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JefiPIC: A 3-D Full Electromagnetic Particle-in-Cell Simulator Based on Jefimenko's Equations on GPU

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Abstract. This paper presents a novel 3-D full electromagnetic particle-in-cell (PIC) code called JefiPIC, which uses Jefimenko's equations as the electromagnetic (EM) field solver through a full-space integration method. Leveraging the power of state-of-the-art graphic processing units (GPUs), we have made the challenging integral task of PIC simulations achievable. Our proposed code offers several advantages by utilizing the integral method. Firstly, it offers a natural solution for modeling non-neutral plasmas without the need for pre-processing such as solving Poisson's equation. Secondly, it eliminates the requirement for designing elaborate boundary layers to absorb fields and particles. Thirdly, it maintains the stability of the plasma simulation regardless of the time step chosen. Lastly, it does not require strict charge-conservation particle-to-grid apportionment techniques or electric field divergence amendment algorithms, which are commonly used in finite-difference time-domain (FDTD)-based PIC simulations. To validate the accuracy and advantages of our code, we compared the evolutions of particles and fields in different plasma systems simulated by three other codes. Our results demonstrate that the combination of Jefimenko's equations and the PIC method can produce accurate particle distributions and EM fields in open-boundary plasma systems. Additionally, our code is able to accomplish these computations within an acceptable execution time. This study highlights the effectiveness and efficiency of JefiPIC, showing its potential for advancing plasma simulations.

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Key words: Particle-in-cell, Jefimenko's equation, plasma simulation, integral method, GPU.

1 Introduction

1.1 Background

The particle-in-cell (PIC) method is a commonly used tool in plasma physics. It utilizes macro-particles to describe charged particles in similar phase space states and model the evolution of the particle distribution and electromagnetic field. This method was initially proposed by Dawson in the 1960s [1] to study the Langmuir wave in 1-D electrostatic plasma. Later, Langdon and Birdsall improved the PIC model by incorporating finite-size particles [2] or particle clouds [3], which solved the issue of Coulomb collision between particles. Marder [4] and Villasenor [5] addressed the electric field divergence error in the current-driven method. In the last decade, the teams from P. Gibbon and A.J. Christlieb have separately established the integral-method based PIC through solving the vector and scalar potential functions, which can be employed in electrostatic, magneto-static, and electromagnetic problems and has expanded the study in grid-free plasma simulation [6–10]. Currently, PIC is used across various fields, including simulating controlled/laser thermonuclear fusion [11, 12], studying nuclear explosions [13–15] and space physics effects [16], and designing vacuum electronic devices [17–19].

The PIC method offers an intuitive representation of charged particles, making it easier for researchers to analyze simulated phenomena and data. As a result, numerous commercial software and open-source PIC codes have emerged for decades, including but not limited to Smilei [20], PIConGPU [22], Warpx [21], UNIPIC [23], and EPOCH [12, 24].

The PIC model comprises two primary components. The first part involves updating the dynamics of EM fields according to Maxwell's equations,

$$\nabla\times\frac{\mathbf{B}}{\mu}=\varepsilon\frac{\partial\mathbf{E}}{\partial t}+\mathbf{J}, \tag{1.1}$$

$$\nabla\times\mathbf{E}=-\frac{\partial\mathbf{B}}{\partial t}, \tag{1.2}$$

$$\nabla\cdot\mathbf{E}=\frac{\rho}{\varepsilon}, \tag{1.3}$$

$$\nabla\cdot\mathbf{B}=0, \tag{1.4}$$

where $\mathbf{E}$ and $\mathbf{B}$ represent electric and magnetic fields, ε and μ denote the permittivity and permeability of the medium, ρ and $\mathbf{J}$ are the electric charge density and electric current density.

The second part involves updating the positions and velocities of macro-particles us-