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Impact of stochastic magnetic fields on plasma rotation and radial electric fields in the plasma edge of the tokamak TEXTOR

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Abstract

In this contribution we report on spectroscopic measurements of plasma rotation and the radial electric field in the plasma boundary under the operation of the dynamic ergodic divertor in TEXTOR. Under the influence of the stochastic magnetic field we observe an increase of both poloidal and toroidal rotation of carbon nuclei into ion-diamagnetic drift/co-current direction. With static magnetic perturbation the electric field in the ergodic region increases by 10 kV/m and becomes positive. Application of dynamic perturbation leads to a comparable change of the rotation, independent of the direction of the rotation of the DED field and only depending on the degree of ergodization. We introduce a model to explain the experimental findings by the onset of transverse currents in the ergodic region and a subsequent torque onto the plasma.

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1. Introduction

Resonant magnetic perturbations produced by external coils and leading to stochastic edge plasmas have been applied in fusion devices to investigate

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ergodic divertors as an alternative concept for power and particle exhaust [1,2]. A further application is the mitigation of edge localized modes in H-mode plasmas [3], which is an important issue with respect to transient heat loads and subsequent material erosion in future devices such as ITER. In this context the influence of the magnetic perturbations on plasma rotation and the radial electric field at the edge is of major importance for the access to H-mode conditions.

Previous studies of stochastic boundary plasmas had observed, that a positive radial electric field is built-up where the stochastic magnetic field is imposed. Such a conclusion had been drawn in the TEXT tokamak based on measurements of the space potential of the plasma with a heavy ion beam probe [4]. This finding had been confirmed in Tore Supra based on spectroscopic measurements of plasma rotation showing a spin up of carbon rotation into ion-diamagnetic drift direction to an extent which indicated a positive electric field [5]. The reversal of the electric field had been interpreted as an extension of the scrape of layer into the ergodic plasma region [1] where a positive field is needed to compensate for the enhanced electron losses.

In this contribution we report on experimental studies of the effect of stochastic magnetic fields on rotation and electric field in the plasma edge of the TEXTOR tokamak based on spectroscopic measurements. We introduce a model for the poloidal and toroidal rotation in the stochastic layer where a torque is exerted onto the plasma resulting from the formation of a transverse current in the stochastic layer [6].

Complementary measurements of turbulence rotation allowing to deduce the radial electric field had been obtained by O-mode correlation reflectometry [7]. A fast reciprocating probe had been used to measure radial profiles of electron density and temperature as well as floating potential [8]. These data confirm the experimental findings reported in this contribution.

2. Experimental set-up

The Dynamic Ergodic Divertor in the TEXTOR consists of 16 perturbation coils and two compensation coils wound helically around the torus on the inboard side, which produce resonant magnetic perturbations centered around the $q = 3$ surface. Depending on the phase of the neighboring coils, the system can be operated in configurations with poloidal/toroidal mode numbers 3/1 (deep penetration of the perturbations up to the $q = 2$ surface), 6/2 and 12/4 (shallow penetration, restricted to the plasma edge). The DED can be operated in DC as well as AC with frequencies up to 10 kHz (cf. [9]). The topology of the perturbed magnetic field is characterized by an ergodic region where the connection length to the wall is large with respect to the de-correlation length (Kolmogorov length) of the field lines and a laminar region radially further outside which has a relatively short connection to the wall.

For the determination of the poloidal rotation by charge exchange recombination spectroscopy (CXRS using CVI emission at $\lambda = 529.5$ nm) a radially injected, modulated hydrogen diagnostic beam has been used [10]. The same observation system has been used for passive spectroscopy of the Doppler shift of CIII emission at $\lambda = 464.74$ nm which originates from a thin emission shell ca 1–2 cm inside the LCFS for the discharge conditions under consideration. In case of active CXRS measurements the radial pressure profile of the C^{6+} ions is used together with the toroidal rotation measured by CXRS with the heating beam at TEXTOR to calculate the radial electric field.

3. Results and discussion

Fig. 1 depicts the poloidal rotation of C^{2+} ions at one radial location in the perturbed region for a series of discharges in the 3/1 configuration ($q_a = 4.8$, $R = 1.76$ m, $a = 0.45$ m), where we display the change of the rotation (positive Δv corresponds to a change towards ion-diamagnetic drift direction). We observe an almost linear increase of the poloidal rotation with the perturbation current while there is no separation outside the error bars of the measurement between the data obtained with static or rotating perturbation in co- or counter direction (AC co-rotation refers to ion-diamagnetic direction of its poloidal component, AC counter-rotation to electron-diamagnetic direction).

