Repetitive Solid Spherical Pellet Injection and Irradiation toward the Repetitive-mode Fast-Ignition Fusion mini-Reactor CANDY.

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Abstract. Pellet injection and repetitive laser illumination are key technologies for realizing inertial fusion energy[1-4]. Neutron generator using lasers also requires a repeating pellet target supplier. Here we present the first demonstration of target injection and neutron generation[5]. We injected more than 1300 spherical deuterated polystyrene(C$_8$D$_8$) bead pellet targets during 23 minutes at 1 Hz(Fig.1). After the pellet targets fell for a distance of 18 cm, we applied the synchronized laser-diode-pumped ultra-intense laser HAMA. The laser intensity at the focal point is $5 \times 10^{18}$ W/cm$^2$, which is high enough to generate neutrons. As a result of the irradiation, we produced 2.45-MeV DD neutrons. Figure 2 shows the neutron time-of-flight signals detected by plastic scintillators coupled to photomultipliers. The neutron energy was calculated by the time-of-flight method. The maximum neutron yield was $9.5 \times 10^4/\pi$ sr. The result is a step toward fusion power and also suggests possible industrial neutron sources.
1. Introduction
We have been doing research and development towards the early realization of a compact laser fusion experimental reactor (we are calling the CANDY). The CANDY is composed by the pellet injection equipment, diode-pumped ultra-high-intense laser drivers, and heat exchanger (converter) which change the heat of the fusion reaction from the reactor chamber. Pellet injection and repetitive laser illumination are key technologies for realizing inertial fusion energy[1]. Industrial neutron and X-ray generators using lasers also require a repeating pellet target supplier. Here we demonstrate flying pellet injection, high power counter laser beams’ irradiation and neutron generation from the pellet.

2. Pellet injection system
Fig. 1 shows the pellet injector, installed in the illumination chamber, which is evacuated to $2.6 \times 10^{-3}$ Pa. The pellet is a spherical CD bead with a diameter of 970±2.7 μm and a sphericity of 99%. A pellet loader stores more than 10,000 CD pellets at a time. The pellets in the loader made to free-fall in gravity onto a rotating disk, which is 110 mm in diameter and rotates at 6 rpm. Each pellet on the disk is conveyed to an exit hole and falls along a parabolic trajectory to the laser focal point 18 cm below. The exit hole is shaped as an ellipse with major and minor axes of 4.0 and 2.0 mm, respectively, and a depth of 8.0 mm. The focal point is irradiated by two counter laser beams at 1 Hz. The signals from the two photodiodes at 60 mm and 100 mm above the focal point are sequentially sent to a laser controller, which forecasts the arrival time at the focal point and sends a shooting-request signal to the laser appropriately. As soon as the laser controller receives the signal, its two laser beams irradiate the injected pellet with an appropriate delay time. Symmetric counter laser beam irradiation induces implosive fusion[3]. The laser energy, pulse duration, and wavelength are 0.63 J per beam, 104 fs, and 811 nm, respectively, and the intensity is $4.7 \times 10^{18}$ W/cm$^2$.

Fig. 2 shows the pellet irradiation. Figs.2(a) and (b) show photographic images before and after the irradiation. We can see the trajectory of the pellet. When the pellet comes to the focal point, the two counter laser beams irradiate the pellet. At that time, the velocity of the pellet is 1.8 m/s. Fig.2(c) shows the shadowgraph using probe laser beam, that is perpendicular to the counter laser beam axis, and is synchronized to it. The image shows that the pellet are irradiated from both side and something comes out from the pellet.

![Pellet injection system](image)

Fig. 1. Pellet injection system.
(a) schematics. (b) photograph. The pellets are stored in the target loader, and are conveyed by the rotating disk to the exit hole. Each pellet falls between a two-step photodiode array. These signals are sent to the laser controller. Then the laser beams are emitted at the appropriate timing.
Fig. 2. Snapshots of pellet irradiation.
(a) and (b) show before and after the irradiation. The pellet trajectory can be seen in (a). When the pellet comes to the focal point, it is irradiated by the two counter laser beams. (c) shows shadowgraph using probe laser beam, that is perpendicular to the counter laser beam axis. The probe shadow and self-emissions clearly show the pellet was irradiated by the two counter laser beams.

Fig. 3. Pellet vertical placement accuracy.
Distribution of the vertical position of the pellet. The distance from the focal point are controlled to $\pm 0.18\text{mm}$ at $2\sigma$.

Fig. 4. Pellet horizontal placement accuracy.
Distribution on the plane of the laser focal point. X-axis and y-axis is perpendicular and parallel to the optical axis, respectively.

Figs. 3 and 4 shows the pellet vertical and horizontal placement accuracy, respectively. We have to control four degree of freedom of the pellet for adequate irradiation. Those are three dimensional position and time. The time is precisely controlled by the developed synchronization system. The vertical position is also well controlled to $\pm 0.18\text{mm}$ at $2\sigma$, which is much less than the diameter of the pellet, as shown in Fig. 3, because it is associated to the time through the vertical velocity of free fall. The distribution of the horizontal position almost falls into the shootable region, too. However it is not actively controlled. We have to control the quality of fabrication of the mechanism and manage static electricity and so on, to achieve this level of convergence.

3. Observation results and discussion
We could execute more than 1,000 times of repetitive pellet injection and irradiation at 1 Hz of repetitive frequency. The irradiation are succeeded at about 70% of probability out of pellet injection. The repetitive measurement system are also required for such a system. We constructed repetitive neutron detecting system using scintillation detector, oscilloscope and computer, for monitoring repetitive laser fusion experiment. We achieved about 20% and 5% of probability of detection for gamma ray and neutron, respectively. Fig. 5 shows an example of waveform observed on the oscilloscope.
An obvious signal peak was observed 63 nsec delayed from gamma ray signal. It can be thought as neutron signal of 2.45 MeV using TOF analysis. The yield was estimated to $1 \times 10^5/4\pi$ sr.

The laser-irradiated pellets fall down into the collecting box. Fig.6 is a scanning electron microscope (SEM) image of the cross section along the laser axis of a pellet after irradiation. The hole through the bead can be observed. The inset image shows a visible light image of the same bead. The black line is the channel. The laser light, having an intensity of $4.7 \times 10^{18}$ W/cm$^2$, appears to bore from both sides through the bead and form a channel. We can see that a hole pierces through the pellet. The radius of the hole is 10 $\mu$m, which is smaller than the laser focal point size of 13 $\mu$m.

We have to make the probability of irradiation and neutron generation higher. There are two way to improve, one is improvement of injection system, and another is laser beam tracking. However our injection system has been already well optimized. And it is difficult to control the focal point position using moving mirror or deformable mirror with appropriate speed and without degradation of aberration for laser beam tracking. Moreover, we don't control the attitude of pellet, because we are using spherical target. If we will use anisotropic pellet, we have to try to control more degree of freedoms.

4. Summary
We succeeded in injection of spherical deuterated polystyrene bead pellets at 1 Hz and symmetrical irradiation and irradiation of them with two ultra-intense laser beams. We observed channel formation through the free-falling pellets, which might be the evidence to support a scheme for fast ignition. On an average, approximately 70% of the pellets were irradiated with the laser. Neutrons were observed for 5% of these pellets. This result represents a step toward repetitive-mode fast-ignition fusion mini-reactor, CANDY.

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