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The influence of resonant magnetic perturbations on edge transport in limiter H-mode plasmas in TEXTOR

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A B S T R A C T

In this contribution, we report on experimental results on edge transport in limiter H-mode plasmas in TEXTOR under the influence of the Dynamic Ergodic Divertor (DED). These plasmas are characterized by a pedestal structure mainly visible in the electron density, resulting in increased electron pressure gradients of up to 30 kPa/m over a pedestal width of 25 mm at high pedestal collisionalities ($\nu_{e^*} = 1 - 10$), and with high frequency ELMs in the range of 300–1500 Hz. Under the influence of DED the pedestal pressure is gradually reduced and completely collapses to L-mode when the laminar zone extends all the way across the pedestal width. Toroidal plasma rotation is maintained at H-mode levels by the torque introduced by DED in the stochastic region. The perturbed magnetic topology has been optimized to access conditions with a density pump-out which are strongly governed by wall pumping capabilities in TEXTOR.

1. Introduction

The application of resonant magnetic perturbations (RMPs) is regarded as one possible option to control edge localized modes (ELMs) in future fusion devices such as ITER. The transient heat loads associated with ELMs pose severe threats to the life time of plasma facing components. The feasibility of the concept to control ELMs by RMPs has been shown at the tokamak DIII-D at ITER- like collisionalities [1]. Recent results at the JET tokamak have shown a reduction of ELM size with the application of perturbations from the error field correction coils [2]. In view of the application of ELM control schemes based on RMPs a further consolidation of the underlying physics base is needed.

The Dynamic Ergodic Divertor [3] in the tokamak TEXTOR is a flexible tool to investigate basic processes in plasmas with stochastic magnetic fields. As part of this programme a limiter H-mode has been developed [4,5]. The power threshold to access H-mode conditions in TEXTOR is considerably larger than predicted for the H-mode in poloidal divertor tokamaks, which is related to larger convective heat losses out of the confined plasma in limiter configuration compared to divertor configurations (cf. [6] for a further discussion). The L–H threshold amounts to a total input power of 1.5–2 MW at $B_t = 1.3$ T and 3.0–3.8 MW at 1.9 T depending on the wall conditions. With the L–H transition we observe ELMs at frequencies in the range of 300–1500 Hz (increasing with pedestal collisionality) [5].

Earlier findings have shown that with $n = 2$ RMPs (6/2 base mode configuration of the DED) the pedestal pressure is steadily reduced with increasing perturbation current in the DED coils down to L-mode levels [4,5]. At the same time, the ELM size is continuously reduced. In contrast, in the $m/n = 3/1$ base mode configuration only a small operational window to influence edge transport and stability exists for edge safety factors $q_a < 4$ [5], as 2/1 tearing modes are excited by the $n = 1$ external error field [7].

In this contribution, we show the impact of DED in 6/2 base mode configuration on the electron pressure profiles across the H-mode profiles based on the high resolution multi-pulse TV Thomson Scattering diagnostics at TEXTOR [8] and relate the

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findings to the topology of the perturbed magnetic field (based on the vacuum description of the perturbation field). We discuss the requirements to observe density pump out conditions in limiter H-mode discharges in TEXTOR which are also a typical signature of H-mode discharges with ELM control by RMPs in both DIII-D [1] and JET [2].

2. Experimental set-up and discharge scenario

TEXTOR is a medium sized tokamak ($R = 1.75$ m,$a \leqslant 0.47$ m), the Dynamic Ergodic Divertor consists of 16 perturbation coils and 2 compensation coils wound helically around the torus on the inboard side. Depending on the phase of the neighboring coils, the system can be operated in configurations with poloidal/ toroidal mode numbers 3/1, 6/2 and 12/4. The topology of the perturbed magnetic field (calculated in vacuum description) 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 [9]. While the laminar region is governed by helical flux tubes with parallel transport of particles and energy towards the divertor target separated by ergodic regions with significantly larger connection length, the ergodic region further inside of the plasma is characterized by enhanced radial transport (cf. [9] for a summary of transport processes in the different topological regions in TEXTOR and [10] for an earlier extensive review of experimental results on transport in stochastic plasmas).

In this contribution, we refer to limiter H-mode plasmas heated by neutral beam injection in co-current direction ($P_{tot} = 1.6$ MW). The discharges are operated at a plasma current $I_p = 235$ kA and toroidal field $B_T = 1.3$ T with minor radius $a = 0.44$ m and major radius $R = 1.72$ m (plasma limited by the inner wall), leading to an edge safety factor $q_a = 3.7$. Fig. 1 shows time traces for a typical H-mode discharge (solid lines) and a L-mode reference discharge (dashed lines) at lower total input power of 1.3 MW (second row). The H-mode discharge (♯107315) exhibits at $t = 1.85$ s the transition to the H-mode, characterized by an increase of the line averaged central electron density (third row) and the onset of ELMs at a frequency of 360 Hz (fourth and fifth rows of Fig. 1).

