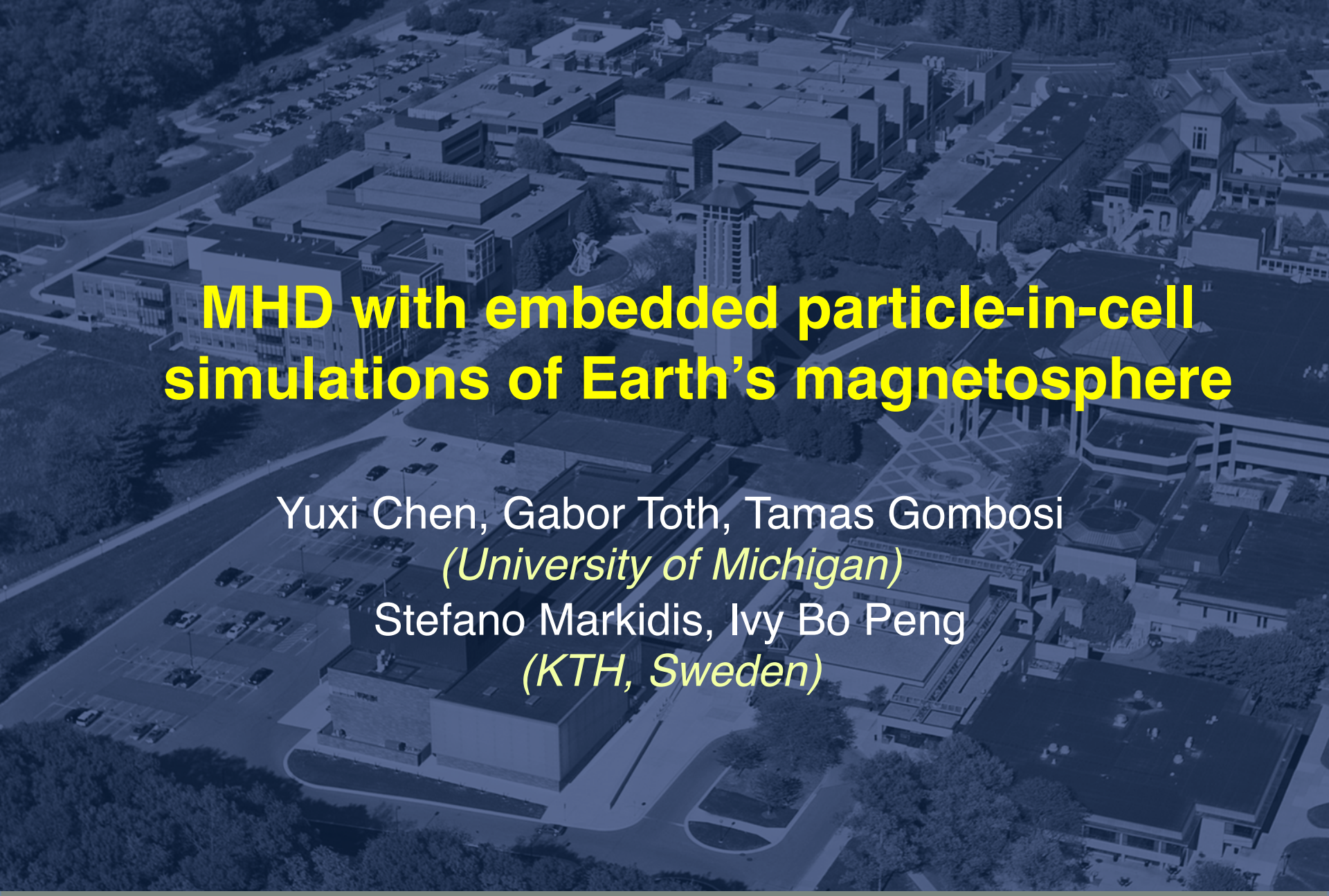


MHD with embedded particle-in-cell simulations of Earth's magnetosphere

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(University of Michigan)

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(KTH, Sweden)

COLLEGE OF ENERGINEERING

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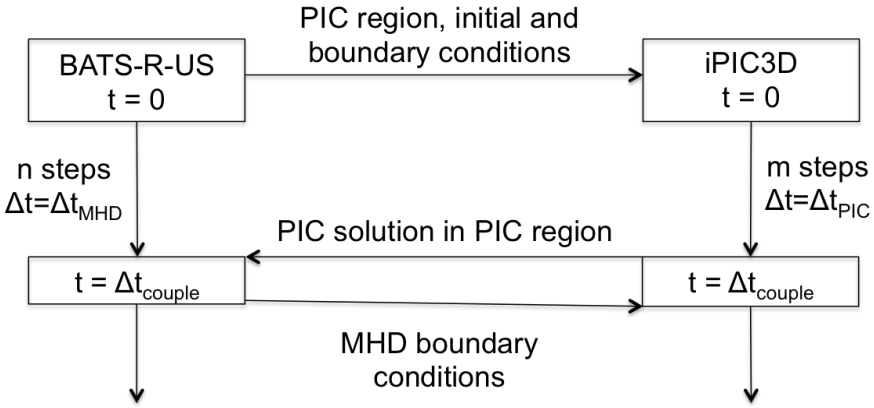
UNIVERSITY OF MICHIGAN

