# Turbulence Regulation and Energy Transfer Dynamics During Zonal Flow Formation

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**Introduction:** Regulation of cross-field turbulent particle transport $(\Gamma)$ is crucial for achieving improved confinement in fusion plasmas. In this context, zonal flows (ZF)s have been identified as transport-reducing phenomena [1], triggering transitions to high-confinement regimes [1–3]. ZFs are poloidal $E \times B$ shear flows, distinguished by a homogeneous potential perturbation on a flux surface [1]. They tap energy from small-scale turbulent structures, which is transferred to the large-scale shear-flows through the Reynolds stress $(\mathfrak{R})$ mechanism [4, 5].

At the edge of fusion plasmas, drift-wave destabilization is linked to significant levels of particle transport [6, 7]. An increase in $\Gamma$ arises when potential fluctuations $(\tilde{\phi})$ decouple from density perturbations $(\tilde{n})$, leading to the growth of the instability [8–10]. Conversely, Reynolds stress requires an adiabatic coupling between $\tilde{n}$ and $\tilde{\phi}$ for the efficient vortex tilting required in the energy transfer [11, 12]. The dependence of $\Gamma$ and $\mathfrak{R}$ on the $\tilde{n} - \tilde{\phi}$ coupling – as measured by the dynamical density-potential cross-phase $(\alpha_{n\phi})$ – accounts for their anti-correlation [13].

However, during the occurrence of ZFs, transport is expected to be co-regulated by fluctuation amplitudes [14, 15]. Energy redistribution between $\tilde{\phi}$ and $\tilde{n}$ likely alters the cross-coupling as transport barriers form. This work experimentally resolves the dynamical energy transfer associated with density-potential coupling during ZFs.

**Experimental Setup:** Experiments were performed at the TJ-K stellarator [16], where drift-wave turbulence dominates the plasma dynamics [17, 18]. An array composed of 128 Langmuir probes (Fig. 1) enables the spatiotemporal measurements of $\tilde{n}$ and $\tilde{\phi}$ on four neighboring flux surfaces.

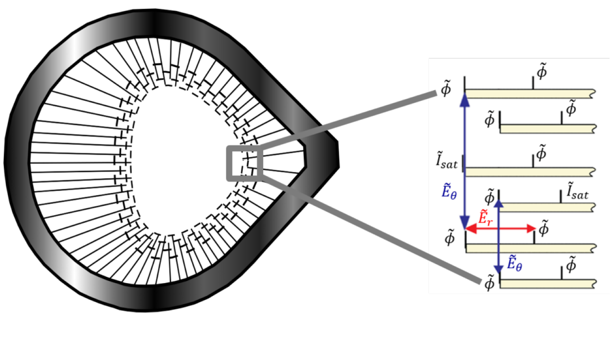

Figure 1: *Probe array for ZF, $\Gamma$, and $\mathfrak{R}$ detection*

The operational mode allows for the estimation of the turbulent particle flux via:

$$\Gamma(t) = \tilde{n}(t)\tilde{v}_r(t) \propto \tilde{I}_{\mathrm{sat}}(t)\frac{-\Delta_\theta \tilde{\phi}(t)}{B\Delta_\theta}, \qquad (1)$$

together with the Reynolds stress according to:

$$\Re(t) = \tilde{v}_r(t)\tilde{v}_\theta(t) \propto \frac{-\Delta_\theta \tilde{\phi}(t)\, \Delta_r \tilde{\phi}(t)}{B^2\, \Delta_\theta\, \Delta_r}. \tag{2}$$

Based on their characteristic homogeneous potential, zonal flows are detected through the flux surface average of the potential measuring probes:

$$\mathrm{ZP}(t) = \langle \tilde{\phi}(t) \rangle_{\mathrm{FS}}. \tag{3}$$

**Turbulence Dynamics:** By conditional sampling, temporal slices of $\Gamma$ and $\Re$ are centered with respect to events in the zonal potential. The average of all sub-windows reveal the evolution of the signals coherent with the trigger event. Fig. 2 shows the dynamical interplay of $\Gamma$ and $\Re$ involved in the formation of ZFs. During the onset of the shear flow, $\Gamma$ is seen to be decreasing as $\Re$ increases. However, both $\Gamma$ and $\Re$ drop to their minimum values as the zonal flow reaches its maximum level. Hence, $\Gamma$ and $\Re$ appear to become in phase during ZFs.

