Relativistic particles-in-cell code SUR/MP for laser-plasma interaction

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Abstract. The relativistic particles-in-cell code SUR/MP for kinetic simulation laser-plasma interaction is presented. The basic feature of this code is asynchronous parallelization is proposed. The modify PIC algorithms used in SUR/MP considered. The test of scalability in high performance calculations is presented. The result of parallel simulation of plasma channel formation by sequence of relativistic pulses is presented.

1 Introduction

The study of plasma dynamics interacting with relativistic and short laser pulses is a very important for recent progress. This topic problems has wide range nonlinear processes under relativistic conditions [8]. Experimentally highly nonlinear relativistic plasma conditions is achieved with subpicosecond and femtosecond muftyterrawatt and pettwatt laser pulses of up to $10^{18}$ W·cm$^{-2}$. Particles energies reached in ultraintense laser-plasma experiments are highly relativistic. In this condition the role of numerical experiment by kinetic simulation is very increased. The parallel relativistic 3D3V PIC-code SUR/MP has been developed for numerical modeling of interaction process of plasma with relativistic laser pulse. The model based on the numerical solution of self-consistent Vlasov-Maxwell equations by particles-in-cell method [1, 7]. The code allows to calculate propagation of relativistic laser pulses with parameters corresponds to modern devices through under-critical and over-critical plasma, as well as the influence of such a pulses to the dense inhomogeneous plasma layer.

2 Numerical algorithms

The collisionless plasma described in framework Vlasov-Maxwell self-consistent equations set:

$$\frac{\partial f_{i,e}}{\partial t} + \mathbf{V} \cdot \frac{\partial f_{i,e}}{\partial \mathbf{r}} + e_{i,e} \left( \mathbf{E} + \frac{1}{c} [\mathbf{V} \times \mathbf{B}] \right) \frac{\partial f_{i,e}}{\partial \mathbf{p}} = 0$$

(1)

$$\frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} = -\nabla \times \mathbf{E}, \quad \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{B} - \frac{4\pi}{c} \mathbf{j}$$

(2)

$$\nabla \cdot \mathbf{E} = 4\pi \rho, \quad \nabla \cdot \mathbf{B} = 0.$$ Here $f_i$ and $f_e$ are distributions functions of plasma particles species. This distribution functions is $f(\mathbf{r}, \mathbf{p}, t) \mathbf{V} = \frac{\mathbf{p}}{m} \sqrt{1 + p^2/(mc^2)}$ particles velocities. Self-consistent electromagnetic fields $\mathbf{E}(\mathbf{r}, t)$ $\mathbf{B}(\mathbf{r}, t)$ concern with $\rho$ and $\mathbf{j}$ are charge and current density:

$$\rho(\mathbf{r}, t) = \sum_\alpha e_\alpha \int f_\alpha d\mathbf{p}, \quad \mathbf{j}(\mathbf{r}, t) = \sum_\alpha e_\alpha \int \mathbf{V} f_\alpha d\mathbf{p}$$

(3)
The current and charge density needed for Maxwell equations is obtained from Vlasov equation. This equation is integrated along particles trajectories. In particles-in-cell simulation for this aim the distribution function is approximated by:

\[
f(r, p, t) = \sum_\alpha \Lambda(r, r_\alpha(t)) \delta(p - p_\alpha(t))
\]

here \(\alpha\) — particle number and \(\Lambda(r, r_\alpha(t))\) — influence function which described weighted method of particles in grid. The influence function with new minimal form-factor \(1 \times 1 \times 1\) is implemented in the SUR/MP code. This function is: \(\Lambda(x, y, z) = \Lambda(x) \times \Lambda(y) \times \Lambda(z),\) here \(\Lambda_{x/y/z} = 0.5 \times (1 + \cos(\pi x/y/z))\) [3]. This very smooth form-factor is decreased numerical noise. The particle motion relativistic equations:

\[
\frac{d\vec{r}_\alpha}{dt} = \vec{V}_\alpha \quad \frac{d\vec{p}_\alpha}{dt} = e_\alpha \left( \vec{E} + \vec{V}_\alpha \times \vec{B} \right)
\]

here \(\vec{V}_\alpha = (\vec{p}_\alpha/m_\alpha)/\sqrt{1 + \frac{\vec{p}_\alpha^2}{(m_\alpha c)^2}}\). The time step of main algorithm of particles-in-cell method is depicted on Fig.1. Here presented follows algorithms:

- \{\vec{J} \rightarrow (\vec{E}, \vec{B})\} — Maxwell equations solving (2),
- \{(\vec{E}, \vec{B}) \rightarrow (\vec{U}E, \vec{U}B)\} — grid interpolated fields calculation \((\vec{U}E, \vec{U}B)\) and calculation of forces affected on particles
- \{(\vec{U}E, \vec{U}B) \rightarrow (\vec{p}, \vec{r})\} — solution of particles motion equations (5) and calculation of particles current contribution
- \{\vec{U}J \rightarrow \vec{J}\} — particles current contribution interpolation \(\vec{U}J\) and grid currents \(\vec{J}\).

3 Asyncronical parallelization and scalability

The complexity of kinetic collisionless plasma simulation escribed Vlasov-Maxwell set requires great calculations. A cure for this difficulty is to apply parallel supercomputers. The traditional synchronous parallelization methods (Domain Decomposition) give not desirable performance increasement because of “burtle neck” problem. This problem concerned with nonuniform loading of some processors. The nonuniform loading is very usual problem in particles-in-cell simulations. For solution this problem we proposed
Figure 2: The scalability of SUR/MP code

Figure 3: Plasma channel formation, $n_0 = 0.2025 n_{cr}$, $t\omega_0 = 800$
new algorithm for asynchronous parallelization that named local space-time decomposition (LSTD) method implemented in SUR/MP code. This method do not required synchronization on each time step. This method is based on finitness of spatio-temporal domain dependence of dynamical values due to the light velocity finitness. The scheme of the algoritm LSTD is presented as a pyramid of dependences wich is based on the Fox’s wall formalism [2]. The meausurement of scalability is presented on Fig.2.

The result of parallel simulation of plasma chanal formation [2, 6] in underdense plasma is presented on Fig.3. The simulation results of laser pulse interaction with overdense plasma and accomplished phenomena such as fast electron beam generation and filament instability is presented in [4, 5].

4 Conclusion

The accelerated algoritms of particles-in-cell method is described. The local space-time decomposition method for asynchronical parallelization of kinetic simulation is presented. This method is suitable for avoiding of buttle-neck phenomenon. With the help of code SUR/MP investigated large number of processes of interaction between underdense and overdense plasma.

This work partly supported by Russian Foundation for Basic Research, grants N 02-01-01004, by Department of Mathematical Sciences RAS, program of basic research, 2003.

References


