10-HZ LASER BEAM STEERING AND ILLUMINATION FOR FREE-FALL TARGETS

[1]Kazuki Matsuo, [1]Hideki Minato, [1]Yuki Yoshimura, [1]Kazuhiro Agatsuma, [1]Yuichiro Hironaka, [1]Masaki Ishii, Ryuji Mori, [1]Kenichi Urabe, [1]Naoki Kanmaki, [1]Takuya Sugimoto, Kento Sugita, Kenichi Sueda, Yu Takagaki, Takuma Chiba, [1]Takahiro Mitsui, [2]Neisei Hayashi, [2]Katsuhiro Ishii, and [1, 2]Yoshitaka Mori
[1]EX-Fusion Inc., Osaka, Japan
[2]The Graduate School for the Creation of New Photonics Industries (GPI), Hamamatsu, Japan
Email: kazuki_matsuo@ex-fusion.com

To realize a laser inertial fusion energy (IFE) reactor, repetitive fuel target injection, as well as multi-beam laser steering, tracking, and illumination, are required at a frequency of 1–10 Hz. The laser fusion start-up EX-Fusion has built a facility to demonstrate a repetitive target injection and multi-beam laser tracking system for the Fast Ignition scheme, scalable to future IFE reactors. As an initial step, we demonstrated laser tracking and illumination of a free-falling stainless steel ball (ϕ 1 mm) at 10 Hz using a femtosecond intense laser in a counter-illumination setup. The achieved laser tracking accuracies were 200 μm horizontally (standard deviation) and 56 μm vertically (standard deviation). These results are within an order of magnitude of the required precision for future IFE reactors, which is approximately 50 μm. The system was successfully operated at 10 Hz for over one hour. To the best of our knowledge, this is the first demonstration of laser tracking and illumination of an injected target at 10 Hz, demonstrating scalability to an inertial fusion energy reactor.

A commercial laser-driven Inertial Fusion Energy (IFE) reactor achieves fusion reactions by engaging injected fuel targets, which are continuously delivered into the reaction chamber and intercepted by laser beams operating at a frequency of 1–10 Hz. Progress at the National Ignition Facility in the United States has demonstrated a target gain, where the fusion pulse energy exceeds the input laser energy. To realize a commercial reactor, the target gain must exceed 100, and the conversion efficiency from plug electricity to laser pulses must surpass 10%. Additionally, repetitive system operation at a frequency of 1–10 Hz is essential for commercialization. In Japan, efforts toward the development of a future IFE reactor system have been ongoing since 2008, focusing on repetitive system operations using high-repetition-rate diode-pumped solid-state lasers [1]. EX-Fusion, a laser fusion start-up established in Japan, builds upon laser fusion research and development activities conducted at institutions such as the Institute of Laser Engineering (ILE), Osaka University [2], and the Graduate School for the Creation of New Photonics Industries (GPI) [1, 3–5]. EX-Fusion has constructed a facility to demonstrate repetitive target injection and a multi-beam laser tracking system for the Fast Ignition scheme, scalable to future IFE reactors. As part of these efforts, we have successfully demonstrated 10-Hz multi-laser beam steering and illumination of a free-falling target using 2-TW ultra-intense laser pulses.

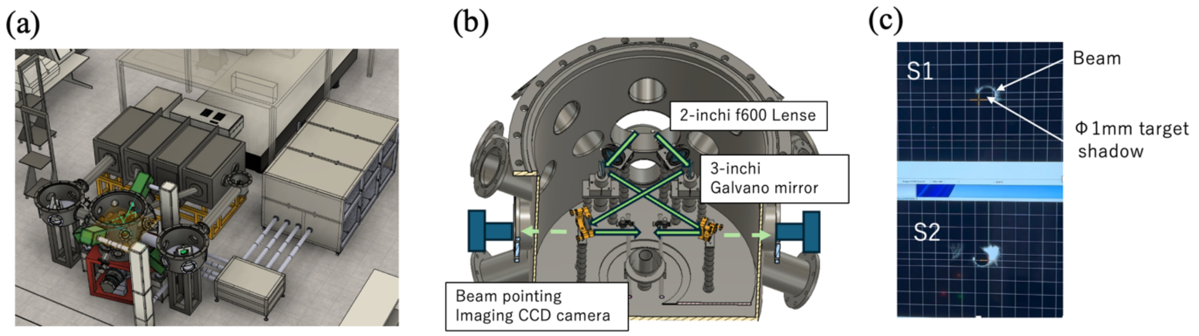

Figure 1: (a) Layout of the integration machine. (b) Optics layout inside of the chamber. (c) Beam pointing images on CCD cameras.

