ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 614–618

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Three-dimensional analysis of the effect of the ergodic magnetic field line structure on particle fueling in the large helical device

M. Shoji *, K. Yamazaki, A. Komori, H. Yamada, J. Miyazawa, LHD Experimental Group

National Institute for Fusion Science, Oroshi-cho 322-6, Toki, Gifu 509-5292, Japan

Abstract

The particle fueling via the ergodic magnetic field line structure formed around the core plasma is investigated by using a CCD camera with an H_α interference filter and a fully three-dimensional neutral particle transport simulation. The measurements of the plasma density profile and the calculations of the radial profile of the particle fueling rate in additional gas fueling experiments show inward plasma transport from around the last closed magnetic surface (LCMS) into the core plasma. The analyses of the particle fueling rate in various plasma density cases prove that the dependence of the particle fueling inside of the LCMS on the line averaged plasma density agrees with that of the measured increments of the plasma content due to the gas fueling, which indicates that particle fueling just inside of the LCMS can effectively contribute to the core plasma density by the effect of the inward plasma transport in large helical device plasmas.

PACS: 52.40.H
Keywords: LHD; Particle fueling; Ergodic layer; Neutral transport simulation; CCD camera

1. Introduction

In helical systems such as the large helical device (LHD), the magnetic field due to helical coils forms ergodic magnetic field line structure (ergodic layer) around the core plasma. The magnetic field lines in the ergodic layer directly connect to divertor plates [1]. It is a concern for helical systems that the ergodic layer prevents the efficient particle fueling from gas puffers because the plasma transport along the magnetic field lines can reverse the ionized particles toward the divertor plates. Thus, detailed investigation on particle fueling to the core plasma via the ergodic layer is an important issue to achieve and sustain high density plasmas, long pulse discharges, etc. in LHD.

In axisymmetric plasma confinement systems such as tokamaks, it has been assumed that the particle fueling is toroidally uniform, which enables easy estimation of the particle fueling rate, the particle confinement time, etc. [2]. In three dimensionally complicated plasmas like LHD plasmas, it is generally difficult to evaluate the particle fueling rate, because it is experimentally and theoretically proved that the distribution of the ion flow onto the divertor plates is three dimensionally complicated, causing the complex distribution of the particle fueling from the divertor plates [3,4]. For this reason, we carried out additional gas fueling experiments by using a local gas puffer (GP 5.5-L) adjacent to the plasma. The gas puffer is located on a helical coil where the plasma is horizontally elongated and the thin ergodic layer is formed, which is favorable for direct particle fueling into

* Corresponding author. Tel.: +81-572 58 2151; fax: +81-572 58 2618.
E-mail address: shoji@lhd.nifs.ac.jp (M. Shoji).

0022-3115/03/$ - see front matter
PII: S0022-3115(02)01442-3

the core plasma. These experiments are also useful for reducing the ambiguity of the energy distribution of ambient neutral particles by plasma-wall interactions. The effect of the additional gas fueling is analyzed by the measurements of an H_α intensity profile and the increment (buildup rate) of the plasma density. For detailed estimation of the fueling rate, a neutral particle transport simulation (DEGAS ver. 63) is applied [5,6].

2. Additional gas fueling experiments

LHD is the largest heliotron type device ($l = 2$, $m = 10$, l and m are toroidal and poloidal mode number, respectively) with a plasma major radius of 3.9 m, an averaged minor radius of 0.65 m, and a magnetic field of about 3 T on the magnetic axis. LHD can flexibly control the position of the magnetic axis to change the thickness of the ergodic layer [1]. We performed the additional gas fueling experiment in an inward axis configuration ($R_{ax} = 3.60$ m, $B = 2.80$ T) because of the thin ergodic layer compared to that in other magnetic configurations.

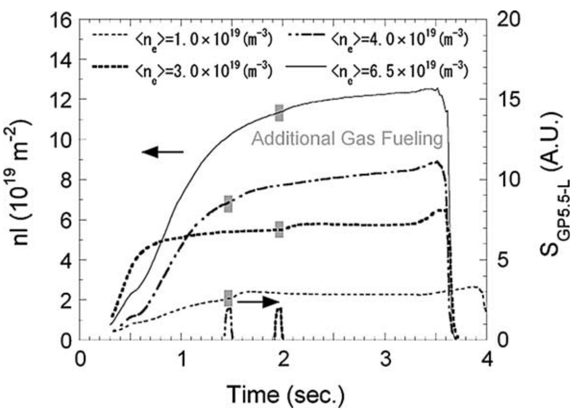

Fig. 1. Time evolution of the plasma line density measured with an FIR interferometer with the waveforms of the additional gas fueling rate from the gas puffer (GP 5.5-L) in various plasma density cases.

