Development of Macro-Micro Interlocked Simulation Algorithm

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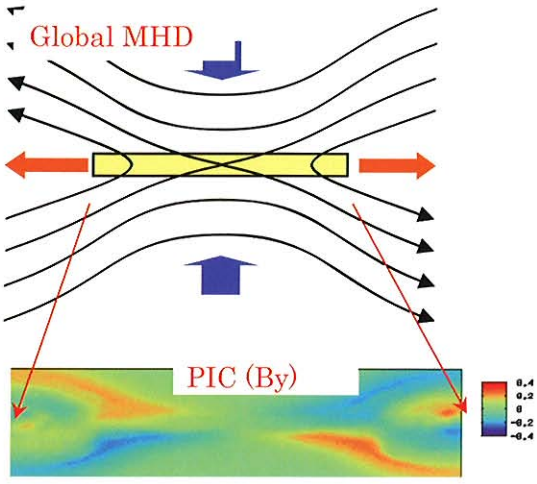
A fluid description of plasmas is useful to investigate the global structure in space plasma, such as the magnetosphere and heliosphere. It can reproduce the time evolution of macroscopic variations of density, bulk velocity and so on. On the other hand, the microscopic dynamics of plasmas should be described by spatial and velocity distribution in the phase space. Wave-particle interaction process is the typical example for the application of the microscopic description. For these micro- and macroscopic description, different kinds of numerical approach may work well, respectively, e.g. MHD simulation for the macroscopic phenomena and PIC simulation for microscopic process. However, it is widely accepted that the cross-scale interaction between micro and macro processes plays a crucial role, for instance, in the diffusion region in the magnetic reconnection process. Therefore, a new model which can treat MHD-scale dynamics including particle kinetic effects is necessary. We have developed the new simulation method called "Interlocked simulation", in which MHD and PIC simulations are simultaneously performed. Here, we show its algorithm and some examples.



Top: A schematic illustration of the interlocked simulation. MHD simulation is performed to solve the global structure of the system, and PIC simulation is performed to investigate the kinetic effects in the diffusion region. Bottom: Results from the PIC simulation in X-Z 2D plane. Plotted is Y component of the magnetic field. By embedding the results from PIC simulation into MHD simulation, we can perform global fluid simulations including particle kinetic effects.

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Simulations in plasma physics

- Fluid dynamics
  - MHD model
    - large scale
- Particle dynamics
  - PIC (Particle in Cell) model
    - kinetics
- Multi-physics This study
  - Interlocked model
    - large scale fluid simulations including kinetic effects are able to be performed.

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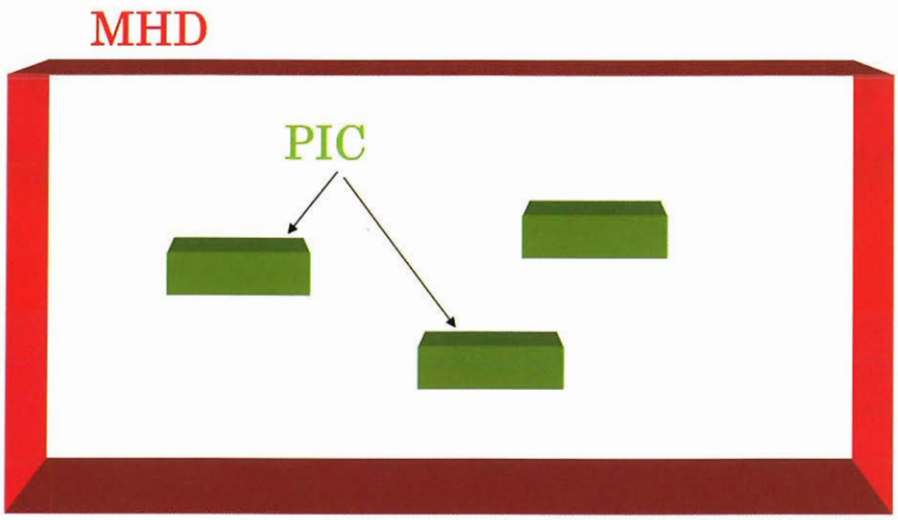
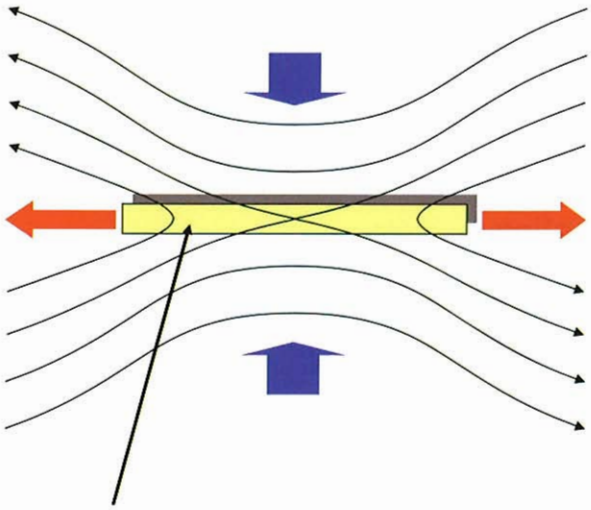
Concept of the Interlocked simulation



