SOL Turbulence Modification by Non-axisymmetric Magnetic Perturbations in L-mode

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Introduction

The application of toroidal non-axisymmetric magnetic perturbations (MP) is a promising technique to mitigate type-I ELMs in H-mode discharges [1, 2]. Furthermore MP cause a change in the scrape-off layer (SOL) transport [3, 4, 5, 6] and change the properties of the turbulence in the SOL [7, 8, 6]. The observations do not deliver a consistent picture. E.g. in some experiments it was observed that with MP the SOL density fluctuation level increases [7] in others that it decreases [8]. In experiments with a Gundestrup probe on MAST it was seen that the turbulence changes depend on the probe orientation [8]. So far these effects are not understood. It is required that the modified SOL transport has to be compatible with the operational limits of the first wall in future fusion experiments. In order to characterize the SOL turbulence and transport modification by MP experiments have been carried out at ASDEX Upgrade in L-mode or I-phase. In this paper there will be no difference made between these two states. The application of MP causes a deformation of the toroidally symmetric outer flux surfaces and a field line mixing. A new separatrix can be defined at the outermost steep increase of the field line connection length to the next wall [9]. The breaking of the toroidal symmetry together with the shear of the magnetic field causes the formation of lobes and strike-line splitting in the divertor [3]. At ASDEX Upgrade this is visible in L-mode at low densities only. With increasing density radial transport increases and the lobe substructure is smeared out [6, 10]. At low densities the MP also cause an increase in the SOL plasma density as well as a reduction of the positive radial electric field on open field lines close to the separatrix [6, 11]. These SOL modifications vanish at higher plasma density. In this paper we present the MP influence on the SOL turbulence in a low density L-mode plasma, anisotropy of MP effects on a Mach probe measurement as well as MP induced turbulence changes related to a vanishing shear layer.

Discharge and diagnostic set up

The measurements presented in this paper were performed in lower single null L-mode discharges with and w/o MP applied. The discharges were at $I_P = 1\,\text{MA}$ plasma current, a toroidal magnetic field of $B_t = -2.5\,\text{T}$, ion grad B drift towards the active lower divertor and an ECRH heating power of $P_{ECRH} \approx 500-600\,\text{kW}$. The selection of I_p, B_t and P_{ECRH} allows for a decent detection of the power flux into the divertor by thermography while staying in L-mode. The plasma line averaged density was usually kept in the range of $\bar{n}_e = 1-2\times10^{19}\,\text{m}^{-3}$. At these densities more power is going into the inner than into the outer divertor. The standard MP for the investigations was a $n = 2$ error field in odd parity using 4 saddle coils above and below the outer midplane. A MP induced transport change is often visible in the main chamber radiation which can be lowered by up to 50 %. Discharge parameters different from the above ones are stated explicitly in the following. The presented measurements are ion saturation current fluctuations $\tilde{I}_{sat}$ measured with Langmuir probes on a fast reciprocating manipulator (FRP) [12]. $\tilde{I}_{sat}$ is a good measure of density fluctuations [13]. The measurements were performed in the far SOL but sufficiently close to the separatrix not to be (or only weakly) influenced by any limiter or the second separatrix. Two probe heads were used, a multi-pin probe [12] and a high heat-flux probe [12], the latter with a Mach probe arrangement.

Strike-line splitting, connection length and separatrix position

The pattern of the strike-line splitting depends on the MP phase, its mode number, parity and strength and the plasma edge safety factor. But the existence of the splitting does not depend on these parameters as shown for a q-scan ($q_{95} = 4.46 \rightarrow 4.2$) in figure 1 a) where the resonant error field component stayed about constant. Strike-line splitting is not a resonance effect but caused by breaking the toroidal symmetry together with the magnetic shear [6]. In figure 1 b) a non-resonant MP with $n = 2$ was applied (all 16 saddle coils powered) in a $q_{95} = 4$ discharge ($B_t = -2.3\,\mathrm{T}$). Additionally the MP phase was turned in 90 degree steps (times indicated by the cyan bars) modifying the strike-line splitting pattern. The mode activity at the discharge end will not be discussed here.

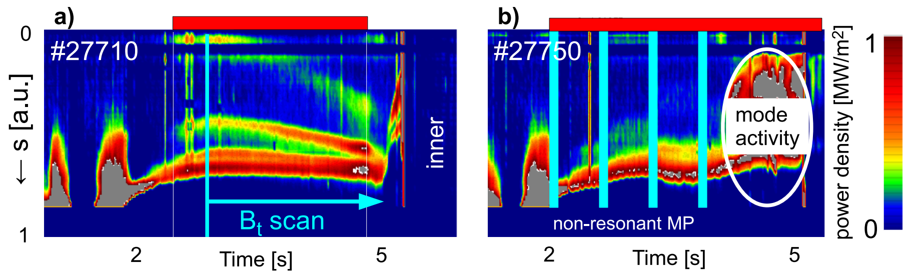

Figure 1: *Power density onto the inner divertor for two discharges with MP. The time interval with MP on is indicated by the red bars on top. a) MP during q-scan (B_t ramp). b) non-resonant MP turned in* 90 *degree steps.*