In quasi-steady-state neutral beam injection (NBI) heated ($\sim$7 MW) plasmas, hydrogen was introduced during a short pulse (<10 ms) in various plasma density cases by controlling the fueling rate from another gas puffer for plasma production. Fig. 1 shows the time evolution of the plasma line density measured with an FIR interferometer [7] with the waveforms of the fueling rate ($S_{GP\ 5.5\text{-}L}$). The changes of the line density due to the gas fueling are prominent for the lowest plasma density ($nl \sim 2 \times 10^{19}$ m^{-2}). The fueling rate from the gas puffer was identical in all plasma density cases, and the plasma density slightly began to change after $\sim$0.1 s of the gas fueling because of the small conductance of the guide pipe of the gas puffer. An H_α line intensity profile was observed by a CCD camera with the interference filter. The camera also detected the slow temporal change ($\sim$1 s) of the intensity due to the small conductance.

Fig. 2 gives plasma density profiles just before and during the gas fueling (after $\sim$0.15 s) obtained by the Abel inversion technique, showing the increment of the plasma density inside of the last closed magnetic surface (LCMS: $\rho = 1$; ρ is a normalized minor radius), which is more prominent for the lowest plasma density. The increment of the plasma line density (raw data) due to the gas fueling measured along the central cord is larger than that along peripheral cords, verifying the finite increase of the core plasma density due to the gas fueling. Fig. 2 shows the presence of the steep gradient of the density profile around the LCMS and the finite plasma

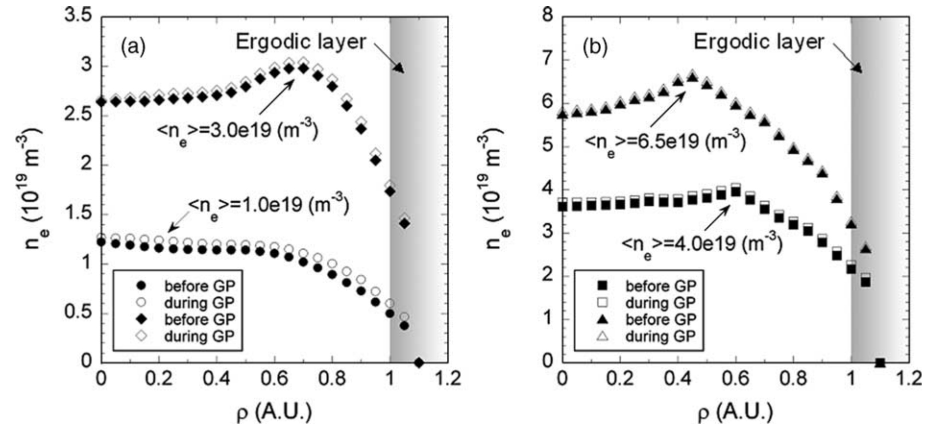

Fig. 2. Radial profiles of the plasma density just before and during the additional gas fueling (after $\sim$0.15 s) in various plasma density cases, showing the finite increments of the plasma density inside of the LCMS.

