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An implicit, conservative, asymptotic-preserving electrostatic particle-in-cell algorithm for arbitrarily magnetized plasmas

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We propose a new electrostatic particle-in-cell algorithm able to use large timesteps compared to particle gyroperiod under a (to begin, uniform) large external magnetic field [1]. The algorithm extends earlier electrostatic fully implicit PIC implementations [2] with a new asymptotic- preserving (AP) particle-push scheme [3] that allows timesteps much larger than particle gyroperiods. In the large-timestep limit, the AP integrator preserves all the averaged particle drifts, while recovering particle full orbits with small timesteps. The scheme allows for a seamless, efficient treatment of particles in coexisting magnetized and unmagnetized regions, conserves energy and charge exactly, and does not spoil implicit solver performance. Key to the approach is the generalization of the particle substepping approach introduced in Ref. [2] to allow for orbit segments much larger than cell sizes without spoiling conservation properties. The uniform-magnetic-field assumption allows us to use the standard Crank-Nicolson (CN) update [2] without modification [3], which is a necessary preliminary step to demonstrate viability of the approach for more general magnetic field topologies (which will otherwise require the general algorithm proposed in Ref. [3]). We demonstrate by numerical experiment with several strongly magnetized problems (diocotron instability, modified two-stream instability, and drift-wave instability) that two orders of magnitude wall-clock-time speedups are possible vs. the standard fully implicit electrostatic PIC algorithm without sacrificing solution quality and while preserving strict charge and energy conservation.

[1] G. Chen and L. Chacón, "An implicit, conservative and asymptotic-preserving electrostatic particle-in-cell algorithm for arbitrarily magnetized plasmas in uniform magnetic fields,"J. Comput. Phys., submitted (2022)
[2] Chen, Guangye, Luis Chacón, and Daniel C. Barnes. "An energy-and charge-conserving, implicit, electrostatic particle-in-cell algorithm." Journal of Computational Physics 230.18 (2011): 7018-7036.
[3] Ricketson, Lee F., and Luis Chacón. "An energy-conserving and asymptotic-preserving charged-particle orbit implicit time integrator for arbitrary electromagnetic fields." Journal of Computational Physics 418 (2020): 109639.

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