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Local and global magnetic shear damping of drift wave turbulence

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Damping of drift waves in a sheared magnetic field early became a central theme in magnetic fusion research [1, 2, 3]. After linear drift waves were found stable in an uncurved sheared slab geometry, it has been noted that the nonlinear instability can overcome complete stabilization [4, 5, 6]. Magnetic shear damping thus has to be studied in a self consistent drift wave system with proper treatment of self sustained turbulence.

Magnetic shear in a toroidal field with circular flux surfaces, $\hat{s} = (r/q)\partial_r q$, is defined as the variation of safety factor q with minor radius r. Parallel coupling of drift wave dynamics causes the perpendicular vortices to be twisted along with the field lines and to be finally nonlinearly torn apart to smaller scales. A similar nonlinear decorrelation of drift wave vortices can also be achieved by sheared poloidal flows that are imposed by an equilibrium radial electric field or self-generated by turbulent Reynolds stress. These latter zonal flows with $k_\theta = k_{||} = 0$ do not participate in cross field transport and provide an energetic sink for drift modes, effectively damping the turbulence.

We show that for resistive drift-Alfvén turbulence zonal flow shear can actually depend on magnetic shear. These simulations are performed in slab geometry with spatially constant (global) magnetic shear. We employ a parallel code, DALF3, in three dimensional globally consistent flux tube geometry [9, 10]. We chose the relevant plasma parameters to reflect typical tokamak edge conditions: collisionality $\hat{\nu} = \nu_e(L_\perp/c_s) = 4$, plasma beta $\hat{\beta} = \epsilon(4\pi p_e/B^2) = 1$, electron inertia $\hat{\mu} = \epsilon(m_e/m_i) = 5$ and $\epsilon = (L_{||}/L_\perp)^2 = 18350$. The simulations are initialized through a density fluctuation amplitude well above unity which is driven nonlinearly and then relaxes to a steady turbulent state.

In a sheared slab homogenous magnetic field, with no interchange coupling, the dynamics is effectively two-dimensional. We find a strong spin-up of zonal flows, evolving over a transient phase of up to $5 \cdot 10^5$ time steps, that suppresses the turbulence to a low level nearly independent of magnetic shear $\hat{s}$. This is in accordance with earlier 2D dissipative coupling models. The zonal flow part of the dynamics can be removed from the simulations by discarding the y-average of the Reynolds stress, $v_{\mathbf{E}} \cdot \nabla\nabla_\perp^2 \tilde{\phi} \equiv 0$. The detailed dependence of turbulent transport Γ_n on magnetic shear $\hat{s}$ in the steady phase of our simulations in the uncurved globally sheared slab is illustrated in Fig. 1a: With full dynamics the suppression is nearly total (lower curve) compared to the case without zonal flows (upper curve), where magnetic shear is rendered effective again.

Inhomogenities in the magnetic field introduce curvature terms $\mathcal{K} = \mathcal{K}^x\partial_x + \mathcal{K}^y\partial_y$ into the drift wave equations. Normal curvature $\mathcal{K}^x$ enables interchange forcing of the turbulence on $k_y \neq 0$ modes.

