Turbulence in Magnetic Islands: An Investigation of the Poloidal Dynamics in the WEGA Stellarator

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The role of resonant magnetic field perturbations leading to the formation of magnetic islands or stochastic fields is of specific interest in toroidal magnetic confinement. Stochastic fields are for example used for ELM mitigation in tokamaks. In stellarators island structures are utilized for the divertor. The naive picture of an island is that it acts as a radial short circuit for the plasma. However, depending on the island width perpendicular transport across the island may well compete with parallel transport[1]. Thus, the study of the influence of islands on turbulence, which dominates the radial transport in the edge of fusion devices is an ongoing object of research.

WEGA as a mid sized classical stellarator with moderate plasma parameters is perfectly situated for systematic turbulence studies aiming on the influence of effects linked to the magnetic field topology. At the WEGA stellarator the existence of non-natural islands at low order ($m = 1,2$) rational surfaces is known from flux surface measurements. The radial width of the $m/n = 1/5$ islands, which are investigated in this article, is about 1 cm on the low and 3 cm on the high field side of the torus, respectively. They can be modelled by a small (≈ 5 mm) radial displacement of the helical windings with respect to the set of toroidal field coils. The width of these islands can be controlled by means of an error field compensation coil (EFCC). It can be reduced by a factor of 2, corresponding to a reduction of the field perturbation by a factor of 4. Due to the low β in WEGA the vacuum magnetic configuration is only negligibly altered during plasma operation. Hence, it is possible to study turbulence in the vicinity of islands and compare results from configurations differing only in amplitude and phase of magnetic field perturbations.

Langmuir probe arrays were used for spatially and temporally resolved measurements of density and potential fluctuations. The common approach of assuming $\tilde{I}_{sat} \propto \tilde{n}_e$ and $\tilde{\Phi}_{fl} \propto \tilde{\Phi}_p$ was used, neglecting temperature fluctuations. A poloidal array aligned to the flux surfaces in the edge gives access to the islands on the low field side. It was used for the transport measurements shown in Fig. 1. A 2D array of 7×9 probes in the poloidal plane with a distance of 6 and 7 mm in poloidal and radial direction, respectively, gives access to the islands on the high field side (see Fig. 2, left).

WEGA has a major radius of 72 cm and an aspect ratio of about 7. Helium plasmas centrally heated by ECRH at a frequency of 28 GHz with an induction of $B_0 = 0.5$ T on axis were used. Electron density and temperature were $n_e \approx 4 \cdot 10^{18}$ m^{-3}, $T_e \gtrsim 50$ eV in the centre and $n_e \approx 2 \cdot 10^{18}$ m^{-3}, $T_e \approx 10$ eV at the edge. In previous experiments turbulence in WEGA was found to be dominated by drift wave dynamics[2]. Turbulent structures with a correlation length perpendicular to **B** of about 1-2 cm propagating in electron diamagnetic drift direction were observed inside the LCFS. Density and potential showed a small phase shift below $\pi/4$.

In this article results from experiments at a low neutral pressure of $p_n \approx 3 \cdot 10^{-4}$ Pa are presented. At these conditions radial profiles of the turbulent radial $\mathbf{E} \times \mathbf{B}$ flux $< \tilde{\Gamma}_{E\times B} > \equiv < (\tilde{\Phi}_{fl,2} - \tilde{\Phi}_{fl,1}) \cdot \tilde{I}_{sat} >$ showed a distinct local elevation in the profile close to the 1/5 island (solid black line in Fig. 1). This "hump" in the profile completely smeared out to a smooth profile at increased neutral pressure of about $4 \cdot 10^{-3}$ Pa. The physical picture behind the influence of the neutral pressure is the reduced collisionality at low pressure. Since WEGA plasmas are partially ionized inelastic collisions with neutrals play an important role for the parallel transport. This observation is consistent with the simulations of heat diffusion in islands[3] showing that temperature profiles are only altered by islands overcoming a critical island width $w_c \propto (\chi_{\parallel}/\chi_{\perp})^{-1/4}$. However, the link between the elevation in the transport profile and the existence of the 1/5 island is evident. Fig. 1 shows, that it can be reduced by reducing the island width. Further on, the hump could be shifted radially by small variations of the rotational transform.

