2-D PSD Diagnostic System for the Pellet Trajectory in LHD Plasmas

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Ablation of a solid hydrogen pellet in hot plasmas of Large Helical Device (LHD) has been studied. A position sensitive detector (PSD) diagnostics has been newly installed to measure the trajectory of ablating pellets. 2-D diagnostics enables the measurement with high time (1 MHz) and spatial resolutions (80 μm). A 3-D pellet trajectory can be described by a combination of 2-D images and information of initial pellet direction and velocity. A deflection of the pellet trajectory in the neutral beam injection (NBI) heated plasmas of LHD has been observed. Means of improving the measurement accuracy of this system are also discussed.

Keywords: fueling, solid hydrogen, ablation, pellet trajectory, position sensitive detector, rocket effect, Large Helical Device

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Pellet injection techniques have progressed over the last thirty years [1]. Pellet injection is the primary fueling technique planned for in International Thermonuclear Experimental Reactor (ITER) [2]. High-speed injection of solid hydrogen pellets results in deep penetration into a target plasma, and therefore improves the fueling efficiency. In addition to fueling, pellet injection triggers an edge-localized mode (ELM), and its application for ELM mitigation is planning for ITER. Irrespective of the pellet injection technique used, it is important to understand the physical mechanisms of pellet ablation in hot plasmas. The deposited mass of the pellet is determined by two stages of dynamics: the ablation process of the pellets and the subsequent drift motion of the ablated plasmoid [3, 4]. With respect to the first stage, from which the initial condition of mass deposition is obtained, the neutral gas shielding (NGS) ablation model [5, 6] is the most reasonable theoretical model. This model explains the experimental results of the Tokamak database [7]. The pellet penetration depth in a data set of Large Helical Device (LHD) can be partially described by the NGS model [8]. The actual penetration depth is influenced by various physical processes that are not included in the NGS model. For example, the presence of energetic particles and the deflection of pellet trajectories in plasmas due to the rocket effect often affect the estimation of the penetration depth. Therefore, the measurement accuracy of the penetration depth should be carefully discussed.

Pellet ablation of neutral beam injection (NBI) heated discharges in LHD has been evaluated by the measurement of H_α line emissions. H_α intensity is measured by a photodiode, which is placed so that it has the entire region of ablation emissions in its view. Information about the duration of pellet ablation, which reflects a one-dimensional radial penetration depth, is obtained from the photodiode. Since it is experimentally validated that the pellet velocity in the direction of the initial pellet trajectory is approximately constant [9], the penetration depth in its initial direction can be estimated from the duration of the H_α signal and the pellet velocity, which is measured by the time-of-flight (TOF) prior to pellet injection. However, a significant deflection of the pellet trajectory due to strong additional heating [1] can break down this 1-D picture with respect to the magnetic surface where the pellet ablates. In fact, a deflection of the pellet trajectory due to the rocket effect which pellets undergo anisotropic heating of fast particles by a tangential beam injection has been observed using the fast camera in the LHD [9]. If the curvature of the magnetic surface and the deflection of the pellet trajectory are significant, 1-D diagnostics of H_α emissions may cause an error in the estimated penetration depth, since the radial position estimated using the duration of pellet ablation does not agree with the 1-D label ρ on the magnetic surfaces of LHD plasmas. Therefore, a 3-D trajectory of the ablating pellet is required for accurate assessment of the penetration depth. To fulfill this requirement, 2-D images with sufficient time and spatial resolutions [10] are combined with the information of the duration of ablation and initial velocity of the pellet. This study reports on a system that comprises position sensitive detector (PSD) diagnostics on the in-situ pipe-gun pellet injector of LHD [11, 12]

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to obtain 3-D experimental data of the pellet trajectory of the NBI heated plasmas.

The PSD is based on the principle that current is generated in proportion to the incident light intensity on the PSD sensor. Therefore, the barycenter of the light spot is estimated by the ratio of the currents at both ends of the sensor. Electric analog signals (X-Y coordinate signals) are obtained serially, since the PSD is not a discrete type in contrast to a CCD. Therefore, a typical position resolution of a few μm is obtained. The LHD system uses the PSD S1300 manufactured by the Hamamatsu Photonics, shown in Fig. 1. As its basic specifications, the wavelength range is from 320 to 1100 nm and the size of the acceptance surface is 13 × 13 mm. The zones with diameters of 5 and 10 mm on the acceptance surface have position detection errors of ±80 and ±150 μm, respectively. The electric circuit of the PSD achieves a sampling rate of 1 MHz.