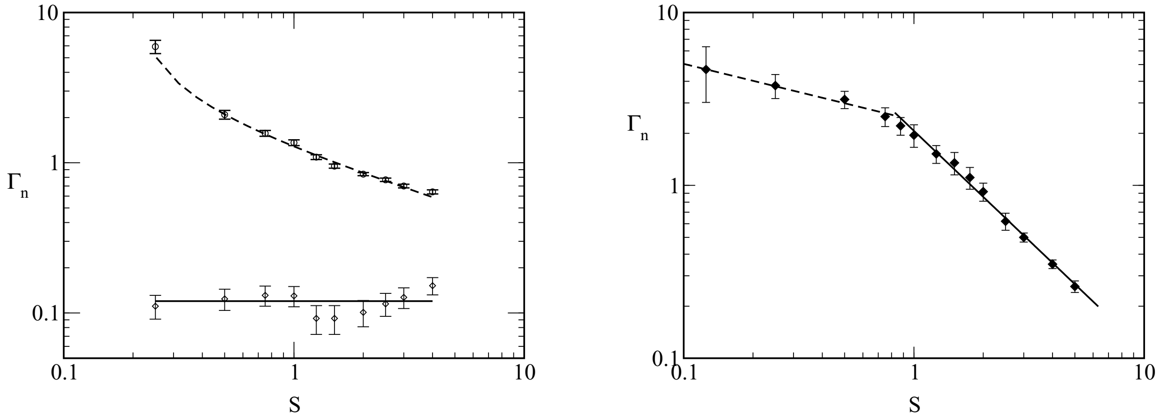

Figure 1: (a) Left: Effective spin-up and suppress scenario of turbulent transport Γ_n by zonal flows in an uncurved globally sheared slab. With full dynamics (lower symbols) the transport is nearly independent of magnetic shear, whose damping effect is only visible when zonal flows are turned off (upper symbols). (b) Right: Magnetic shear damping of turbulent drift-Alfvén wave transport in a toroidal magnetic field. The power law scaling changes coefficient for $\hat{s} \sim 0.8$

Moreover, the geodesic curvature $\mathcal{K}^y$ couples the zonal flow mode to global ($k_y = 0$) Alfvén modes which dissipate into the thermal bath and present a loss channel to zonal flows. The zonal flow dynamics therefore gives the turbulence an overall different character in toroidal geometry. In the following, a basic toroidal field with respective $\mathcal{K}$ and $\mathcal{K}^y$ is assumed [10]. We again vary global magnetic shear $\hat{s}$ and leave all other parameters constant and show the result in Fig. 1b. As expected, stronger magnetic shear damps the transport. Zonal flows affect but do not suppress the turbulence. We observe that the shear dependence of transport resembles a power law with approximately $\Gamma_n \sim \hat{s}^{-1/3}$ for $\hat{s} < 0.8$, and $\Gamma_n \sim \hat{s}^{-4/3}$ for larger magnetic shear (compare Ref. [9]). The difference is based on the respective zonal flow structure for low and high shear. The ratio of turbulent transport levels between the case with complete dynamics and the case with zonal flows excluded is plotted against $\hat{s}$ in Fig. 2a. An analysis of the radial structure of the flux surface averaged absolute vorticity, $\langle|\tilde{\Omega}(x)|\rangle_{y,z}$, shows that for the low shear case a zonal flow structure with one crest ($i = 1$) in x has evolved. For higher shear $i = 2$ and $i = 3$ radial modes of zonal flows develop. The cases for $\hat{s} = 0.5, 1.5$ and 3.5 are shown in Fig. 2b. The crests are not directly linked to rational surfaces: when periodic boundary conditions in x are employed instead of Dirichlet, the zonal flow structures remain qualitatively similar, but drift in x and are unconnected to possible rationals. The radial width of zonal flow modes thus should rather be linked to the scale of primary vortices, which decreases for higher magnetic shear.

However, magnetic shear can vary rapidly locally along a flux tube both in divertor tokamaks and generically in stellarators. We thus now withdraw the constraint of constant, global shear $\hat{s}$ and allow for general variations of local shear $\sigma(z) = \partial_z(g^{xy}/g^{xx})$ in a field aligned unit Jacobian coordinate system where y is locally perpendicular to z and the down gradient direction x. Metric elements are denoted by $g^{xy} = \nabla x \nabla y$. Global shear $\hat{s} = \langle\sigma\rangle_{y,z}$ then is the flux surface average of local shear. The importance of local shear for turbulent plasma edge transport has been noted before when the exact geometry of an advanced stellarator fusion experiment had been considered in simulations [11]. That local shear indeed has a significant damping effect can best be demonstrated when its global average is allowed to vanish. Such a scenario is also of high significance for advanced stellarators with low overall global shear. Therefore we consider the ansatz $g^{xy} = \hat{s}_0 \cdot z + \hat{s}_L \cdot \Delta \cdot \exp\left[(1/2 - (1/2)z^2/\Delta^2\right]$ and $g^{xx} = 1$ (in straight metric terms) from which the local shear $\sigma(z) = \partial_z(g^{xy}/g^{xx})$ is obtained. For global shear $\hat{s}_0 = 0$ the function $\sigma(z)$ is portrayed in Fig. 3a for different values of local peak shear $\hat{s}_L$ and width Δ. The set of solid curves shows cases for which $\bar{\sigma} \equiv \langle|\sigma(z)|\rangle$ is held constant by increasing the peak shear $\hat{s}_L$ when shrinking the width Δ of the structure. In the set of dashed curves $\bar{\sigma}$ is allowed to vary as we keep the maximum shear fixed but change the width of the function.

