Enhancement of zonal flow drive through equilibrium shear flows

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Introduction Turbulence generated zonal flows (ZFs) are known to be capable of regulating turbulent transport and, therefore, are suspected to be involved in spontaneous transitions from low to high confinement regimes in toroidal fusion plasmas [1]. ZFs are driven by radial gradients of the turbulent Reynolds stress (RS) $\langle \widetilde{v}_\theta \widetilde{v}_r \rangle$, which de facto measures the tilt of vortices. Therefore, equilibrium shear flows can constitute a seed flow for initially tilting vortices, initiating the ZF drive, which opens a loss channel for turbulence energy.

The approximate flux surface averaged RS, the RS drive, and even zonal potential structures are experimentally analysed with respect to background flow shear. Shear induced changes in the RS are considered a consequence of a modification in the non-linear wave coupling process, in which the amount of coupling modes is reduced as to increase efficiency in the energy transfer into the zonal flow. This paradigm is tested by means of bispectral analysis carried out on the measured RS data.

Stellarator TJ-K The experiments were carried out in the low-temperature plasmas of the stellarator TJ-K. The poloidal $E\times B$ background flow in the stellarator TJ-K is controlled via plasma biasing. A ring-shaped electrode is positioned in the plasma and set on a positive potential with respect to the floating potential. The current drawn from the plasma changes the equilibrium plasma potential profiles and therefore imposes strong $E\times B$ background flows [2]. The plasma potential $\phi(r)$, from which the shearing rate is deduced, is measured with a radially moving emissive probe. For measurements of the poloidal RS distribution and related radial

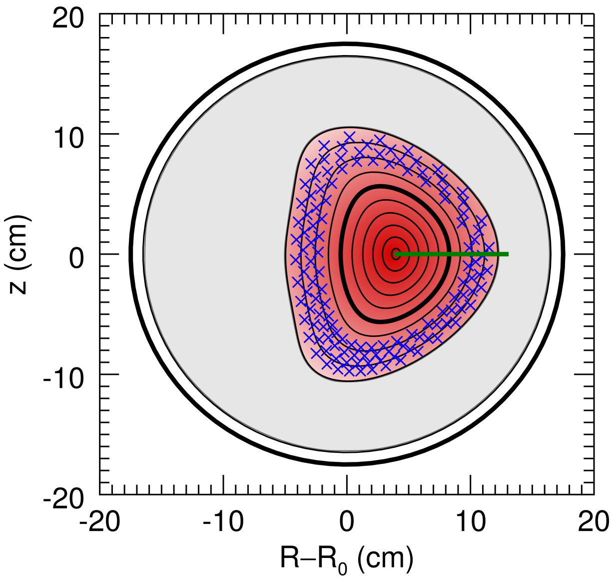

Figure 1: *Triangular cross-section of TJ-K plasmas. Grey: SOL as defined by poloidal limiters. Blue: GARM pin positions. Black (thick): Projection of ring-electrode. Green: Path of ϕ_{pl}-profile measurements*

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gradients, a specifically designed poloidal Langmuir probe array is employed. The Array (GARM - Global Array for Reynolds-Stress Measurements) consists of 128 probes covering four neighbouring flux surfaces in the edge of the confinement region and measuring potential fluctuations.

Imposed flow shear Through biasing a current is drawn from the plasma, changing the plasma potential profiles (Fig. 2). In the unbiased case at $U_{Bias} = 0\,\mathrm{V}$ the plasma potential in the plasma center is nearly flat, drops between $R - R_0 = 8 - 10\,\mathrm{cm}$, raises slightly at higher radii and saturates in the limiter region.

