Electromagnetic Particle Code With Adaptive Mesh Refinement Technique: Application to the Plasma Sheet

K. Fujimoto* and S. Machida
Department of Geophysics, Graduate School of Science, Kyoto University
(* E-mail : keizo@kugi.kyoto-u.ac.jp)

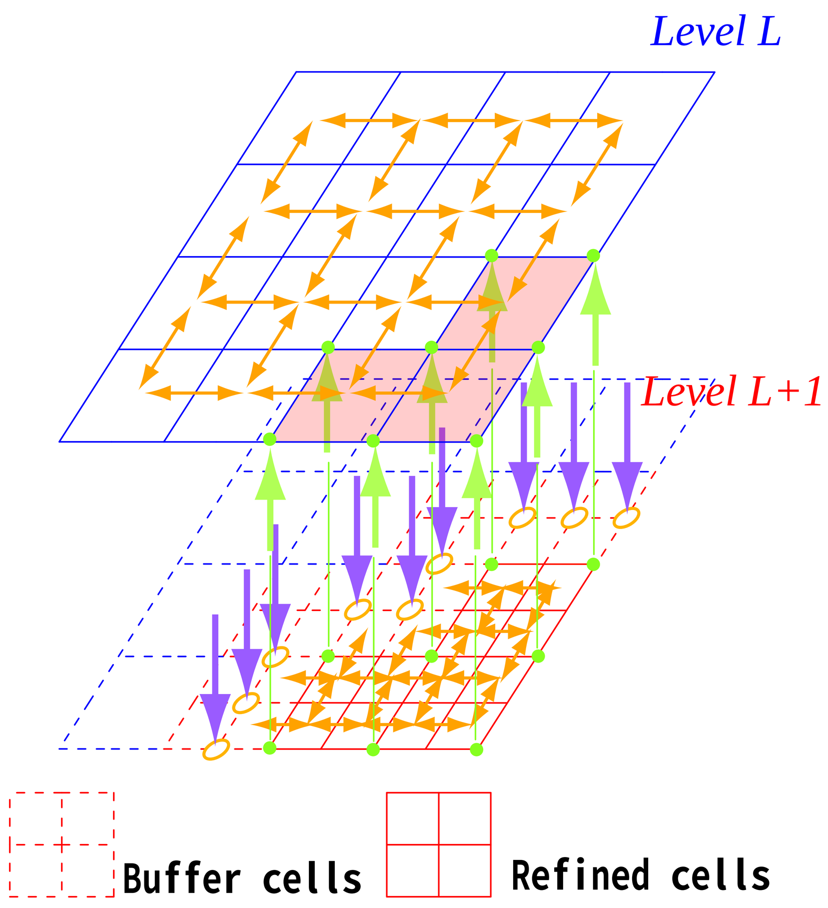
It is widely believed that magnetic reconection plays an important role in the magnetospheric substorm and the solar flare. However, physical processes around the diffusion region are not well understood. Recently, it has been suggested that multi-scale coupling process should be important in the reconnection 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 developed 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, and it is quite effective to achieve high-resolution simulations such as those around the X-line.

AMR Techique used in Electromagnetic Particle Code

[Calculations of Electromagnetic Field]

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. We also split the buffer cells that are adjacent to the refined cells to calculate electromagnetic field. 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 electromagnetic 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.



[Particle Splitting & Coalescence Algorithm]

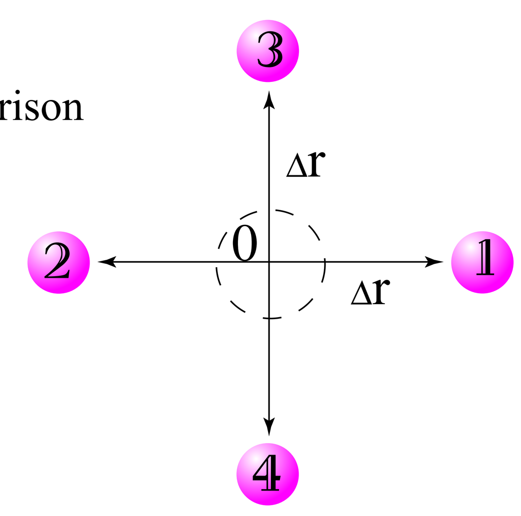
The AMR technique in our particle code resorts to the particle splitting and coalescence algorithm developed by *Lapenta* [2002] in order to control the number of particles per cell.
Processes of particle splitting and coalescence should conserve