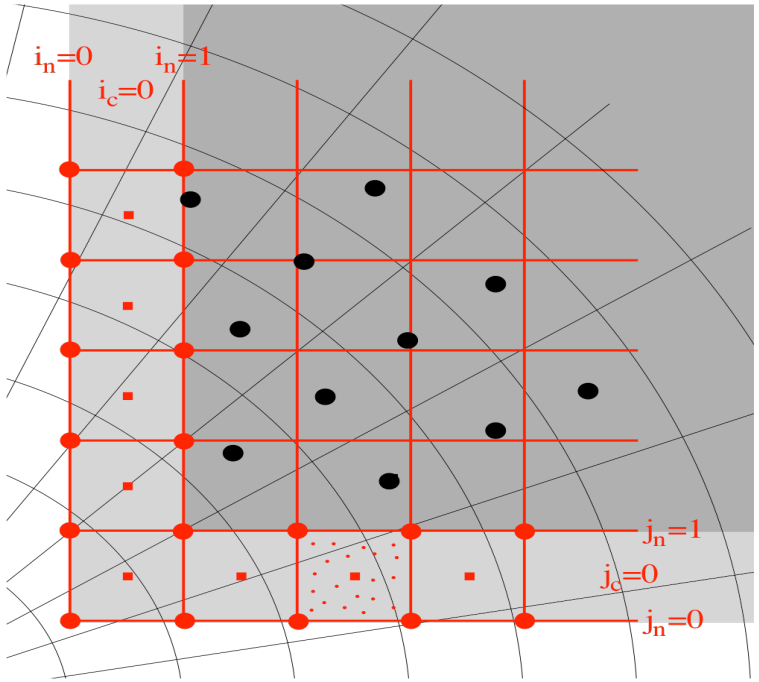
Center for Space Environment Modeling

Space Weather Modeling Framework

Couple MHD and PIC

- **MHD with embedded PIC model (MHD-EPIC): combine the efficiency of the global fluid code with the physics capabilities of the local PIC code**
  - MHD provides the initial state and boundary conditions for PIC
  - PIC overwrites the overlapped MHD cells
- **Improvements**
  - Multi-ion MHD. Separate electron pressure.
  - Different PIC and MHD grids including non-Cartesian AMR MHD grids.
  - Different PIC and MHD time steps
  - Multiple PIC domains
  - Efficiency and robustness





3D MHD-EPIC Simulation Setup

- **Physical parameters**
  - Artificially increase ion inertial length by a factor of 16, so $d_i \sim 1/6\ R_E$
  - Typical solar wind conditions:
    ρ= 5 amu/cm^3, U_X = -400km/s, B = [0,0,-5] nT
- **Hall MHD with separate electron pressure equation**
  - MHD domain: $-224 < x < 32$, $-128 < y, z < 128 R_E$
  - At the magnetopause $\Delta x = 1/16 R_E$ (~400km)
  - MHD uses ~20% CPU time
- **PIC**
  - PIC domain: $8 < x < 12$, $-6 < y < 6$, $-6 < z < 6 R_E$
  - $\Delta x = 1/32 R_E$: 5 cells per d_i (for f = 16)
  - 216 particles per cell per species: 8B total
  - Consuming ~80% simulation time
- **~18000 core hours modeling 1min**

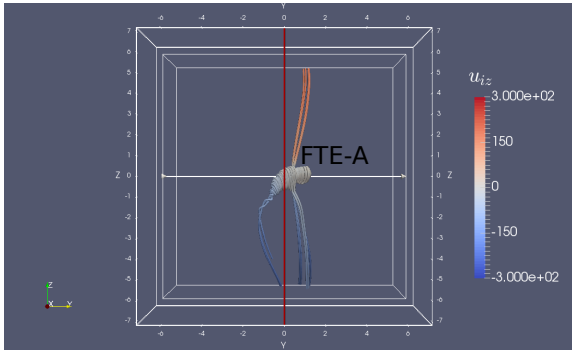
p [nPa]



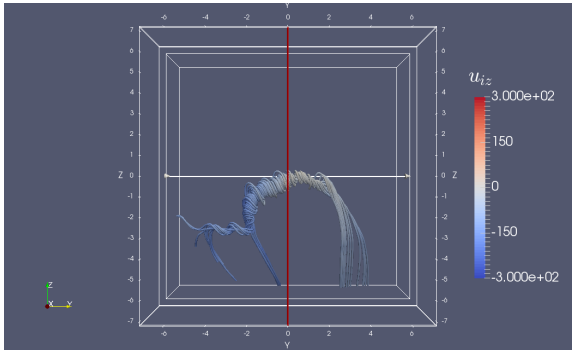
Evolution of FTEs (1)

- **FTEs colored by u_{iz}**
  - IMF is purely southward
  - FTEs grow in the dawn-dusk direction
  - u_{iz} varies along the FTE, and the FTE becomes tilted
  - Two FTEs can merge into one

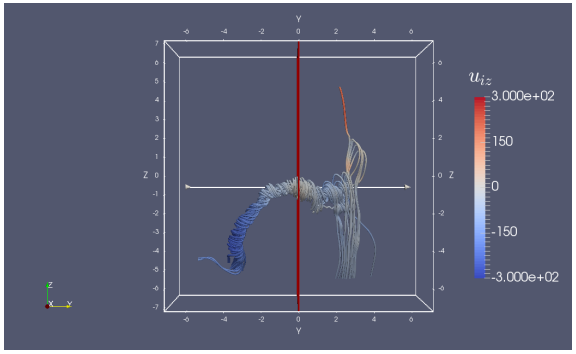
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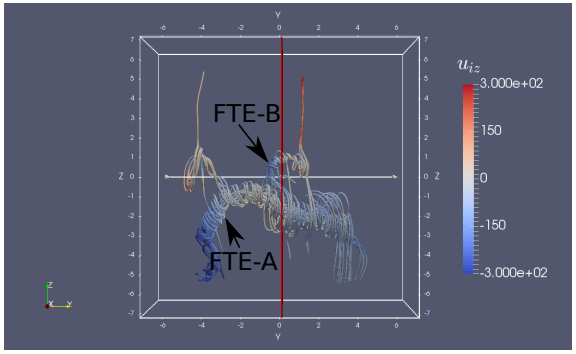
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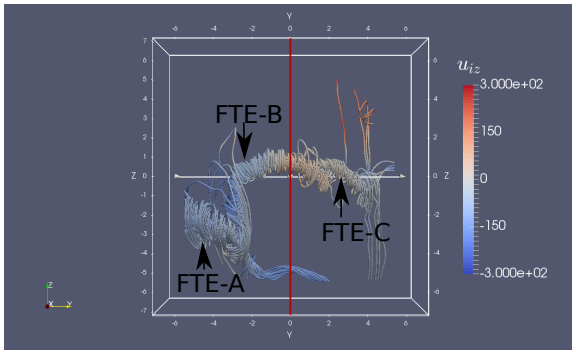
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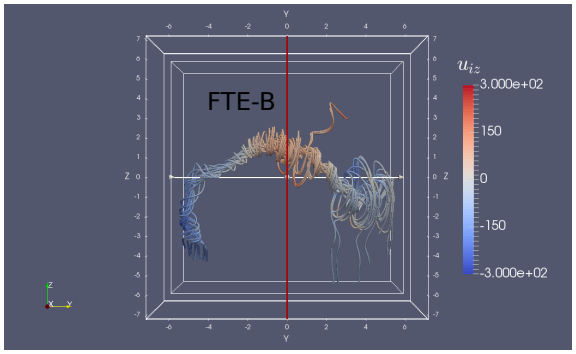
t=320s



