ELSEVIER

Journal of Nuclear Materials 241–243 (1997) 1234–1237

journal of nuclear materials

The fluctuations and flow velocities measured with a Mach probe array on the HL-1M tokamak

W.Y. Hong *, E.Y. Wang, L.B. Ran, S.K. Yang, Y.D. Pan, L.Y. Chen, S.J. Qian

Southwestern Institute of Physics, P.O. Box 432, Chengdu, Sichuan 610041, PR China

Abstract

This paper describes a Mach probe array with four pins which can measure not only parallel flows but the flow perpendicular to the magnetic field as well. Experimental measurements of the fluctuations and velocities of the toroidal and the poloidal flow have been carried out on both of SOL and the boundary region of HL-1M for ohmic, biased H-mode and LHCD discharges. The results show that the suppressions of the fluctuations are related to poloidal rotations produced by electrode biasing and LH waves injecting in the improved particle confinement modes.

Keywords: HL-1M; Tokamak; SOL plasma; Radial electric field; Plasma flow diagnostic

1. Introduction

The determination of flow velocity in scrape-off layer (SOL) and the boundary of tokamak plasma has become of prime importance due to its possible role in confinement and the L–H mode transition [1–3]. Several experiments have used Mach probes to measure velocities [4–9]. With these probes, two collectors aligned with the magnetic field, and shadowed from one another collecting ion saturation current from the upstream and downstream, are used to obtain the Mach number of the flow [10]. This method is usually applied for determination of the velocity parallel to the magnetic field.

A Mach probe array with four pins is described in this paper. It can measure not only parallel flows but the flow perpendicular to the magnetic field as well. Measurements of the fluctuations and flow velocities are carried out on HL-1M with this probe array for ohmic, biased H-mode and LHCD experiments in the boundary and SOL regions.

2. Experimental arrangement and Mach 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, pulse duration up to 1 s, $n_e = 1\text{–}6 \times 10^{19}$ m^{-3}, $T_e(0) \sim 1$ keV and two full poloidal graphite limiters located at 180° from each other toroidally. A simple chamber wall boronization technique was employed in HL-1M [11].

A Mach probe array assembly is mounted on a long shaft which can be moved radially inboard and outboard, and rotated around the axis of the shaft by a magnetometric transmission rod and at 22.5° from outboard midplane. The probe shaft was located at 22.5° toroidally from the annular poloidal limiter.

The Mach probe array uses four tips (labels a, b, c and d) mounted on a 20 mm diameter cylindrical head made of graphite as shown in Fig. 1. With these probes, tips a–b and d–c were aligned with the magnetic field, tips a–d and b–c were aligned perpendicularly to the magnetic field. The four tips shadowed from one another collect ion saturation currents from the upstream and downstream directions of the parallel magnetic field as well as perpendicular to the magnetic field. The parallel flow Mach number M of the plasma is defined as a ratio of the drift velocity V_f in magnetic field direction to the ion acoustic speed C_s:

$$M = V_f / C_s, \tag{1}$$

$$C_s = \left[k(T_i + T_e)/m_i \right]^{1/2}, \tag{2}$$

where T_i and T_e are the electron and ion temperature respectively, k is the Boltzmann constant, and m_i is the

---

* Corresponding author. Tel.: +86-28 558 1122; fax: +86-28 558 1053.

PII S0022-3115(96)00705-2

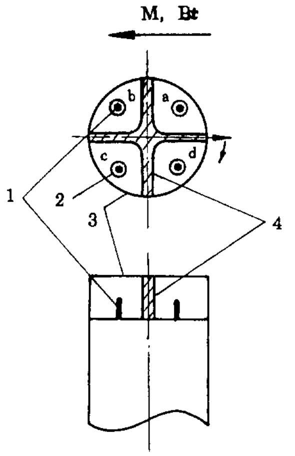

Fig. 1. Schematic of a Mach probe array: 1 – Mach probe, 2 – ceramic pipe, 3 – graphitic socket, 4 – graphitic separator.

ion mass. The Mach number can be determined using the expression [9]

$$M = 0.6\ln(J_u/J_d), \tag{3}$$

where J_u and J_d are the upstream and downstream ion saturation current collected by the pins a(d) and b(c), respectively. The poloidal velocity V_{pol} is estimated by [12]:

$$J_{pol} = n_e e V_{pol}, \tag{4}$$

where V_{pol} is the poloidal flow velocity which is basically the $E \times B$ flow, and J_{pol} and n_e are poloidal current density and density, respectively.

The parallel flow velocity shear $U_{\|}$ of the plasma parallel velocity change could be calculated from $(L_n/C_s)(\mathrm{d}V_f/\mathrm{d}r)$ [13]; it is the normalized radial derivative of the ion parallel velocity, where L_n is the density gradient scale length, $L_n = n/(\mathrm{d}n/\mathrm{d}r)$.