1. the grid moments (ρ_c , $\boldsymbol{j}$),
2. the charge and mass of particles (Σq, Σm),
3. the total momentum and energy of particles ($\Sigma m\boldsymbol{v}$, $\Sigma m v^2/2$)
4. the velocity distributions ($f(\boldsymbol{v})$).

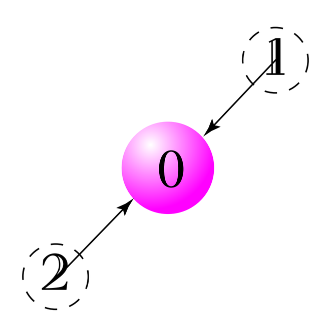
*** Particle Splitting**

Δr : Small value in comparison with grid spacing

$x_{1,2} = x_0 \pm \Delta r;\quad x_{3,4} = x_0$
$y_{1,2} = y_0;\quad y_{3,4} = y_0 \pm \Delta r$
$\boldsymbol{v}_{1,2,3,4} = \boldsymbol{v}_0$
$q_{1,2,3,4} = q_0/4$
$m_{1,2,3,4} = m_0/4$



*** Particle Coalescence**



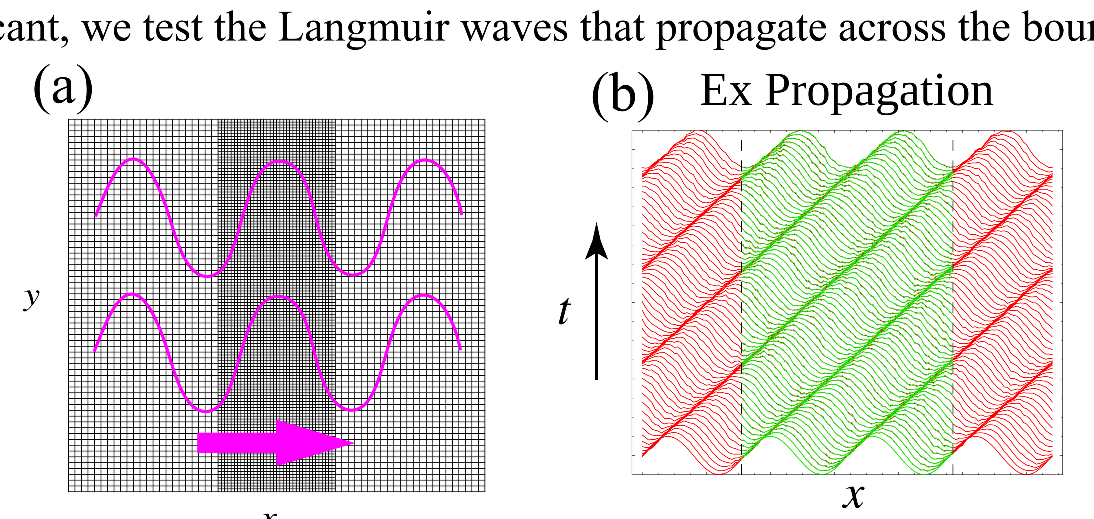
$q_1 = q_2;\quad m_1 = m_2$
$\boldsymbol{x}_0 = (\boldsymbol{x}_1 + \boldsymbol{x}_2)/2$
$\boldsymbol{v}_0 = (\boldsymbol{v}_1 + \boldsymbol{v}_2)/2$
$q_0 = q_1 + q_2$
$m_0 = m_1 + m_2$

