J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 209–212

Edge Plasma Radial Profiles and Confinement Property on the HL-1M Tokamak

HONG Wen-yu*, WANG En-yao, PAN Yu-dong and LI Qiang
Southwestern Institute of Physics, P. O. Box 432, Chengdu 610041, China

(Received: 5 December 2000 / Accepted: 27 August 2001)

Abstract

The relation of edge plasma radial profiles and confinement property was described by means of the measurement results with a Mach/Langmuir mixed probe array on the HL-1M Tokamak. The probe array can measure not only parallel flows and the flow perpendicular to the magnetic field but the radial and the poloidal electric field E_r and E_θ as well. Measurements of the edge fluctuations, velocities of the toroidal and the poloidal and electric field have been carried out on both of scrape-off layer (SOL) and the boundary region of HL-1M under the condition of Ohmic, Lower Hybrid Current Drive (LHCD), Supersonic Molecular Beam Injection (SMBI), Multi-shot Pellet Injection (MPI) and Neutral Beam Injection (NBI) discharges. The results show that the suppressions of the fluctuations are related to poloidal rotations produced by different discharges in improved particle confinement mode. The changes of the radial and poloidal electric field is generated simultaneously and becomes more negative at the tokamak plasma edge and the sheared poloidal flow is related to the reduction in fluctuation level. The poloidal rotation velocity is mainly dominated by the $\vec{E} \times \vec{B}$ drift.

Keywords:
poloidal rotation velocity, radial electric field, poloidal electric field

1. Introduction

The determination of flow velocity in SOL and the boundary of tokamak plasma have become of prime importance due to its possible role in plasma confinement and the L-H mode transition [1-3]. Recently, a radial electric field E_r near the plasma edge has been found both experimentally and theoretically to play an important role for the L-H transition [4-7]. In brief, theories attempting to explain the L-H transition focus on E_r, dE_r/dr and/or poloidal velocity V_{pol} structure at the edge [8]. However, recent theoretical calculations show that shear and/or curvature of $E_r \times B$ flow is the parameter capable of suppressing the plasma fluctuations and reducing the outward plasma transport [9].

Corresponding author's e-mail: hongwy@swip.ac.cn

2. Experimental Arrangement and Mach/Langmuir Probe Array

HL-1M is a circular cross-section tokamak, with R = 1.02 m, a = 0.26 m, B_t < 3 T, I_p < 350 kA, n_e = 1–8×10^{19} m^{-3}, $T_e(0)$ ~ 1 keV and two full poloidal graphite limiters located at 180° from each other toroidally. In the present experiments, the toroidal current in the HL-1M tokamak lasted for about 1 s with a flat top of about 800 ms, producing a reasonable stable boundary region. A wall boronization, siliconization and lithium coating were employed in HL-1M [10].

A Mach/Langmuir probe array [11] assembly is mounted on a long shaft which can be moved radially inboard and outboard, and can be rotated with an angle of 360° around the axis of the shaft by a magnetometric transmission rod and at 22.5° from outboard midplane. One probe array is consisted of five tips for measuring poloidal and toroidal velocities in the edge, and another is consisted of six tips for measuring edge radial and poloidal electric field. The parallel flow Mach number M and the poloidal velocity V_{pol} is estimated by [6,12]:

$$M = 0.6 \ln (J_u / J_d) \tag{1}$$
$$V_{pol} = J_{pol} / en_e \tag{2}$$

where J_u and J_d are the upstream and downstream ion saturation current collected by the pins of upstream and downstream respectively, V_{pol} is the poloidal flow velocity which is basically the $\vec{E} \times \vec{B}$ flow, J_{pol} and n_e are poloidal current density and electron density respectively.

