Pellet Injection and Internal Diffusion Barrier Formation in Large Helical Device

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(Received 21 August 2007 / Accepted 22 October 2007)

A high density internal diffusion barrier has been produced in the intrinsic helical divertor configuration in LHD by optimizing the pellet fueling scenario and magnetic configuration. The internal diffusion barrier easily appears in the outer shifted magnetic configuration in which magneto-hydrodynamic stability properties are considered to be favorable. The attainable central plasma density becomes higher as the magnetic axis shifts outward and the central density exceed $5 \times 10^{20}\,\mathrm{m}^{-3}$. Central pressure exceeds 130 kPa and, therefore, very large Shafranov shift is observed, even at high magnetic field ($B_t > 2.54\,\mathrm{T}$).

Keywords: stellarator, internal diffusion barrier, pellet fueling, divertor, magnetic configuration

DOI: 10.1585/pfr.2.047

Confinement improvement is one of the most important issues of magnetic confined fusion plasma research. The internal diffusion barrier (IDB) which enables core plasma to access high-density/high-pressure regime has been found in pellet fueled high density discharges with an active pumped local island divertor (LID) configuration in Large Helical Device (LHD) [1]. The IDB is similar to pellet enhanced performance (PEP) mode, which is first found in JET [2] then in the other tokamaks [3, 4], on the point that both lead to strongly peaked pressure profile. On the other hand, unlike the tokamak PEP mode, there is no clear indication of increase in the temperature gradient and inward particle convection in IDB. Although the LID configuration has efficient pumping due to the localized installation, heat removal is problem for the same reason with the present LID design. Therefore, IDB formation in intrinsic helical divertor configuration which has about 50 times larger heat receiving area than LID configuration is highly desired from a standpoint of compatibility with a fusion reactor. An experimental study has been performed in order to explore the operational space of the IDB discharge with the intrinsic helical divertor configuration in LHD.

LHD is a heliotron type full superconducting stellarator and is equipped with a pair of continuously wound helical coils and three pairs of poloidal coils. The plasma major radius at zero beta is variable in the range of 3.5 m to 4.0 m, the averaged plasma minor radius is ~ 0.6 m and the magnetic field strength is ≤ 3 T [5].

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Typical plasma profiles of the gas-puff and pellet fueled discharges at the same magnetic configuration $R_{ax} = 3.75$ m in the same line integrated density $n_e l = 3 \times 10^{20}\,\mathrm{m}^{-2}$ are shown in Fig. 1. The normalized minor radius ρ is expressed as flux coordinate, namely, $\rho = \sqrt{\Phi}$ where Φ is the toroidal flux function, which is normalized by the value of the last closed flux surface. The negative and positive ρ value indicate inboard and outboard side of the plasma, respectively. Since particle source is limited to peripheral for the gas-puff fueling, the density profile typically becomes flat or slightly hollow. In the case of the pellet fueling, the IDB which has a steep density gradient inside $\rho = 0.55$ is formed and the central density is remarkably increased while peripheral density is reduced. A noteworthy finding is that the electron temperature of the pellet fueled plasma is higher in spite of the fact that the central density is more than double. The plasma pressure profile calculated assuming the ion temperature profile is the same as measured electron temperature profile, shows an obvious increase of the plasma energy density in the core region ($\rho < 0.55$). The attainable central pressure of the pellet fueled plasma is about four times larger than that of the gas-puff fueled plasma, even exceeding atmospheric pressure.

The global energy confinement time reaches a maximum in inward shifted magnetic configurations ($R_{ax} = 3.60 - 3.65$ m which give a maximum plasma volume) by employing pellet fueling [6]. The IDB, on the other hand, is easy to be produced in outward shifted magnetic configurations ($R_{ax} > 3.7$ m). One characteristic difference

