JIFT Workshop

PIC model for magnetic reconnection interlocked simulation model

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Outline

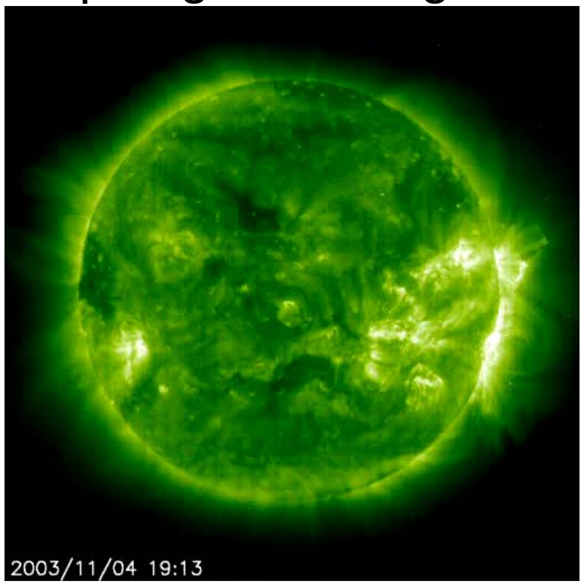
- Introduction of PASMO
  - Open system
- Simulation Model
- Simulation results
  - Discussion of connection between macro and micro
- Conclusions

Introduction of PASMO

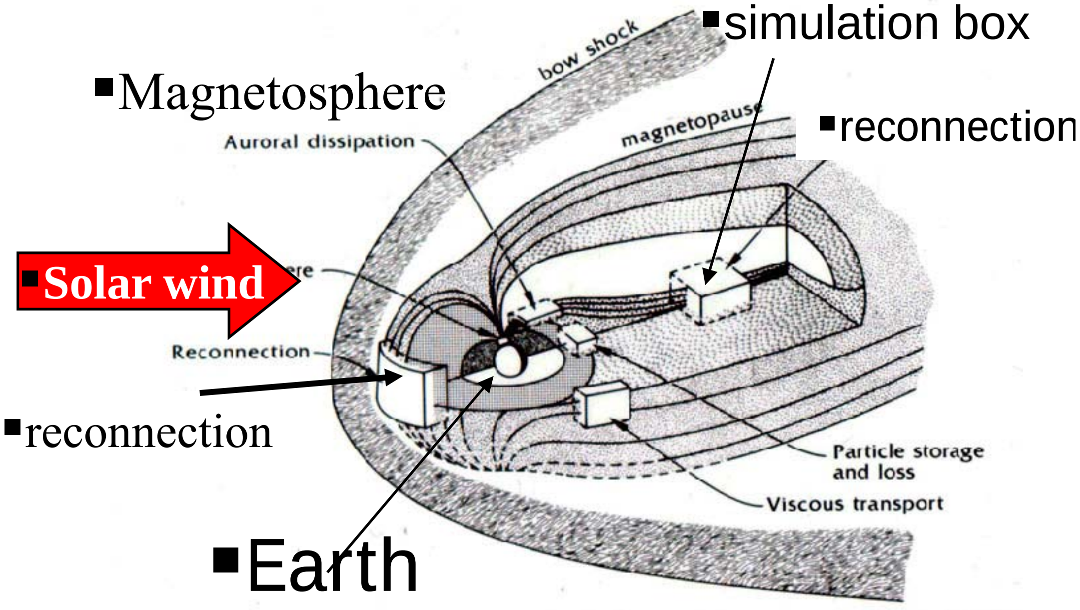
- Whole physical picture of reconnection in an open system by PIC code.
- **Magnetic Reconnection**
  - Solar corona, magnetosphere substorm and tokamak discharge.
  - Fast energy release from magnetic field to plasmas, and change of the field topology.
  - Microscopic phenomena

    Generation of electric resistivity (wave-particle interaction, a binary collision, and so on)
  - Macroscopic phenomena

    Topological change of magnetic field, global plasma transport and so on.



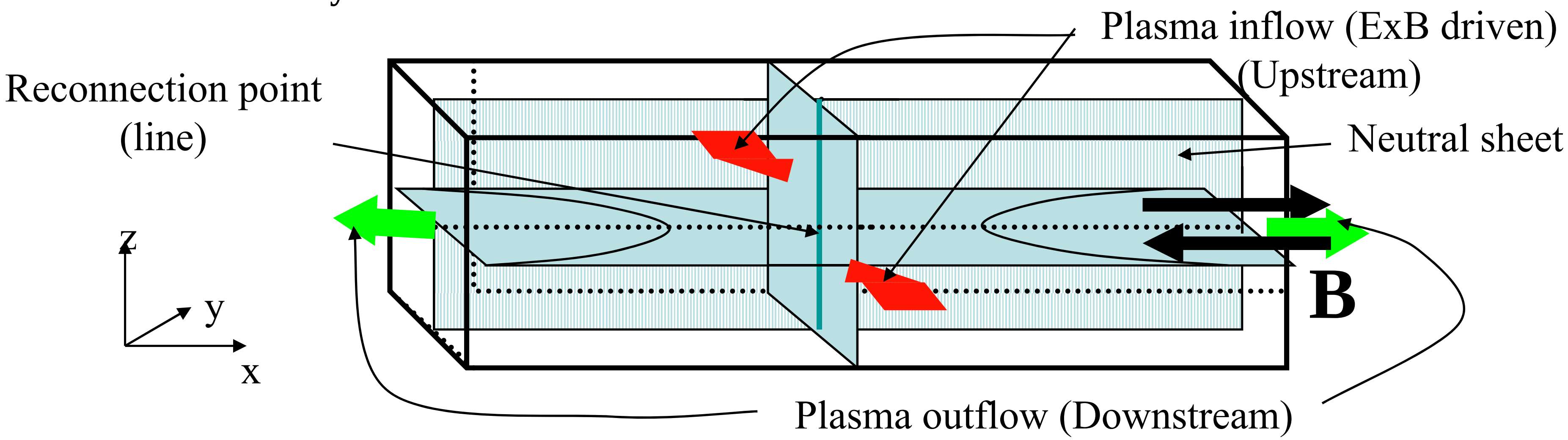
▪SOHO



▪Earth

Introduction of PASMO

- **Open system**
  - Energy inflow and outflow through the simulation boundary.
  - Information of physics in the external system: as a boundary condition.
  - Only a local reconnection system is solved under the given boundary condition.
- **PArticle Simulation code for Magnetic reconnection in an Open system (*PASMO*).**
  - Downstream boundary: free boundary condition
  - For investigation of microscopic region: boundary condition at upstream is given; T: const. v=ExB. E: driven force. B: Maxwell eq. at upstream.
  - For micro-macro interlocked model, this code is designed to connect with the code for macroscopic system.
  - For the interconnection, macroscopic information (T, v, B, E) at upstream →microscopic quantities at upstream boundary .
- **Investigation**
  - **Anomalous resistivity due to plasma-wave interaction**
  - **Microscopic kinetic effects due to particle dynamics**
  - **Nonlinear dynamics of collisionless driven reconnection**



