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Linear theory and chaos: breakthrough in the description of wave-particle interaction in plasmas

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Landau damping was discovered in 1946, but textbooks still give unprecise and sometimes wrong physical pictures of its physical nature. Quasilinear (QL) theory was derived in 1962, but a controversy is still unsettled about its validity in the saturation regime it was meant to describe. At a moment where the development of gyrokinetic codes is of paramount importance for the study of transport in magnetic fusion plasmas, it is necessary to clarify the nature of wave-particle interaction and to provide analytical tools enabling its rigorous description, at least for basic examples. This is done in a book describing a non Vlasovian approach to Langmuir wave-particle interaction published recently [1]. This approach relies upon a symmetrical description of the interaction of M>>1 Langmuir waves with N>>1 particles in a Hamiltonian setting originally derived for the cold beam-plasma instability [2].

The Landau and van Kampen theories are recovered with analytical tools not more difficult than the finite Fourier sum. In the linear regime, Landau damping or growth of a single wave with a rate γ_L turns out to correspond to the synchronization of particles with a velocity within $|\gamma_L|/k$ of the wave phase velocity; trapping plays no role at all, which rules out the surfer model to explain the Landau effect. The wave damping does not correspond to an eigenmode, but is the result of the phase mixing of many van Kampen modes. If the spectrum of Langmuir waves is broad, in the linear regime the Landau effect corresponds to the QL diffusion of particles.

In the nonlinear regime where the time of spreading due to diffusion is shorter than the wave growth time γ_L^{-1}, chaos is important and precludes the use of any “close to linear” technique. The description of chaotic diffusion is first tackled in the case of a prescribed spectrum of Langmuir waves. Two new techniques enable to prove rigorously that a QL diffusion occurs in the limit of a continuous spectrum (strong resonance overlap) [1,3]. The QL estimate in this limit is shown to be due to a cross-over between an initial non chaotic QL diffusion and a final chaotic diffusion which is not quasilinear by essence, but which is linked to a rigorous version of Dupree’s resonance broadening effect.

In the wave-particle self-consistent case a non rigorous version of the same two techniques enables the derivation of the QL equations in the saturation regime of the weak warm beam-plasma instability [1,3,4]. The calculation is made up of a few explicit steps which can be easily followed by a graduate student. This might help settling the QL controversy.

[1] Y. Elskens et D.F. Escande, Microscopic Dynamics of Plasmas and Chaos (IOP, Bristol, 2002).
[2] I.N. Onishchenko, A.R. Linetskii, N.G. Matsiborko, V.D. Shapiro, and V.I. Shevchenko, ZhETF Pis. Red. 12, 407 (1970) [JETP Lett. 12, 281 (1970)]; T.M. O'Neil, J.H. Winfrey, and J.H. Malmberg, Phys. Fluids 14, 1204 (1971); H.E. Mynick and A.N. Kaufman, Phys. Fluids 21, 653 (1978).
[3] D.F. Escande and Y. Elskens, Phys. Lett. A302, 110 (2002).
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