Laser-driven Ion Acceleration on LFEX for Fast Ignition: State of the Art and Applications

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Abstract:

In order to realize fusion fast ignition assisted by laser-driven ion beams, we experimentally investigate the ion acceleration mechanism using one of the world most powerful laser system LFEX providing kilojoule multi-picosecond high-intensity laser pulses. We show that the conversion efficiency into protons is enhanced by finding an optimum duration of the laser pulse. The efficient ion generation is attributed to the hot electrons heated time-dependently by the laser beyond a typical scaling. The electron temperature is well reproduced by a Particle-in-Cell simulation. We also show the target design for the ion-driven fusion fast ignition experiments using LFEX.

1 Introduction

The acceleration of energetic (>1 MeV) ions driven by relativistic-intensity ($> 10^{18}$ Wcm^{-2}) laser pulses [1, 2] is attracting large interest on the prospects of realizing a novel source of intense ions for ion-driven fast ignition [3, 4, 5]. Fusion fast ignition assisted by laser-driven ion beams requires 10 kJ energy deposition onto the fuel core having ~ 500 g/cm^3 densities. Assuming 100 kJ as a technically manageable energy of the driving laser,

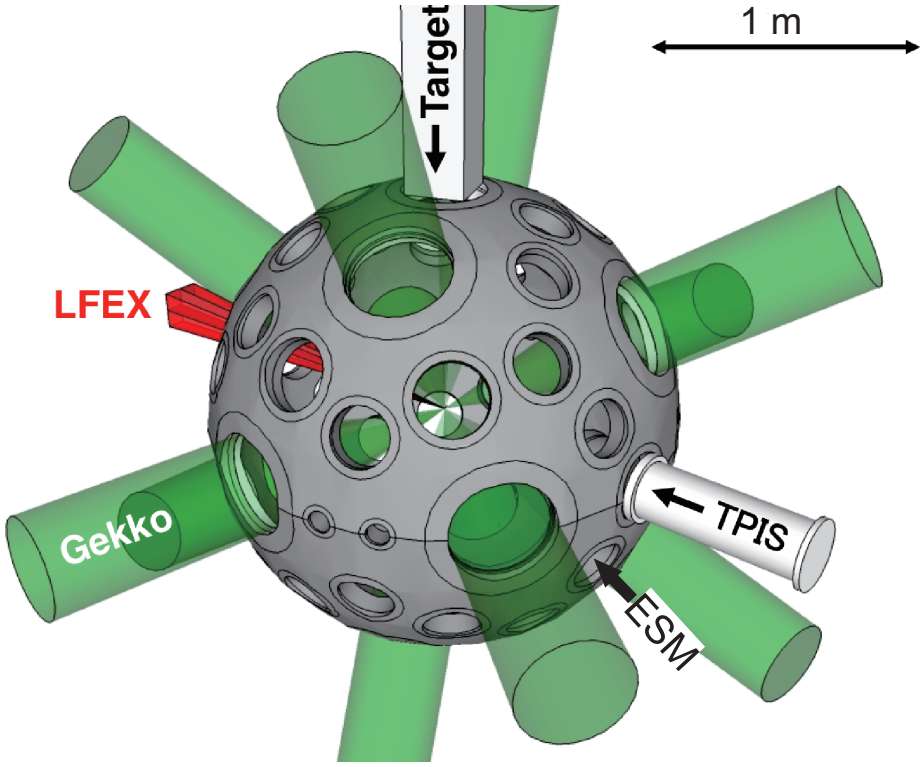

FIG. 1: A schematic picture of laser irradiation chamber.

the first milestone can be found on 10% conversion efficiency from the laser energy into ions having kinetic energies of 10-30 MeV/u.

Laser-ion acceleration by a strong charge-separation field generated on a thin foil target is governed by the absorption mechanism of laser energy into electrons. In the interaction between a laser pulse having relativistic intensity and overdense plasma, electrons are anomalously heated beyond the ponderomotive energy [6]. This phenomenon has been investigated intensively by several groups [7, 8, 9, 10] revealing that nonlinear motion of electrons takes a predominant role in the electron heating.