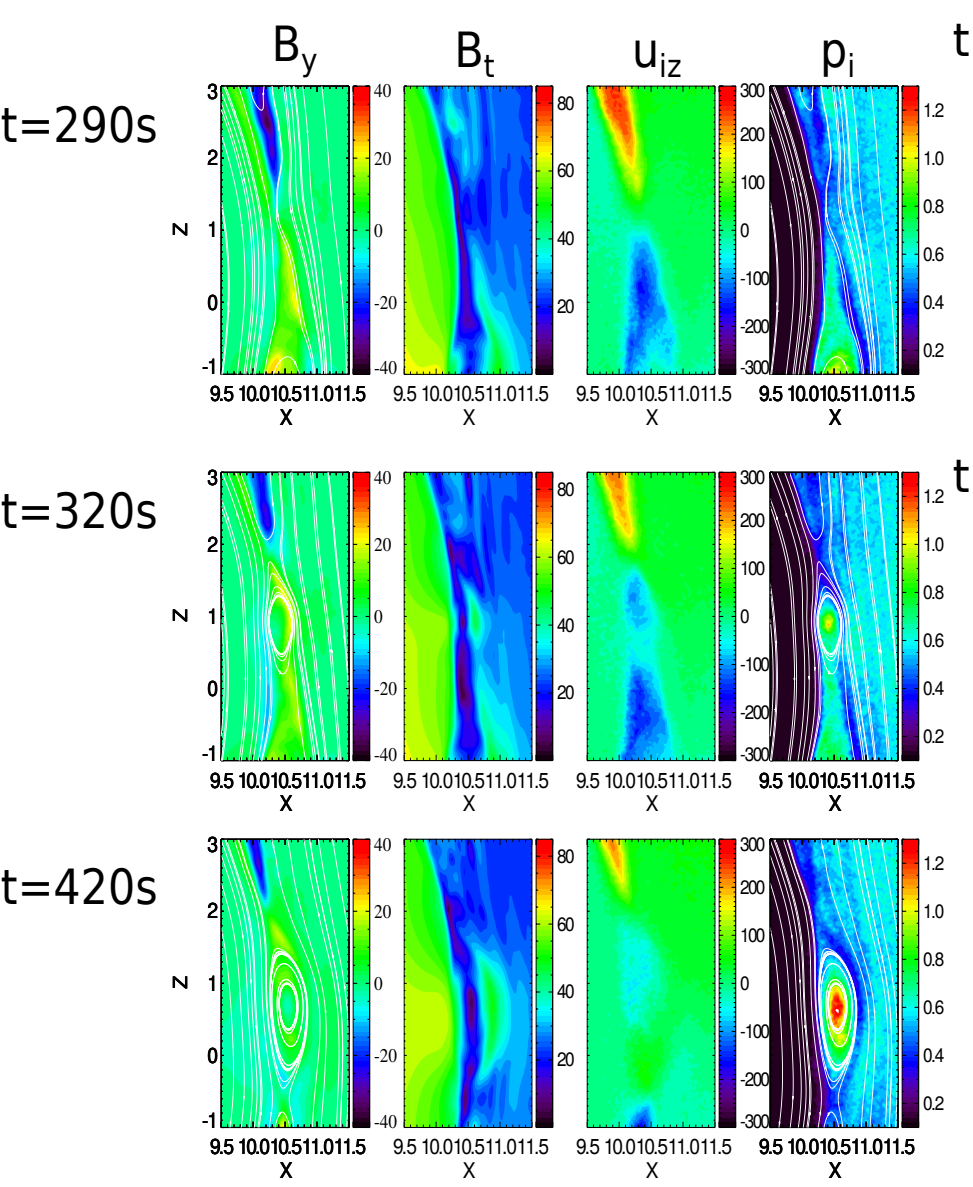
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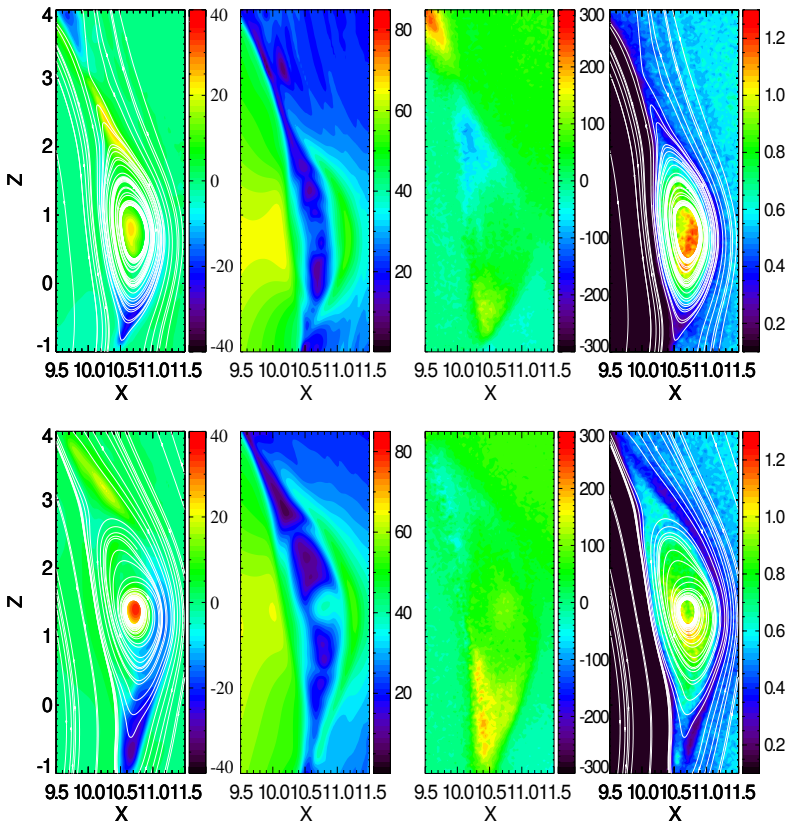