In the 12/4 configuration of the DED we have measured the poloidal rotation profile of C^{6+} ions (Fig. 2(a)). In this plasma discharge ($q_a = 3.3$, $R = 1.68$ m, $a = 0.40$ m, $I_{DED} = 11$ kA), in a radial zone between $R = 2.05$ m and the last closed flux surface at $R = 2.09$ m, we measure a change of rotation from electron (positve velocity) to ion-diamagnetic drift direction (negative velocity) in the radial

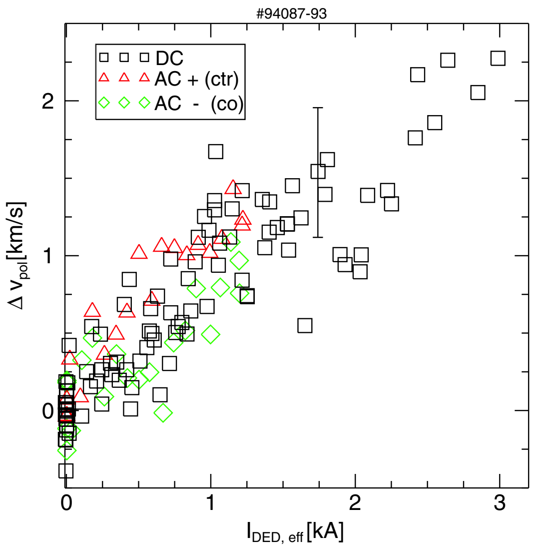

Fig. 1. Change of poloidal rotation in the perturbed region with increasing ergodization strength, represented by the perturbation current, $I_{DED,eff}$, in the DED coils (3/1 configuration).

region where the ergodic region builds up (Chirikov parameter σ larger that one). Using further data for toroidal rotation 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* ($\Delta E_r = 10$ kV/m, cf. Fig. 2(b)).

These spectroscopic results are confirmed by measurements published before with our reflectometry and fast reciprocating probe under the influence of DED. Reflectometry confirms the reversal of the poloidal turbulence rotation from electron (no DED case) to ion diamagnetic drift direction with DED in the 12/4 configuration. In the 3/1 configuration we deduce from the turbulence rotation and the radial electron pressure profile a reversal of the electric field from -2 kV/m to $+6$ kV/m for $q_a = 4.8$, $R = 1.76$ m, $a = 0.45$ m, $I_{DED} = 2$ kA [7]. In the 6/2 configuration E_r measured with the probe system changes from -5 kV/m in the reference case to $+5$ kV/m with DED ($q_a = 4.9$, $R = 1.73$ m, $a = 0.46$ m, $I_{DED} = 6$ kA) [8].

For all different base mode configurations of the DED (3/1, 12/4 and 6/2 configuration) a common qualitative picture arises: both poloidal and toroidal rotation change with increasing perturbation (caused by an increasing current in the perturbation coils), the poloidal rotation spins up into ion diamagnetic drift direction (it is usually in electron diamagnetic drift direction for the unperturbed case just inside the LCFS), the toroidal rotation into co-current direction. With increasing stochastization the radial electric field changes from negative (pointing inward) to positive values (pointing outward).

We now want to compare the experimental results for the 12/4 configuration shown in Fig. 2 quantitatively to a simple local model of rotation and electric field where the crucial aspect is the

