磁気リコネクションのAMR-PICシミュレーションにおける開放境界条件の開発

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Motivation

Magnetic reconnection is a key process in geomagnetic substorms and solar flares, releasing explosively the magnetic field energy into plasma kinetic energy. However, because of its multi-scale nature, the impact of reconnection on the global dynamics is poorly understood.

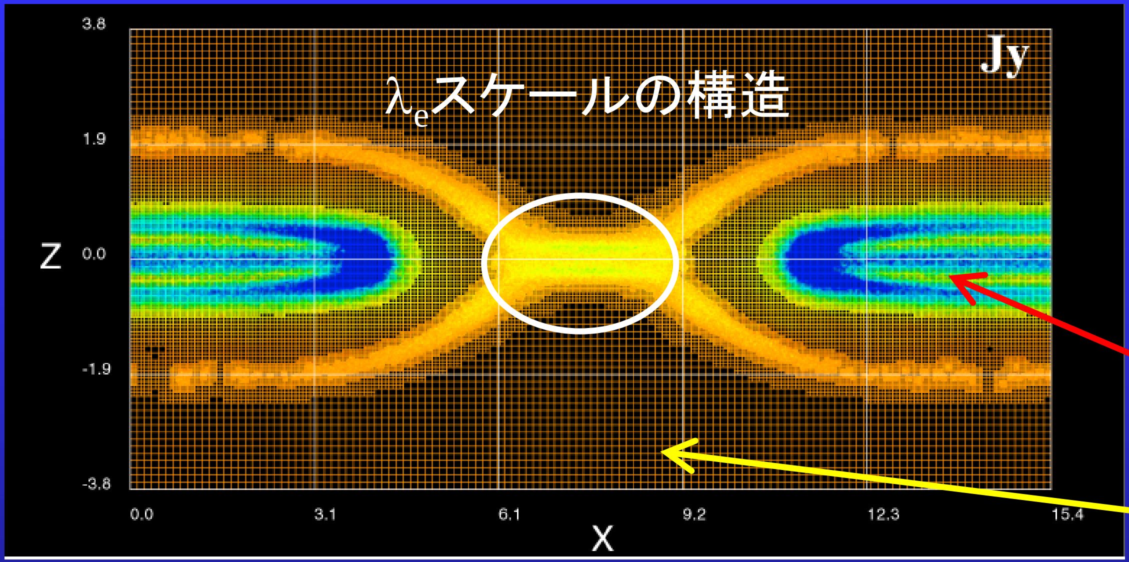
Recent large-scale kinetic simulations have revealed the electron dynamics taking place just around the magnetic x-line. However, the ion-scale (meso-scale) dynamics connecting the electron dynamics with the fluid dynamics has been hardly investigated.

The present study has developed an open boundary model for the particle-in-cell (PIC) code with the adaptive mesh refinement (AMR), which enables long-time simulations of magnetic reconnection and the investigation of the ion-scale dynamics.

AMR-PICコード

(Adaptive Mesh Refinement – Particle-in-Cell)

[Fujimoto & Machida, JCP, 2006; Fujimoto, JCP, 2011]



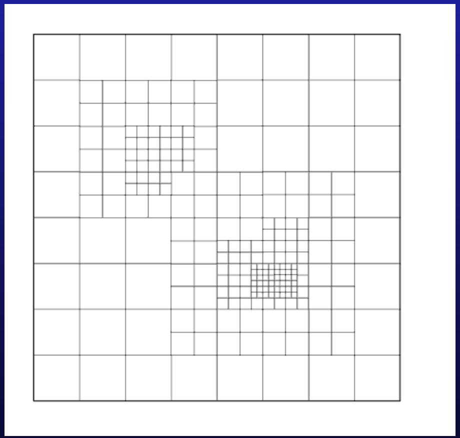
陽解法の制約

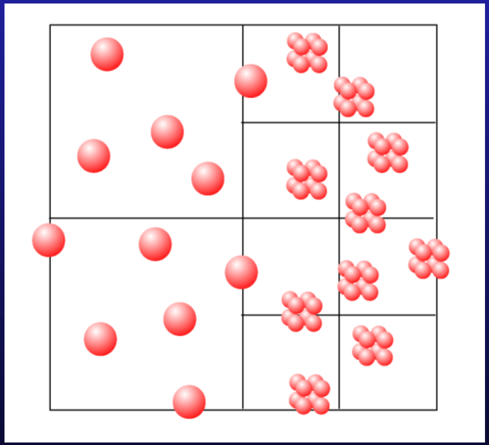
$\Delta x < \lambda_{De}$, $\omega_{pe}\Delta t < 1$