t=660s



Evolution of FTEs (2)



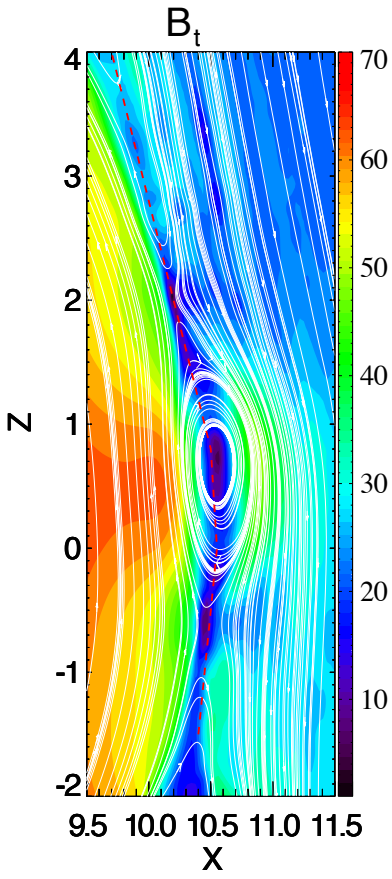


- The FTE is surrounded by two X lines
- The core field gradually increases to a significant value
- The core field is anticorrelated with plasma pressure

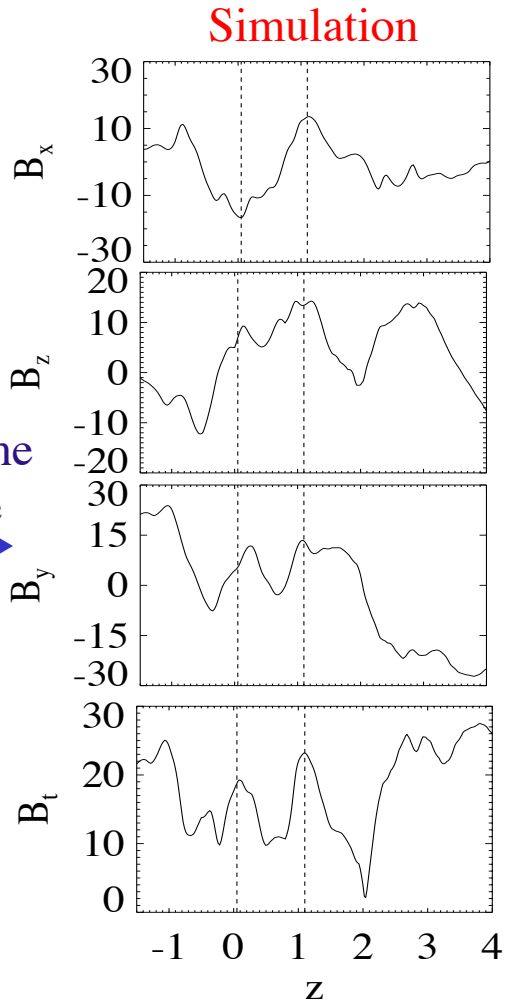
Crater FTE

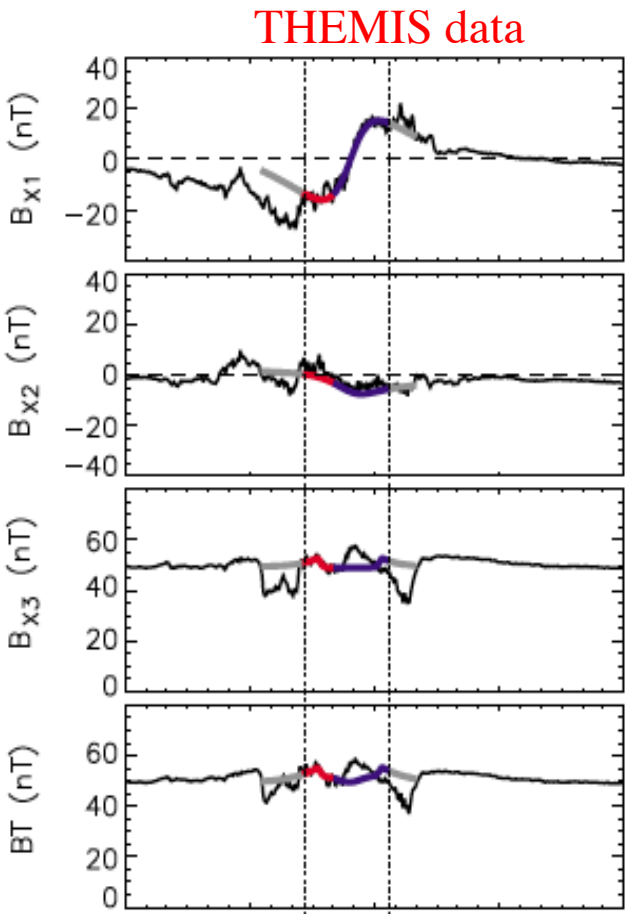
FTE from simulation

- B_x jumps from the negative peak (z=0) to the positive peak (z=1R_E)
- Bounded by the depressed magnetic field 'trenches' at z=-0.2R_E and z =2R_E
- B_t reaches local minimum at the center



