Ten hertz bead pellet injection and laser engagement

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Abstract

A laser inertial fusion energy (IFE) reactor requires repetitive injection of fuel pellets and laser engagement to fuse fusion fuel beyond a few Hz. We demonstrate 10 Hz free-fall bead pellet injection and laser engagement with γ-ray generation. Deuterated polystyrene beads with a diameter of 1 mm were engaged by counter illuminating ultra-intense laser pulses with an intensity of \(5 \times 10^{17}\) W cm\(^{-2}\) at 10 Hz. The spatial distribution of free-fall beads was 0.86 mm in the horizontal direction and 0.18 mm in the vertical direction. The system operated for more than 5 min and 3500 beads were supplied with achieved frequencies of 2.1 Hz for illumination on the beads and 0.7 Hz for γ-ray generation; these frequencies were three times greater than with the previous 1 Hz injection system. The duration of operation was limited by the pellet supply. This injection and engagement system could be used for laser IFE research platforms.

Keywords: inertial fusion energy, pellet injection, high-repetition laser, laser engagement

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser-driven inertial fusion energy (IFE) reactors drive fusion of injected cryogenic fuel pellets that are continuously delivered into the reactor with repetition of a few Hz. The design for pellet injection has been conducted so far with a focus on reactor scale [1–9]. In addition to reactor-scale design, development of laboratory-scale pellet injection or supply systems has been considered in relation to the recent progress in repetitive high-power laser systems. With laser fusion neutron sources [10–12], the use of a repetitive high-power laser system could trigger the development of a pellet injection system as a research and development platform for
IFE [13–15] in feasibility studies of technological components as well as energy conversion from fusion neutrons.

Development of a laboratory-scale repetitive pellet injection system has been conducted by utilizing an ultra-intense laser system with generation of fusion neutrons. Komeda et al demonstrated laser engagement of 1 Hz injected flying pellets and neutron generation [16, 17]. This injection system utilized 1 mm diameter deuterated polystyrene beads with more than 600 pellets on average at 1 Hz and 10 min per cycle for 4 years [18]. Flying beads were engaged by an ultra-intense laser (11 TW, 0.6 J/110 fs for two beams with a focal intensity of $5 \times 10^{18}$ W cm$^{-2}$) with counter illumination [19] resulting in a shot probability of 27% for $\gamma$-ray generation and 22% for detection of signals corresponding to fusion neutrons with a maximum yield of $10^5$ neutrons/shot. The operating frequency of 1 Hz was limited by an amplification of the HAMA laser driver [20]. HAMA is seeded by the 10 Hz BEAT laser pulses [21]. However, the remaining 9 Hz laser pulses from BEAT were dumped.

This paper describes progress of room temperature bead pellet injection and engagement at 10 Hz, a comparable frequency to the future IFE plant. To improve the pellet injection frequency at the same frequency as the 10 Hz seeding laser, the injection machine has been upgraded from the previous 1 Hz injection system by increasing the number of holes on the disk rotor from 20 to 200. The upgraded system was operated for 5 min at room temperature with an illumination frequency of 2.1 Hz and with $\gamma$-ray generation of 0.7 Hz; these frequencies were three times those achieved with the previous 1 Hz injection system.

The remainder of this manuscript is organized as follows. The experimental setup is described in section 2. The performance of the 10 Hz bead injection system is described in section 3, followed by discussions in section 4 and the conclusions in section 5.

2. Experimental setup

The design of the injection header defines the number of pellets and repetition for laser engagement. Figure 1(a) shows the 10 Hz bead injection system installed in a counter laser illuminating chamber. The injection machine was upgraded from the previous 1 Hz injection system by increasing the number of holes on the disk rotor from 20 to 200 as shown in figures 1(b) and (c). The diameter of the disk rotor was 110 mm, and the diameter of the hole region on the rotor was 100 mm. The diameter of each hole was 1.1 mm. The injected pellets were deuterated polystyrene spherical beads with a diameter of 1 mm. The beads were stored in a target loader with a capacity of 10,000 beads. This injection system delivers beads by disk rotation and drops them under free-fall through a hole. The rotation speed of the disk was 20 s/rotation, with a corresponding bead supply period of 0.1 s for 200 holes and 1 s for 20 holes.

