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Long-duration sustainability of pellet fueled high performance plasma

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Introduction

Our previous study indicates that the pellet fueling has transiently extended the operational region of the Large Helical Device (LHD) to higher densities while maintaining the favorable dependence of the energy confinement on the density[1]. What seem to be lacking, however, is a scenario of steady state operation, which is absolutely essential in future reactor. If the advantages of the pellet fueling are demonstrated in steady state operation, it will offer significant advantage for a fusion reactor.

Although one of the most important aims of the pellet injection is to provide particles in the core plasma, it is not to be denied that even high-velocity pellet cannot penetrate to the plasma center in high-temperature fusion plasma from a view point of the pellet ablation theory. An epoch-making improvement of the effective pellet penetration length due to high field side pellet injection is observed in tokamak experiments[2] and this is very promising method for core fueling. On the other hand, such improvements cannot be expected in helical device because of the difference of the confinement field structure[5], i.e. large $\iota/2\pi$ and large helical ripple. Even if the pellet can penetrate to plasma center, it cause temperature drop and it should affect the fusion reaction in burning plasma. A moderate pellet penetration is, therefore, feasible and rather favorable solution in terms of steady state refueling for burning plasma.

For the purpose of investigating fueling issues towards the steady state operation, we have been launched pellet refueling experiment on LHD by using the repetitive pellet injector[3, 4]. We have been performed long duration discharge with newly-installed pellet injection timing control system, which is capable of controlling a plasma density in real time. This paper explores the confinement property and sustainability of pellet refueled plasma.

Experimental set-up

The pellet injector is based on a pipe-gun accelerator with a screw-extruder, which is capable of continuous solidification and extrusion of a 3 mmϕ solid hydrogen rod at a rate of up to 50 mm/s. The pellet is formed by in-situ cutting from the solid hydrogen rod. Maximum pellet size is 3 mm$\phi \times$3mmϕ and the pellet size is variable by changing the ratio of the solid hydrogen extruding speed to the cutting frequency. In order to prevent disturbance in a plasma center due to a deep fueling, we employ relatively small and slow pellets for the shallow pellet mass deposition. The mass and velocity of the pellet are maximum 8×10^{20} atoms and 350 m/s, respectively. The density rise; $\Delta\bar{n}_e$ per pellet is 2.0×10^{19} m^{-3} and the normalized pellet penetration depth, which is estimated by an neutral gas shielding model, is typically 0.5. The pellets are injected into the neutral beam heated (1.2 - 7 MW, 6 - 30 s) LHD plasmas from the outboard side midplane. The pellet injection timing is automatically controlled in real time to keep desired line averaged electron density at the timing of just before pellet injection by comparing reference value and measured line averaged electron density signal.

Results and Disccusion

Figure 1 shows temporal evolution in a repetitive pellet refueling discharge. Pellets were continuously injected from $t = 0.4$ s with and only pellet injection was employed to build-up plasma density. The reference value of line averaged electron density ($\bar{n}_e$) was set to 0.7×10^{20} m^{-3} during discharge. At the build-up phase ($t < 0.2$ s), pellet was injected with maximum frequency, 10 Hz. After reaching 0.7×10^{20} m^{-3}, the pellet injection interval has gotten longer (0.6 – 0.7 S) to keep 0.7×10^{20} m^{-3} at the pellet injection timing. The important point to note is that the local measurements at plasma center such as $T_e(0)$, $T_i(0)$ and $n_e(0)$, and the plasma stored energy, W_p are maintained virtually constant in spite of pellet sequence. This quasi-stationary phase can be continued until the end of the neutral beam heating ($t = 10.3$ s).

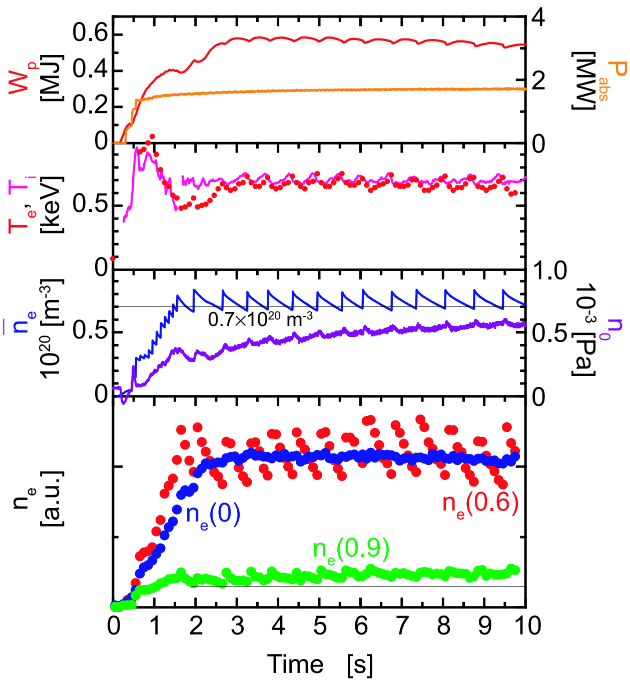

Figure 1: The temporal evolution of the key parameters in a repetitive pellet refueled discharge. The pellet firing interval is automatically controlled in real time to keep 0.7×10^{20} m^{-3} at the pellet injection timing.