PIC simulations embedded in MHD simulation

Application of the Interlocked simulations: Magnetic Reconnection

Global MHD Simulation



PIC Simulation in the diffusion region

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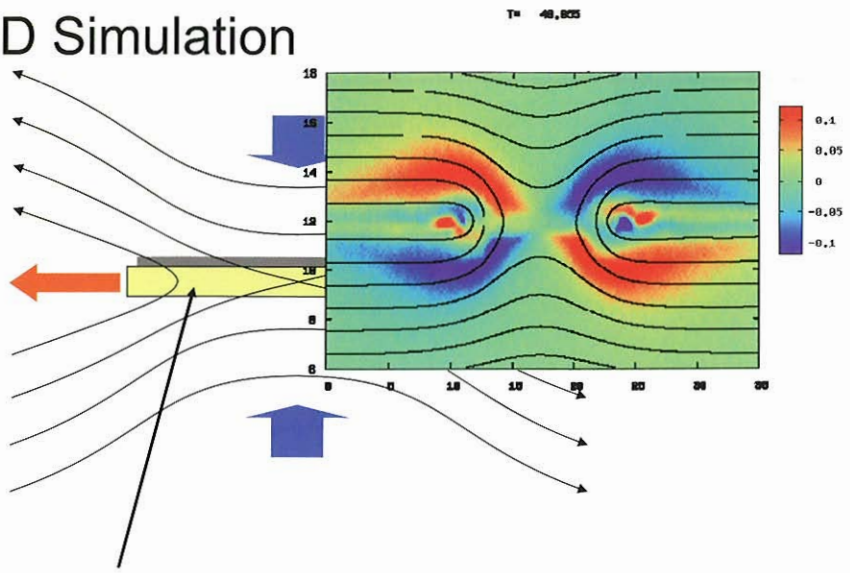
Application of the Interlocked simulations: Magnetic Reconnection

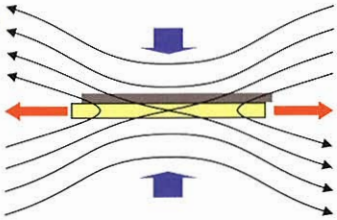
Global MHD Simulation



PIC Simulation in the diffusion region

Useful Points of the Interlocked simulation

- For MACRO part (MHD)
  Diffusion process is precisely included.
- For MICRO part (PIC)
  - Realistic boundary conditions are imposed.
    - Non uniform conditions in space
    - Non stationary conditions in time



