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Experimental studies on the mechanism for the spin-up of poloidal rotation in ergodic plasmas at the tokamak TEXTOR

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Introduction

Sheared plasma rotation is thought to play a major role in improving plasma confinement [1]. The Dynamic Ergodic Divertor (DED) at the tokamak TEXTOR influences the plasma rotation by creating an open ergodic system at the plasma edge via resonant coupling of a magnetic perturbation to the $q = 3$ surface. In this contribution we report on experimental studies of the effect of such magnetic fields on rotation and the radial electric field in the plasma edge TEXTOR. We compare our findings to a model where a torque is exerted resulting from the formation of a transverse current in the stochastic layer [2].

Experiment

The Dynamic Ergodic Divertor in TEXTOR consists of 16 perturbation coils wound helically around the torus on the inboard side. They produce resonant magnetic perturbations centered around the $q = 3$ surface. The phase of neighboring coils can be chosen such that configurations with different poloidal/toroidal mode numbers like 3/1 and 12/4 arise. Static as well as dynamic operation is possible with frequencies up to 10 kHz (cf. [3]). The perturbed magnetic field is characterized by an ergodic region with a large connection length of the fieldlines to the wall (with respect to the de-correlation length (*Kolmogorov* length)) and a laminar region radially further outside with a relatively short connection to the wall.

For the determination of the poloidal rotation active charge exchange recombination spectroscopy (*CXRS* using CVI emission at $\lambda = 529.5\,\text{nm}$) on a modulated diagnostic hydrogen beam has been used [4]. From the radial pressure profile of the C^{6+} ions and the toroidal rotation measured by CXRS with the heating beam at TEXTOR the radial electric field has been calculated. The same observation system has also been used for passive spectroscopy of the Doppler-shifted CIII emission at $\lambda = 464.74\,\text{nm}$.

Results and Discussion

For two different DED base mode configurations (3/1 and 12/4) both poloidal and toroidal rotation change with increasing perturbation and DED current respectively. The poloidal rotation just inside the limiter radius spins up into ion diamagnetic drift direction and the toroidal rotation in co-current direction. With increasing stochastization the radial electric field changes from negative (pointing inward) to positive values (pointing outward).

Figure 1 depicts the *change* of the poloidal rotation of C^{2+} ions at one radial location in the perturbed region for a series of plasma discharges in the 3/1 configuration ($q_a = 4.8$, $R = 1.76\,\mathrm{m}$, $a = 0.45\,\mathrm{m}$). Positive Δv corresponds to a change into ion diamagnetic drift direction. The increase of the poloidal rotation is almost linear with the perturbation current $I_{DED,eff}$ while there is *no separation* outside the error bars *between the data obtained with static or rotating perturbation*, neither into co- nor counter-direction.

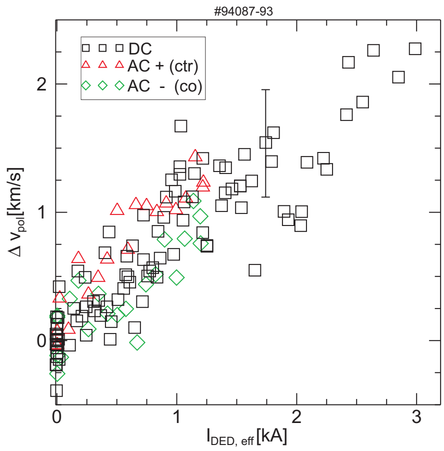

Figure 1: Change of poloidal rotation in the perturbed region with increasing ergodization, represented by the DED current $I_{DED,eff}$.

In the discharge from 12/4 configuration ($q_a = 3.3, R = 1.68\,\mathrm{m}, a = 0.40\,\mathrm{m}, I_{DED} = 11\,\mathrm{kA}$) the poloidal rotation profile of C^{6+} ions changes from electron to ion-diamagnetic drift direction (positive to negative velocity) in a radial zone between $R = 2.05\,\mathrm{m}$ and the limiter radius at $R = 2.09\,\mathrm{m}$ (Fig. 2 a)). Here the ergodic region builds up ($\sigma_{\mathrm{Chirikov}} > 1$). Using toroidal rotation data from CXRS with the heating beam we have calculated the radial electric field from the radial force balance for C^{6+} ions. The diamagnetic and the toroidal rotation term give no significant contribution to the change in E_r, so that the *reversal of the poloidal rotation* is directly linked to a *reversal from a negative to a positive radial electric field* ($\Delta E_r = 10\,\mathrm{kV/m}$, cf. Fig. 2 b)).

We compare the experimental results from the stochastic region to a simple local model of rotation and electric field where the crucial aspect is the formation of a transverse current in this region [2]. This current is sustained by the finite ion crossfield conductivity related to viscosity and friction with neutrals and is derived for the collisional limit. It leads to a $\mathbf{j} \times \mathbf{B}$ force,

$$\alpha\,(v_\theta - v_{neo}) = -\langle j_{\perp,r}\rangle B_\phi - (1+2q^2) M v_\theta \quad (1)$$

$$M v_\phi = \langle j_{\perp,r}\rangle \theta B_\phi + F_{beam} \quad (2)$$

$$E_r = E_{r,\nabla p} - v_\theta B_\phi + v_\phi \theta B_\phi \quad (3)$$

$$\langle j_{\parallel,r}\rangle = -\langle j_{\perp,r}\rangle = \sigma_{erg}\,(E_r - E_a) \quad (4)$$

