Magnetohydrodynamic with Adaptively Embedded Adaptive Mesh Particle-in-Cell Model

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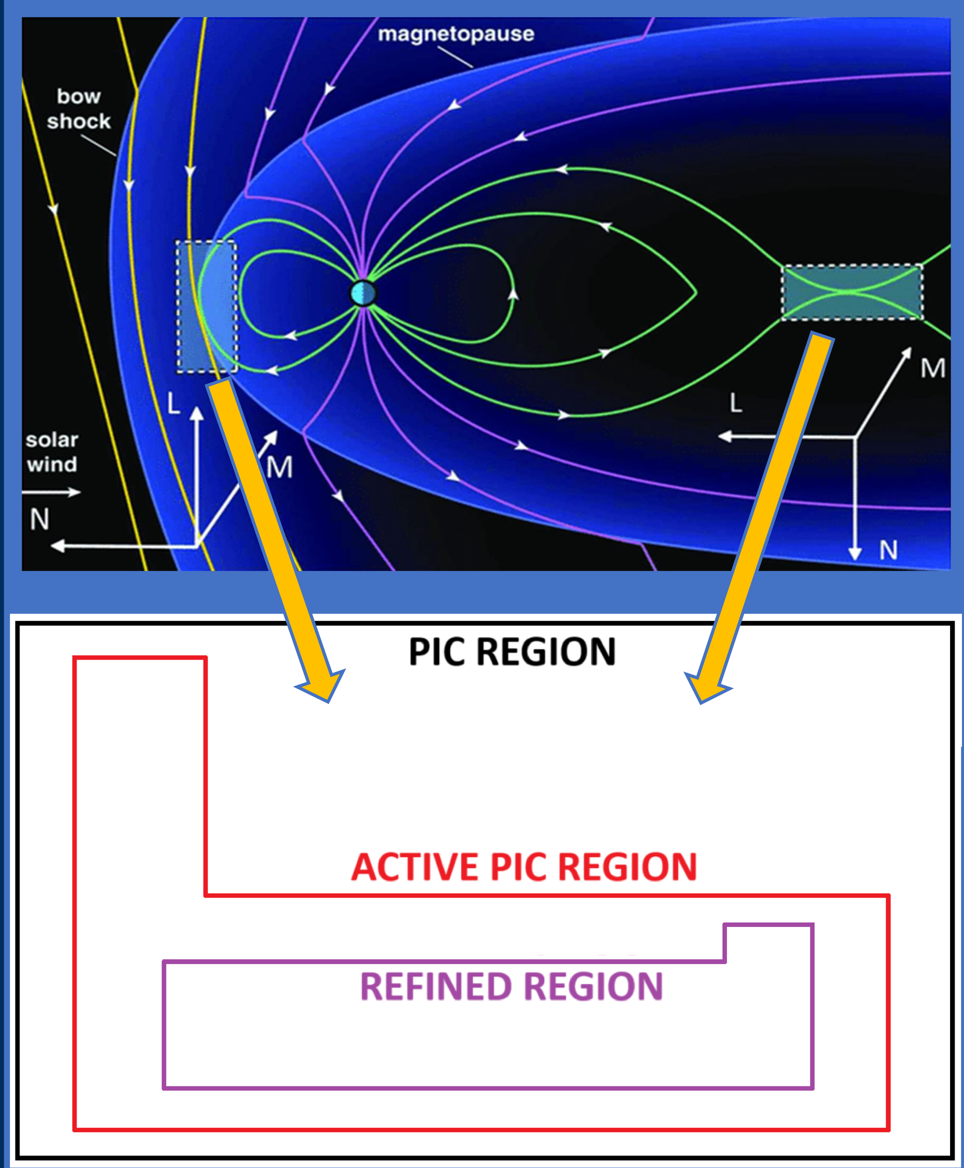
ABSTRACT

