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Henri Vincenti, Jean-Luc Vay

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Ultrahigh-order Maxwell solver with extreme scalability for electromagnetic PIC simulations of plasmas.

Henri Vincenti\textsuperscript{1a,b,*}, Jean-Luc Vay\textsuperscript{2b}

\textsuperscript{1}LIDYL, CEA, CNRS, Universit\`e Paris-Saclay, CEA Saclay, 91 191 Gif-sur-Yvette, France 
\textsuperscript{2}Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

The advent of massively parallel supercomputers, with their distributed-memory technology using many processing units, has favored the development of highly-scalable local low-order solvers at the expense of harder-to-scale global very high-order spectral methods. Indeed, FFT-based methods, which were very popular on shared memory computers, have been largely replaced by finite-difference (FD) methods for the solution of many problems, including plasmas simulations with electromagnetic Particle-In-Cell methods. For some problems, such as the modeling of so-called “plasma mirrors” for the generation of high-energy particles and ultra-short radiations, we have shown that the inaccuracies of standard FD-based PIC methods prevent the modeling on present supercomputers at sufficient accuracy. We demonstrate here that a new method, based on the use of local FFTs, enables ultrahigh-order accuracy with unprecedented scalability, and thus for the first time the accurate modeling of plasma mirrors in 3D.

Keywords: Electromagnetic Particle-In-Cell method; Massively parallel pseudo-spectral solvers; Relativistic plasma mirrors; Pseudo-Spectral Analytical Time Domain solver; Finite-Difference Time-Domain solver

Introduction

Challenges in the modeling of Ultra-High Intensity (UHI) physics

The advent of high power petawatt (PW) femtosecond lasers has paved the way to a new, promising but still largely unexplored branch of physics called Ultra-High Intensity (UHI) physics [1]. Once such a laser is focused on a solid target, the laser intensity can reach values as large as $10^{22}\text{W/cm}^2$, for which matter is fully ionized and turns into a “plasma mirror” that reflects the incident light [2, 3] (See Fig. 1).

The corresponding laser electric field at focus is so high, that “plasma mirror” particles (electrons and ions) get accelerated to relativistic velocities upon reflection of the laser on its surface. A whole range of compact “tabletop” sources of high-energy particles (electrons, protons, highly charged ions) and radiations ranging from X-rays to $\gamma$-rays may thus be produced from the interaction between this plasma mirror and the ultra-intense laser field at focus [3, 4, 5, 8].

The success of PW laser facilities presently under construction worldwide, which aim at understanding and controlling these promising particle and light sources for future application experiments [9, 10, 11], will rely on the strong coupling between experiments and large-scale simulations with Particle-In-Cell (PIC) codes. Nevertheless, standard PIC codes currently in use partly fail to accurately describe most of UHI laser-plasma interaction regimes because the finite-difference time domain (FDTD) Maxwell solver produces strong instabilities and noise when the accelerated particles move at relativistic velocities [12, 13] or when the produced short-wavelength radiations span broad emission angles and frequencies [14]. With standard PIC codes, the mitigation of these instabilities often requires spatial and temporal resolutions that are so high that they are not practical for realistic 3D modeling on current petascale supercomputers and, it is projected, even on upcoming exascale machines.

Goal and outline of the paper

To address this challenge, the solution that we propose here is to use highly precise pseudo-spectral methods to solve Maxwell’s equations. Despite their high accuracy, legacy pseudo-spectral methods employing global Fast Fourier Transforms (FFT) on the whole simulation domain have hardly been used so far in large-scale 2D/3D simulations due to their difficulty to efficiently scale beyond 10,000s of cores [15, 16], which is not enough to take advantage of the largest supercomputers required for 3D modeling.

To break this barrier a pioneering grid decomposition technique was recently proposed for pseudo-spectral FFT-based electromagnetic solvers [17]. The new technique was first validated by an extensive analytical work [18] and then implemented in our PIC code Warp+PXR.

In this paper, we will first demonstrate that the new technique enables, for the first time, the scaling of pseudo-spectral solvers on up to a million cores. We will then compare the speedup brought by our pseudo-spectral solvers against FDTD solvers in terms of time-to-solution, on a 3D simulation of relativistic plasma mirrors.
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