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Effects of supersonic beam and pellet injection on edge electric field and plasma rotation in HL-1M

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Abstract

Experimental measurements of edge electric field and plasma rotation have been carried out on both of scrape-off layer (SOL) and the boundary region of HL-1M for Ohmic, Supersonic Beam Injection (SBI) and Multi-shot Pellet Injection (MPI) with a Mach/Langmuir probe array. The radial profiles of the toroidal flow Mach number M, the poloidal flow rotation velocity V_{pol} and the electric field E_{r} are measured during experiments of MPI and SBI respectively. The effects of supersonic beam injection and multi-shot pellet injection on the edge electric field, plasma rotation and fluctuation have been observed. The results show that the change of the radial electric field E_r is generated and becomes more negative at the tokamak plasma edge and the sheared poloidal flow relates to the reduction in fluctuation level. During SBI and MPI, poloidal rotation velocities of 3.8 km/s and 10 km/s in the electron diamagnetic direction are measured, respectively. From the measurements we also obtain radial electric fields of −8 and −14 kV/m, respectively in the plasma edge region. It appears that the poloidal velocity is mainly dominated by the $\boldsymbol{E} \times \boldsymbol{B}$ drift. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Supersonic beam injection; Multi-shot pellet injection; Radial electric field

1. Introduction

In a tokamak with full poloidal limiter it is reasonable to expect that the plasma parameters in the limiter scrape-off layer (SOL) and edge will vary toroidally and poloidally [1]. Recently, a radial electric field E_{r} near the plasma periphery has been found both experimentally and theoretically to play an important role in the L–H transition [2–10]. In brief, theories attempting to explain the L–H transition focus on E_{r}, $\mathrm{d}E_{\mathrm{r}}/\mathrm{d}r$ and/or poloidal velocity V_{pol} structure at the edge [11]. However, recent theoretical calculations show that shear and/or curvature of $\boldsymbol{E}_{\mathrm{r}} \times \boldsymbol{B}$ flow is the parameter capable of suppressing the plasma fluctuations and reducing the outward plasma transport [12].

The experiments and research of the formation of electric field E_{r}, subsequent poloidal plasma rotation velocity V_{pol} and their influence on fluctuations is equally important, especially the flow velocity is one of the key parameters in the boundary plasma and needs to be measured quantitatively [12,13]. To obtain experimental insight into the physical mechanism responsible for improved confinement, the radial profile of the electric field and plasma rotation velocity should be measured simultaneously. In the paper we present these parameters in the HL-1M tokamak obtained during normal Ohmic discharges, multi-shot pellet injection and supersonic beam injection, respectively, with a Mach/Langmuir probe array.

2. Experiment

For the present experiments, the toroidal current in the HL-1M tokamak lasted for about 1 s with a fiat top of about 800 ms, producing a reasonable stable boundary region. The tokamak operational parameters during MPI and SBI are $B_{\mathrm{t}} = 2$–2.5 T, $I_{\mathrm{p}} = 100$–160 kA, $\bar{n}_{\mathrm{e}} = 1$–3×10^{19} m^{-3} and $T_{\mathrm{e}}(0) = 0.5$–1 keV.

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A Mach/Langmuir probe array has been successfully operated in the HL-1M tokamak. It is comprised of five probe elements, one center tip probe acting as a standard single probe to measure the floating potential and four side pins acting as collecting electrodes of a Mach probe to collect ion saturation currents. It is used to measure plasma poloidal and toroidal rotation velocities in the edge region [14], as shown in Fig. 1. A Mach/Langmuir probe array can be moved radially from 27 to 21 cm. Simple chamber wall boronization, siliconization and lithium coating techniques were employed in HL-1M [15]. The plasma current is in the direction of the toroidal magnetic field. Hydrogen plasma is used for the experiment.

In recent experiments of HL-1M tokamak, MPI (with up to 8 pellets) and SBI were used to study confinement, edge fluctuations and radial transport.

3. Experimental results

3.1. Pellet injection

The hydrogen pellet injection in the tokamak plasma is one of the most important methods for fueling, controlling the density profile and improving the confinement of a tokamak plasma. In addition, the interaction of pellets with a high-temperature tokamak plasma induces the phenomena of rapid pre-cooling, a large and rapid change of the local plasma potential and a jump of edge electric-field [16]. A large potential gradient at the plasma surface is also considered to be the origin of the H-mode in tokamak plasma. Therefore, to clarify the mechanism that produces the potential and electric-field in the edge plasma is very important.

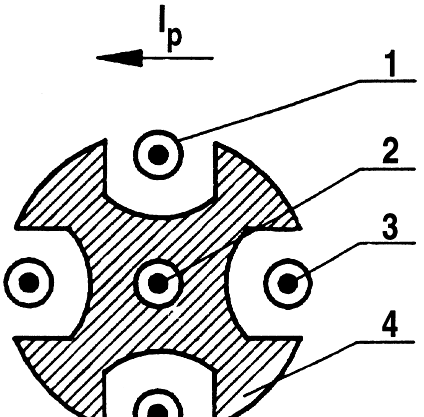

Fig. 1. Schematic of Mach/Langmuir probe array. 1 – Ceramic pipe, 2 – Langmuir probe, 3 – Mach probe, 4 – Graphitic separator.

