Development of Target Injection and Tracking for IFE in Japan

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Abstract. The study of target injection, detection, measurement of laser focal point, and laser beam steering have started under co-research in Japan. The smooth-bore gas gun is developed for accurate injection. The applications of divergent laser beam and Arago spot are described for accurate measurement of target position and laser focal point. Magnetic lens for target trajectory adjustment by centering force is proposed. The piezoelectric actuator driven mirror is studied for laser beam steering device.

1. Introduction

Target injection and tracking have begun to be developed for inertial-fusion-energy (IFE) power plants [1-2]. The requirements of target injection systems are to inject targets accurately, not to damage targets, and to be operatable stably for a long time. The required accuracy of the flight direction is about 1 mrad, and that of the flight attitude is about 2 deg. The accuracy of irradiated laser on an injected target is required in ± 20 μm. In an attempt to meet these requirements, a coordinated injection-tracking system is pursued by the co-research in Japan. Some of the unique features of this system are: 1) it is a combination of two-stage accelerator with the main gas gun, and the additional accelerator coil gun, 2) it is high accurate position measurement of target and laser focus based on Arago spot, 3) it is target trajectory adjustment system by magnetic lenses, 4) it is a beam steering device of piezo-actuator driven mirror.

In order to clarify key elements for the accurate target injection, we constructed a smooth-bore gas gun for projectile-shooting experiments. In the experiments, we shot cylindrical projectiles surrogating sabots for IFE fuel capsules. In the next section, we show experimental results on the influences of the projectile length upon the flight accuracy.

Required accuracy of the engagement between a spherical fuel target and driver beams is ± 20 μm at the center of the reaction chamber. The position measurement of the target must be carried out with greater accuracy. Recently, the Arago spot was used for an IFE target tracking system [3]. The measurement of target position and laser focus is described in third section.

The technologically difficult problem of the real-time steering mirror (or lens) system, where few tens of final mirrors of large diameter (~ 1 m) must be simultaneously controlled in few milliseconds, is left to be solved. Greater target injection accuracy could reduce the amount or even eliminate the need for laser beam steering. To adjust the trajectory of the target in flight, the magnetic lens [4-5] is proposed in fourth section.

Two types of laser beam steering system have been studied. One is standing on Stimulated Brillouin Scattering (SBS) phase conjugate mirror (PCM). Some partially scattered probe laser beam is amplified and reflected backward by the SBS-PCM. The other is a mechanical steering mirror driven by piezo-actuators (PZT: lead zirconium titanate). The characteristics and progress of later is reported in the fifth section.

2. Smooth-Bore Gas Gun

The experimental arrangement is schematically shown in Fig. 1. The gas gun is composed of three main parts: a gas reservoir, a 3-way valve, and an acceleration tube. The gas reservoir has the volume of 0.017 m^3, which is approximately 100 times as large as that of the acceleration tube. A solenoid 3-way valve is used to control the projectile shooting. The acceleration tube has a smooth bore. A projectile was shot into the observation vacuum chamber. The flight speed was measured by the laser-path-cut method. The flight direction was measured by using the target catcher at the end of the observation chamber. The flight attitude was directly observed by using LED flashes and a digital still camera.