The PSD system is assembled in a connecting chamber of the pellet injector located on the outer port of the LHD, as shown in Fig. 2. Light emission from pellet ablation in the plasma is relayed by a mirror, which reflects the light to focus it on the acceptance surface of the PSD using a lens and an H_α filter. The detection property of the PSD is not affected by the change in the transmission factor of the filter due to the field angle of 6°. The viewing field of this system is a circle with a diameter of about 40 cm at the last closed flux surface of the vacuum magnetic configuration in LHD plasmas. In addition, the light is divided into two directions (one straight, the other perpendicular) since two half mirrors of the cube are used. This arrangement enables simultaneously measurement of the ablation light by means of other diagnostics (the photodiode and the fast camera).

After installing the chamber and the PSD, an alignment test is conducted to identify both the actual axes of the PSD in the direction of Z_{PSD} (see Fig. 2) and pellet injection (i.e., 10 guide tubes in the pellet injector). Using a laser along both axes, the misalignment of the axes is accurately measured by assessing the reflected points of the inner wall in the LHD. A maximum angular misalignment of ~1.5° in the toroidal direction is observed with respect to the axis of the pellet injector. This misalignment is caused by rotation and shift of the pellet injector due to its connection with the LHD. As a result, the initial pellet direction and actual position of the PSD axis are defined for precise estimation of the penetration depth.

Calibration experiments are performed to relate the output of the PSD to the position in real space. The coordinate system of the PSD is shown in Fig. 2. The origin O is defined as the center of the mirror that reflects the ablation light. The origin corresponds to the center of the acceptance surface of the PSD. The axis Z_{PSD} connects the origin O and the major axis of the LHD plasma on the equatorial plane. X_{PSD} and Y_{PSD} are defined as horizontal and vertical axes with respect to Z_{PSD}. The relative position of the light spot is defined by the following relation of currents obtained from each sensor:

$$X_{\mathrm{relative}} = \frac{I_{X2} - I_{X1}}{I_{X2} + I_{X1}},$$
$$Y_{\mathrm{relative}} = \frac{I_{Y2} - I_{Y1}}{I_{Y2} + I_{Y1}}.$$

The connecting chamber and the target for calibration are arranged along a straight line, where the distance Z'_{PSD} is 3.930 m. The board with 1 cm diameter holes (white circles) at intervals of 0.100 m is used as the target (see Fig. 3). The light illuminated from one hole does not leaked into another hole. It is confirmed that the PSD detects the position of the light of 1 cm in diameter with

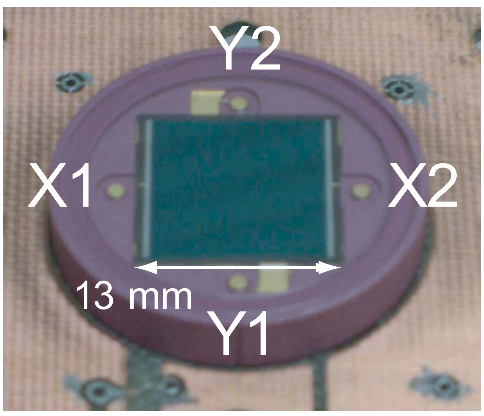

Fig. 1 Position sensitive detector S1300.

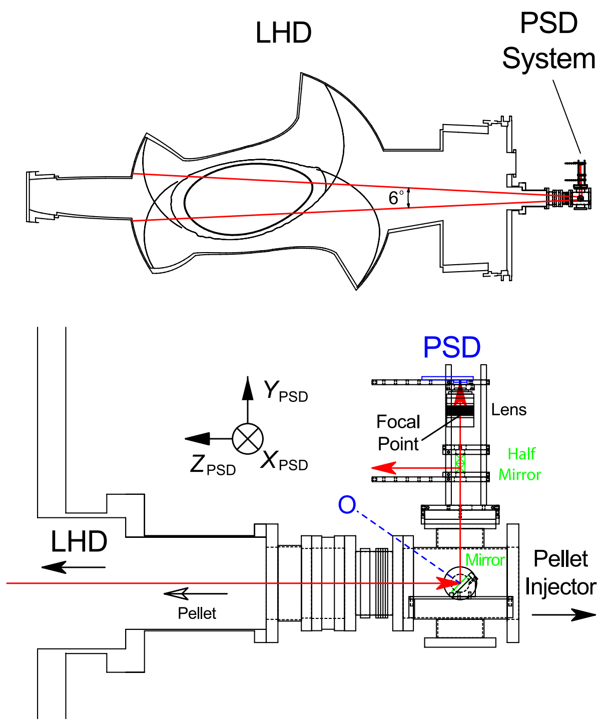

Fig. 2 Field of view of the PSD and a schematic diagram of the PSD system installed in the LHD.