Figure 2 shows the connection length L_c towards the inner and outer divertor as well as the total L_c from wall to wall on open field lines as function of the radial and toroidal coordinates at the poloidal position of the FRP. The solid horizontal line represents the separatrix position from the CLISTE equilibrium reconstruction $R_{sep,EQ}$ and the green broken line the disturbed separatrix following the definition of Fuchs [9, 14]. It is obvious that the L_c variations towards the outer and inner divertor are phase shifted. This is a possible ingredient for the observed anisotropy of the MP induced turbulence changes. The figure also shows the challenge to relate a measurement po-

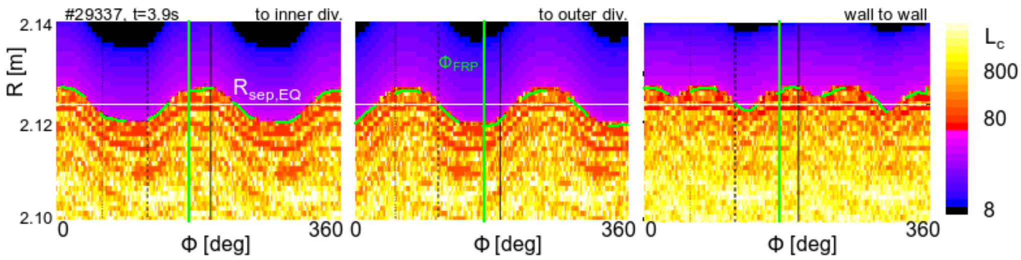

Figure 2: *Connection length towards a) the inner divertor, b) the outer divertor, c) total connection length from wall to wall. The white horizontal line represents $R_{sep,EQ}$, the green vertical line the toroidal position of the FRP.*

sition to a separatrix equivalent when the MP is switched on. Earlier investigations at ASDEX Upgrade have shown that a shear layer in the turbulence poloidal propagation velocity v_{pol} follows closely $R_{sep,EQ}$ when the MP is applied [15]. Therefore, we use $R_{sep,EQ}$ in the following for the separatrix position albeit the real position might be $1-3$ mm further inside with MP on.

Turbulence in the SOL of low density L-modes with and without MP

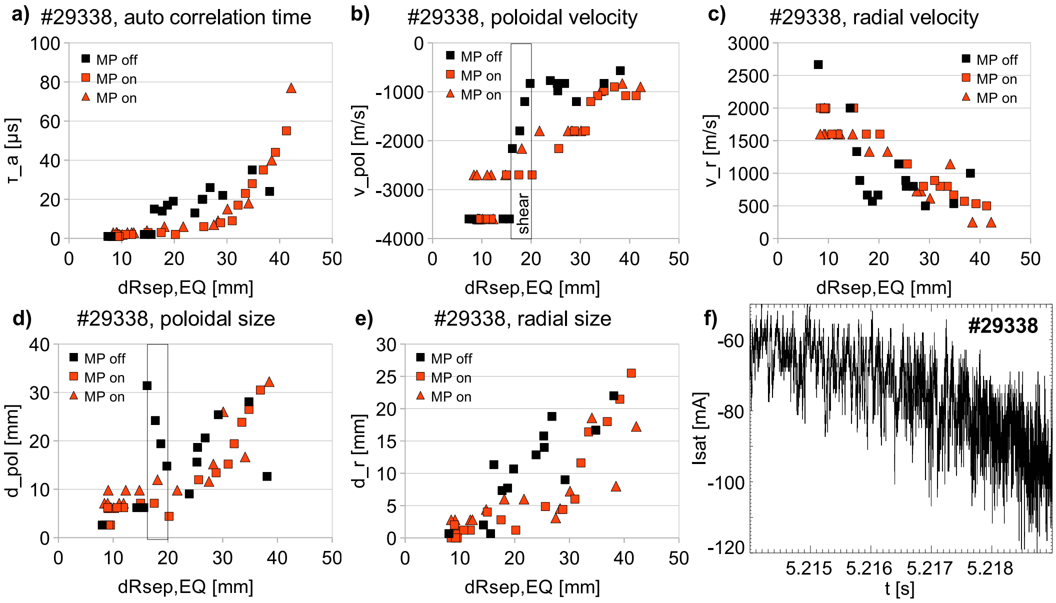

Figure 3: *a)-e) Data over $dR_{sep,EQ}$ for 3 FRP strokes, one w/o MP (black), two with MP switched on (orange squares and triangles). a) τ_a, b) v_{pol}, c) v_r, d) d_{pol}, e) d_r. f) I_{sat} probe measurement w/o MP at $dR_{sep,EQ} \approx 15$ mm.*

