**LETTER**

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Letter

# Plasma rotation from momentum transport by neutrals in tokamaks

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## Abstract

Neutral atoms can strongly influence the intrinsic rotation and radial electric field at the tokamak edge. Here, we present a framework to investigate these effects when the neutrals dominate the momentum transport. We explore the parameter space numerically, using highly flexible model geometries and a state of the art kinetic solver. We find that the most important parameters controlling the toroidal rotation and electric field are the major radius where the neutrals are localized and the plasma collisionality. This offers a means to influence the rotation and electric field by, for example, varying the radial position of the X-point to change the major radius of the neutral peak.

Keywords: neutrals, rotation, radial electric field, tokamak, edge

(Some figures may appear in colour only in the online journal)

The level of plasma rotation has a fundamental impact on the performance of magnetically confined plasmas. Establishing what determines plasma rotation is important both from a theoretical and practical point of view, since rotation has a strong effect on the confinement and stabilizes magnetohydrodynamic instabilities, such as resistive wall modes.

In future magnetic fusion devices, where the effect of alpha-particle heating will be dominant, the influence of external torque from auxiliary heating will be considerably lower than in current devices. It is therefore important to understand the intrinsic toroidal rotation that arises independently of externally applied momentum sources; momentum transport by neutral atoms generates intrinsic rotation.

There is a wealth of experimental evidence showing that neutrals have a substantial influence on tokamak edge processes. They influence global confinement [1, 2] and the transition from low (L) to high (H) confinement mode [3–11], which are critical to the performance of tokamak fusion reactors. While the physics of the transition to H-mode is far from fully understood, it is clear that rotational flow shear plays an important role [12]. It is therefore important to be able to model the effect of neutral viscosity on the flow shear in the edge plasma.

Neutrals influence the ion dynamics in plasmas through atomic processes, mainly charge-exchange (CX), ionization, and recombination. Due to their high cross-field mobility they can be the most significant momentum transport channel even at low relative densities. The effect of the neutrals is typically significant if the neutral fraction in the plasma exceeds about $10^{-4}$ [13], which is usually the case in the tokamak edge not too far inside the separatrix; the neutrals can penetrate to the pedestal top in the JET tokamak [14] and may be expected to penetrate further in an L-mode plasma due to the lower edge density.

Recent experimental results at JET demonstrate that changes in divertor strike point positions are correlated with strong modification of the global energy confinement [1, 2]. It was speculated that this may be because neutrals directly affect the edge ion flow and electric potential [1]. Other observations correlate the edge intrinsic toroidal rotation with CX dynamics [14] or the major radius of the X-point [15, 16]. These recent observations triggered renewed interest in the role of the neutrals in the tokamak edge.

Previous analytical work has shown neutrals can modify or even determine the edge plasma rotation and radial electric field [13, 17–23]. Even without input of external momentum into the plasma, neutrals drive intrinsic momentum transport and hence rotation. However, analytical solutions for the neoclassical ion distribution function can only be obtained in the asymptotically low or high collisionality regimes. The trends in radial electric field and toroidal rotation with the location of the neutrals both reverse their direction between these two regimes [21]. Realistic plasma parameters in the tokamak edge are intermediate between these limits. The analytical results therefore cannot be used to determine the parametric dependence, for experimentally relevant conditions, of the ion flow and radial electric field or even predict the direction of the trends with, for instance, X-point major radius. With numerical solutions we remove the restriction on collisionality.

We couple neutrals to a neoclassical kinetic solver and determine the radial electric field and plasma flows just inside the separatrix. We use ITER-relevant model geometries and plasma parameters. As an example application, we demonstrate the effects of changing the shaping and the X-point position, due to their recent experimental relevance [1, 2, 15, 16]. We show there is a link between the X-point radial position and neutral mediated rotation. Consequently, control of the X-point location may offer a straightforward means of control over the ion flow and radial electric field. Our results may have relevance for the mechanism underlying recent observations indicating improved global confinement with the corner divertor configurations in JET [1, 2].

