Effect of Poloidal Density Variation of Neutral Atoms on the Tokamak Edge

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Abstract

Neutral atoms in the tokamak edge affect the radial electric field and plasma flow velocity through charge-exchange (CX) interactions. Neutral effects are more important than neoclassical processes if the fraction of atoms in the plasma exceeds about 10^{-4}, as is typical in the plasma edge region, just inside the separatrix. The effect of neutral atoms depends sensitively on the poloidal location of the atoms. It is found that the radial electric field and toroidal flow velocity in the edge plasma tend to be larger if the atoms are concentrated on the inboard side rather than on the outboard side. This effect may offer an explanation for recent observations on MAST and COMPASS-D indicating easier H-mode access with inboard fueling.

1. Introduction

Recent experimental observations on MAST and COMPASS-D indicate easier H-mode access when gas is puffed from the inboard side of the tokamak [1-3], suggesting that the poloidal distribution of the neutrals has an essential influence on the L-H transition. This motivates the present work, where we use earlier theory [4-7] to investigate the effect of a poloidally varying source of atoms on the electric field and flow velocity of a collisional edge plasma. A longer and more detailed account will be published elsewhere [8]. Our results suggest an external means for controlling the toroidal flow and radial electric field and their shearing rates, and have motivated further measurements on MAST which appear to support the predictions [2].

2. Plasma flow and radial electric field

In general, when the neutral fraction is increased, the neutrals will influence the plasma confinement in different ways: they act as a particle source via ionization in the particle balance equation; they modify the parallel and poloidal ion flow and flow shear; they contribute to a radial heat loss through the neutral plus ion energy balance equation; and perhaps more significantly, they can modify the radial electric field through the transport of toroidal angular momentum.

If the density of the neutrals in the plasma is relatively high, namely, $n_n/n_i \gtrsim \rho_i/qR \sim 10^{-3}$, the bulk ion parallel flow is modified in a way calculated in Refs. [6, 7]. Here q is the safety factor, ρ_i is the ion gyroradius, and n_n and n_i denote the density of neutral atoms and ions, respectively. The neutrals affect the plasma flow through the additional parallel viscosity provided by the neutral population, and through the direct modification of the ion distribution function by ion-neutral CX collisions.

When the density of the neutrals is too low to influence the ion parallel and poloidal flow directly, the neutrals can still affect the radial electric field, if $n_n/n_i \gg$

$(\epsilon q\rho_i)^2/(L_n\lambda_i)\sqrt{\nu_x/\nu_z} \sim 10^{-4}$ [9], where L_n is the density scale length, ϵ is the inverse aspect ratio, λ_i is the ion mean-free path, and ν_x and ν_z are the CX and ionization frequencies, respectively. In a steady state plasma without momentum sources, there can be no radial transport of toroidal angular momentum, $\langle R\hat{\boldsymbol{\varphi}} \cdot (\boldsymbol{\pi}_i + \boldsymbol{\pi}_n) \cdot \nabla\psi\rangle = 0$, where $\boldsymbol{\pi}_i$ and $\boldsymbol{\pi}_n$ are the viscosity tensors of ions and neutral atoms, respectively. At the edge, the neutral viscosity dominates over its purely neoclassical counterpart, $\langle R\hat{\boldsymbol{\varphi}} \cdot \boldsymbol{\pi}_i \cdot \nabla\psi\rangle \ll \langle R\hat{\boldsymbol{\varphi}} \cdot \boldsymbol{\pi}_n \cdot \nabla\psi\rangle$. If the neutral viscosity is dominant, the radial electric field is determined by neutral atoms rather than neoclassical processes. It is also possible that anomalous viscosity due to turbulence overwhelms both the neutral and the ion viscosities, in which case the electric field is determined by turbulence rather than by neutrals or neoclassical processes. Poloidal variation of the neutral fueling can also drive a convective radial ion heat, but this has recently been evaluated and shown to be smaller than the radial neutral heat flux in the absence of asymmetry [9].

In neoclassical theory, the ion flow velocity within a flux surface is of the form

$$\mathbf{V}_i = \omega(\psi)R\hat{\boldsymbol{\varphi}} + u_{i\theta}(\psi)\mathbf{B}, \tag{1}$$

where ψ is the poloidal flux function, φ the toroidal angle in the direction of plasma current, $\hat{\boldsymbol{\varphi}} = R\nabla\varphi$ is the toroidal unit vector and $\omega(\psi) = -\Phi' - p_i'/(n_i e)$, with Φ denoting the electrostatic potential, the prime denotes a derivative with respect to ψ, and $p_i = n_i T$ the ion pressure. In a pure hydrogen plasma $u_{i\theta}(\psi) = -kIT'/(e\langle B^2\rangle)$ where the parameter k depends on collisionality, $I = RB_\varphi$, and $\langle \ldots \rangle$ denotes flux-surface average. In this paper, we consider the Pfirsch-Schlüter regime, where $k \simeq 1.8 + 0.05\langle B^2\rangle\langle(\nabla_\parallel \ln B)^2\rangle/\langle(\nabla_\parallel B)^2\rangle$ [8]. As suggested by Eq. (1), the radial electric field is intimately coupled to toroidal rotation, and it can be calculated from the transport equation of angular momentum.