During the period of the experiments, the hydrogen pellet with velocity of 500–800 m/s and diameter of 1.0 and of 1.4 mm was 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. The energy confinement time τ_E of the plasma was enhanced by up to 30% compared with gas fueling discharge. The large changes both in the toroidal flow Mach number M and the poloidal flow velocity V_{pol} of the edge plasma were found (Figs. 2 and 3), and the plasma poloidal rotation V_{pol} begins to increase from the small values, observed in the OH-phases ($|V_{pol}| \leqslant 1.0$ km/s) to high values ($|V_{pol}| \leqslant 14$ km/s) in the electron diamagnetic direction (Fig. 3). In the experiment, we found that the reactions

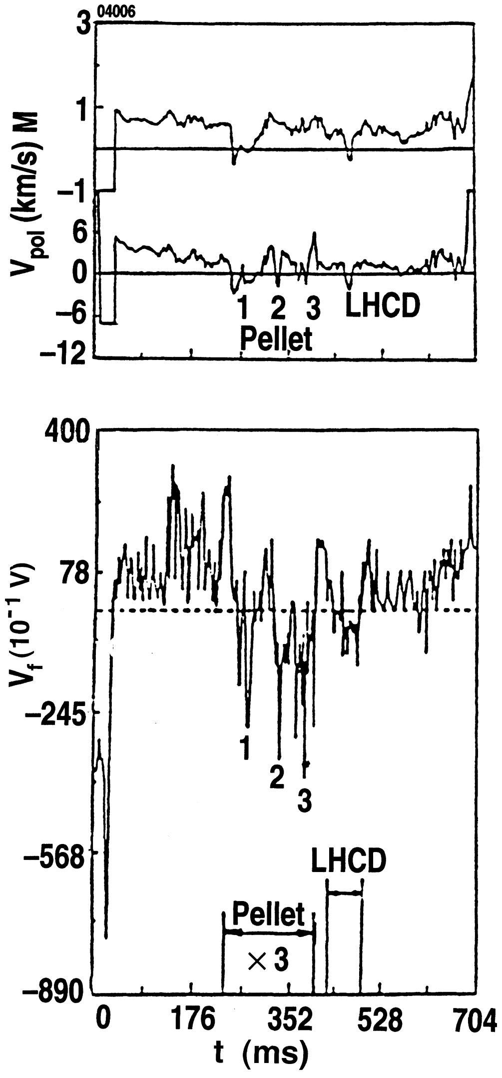

Fig. 2. Time evolution of plasma toroidal flow Mach number M, poloidal flow Velocity V_{pol} and plasma floating potential V_f in HL-1M, during Multi-shot Pellet Injection.

of pellet injection on the plasma potential are characterized by very large, sharp changes, see Fig. 2, and the electric-field becomes more negative, as shown in Fig. 3. These observations are approximate with the experiment results of the JIPP T-IIU tokamak [16].

3.2. Supersonic beam injection

The experiment of supersonic beam injection in the tokamak plasma is also an important method for fueling, controlling the density profile and improving the confinement of a tokamak plasma. Pulsed supersonic beams are of great advantage for having high speed, small spread of velocity, small angular distribution and high instantaneous intensity. The mean particle velocity of the hydrogen molecular beam at a distance of 1 m is about 500 m/s, but the local sonic velocity is about 260 m/s, so that the Mach number of the beam is $M = 2$.

In the experiment of SBI fueling τ_E increases with increasing plasma density up to $n_e = 6 \times 10^{19}$ m^{-3}. Estimation of the energy confinement time has shown that τ_E increases from 15–18 ms for normal ohmic discharge to 26 ms for SBI. These results have indicated a significant increase in the confinement behavior during SBI. SBI 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 by 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 of the boundary plasma have been changed sharply. The poloidal rotation velocity V_{pol} begins to increase from the small values observed in the OH-phases ($|V_{pol}| \leqslant 1.0$ km/s) to higher values ($|V_{pol}| \leqslant 3.8$ km/s) in the electron diamagnetic direction, because the electric field becomes more negative (Fig. 3).