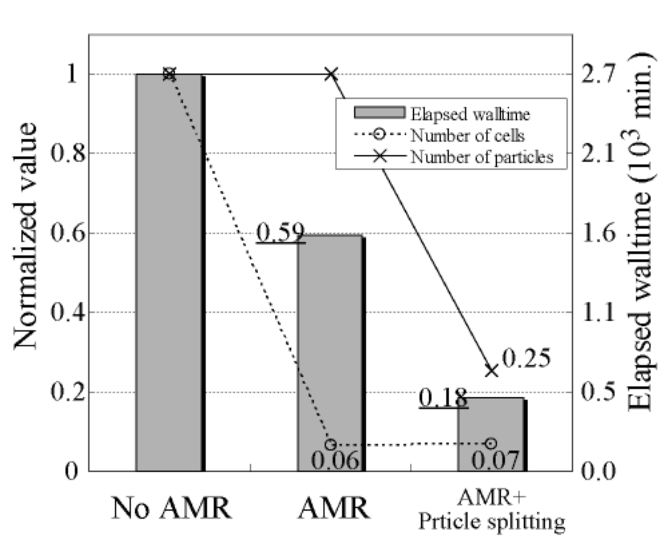
$\Delta x/\Delta t > c$

$\lambda_{De,ps} \sim 3 \times 10^2$ m

$\lambda_{De,lobe} \sim 6 \times 10^3$ m







AMR-PICコードの開発

2003 2006 2008 2011 2013

開発スタート

2D AMR-PIC
コード完成

[Fujimoto & Machida, JCP, 2006]

3D AMR-PIC
コード完成

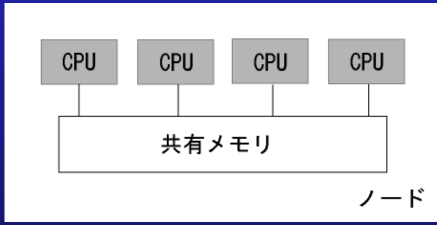
[Fujimoto & Sydora, CPC, 2008]

超並列化完了

[Fujimoto, JCP, 2011]