The laser beams are counter-illuminated into the center of target chamber where the injector is installed. Figure 2 shows plasma emission by laser engagement with an injected pellet taken by a color CCD camera. The laser system was the 10 Hz BEAT laser with an on-target energy of 0.11 J/beam, a pulse duration of 120 fs, a focal spot of 15 μm and a resulting focal intensity of $5 \times 10^{17}$ W cm$^{-2}$. The focal positions of the counter beams were 0.5 mm off center settled on the surface of a 1 mm diameter bead pellet injected at the center of the chamber.
Laser engagement of the injected pellet was monitored using a three-dimensional probe system and plastic scintillators. Figure 3 shows post-process data analyses including three-dimensional probe images (right) and plastic scintillator signals (left) at 10 Hz operation. These data were captured every shot at 10 Hz and integrated into an animation movie post-process. This post-process procedure was upgraded from the previous 1 Hz injection system where the in situ diagnostic output on a PC monitor was integrated into a monitor combiner and recorded in a movie format. The post-process movie was used to look at the shot history for detailed analysis of the position of injected beads, clarification of laser engagement from the probe images and γ-ray or neutron generation from the plastic scintillator signals.

3. Performance of the 10 Hz bead pellet injection system

The three-dimensional probe system identified spatial distributions of flying bead pellets with numbers beyond 1800 at 10 Hz. Using the upgraded machine, 10 Hz pellet injection and laser engagement beyond 5 min has been achieved. The duration of operation was limited by the pellet supply. Figure 4 shows three-dimensional distributions of the position of injected bead pellets at 10 Hz for the first part; 3 min (1828 shots) of a 5 min operation. Injected pellets were categorized as follows by numbers: captured (light blue) 1704, illuminated (blue) 385, γ-ray generation (red) 135. Corresponding probabilities were 93% for capture, 21% for illumination and 7.4% for γ-ray generation, respectively.

Distribution of beads in the horizontal or vertical plane can clarify properties and accuracy of the rotating disk pellet supply system. Figures 5(a) and (b) show the distributions of injected bead pellets in the horizontal (x–y) and vertical (y–z) planes, respectively. The x- or y-directions denote the tangential or radial direction of the rotating disk, respectively. As shown in figure 5(a), most of the illuminated pellets were distributed in a region ±2 mm in the x-direction and ±0.1 mm in y-direction. Differences in distributions in the x–y plane can be explained by guiding in space. At a bead release point on the injection header there is no guiding for the tangential or x-direction. In contrast, the radial or y-direction is guided by the hole with a diameter of 1.1 mm. A bead position along the vertical direction or z-direction is controlled by synchronizing the timing of laser illumination onto a bead. Therefore, the distribution in the z-direction was within 0.5 mm, as shown in figure 5(b).

Figures 5(c)–(e) shows the histograms of beads along the x-, y- and z-axes, respectively. Values of mean and standard deviation (SD) of beads along the axes are listed in table 1.

The SD for the tangential direction can be explained by fluctuation of translation of the rotating disk. The rotating disk gives a speed of translation of 15.7 mm s⁻¹ for beads at the release point. The translational distance is 3.0 mm at the height.
Figure 5. Distributions of injected beads pellets for capture (light blue), illumination (blue) and $\gamma$-ray generation (red): (a) $x$–$y$ plane, (b) $y$–$Z$ plane. Histogram of (c) $x$-axis, (d) $y$-axis and (e) $z$-axis.