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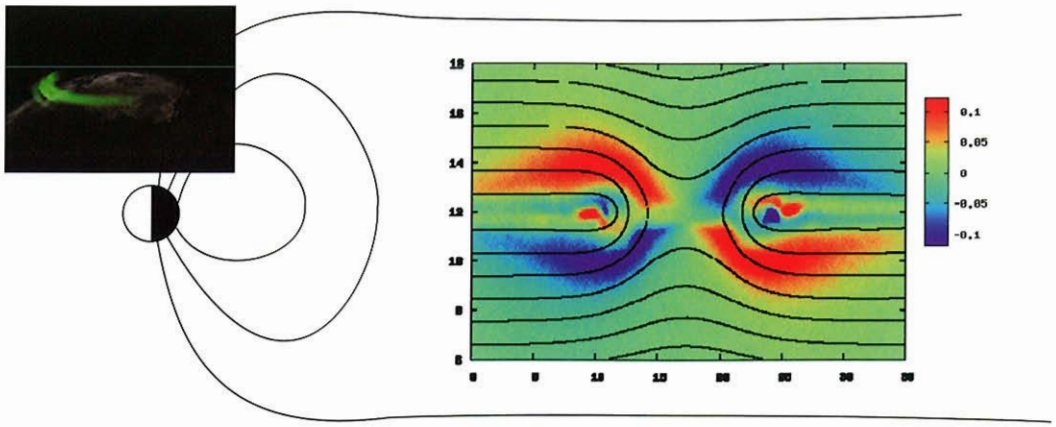
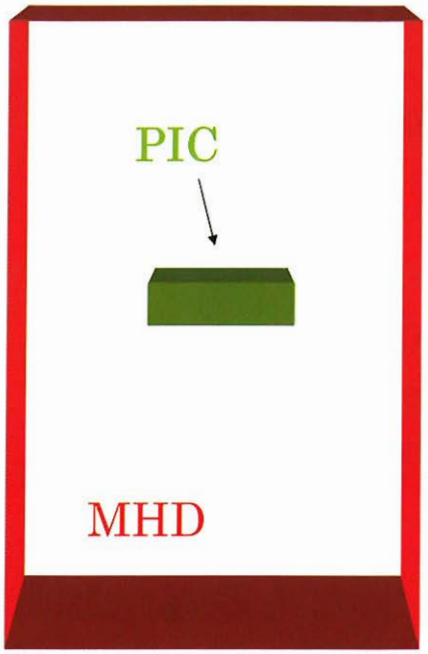
M-I Coupling and Magnetic Reconnection



Magnetic Field Profile
color contour : out of plane component
curves: on the plane

PIC simulations in MHD simulation



Boundary Conditions
E, B, J, V, N, P

In PIC area,
Replacement
E, J, B, V, N, P

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Electric-Field Current-Density (MHD)

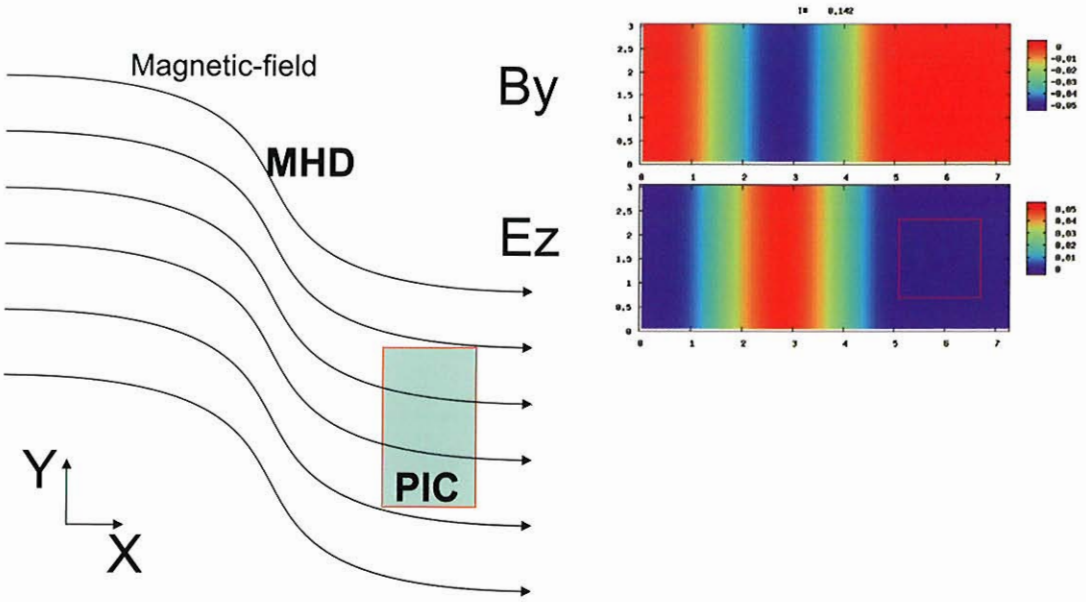
$$\mathbf{E}+\mathbf{V}\times\mathbf{B}=\eta\mathbf{J}+\frac{1}{ne}\mathbf{J}\times\mathbf{B}-\frac{1}{ne}\nabla\cdot\mathbf{P_e}+\frac{m_e}{ne^2}\frac{\partial\mathbf{J}}{\partial t}$$