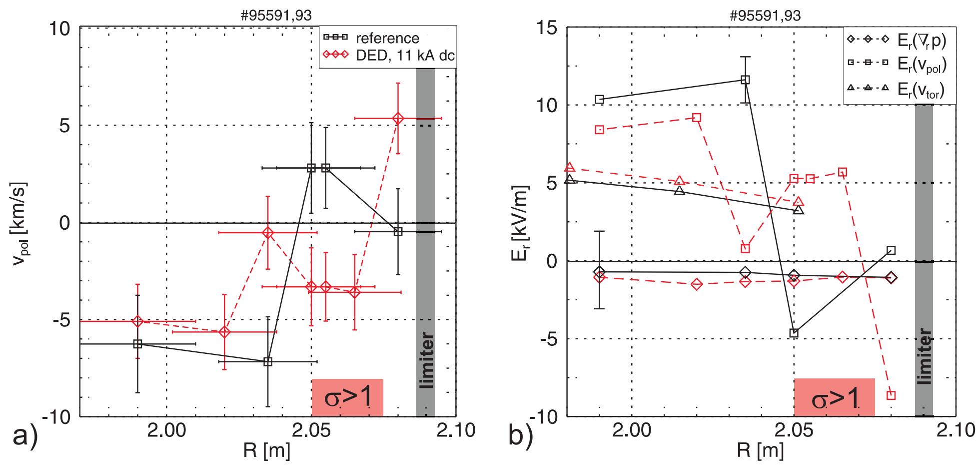

Figure 2: a) Poloidal rotation profiles during DED phase (– – –) and a reference (—), b) Contributions to radial electric field from pressure gradient, poloidal and toroidal rotation. The outermost points at 2.08 m can be assigned to the laminar zone and are not discussed here.

producing the plasma rotation we observe. The poloidal and toroidal momentum balances come from a single fluid description [5] together with the radial force balance of ions.

All information for density and temperature profiles of electrons and ions is taken from experiment. The equations 1-4 are solved for the unknown poloidal and toroidal rotation, the radial electric field and the transverse current. Here v_{neo} is the neoclassical rotation velocity in the Plateauregime relevant for our conditions, α the corresponding parallel viscosity coefficient from [5], M the sum of the coefficients for anomalous perpendicular viscosity and friction with neutrals [5], F_{beam} the force exerted by the neutral heating beam, $E_{r,\nabla p}$ the part of the electric field related to the ion diamagnetic term, $\theta = B_\theta / B_\phi < 0$ for our coordinate system (toroidal field and plasma current antiparallel), $\sigma_{erg} = \sigma_{\|} D_{Fl}/L_K$ the cross field conductivity in the ergodic region with $\sigma_{\|}$ being the parallel conductivity, D_{Fl} the fieldline diffusion coefficient and L_K the Kolmogorov length. The latter two are taken from mapping calculations of the perturbed topology [6], where D_{Fl}/L_K scale proportional to the strength of the perturbation current in the DED coils with a power of 8/3. In Eqn. 4 we used $E_a = -T_e/e \cdot d\ln n_e/dr - 1.71/e \cdot dT_e/dr$ to express the ambipolar field corresponding to zero parallel current [6].

For the experimental conditions of Fig. 2, Fig. 3 shows the results of calculations for the poloidal and toroidal rotation, the radial electric field and the transverse current density as a function of the external perturbation current. The gradient lengthes of densities and temperatures are taken from experiment. The coefficient $M = 2.2 \cdot 10^{-4}$ Ns/m^4 related to anomalous viscosity and friction with neutrals and the force $F_{beam} = 5\,\mathrm{N/m^3}$ exerted by the NBI have been adapted to match the experimental findings for the no-DED reference case. This simplified de-

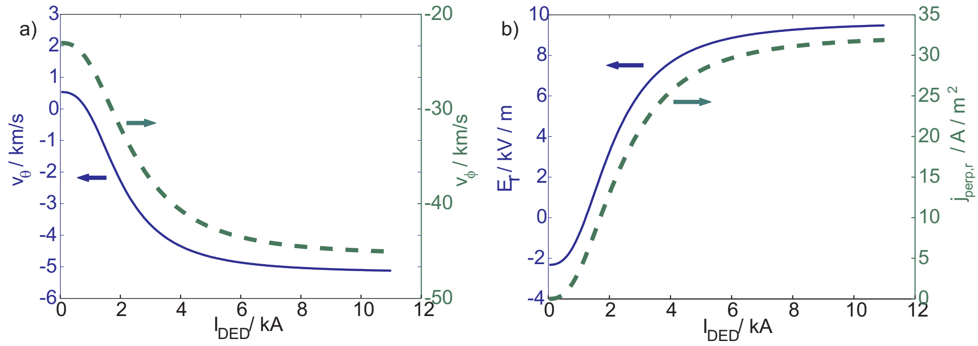

Figure 3: Impact of magnetic perturbation expressed as perturbation current I_{DED} on a) poloidal(solid line) and toroidal rotation (dashed) and b) radial electric field (solid line) and transverse current density (dashed) following as solution from eqns. 1 - 4 (see text for details).

scription reveals a maximum increase of E_r by about 10 kV/m comparable to what is seen in the experiments. The resulting transverse current density in the stochastic region can reach up to 30 A/m^2 resulting in a poloidal force density of 40 N/m^3 in ion diamagnetic drift direction and a toroidal force of 4 N/m^3 in co-current direction. The corresponding local torque is comparable to the one exerted by the tangential neutral beams in TEXTOR.

Summary

Plasma rotation and the radial electric field have been investigated under influence of magnetic perturbations imposed by the Dynamic Ergodic Divertor in TEXTOR. In the stochastic edge plasma the poloidal rotation changes from electron to ion diamagnetic drift direction and the toroidal rotation increases into co-current direction. These variations are governed by the strength of the magnetic perturbation rather than by its rotation. The radial electric field becomes positive here. The changes of rotation and electric field can be reproduced in a simple model for the rotation with a torque produced by a transverse current in the stochastic layer.

Acknowledgments

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