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Thickness of the layer of high shear radial electric field in JFT-2M H-mode plasmas

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The poloidal rotation velocity profiles both in low-confinement (L) and high-confinement (H) mode measured in JAERI Fusion Torus 2 Modified (JFT-2M) [Phys. Rev. Lett. **65**, 1364 (1990)] are compared with H-mode models based on ion orbit loss. The profiles of poloidal rotation velocity measured in L and H modes are consistent with the calculation which consists of ion orbit loss model. The observed dependence of the thickness of the layer of high shear E_r on poloidal gyroradius is explained by the radial transport of poloidal rotation velocity.

I. INTRODUCTION

Since the transition from low-confinement mode (L mode) to high-confinement mode (H mode) was discovered in 1982 on axisymmetric divertor experiment (ASDEX),[1] the H-mode plasma has been investigated from both the experimental and theoretical aspects. Recently the poloidal rotation velocity and the radial electric field near the plasma periphery have been found to play an important role at the L- to H-mode transition. The edge poloidal rotation velocity increases in the electron diamagnetic direction in the H-mode plasma heated by the neutral beam injection (NBI), which indicates the existence of large shear of negative radial electric field, E_r, just inside the separatrix. It has been observed in (DIII-D),[2–4] JAERI Fusion Torus 2 Modified (JFT-2M)[5–7] and ASDEX.[8] This negative radial electric field may be driven by large outward fluxes of ions, such as ion orbit loss at the plasma edge. The bias experiments[9,10] demonstrated that the induced radial current can trigger the L- to H-mode transition and support the hypothesis[11–14] that the ion outward fluxes causes the L- to H-mode transition. Since the discovery of H mode, various theoretical models for the L- to H-mode transition have been developed.[15–20] The H-mode models based on ion orbit loss have been proposed to explain fast phenomena such as E_r change at the L- to H-mode transitions. In these models, the thickness of the layer of high shear radial electric field is expected to have some poloidal gyroradius dependence, because the ion orbit loss is localized within the size of poloidal gyroradius, ρ_{pi}, near the separatrix. Although the "source of torque" by orbit loss should be localized within ρ_{pi}, the thickness of the layer of high shear E_r is expected to be larger than ρ_{pi} because of the radial transport of poloidal momentum.[21–24] In this paper we present the transport analysis of poloidal momentum measured in the JFT-2M and discuss how sensitive the thickness of shear flow is to ρ_{pi}.

II. POLOIDAL MOMENTUM BALANCE EQUATION

The plasma flow velocity **V** is governed by the momentum equation[13,15]

$$m_i n_i \frac{\partial \mathbf{V}}{\partial t} + m_i n_i \mathbf{V}\cdot\nabla\mathbf{V} = -\nabla p - \nabla\Pi + \rho\mathbf{E} + \mathbf{j}\times\mathbf{B} + \mathbf{F}, \tag{1}$$

where m_i is ion mass, n_i is ion density, p is plasma pressure, $\nabla\Pi$ is viscosity, ρ is charge density, and **F** is force to provide plasma flow. Assuming the poloidal symmetry of flow and pressure, $\mathbf{V}\cdot\nabla\mathbf{V}$ and ∇p term in poloidal component can be neglected. The profile of radial electric field is determined through poloidal momentum balance equation:

$$m_i n_i \frac{\partial V_\theta}{\partial t} = j_r \times B_\phi + \rho E_\theta + F_\theta - \langle \nabla_\parallel \Pi \rangle_\theta - \langle \nabla_\perp \Pi \rangle_\theta, \tag{2}$$

where $-j_r \times B_\phi = \epsilon_0 B_\phi \ \partial E_r/\partial t \approx \epsilon_0 B_\phi^2 \partial V_\theta/\partial t$ and $\rho E_\theta \leqslant |\tilde{j}_r \tilde{B}_\phi| \leqslant |(k/\mu_0)\tilde{B}^2|$. The $j_r \times B_\phi$ term is a factor of $\epsilon_0 B_\phi^2/(n_i m_i)$ smaller than the $m_i n_i \, \partial v_\theta/\partial t$ term and can be neglected. The time averaged ρE_θ becomes finite, when magnetic fluctuation exists in the plasma. However, this term is also negligible, because the fluctuation level of $\Delta B/B$ is of the order 10^{-3}–10^{-4}, wave number k [$=(m/2\pi r)$, where m is mode number and r is plasma minor radius] of magnetic fluctuation is $\sim$0.5. The third term, F_θ, is a poloidal force due to nonambipolar flux of ions and electrons in the plasma and $\langle \nabla_\parallel \Pi \rangle_\theta$ and $\langle \nabla_\perp \Pi \rangle_\theta$ are poloidal component of parallel and perpendicular viscosity, respectively.

