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Speed-limited Particle-in-cell for Fast Simulation of Slow-plasma Problems

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Speed-limited particle-in-cell simulation (SLPIC) is a method of increasing the time-step in a PIC simulation by slowing down the fastest particles in such a way that the end state of the simulation is unaffected, while significantly reducing the number of time-steps required to reach this end state. SLPIC is useful when the simulation requires a kinetic treatment of fast particles (e.g. electrons) while the physics of interest occurs on the time-scale of slow particles (e.g. ions).

In a SLPIC simulation, the true velocities and weights of particles are tracked, but particles are moved through the simulation at a lower speed specified by the "speed-limiting" function, and weighted to the grid with a reduced weight. By moving fast particles at a lower velocity, the time-step of the simulation can be significantly increased relative to that of a PIC simulation.

We show that for steady-state problems, SLPIC can achieve the same accuracy as PIC with a computational speed-up that is bounded by $\sqrt{\frac{m_{\text{ion}}}{m_{\text{electron}}}}$. For an argon-electron plasma sheath simulation, a speed-up factor of approximately 200 for reaching steady-state is demonstrated.

The trade-off of the large SLPIC time-step is an increased algorithmic complexity, since the equations of motion and grid-weighting are each modified by the velocity-dependent speed-limiting function. We discuss ways of dealing with these complexities and their effect on accuracy in certain cases, as well as the implications of choosing various speed-limiting functions.

To demonstrate the limits of SLPIC in dynamic problems we simulate the interaction of a wave with speed-limited particles and show that SLPIC is accurate only when the speed-limit is sufficiently higher than the wave velocity. This implies that SLPIC is useful for problems where the wave speed is slower than the fastest particles, for example, in ion-acoustic Landau damping.

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