§30. Improvement in the Fueling Efficiency of Supersonic Gas Puffing Using Long Laval Nozzles in LHD

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Supersonic gas puffing (SSGP) has been successfully applied to the Large Helical Device (LHD). In SSGP, fuel gasses are ejected through a fast solenoid valve equipped with a Laval nozzle. Because of the solenoid valve and the Laval nozzle, a higher working pressure of < 8 MPa and more convergent gas flow than those of the ordinary GP are available. Recently, improvement in the fueling efficiency has been observed in LHD experiments using an improved Laval nozzle.

The SSGP device is installed on a lower port in LHD. Three solenoid valves with different Laval nozzles ϕ 0.3 and two 0.6 mm throat diameter, which we refer to ϕ 0.3, ϕ 0.6, and ϕ 0.6L, respectively, are employed in the SSGP device. The ϕ 0.3 and ϕ 0.6 Laval nozzles are similarly designed to generate the gas flow of Mach number M = 8 with the angle of inflection point q of 12º. The ϕ 0.6L Laval nozzle is designed to generate the gas flow of M = 11.5 with q = 4º. The length of ϕ 0.6L Laval nozzle is 40 cm and 4 times longer than that of the ordinary ϕ 0.6 Laval nozzle. It is expected that the gas flow through the ϕ 0.6L Laval nozzle will become more convergent and faster than those of the ordinary ϕ 0.6 Laval nozzle.

The fueling efficiency of SSGP, η_{tot} is defined as a ratio of increase in the total electron inventory in the plasma due to SSGP to the number of electrons in the injected gas. The total electron inventory is estimated by the volume-integration of the electron density profile inside a_{99}, where a_{99} is the effective minor radius in which 99% of the plasma kinetic energy is confined. η_{tot} is then given by,

$$\eta_{tot} = \frac{\Delta N_e}{\Gamma_{SSGP}\Delta t} \times 100\,, \qquad (1)$$

where Γ_{SSGP} is the flow rate of SSGP, ΔN_{e} is the increase in the total electron number due to SSGP and Δt is the pulse length of SSGP. η_{tot} of 10 - 25 % in the case of ϕ 0.3 Laval nozzle was revealed in the former study [1].

The fueling efficiency improves suddenly during SSGP when the target plasma is close to the density limit. Figures 1(a) and 1(b) show the time evolutions of the line-averaged density and the plasma stored energy in the discharges with an improved efficiency and an ordinary efficiency. In these discharges, R, a, B_0, and P_{NB} were fixed to 3.6 m, 0.6 m, 1.5 T, and 13 MW, respectively. SSGP was injected through ϕ 0.6L Laval nozzle at t = 3.730 s with the pulse length of 130 ms and 150 ms. The backing pressure was ~2 MPa and the flow rate was 170 Pa·m^3/s. The line-averaged density in the case of Δt = 150 ms abruptly increased at t ~ 3.9 s while the plasma stored energy decreased. The plasma stored energy increased again at t ~ 4.0 s and became higher than that of Δt = 130 ms at t ~ 4.1 s. As a result of this, the fueling efficiency was improved for two times even though the difference in the number of supplied particles was less than 20 %. Figure 1(c) shows the time evolutions of the position of a_{99} in both cases. In these discharges, the position of the last-closed-flux-surface (LCFS) in vacuum was 0.63 m. The position of a_{99} is close to LCFS when the density increased while the plasma stored energy decreased at t = 3.9 s. Figure 2 shows radial profiles of the electron density in the discharges shown in Fig.1. At t = 3.866 s, the density at r_{eff} ~ 0.65 m in both cases is larger than the Sudo density limit of ~9.2 × 10^{19} m^{-3} in these discharges. On the other hand, the density at t = 3.900 s in the region of r_{eff} > 0.6 m in the case of Δt = 150 ms exceeds the Sudo density limit, while the density decreased to smaller than the Sudo limit in the case of Δt = 130 ms. It has been revealed that the plasma column tends to shrink when the edge plasma density increases to the Sudo limit. In the discharge with Δt = 150 ms, the plasma column shrunk and SSGP deposited the particles inside LCFS. This is why the density increased rapidly. Similar phenomena are frequently observed when the edge density of the target plasma is close to the density limit. Since SSGP was turned off before the plasma collapse, the position of a_{99} was restored to the ordinary position after t ~ 4.1 s.

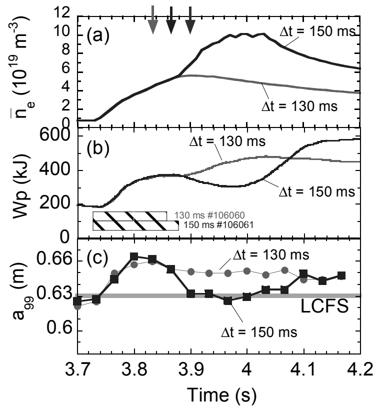

Fig. 1. Temporal evolutions of (a) the line-averaged density, (b) the plasma stored energy, and (c) a_{99} in the cases with the pulse length of 130 ms (red) and 150 ms (blue). a_{99} is close to LCFS at t = 3.9 s in the case of the improved fueling efficiency. Three arrows denote the timings where profiles are shown in Figs. 2 (a) and (b).

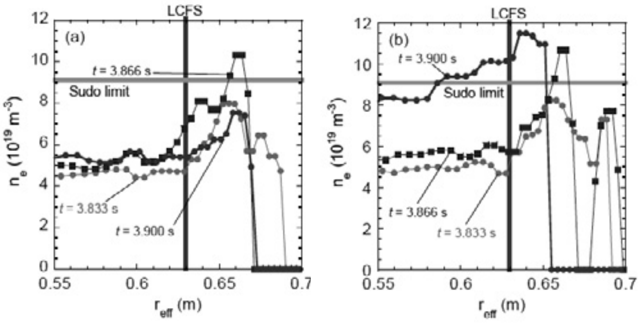

Fig. 2. Radial profiles of the electron density in the cases with the pulse length of (a) 130 ms and (b) 150 ms.

1) Murakami A. et al.: Plasma Phys. Control. Fusion **54** (2012) 055006.