Full Particle Simulation of the Plasma Sheet Using Adaptive Mesh Refinement (AMR) Technique

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It is widely believed that magnetic reconection plays an important role in the magnetospheric substorm and the solar flare. However, physical processes around the diffusion region are not well understood. Recently, it has been suggested that multi-scale coupling process should be important in the reconnection triggering and the anomalous plasma heating and acceleration around the diffusion region. Now, it is necessary to conduct a self-consistent large-scale simulation including phenomena with various scales to describe multi-scale coupling. However, a realization of such a simulation with an ordinary PIC technique is still difficult because electron-scale phenomena are very localized in ion-scale or MHD-scale system.

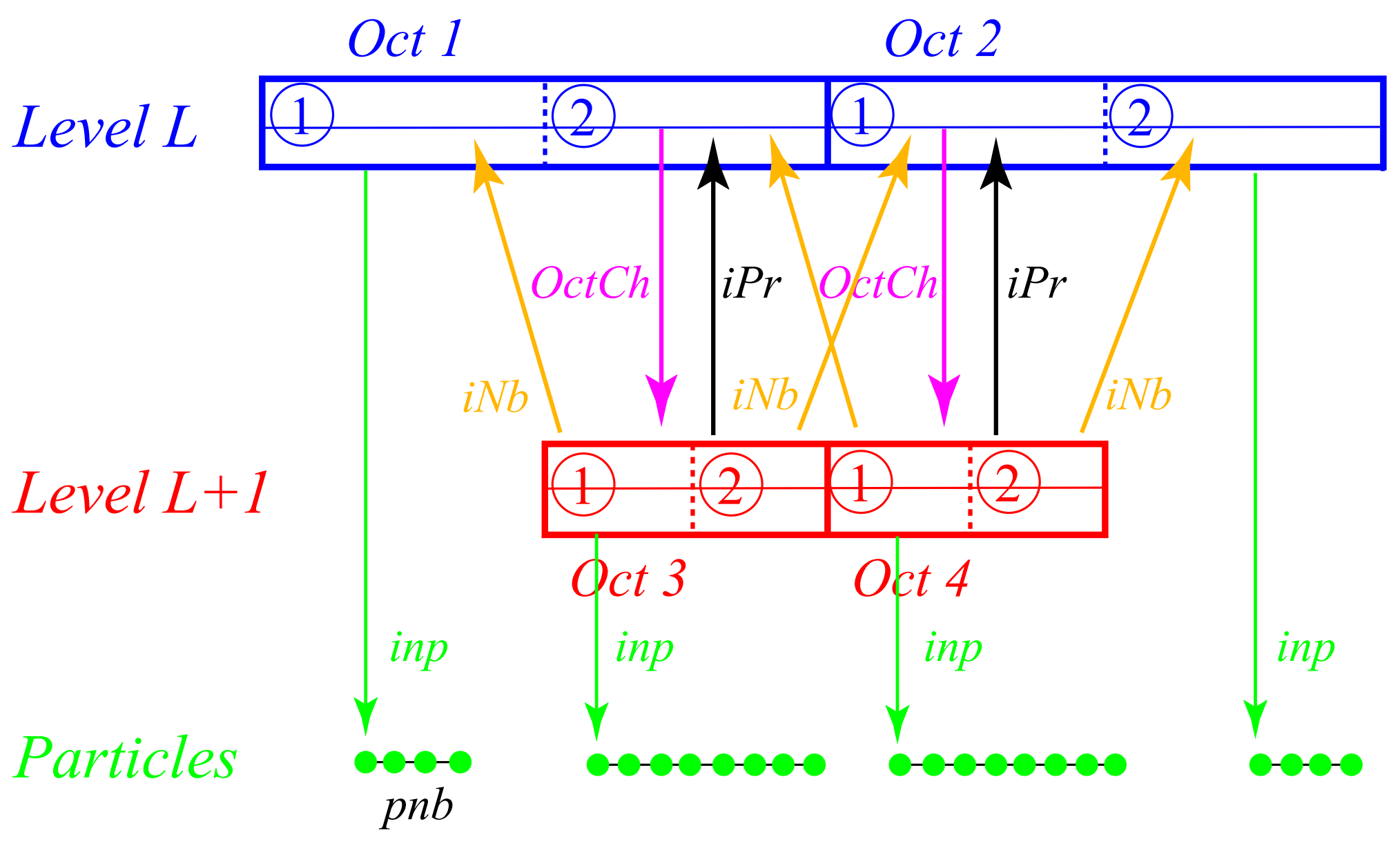
To overcome this difficulty, we have made a new 2-1/2 dimensional electromagnetic particle code with adaptive mesh refinement (AMR) technique. The AMR technique dynamically subdivides the cells that satisfy a certain refinement criterion, which is defined by local electron Debye length and electron flow velocity in the present case, and it is quite effective to achieve high-resolution simulations such as those around the X-type neutral line.

