Ion Energization During Macroscale Reconnection

Marc Swisdak[1], Harry Arnold[1], James Drake[1], Fan Guo[2], Joel Dahlin[3]
[1]University of Maryland, [2]Los Alamos National Laboratory, [3]Goddard Space Flight Center

1. Abstract

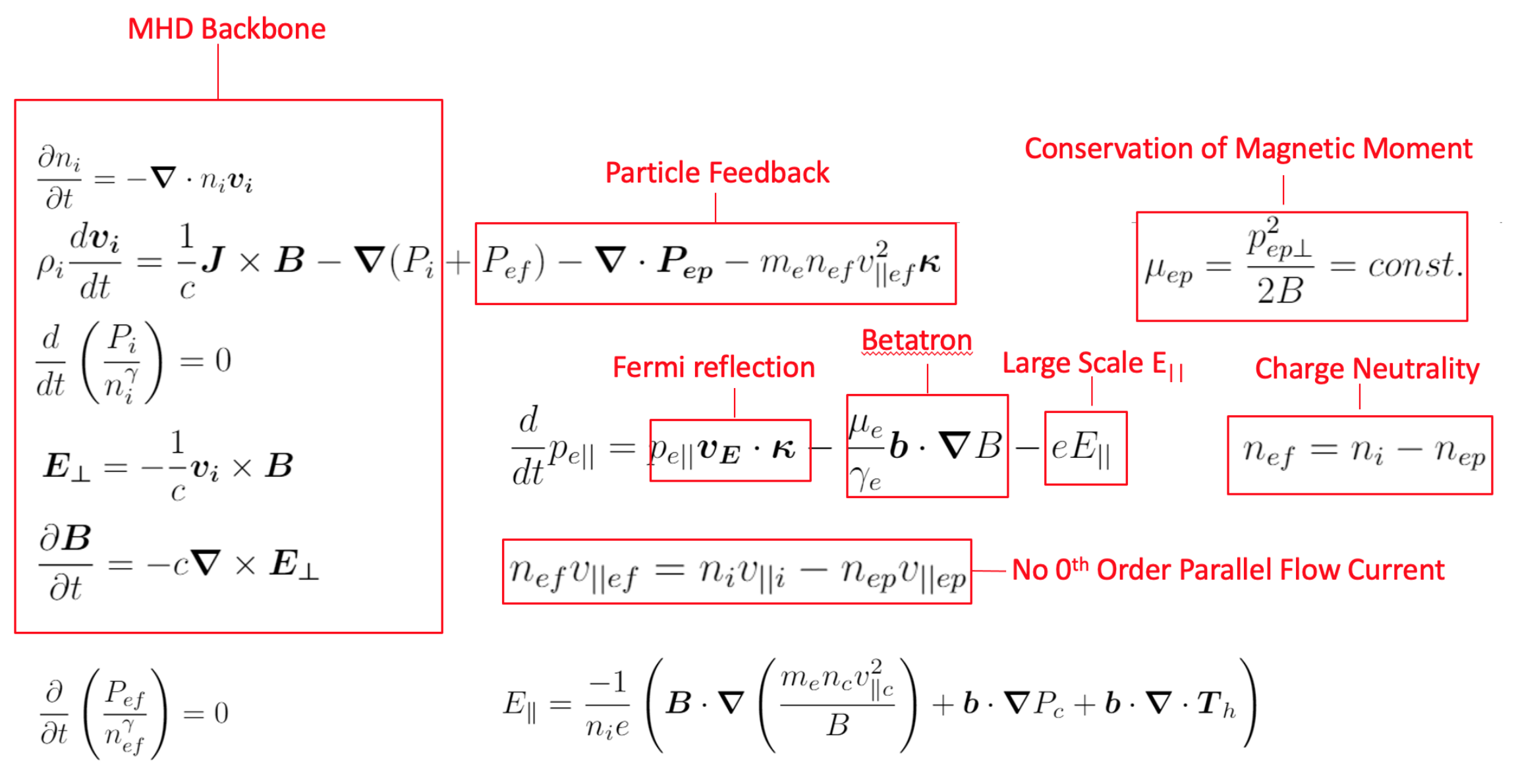
The computational model *kglobal* was developed to explore energetic particle production via magnetic reconnection in macroscale systems. It is based on the observation that the production of energetic particles during reconnection is controlled by Fermi reflection in large-scale magnetic fields and not by parallel electric fields localized in kinetic scale boundary layers. Earlier work with *kglobal* has produced the first self-consistent simulations of non-thermal electron acceleration during reconnection in a macroscale system. Although the original formulation of *kglobal* only treated the nonthermal energization of electrons, the equations can be extended to include ions as long as they remain magnetized so that a guiding center description remains valid. In this poster we discuss the appropriate extension of the *kglobal* equations and simulation plans.

