Investigation of the energy transfer to zonal flows at the stellarator TJ-K

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Introduction In fusion devices, an increased zonal flow activity is found when the bifurcation to high confinement (H-mode) is reached. For zonal flows, it has been shown that they can reduce turbulent transport [1]. With their $m = n = 0$ topology and finite radial wave number k_r, the zonal flow is intrinsically connected to a poloidal shear flow. Drift-wave eddies are tilted and drive the shear flow, which leads to a self-amplification of the zonal flow. The zonal flow energy is then dissipated through collisional losses or transferred via the geodesic transfer effect to the geodesic acoustic mode. A key parameter in the drift wave - zonal flow system is the collisionality. It determines the coupling strength between the density and potential. By changing the collisionality, the scaling of the spectral energy transfer into the different channels can be studied.

Stellarator TJ-K The experiments were carried out in the low-temperature plasmas of the stellarator TJ-K. To study the energy transfer from the drift waves to the zonal flow and to the geodesic acoustic mode (GAM), a poloidal Langmuir-probe array was used for the measurements (Figure 1). The array covers four neighbouring flux surfaces in the edge of the confinement region, whereby it is possible to investigate the energy transfer directly in wave-number space. Simultaneous measurements of density and potential fluctuations allow to also address the nonlinear cross-coupling in drift-wave turbulence [2]. With respect to parameter settings, the experiment has a high flexibility, which allows an operation in different collisionality regimes. Mainly by changing the ion mass and magnetic field

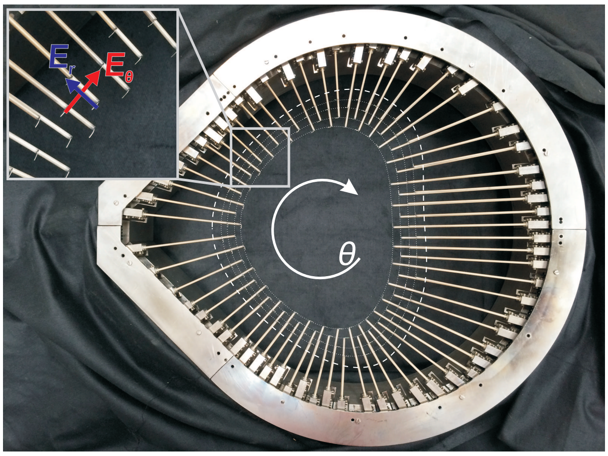

Figure 1: *Poloidal Reynolds-stress array with Langmuir probes on four flux surfaces (dotted white lines) just inside the separatrix (dashed white line). The detail illustrates how the electric field components are measured.*

strength, the collisionality can be varied by about two orders of magnitude. Thereby it is possible to study the transition from the hydrodynamic case ($C > 1$) to the adiabatic case ($C < 1$).

Scaling of the energy transfer to the zonal flow It was shown that the turbulence in the stellarator TJ-K is drift-wave dominated [3] and for the analysis it is assumed that it satisfies the nonlinear wave-coupling equation. Using the modified Ritz method, developed by Kim et al [4], which incorporates moments of fourth-order, it is then possible to estimate the spectral transfer of density fluctuation activity, which includes the nonlinearity of the $E \times B$-drift. A conditional averaging technique is used to calculate the temporal ensemble average. For the zonal flow as

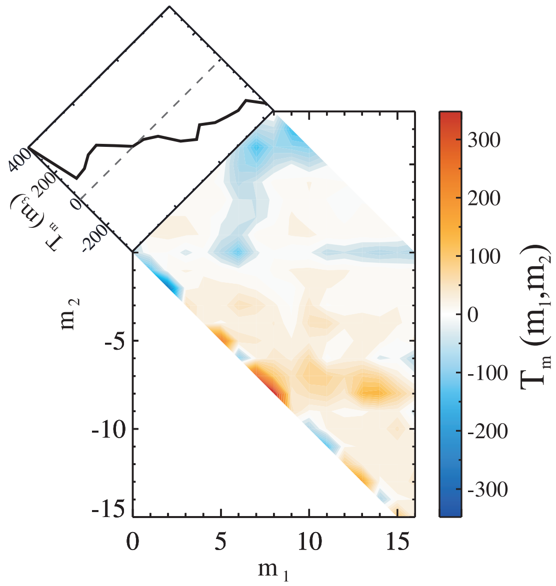

Figure 2: *Nonlinear power transfer function in wavenumber space (contour plot) and the integrated spectrum (line plot) showing the energy transfer to the* $m_3 = 0$ *mode.*

