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An experimental and theoretical study on the formation of electric field induced flow shear in the tokamak edge

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Abstract

The plasma edge plays an important role in the physics of improved confinement. In this region, shear in the $\vec{E} \times \vec{B}$ flow can be responsible for the suppression of turbulence. An electric field and sheared flows are set up by plasma edge polarisation and are measured by probe and atomic beam diagnostics. The measurements are then compared with the predictions of a one dimensional fluid model. In this model, parallel viscosity, neutral friction and compressibility were already identified as important components to explain the strong and localised electric fields and rotation velocities. In the present paper we focus on anomalous convection and shear viscosity and their subsequent reduction by the quenching of the turbulence. We show that without this effect, it is impossible to explain the magnitude and the shape of the measured electric field.
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1. Introduction

It is well known that in polarisation experiments important poloidal and toroidal flows can be created in the plasma edge [1,2]. By biasing an electrode a radial electric current is forced through the plasma. This current drives the flows and tends to create a very important electric field in a narrow spatial region. It is balanced by a number of friction mechanisms. In earlier publications we already discussed the importance of the neutral density and the parallel viscosity [1,3,4] to explain the electric field, while compressibility [5] was identified as a necessary ingredient to explain the measured toroidal velocity. The bias method can trigger an L to H-mode transition and opens the gateway to the study of transport barriers [6,7]. The highly sheared flows are held responsible for the reduction of the turbulence [8], the turbulence driven radial transport and the subsequent steepening of the edge density profile. We have developed a set of experiments [9,10] by which we can determine all the relevant quantities of the plasma. As described in earlier work an inclined Mach probe was used to measure flows parallel as well as perpendicular to the magnetic field [11]. The monitoring of the temporal evolution of the electric field and density profile has allowed us to determine a critical $\vec{E} \times \vec{B}$ shear necessary to start the quenching of the turbulence. By comparing the measured quantities with the results of a theoretical model we prove that the quenching has to effectively take place as otherwise the measured electric field cannot be explained.

2. Experiments

In the plasma edge of TEXTOR a mushroom-shaped electrode is inserted a few centimeters beyond the last

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closed flux surface (LCFS). The conducting tip of the electrode is biased with respect to the toroidal belt limiter ALT-II. The electrode voltage is slowly ramped up from 0 to +600 V during the flat-top phase of a deuterium discharge at standard parameters of a line-averaged central target density $\langle \bar{n}_{e,0} \rangle = 1.0 \times 10^{19}$ m^{-3}, a plasma current $I_p = 200$ kA and a central toroidal magnetic field $B_{\phi,0} = 2.33$ T. Other relevant parameters are $R_0 = 1.75$ m, $q(0) = 0.88$, $q(\mathrm{LCFS}) = 6.7$, $T_e = 40$ eV, $T_i = 40$ eV. An electrode current of 150 A (L-mode) and 80 A (H-mode) is drawn, leading to poloidal rotation and high radial electric fields E_r. The fields are measured with a temporal resolution of 40 μs and a spatial resolution of 4 mm using a rake probe, which resides in the plasma for the whole pulse. The contribution of the pressure gradient to E_r is about −6 kV/m and that of the induced rotation 47 kV/m. The density profiles are obtained from an atomic beam diagnostic with a temporal and spatial resolution of respectively 2 ms and 1 mm. The electric field develops gradually until a sudden decrease of the parallel viscosity and a drop in the electrode current. This bifurcation leads to very high and localized E_r-profiles. Together with the electric field a poloidal and toroidal rotation sets-up, whose shear quenches turbulent cells. This leads to transport barriers, which exhibit themselves by a steepening of the edge density profile, and an improvement of the confinement, as indicated by the increasing particle content and particle confinement time [9]. Two mechanisms are at work to reduce the turbulent transport: radial scattering and poloidal shearing. The balance of both is governed by the so-called critical $\vec{E} \times \vec{B}$ flow shear [12,13]:

$$\nabla E_{\mathrm{crit}} = \sqrt{2}(\langle k_\perp^2 \rangle D_0) B_\phi(r), \quad (1)$$

where D_0 is the particle diffusion coefficient for the anomalous transport in the absence of shear and $\langle k_\perp^2 \rangle_0$ is the ensemble average of the perpendicular wave number. The experimentally determined ∇E_{crit} will be later used in the simulation of the measured edge profiles. A comparison of the experimentally derived ∇E_{crit} with the predicted once [13] has confirmed Eq. (1).