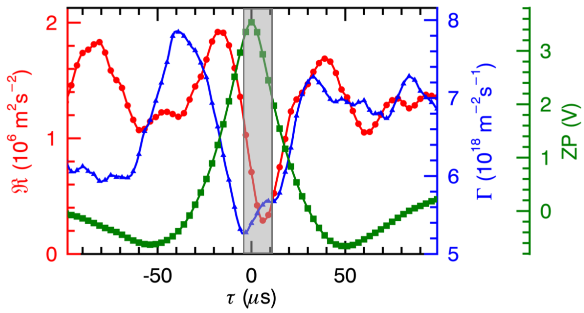


Figure 2: *Evolution of $\Gamma$ and $\Re$ during ZF*

**Spectral Analysis:** Taking the conditionally averaged spectral cross-phase $\alpha_{n\phi}(\tau)$ and - amplitude $A_{n\phi}(\tau)$, the dynamical $\tilde{n} - \tilde{\phi}$ coupling and power contribution can be associated with the evolution of the ZF and the coherently coupled phenomena. Fig. 3 shows that the initial drop in $\Gamma$ and increased $\Re$ is correlated with a decreasing $\alpha_{n\phi}$. Around the peak of ZF amplitude, the density-potential cross-phase increases significantly with no visible variation in $\Gamma$. At the same time, the cross-amplitude is observed to decrease and thus, maintaining particle transport in the shaded region. The behavior of $\Gamma$ readjusts to the cross-phase as the ZF event is terminated.

**Dynamical Energy Transfer:** The spectral power transfer associated with the fluctuations is obtained from the energy flow in the nonlinear wave-coupling equation, using the one-field model shown by Kim *et al* [19]. The relevant energy transfer functions for the nonlinear formation of zonal flows in plasmas cover the kinetic energy, given by:

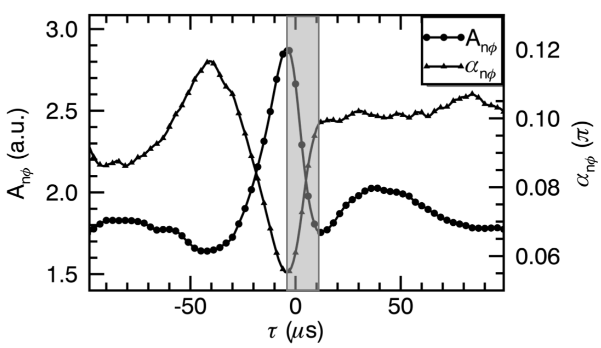


Figure 3: *Coherent evolution of $\alpha_{n\phi}$ and $A_{n\phi}$*

$$T^{\phi}(k,t) = \mathrm{Re}\left[\Lambda_k\, \phi(k_1,t)\phi(k_2,t)\phi^*(k_3,t)\right], \tag{4}$$

and the density fluctuation activity:

$$T^n(k,t) = \mathrm{Re}\left[\Lambda_k n(k_1,t)\phi(k_2,t)n^*(k_3,t)\right], \tag{5}$$

The conditional average of the power transfer with respect to the ZF, shown in Fig. 4, reveals a dominance of the kinetic energy transfer on the $k_1^\phi = -k_2^\phi$ diagonal, while the density activity is most significant at the horizontal, corresponding to $k_2^\phi = 0\,\mathrm{m}^{-1}$. During the rise and

