

CONFERENCE PRE-PRINT

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

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Abstract

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 named the EX-Fusion Continuous Operation Laser Reactor (XF-COLR) 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 (f 1 mm) at 10 Hz using a femtosecond intense laser in a counter-illumination setup. Laser tracking accuracies evaluated as standard deviations were achieved in the range of 106–150 μm horizontally and 60–110 μm vertically. 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.

1. INTRODUCTION

In a commercial laser-driven IFE reactor, a fusion process relies on a repeated injection of fuel targets into a reaction chamber, followed by their irradiation with high-power laser pulses. This pulsed sequence, operated at a frequency of 1–10 Hz, enables steady-state energy output through rapid repetition. Recent progress at the National Ignition Facility (NIF) in the United States has marked a significant milestone toward IFE. In August 2021, the Lawson criterion for ignition was surpassed by NIF through an indirect-drive DT experiment with a target gain of 0.72 defined as the ratio of fusion energy yield to the total laser energy delivered to the target [1-3]. A subsequent experiment in December 2022 set a new record with a target gain of 1.5 achieving scientific breakeven and meeting the ignition threshold as defined by the National Academy of Sciences (NAS) [4]. This achievement represents a major step forward in the pursuit of inertial fusion energy. However, the realization of a viable commercial IFE power plant imposes more stringent requirements. In particular, the energy delivered to the laser must be fully compensated by the fusion energy output, which is known as engineering breakeven. Assuming a conversion efficiency of 33% from thermal energy to electricity in a turbine and approximately 10% efficiency from electrical power to laser output, the target gain required to reach engineering breakeven is roughly 30. For a commercial reactor, output in the range of 100 MW to 1 GW is expected to cover construction and operational costs while remaining competitive with other energy sources. Achieving this economic breakeven often requires a target gain of around 100 with repetitive operation at frequencies of 1–10 Hz since each fusion event is pulsed and rapid repetition is necessary to sustain continuous energy production.

In Japan, research and development toward future IFE systems has been ongoing since 2008, with a particular emphasis on high-repetition-rate diode-pumped solid-state laser systems [5]. Based on foundational work conducted at the Institute of Laser Engineering (ILE), Osaka University [6], and the Graduate School for the Creation of New Photonics Industries (GPI) [6–12], the startup company EX-Fusion was established to advance the commercialization of laser fusion technology. EX-Fusion has constructed a facility to develop and demonstrate key enabling technologies for high-repetition IFE operation, including a repetitive target injection system and a multi-beam laser tracking system based on the fast ignition scheme. This first demonstrator was named the EX-Fusion Continuous Operation Laser Reactor (XF-COLR). Through these efforts, a 10-Hz multi-laser beam steering system has been successfully demonstrated, achieving precise illumination of a free-falling target using ultra-intense 2-terawatt laser pulses.

This article is organized as follows. Section 2 describes the experimental setup at Hamamatsu facility in Japan. Section 3 presents the experimental results, and Section 4 provides concluding remarks.

2. EXPERIMENTAL SETUP

The integration facility is located in Hamamatsu, Japan, and the layout of XF-COLR is shown in Fig. 1. It was constructed to demonstrate key technologies for the fast ignition scheme in IFE, specifically target injection and multi-beam laser tracking. The facility contains two laser systems. One is a nanosecond green laser with an energy range of 0.1–1 J for the implosion beamline, and the other is a femtosecond Ti:sapphire laser with a peak power of 2 TW (0.2 J / 100 fs) for the heating beamline. The implosion beamlines are arranged in a quasi-regular tetrahedral configuration meeting the minimum requirement for three-dimensional symmetry shown in Fig. 2. The heating beamlines consist of two counter-propagating femtosecond lasers enabling advanced heating mechanisms such as enhanced counter-streaming fast electron flows and shock-driven heating [9,10]. Each femtosecond laser delivers 40 mJ per 100 fs pulse, with a beam diameter of 30 mm and a focal length of 1500 mm resulting in an F-number of 50 and a designed focal spot size of 51 μm . To track target positions, the implosion beams are guided by using 2-inch steering mirrors, while the heating beams are steered using 5-inch steering mirrors. The steering of both beamlines is calibrated with reference to the target injection system. Both beam pointing and target positions are monitored via imaging systems installed along the laser beam paths.