Without MP close to the separatrix ($dR_{sep,EQ} \leq 16$ mm) the auto correlation time τ_a of $\tilde{I}_{sat}$ measured with pin probes is always small, $< 5\,\mu$s for $\bar{n}_e = 1-3.2\times10^{19}\text{m}^{-3}$, see also figure 3a). Here τ_a was determined in 2 ms boxcar windows. Moving outside, to $dR_{sep,EQ} \approx 15$ mm τ_a suddenly jumps to $15-20\,\mu$s and rises further. At the same position the poloidal velocity v_{pol}, which is in ion diamagnetic drift direction, decreases suddenly (figure 3b) and the radial velocity v_r becomes rather constant at $500-800$ m/s outside a steep decrease further inside (figure 3c)). The velocities come from cross correlation of neighboring pins. From τ_a and v_{pol} (v_r) the poloidal d_{pol} (radial d_r) extension of the turbulent structures was calculated (shown in figure 3d) and e)). Both show a fast rise when τ_a jumps. d_{pol} and d_r are a lower boundary since τ_a is determined by the shorter process - either the turbulent structure crosses the pin faster in poloidal or in radial direction. The size in the direction perpendicular to the dominating motion is then underestimated. Nevertheless, at least the jump in d_{pol} or d_r is real. The high v_{pol} shear might create poloidally elongated structures. Then the increase in d_r can be attributed to the increase in τ_a due to the d_{pol}, v_{pol} change and it is likely that the innermost d_r close to 0 are underestimated. The reduction in v_r might be related to the v_{pol} shear hampering a radial motion. After the initial jump in the v_{pol} shear layer d_{pol} decreases before d_{pol} and d_r rise while both velocities stay rather constant. A possible, although not confirmed, explanation of the d_{pol} decrease can be a break up of elongated structures or straining out [16]. Figure 3f) shows the I_{sat} measurement when τ_a jumps at $t = 5.216-5.217$ s. A clear change in the fluctuation behavior is visible. The v_{pol} shear is most probably related to a minimum in the divertor T_e profile [17].

With MP applied shown in figure 3a) τ_a increases smoothly and $\tau_a \approx 15\,\mu$s is reached 15 mm further outside. This smooth τ_a rise is accompanied by a smooth decrease in v_{pol} and v_r. Accordingly d_{pol} and d_r increase rather constantly across $dR_{sep,EQ}$. With MP the values of all quantities under consideration (τ_a, v, d) match at $dR_{sep,EQ} \sim 10$ mm and $dR_{sep,EQ} \sim 35$ mm quite well the measurements of the reference case. A sufficiently strong field line mixing would forbid steep gradients and could explain the changes with MP. An effect of the MP on the radial electric field is described in [11]. In the far SOL there is the general trend that MP lead to an increased I_{sat} which corresponds to a higher density.

Figure 2 suggests that the MP effect on turbulence might be anisotropic. Here we compare the MP influence on the two sides of a Mach probe. With MP there is the tendency that the probe facing the inner divertor gets closer to a long L_c than the probe on the opposite side. Nevertheless, the probe facing the outer divertor always receives a higher flux and the parallel flow going from the outer mid-plane towards the inner divertor is even slightly enhanced with MP (10% in # 27680, $\bar{n}_e = 1.8 \times 10^{19}\text{m}^{-3}$). A virtual pin probe was created by adding the signals of both probe sides. Depending on the orientation we get different answers about the influence of MP on the $\tilde{I}_{sat}/\bar{I}_{sat}$. Facing the outer divertor $\tilde{I}_{sat}/\bar{I}_{sat}$ rises steeper with $dR_{sep,EQ}$ than in the reference case (assuming a linear dependence on $dR_{sep,EQ}$), for the virtual pin probe the rise is close to the reference case w/o MP while for the probe facing the inner divertor $\tilde{I}_{sat}/\bar{I}_{sat}$ decreases with $dR_{sep,EQ}$ and MP applied contrary to the reference case. The dependence of the MP influence on the probe orientation needs further investigations. It seems to be an important ingredient to understand the effect of MPs on the SOL transport and it might become important for plasma-wall interactions since the PFCs receive the incoming flux with a certain orientation.

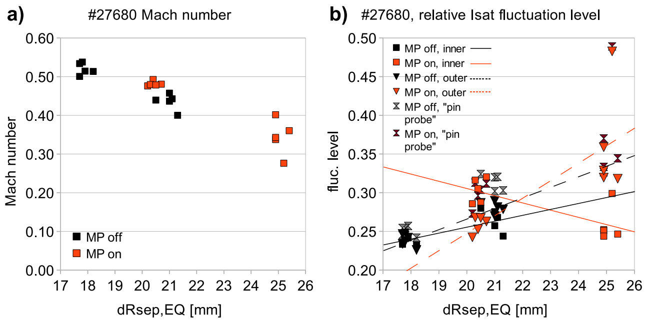

Figure 4: *a) Mach number with and w/o MP. b) Relative I_{sat} fluctuation level for the probes facing the inner and outer divertor as well the virtual pin probe. Linear regressions of the MP off and MP on data sets for the probes facing the inner (solid line) and outer (broken line) divertor are shown.*

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