In this study, we experimentally investigate the ion acceleration mechanism using one of the world most powerful laser system LFEX [11, 12] of ILE, Osaka University providing kilojoule multi-picosecond high-intensity laser pulses. We show that the conversion efficiency into protons is enhanced by finding an optimum duration of the laser pulse. The efficient ion generation is attributed to the hot electrons heated time-dependently by the laser beyond a typical scaling. The electron temperature is well reproduced by a Particle-in-Cell simulation. We also show the target design for the ion-driven fusion fast ignition experiments using LFEX.

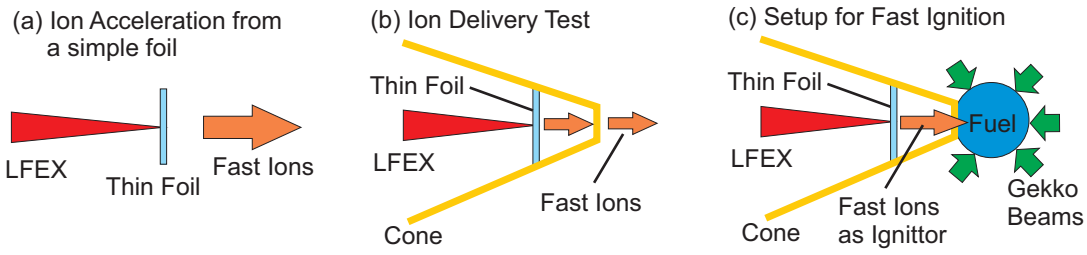

FIG. 2: Setup for (a) Ion acceleration experiment, (b) Ion delivery experiment and (c) Fast ignition by laser-driven ions.

2 Experiment

Laser-driven ion acceleration experiment has been performed using LFEX. The setup is shown in Fig. 1. On the center point of the vacuum chamber, the ps pulses from LFEX can be focused simultaneously with ns pulses from Gekko-XII. LFEX delivers four independent laser pulses having a duration of 1.5 ps (FWHM), central wavelength of 1.05 μm and energy of 1000 J in total (250 J for the single beam). The pulse is focused by an F/10 off-axis parabolic mirror (OAP) onto the target placed on the center of the spherical vacuum chamber. The laser intensity reaches 2.5×10^{18} Wcm^{-2} for each beam, 1×10^{18} Wcm^{-2} when the four beams arrive at the same time.

As shown in Fig 2, the experimental investigation on our laser-ion driven fast ignition of fusion can be devided into 3 steps. In the first step [Fig. 2(a)], the laser pulse is normally incident on a simple foil target that generates ions. The ions accelerated from the rear side of the target are observed by a Thomson-parabola ion spectrometer (TPIS) or Radiochromic film (RCF) detectors located in the normal direction of the target rear surface. In the second step [Fig 2(b)], the LFEX laser pulse is injected into the foil target located inside the cone-shaped structure shielding the expanding plasma aticipated in the fuel implosion by the beams of Gekko-XII. The third step [Fig. 2(c)] is the integrated experiment using Gekko-XII for implosion and LFEX for fast ignition.

In this work, we have performed the first step experiments, mentioned above, in order to investigate the fundamental properties required for ion generation with high efficiency. As mentioned in Introduction, we also show the first design of targets for the second-step experiments.

3 Results and Discussion

In this section, we investigate the ion acceleration mechanism using kilojoule picosecond laser LFEX, the laser contrast of which has been improved drastically. The laser pulse having a duration of 1.5 ps is focused onto an aluminum foil target with an energy of 1 kJ at maximum, which corresponds to the peak intensity of 1.2×10^{19} Wcm^{-2}. The proton