3. Experimental Results

3.1 LH Wave Injection

The HL-1 and HL-1M experiments have observed significant density increase (up to factor of 2) during combined Ohmic and LHCD discharges [13]. In these experiments, decrease in H_α signals by ~ 40–60% is observed during LHCD. Estimation of particle confinement time τ_p increases by a factor of 2.5 for normal current drive and a factor of 1.5 for anti-current drive during LH wave injection with the injection power P_{LH} = 100 kW, $n_e \sim 1\times10^{19}$ m^{-3}. These results have commonly indicated a significant decrease in edge density fluctuations in improved confinement mode with LH wave injection. The radial profiles of ion saturation current fluctuations $I_{s,rms}$ during Ohmic and LHCD are given in Fig. 1. The radial profiles of the poloidal rotation velocities V_{pol} measured by a Mach/Langmuir Probe Array during ohmic discharge, LHCD (P_{LH} = 100 kW) and LHCD (P_{LH} = 200 kW, B_t-reversed) are also shown in Fig. 1. It was found that the direction of poloidal flow velocity V_{pol} is along the ion diamagnetic drift direction, when the toroidal B_t is reversed on its direction, poloidal rotation velocity V_{pol} also changed to opposite direction. It is clear that on reversing the direction of B_t the direction of V_{pol} also reverses. Direction changes of the edge radial electric field E_r and edge poloidal electric field E_θ were observed during LHCD (see Fig. 1). The altered edge electric field by LH wave injection leads to noticeable changes in the plasma poloidal rotation velocities. Changes in the poloidal rotation velocities during LH wave injection can be explained by the modification of the radial profiles of E_r. The observed changes in the poloidal flow velocity direction with B change in direction suggests that the

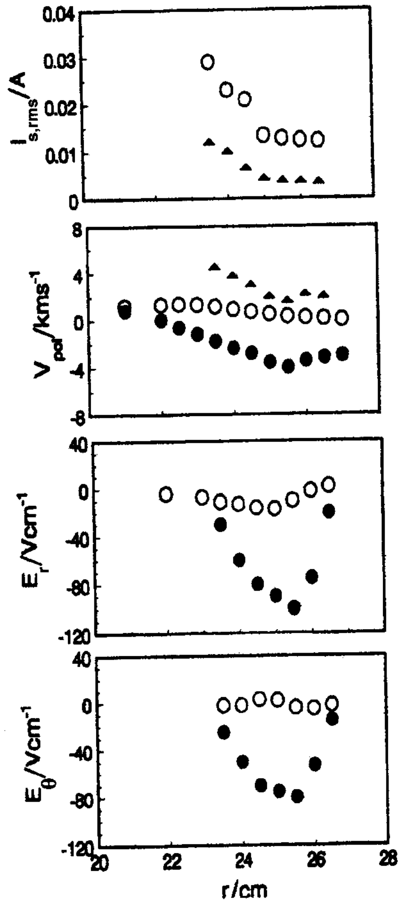

Fig. 1 The radial profiles of $I_{s,rms}$, V_{pol}, E_r and E_θ during Ohmic-heated discharge and LHCD. ○-Ohmic, ▲-LHW (100 kW), ●-LHW (200 kW, B_t-reversed).

effect of the radial electric field induced by LH wave injection dominates the poloidal rotation. A strong shear of the poloidal rotation velocity and the suppressions of the density fluctuations were observed in the region of 24.5 < r < 25.5 cm during LHCD (see Fig. 1).

3.2 Pellet Injection

The hydrogen pellets with velocity of 500–800 ms^{-1} (diameters of 1.0 mm and of 1.4 mm) were injected into an ohmically heated discharge. A peaked plasma density profile with peaking factor $n_e(0)/\langle n_e\rangle$ of 1.8 was obtained $\langle n_e\rangle$-volume averaged density). The energy confinement time τ_E of the plasma was enhanced by up to 30% compared with that of gas fueling discharge. The large changes both in the toroidal flow Mach number M and the poloidal flow velocity V_{pol} of the edge plasmas were found (see Fig. 2 and Fig. 3). And the plasma poloidal rotation velocity V_{pol} begins to increase from $|V_{pol}|_{\max} \leq 1.0$ km/s to $|V_{pol}|_{\max} \leq 14$ km/s in the electron