Basic Equations

Electromagnetic Particle Simulation (PIC) on the explicit algorithm

The Equations of motion

$$\frac{d(\gamma_j \mathbf{v}_j)}{dt} = \frac{q_j}{m_j}\left(\mathbf{E} + \frac{\mathbf{v}_j}{c} \times \mathbf{B}\right)$$

$$\frac{d\mathbf{x}_j}{dt} = \mathbf{v}_j$$

$$\gamma_j = 1 \Big/ \sqrt{1 - (\mathbf{v}_j \cdot \mathbf{v}_j)/c^2}$$

$$\begin{cases} \mathbf{j}(\mathbf{x},t) = \sum_j q_j \mathbf{v}_j(t) S[\mathbf{x} - \mathbf{x}_j(t)] \\ \rho(\mathbf{x},t) = \sum_j q_j S[\mathbf{x} - \mathbf{x}_j(t)] \end{cases}$$

$S[\mathbf{x} - \mathbf{x}_j(t)]$ **is the form function.**

Maxwell equations

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

$$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

$$\nabla \cdot \mathbf{B} = 0$$

Normalization

$$m = \tilde{m} m_e^{SP}, q = \tilde{q} e, t = \tilde{t} / \omega_{ce}, v = \tilde{v} c$$

$$x = \tilde{x} c / \omega_{ce}, E = \tilde{E}\frac{m_e c \omega_{ce}}{e}, B = \tilde{B}\frac{m_e c \omega_{ce}}{e}$$

Distributed parallel algorithm

- Particle distribution method
- High Performance Fortran (HPF)
- Message Passing Interface(MPI)

H.Ohtani, et al: *LNCS* **4579** (2008) pp.329-343.

Initial Condition & Boundary Condition for Fields

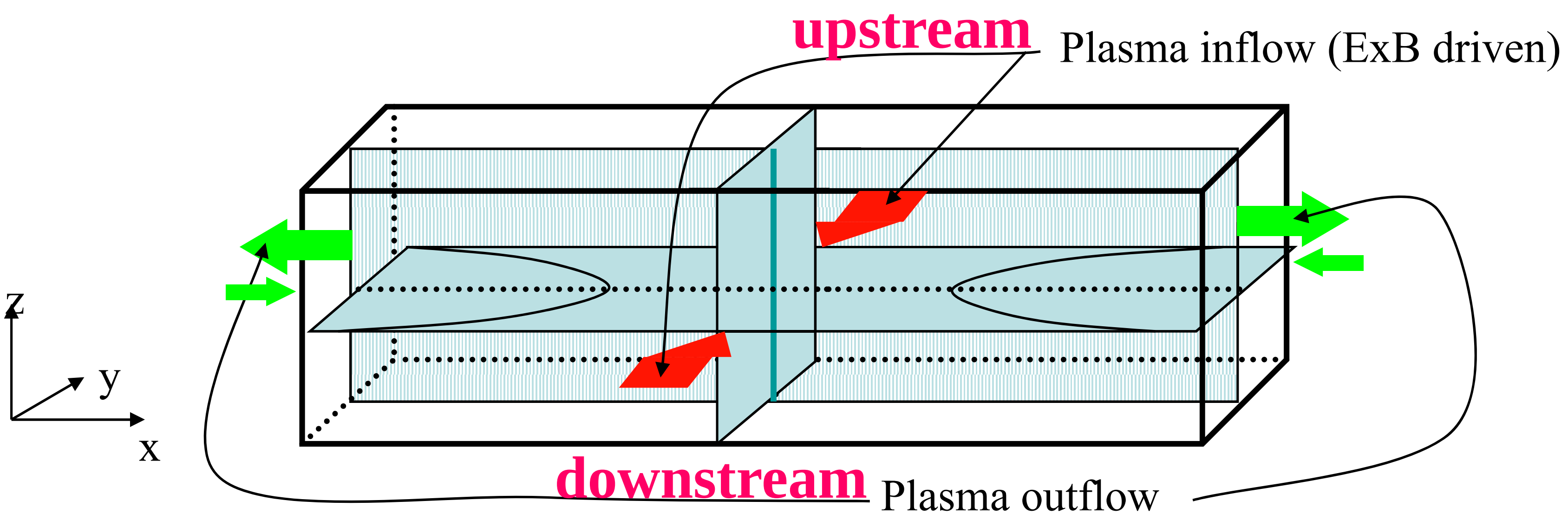
- Initial condition : Harris type equilibrium

$$B_x = B_0 \tanh(y/L)$$
$$P = (B_0^2/8\pi)\mathrm{sech}^2(y/L)$$
$$j_z = -(cB_0/4\pi L)\mathrm{sech}^2(y/L)$$
$$B_0 = const. \; L : \text{spatial scale.}$$

Particles:
The shifted Maxwellian distribution
with $T_e = T_i$ at initial time.

- Boundary conditions for fields
  - **upstream(y):** $E_x = 0, \dfrac{\partial E_y}{\partial y} = 0, E_z = E_z^{ub}(\mathrm{x}, \mathrm{t})$ (driving field)
  - **downstream(x):** $\dfrac{\partial E_x}{\partial x} = \dfrac{\partial B_y}{\partial x} = \dfrac{\partial B_z}{\partial x} = 0$
  - **z : periodic boundary condition**
  - **Another field variables: Maxwell eq.**

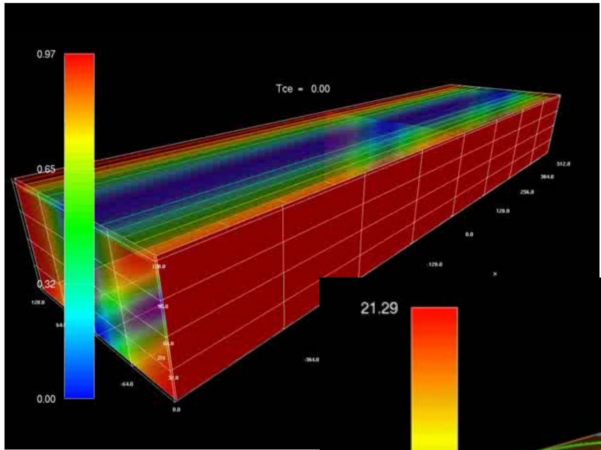
Boundary Condition for Particles in Open System



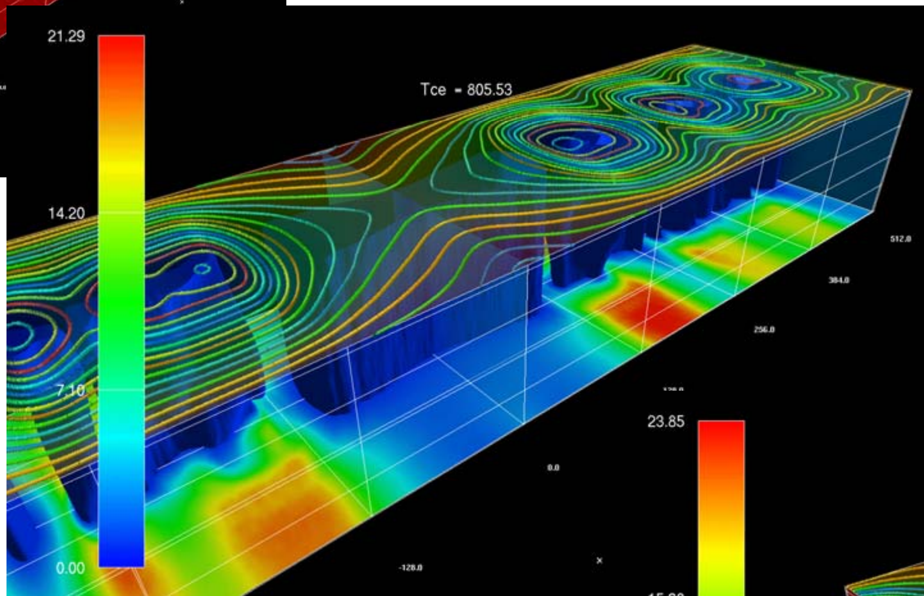
1. **Upstream：Particles of plasma inflow come into the simulation box due to E×B drift.**
2. **Downstream: Particles of plasma outflow go out and come into the simulation box by free boundary**
3. **Total number of particles depends on time.**
4. **Charge neutrality condition.**

Information is given from macro region in Interlocked model, while it is given as boundary condition in microscopic research.

