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Particle Confinement Study from the Modulated Electron Density Profile Structures on LHD

TANAKA Kenji*, KAWAHATA Kazuo, TOKUZAWA Tokihiko, YAMADA Hiroshi, MURAKAMI Sadayoshi, WAKASA Arimitsu[1], KANEKO Osamu, MIYAZAWA Junichi, WATANABE Kiyomasa, KOMORI Akio and LHD Experimental Group

National Institute for Fusion Science, Toki 509-5292, Japan

[1]Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan

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Abstract

The particle transport characteristics have been investigated in the Large Helical Device (LHD) from the density modulation experiments. External gas puff modulation induces the perturbation of the electron density. The particle transport coefficients, which are diffuison coefficients (D) and convection velocity (V), were estimated from the fitting of the solution of perturbed particle transport equation with modeled D and V to the experimentally obtained modulation amplitude and phase. The difference of D and V between two different magnetic configurations, of which magnetic axis position (Rax) is 3.6m and 3.75m, were observed. More than factor two lower D are obtained at Rax=3.6m than values at Rax=3.75m in the whole region of plasma. In the core region, no convection was obtained at $\rho<0.6$ of Rax=3.6m and small outward convection was obtained at $\rho<0.8$ of Rax=3.75m. In the edge region ($\rho>0.6$ at Rax=3.6m, $\rho>0.8$ at Rax=3.75m), inward pinch was obtained at both configurations.

Keywords:

gas puff modulation, FIR interferometer, diffusion coefficient, convection velocity, neoclassical theory, density profile structure

1. Introduction

The characterization of the particle transport of electron is very important issue in the magnetically confined plasma studies. It is less known compared with energy transport. This is mainly due to the difficulty of the estimation of particle source rate. Because fueling species profiles are sometimes highly asymmetric and their magnetic flux averaged spatial profile are extremely difficult to be measured. Gas puff modulation experiments, which were first tried by Gentle [1,2], are one approach to estimate the particle transport coefficients without knowing the absolute values of particle source rate. The electron density is modulated by the modulated gas-fueling rate. The propagation of the modulated density is characterized by the transport characteristics. Its amplitude and phase profiles are uniquely determined by the given spatial profile of D and V. And these values are independently determined of the absolute value of particle source rate. This is a big contrast to solve the particle balance equation from the temporal change of the density profiles, because the estimation of D and V are strongly influenced by the absolute value of the source rate. In this article, the quantitative difference of the D and V between inward axis shifted (Rax=3.6m) and standard (Rax=3.75m) configuration are described.

*Corresponding author's e-mail: ktanaka@lhd.nifs.ac.jp

2. Principle of Gas Puff Modulation Experiments

The particle balance equation is shown by the bellow;

$$\frac{\partial n}{\partial t} = -\nabla \cdot \Gamma + S = -\frac{1}{r}\frac{\partial}{\partial r} r\Gamma + S \qquad (1)$$

n; electron density, Γ; particle flux, S; particle source rate

$$\Gamma = -D\frac{\partial n}{\partial r} + Vn \qquad (2)$$

D; diffusion coeeficent, V; convection velocity

Here, we assume the equilibrium and modulated component are independent.

$$n = n_{eq} + \tilde{n},\ \Gamma = \Gamma_{eq} + \tilde{\Gamma},\ S = S_{eq} + \tilde{S} \qquad (3)$$

$$\tilde{S} = \tilde{S}e^{i\omega t},\ \tilde{n} = \tilde{n}e^{i\omega t},\ \partial\tilde{n}/\partial t = i\omega\tilde{n} \qquad (4)$$

Then the following particle balance equations for modulated components, of which modulation frequency is ω, are obtained.

$$\frac{\partial^2 \tilde{n}}{\partial r^2} + \left(\frac{1}{r} + \frac{1}{D}\frac{\partial D}{\partial r} - \frac{V}{D}\right)\frac{\partial \tilde{n}}{\partial r} - \left(\frac{V}{rD} + \frac{1}{D}\frac{\partial V}{\partial r}\right)\tilde{n} - i\frac{\omega}{D}\tilde{n} + \frac{\tilde{S}}{D} = 0 \qquad (5)$$

In eq. (5), $\tilde{n}$ is a complex function, and its real part $\tilde{n}_R$ and imaginary part $\tilde{n}_I$ satisfy the following equations.

