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Theoretical and experimental study of toroidal and poloidal flows in the edge plasma of TEXTOR-94 polarisation discharges.

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1. Introduction

The plasma edge plays an important role in the physics of improved confinement. In this region, the shear in the radial electric field is responsible for the suppression of turbulence [1]. The associated flows are measured during electrode polarisation discharges with a Mach probe [4,6]. These measured radial profiles can also be predicted by a fluid model [2,3]. The aim of this study is to compare the theoretical predictions with the experimentally obtained profiles.

The experiment is described in section 2 and the fluid model in section 3. The experimental and predicted profiles are compared in section 4. Discussion and conclusions are handled in section 5.

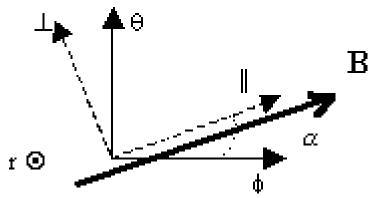

Fig. 1.: The parallel and toroidal system of reference, where α is the pitch of the magnetic field.

2. Experimental set-up and results.

Poloidal and toroidal flows can be measured in the outboard equatorial plane of TEXTOR-94 with a Mach probe [4,6]. The probe consists of two graphite collectors separated by an insulator, used in a double probe configuration. A 1D fluid model, described in [4], is used to derive the parallel and perpendicular Mach number from the experimental data. The velocities are calculated from the measured Mach number via $v = M.c_s$ in which the sound speed c_s is given by $c_s \equiv \left(k(T_e + T_i)/m_i\right)^{1/2}$. The profile of the radial electric field is measured with the Mach probe by using the two collectors of the probe in a floating potential configuration (I_{probe}=0).

Significant flows are in particular generated during edge polarisation experiments, the experimental set-up of which has been described previously [8]. A voltage is applied between the limiter (r=46cm) and an electrode of which the conducting tip is located at 41 < r(cm) < 42.5. During the experiments reported here, the bias voltage V_E is +350V and the bias current I_r is 120A. The plasma parameters are B_T = 2.35 T, I_p = 210 kA and the pre-bias line-averaged electron density is 1.0×10^{19} m^{-3}.

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Figures 2, 3 and 4 show the measured radial profiles of the radial electric field E_r, the poloidal velocity V_θ and the toroidal velocity V_ϕ respectively.

3. Theory.

A theoretical fluid model has been developed to predict V_θ, V_ϕ and E_r in dependence of the radial current and is based on the toroidal and parallel projections of the toroidal momentum equation in which the neutral drag and parallel viscosity are retained as damping mechanisms [2].

The development starts with the toroidal total momentum equation from which we obtain an expression for the radial current density:

$$J_r = \frac{1}{B_\theta}\nu V_\phi, \tag{1}$$

where B_θ is the magnetic induction in the poloidal direction and V_ϕ the flow velocity in the toroidal direction. The friction coefficient

$$\nu = n_i.m.n_o.\langle \sigma V \rangle = n_i.m.n_o.\left(10^{-8} T_i^{0.318}\right) \tag{2}$$

is supposed to be constant on a magnetic surface; n_o is the neutral density, n_i the ion density, m the ion mass and T_i the ion temperature in eV [5]. Integrated over a magnetic surface, Eq. 1 gives the current flowing through the surface

$$I_r = \frac{1}{\Theta B_o R_o}\nu \int_\theta R^2 V_\phi 2\pi r d\theta = \frac{1}{\Theta B_o}\nu \left\langle \frac{R}{R_o} V_\phi \right\rangle .S \quad , \tag{3}$$

where $\Theta = \mathrm{tg}\alpha$ is the pitch of the magnetic field, R the major radius, Ro the major radius of the plasma center, S the surface of a magnetic flux surface and <X> the surface average of the quantity X. The magnetic field is modeled using Ampere's law, neglecting the Shafranov shift.