$$\mathbf{J}=\nabla\times\mathbf{B}$$

are not advanced in time.

Data from PIC simulations are used.

Test on Alfvén Wave propagation



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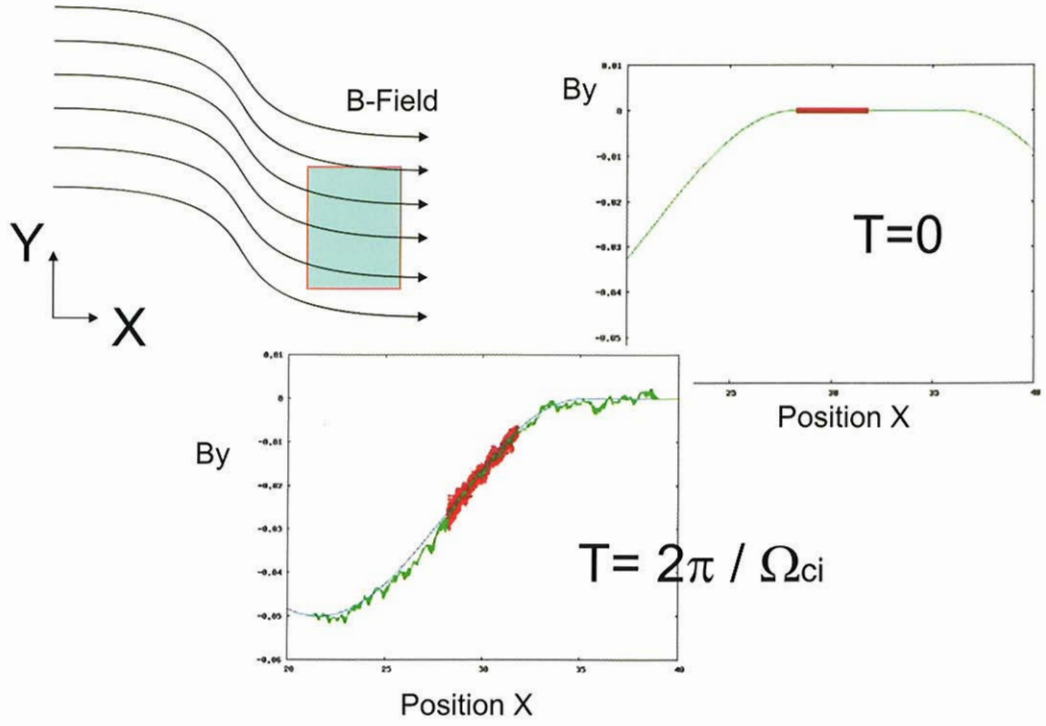
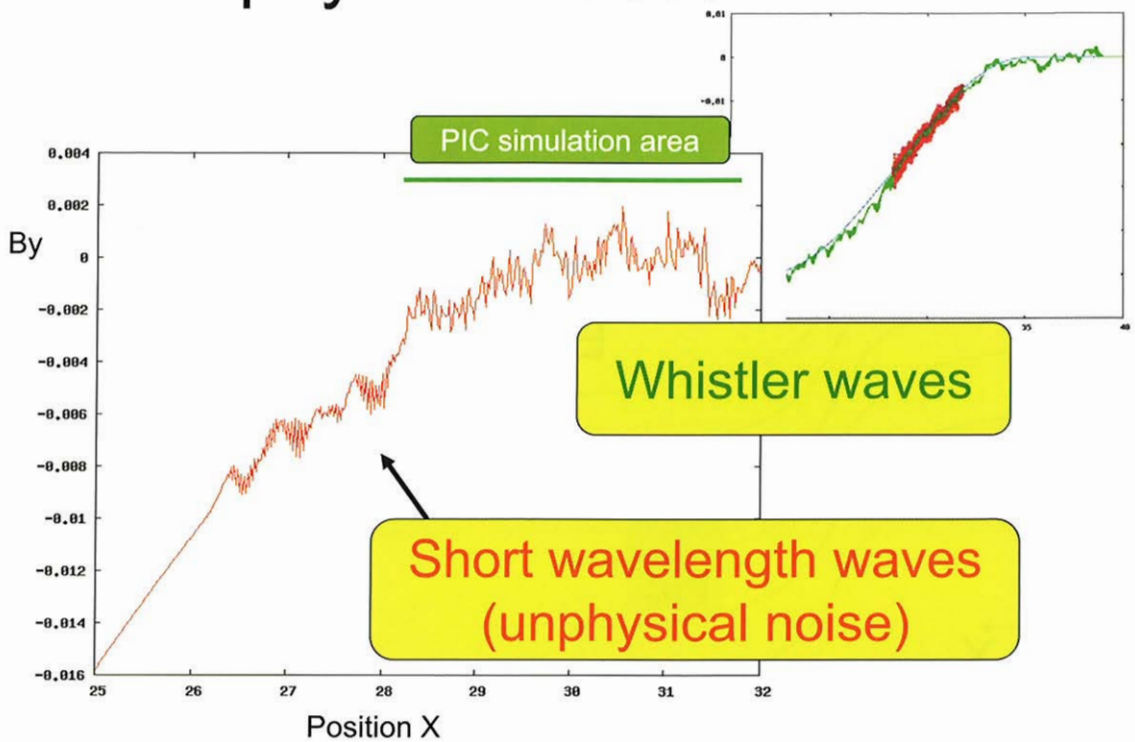
Detailed waveform