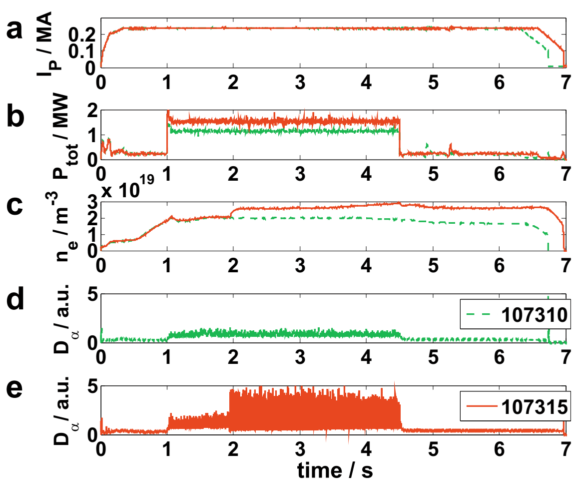

Fig. 1. Time traces of (a) plasma current, (b) total input power and (c) line averaged central electron density for a limiter H-mode discharge (solid) and a L-mode reference (dashed), panel (d) shows the D_α emission at the ALT-II limiter at the LFS for the L-mode discharge and (e) for the limiter H-mode.

3. Change of pedestal characteristics with DED

The topology of the RMPs has been optimized for the discharge scenario presented here to access pump out conditions, which is favored if the width of the ergodic region compared to the width of the laminar region is maximized [11]. Under these conditions, we observe a drop of the particle confinement time τ_p as a result of the enhanced cross field transport in the ergodic region [11]. However, this is only a necessary condition for a density pump out as also the wall pumping has to be sufficiently large for the discharge scenario under consideration, where the pumping efficiency of the toroidal pump limiter ALT-II at the LFS is small as the plasma is shifted towards the HFS. Under conditions of pumping walls, also the effective particle removal time $\tau_{p*} = \tau_p/(1-R)$ with R the global recycling coefficient drops with the application of the RMPs (cf. the detailed discussion in [11]). Fig. 2 shows the response of the

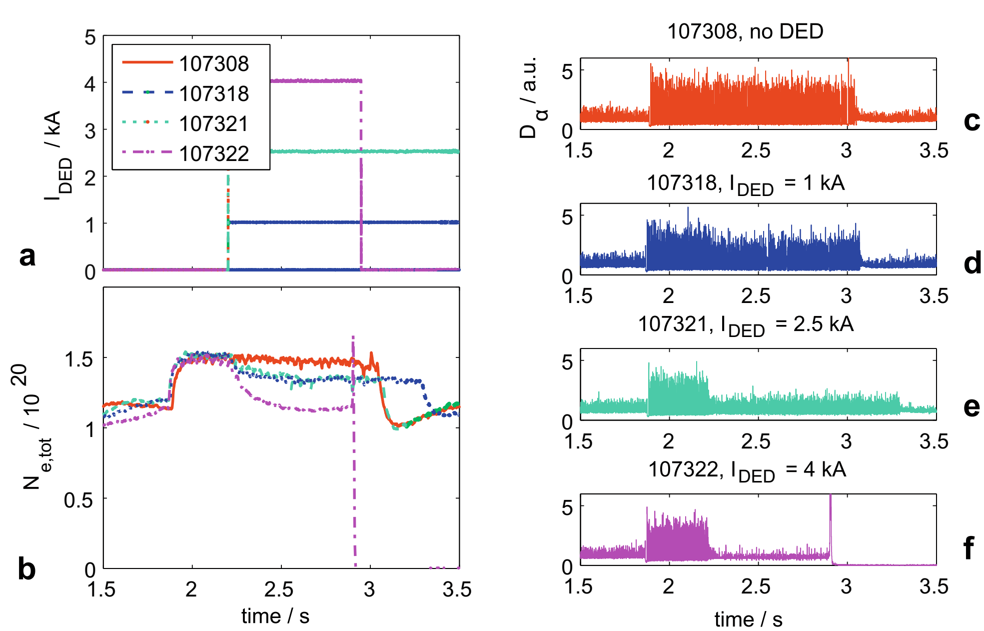

Fig. 2. Scan of the DED perturbation current: (a) perturbation current, (b) total electron content, (c)–(f) D_α emission at the ALT-II limiter at the LFS for limiter H-mode without perturbation and with different DED currents.

total electron content of the discharge (panel b) to the application of DED with the perturbation currents as depicted in panel a. Panels c–f show the resulting D_α emission at the ALT limiter at the LFS from which the decreasing size of the ELMs can be concluded. With a perturbation current of $I_{DED} = 1.0$ kA (corresponding to a perturbation field of $b_{r,\max} \approx 2.5$ mT at $q = 3$) we observe a small reduction of the D_α amplitude (panel d) and already a marked density drop, at $I_{DED} = 2.5$ kA ($b_{r,\max} \approx 6.5$ mT at $q = 3$) the ELM amplitude (as visible in the D_α spikes representing the particle bursts) is strongly reduced, at $I_{DED} = 4.0$ kA ($b_{r,\max} \approx 10.5$ mT at $q = 3$) the D_α emission is reduced to L-mode level. At $t = 2.9$ s the discharge is terminated by an impurity event.