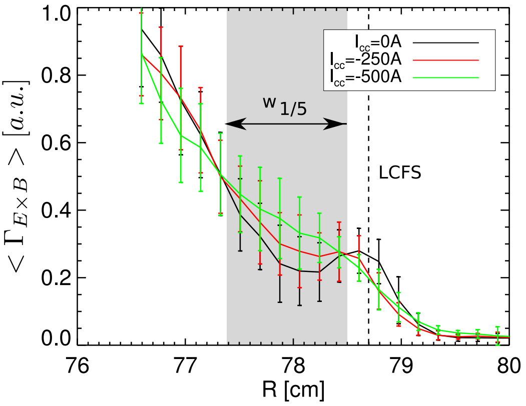


Figure 1: Radial profiles of the net radial $\mathbf{E} \times \mathbf{B}$ flux caused by fluctuations.The grey shaded region shows the location and width of the $m/n = 1/5$ magnetic island along the probes line of sight. With increasing I_{cc} the island width is reduced.

In order to highlight the mechanisms behind the observed transport effects, the 2D array was used to investigate the perpendicular dynamics of turbulence in the plasma states under consideration. The conditional averaging method[4] was used to extract coherent parts from the turbulent background. The reference probe can be set to an arbitrary point in the matrix. An amplitude condition of a rising slope overcoming two times the standard deviation of the reference signal was chosen, which gives results comparable to the cross correlation analysis but at a much faster computation time.

Fig. 2 shows a snapshot of conditionally averaged structures of the floating potential where

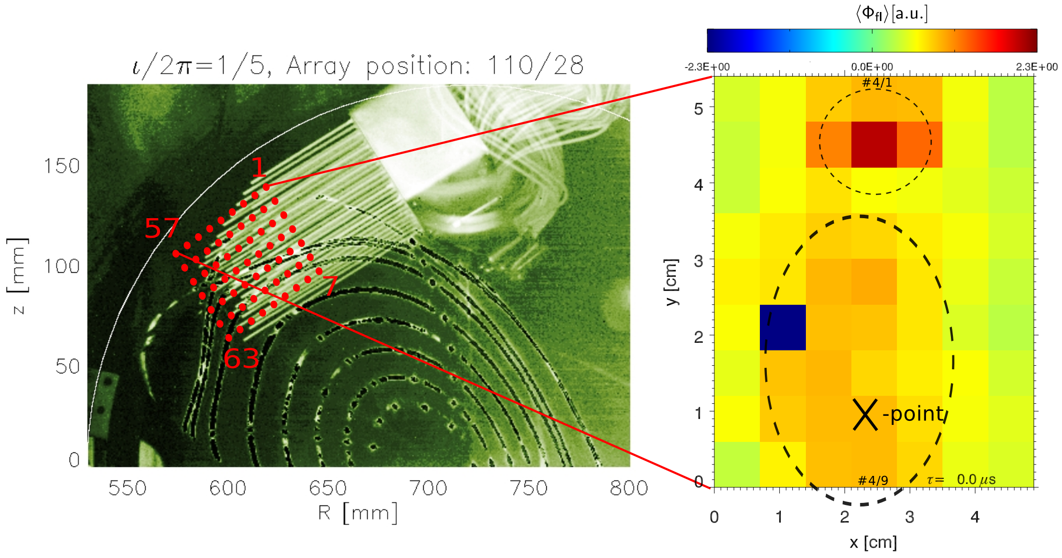
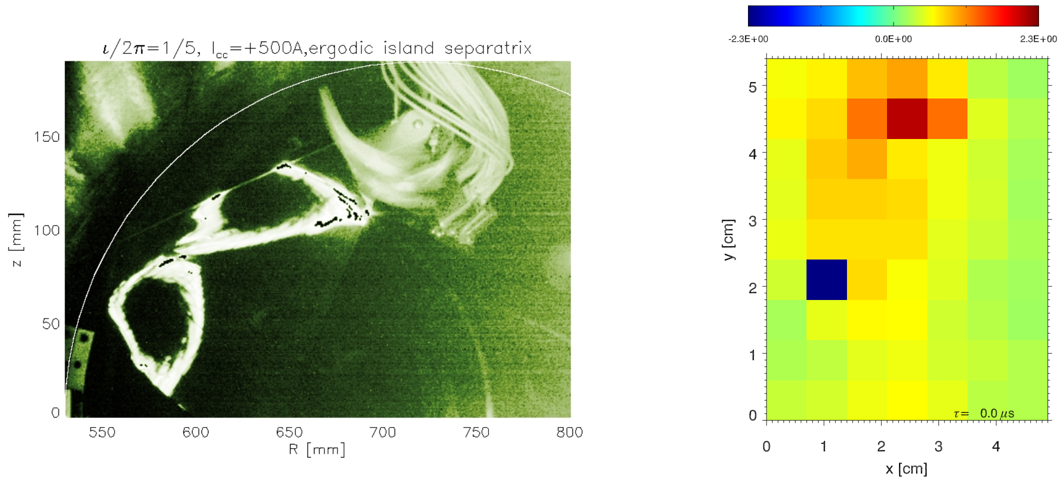


