THE IMPACT OF THE DYNAMIC ERGODIC DIVERTOR ON PLASMA EDGE STRUCTURE AND TRANSPORT IN THE TOKAMAK TEXTOR

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Abstract. The Dynamic Ergodic Divertor (DED) has recently been installed in the Tokamak TEXTOR. The magnetic perturbations are centred at the q=3 surface with mode numbers 12/4, 6/2 or 3/1. With increasing magnetic perturbation an ergodic region is formed in the plasma edge with overlapping magnetic islands, characterised by very long connection lengths to the target, and a laminar zone with short connection lengths. In the laminar zone a helical divertor is formed. In this contribution, we describe the edge structure resulting from the magnetic perturbation in terms of the particle flux distribution on the divertor target and the plasma properties upstream of the divertor. In the 12/4 configuration with increasing ergodization the stripes on the target formed by the DED split up with a private flux region in between, and a reduction of the edge density and edge pressure is observed at the low field side where flux tubes with a short connection length to the divertor target open up in the laminar zone. At the same time the electron temperature in the ergodic zone is reduced. In the 3/1 configuration with its much deeper penetration of the error field the effect of the ergodization by the DED is enhanced by the onset of 2/1 and 3/1 tearing modes. At the onset of the 2/1 tearing mode the poloidal rotation at the edge is reduced and even reversed once the 3/1 tearing mode sets in. These findings can be referred to a reduction and even reversal of the radial electric field in the ergodic region. Such an impact of the ergodization on the radial electric field is supported by probe measurements.

1. Introduction

The Dynamic Ergodic Divertor (DED) [1] has been built into the tokamak TEXTOR to study the impact of stochastic magnetic fields on the plasma edge and to investigate its potential for particle and power exhaust from magnetically confined high temperature plasmas. Such a potential has been first demonstrated by the Ergodic Divertor in Tore Supra [2, 3]. Furthermore, the possibility to mitigate type-I ELMs by imposing an ergodization of the plasma edge as first discovered in JFT-2M [4] and recently confirmed in DIII-D [5] represents an application of external magnetic perturbations with special importance for future fusion reactors. A novel and unique feature of the DED in TEXTOR is its capability to rotate the perturbation field with frequencies up to 10 kHz. While the latter feature gives – in addition to the possibility to smear out the heat load onto the plasma-facing components – the prospect of driving both internal MHD modes and plasma rotation and thus of controlling transport and stability of the plasma [6] [7] [8], we concentrate in this contribution on the impact of the DED on the plasma edge properties. Initial results in this context have been described in [9].

2. Experimental set-up

The DED consists of 16 perturbation coils and 2 compensation coils wound helically around the torus on the inboard side, which cover around 30% of the wall and produce resonant magnetic perturbations centred at the q=3 surface. The superposition of the equilibrium and the perturbation field of the DED results in an ergodization of the plasma edge and a smooth helical divertor at the high field side (HFS) of TEXTOR. The coils are covered by carbon tiles which act both as divertor target and bumper limiter. The maximum perturbation current for DC operation amounts to 15 kA per coil. The feeders of the coils are located outside of the vessel allowing for flexible interconnections. Up to now, configurations with mode numbers m/n=12/4 and 3/1 have been used. In 12/4 configuration neighbouring coils are supplied with a phase difference of 90^o whereas in the 3/1 configuration four neighbouring coils are switched in parallel. For DC operation in 12/4 (3/1) configuration the resulting ergodization is maximal if the current in 2 (8) neighbouring coils is parallel and anti- parallel for the next 2 (8) coils. In the 12/4 configuration the perturbation is restricted to the plasma edge while the 3/1 configuration is characterized by a deeper penetration into the plasma. AC operation can be performed at frequencies of 50 Hz and from 1-10 kHz. Slow strike point sweeps also are possible to move the structures induced by DED across the observation volume of diagnostics installed at fixed toroidal and poloidal positions. During operation in the 12/4 configuration the plasma is generally shifted to the HFS to reduce the distance between the coils and the q=3 surface. In this case the plasma is no longer limited by the toroidal belt limiter ALT-II of TEXTOR but by the DED target. Correspondingly, the minor radius is reduced with respect to the standard value of TEXTOR, a=0.46 m.

