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Fueling efficiency of gas puffing on large helical device

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Abstract

Fueling efficiency of gas puffing has been estimated for the net current free plasmas heated by the neutral beam injection in LHD. The particle balance has been analyzed in the latter phase of the density ramp up discharges. The increase rate of the plasma density is correlated to the particle flux of gas puffing alone and not to the other parameters such as the recycling flux, at that phase. The fueling efficiency of 12% has been obtained with this method. The fueling efficiency obtained by this method is insensitive to the heating power or the existence of the magnetic island.

Keywords: Fueling efficiency; Gas puffing; Large helical device; Particle balance; Density control; Recycling

1. Introduction

Gas puffing is routinely used on the large helical device (LHD) [1] to control the electron density. The gas puff system of LHD consists of nine piezo valves distributed to three locations. Three kinds of piezo valves, of which the hydrogen flow rate at the maximum are 5, 50, and 100 Pa m^3/s, respectively, are utilized in the system. The fueling efficiency of gas puffing is one of the important parameters to describe the particle balance of the fusion plasmas, and has been studied in numerous tokamaks [2–8]. For example, the order of the fueling efficiency of gas puffing on the diverted tokamaks is 10% [9]. This paper is the first attempt to estimate the fueling efficiency for the large net current free plasmas with a continuous helical divertor configuration.

Conventional method to estimate the fueling efficiency of gas puffing is to compare the time derivative of the electron density before and after the gas puff termination [2,3]. However, this method has a difficulty; i.e. it is necessary to assume the related parameters, such as the fueling efficiency or the recycling rate, are constant around the termination, and this inevitably includes the inconsistency since gas puff termination itself is transient. Another simple method is to compare the total amount of the particles puffed during the discharge and the total particle number of the plasma [4,5]. This method also has a difficulty since the plasma density of the previous discharges largely affects the total particle number of the plasma.

In this study, the fueling efficiency is investigated based on the particle balance model. According to the model, it is possible to estimate the fueling efficiency from the ratio of the density increase rate to the gas puff particle flux, as long as the change in the plasma density is due to the gas puffing only. This method is robust to the density of the previous discharges, since it uses the time derivative of the plasma density.

2. Fueling efficiency

The particle balance of gas-fueled hydrogen plasma heated by the neutral beam (NB) injection can be modeled by the equation below;

$$N_e' = \alpha(\Phi_{puff} + R_{div}\Gamma_{div} + R_{wall}\Gamma_{wall}) + \Phi_{NB} - \frac{N_e}{\tau_p}, \qquad (1)$$

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where N_e is the total number of the electrons confined in the plasma, $N'_e = dN_e/dt$ is the time derivative of N_e, α is the fueling efficiency, Φ_{puff} is the particle flux supplied by gas puffing, R_{div} (R_{wall}) and Γ_{div} (Γ_{wall}) are the recycling coefficient and the outward flux on the divertor tiles (the first wall of the vacuum vessel), Φ_{NB} is the particle flux supplied by NB, and τ_p is the particle confinement time, respectively. Note that each parameter possibly depends on the others. For example, Γ_{div} might depend on Φ_{puff}. Experimentally, Φ_{puff} is mainly used to control the plasma density, or N'_e. The response of N'_e to Γ_{puff} can be directly related to α;

$$\alpha \approx \frac{\partial N'_e}{\partial \Phi_{puff}}, \tag{2}$$

as long as the other parameters are insensitive to the change of Φ_{puff}. In order to estimate α by Eq. (2), the relations below should be satisfied;

$$\frac{\partial (R_{div}\Gamma_{div})}{\partial \Phi_{puff}} \ll 1, \tag{3}$$

$$\frac{\partial (R_{wall}\Gamma_{wall})}{\partial \Phi_{puff}} \ll 1, \tag{4}$$

$$\frac{\partial \Phi_{NB}}{\partial \Phi_{puff}} \ll 1, \tag{5}$$

$$\frac{\partial (N_e/\tau_p)}{\partial \Phi_{puff}} \ll 1. \tag{6}$$

As will be shown later, typical orders of Φ_{NB}, Φ_{puff}, and Γ_{div} in LHD are 10^{20}, 10^{21}, and 10^{22}, respectively, and that of N'_e is 10^{20}, in the unit s^{-1}. Therefore, it is more difficult to satisfy Eq. (3), than Eq. (5). As for Eq. (4), we have no information about Γ_{wall} itself to date. In this study, we refer to the H_α signal to assure that the recycling terms of $R_{div}\Gamma_{div}$ and $R_{wall}\Gamma_{wall}$ are constant. The H_α signal is proportional to the neutral particle density in our experimental regime [10]. To confirm the last criterion, Eq. (6), it is necessary to obtain τ_p which has not been estimated experimentally at this moment. Meanwhile, the energy confinement time, τ_E^{dia}, has been routinely estimated from the diamagnetic plasma stored energy, W_p^{dia} as $\tau_E^{dia} = W_p^{dia}/(P_{NB} - dW_p^{dia}/dt)$, where P_{NB} is the NB heating power. Typical order of τ_E^{dia} is 0.1 s in LHD. In this study, we assume that the behavior of τ_p resembles to that of τ_E^{dia} and use τ_E^{dia} to see whether Eq. (6) is satisfied or not.