Figure 2: (Left): Poincaré cut of flux surfaces measured with a fluorescent rod. The $m/n = 1/5$ island can be seen in the edge. The probe shafts pointing into the islands on the high field side can be seen. The red dots mark the sampling points ot the individual probe tips in the poloidal plane of the mapped island. (Right):Snapshot of conditionally averaged structures of the floating potential with the reference probe close to the island's O-point.

the reference was set close to the island O-point. The snapshot shows two independent structures of different size which are indicated by the dashed ellipses. The small scale structure with a perpendicular width of $d_\perp \approx 1$ cm is comparable to the previously described structures showing features of drift wave dynamics. It occurred in Φ_{fl} as well as I_{sat} measurements at the location of the reference probe, independently of where it was placed. The structure propagated in electron diamagnetic drift direction. The second structure which is located around the X-point in Fig. 2 behaved completely different. It had a poloidal size of about 3 cm in the observed window, although in cannot be stated if it extends further into the next island, which is not sampled. The location of this huge structure remained close to the X-points, independently of the position of the reference probe and did not show any poloidal velocity. It showed up only in Φ_{fl} fluctuations and not in I_{sat} which is an indicator that a mechanism different to the drift wave must be considered here. On the other hand the huge structure must occur phase coherent with the small one since it would cancel by the conditional averaging method applied in Fig. 2 where the reference is far away from the X-point. The occurence of this huge structure might be linked to the increased transport in the vicinity of the island. By mixing length arguments an anomalous diffusion coefficient $D_\perp$ describing the turbulent convective transport can be estimated as $D_\perp = d_\perp^2/\tau_l$ [5], where τ_l is the lifetime of the structure. For the newly



(a) ergodic island separatrix

(b) potential structures

Figure 3: (a) Poincaré snapshot of the ergodized island separatrix. (b) Snapshot of conditionally averaged potential structures measured for the island structure shown in (a)

observed potential structures $d_\perp$ was strongly increased although their lifetime was also found to be higher by a factor of four. The connection between the turbulent transport and the potential structures at the X-point shall be assessed in future experiments.

In a next step, potential fluctuations were measured in configurations using the EFCC to manipulate the islands. It was polarized in a direction which increases the native island size. As shown in Fig. 3 (a) the island width was not simply increased but ergodization set on at the island separatrix by overlapping of the 1/5 island with higher harmonics induced by the EFCC. In this case, the size and dynamics of the small scale structures remained unaffected. But it could be shown, that the huge structure was reduced in amplitude and decorrelated as shown in Fig. 3 (b). This decorrelation may be explained by the strong local shear of individual field lines in ergodic layers. Thereby the turbulent structures may be torn apart since they are typically strongly elongated parallel to the magnetic field lines.

References

[1] Fitzpatrick, R., Phys. of Plasmas **2**, 825-838 (1995)

[2] S. Marsen *et al.*, Plasma Physics and Controlled Fusion **51**, 085005 (2009)

[3] M. Hölzl *et al.*, Nucl. Fusion, **49**, 115009 (2009)

[4] H. Johnsen *et al.*, Phys. of Fluids **30**, 2239-2254 (1987)

[5] Endler, M. *et al.*, Physica Scripta **51**,610-616 (1995)