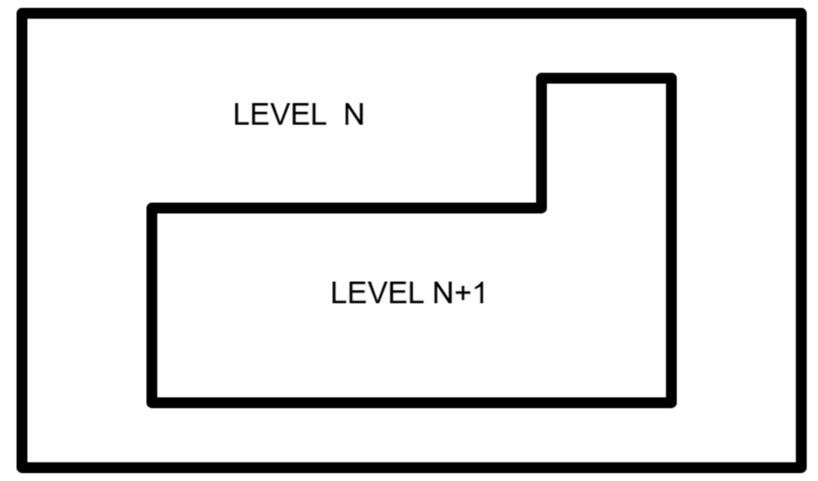
Magnetic reconnection that involves the electron scales plays a crucial role in space physical systems. We develop an efficient numerical model to capture electron scales and global scales at the same time. We introduce adaptive mesh refinement (AMR) into our semi-implicit particle-in-cell (PIC) code FLEKS (Flexible Exa-scale Kinetic Simulator). Since resolving electron skin depth across the entire PIC domain is computationally very expensive, the grid will be refined around the electron diffusion region to resolve the electron skin depth, while only the ion inertial length is fully resolved elsewhere.



GOALS

- Better resolve electron scales at the electron diffusion region
- Develop an adaptive mesh refinement semi-implicit particle-in-cell algorithm
  - Semi-implicit PIC allows changing grid resolution without stability restrictions
- All refinement levels share the same particles i.e. particles can cross-over from one refinement level to another
  - Different from Multi-level-multi-domain approach [Innocenti+ 2013]
- Maintain similar particles-per-cell numbers at all refined levels
  - Split / merge particles
- Minimize errors at refinement interfaces
- Satisfy Gauss law by correcting particle positions at the end of each time step

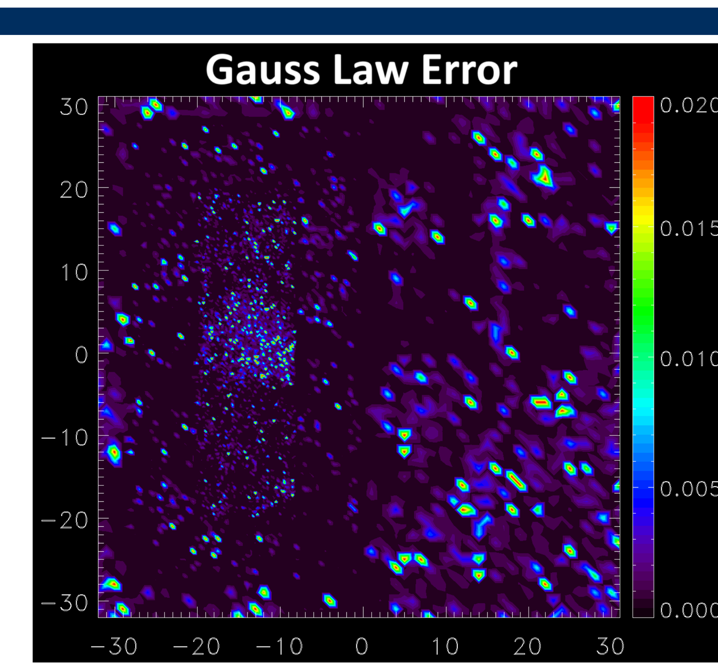
ALGORITHM



- Grid is initialized with electric / magnetic fields as well as particles
- Particles exist on the finest level only
- Particles deposit current on all underlying grid levels using their respective shape functions
- After current deposition, electric and magnetic fields are updated on level N
- The updated value of EM fields on level N act as boundary condition for level N+1
- After updating level N+1, EM fields from level N+1 are projected down back to level N, this ensures that both levels always have consistent solutions
- Particles are moved using the new field data
- Number of particles per cell is controlled by particle splitting and merging. A novel merging algorithm is used that ensures conservation of mass, momentum and energy while minimizing change in mass of individual particles [Chen+ 2024]
- Gauss law error is corrected by introducing a small displacement to the particle positions. Using a novel algorithm, we can correct Gauss law error perfectly even around the refinement interface