B field along the red dashed line

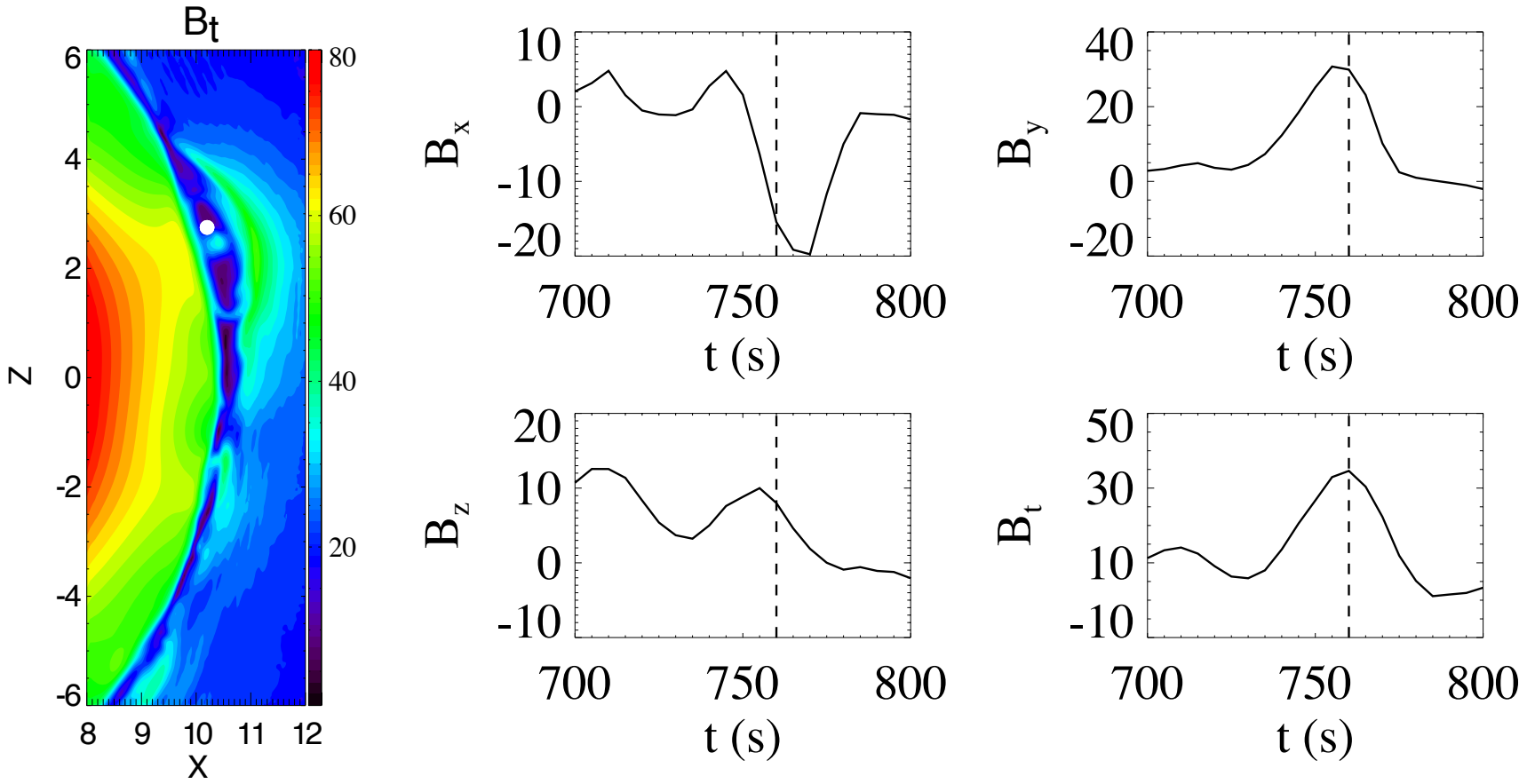




From *Zhang et al. (2010)*

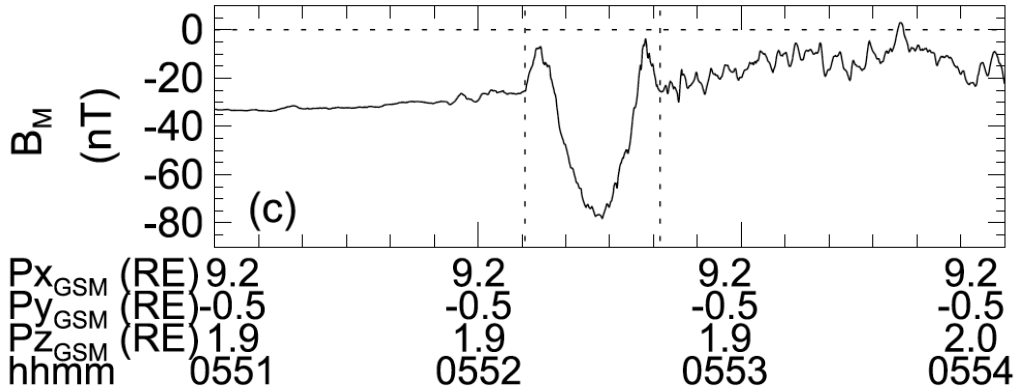
FTE with Typical Flux Rope Structure

- Core field grows to a significant value
- Both the core field B_y and the total field B_t reach local maximum near the center