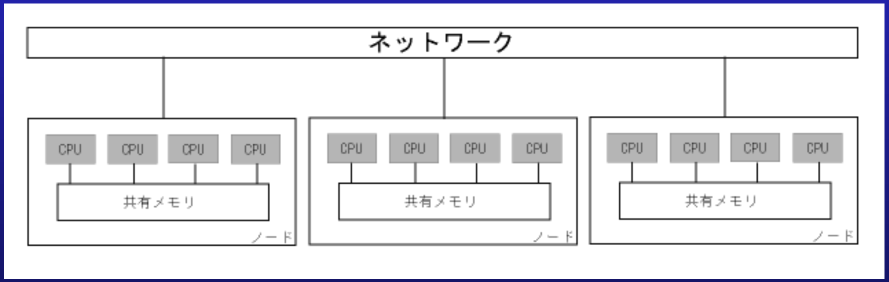
開放境界条件
開発中．．．

- ノード内並列



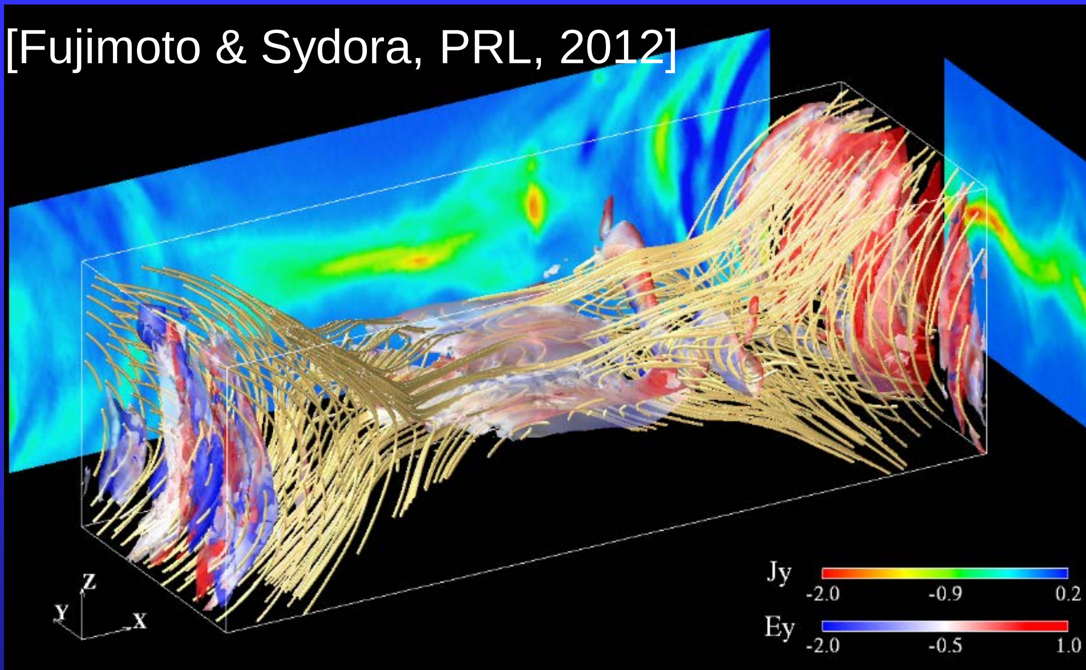
CPU数、メモリ容量の制約

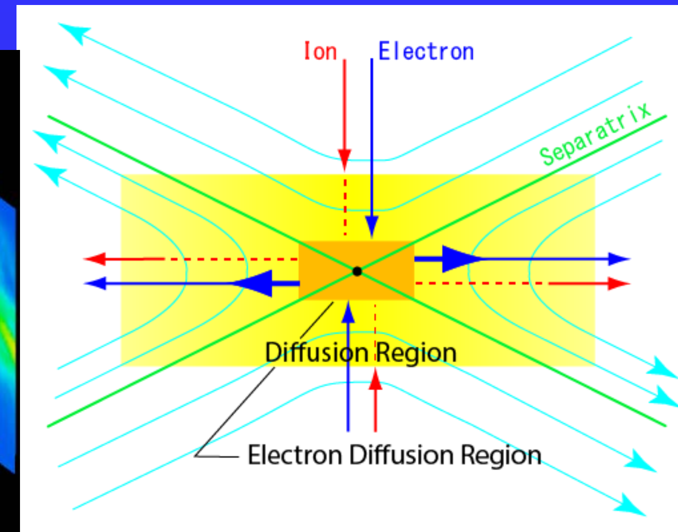
- 電荷保存法
- 適合ブロック法



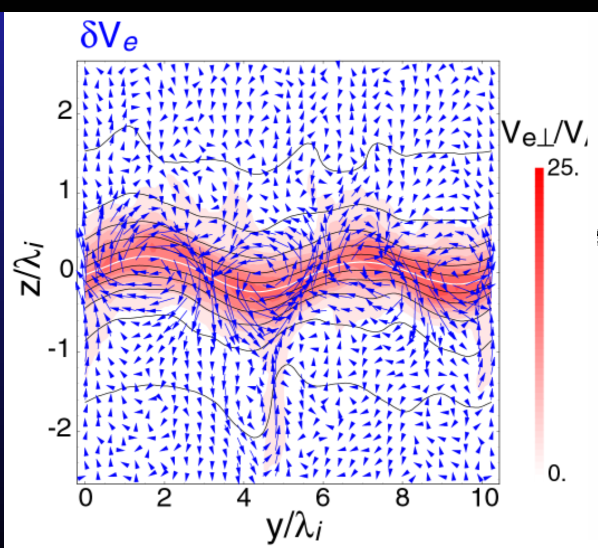
より多くの計算機資源が利用可能！