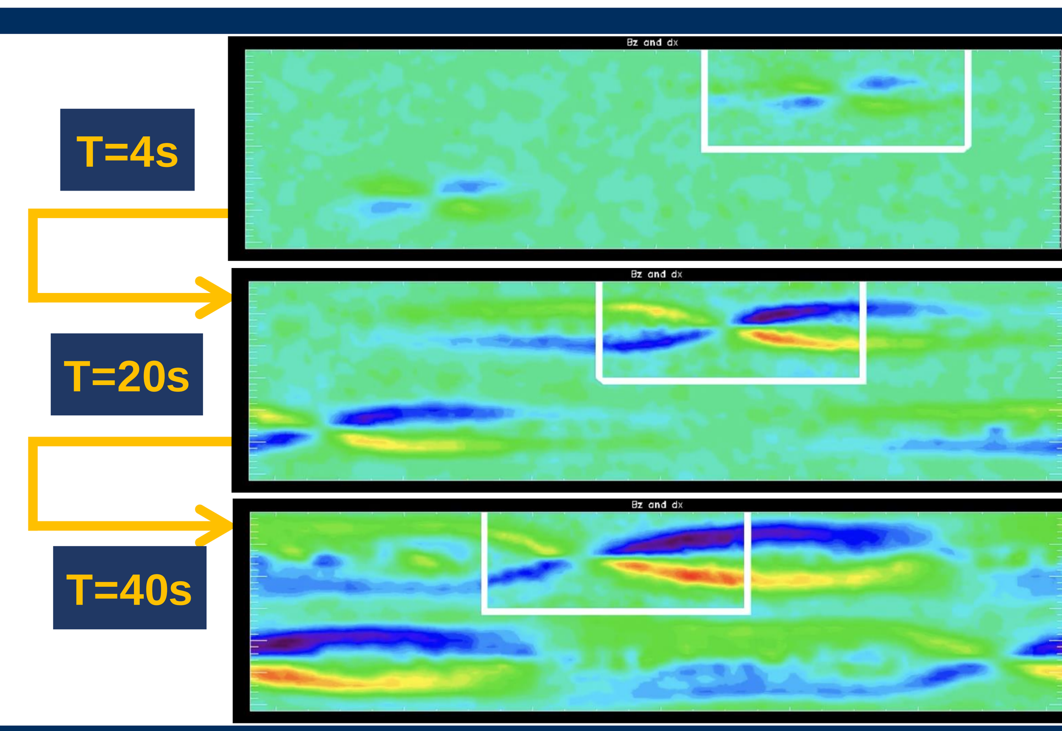
Gauss Law / Charge Conservation

- Numerical inaccuracies lead to build up of errors in Gauss law satisfaction
- Our method applies a slight displacement to particles such that Gauss law error is eliminated / reduced [Chen+ 2024]
- The method is now generalized to multiple grid levels :
  - Particles at level N+1 are adjusted to satisfy Gauss Law
  - At level N only the particles that don't influence level N+1 are adjusted