Unphysical noises in MHD



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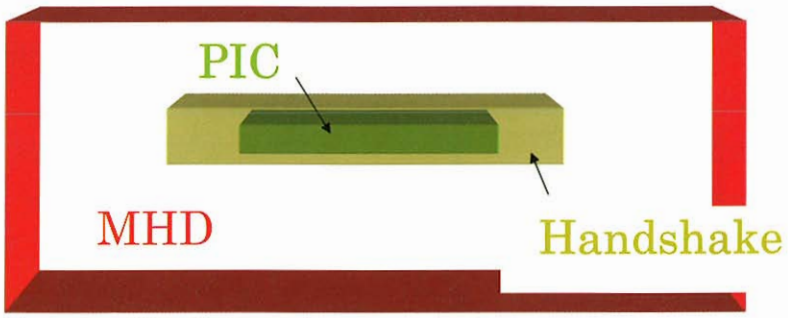
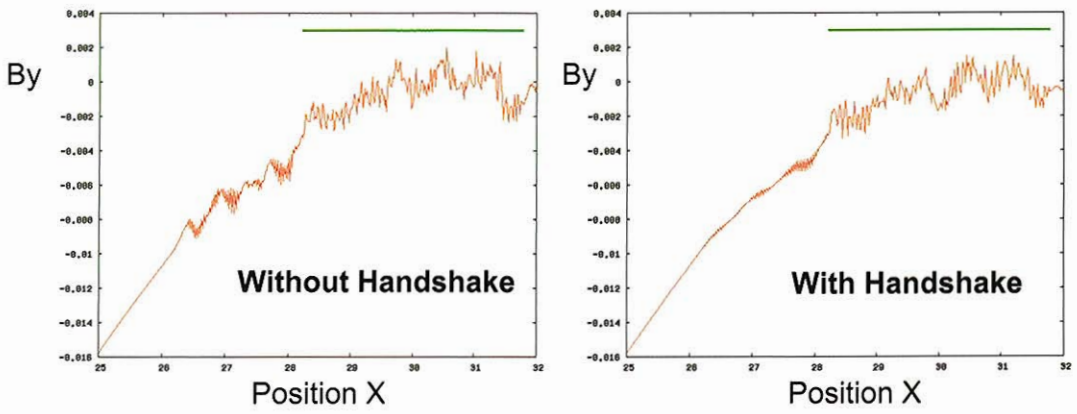
PIC simulations in MHD simulation