In the steady-state phase of H mode, the poloidal force, F_θ, should be balanced with viscosity; $F_\theta = \langle \nabla_\parallel \Pi \rangle_\theta + \langle \nabla_\perp \Pi \rangle_\theta$. It has been experimentally found that the perpendicular viscosity is anomalous and the parallel viscosity is neoclassical.[25] Therefore, we estimate parallel viscosity using neoclassical theory:[13]

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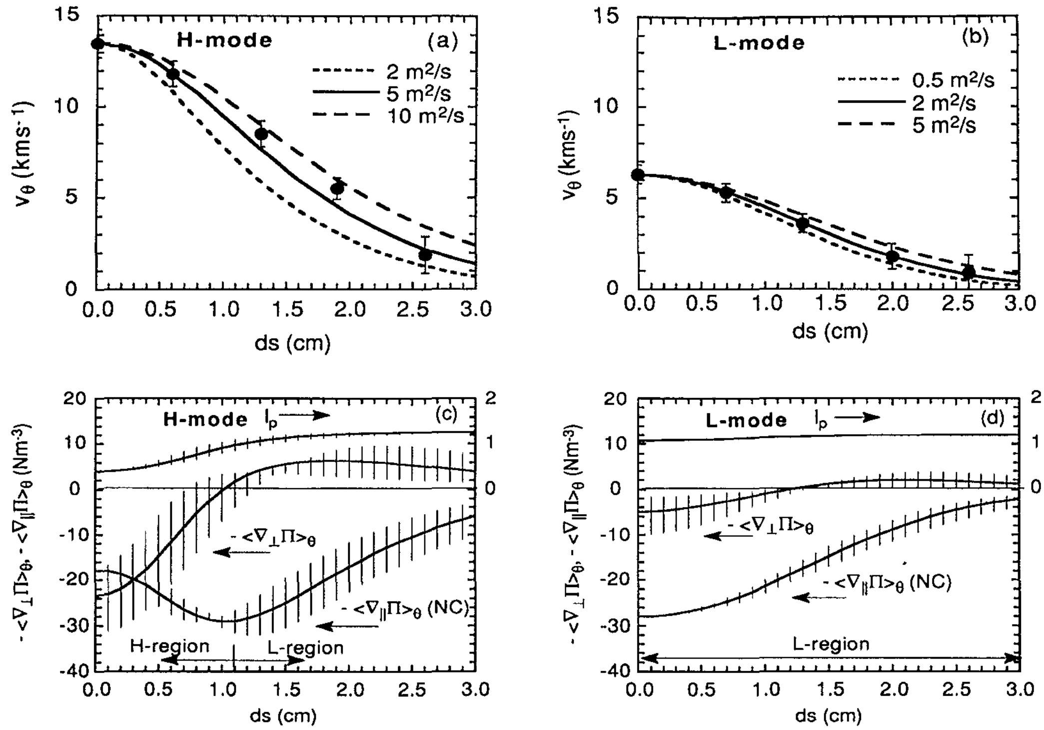

FIG. 1. Radial profile of poloidal rotation velocity for (a) H mode and (b) L mode, and parallel viscosity, perpendicular viscosity, and Ip for (c) H mode and (d) L-mode plasmas. In (c) and (d) the μ_θ values are 5 m^2/s for H mode and 2 m^2/s for L mode. The ds stands for the distance from the peak of poloidal rotation velocity; $ds=r_{\text{peak}}-r$.