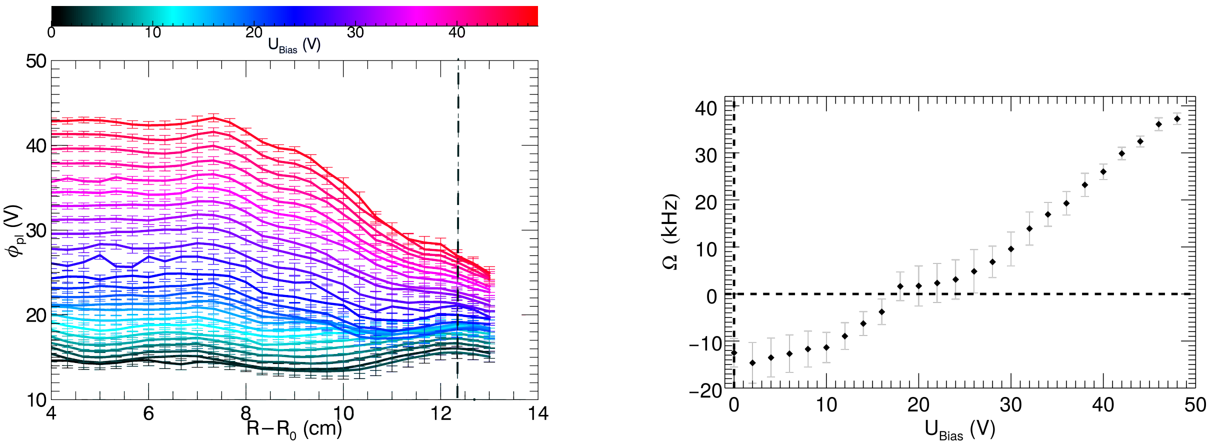

Figure 2: *Flow shear imposed by plasma biasing (electrode at* $R - R_0 \approx 8\,\mathrm{cm}$*). Left: Plasma potential profiles for different bias voltages (color-coded). The vertical line marks the separatrix.* ϕ_{pl} *shows a local minimum within* $R - R_0 \approx 9 - 10\,\mathrm{cm}$ *in the unbiased case. At* $U_{Bias} \approx 20\,\mathrm{V}$ *this minimum is equalized. Right: Shearing rate versus bias voltage. At around* $U_{Bias} \approx 20\,\mathrm{V}$ *the shearing rate is zero.*

The change in the potential profile through biasing leads to a gradual increase in the poloidal $E \times B$ -flow at around $R - R_0 \approx 10\,\mathrm{cm}$, locally enhancing the flow shear. From the plasma potential profiles the shearing rate ($\Omega = (RB_0)^2 B^{-1} \partial_r (RB_\theta)^{-1} \partial_r \phi$) is calculated according to Ref. [3]. For comparison with fluctuation data, Ω is averaged in the range $R - R_0 = 8 - 9\,\mathrm{cm}$. As a consequence of potential flattening at $U_{Bias} \approx 20\,\mathrm{V}$, the associated shearing rate approaches zero, as can be seen in the right hand-side of Fig.2. Moreover the flow shear increases steadily, almost linearly, with bias voltage.

Reynolds stress measurements The Reynolds stress as defined by $R = \langle \tilde{v}_\theta \tilde{v}_r \rangle$ can be seen as a measure of the tilt of vortices in a velocity field. $\tilde{v}_\theta$ and $\tilde{v}_r$ are fluctuations in the poloidal and radial flow components, respectively, and the brackets denote the ensemble average. At TJ-K, it could be shown [4] that R is not homogeneous on a fluxsurface and that vortices experience a tilt with $R \neq 0$ only locally in distinct regions with negative normal fieldline curvature. Formally the gradient of the flux surface averaged RS $\partial_t \langle \tilde{v}_\theta \rangle = \partial_r R$ drives the ZF. In Fig. 3, this RS is shown in dependence of the shearing rate. Starting at negative shearing rates the RS decreases with Ω approaching zero, where also the RS takes minimum absolute values. Then, up to $\Omega = 5\,\text{kHz}$, the RS proceeds more into the negative, taking a local maximum at $\Omega = 0$ in absolute value and for $\Omega > 5\,\text{kHz}$ proceeding towards zero again. In the range $\Omega \leq 5\,\text{kHz}$, the trend of the ZF power is consistent with the RS. For $\Omega > 5\,\text{kHz}$ the plasma equilibrium may be distorted too massively by biasing. This regime is still under investigation.