3. Short neutral mean-free path

If the scale length of plasma density and temperature variation exceeds the neutral-atom mean-free path with respect to CX, then the radial transport of toroidal angular momentum becomes, [4] $\langle R\hat{\boldsymbol{\varphi}} \cdot \boldsymbol{\pi}_n \cdot \nabla\psi\rangle = -\langle \nabla\psi \cdot \nabla\left[RTn_n\left(V_{i\varphi} + (2q_{i\varphi}/5p_i)\right)\right]\rangle/\nu_x$, where $\nu_x = 2.08\sigma_x n_i v_T = K_x n_i$, $\sigma_x \simeq 6\cdot 10^{-19}$ m^2 is the CX cross section, $v_T = (2T/M)^{1/2}$ is the ion thermal velocity, and $\boldsymbol{q}_i$ is the ion heat flux.

In the Pfirsch-Schlüter regime the toroidal component of the ion heat flux is equal to $q_{i\varphi} = -5Rp_iT'/(2e)\left(1 - B_\varphi^2/\langle B^2\rangle\right)$. Furthermore, if the radial scale of the neutral density variation $L_n = \sqrt{\lambda_x\lambda_z}$ is comparable to the plasma density scale length, but much shorter than the ion temperature scale length (as is normally observed), the condition of no radial transport of toroidal angular momentum simplifies to

$$\left\langle R^3 B_\theta^2 V_{i\varphi} n_n' \right\rangle = \frac{T'}{e}\left\langle R^4 B_\theta^2 \left(1 - \frac{B_\varphi^2}{\langle B^2\rangle}\right) n_n' \right\rangle. \tag{2}$$

Here, λ_x and λ_z are the CX and ionization mean-free paths, respectively.

If the neutral fueling source is poloidally localized, then from Eqs. (1) and (2), respectively, we obtain the toroidal flow velocity at that location as

$$V_{i\varphi}^{\rm puff} = \frac{RT'}{e}\left(1 - \frac{B_\varphi^2}{\langle B^2\rangle}\right)\bigg|_{\rm puff} = \omega R_* + \frac{Iu_{i\theta}}{R_*}, \tag{3}$$

where R_* denotes the value of R at the position of the gas puff. Using Eq. (1) to find $V_{i\varphi}$ on the flux surface in question, and eliminating ω and $u_{i\theta}$, we obtain

$$V_{i\varphi} = \frac{I^2 T'}{e\langle B^2\rangle R}\left[k\left(\frac{R^2}{R_*^2}-1\right)+\frac{\langle B^2\rangle R^2}{I^2}-\frac{R^2}{R_*^2}\right] \equiv \frac{I^2 T'}{e\langle B^2\rangle R} F_V. \tag{4}$$

Note that the ion toroidal flow in Eq. (4) is independent of the neutral density provided the neutral viscosity dominates over anomalous and ion viscosities. Figure 1 shows the normalized toroidal flow velocity at the outer midplane as a function of the poloidal angle of the gas puff for typical equilibria from Alcator C-Mod and MAST. Note that the flow velocity is much larger if the puff is applied on the inboard side rather than elsewhere on the flux surface. For a normal profile ($T' < 0$) $V_{i\varphi}$ is in the counter-current direction ($V_{i\varphi} < 0$) since $F_V > 0$. Flow shear is introduced by the localization of the neutrals to a penetration depth L_n, and possibly by the change in k as the plasma becomes less collisional towards the core.

