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Final Technical Report of DoE Grant DE-SC0017908

**Zhenyu Wang
Final Technical Report**

Federal Grant: DE-SC0017908, DoE

**Project Title: Collaborative Research: Particle Simulation of Collisionless
Magnetic Reconnection Under Finite Guide Field**

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Report Term or Frequency: Final Technical Report

Accomplishments

1. What are the major goals of the project?

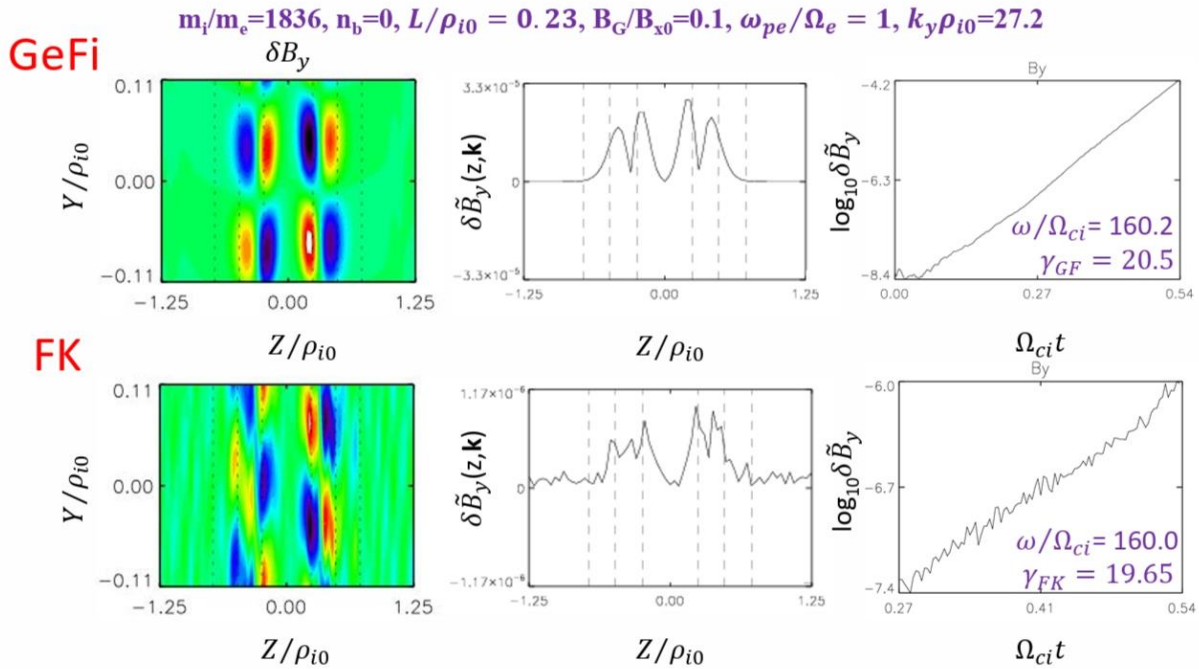
The major goal of our DoE grant DE-SC0017908 as stated in our grant proposal is to address the 3-D current sheet instabilities associated with collisionless reconnection under a broad range of guide field under realistic ion-to-electron mass ratio m_i/m_e , through particle simulations using gyrokinetic electron and fully kinetic ion (GeFi) models.

2. What was accomplished under these goals?

Under the support of this DoE grant, the structure and properties of 3-D, fully electromagnetic (EM) linear instabilities in a Harris current sheet have been investigated with the linearized GeFi simulation model. The results are being compared with the fully kinetic (FK) delta-f particle simulations. The nonlinear GeFi simulations of instability have been carried out as well. The details of the research at Princeton University are described as follows.