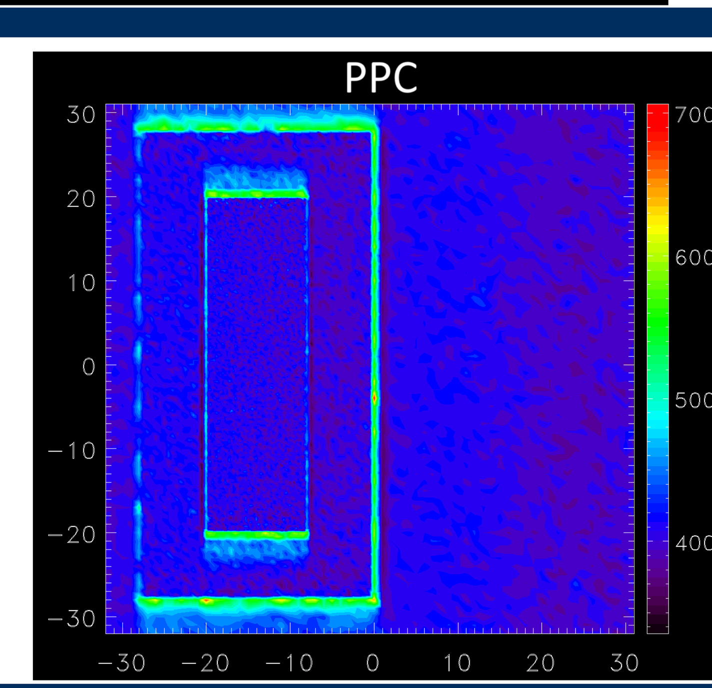
Dynamic Mesh Refinement

- Refinement regions are dynamic and can be used to track structures of interest
- Left moving symmetric reconnection is shown. The refinement moves left and always keeps the reconnection site in focus