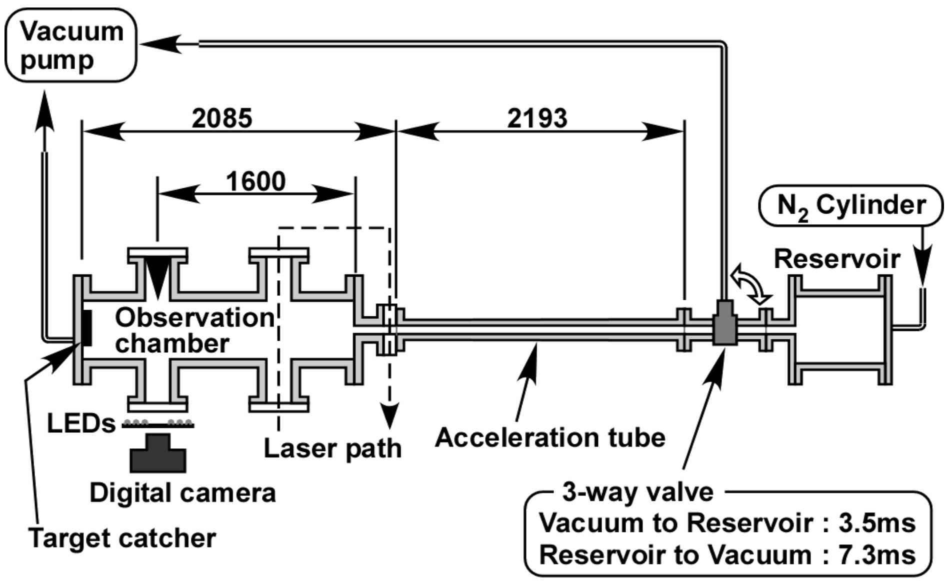


FIG. 1. Experimental arrangement.

Figure 2 shows the acceleration tube and projectiles we used. The length of the acceleration tube is 2193 mm, and its inner diameter is 10.21 mm. The projectiles were made of duracon acetal copolymer (a kind of polyoxymetheylene resin). The diameter of the projectiles was approximately 10.15 mm. The lengths of the projectiles were 10.5, 21.0, 42.0, and 84.0 mm. The masses were 1.19, 2.38, 4.79, and 9.60 g.

The valve-open duration was determined by preliminary experiments. In the preliminary experiments, we investigated the effects of the valve-open duration upon the flight direction and the flight attitude. We determined the valve-open duration so that the repeatability of the flight direction was made highest.

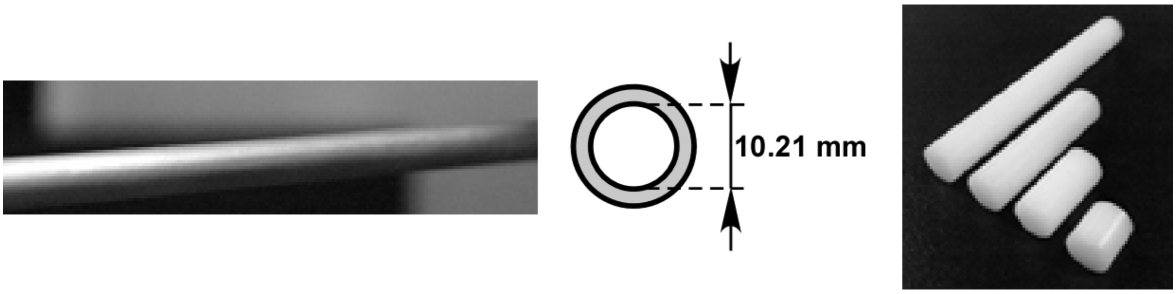


FIG. 2. The acceleration tube and projectiles.