Defining now the surface function

$$G(r) = \left\langle \frac{R}{R_o} V_\phi \right\rangle, \tag{4}$$

we obtain an expression for the current:

$$I_r = \frac{S}{\Theta B_o}\nu G(r) \ . \tag{5}$$

The electric field is introduced in the equations via the surface quantity V(r) defined by:

$$V(r) = -E_r + \frac{1}{en}\frac{\partial p_i}{\partial r} \ . \tag{6}$$

It defines the perpendicular velocity via the radial ion momentum equation [3]:

$$V_\perp = \frac{R}{R_o} Cos\alpha \frac{V(r)}{B_o} \ . \tag{7}$$

Note that we suppose that the electric field and the pressure gradient are poloidally constant. Via the continuity equation, the flux function F(r) defines the poloidal velocity:

$$V_\theta = \frac{R_o}{R}\frac{F(r)}{R_o} \tag{8}$$

The velocities can then be expressed as a function of G(r) and V(r):

$$V_\phi = G(r).\left[\frac{R_o}{R}\right] + \frac{V(r)}{B_o}\frac{1}{\Theta}\left[\frac{R_o}{R}\left(1+\frac{3}{2}\varepsilon^2\right) - \frac{R}{R_o}\right] \tag{9}$$

$$V_\theta = \frac{R_o}{R}\left(\Theta G(r) + \frac{V(r)}{B_o}\left[1+\frac{3}{2}\varepsilon^2\right]\right) \tag{10}$$

ε is the ratio r/R_o. To compute G(r) and V(r) a supplementary equation is needed, our choice being the parallel momentum equation in which we retain parallel viscosity and neutral friction:

$$C\left[\frac{F(r)}{R_o} - V_{neo}\right] + \langle \nu V_{//} B \rangle \quad = \quad 0 \tag{11}$$

The expressions for the viscosity coefficient C and V_{neo} in the plateau regime (the relevant regime for the edge of TEXTOR-94 [8]) are given in [2, 3].
We obtain an expression for V(r) by eliminating G(r) between Eqs. 5 and 11:

$$\frac{V(r)}{B_o} = \frac{-\frac{I_r \Theta B_o}{S\nu}\left(C\Theta + \frac{B_o \nu}{Cos^2\alpha}\left(1+\frac{\varepsilon^2}{2}\right)\right) + CV_{neo}}{C\left(1+\frac{\varepsilon^2}{2}\right) + \frac{B_o \nu}{Cos\,\alpha}\kappa}. \tag{12}$$

Note that C is a non-linear function of E_r, so that the Eq. 12 has to be solved in an iterative way. Once the two flux functions G(r) and V(r) are known, the velocities can be computed from Eqs. 9 and 10, the electric field profile via Eq. 6.

4. Comparison and conclusions

In the theoretical modelling we use the experimental profiles of n_i, T_i, and T_e. In the relevant region $T_e \approx 35$eV, $T_i \approx 70$eV. The n_i-profile is plotted in Fig. 5. Also shown there is the assumed neutral density n_o, which is used as a fitting parameter and is modeled by an exponential function with an absolute scale such as to match the maxima of the modeled and measured electric field.

Figures 2-4 allow to compare theory and experiment. The measured E_r profile and magnitude is reproduced by the fluid model and an equally reasonable agreement is found for the poloidal velocity. The toroidal velocity compares less satisfactorily. Whereas the correct magnitude of the toroidal velocity is reproduced, the calculated profile shows a maximum at the position of maximal E_r which is not found experimentally.