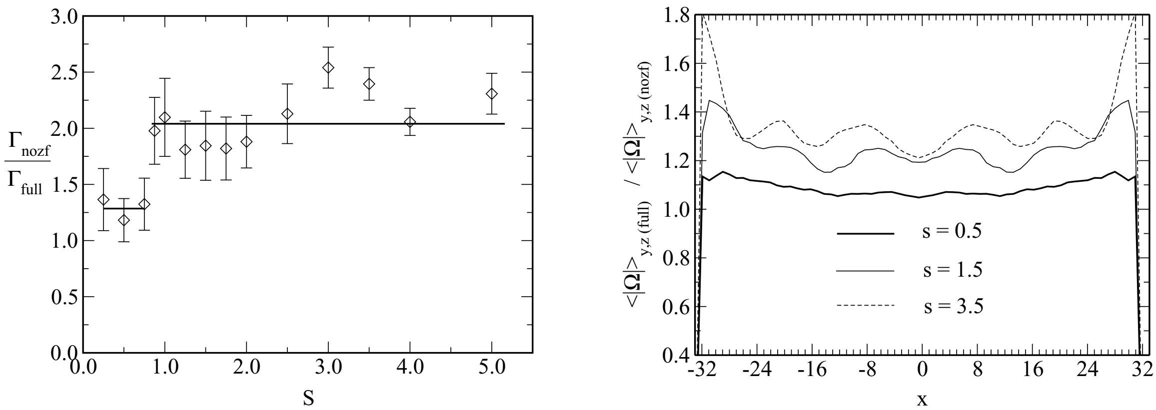

Figure 2: (a) Left: Ratio of turbulent transport without zonal flows to the case with full dynamics in respect to global magnetic shear $\hat{s}$ in a toroidal field. (b) Right: Flux surfaced average absolute vorticity ratio $\langle|\tilde{\Omega}(x)|\rangle_{y,z}$ for three cases of global shear $\hat{s}$. With rising shear the radial mode number of the zonal flow mode increases

The obtained turbulence levels for these two scenarios (including toroidal curvature) are depicted in Fig. 3b: For constant average absolute local shear $\bar{\sigma} = 1$ the transport Γ_n (blank symbols) remains similar within the error bars of the time average taken during the saturated phase of the simulations. Still, the transport level is a factor of two lower than in a toroidal geometry with constant zero local shear and corresponds to about $\hat{s} = 0.1$ in a globally sheared toroidal flux tube. We also see that the average of the absolute local magnetic shear, $\bar{\sigma}$, constitutes an effective damping mechanism at vanishing global shear. An increasing width of the local shear structure when keeping the maximum fixed also increases $\bar{\sigma}$, and significantly reduces the transport as illustrated by the filled symbols in Fig. 3b.

Advanced stellarator configurations often exhibit very low overall global magnetic shear in order to inhibit magnetic islands on low-order rationals of the rotational transform. In spite of generic differences in the confining magnetic field, low-shear ($\hat{s} < 0.1$) stellarators featured the paradox of showing similar global confinement and edge transport levels compared to tokamak experiments [8]. In the latter, edge magnetic shear usually is in order of $\hat{s} > 1$ for otherwise similar plasma parameters. Evidence of efficient local shear damping of advanced stellator edge turbulence has recently been put forward in Ref. [11]. We have shown in a simple local shear model that the average absolute local shear is indeed an effective substitute for global shear.

