Development of position measurement unit for flying inertial fusion energy target

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Abstract. We have reported the present status in the development of a position measurement unit (PMU) for a flying inertial fusion energy (IFE) target. The PMU, which uses Arago spot phenomena, is designed to have a measurement accuracy smaller than 1 μm. By employing divergent, pulsed orthogonal laser beam illumination, we can measure the time and the target position at the pulsed illumination. The two-dimensional Arago spot image is compressed into one-dimensional image by a cylindrical lens for real-time processing. The PMU are set along the injection path of the flying target. The local positions of the target in each PMU are transferred to the controller and analysed to calculate the target trajectory. Two methods are presented to calculate the arrival time and the arrival position of the target at the reactor centre.

1. Introduction

In a direct drive inertial fusion energy (IFE) power reactor, a spherical fuel target is injected into a reactor chamber and irradiated by the driver laser beams. The target must be shot by the driver laser beams with an accuracy of less than 20 μm [1]. To calculate the arrival time and the arrival position of the flying IFE target at the reactor centre, we must measure and analyse the time data and the position data of a flying IFE target in real time.

In Japan, a demonstration experiment of the target injection is under way [2]. In the experiment, the target with a diameter of 3–5 mm with (or without) a cone will be injected at a speed of 100 ± 1 m/s. Our goals are (1) to make a position measurement unit (PMU) with a position measurement accuracy of 1 μm and (2) to make a system that can calculate the trajectory of a flying IFE target in real time.

In this paper, we report the present status of the development of the position measurement unit and propose the methods to calculate the target trajectory.

2. Principle of position measurement and the conceptual design of the PMU

Position measurement methods using an Arago spot have been proposed to measure the position of a flying IFE target [3, 4, 5]. An Arago spot is a bright spot which appears at the centre of a shadow of a spherical object, as shown in figure 1. This is because the diffracted waves from the edge of a spherical object interfere constructively on the central axis. We demonstrated that a position measurement accuracy of less than 1 μm can be achieved for a stationary ball bearing [5].

Two orthogonal laser beam illuminations on the target gives a three-dimensional position of the flying target, (X, Y, Z), as shown in figure. 2 [6]. If a pulsed laser with a pulse width smaller than 10 ns is used, then the flight distance of the target at laser illumination is smaller than 1 μm for a target
velocity of 100 m/s. Use of a pulsed laser and a clock gives the time, $T$, of the laser illumination. Our
PMU employs the Arago spot formed by the pulsed, orthogonal laser beam. A divergent beam was
also employed [6]. Divergent beams magnify the shadow of the target and magnify the displacement
of the target i.e. displacement of the Arago spot. It enabled accurate measurement of the Arago spot at
a large distance.

Figure 1. The Arago spot. Figure 2. Three-dimensional position measurement.

A data reduction technique is essential for real-time data processing. Figure 3 shows the shadow
and Arago spot. Two-dimensional imaging data has ~ MB (1000 × 1000 pixels). For simplicity of the
discussion of the data reduction, it is assumed that the intensity distribution of the Arago spot can be
approximated by the Gaussian function. Consider two-dimensional Gaussian function, as

$$F(x, y) = \exp(-x^2 - y^2) = \exp(-x^2)\exp(-y^2).$$

Integrating (1), a one-dimensional Gaussian function can be obtained, as

$$G(x) = \int \exp(-x^2 - y^2) dy = C \exp(-x^2).$$

The above integration can be done physically by the cylindrical lens. Functions (1) and (2) have a
maximum at $x = 0$. Figure 4 shows the compression of the Arago spot image by the cylindrical lens [7].

Figure 3. Shadow and the Arago spot (central point). Figure 4. Compression of the Arago spot.

One-dimensional imaging data has ~ kB (1000 pixels), and it is easy to analyse one-dimensional data
in real time. A linear sensor is placed at the focal point of the cylindrical lens, as shown in figure 5.

The conceptual schematic diagram of PMU is presented in figure 6. When a flying target crosses
the PMU, a trigger signal is transmitted to the pulsed laser. A laser pulse is emitted and divided by the
beam splitter and a flying target is irradiated by the orthogonal laser beams, which are reflected by the
mirror. The Arago spot image is divided by the beam splitter and compressed by the cylindrical lens.
The compressed Arago spot image is measured by the linear CMOS (or CCD) sensor. Measured position data are then transferred to the controller. And a part of the laser pulse is detected by the photo sensor to measure the time of illumination. The controller collects the time data and the position data in each PMU and calculates the arrival time and the arrival position of the target at the reactor centre. Some key technologies were tested but system integration of the PMU is under development.