In this paper, we show our recent results of test simulations and preliminary results on the time developing of the Harris plasma sheet using the newly developed electromagnetic full-particle code with AMR technique.

AMR Techique used in Electromagnetic Particle Code

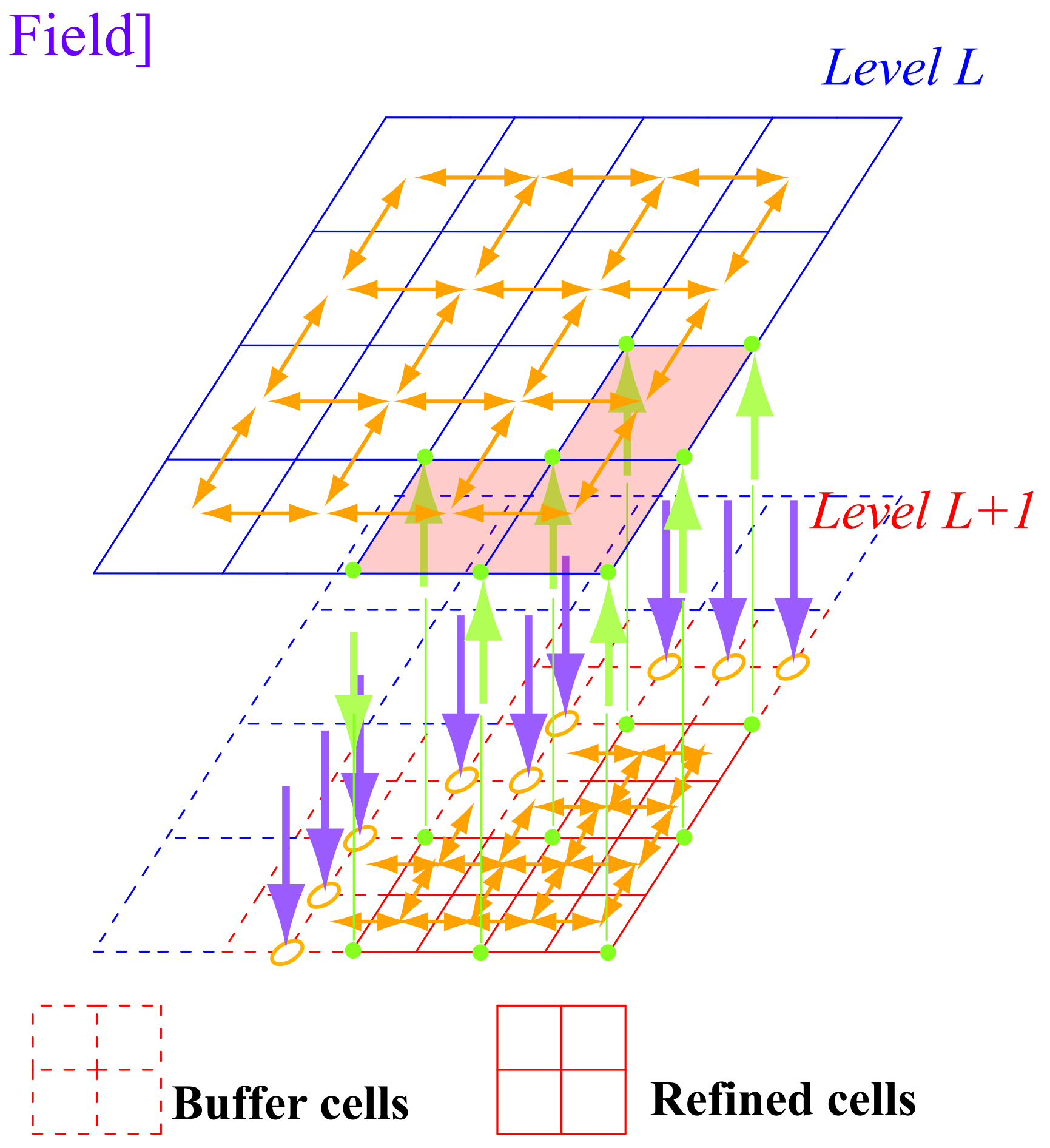
[Data Structure]