trigger event, an energy transfer from small-scale drift waves to the $m_3 = 0$ potential mode is found, corresponding to an nonlocal invers energy transfer (Figure 2). This energy transfer to the zonal flow is calculated for various measurements with different collisionality. The collisionality is thereby given as

$$C = \frac{\hat{\nu}}{\hat{k}_{\|}^2} \propto \frac{B\, n_e}{k_{\|}^2\, m_i\, T_e^{5/2}} \,,$$

where $\hat{\nu}$ is the normalised collision frequency and $\hat{k}_{\|}$ is the normalised parallel wavelength. With the collision frequency as inverse of the collision time, one gets the shown dependencies on ion mass, magnetic field, electron density and temperature. The relative zonal flow power $P_{\mathrm{ZF}}/P_{\mathrm{total}}$ as a function of the collisionality is shown on the left hand side of figure 3. In the limit of the adiabatic case ($C \to 0$), the zonal flow contribution to the complete spectrum strongly increases. On the right hand side of figure 3, the scaling of the energy transfer to the zonal flow ($m_3 = 0$) is plotted. For low collisionality the energy transfer to the zonal flow also increases, showing the increased drive by the drift waves. The collisionality is a key parameter in drift-wave turbulence.

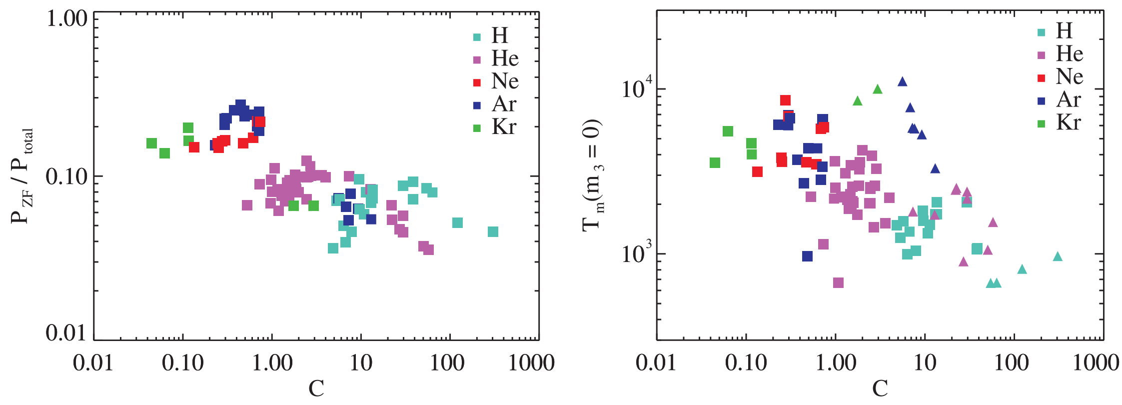

Figure 3: *Scaling with collisionality of relative spectral zonal flow power* (left) *and energy transfer to the zonal flow* (right)*. Measurements with high magnetic field are drawn as triangles.*

In the two dimensional Hasegawa-Wakatani equations, as a model for drift-wave turbulence, it determines the coupling of the density and the potential field,

$$\partial_t n + \{\phi, n\} + \kappa_n \partial_y \phi = C^{-1}(\phi - n) \; ,$$
$$\partial_t \Omega + \{\phi, \Omega\} = C^{-1}(\phi - n) \; .$$

