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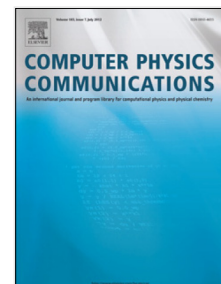
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A spectral, quasi-cylindrical and dispersion-free Particle-In-Cell algorithm

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Abstract

We propose a spectral Particle-In-Cell (PIC) algorithm that is based on the combination of a Hankel transform and a Fourier transform. For physical problems that have close-to-cylindrical symmetry, this algorithm can be much faster than full 3D PIC algorithms. In addition, unlike standard finite-difference PIC codes, the proposed algorithm is free of spurious numerical dispersion, in vacuum. This algorithm is benchmarked in several situations that are of interest for laser-plasma interactions. These benchmarks show that it avoids a number of numerical artifacts, that would otherwise affect the physics in a standard PIC algorithm – including the zero-order numerical Cherenkov effect.

Keywords: particle-in-cell, pseudo-spectral, Hankel transform, cylindrical geometry

Introduction

Particle-In-Cell (PIC) algorithms [1, 2] are extensively used in several areas of physics, including the study of astrophysical plasmas, fusion plasmas, laser-plasma interactions and accelerator physics. Yet, despite their wide use, PIC algorithms can be very computationally demanding, especially in three-dimensions, and are still subject to a range of numerical artifacts. These shortcomings can be particularly significant when simulating accelerated particle beams, or laser-plasma interactions (such as laser-wakefield acceleration) for two reasons:

- these systems often have close-to-cylindrical symmetry (e.g. particle beams and laser pulses are often cylindrically symmetric). This prevents the use of 2D Cartesian or 2D cylindrical PIC algorithms (which are only well-suited for slab-like and azimuthal symmetry), and is instead often dealt with by using 3D Cartesian PIC algorithms, which can be very computationally expensive;
- the physical objects of interest (e.g. the laser, or the accelerated particle beam) often propagate close to the speed of light. This makes them very sensitive to *spurious numerical dispersion*, i.e. the fact that the electromagnetic waves do not propagate exactly at the physical speed of light in a standard PIC code, but travel instead at a spuriously-altered, resolution-dependent velocity. In the above-mentioned cases, spurious numerical dispersion can lead to substantial numerical artifacts which can mask or disrupt the physics at stake in the simulation. This includes, for instance, numerical Cherenkov effects in general [3], but also more specific artifacts, such as e.g. the erroneous prediction of the dephasing length in laser-wakefield acceleration [4].

Yet several modifications can be made to the PIC algorithm, in order to mitigate these difficulties and increase the speed and accuracy of the simulations in these physical situations:

- one of these modifications is the development of cylindrical PIC algorithms with azimuthal Fourier decomposition [5, 6, 7] of the electromagnetic field components (sometimes referred to as *quasi-3D* algorithms, or as *quasi-cylindrical* algorithms as we do here). By taking into account the symmetry of the system, these algorithms can typically reduce the cost of the simulation to a few times that of a 2D Cartesian simulation, instead of that of a full 3D Cartesian simulation. Moreover, unlike 2D Cartesian algorithms, these algorithms are well adapted to close-to-cylindrical physical systems and can accurately capture physical effects that are intrinsically 3D (such as e.g. the non-linear self-focusing of an intense laser in a plasma [8]);

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