9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Experimental Investigation of Fast Ignition Toward High-Efficiency Ignition

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To realize inertial fusion energy (IFE) in a practical setting, a high energy gain (>100) and a repetition rate (> 10 Hz) of the fusion reaction are essential. Direct-drive fast ignition (FI) offers a promising pathway to achieving high-efficiency inertial confinement fusion (ICF). In the FI scheme, fuel compression and heating processes are decoupled, facilitating independent optimization of each. The primary heating mechanism involves the collision of laser-accelerated electrons or ions with the compressed fuel. In this presentation, we describe our recent experiments aimed at advancing plasma compression and plasma heating in support of FI.

A solid ball target provides significant advantages for IFE [1 - 3]. First, its fabrication is straightforward—an important consideration given that millions of fuel targets must be produced daily for energy production. Second, it exhibits superior hydrodynamic stability, enabling low-adiabat compression that efficiently achieves high fuel density. Notably, solid ball targets are uniquely suited to FI, where the self-heating of fuel is not required. Nevertheless, successful compression of a solid sphere requires quasi-isentropic compression, which depends on synchronizing multiple shock waves produced by a tailored laser pulse [4], even in the absence of a complete equation of state and comprehensive laser-plasma interaction models.

In this study, we employed a data-driven approach to compare experimental data with simulation results, thereby enabling more accurate predictions and improved optimization of laser waveforms for achieving higher fuel densities. Experiments were performed using 200-μm-diameter deuterated polystyrene (CD) solid spheres as targets, compressed by the Gekko-XII laser system at the University of Osaka, which comprises twelve terawatt-class laser beams arranged in a dodecahedral geometry. A three-step laser waveform, initially optimized through one-dimensional radiation hydrodynamic simulations, was iteratively refined using experimental results acquired in each shot. We combined a spherical crystal imager with an X-ray backlighting technique to characterize the compressed plasma and obtained two-dimensional X-ray transmittance images. The outer radius of the plasma, extracted from these transmittance images, was then compared directly with simulation results [5]

Because of the high conversion efficiency of laser energy into relativistic electron beams (REBs), we focused primarily on plasma heating through REB collision with the compressed fuel. Improving the heating efficiency is crucial to realize FI. The overall efficiency can be expressed as the product of three factors: (i) laser-to-REB conversion efficiency (η_{REB}), (ii) REB transport efficiency to the fuel core (η_{col}), and (iii) REB energy deposition efficiency within the fuel core (η_{dep}) [6]. A significant limitation is the large divergence angle of the REB, which adversely affects η_{col}.

Here, we enhanced the REB's directionality, thereby improving heating efficiency by a factor of 2.8 using a high-contrast heating laser and a cone-shaped target [7]. The high reflectivity of the high-contrast laser, combined with the reflection of the cone's inner walls, aligns the beam toward the cone tip and thereby directs electron acceleration into the fuel core. This significantly improves the fraction of electrons entering the compressed fuel. The heating laser employed in this work was LFEX at Osaka University—a picosecond, kilojoule-class, petawatt laser. A plasma mirror was utilized to enhance the laser contrast by two orders of magnitude. The fuel was compressed using six beams from the GXII laser system, after which the LFEX laser was irradiated into the compressed plasma.

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