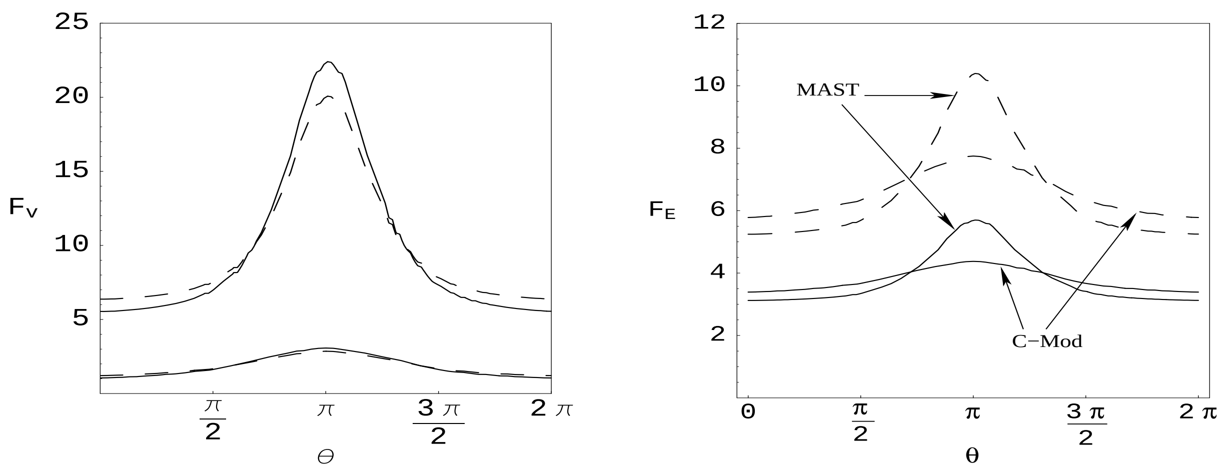

Figure 1: *Predicted normalized toroidal flow velocity (left) and radial electric field (right) at the outer midplane of MAST and Alcator C-Mod as a function of the poloidal angle of the gas puff, with $\theta = \pi$ at the inboard mid-plane. In the left figure, the solid lines represent the short mean-free path limit, the dashed lines are finite mean-free path results, with the parameters $C_T = 1.15$ and $C_P = 0.04$, corresponding to $\alpha = 3.1$ and $\gamma = 0.5$ and the upper pair of curves is for MAST, the lower pair of curves is for Alcator C-Mod. In the right figure, the solid and dashed lines represent the short mean-free path limits for $\eta_i = 1$ and $\eta_i = 2$, respectively.*

The radial electric field can be calculated by solving for ω in Eq. (1) and inserting $V_{i\varphi}^{\rm puff}$ from Eq. (3), to find

$$-\Phi' = \frac{T n_i'}{e n_i}\left[1+\eta_i\left(\frac{(k-1)I^2}{\langle B^2\rangle R_*^2}+2\right)\right] \equiv \frac{T n_i'}{e n_i} F_E \tag{5}$$

where $\eta_i = (\ln T)'/(\ln n_i)'$. Figure 1 shows F_E as function of the poloidal angle of the gas puff for MAST and Alcator C-Mod parameters. Since $F_E > 0$, for normal density and temperature profiles ($n_i' < 0$, $\eta_i > 0$), the edge radial electric field is inwards, as is usually observed in experiments. Note that the effect of the inboard gas puffing on the radial electric field is weaker than on the toroidal ion flow, and it depends on η_i.

4. Self-similar neutrals

The short mean-free path assumption is only marginally satisfied just inside the separatrix in most tokamaks. To include long mean-free path effects, the neutral viscosity can be evaluated using the self similar distribution from Ref. [10], obtained under the assumption that the ratio of mean-free path to the macroscopic scale length is constant throughout the region of interest: $\gamma \equiv -v_T/(n_i(K_x+K_z))|\nabla\psi|(\ln T)' = \text{constant}$. Then, for a poloidally localized gas puff, the toroidal ion flow is

$$V_{i\varphi} = \frac{I^2 T'}{e\langle B^2\rangle R}\left[k\left(\frac{R^2}{R_*^2}-1\right)+C_T\left(\frac{\langle B^2\rangle R^2}{I^2}-\frac{R^2}{R_*^2}\right)+C_P\frac{R^2 B_{\theta*}^2}{I^2}\right] \equiv \frac{I^2 T'}{e\langle B^2\rangle R}F_V, \quad (6)$$

where $B_{\theta*} = B_\theta(R_*)$ and we define $C_T = 2\int dxe^{-x^2}(x^4+9x^2/2-3)J/(15\int dxe^{-x^2}J)$, $C_P = \int dxe^{-x^2}(x^4-3x^2+3/4)J/(4\int dxe^{-x^2}J)$, with

$$J = \begin{cases} \int_1^\infty \exp\left(-\frac{2(s-1)}{\gamma x s}\right)\frac{ds}{s^{2\alpha-4}} & , \quad x>0 \\ -\int_0^1 \exp\left(-\frac{2(s-1)}{\gamma x s}\right)\frac{ds}{s^{2\alpha-4}} & , \quad x<0 \end{cases}.$$

In the short mean-free path limit $\gamma \to 0$, Eq. (6) agrees with the expression in Eq. (4). For finite mean-free path, C_T departs from unity and makes the effect of the neutral atoms on the toroidal ion flow weaker, while C_P remains quite small. Plots of C_T and