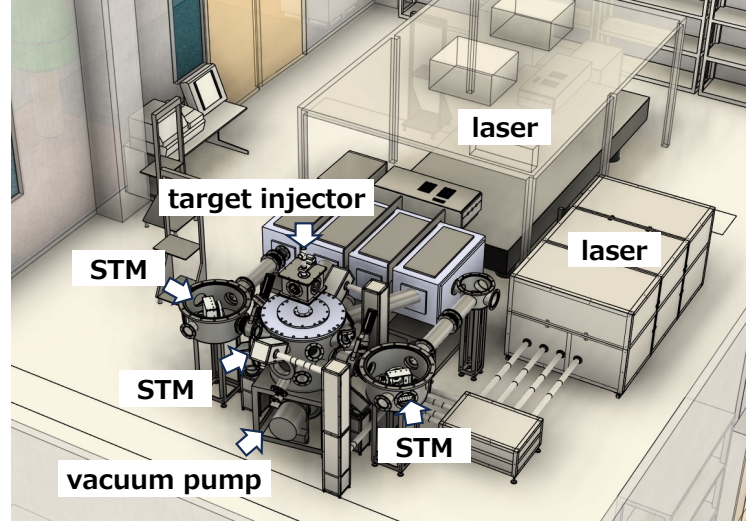


FIG. 1. Schematic of the XF-COLR. The system consists of a free-fall type target injector and multi-beam laser tracking. To track target positions, the nanosecond beams are steered with 2-inch steering mirrors (STMs) while the femtosecond beams are guided by using 5-inch steering mirrors.

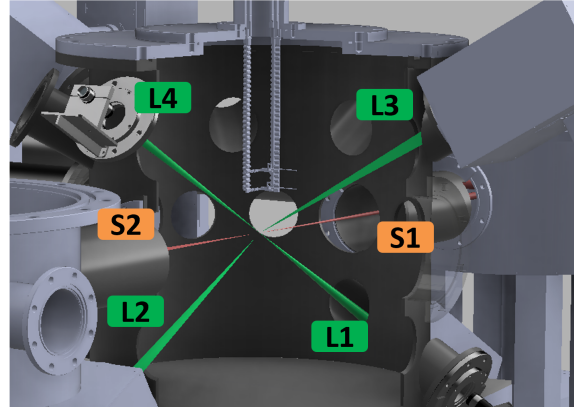


FIG. 2. Four green beamlines for implosion, labelled as L1, L2, L3, and L4, are arranged in a quasi-regular tetrahedral configuration. Two red beamlines for heating, labelled as S1 and S2, form a counter-propagating configuration as part of the fast ignition scheme.

The installed target injection system, shown in Fig. 3, is of the free-fall type originally developed at the Graduate School for the Creation of New Photonics Industries (GPI) [11,12] and further refined in collaboration with EX-Fusion [13]. Solid spheres with a diameter of 1 mm are released from a rotating disk at a frequency of 10 Hz. The released pellets pass through a set of tracking sensors consisting of three photodiode arrays and two optical position sensors before reaching the engagement point. A photodiode line sensor and two position sensors (Ready, PoS1, and PoS2) are assembled to form the homing laser system. These sensors measure the timing of the pellets' free-fall motion and detect their horizontal positions in two dimensions. The Ready sensor signal is used to trigger the acquisition of position sensor signals. PoS1 and PoS2 incorporate shadow sensors consisting of a photoemitter and photoreceiver operating with visible red light. A pulse voltage is generated when a pellet interrupts the light path and casts a shadow. Two additional photodiodes, PASS1 and PASS2, are used to synchronize the laser illumination with the pellet's arrival at the engagement point. The tracking system is described in detail by K. Agatsuma et al. [13] where its performance was validated in offline experiments conducted at a repetition rate of 10 Hz.