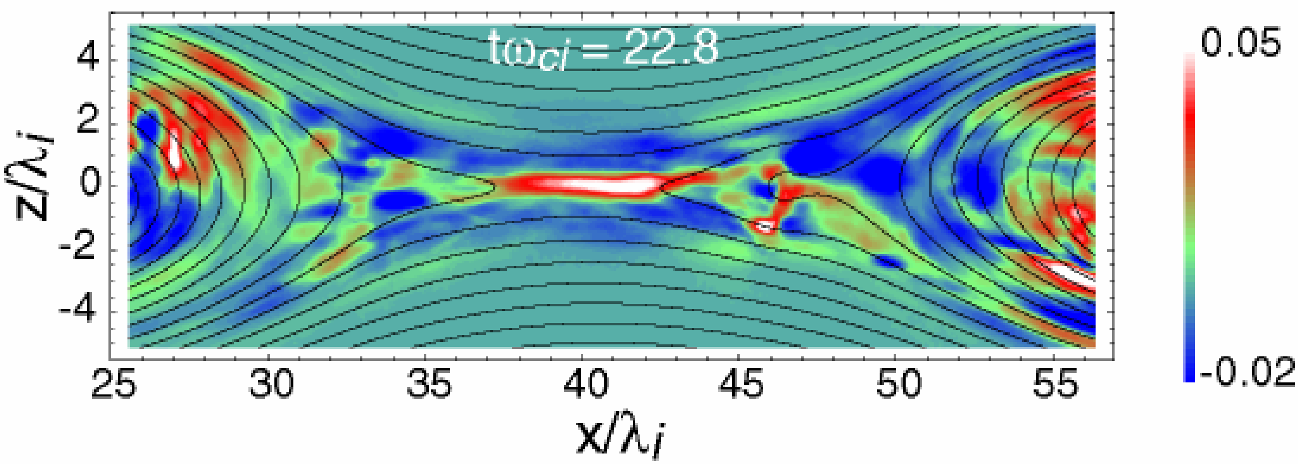
Electron-Scale Dynamics





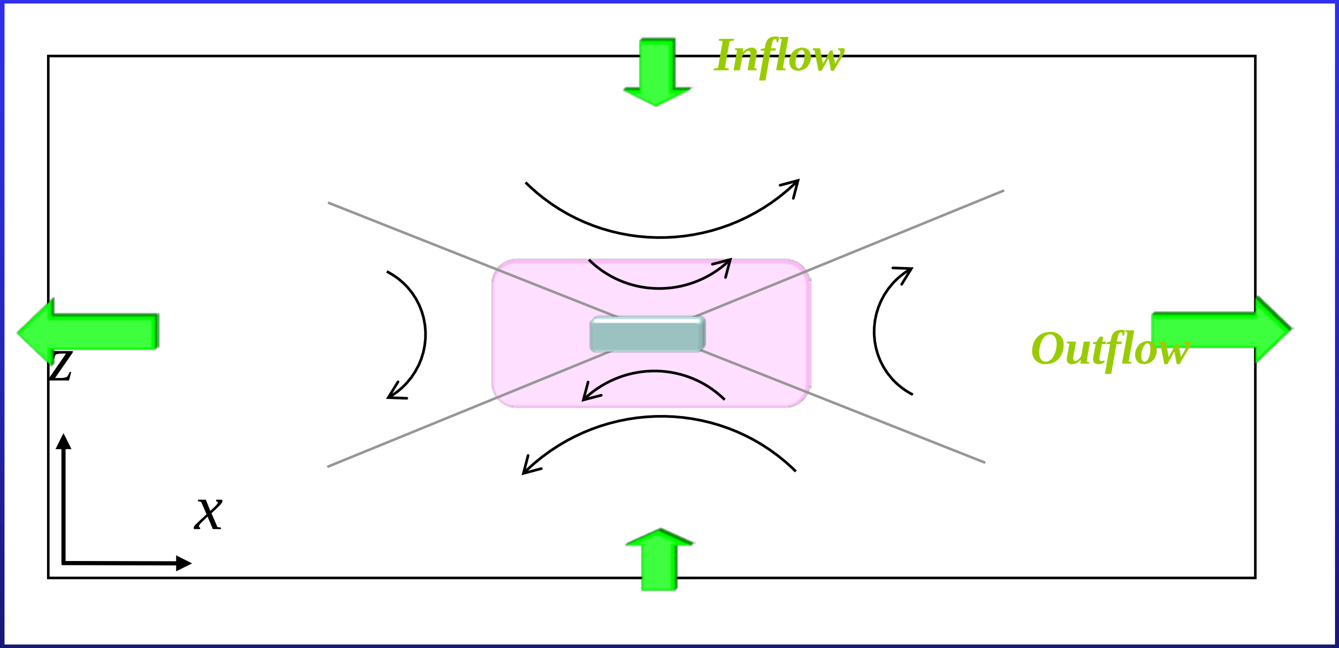
$$\langle -E_y \rangle = 1/\langle n_e \rangle \left\langle \delta(n_e \vec{V}_e) \times \delta \vec{B} \right\rangle$$