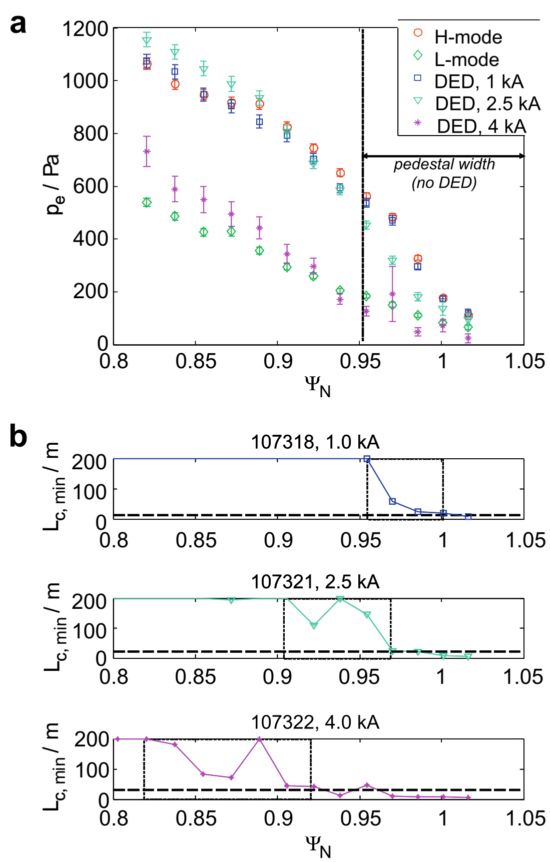

Fig. 3. (a) Electron pressure profiles for DED current scan, (b) shortest connection lengthes to target for discharges with DED (see text for details).

In Fig. 3(a) we show the response of the electron pressure profiles to the RMPs. The data measured from the high resolution Thomson scattering system has been averaged over the inter-ELM phases for this purpose, mapped onto magnetic flux surfaces and plotted here as a function of the normalized poloidal flux. All profiles have been measured during the quasi- steady state phases of the discharges ($t = 2.0$ s for the H- and L-mode cases without DED, $t = 2.7$ s for the DED cases). The circles denote the limiter H-mode phase, while the diamonds show the L-mode reference discharge. We clearly note the pedestal formation in the H-mode. The dashed line denotes the pedestal width as deduced from a modified tanh fit, $\delta = 25$ mm. For this discharge the maximum electron pressure gradient is 28 kPa/m (normalized pressure gradient $\alpha_{MHD} = 1.8$ for $p_i = p_e$, close to the pedestal top we measure equal ion and electron temperatures but the CXRS system of the H diagnostic beam cannot resolve the pedestal structure).

At a perturbation current of $I_{DED} = 1.0$ kA (boxes) the profile across the pedestal is only marginally reduced with a drop of the pressure at the location of the barrier top of the unperturbed H-mode from $p_e = 581$ Pa to $p_e = 536$ Pa. At $I_{DED} = 2.5$ kA (upper triangles) the electron pressure drops to $p_e = 453$ Pa, in the last step at $I_{DED} = 4.0$ kA (stars) the whole electron profile collapses to L-mode level across the pedestal. Next we discuss the relation of these findings to the perturbation of the magnetic topology.

Fig. 3(b) shows the width of the stochastic region for the three steps of our scan of the DED perturbation current for comparison. We plot here the shortest connection length to the DED target as a function of the normalized poloidal flux at the location of the measurement of the TS profile which has been determined from field line tracing with the Gourdon code (cf. [11] for a description of the topology calculations). The Kolmogorov length is marked by a dashed horizontal line in each panel. We have marked with vertical dashed lines the inner boundary of the stochastic region (left line) and the border between ergodic and laminar zone (right line). With application of DED at $I_{DED} = 2.5$ kA the stochastic region covers well the pedestal width, at $I_{DED} = 4.0$ kA, where the pedestal is

