Gyrokinetic Simulations of Tearing Instability

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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.

•We present a comprehensive linear study (though our ultimate goal is to understand nonlinear evolution) of the parameter space covering both the collisional and the collisionless regimes in a strong guide magnetic field limit using AstroGK [1] astrophysical gyrokinetics code. Recently implemented model collision operator enables to simulate the collisionless and collisional regimes and their intermediate seamlessly.

•Primary aim of this study is to trace from macroscopic MHD scale down to electron inertial scale (d_e) by changing collisionality. We may pass through two-fluid (d_i) regime, kinetic ion regime (ρ_i or ρ_s), and then reach at collisionless regime where the electron inertia mediates magnetic reconnection process.

•Only the kinetic description can capture these collisionless effects accurately. This study also enables to identify the regions of validity of various fluid modelings.

Simulation setup

Simulations are performed using AstroGK in doubly periodic slab domain

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

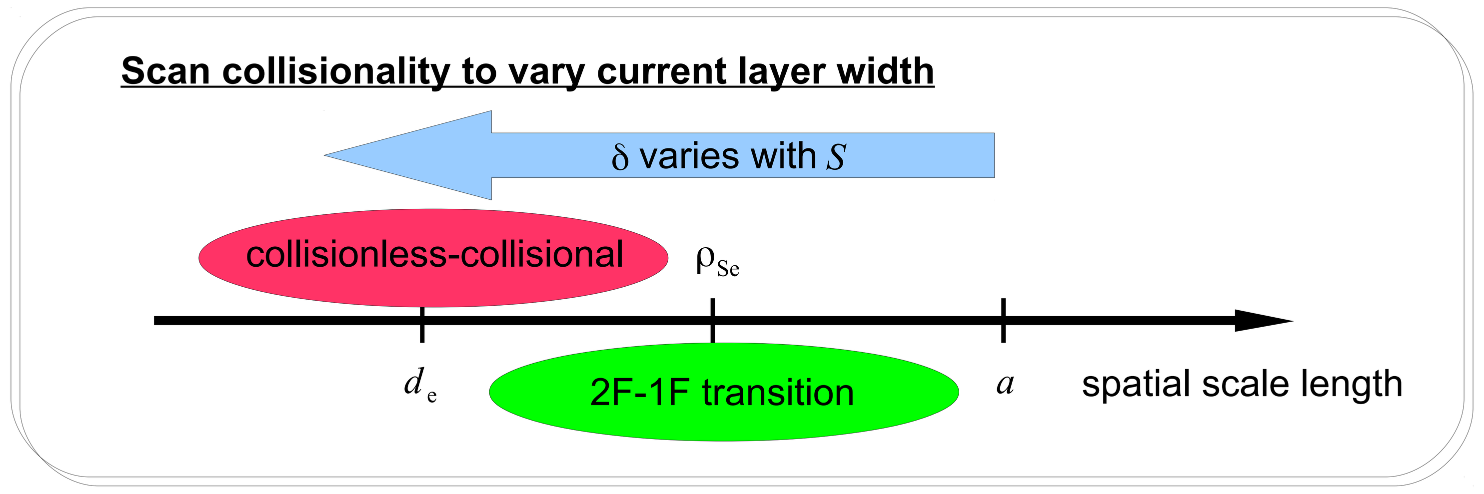
Initial condition: shift Maxwellian electron ($n_{0e}=1, T_{0e}=1, u_{\|,e}$)
non-shifted Maxwellian ion ($n_{0i}=1, T_{0i}=\tau T_{0e}, u_{\|,i}=0$)
→ Electron flow (amplitude and profile) is chosen to give

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

Parameters: $\Delta' a=23.2,\ aB_y'(0)/B_y^{max}=2.6,\ ka=0.8,\ \nu_i=0$ (inviscid ions)
$(m_e/m_i,\beta_e)=(0.01,0.3),(0.0025,0.075),(0.000625,0.01875)$

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 scan collisionality to study collisional – collisionless transition. As ν_e is decreased, the current layer width δ becomes narrower, and the different ion and electron kinetic scales becomes important. We split our study into two sets:
Case 1) $\text{electron scale} \ll \text{ion scale} \sim \delta \ll a$
Case 2) $\text{electron scale} \sim \delta \ll \text{ion scale} < a$