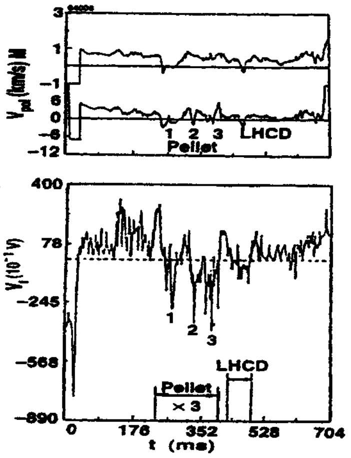

Fig. 2 Time evolution of M, V_{pol} and V_f in HL-1M, during multi-shot pellet injection.

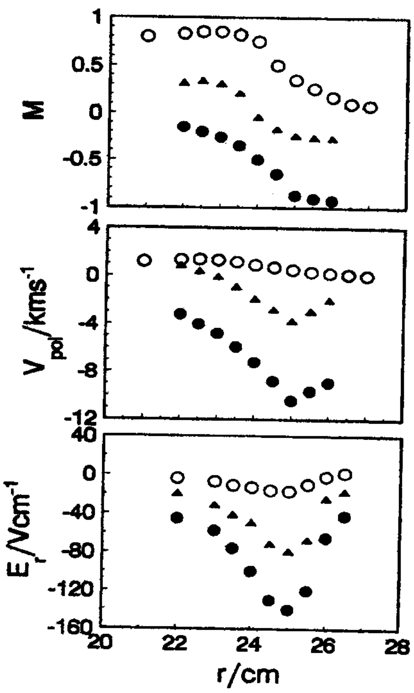

Fig. 3 The radial profiles of M, V_{pol} and E_r during ohmic-heated discharge, MPI and SMBI. . ○-Ohmic, ●-Pellet, ▲-SMBI.

diamagnetic direction (see Fig. 3). In the experiment, we found that the reactions of pellet injection on the plasma potential are characterized by very large, sharp changes, see Fig. 2, and the radial electric field becomes more negative, as shown in Fig. 3. These observations are approximately coinciding with the experimental results of the JIPP T-IIU tokamak [14].

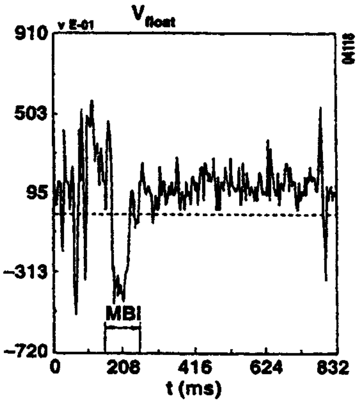

Fig. 4 Time evolution of plasma floating potential V_f during SMBI.

3.3 Supersonic Molecular Beam Injection

In the experiment of SMBI fueling, the profile peaking factor of electron density $Q_n = n_e(0)/\langle n_e \rangle$ is more than 1.5. The energy confinement time τ_E was increased from 15–18 ms for gas puffing (GP) discharge to 26 ms for SMBI, which is over 30% longer than that of gas puffing under the same operation conditions. The SMBI influence on the boundary plasma flow is similar to pellet injection, as shown in Fig. 3. The rapid change in the local plasma potential is also found to be induced during the supersonic molecular beam injection into a tokamak plasma, as shown in Fig. 4, and the electric-field also becomes more negative, as shown in Fig. 3. This suggests that the profile of the edge electric field was changed, thus both the flow velocity and the direction in the boundary plasma have been changed sharply. The poloidal rotation velocity V_{pol} begins to increase from $|V_{pol}|_{\max} \le 1.0$ km/s to $|V_{pol}|_{\max} \le 3.8$ km/s in the electron diamagnetic direction, because the electric field becomes more negative (see Fig. 3).

