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Title: Fully implicit algorithm for electrostatic PIC simulation of plasmas

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Classical particle-in-cell (PIC) algorithms employ an explicit approach (leap-frog) to advance Vlasov-Maxwell (or Vlasov-Poisson) system using particles coupled to a grid. Explicit PIC is subject to both temporal stability constraints (CFL-type) and spatial stability constraints (i.e., the grid size has to be comparable to the Debye length). In many situations of interest, these stringent stability conditions make it impractical to solve realistic multi-scale kinetic problems, even with the aid of modern super-computers. Implicit algorithms can avoid both spatial and temporal stability constraints, thus potentially being orders of magnitude more efficient than explicit PIC methods. However, due to the lack of efficient nonlinear solvers for the resulting system of fully implicit, nonlinearly coupled particle-field equations, these early implicit PIC studies employed algorithmic simplifications such as linearization and/or lagging, which led to accumulation of numerical error in long term simulations. As a consequence, significant self-heating/cooling were often observed in implicit simulations, especially when large timesteps were employed. The goal of this work is to demonstrate a fully implicit, nonlinear PIC algorithm using a Jacobian-Free-Newton-Krylov method on a one-dimensional electrostatic model [G. Chen, L. ChacÛn, D. C. Barnes, {\em J. Comput. Phys.} (2011)]. The formulation is based on the Vlasov-AmpËre formulation (rather than Vlasov-Poisson), because it allows an exact energy-conserving formulation. Exact local charge conservation is ensured by a novel particle mover strategy. While momentum is not exactly conserved, errors are kept small by an adaptive particle sub-stepping orbit integrator, which is instrumental to prevent particle tunneling (a deleterious effect for long-term accuracy). As a result, very large timesteps, constrained only by the dynamical time scale of interest, are possible without accuracy loss.