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Ion acceleration in a high-intensity laser-driven collisionless shock

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Collisionless shock is a shock wave generated in a collisionless plasma, in which Coulomb collisions are negligible. Whereas the shock-front thickness of collisional shock is of the order of Coulomb mean-free-path (mfp), that of collionless shock is much smaller than the mfp, and wave-particle interactions and collective effects of electric and magnetic fields play essential roles in the shock formation. Collisionless shock is ubiquitous in space and astrophysical plasmas, such as Earth's bow shock and supernova remnant shocks, and is believed to be a source of cosmic rays. Thanks to the development of high-power lasers, a new method of studying high-energy astrophysics, such as the formation and evolution of collisionless shocks, in the laboratory, Laser Astrophysics, is emerging [1-3].

Intense laser-plasma interactions are an essential tool for the laboratory study of ion acceleration at a collisionless shock. With two-dimensional (2D) particle-in-cell (PIC) calculations of a multicomponent plasma we observe two electrostatic collisionless shocks at two distinct longitudinal positions when driven with a laser at normalized laser vector potential a0 that exceeds 10 [4,5]. These shocks, associated with protons and carbon ions, accelerate ions to different velocities in an expanding upstream with higher flux than in a single-component hydrogen or carbon plasma. This results from an electrostatic ion two-stream instability caused by differences in the charge-to-mass ratio of different ions.

Electrostatic two-stream instabilities play essential roles in an electrostatic collisionless shock formation. They are a key dissipation mechanism and result in ion heating and acceleration. 2D PIC simulations in a multicomponent plasma reveal excitation of a longitudinally propagating electrostatic instability due to a non-oscillating component of the electrostatic field in the upstream region of the shock, and generation of up- and down-shifted velocity components within the expanding-ion components [6]. A linear analysis of the instabilities for a C2H3Cl plasma using the 1D electrostatic plasma dispersion function, which includes electron and ion temperature effects, shows that the most unstable mode is the electrostatic ion-beam two-stream instability (IBTI), which is weakly dependent on the existence of electrons [6]. The IBTI is excited by velocity differences between the expanding protons and carbon-ion populations. There is an electrostatic electron-ion two-stream instability with a much smaller growth rate associated with a population of protons reflecting at the shock. The excitation of the fast-growing IBTI associated with laser-driven collisionless shock increases the brightness of a quasimonoenergetic ion beam.

Particle acceleration in collisionless shocks in multicomponent plasma are ubiquitous in space and astrophysics, and these calculations identify the possibility for studying these complex processes in the laboratory.

References

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