Handshake region is necessary to absorb
- High frequency waves (Whistler etc.) in PIC.
- Abrupt change of boundary condition from MHD to PIC.

$$\mathbf{E}_{HS} = \alpha \mathbf{E}_{PIC} + (1-\alpha)\mathbf{E}_{MHD} \qquad (0 \le \alpha \le 1)$$

Noise reduction using the handshake area



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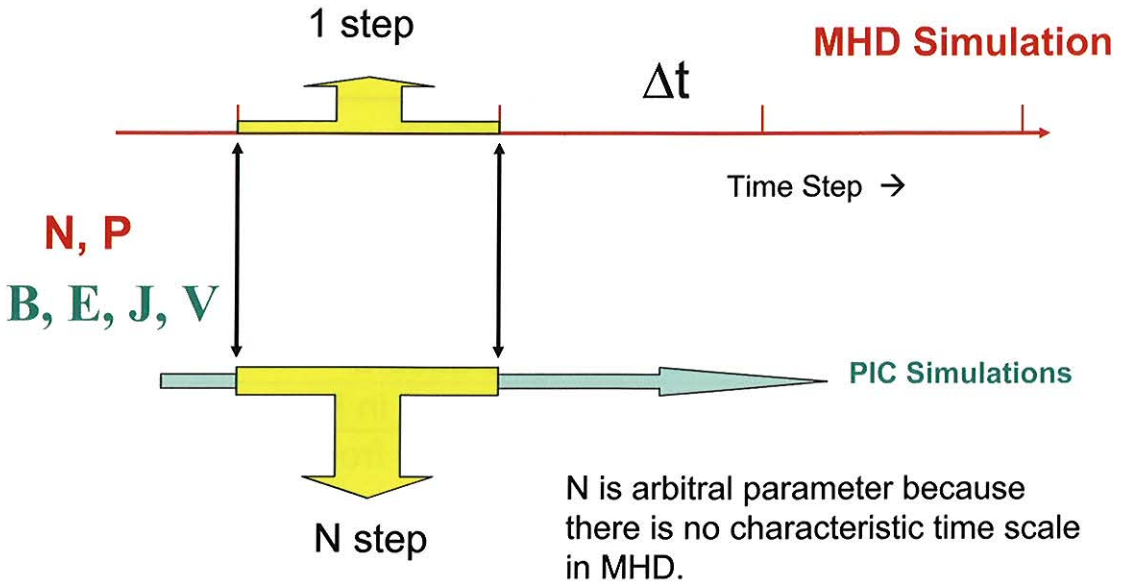
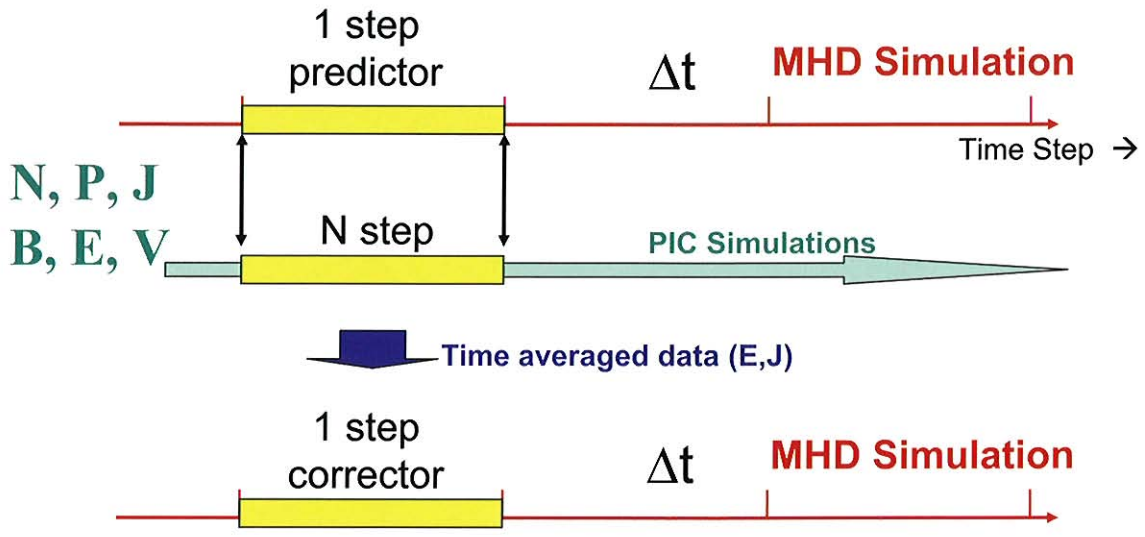
Time sequence of the interlocked simulation