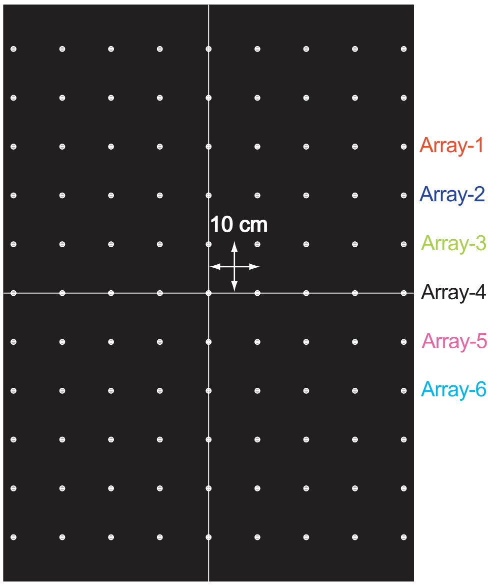

Fig. 3 Board with holes of 1 cm diameter (white circles) at intervals of 0.100 m for calibration.

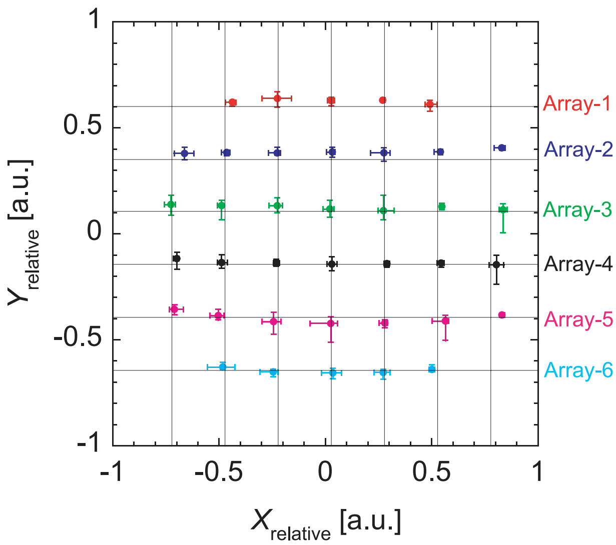

Fig. 4 Results of the calibration. The position of the light from a region of 1 cm diameter is detected by the PSD output within an error of a few centimeters.

a maximum error of a few centimeters, as seen in Fig. 4. The relative position values (X_{relative} and Y_{relative}) of 0.250 can be assumed to correspond to a distance of 0.100 m in the actual arrangement, because the equally spaced lattice is approximately reproduced. In other words, the output of PSD (0.250) represents an interval of 0.100 m on the X-Y plane for Z'_{PSD}. The outputs of X_{relative} and Y_{relative} must be corrected to correspond to the zero point of the XY coordinate system, where $X_{\mathrm{offset}} = -0.029$ and $Y_{\mathrm{offset}} = -0.137$. By relating the position obtained from the constant pellet velocity and the axis of the initial pellet direction with the distance on the axis of the PSD (Z_{PSD} in LHD plasmas), the specific lattice X-Y can be determined. Therefore, the relationship of X_{PSD} and Y_{PSD} is estimated by the following expressions:

$$X_{\mathrm{PSD}} = \frac{Z_{\mathrm{PSD}} + L_Z}{Z'_{\mathrm{PSD}} + L_Z}\frac{0.100}{0.250}(X_{\mathrm{relative}} + X_{\mathrm{offset}}),$$
$$Y_{\mathrm{PSD}} = \frac{Z_{\mathrm{PSD}} + L_Z}{Z'_{\mathrm{PSD}} + L_Z}\frac{0.100}{0.250}(Y_{\mathrm{relative}} + Y_{\mathrm{offset}}),$$

where L_Z is the distance between the origin and the focal point of the light. As a result, the actual position in 3-D space can be evaluated by considering the position of the light source on the Z_{PSD}-axis.

