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The Nonlinearly Saturated State of Strong Interchange Turbulence

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Strong interchange-type turbulence occurs in many contexts, most notably as a ubiquitous feature of edge and Scrape-Off Layer (SOL) turbulence in all magnetic confinement devices. It is unique in its large amplitudes -- fractional fluctuation levels ~50%, indicative of a strength of nonlinearity not seen in the interior of confined plasmas. It is thus not surprising that the various mechanisms that saturate the weaker interior turbulence at much lower amplitudes do not suffice to explain this physics. Given the complexity of the problem, it is useful to begin with the simplest model system, and one that is easy to diagnose. This simplest configuration is the cylindrical slab, an azimuthal magnetic field providing magnetic curvature, plasma uniform and infinite in z, and with slab variation only in R; the plasma is interchange unstable where the density gradient finds unfavorable curvature. The Helimak is an experimental realization/approximation to this geometry. The essential modification is the addition of a weak B_Z, which allows return current at the ends to neutralize charge separation and establishes a stable MHD equilibrium. The field lines are therefore helices on cylindrical "magnetic surfaces." The equilibrium is slab-like, the plasma parameters varying in R with little z dependence. The physical size is sufficient to justify the slab model: the radial extent is large compared with both gradient scale lengths and correlation lengths, and the vertical extent -- equivalent to the poloidal direction in a torus -- is very much larger than both wavelengths and correlation lengths. An additional experimental feature, enabled by the open helical field lines terminating on the top and bottom, is the ability to modify the natural plasma flows (v_Z) by applying a bias to an annular region of field lines, changing the E_r pattern and thus the ExB flows.

Although the Helimak plasma is low temperature (~10eV), low density (~$10^{10}/m^3$), and low B (0.1T), the dimensionless parameters are similar to those of the SOL in modern confinement devices. Experimentally, this enables extensive use of Langmuir probe diagnostics, including a unique new magnetically-baffled probe array that measures true plasma potential (vorticity, not floating potential), electron temperature fluctuations, and the local fluctuating E_Z required to infer the radial turbulence-driven fluxes of particles and thermal energy. For simulations, which are essential to model and understand this highly nonlinear system, it allows the use of the same codes developed for the SOL, but in a less complex geometry for exploration and validation.

The plasma has been fully characterized in terms of equilibrium density and electron temperature profiles, fluctuation levels of density, electron temperature, and true plasma potential (n,T,V), and radial turbulence-driven fluxes of particles and electron energy over a broad operating range of B_Z/B (affecting field line connection length and helical pitch), flow perturbations (amplitude and location of bias application), and a limited range of collisionality (changing the background neutral gas pressure). Collisionality is not an important effect; a factor of four increase merely decreases turbulent amplitudes slightly, implying that resistivity is not a driving force. Changing the helical pitch causes some quantitative variations, but varying the connection length from 10 m to 1 km does not alter the significant qualitative features. In addition to the aforementioned factors, the behavior varies with location on the equilibrium profile. The turbulence is uniformly of large amplitude in density, temperature, and potential, having a broad frequency spread with no distinct modes and short spatial correlation lengths, ≤0.05m compared with the 1m plasma dimensions. The behavior is otherwise complex. There is no consistent relation between the local values of $\Delta n/\langle n\rangle$, $\Delta T/\langle T\rangle$, and $\Delta V/\langle T\rangle$, as would be characteristic of normal modes. Although the interchange-unstable region includes most of the profile, the saturated amplitudes are not proportional to the local pressure gradient, and strong turbulence even extends across the stable region. The transport fluxes are equally complex. Although they are obviously limited by the turbulent amplitudes that enter the flux expression, the observations are more variable. The universal feature is that the PDF of transport events has a maximum at 0 flux. For locations where the flux approaches the maximum permitted by the turbulent amplitudes, the PDF is strongly skewed, whereas many instances of low net flux are seen with nearly symmetric PDFs.

The strongest and most consistent effects on turbulence and transport are produced by applying bias -- changing the self-organized equilibrium flow pattern $v_Z(R)$. As a first approximation, this is the "most unstable" state with the largest turbulent amplitudes and highest transport rates. Perturbing this state by biasing generally decreases turbulence amplitudes[1], sometimes by as much as 80%, and often reduces transport even more than implied by the turbulence reductions. The process is complicated because, although the bias application is well localized, the plasma adjusts itself to a new self-consistent equilibrium with changes generally extending well beyond the region directly biased.

These experiments have now provided an extensive characterization of the turbulence and transport from highly nonlinear interchange-type instabilities in a simple geometry. The observations suffice to exclude mechanisms seen in weaker turbulence -- flow shear, zonal flows, etc. -- as relevant, but appropriate nonlinear simulations will be necessary to understand the nonlinear physics governing these experiments and similar SOL behavior. This work has begun with encouraging results replicating some important features of the observations. A fully nonlinear two-fluid code has found turbulence reductions caused by biasing[2], and recent gyrokinetic simulations have fit the level of saturated turbulence for a case specifically matched to the parameters of one experiment.[3] We are developing the tools to understand the new physics of highly nonlinear plasma turbulence.

References

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