In the model, the latter maximum results from a pure geometrical effect as can be seen by analysing Eq. 9. At small pitch angles, V(r), and hence E_r, has a strong influence on the local toroidal velocity, the value of which at the outboard equator (θ=0°) becomes

$$V_\phi(r, \theta = 0°) = (1-\varepsilon).G(r) - \frac{2\varepsilon}{\Theta}\frac{V(r)}{B_o}. \tag{13}$$

The surface averaged toroidal velocity should however not at all be affected by E_r (see Eq. (4)) and is in that respect in line with the experimental observation. The higher E_r grows the more the theoretical local velocity should differ from the surface average value. What is at stake here is presumably our insistence on sticking to the magnetic surface as a constant density surface. Indeed, as shown in [7], at high poloidal rotation speeds a significant poloidal modulation of the plasma density can occur which in first approximation might result in a cancelling of the second term on the right in Eq. 13. We are currently improving our theoretical model to take this effect consistently into account.

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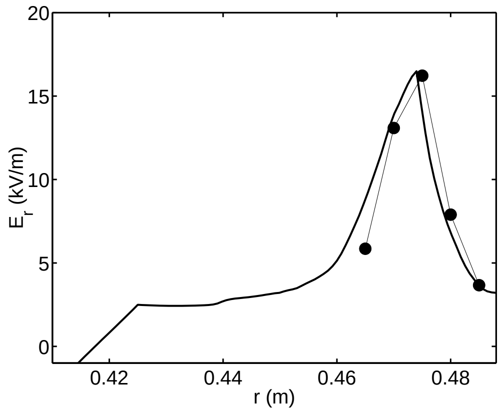

Fig. 2: E_r *vs* r: calculated E_r (solid line), measured E_r (•).

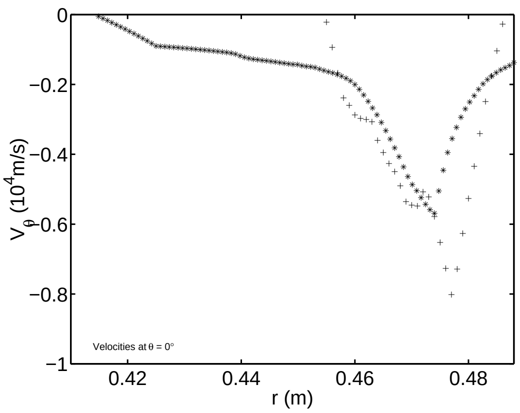

Fig. 3: V_θ *vs* r: calculated V_θ (∗), measured V_θ (+).

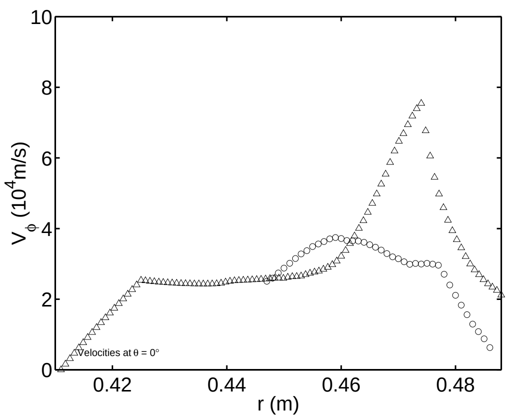

Fig. 4: V_ϕ *vs* r: calculated V_ϕ (Δ), measured V_ϕ (o).

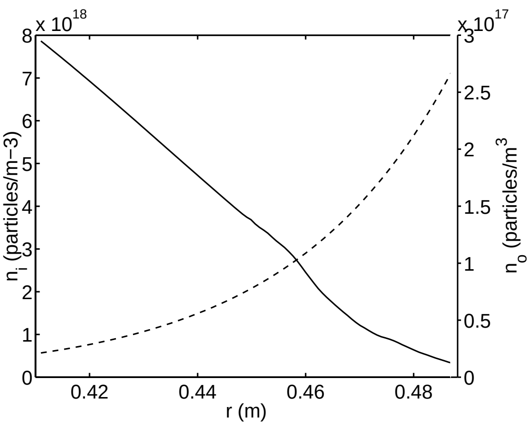

Fig. 5: n_i (solid line) and n_o (dashed line) *vs* r.