Time sequence of the interlocked simulation (Predictor-Corrector algorithm)



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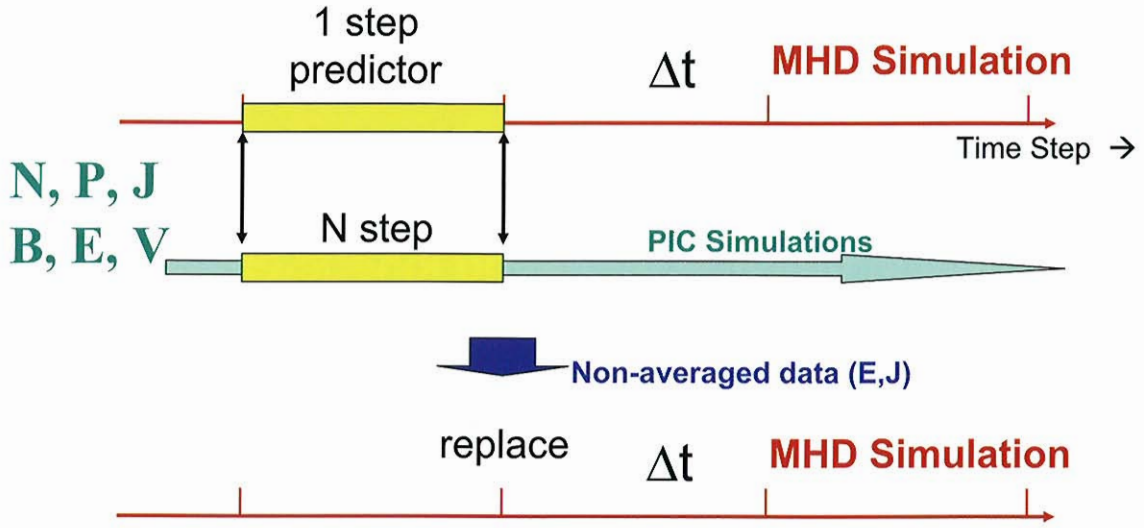
Time sequence of the interlocked simulation (Predictor-Replace algorithm)