3. Results and discussion

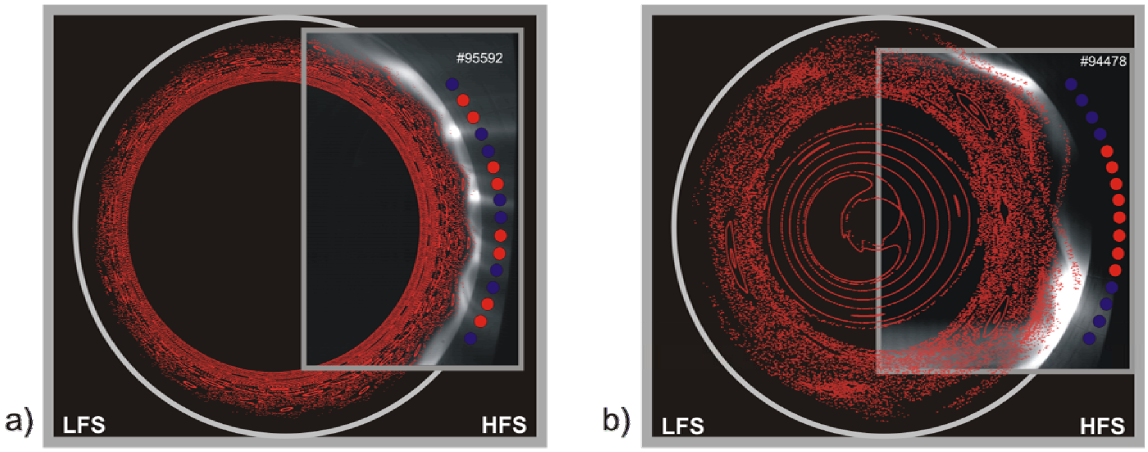

Fig.1. Divertor structure as seen in CIII light: a) example with 12/4 configuration, b) example with 3/1 configuration of the DED coils

When increasing the current in the DED coils, an ergodic region is formed with overlapping magnetic islands, which is characterized by very long connection lengths to the divertor target tiles compared to the length over which the field lines are de-correlated (Kolmogorov length). In between the ergodic region and the divertor target, a so called laminar zone is formed where the connection length to the target is short with respect to the Kolmogorov length. In the laminar zone the helical divertor structure is established. However, both zones are not sharply separated but finger-like ergodic structures reach out up to the target [10, 11]. The resulting divertor structure is seen in Fig. 1 in the light of CIII emission as observed with a CCD camera which views the poloidal cross section TEXTOR. Superimposed onto the camera picture are the structure of the magnetic field calculated from field line mapping [10, 11] and the current distribution in the DED coils.

Fig. 1a) shows a discharge where DED was applied in 12/4 configuration (I_{DED}=12 kA, I_p= 320 kA/ B_T=1.9 T, a=0.4 m, R=1.68 m). The divertor strike zones (4 pairs of 2 stripes) are readily recognized and well aligned to the ergodic fingers reaching out to the DED target. Fig 1b) displays a discharge in the 3/1 configuration (I_{DED}=3.75 kA, I_p= 300 kA/ B_T= 2.25 T, a= 0.46 m, R= 1.75 m) where two strike zones can be seen as well as the X-point at the connection of both. In this experimental situation a 2/1 and 3/1 tearing mode are excited by the DED which are thought to further enhance the magnetic field perturbation with respect to the vacuum field displayed in the figure. As demonstrated later in this contribution, at the onset of the tearing modes the interaction with the divertor target is strongly enhanced according to the sudden increase of the ergodization.

Divertor structure and edge transport in the 12/4 configuration

The resulting re-distribution of power and particle flux over the DED target tiles – consequence of the formation of the helical divertor structure with increasing perturbation – is measured by a thermography and CCD cameras with various interference filters viewing normally onto the divertor target. The evolution of the divertor structure can be best illustrated by plotting the time evolution of the poloidal particle flux distribution across the divertor target as observed in D_α light during a ramp of the DED current. Fig. 2 shows the poloidal distribution of D_α in the 12/4 configuration (I_p= 450 kA / B_T= 1.9 T, a= 0.44 m, R= 1.71 m) together with the time trace of the DED current. At lower perturbation levels a characteristic, four-fold striped pattern appears which is aligned along the perturbation coils underneath the divertor tiles. When a critical perturbation strength is reached (I_{DED}= 4 kA), each of the strike zones splits into two divertor legs with the occurrence of a private flux zone in between. Both divertor legs are connected by a flux tube with one poloidal turn. The formation of such a flux tube is accompanied by a reduction of the electron density and pressure upstream of the target at the low field side as seen in Fig. 3 (I_p= 350 kA, B_T= 1.9 T, a= 0.46 m, R= 1.75 m).

