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Overview of Turbulence Studies in the WEGA Stellarator

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The understanding of turbulence, the cause of the major losses in magnetic confinement devices, is a key issue on the way to a fusion reactor. In recent years it has been shown, that also small machines, with dimensions and plasma parameters far away from fusion relevant values, can contribute significantly to this research area [1]. In this work experimental results on turbulence in the WEGA stellarator are presented. Two topics are treated. The first is a detailed study of the spatio-temporal structure of turbulence, and secondly some initial results on turbulence and transport in the region of magnetic islands.

WEGA is a medium-sized classical stellarator in a l=2, m=5 configuration. Its high flexibility combined with good experimental access make it perfectly suited for turbulence studies. It can be operated at magnetic field strengths up to $B_0 = 0.9$ T and a rotational transform from $\iota \approx 0\dots1$. Since the plasma is heated by ECRH at 2.45 GHz and 28GHz, respectively, two main working points are defined by the appropriate resonant magnetic field strength of $B_0 = 57$ mT and $B_0 = 500$ mT, respectively. Turbulence studies in WEGA concentrate on the edge region about 1-2 cm inside the last closed flux surface (LCFS), a region which is hardly accessible with high spatial and temporal resolution in large fusion devices. WEGA's moderate plasma parameters with electron temperatures of about 10 eV and densities up to about 10^{18} m^{-3} in the region of interest allow access with Langmuir probes providing a perfect resolution to study details about the structure of turbulence. To this end a set of multiple Langmuir probes as shown in fig. 1 has been installed. Direct poloidal resolution is achieved by an array of 13 probes with tips aligned to the flux surface shape in the edge region. In a radial scan a section of the $r-\theta$-plane is sampled by the array. Using an additional single probe which is toroidally separated from the array, a three-dimensional reconstruction of turbulent structures is possible. This

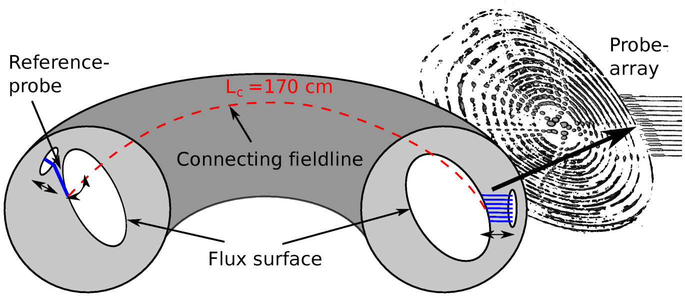

Figure 1: The Langmuir probe setup used to study turbulence in WEGA. The array is shown together with measured flux surfaces, both measured with the same camera setup.

so-called reference probe can be placed in a manner, that a field line starting at its tip intersects the plane sampled by the array after a connection length of $L_c = 170$ cm providing information about the parallel dynamics of turbulence. Turbulence in WEGA has been found to be dominated by drift wave dynamics. The argument behind this is mainly the observation of a small cross-phase between density and potential fluctuations. Further characteristic features of drift waves could also be shown, as there are the highest fluctuation amplitude in the density gradient region and a phase velocity coinciding with the electron diamagnetic drift velocity, $v_{dia,e}$. In a $k_\theta - \nu$-spectrum a broad distribution of power was found with most power being located around the drift wave dispersion relation, $\nu = \frac{2\pi v_{dia,e} k_\theta}{1+(k_\theta \rho_s)^2}$, with $\rho_s = \sqrt{m_i k_B T_e}/eB$ being the so-called drift parameter.

Turbulence in the two operational regimes of WEGA at 57 mT and 500 mT, respectively, show qualitatively the same behaviour inside the LCFS. But there is one remarkable difference, i.e. the perpendicular scaling length of turbulent structures characterised by the poloidal correlation length d_θ. At 500 mT d_θ is about 2 cm and thus comparable to typical values from other experiments. d_θ is in this case small compared to the plasma dimensions of $a \approx 11$ cm. The situation is different at 57 mT, where $d_\theta \gtrsim a$ was found.

The parallel dynamics of turbulence has been studied for these two cases. To this end, the correlation function between data from the reference probe and individual subwindows in the $r - \theta$ plane sampled by the array is calculated. This analysis provides a kind of three-dimensional reconstruction of turbulent structures. The results don't give information about the actual shape of individual structures but resembles a statistical average giving information about parameters like size, lifetime and velocity of structures. The result of this analysis for a discharge at 500 mT is shown in fig. **??**. Each plot is a snapshot of the correlation function for a fixed time-lag τ. The region of high correlation shows a structure as it is observed along a toroidal distance of $L_c = 170$ cm. In the series of snapshots the temporal evolution of the structure can be seen. It propagates along a flux surface in electron diamagnetic drift direction. The correlation amplitude increases up to a certain point and eventually the structure decays. The highest correlation was observed for a time-lag of about $-10\,\mu$s, independent of strength and direction of the ambient magnetic field. The observation of a correlation maximum at $\tau \neq 0$ shows that there is an anisotropy in the occurrence of fluctuation events along the magnetic field, i.e. structures arise preferably in a certain region along $\mathbf{B}$. The conservation of the sign of τ at maximum correlation when $\mathbf{B}$ is inverted is interpreted in a manner, that structures arise preferably in the region of unfavourable magnetic curvature on the low field side of the torus, where the probe array is located in these measurements.