(1) EM lower hybrid drift instability

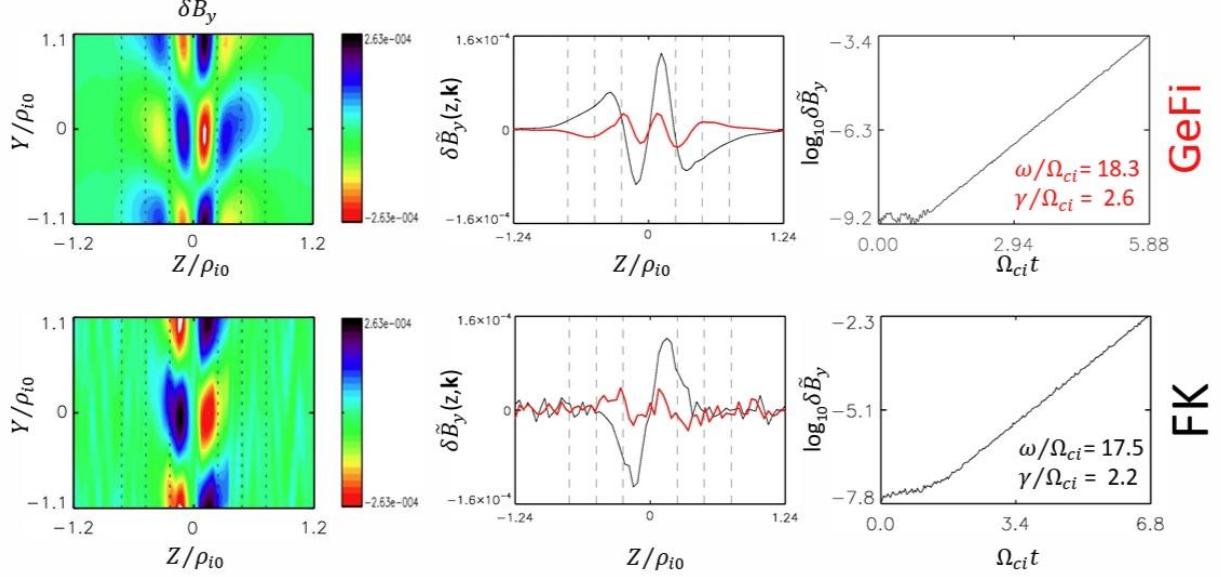
The lower hybrid drift instability (LHDI) on the 2D out-of-plane under a small but finite guide magnetic field has been obtained by the GeFi linear simulation and the FK delta-f particle simulation. The comparison shows that the real-space structure, eigen-mode structure and the growth-rate of the LHDI from both simulations agree.



Linear electromagnetic LHDI: GeFi vs FK

(2) EM instability with odd parity

An electromagnetic instability with the frequency in the low frequency range ($\omega \sim 10\Omega_i$) has been found by the linear GeFi simulation under an intermediate guide field. It has been further compared with the FK delta-f simulation. Both simulations show the odd-parity structure in the real-space plot. The eigen-mode structure and the growth rate of the instability from both simulations are consistent.