3. Experimental results and discussions

In the tokamak the plasma dynamics in the bulk region and in SOL are significantly different from each other. As a consequence, there must be a transition region around the edge of the limiter or the last closed flux surface (LCFS), where some of the plasma parameters change rather rapidly across this region. In other words, the edge plasma is characterized by a rapid radial dependence of plasma parameters such as parallel plasma flow. Particles may move freely along the magnetic field lines in the bulk plasma, while such freedom does not exist in SOL due to the presence of limiters or divertor plates.

The instability driven by the cross-field gradient (shear) of the plasma mass flow velocity parallel to the magnetic field in an inhomogeneous plasma has been investigated extensively since the early 1970's [14]. Recently, the L-mode to H-mode (L–H) transition in tokamak plasma confinement was modeled to be related to the presence of the poloidal flow shear near the plasma edge [13,15].

3.1. Ohmic discharge

The edge radial profiles of plasma density, Mach number, parallel velocity shear and poloidal velocity measured by Mach probe array for I_p = 150 kA and 310 kA are shown in Fig. 2. It shows that there is a sharp radial gradient of parallel ion mass flow from a confined interior plasma to SOL plasma regulated by the cold plasma sheath surrounding the limiter. For higher I_p, the flow velocity increases only slightly. The turbulence of plasma is driven by the free energy associated with the radial gradient of the parallel flow velocity and in turn produces an acceleration in the poloidal direction [13]. Fig. 2 indicates that the

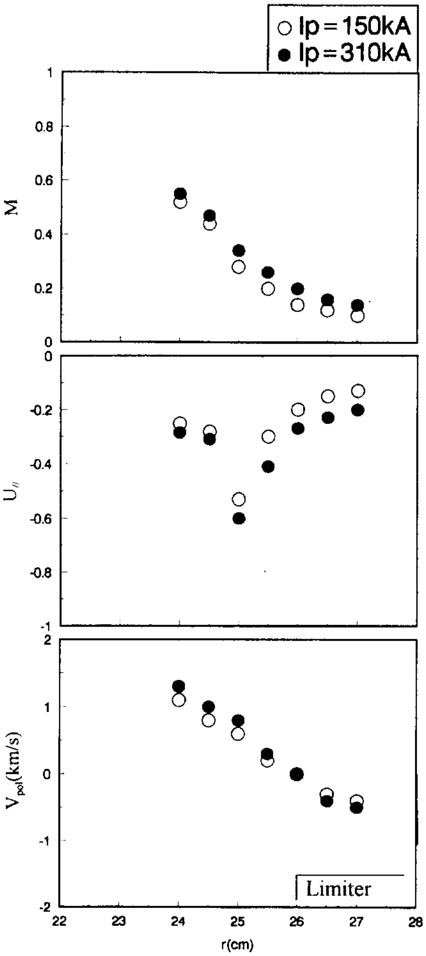

Fig. 2. The radial profiles of parallel flow Mach number M, parallel flow velocity shear $U_{\|}$ and poloidal flow velocity V_{pol} in the HL-1M tokamak edge for different ohmic discharge currents.

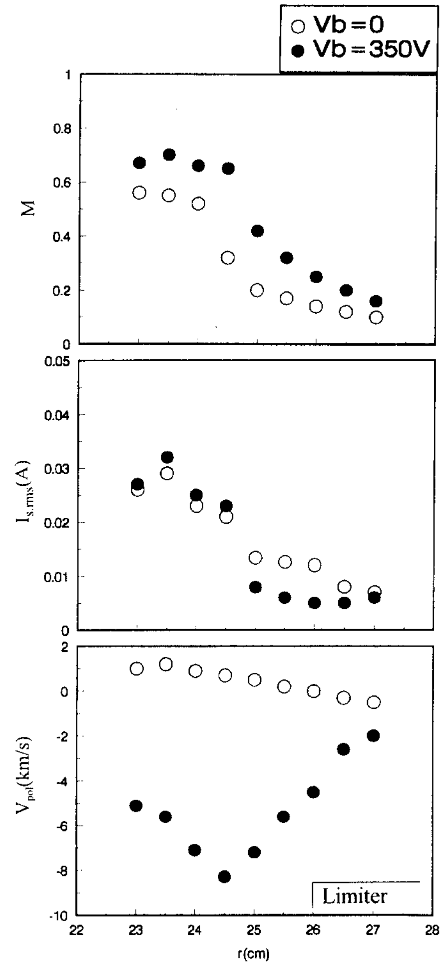

Fig. 3. The radial profiles of Mach number M, ion saturation current fluctuations $I_{s,rms}$ and poloidal flow velocity V_{pol} when the biased electrode is at $r_b = 24$ cm and bias voltage $V_b = 0$ and $V_b = 350$ V, respectively, in the HL-1M tokamak.

maximum gradient of parallel flow occurs at the same radial position as the location of maximum poloidal velocity. It is much more obvious in Fig. 3 which is for biased H-mode. The Mach number was increased with boronization and decreased with gas puffing and laser blow off.