Simulation results

Case 1: $\rho_{Se}/a=0.014$ (MHD and Two-fluid MHD)

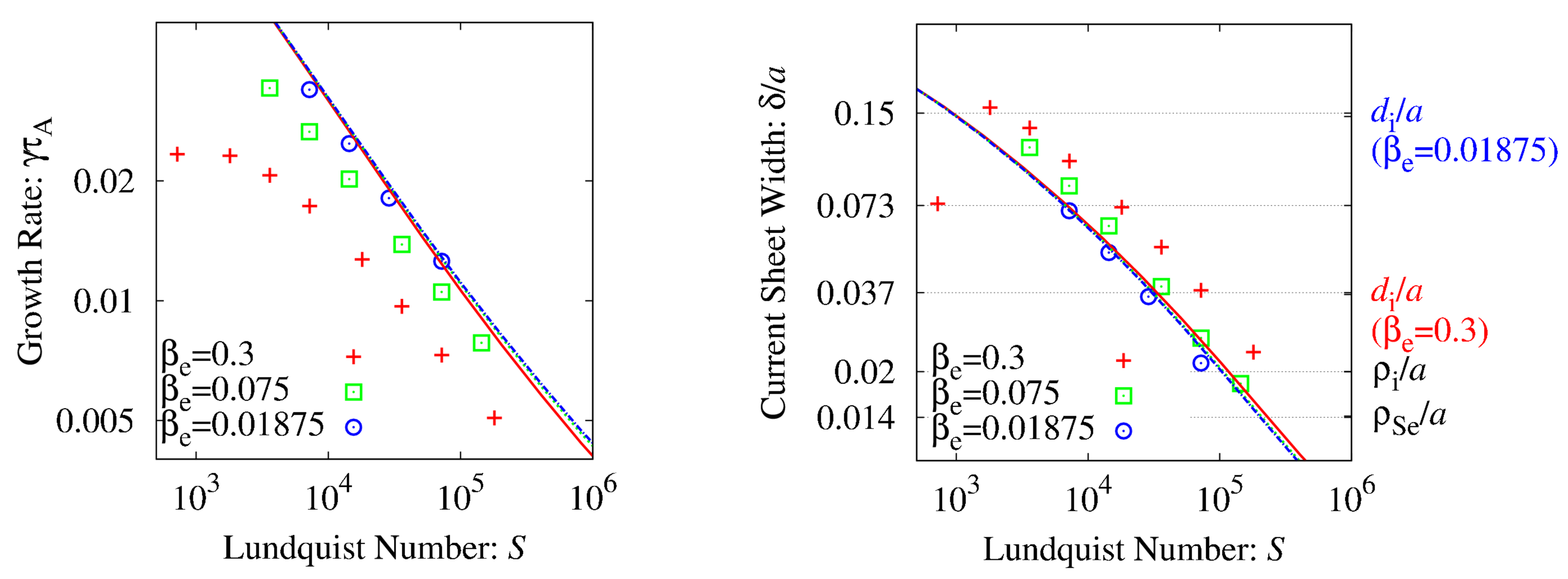


Figure 1. Scaling of growth rate and current sheet width against S for $\rho_{Se}/a=0.014$.

•Comparisons between GK simulation and a reduced two-fluid model [2] show excellent agreement when beta is very low.
•The reduced two-fluid model requires $\beta_e \ll \sqrt{m_e/m_i}$. This condition is marginally satisfied only for $\beta_e=0.01875$.
•The over-estimation of the growth rate by the two-fluid model at higher $\beta_e=0.3$ is possibly due to either a breakdown in the low-β_e ordering of the fluid model or a gradual onset of kinetic effects (e.g., the invalidity of a simple isothermal equation of state.)