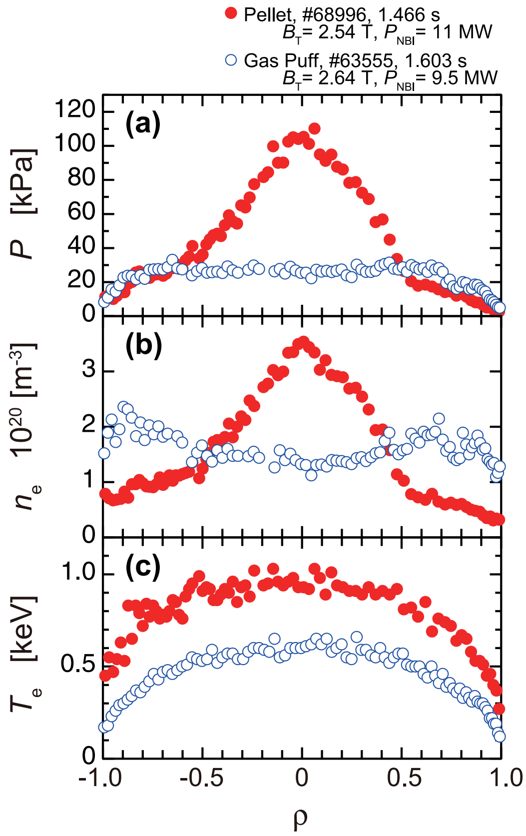

Fig. 1 Comparison of (a) plasma pressure, (b) electron density and (c) electron temperature in the gas-puff (blue open circle) and pellet (red filled circle) fueled discharges at the same magnetic configuration R_{ax} = 3.75 m.

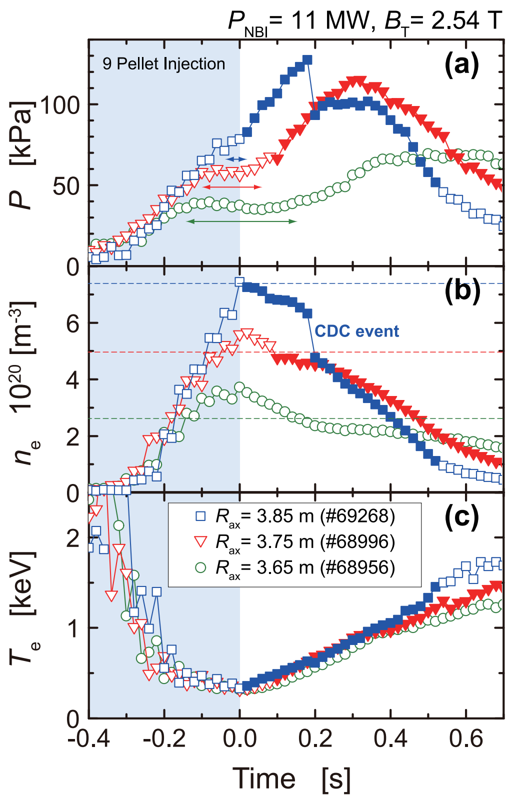

Fig. 2 The temporal evolution of (a) plasma pressure, (b) electron density and (c) electron temperature in nine-pellets fueled discharges at magnetic axes R_{ax} = 3.65 m (green circle), 3.75 m (red triangle) and 3.85 m (blue square). The magnetic field strength and NB heating power are 2.54 T and 11 MW, respectively. Filled symbols denote the formation of IDB.

between the two configurations is magneto-hydrodynamic stability properties, considered to be favorable as the magnetic axis shifts outward [7] because the region with magnetic well is wide, especially at finite β. It is also important that the poloidal distribution of a divertor flux changes with magnetic configurations [8]. The divertor flux tends to concentrate on the inboard side and this leads to a localized increase of neutral pressure due to recycling in the inward shifted magnetic configurations. This situation is estimated to cause a peripheral density rise which is incompatible with the core fueling. Contrary to this, the divertor flux tends to spread uniformly poloidally in the outward shifted magnetic configurations and this behavior leads to suppression of peripheral particle source. This situation is expected to compensate the lack of pumping capacity at helical divertor.