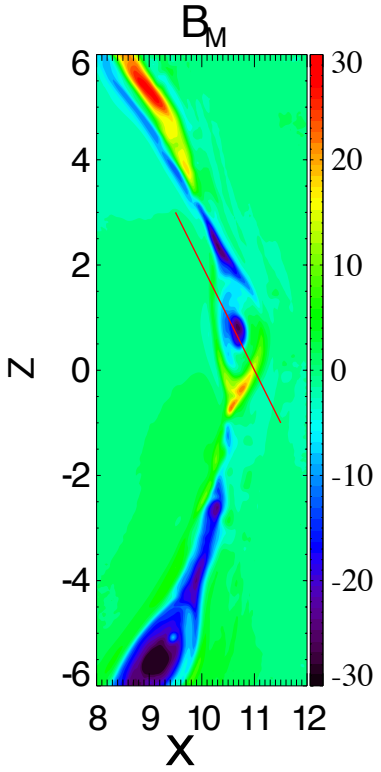
Tripolar Guide Field

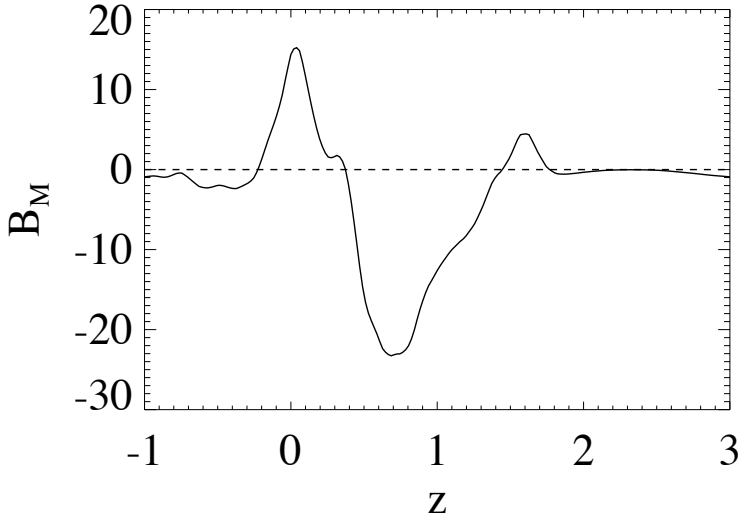
Polar observation



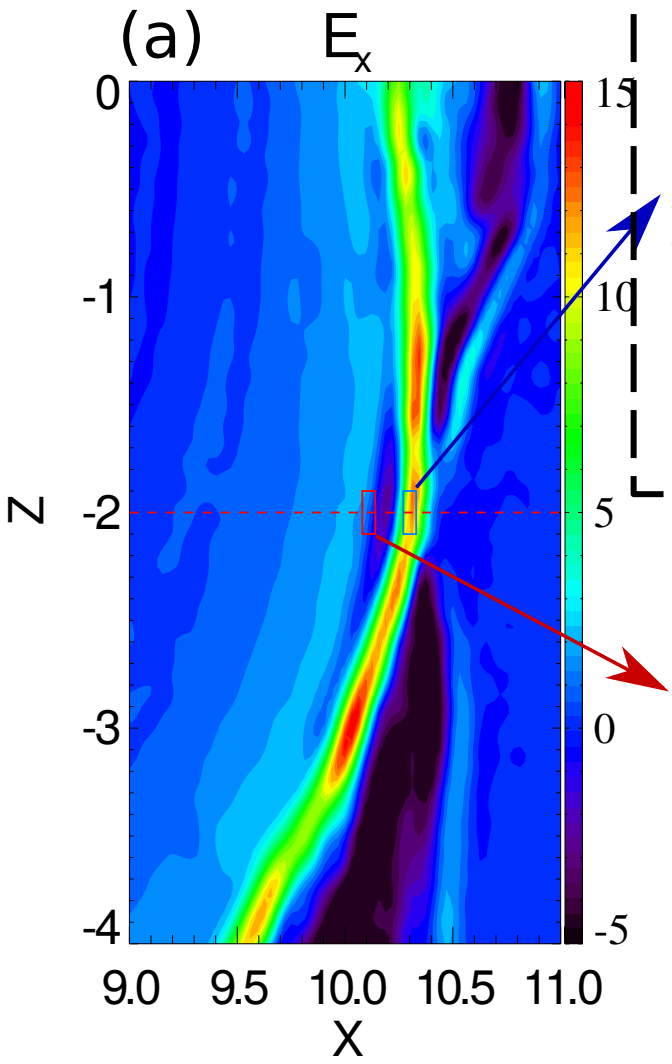
From *Eriksson et al. (2016)*

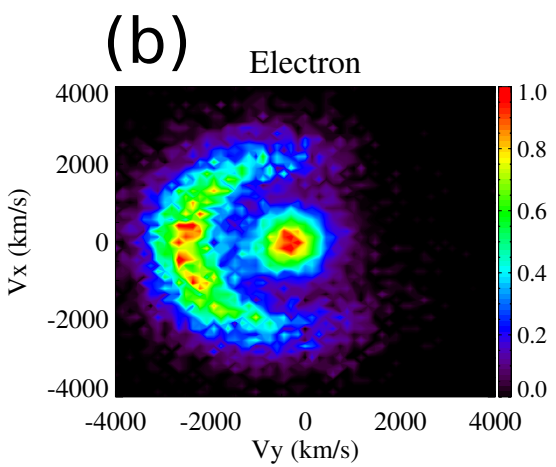
Simulation