The photodiode signal from H_α line emissions in the pellet-fueled plasma is compared with the sum of four outputs (I_{X1}, I_{X2}, I_{Y1}, I_{Y2}) from the PSD, as shown in Fig. 5 (a). Blue dashed lines represent the ablation beginning and ending times. The beginning time can be estimated by assuming the location of the last closed flux surface of the vacuum magnetic configuration in LHD plasmas and the constant pellet velocity measured in the pellet injector. The pellet penetration depth estimated by the H_α signal is 0.58 m, where the measured pellet velocity and the duration of the ablation are 1185.43 m/s and 0.49 ms, respectively. The beginning of the ablation observed by PSD is earlier than that of the H_α signal. This fact may result in a difference in sensitivity of the PSD and the photodiode. The output of PSD, which is different from the behavior of the H_α signal, is represented by green lines. The pellet trajectory obtained by the PSD diagnostics in the plasma is shown in Figs. 5 (b1)-(b3). The initial trajectory of the pellet is represented by an arrow. The deflection of the pellet trajectory to the same toroidal direction as the tangential NBI is observed (see Fig. 5 (b2)). This observation is consistent with the previous experimental result using the fast camera [9]. The following are the major issues of the present PSD diagnostics system.

First, the time response of the PSD should be improved. As shown in Fig. 5 (a), the output of the PSD is different from the H_α signal of the photodiode following the peak of the H_α signal intensity. Since the output on the PSD as a photodiode with spatial resolutions must correspond to the output of the photodiode to measure H_α emission, the PSD data following the H_α signal peak cannot be used. A postulated cause of this problem is the accumulation of charges on the acceptance surface of the PSD. A new amplifier for the PSD is designed to short-circuit at intervals of a few to 10 µs. In the phase before the peak of H_α intensity, the barycenter may be also shifting in the direction of the initial position of pellet ablation due to the accumulation of charges. The second problem is the identification of the initial position of pellet ablation on the coordinates X_{PSD} and Y_{PSD}. Figure 6 illustrates a representative image, and the field of view of the PSD is represented by a light blue circle. The X-point of the separatrix is shown in transverse view from the upper left to the lower right direction. Since recycling is localized at

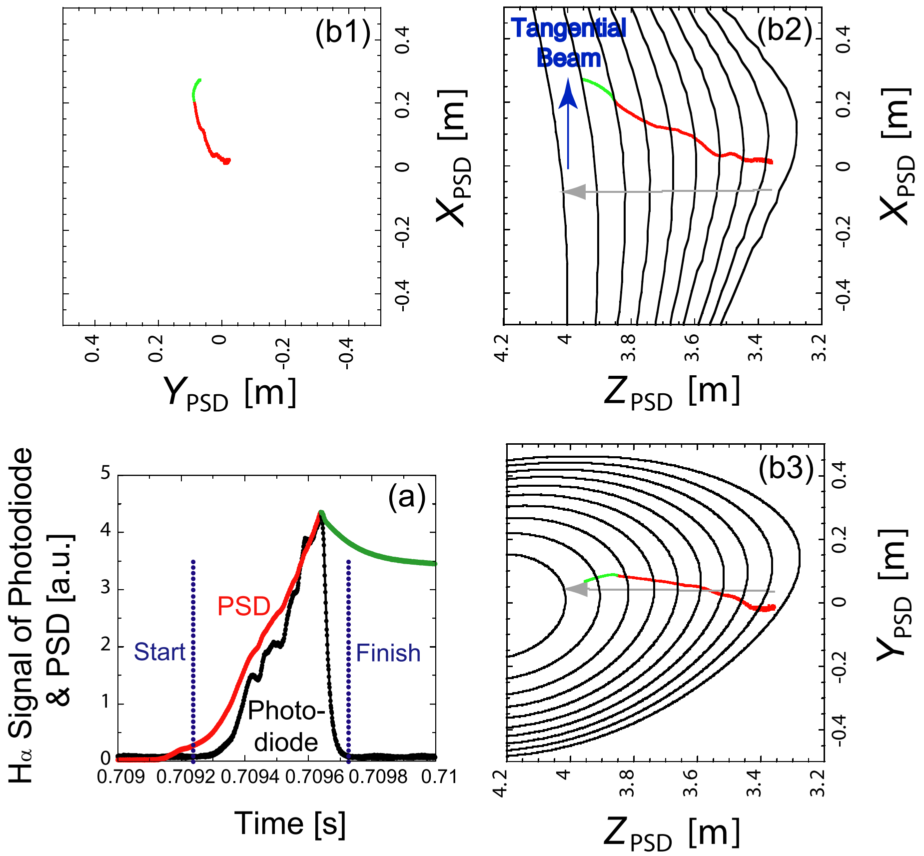

Fig. 5 (a) Comparison with the H_α signal of the photodiode and the total PSD outputs, and the pellet trajectory observed by the PSD in the (b1) X-Y, (b2) X-Z, and (b3) Y-Z planes in the LHD discharge 70848.