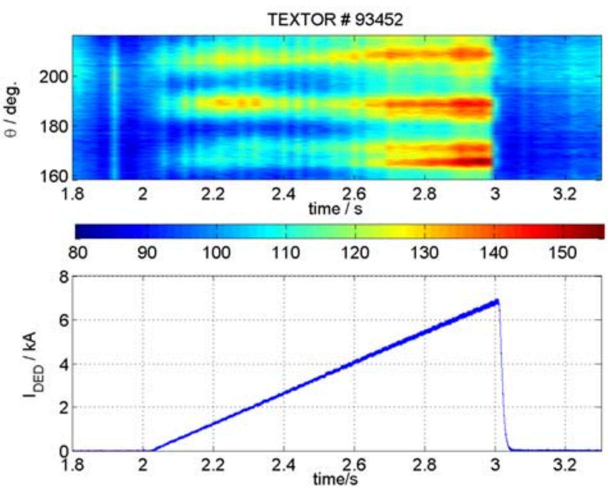

Fig. 2. Temporal evolution of a poloidal profile of D_α emission across the DED target (top) and time trace of the DED current (bottom) in the 12/4 configuration (I_p= 450 kA / B_T= 1.9 T, a= 0.44 m, R= 1.71 m).

A poloidal movement of the DED structure by a strike point sweep has shown that the flux tubes indeed have helical structure. At a fixed toroidal position the poloidal structure can be resolved. The structures observed experimentally can be understood based on the magnetic topology as calculated from field line tracing and mapping techniques [10, 11]. As a next step we start to compare the experimental results to modelling results with the EMC3- Eirene [12] code which has originally been developed to study edge transport in stellarators and has been adapted to the DED in TEXTOR. The code has been applied to the discharge scenario depicted in Fig. 2 has and confirmed qualitatively the poloidal density modulation at the low field side (LFS) as long as the structures are not smeared out by cross field transport.

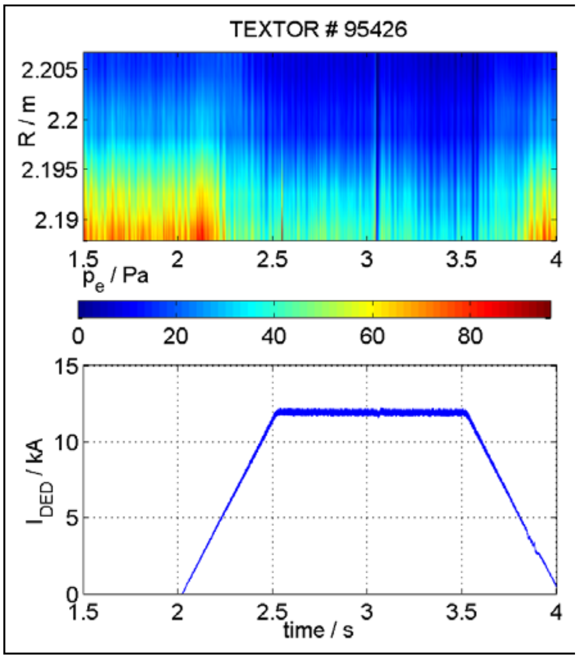

Fig.3. Temporal evaluation of the electron pressure profile at the LFS (top) and the time trace of the DED current (bottom) in the 12/4 configuration (I_p= 350 kA, B_T= 1.9 T, a= 0.46 m, R= 1.75 m)

LCFS of the unperturbed equilibrium as expected from the increased ohmic heating. At around q_a =3.25 T_e starts to decrease. A comparison with the magnetic field structure indicates the onset of ergodization via the overlap of the magnetic island chains at the resonances which starts at this value. For comparison we plotted the value of the *local* Chirikov parameter, σ_{Chir} (σ_{Chir}>1 indicates the overlap of islands). At the end of the ramp of the plasma current also the DED current is ramped down under otherwise constant conditions, and we see a dramatic increase of the edge temperature by about 100 eV. The temperature drop in the ergodic region can be explained by the increase of the effective perpendicular heat transport in the stochastic magnetic field, an effect well known from previous experiments with ergodic limiters and divertors (cf. review paper [2]). The onset of ergodization is accompanied by the splitting of the strike zones seen in the poloidal D_α profile as depicted in Fig. 4 (bottom).

