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Scaling of turbulent diffusion in the quasilinear resonance-broadening regime and beyond

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Quasilinear theory successfully models turbulent diffusion in a weakly turbulent plasma. We restrict ourselves to electrostatic turbulence. According to quasilinear theory, for low enough amplitudes, diffusion (in velocity-space) scales as $D \sim E^2$, where E is a typical amplitude of the turbulent electric field. For larger amplitudes, a wave can significantly exchange energy with particles over a larger range of velocities around its phase-velocity. The width of this range depends on diffusion itself. This phenomenon is successfully accounted for by resonance broadening theory.

However, for even larger amplitudes, particles are trapped for long durations in potential wells. They describe bounce trajectories, which are not accounted for by these theories. In terms of Kubo number $K = \tau_{ac}/\tau_b$, which is the ratio of a typical bounce time τ_b over the autocorrelation time of the turbulent electric field, $\tau_{ac} = \int_0^\infty \langle E(x,0)E(x,t)\rangle dt \,/\langle E^2\rangle$, quasilinear and resonance broadening theories are in principle limited [1] to a regime of $K < 1$. If E is large enough, $K \gg 1$, meaning that during a turbulence autocorrelation time, a particle typically bounces many times before the potential well loses or changes its structure.

Here we focus on a 1D homogeneous plasma with periodic boundary conditions, and a prescribed, random-phases, turbulent electric field of typical (root-mean-square) amplitude E, as a paradigm for more complex configurations. Our results are based on numerical simulations of trajectories of many test particles, which feel the electric field without affecting it. The self-consistent Vlasov-Poisson problem is left for future work. Compared to earlier works [2-3], the wave dispersion relations and turbulent power spectrums are more realistic. We analyze both cases of Langmuir waves (Bohm-Gross dispersion) and of ion-acoustic waves. The main conclusions stand for both types of waves.

The diffusion coefficient $D(v)$ is measured from the time evolution of the variance of velocities of particles initialized in a narrow neighborhood of v. Fig. 1 shows $D(v)$ for several values of Kubo number K. For $K < 0.1$, the simulations quantitatively recover quasilinear theory. The effect of resonance broadening becomes significant for $K > 10^{-2}$. Significant discrepancy is found for $K \sim 1$.

Fig. 2 shows how diffusion scales with the amplitude of turbulence [4]. For $K < 0.003$, $D \sim E^2$ as expected from quasilinear theory without resonance broadening. For $K > 0.1$, $D \sim E^{3/2}$, rather than $D \sim E$ as could be expected from a simple random walk model.

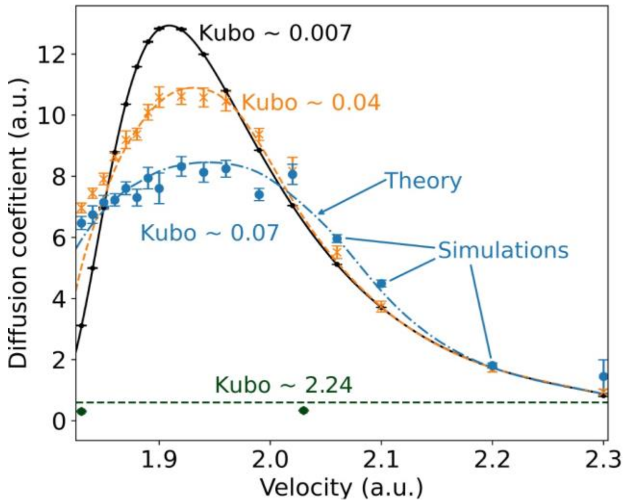

Figure 1. Diffusion coefficient, normalized to $\langle E^2\rangle$, for Langmuir turbulence and 4 values of Kubo number. Note that unnormalized D increases with increasing K., while, in the normalization of this graph, $D/\langle E^2\rangle$ decreases.

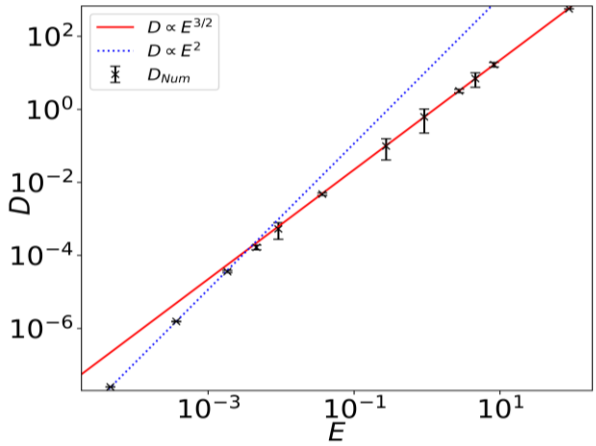

Figure 2. Diffusion coefficient D against the amplitude E of the turbulent electric field.

References

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