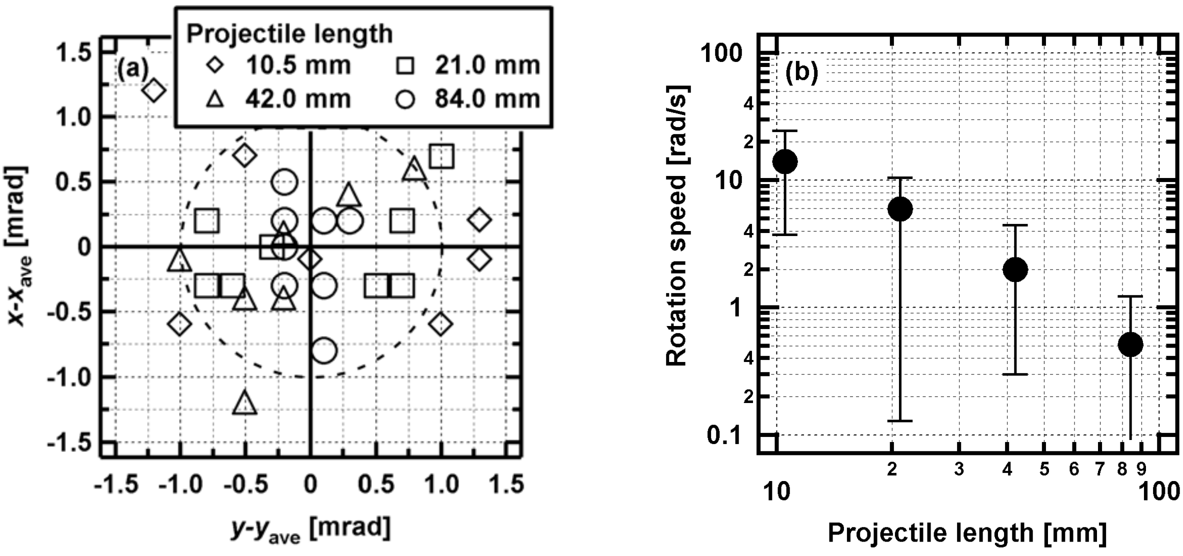


FIG. 3. Experimental results. (a) Flight direction, (b) Flight attitude.

Figures 3 and 4 show the experimental results where $p_{reservoir}$ = 300 kPa and $p_{obs.chamber}$ = 300 Pa. Figure 3(a) shows the flight direction. This figure shows that the higher repeatability of the flight direction was attained by the longer projectiles. As shown in FIG. 3(a), the required accuracy of the flight direction was almost satisfied. Figure 3(b) shows the flight attitude where the vertical axis shows the angular velocity of the rotation of the flight attitude. The observed projectiles in flight are shown in FIG. 4. As shown in FIG. 3(b), the flight attitude was significantly improved by using longer projectiles. Typical flight speed of over 100 m/s and angular velocity of the tumbling of the flight attitude of 1 rad/s correspond to the inclination of the flight attitude of 1.7 deg., which almost satisfies the requirement.

From the experiments, it has been found that the projectile length is one of key parameters governing the performance of projectile shooting by a gas gun. Although the projectiles we used were rather long and heavy compared against IFE fuel capsules, the required accuracy of the IFE-target injector was almost fulfilled.

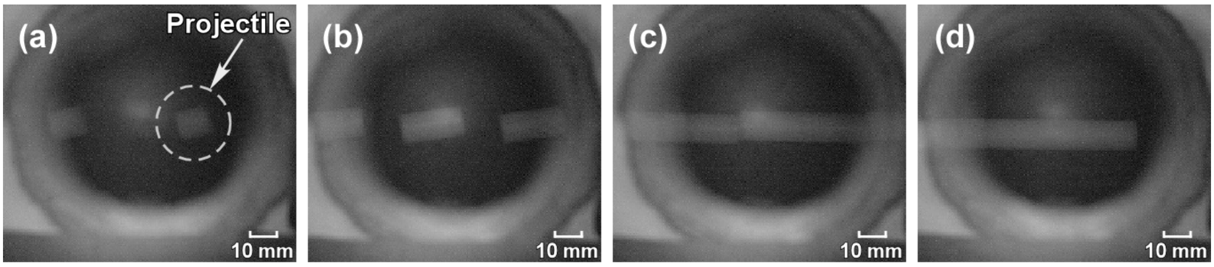


FIG. 4. Projectiles in flight. Projectile lengths are (a) 10.5 mm, (b) 21.0 mm, (c) 42.0 mm, and (d) 84.0 mm.

3. Target Position Measurement and Focal Point Measurement by Arago spot

The Arago spot, which is also known as the Poisson spot, appears at the central portion of the diffraction pattern formed in the geometrical shadow of a spherical object, as shown in FIG. 5.