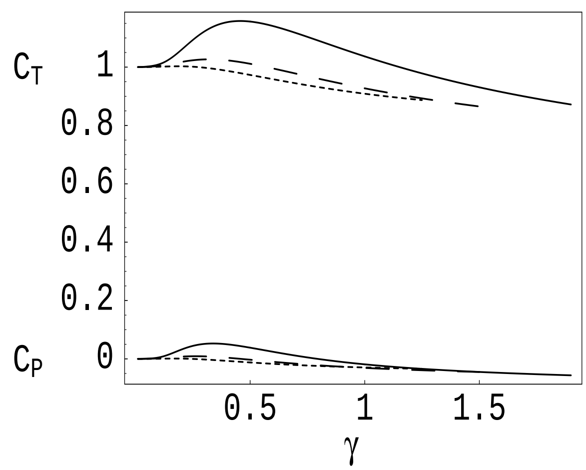

Figure 2: *C_T and C_P as functions of γ for $\alpha =$ 3.1 (solid), $\alpha =$ 3.25 (dashed) and $\alpha =$ 3.4 (dotted).*

C_P are given in Figure 2. A finite and outward neutral heat flux and reasonable values for the ionization and CX rates restrict the parameters to lie in the range $3 < \alpha < 3.5$ and $\gamma \lesssim 2$. The circumstance that C_T remains close to unity and C_P is relatively small implies that the finite mean-free path corrections to the short neutral mean-free path results are modest.

For general γ and localized puffing, the radial electric field becomes

$$-\Phi' = (T/e)(\ln n_i)'\{1+\eta_i[(1+C_T)+(k-C_T)I^2/(\langle B^2\rangle R_*^2)+C_P B_{\theta*}^2/\langle B^2\rangle]\} \equiv F_E T(\ln n_i)'/e$$

which agrees with the expression in Eq. (5) for short mean-free path.

5. Conclusions

The toroidal flow of the ions and the radial electric field are significantly affected by the poloidal location of the neutrals in the edge plasma, just inside the separatrix. The effect is particularly large for spherical tokamaks, it is relatively insensitive to the neutral mean-free path, and does not depend on neutral density if the neutral viscosity is larger than the ion and anomalous viscosities. In particular, if the neutrals are introduced as an inboard brake on plasma rotation, then localization of the neutrals to a penetration depth introduces flow shear on the outboard side where the turbulence is expected to be localized by ballooning - thereby possibly reducing the fluctuation level.

Very recently, experiments have been carried out on MAST to verify this theory by comparing the toroidal flow velocity with inboard and outboard gas puffing [2]. If the results presented here, which appear to be in at least qualitative agreement with the latest MAST observations [2], can be reproduced in other tokamaks with collisional edges such as Alcator C-Mod, where such experiments are currently being planned, then external control of the radial electric field, toroidal flow, and their shear; and possibly the transition from low (L) to high (H) confinement regimes, will be possible.

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[1] A. R. FIELD, P. G. CAROLAN, R. J. AKERS, E. R. ARENDS et al., Plasma Phys. and Control. Fusion, **44**, A113 (2002).

[2] A. R. FIELD, E. R. ARENDS, P. G. CAROLAN, et al., Proc. of the 29th EPS Conf. on Plasma Phys. and Control. Fusion in Montreux, 17-21 June 2002.

[3] M. VALOVIC, P. G. CAROLAN, A. R. FIELD, S. J. FIELDING et al., Plasma Phys. and Control. Fusion, **44**, A175 (2002).

[4] P. J. CATTO, P. HELANDER, J. W. CONNOR, R. D. HAZELTINE, Phys. Plasmas **5**, 3961 (1998).

[5] T. FÜLÖP, P. J. CATTO, P. HELANDER, Phys. Plasmas **5**, 3398 (1998).

[6] T. FÜLÖP, P. J. CATTO, P. HELANDER, Phys. Plasmas **5**, 3969 (1998).

[7] T. FÜLÖP, P. J. CATTO, P. HELANDER, Phys. Plasmas **8**, 5214 (2001).

[8] T. FÜLÖP, P. HELANDER, P. J. CATTO, "Effect of poloidal density variation of neutral atoms on the tokamak edge", to appear in Phys. Rev. Lett. (2002).

[9] A. N. SIMAKOV, P. J. CATTO, "Effects of poloidal variation of neutral density on Pfirsch-Schlüter transport near tokamak edge", submitted to Physics of Plasmas.

[10] P. HELANDER and S. I. KRASHENINNIKOV, Phys. Plasmas **3**, 226 (1995).