Conventional method to obtain α is to compare N'_e before and after the termination of the gas puffing with Φ_{puff} [2,3];

$$\alpha \approx \frac{(N'_e)_{before} - (N'_e)_{after}}{\Phi_{puff} - 0} \approx \frac{N''_e}{\Phi_{puff'}}, \tag{7}$$

where N''_e and $\Phi_{puff'}$ are the time derivative of N'_e and Φ_{puff}, respectively. Therefore, this method corresponds to the use of time differentiated Eq. (1), and Eq. (7) is acceptable as long as $R_{div}\Gamma_{div}$, $R_{wall}\Gamma_{wall}$, Φ_{NB} and N_e/τ_p are constant around the gas puff termination. However, the gas puff termination itself is a transient phenomenon and it is difficult to adopt such an assumption.

3. Experimental results

Density ramp up experiment has been carried out on LHD. The major radius, R_{ax} and the strength of the magnetic field, B_0 at the magnetic axis were set to 3.6 m and 2.8 T, respectively. One piezo valve, of which the hydrogen flow rate at the maximum is 50 Pa m^3/s, was used throughout the experiment. Discharges were initiated by the electron cyclotron heating (ECH) and then sustained by the NB injection. Two or three beam lines of high-energy negative-ion based NB systems supplied ~3.5 or ~5 MW of the heating power. The P_{NB} is estimated from the direct heat-load measurement of NB shine-through power on the armor plate [11]. Electrostatic probes set on the divertor tiles were used to measure the electron temperature, T_e^{div} and the electron density, n_e^{div} [12]. Using these parameters, Γ_e^{div} is estimated as the multiple of the ion saturation current density at the peak position and the assumed wetted area of 2 m^3. The H_α signals measured at two different toroidal positions showed similar behavior in this experiment. From this observation, we assume the toroidal uniformity of neutral particle behavior and use one H_α signal in the analysis below. LHD is equipped with the 10 sets of magnetic coils located at every upper and lower port [1]. The magnetic field generated by these coils interferes in the main helical magnetic field and is able to control the width of the magnetic island ($m/n = 1/1$ or $2/1$, where m and n are the poloidal and toroidal mode number). Without using these coils, there naturally exists the $m/n = 1/1$ magnetic island in LHD. The $m/n = 1/1$ magnetic island is located around $\rho \sim 0.9$, where $\rho = r/a$ is the normalized minor radius [1,13].

In this study, five discharges from the series of the density ramp-up experiment are selected to examine Eq. (2) and estimate α. These five discharges consist of the plasmas heated by different P_{NB} with the natural/cancelled/extended magnetic island of $m/n = 1/1$. Typical parameters of the five discharges are summarized in Table 1. An example of the influence of the magnetic island on the plasma performance can be seen in the table; i.e. the maximum of W_p^{dia} is smaller in the shot with the extended magnetic island (#28189) than in the shot with the cancelled magnetic island (#28179), although the other parameters such as P_{NB} and the line-averaged electron density, $\bar{n}_e$, are similar in both shots. Waveforms from the one of the five discharges are

Table 1
Summary of the typical parameters of the five discharges selected to estimate the fueling efficiency

Experimental condition	Shot number				
	#28163	#28166	#28178	#28179	#28189
R_{ax} (m)	3.6	←	←	←	←
B_0 (T)	2.8	←	←	←	←
Magnetic island	Natural	←	Canceled	←	Extended
$(P_{NB})_{max}$ (MW)	3.5	5.0	4.7	4.7	4.7
$(\overline{n}_e)_{max}$ (10^{19} m^{-3})	5.2	5.9	4.5	5.2	5.2
$(W_p^{dia})_{max}$ (kJ)	535	661	606	606	526

$(P_{NB})_{max}$, $(\overline{n}_e)_{max}$, and $(W_p^{dia})_{max}$ are the maximum of P_{NB}, $\overline{n}_e$, and W_p^{dia}, respectively. The arrow (←) denotes that the experimental condition is identical to the left column.

shown in Fig. 1. The density feedback starts at 1 s, where $\overline{n}_e$ is $\sim 2 \times 10^{19}$ m^{-3}. Then the density is increased to $\sim 5 \times 10^{19}$ m^{-3} during 1.5–3 s, by the feedback control of Φ_{puff}. This ramp up phase is indicated as 'Phase I', in Fig. 1. After the density reaches to $\sim 5 \times 10^{19}$ m^{-3}, Φ_{puff} is reduced at 3–4 s. This phase is indicated as 'Phase II'. This ramp up scheme is also used in the other four discharges. Therefore the Phase I and the Phase II correspond to the same times in all of the five shots, in the discussion below.