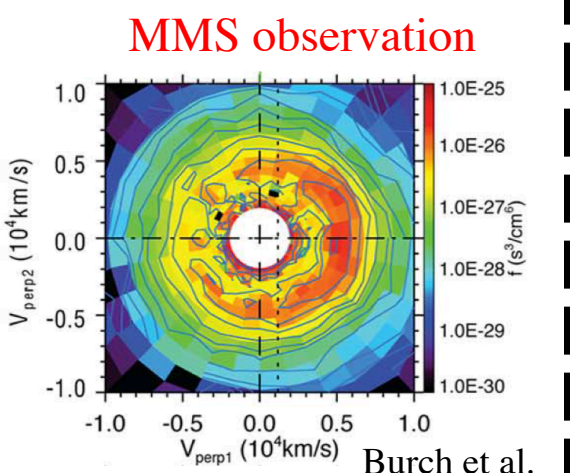




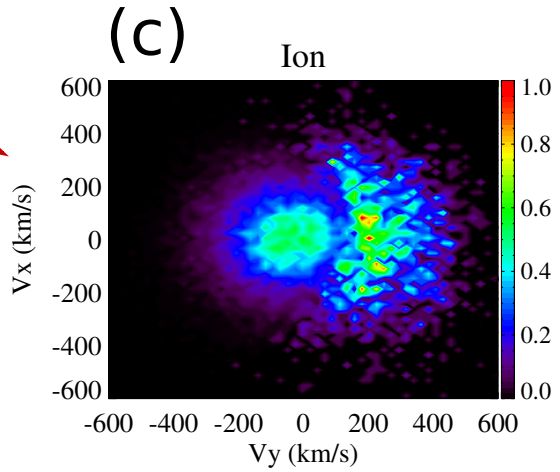
Crescent Distribution and Larmor Electric Field

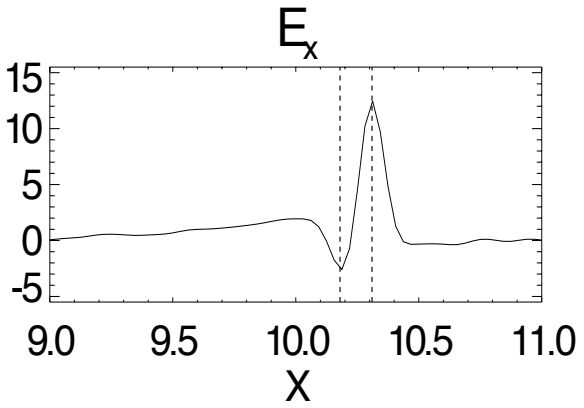






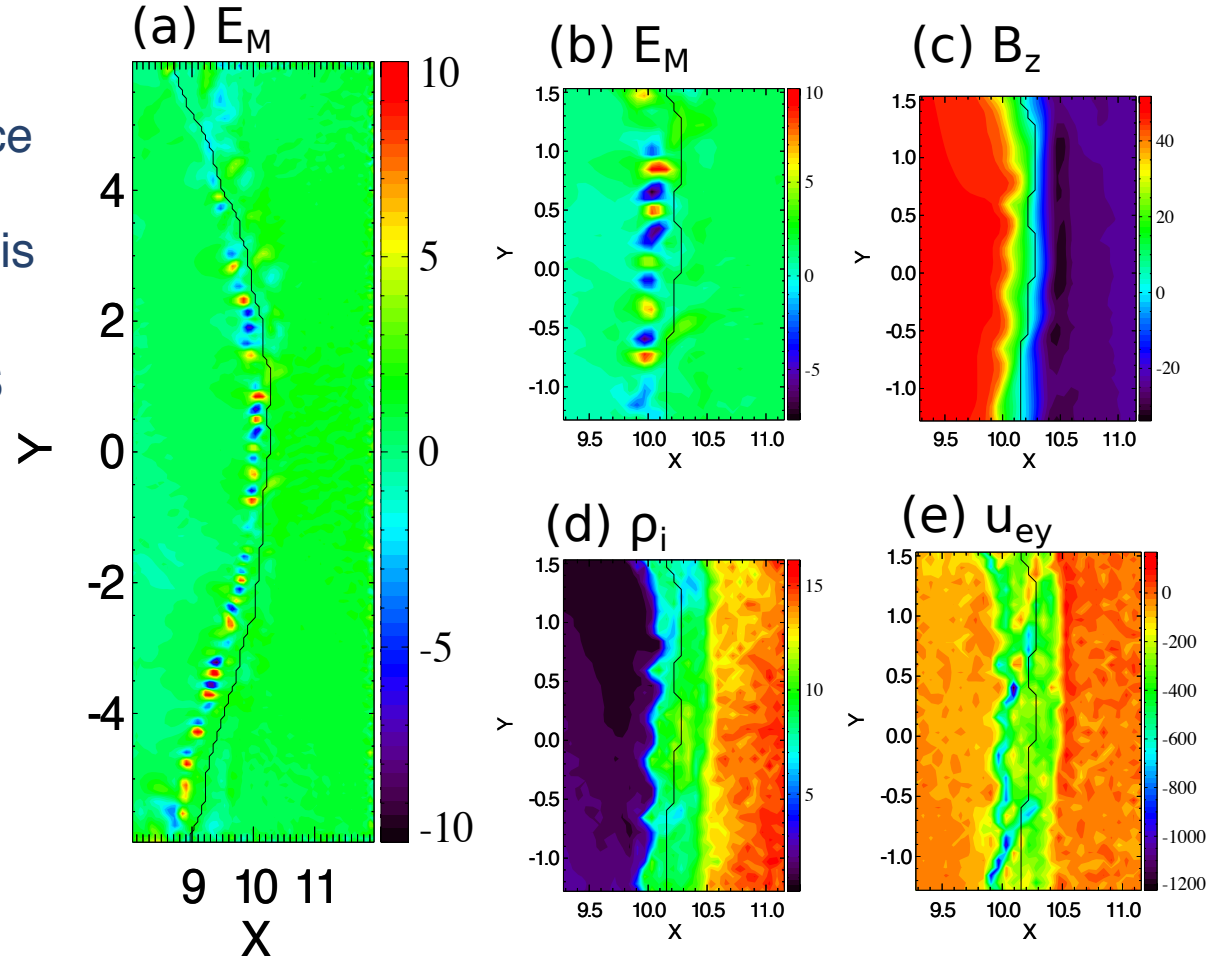
Burch et al.
Science, 2016





Low Hybrid Drift Instability (LHDI)