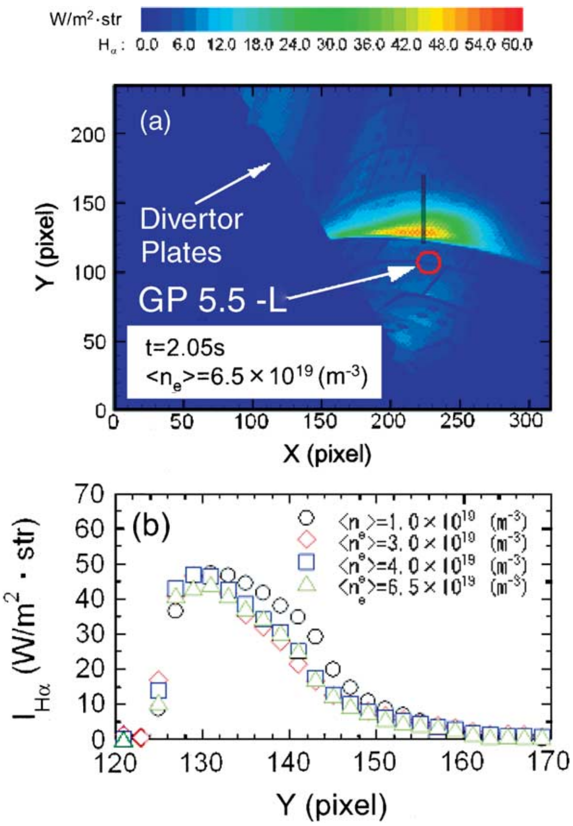

Fig. 3. Measured H_α intensity profile for the highest plasma density observed with a CCD camera during the gas fueling (a), and line profiles of the H_α intensity on a black line shown in (a) in various plasma density cases (b).

density in the ergodic layer ($\rho > 1.0$). Fig. 3(a) depicts an H_α intensity profile during the gas fueling for the highest plasma density. The bright emission above the gas puffer indicates strong localization of neutral hydrogen. Fig. 3(b) gives the line profile in various plasma density cases after the reduction of the reflected light from the vacuum wall, indicating that the intensity profile for the lowest plasma density is broad. It shows weak attenuation of neutral hydrogen due to less interaction with the peripheral plasma.

3. Fully three-dimensional analysis of neutral particle transport

The three-dimensional neutral particle transport simulation is applied to the detailed estimation of the particle fueling from the gas puffer. In the simulation, neutral particles are treated as test particles which trajectories and reactions with plasmas and vacuum vessels are traced by the Monte Carlo technique. We made a three-dimensional model simulating the one toroidal pitch of the LHD plasma, which regards two toroidal boundaries as exits (no particle reflection). The vacuum vessel consists of triangles, one of which is regarded as the gas puffer for shooting the test particles at a velocity randomly selected from a Maxwellian velocity distribution (300 K). The plasma is simulated as hexahedrons in which plasma parameters are constant. The parameter profiles are determined from the measurements with the FIR interferometer (for electron density) and Thomson scattering (for electron temperature). The measurements with Langmuir probe arrays are also used for the electron density and temperature in the plasma periphery [4]. Here, the ion temperature and density profiles are assumed to be identical to the electron ones, which is a reasonable assumption because of the no significant difference between measured electron and ion temperature in standard NBI heated plasmas.

4. Analysis of the particle fueling rate

The distribution of the particle fueling from the gas puffer is derived from the measured H_α intensity profile and the calculation by the simulation. For determining the absolute value of the neutral particle density, the calculated H_α intensity profiles, which are obtained by the line integration of the brightness along the lines of sight, are normalized to the measurements to show reasonable agreement. Fig. 4 illustrates a calculated density profile of neutral hydrogen atoms for the lowest plasma density, showing that the neutral particles are

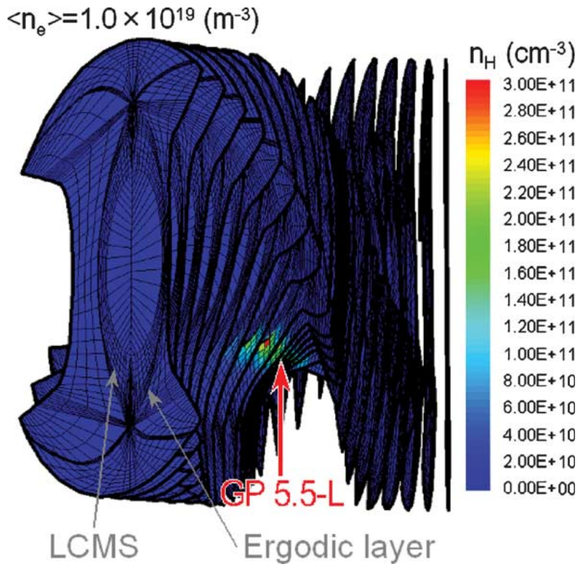

Fig. 4. Calculation of the three-dimensional density profiles of neutral hydrogen atoms supplied from the gas puffer (GP 5.5-L) in the case of the lowest plasma density.