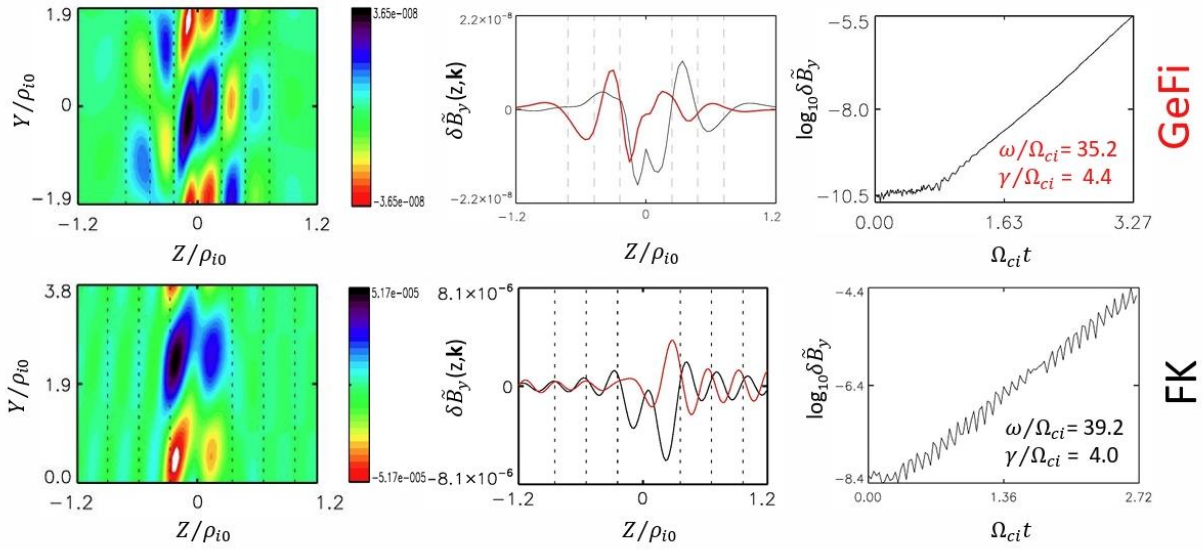


$$m_i/m_e=1836, n_b=0, L/\rho_{i0} = 0.25, B_G/B_{x0}=0.3, \omega_{pe}/\Omega_e = 1, \\ k_y\rho_{i0} = 2.8, k_x\rho_{i0} = 0.4 \text{ (GeFi) and } k_x\rho_{i0} = 0 \text{ (FK)}$$

The EM instability with odd parity structure

(3) EM instability with even parity

Another EM instability with the real-space structure showing even parity has been found by the linear GeFi simulation and the FK delta-f simulation. The real-space structure, eigen-mode and growth rate of the instability from both simulations are consistent.

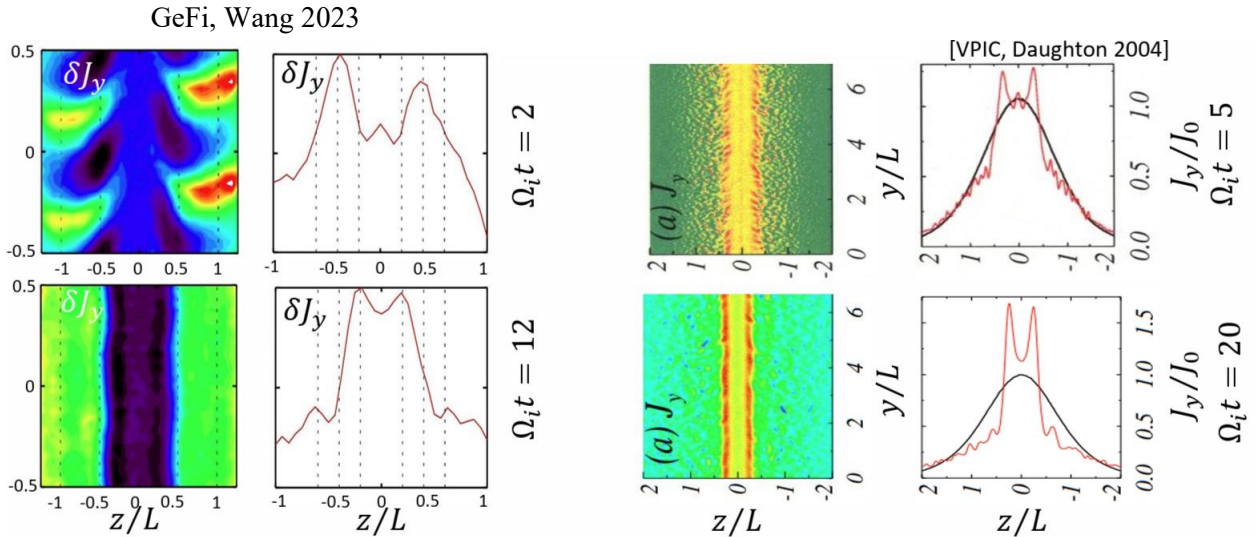


$m_i/m_e=1836$, $n_p=0$, $L/\rho_{i0} = 0.25$, $B_G/B_{x0}=0.2$, $\omega_{pe}/\Omega_e = 1$,
 $k_y\rho_{i0} = 5.2$, $k_x\rho_{i0} = 2.4$ (FK) and $k_x\rho_{i0} = 0.8$ (GeFi)

The EM instability with even parity structure

(4) Nonlinear GeFi simulation of LHDI

The EM LHDI has been investigated by the nonlinear GeFi simulation. The simulation found that LHDI occurs at edge of current sheet at the early stage, penetrates into the current sheet center at later stage. The time evolution of parallel current density is consistent with that from the full-f PIC simulation [Daughton 2004].