3.4 Neutral Beam Injection

The NBI experiments were performed on the HL-1M tokamak with power range of 0.15–0.2 MW. The edge plasma poloidal rotation velocity V_{pol} are reversed and the poloidal rotation velocity V_{pol} was increased from $|V_{pol}|_{\max} \le 1.0$ km/s to $|V_{pol}|_{\max} \le 5$ km/s in the electron diamagnetic direction during NBI, because the radial electric field becomes more negative. The poloidal electric field E_θ are also increased along the anti-direction, as shown in Fig. 5.

4. Discussion and Conclusions

Experimental results indicate that the poloidal velocity is mainly dominated by the $\vec{E} \times \vec{B}$ drift in HL-

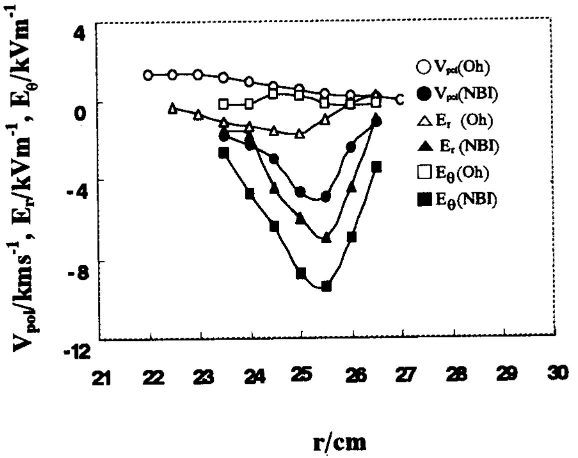

Fig. 5 The radial profiles of V_{pol}, E_r and E_θ during Ohmic-heated discharge and NBI.

1M. The decreases of the edge particle radial transport are related to suppressions of fluctuations, and the plasma confinement thereby improves.

In the tokamak plasma, the basic relation between the poloidal flow velocity of the edge plasma and E_r can be written as [15]:

$$V_{pol}=\frac{E_r}{B}-\frac{1}{eZ_i n_i B}\frac{dp_i}{dr}+\frac{B_{pol}}{V}V_t \qquad (3)$$

here eZ_i, n_i and p_i are the ion charge, density and pressure respectively. B_{pol} is the poloidal component of the toroidal magnetic field. V_t is the plasma toroidal flow velocity. It is clear that the poloidal velocity is determined by three factors: (1) the poloidal component of the $\vec{E}\times\vec{B}$ drift; (2) the plasma diamagnetic drift, which depends upon the charge and arises from the gyration of ions; and (3) the poloidal projection of the parallel flow.

During LHCD, MPI, SMBI and NBI, the changes of the radial electric field E_r and the ion pressure gradient dp/dr, which are induced by the change of the local plasma potential and the generation of the high-density plasma, cause the change of the plasma poloidal rotation velocity V_{pol}. We can see from Figs. 1, 3 and 5, during LHCD, MPI, SMBI and NBI, the peak value of the negative radial electric field (inwardly directed) is of the order of –9.6 kV/m (at B_t = 2.6 T), –14 kV/m (at B_t = 2.0 T), –8 kV/m (at B_t = 2.5 T) and –7.0 kV/m (at B_t = 2.0 T) respectively. The corresponding peak value of the poloidal velocity V_{pol} is of the order of –4.3 km/s, –10 km/s, –3.8 km/s and –5 km/s respectively. These results are consistent with the presence of a strong negative radial E-field. It appears that the poloidal velocity is mainly dominated by the $\vec{E}\times\vec{B}$ drift. Simultaneity, the sign of V_{pol} reverses when the direction of the magnetic field is reversed. This observation supports the conclusion that the measured poloidal fluid velocity is due to the $\vec{E}\times\vec{B}$ drift of the ion. The shear of the poloidal rotation velocity decreases the level of the turbulent fluctuations [16].

In the experiment of the MPI and SMBI, the Mach number M becomes negative, which is the direction of the local plasma toroidal flow is reversed. The mechanism that produces this phenomenon is under study and discussion.

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