The toroidal ion flow and radial electric field can be calculated from the steady state condition in a plasma without momentum sources, where the radial transport of toroidal angular momentum vanishes,

$$0 = \langle R\hat{\zeta} \cdot (\boldsymbol{\pi}_i + \boldsymbol{\pi}_n) \cdot \nabla\psi \rangle \approx \langle R\hat{\zeta} \cdot \boldsymbol{\pi}_n \cdot \nabla\psi \rangle. \quad (1)$$

Here $\boldsymbol{\pi}_i$ and $\boldsymbol{\pi}_n$ are the ion and neutral viscosity tensors, $R$ is the major radius, $2\pi\psi$ is the poloidal magnetic flux, $\hat{\zeta} = \nabla\zeta/|\nabla\zeta|$ with $\zeta$ the toroidal angle in the direction of the plasma current, and $\langle ... \rangle$ is the flux surface average. The second form follows because the contribution of the ion viscosity is negligible at first order [24] in the expansion in normalized gyroradius $\rho_* = \rho/L$, where $\rho$ is the gyroradius and $L$ is a typical length scale of plasma gradients.

For modest relative neutral densities, $n_n/n_i \gtrsim 10^{-4}$, where $n_n$ and $n_i$ denote the density of neutrals and ions, the neutral viscosity is higher than the neoclassical viscosity [13]. The turbulent momentum flux will also be assumed to be lower than the neutral momentum flux, which may be questionable. However, it is plausible that the neutral and turbulent momentum fluxes should be at least comparable, as in steady state particle losses are balanced by fuelling and recycling. The neutral particle transport is then equal to ion particle transport due to both collisions *and* turbulence, since every recycling ion that leaves the plasma comes back as a neutral [21]. Therefore considering the neutral momentum transport in isolation is an important step in understanding plasma rotation

in regions where neutrals are present. Moreover experimental evidence shows that neutrals do affect plasma rotation at the edge.

We can solve the neutral kinetic equation $\boldsymbol{v} \cdot \nabla f_n = \tau^{-1}(n_n f_i/n_i - f_n)$ perturbatively. Here $f_i$ and $f_n$ are the ion and neutral distribution functions respectively and $\tau^{-1} = n_i \langle \sigma v \rangle_x \simeq 2.93 n_i \sigma_x (T_i/m_i)^{1/2}$ is the CX frequency, which is larger than the ionization or recombination rates for tokamak edge parameters [25]. $\sigma_x$ is the CX cross section for thermal particles, $\langle \sigma v \rangle_x$ the rate coefficient for CX reactions, $T_i$ the ion temperature, and $m_i$ the ion mass. The mean free path for CX is $\lambda_{\mathrm{mfp,n}} = \tau v_{\mathrm{th}} \simeq 0.483/n_i\sigma_x$, with $v_{\mathrm{th}}$ the thermal velocity, which we may estimate as $\lambda_{\mathrm{mfp}} \simeq 0.8$ cm using $n_i = 10^{20}$ m$^{-3}$ and $\sigma_x = 6 \times 10^{-15}$ cm$^2$ [13]. This is short compared to typical gradient scale lengths $L$ in the plasma, so we expand the neutral distribution function for small $\lambda_{\mathrm{mfp}}/L$ as $f_n = f_{n0} + f_{n1} + \dots$. To lowest order $f_{n0} = n_n f_i/n_i$, and to next order $f_{n1} = -\tau\boldsymbol{v} \cdot \nabla(n_n f_i/n_i)$. Thus the neutral distribution function can be calculated from the distribution function of the ions. For neutral fractions $n_n/n_i \lesssim 10^{-3}$, the direct effect of the neutrals on the ion distribution function can be neglected [17, 18], and we can construct the neutral viscosity tensor as $\pi_{n,jk} = \int m_i(v_j v_k - (v^2/3)\delta_{jk})f_n(\boldsymbol{v})d^3v = -\tau\frac{\partial}{\partial x_l}\int m_i v_j v_k v_l (n_n/n_i) f_i(\boldsymbol{v})d^3v + (\dots)\pi_{i,jk} + (\dots)\delta_{jk}$. The last two terms are negligible compared to the first so
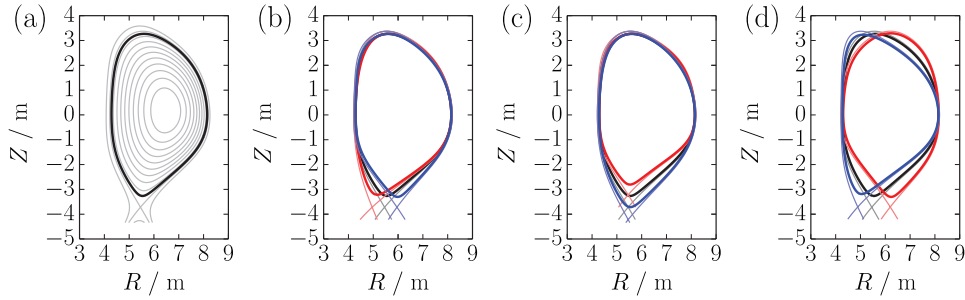
$$\langle R\hat{\zeta} \cdot \boldsymbol{\pi}_n \cdot \nabla\psi \rangle \approx \left\langle \frac{R\tau m_i}{n_i} \frac{\partial n_n}{\partial \psi} \int d^3v \, (\nabla\psi \cdot \boldsymbol{v})^2(\hat{\zeta} \cdot \boldsymbol{v})f_i \right\rangle, \quad (2)$$

