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Stabilizing numerical electrostatic PIC instabilities for channel expansion simulations

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We have performed periodic, one-dimensional particle-in-cell (PIC) simulations to test the numerical stability of a variety of explicit energy-conserving PIC algorithms. When an optical-field-ionized (OFI) plasma column expands, it can create a radially propagating shock in the surrounding gas. Ionization of this shocked gas has enabled recent experiments to achieve low density (~10^{17} cm^{-3}) plasma channels with matched spot sizes on the order of $10 \backslash mu$m and attenuation lengths in excess of one meter [Picksley (2020), Shrock (2022)]. However, these experiments are operating on the edge of the validity of fluid approximations: the elastic cross section for hydrogen is approximately 10^{-19} m^2 which yields a mean free path of $10 \backslash mu$m at a gas density of 10^{18} cm^{-3}. Thus, creation of lower density plasma waveguides will require a careful study of the kinetic interactions between the expanding ions and the surrounding gas using PIC simulations.

Unfortunately, PIC suffers numerical instabilities when the Debye length is not resolved, and when the drift velocity of the plasma exceeds the thermal velocity. We present numerical measurements of the stability and noise for each of the considered methods, as well as analytic results for some stability conditions. We find that energy-conserving PIC algorithms are ideally suited for simulating plasma channel expansion, and that numerical instabilities do not arise in this region of parameter space.

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