- LHDI arises near the interface of magnetosheath and magnetosphere, where there is a sharp density gradient
- Simulation agrees with MMS observation
  - $E_M \sim 8$ mV/m
  - $kr_e \sim 0.4$, $\lambda \sim 16\ r_e$



Summary

- **The generation and evolution of FTEs**
  - FTE grows in dawn-dusk direction
  - Core field gradually increases
  - The core field strength is anticorrelated with plasma pressure
- **Confirms that the magnetic field signature of crater FTE can be found at the early stage of an FTE formation**
- **Kinetic features**
  - crescent electron phase space distribution
  - Larmor electric field
  - lower hybrid drift instability (LHDI)

PIC Initialization

Ideal MHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + I \left(p + \frac{1}{2\mu_0} B^2 \right) - \frac{1}{\mu_0} \mathbf{B}\mathbf{B} \right] = 0$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\mathbf{u} \left(e + p + \frac{1}{2\mu_0} B^2 \right) - \frac{1}{\mu_0} \mathbf{u} \cdot \mathbf{B}\mathbf{B} \right] = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = 0$$

$$e = \frac{p}{\gamma - 1} + \frac{\rho u^2}{2} + \frac{B^2}{2\mu_0}$$

Particle-in-Cell:

$$\nabla \cdot \mathbf{E} = \frac{\rho_q}{\epsilon_0},$$

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

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

$$\frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mu_0 \mathbf{j},$$

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p,$$

$$\frac{d\mathbf{v}_p}{dt} = \frac{q_s}{m_s} \left(\mathbf{E}_p + \mathbf{v}_p \times \mathbf{B}_p \right),$$

Initialize PIC from MHD

- Calculate Electric field from Ohm's law: $\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B}}{q_e n_e}$
- Assume charge neutral: $n_i = n_e$
- Ion and electron velocities can be obtained from the fluid momentum and current: $n(m_i \mathbf{u}_i + m_e \mathbf{u}_e) = \rho \mathbf{u}_{\mathrm{MHD}}$ $n(q_i \mathbf{u}_i + q_e \mathbf{u}_e) = \mathbf{J}_{\mathrm{MHD}}$
- Pressure
  1) Assume a fixed p_i/p_e ratio: $p_i = (1-\alpha) p_{\mathrm{MHD}}$ $p_e = \alpha p_{\mathrm{MHD}}$
  2) Solve the electron pressure equation: $\frac{\partial p_e}{\partial t} + \nabla \cdot (p_e \mathbf{u}_e) = (\gamma - 1)(-p_e \nabla \cdot \mathbf{u}_e)$
- Generate macro-particles from Maxwellian distribution

Particle-in-Cell (PIC) Methods

- Maxwell's equations

$$\nabla \cdot \mathbf{E} = \frac{\rho_q}{\epsilon_0},$$

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

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

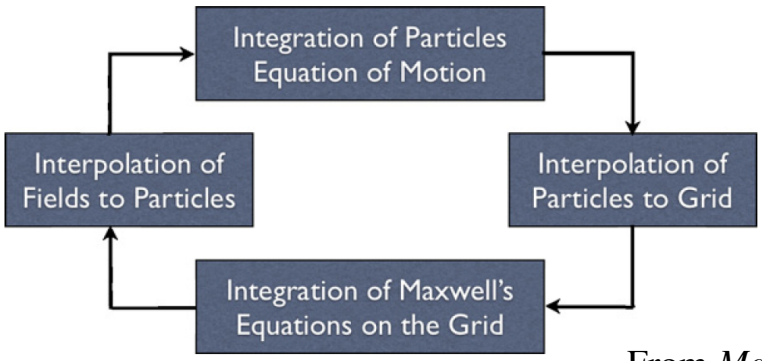
$$\frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mu_0 \mathbf{j},$$

- Motion of the macro-particles

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p,$$

$$\frac{d\mathbf{v}_p}{dt} = \frac{q_s}{m_s}\left(\mathbf{E}_p + \mathbf{v}_p \times \mathbf{B}_p\right),$$

- A computational cycle



PIC methods

- Sample the plasma phase space distributions with macro-particles. Electromagnetic field is stored and calculated on mesh nodes.
- Trace the macro-particle motion in the electromagnetic field. Macro-particles effect the EM field through charge density and current
- Widely used for kinetic physics study

Implicit code iPIC3D (Markidis et al. 2010)

- Solve the evolution of EM field, and the motion of macro-particles implicitly
- Larger cell size and time step can be used compared with explicit PIC codes

From *Markidis et al. (2010)*

Changing the Kinetic Scales

- $$d_i = \sqrt{\frac{M_i}{n_i q_i^2 \mu_0}} = \frac{m_i}{q_i}\sqrt{\frac{1}{\rho_i \mu_0}}$$
- d_i is about 60km ~ 1/100Re in the magnetosheath: too small to resolve!
- Reduce q_i/M_i by a scaling factor f to increase d_i, while the number density, pressure, thermal velocity do not change.