In order to realize an effective high-resolution simulation, the AMR technique subdivides only cells that satisfy a refinement criterion and add data sets for finer cells (with higher level) onto the uniform base cells (with the lowest level) hierarchically. The data structure that we use to organize the hierarchical cell structure is similar to the implemented fully threaded tree structure [Khokhlov, 1998]. Each cell is needed to access the parent, child, and neighboring cells. In our code, we group four cells togather that have a same parent cell in order to save memory for pointers and facilitate parallel computing. We call this group an oct (after an octet in the case of a cubic cell). Each cell has a pointer to the child oct (***OctCh***). Each oct has pointers to the parent cell (***iPr***), the parent cells of neghboring octs (***iNb***), and a representative particle belonging to the oct (***inp***). Each particle has a pointer to any other particle in the same octs, which leads to a beaded structure of particles.



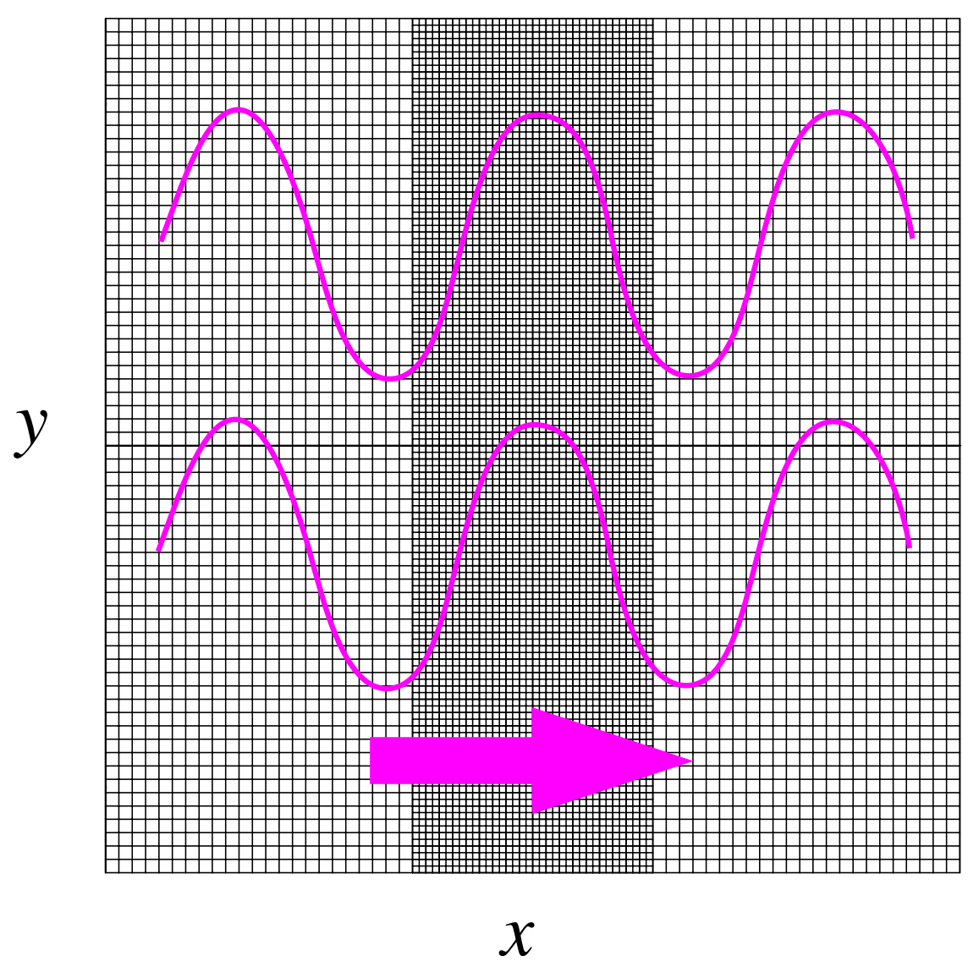
[Calculations of Electromagnetic Field]

