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Energy distribution of fast electrons accelerated by high intensity laser pulse depending on laser pulse duration

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Abstract. The dependence of high-energy electron generation on the pulse duration of a high intensity LFEX laser was experimentally investigated. The LFEX laser (λ = 1.054 and intensity = $2.5 - 3 \times 10^{18}$ W/cm^2) pulses were focused on a 1 mm^3 gold cubic block after reducing the intensities of the foot pulse and pedestal by using a plasma mirror. The full width at half maximum (FWHM) duration of the intense laser pulse could be set to either 1.2 ps or 4 ps by temporally stacking four beams of the LFEX laser, for which the slope temperature of the high-energy electron distribution was 0.7 MeV and 1.4 MeV, respectively. The slope temperature increment cannot be explained without considering pulse duration effects on fast electron generation.

1. Introduction

In the fast-ignition (FI) scheme, the energy of the ignitor laser beams is converted into fast electrons, and the fast electrons heat a compressed fuel core to the ignition temperature. Laser power on the order of petawatts is required to induce fusion ignition using the FI scheme [1].

A realistic ignitor laser pulse must have a relatively long pulse duration ($\approx$ 20 ps) compared to that of standard petawatt laser systems ($\leq$ 10 ps) to keep the peak intensity of the ignitor beam within the acceptable level (10^{21} W/cm^2) [2]. This is because a higher-intensity laser generates higher-energy electrons that deposit less energy in the fuel core. When the pulse duration is much longer than 1 ps, the fast-electron generation can be affected significantly by plasma expansion that takes place over the duration of the ignitor laser pulse. A recent computational study indicated that a longer ignitor laser pulse produces a plasma with a longer density scale length, and consequently more energetic electrons are produced in the longer under-dense region of the plasma [3]. In this study, we investigate the dependence of the fast-electron energy distribution on the pulse duration of a high-intensity LFEX laser under pre-plasma-free conditions.

2. Reduction of preformed plasma by using plasma mirror

The experiment was carried out using the LFEX laser system at the Institute of Laser Engineering at Osaka University. The LFEX system consists of four beams. Each beam was compressed by two sets of double gratings, and they were focused onto the target by a common f/10 large off-axis parabolic mirror. Each LFEX laser pulse ($\lambda = 1.054\mu m$) is able to deliver $>$ 500 J in a 1.2 ps duration. The on-target FWHM spot size was 70 μm, and 30% of the laser energy was contained in the spot. At the rear side of the LFEX system, the intensity contrast ratio of the LFEX laser was 10^{-9} at 2 ns before the main pulse, as measured by a 20 ps rise-time photodiode connected to a 20-GHz oscilloscope. The detailed shape of the LFEX pulse including the preceding pulses was measured at the front end of the LFEX system with a third-order correlation . A two-dimensional (2D) radiation hydrodynamic simulation (PINOCO-2D) [4] predicted the plasma scale length just before the main pulse irradiation to be 7 μm. This contrast is not small enough to experimentally investigate the effect of the pulse duration on fast-electron generation under pre-plasma-free conditions. (When laser interaction with overdense plasma occurs for a pulse duration of 4 ps and focal intensity of 3×10^{18} W/cm^2, the plasma scale length is predicted by particle-in-cell calculations to be about 10 μm. The initial plasma scale length should be an order of magnitude smaller than that.

A plasma mirror (PM) was installed in the LFEX laser system to significantly reduce the scale length of the preformed plasma prior to the arrival of the main pulse. The PM is an anti-reflection coated spherical concave glass substrate with a reflectivity of $< 0.5\%$. Using the PM considerably improved the contrast ratio of the LFEX pulse by a factor of 10^2. Due to the geometric constraints of the LFEX laser system, the PM was placed behind the target. The LFEX beams were focused 3 mm above the target and defocused on the PM. In this configuration, 99.5% of the foot pulse and pedestal passes through the PM and only 0.5% is reflected and focused by the PM. Once a plasma was produced on the PM surface by the leading edge of the main pulse, the reflectivity of the PM increased to $> 50\%$. The reduction of the preformed plasma produced by the preceding pulses was confirmed using optical interferogram diagnostics. A 1 mJ laser pulse with a wavelength of 630 nm and a pulse duration of 20 ps was used to measure the density profile for the preformed plasma. Plasma expansion was observed 1.3 ns before the arrival of the main pulse without the PM, while the target retained its sharp boundary 140 ps before the arrival of the main pulse at the PM. Figure 1 shows interferogram images of a preformed plasma measured with and without the PM at the same laser intensity. Calculations of the scale length for the preformed plasma carried out using the PINOCO code agree well with the experimentally measured values. The PINOCO calculations indicate that the density scale length for the preformed plasma is 1.5 μm with the PM. Details of the analysis will be reported elsewhere.