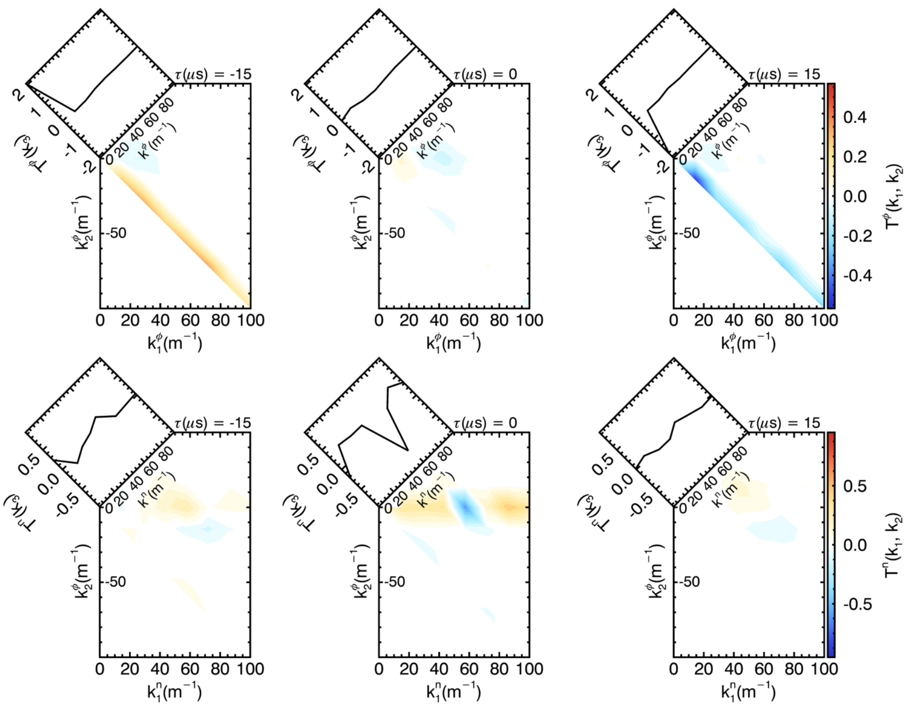


Figure 4: *Dynamical transfer of kinetic energy (top) and density activity (bottom) during ZFs.*

decay of the ZF, energy is transferred to and from the $k_\theta^\phi = 0\,\mathrm{m}^{-1}$ through the interaction of similarly scaled potential structures. A quiescent interval, where no transfer of kinetic energy is observed, coincides with the de-correlation state of $\Gamma$ and $\alpha_{n\phi}$. Within this idle period, the ZF is sustained by the transfer of energy from the density at $k_3^n = 60\,\mathrm{m}^{-1}$ to the macroscopic potential at $k_2^\phi = 0\,\mathrm{m}^{-1}$. The increased $\alpha_{n\phi}$ is compensated by the drop in $A_{n\phi}$ through the transfer, where energy is redistributed from transport affected small to unaffected zonal scales. The exclusive energy gain of the homogeneous potential reflects the constant $\Gamma$ levels as no radial velocity is associated with $k_\theta^\phi = 0\,\mathrm{m}^{-1}$.

**Conclusion:** The dynamical coupling and energy transfer mechanism during the formation of ZFs is experimentally investigated. The occurrence of zonal flows was found to deteriorate the anti-correlation between $\Gamma$ and $\Re$. Around the peak of the ZF, levels of $\Gamma$ where observed to be maintained by the decreasing cross-amplitude as $\alpha_{n\phi}$ increases. The de-correlation interval is shown to coincide with a period of idle kinetic energy transfer, during which the shear flow is sustained by the transfer of energy from the density at intermediate scales to the $k_2^{\phi} = 0\,\mathrm{m}^{-1}$. The fluctuation power at transport related scales drops in favor of zonal scales as consistent with the energy transfer.

**Funding:** This work is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)- #471314753.

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