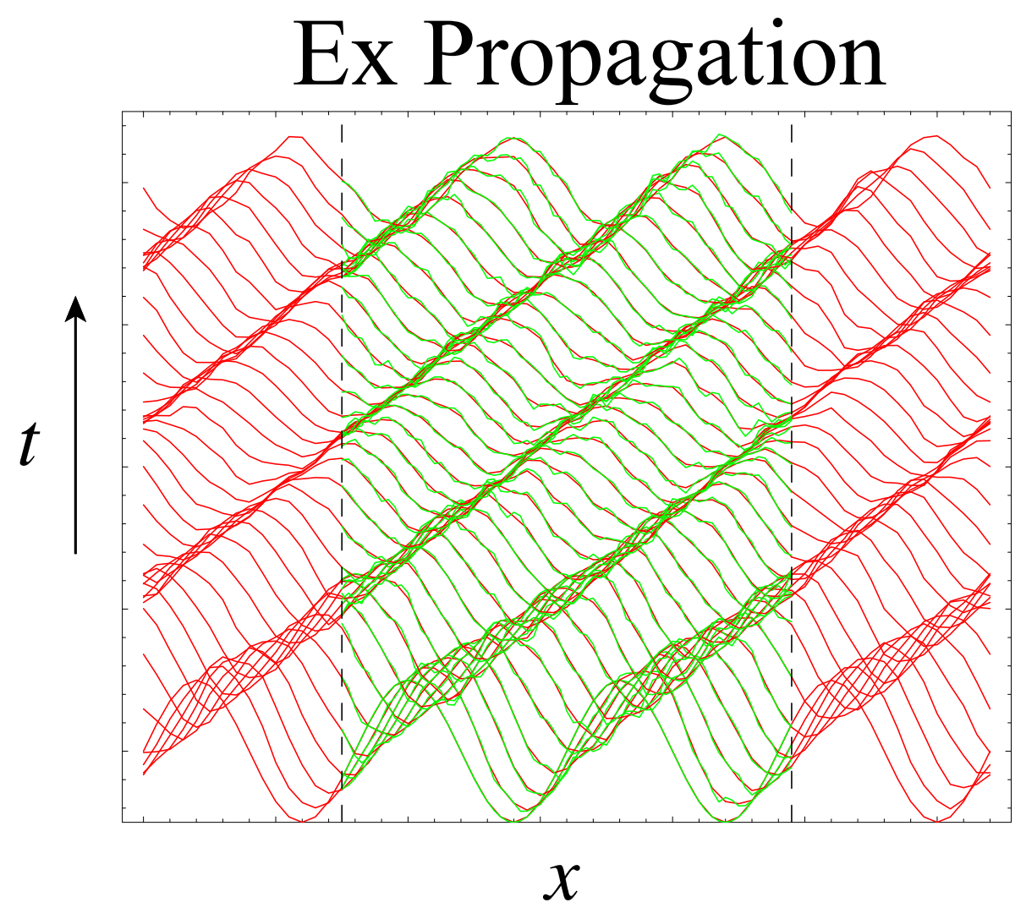
In addition to the above refined cells that satisfy the refinement criterion, we also split the buffer cells that are adjacent to the refined cells. Calculations of electromagnetic field are performed first on the coarsest cells, which are the root cells in the hierarchical structure. The solutions are projected onto the buffer cells in the next level cells as their boundary conditions. Then the elecromagnetic field is calculated on the cells with this level. This process is recursively repeated to reach the dynamic range level. Eventually the solutions in each cell are replaced by those in the finest cells after proper smoothing operations to avoid the aliasing.



