Nonlinear Gyrokinetic Simulations of Tearing Instability

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Abstract

It is known that collisions cannot be simply ignored just because collision frequency is small. Landau damping or finite Larmor radius effects can create small scale structures in velocity space, and can significantly enhance collision effect. We demonstrate by gyrokinetic simulation that these phase mixing effects can cause electron heating during magnetic reconnection process. Same mechanism may work for ions for high-β plasma.

Introduction

•Magnetic reconnection is ubiquitous in fusion and astrophysical plasmas, which allows topological change of field lines, and convert field energy into plasma flow and heat. A detailed understanding of the phenomena in collisionless (kinetic) regime is still missing. Our goal is to provide comprehensive picture of the magnetic reconnection phenomena using kinetic model.

•In the previous gyrokinetic simulation study for linear tearing instability [1,2], we obtained linear growth rate scaling against Lundquist number S, and successfully confirmed the scaling agrees well with two-fluid [3] and kinetic theories [4] in low-β regime. In high-β regime, coupling between Alfvén wave and ion sound wave becomes significant, and general non-polytropic equation of state for ion should be considered.

•Following the theory [5] and simulation [6] of electron heating during reconnection, we perform gyrokinetic simulations of tearing mode reconnection, and observe electron heating during the process. Since most of astrophysical and laboratory plasmas are considered to be weakly collisional, heating may occur due to Landau damping (linear phase mixing) or nonlinear phase mixing [7,8,9] with small but finite collisionality.

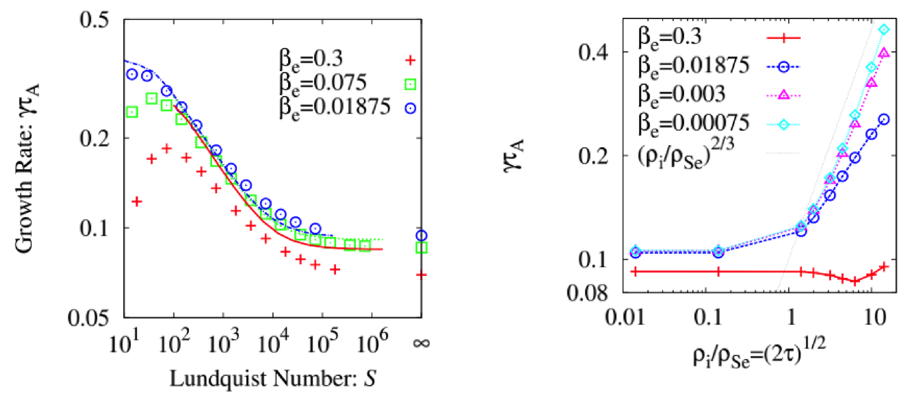


Figure 1: Examples of linear scaling study. Left: scaling against collisionality compared with the two-fluid theory, Right: scaling against ion temperature compared with the kinetic theory.

Simulation results

Overall dynamics is almost independent of collision frequency (collisionless regime)

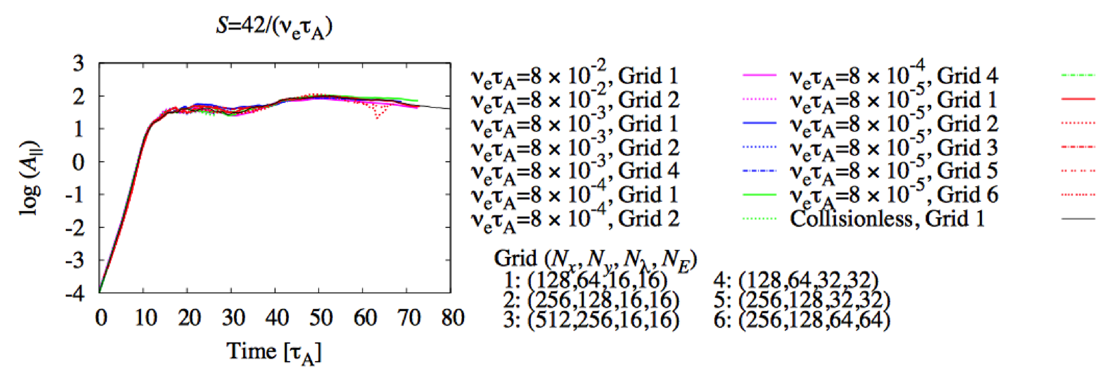


Figure 3: Growth of $A_\parallel$ at the X point for different collision frequency.