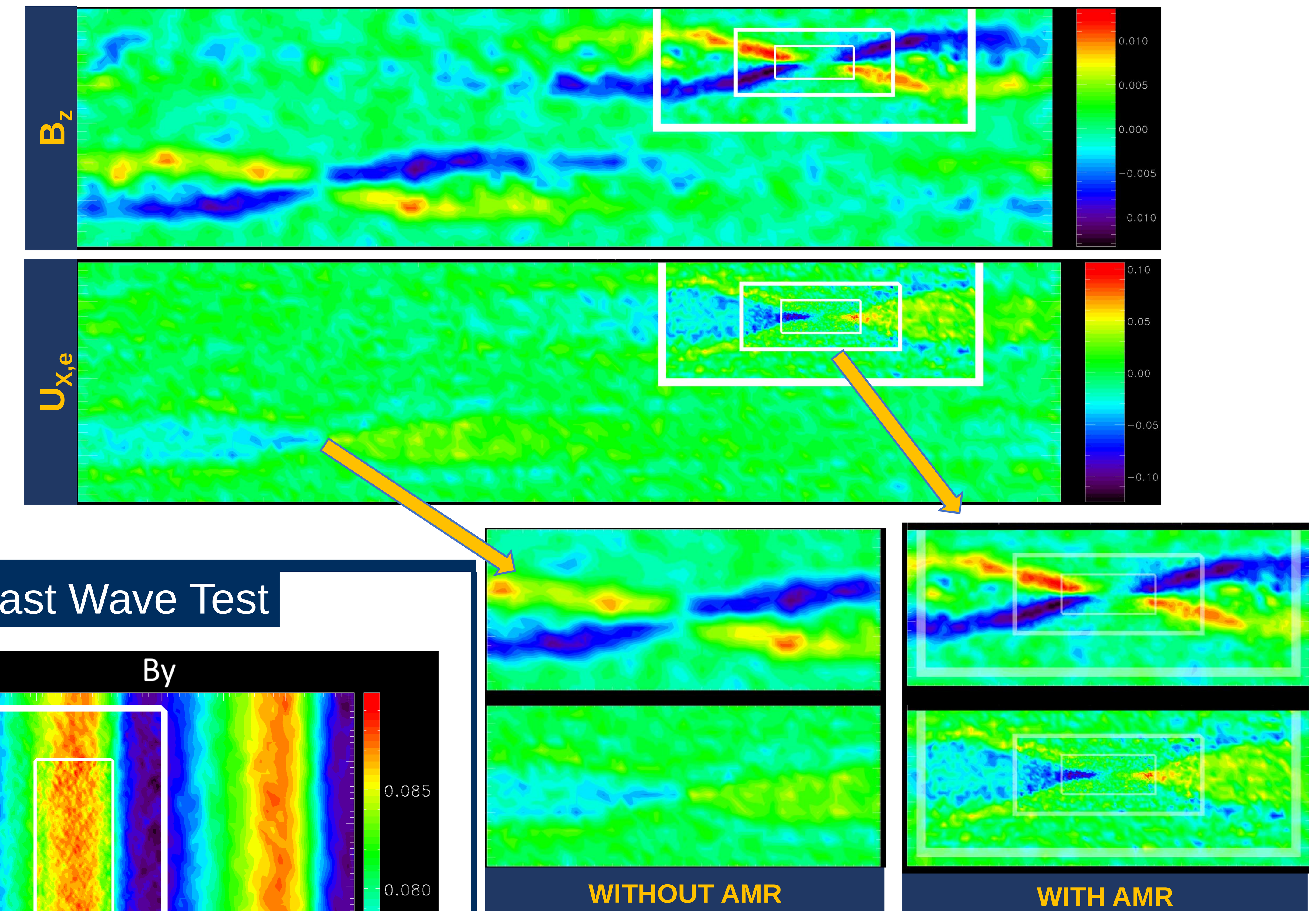
Particle merging/splitting

- Particles are split from one to two to keep the number of particles per cell constant
- Merging involves converting N particles to M particles such that mass, momentum and energy are conserved.
- Merging also uses a Lagrange multiplier method to minimize the relative change in the masses of the remaining M particles.
- Number of particles per cell increases drastically as fine level particles cross into the coarse region, which necessitates aggressive merging to keep the code efficient

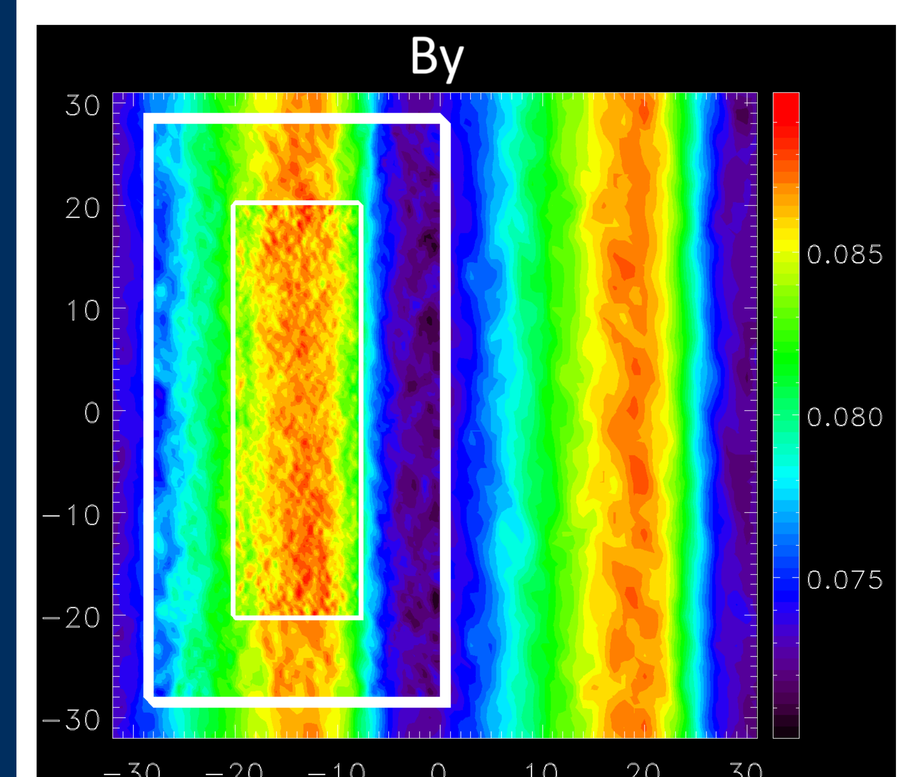


2D Reconnection Test

- 2D double current sheet reconnection test with only one reconnection site refined
- White rectangular boxes show refinement level changes. The refinement ratio is 2.
- There are 3 levels of refinement so the grid resolution on the finest grid is 8 times higher than on the coarsest grid
- B_z and electron velocity $U_{x,e}$ are shown
- The reconnection site with AMR is much better resolved



2D Fast Wave Test



- 2D fast wave test with only the left side of the domain refined
- There are 2 refinement levels
- Resolution of finest level is 4 times higher than the base grid
- The fast wave moves through the resolution changes without any artifacts

Summary

- A semi-implicit particle in cell code with adaptive mesh refinement has been developed
- Multi-level dynamic refinement works
- Particles from one level can cross over to the other level with minimal errors at the refinement interface
- Number of particles per cell can be maintained with sophisticated merging and splitting algorithms
- Gauss law is satisfied at all refinement levels including resolution change interfaces
- The method has been verified by 2D fast wave and reconnection tests.

Future Steps

- Apply MHD with embedded AMR PIC to 3D magnetosphere simulations.

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