3. Dependence of fast electron energy distribution on pulse duration

Each pulse of the LFEX laser has a FWHM duration of 1.2 ps and a peak intensity of 2.5×10^{18} W/cm^2. The LFEX laser pulses are temporally stacked to create several pulse shapes of various pulse duration and intensity, as shown in Fig. 2. These pulses were focused by the PM onto a 1 mm^3 cubic gold block. Energy distributions of the fast electrons were measured with a vacuum electron spectrometer located at 20.9° from the incident axis of the LFEX beams. The slope temperature of the fast-electron energy distribution was 0.7 MeV in Case A and 1.4 MeV in Case B. In Case B, the slope temperature was two times higher than that in Case A, even though the peak intensities in Cases A and B are almost same. This increase in slope

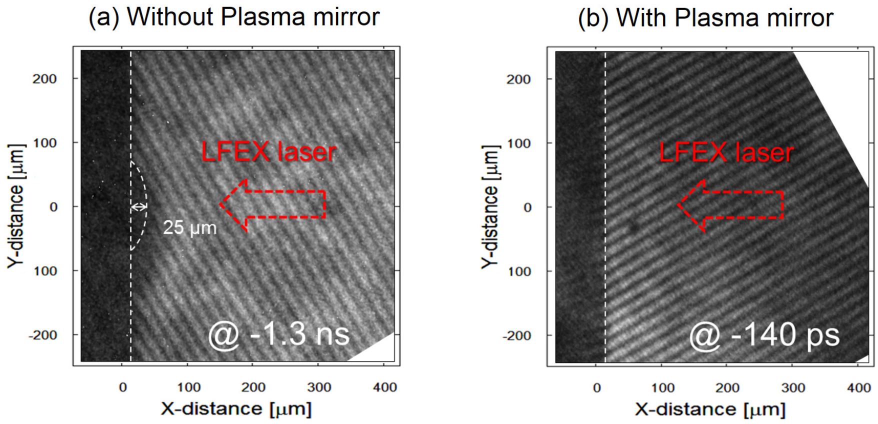

Figure 1. (Color online) Interferograms of preformed plasma on the target with (right) and without (left) the PM at the same laser intensity. The preformed plasma was observed using optical interferogram diagnostics with a 630 nm probe pulse of 21 ps duration. When using the PM, a preformed plasma was not created 140 ps before the main peak, while a preformed plasma was observed 1.3 ns before the main peak for the original LFEX.

temperature is inconsistent with conventional energy scaling [5][6][7], which does not take into account the effects of pulse duration.

We attempted to reproduce the experimental results using a two-dimensional particle-in-cell code (PICLS2D) [8]. The gold block target was simulated using a 20 μm planar plasma with an electron number density of $40n_{\rm cr}$. The initial surface of the plasma has a preformed plasma with a scale length of 1 μm from $0.1n_{\rm Cr}$ to $40n_{\rm cr}$, where $n_{\rm cr}$ is the critical electron density. The intensity and pulse duration used in the calculation were the same as those in the experiment. The PICLS2D calculation shows that energetic electrons are generated in a long-scale-length, under-dense plasma produced by the main laser pulse during the main pulse duration. For a 1.2 ps pulse, the energetic electrons were primarily generated at the peak intensity of the laser pulse, while for a 4.0 ps pulse, energetic electrons were mainly accelerated by the latter part of the longer main pulse ($>$ 3 ps).

