Plasma structure formation in relativistic and non-relativistic beam interactions with magnetized plasmas

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We systematically demonstrate various structure formation mechanisms arising from interactions between particle beams and magnetized plasmas, using a relativistic particle-in-cell (PIC) simulation code that incorporates radiation and other quantum effects in strong electromagnetic fields.

The PIC code was originally developed to model plasma–solid target interactions in positron production experiments with high-power lasers [1]. These interactions involve particle acceleration in the ablation plasma at the front side of the target and in the sheath electric field at the rear side. The code includes high-energy photon propagation within a multi-dimensional fluid description, where these photons serve as seeds for pair production. Bremsstrahlung and pair production in high-Z nuclear fields are modeled using a Monte Carlo method that links computational particles and photon fluids in phase space. The framework has been extended to simulate radiation and pair production in strong external electromagnetic fields [2]. These quantum electrodynamics (QED) processes are relevant to active astrophysical phenomena and particle dynamics under ultra-intense lasers. Unlike those occurring in nuclear fields, such QED processes in vacuum can potentially contribute to collisionless plasma dynamics and structure formation. The implementation of these mechanisms has been carefully benchmarked against prior laser–beam collision experiments and theoretical predictions [3].

The present beam–plasma interaction may be analogous to the interaction between the solar wind and objects of various scales [4,5], as the background magnetized plasma appears as an incoming flow in the beam rest frame. Moreover, the QED effects in vacuum, which are characterized by the field strength in the beam rest frame, become significant at higher beam energies under a given background magnetic field.

In the case of a non-relativistic beam smaller than the ion inertial length, we observe a magnetic wake structure associated with two-fluid dynamics [6], along with an electrostatic wake structure resulting from the Coulomb field surrounding the beam. The plasma structure evolves into a more complex configuration, featuring shocks, tail structures, and turbulence, as the beam size increases. In the relativistic regime, the wake structures in small-scale beams develop into an electrostatic bubble chain that trails the beam. The structures associated with larger-scale beams become more distinct, exhibiting a sharp, stable shock surface and an elongated tail. In the ultra-relativistic regime, the background magnetic field appears significantly stronger in the beam rest frame, and the resulting strong-field QED effects emerge during the interaction. High-energy photon emission is observed around specific plasma structures, such as the bubbles and the tail, in addition to primary photon emission from the beam electrons.

The magnetic field structures observed in the non-relativistic regime resemble those generated by the solar wind interacting with small-scale objects, such as whistler and magnetosonic wakes, and simplified magnetospheres with bow waves and magnetotails, which can be decomposed into fundamental linear and nonlinear plasma dynamics. This correspondence becomes particularly evident when we employ a quasi-neutral beam without surrounding electromagnetic fields. The bubble chains observed in small-scale relativistic beam interactions are reminiscent of wakefields in laser–plasma interactions. In the present context, these structures can be interpreted as relativistic extensions of the wake structures in small-scale magnetospheres.

We will present the transition mechanisms among these structural formations, along with the underlying fundamental plasma dynamics in relativistic and strong-field QED regimes.

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