where the radial gradient of $n_n$ dominates. Although we assume that the neutrals are too few to affect the ion distribution directly, they affect the ion toroidal rotation and the radial electric field by dominating the transport of angular momentum. Interestingly, for the case we consider here where the neutral viscosity is larger than the ion neoclassical and turbulent viscosities, the steady state depends on the poloidal distribution of the neutral density, but is independent of its overall magnitude and also of the CX cross section; the latter are independent of the poloidal angle and so are just prefactors to the neutral momentum flux in equation (2), which vanishes by equation (1).
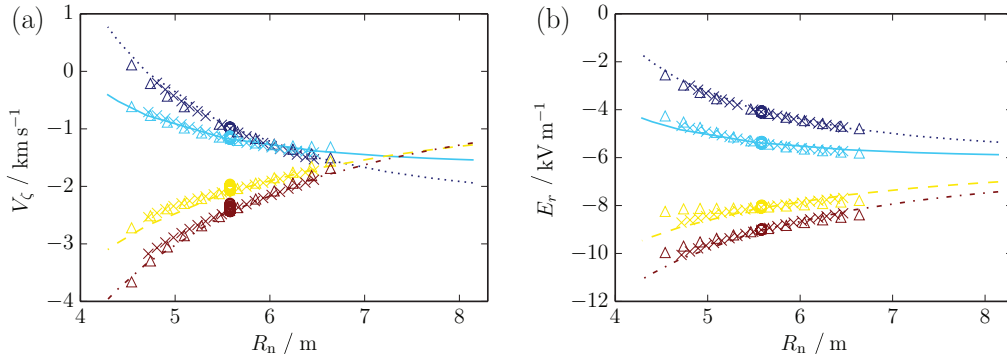
The neutrals couple to the particle distribution $f_i$, given by

$$f_i(\boldsymbol{r}) = f_{i,gc}^M(\boldsymbol{R}) + \delta f_{i,gc}(\boldsymbol{R})$$
$$\approx f_{i,gc}^M(\boldsymbol{r}) - \boldsymbol{\rho} \cdot \nabla f_{i,gc}^M(\boldsymbol{r}) + \delta f_{i,gc}(\boldsymbol{r}). \quad (3)$$

Here $\boldsymbol{r}$ is the particle position, $\boldsymbol{R}$ the guiding centre position, $\boldsymbol{\rho} = \boldsymbol{r} - \boldsymbol{R}$ the gyro-radius vector, subscript 'gc' denotes guiding centre distributions, $f_{i,gc}^M$ is the Maxwellian distribution which is the leading order part of $f_{i,gc}$ in the $\rho_*$ expansion, and $\delta f_{i,gc}$ is the perturbed part of the distribution. We model here deuterium ions and neutrals (electron dynamics are negligible due to the small electron-ion mass ratio). We calculate $\delta f_{i,gc}$ with the pedestal and edge radially-global Fokker–Planck evaluation of collisional transport (PERFECT) neoclassical solver [26], used here in local mode.