4. Discussion

As can be seen in Fig. 1, $N_e' = dN_e/dt$ well correlates with Φ_{puff} during Phase II, while these are not correlated during Phase I. Instead, Φ_{puff} and Γ_{div} show similar increase during the Phase I. This suggests that the criterion of Eq. (3) is not satisfied here, and Eq. (2) is not adequate to estimate α. The H_α signal also increases with Φ_{puff} during the Phase I, suggesting Eq. (4) is not satisfied in this phase. Although it is natural that $\overline{n}_e$ increases with Φ_{puff} during the Phase I, the constant nature of the τ_E^{dia} suggests the violation of Eq. (6) at this phase. The linear correlation between Φ_{puff} and the reference parameters (N_e', Γ_{div}, H_α, Φ_{NB}, and N_e/τ_E^{dia}) is calculated to estimate α with Eq. (2), while confirming the four criteria of Eqs. (3)–(6). Here, we investigate two ensembles of the data from Phase I and Phase II of the five discharges. Note that this ensemble method is suitable to find out the robust correlation. For instance, a large correlation factor can be obtained between any two irrevelent parameters of a discharge, only if these two are monotonically changing in time. In the data ensemble composed from several discharges with different experimental conditions, such a feigned correlation tends to disappear. The linear correlation coefficient, R_c, is summarized in Table 2. At the Phase I, the linear correlation between Φ_{puff} and N_e' is weak and it is not possible to estimate α with Eq. (2). At the same phase, strong correlation between Φ_{puff} and H_α (or N_e/τ_E^{dia}) is observed, which indicates the violation of Eq. (4) (or Eq. (6)). Furthermore, there is a possibility that R_{div} is changing since the electron temperature at the divertor, T_e^{div} is decreasing during Phase I (see Fig. 1). As for the Phase II, on the other hand, there recognized is a strong correlation of $R_c = 0.95$ between Φ_{puff} and N_e'. Meanwhile, other reference parameters indicate small linear correlation factors of less than 0.3, which assure the criteria of Eqs. (3)–(6). These results support the validity of applying Eq. (2) for the data from the Phase II. The relation between Φ_{puff} and N_e' is shown in Fig. 2. The least square fit of N_e' with Φ_{puff} gives the linear equation below;

$$N_e' = 0.12 \times \Phi_{puff} - 12, \quad (8)$$

where the unit is 10^{19}/s. Comparing Eq. (8) with Eq. (1) (or, Eq. (2)), the fueling efficiency is obtained from the slope of Eq. (8); i.e. $\alpha = 0.12$. The offset of Eq. (8) (= 12) corresponds to the sum of the other terms than $\alpha\Phi_{puff}$ in the right-hand-side of Eq. (1).

As seen in Fig. 2, all of the five discharges have similar slopes as Eq. (8), although the offsets are different. The slopes (offsets) individually calculated for the five discharges at Phase II are; 0.12 (−8.3), 0.13 (−16), 0.11 (−12), 0.10 (−8.3) and 0.14 (−21), for #28163, #28166, #28178, #28179, and #28189, respectively. Note that the slopes calculated individually are identical to that of Eq. (8) within 20%. This suggests that α is insensitive to the heating power or the existence of the magnetic island, within the experimental conditions studied here. The fueling efficiency of about 10% obtained here is similar to that obtained in diverted tokamaks [9], although the estimation method is different. As for the offsets, it seems to change according to the experimental condition. Recycling is one of the most important keys to understand this. Therefore, the neutral particle behavior is an urgent subject to be clarified.

Where does the residual gas, which corresponds to nearly 90% of the fueled gas, disappear? In LHD, typical order of the neutral pressure during the NB heated discharge is 10^{-3} Pa [14], and is much smaller than that expected from the total gas puff flux (of 10–100 Pa m^3)