3. Theory

We start with the fluid equations [1]:

$$\vec{\nabla} \cdot (n\vec{V}) = 0, \quad (2)$$

$$\vec{\nabla} \cdot (mn\vec{V}\vec{V}) = -\vec{\nabla} p - \vec{\nabla} \cdot \vec{\vec{\pi}} + (\vec{J} \times \vec{B}) + \vec{F}_n, \quad (3)$$

where the symbols have their usual meaning and where $\vec{F}_n = -\nu \cdot \vec{V}$ is the neutral drag force, with ν a drag coefficient as defined in [14]. These equations will be used to compute the radial electric field E_r and the rotation velocities. We will work in a circular toroidal geometry (r, θ, ϕ are the radial, poloidal and toroidal co-ordinates) and neglect the Shafranov shift as we are mainly interested in the edge where it is small. Whereas in earlier work only the parallel viscosity and the neutral drag were retained as important friction mechanisms, we will now also retain the inertia (convection) term and introduce a shear viscosity, both of which are determined by the (anomalous) radial diffusion [3]. Note that this introduction does not impair the earlier descriptions as we will show that an important reduction of the new terms is necessary. Compressibility also takes place in the region of the induced electric field, but tends to bring the locally measured flows close to the average flows [5], while the electric field is not influenced. As a consequence we will only have to investigate the flux surface averaged quantities.

The surface integral of the toroidal projection of Eq. (3) gives an expression for the radial current:

$$I_r = \left\langle\left\langle \frac{1}{B_\theta} (\vec{\nabla} \cdot (mn\vec{V}\vec{V})_\phi \right\rangle\right\rangle + \left\langle\left\langle \frac{1}{B_\theta} (\vec{\nabla} \cdot \vec{\vec{\pi}})_\phi \right\rangle\right\rangle - \left\langle\left\langle \frac{1}{B_\theta} (\vec{F}_n)_\phi \right\rangle\right\rangle, \quad (4)$$

the tensorial quantities of which can be simplified by the use of the following general property:

$$\left\langle\left\langle \frac{(\vec{\nabla} \cdot \vec{\vec{T}})_\phi}{B_\theta} \right\rangle\right\rangle = \frac{2\pi}{B_0 \cdot R_0 \Theta} \frac{\partial}{\partial r} \int_\theta (rR^2 \cdot T_{r,\phi})\, d\theta, \quad (5)$$

where $\vec{\vec{T}}$ is a tensor which can be the inertia or the viscosity tensor. Note that this form implies that the parallel or bulk viscosity has no contribution in Eq. (4) as $\vec{\vec{\pi}}^0_{r,\phi} = 0$. We can introduce an anomalous viscosity by posing $(\vec{\vec{\pi}}^{\mathrm{AN}})_{r,\phi} = \eta^{\mathrm{AN}}(\partial V_\phi/\partial r)$ with $\eta^{\mathrm{AN}} = mnD$ and D an anomalous diffusion coefficient. In the same way the contribution of the inertia term is introduced by the element $(mn\vec{V}\vec{V})_{r,\phi} = mnV_rV_\phi$. Here again an anomalous effect is introduced via the radial velocity, modelled as: $V_r = -D(1/n)(\partial n/\partial r)$.

The continuity equation allows us to write the poloidal velocity as: $V_\theta = (R_0/R)(F(r)/R_0)$, while the radial projection of the ion momentum equation can be used to compute the perpendicular velocity: $V_\perp = (1/B)((1/en_i)(\partial p_i/\partial r) - E_r) = (R/R_0)\cos\alpha(V(r)/B_0)$ (α is the pitch of the magnetic field) thus introducing two flux functions $F(r)$ and $V(r)$, related to the average poloidal rotation and the electric field respectively, that can be used to express the velocity components in Eq. (4). The system is closed by the parallel projection of Eq. (3), multiplied by B and averaged over the magnetic surface. In this equation the parallel viscosity is modelled as in [1,3]. Obviously, due to the inertia and shear viscosity terms we obtain a system of two second order differential equations so that boundary conditions have to be defined. At the LCFS we will suppose that the rotation is small because of the inhibiting effect of the limiter. In the center of the machine the poloidal rotation should become zero, as imposed by the geometry. A fourth constraint can be discovered by analytically integrating Eq. (4) with respect to r:

$$\int R^2(\vec{\vec{\mathrm{Co}}}_{1,3} + \vec{\vec{\pi}}_{1,3})\,\mathrm{d}\theta = \frac{B_0}{2\pi r}\int \frac{rI_r(r)}{q}\,\mathrm{d}r + \frac{C}{r}, \qquad (6)$$

where we made use of Eq. (5) and where $\vec{\vec{\mathrm{Co}}}$ and $\vec{\vec{\pi}}$ represent the inertia and the anomalous viscosity tensor respectively. As we are essentially looking for a boundary condition at the center of the machine, we put the neutral drag force $F_{\mathrm{n}} = 0$. Under this form it is evident that the constant of integration C must be zero to avoid problems in the center. In this way the fourth constant of integration is determined analytically and the problem of what value to impose for the toroidal velocity at the center is solved. Indeed, the plasma can rotate freely in the toroidal direction and a boundary condition is not obvious.