Program

```
if(rank==Macro) then
   do iT = 1, Nstep_Macro
      call Macro_work1
      …
      call MPI_SEND
      call MPI_RECV
      …
      call Macro_work2
   enddo
endif
```

```
if (rank==Micro) then
   do iT = 1, Nstep_Micro
      call Micro_work1
      …
      call MPI_RECV
      call MPI_SEND
      …
      call Micro_work2
   enddo
endif
```

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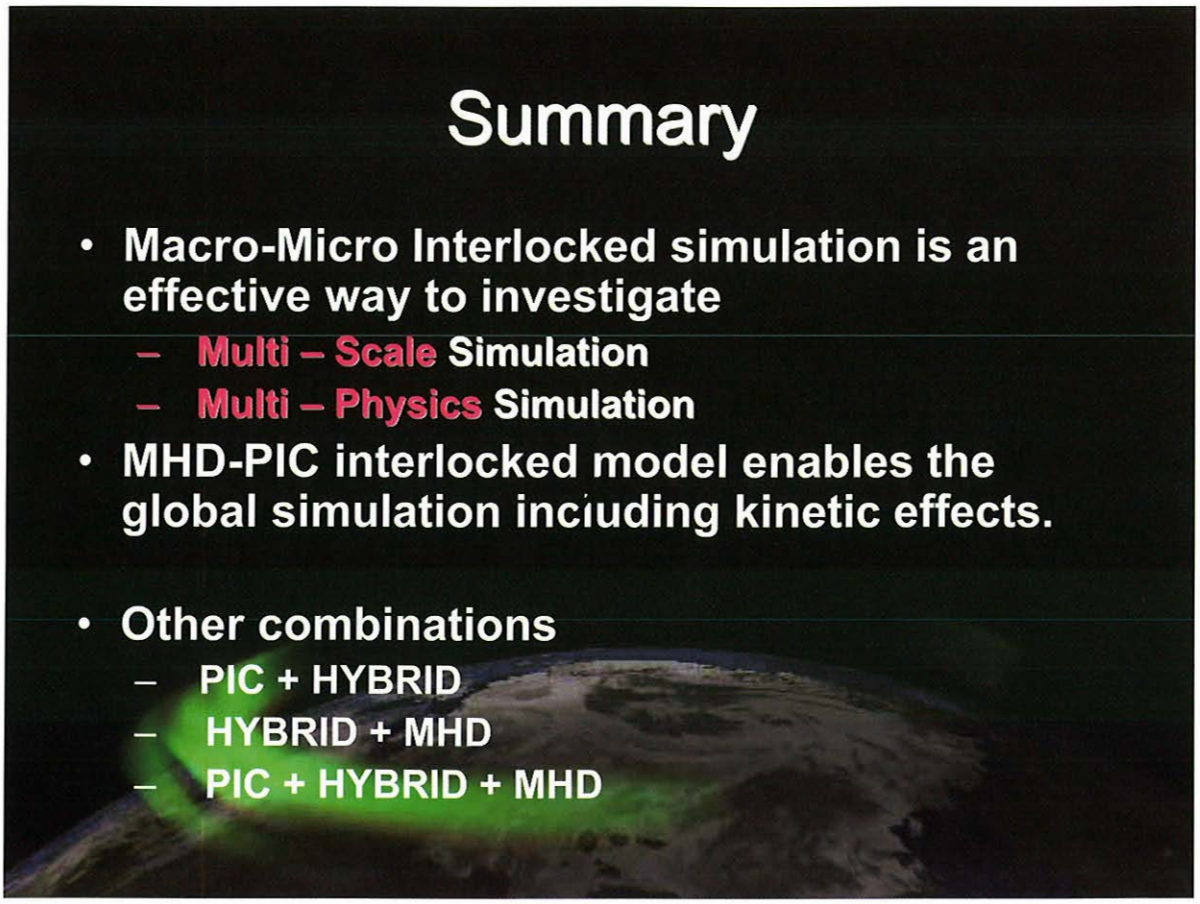

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