Results（2）Downstream model fulfills its function very well

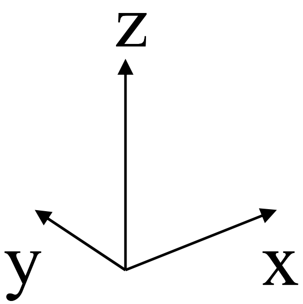


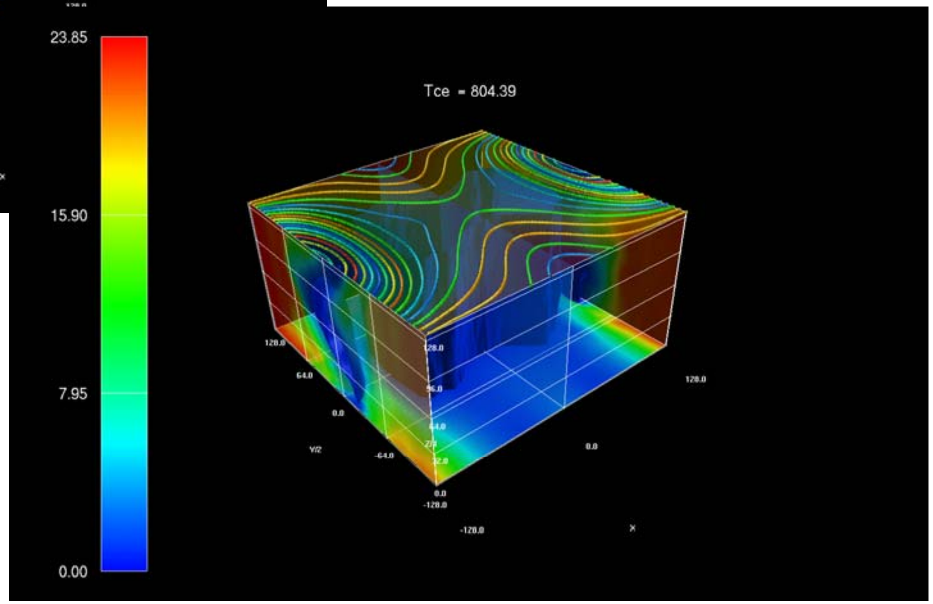
Long simulation box (N_x=1026)



Isoline of magnetic flux

Isosurface of $B_x^2 + B_y^2$

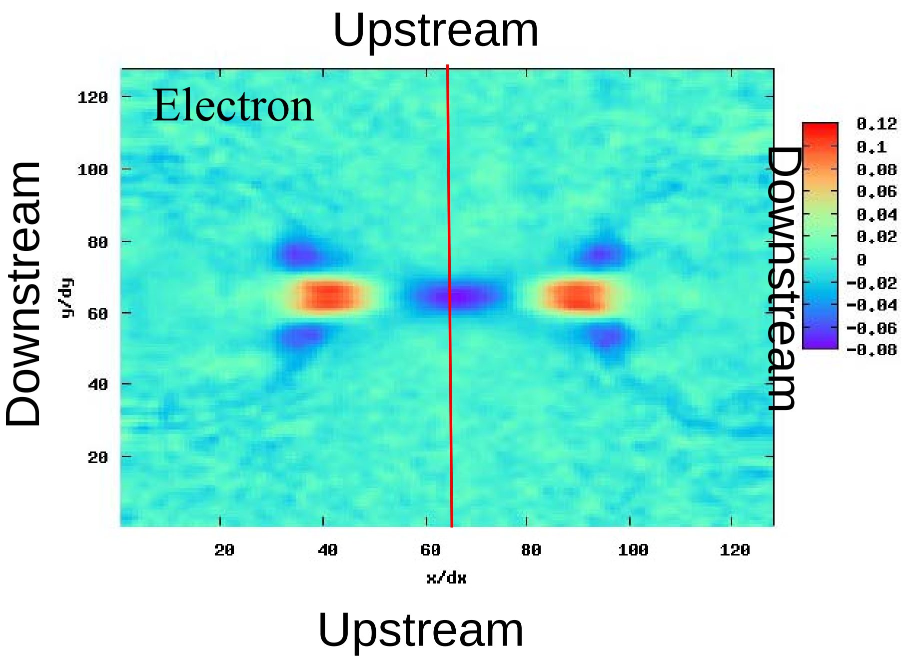


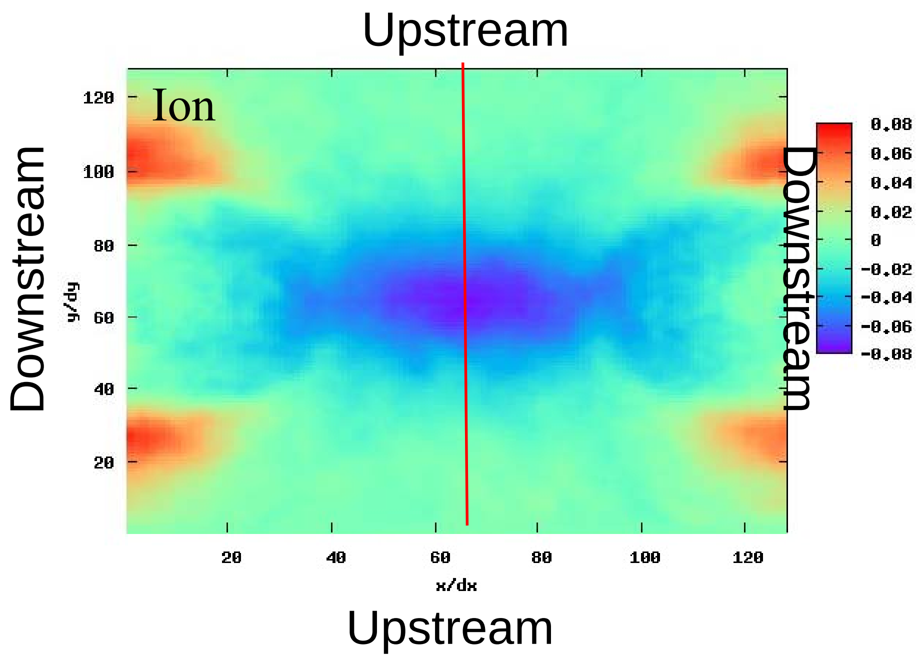


Short simulation box (N_x=258)