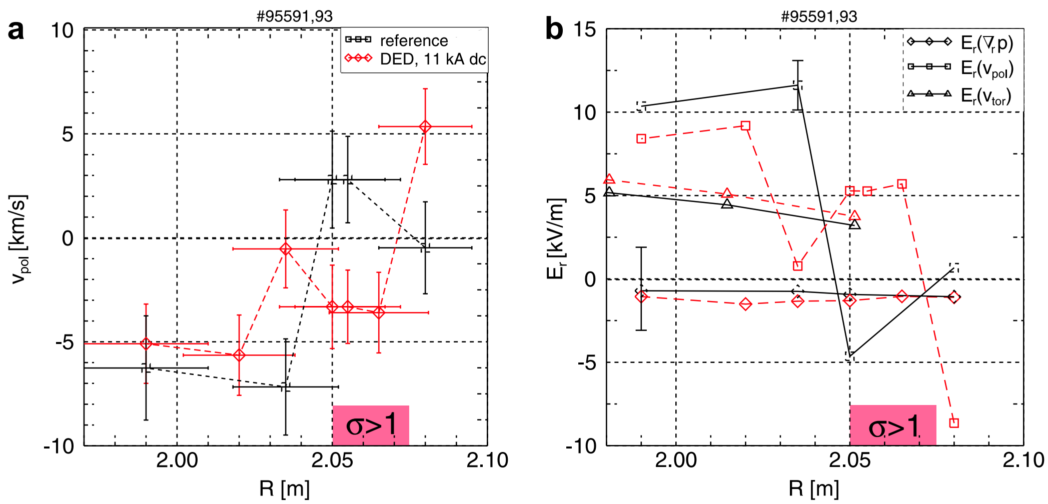

Fig. 2. (a) Poloidal rotation profiles during DED phase (12/4 configuration) and a reference, and (b) contributions to the radial electric field from pressure gradient, poloidal and toroidal rotation (dashed lines: DED case, solid lines: reference discharge).

formation of a transverse current in the stochastic region [6] which we have combined with the poloidal and toroidal momentum balance in the single fluid description as given in [11]. This current is sustained by the finite cross-field conductivity of ions related to viscosity and friction with neutrals and discussed e.g. in context with biasing experiments. The transverse current (taken in the collisional limit) has a radial component directed outward which compensates the radial component of the parallel current along the field lines caused by electron losses in the stochastic field. While the latter parallel current does not lead to a $j \times B$ force, the transverse current does, causing the plasma rotation observed experimentally. All information for the density and temperature profiles of electrons and ions is taken from experiment. The system of Eqs. (1)–(4) is used to solve for the unknown poloidal and toroidal rotation, the radial electric field deduced from the radial force balance and the transverse current density. The most uncertain prescription is made by fixing the gradient length of the toroidal rotation to the minimum of the gradient length of the ion temperature and the width of the ergodic region. However, and as seen from the experimental results in Fig. 2, the strongest influence for the evolution of the radial electric field stems from the change of poloidal rotation.

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

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

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

$$\langle j_{\|,\text{r}}\rangle = -\langle j_{\perp,\text{r}}\rangle = \sigma_{\text{erg}}(E_\text{r} - E_\text{a}). \quad (4)$$

Here v_{neo} is the neoclassical rotation velocity in the Plateau-regime relevant for our conditions, α the corresponding parallel viscosity coefficient as given in [11], M the sum of the coefficients for anomalous perpendicular viscosity and friction with neutrals [11], F_{beam} the force exerted by the tangential neutral beam injection, $E_{\text{r},\nabla p}$ the part of the electric field related to the ion diamagnetic term, $\theta = B_\theta/B_\phi$ is negative for our coordinate system (toroidal field and plasma current anti-parallel) and $\sigma_{\text{erg}} = \sigma_\| D_{\text{Fl}}/L_\text{K}$ the cross field conductivity in the ergodic region with $\sigma_\|$ the parallel conductivity, D_{Fl} the field line diffusion coefficient and L_K the Kolmogorov length, both taken from mapping calculations of the perturbed topology [12]. These calculations also show a scaling of D_{Fl}/L_K proportional to the strength of the perturbation current in the DED coils with a power of 8/3. In Eq. (4) we used $E_\text{a} = -T_\text{e}/e \cdot \text{d}\ln n_\text{e}/\text{d}r - 1.71/e \cdot \text{d}T_\text{e}/\text{d}r$ to express the ambipolar field which corresponds to zero parallel current.

For illustration we give in the following an analytical solution of the equation system (1)–(4) *disregarding* the toroidal rotation and introduce the cross field ion conductivity $\sigma_\perp = (\alpha + M)/B_\phi^2$. While, for $\sigma_{\text{erg}} \ll \sigma_\perp$ the poloidal rotation, the radial electric field and the transverse current increase linearly with σ_{erg}, in the limit of high ergodization with $\sigma_\perp \ll \sigma_{\text{erg}}$ the radial field approaches the ambipolar field E_a and the poloidal rotation is given by the sum of the poloidal $E_\text{a} \times B$ drift and diamagnetic drift velocity. The transverse return current is governed by the cross field conductivity and the difference between E_a and $E_{\text{r},\nabla p}$:

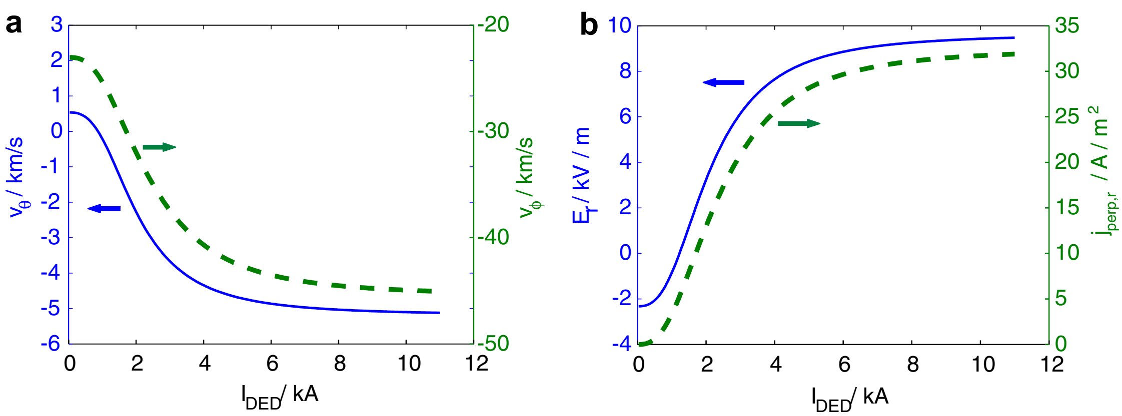

Fig. 3. Impact of magnetic perturbation expressed as perturbation current I_{DED} on: (a) poloidal (solid line) and toroidal rotation (dashed) and (b) radial electric field (solid line) and transverse current density (dashed) following as solution from Eqs. (1)–(4) (see text for details).

$$v_\theta = -\frac{1}{B_\phi}\frac{\sigma_{\rm erg}(E_{\rm a} - E_{{\rm r},\nabla p}) - \frac{\alpha}{B_\phi^2} v_{\rm neo} B_\phi}{\sigma_{\rm erg} + \sigma_\perp}, \quad (5)$$

$$E_{\rm r} = \frac{\sigma_{\rm erg} E_{\rm a} - \sigma_\perp E_{{\rm r},\nabla p} + \frac{\alpha}{B_\phi^2} v_{\rm neo} B_\phi}{\sigma_{\rm erg} + \sigma_\perp}, \quad (6)$$

$$\langle j_{\perp,{\rm r}}\rangle = -\langle j_{\parallel,{\rm r}}\rangle = \frac{\sigma_{\rm erg}\left(\sigma_\perp E_{\rm a} - \sigma_\perp E_{{\rm r},\nabla p} + \frac{\alpha}{B_\phi^2} v_{\rm neo} B_\phi\right)}{\sigma_{\rm erg} + \sigma_\perp}. \quad (7)$$

For the experimental conditions of Figs. 2, 3 shows the results of calculations for the poloidal and toroidal rotation, the radial electric field and the transverse current density from Eqs. (1)–(4) as a function of the external perturbation current with $\sigma_{\rm erg} \propto I_D^{8/3}$. The gradient lengthes of densities and temperatures are taken from experiment and the coefficient $M = 2.2 \times 10^{-4}$ Ns/m^4 related to anomalous viscosity and friction with neutrals and the force $F_{\rm beam} = 5$ N/m^3 exerted by the NBI have been adapted to match the experimental findings for the no-DED reference case and kept constant. This simplified description reveals a maximum increase of $E_{\rm r}$ by about 10 kV/m comparable to what is seen in our experimental results.

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 density of 4 N/m^3 in co-current direction (leading to a local torque which is comparable to the one exerted by the tangential neutral beams in TEXTOR).

4. Summary and conclusions

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, while the toroidal rotation increases into co-current direction. These variations are governed rather by the strength of the magnetic perturbation than by the rotation of the perturbation field. The radial electric field becomes positive in the stochastic region. In the 12/4 base mode configuration the changes of rotation and electric field can quantitatively be reproduced in a simple model for the rotation with a torque resulting from a transverse current in the stochastic layer.

In our consideration we have not included a possible torque transfer from DED on the plasma attributed to shielding currents at the resonance layer of the magnetic perturbation. Also this torque is predicted to spin up the plasma into ion diamagnetic drift direction as long as the perturbation frequency is smaller than the electron diamagnetic drift frequency [13,14]. While our analysis presented in this contribution indicates, that the torque resulting from the transverse return current in the stochastic edge region could be large enough to explain the experimental findings on rotation at least for the 12/4 configuration of the DED with its shallow penetration depth of the perturbation field, further work to combine these two different mechanisms of torque transfer into one model is planned for the near future.

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