4. Discussion

First we will investigate solely the effect of the inertia and shear viscosity terms by assuming several values for the diffusion coefficient. Hereafter a reduction of D, which is linked to the profile shape of the electric field, will be included. The resulting neutral density profile as well as the comparison with our experimental data will be the criterion to judge the relevance of the different effects.

We will study profiles obtained in the L-mode as well as in the H-mode. To model these experiments we take the measured temperature and ion density profiles. We then solve Eq. (6) together with the averaged parallel momentum equation and determine the functions $F(r)$ and $V(r)$, which give rise to the velocity and electric field profiles. The neutral density is modelled as: $n_{\mathrm{n}} = n_{\mathrm{n0}}\exp(-(r-a)/\lambda)$, where n_{n0} is the neutral density at the LCFS, λ is the decay length and a is the radial position of the LCFS. To study the influence of D we start by setting $D = 0$ m^2/s. The parameters n_{n0} and λ are then adjusted so as to have a good agreement between the measured and computed electric field (Fig. 1). Without inertia and shear viscosity we have to choose λ of the order of a meter to avoid that the field becomes too large in the region of 1 cm inside of the LCFS to model the H-mode. Indeed if the friction is not high enough, the conductivity is high and the field increases. Obviously, this value of λ is unphysically high. Increasing D (while the same values for n_{n0} and λ are maintained), shows that the conductivity increases and that as a consequence the field is reduced. When $D = 1$ m^2/s, a reasonable value in TEXTOR, the field is reduced to about 1/7 of its original size.

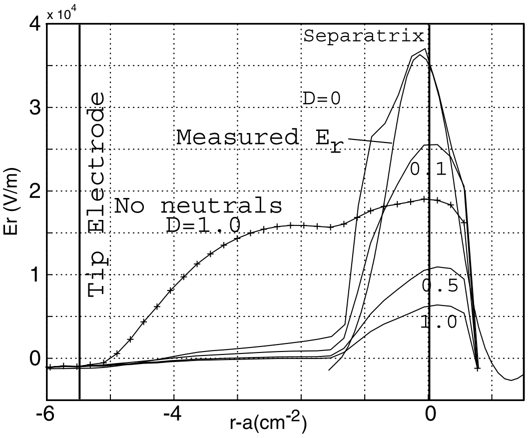

Fig. 1. The radial electric field in H-mode with $D = 0.0$; 0.1; 0.5; 1.0 m^2/s ($n_{\mathrm{n0}} = 8.6\times10^{15}$ m$^{-3}\simeq 1\%$ of $n(a)$) and with $D = 1.0$ m^2/s and the neutral density reduced by a factor of 100 (no neutrals).

The same conclusions are valid in the case of the toroidal velocity (Fig. 2). We find that it decreases with increasing diffusion. When $D = 0$ m^2/s we see that the rotation is limited to the region where the radial current flows. Indeed the toroidal momentum equation is reduced to $I_r = \langle J_r\rangle S = \langle(\nu V_\phi/B_\theta)\rangle S$ (S being the surface through which the current flows), and the rotation must be zero beyond the reach of the electrode where $J_r = 0$. When $D \neq 0$ the velocity is carried inwards by the shear viscosity: in the core region ($J_r = 0$, $\nu = 0$) and without the inertia term, Eq. (4) is reduced to $(\partial V_\phi/\partial r) = 0$, which means the velocity must be constant. The additional effect

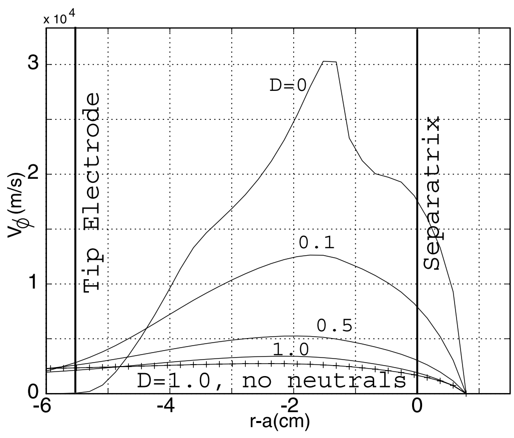

Fig. 2. The toroidal rotation in H-mode with $D = 0.0$; 0.1; 0.5; 1.0 m^2/s ($n_{\mathrm{n0}} = 8.6\times10^{15}$ m$^{-3}\simeq 1\%$ of $n(a)$) and with $D = 1.0$ m^2/s and the neutral density reduced by a factor of 100 (no neutrals).

of the inertia tends to reduce the velocity towards the center.

