テアリング不安定性のジャイロ運動論シミュレーション

沼田 龍介*

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*兵庫県立大学大学院シミュレーション学研究科
Physics to break flux-freezing is necessary for field lines to change its topology: primarily by collisions (resistivity).

⇒ Only collisions set a spatial scale in MHD model.

Resistive spatial scale for weakly collisional plasmas falls below kinetic scales (MHD theory is not valid).

Relevant kinetic scales: $d_{i,e}$ [inertia], $\rho_{i,e}$ [FLR], $\rho_S$ [Sound].
AstroGK: Astrophysical Gyrokinetics Code

- Magnetic reconnection is multiscale problem
- Publicly available at https://sourceforge.net/projects/gyrokinetics/.

**Weak Scaling @ Kraken [Cray XT5]**

![Weak Scaling Graph]

**Strong Scaling @ Kraken [Cray XT5]**

![Strong Scaling Graph]
Recently, linearized collision operators for gyrokinetic simulations, which satisfies physical requirements are established and implemented in AstroGK [Abel et al, 2008; Barnes et al, 2009]

The operators are the pitch-angle scattering (Lorentz), the energy diffusion, and moments conserving corrections to those operators for like-particle collisions. Electron-ion collisions consists of pitch angle scattering by background ions and ion drag are also included.
Collisionality $\nu_e$ is scanned to vary current layer width $\delta$. As $\nu_e$ is decreased, the current layer width becomes narrower, and the ion and electron kinetic scales become important.

Case 1  electron scale $\ll$ ion scale $\sim \delta \ll$ equili. scale
Case 2  electron scale $\sim \delta \ll$ ion scale $\lesssim$ equili. scale
Typical form of dispersion relation of tearing instability.

![Graph](Fig. taken from Rogers et al., 2011)

\[
\begin{align*}
\text{Large } \Delta' & \quad \gamma \tau_A \sim S^{-1/3} \\
\text{Small } \Delta' & \quad \gamma \tau_A \sim S^{-3/5}
\end{align*}
\]
Growth rate and current layer width scaling against Lundquist number \( S \) are obtained from GK simulation. [dots]

Scalings are compared with reduced two-fluid model by Fitzpatrick (Fitzpatrick, 2010). [lines]

GK and 2F results agree well only for low-\( \beta_e \).

2F model assumes \( \beta_e \ll \sqrt{m_e/m_i} \), which is marginally satisfied for \( \beta_e = 0.01875 \) case.

Eqn. of state used in 2F model may not be valid.
Collisional-collisionless transitional regime is reproduced:
For large $S$, electron inertia mediates reconnection instead of collisions.
Magnetic reconnection is multiscale problem
AstroGK: Astrophysical Gyrokinetics Code
Collisions in AstroGK
Problem setup
Dispersion relation
MHD to two-fluid MHD
Collisional–collisionless transition
Ion temp. dependence: kinetic
Alfvén wave
Summary

- Ion temperature \( (\tau \equiv T_{0i}/T_{0e}) \) dependence.
- Theoretical prediction, \( \gamma \tau_A \sim \tau^{1/3} \), because of the transition of Alfvén wave to kinetic Alfvén wave.
- For higher \( \beta_e \), sound wave couples to Alfvén wave. A compressible effect play a role, and \( \tau^{1/3} \) dependence is no longer seen.
Magnetic reconnection is a multiscale problem. AstroGK: Astrophysical Gyrokinetics Code

Collisions in AstroGK:

Problem setup

Dispersion relation

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Ion temp. dependence: kinetic Alfvén wave

Summary

☐ We have performed linear GK simulations of tearing instability. It is shown that growth rate scaling with collisionality agrees well with prediction by 2F model only for low beta case.

☐ For large beta, coupling of Alfvén wave with ion sound wave becomes significant. General non-polytropic equation of state should be considered for pressure perturbations.

☐ See Numata et al., Phys. Plasmas 18, 112106 (2011) for more detail.

☐ Related future works planned: Nonlinear simulations to study kinetic effects on magnetic reconnection, diamagnetic stabilization of tearing instability [@Dartmouth], microtearing turbulence [with Loureiro et al.]

☐ Gyrokinetics is a suitable approach to multiscale kinetic plasmas. AstroGK is a well-established gyrokinetics code. It is free!