Observation of Intermittent Breakaway of Pellet Plasmoid in LHD

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Introduction

Solid hydrogen pellet injection can provide fuel particles directly to high temperature plasma, and therefore it is one of the promising candidates for fueling in fusion reactor. In fact, pellet injection has extended the operational regime to higher densities while maintaining a favorable confinement properties[1, 2, 3]. At the same time, the pellet fueling is still far from adequate on core fueling under fusion reactor condition. One of the difficulties is shortening of the pellet penetration length as increase plasma temperature, and the other is drift of pellet ablatant toward the low magnetic field direction. The former can be solved only through higher speed pellet injection. Higher speed injection, however, cannot be effective in increasing penetration length despite the technological difficulty. The latter can be utilized by optimizing pellet injection location and it has been confirmed in tokamaks that the high field side pellet injection can improve effective pellet fueling performance [4, 5]. $\nabla \mathbf{B}$ induced drift model[6, 7, 8] is widely accepted as a mechanism of the pellet plasmoid drift in tokamak device, while on the other hand, the drift behavior remain incompletely understood in the case of helical systems such as the Large Helical Device (LHD) due to the three-dimensional characteristic of the confinement magnetic field configuration.

In order to optimize the pellet fueling based on an understanding of the mechanism, experimental observation of the pellet ablation has been performed by employing fast imaging camera with stereoscopic viewing[9] and two-dimensional bundled fiber optics in a mutually complementary manner on LHD.

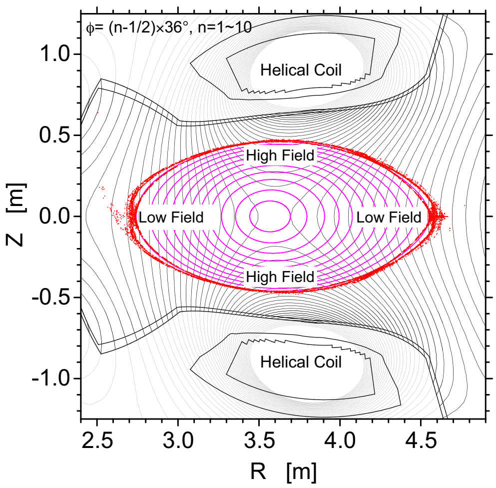

Figure 1: Magnetic field structure and flux surface of LHD.

Experimental setup

Pellet injection experiments was performed in LHD, which is a heliotron-type fully superconducting device with a pair of $l/m = 2/10$ continuous winding helical coils and three pairs of poloidal coils. Representative major radius, averaged plasma minor radius and the magnetic field strength are 3.9 m, 0.6m and ≤ 3 T, respectively. Since all magnetic components are generated by the external coils, the considerable helical ripple effect with three dimensional structure dominate the confinement field in addition to a toroidal effect. Figure 1 shows contour plot of the magnetic field strength in the horizontally elongated poloidal cross-section. There is a saddle point of magnetic field strength in the plasma center and therefore inboard side is not necessarily high field side. In this study, pellet is injected from out board side in the horizontally elongated poloidal cross-section and this injection location is a low field side from the both viewpoints of the toroidal and helical ripple effects.

A pair of stereo images, which are taken from different locations, has been focused onto the single fast imaging camera's focal plane by employing a bifurcated fiber scope[9], to ensure the simultaneity of the both images. The frame rate of the fast imaging camera is 20,000 fps (frame per second) for 464×192 pixels spatial resolution and the exposure time is 2 - 48 μs. On the other hand, time resolution of the fast imaging camera is still not sufficient to observe pellet ablation related phenomena. Thus, the fast time resolution (>1 MHz) observation with limited spatial resolution (10×10 pixels) is performed by using a two-dimensional bundled fiber optics with fast PIN-photodiode. Viewing angle of the two-dimensional bundled fiber optics is the same as that of the fast imaging camera. However, simultaneous observation has not been performed in this study.