Case 2: $\rho_{Se}/a=0.14$ (Collisional – Collisionless Transition)

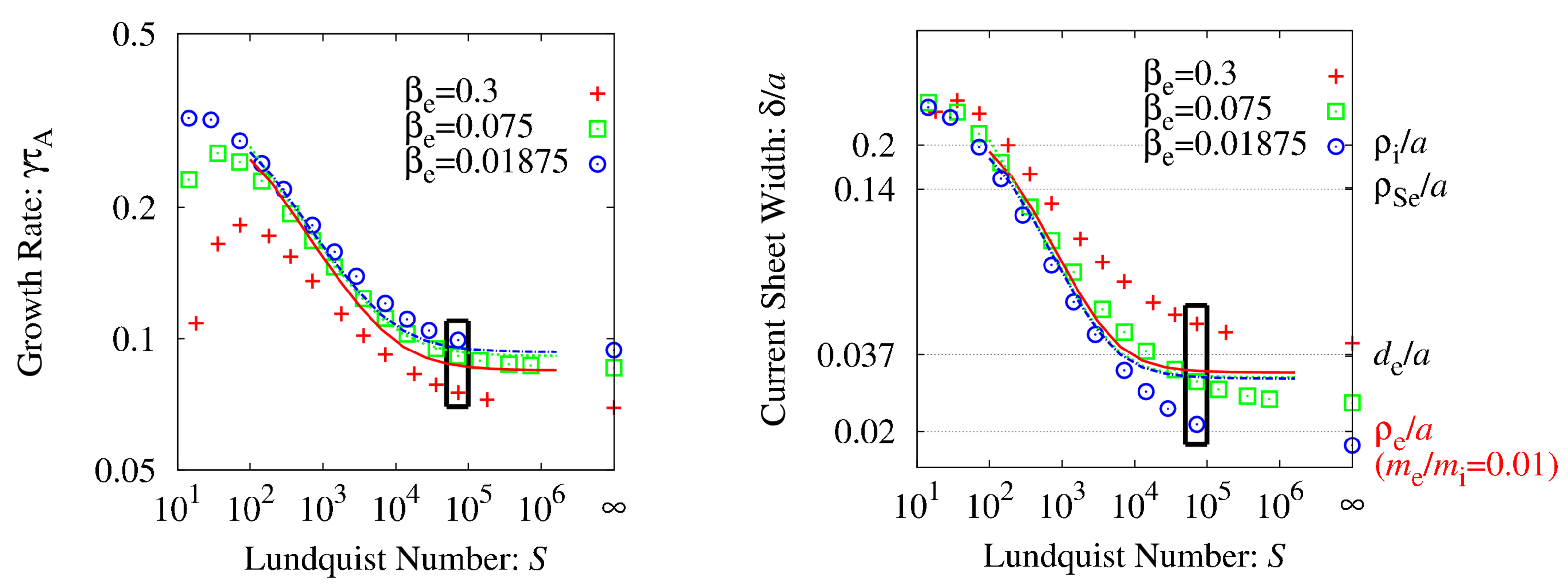


Figure 2. Scaling of growth rate and current sheet width against S for $\rho_{Se}/a=0.14$.

We observe transition from collisional to collisionless regime. We observe better agreement between GK and 2F for lower values of β_e; however, S increases and the collisionless regime is approached, the agreement becomes poorer for any values of β_e. In this regime, electron kinetic effects (Landau damping and even finite electron orbits [note that for $\beta_e=0.3$, $\delta/\rho_e\approx 2$) play an important role.