$$\frac{\partial^2 \tilde{n}_R}{\partial r^2} + \left(\frac{1}{r} + \frac{1}{D}\frac{\partial D}{\partial r} - \frac{V}{D}\right)\frac{\partial \tilde{n}_R}{\partial r} - \left(\frac{V}{rD} + \frac{1}{D}\frac{\partial V}{\partial r}\right)\tilde{n}_R + \frac{\omega}{D}\tilde{n}_I + \frac{\tilde{S}}{D} = 0 \qquad (6)$$

$$\frac{\partial^2 \tilde{n}_I}{\partial r^2} + \left(\frac{1}{r} + \frac{1}{D}\frac{\partial D}{\partial r} - \frac{V}{D}\right)\frac{\partial \tilde{n}_I}{\partial r} - \left(\frac{V}{rD} + \frac{1}{D}\frac{\partial V}{\partial r}\right)\tilde{n}_I - \frac{\omega}{D}\tilde{n}_R = 0 \qquad (7)$$

$\tilde{n}_R$ and $\tilde{n}_I$ are function of the magnetic flux surface in other word they are function of the averaged radius of each fluxes. The solution of eq. (6) and (7) are solved numerically by using matrix technique [3] with the following boundary condition.

$$\partial\tilde{n}_R/\partial r = \partial\tilde{n}_I/\partial r = 0 \text{ at } r = 0,$$
$$\tilde{n}_R = \tilde{n}_I = 0 \text{ at } r = a \qquad (8)$$

a is average radius of the plasma boundary

On the other hands, the modulated density propagation was measured by using FIR interferometer [4] in these series of experiments. Since interferometer measures integration of modulated density propagation, integration of $\tilde{n}_R$ and $\tilde{n}_I$ in eq. (6) and (7) are compared with the measured one, and iteration processes, changing model of D and V, are continued until measured modulated amplitude and phase fit calculated ones reasonably. The spatial profiles of $\tilde{S}$ are calculated from 1-D calculation routines, which is included in energy transport code PROCTR [5] by using density and temperature profiles from the experiments. Here, we need only relative profile of $\tilde{S}$.

In this analysis, we need three assumptions. At first, $\tilde{S}$ does not have spatial phase change. This is justified because neutral penetration time is much faster than modulation time periods. Therefore, the shape of $\tilde{S}$ is assumed to be as same as equilibrium source profiles. Secondly, we assume perturbed components are independent of equilibrium components, otherwise, $\partial\tilde{n}/\partial t = i\omega\tilde{n}$ are not satisfied. This will be possible to modulate the density under constant background density. Finally, modulation amplitude has to be small enough not to change transport characteristics during modulation. On the other hands, modulation amplitude has to be large enough to be measured. The line density modulation amplitude of central chord of interferometer was controlled less than ±10% of the background line density in order to satisfy this requirement reasonably.

3. Results and Discussion

Modulation experiments were examined on two typical magnetic configurations. One is the inward shifted configuration (Rax=3.6m) and the other one is standard configuration (Rax=3.75m). The former one is characterized by better neoclassical transport and worse MHD stability than the latter one, and the former one shows factor 1.5 enhancement of energy confinement time compared with latter one [6]. Figure 1 shows the comparison of the electron density profiles between inward and standard configurations, which are obtained from Abel inversion from 13 ch FIR interferometer measurement [7]. The density profiles are flat one at Rax=3.6m and slightly hollow one at Rax=3.75m. These are profiles of background density of the modulation experiment and both are from NBI heated discharges under almost same toroidal magnetic field. And almost same temperature profiles ($T_e(0)$~1.0keV) were obtained adjusting NBI power. The beta was almost same value (shot 21607 0.27% at Rax=3.6m, shot 19627 0.22% at

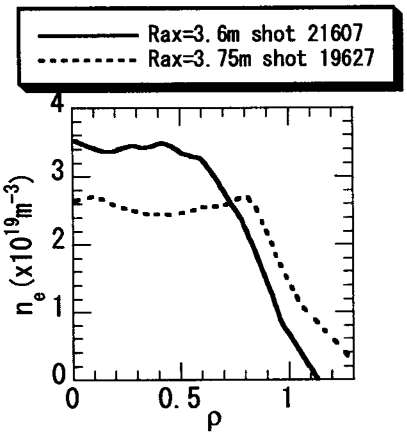

Fig. 1 Comparison of the electron density profiles between inward shifted (Rax=3.6m) and standard (Rax=3.75m) configuration.

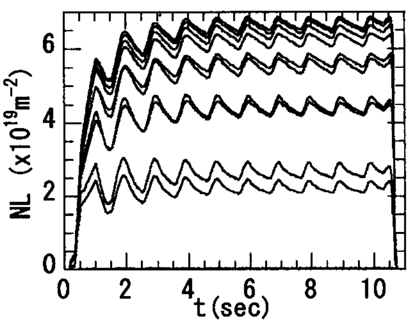

Fig. 2 Time trace of density modulation at inward shifted (Rax=3.6m) configuration.