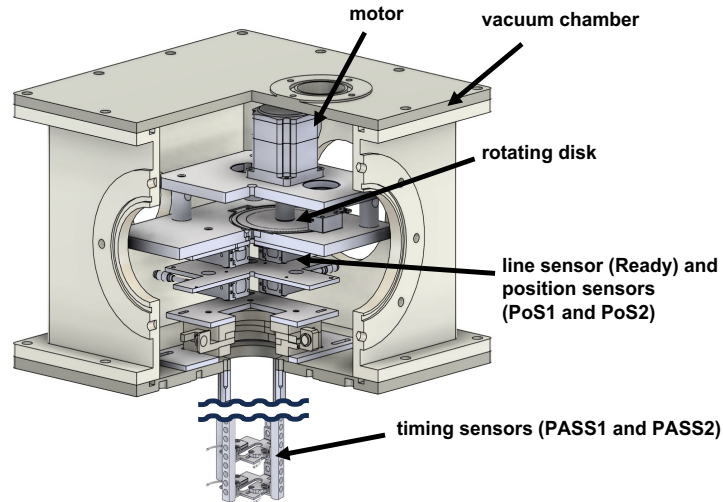


FIG. 3. Free-fall target injector mounted at the top of the chamber. Pellets are released from a rotating disk. The timing of the fall is detected by three photodiode sensors (Ready, PASS1, and PASS2), and the horizontal position detected by two position sensors (PoS1 and PoS2).

Beam tracking stability relative to the free-falling target was evaluated using the imaging systems. Multiple CMOS cameras (Basler ac A1920-25) synchronized with the laser pulse observe the target at the engagement point. Note that each CMOS camera's sensing plane is oriented perpendicular to its corresponding laser beam. Hence, in this article, the horizontal and vertical tracking axes in the captured images are defined relative to the respective sensor plane, rather than with respect to gravity.

3. RESULTS

Fig. 4 shows a captured image of a 1 mm-diameter stainless-steel target illuminated by the laser. The bright spot indicated by a red circle confirms that the steered laser successfully intercepted the target, which falls at approximately 4 m/s. As shown in Fig. 5, the steering of one of the laser beams was recorded using a CMOS camera. A bright white spot indicates the beam position with its center marked by a blue plus sign, while the target sphere casts an eclipse-like shadow with its center marked by a red cross, allowing precise determination of the beam-target alignment. Based on these images, tracking performance of the target during 2.5 to 3 minutes of continuous operation is summarized in Table 1. Figs. 6(a) and 6(c) show the beam pointing positions relative to the target in the horizontal and vertical directions, respectively. The laser beams were dynamically steered to the expected target position that was calculated using a projectile motion equation with real-time data obtained from the injection system. The timing of the laser pulse was synchronized with the predicted position of the falling target, ensuring accurate coordination with the target motion.

For practical IFE reactor applications, beam-pointing accuracy within 50 μm is considered necessary to achieve sufficient implosion symmetry for ignition. Although the current results are slightly below this requirement, the achieved accuracies remain within the same order of magnitude. Tracking performance was recorded over a 2.5-minute period (> 1500 shots), and data acquisition for continuous operation over one hour (corresponding to 36,000 shots) is also planned for future research.

