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First Mach probe measurements of rotation, electric field and particle transport in the DED-ergodized edge plasma of TEXTOR

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1. Introduction

A long lasting challenge in controlled fusion research is the control of plasma-wall interaction. An externally applied magnetic field perturbation is one aid to modify the scrape-off layer transport. In TEXTOR a set of 16 coils, called dynamic ergodic divertor (DED), wrapped around the vessel at the high field side and that creates a perturbation field roughly resonant to the q=3 surface, has been installed. The DED can be operated with poloidal/toroidal mode number equals 3/1, 6/2 and 12/4 [1], whereby only results referring to the first two configurations are presented here. The different operation modes will lead to different perturbation volumes of the plasma. Three different settings of the DED-currents have been studied: (1) the static case, (2) AC co-DED operation with a phase in the two coil currents such that a co-rotation is imposed and (3) AC counter-DED. The "co-rotation" means with respect to the poloidal direction the ion diamagnetic direction and with respect to the toroidal one the direction of the plasma current.

2. Probe diagnostic

A Mach probe head, carrying two radially separated rows of four collector pairs and four additional cylindrical pins on top, has been installed on TEXTOR to measure simultaneously profiles of toroidal and poloidal rotation, of the radial electric field and of density and potential fluctuations (see Fig. 1). Flush mounted flat collectors have been chosen for higher precision of the flow measurements. The collectors are 4 mm x 4 mm in size, which is sufficiently large to ensure that the condition of a strongly magnetized probe is satisfied, and distributed poloidally by an angle of 18^o. The flows are inferred from the up- and downstream ion saturation current ratio using a 1D-model based on Hutchinson's approach [2], which was extended for perpendicular flow by Van Goubergen [3]:

$$\ln\left(\frac{I_{sat,up}(\alpha)}{I_{sat,down}(\alpha)}\right) = c(M_{\|,\infty}, M_{\perp}, \alpha)\left(M_{\|,\infty} - M_{\perp}\tan\alpha\right) \qquad (1)$$

with α as the angle between the surface normal and the magnetic field, $I_{\text{sat,up}}$ and $I_{\text{sat,down}}$ as up- and downstream ion saturation current, $M_{\|,\infty}$ and $M_{\perp}$ as parallel and perpendicular unperturbed Mach number. The function $c(M_{\|,\infty}, M_{\perp}, \alpha)$ has a weak dependence on $M_{\|,\infty}, M_{\perp}$ and α, which has been studied in [4] in more detail. For the analysis here a constant value of 2.21 has been used for *c*. A sinusoidal voltage (f=250 Hz) has been applied to the flat collectors. At a speed of 0.7 m/s a spatial resolution of ~3 mm is achieved. The cylindrical pins, which have a poloidal distance of 7.5 mm, have been operated as triple probe. For the turbulent particle flux measurements, a dedicated probe head with pins, poloidally separated by 3 mm has been used to gain a higher accuracy [5].

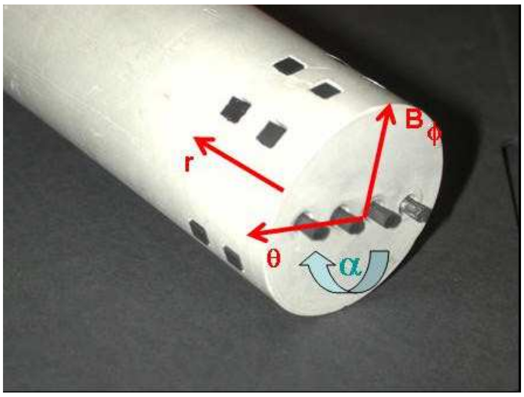

Fig. 1: Mach probe head.