Figure 2 shows the temporal evolution of characteristic plasma parameters in several nine-pellet fueled discharges at magnetic axes R_{ax} = 3.65 m, 3.75 m and 3.85 m. Let timing of the final pellet injection be t = 0. In each cases, NB heating power and magnetic strength are 11 MW and 2.54 T, respectively. The IDB formation period is denoted by filled symbol. It is difficult to define onset and termination timing of the IDB regime because the IDB profile gradually changes in time. The IDB is temporarily defined by existence of a clear bend in the density profile. While the same number of pellets were injected, attainable central plasma density becomes higher as the magnetic axis shifts outward and the maximum central density at R_{ax} = 3.85 m is doubled compare to the density at R_{ax} = 3.65 m. At the same time, the central temperature follows quite a similar course after pellet injection although central density varies widely depending on magnetic configuration. As the result, higher central pressure is attainable in the outward shifted magnetic configurations where the IDB is formed. The point to observe is that there is a plateau of the pressure rise in the high density phase as shown by two-headed arrows in Fig. 2 (a). The plateau begins to appear during the pellet injection phase, namely density increase phase, and continues until the excess density drops to the onset level. This phenomena indicate confinement degradation in high density regime. As the magnetic axis shifts outward, the onset density level increases as indicated by broken line in Fig. 2 (b), namely 2.7×10^{20} m^{-3} at R_{ax} = 3.65 m and 5.0×10^{20} m^{-3} at R_{ax} = 3.75 m, and duration of the plateau becomes shorter. Finally the plateau of the pressure rise is hardly observed at R_{ax} = 3.85 m and the pressure is in-

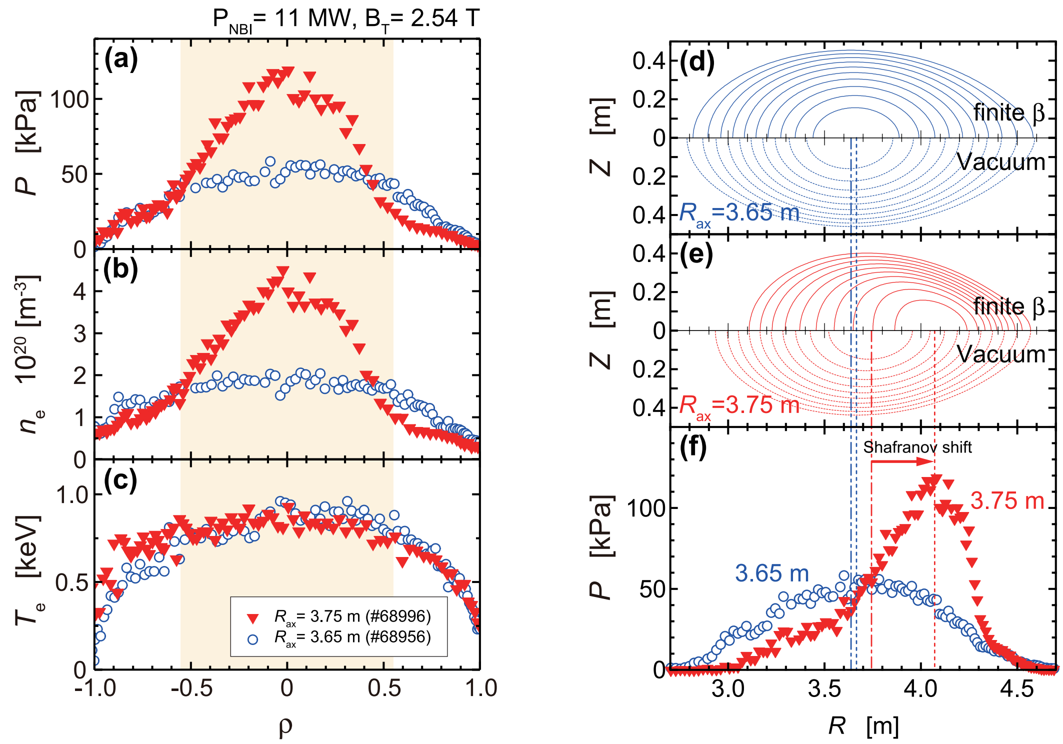

Fig. 3 Comparison of (a) plasma pressure, (b) electron density and (c) electron temperature between R_{ax} = 3.65 m (blue open circle) and 3.75 m (red filled triangle) at the timing of $T_e(0)$ = 1 keV. The magnetic field strength and NB heating power are 2.54 T and 11 MW, respectively. Hatching denotes IDB formation region (ρ = 0.55). (f) Comparison of pressure profiles in a real space coordinate. Very large Shafranov shift over half radius is observed in the case of R_{ax} = 3.75 m. Flux surface in vacuum and equilibrium configuration at (d) R_{ax} = 3.65 m and (e) R_{ax} = 3.75 m, respectively.

creased in a linear fashion during and after pellet injection. After that, the pressure and density decrease suddenly at t = 0.18 s, while any noticeable changes are not observed in the temperature. This unexpected event is referred to as core density collapse (CDC) and will be discussed later. It must be also noted that the final density levels out after the disappearance of the IDB. The final density becomes lower as the magnetic axis shifts outward, contrary to the IDB phase, and this observation supports a reduced recycling in the outward shift configurations.