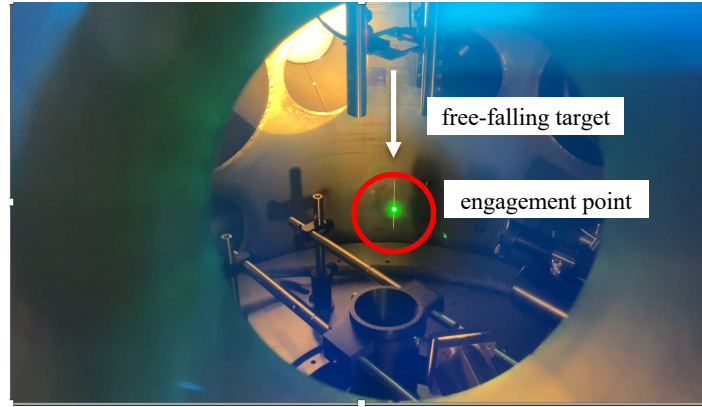


FIG. 4. Captured image of a 1 mm-diameter target illuminated by multi-beam lasers. The bright green emission, highlighted by a red circle, indicates successful laser interception of the free-falling target. A faint path reveals the trajectory of the target during its free fall.

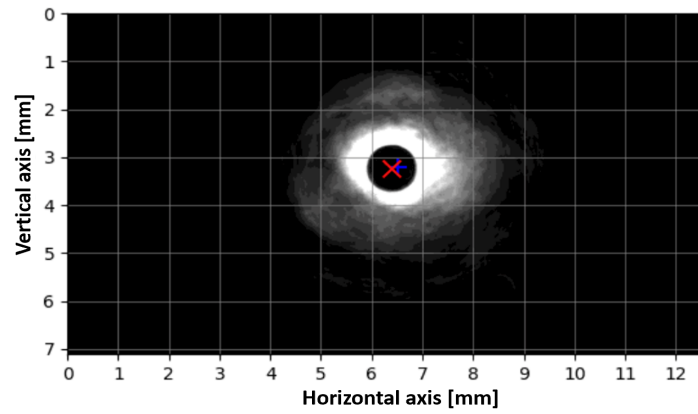


FIG. 5. Steering beam image for the L1 laser path recorded by the CMOS camera. White spots indicate laser beam positions, the shadow shows the target location, and the target center is marked with a red cross.

TABLE 1. Standard deviation of homing errors in the horizontal and vertical directions for each steering mirror with horizontal errors ranging from 112 to 150 μm and vertical errors ranging from 60 to 110 μm .

	S1	S2	L1	L2	L3	L4
Standard deviation of homing errors in the horizontal direction (μm)	142	150	106	124	116	112
Standard deviation of homing errors in the vertical direction (μm)	67	93	60	110	82	68
Percentage of shots within 500 μm	98.9	98.9	98.2	98.3	98.7	98.8
Number of recorded shots	1799	1743	1526	1526	1526	1526