2. Introduction

Flares convert magnetic energy into particle energy through magnetic reconnection. While some released energy goes into bulk flows and thermal energy, a significant fraction appears in nonthermal particles. Observations reveal distributions with power-law tails and total particle pressures approaching the ambient magnetic pressure. These observations rule out a picture in which reconnection-driven particle acceleration occurs in a boundary layer associated with a single, large-scale reconnection site and instead argue for acceleration in magnetic islands.

Conventional PIC codes cannot treat large-scale systems because the Debye length has to be resolved; other computational models have similar difficulties. *kglobal* was developed to address these issues. Fortunately, kinetic scales and kinetic scale boundary layers do not appear to play an important role in particle energization. They control the regions where $E_{||}$ is non-zero but it is Fermi reflection and not $E_{||}$ that is the dominant driver of energization [1, 2]. Energy gain from Fermi reflection occurs on macro-scales and even where $E_{||} = 0$. Particles have curvature drifts along the reconnection electric field and therefore gain energy as long as $\boldsymbol{\kappa} \cdot \mathbf{v_E} > 0$ ($\boldsymbol{\kappa}$ is the curvature, $\mathbf{v_E}$ the $\mathbf{E} \times \mathbf{B}$ drift). Including kinetic scales is not required to describe the formation of non-thermal distributions.

3. Original *kglobal* Equations



MHD Backbone

$$\frac{\partial n_i}{\partial t} = -\boldsymbol{\nabla} \cdot n_i \boldsymbol{v_i}$$

$$\rho_i \frac{d\boldsymbol{v_i}}{dt} = \frac{1}{c}\boldsymbol{J} \times \boldsymbol{B} - \boldsymbol{\nabla}(P_i + \boxed{P_{ef}) - \boldsymbol{\nabla} \cdot \boldsymbol{P_{ep}} - m_e n_{ef} v_{||ef}^2 \boldsymbol{\kappa}}$$

$$\frac{d}{dt}\left(\frac{P_i}{n_i^\gamma}\right) = 0$$

$$\boldsymbol{E}_\perp = -\frac{1}{c}\boldsymbol{v_i} \times \boldsymbol{B}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\boldsymbol{\nabla} \times \boldsymbol{E}_\perp$$

Particle Feedback

Conservation of Magnetic Moment

$$\boxed{\mu_{ep} = \frac{p_{ep\perp}^2}{2B} = const.}$$

Fermi reflection

Betatron

Large Scale $E_{||}$

Charge Neutrality

$$\frac{d}{dt}p_{e||} = \boxed{p_{e||}\boldsymbol{v_E} \cdot \boldsymbol{\kappa}} - \boxed{\frac{\mu_e}{\gamma_e}\boldsymbol{b} \cdot \boldsymbol{\nabla} B} - \boxed{eE_{||}}$$

$$\boxed{n_{ef} = n_i - n_{ep}}$$

$$\boxed{n_{ef} v_{||ef} = n_i v_{||i} - n_{ep} v_{||ep}}$$

No 0th Order Parallel Flow Current

$$\frac{\partial}{\partial t}\left(\frac{P_{ef}}{n_{ef}^\gamma}\right) = 0$$

$$E_{||} = \frac{-1}{n_i e}\left(\boldsymbol{B} \cdot \boldsymbol{\nabla}\left(\frac{m_e n_c v_{||c}^2}{B}\right) + \boldsymbol{b} \cdot \boldsymbol{\nabla} P_c + \boldsymbol{b} \cdot \boldsymbol{\nabla} \cdot \boldsymbol{T}_h\right)$$

