

# **An implicit, energy conserving and asymptotic preserving full-orbit time-integrator for particle-in-cell schemes\***

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While the gyrokinetic approximation has been extremely successful in accelerating simulations of strongly magnetized plasmas, there is increasing interest in full-orbit simulation in key contexts in which the gyrokinetic ordering may break down. Motivated by this, we present an implicit time-stepping scheme for charged particle motion that recovers the gyrokinetic limit when stepping over the gyration scale while converging to the exact, full-orbit dynamics in the small time-step limit. Such a scheme provides, for the first time, a uniform multiscale treatment of strongly and weakly magnetized regimes without the need to resolve gyration scales. The scheme is designed to function as a piece of recent implicit particle-in-cell schemes – most notably, it preserves the exact total energy conservation enjoyed by those schemes.

The development proceeds in two stages. First, the classical Crank-Nicolson scheme is modified to capture all guiding-center drift motions when stepping over the gyration scale – while still conserving energy - by introducing an effective force that induces the magnetic drift for large time-steps. Second, to capture finite Larmor radius (FLR) effects, we introduce alternating large and small time-steps to sample equispaced gyrophases in the time-stepping process. The numerical time-scales introduced by the new scheme are analyzed and resulting bounds on time-step are derived. These bounds still permit stepping over the gyration time-scale by large factors in strongly magnetized contexts.

We conclude with several numerical tests on single particle motion in complex field configurations. The ability to step over the gyration time-scale and recover correct long-time dynamics is demonstrated - even in field configurations featuring structure on the gyroradius scale - along with the scheme's energy conservation properties.

\*Prepared by LLNL under Contract DE-AC52-07NA27344.