In addition to an increase of the DED current, two further parameters turned out to be strongly influencing the degree of ergodization and the width of the ergodic and laminar zones: the safety factor at the edge, q_a, and the horizontal position of the plasma column. Both, a decrease of q_a and a shift of the plasma towards the HFS decreases the distance between the DED coils and the rational surfaces where the main resonances are located (q= 10/4, 11/4, 12/4 and 13/4).

Fig. 4 shows the response of the plasma edge to a variation of q_a (estimated in large aspect ratio approximation) in an ohmically heated plasma which has been shifted to the DED target (B_T= 1.9 T, I_p ramped from 200 – 400 kA, R= 1.68 m, a= 0.4 m). Starting from a high q_a we observe a modest increase of the electron temperature measured by ECE at the

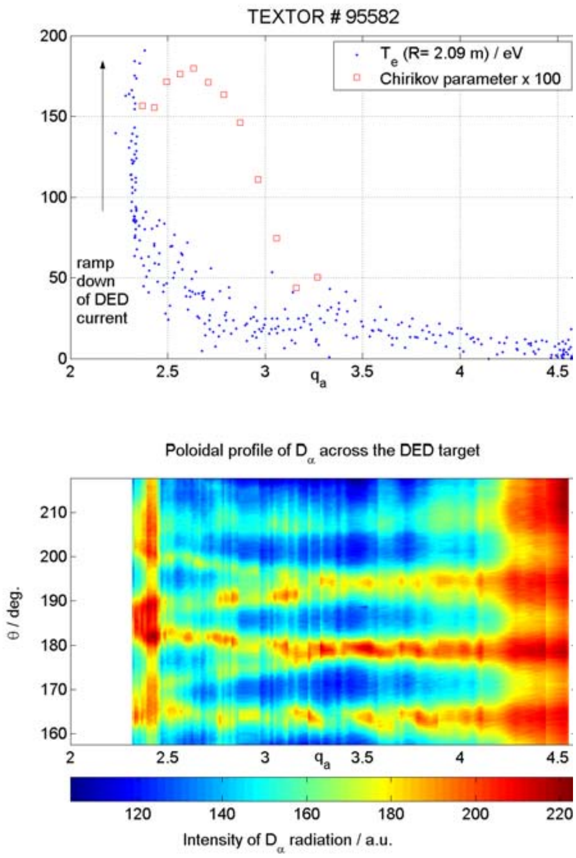

Fig.4. Electron temperature and Chirikov parameter at R= 2.09 m (top) and evolution of a poloidal profile of D_α emission across the DED target (bottom) as a function of q_a (12/4 configuration, B_T= 1.9 T, I_p ramped from 200 – 400 kA, R= 1.68 m, a= 0.4 m).

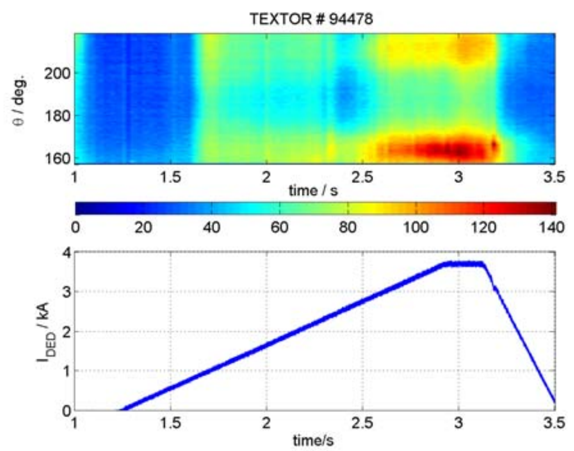

Fig 5. Temporal evolution of a poloidal profile of D_α emission across the DED target (top) and time trace of the DED current (bottom) in the 3/1 configuration (I_p = 300 kA, B_T= 2.25 T, a= 0.46 m, R= 1.75 m).