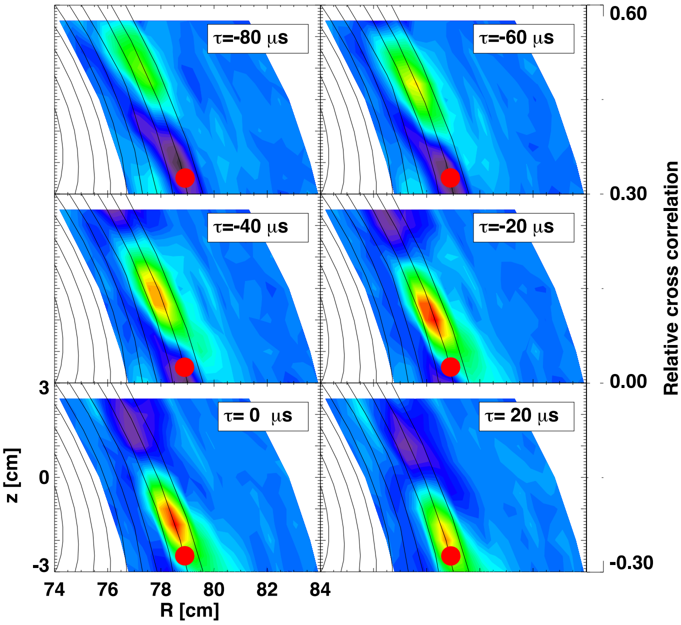

Figure 2: Temporal evolution of the correlation between reference probe and the array. The red dot shows the intersection point of the connecting field line.

At $\tau = 0$ the correlation maximum is displaced with respect to the intersection point of the connecting field line (red dot in fig. **??**) by $\delta_{\theta,0} = (1.1 \pm 0.3)$ cm. This displacement yields a finite average parallel wavenumber, where the ratio between parallel and poloidal wavenumber is given by: $\bar{k}_{\parallel}/\bar{k}_{\theta} = \delta_{\theta,0}/L_c = (0.6 \pm 0.17) \cdot 10^{-2}$. The small but finite $\bar{k}_{\parallel}$ is expected for drift waves and is in good agreement with experimental results from other devices, where drift wave turbulence inside the LCFS has been observed [2]. The parallel phase velocity $v_{\parallel}$ of structures is obtained from the time lag of maximum correlation between two points aligned along a field line. This yield a value of $v_{\parallel} = (7 \pm 0.74) \cdot 10^4$ m/s for the discharge condition under consideration. The absolute value of $k_{\parallel}$ can be deduced from the phase shift $\alpha_{\parallel}$ between the signal of the two probes on a field line. As we are dealing with turbulence, a broad band phase spectrum has to be considered. The phase spectrum can be merged into a single value by taking a power weighted mean following the definition given in [3]. This yield an average value of $\bar{k}_{\parallel} = (0.51 \pm 0.04)$ m^{-1}. An interesting and intuitively unexpected observation follows from the phase spectrum between the reference probe and the point, where the correlation maximum at $\tau = 0$ was observed. For a plane wave this phase can be expected to vanish because the two points are aligned along a wavefront. A vanishing phase shift between these two points was observed in the whole spectral range of significant coherence. This allows the interpretation of turbulent structures as an interaction of wavenumber components with parallel wavefronts, i.e. the ratio $k_{\parallel}/k_{\theta}$ is constant.

The situation appeared to be different at 57 mT, where large structures have been observed. In this case the cross-phase between the two points mentioned above did not vanish. The parallel wavenumber spectrum showed components pointing both parallel and antiparallel to the magnetic field, although the power weighted mean still showed a small but finite value.

Turbulence in magnetic islands

WEGA offers the possibility to study turbulence in the region of magnetic islands, i.e. perturbed regions in the flux surfaces where ι shows a low order rational value which is in resonance with a perturbation field. It is well known, that the existence of rational surfaces in the magnetic configuration has a strong impact on confinement, which cannot simply be explained by the intuitive picture of an island as being a radial short circuit for the plasma. However, it is not known how turbulence and the connected radial transport is affected by field perturbations causing islands at rational surfaces. The existence of islands in WEGA is known from flux surface measurements, and is probably caused by a small misalignment in the coil system. These islands can be manipulated with an external error field compensation coil (EFCC). The EFCC allows a reduction of the radial width of an island at $\iota = 1/5$ by a factor of about 2, corresponding to a reduction of the field perturbation by about 4. An initial experimental campaign on turbulence in the region of these islands at 500 mT has shown some interesting and unexpected effects which could be clearly related to the application of the EFCC. Without EFCC a distinct local increase of the fluctuation amplitude and the net radial turbulent particle flux was observed. Fig. 2 shows a radial profile of the turbulent transport measured locally with three Langmuir probes. The hump in the region of the island (black line) disappeared when the EFCC was applied (red line). Furtheron an effect on the poloidal dynamics of turbulence was observed, i.e. a changed lifetime of structures and a shift in the profile of v_θ. At 500 mT v_θ typically changes sign at the LCFS due to a sheared poloidal $\mathbf{E} \times \mathbf{B}$ velocity profile. The point of reversal shifted radially depending of the width and the radial location of the island.

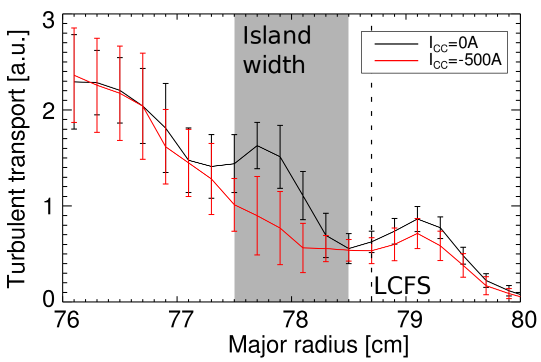

Figure 3: Radial profile of the net radial turbulent particle flux without (black) and with (red) application of the EFCC

These results represent only a first step into a new field of research. Therefore, no explanation for the observed effects can be given. But the topic will be studied intensively in future turbulence experiments in WEGA.

References

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