Rax=3.75m). The collisionalities were almost same in edge (ρ>0.6) in the both discharge, and they were the values in the plateau regime.

Figure 2 shows time trace of modulated lined density at Rax=3.6m. Using the pre-programming of the fueling control, density was modulated at 1Hz. The background density is almost constant, therefore, $\partial\tilde{n}/\partial t = i\omega\tilde{n}$ is well satisfied. The modulate density is not pure sinusoidal, the modulated signals consist of several harmonics. However, the 1Hz component are 2.5 times lager than side band (0.5 and 2Hz components) and more than 7 times larger than other higher harmonics components. The harmonics components do not affect the estimation of amplitude and phase of main 1Hz components. The frequency of the modulation (1Hz) was determined low enough to modulate core region.

Figures 3 (a) and (b) show spatial profile of

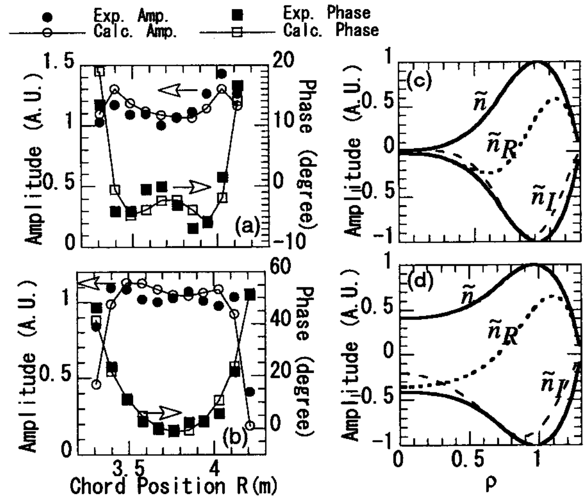

Fig. 3 Integrated modulation amplitude and phase profile (a) Rax=3.6m (b) Rax=3.75m and Fitted radial modulation amplitude (c) Rax=3.6m (d) Rax=3.75m.

measured integrated modulation amplitude and phase. Fitted data were calculated by using the model of *D* and *V* shown in Figs. 4. Figures 3 (c) and (d) show radial profile of $\tilde{n}$. The modulation amplitude is more localized in edge region at Rax=3.6m than at Rax=3.75m. The low diffusion character in the core prevents the penetration of modulation at Rax=3.6m.

From Fig. 1, the density gradient changes at ρ=0.6 of Rax=3.6m and at ρ=0.8 of Rax=3.75m, the particle confinement characteristic also are suggested to be changed at same radial location. Therefore, simple model, which have two different value of *D* and V_o ($V=r/a\ V_o$) at inner and outer of these radial locations, are tried for the model fitting.

Figures 5 show the comparison of density profiles form Abel inversion (also shown in Fig. 1) and reconstructed profile by using *D* and *V* profiles in Figs. 4 and calculated particle source profile. Here, the absolute values of the particle source were adjusted to match the reconstructed profiles to experimentally obtained density profiles in order to compare the shape of profiles. These agree each other.

As shown in Figs. 4 (a) and (c), there is a clear difference of *D* between two configurations. *D* at Rax=3.75m is more than factor two larger than *D* at Rax=3.6m. On the other hands, *V* does not show clear difference especially in the edge. At ρ<0.8, outward convection at Rax=3.75m fits data well. This is consistent that background density profiles are hollow at