Electron heating diagnostics

$$\delta f_s = -\frac{q_s \varphi}{T_{0s}} f_{0s} + h_s$$

In gyrokinetics, there exists a generalized energy, which conserves in the collisionless limit, but, dissipate due to collisions as follows [5,8,10]:

$$W = \int \left[\sum_s \int \frac{T_{0s} \delta f_s^2}{2 f_{0s}} \mathrm{d}\boldsymbol{v} + \frac{|\delta \boldsymbol{B}|^2}{2\mu_0} \right] \mathrm{d}\boldsymbol{r} \qquad \frac{\mathrm{d}W}{\mathrm{d}t} = \sum_s \int \left\langle \frac{T_{0s} h_s}{f_{0s}} \left(\frac{\partial h}{\partial t} \right)_{\mathrm{coll}} \right\rangle_r \mathrm{d}\boldsymbol{v}\, \mathrm{d}\boldsymbol{r} < 0$$

The dissipated energy is converted to bulk electron thermal energy, which is out of scope of the delta-f gyrokinetic framework.

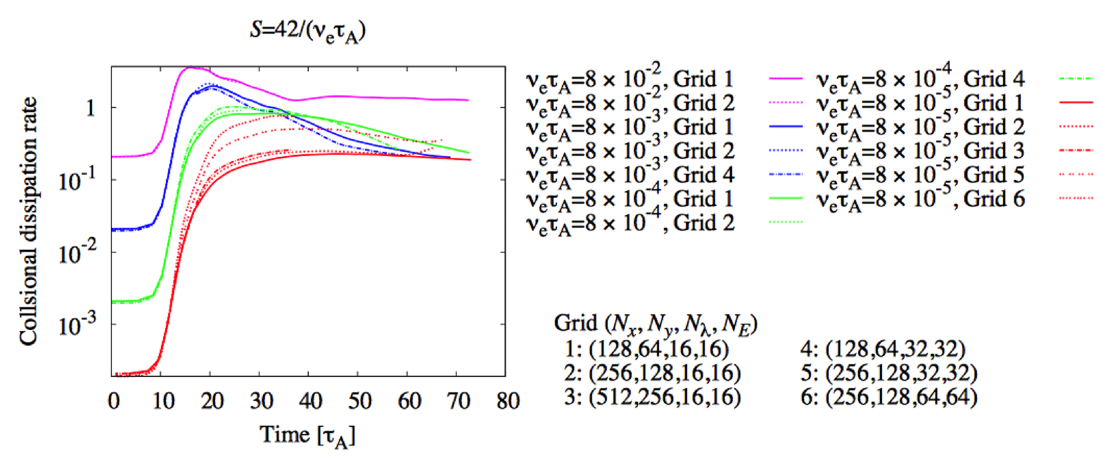


Figure 4: Collisional dissipation rate of electron for different collisionality. Convergence study is also show.

•Collisional dissipation rate of electron remains finite as $\nu_e \to 0$.

•To resolve the velocity space structure for the very weak collision case, same orders of grid points are necessary as in the position space.

•These observations indicate fine velocity space structures: Landau damping or FLR nonlinear phase mixing!?

Acknowlegements

This work was supported by JSPS KAKENHI Grant Number 24740373. This work was carried out using the HELIOS supercomputer system at Computational Simulation Centre of International Fusion Energy Research Centre (IFERC-CSC), Aomori, Japan, under the Broader Approach collaboration between Euratom and Japan, implemented by Fusion for Energy and JAEA.

Simulation Setup

Simulations are performed using AstroGK [2] in doubly periodic slab domain.

We assume uniform background ($\nabla n_0 = \nabla T_0 = \nabla B_0 = 0$), and $\partial/\partial z = 0$.

Parameters are $k_y a = 0.8$, $\Delta' a = 23.2$, $aB_y'(0)/B_y^{\max} = 2.6$, $\nu_i = 0$ (inviscid ions), $m_i/m_e = 100$, $\beta_e = 0.01$, $T_{0i}/T_{0e} = 1$, and $\rho_i/a = 0.25$. For these parameters, other kinetic scales are $\rho_i = d_e = 0.1 d_i = 10\rho_e$.

Initial cond.: shifted Maxwellian electron (finite $u_{\parallel e}$), non-shifted Maxwellian ion ($u_{\parallel i}$=0)
→ Electron flow (amplitude and profile) is chosen to give

$$A_\parallel^{\mathrm{eq}} = \frac{A_{\parallel 0}^{\mathrm{eq}}}{\cosh^2((x - L_x/2)/a)} S(x) \qquad (S(x) \text{ is to make periodic})$$

AstroGK accurately reproduces the Spitzer resistivity, for which the electron-ion collision frequency (ν_e) and the resistivity (η) are related by $\eta/\mu_0 = 0.380 \nu_e d_e^2$.

The resistivity is recast in terms of the Lundquist number $S = 2.63\ (\nu_e \tau_A)^{-1}\ (d_e a)^{-2}$

where $\tau_A = a/V_A$, V_A is the Alfvén velocity corresponding to $B_y^{\max}$.

We compare electron heating for cases of $\nu_e \tau_A$=0.08~8×10^{-5} corresponding to S = 526~526000. Growth rate and current sheet width in the linear regime are shown in Fig. 2.