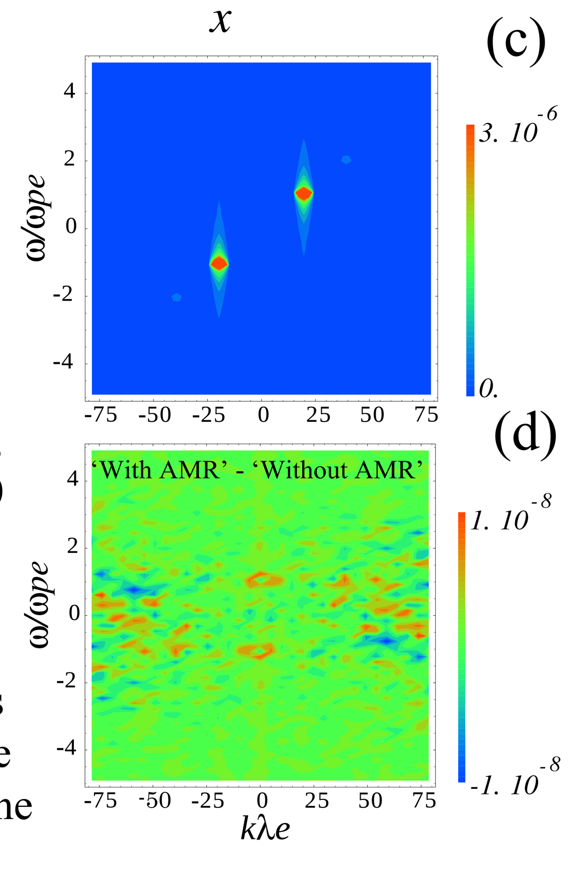
The process of particle coalescence conserves the grid moments and the total charge and momentum of particles, but perturbs the energy conservation and velocity distribution of particles. We choose two particles close in space and velocity to reduce the perturbation.

Test Simulations

One of the sources causing numerical noise in the AMR simulation is the wave reflections at the boundaries of the refined regions. The reflections are attributed to the difference in the dispertion relation, which differs from the physics for point particles and is dependent on the grid spacing.

In order to check whether the wave reflections at the boundaries are significant, we test the Langmuir waves that propagate across the boundaries.





(b) The Langmuir waves seems to propagate properly.
(c) Wave specrum is shown. The strong spectra around $\omega = \pm\,\omega_{pe}$ are those of the normal Langmuir waves and the weak spectra around $\omega = \pm\,2\omega_{pe}$ are those of the higher harmonics. If the waves reflect at the boundaries, the spectra around $\omega = \pm\,\omega_{pe}$, $\omega/k < 0$ should be present. However, such spectra are not detected in this case ($\lambda = 32\Delta$).
(d) Differences of the spectra in the cases of 'With AMR' and 'Without AMR' are much smaller than the peak value of the normal Langmuir waves.

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 particle splitting and coalescence algorithm allows us to subdivide cells around the X-line, where the plasma number density is very small, and realize effectively high-resolution simulations of the plasma sheet.

We will extend the simulation box and 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 $L_x \times L_z = 20.5\,\lambda_i \times 41.0\,\lambda_i$.

