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New mechanisms of high-current relativistic electron beam transport in plasmas

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The transport of high-current charged particle beams in plasma is a fundamental process that is relevant to many fields of physics, ranging from the microscopic plasma kinetics to astrophysics. However, so far the mechanism of such beam-plasma interaction is still not well understood due to the appearance of small time- and space-scale effects. Here we report a new secondary filamentation scenario on the kinetic electron scale related to the microscopic electron current filaments and that such process significantly affects the beam evolution in dense plasma. In this regime the electron beam evolves into layered short microelectron bunches when collisions are relatively weak. The phenomenon is attributed to a secondary instability, on the space- and timescales of the electron skin depth (tens of nanometers) and few femtoseconds of strong electrostatic modulation of the microelectron current filaments formed by Weibel-like instability of the original electron beam. In addition, we build an analytical model to describe the transport process of such micro electron filament in solid-density plasmas. Our analytical analysis on the amplitude, scale length, and excitation condition of the self-generated electrostatic fields is clearly validated by the simulations.

On the other hand, we show for the first time that when a high-current relativistic electron beam propagates into a porous foam target with randomly uneven density distribution, the electron beam can form pronounced branch patterns, presenting a completely new transport regime of high-current electron beam in plasmas. Such branch formation is attributed to the self-generated disordered electromagnetic fields related to the unevenness of background plasma, and is distinct from the current filamentation instability.

These new results on high-current electron beam transport in plasmas can potentially lead to novel applications, such as the ultrafast heating of materials, charged particle beam focusing, and the generation of bright radiation sources. In particular, branched flow of relativistic charged beams may also be a laboratory analogy of cosmic rays propagation in interstellar dust clouds.

Figure 1. Three-dimensional PIC simulation of a micro electron filament transport in solid-density plasmas.

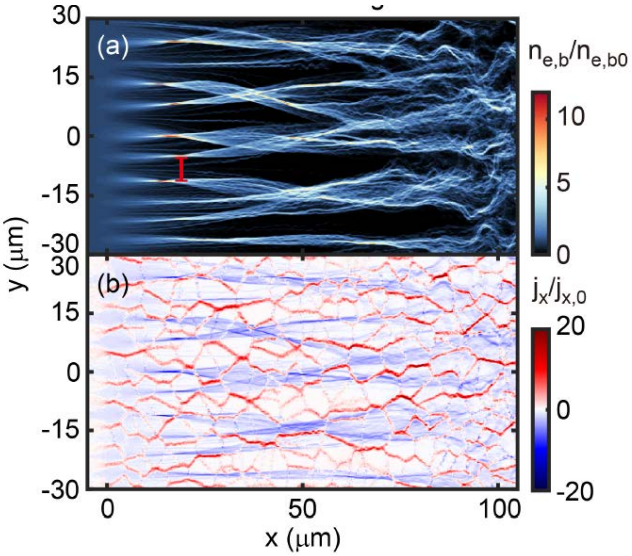

Figure 2. Branch pattern formation as high-energy-density relativistic electron beams propagate through the porous foam along the x-direction, where (a) is for the beam density distribution and (b) is for the current density distribution.

References

[1] R. Li, T. W. Huang, et al., "Nanoscale Electrostatic Modulation of Mega-Ampere Electron Current in Solid-Density Plasmas", Physical Review Letters 127, 245002 (2021)

[2] K. Jiang, T. W. Huang, et al., "Branched transport of high-energy-density relativistic electron beams in uneven plasmas" to be submitted.