Experimental Result

Figure 2(a) shows a parallelized stereo pair image of the pellet ablatant. Spindly bright part is a high density pellet ablatant which expand along the field line. Several low intensity blobs which are located parallel to the pellet ablatant is observed. Similar phenomenon has been reported from TEXT[10] and ASDEX-U[11], and it can be explained by intermittently breakaway plasmoid from the pellet ablatant. This observation suggests that the pellet ablated particles are expelled from the pellet ablated position before depositing particles there and effective pellet deposition profile must be influenced. From the viewpoint of fueling efficiency, direction of the plasmoid movement is important. Assuming that the brightet point represent the plasmoid, namely, ablatant and/or blob position, three-

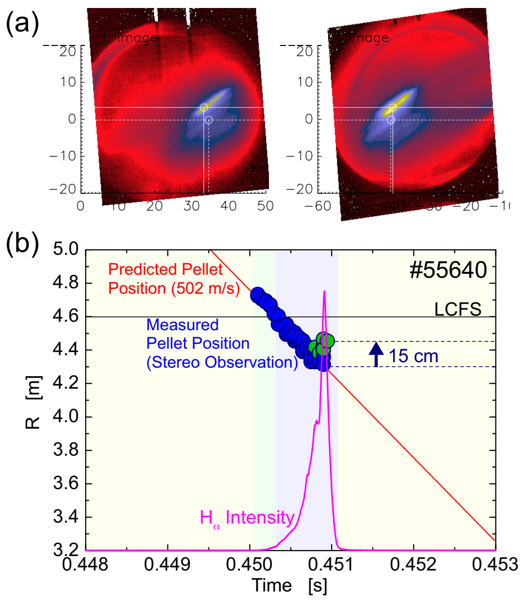

Figure 2: (a) Typical stereo pair of the pellet ablation image, and (b) temporal evolution of the stereo reconstructed pellet position

dimensional positions are estimated from the stereo observation. Stereo reconstructed plasmoid position in major radius is shown in Figure 2(b). Red line, blue and green symbols denote a predicted pellet ablation position assuming the constant pellet velocity, measured pellet ablatant and blob position. Correspondence of the blue symbol with the red line suggests that the initial pellet injection velocity is maintained during the pellet lifetime and the pellet eventually penetrate to R= 4.3 m. On the other hand, the intermittently breakaway plasmoid, which is denoted by green symbol, is observed up to 15 cm outer side of the pellet ablation position. This observation suggests that a portion of the pellet fueled particles are lost from the ablation position toward the major radius direction. This speculation is also supported by effective pellet deposition profile, which is estimated from density profile change just before and after pellet injection, namely, the pellet deposition peak is located around R= 4.5 m as shown in Figure 3 despite the pellet penetrate to R= 4.3 m.

In order to investigate dynamics of the intermittently breakaway plasmoid, which play a key role in fueling, the fast time resolution (>1 MHz) observation with limited spatial resolution (10×10 pixels) has been performed by using a two-dimensional bundled fiber optics with fast PIN-photodiode. Figure 4(a) shows alteration of H_α intensity from moment to moment at an array of channels along the pass of the intermittently breakaway plasmoid. Ch. 58 is located on the pellet trajectory and the other channel is observing only the breakaway plasmoid. The H_α intensity is consist of a lot of spikes and they are propagated. It is satisfactory to consider the spikes as the intermittently breakaway plasmoid and its breakaway frequency is estimated at around 100 kHz. A number of the spikes decrease as

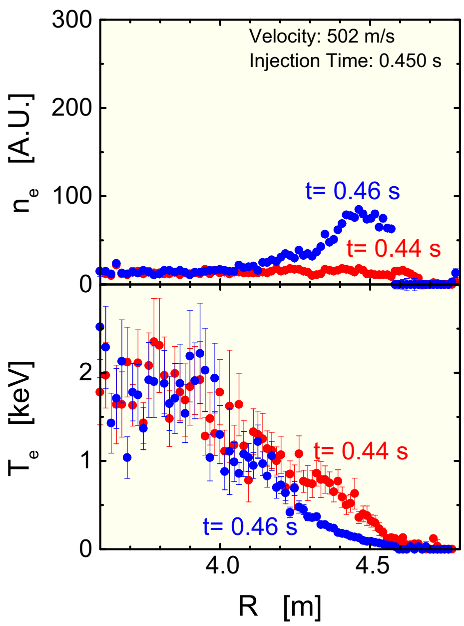

Figure 3: Density and temperature profile just before and after pellet injection.