$$\langle \nabla_\| \Pi \rangle_\theta = (\sqrt{\pi}/4)(r/R^2) n_i m_i v_{\text{th}} (B/B_\theta)(I_p V_\theta + I_T V_{p0}),$$

where I_p and I_T are coefficients of energy integral and V_{p0} is defined as $-\rho_i v_{\text{th}}\,(\partial T/\partial r)/2T$. The parallel viscosity is almost proportional to the magnitude of poloidal rotation velocity since V_{p0} term is much smaller than v_θ and energy integrals I_p and I_T are of the order unity. The perpendicular viscosity term is determined by the velocity shear in the different magnetic surface with a coefficient of shear viscosity μ_θ as $\langle \nabla_\perp \Pi \rangle_\theta = -n_i m_i \mu_\theta\, \partial^2 V_\theta/\partial x^2$. The coefficient of shear viscosity is known to be of the order of the anomalous energy transport coefficient experimentally[26] and theoretically.[27] The coefficient μ_θ is given as a parameter in this analysis. The poloidal force F_θ is a $j\times B$ force due to ion orbit loss and is considered to increase as exponential form toward the separatrix; $F_\theta = F_\theta(0) \times \exp(-c^2x^2/\rho_{\theta i}^2)$. The x here is a distance from the location of poloidal rotation peak, r_{peak}. The coefficient c is a shape factor of poloidal force and is of order unity. The poloidal rotation velocity profile is determined by solving the equation

$$F_\theta(0)\exp\left(\frac{c^2x^2}{\rho_{\theta i}^2}\right) = \frac{\sqrt{\pi} r n_i m_i v_{\text{th}} B}{4R^2 B_\theta}(I_p V_\theta + I_T V_{p0}) - n_i m_i \mu_\theta \frac{\partial^2 V_\theta}{\partial x^2}. \quad (3)$$

The boundary conditions in this calculation are $\partial v_\theta(0)/\partial r = 0$ and $v_\theta(\infty)=0$. The poloidal force $F_\theta(0)$ is chosen to match the peak poloidal rotation velocity $v_\theta(0)$ to the measured values. The shape factor of poloidal force F_θ is fixed ($c=1$) in the analysis presented in this paper.

III. POLOIDAL ROTATION VELOCITY PROFILES IN JFT-2M

The poloidal rotation velocities are measured with multichord spectroscopy[28] for the deuterium plasma in the JFT-2M tokamak with a major radius R of 1.3 m, a minor radius a of 0.3 m, a toroidal field B_θ of 1.26 T, a plasma current of 280 kA, a safety factor $q=2.8$ in an upper single-null-divertor configuration. The neutral beam (NB) is injected at $t=700$ ms with the power of 1.2 MW in balanced NB injection. The power of NB decreases below H-mode threshold power (0.7 MW) at $t=825$ ms. The plasma shows L- to H-mode transition at $t=730$ ms and H- to L-mode transition at $t=835$ ms. The edge electron density and ion temperature at the peak of poloidal rotation velocity are 3.7×10^{19} m^{-3} and 82 eV (in L mode after H–L transition) and 2.8×10^{19} m^{-3} and 96 eV (in H mode), respectively. Figures 1(a) and 1(b) show the radial profiles of measured poloidal rotation velocity and calculated ones with various μ_θ values for L-mode phase ($t=875$ ms) and H-mode phase ($t=742$ ms), respectively. Figures 1(c) and 1(d) show the perpendicular, parallel viscosities and coefficient Ip for the μ_θ value in which the calculated poloidal rotation velocity profile show good agreement with measured profile. In L mode, the poloidal rotation velocity is below critical velocity for $\langle \nabla_\| \Pi \rangle_\theta$ change,[29] and the coefficient of Ip is around unity in all

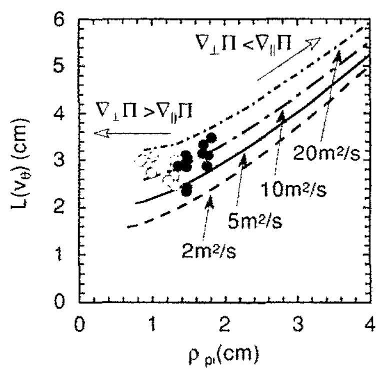

FIG. 2. The width of the poloidal rotation velocity shear, $L(v_\theta)$, as a function of poloidal gyroradius. Open circles are for hydrogen plasma and closed circles are deuterium plasma. Three lines are width of poloidal rotation velocity simulated with neoclassical parallel viscosity and anomalous perpendicular viscosity with three different magnitudes.