Here n, ϕ and Ω denote the density, the potential and the vorticity, respectively. κ_n is the normalised background gradient and $\{.,.\}$ represents Poisson brackets. For high collisionality, the two equation decouple and for low collisionality the density and potential act similar. Since the zonal flow is a pure potential structure, but the drift waves are sheared in the density, the drive is more efficient for higher coupling.To further investigate this coupling, also measurements with a different bias setting of the poloidal probe array were performed. For this setting, blocks of probes measuring ion-saturation current alternate with probes on floating potential when going around the circumference. So it is possible to calculate the Reynolds stress from the density fluctuations, the so called pseudo-Reynolds stress, together with the Reynolds stress from potential fluctuations [5]. Since Reynolds stress and pseudo-Reynolds stress can be measured on two fluxsurfaces, the corresponding zonal flow drive $-\partial_r(\langle \mathrm{R} \rangle_{\mathrm{fs}})$ of both quantities is obtained. The scaling of the maximum crosscorrelation between Reynolds-stress drive and pseudo Reynolds-stress drive with collisionality is shown in figure 4. For lower collisionality the corre-

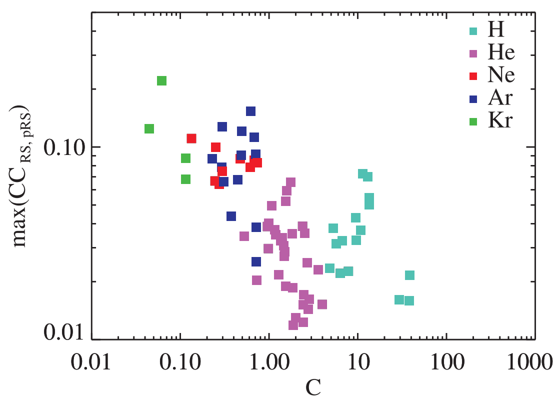

Figure 4: *Scaling of the maximum cross-correlation between Reynolds-stress drive and pseudo Reynolds-stress drive with the collisionality.*

lation between both increases, pointing to an increased coupling between density and potential.

Energy transfer to the GAM For measurements with high magnetic field (triangles in figure 3), and therefore low $\rho_s = \sqrt{m_i T_e}/eB$, an increased coupling between zonal flow and $m_1 = m_2 = 6$ density mode is found. The scaling of the energy transfer to this $m = 6$ mode is shown in figure 5. For decreasing collisionality more energy is transferred from the zonal flow ($m_3 = 0$ potential mode) to the $m = 6$ density mode, where the trend is similar as the scaling shown in figure 3. As stated above, energy can be transferred from the zonal flow to the geodesic acoustic mode. Due to the asymmetric poloidal flow structure, density will be advected into regions with high geodesic curvature. Therefore, the GAM in tokamak geometry has a $m = 1, n = 0$ density mode structure. Since the stellarator TJ-K has a sixfold magnetic field symmetry, this mode could indicate a GAM whose mode structure reflects the magnetic field geometry of the stellarator.

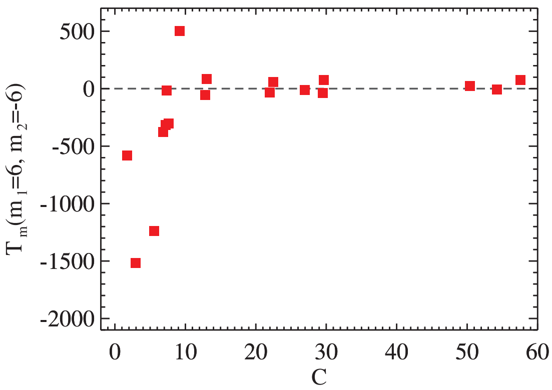

Figure 5: *Energy transfer to the $m = 6$ density mode for measurements with high magnetic field, i.e. low ρ_s.*

Conclusion Various measurements at different collisionalities have been carried out at the stellarator TJ-K to study the scaling of the energy transfer to zonal flows. For low collisionality an increased energy transfer to the zonal flow was found. Along with this, also the relative power of the zonal flow in the total spectrum strongly increases. With a different measurement setting, also Reynolds stress and density-based pseudo-Reynolds stress are obtained. The correlation between these two quantities increases with lower collisionality, pointing to a higher coupling of density and potential. For shots with high magnetic field, a prominent energy transfer to a $m = 6$ density mode is observed, showing the same scaling behaviour as the zonal flow. This mode could be the geodesic acoustic mode, reflecting the magnetic field structure of the stellarator.

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