EXPERIMENTAL UPDATE ON THE COUNTER-ILLUMINATING FAST IGNITION SCHEME USING THE KJ-CLASS ULTRA-INTENSE LASER LFEX

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Fast Ignition is a scheme that separates the implosion and heating of imploded fuel, allowing for the optimization of each process to achieve a high-gain target design. According to particle-in-cell simulations, the counter-illuminating Fast Ignition scheme potentially enhances energy coupling between laser-driven fast electrons and the imploded fuel, aided by mega-gauss magnetic fields generated by counter-propagating fast electron flows. However, experimental validation of the energy coupling enhancement at a scale relevant to ignition target design remains an open issue. We have successfully developed a counter-propagating laser beam platform using a spherical plasma mirror for the kilojoule-class petawatt LFEX laser, achieving intensities of 5×10^{18} W/cm^2. Experiments using this platform reveal that laser-plasma interactions are a critical factor in demonstrating the counter-illumination configuration. To achieve high energy density with electron temperatures exceeding 1 keV, the LFEX laser should be focused using a laser guiding cone, with pulse cleaning facilitated by spherical plasma mirrors.

The Fast Ignition (FI) experiments conducted so far have applied one-directional heating laser illumination [1]. These experiments reveal that energy transport from fast electrons produced by the heating laser—acting as the heating carrier for the imploded fuel—into the imploded fuel is a critical issue for achieving high-gain target design [2]. To enhance energy coupling from the heating laser or fast electrons into the fuel, we introduced the counter-illuminating FI scheme [3]. Previous experiments and simulations revealed that counter-propagating fast electron flows generate mega-gauss magnetic fields through two-stream Weibel instability, which suggests the potential to improve fast electron energy deposition into high-density plasma. While these experiments were conducted using joule-class laser systems, kilo-joule class experiments have not yet been performed due to challenges with beam steering in large-scale laser systems. To address this, we have developed and demonstrated the use of a spherical concave plasma mirror for the kilojoule-class petawatt LFEX laser to achieve a counter-beam configuration [4]. As a preliminary step toward evaluating the significance of counter-laser irradiation, we report here on an experiment focusing on single-side irradiation to investigate the interaction between high-intensity lasers and matter.

Figure 1 (a) illustrates the counter-propagating LFEX laser configuration utilizing a spherical plasma mirror. In this setup, four laser beams are focused by off-axis parabolic mirrors (OAPs) into the target chamber center (TCC). For the counter-illuminating configuration, beams 2 and 4 are focused 3 mm above the TCC and then reflected by the spherical concave plasma mirror. This specially designed spherical concave plasma mirror reflects and focuses beams 2 and 4 onto one side of a planar target positioned at the TCC. Meanwhile, the other two beams (1 and 3) are directly focused onto the planar target surface using the OAP mirrors. The timing synchronization between the counter-propagating pulses was achieved through optical interference measurements, resulting in a timing jitter of 1.9 ps, comparable to the laser pulse duration of 1.5 ps (full width at half maximum). The spatial overlap of the counter-propagating laser beams was well controlled within a spot size of 60 μm, ensuring precise beam alignment for the experiments.

As a preliminary step to evaluate the significance of counter-laser irradiation, we conducted experiments focusing on single-side irradiation to investigate the interaction between high-intensity lasers and matter. Figures 2 illustrate the experimental setup and results. In the experiment, the target was a titanium-doped deuterated polystyrene film with a thickness of 10 μm, sandwiched between non-doped polystyrene films, each 1 μm thick. To control pre-plasma formation, laser shots were directed at the target both directly (Fig. 1(b)) and via a plasma mirror (Fig. 1(c)). Additionally, to enhance laser focusing capability, a laser guiding cone was attached to the thin-film target (Fig. 1(d)). The laser irradiation conditions were as follows: an energy of 160 J, a pulse duration of 1.5 ps, and a focusing intensity of 2×10^{18} W/cm^2. Diagnostics included an x-ray pinhole camera to evaluate the laser focusing region (Figs. 1 (b)-(d), middle) and an x-ray energy spectrometer using Ti-RbAp to determine electron temperature from the titanium radiation lines (Figs. 2 (b)-(d), bottom). The electron temperature, Te, was evaluated through x-ray spectrum simulations that accounted for both background and hot electrons.

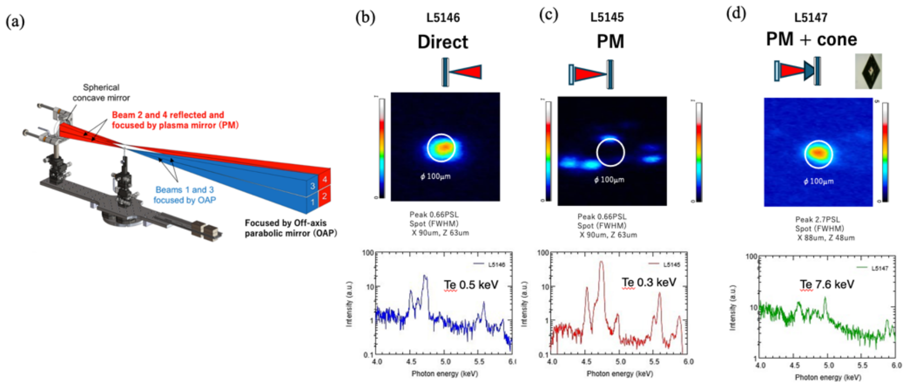

Figure 1: (a) Configuration of counter-laser irradiation using a spherical plasma mirror for the kilojoule-class petawatt LFEX laser system. Single-side irradiation experiments to investigate the interaction between high-intensity lasers and matter: (b) direct illumination, (c) plasma mirror illumination, and (d) plasma mirror illumination with a laser guiding cone. (Middle) X-ray pinhole images showing the laser focusing region. (Bottom) X-ray energy spectra measured using Ti-RbAp, with the electron temperature TeTe evaluated from x-ray spectrum simulations, accounting for background electrons and hot electrons.

From Fig. 2(c) (middle), laser irradiation through the plasma mirror onto targets equipped with laser guiding cones achieved a bright x-ray spot, which was an order of magnitude brighter than those observed under the other conditions shown in Fig. 2(a) or (b). Additionally, as shown in Fig. 2(c) (bottom), a heating temperature of 7.6 keV was achieved. The x-ray spectroscopy results suggested that the observed x-rays were emitted during the recombination process following the complete ionization of titanium (Ti). The achieved heating temperature of 7.6 keV closely matches the predicted temperature of 8 keV from 2D-PIC simulations. This close agreement indicates that the experimental conditions, including pre-plasma formation and focusing performance, were well-aligned with the simulation parameters. According to the 2D-PIC simulation of counter configuration, electron temperature was predicted beyond 10 keV. Therefore, pre-plasma formation and focusing performance for counter configuration in experiments is required.

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