regions of the plasma. Neoclassical parallel viscosity is more dominant than perpendicular viscosity in L mode. Calculated poloidal rotation velocity profile is mainly determined by the balance of poloidal force and neoclassical parallel viscosity and is less sensitive to the magnitude of μ_θ in L mode. However, in H mode, the peak poloidal rotation velocity exceeds the critical velocity, and the coefficient Ip starts to decrease below unity (~ 0.4) toward the peak of poloidal rotation velocity. The neoclassical parallel viscosity becomes less important and the perpendicular viscosity becomes large enough to limit the peak poloidal rotation velocity, due to the sharp gradient of poloidal rotation velocity. The best fit of calculated poloidal rotation velocity profile to measured ones is obtained for $\mu_\theta = 5$ m^2/s in H mode. This perpendicular viscosity is comparable to the anomalous momentum diffusivity of toroidal rotation velocity or ion thermal diffusivity that are determined with transport analysis of the core plasma. It is noted that H region ($Ip < 1$) is located only near the peak of poloidal rotation velocity and the rest remains in L mode ($Ip > 1$). This result confirms analytical H-mode model.[21]

Figure 2 shows the width of the layer of the poloidal rotation velocity shear for various poloidal gyroradius ρ_{pi} with plasma current of 170 to 280 kA and with hydrogen and deuterium working gas. Since the influence of the perpendicular viscosity can be significant only in H mode, the calculation with various μ_θ values was done only in H mode. The widths of poloidal rotation velocity shear, $L(v_\theta)$, are defined as twice of the half-width at half-maximum (2HWHM) of the poloidal rotation velocity profile estimated only inside the separatrix in the H-mode plasmas. (The widths of poloidal rotation velocity shear were estimated with profiles both inside and outside the separatrix in the previous analysis.[6]) The linear dependence of the size of poloidal rotation velocity profiles on poloidal gyroradius is not observed with the existence of radial transport. The bold lines are calculated values for the width of poloidal rotation velocity profile with the constant density, n_e of 3×10^{19} m^{-3}, ion temperature, T_i of 100 eV, poloidal mach number, $B_\phi v_\theta / (B_\theta v_{\rm th})$ of 2, poloidal force profile parameter, c of 1, and various μ_θ values. This calculation demonstrates that the thickness of the layer of poloidal rotation velocity shear has offset linear like dependence on poloidal gyroradius in the large ρ_{pi} limit, and that the absolute value of the size agree with the measured ones. When μ_θ becomes smaller or poloidal gyroradius becomes large, perpendicular viscosity becomes less important, so that linear relation between the size of poloidal rotation velocity profile and poloidal gyroradius becomes clear. On the other hand, when μ_θ becomes larger or the poloidal gyroradius becomes smaller, the radial transport becomes more dominant, i.e., perpendicular viscosity is as large as parallel viscosity. In the limit of $\rho_{pi} = 0$, the size of poloidal rotation velocity shear are roughly proportional to $\mu_\theta^{1/2}$. In the condition of the H-mode experiment on JFT-2M tokamak discussed here, perpendicular viscosity at the peak is comparable to parallel viscosity.

IV. DISCUSSIONS

Recently, the effects of orbit squeezing[30] has been studied by Shaing,[22] and it was proposed theoretically that the width of the edge radial electric-field layer in the H mode, as estimated from the ion orbit loss model, does not depend explicitly on the poloidal gyroradius. However, the expression of the layer thickness in Ref. 22 contains $\partial E_r / \partial r$ (which is a function of the layer thickness), so that the explicit form of the gradient layer width is not completed. In other words, the determination of the layer width would be given waiting the solution of the radial structure. The experimental data in larger poloidal gyroradius is required to complete more definite test of the ion orbit loss H-mode model. However, the scanning range of poloidal gyroradius is relatively narrow. This is not due to the limitation of operating range in JFT-2M but due to the feature in tokamak plasma, since the decrease of poloidal magnetic field to access higher ρ_{pi} is compensated with the decrease of ion temperature.

In this analysis, the magnitude of poloidal force is chosen to match the measured peaked poloidal rotation velocity. The steady-state analyses cannot determine the magnitude of $F_\theta(0)$. The value $F_\theta(0)$ remains a fitting parameter. A direct measurement of poloidal force requires studies on the dynamic time scale of the transition. The measurements of poloidal rotation velocity at the transit phase, such as L–H transition can give lower limit of poloidal force F_θ. Theory based on the ion orbit loss has predicted a typical transition time of $\sim 30\ \mu$s,[15] which is far beyond the presently available time resolution. Since the time resolution of the measurements is planned to be improved up to 8 kHz, the complete test is left in future study. In conclusion, the thickness of poloidal rotation velocity shear and its weak dependence on poloidal gyroradius measured in JFT-2M could not give a definite confirmation of the model, but clearly show the existence of perpendicular viscosities of 2 m^2/s–20 m^2/s.

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