Temporal evolution of particle transport of Super Dense Core plasma in LHD

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Abstract. A highly peaked density profile was obtained in pellet-injected discharges in LHD. The peaking factor, which is the ratio of the central to volume-averaged densities, increased from around 0.8 in the gas puff fuelled phase, up to more than 2.0 after multiple pellet injection. The core density reached to several times 10^{20}m^{-3}. Temporal changes of density profiles were measured using a CO_2 laser imaging interferometer. The change of the particle flux was estimated from temporal variations of measured density profiles. The diffusion coefficient (D) and the convection velocity (V) were then obtained from temporal traces of the relationship between the normalized density gradient and the normalized particle flux. Thus-obtained diffusion coefficients increased monotonically toward the plasma edge, while the convection velocity was inwardly directed. These observations are clearly different from those in the low collision regime, where D was spatially almost constant and V was outwardly directed. Three different regimes of particle transport were identified after the pellet injection. The first phase is characterized by a constant density peaking just after the pellet injection. In this phase, negative slopes between the normalized particle flux and the normalized density gradient were found, implying that D and V could not be determined. The second phase is at an additional density peaking, where the normalized particle flux increased with an increase in the normalized density gradient. In this phase, the core diffusion coefficient (ρ < 0.6) was reduced compared with that before the pellet injection, and an inwardly directed pinch was observed. The third phase is with the density broadening, where the normalized particle flux was reduced with a decrease in the normalized density gradient. Here, the core diffusion coefficients were further reduced, and the core pinch velocity (ρ < 0.8) became close to zero. The transition from the first (the constant peaking phase) to the second phase (the additional peaking phase) occurred almost simultaneously in the entire region of the plasma, while the transition from the second to third phase (the broadening phase) occurred from the outer region to the inner region of the plasma. The collisionality dependence of D and V at ρ = 0.4-0.7 was studied in the wide range of collisionality (ν_b = 0.3-30) from density modulation experiments and the SDC analysis. A minimum value of D was likely to exist in the plateau regime (ν_b = 1-5) together with almost zero convection velocity. This may be favourable for future high density reactor operations of the heliotron reactor.
1. Introduction

Large Helical Device (LHD) is a superconducting heliotron. The aim of the LHD project is to demonstrate scientific feasibility of helical reactors and also to provide comprehensive understanding of toroidal plasmas from comparison between heliotron and tokamak plasma behavior. One of the big advantages of LHD is good capability of steady state operation and of performance at high density. There is no operational limit in density like the Greenwald density limit in tokamaks, as the density limit in LHD is determined by the balance of input power and radiation loss. Recently, an extremely high density (~several times of $10^{20}$ m$^{-3}$) was achieved by multiple pellet-injection with local island divertor [1]. This extreme high density shot is called “Super Dense Core (SDC)” plasma. The magnetic configuration and discharge condition were optimized to achieve as high density as possible [2,3]. SDC plasma suggests a possibility of a high density (~$5 \times 10^{20}$ m$^{-3}$) and moderate temperature (~5 keV) fusion reactor scenario. However, details of particle transport characteristics have not yet been understood. In this article, particle transport of SDC was quantitatively studied from the temporal evolution of density profiles for the first time.

2. Experimental results

2.1 Temporal behavior of SDC plasma

Figure 1 shows temporal behavior of electron temperature and density. Here, the plasma was produced by 82.7, 84 and 168 GHz ECH at $t = 0.15$–0.67 sec then additionally heated by 3.6 MW co-injected and 6.7 MW counter-injected NBI at $t = 0.3$–2.17 sec. The magnetic configuration was the so-called standard configuration, where the magnetic axis position ($R_{ax}$) was at 3.75 m and the toroidal magnetic field at the magnetic axis was 2.64 T.

Electron temperature profiles were measured using YAG Thomson scattering [4] and electron density profiles were measured using a 65-channel CO$_2$ laser imaging interferometer [5,6]. The CO$_2$ laser imaging interferometer covered from the plasma center to the plasma boundary. The spacing between channel chords were 7.5 mm [6]. Both profiles are a function of magnetic flux surfaces.