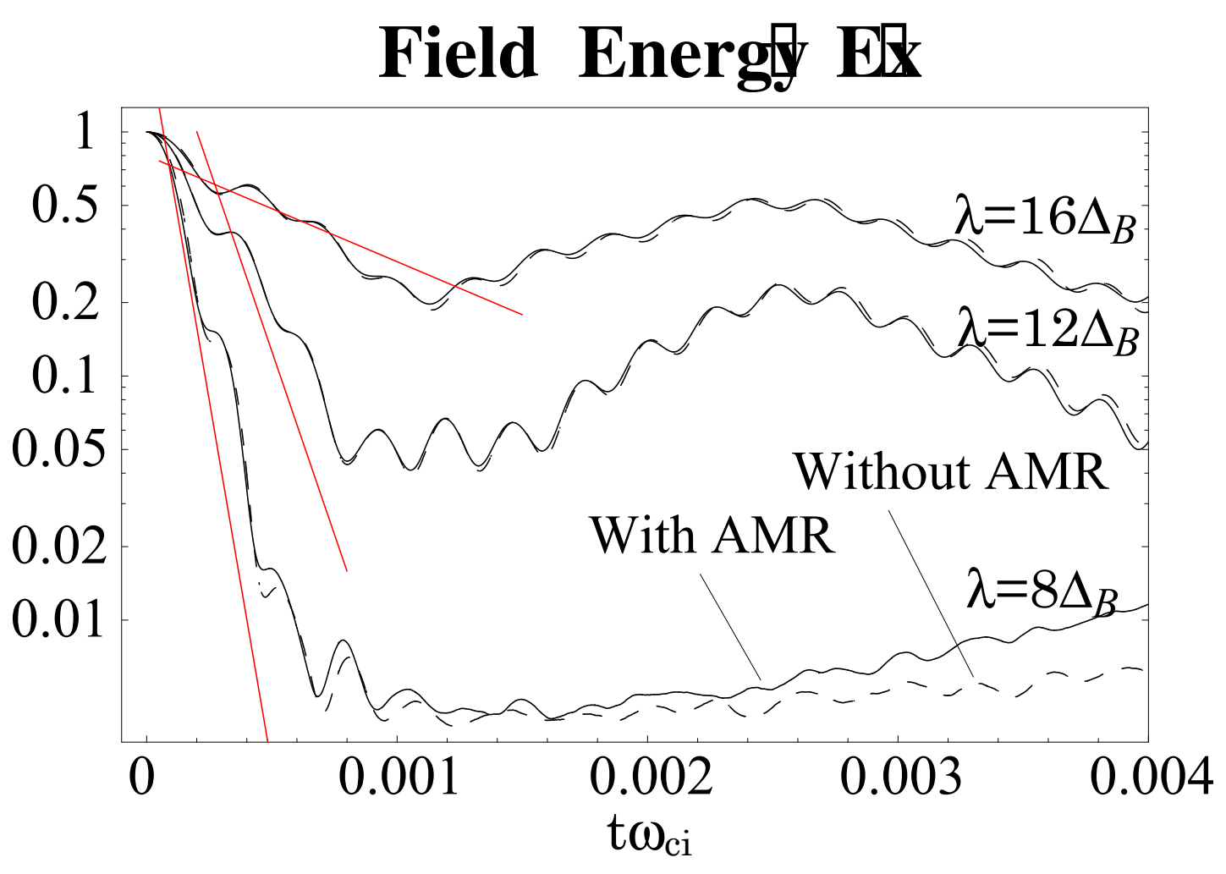
Test Simulations

Our code is checked against the Landau damping of the Langmuir waves that propagate across the regions with different size of cells. We find the Langmuir waves propagate properly across the boundaries, that is, neither remarkable noise nor wave reflection are shown in the boundaries.





The theoretical profiles deduced from the linear analysis of the Landau resonance are plotted in red lines. The simulation result provides a good fit to the theoretical profile. We also compare the results using the AMR technique with those without the AMR. We find 'With AMR' run is in good agreement with 'Without AMR' run, which indicates the application of the AMR technique to the ordinary PIC code is successful.



Summary

We have developed a new electromagnetic full particle code with the AMR technique, which is able to increase a spatial resolution dynamically by subdividing cells that satisfy a refinement criterion.

The simulations of the Landau damping and Harris-type plasma sheet indicate that the AMR technique is successfully applied to the ordinary PIC code and high-resolution simulations are effectively realized.

We are now parallelizing our code and will achieve a particle simulation with the spacial dynamic range of 10^4 to 10^5, which enables us to perform a global simulation including multi scales from the electron scale to the MHD scale.

Simulation Results of the Plasma Sheet

We have performed simulations of the plasma sheet using our AMR code. We adopt the Harris current sheet as an initial condition. The initial parameters are as follows;