Figure 3 shows a comparison of plasma profiles between R_{ax} = 3.65 m and 3.75 m at the timing of $T_e(0)$ = 1 keV. Density profiles of the two configurations are quite different even though the temperature profiles are identical. For R_{ax} = 3.65 m, the density profile has a parabolic shape. On the other hand, the IDB with steep density gradient is formed on the inside of ρ = 0.55 and central density reached to almost double in the case of R_{ax} = 3.75 m. The plasma β becomes high even though the magnetic field is high (B_t > 2.54 T) and thus the plasma profiles suffer very large Shafranov shift ($\Delta/a_{eff} \sim 1/2$) as shown in Fig. 3 (f). Thus magnetic configuration is another factor of the IDB formation in addition to pellet core fueling.

The magnetic axis dependence of the IDB plasmas is summarized in Fig. 4. Attainable central density becomes higher as the magnetic axis shifts outward and the central density exceeds 5×10^{20} m^{-3}. The point to observe is that there is a sharp increase in central density and pressure around R_{ax} = 3.7 m and central pressure reach its greatest value, ~ 130 kPa, at the neighborhood of R_{ax} = 3.85 m. The maximum central pressure is limited by the CDC event as shown in Fig. 2. In the CDC event, the high density core plasma is expelled on the sub millisecond time scale without having any impact on temperature profile. The CDC event is typically observed in the high performance discharges with IDB and it may be involved with MHD instability and/or equilibrium arising from very large Shafranov shift. It has been revealed that the CDC event can be mitigated by suppression of Shafranov shift with ellipticity κ control of the magnetic configuration and the attainable central pressure goes up to 20% by vertical elongation (large κ).

An experimental study is performed to explore the operational space of a high density plasmas due to the IDB which was originally found in pellet fueled high density discharges with the active pumped LID configuration in LHD. The IDB with steep density gradient has been produced at an intrinsic helical divertor configuration as in LID configration by optimizing the pellet fueling and magnetic configuration. Core fueling by multiple pellet injection is essential for the IDB formation and the IDB easily appears in the outer shifted magnetic configuration

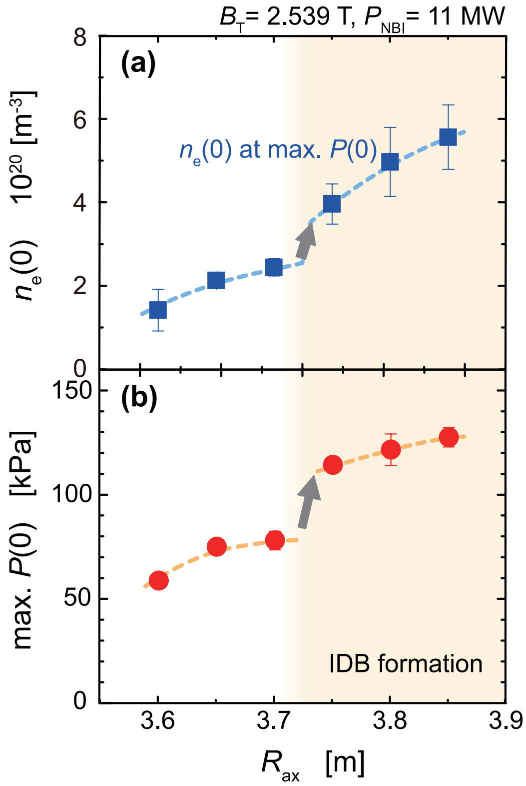

Fig. 4 Configuration dependence of (a) central electron density at the instant of maximum central pressure and (b) maximum central pressure. The magnetic field strength and NB heating power are 2.54 T and 11 MW, respectively.

(R_{ax} > 3.7 m). The mechanism of the CDC event which restricts the pressure increase has not been thoroughly explained. This warrants future work on the mitigation and full control of the CDC event. In addition to this, investigation of long-duration sustainability of the pellet fueled IDB is critically important from a perspective of extrapolation to fusion reactor scenario. Nonetheless, the IDB is an encouraging finding and it demonstrates the potential for alternative path to high-density/low-temperature fusion reactor in helical devices.

This work is supported by NIFS06ULPP521.

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