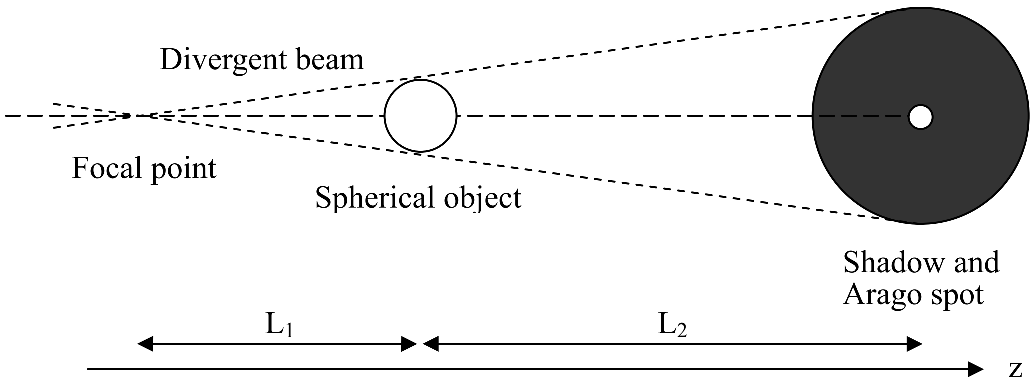


FIG. 5. Schematic diagram of construction of the Arago spot.

This is because the diffracted waves from the edge of a spherical object interfere constructively on the central axis. By means of divergent beam illumination, we can magnify the displacement of the Arago spot with respect to the actual displacement of the targe, which enables us to measure the target position accurately [3][6]. The target shadow is magnified also, which enables us to detect the Arago spot in the shadow easily, while the Arago spot is not enlarged significantly. If the focal point is fixed and the spherical object moves, then the Arago spot moves. We assume that the laser focal point is fixed at (0, 0, 0). In this case, if the center of the spherical target moves to (X, Y, L_1), then the Arago spot appears at (kX, kY, L_1+L_2) where k is $(L_1+L_2)/L_1$. The position measurement method using a divergent He-Ne laser beam was demonstrated [3]. Table I shows a summary of the position measurement experiment for various distances L_1 and L_2 .

TABLE I: SUMMARY OF POSITION MEASUREMENT EXPERIMENT.

L_2 (m)	L_1 (m)	k	Standard deviation (μm)	Maximum deviation (μm)
2	0.11	19.2	0.10	0.17
	0.70	3.86	0.20	0.39
5	0.11	46.5	0.06	0.13
	0.58	9.62	0.19	-0.42
10	0.10	101.0	0.08	0.17
	0.40	26.0	0.13	0.30

Measurement accuracy lower than 0.2 μm can be achieved for the case that the distance between the focal point and a 5-mm-diameter spherical target L_1 is within the range from 0.11 to 0.7 m and the distance between the target and a CCD detector L_2 is within the range from 2 to 10 m. Three-dimensional target position in flight can be obtained by two orthogonal divergent pulsed laser beams.

In practical IFE reactor system, reactor operation may cause thermal expansion, deformation of the reactor and the building, resulting in deviation of the laser focal point in the reactor. In the measurement of the target position by divergent beam and the Arago spot mentioned above, the deviation of the laser focal point induces the measurement error of the target position. The detection of the deviation of the laser focal point is important to measure and compensate the target position accurately. Moreover, it is important to steer and align all driver laser beams within the accuracy of lower than 20 μm before the shot. The measurement method of detecting the laser focal point using a divergent beam and Arago spot is proposed [7]. The principle of the methods of detecting the focal point is similar to that of the sundial. If spherical object is fixed and focal point moves then the Arago spot moves. We assume that the laser focal point is set at (0, 0, -L_1) initially and the center of the spherical object (not spherical target) is fixed outside the reactor at (0, 0, 0) and CCD detector is placed at the distance L_2 from the center of the spherical object as shown in Fig. 1. In this case, if the Arago spot appears at (X, Y, L_2), then we can conclude that the laser focal point deviates to ($-kX$, $-kY$, $-L_1$) where k is L_1/L_2 .