Table 1. Values of mean and SD of beads along the axes.

| Tangential: $x$ (mm) mean/SD | Radial: $y$ (mm) mean/SD | Vertical: $z$ (mm) mean/SD |
|-----------------------------|--------------------------|--------------------------|
| Capture                     | $-0.355/0.862$           | $-0.333/0.860$           | $0.149/0.183$ |
| Illumination                | $-0.179/0.761$           | $0.008/0.127$            | $0.124/0.144$ |
| Gamma-ray                   | $-0.055/0.201$           | $0.028/0.070$            | $0.120/0.151$ |

of laser illumination. The SD along the $x$-direction for capture (0.86 mm) corresponds to 29% of the translational distance. Collisions of beads within holes on the disk before release would cause fluctuations in the speed of translation.

Fine alignment along the $x$-direction has the potential to increase the probability of illumination or $\gamma$-ray generation. From figure 5(c) and table 1, the mean value along the $x$-axis for capture ($-0.355$ mm) was shifted from that for $\gamma$-ray generation ($-0.055$ mm). This displacement can be aligned using a target stage. The previous 1 Hz operation achieved an illumination probability of 79% where the mean value of displacement between capture and $\gamma$-ray generation was within 0.1 mm [18].

For the radial direction, triple distributions of beads can be explained by collisions of beads with an injector wall. From figure 5(a), there are triple peaks along the radial direction with peaks of $-0.8$ mm, $+0.1$ mm and $+1.0$ mm, respectively. The second peak corresponds to the position of the hole on the disk. The displacement of the first and third peaks is 1.8 mm. This value is comparable to the space of a disk supporter (2.0 mm) on the injection header. Therefore, distributions for the first and third peaks can be explained by the fact that released beads collided with a wall of width 2 mm along the radial direction and were then guided by the wall. As for the second peak, the released beads were guided by the holes on the disk without collisions with the wall.

The reason for deviation in the vertical direction is under consideration. The synchronization timing along the $z$-direction was calculated assuming a fixed acceleration from a timing difference of beads passing through the two photodiode arrays with 40 mm vertical separation [18]. The flying beads are accelerated by gravity. The vertical velocity at the laser illumination height is evaluated as 0.181 m s$^{-1}$. From figure 5(e) and table 1, the SD along the vertical axis for capture is 0.183 mm. This value is consistent if we assume a timing jitter of 1 ms or an acceleration jitter of 0.01 m s$^{-2}$. The reason for the SD is an issue for the future.
Figure 6. Shot history of injected bead position: tangential, $x$ (top); radial, $y$ (middle); vertical, $z$ (bottom).

The time history of bead distribution clarifies the periodic pattern of the injector along the tangential direction. Figure 6 shows the shot history of the injected bead position: tangential, $x$ (top); radial, $y$ (middle); vertical, $z$ (bottom). As shown in figure 6(a), a tangential or $x$ position of beads indicates a periodic jump around 3 mm or $-2$ mm for every 200 shots. These jumps are also shown in figures 5(a) and (c). The 200 shots correspond to one cycle of disk rotation. This indicates that the disk was tilted along the $x$-direction. Tilt control of the disk would improve deviations in distribution.

A $\gamma$-ray signal with correlation along the laser focusing direction can be an indicator of bead position. Figure 7 represents a $\gamma$-ray signal from ND1 (−$x$ direction) in relation to the pellet position $x$. From figure 7, the $\gamma$-ray signal increases when the bead position is close to $x = 0$ mm. The $\gamma$-ray signal represents generation of relativistic fast electrons though ultra-intense laser–matter interaction. Generation of fast electrons depends on focal intensity rather than laser energy or power. Therefore, the $\gamma$-ray signal can be used to indicate whether beads or pellets are located at the designated positions where the lasers are focused.

Operation at 10 Hz improves illumination or $\gamma$-ray generation frequencies by three times compared with the previous 1 Hz injection system. Figure 8 represents the progress of the bead pellet injection system: (a) number of monitored injected pellets, (b) frequency of illumination and $\gamma$-ray generation. Figure 8(a) shows that with 10 Hz operation in 2018 the number of injected beads reached 3500, a three-fold increase compared with the previous 1 Hz operation. Figure 8(b) shows that illumination frequency improved to 2.1 Hz and $\gamma$-ray generation frequency to 0.7 Hz. These values are three times those achieved with the previous 1 Hz injection system. In addition, we demonstrated for the first time the use of an inserter that works at the same frequency as the laser toward the reactor.