3. Experimental results

During the steady-state phase of the discharge currents have been applied to the DED-coils. The probe profiles were taken before and during the plateau phase of the DED. The experiments in 3/1 configuration were performed at B_t=1.9 T, I_p=255 kA, $\langle n_e \rangle = 1.5 \times 10^{19}$ m^{-3}. The 6/2-discharges had a slightly higher plasma current of 270 kA with otherwise identical parameters. In the 6/2 configuration the ergodic zone is smaller than in the 3/1, but has the advantage that the DED-current threshold for the onset of a 2/1 tearing mode, which is observed for most cases during 3/1-operation is higher and can thus be avoided. Between the ergodic region (ER) and the far SOL is a laminar zone (LZ) with finite connection lengths.

The DED can induce rotation in two ways. First, the change of the magnetic field pattern leading to high field line diffusion causes large electron losses. These losses have to be compensated by an additional positive ambipolar electric field, which will affect via the *E*x*B* force the poloidal and toroidal rotation. In [6] the resulting transverse current in a stochastic region has been predicted: $j_r \approx 0.1\, e^2 D_{fl} n_e \sqrt{2/\pi m_e T_e}\, E_r^{neo}$. Using a typical value of 10^{-5} m^2/m for the field line diffusion coefficient D_{fl}, one expects a current density of about -60 A/m^2. With a conductivity of about 2×10^{-3} A/Vm a positive electric field in the order of 30 kV/m would be required to balance the loss current. As seen in Fig. 2a the radial electric field changes in the LZ from negative before the DED-phase (black curves) to positive during the DED (red curves). The vertical dashed line indicates the LCFS inferred from the drop in the floating potential profile before the DED switch-on and the punctuated line the approximate transition from the ER to the LZ. Though the change in the toroidal rotation is larger during the DED (Fig. 2b), the change in the electric field is mainly due to the poloidal rotation because of its larger contribution in the radial force balance. The edge profiles are affected in the ergodic as well as in the laminar zone (Fig. 2c). The temperature is strongly reduced in the edge, which has also been observed during the ergodic-divertor operation at TORE SUPRA [7]. There are two potential explanations for this observation. One is the enhanced carbon radiation during DED, which is seen as an increase of ~20% of the radiated power during DED, the other one are the additional convective losses to the wall due to the ergodization. The electron density increases throughout the edge region and hence also the pressure is larger in the ergodic region. Nevertheless, a change in the global confinement has not been observed, which indicates that these are local effects.

The ergodization of the plasmas edge is largely influencing the turbulence at the edge, which can be inferred from figure 3. The data have been taken with the turbulence probe head in another discharge with the same plasma parameters as above, besides of small variation in the plasma position [5]. The boxes show from top to bottom the density fluctuation $<n_{e,rms}>$, deduced from I_{sat}-fluctuations, the poloidal electric field fluctuation $<E_{\theta,rms}>$ and the resulting turbulence driven particle transport flux Γ_{turb} before (black symbols) and during DED (red symbols). The density fluctuation levels are slightly increased, which is opposite to our previous observation during 3/1-DED-DC, where a strong reduction has been observed. However, the most remarkable effect is on Γ_{turb}. Already for small DED-current amplitudes Γ_{turb} is reduced and even reverses sign (positive Γ_{turb}-values correspond to particle losses), which is probably the cause for the increased electron pressure seen in the ergodic region. The drastic change in Γ_{turb} are mainly due to a phase shift of $<n_{e,rms}>$ and $<E_{\theta,rms}>$. Despite of the sign reversal of the electric field during DED, it is impossible that the resulting *E*x*B* flow shear is responsible for the observed Γ_{turb} reversal.