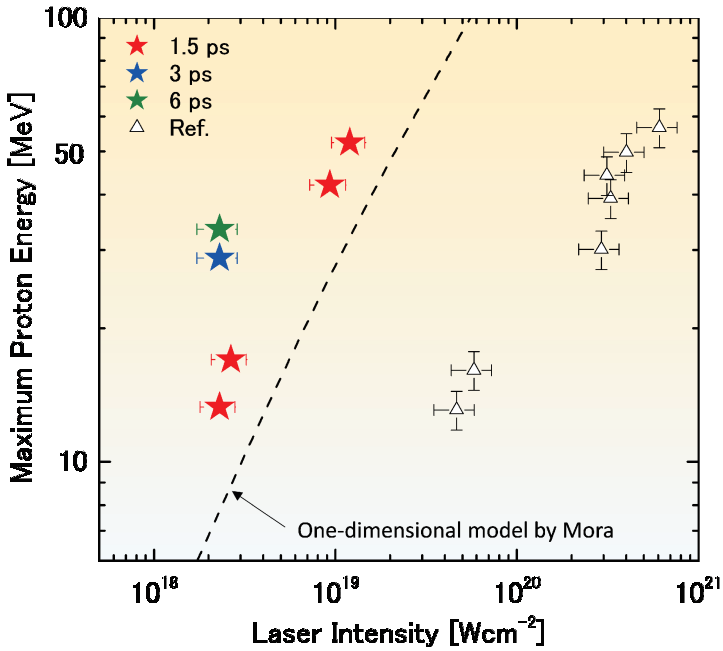

FIG. 3: The proton energies obtained with LFEX laser pulses having a duration of 1.5 ps (red stars), 3 ps (blue star) and 6 ps (green star) as a function of the laser intensity. The reference data (triangles) were obtained in [13] using 1-ps laser pulses.

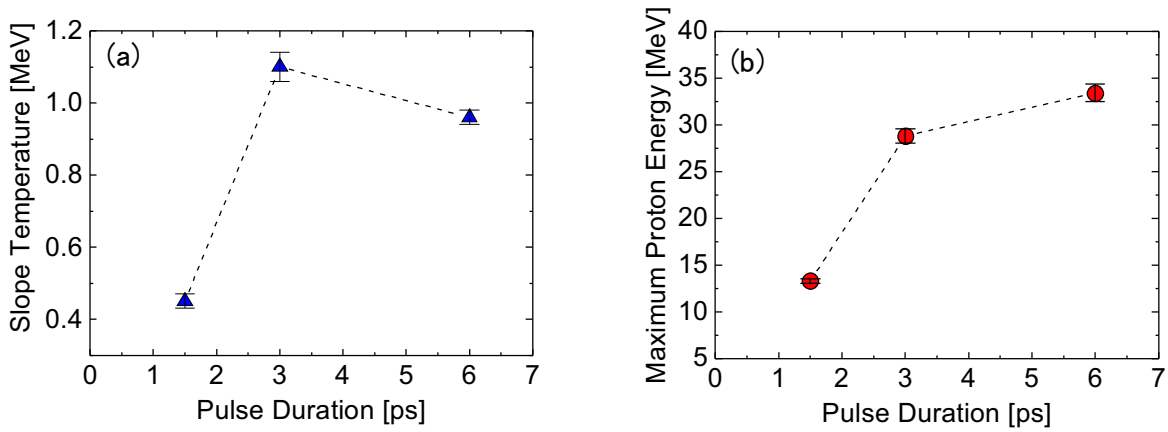

FIG. 4: (a) The slope temperature of high-energy electrons as a function of the laser pulse duration. (b) The accelerated proton energy observed simultaneously with the electron temperature.

energy spetra are obtained with several laser intensites, when the laser energy is varied from 0.25 to 1 kJ. As a result, protons having energy exceeding 50 MeV are observed, as shown in Fig. 3. Note the observations above have been performed without plasma mirror in the laser path. In a previous energy scaling of ion acceleration [14], 50-MeV protons were obtained with the laser intensity exceeding 10^{20} Wcm^{-2}, which is higher by an order of magnitude than the present one. To explain the experimental results, we discuss the ion acceleration mechanism via time-dependent heating of electrons, where the temperature of electrons and the charge separation field grow as a function of time, indicating that longer duration of the laser pulse can make a beneficial effect on the ion acceleration.