![Figure 1](image-url)

**Figure 1.** Temporal histories of (a) central electron temperature ($T_{e}(0)$), volume-averaged electron temperature $<T_{e}>$ and the peaking factor, (b) contours of equi-electron temperatures in a flux surface coordinate ($T_{e}(\rho)$), (c) central electron density ($N_{e}(0)$) and volume-averaged electron density $<N_{e}>$, and (d) contours of equi-electron densities in a flux surface coordinate ($N_{e}(\rho)$).
The magnetic flux was determined from the data base of equilibrium configurations calculated using the VMEC code [7]. In the magnetic flux coordinate used in the VMEC equilibrium calculation, the position of a flux surface was indicated by $\rho$. The value of $\rho$ was defined as the square root of the ratio of a surface inside a particular toroidal flux against that of the last closed flux surface (LCFS). The value of $\rho$ was approximately equal to the ratio of averaged radius of each flux to that of LCFS. The appropriate flux surface was selected from the Abel inversion of measured density profiles along laser chords, using least square fitting with regularization [6]. The procedure was carried out so as to minimize the discrepancy between measured line densities and line densities calculated by integration of reconstructed radial density profiles. The radial density was calculated every 10 msec. Thomson scattering data were obtained using four different lasers having repetition rates of 20 msec and 100 msec. $T_e$ profiles obtained using Thomson scattering were converted into flux surface coordinates obtained as was described above. Then, $T_e$ profiles were fitted with the 8th order polynomial function and temporarily interpolated at interferometer measurement times in order to compare $T_e$ (from Thomson scattering) and $N_e$ (from interferometer) profiles. The volume-averaged density was calculated inside LCFS. The peaking factors of $T_e$ and $N_e$ were defined as the ratio of the central value at $\rho = 0$ against the volume-averaged value.

The time history of density profiles is characterized by three different phases (phase (1), (2) and (3)) after pellet-injection which are separated by dashed lines in figure 1, where the phases were defined when the peaking factors changed. The phase (1) ($t = 1.3$–1.5 sec) is the constant peaking phase after the final pellet-injection. The central and volume-averaged densities both decreased resulting in keeping almost the same ratio, while electron temperature profiles started peaking. The phase (2) ($t = 1.5$–1.8 sec) is the additional peaking phase, where the density peaking factor increased again without pellet-injection. The phase (3) ($t = 1.8$–2.17 sec) is the broadening phase, and the density peaking factor started to decrease.

Electron density and temperature profiles before pellet-injection and profiles at the transitions of three phases are shown in figure 2. A hollow density profiles was observed for the gas puff fueling phase [9,10]. This hollow density profile is an observation particularly in outwardly shifted configurations, where neoclassical transport becomes the larger. Experimentally estimated outward convection velocities were comparable with neoclassical values [10]. Peaked density profiles were observed with pellet-injected discharges as shown in figure 2 (c). Discrete changes of density gradients

![Figure 2](image-url)
were seen at $\rho = 0.6$ at $t = 1.8$ and 2.17 sec as shown in figure 2 (c). Changes of the peaking factor in the additional peaking and broadening phases are due to the change of density profiles at $\rho < 0.6$.

The observed dramatic variation of electron density profiles after the final pellet-injection indicates that particle transport changed temporally.

### 2.2 Analysis of particle transport

The equations of particle balance are

$$\frac{\partial N_e}{\partial t} = \nabla \cdot \Gamma + S = -\frac{1}{r} \frac{\partial}{\partial r} r \Gamma + S \tag{1}$$

$$\Gamma = -D \nabla N_e + N_e V \tag{2}$$

Here, $N_e$ is the local density, $\Gamma$ is the particle flux, $S$ is the particle source rate, and $r$ is the spatial coordinate and is an averaged-radius of each flux surface. For simplicity of analysis, a cylindrical coordinate was employed. In equation (2), $D$ is the diffusion coefficient and $V$ is the convection velocity. Equation (1) is rewritten as

$$\Gamma(r) = \frac{1}{r} \int_{0}^{r} \left( S - \frac{\partial N_e}{\partial t} \right) dr \tag{3}$$

Particle fueling is from external gas puffing, wall recycling, beam fueling, and pellets injection. Pellets ablate within several milliseconds, thus pellets do not contribute to further particle fueling after several milliseconds from the final pellet-injection. The neutral beam injection in the discharges analyzed in this article was based on the negative ion tangential injection with a beam energy of 180 kV. Even in the low density regime (having a line-averaged density of 1−2×10$^{19}$ m$^{-3}$), the particle source from 11 MW NBI, where deposition profile was centralized and was around 0.6×10$^{20}$/m$^{3}$s, does not contribute to the peaking of density profiles [9,10,12]. In SDC discharge, the effect of the beam fueling is much smaller because density is much higher. Although external gas fueling and recycling are difficult to estimate, both are localized close to the plasma boundary. According to the three dimensional Monte Carlo simulation in LHD [10,11,12], the particle source is localized around $\rho = 1.1$ and decreases by one order of magnitude at $\rho = 1.0$ when an electron density is near to 1.5×10$^{19}$ m$^{-3}$, and electron temperature is close to 250 eV at the same magnetic configuration. Therefore, it is reasonable to neglect particle source from gas fueling and wall recycling inside of LCFS ($\rho = 1.0$). Thus, the particle source rate $S$ in equation (3) was neglected in the analysis, and the particle flux was calculated from temporal evolution of density profiles.

