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

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Abstract

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/cm². 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.

1. INTRODUCTION

On December 5, 2022, the National Ignition Facility achieved the scientific break-even in controlled thermonuclear fusion, where the output fusion energy of 3.15 MJ exceeded the input laser energy of 2.05 MJ, achieving a target gain of 1.5 [1]. This accomplishment marks a significant milestone toward Inertial Fusion Energy (IFE), which requires a target gain exceeding 100. The "direct-drive fast ignition" scheme optimizes the implosion and heating processes separately to achieve high gain by externally generating a hot spot with the assistance of a heating laser.

The Fast Ignition (FI) experiments conducted so far have applied one-directional heating laser illumination [2]. 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 [3]. To enhance energy coupling from the heating laser or fast electrons into the fuel, we introduced the counter-illuminating FI scheme [4]. 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 counterbeam configuration [5]. 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.

2. COUNTER ILLUMINATING LASER BEAM CONFIGURATION

Figure 1 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.

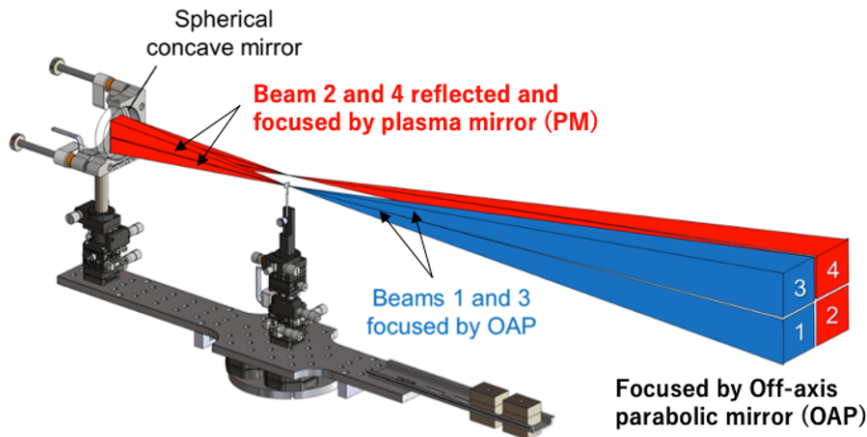


Figure 1: Configuration of counter-laser irradiation using a spherical plasma mirror for the kilojoule-class petawatt LFEX laser system.

3. PRELIMINARY EXPERIMENT ON SINGLE-SIDE IRRADIATION

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. 2(a)) and via a plasma mirror (Fig. 2(b)). Additionally, to enhance laser focusing capability, a laser guiding cone was attached to the thin-film target (Fig. 2(c)). The laser irradiation conditions were as follows: an energy of 160 J, a pulse duration of 1.5 ps, and a focusing intensity of $2 \times 10^{18} \text{ W/cm}^2$. Diagnostics included an x-ray pinhole camera to evaluate the laser focusing region (Figs. 2, middle) and an x-ray energy spectrometer using Ti-RbAp to determine electron temperature from the titanium radiation lines (Figs. 2, bottom). The electron temperature, T_e , was evaluated through x-ray spectrum simulations that accounted for both background and hot electrons.