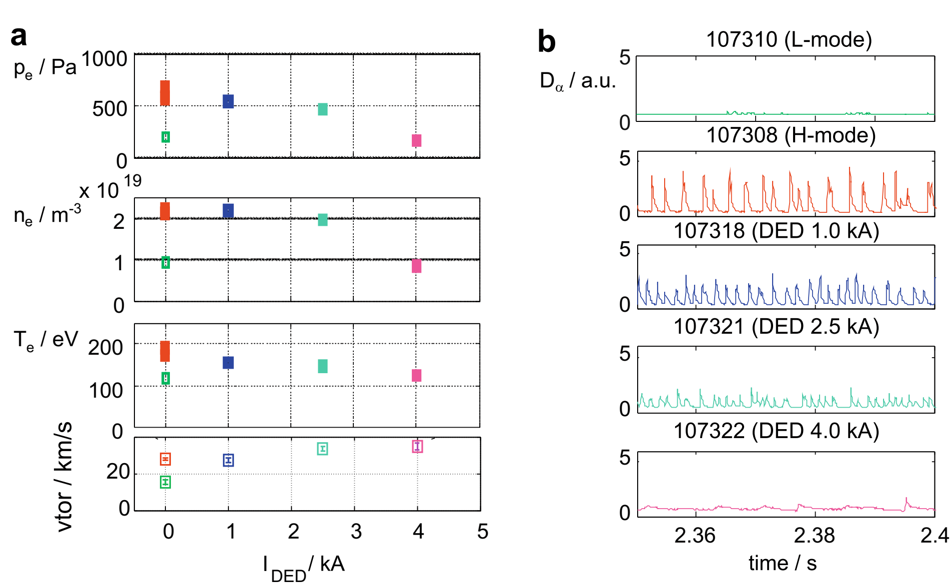

Fig. 4. (a) Plasma parameters at the pedestal top as a function of DED current, (b) D_α emission at the ALT-II indicating ELM activity.

completely diminished, the pedestal region is fully covered with field lines of short connection length (i.e. the laminar zone).

In TEXTOR, the analysis of the heat and particle footprint and its comparison to the magnetic footprint pattern of the perturbed field lines provides an unambiguous indication of the penetration of the perturbation field to the resonant magnetic surfaces [12]. Already at $I_{\mathrm{DED}} = 1.0$ kA we observe the characteristic splitting of the strike zones according to our expectations from the vacuum topology of the perturbed field.

Next, we depict in Fig. 4(a), first three panels, how the drop of the pedestal pressure with increasing perturbation current results from a drop of both the electron density and temperature. We note again that going from L- to H-mode the pedestal density doubles while the electron temperature only increases by about 30%. The 20% reduction of the electron pressure at $I_{\mathrm{DED}} = 2.5$ kA consists of both a 10% reduction of electron density and temperature at the location of the pedestal top for the unperturbed limiter H-mode phase. When increasing the perturbation current to $I_{\mathrm{DED}} = 4.0$ kA both density and temperature return to L-mode level.

In contrast, the toroidal rotation of carbon nuclei deduced from CXRS does not reduce with increasing perturbation current. In Fig. 4(a) (fourth panel) we show the toroidal rotation at $\Psi_N = 0.89$ (no CXRS channel at the exact location of the pedestal top). When going from L- to H-mode the rotation increases from 15 km/s to 28 km/s (in co- current direction), with increasing perturbation current the rotation velocity even further increases to 35 km/s although the pedestal pressure collapses at $I_{\mathrm{DED}} = 4.0$ kA. This finding can be related to the torque exerted onto the plasma in the ergodic region, which is caused by the perpendicular return current built-up to balance the parallel electron losses [13].

With the reduction of the size of the ELM bursts as seen in the D_α emission, the frequency of the ELMs increases with increasing DED current (560 Hz at $I_{\mathrm{DED}} = 1.0$ kA and 700 Hz at $I_{\mathrm{DED}} = 2.5$ kA in comparison to 360 Hz without RMPs), cf. Fig. 4(b).

4. Summary and conclusions

We have described the changes of pedestal properties in limiter H-mode plasmas under the influence of the Dynamic Ergodic Divertor in 6/2 base mode configuration. With increasing perturbation current the electron density, temperature and pressure at the pedestal top are degraded until L-mode conditions are reached when the laminar region with short connection lengthes to the target fully covers the pedestal region. In contrast, the toroidal rotation is kept at H-mode levels by the torque in the stochastic region for conditions with co-current neutral beam heating. Density pump-out is observed for optimized magnetic topology (maximum width of the ergodic region) if the wall is capable of pumping particles.

These findings show that RMPs can be used to control plasma edge profiles in the tokamak TEXTOR. For the H-mode conditions in TEXTOR (high collisionality, power input not largely exceeding the L–H threshold power) ELMs are not suppressed but steadily reduced until the plasma is finally driven back to L-mode.

Acknowledgements

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