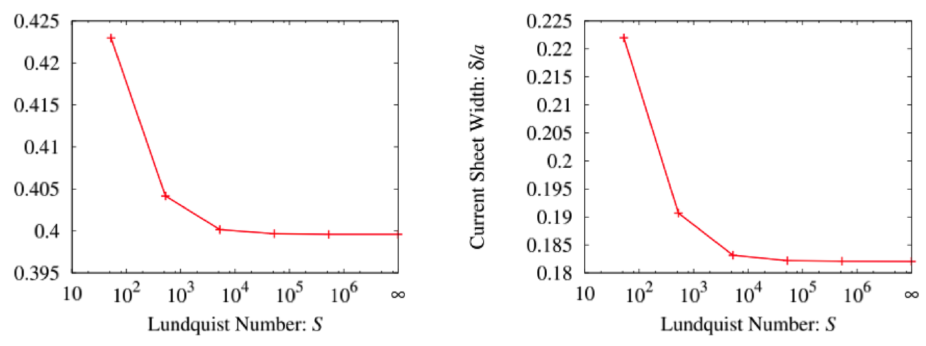
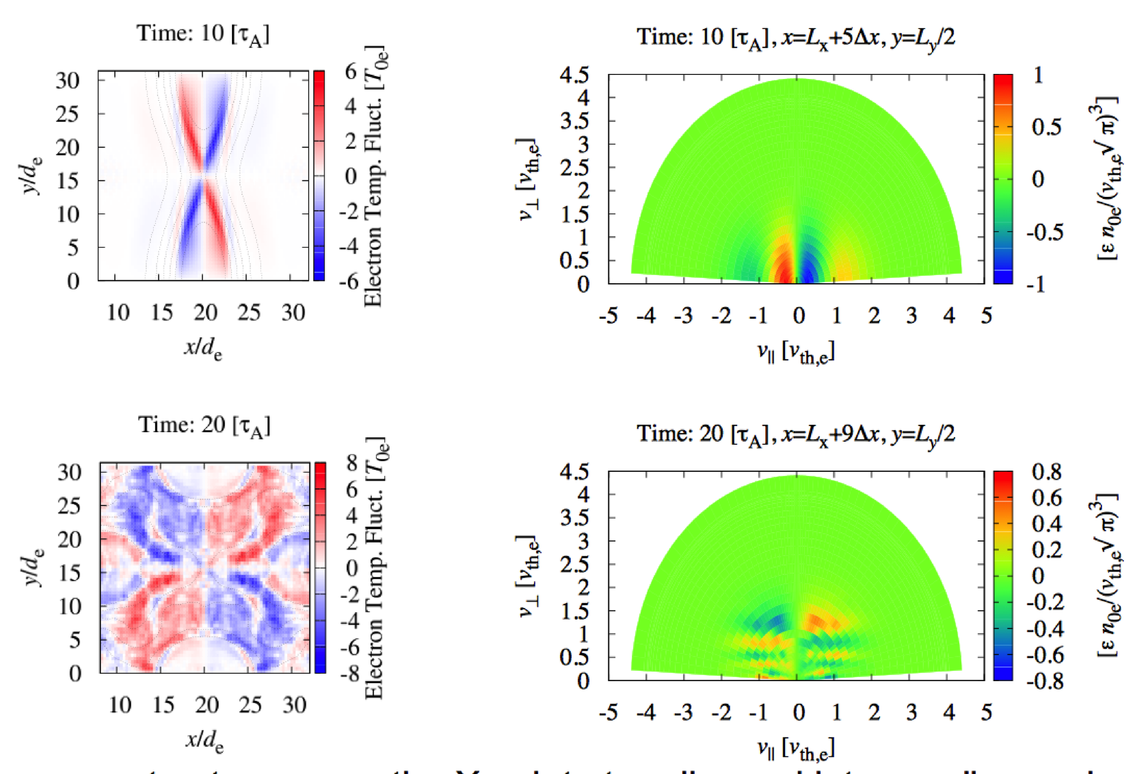


Figure 2: Linear growth rate and the current sheet width for the given parameters. For $S > 5000$, collisionless dynamics is dominant and the growth rate does not depend on collisionality.

Velocity space structure

Figure 5: Magnetic flux and electron temperature (left), and velocity space structure (right).



Velocity space structures near the X point at earlier and later nonlinear phase show oscillatory structures in both the parallel and perpendicular direction.

Conclusion

We have performed gyrokinetic simulation of magnetic reconnection using AstroGK. We have shown oscillatory velocity space structures enhance collisional dissipation rate and electron heating rate. The dissipation and heating rate remain finite as $\nu_e \to 0$.

Result is consistent with simulation of reduced kinetic model for low-β [6]. Same mechanism may work for ion heating in high-β regime.

References

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