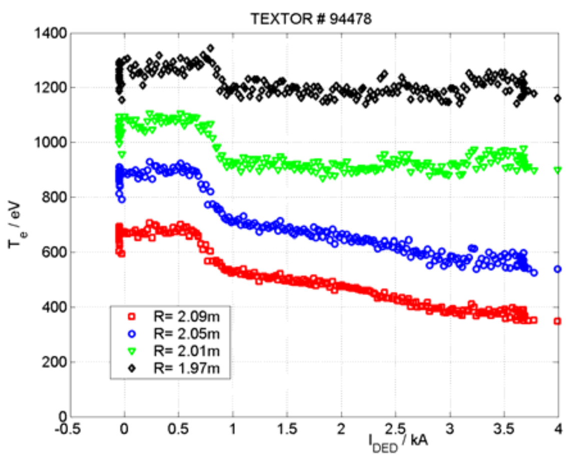

Fig. 6. Evolution of the electron temperature measured by ECE with DED current at different radii in the 3/1 configuration (I_p =300 kA, B_T= 2.25 T, a= 0.46 m, R= 1.75 m).

Divertor structure and edge transport in the 3/1 configuration

In the 3/1 configuration the divertor characteristics are strongly influenced by the onset of 2/1 and 3/1 tearing modes which are triggered by the deeply penetrating error field. Under the discharge conditions depicted in Fig. 5 (Ip=300 kA, B_T=2.25 T, a=0.46m, R=1.75m), the threshold for the onset of the 2/1 tearing mode is around I_{DED}=0.8kA and for the 3/1 mode I_{DED}=2.3kA [7]. The two strike zones already observed in Fig 1b) are clearly seen in the poloidal profile of the D_α emission across the divertor target. Corresponding to the structure of the 3/1 mode we do also observe helical recycling patterns on the toroidal belt limiter ALT-II at the LFS and on a poloidal limiter at the top of the machine.

First experiments in the 3/1 configuration to investigate the divertor properties when the plasma density is raised up to the density limit have shown the possibility to access a regime of enhanced divertor recycling [9] where the density measured by target probes increases non- linearly with the edge density at the LFS. This regime is followed by a detachment from the divertor target. The discharge is then terminated by the formation of a MARFE at the X- point of the near field. Such a non- linear density regime and divertor detachment in an Ergodic Divertor has been found before in Tore Supra [3].

The onset of the 2/1 tearing mode excited by the DED in the 3/1 configuration is also seen in the electron temperatures measured by ECE and depicted as a function of the DED current in Fig. 6. After the mode onset at I_{DED} ~ 0.8 kA the temperature well inside the q=2 surface (around R=2.05m) remains constant when I_{DED} is further increased, however, from q=3 (R=2.17m) up to q=2 the ongoing ergodization (cf. Poincaré plot in Fig. 1b) leads to a steady decrease of T_e. At the q=3 surface a marked reduction of density fluctuations measured by reflectometry is observed after the onset of the 2/1 mode [13], suggesting a zone of reduced transport. At the locus of the q=3 surface no local measurement of the density gradient had been available. However, measurements with a thermal helium beam diagnostics slightly outside this region indicate a steep density gradient. Fig. 7 shows the dependence of the electron temperature (upper left), density (upper right) and pressure (lower left) on the DED current for 3 different radii. Additionally, the pressure gradient in between these radii is shown (lower