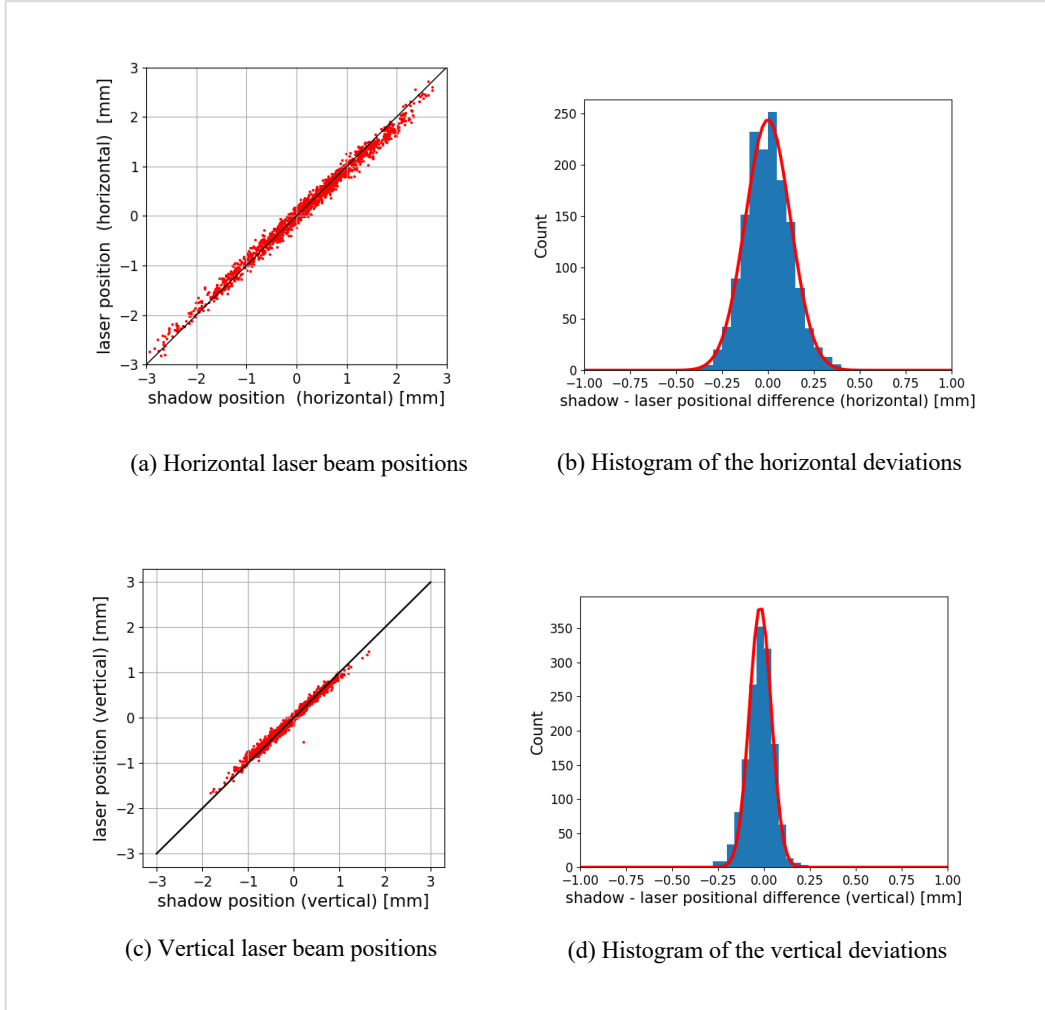


FIG. 6. Horizontal and vertical positions of the L1 laser beam relative to the shadow of the free-falling target, recorded by the CCD camera, are shown in (a) and (c), respectively. Histograms of horizontal deviations from the shadow position are shown in (b) and (d). The one-sigma standard deviations are $106\ \mu\text{m}$ for the horizontal direction and $60\ \mu\text{m}$ for the vertical direction.

4. CONCLUSIONS

A demonstrator of the EX-Fusion Continuous Operation Laser Reactor (XF-COLR) was launched that consists of four nanosecond lasers, two femtosecond lasers, multiple steering mirrors, and a free-falling target injector. Laser beam tracking and illumination of a free-falling target were successfully demonstrated at a repetition rate of 10 Hz using multi-beam lasers and a 1 mm diameter steel ball injection system. The targets descended under free-fall conditions, and the system continuously tracked and corrected the positions of multiple beams in real time. Tracking accuracies of $150\ \mu\text{m}$ in the horizontal direction and $110\ \mu\text{m}$ in the vertical direction were achieved, with the best vertical accuracy reaching approximately $60\ \mu\text{m}$. These results are within the same order of magnitude as the precision required for inertial fusion energy reactors. The experiments were conducted continuously for 2.5 to 3 minutes corresponding to over 1500 consecutive shots without interruption. To the best of current knowledge, this represents the first demonstration of multi-beam laser tracking and target illumination at 10 Hz under free-fall conditions that is scalable to a reactor-relevant IFE system, providing a quantitative benchmark for the development of high-repetition-rate target engagement and precision laser control in fusion experiments.

ACKNOWLEDGEMENTS

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