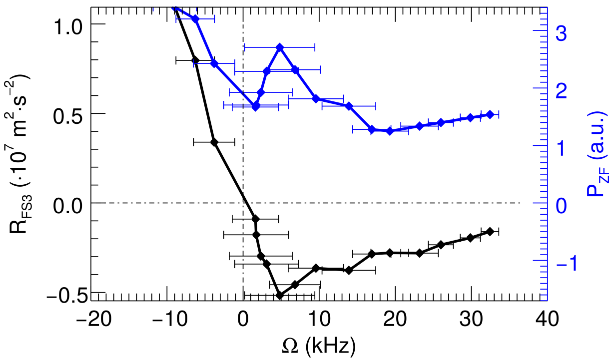

Figure 3: *Reynolds stress (black) and zonal flow power (blue) versus shearing rate.*

Energy transfer into ZF The drive of the ZF can be understood as consequence of non-linear interactions between drift-waves. In the Hasegawa Mima model the energetic drive is given by [6]

$$\partial_t \langle \phi_k(t) \phi_k^*(t) \rangle + i\omega_k^* \langle \phi_k(t) \phi_k^*(t) \rangle = \Lambda \langle \phi_{k_1}(t) \phi_{k_2}(t) \phi_k^*(t) \rangle = T' \quad , \tag{1}$$

where ω_k^* is the normalized drift-wave frequency, Λ the non-linear interaction coefficient and $T = \Re(T')$ the energy transfer function [5]. Here, the ensemble for averaging is constructed conditionally by triggering on zonal potential amplitudes higher than 2σ, since ZFs in the low temperature plasmas in TJ-K do not saturate but rather show up in transient events. $T(k_1, k_2, k)$ has been integrated over $k_1 + k_2 = k$, whereas the transfer into the ZF ($k = 0$) is of special interest. $T(k = 0)$ versus the shearing rate is shown in Fig. 4. Both ZF power and energy transfer show a similar trend, which in principle reflects that of the flux surface averaged RS: The energy transfer into the ZF increases with increasing $|\Omega|$ (in the range $-10\,\text{kHz} \leq \Omega \leq 5\,\text{kHz}$) with a minimum at $\Omega \approx 0kHz$. This shows that the energetic drive of ZFs can be enhanced through background flow shear.

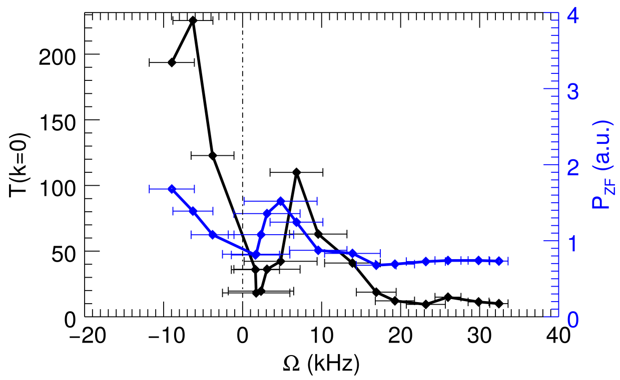

Figure 4: *Energy transfer into ZF ($T(k = 0)$ black) and ZF power (P_{ZF} blue) as a function of the shearing rate.*

Summary The background $E \times B$ flow and thus the equilibrium flow shear can be controlled at TJ-K by plasma biasing, providing the opportunity to systematically study the ZF and RS dependence on the background flow shearing rate. It has been found that the RS, as well as the ZF power, evolves as consistent with the effect of vortex tilting through flow shear. In particular lowest RS and ZF activity are observed at zero shearing rates. This is reflected in the energy transfer into the ZF, too. These results point to the important role equilibrium shear flows could play in turbulence reduction as in line with the results at ASDEX Upgrade [7]. In TJ-K, equilibrium shear flows turn out to facilitate RS and related energy transfer into ZFs, opening and potentially maintaining a loss channel for turbulence energy.

References

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