3. Setting of the PMU
PMUs are set along the target injection path, as shown in figure 7. In the reactor chamber, the position of the target can be measured by the illumination of the pulsed divergent laser beam, as shown in figure 8. The Arago spot of the target is detected outside of the reactor chamber.

4. Determination of target trajectory
The PMU measures the local position of the target in each PMU with an accuracy of less than 1 μm. Is it possible to convert the local coordinates into a global coordinates? If all of the local coordinate centres of the PMUs are set at a scheduled position, as shown in figure 9(a), then the task of the data conversion is easy. However, it is difficult to set and keep PMUs at the scheduled position.

The actual setting is shown in figure 9(b). Even in this case, the setting error of PMU can be compensated as follows [8]. To show the principle of compensation simply, consider the target motion with a constant velocity. First, the z-axis is defined as the line between the centres of the first PMU
and the last PMU, as shown in the solid line in figure 10(a). The target trajectory is represented as the dotted line. Assuming a constant velocity, the ratio of the time interval between PMUs equals the ratio of the distance between PMUs from the equation \( V dt = dZ \). Therefore, the z-coordinate of the centre of the PMU, \( dZ_i \), is determined. If the data \((dZ_i, Y_i)\) are plotted, a zigzag line appears, as in figure 10(b). Comparing the dotted line with the zigzag line, the setting error \( dY_i \) can be determined.

![Figure 10](image)

(a) (b)

**Figure 10.** (a) Left: Actual setting of PMUs (box). The cross in the box represents the centre of the local coordinate system. The solid line represents the z-axis. The dotted line represents constant velocity motion. The thick arrow represents setting error \( dY_i \). The thin arrow represents local position data \( Y_i \). (b) Right: Plotting data.

### 4.1. Trajectory determination using equation of motion

First, a heavy reference target is injected. The data \((T_i, X_i, Y_i, Z_i)\) for the reference target in the i-th PMU are obtained. Comparing the data with a parabolic trajectory, the compensations \((dX_i, dY_i, dZ_i)\) are determined. Then, the IFE target is injected. The local data \((T_{it}, X_{it}, Y_{it}, Z_{it})\) of the injected target are obtained and these data are converted into global data \((T_{it}, X_{it}+dX_i, Y_{it}+dY_i, Z_{it}+dZ_i)\). In cases of no air resistance (in case of a dry wall reactor, HIB reactor, or target with cone), assuming the parabolic trajectory, the arrival time and the arrival position at the reactor centre can be determined [8]. In cases where air resistance exists (in case of a spherical target in wet wall reactor), giving the pressure data and solving the equation of motion with air resistance, the arrival time and the arrival position can be determined, as well.

### 4.2. Trajectory determination as an optimization problem

First, a few tens of IFE targets are injected sequentially and the data \((T_{ij}, X_{ij}, Y_{ij}, Z_{ij})\) for the j-th target in the i-th PMU are obtained. Approximate forms for the arrival time and the arrival position are constructed by minimizing the error at the reactor centre (optimization problem). Then, the IFE target is injected and the local data \((T_{it}, X_{it}, Y_{it}, Z_{it})\) of the injected target are obtained. Substituting these data into the approximate forms, the arrival time and the arrival position is determined.

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### References

[1] Goodin D, Gibson C, Petzoldt R, Siegel N, Thompson L, Nobile A, Besenbruch G and Schultz K 2002 *Fusion Eng. Des.* 60 27-36

[2] Norimatsu T, Endo T, Yoshida H, Tsuji R, Kajimura Y, Nagata M, Matsumoto M and Azechi H Release of Real Size, Fast Ignition Target from Sabot: IFSA 2013 Nara (Nara, Japan, 8-13 Sept. 2013) O.Th_C10

[3] Petzoldt R, Alexander N, Carlson L, Flint G, Goodin D, Spalding J and Tillack M 2007 *Fusion Sci. Technol.* 52 454-58

[4] Carlson L, Tillack M, Lorentz T, Spalding J, Alexander N, Flint G, Goodin D and Petzoldt R 2007 *Fusion Sci. Technol.* 52 478-82

[5] Saruta K and Tsuji R 2007 *Jpn. J. Appl. Phys.* 46 6000-06

[6] Saruta K and Tsuji R 2008 *Jpn. J. Appl. Phys.* 47 1742-44

[7] Sakauchi H and Tsuji R 2009 *Plasma Fusion Res.* 4 S1012

[8] Tsuji R, Endo T, Yoshida H, Matsumoto M and Norimatsu T 2012 Trajectory Calculation of Injected Inertial Fusion Energy Target: Conference of Inertial Fusion Energy CIFE 2012 (Yokohama, Japan, 25-27 Apr. 2012) CIFE5-3