Toward Long-Time Simulations

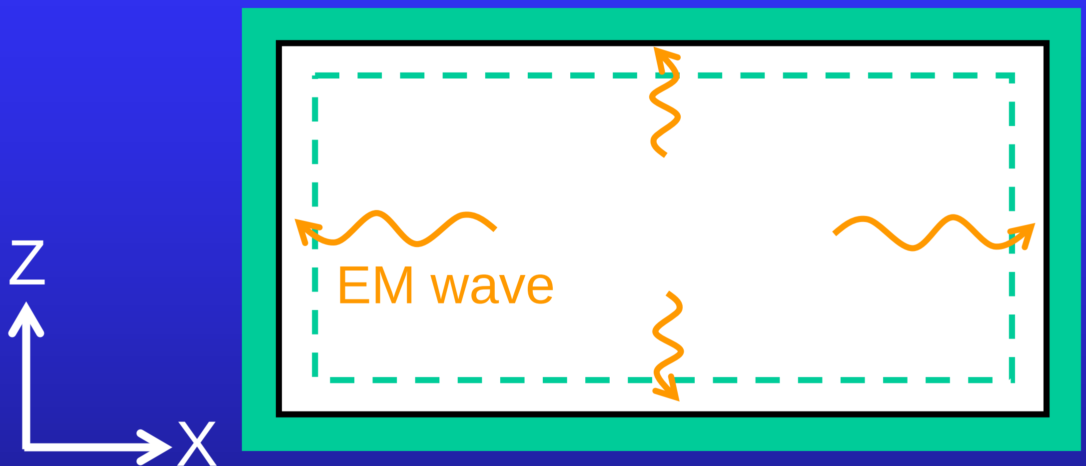
開放境界 ⇒ アウトフロープラズマを領域外へ ⇒ 長時間計算



An Open Boundary Condition

粒子情報のコピー
（∂ f/∂n = 0）

Birdsall & Langdon, IOP, 1995

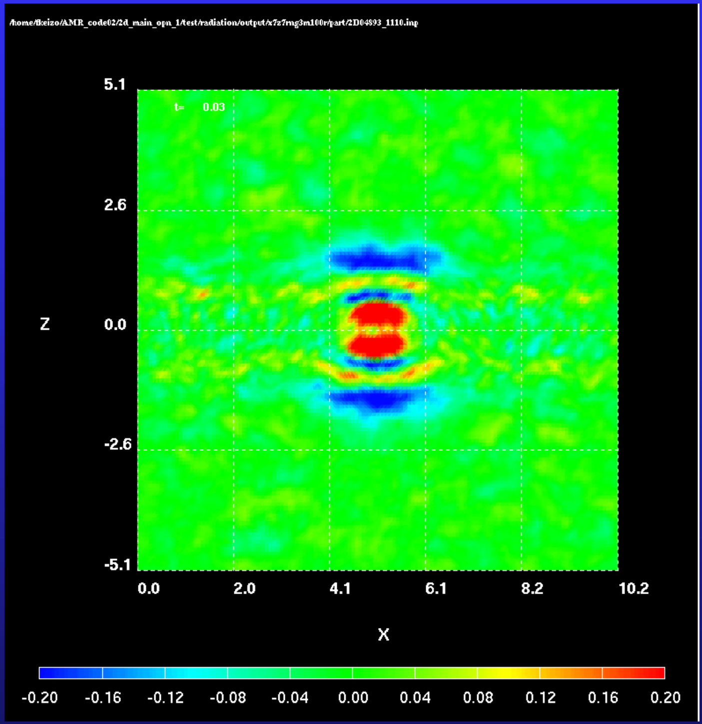


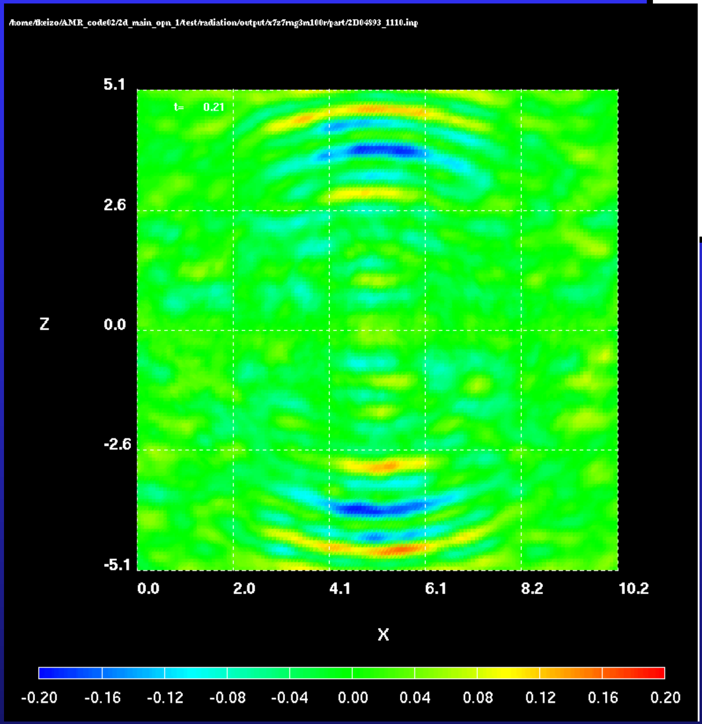
$$E_y = \pm c B_z$$
$$E_z = \mp c B_y$$
$$\frac{\partial E_y}{\partial t} = -c^2 \frac{\partial B_z}{\partial x}$$
$$\frac{\partial E_z}{\partial t} = -c^2 \frac{\partial B_y}{\partial x} - c^2 j_z$$

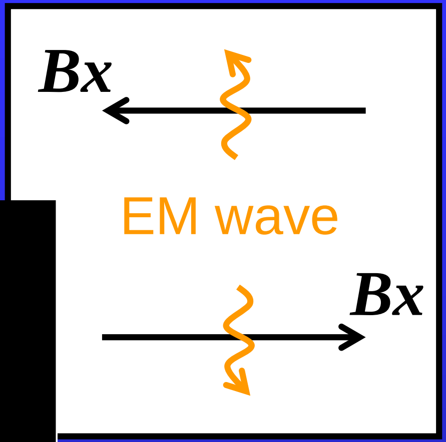
$$E_x = \pm c B_y$$
$$E_y = \mp c B_x$$
$$\frac{\partial E_x}{\partial t} = -c^2 \frac{\partial B_y}{\partial z} - c^2 j_x$$
$$\frac{\partial E_y}{\partial t} = c^2 \frac{\partial B_x}{\partial z}$$