Equation of states are not polytropic

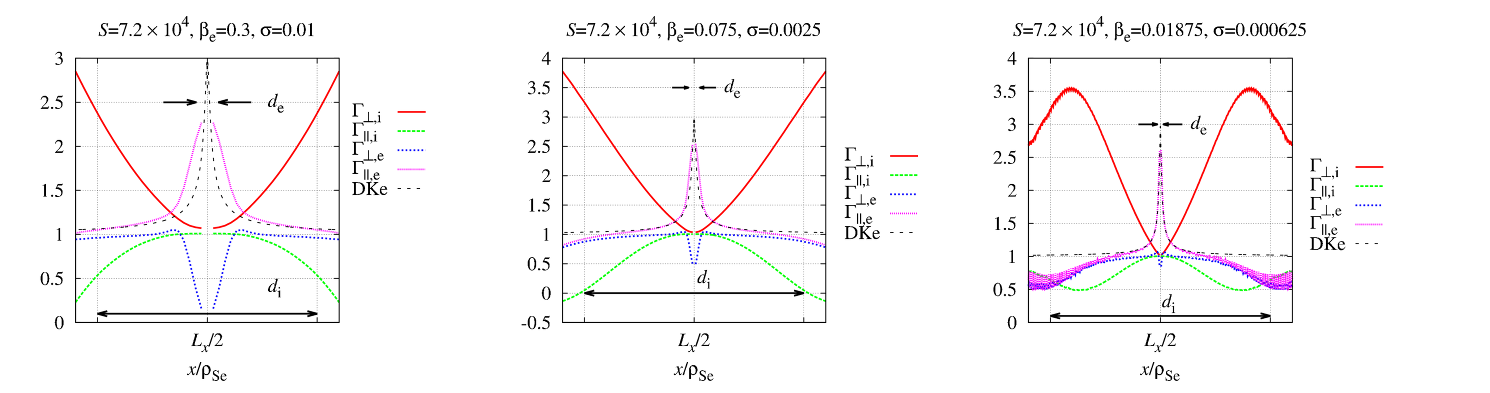


Figure 3. Polytropic indices of ions and electrons in the perpendicular and the parallel directions.

If an equation of state is polytropic $p\propto n^{\Gamma}$, the polytropic index is calculated from the density and pressure fluctuations as $\Gamma_s=\tilde{p}_s/(T_{0s}\tilde{n}_s)$. It is seen that while $\Gamma_{\|e}\approx 1$ outside the current layer, it is highly peaked in the current layer due to the Landau damping. A spatially varying polytropic index means that the equation of state is not polytropic. Γ_i also varies widely over the ion inertial scale in all cases.

Kinetic Aflvén wave dynamics is dominant only for low beta

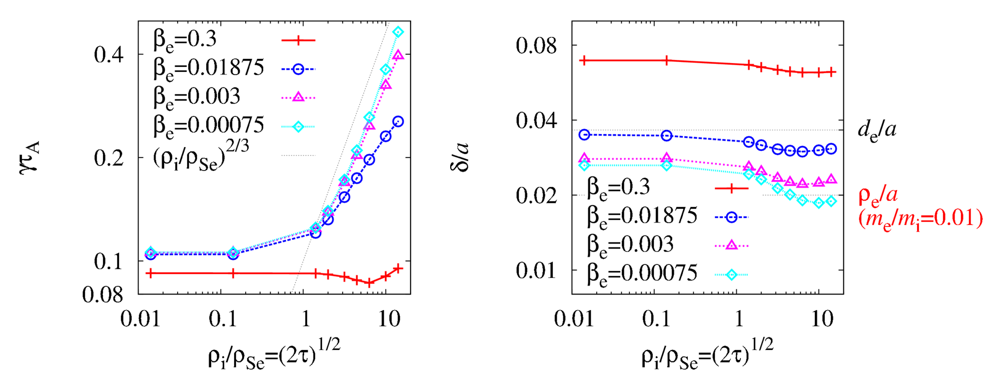


Figure 4. Scaling of growth rate and current sheet width against $\tau=T_{0i}/T_{0e}$.

It is known that for high ion temperature plasmas, the tearing growth rate scales as $\gamma\tau_A\sim\tau^{1/3}$ because of the dispersion of the kinetic Alfvén wave [3]. However, the previous GK tearing mode simulation [4] shows the growth rate seems not depending on ion temperature. We have revealed that the predicted scaling only holds for very low beta.

Conclusions

•We have performed linear gyrokinetic simulations of the tearing instability.
It is shown that the growth rate scaling with collisionality agrees well with the prediction by a two-fluid model only for a low plasma beta case.
•Electron wave-particle interactions, FLR, and other kinetic effects invalidate the fluid theory in the collisionless regime, where general non-polytropic equation of state for pressure perturbation should be considered.
•We have also shown that the theoretical scaling against the ion background temperature can be recovered only in the very low beta limit.
•See [5] for more detailed discussions.

References

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