3.2. Biased H-mode

Biased H-mode experiments were performed in HL-1M. The electrode used to achieve an H-mode consists of a cylindrical graphite head, 4.4 cm in diameter and 2.0 cm in length, mounted on a steel shaft housed in an insulating sleeve made of ceramic. The electrode is inserted approximately 2 cm inboard of the limiter into the plasma from the top of the chamber.

The biasing potential on the electrode modifies the electric field at the plasma edge and causes a change in the fluctuations and flow velocity which is observed with the Mach probe array. In Fig. 3, we present the radial profiles of Mach number M, ion saturation current fluctuations and poloidal velocity for bias voltage $V_b = 0$ and $V_b = 350$ V on electrode, respectively. Across the edge at $r/a \sim 0.9$–1.0, the toroidal Mach number M increases by about 20–50%, fluctuations reduce by about 10–50%, the poloidal plasma rotation speed varies from less than 1 km/s to 8.5 km/s for biased H-mode corresponding to $E_r \sim 20$ kV/m towards the outward direction.

3.3. LH wave injection

The HL-1 and HL-1M experiments showed significant density increase (up to a factor of 2) during combined ohmic and LHCD discharges [16]. In these experiments, decreases in H_α signals by ~ 40–60% and slight decreases in large impurity emissions also observed. Estimation of particle confinement time at $n_e \sim 1 \times 10^{19}$ m^{-3} has shown that 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 100 kW. 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 and poloidal rotation speed during ohmic and LHCD are given in Fig. 4. It shows that the suppressions

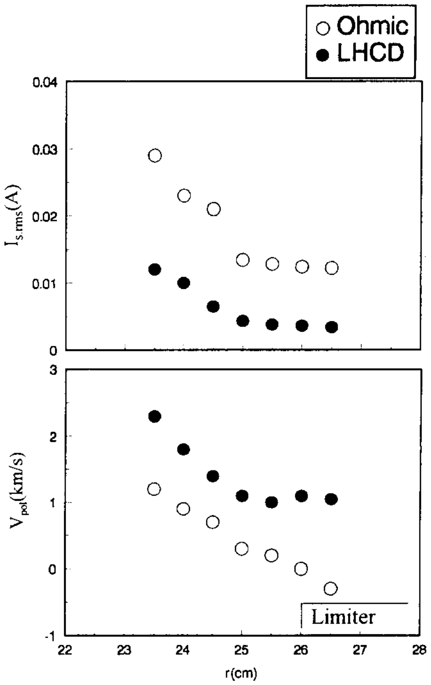

Fig. 4. The radial profiles of $I_{s,rms}$ and V_{pol} when LHCD is turned on during ohmic discharge of the HL-1M tokamak.

of the density fluctuations are accompanied by a higher poloidal rotation induced by LH wave injection.

4. Conclusions

Experimental measurements of the radial profiles of the plasma parallel and perpendicular flows have been carried out on both SOL and the boundary region of HL-1M for different discharge conditions. It indicates that the L-mode to H-mode (L–H) transition of tokamak confinement was found to be accompanied by poloidal rotation. The change of instability of edge plasma driven by the cross-field gradient (shear) of the plasma mass flow velocity parallel to the magnetic field is also related to the poloidal rotation. Experimental results indicate that the parallel flow velocity obviously changes at about the same radial location as the location of maximum poloidal velocity and maximum toroidal flow shear layer which suppressed the plasma density fluctuations and affects the stability of the local plasma.

References

[1] R.J. Groebner, K.H. Burrell and R.P. Seraydarian, Phys. Rev. Lett. 64 (1990) 3015.
[2] S.-I. Itoh and K. Itoh, Phys. Rev. Lett. 60 (1988) 2276.
[3] K.C. Shang and E.C. Crume, Jr., Phys. Rev. Lett. 63 (1989) 2396.
[4] P.J. Harbour and G. Proudfoot, J. Nucl. Mater. 121 (1984) 222.
[5] P.J. Harbour et al., J. Nucl. Mater. 128–129 (1984) 359.
[6] P.J. Harbour et al., J. Nucl. Mater. 162–164 (1989) 236.
[7] I.H. Hutchinson, Phys. Fluids 30 (1987) 3777.
[8] I.H. Hutchinson, Phys. Fluids 31 (1988) 2726.
[9] G. Proudfoot, P.J. Harbour, J. Allen and A. Lewis, J. Nucl. Mater. 128–129 (1984) 180.
[10] P.C. Stangeby, Phys. Fluids 27 (1984) 2699.
[11] O.I. Buzhinsky et al., J. Nucl. Mater. 191–192 (1991) 1413.
[12] C.S. MacLatchy et al., Rev. Sci. Instrum. 63(8) (1992) 3923.
[13] J.Q. Dong and W. Horton, Phys. Plasma 1(10) (1994) 3250.
[14] P.J. Catto et al., Phys. Fluids 16 (1973) 1719.
[15] X.N. Su et al., Phys. Plasmas 1 (1994) 1905.
[16] X.D. Ding et al., LHCD Experiments on the HL-1 and HL-1M tokamak, Res. Rep., SWIP, 1995.