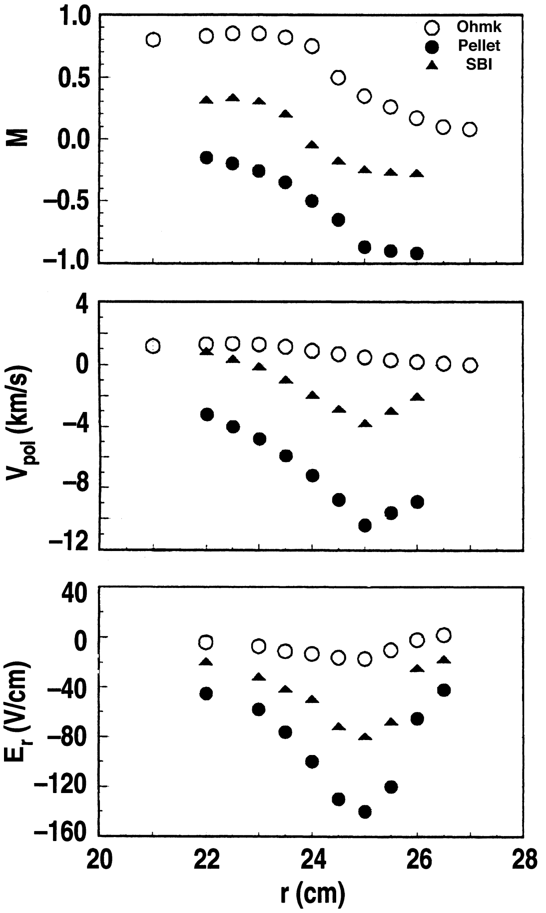

Fig. 3. The radial profiles of M, V_{pol} and radial electric-field E_r, during ohmic-heated discharge, MPI and SBI.

4. Discussion

The basic relation between the macroscopic drift velocity of a particle and a radial electric field E_r is obtained from the radial component of the equation of

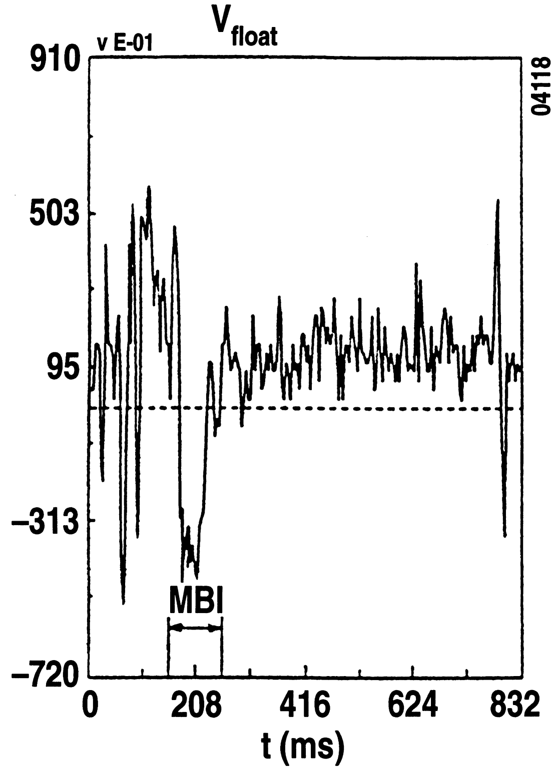

Fig. 4. Time evolution of plasma floating potential V_f, during SBI.

motion for a particle. In the tokamak plasma, the basic relation between the perpendicular fluid velocity of a particle $V_{i\perp}$ and E_r is the radial force balance [17]

$$eZ_i n_i(E_\mathrm{r} - V_{i\perp}B) = \frac{\mathrm{d}p_i}{\mathrm{d}r}, \qquad (1)$$

where eZ_i, n_i and p_i are the ion charge, density and pressure. In Eq. (1), the perpendicular component of plasma flow velocity $V_{i\perp}$ is tangential to the magnetic surfaces and nearly in the direction of the poloidal flow velocity V_pol. We can rewrite Eq. (1) as

$$V_\mathrm{pol} = V_{i\perp} = \frac{E_\mathrm{r}}{B} - \frac{1}{eZ_i n_i B}\frac{\mathrm{d}p_i}{\mathrm{d}r}. \qquad (2)$$

If we consider the poloidal projection of the plasma parallel flow: $V_t B_\mathrm{pol}/B$ (B_pol is the poloidal component of the toroidal magnetic field. V_t is the plasma toroidal flow velocity). The poloidal flow velocity of the edge plasma can be written as

$$V_\mathrm{pol} = \frac{E_r}{B} - \frac{1}{eZ_i n_i B}\frac{\mathrm{d}p_i}{\mathrm{d}r} + \frac{B_\mathrm{pol}}{B}V_\mathrm{t}. \qquad (3)$$

It is clear that the poloidal velocity is determined by three factors: (1) the poloidal component of the $\boldsymbol{E} \times \boldsymbol{B}$ 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 the experiment of the MPI and SBI on the HL-1M tokamak, the changes of the radial electric field E_r and the ion pressure gradient d*p*/d*r*, 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 Fig. 3, during MPI, the peak value of the radial electric field E_r is of the order of -14 kV/m (at $B_\mathrm{t} = 2.0$ T) and the corresponding peak value of the poloidal velocity V_pol is of the order of -10 km/s; during SBI, the peak value of the radial electric field E_r is of the order of -8 kV/m (at $B_t = 2.5$ T) and the corresponding peak value of the poloidal velocity V_pol is of the order of -3.8 km/s. 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 $\boldsymbol{E} \times \boldsymbol{B}$ drift. The increase of the poloidal rotation velocity decreases the level of the turbulent fluctuations, and the plasma confinement thereby improves.

In the experiment of the MPI and SBI, we also found that the toroidal flow Mach number becomes negative, that 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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