$$m_i/m_e = 100,\ T_{i,ps}/T_{e,ps} = 8.0,\ c/v_{e,th} = 3.3,\ \lambda = 0.5\ \lambda_i,$$

4.1×10^6 particles for each species.

The initial magnetic fields are given by,

$$Bx(x,z) = -B_0 \tanh(z/\lambda) - 2\delta/\lambda \cos(2\pi x/L_x)\mathrm{sech}^2(z/\lambda)\tanh(z/\lambda)$$

$$Bz(x,z) = 2\pi\delta/L_x \sin(2\pi x/L_x)\mathrm{sech}^2(z/\lambda)$$

$$\delta = 0.02\ B_0\lambda i.$$

System size is $L_x \times L_z = 20.5\ \lambda_i \times 41.0\ \lambda_i$.

Boundary conditions are periodic boundaries in x and conductive walls in z.

Grid spacing is $\Delta_B = 0.32\ \lambda_i$ in the base layer and $\Delta_D = 0.02\ \lambda_i$ in the dynamic range layer. Time step is $\Delta t = 0.0016\ \omega_{ci}^{-1}$, which is the same in all layers.

The refinement criterion is simply defined by the local electron Debye length and electron flow velocity as

$$\lambda_{De} < \Delta < 2\lambda_{De}$$

or

$$V_e > 1.8\ V_A$$

This condition must be satisfied in all cells.

The most significant advantage of the AMR technique is to effectively reduce the number of cells in the simulation box. In the case of plasma particle simulations, the AMR technique is also useful to reduce the number of background particles, which is needed to suppress the numerical noise that arises where the number of particles par cell is small.

	Without AMR	With AMR	Ratio
Cells	2.1×10^6	5.0×10^4	42
Particles	$> 2.1 \times 10^7$	4.1×10^6	5

We confirmed the cells that satisfy the refinement criteria are dynamically and adequately divided in our code . We realized effectively high-resolution simulations of the plasma sheet.