Temporal resolution criterion for correctly simulating relativistic electron motion in a high-intensity laser field

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Particle-in-cell (PIC) codes are commonly used to simulate electron acceleration by a laser beam propagating though a plasma. We are particularly interested in the regime where the plasma density is significantly sub-critical. In this case, a sufficiently long laser beam can generate energetic electrons by directly accelerating them in the forward direction. Electron energy can be further enhanced with the help of static transverse and longitudinal electric fields [1,2,3]. How should one choose the spatial resolution and the time step in this regime to accurately determine the electron energy gain? We propose using the dynamics of a single free electron irradiated by a high-intensity plane electromagnetic wave as a test problem for evaluating the performance of a PIC code. Using this test problem, we show that the numerical accuracy deteriorates with the increase of wave amplitude $a_0$ for a fixed time-step. At first this appears counterintuitive, since the frequency of electron oscillations decreases with $a_0$ due to the increased longitudinal $\gamma$-factor and the electron trajectory should be better resolved. Motivated by this result, we derive a criterion that must be considered when simulating electron acceleration by a high amplitude electromagnetic wave in an under-dense plasma. We show that the electron dynamics can be correctly reproduced only if the time-step is sufficiently small to resolve the electron motion near stopping points along the trajectory. This condition requires that the time-step in the simulation is significantly less than $1/\omega a_0$, where $\omega$ is the wave frequency [4]. We thus propose adaptive electron sub-cycling as an efficient remedy. The idea is to reduce the time step for a given electron when the acceleration can no longer be correctly reproduced using the original time step. Our results show that the sub-cycling allows us to achieve a dramatic increase in accuracy with only a modest increase in the total number of time steps [4].