As shown in Fig. 4(a), when we expand the pulse duration (FWHM) of the laser from 1.5 ps to 3 ps at the fixed laser intensity of 2.3×10^{18} Wcm^{-2} (See also Fig. 3), the electron temperature measured by Electron Spectrometer (ESM) is drastically enhanced up to 1.1 MeV, which clearly exceeds the ponderomotive energy around 0.2 MeV for the laser intensity of 2.3×10^{18} Wcm^{-2} used in this measurement. At the duration of 6 ps, the electron temperature turns to decrease, indicating that an optimum duration can be found around 3 ps. In addition, the proton energy, analyzed simultaneously with the electron temperature, reaches 29 MeV at 3 ps and saturates around 33 MeV at 6 ps. Using Particle-in-Cell simulation code [15], we obtain the electron energy distribution for the 3 ps duration having a slope temperature of $T = 1.1$ MeV (Fig. 5), which is well in agreement to the ESM result. The simulation reveals that electrons continue to recirculate between the front and rear sides of the foil plasma during the laser incidence and are heated anomalously depending on the laser pulse duration. Too long pulse duration (6 ps in this work) leads to a large plasma expansion that can weaken the recirculation effect of electrons, resulting in the adiabatic decrease of electron temperature.

The maximum proton energies obtained experimentally [Fig. 4(b)] are well repro-

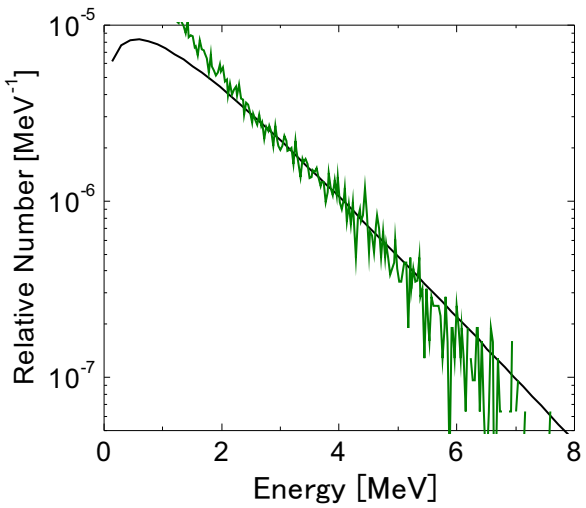

FIG. 5: The electron energy distribution obtained with a Particle-in-Cell simulation code for the laser pulse duration of 3ps, showing a Maxwellian distribution ($\propto \sqrt{E}\exp(E/T)$) having a temperature of $T = 1.1$ MeV.

duced by an analytical model that involves the time-dependent heating of electrons uner the framework of self-similar expansion of plasma [16, 17]. The details were discussed wlsewhere [18].

As a next step, to demonstrate the ion delivery through the cone structure [Fig. 2(b)], we have developed a thin foil built-in cone. Figure 6 shows a picture of the ion-acceleration foil located inside a gold cone. Here, an aluminum foil, the size of which is 1×1 mm^2, is supported by two thin line. The laser beams of LFEX are focused on this thin foil and generates MeV-energy ions from the rear surface of the foil. the ions are delivered through the bottom of the cone and arrive at the imploded fuel.

References

[1] Macchi, A., Borghesi, M. & Passoni, M. Ion acceleration by superintense laser-plasma interaction. *Rev. Mod. Phys.* **85**, 751-793 (2013).

[2] Daido, H., Nishiuchi, M. & Pirozhkov, A. S. Review of laser-driven ion sources and their applications. *Reports Prog. Phys.* **75**, 056401 (2012).

[3] Roth, M. *et al.* Fast ignition by intense laser-accelerated proton beams. Phys. Rev. Lett. **86**, 436-439 (2001).

[4] Fernández, J. C. et al. Progress and prospects of ion-driven fast ignition. *Nucl. Fusion* **49**, 65004 (2009).