**Figure 1.** Flux surface shapes: (*a*) baseline ITER-like equilibrium, (*b*) changing the major radius of the X-point $R_X$, (*c*) changing the vertical position of the X-point $Z_X$, and (*d*) changing the triangularity $\delta$. Thick lines show the $\psi_N = 0.95$ surface used for simulations.



**Figure 2.** (*a*) Toroidal flow velocity and (*b*) radial electric field at the outboard midplane as a function of the major radius where the neutrals are localized. Lines show the effect of changing the poloidal position of neutrals in the baseline geometry. Markers show the effect, with neutrals kept fixed at the X-point, of changing the geometrical parameters $R_X$ (crosses), $Z_X$ (circles), and $\delta$ (triangles). Line styles correspond to collisionality: solid cyan is the baseline corresponding to $n_i = 10^{20}$ m$^{-3}$ and $T_i = 300$ eV, dotted blue is 10 times lower, and dashed yellow and dash-dotted red are 10 and 100 times higher respectively. Simulations plotted with markers use the same plasma parameters as the nearest line. The ion temperature scale length is taken to be 10 cm.

The density gradient $\partial n_i/\partial\psi$ and electrostatic potential gradient $\partial\Phi/\partial\psi$ terms in the drift kinetic equation have identical velocity space structures. Therefore when we solve for $\partial\Phi/\partial\psi$ any density gradient gives an offset to $\partial\Phi/\partial\psi$ without affecting the flow on the flux surface we consider. We therefore set $\partial n_i/\partial\psi = 0$ here.

The system is driven by the ion temperature gradient $dT_i/d\psi$ and we must solve for the gradient of the electrostatic potential $d\Phi/d\psi$. Taking a guess for $d\Phi/d\psi$ we calculate $\delta f_{i,gc}$ with PERFECT and compute the momentum flux from equations (3) and (2). We iterate to find the $d\Phi/d\psi$ value for which the momentum flux vanishes.

For this study we use model magnetic equilibria given by analytic solutions to the Grad-Shafranov equation [27], and take ITER-like parameters, to scan the parameter dependence of the system. Their geometries are specified by fixing the shape of the boundary surface in terms of the inverse aspect ratio $\epsilon$, elongation $\kappa$, triangularity $\delta$, and X-point major radius $R_X$ and height $Z_X$ along with two more constraints. For the constraints we take the toroidal $\beta$, $2\mu_0\langle p\rangle/B_0^2$ (where $\langle p\rangle$ is the volume averaged pressure and $\mu_0$ is the vacuum permeability), to be 0.05 and fix the safety factor $q_{95}$ of the flux surface with $\psi_N = 0.95$, where $\psi_N$ is the normalized poloidal flux, to the value that corresponds to a plasma current of 15 MA in the baseline equilibrium. Scales are set by giving $R_0$, the major radius of the plasma centre, and $B_0$, the vacuum toroidal field at $R_0$. The baseline parameters are [27]: $R_0 = 6.2$ m,

$B_0 = 5.3$ T, $\epsilon = 0.32$, $\kappa = 1.7$, $\delta = 0.33$, $R_X = (1 - 1.1\ \delta\epsilon)R_0$, $Z_X = -1.1\ \kappa\epsilon R_0$. The variation of the X-point position and triangularity, while keeping the other shaping parameters fixed, are illustrated in figure 1.

We investigate the effect of a localized concentration of deuterium neutrals, represented by a delta function in poloidal angle, on a pure deuterium plasma. Such localization may represent the location of a gas puff, or neutral concentration near the X-point when the recycling from the targets is strong [14, 28] or the plasma is gas fuelled from the private flux region. Therefore we consider two scenarios. Firstly we vary the poloidal location of the neutrals in the baseline geometry and secondly vary the geometry while keeping the neutrals fixed at the X-point. In all cases we consider a single flux surface at $\psi_N = 0.95$, as highlighted with thick lines in figure 1.