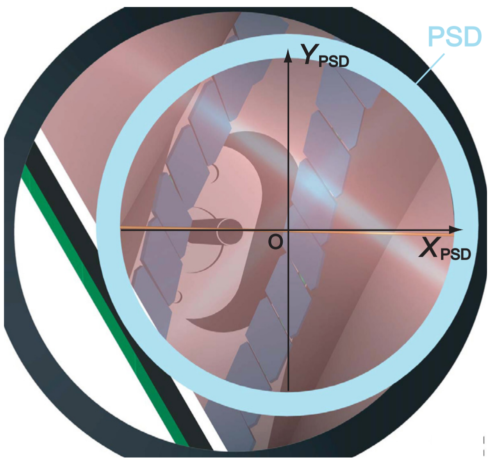

Fig. 6 Viewing field of the PSD indicated by a light blue circle.

the X-point, this bright curve causes misalignment of the initial position. In particular, when the H_α intensity is relatively low (typically at the beginning and the end of the ablation), the signal of H_α emission from the X-point significantly affects the output from the PSD, although the H_α intensity in background plasma is at most a thousandth of that in pellet ablation. The change of the barycenter of H_α intensity in cases where the ratio of the intensity of the ablation and X-point is 1000:1, 10, 50, 100, is shown in Fig. 7. Red and blue zones correspond to the area of pellet ablation and the X-point, respectively (the ratio of the area is 1:73). On the viewing field of the PSD, the output position shifts to the upper right direction because of the geometry of the X-point. The X-point also affects the position of the PSD output even in the case of low intensity ($< 1\%$). The fast camera detects the intensity and position of the light spot, however the PSD obtains the information only of the barycenter. Therefore, it is important to measure the intensity of the emission from the X-point by the fast camera, particularly when the pellet begins to ablate (the emission intensities of pellet ablation and the X-point are comparable). Then, if the PSD output can be compensated by this information, more accurate identification of the pellet trajectory using the PSD can be expected. Finally, another important problem is the effect of the size of the ablated plasmoid. Since the ablation cloud is elongated along the field line at the speed of sound, the PSD detects the emissions integrated along the line of sight from this cloud. Therefore, the barycenter evaluated by the PSD diagnostics does not necessarily agree to the real position of pellets. In Ref. [9], it is assumed the brightest point on the images from the fast camera corresponds to the position

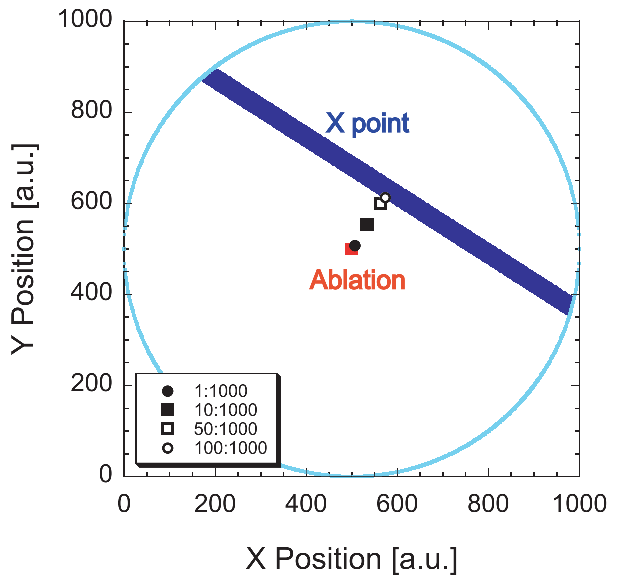

Fig. 7 Barycenter of H_α intensity calculated in the cases where the ratios of the intensity of the ablation and the X-point are 1000:1, 10, 50, 100, respectively.

of the pellets. The position does not necessarily agree with the center of a cigar-shaped plasmoid of length 20–100 cm. Accordingly, the measurement accuracy of a plasmoid extended along the magnetic field line should be discussed by comparing results from the PSD diagnostics with the fast camera.

In summary, the system of position sensitive detector (PSD) diagnostics on the pellet injector in LHD has been developed to obtain 3-D experimental data on the pellet trajectory in plasmas. These simple diagnostics equip the position detection with higher time and spatial resolutions than those of the fast camera. A calibration scheme has been established to relate the output of the PSD to the position in the real space. By finding the position of the light spot on the Z_{PSD}-axis, the real position in the 2-D plane (X-Y) can be estimated. The deflection of pellets in the direction of the tangential neutral beam in LHD plasmas is identified by this system. Consideration of the effect of the emission from the X-point improves the accuracy of the initial position of pellet ablation in the PSD system. The real position of pellets considering line-integrated effects of a plasmoid extended along the magnetic field line will be discussed by comparing results from the PSD with the fast camera in a future study.

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