Results（1）Frozen-in condition near the upstream boundary

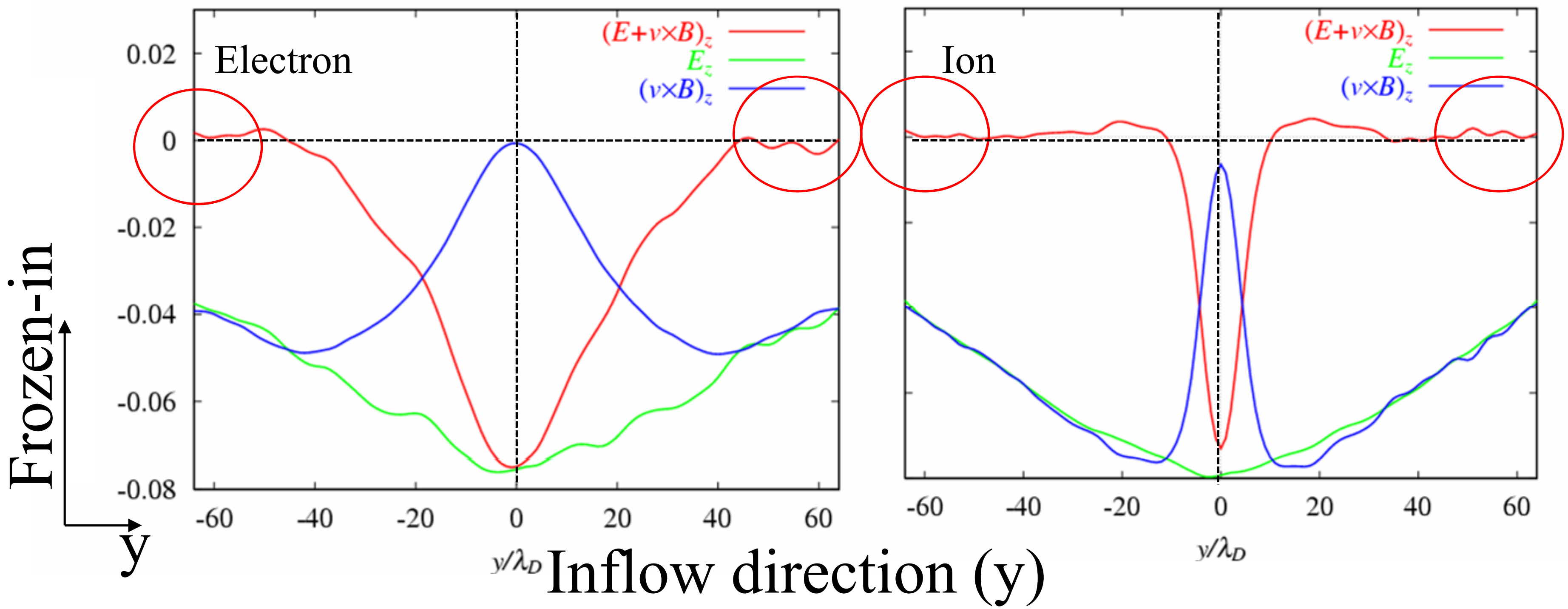
Contour plots of E_z+$(uXB)_z$ in xy plane.
When E_z+$(uXB)_z$ is vanished, the frozen-in condition is satisfied.





Results（1）Frozen-in condition near the upstream boundary

Profiles of $E_z+(uXB)_z$. along inflow direction(y) through reconnection point. When $E_z+(uXB)_z$ is vanished, the frozen-in condition is satisfied.



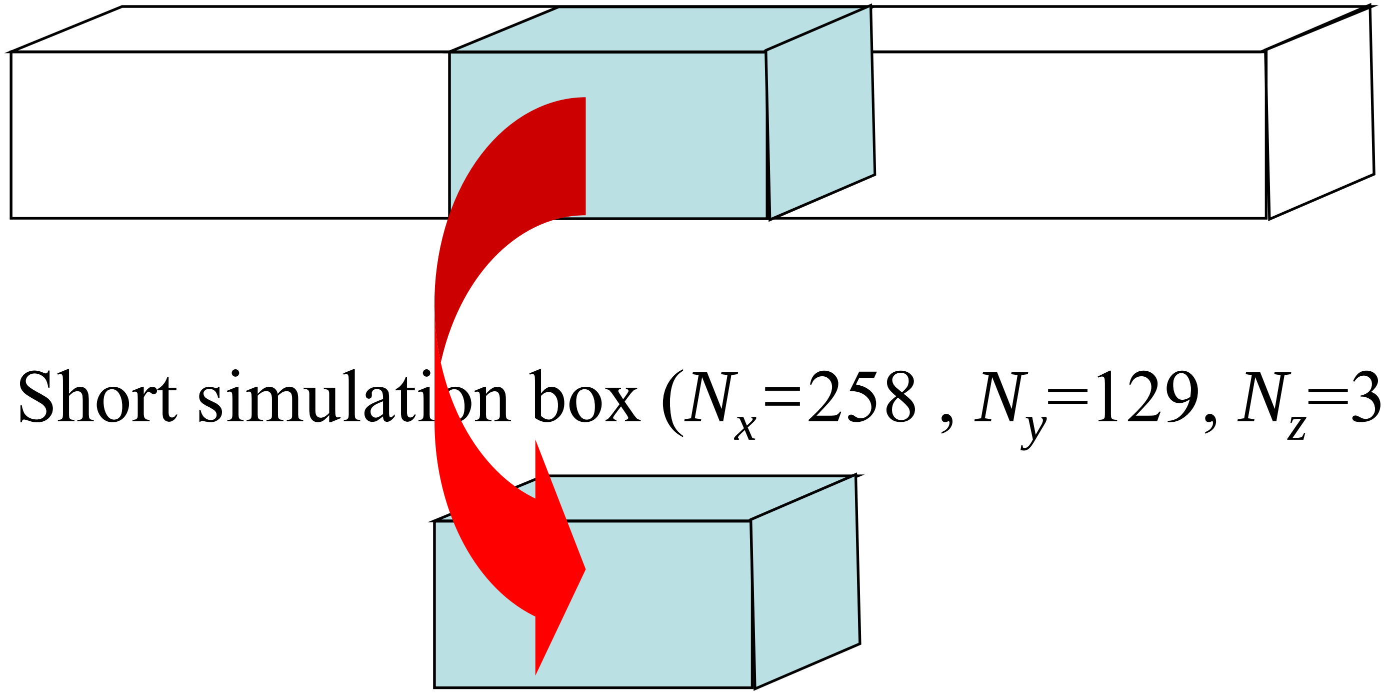
$E_z+(uXB)_z$ is zero both for electron and ion at upstream boundary. This means that this model can realize a satisfaction of frozen-in condition with high accuracy.

⇒Direct connection with MHD model.

Results（2）Effect of downstream model

In order to check the effect of downstream boundary model,
we perform simulations with long and short boxes.
We check whether the short simulation can mimic the part of long simulation.