境界に沿った静電場

Test Simulation – Radiation emission



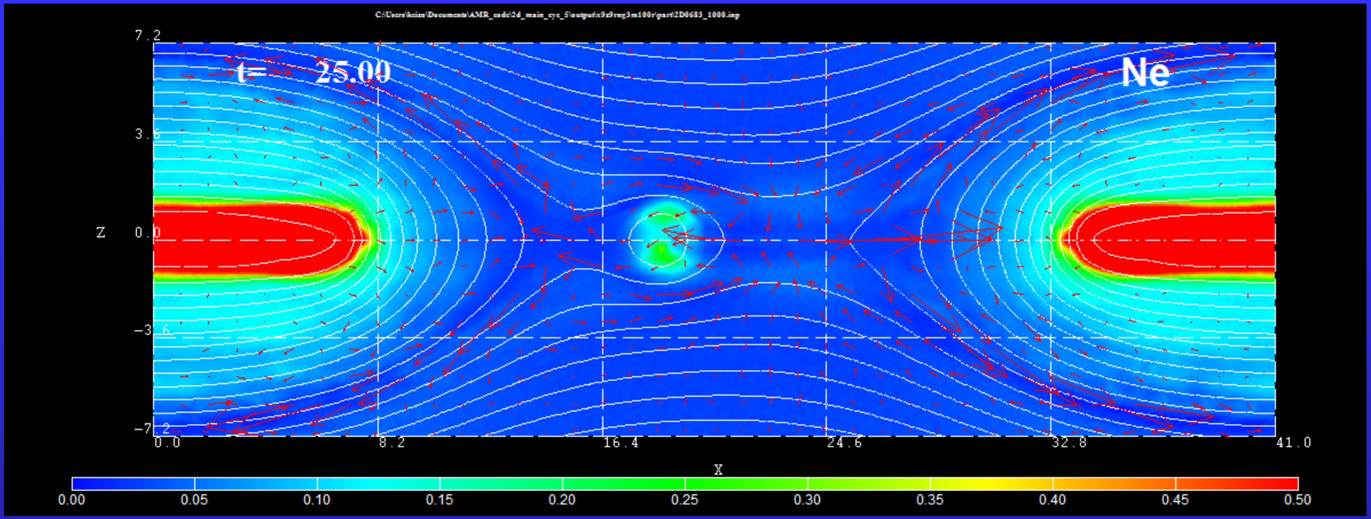




Test Simulation – Current sheet evolution

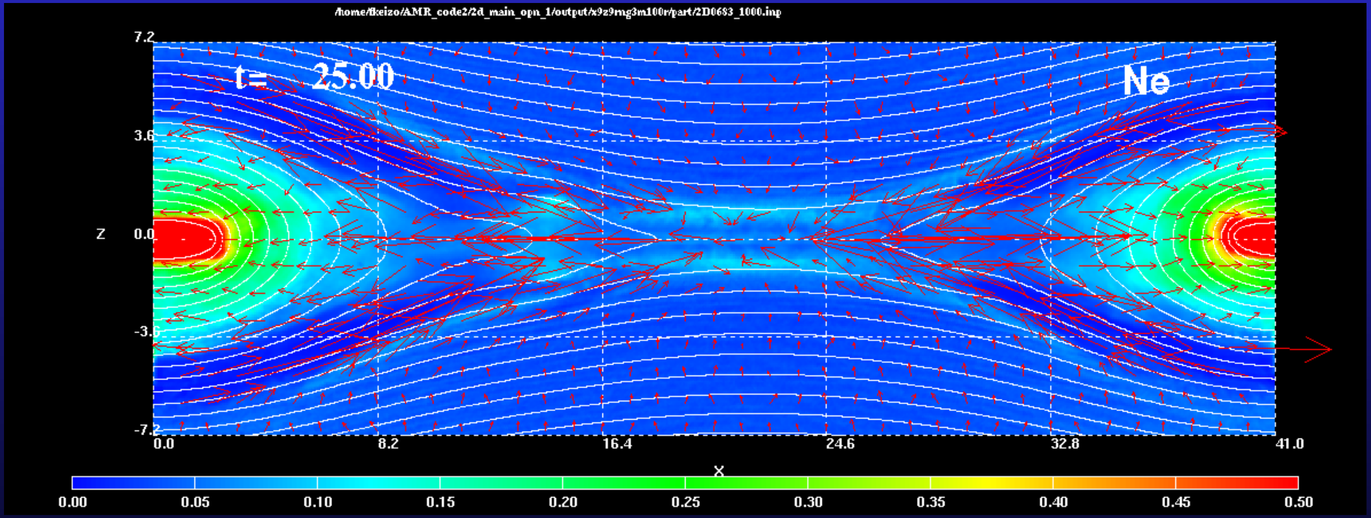