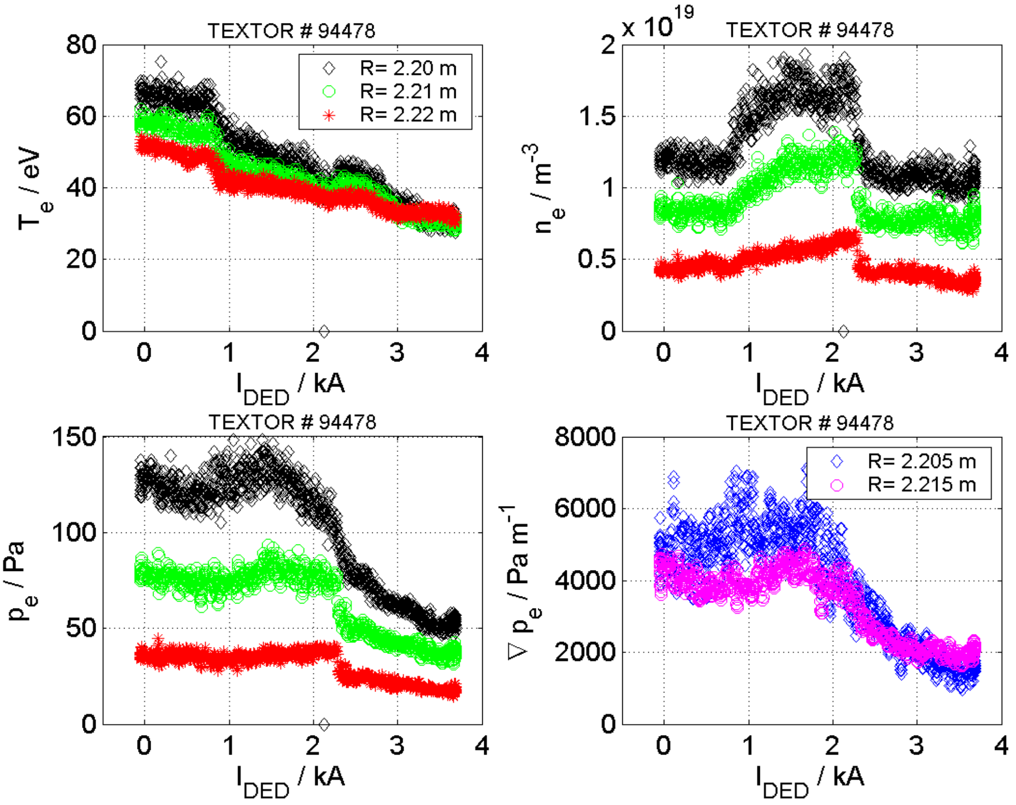

Fig.7. Electron temperature (upper left), density (upper right) and pressure (lower left) measured at the LFS at 3 radii, electron pressure (lower right) gradient at 2 radii deduced from the pressure profile as a function of the DED current (3/1 configuration, I_p = 300 kA, B_T= 2.25 T, a= 0.46 m, R= 1.75 m).

right). While both the temperature and its gradient are steadily decreasing with I_{DED}, the density and its gradient are markedly increased at the 2/1 onset (I_{DED} ~ 0.8 kA). At the onset of the 3/1 tearing mode (I_{DED}~ 2.3 kA) the density drops abruptly. The pressure is rather constant until the 3/1 mode occurs. The mode onset leads to a sudden pressure drop and a flattening of the pressure profile. A poloidal movement of the DED structure by a strike point sweep showed that the poloidal structure of electron density and pressure is closely linked to the magnetic topology. Maxima of the density and pressure occur at positions with long connection lengths to the divertor target, minima occur in flux tubes with short connection lengths. However, as stated before, a detailed comparison for conditions, where the 2/1 and 3/1 tearing modes are present, is difficult because of the impact of the modes on the ergodization.

The increasing ergodization significantly alters the radial electric field at the plasma edge. This fact has first been concluded from the variation of the poloidal rotation of C^{2+} ions with the DED current as measured form the Doppler shift of CIII emission. Fig. 8 shows the poloidal rotation velocity as a function of the DED current in a set of discharges with various ramps of the DED current under otherwise constant plasma conditions (I_p= 300 kA, B_T= 2.25 T, a= 0.46 m, R= 1.75 m). We clearly see two steps corresponding to the onset of the 2/1 and 3/1 mode indicated by the dashed lines. While the direction of the rotation before the onset of the 2/1 tearing mode corresponds to the ExB drift direction in the confined plasma as usually observed (E_r directed towards the plasma centre), the rotation is stopped with the onset of the 2/1 mode and even reversed at the onset of the 3/1 mode.

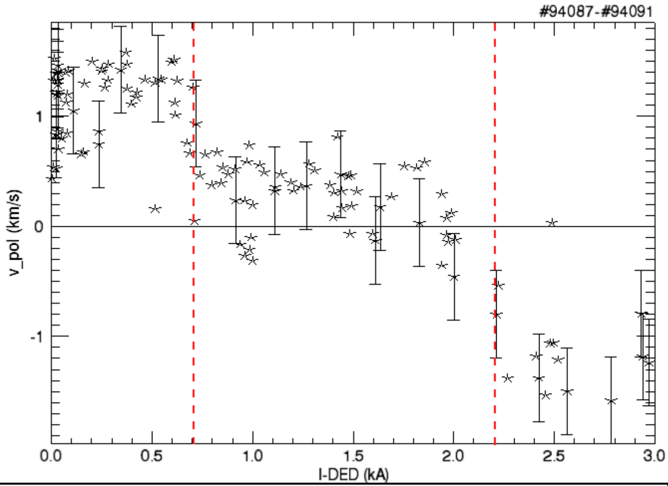

Fig. 8. Poloidal rotation deduced from the Doppler shift of C^{2+} ions as a function of the DED current in the 3/1 configuration (I_p= 350 kA, B_T = 2.25 T, a= 0.46 m, R= 1.75 m).