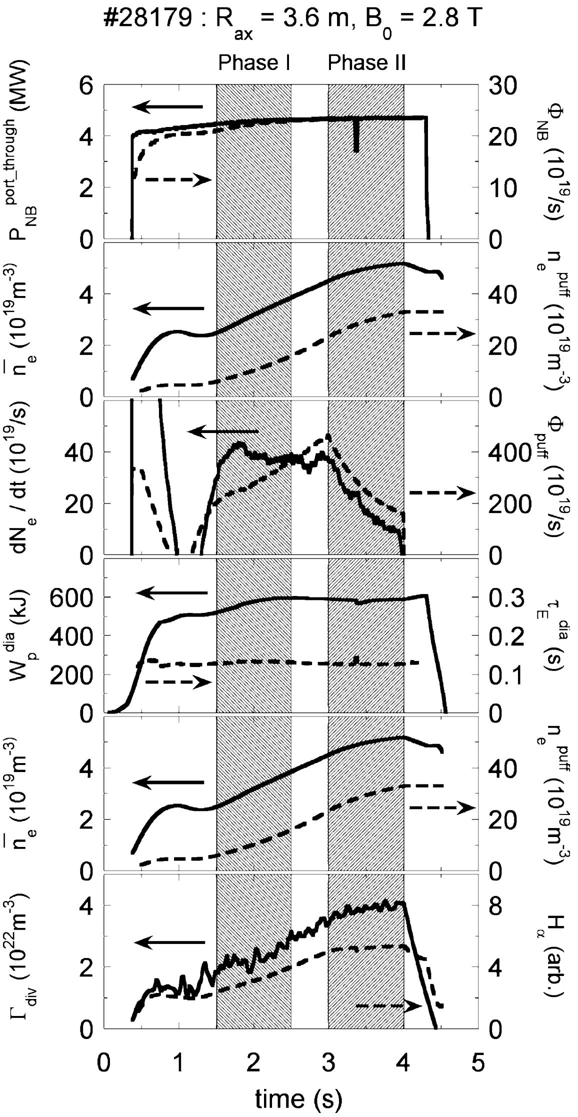

Fig. 1. Waveforms of typical parameters in the density ramp up discharge of #28179. Depicted from the top to the bottom are; the port through power of NB, $P_{NB}^{port\_through}$ and Φ_{NB}; $\bar{n}_e$ and the electron density calculated from the integrated particle number supplied by gas puffing with assumption of 100% efficiency, n_e^{puff}; $N_e' = dN_e/dt$ and Φ_{puff}; W_p^{dia} and τ_E^{dia}; n_e^{div} and T_e^{div} measured by the electrostatic probes on the divertor tile; Γ_{div} and H_α signal. The density ramp up phase and the latter phase are hatched and denoted as Phase I and Phase II, respectively.

and the volume of the vacuum vessel (of 210 m^3). The maximum pumping speed of the LHD vacuum system is less than 200 m^3/s [14], and the resultant exhaust flux is also smaller than the gas puff flux. One of the possible scenarios to answer this is that the residual gas is absorbed in the plasma facing materials, such as the divertor tiles and the first wall of the vacuum vessel. This

Table 2
Linear correlation coefficients R_c between Φ_{puff} and the reference parameters (N_e', Γ_{div}, H_α, Φ_{NB}, and N_e/τ_E^{dia}), at Phase I and Phase II

Reference parameter	R_c	
	Phase I	Phase II
N_e'	0.49	0.95
Γ_{div}	0.53	0.17
H_α	0.80	0.24
Φ_{NB}	0.51	0.20
N_e/τ_E^{dia}	0.91	0.08

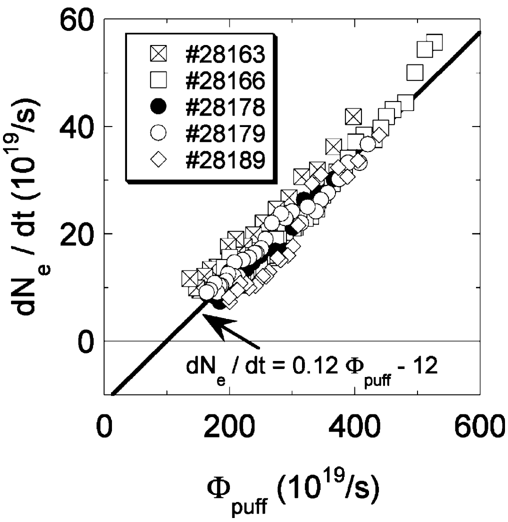

Fig. 2. Relation between Φ_{puff} and $N_e' = dN_e/dt$. Shown are the data from the Phase II of five discharges with different experimental conditions. Solid line is the least square fit of the data ensemble (Eq. (8)).

scenario predicts the saturation in the gas absorption ability of the plasma facing materials. Whether the fueling efficiency and the recycling coefficients will change in such a situation should be investigated before constructing the nuclear fusion reactor.

5. Conclusions

The fueling efficiency of the hydrogen gas puffing has been estimated for the NB heated plasmas in LHD. A simple particle balance model together with the criteria to examine the applicability of the model was used for the estimation. Five discharges were chosen from the series of density ramp up experiment, to apply the model. The latter phase of the discharges satisfied the criteria, whereas the ramp up phase was not adequate to estimate the fueling efficiency. The fueling efficiency of 0.12 has been obtained from the data ensemble at the latter phase of the five discharges. It was also suggested that this fueling efficiency of about 10% is not sensitive to the NB heating power or the existence of the magnetic island.

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