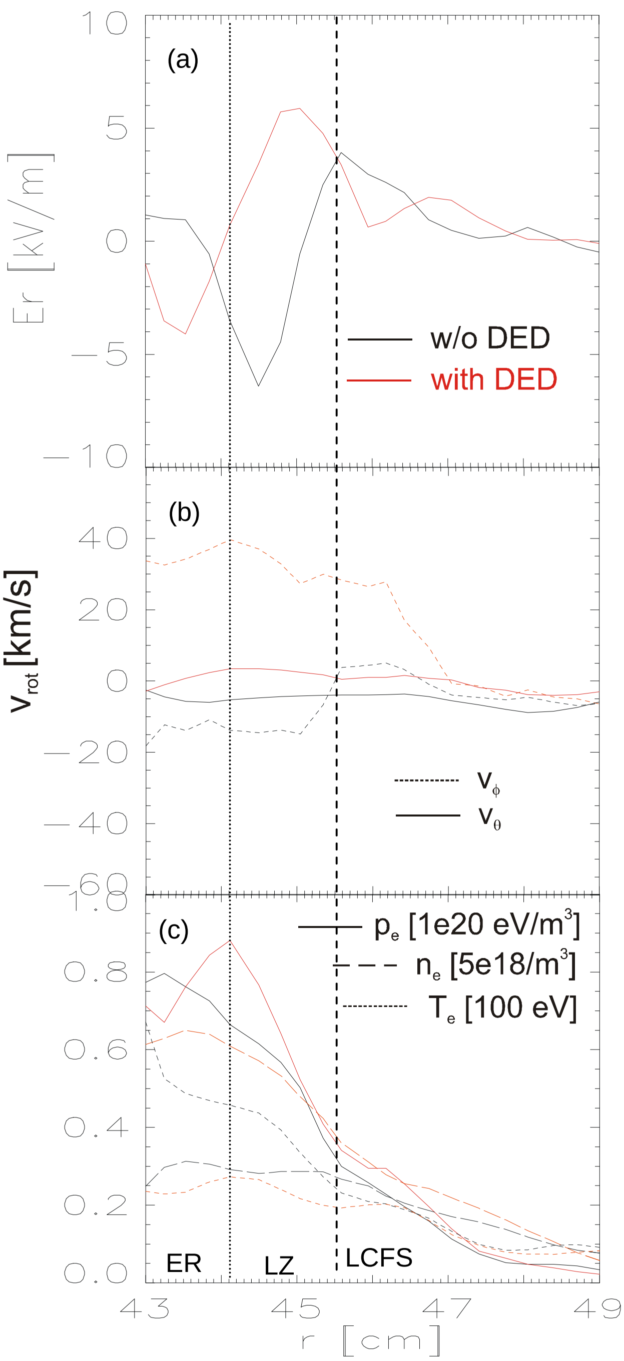

Fig. 2: Profiles of (a) E_r, (b) toroidal v_ϕ and poloidal v_θ rotation and (c) p_e, n_e and T_e, before (black) and during 6/2-DED (red).

The second possibility to induce rotation could be studied only in the 3/1 configuration due to technical reasons. In case of the dynamic operation of the ergodic divertor, a torque perpendicular to the magnetic field line is applied to the plasma. However, since the poloidal damping is much stronger than the toroidal one, the effects are expected to be larger in the toroidal direction than in the poloidal. In the 3/1-configuration the perturbed region is larger than in 6/2 and typically an onset of a 2/1 tearing mode observed, which causes a deterioration of the confinement. However, for the study presented here this is of minor importance. To the two sets of coils a sinusoidal perturbation current with a frequency of 1 kHz has been applied with a phase-shift either in the direction of the plasma current or opposite. The results are shown in Figure 3. The black curves correspond to the non-DED phase, the red to co-direction (in the sense of ion-diamagnetic drift direction), the yellow to counter-direction. Against the predictions, no significant difference in the floating potential profile for the AC-co and AC-counter case (Fig. 3a) are seen. The direction of the DED-AC phase has also only little influence on the rotation. The possible imposed torque is overwhelmed by the enhanced conductivity. Both Mach numbers, parallel and perpendicular are changing sign independent of DED-rotation, although the perpendicular flow seems more affected in the AC-counter discharge. Interestingly, the change in rotation and *ExB* flow shear causes in the AC-counter pulse an enhancement of the edge turbulence and the turbulent particle transport. On the contrary, in the DED-AC co case, Γ_{turb} is reduced and even reverses sign.