4. Magnetic Lens Target Trajectory Adjusting System

This method uses the force of repulsion between the magnets and a Pb-coated, spherical, superconducting fuel target. The Pb layer on the fuel target cooled below 7.2 K becomes a superconductor. The magnets are symmetrically placed along the line (broken line in Fig. 2) between target injection point and the laser shot point as shown in FIG. 6. The deviation of the trajectory of the superconducting sphere at the magnetic lens Δ, results in a centering force, F, which adjusts the trajectory of the sphere. Centering force F is represented as the series of the odd powers of deviation as

$$F = C_1\Delta + C_3\Delta^3 + O(\Delta^5) + \dots \qquad (1),$$

where C_1 and C_3 are proportional constant. If deviation Δ is small enough then the centering force F is primarily proportional to the deviation Δ, resulting in focusing the target trajectory to a fixed point as shown in FIG. 6. The focal length depends on parameters, such as mass, radius, speed of the target, separation, magnitude of the magnet.

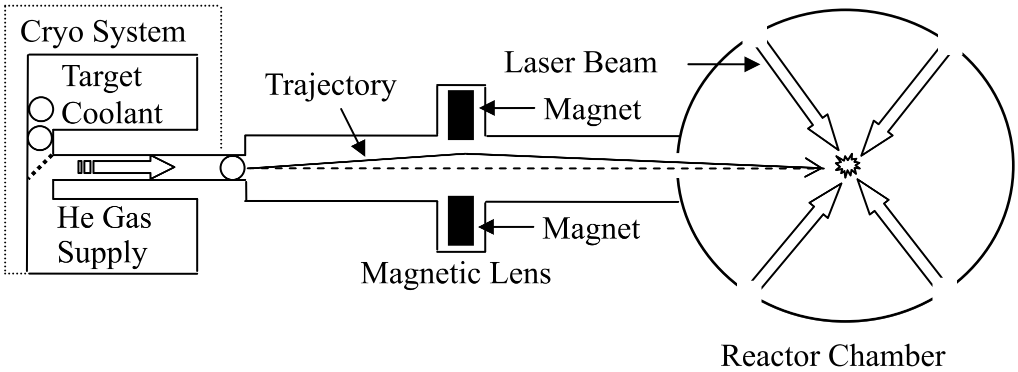
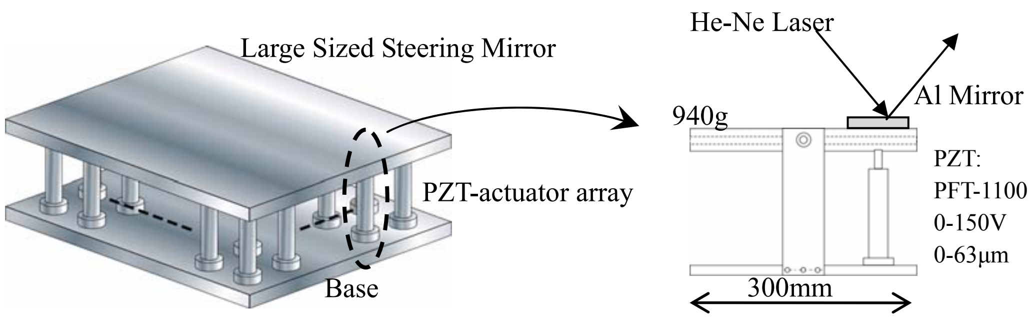


FIG. 6. Gas gun type target injection and trajectory adjusting system using magnetic lens.

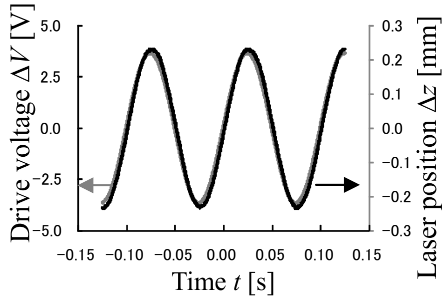
5. PZT-Actuator Driven Beam Steering Mirror

The mechanical specification of beam steering mirror for IFE reactor should be a few meter and several hundred kilograms. Over 10 Hz repetition speed and around ten μrad steering angle are required at enough accuracy for laser irradiation on a injected target. Multi PZT-actuator array is one of candidates for that mechanical steering mirror. In order to design and develop it, fundamental characteristics were evaluated for single PZT-actuator driven mirror.