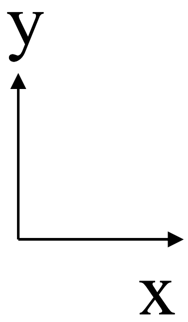
Long simulation box (N_x=1026, N_y=129, N_z=36)

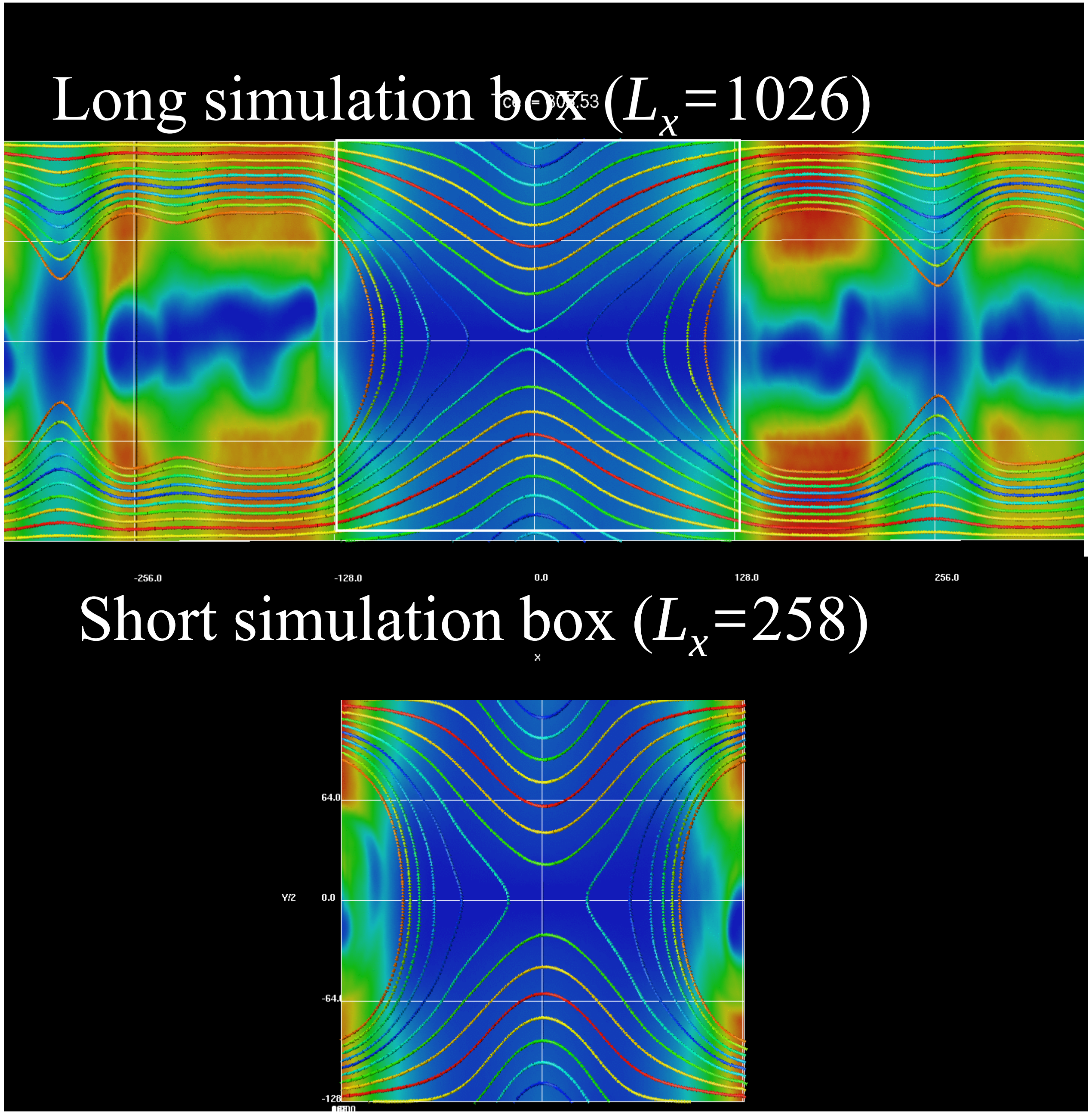


Short simulation box (N_x=258 , N_y=129, N_z=36)

Results（2）Effect of downstream model

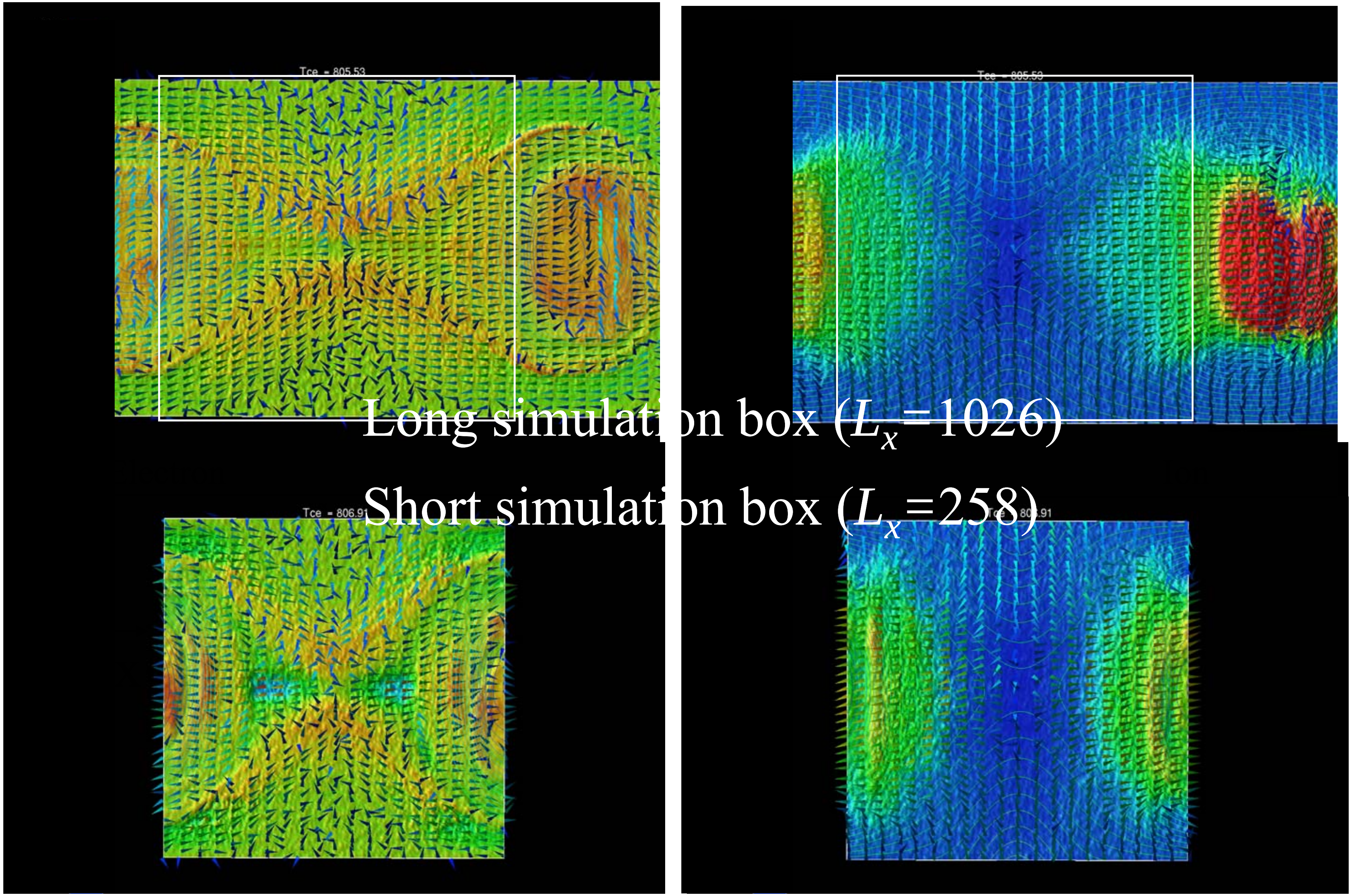
- Magnetic field structure at the steady state.





