Formation of Weibel-mediated collisionless shocks: analytical model for symmetric colliding flows and numerical study of laser-driven shocks in overdense plasmas

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Collisionless shocks play a major role in powerful astrophysical objects (e.g., gamma-ray bursts, supernova remnants, pulsar winds, etc.), where they are thought to be responsible for nonthermal particle acceleration and radiation [1]. Numerical simulations have shown that, in the absence of an external magnetic field, these self-organizing structures originate from electromagnetic instabilities triggered by high-velocity colliding flows. These Weibel-like instabilities [2] are indeed capable of producing the magnetic turbulence required for both efficient scattering and Fermi-type acceleration [3,4]. Along with rapid advances in their theoretical understanding [5], intense effort is now underway to generate collisionless shocks in the laboratory using energetic lasers [6].

In a first part, we will present a predictive kinetic model of the nonlinear phase of the Weibel instability induced by two counterstreaming, symmetric and nonrelativistic ion beams. This self-consistent, fully analytical model allows us to follow the evolution of the beams' properties up to a stage close to complete isotropization and shock formation. Its predictions are supported by 2D and 3D particle-in-cell (PIC) simulations of the ion Weibel instability in uniform geometries, as well as shock-relevant non-uniform configurations. Moreover, they are found in correct agreement with a recent laser-driven plasma collision experiment [6].

In a second part, we will investigate the ability of relativistic-intensity laser pulses to induce Weibel instability-mediated shocks in overdense plasma targets, as first proposed in Ref. [7]. By means of 2D PIC simulations, we will demonstrate that, in contrast to the standard astrophysical scenario, the early-time magnetic fluctuations generated by the suprathermal electrons are strong enough to isotropize the target ions and, therefore, induce a collisionless electromagnetic shock. Analytical estimates of the shock formation time and threshold laser energy are derived and successfully compared to the simulation results.

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