MeV than the expected value, a few MeV to cause efficient energy deposition in the present level of the expected fuel ρR, 100–300 mg cm^{-2}.

According to a separate measurement of the preformed plasma and simulation analyses, it was attributed to the preformed long-scale length plasma created with a prepulse in the LFEX beam and confined in the cone. This is also inferred from the fact that the size of the x-ray emission region inside the cone shown in figure 3 is larger than the spot size shown in figure 2. It is of considerable importance to understand the condition of the preformed plasma at the time of the heating pulse injection. It is expected to reduce such a prepulse to increase the heating efficiency and to enhance neutron yield.

The prepulse level was significantly reduced in the 2010 experiment to improve the heating efficiency. Also we have improved the plasma diagnostics significantly which enabled us to observe the plasma even in such a hard x-ray harsh environment. In the 2010 experiment, we have observed neutron enhancement up to 3.5×10^7 with total heating energy of 300 J on the target, which is higher than the yield obtained in the 2009 experiment and the previous data in 2002. The estimated ion temperature is up to 0.8 keV. We found the estimated heating efficiency is at a level of 10–20%. In the next experiment from 2012, heating up to 2–3 keV is expected with 2–3 kJ heating, and 5 keV with 7–10 kJ, if we can keep a heating efficiency of 20%.

The heating efficiency depends on several parameters of the fast electron beam and its transport to the core. According to the simulations including Fokker–Planck transport [11] for an almost similar laser–plasma condition, the efficiencies without preformed plasma were estimated to be 48% from the heating laser to the fast electrons (39% to the electrons less than 10 MeV), 16% from the fast electrons to the core, resulting in the total efficiency being about 8%. The value obtained in the 2010 experiment, 10–20%, is near but higher than that. It is as yet difficult to have a decisive view of the heating process, because there are so many unknown factors in the electron beam parameters as well as the heating model. Further investigations are needed.

Data for only two target shots in 2010 are plotted in figure 4, although we made almost 40 integrated target shots. Unfortunately, the neutron signals were completely overwhelmed with the afterglow of the scintillator signal of intense x-rays and some other nuclear reactions in the target shots with energy larger than 400 J. Further improvement of the diagnostics is essential in the next experiments.

4. Conclusions and future prospect

Enhancement of the neutron generation up to 3.5×10^7 due to fast heating of the imploded fuel plasma has been achieved in the reactivated integrated experiment of fast ignition with the

LFEX laser at ILE, Osaka. Results of the 2002 experiment were reconfirmed with much more accurate plasma diagnostics in 2010. The estimated efficiency in 2010 is 10–20%.

Further tuning of LFEX is underway to extend the FI integrated experiments. The full four beams will be activated in 2011–2012. 5 keV heating is expected with full output of LFEX. Further improvement in the heating efficiency with advanced target concept will result in the achievement of 5 keV heating with even smaller energy of the heating beam.

Acknowledgments

The authors would like to thank the Gekko-XII and LFEX laser operation crew, the target fabrication group, the plasma diagnostics group, and the computer operation staffs for their great contribution to this work.

References

[1] Yamanaka T 1983 unpublished
[2] Basov N G, Gus'kov S Yu and Feoktistov L P 1992 *J. Sov. Laser Res.* **13** 396
[3] Tabak M, Hammer J, Glinsky M E, Kruer W L, Wilks S C, Woodworth J, Campbell E M, Perry M D and Mason R J 1994 *Phys. Plasmas* **1** 1626
[4] Kodama R *et al* 2001 *Nature* **412** 798
Kodama R *et al* 2002 *Nature* **418** 933
[5] Azechi H *et al* 2009 *Nucl. Fusion* **49** 104024
[6] Zhong J, Shiraga H and Azechi H 2008 *Rev. Sci. Instrum.* **79** 10E907
[7] Shiraga H, Lee M, Mahigashi N, Fujioka S and Azechi H 2008 *Rev. Sci. Instrum.* **79** 10E920
[8] Tanabe M, Fujiwara T, Fujioka S, Nishimura H, Shiraga H, Azechi H and Mima K 2008 *Rev. Sci. Instrum.* **79** 10E908
[9] Koga M, Fujiwara T, Sakaiya T, Lee M, Shigemori K, Shiraga H and Azechi H 2008 *Rev. Sci. Instrum.* **79** 10E909
[10] Nagai T *et al* 2011 *Japan. J. Appl. Phys.* **50** 080208
[11] Johzaki T, Nagatomo H, Sunahara A, Cai H-B, Sakagami H, nakao Y and Mima K 2011 *Nucl. Fusion* **51** 073022