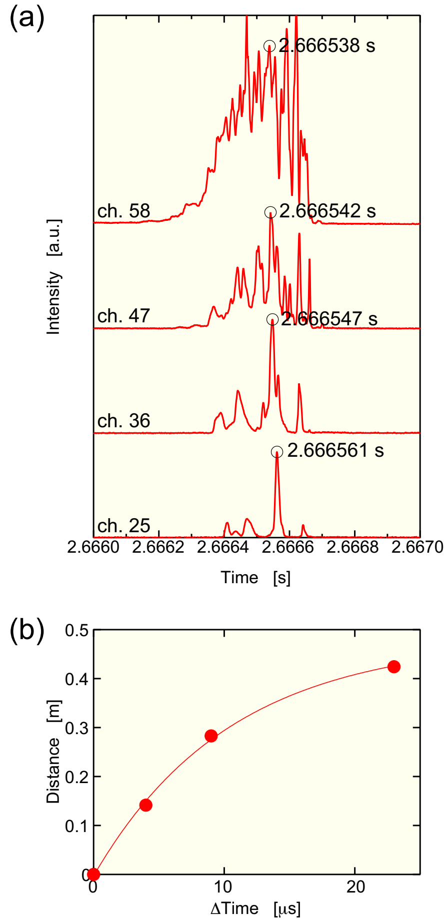

Figure 4: (a) H_α intensity of the intermittently breakaway plasmoid, and (b) movement of a breakaway plasmoid.

the distance and drop to one-third within 4 ch., namely, about 40 cm. Figure 4(b) shows the movement of a representative breakaway plasmoid. A drift speed of the breakaway plasmoid has attained up to 30 km/s in the beginning of drift and then slows down in the end of the drift. The lifetime of the breakaway plasmoid is several 10 μs. The velocity and moved distance of the breakaway plasmoid should be compare to theoretical model, which takes into account the $\nabla\mathbf{B}$ induced drift under the three-dimensional helical confinement field.

Summary

Experimental observation of the pellet ablation has been performed by employing fast imaging camera and two-dimensional bundled fiber optics in a mutually complementary manner on the Large Helical Device (LHD). It has been confirmed that the pellet penetrates into hot plasmas with maintaining an initial velocity during ablation. At the same time, intermittently breakaway plasmoid from the pellet ablatant, which is generated around the pellet substance, has been observed. The intermittent breakaway of the pellet ablatant recurrently develops at the rate of about 100 times per millisecond and the velocity of the breakaway plasmoid is estimated to be far exceeding the pellet injection velocity in the direction opposite to the pellet injection, namely low magnetic field side. The maximum moving distance of the breakaway plasmoid attains to more than 15 cm within its lifetime. These observations suggest that there is a non-diffusive transport of the pellet ablatant to the low magnetic field side simultaneously with the pellet ablation. A part of the ablated pellet mass is, therefore, promptly lost from a flux surface in which pellet is ablated. In order to understand the pellet fueling properties with sufficient accuracy, it is important to evaluate non-diffusive transport of the pellet ablatant in addition to the pellet ablation. The non-diffusive transport to the low magnetic field side is qualitatively consistent with the ∇B induced drift model in the tokamak system which is based on the assumption that the magnetic field strength is proportional to 1/R. However, advanced modeling that takes into account three-dimensionality of the helical magnetic configuration is required in order to identify the ∇B induced drift effects in the LHD plasmas.

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