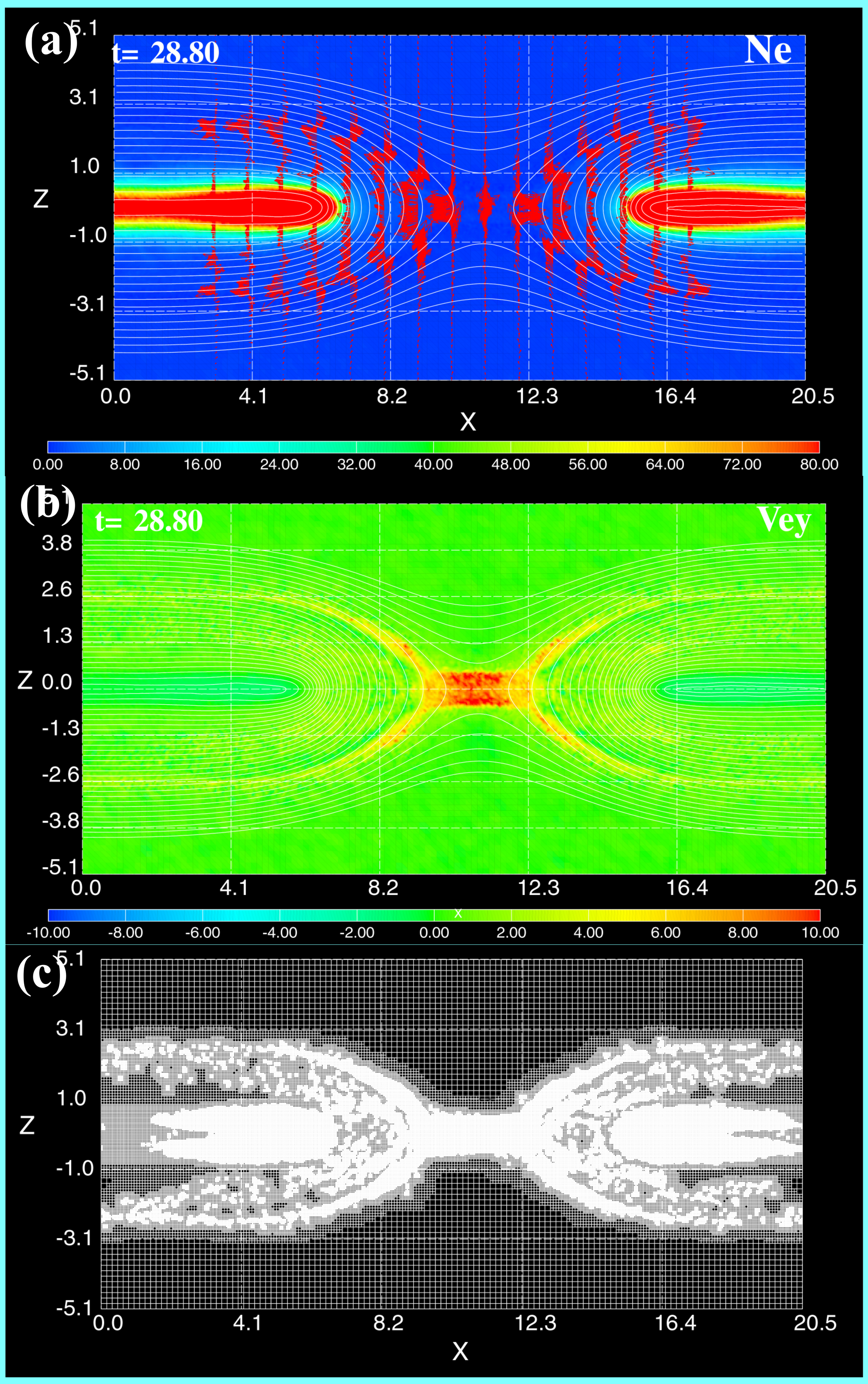
Boundary conditions are periodic boundaries in x and conductive walls in z.

Grid spacing is $\Delta_B = 0.16\,\lambda_i$ 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 defined by the local electron Debye length, the out-of-plane flow velocity of electrons, and the in-palne electron current density.

$\lambda_{De} < \Delta < 2\lambda_{De}$ or
$V_{ey} > 2\,V_A$ or
$\sqrt{jx^2 + jz^2} > 1.2\,en_{ps}V_A$

This condition must be satisfied in all cells.



The number density and flow vector of electrons are shown in (a). In this time, the velocity of the electron outflow reach nearly the electron Alfven velocity.

Structure of the electron diffusion region, which is characterized by the strong out-of-plane flow of electrons (b), is quasi-equilibrium.

Overall evolution of the plasma sheet is basically same as that conducted by the conventional PIC codes, even though in our code the finest cells are distributed only around the electron diffusion region (c).

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.