The results show that the toroidal flow and electric field are largely determined by the major radius where the neutrals are localized, $R_n$, for each plasma collisionality. This is illustrated in figure 2, where we show the toroidal ion flow and radial electric field as functions of the neutral location, for a wide range of collisionalities. These results are built from scans of the major radius of the X-point $R_X$, height of the X-point $Z_X$, and triangularity $\delta$, all of which had the neutrals located at the X-point. We also scanned the poloidal location $\theta$ of the neutrals in the baseline equilibrium (the difference between the results for the upper $0 < \theta < \pi$ and lower $\pi < \theta < 2\pi$ halves of the flux surface as functions of $R_n$ is too small to plot, so only

a single curve appears in figure 2). We see that the scans in $\theta$, $R_X$, $Z_X$, and $\delta$ collapse on a single curve for each collisionality, indicating that the position of the X-point and triangularity affect the flow primarily by changing $R_n$, while the details of changes to the flux surface geometry are much less significant. The shaping parameters we scan here are those most relevant to control of a given machine, note however that lower order shaping that we do not analyse here, for example the inverse aspect ratio, may affect the solutions significantly.

We have verified our results from the poloidal angle scans against analytical limits [20, 21], finding good agreement in both high and low collisionality regimes. The toroidal flow caused by the neutrals is generally counter-current, increasingly so for higher collisionality. The magnitude of the outboard rotation in JET L-mode plasmas without strong external torque (e.g. NBI heating) is of order 10 km s$^{-1}$ [29]; thus the speeds of a few km s$^{-1}$ found here are of the same order of magnitude and likely to compete with other effects driving intrinsic edge rotation. We find that the electric field is always inwards and is larger for higher collisionality. The effect of collisionality is enhanced when the neutrals are located at smaller major radii.

Neutrals cause the plasma to rotate toroidally without external momentum input as toroidal flow is needed to give a radial momentum flux balancing that due to the toroidal heat flux, which is driven by the radial temperature gradient [21]. In the limit $R_n \to \infty$ in figure 2 the electric field $E_r$ approaches $-6$ kV m$^{-1} = -2T_i/(eL_{T_i})$, where $L_{T_i}$ is the gradient scale length of the ion temperature. This is because in this limit only the rigid rotation parts of the flow and heat flux contribute to drive the radial momentum flux and these depend only on the radial gradients, not on $\delta f_{i,gc}$; they are therefore independent of collisionality and so is the electric field which is set directly. The plasma flow does however also have a contribution from the part of the flow parallel to the magnetic field (governed by the neoclassical coefficient $k$) and so does depend slightly on collisionality. It does not contribute to the momentum flux as the magnetic field vanishes $B(R_n) \to 0$ in this limit. It is also notable that the trends in $V_\zeta$ and $E_r$ with $R_n$ (figure 2) reverse their direction as the collisionality changes from low to high. This follows from the change in sign of the neoclassical flow coefficient $k$ between low (banana) and high (Pfirsch–Schlüter) collisionalities.

Allowing higher neutral densities requires including the reaction of the ion distribution to the neutrals [17], which will be implemented numerically in the future. PERFECT has the capability to include finite orbit width effects [26, 30], allowing density pedestals to be modelled and the study of the interaction between neutral momentum transport and pedestals is of the highest importance. The importance of and interaction with other effects such as ion orbit loss [31–33] could also be considered.

*Summary.* We have built a framework to investigate the toroidal rotation and radial electric field in the edge plasma, when these are regulated through momentum transport by neutrals, by coupling neutrals to a neoclassical kinetic solver. Experimentally relevant parameters are not described by the asymptotic collisionality limits that can be studied analytically [17–22]. As the limits have opposite trends with $R_n$, it is not possible to say *a priori* which limit is 'closer' to the intermediate collisionality typical of experiments, see the cyan curve for baseline parameters in figure 2. Therefore quantitative comparison with experiment (which is beyond the scope of the present paper) and predictive power for future devices both require the numerical solutions that we present here.

We find that the most important parameters controlling the toroidal flow and electric field are the major radius where the neutrals are localized, $R_n$, and the plasma collisionality. These results suggest that altering the X-point position may offer a means to manipulate the edge rotation in the layer inside the separatrix when neutral viscosity dominates. This sets the boundary condition for the core rotation profile and influences the stability of magnetohydrodynamic instabilities such as resistive wall modes. Further, shear in the edge rotation can lead to the suppression of edge turbulence. Consequently the neutrals are also likely to affect the L-H transition and H-mode confinement. Our results demonstrate that the effects of neutrals on momentum transport are significant and should be accounted for both in the interpretation of current experiments and in the design of future machines.

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