Periodic Boundary

$L_x \times L_z = 41\lambda_i \times 41\lambda_i$



Open Boundary

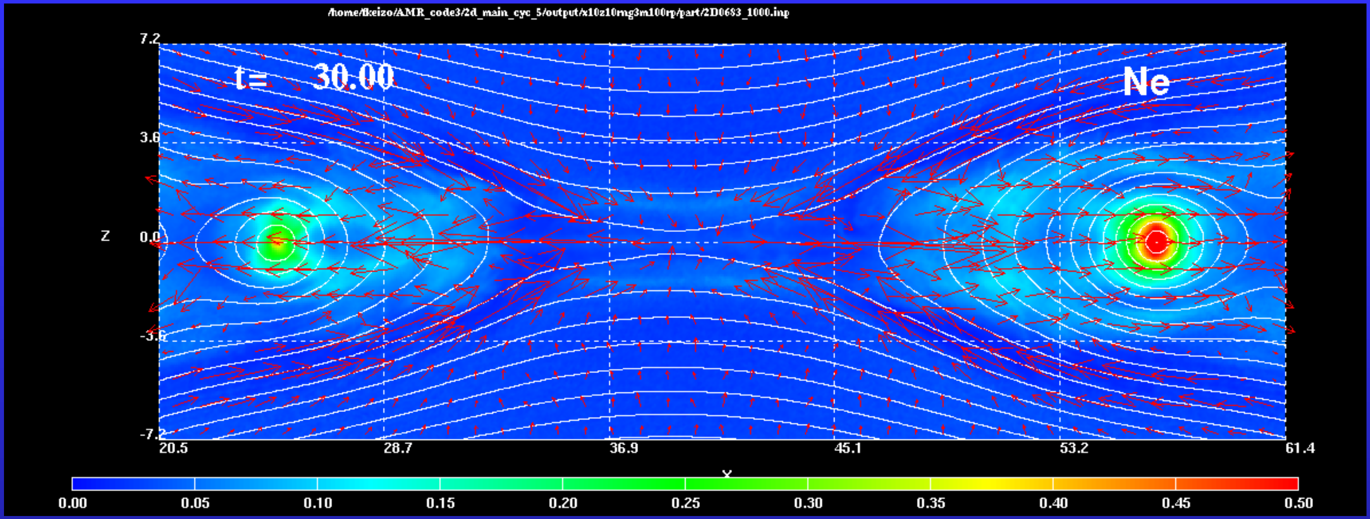
$L_x \times L_z = 41\lambda_i \times 41\lambda_i$