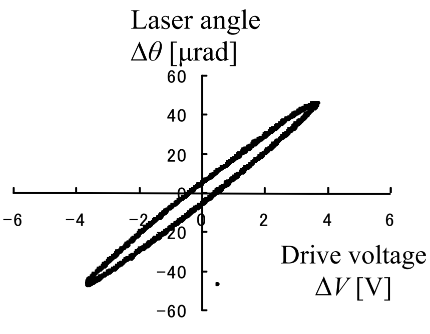
The structure of the single PZT-actuator driven mirror is shown in FIG. 7(a). A small mirror is attached on a seesaw mechanism mount. The position / steered angle of reflected He-Ne laser beam is measured by the position sensitive device (Hamamatsu Photonics, S1880). The PZT-actuator (Japan Ceralock, PFT-1100) actuates the seesaw mechanism mount which inertial moment is 0.1 kgm^2. The time response of single PZT-actuator driven mirror is shown in FIG. 7(b) at the frequency of 100 Hz. The steered beam position is plotted with drive voltage. We can see some deviation in it and hysteresis in FIG. 7(c) which can be minimized by compensated drive signal. From the relation between the input signal to single PZT device and reflected laser beam from it, the frequency characteristic is plotted in FIG. 8. Its characteristics are basically determined as the classical second-order lag system with the response frequency of ~100 Hz for 0.1 kgm^2 inertia moment. The resonant frequency of the PZT-actuator gives small affects at around 60 Hz. These characteristics can be extrapolated for a multi PZT-actuators driven large-sized steering mirror and its controller.



(a) Design of PZT-actuator array driven mirror and single PZT-actuator one.

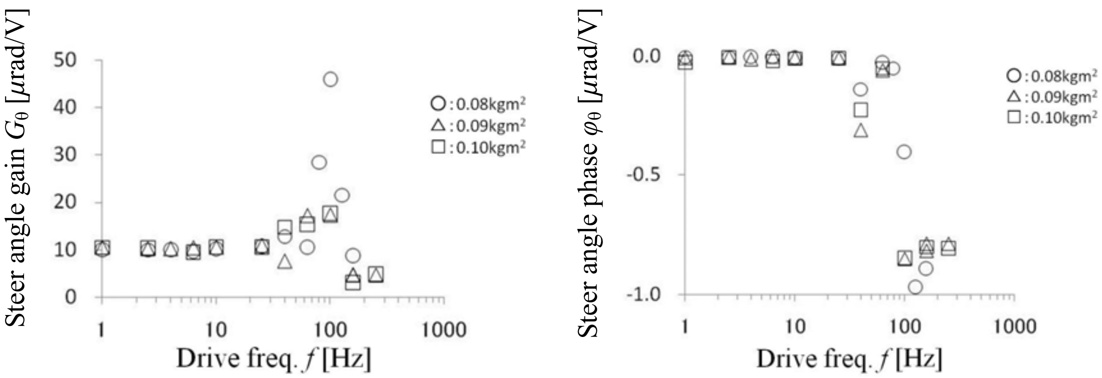


(b) Drive voltage- beam position



(c) hysteresis characteristics

FIG. 7. Single PZT driven mirror and typical charcteristics at 100Hz.



(a)Beam steering angle (b) Phase response

FIG. 8 Frequency response of the single PZT driven mirror.

6. Summary

The current status and progress of target injection and tracking related research in Japan are described. The requirements of injection speed and flight accuracy are almost fulfilled with the smooth-bore gas gun. Target position was measured with accuracy of less than 0.2 μm by a divergent beam and Arago spot. The laser focal point also can be measured by the similar principle. The magnetic lens target trajectory adjustment system is proposed for a Pb-coated, spherical, superconducting target. The fundamental characteristics of PZT-actuator driven steering mirror were evaluated. The integrated experiments of above systems are promising future practical IFE reactors.

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