Results（2）Effect of downstream model

- Flow velocity and temperature at the steady state.



Long simulation box (L_x=1026)

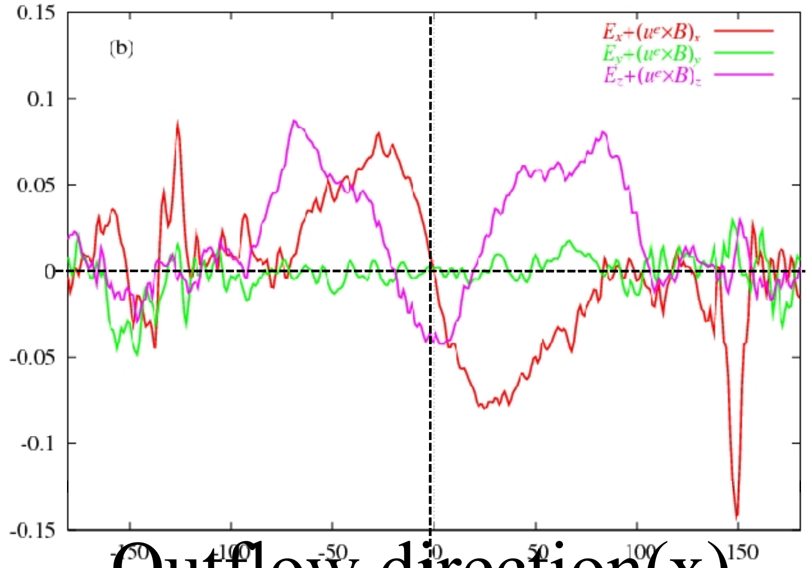
Short simulation box (L_x=258)

Results（2）Effect of downstream model

- Electron frozen-in condition along outflow direction(x) through reconnection point.

Long simulation box

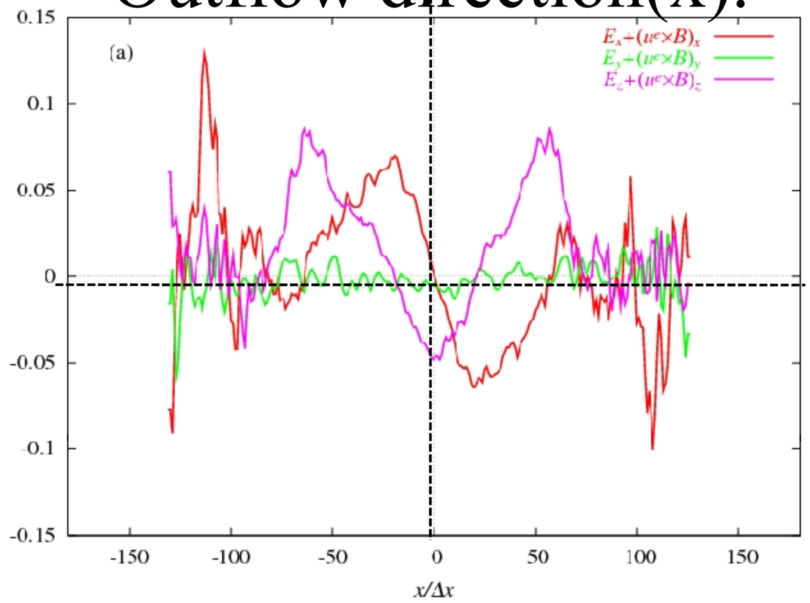
(L_x=1026)

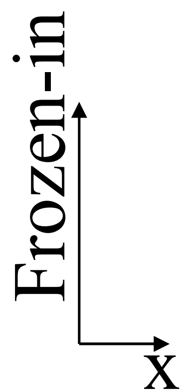


Outflow direction(x).

Short simulation box

(L_x=258)



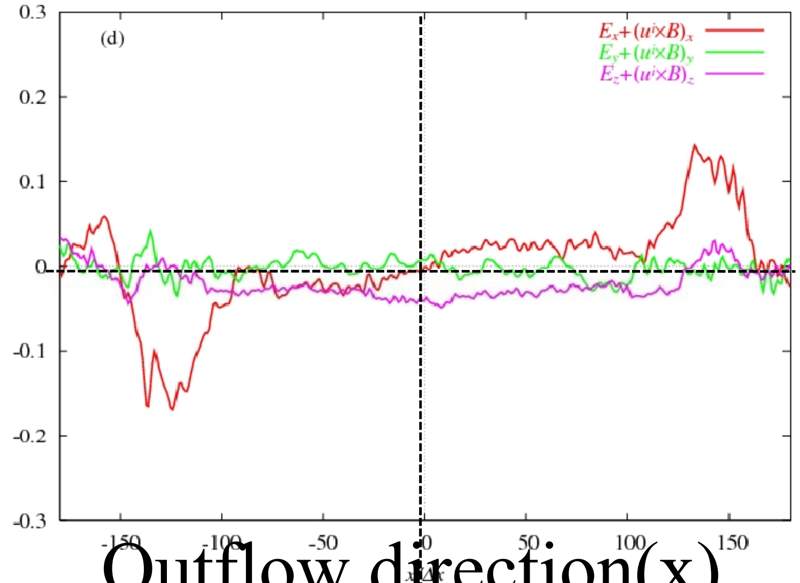


Results（2）Effect of downstream model

- Ion frozen-in condition along outflow direction (x) though reconnection point.

Long simulation box

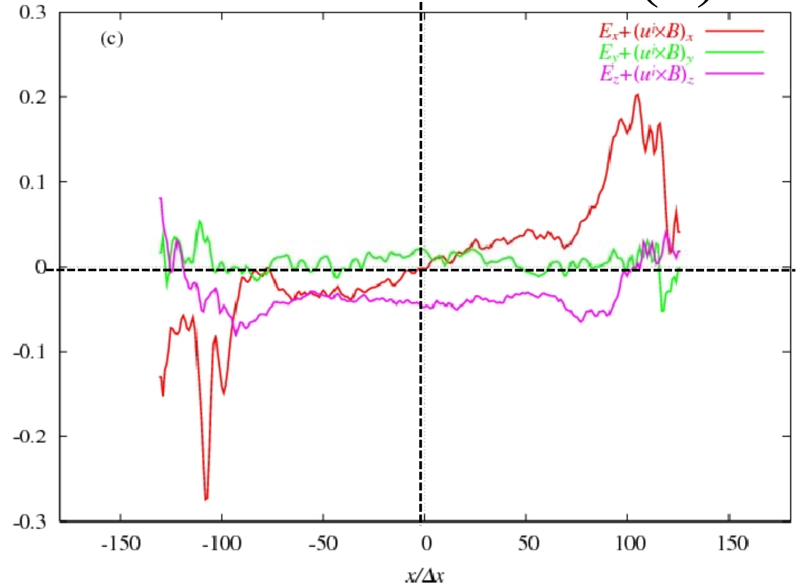
(L_x=1026)

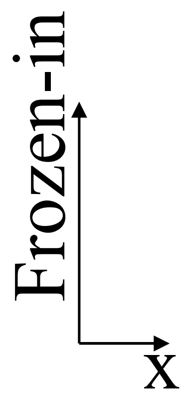


Outflow direction(x).