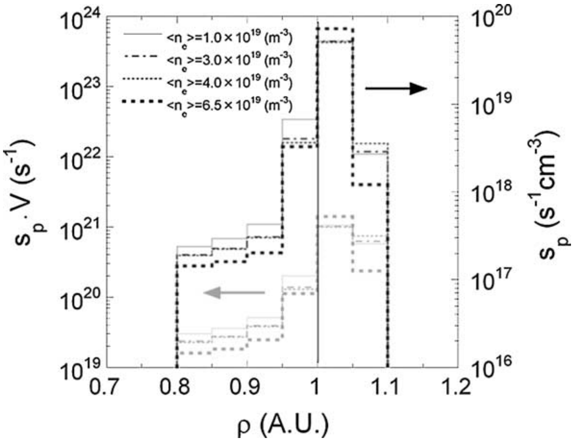

Fig. 5. Calculations of the radial profile of the particle fueling rate supplied from the gas puffer (s_pV) and these per a unit volume (s_p) in various plasma density cases.

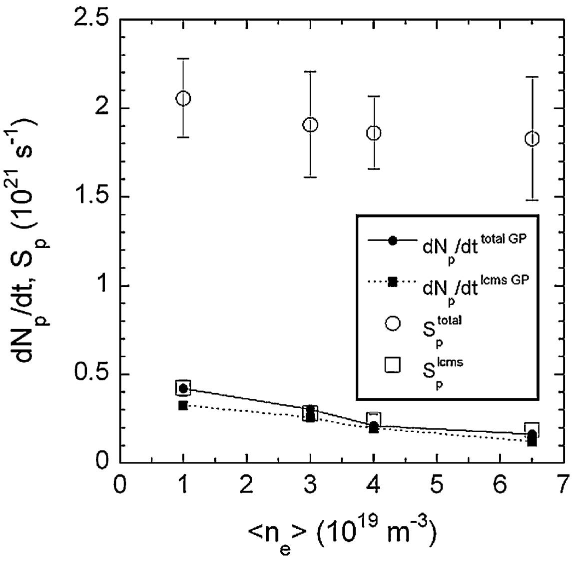

Fig. 6. Dependence of the increments of the total plasma content inside of the LCMS ($dN_p/dt^{lcms\,GP}$: ■) and these including the ergodic layer ($dN_p/dt^{total\,GP}$: ●) on the line averaged plasma density. The calculations of the total particle fueling rate inside of the LCMS (S_p^{lcms} : □) and these including the ergodic layer (S_p^{total} : ○) are also plotted.

localized close to the gas puffer. Fig. 5 gives the radial profiles of the particle fueling rate (s_pV) and these per a unit volume (s_p). It indicates that the particle fueling mainly deposits in the plasma periphery ($\rho > 0.8$) and the predominant particle fueling just outside of the LCMS ($\rho = 1.0$–1.05). The attenuation of the fueling rate in the core plasma ($\rho < 1$) is significant for the highest plasma density. As shown in Fig. 2, the finite increments of the plasma density inside of the LCMS ($\rho < 1$) were observed by the additional gas fueling, which shows the presence of the inward transport of the plasma, because the calculated fueling rate deposited inside of the intermediate region ($\rho < 0.7$) is too small to explain the increment of the plasma density.

Closed circles and squares in Fig. 6 respectively represent the dependences of the increment (buildup rate) of the total plasma content (dN_p^{total}/dt; $N_p = \sum n_eV$; V is a plasma volume) and that inside of the LCMS (dN_p^{lcms}/dt) due to the gas fueling on the line averaged plasma density ($\langle n_e\rangle$), showing the increment inside of the LCMS is dominant. We derived these increments by subtracting the buildup rate just before the gas fueling from that during the gas fueling. This figure shows that the increments monotonically decrease with the plasma density. The calculations of the total fueling rate deposited inside of the LCMS $\left(S_{lcms}; S = \sum s_pV\right)$ and that including the ergodic layer (S_{total}) are plotted in this figure as open squares and circles, respectively. It shows no clear dependence of the total fueling rate (S_{total}) on the plasma density and the fueling rates is about 6 to 15 times more than the measurements, while the fueling rate inside of the LCMS (S_{lcms}) agrees with the measurements. We, thus, conclude that the direct particle fueling inside of the LCMS (S_{lcms}) can effectively contribute to the core plasma density. These calculations show that the most of the fueled particles (83–93%) supplied from the gas puffer does not contribute to the plasma density due to the screening effect of the ergodic layer where the ionized particles escape from the plasma to the divertor plates along the magnetic field lines and the ionized particles diffuse to the outside because of the steep gradient of the plasma density profile.