4. Discussion

Ten hertz operation revealed properties of the disk rotating injector required to improve illumination or $\gamma$-ray generation. For example, the requirement for fine alignment along the tangential (laser focusing) direction or existence of disk tilt were clarified at 10 Hz operation. Improved illumination might be achieved by considering the revealed properties of the rotating disk injector; bead motions are locked along the radial direction by the holes and are free along the tangential direction. By rotating the injector by $90^\circ$, tangential motion of beads is converted from the laser-focusing direction to the laser-rotation direction. Beads scattered along the laser-rotation direction can be engaged by pointing control of the mirrors.

Gamma-ray generation or neutron generation were limited by a focal intensity that was slightly below relativistic laser–matter interaction. The previous 1 Hz operation achieved shot probabilities of 27% for $\gamma$-ray generation and 22% for detection of signals corresponding to fusion neutrons with a maximum yield of $4 \times 10^5$ neutrons/shot. The 10 Hz operation presented here achieved shot probabilities of 7.4% for $\gamma$-ray generation, as shown in figure 4, four times lower than with 1 Hz operation. Previous experiments were conducted with the HAMA laser with a laser focal intensity of $5 \times 10^{18}$ W cm$^{-2}$ and a corresponding normalized vector potential of $a_0 = 1.5$. The value of $a_0$ is an index of relativistic laser–matter interaction. An $a_0$ beyond 1 provides relativistic motion for electrons and fast ions with MeV energies that triggers beam-like fusion neutrons. In contrast, for the present 10 Hz operation, the focal intensity was $5 \times 10^{17}$ W cm$^{-2}$ resulting in an $a_0$ of 0.48. An $a_0$ below 1 limits the relativistic laser–matter interactions, resulting in a lower probability of $\gamma$-ray generation or neutron generation.

Electrostatic charge is a key issue in free fall type injection systems. Electrostatic charge makes stuff beads on the hole, with the result that the bead supply ratio to the laser
Figure 8. Progress of bead pellet injection system: (a) number of monitored injected pellets, (b) frequency of illumination and γ-ray generation.

illumination point is reduced. To release electrostatic charge on the beads we installed an ultraviolet ionizer on the injection header. We have not examined the electrostatic effect on the scatter distribution yet; it might also be disturbed by electrostatic charge.

To achieve IFE, a target position within 10 μm is required. In this configuration, an improvement in pellet position to within less than 100 μm is the next goal. To achieve this goal, guiding of pellet position by application of an electrostatic field is being considered. In addition, to improve the effectiveness of illumination, laser beam pointing by steering the mirror is also under consideration.

The key issue for the injection system for IFE is cryogenic operation. For cryogenic operation, the most important effects are the electrostatic field on the shell, adhesive forces and the effects of static electricity at the moment of target release, which may all differ significantly at cryogenic temperatures. The result obtained here at room temperature can be a reference prior to cryogenic operation in an integrated system that demonstrates steady state pellet injection and laser engagement.

The advantage of the injection system is accessibility to the laser illumination space. The flying injection system offers free space around the laser illumination area. The commonly used target supply systems such as tape or disk occupy this free space. Free space around the illumination permits accessibility of material test pieces to increase fluence of radiation or neutrons produced from the source. In addition, this free space can minimize the size of the neutron capture system used in tritium breeding tests or energy conversion in a laser-driven IFE research platform.

5. Conclusions

Ten hertz pellet injection and laser engagement have been achieved for longer than 5 min using 1 mm diameter deuteride polystyrene beads. Illumination of 2.1 Hz and γ-ray generation of 0.7 Hz was achieved. This was demonstrated for the first time using an inserter that works at the same frequency as the laser toward the reactor. The results obtained here at room temperature can be a reference prior to cryogenic operation.

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