Assumptions:

- Fluid (MHD) ions, fluid and particle electrons
- Particle electrons give feedback to momentum equation
- Electrons are assumed to be magnetized (conserved μ)
- Charge neutrality, no parallel current
- Perpendicular motion given by $\mathbf{E} \times \mathbf{B}$

4. Previous Electron Results

Using the equations to the left produces power-laws

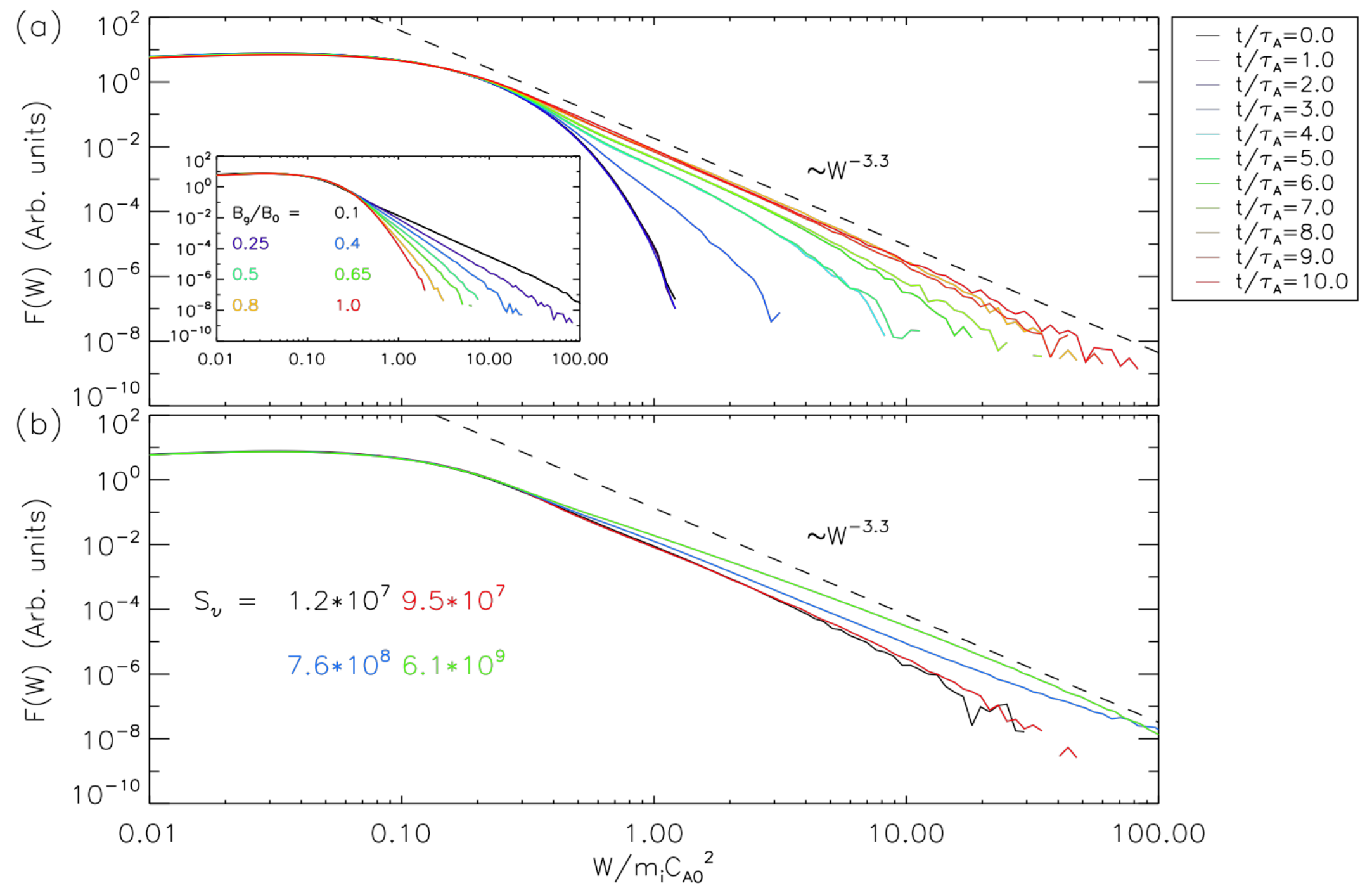


Figure 1:In (a): The electron distribution function versus energy at multiple times for a simulation with a guide field $B_g/B_0 = 0.25$. Inset: the late time distribution for several guide fields. In (b): the late time distribution for $B_g/B_0 = 0.25$ with various values of S_ν (effective system size). From [3].

Important Result

The equations for including ions in *kglobal* have been derived. They are actively being implemented. Stay tuned.

5. Extension to Ions

It might seem that the particle ions could be treated exactly as the particle electrons are. This is not the case, however, as the inertia of the particle ions – unlike that of the particle electrons – needs to be included. As a result, extra inertial terms must also be included in the momentum equation for the MHD fluid. We also make the following assumptions:

- Ions remain magnetized (conservation of μ).
- Perpendicular velocity of particle and fluid ions ($\mathbf{v}_{\mathbf{p},\perp}$ and $\mathbf{v}_{\mathbf{f},\perp}$) are both given by the $\mathbf{E} \times \mathbf{B}$ drift.
- $v_{p,||}$ and $v_{f,||}$ differ.

6. New *kglobal* Ion Equations

$$\partial n_{i,f}/\partial t = -\boldsymbol{\nabla}\boldsymbol{\cdot}\, n_{i,f}\mathbf{v}_{i,f} \tag{1}$$