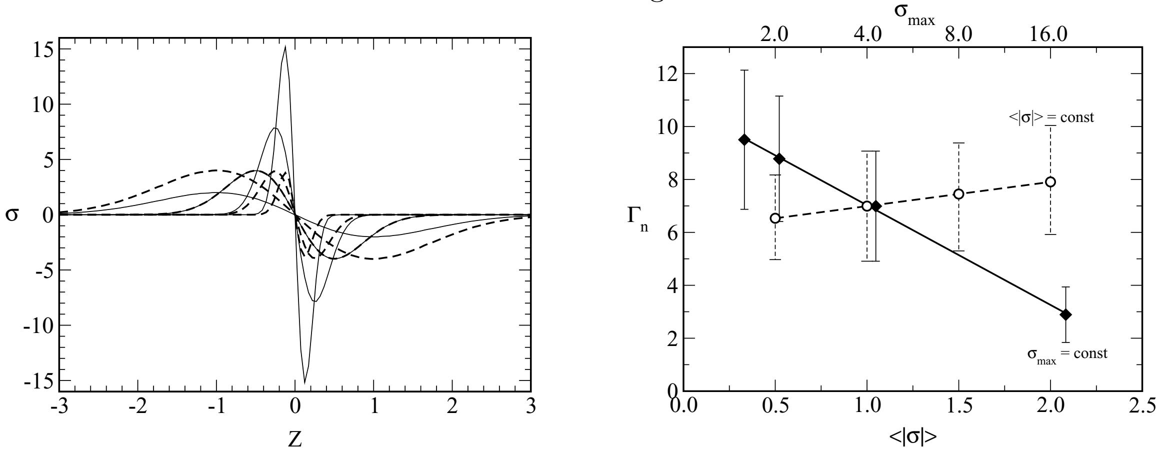

Figure 3: (a) Left: Locally sheared slab model: functions of $\sigma(z)$ for either $\langle|\sigma|\rangle = const$ or $\sigma_{max} = const$ with varying width. (b) Right: Transport in the locally sheared slab model: varying the local shear peak values while keeping $\bar{\sigma} = \langle|\sigma(z)|\rangle = const$ leaves the turbulence level (blank symbols) unchanged within the error bars of the fluctuation average. The turbulence strongly depends on $\bar{\sigma}$ when the maxima are fixed (filled symbols).

A prominent case of finite global magnetic shear on a flux surfaces which features additional strong local shear peaks is the edge of a divertor tokamak where the X point introduces a strong shaping of the flux surfaces. We model this scenario (including curvature drive) by $g^{xy} = \hat{s}_0 \cdot (z - \sin z) + \hat{s}_L \cdot \Delta \cdot \arctan[(z + 3/2)/\Delta]$ and, for simplicity, $g^{xx} = 1$. The sinusoidal term represents deformation of the flux surfaces by Shafranov shift, and the global shear term is set to $\hat{s}_0 = 1$. Also for this case the turbulent transport is reduced with increasing width and maximum of the local shear peak while both $\bar{\sigma}$ and $\langle\sigma\rangle_{y,z}$ remain unchanged and equal to each other. For $\hat{s}_L = 4$ and $\Delta = 0.05$ the transport is at level $\Gamma_n = 2.5 \pm 0.2$. Quintupling the peak width leads to a reduction of transport by a third. Additional doubling of the peak maximum further reduces turbulence to maintain $\Gamma_n = 1.5 \pm 0.2$. This result shows the importance to consider exact flux surface shapes when simulating tokamak turbulence at the plasma edge region [10]. Finally we point out that our results for local and global magnetic shear damping were obtained for dissipative drift wave turbulence. Reactive (e.g adiabatic temperature gradient driven) drift turbulence can exhibit different character [12].

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