Equation (2) can be re-written as follows.

$$\frac{\Gamma}{N_e} = -D \frac{\nabla N_e}{N_e} + V \tag{4}$$

The change of density profiles provides a data set of the relationship between $\Gamma/N_e$ and $\nabla N_e/N_e$. If the straight line is fitted to an experimentally obtained trace of equation (4), the diffusion coefficient can be obtained from the slope of the trace, and the convection velocity can be obtained from an offset of the fitted line.

The density profiles derived from the Abel inversion of CO$_2$ laser interferometer data and their temporal evolution were not smooth. For stable analysis, the temporal profiles of radial densities were fitted by two-dimensional spline curves using the least square approximation. The comparison of reconstructed density profiles and fitted profiles is shown in figure 3.
Figure 3. (a) Reconstructed radial density profiles (in black) and spline fitted profiles (in red), and (b) temporal traces of local densities from reconstructed profiles (in black) and from spline fitted data (in red). The data in (b) are of $\rho = 0.025$–1.025 ($\rho = 0.05$ step).

Figure 4 shows traces of $\Gamma/N_e$ versus $-\nabla N_e/N_e$ (see figure 1 (c) for the three different phases). Data were obtained every 10 msec from $t = 1.3$ sec, namely just after the final pellet-injection, to $t = 2.17$ sec, namely the time of the NBI switch off. Shapes of traces vary depending on the radial location as is shown in figure 4. Temporally, the normalized particle flux went from high values, reaching minima to further maxima. The gradients and offset values of the traces between $\Gamma/N_e$ versus $\nabla N_e/N_e$ changed before and after maxima and minima of normalized fluxes. These times are when particle transport changed, and we call these times as “transition times” of particle transport. The minima and maxima of $\Gamma/N_e$ correspond to the first and second transitions, respectively.

As stated previously regarding to figure 1, three different phases (from $t = 1.3$ sec until the first transition, from the first to the second transition and from the second transition until $t = 2.17$ sec) were observed. The important point is that the transitions depend on radial locations. Figure 5 shows the spatio-temporal changes of the transitions. The first transition began almost simultaneously in the whole region, while the second transition started from the edge and moved to the core.

The data before the first transition (the constant peaking phase) is marked in green in figure 4. During this time period, the traces show negative derivatives and diffusion coefficients cannot be defined.

Figure 4. Experimentally obtained traces between $\Gamma/N_e$ and $-\nabla N_e/N_e$, at (a) $\rho = 0.25$, (b) $\rho = 0.5$, and (c) $\rho = 0.75$. Colored symbols are from spline fitted profiles, while black crosses are from reconstructed profiles without spline fitting.
The data between the first and the second transitions (the additional peaking phase) are marked in red in figure 4. The most of the data points showed positive slope at $\rho = 0.25$ and 0.50 as shown in figures 4 (a) and (b). At $\rho = 0.5$, the slope deviates from a straight line and follows a curved line. This indicates that the diffusion coefficient and the convection velocity changed in time. On the other hand, it is difficult to determine any positive gradient at $\rho = 0.75$, thus the diffusion coefficient and the convection velocity cannot be defined during this period.

The data after the second transition (the broadening phase) is marked in blue in figure 4, and almost a straight line can be fitted. This indicates that the diffusion coefficient and the convection velocity were temporally constant.

The diffusion coefficient and the convection velocity were obtained between the first and second transitions (the additional peaking phase) and after the second transition (the broadening phase). The profiles of $D$ and $V$ thus obtained are shown in figure 6. Values of $D$ and $V$ were derived from fitted lines when correlation coefficients were larger than 0.5 and positive values of $D$ were obtainable.

**Figure 5.** Spatio-temporal changes of transition times. The red and blue lines indicate the first and the second transitions, respectively.

**Figure 6.** Profiles of (a) the diffusion coefficient ($D$) and (b) the convection velocity ($V$), obtained from density modulation experiments (black lines) and from the analysis of the SDC discharge after pellet-injection at time periods between the first and the second transition (red line) and after the second transition (blue line). Negative values of $V$ indicates an inwardly directed pinch. Dotted lines indicate ranges of uncertainty in the determination of $D$ and $V$ from density modulation experiments.
Although traces between \( \Gamma/N_e \) versus \( \nabla N_e / N_e \) were not constant at some locations, a linear line was fitted to determine representative values of \( D \) and \( V \).

