Nonlinear Consequences of Energetic Particle Instabilities

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The build-up of the energetic particle population in fusion plasmas is typically slow compared to the growth times of energetic-particle-driven instabilities. This feature draws special attention to nonlinear studies of unstable waves in the near-threshold regimes. The goal is to characterize the long-time behavior of the weakly dissipative waves and resonant particles in the presence of particle sources and sinks.

There are numerous experimental observations of energetic-particle-driven instabilities. In some cases the unstable modes grow to a level at which they cause enhanced transport and anomalous losses of the fast particles. In other cases, the losses are small but the modes exhibit an intricate nonlinear behavior: generation of sidebands, quasi-periodic bursts, change of the mode frequency in time, etc. This lecture presents a first-principles physics basis for understanding these phenomena. An important advantage of the near-threshold theory is its relative simplicity and universality. The evolution of unstable modes in this regime is governed by wave-particle interaction and collision-like relaxation process for resonant particles. These two factors determine whether the initial instability saturates or grows explosively, providing a seed for spontaneous formation of phase-space holes and clumps. A single weakly unstable mode is mostly benign in terms of fast particle losses since it only affects a relatively small resonant area of phase space. Global diffusion and strong losses are usually associated with multiple modes that can give rise to avalanche-type phenomena when nonlinear resonances overlap. The lecture combines description of nonlinear scenarios with a discussion of how the present theory responds to the experimental challenges.