Short simulation box

(L_x=258)





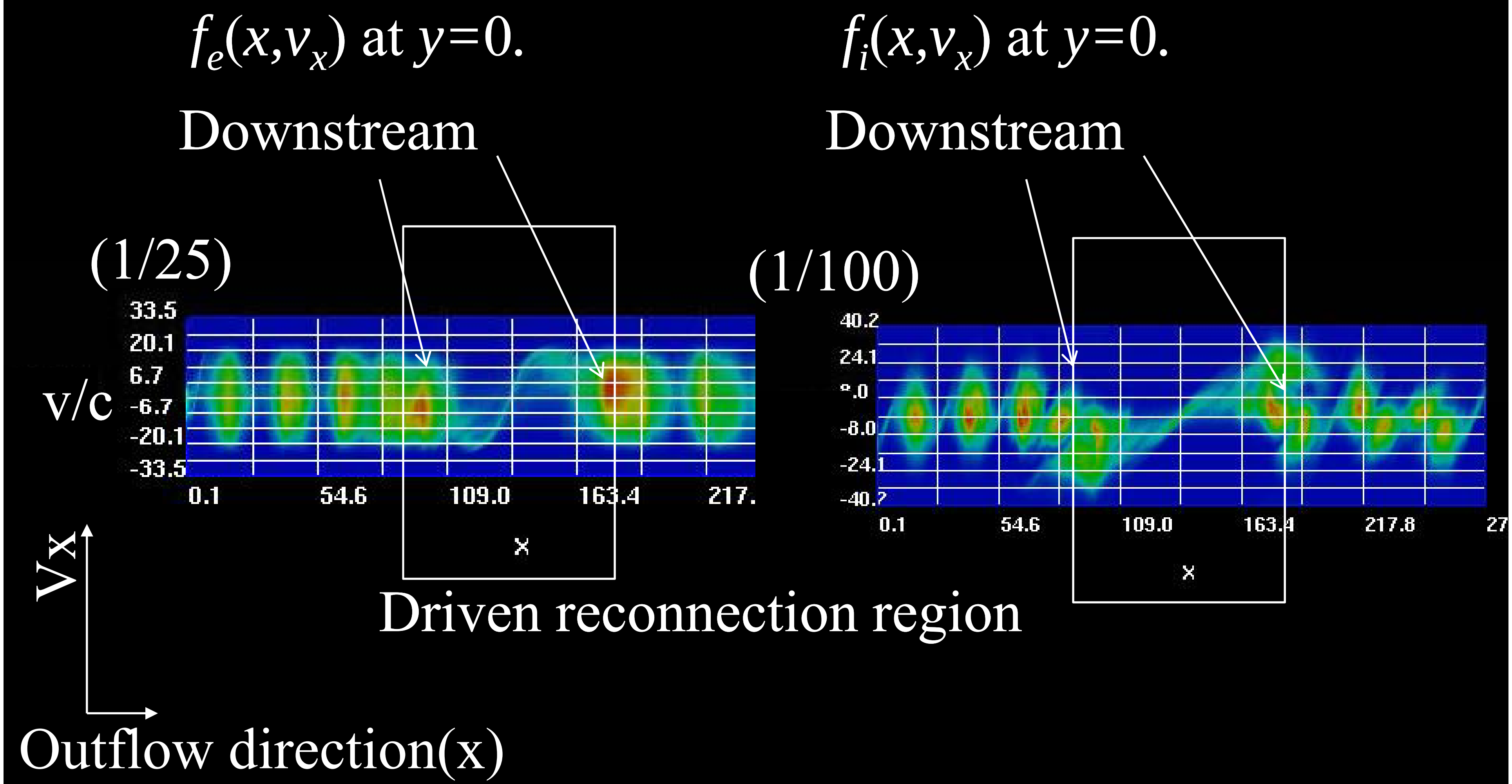
Results（2）Effect of downstream model

All of these data indicate that downstream model fulfills its function very much!

It is successful to develop the open boundary model to investigate reconnection from microscopic view point!

There is a problem in connection with macroscopic region in the interlocked model.

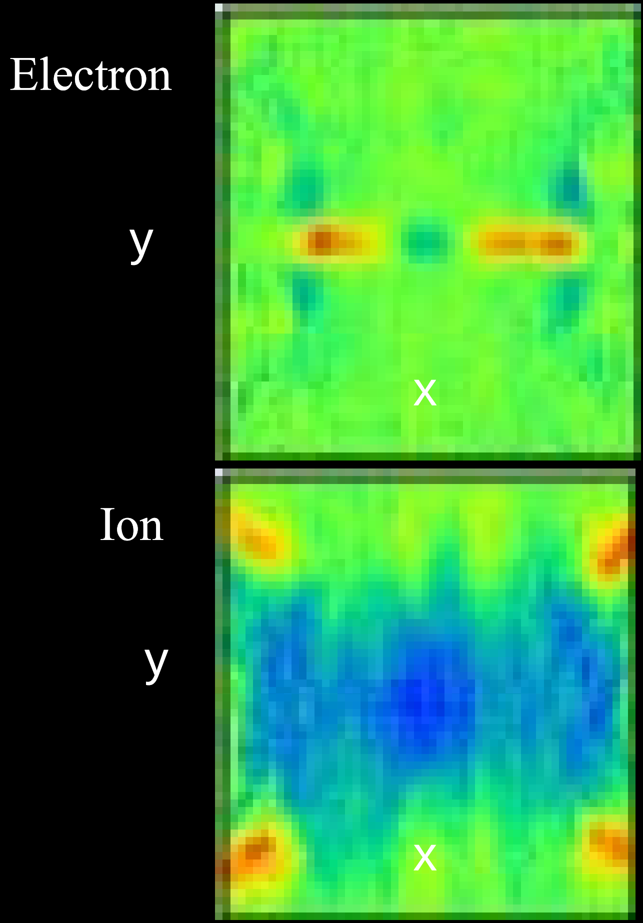
Results(7) Velocity Distribution



Velocity distribution at downstream is not a simple Maxwellian.

Results (8) Frozen-in condition near the downstream boundary

Contour plots of $E_z+(uXB)_z$.



Frozen-in condition is broken at downstream condition. Then downstream region can not be connected directly with MHD model.