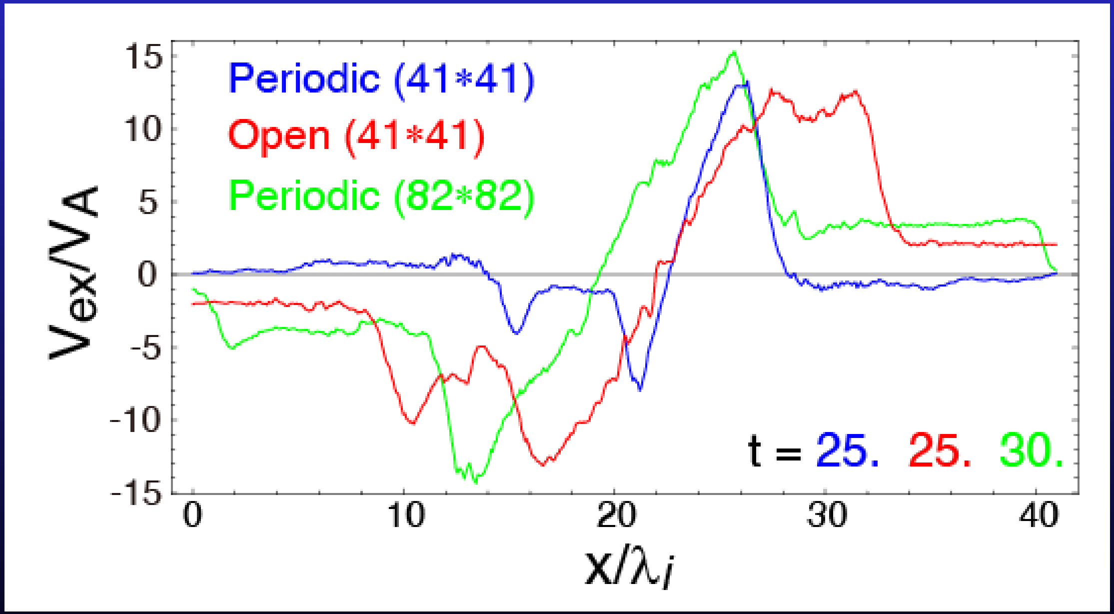


Test Simulation – Current sheet evolution

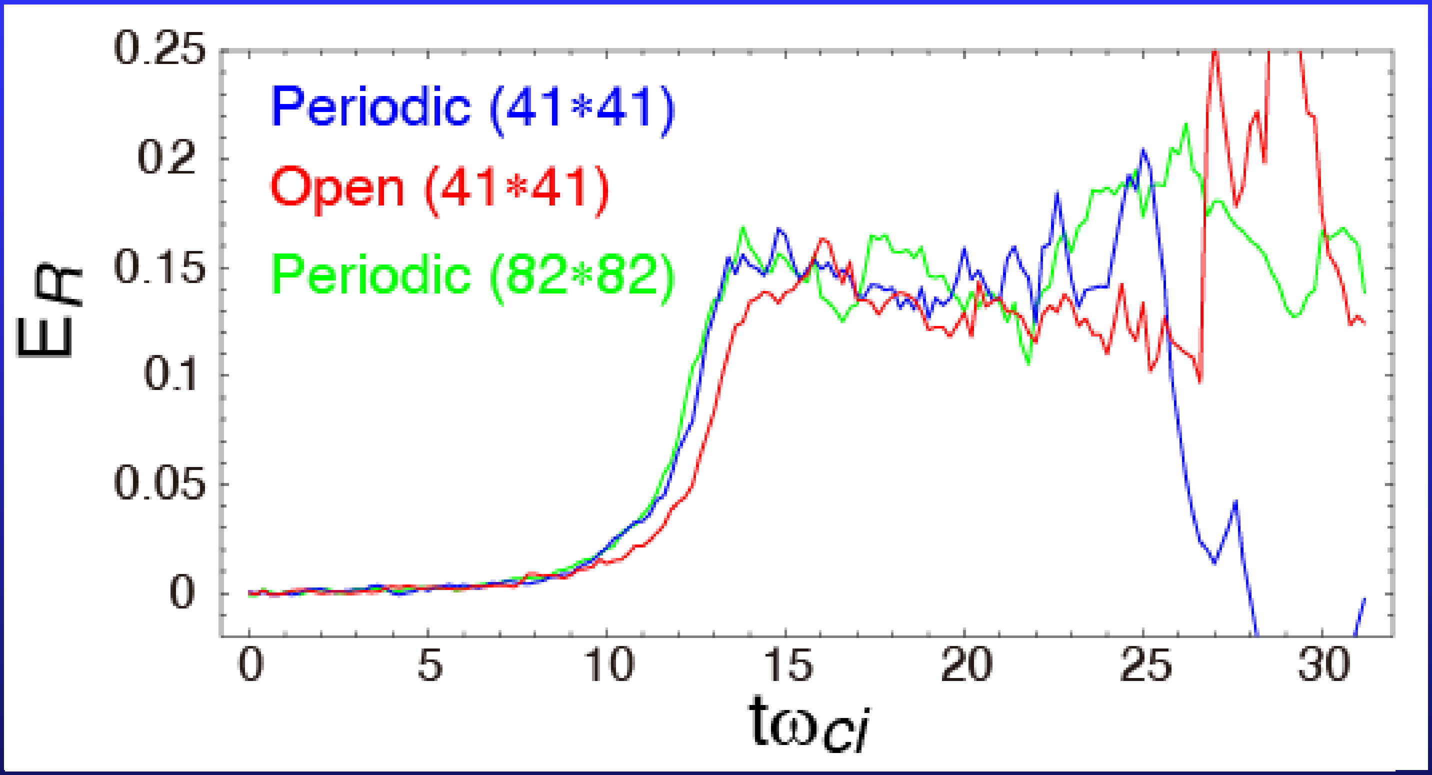
Periodic Boundary

$L_x \times L_z =$
$82\lambda_i \times 82\lambda_i$





Test Simulation – Reconnection rate



Summary

The present study has developed an open boundary model for the AMR-PIC code (Fujimoto, JCP, 2011), aiming long-time simulations of magnetic reconnection which enables one to investigate the ion-scale (meso-scale) dynamics.

The model was checked against the EM radiation and the current sheet evolution. We confirmed that

- the EM waves hardly reflect at the open boundary, and
- a fast reconnection is sustained longer time under the open boundary than under the periodic boundary for the same system size.