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Mechanisms of Energetic-Particle Transport in Magnetically Confined Plasmas

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Super-thermal energetic particles (EP) are produced by RF heating, neutral-beam injection, fusion reactions, and (in the case of runaways) by parallel electric fields. This tutorial uses animations and examples drawn from both fusion and basic plasma experiments to illustrate physical mechanisms that cause cross-field transport of energetic particles. Because guiding-center drifts are proportional to energy, the EP orbits are necessarily large. Orbits are described by conserved constants of motion that define topological boundaries for different orbit types. Electric and magnetic field perturbations produced by instabilities can disrupt particle orbits, causing the constants of motion to change. A unifying theme of the tutorial is the importance of phase in wave-particle interaction. A distinction is made between field perturbations that resonate with an aspect of the orbital motion and those that do not. Resonance occurs when the wave phase returns to its initial value after an integer number of orbits. Resonant instabilities with unvarying wave-particle phase cause convective transport. Alternatively, multiple wave-particle resonances tend to decorrelate the phase, resulting in diffusive transport. Large orbits increase the number of important resonances and can cause stochasticity even for relatively small amplitude waves. In contrast, in the case of non-resonant perturbations, orbital phase averaging reduces transport. Large field perturbations introduce additional effects, including nonlinear resonances at fractional values of the orbital motion. For large non-resonant perturbations, phase-space island chains associated with the large orbits can overlap, inducing stochasticity. In summary, large orbits are a blessing and a curse: For non-resonant modes, orbit-averaging reduces transport but, for resonant transport, large orbits facilitate jumps across topological boundaries and enhance the number of resonances.