$$dp_{i,p,||}/dt = p_{i,p,||}\mathbf{v_E}\boldsymbol{\cdot}\boldsymbol{\kappa} - \frac{\mu_i}{\gamma_i}\boldsymbol{b}\boldsymbol{\cdot}\boldsymbol{\nabla}\, B + eE_{||} \tag{2}$$

$$\begin{aligned}\frac{\partial}{\partial t}\rho_i\mathbf{v}_{i,f} = {} & \mathbf{J} \times \mathbf{B}/c - \boldsymbol{\nabla}(P_{ef} + P_{if}) + en_iE_{||}\boldsymbol{b} - m_en_{ef}v_{||,ef}^2\boldsymbol{\kappa} \\ & -(\boldsymbol{\nabla}\boldsymbol{\cdot}\mathbf{P}_{ep})_\perp - (\mathbf{I} - \mathbf{bb})\boldsymbol{\cdot}(\boldsymbol{\nabla}\boldsymbol{\cdot}\,\mathbf{P}_{ip}) - \frac{n_{ip}}{n_{if}}\mathbf{bb}\boldsymbol{\cdot}(\boldsymbol{\nabla}\boldsymbol{\cdot}\mathbf{P}_{if}) \\ & -v_{f,||}\mathbf{b}\left(\frac{n_{ip}}{n_{if}}\frac{\partial\rho_{if}}{\partial t} - \frac{\partial\rho_{ip}}{\partial t}\right) - \rho_{ip}\frac{v_{ip,||} - v_{if,||}}{B}(\mathbf{I} - \mathbf{bb})\boldsymbol{\cdot}\frac{\partial\mathbf{B}}{\partial t}\end{aligned} \tag{3}$$

Note: **P** represents the stress tensor. red terms come from the original MHD equation, green terms from the particle ion feedback, and blue terms from inertial differences between the particle and fluid ions

7. Conclusions

Extended *kglobal* equations including particle ions have been developed. They will facilitate the study of (1) proton power-law formation in macro-scale reconnecting systems, including the low- and high-energy cutoffs of the distributions; (2) the partitioning of released magnetic energy into bulk flow and energetic particles; and (3) the acceleration of trace high M/Q ions. Their implementation is ongoing.

8. References

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Contact Information

- Email: swisdak@umd.edu