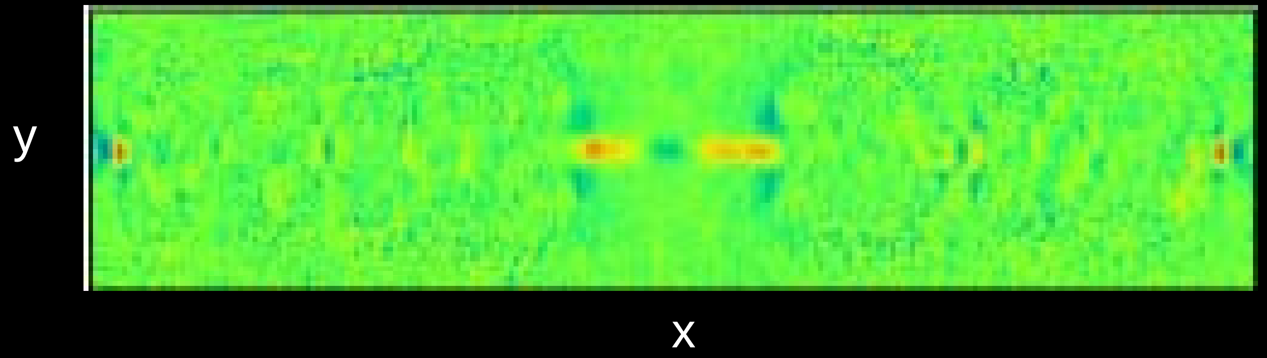
Enlarge of simulation box.

Buffer region between micro and macro regions.

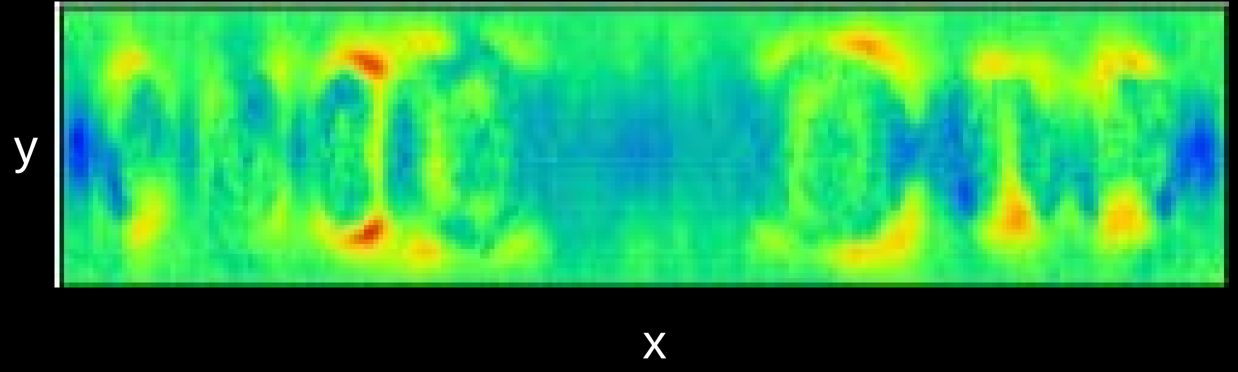
Results（8）Frozen-in condition near the downstream boundary

Contour plots of $E_z+(uXB)_z$.

Electron



Ion



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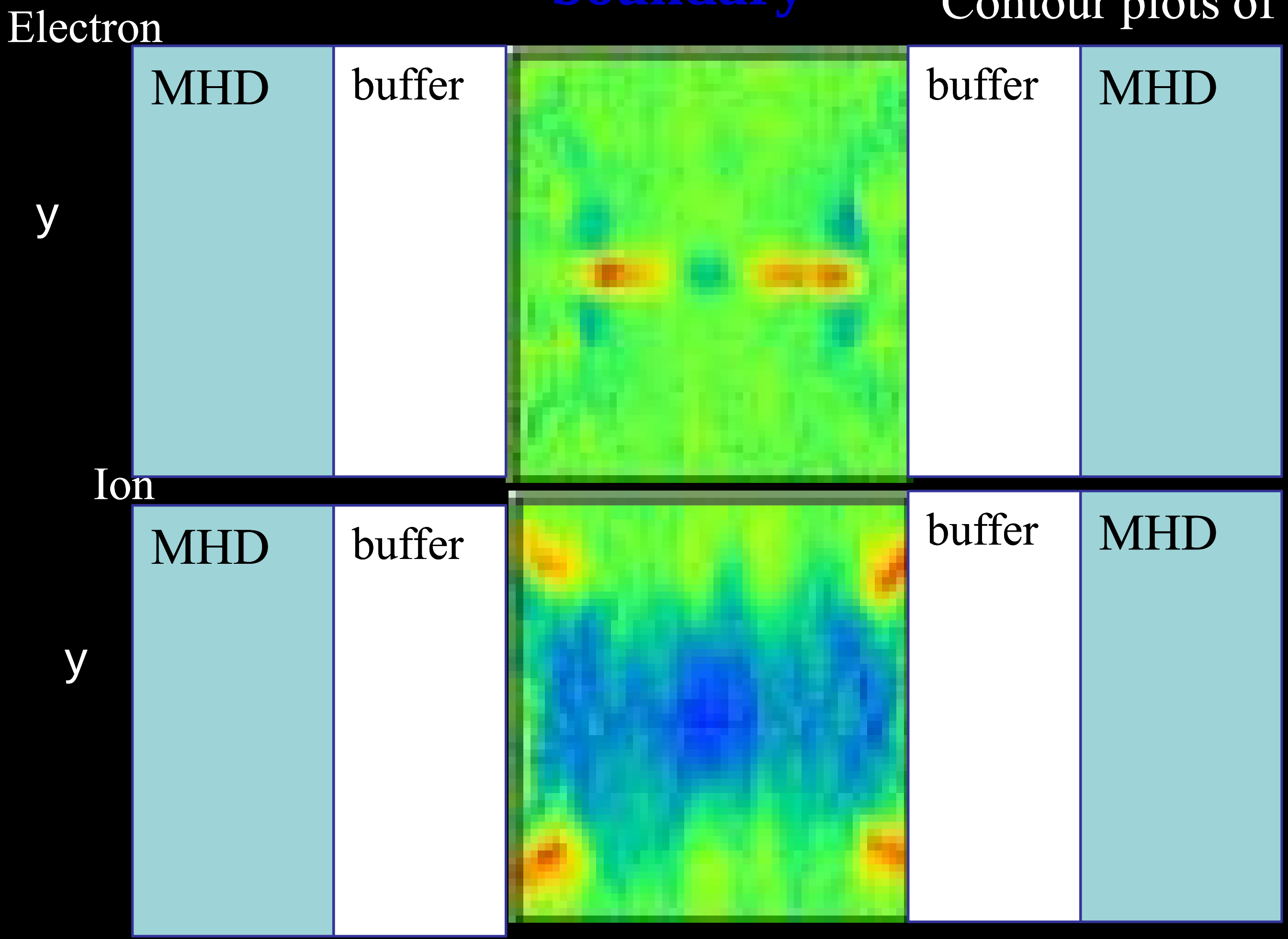

Frozen-in condition is broken at downstream condition. Then downstream region can not be connected directly with MHD model.

Enlarge of simulation box.

Buffer region between micro and macro regions.

Conclusions

- In order to investigate the mechanism of triggering collisionless magnetic reconnection from microscopic view point, we develop a three-dimensional electromagnetic particle simulation in an open system \`***PASMO***’.
- PASMO can be also used for the interlocked model.
- We developed a boundary condition for upstream and downstream boundaries for the open boundary condition in order to increase accuracy of simulation.
- The frozen-in condition is satisfied at the upstream boundary with high accuracy. The upstream can be directly connected to macro region.
- Unphysical noise is reduced at the downstream.
- MHD condition is broken at the downstream region. We need some methods in order to connect micro region to MHD region at the downstream, elongation of simulation box, buffer region, and so on.