The integration facility is located in Hamamatsu. Figure 1 (a) shows the layout of the integrated facility. This facility is designed to demonstrate target injection and multi-beam laser tracking for the fast ignition scheme. Two laser systems are installed: one is a nanosecond green laser with an energy range of 0.1–1 J, intended for the implosion beamline, and the other is a femtosecond Ti:sapphire laser with 2 TW (0.2 J/100 fs), intended for the heating beamline. The implosion-intended beamlines are arranged in a quasi-regular tetrahedral configuration, satisfying the minimum requirement for three-dimensional symmetry. The heating-intended beamlines consist of two lasers in a counter configuration, which is expected to enable advanced heating mechanisms, such as enhanced counter fast electron flow or shock-based heating [4]. The knowledge gained from this integrated device will be reflected in the design of future laser fusion integrated devices, taking into account DT fusion neutron generation and radiation shielding.

The installed target injection system is a free-fall type, developed at GPI [5] and further improved through collaboration with EX-Fusion [6]. The target is a stainless steel ball with a diameter of ϕ 1 mm. This target size serves as a scaled-down model of the ϕ 3–4 mm diameter targets envisioned for future reactors. The shape and material of the target were selected to facilitate handling during repetitive operations at room temperature. This target injection system delivers ϕ 1 mm solid balls by rotating a disk at 10 Hz. It is capable of detecting the target's horizontal position in two dimensions and its falling timing in the vertical direction. The performance of the target tracking system has been validated through offline experiments conducted at 10 Hz [5].

Femtosecond laser beams were steered by Galvano mirrors in a counter configuration. Figure 1(b) shows the optics layout inside the chamber. Each femtosecond laser delivers 100 mJ per 100 fs and is focused into the chamber center in a counter configuration. The beam size is 30 mm in diameter, and the focusing length is 600 mm, resulting in an F-number of 20 and a designed focal spot size of 32 μm. The focusing beams are steered by 3-inch Galvano mirrors to track the target positions, which are calibrated by the injection system. Beam pointing and target positions are monitored using imaging systems mounted along the laser axes.

Beam tracking stabilities in relation to the free-fall target were analyzed using imaging systems. Beam tracking positions were monitored using CCD cameras. Figure 1(c) presents beam-pointing images for the S1 and S2 beams. In Fig. 1(c), the white spots represent the steering beam positions, while the shadow image corresponds to the 1-mm-diameter steel ball. Tracking performances are illustrated in Figs. 2. Beam-pointing positions relative to the target position are shown in Fig. 2(a) for the horizontal direction and Fig. 2(c) for the vertical direction. In the horizontal direction, beams were steered in relation to the target positions detected by the injection system. In the vertical direction, the beams were locked, and the laser illumination timing was synchronized with the free-fall motion. Distributions of beam-pointing accuracy are shown in Fig. 2(b) for the horizontal direction and Fig. 2(d) for the vertical direction. The resulting tracking accuracies were 200 μm horizontally (standard deviation) and 56 μm vertically (standard deviation). For a reactor, the required beam-pointing accuracy is within 50 μm to generate the imploded fuel necessary for ignition. Therefore, the results obtained here are within the same order of magnitude as the required accuracy. Analysis data were collected over a 1-minute period (600 shots). The device operated continuously for over 1 hour, corresponding to 36,000 shots.

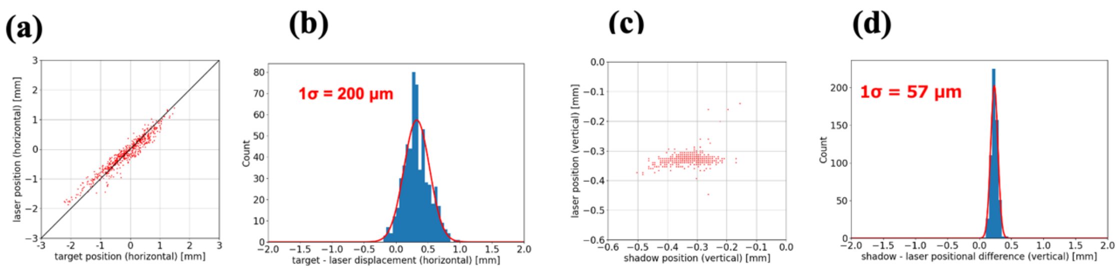

Figure 2: Tracking performances for the horizontal direction ((a) and (b)) and vertical direction ((c) and (d)). Beam pointing positions relative to the target position are shown in (a) for the horizontal direction and (c) for the vertical direction. Distributions of beam pointing accuracy are shown in (b) for the horizontal direction and (d) for the vertical direction.

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