It should be considered the accompanying particle fueling from the divertor plates induced by the plasma flow produced in the ergodic layer due to the additional gas fueling. The plasma flow onto the divertor plates is calculated by the total fueling rate in the ergodic layer. We obtained the fueling ratio (S_{lcms}/S_{total}) by shooting the test particles from plasma striking points on the divertor plates, and estimated the recycling coefficient (R) to be less than 0.6 (strong pumping) from the analyses of a simple particle balance model at the plasma startup phase [8]. Considering the plasma flow, the fueling ratio and an assumed recycling coefficient ($R = 0.4$), we found that the total fueling rates inside of the LCMS (S_p^{lcms}) can be slightly modified upward in the range from ~15% (in the highest $\langle n_e\rangle$) to ~20% (in the lowest $\langle n_e\rangle$), which are not so large modification to upset the above conclusion of the effect of the particle fueling inside of the LCMS on the core plasma density.

It is experimentally supported by the fact that the fueling rate to sustain the plasma density in the inward magnetic axis configuration ($R_{ax} = 3.60$ m) is less than that in the standard configuration ($R_{ax} = 3.75$ m) in which a thicker ergodic layer is formed around the core plasma [9]. A fueling pellet injector can directly supply the fueling source inside of the LCMS ($\rho = 0.6$–1.0), which enables achievement of higher plasma density. In the pellet injection, we have not yet observed a density limit induced by a MHD instability or plasma disruption such as Tokamaks [10]. These experimental results also support that the direct particle fueling inside of the LCMS is essential in raising the core plasma density.

On the basis of the above analyses, we propose that cluster beam or supersonic molecular beam injection can be useful techniques to achieve and sustain high density plasmas in LHD [11,12]. This is because particle fueling just inside of the LCMS can contribute to the core plasma density by the inward plasma transport, though the fueled particles by the above two techniques cannot penetrate deeply into the core plasma.

5. Summary

Three-dimensional neutral particle transport simulation was successfully applied to the detailed estimation of particle fueling in the additional gas fueling experiment. The analyses of the increments of the plasma density due to the gas fueling show inward plasma transport. While no clear dependence of the total particle fueling rate including the ergodic layer on the plasma density is found, the total fueling rate inside of the LCMS monotonically decreases with the plasma density, which agrees with the measured increment of the plasma content in various plasma density cases. It indicates that the particle fueling just inside of the LCMS can effectively contribute to raising the core plasma density due to the inward plasma transport.

Acknowledgements

The authors gratefully acknowledge Professor M. Fujiwara and O. Motojima, for their encouragement. The author (M.S) would like to thank technical officers in department of engineering and technical services at NIFS for their support, Mr. S. Ichimoto for his instrumental assembly, and fruitful collaboration with Professor Y. Nakashima in the University of Tsukuba.

References

[1] T. Morisaki et al., Contribution Plasma Phys. 40 (2000) 266.
[2] P.C. Stangeby, J. Nucl. Mater. 145–147 (1987) 105.
[3] O. Kaneko et al., Phys. Plasma 9 (2002) 2020.
[4] S. Masuzaki et al., J. Nucl. Mater. 290–293 (2001) 12.
[5] D.B. Heifetz et al., J. Comput. Phys. 46 (1982) 309.
[6] D.P. Stotler et al., J. Nucl. Mater. 196–198 (1992) 894.
[7] K. Kawahata et al., Rev. Sci. Instrum. 70 (1999) 707.
[8] Y. Nakamura et al., J. Nucl. Mater. 290–293 (2001) 1040.
[9] S. Morita et al., in: Proceedings of the 26th EPS Conference on Plasma Physics and Controlled Nuclear Fusion, Maastricht, 1999, p. 1321.
[10] R. Sakamoto et al., Nucl. Fusion 41 (2001) 381.
[11] M. Matsuoka et al., J. Plasma Fusion Res. 77 (2001) 237 (in Japanese).
[12] E.Y. Wang et al., J. Plasma Fusion Res. 77 (2001) 242 (in Japanese).