The electron density profiles just before and after pellet injection at $t = 6.158$ s and difference between these profiles (Δn_e) are shown in Figure 2 (a). The pellet is ablated until about half radius and an obvious hollow density profile, which have density peak at $\rho = 0.6$, is formed just

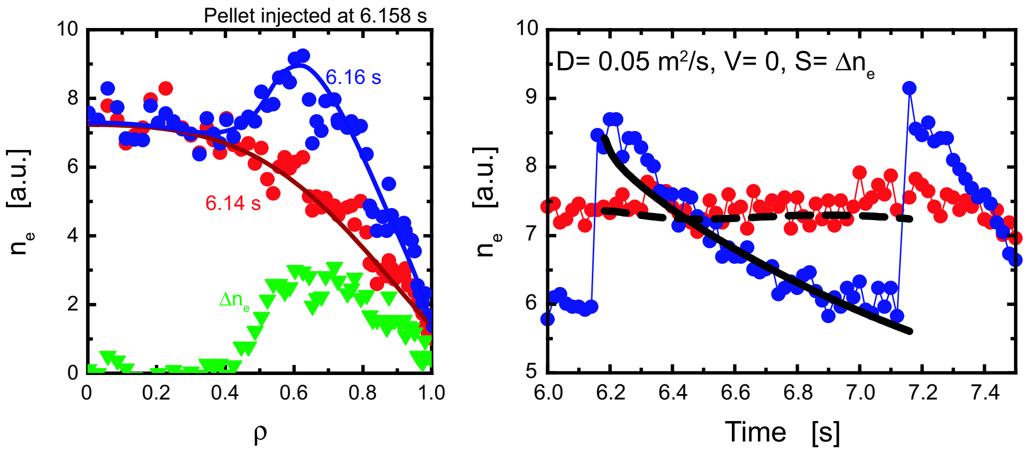

Figure 2: Comparison between measurement and simple diffusion calculation. The circles and lines denote the measurements and calculation results, respectively. (a)Measured and calculated density profiles change in the density profile relaxation phase after pellet injection. (b)Local electron density evolution at $\rho = 0$ and $\rho = 0.6$.

after pellet injection. The hollow profile is gradually relaxed and returns back to the original profile. Even in the density profile relaxation phase after pellet injection, the central density $n_e(0)$ is maintained virtually constant in spite of significant changes of the $n_e(0.6)$ as shown in Figure 2 (b).

In order to estimate the diffusion coefficient, these density profile change was fitted using following equation.

$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma) + S = -\frac{1}{r}\frac{\partial}{\partial r}\left(r(-D\frac{\partial n}{\partial r} + nV)\right) + S \approx D\frac{\partial^2 n}{\partial r^2} + \frac{D}{r}\frac{\partial n}{\partial r} + S$$

The assumptions made in the above derivation are that the particle source, S is defined as Δn_e, convection velocity, V is negligible small and diffusion coefficient D is constant in terms of time and radial distribution. Assuming $D = 0.05\ \mathrm{m}^2/\mathrm{s}$, the calculated density change adequately corresponds with the measurements as shown by solid lines in Figure 2 (b). Thus we see that the inward diffusion due to inversed density gradient supply particle constantly to the plasma center suppressing a density perturbation in the core region despite a lack of inward pinch velocity. And constant central density; $n_e(0)$ is sustained quasi-stationary during pellet sequence. Since drastic improvement of the pellet penetration length due to high field side pellet injection, which is expected to provide a pellet mass to the high-temperature core plasma in tokamaks, cannot be expected in helical device because of the difference of the confinement field structure[5], the inversed density gradient induced core fueling is promising in a helical reactor.

In these repetitive pellets refueled discharge, a confinement index, which is normalized by International Stellarator Scaling (ISS95), is 1.4 despite the high density operation. The confinement property is equal to peaked density profile plasma, which is transiently attained by deep pellet penetration experiments.

However, we should not overlook that the increase of pellet firing interval, which is necessary to keep constant density, due to increase of the density decay time, τ_{decay} after pellet ablation, which is obtained by curve fitting with an exponential function, $Ce^{-t/\tau_{decay}}$, as shown in Figure 3. This tendency is caused by increase of boundary density while keeping constant line averaged electron density during quasi-stationary phase as shown by $n_e(0.9)$ in Figure 1 and it have liner correlation with neutral density (n_0). Another point to observe is that the plasma stored energy, W_p is gradually continued decline with increasing the boundary density and neutral density. It is speculated that the plasma stored energy, namely, plasma confinement property is respond to neutral pressure through the boundary plasma density.

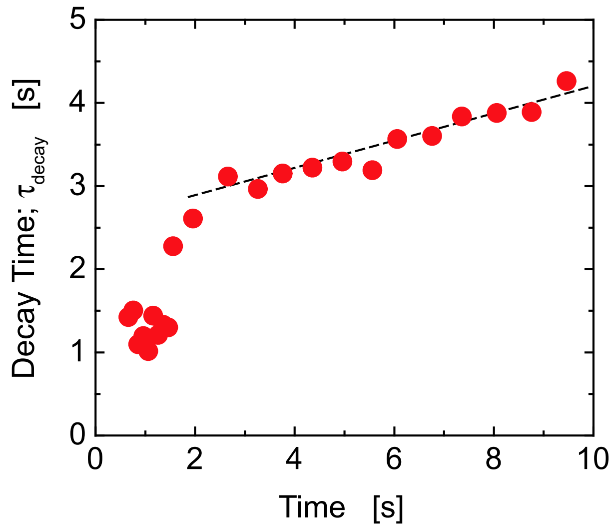

Figure 3: The change of density decay time in the density profile relaxation phase after pellet injection.

Acknowledgements

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