4. Conclusion

We have experimentally investigated the dependence of the fast-electron energy distribution in FI on the LFEX laser pulse duration. Preformed-plasma-free conditions were achieved by installing a PM in the LFEX laser system. The slope temperatures for the fast electrons accelerated by 2.5×10^{18} W/cm^2 were 0.7 MeV and 1.4 MeV for FWHM pulse durations of 1.2 ps (Case A) and 4.0 ps (Case B), respectively. The temperature increment cannot be explained without considering the effects of pulse duration on the fast electron generation. The calculations carried out using the PICLS2D code show that the plasma expansion driven by the main laser pulse during the main pulse duration results in the generation of a high-energy tail in the fast-electron distribution. Future calculations must consider interference between the beams in both the time and space domains. Because the 1.054 μm beams overlap each other with an incident angle of 2.86° with respect to the target normal in the experiment, the calculated separation between interference fringes is 10 μm ($<$ laser focal spot) under these conditions[9]. The interference fringes create perturbations on the critical surface of an expanding plasma due to the spatial nonuniformity of the focus pattern intensity. The density profile of the expanded plasma may be significantly affected by the hydrodynamic instabilities initiated by the perturbation. Details of this analysis will be published elsewhere in the near future.

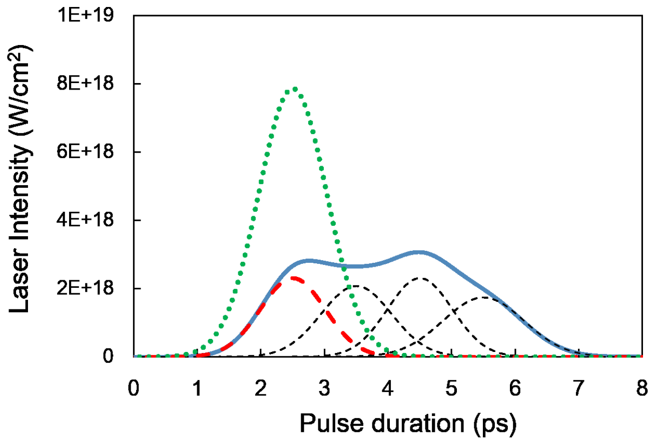

Figure 2. (Color online): LFEX laser pulses temporally stacked to generate various pulse shapes. Case A (red broken line): 1.2 ps single pulse with peak intensity of 2.5×10^{18} W/cm^2; Case B (blue solid line): 1.2 ps trained four pulse with pulse intensity of 3×10^{18} W/cm^2; Case C (green dotted line): 1.2 ps temporal overlap four pulse with pulse intensity of 7.6×10^{18} W/cm^2.

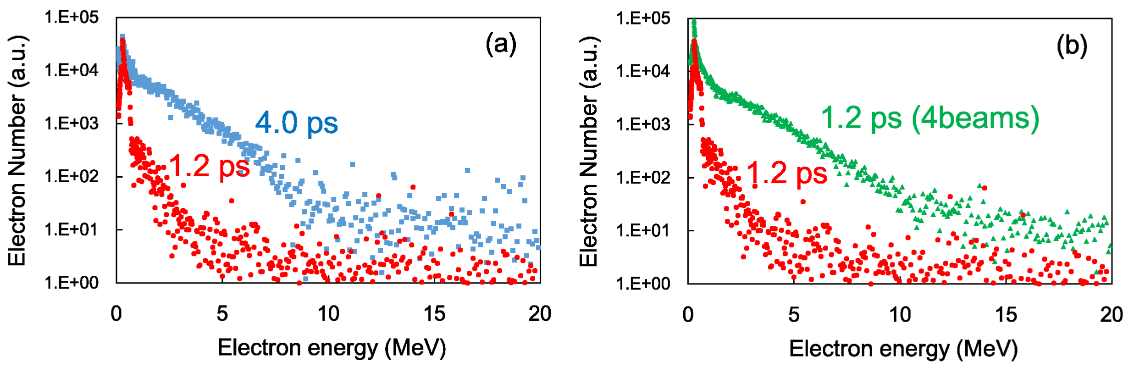

Figure 3. (Color online) (a) Electron energy distributions for the same laser irradiation intensity but different pulse durations (Case A vs. Case B). (b) Electron energy distributions for the same pulse duration but different laser irradiation intensities (Case A vs. Case C).

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