Such a change of E_r, which could explain these findings, is indeed observed in a similar discharge (I_p= 250 kA / B_T= 1.88 T). Fig. 9 shows the radial profile of the floating potential measured with a 13 pin rake probe inserted into the boundary plasma. Starting from a negative E_r (pointing to the centre) we observe a flattening of the V_{fl} profile from t=1.15s and even a reversal at around t=1.35 s. Thus, the inversion point of E_r is moved further inside of the plasma. This fact further is supported by the reflectometer measurements which show a reversal of the rotation direction of quasi-coherent fluctuations at the q=3 surface [13]. Note, that also such an impact of edge ergodization on E_r has already been observed in earlier experiments on TEXT and Tore Supra (cf. review paper [2]). It can be attributed to the enhanced electron losses along the field lines from the ergodic region.

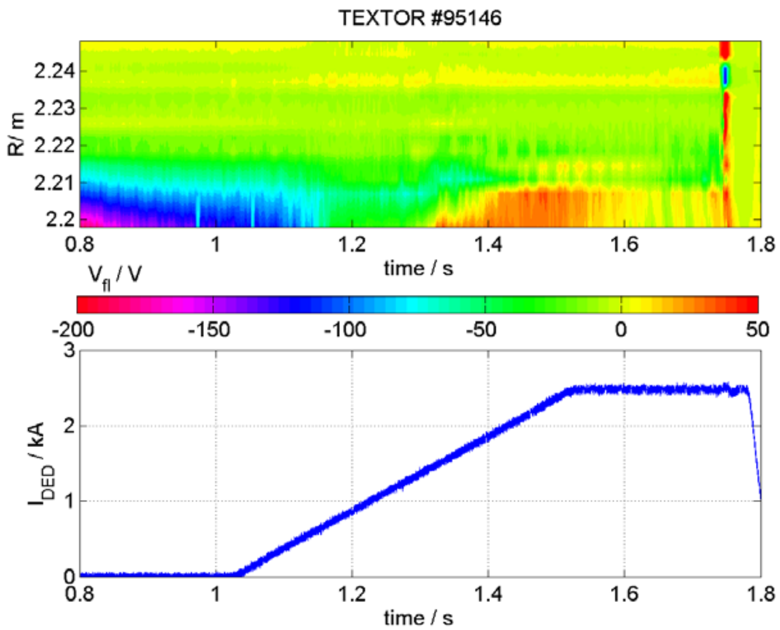

Fig. 9. Time evolution of the profile of the floating potential measured by a rake probe and time trace of the DED current (3/1 configuration, I_p= 260 kA, B_T = 1.89 T, a= 0.45 m, R= 1.76 m)

4. Summary, conclusions and outlook

During the first campaigns with 12/4 and 3/1 configuration the Dynamic Ergodic Divertor has proven to be a versatile tool to influence the plasma edge. The complex structure of the ergodic region and the laminar zone with the helical divertor at the high field side of TEXTOR has been examined and can be well correlated with the magnetic field topology as calculated from field line tracing and mapping techniques. Characteristic properties as the formation of the divertor strike zones and related helical flux tubes to the divertor target can be observed. A reduction of the electron temperature and a strong impact of the DED on the radial electric field have been found as expected from previous experiments with ergodic divertors and limiters in other devices. Based on these results, now more detailed studies on transport in the ergodic edge region have started to deepen the understanding of the physical mechanisms and to relate the findings in TEXTOR to the issue of ELM mitigation by edge ergodization. Initial experiments to characterize the divertor properties have revealed promising results on non-linear divertor regimes at high density and possible impurity screening in the laminar zone [14]. These studies will be extended in future. The characterization of the divertor properties under AC operation is still in its infancy. While the distribution of the heat to the total divertor area and the subsequent reduction of the increase of the surface temperature with respect to the DC case have been observed, no detailed measurements of the impact of the AC operation on the spatial structures are available so far. Such investigations are the aim of the coming experimental campaigns.

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