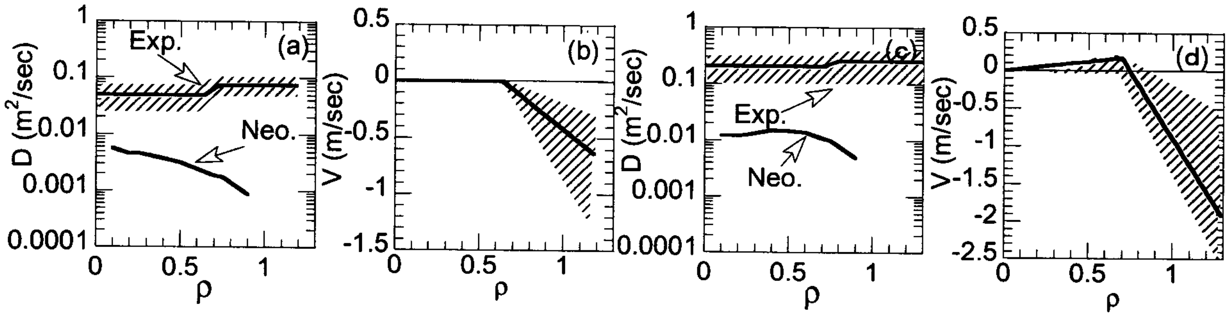

Fig. 4 Fitted transport model and neoclassical prediction
D profile (a) Rax=3.6m, (c) Rax=3.75m, V profile (b) Rax=3.6m, (d) Rax=3.75m. Exp. indicate experimentally obtained values, and Neo. indicate neoclassical predictions. Hatching region is approximate fitting error. Negative V indicates inward direction.

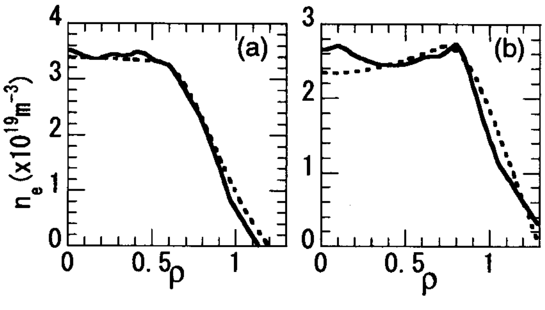

Fig. 5 Comparison of the electron density profiles between measured (thick line) and fitted (dotted line) (a) Rax=3.6m and (b) Rax=3.75m.

Rax=3.75m as shown in Fig. 1.

The neoclassical electron particle flux is written by

$$\Gamma_{e\_neo} = -D_{ne\_neo}(\nabla n + eEr(n/T)) - D_{te\_neo} n \nabla T/T \quad (9)$$

In Fig. 5 (a) and (c), neoclassical diffusion coefficients (D_{ne_neo}) are also shown. These are evaluated from DCOM (Diffusion Coefficient calculator by Monte-carlo method) code [8,9]. D from modulation experiments at ρ>0.7 are more than factor 35 larger than D_{ne_neo} at Rax=3.6m and more than factor 20 larger than D_{ne_neo} at Rax=3.75m. The difference of D from D_{ne_neo} is larger at Rax=3.6m. This suggest contribution of anomalous transport is higher at Rax=3.6m than at Rax=3.75m.

In the edge region (ρ>0.6 at Rax=3.6m, ρ>0.8 at Rax=3.75m), inward convection is obtained. Er is negative because the parameters of these series of experiments were ion root, and temperature gradient is negative in whole region of plasma. Therefore, from eq. (9), neoclassical theory does not predict inward flux. Obtained inward pinch in the edge region does not agree with neoclassical predictions.

4. Sumary

The particle confinement characteristics of two typical configurations (Rax=3.6m inward shifted and Rax=3.75m standard configuration) were studied from the gas puff modulation experiments. Clear difference of D and small difference of V were observed. The better confinement characteristic at Rax=3.6m is possibly due to lower diffusion character. However, the difference between D and D_{ne_neo} at ρ>0.7 is larger at Rax=3.6m than at Rax=3.75m. The flat or hollow density profile on LHD is due to the absence of the inward pinch in the core region unlike same size tokamaks. Inward convection in the edge region can well fit the experimental data. But still error bar is large in the edge region, optimization of fitting routine will be necessary to confirm the existence of the inward pinch. The survey of D and V changing collisionality and gyro-radius are planned.

References

[1] K.W. Gentle, B. Richards and F. Waelbroeck, Plasma Phys. Control. Fusion **29**, 1077 (1987).

[2] K.W. Gentle, O. Gehere and K. Krieger, Nucl. Fusion **32**, 217 (1992).

[3] K. Nagashima and A. Sakasai, Rep. JAERI-M 92-057. JAERI, Ibaraki (1992).

[4] K. Kawahata, K. Tanaka, Y. Ito, A. Ejiri and S. Okajima, Rev. Sci. Instrum. **70**, 1, p.707, (1999).

[5] H.C. Howe, ORNL/TM-11521 (1990).

[6] H. Yamada *et al.*, to appear in Fusion Energy

(2000) (Proceedings of 18th Conference on Fusion Energy), IAEA.

[7] K. Tanaka *et al.*, Proceedings of 26th EPS (1999), Maastricht, p.1329.

[8] A. Wakasa *et al.*, *this proceedings*.

[9] S. Murakami, A. Wakasa *et al.*, *to be published*, Nucl. Fusion.