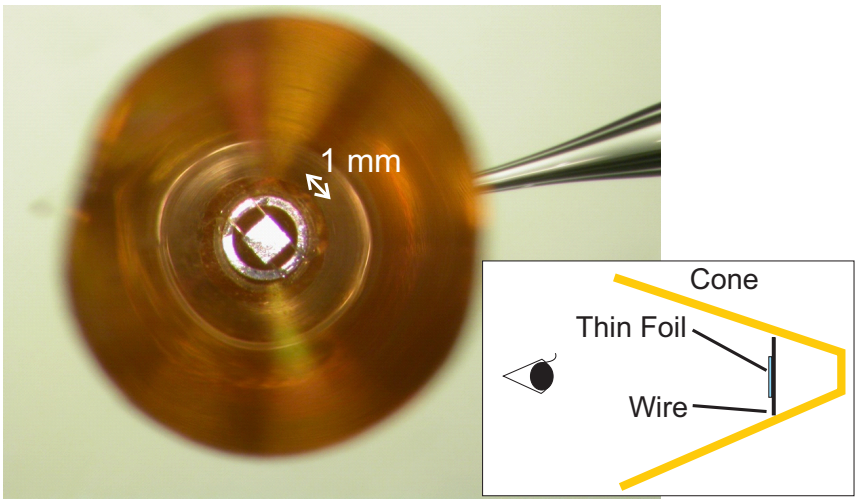

FIG. 6: The photoe of an aluminum thin foil located inside the cone-shaped shield.

[5] Fujioka, S. *et al.* Fast ignition realization experiment with high-contrast kilo-joule peta-watt LFEX laser and strong external magnetic field. Phys. Plasmas **23**, 056308 (2016).

[6] Wilks, S., Kruer, W., Tabak, M. & Langdon, A. Absorption of ultra-intense laser pulses. *Phys. Rev. Lett.* **69**, 1383-1386 (1992).

[7] Kemp, A. J. & Divol, L. Interaction physics of multipicosecond petawatt laser pulses with overdense plasma. *Phys. Rev. Lett.* **109**, 1-5 (2012).

[8] Paradkar, B. S., Krasheninnikov, S. I. & Beg, F. N. Mechanism of heating of pre-formed plasma electrons in relativistic laser-matter interaction. *Phys. Plasmas* **19**, 060703 (2012).

[9] Yogo, A. *et al.* Ion acceleration via 'nonlinear vacuum heating' by the laser pulse obliquely incident on a thin foil target. *Plasma Phys. Control. Fusion* **58**, 025003 (2016).

[10] Bulanov, S. V. *et al.* Stochastic regimes in the driven oscillator with a step-like nonlinearity. *Phys. Plasmas* **22**, 063108 (2015).

[11] Kawanaka, J. *et al.* 3.1-kJ chirped-pulse power amplification in the LFEX laser. *J. Phys. Conf. Ser.* **112**, 032006 (2008).

[12] Arikawa, Y. *et al.* Ultrahigh-contrast kilojoule-class petawatt LFEX laser using a plasma mirror. Appl. Opt. **55**, 6850 (2016).

[13] Robson, L. *et al.* Scaling of proton acceleration driven by petawatt-laser-plasma interactions. *Nat. Phys.* **3**, (2007).

[14] Fuchs, J. *et al.* Laser-driven proton scaling laws and new paths towards energy increase. *Nat. Phys.* **2**, 48-54 (2006).

[15] Kishimoto, Y. & Masaki, T. A paradigm of kinetic simulation including atomic and relaxation processes: a sudden event in a lightning process. *J. Plasma Phys.* **72**, 971 (2006).

[16] Gurevich, A. V., Pariiskaya, L. V. & Pitaevskii, L. Self-similar motion of rarefied plasma. *J. Exp. Theor. Phys.* **22**, 449454 (1966).

[17] Mora, P. Plasma expansion into a vacuum and ion acceleration. *Phys. Rev. Lett.* **90**, 5-8 (2003).

[18] *submitted to Nat. Comm.*