The profiles of \( D \) and \( V \) from density modulation experiments are also plotted in black lines in figure 6. Electron temperature and density profiles at the density modulation experiments were almost the same as the ones just before the first pellet-injection (figures 2 (a) and (b)). The diffusion coefficient and the convection velocity were determined from the propagation of the modulated density and the density profile in an equilibrium state. The core and edge values of \( D \) and \( V \) were determined from the analysis. The analysis method was described in reference [12]. Because the profiles of \( D \) and \( V \) from the density modulation experiments represent \( D \) and \( V \) before the first pellet injection as stated above, we can argue the differences of \( D \) and \( V \) before and after pellet-injection.

As shown in figure 6, \( D \) and \( V \) profiles changed dramatically after the first transition (during the additional peaking phase) compared with \( D \) and \( V \) before pellet-injection. The diffusion coefficient increased monotonically toward the edge and the convection direction was reversed from outward to inward. Small values of the diffusion coefficient in the central region, together with an inwardly directed pinch, induced the additional peaking. After the second transition (the broadening phase), the convection velocity was nearly zero at \( \rho < ~0.8 \), resulting in an only diffusive process in this region. This caused a reduction of the density gradient in this region, and reduced the peaking factor.

In a low collisionality regime, the collisionality dependence of \( D \) and \( V \) had systematically been studied [10]. Figure 7 shows comparison of \( D \) and \( V \) from the density modulation experiments in the low collisionality regime and values from the SDC discharge in the high collisionality regime. Here, the electron ion-collision frequency was normalized by the trapped electron bounce frequency \( (\nu^*_{eb}) \), expressed as \( \nu^*_{eb} = \nu_e/(\epsilon^{-1/2}v_T/qR) \). Here, \( \epsilon \) is an inverse aspect ratio, \( v_T \) is an electron thermal velocity, \( q \) is a safety factor and \( R \) is a major radius. The values of \( D \) and \( V \) were averaged between \( \rho = 0.4\sim0.7 \). The values of \( D \) and \( V \) in the additional peaking phase of the SDC discharge were averaged at \( \rho = 0.4\sim0.6 \), because \( D \) and \( V \) cannot be obtained from the analysis at \( \rho > 0.6 \) of additional peaking phase.

On the other hands, in the high collisionality regime, the diffusion coefficient from the SDC discharge shows a positive collisionality dependence. This is the same dependence with the neoclassical diffusion coefficient in Pfirsch-Schlüter regime. The convection velocity in high collisionality showed a negative collisionality dependence. The negative convection (inwardly directed convection) increases with collisionality.

Figure 7 suggests the existence of a minimum value of the diffusion coefficient at around \( \nu^*_{eb} = 1\sim5 \), and the convection velocity may be at minimum of around zero when the diffusion coefficient takes

![Figure 7](image-url)

**Figure 7.** Collisionality dependences of (a) \( D \) and (b) \( V \). Values from density modulation experiments (in blue) and from the SDC discharge (in red) are shown.
the minimum value. This diffusion minimum with zero convection point will be favorable for the future reactor operation of high density and moderate temperature \( n_e(0) \sim 5 \times 10^{20} \text{m}^{-3}, T_i(0) \sim 5 \text{ keV} \) scenario, because good particle confinement without impurity accumulation may be possible.

3. Discussion and summary
The behavior of particle transport in the pellet-injected super dense core (SDC) plasma was investigated from the temporal change of density profiles. As the result, three different phases were identified which occurred after multiple pellet-injection; namely, the 1st phase was characterized by a decrease of the normalized flux together with an increase of negative normalized density gradient, occurring after the final pellet-injection, the 2nd phase occurred by a transition simultaneously in the whole region of the plasma where the normalized flux increased together with an increase in the negative normalized density gradient, and finally the 3rd phase occurred by the second transition when both the diffusion coefficient and the inward pinch reduced. This second transition appeared initially at the edge then penetrated to the core region.

Peaked density profiles were achieved by pellet injection at first. Then, additional peaking occurred by a small value of the diffusion coefficient in the core and an enhanced diffusion coefficient in the edge and an inwardly directed pinch. After the second transition, both the diffusion coefficient and the inwardly directed pinch were reduced.

The collisionality dependence of \( D \) and \( V \) suggest a plasma operation having a minimum value of \( D \) together with zero convection at \( \nu_b^* = 1~5 \). An operation at around this collisionality may be a candidate of future heliotron reactor operation.

The analysis used spatio-temporal derivatives of radial densities. The accuracy of spline fitting affects the results. In order to confirm results obtained here, optimization of the fitting is necessary. A coupling of particle transport with heat transport is also important and will be studied in future.

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