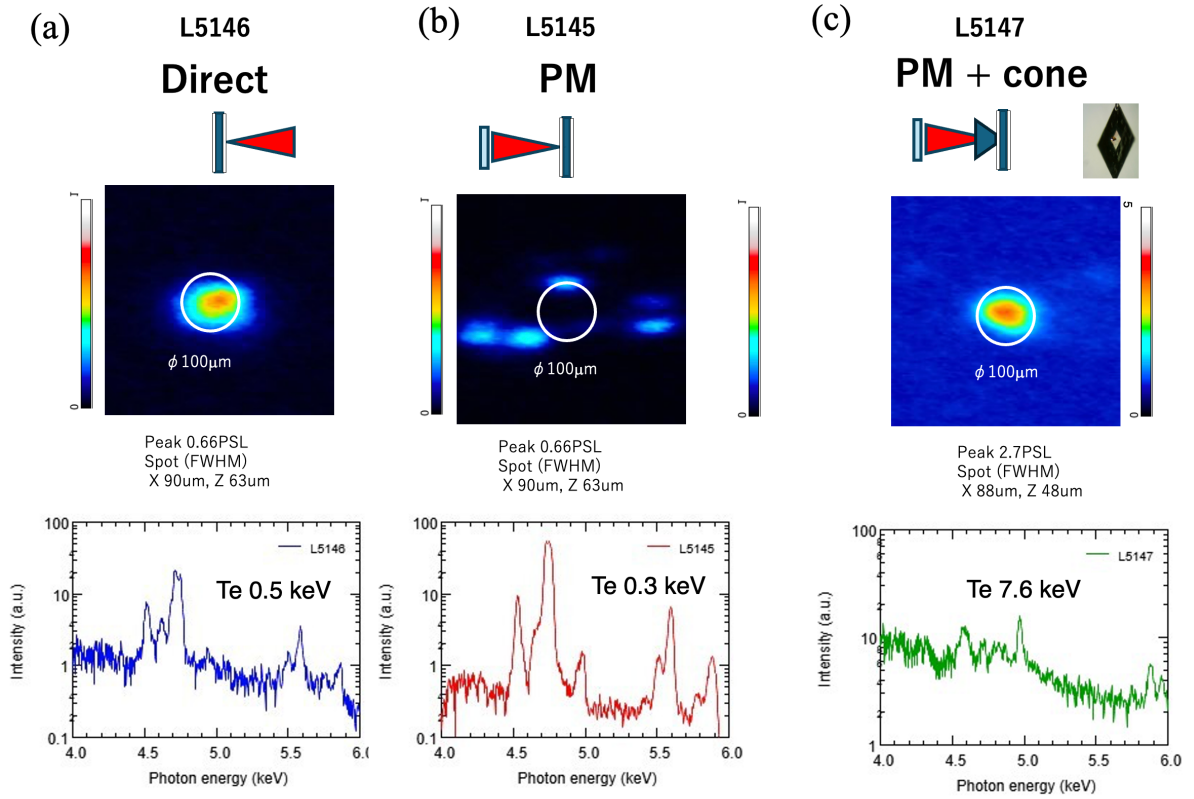


Figure 2: Single-side irradiation experiments to investigate the interaction between high-intensity lasers and matter: (a) direct illumination, (b) plasma mirror illumination, and (c) plasma mirror illumination with a laser guiding cone. (Middle) X-ray pinhole images showing the laser focusing region. (Bottom) X-ray energy spectra measured using Ti-RbAp, with the electron temperature T_e 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.

4. CONCLUSIONS

In conclusion, the counter-propagating laser platform utilizing a spherical plasma mirror for the kilojoule-class petawatt LFEX laser system was successfully operated in experiments. As a preliminary step to evaluate the significance of counter-laser irradiation, single-side irradiations were performed to investigate the interaction between high-intensity lasers and matter. The results indicate that, to achieve high energy density with an electron temperature exceeding 1 keV, the LFEX laser should be focused using a laser guiding cone, combined with pulse cleaning provided by spherical plasma mirrors.

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REFERENCES

- [1] H. Abu-Shawareb et al., Phys. Rev. Lett. 132 (2024) 065102.
- [2] Kodama, R. et al., Nature 412 (2001) 798, Kitagawa, Y et al., Phys. Rev. E 71 (2005) 016403, Kitagawa, Y. et al., Phys. Rev. Lett. 114 (2015) 195002, Sakata, S. et al., Nature Commun. 9 (2018) 3937, Matsuo, K. et al., Phys. Rev. Lett. 124 (2020) 034001.
- [3] Fujioka, S. et al., Phys. Rev. E 91 (2015) 063102, Jarrott, L. C. et al., Nature Phys 12 (2016) 499, T. Gong. et al., Nature Commun. 10 (2019) 5614.
- [4] Mori, Y. et al., Phys. Rev. Lett. 117 (2016) 005001, Mori, Y. et al., Nucl. Fusion 57 (2017) 116031.
- [5] Kojima, S. et al., Opt. Express 30 (2022) 43491.
- [6] Ikeda, T. et al., Nucl. Fusion 63 (2023) 016010.