The nonlinear EM LHDI: GeFi vs VPIC

3. What opportunities for training and professional development has the project provided?

The PI is an early career scientist, obtained Ph.D degree in 2016. This project has provided the PI a great opportunity for leading a research project in the field of computational plasma physics.

4. How have the results been disseminated to communities of interest?

The results have been disseminated to the plasma physics community through presentations at the conference meetings. Frequent communications with other plasma physicists have also helped to disseminate our findings and accomplishments.

Products

Journal paper:

Zhenyu Wang, Yu Lin, Xueyi Wang, Liu Chen, 3D Electromagnetic Gyrokinetic Electron and Fully Kinetic Ion Simulation of Current Sheet Instabilities, in preparation.

Conference presentations:

Zhenyu Wang, Yu Lin, Xueyi Wang, Liu Chen, 3-D Particle Simulation of Electromagnetic Instabilities in Harris Current Sheet under Realistic Mass ratio and Finite Guide Field, poster presented at the annual APS-DPP meeting, November 2018, Portland, Oregon.

Zhenyu Wang, Yu Lin, Xueyi Wang, Liu Chen, 3-D Particle Simulations of Nonlinear Lower Hybrid Drift Instability, poster presented at the annual APS-DPP meeting, October 2019, Fort Lauderdale, Florida.

Participants

Collaborators: Yu Lin (consultant), Xueyi Wang (consultant), Liu Chen (consultant).

The PI, Dr. Zhenyu Wang at Princeton University, is in charge of the overall performance of the project. The PI is responsible for the proposed simulations of current sheet instabilities.

Impact

What is the impact on the development of the principal discipline(s) of the project?

Current sheet instabilities are thought to be the source of anomalous resistivity which may significantly contribute to the onset of magnetic reconnection. To date, because of its complex configuration, there is no analytical exact solution for the instabilities in current sheet even for the linearized limit. Kinetic simulation is an alternative for the solution, however, such simulations in full 3D space under realistic mass ratio require tremendous computing resources if electrons are treated as FK particles. Most of kinetic simulations take reduced ion-to-electron mass ratio to relieve the computing burden.

The current sheet instabilities are in the broad range from ion gyrofrequency to electron gyrofrequency, in which, resolving ion FK motion is essential but electron FK motion is not necessary. GeFi model, which averages out electron rapid cyclotron motion but retains electron finite Larmor radius effect, off-diagonal pressure tensor, meaning while keeps fully kinetic ion cyclotron motion, is particularly suitable for studying current sheet instabilities in full 3D space.

In this work, the GeFi simulations systematically investigated the current sheet instabilities in the broad range of guide magnetic field under realistic ion-to-electron mass ratio. The linearized GeFi code obtained three electromagnetic instabilities, each of them can contribute to anomalous resistivity. The nonlinear simulation of LHDI by GeFi code found the instability penetrate into the current sheet center at nonlinear stage. These results will help understand how the instabilities contribute to anomalous resistivity associated with the onset of magnetic reconnection.

What is the impact on other disciplines?

Our development of novel, large-scale, particle simulation schemes may have a broad impact to the computational physics.

What is the impact on the development of human resources?

N/A

What is the impact on physical, institutional, and information resources that form infrastructure?

N/A

What is the impact on technology transfer?

N/A

What is the impact on society beyond science and technology?

N/A

Changes/Problems

Actual or anticipated problems or delays and actions or plans to resolve them:

The project had been extended since we had an important scientific discovery that needed extra time to study. The DoE program manager granted the extension.

Acknowledgement

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