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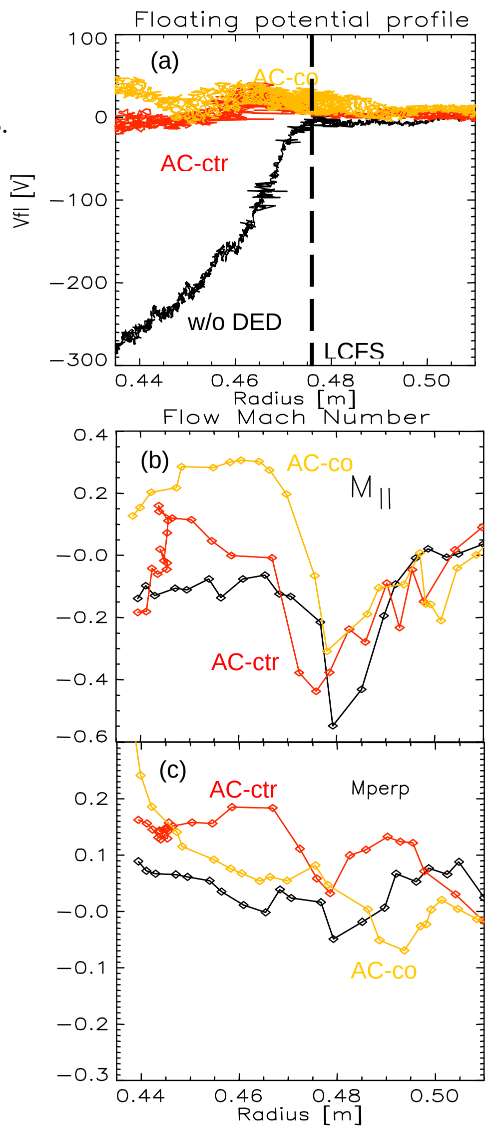

Fig. 4: Profiles of (a) float. pot., (b) paral. and (c) perp. Mach numbers during AC-co and AC-ctr. 3/1 DED.

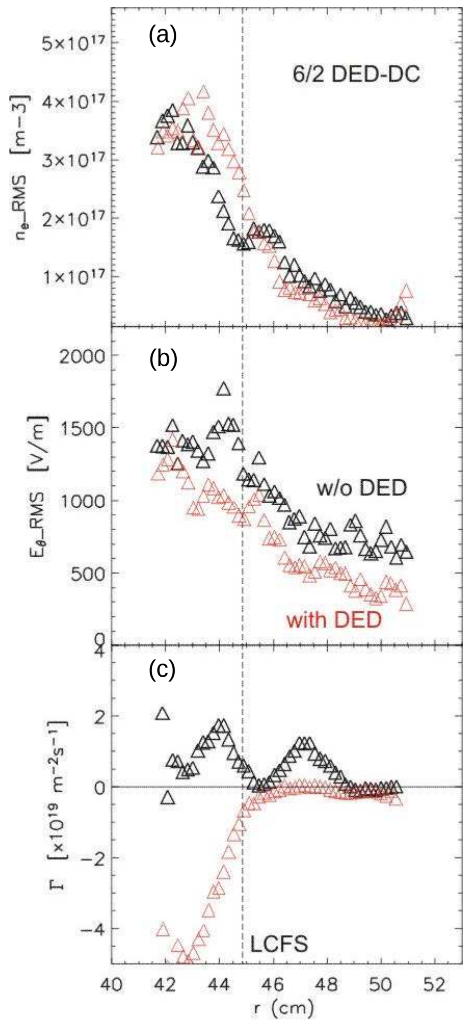

Fig. 3: Profiles of (a) density-, (b) pol. electr. field-fluctuations and (c) turb. part. flux in 6/2 DED.