Setting $D = 1$ m^2/s, we can now ask weather the correct field can be reproduced by decreasing the neutral density. Reducing the neutral density by a factor of 100, results in the curve (+) shown on Fig. 1 and shows that with $D = 1$ m^2/s it is impossible to reproduce the field. At least in the region where the field exists, the value of D must be reduced. A possible explanation for this reduction is the quenching of turbulence due the shear in the $\vec{E} \times \vec{B}$ velocity, imposed by the electric field gradient, which leads to the following dependence [8]:

$$D = D_1 + \frac{D_2}{1 + \left(\frac{\nabla E_r}{\nabla E_{\rm crit}}\right)^2}, \qquad (7)$$

with $\nabla E_{\rm crit}$ as defined in Eq. (1). The analysis of the density profiles leads to the conclusion that $\nabla E_{\rm crit} = 75$ V/cm^2 [13]. Let us now suppose that the turbulence is reduced at the maximum by a factor of 10 such that e.g. $D_1 = 0.1$ m^2/s and $D_2 = 1$ m^2/s. We then obtain the profiles shown in Fig. 3, where we consider an L-mode (upper figure) and an H-mode (lower figure), taken during the same shot. The neutral density was chosen so as to have good agreement between the measured and experimental profiles (L-mode: $n_{n0} = 1.0 \times 10^{17}$ m^{-3}, $\lambda = 7$ cm; H-mode: $n_{n0} = 7.4 \times 10^{15}$ m^{-3}, $\lambda = 7$ cm). Note that the decay length is of the order of centimeters instead of meters now. This is of the same order (although slightly larger) as predicted by the (E)B2-EIRENE code, a two dimensional edge model. Because of the higher conductivity due to the inertia and shear viscosity the high value of the electric field 1 cm inside of the LCFS (see Fig. 3, case $D = 0$ m^2/s), which is very pronounced in the H-mode case, can be avoided. The necessary reduction of the neutral density between the L and H-mode was already mentioned in [1,3] and has also been observed experimentally. As for the velocities, we see that the toroidal velocity has a maximum that is slightly deeper in the plasma then the electric field as was confirmed by measurements. However, as the reduction of the diffusion coefficients only takes place in the narrow region where the electric field reigns, the computed velocity only reaches a maximum of about 2×10^4 m/s while the measured velocity (not available in this experiment, but measured as described in [5]) reaches about 3×10^4 m/s.

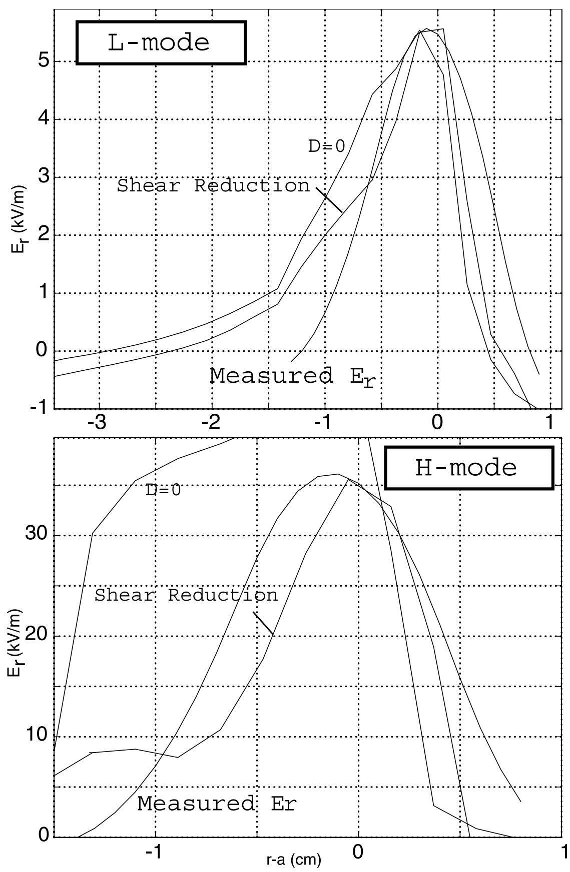

Fig. 3. E_r in L- and H-mode for two cases: (i) without inertia and shear viscosity ($D = 0$ m^2/s) and (ii) with shear reduction.

5. Conclusions

We established a method to introduce the inertia and shear viscosity terms in our one dimensional model. Particular attention was paid to the boundary conditions. We have shown that it is necessary to include the mechanism of particle transport reduction in the fluid equations to explain the measured electric fields. Once the reduction of the anomalous diffusion by the shear in the $\vec{E} \times \vec{B}$ velocity is included, the measured electric field profiles are reproduced quite well, with reasonable decay lengths for the neutral density. A detailed fitting of the toroidal velocity might further lead to an evaluation of the magnitude of the diffusion coefficients.

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