Kinetic Effects in Gyrokinetic 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 have performed 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.

•In this presentation, we focus on the collisionless case, and investigate how kinetic effects affect the tearing instability.

Simulation setting

AstroGK solves electromagnetic δf-gyrokinetic equations in periodic slab domain

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

Initial condition: shifted Maxwellian electron ($n_{0e}=1, T_{0e}=1, u_{\parallel,e}$)
non-shifted Maxwellian ion ($n_{0i}=1, T_{0i}=1, u_{\parallel,i}=0$)
electron flow (amplitude and profile) is chosen to give $A_{\parallel,\mathrm{eq}}=\frac{A_{\parallel,0}}{\cosh^2(x/a)}S(x)$ ($S(x)$ is to make periodic)

fixed parameters: $\Delta' a=23.2,\ \tau_H/\tau_A=0.486,\ ka=0.8,\ \nu_i=0\,(\text{inviscid ion})$

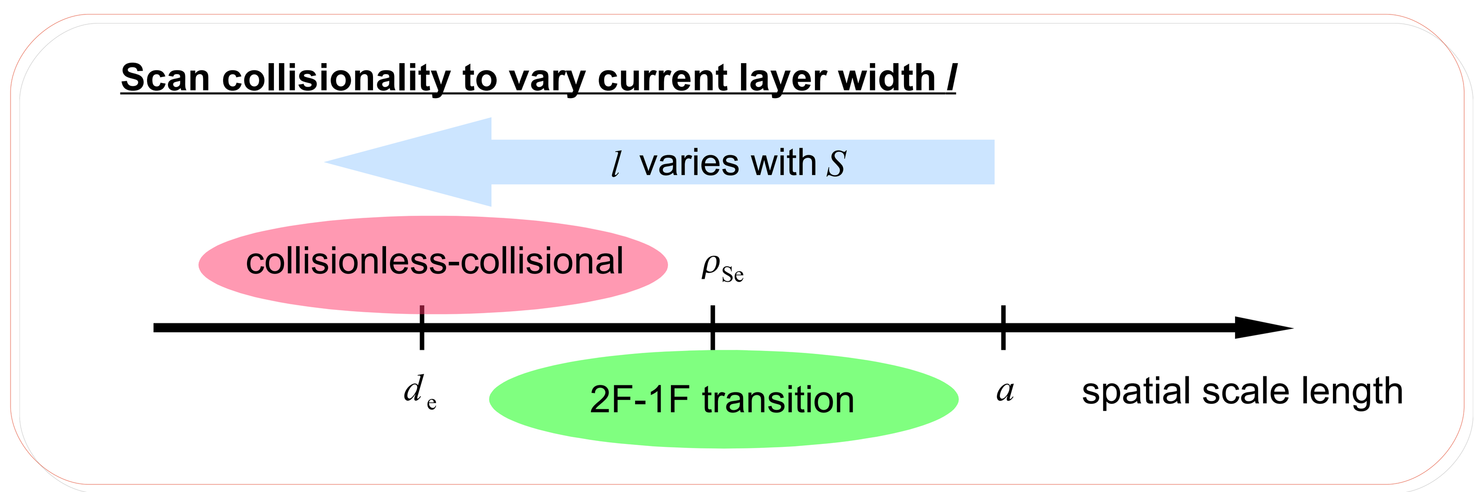
parameters and length scales:

$$\sigma=m_e/m_i,\ \tau=T_{0i}/T_{0e},\ \beta_e=n_0T_{0e}/(B_g^2/2\mu_0),\ r=\rho_{Se}/a$$

$$\rho_i/a=\tau^{1/2}r,\quad d_i/a=\beta_e^{-1/2}r,\quad \rho_e/a=\sigma^{1/2}r,\quad d_e/a=\beta_e^{-1/2}\sigma^{1/2}r,\quad \rho_S/a=\left(\frac{1}{2}(\Gamma_e+\Gamma_i\tau)\right)^{1/2}r$$

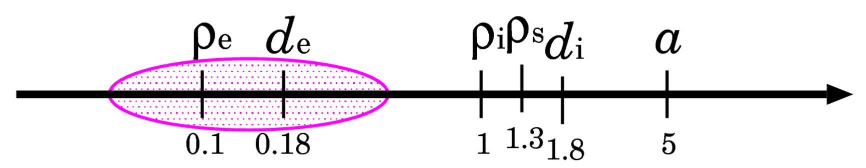
where $\rho_{Se}=\sqrt{T_{0e}/m_i}/\Omega_{ci}$ is the ion sound Larmor radius with isothermal electrons and cold ions defiining a typical ion scale. We formally use $\Gamma_e=\Gamma_i=5/3$ as the polytropic index (adiabatic).

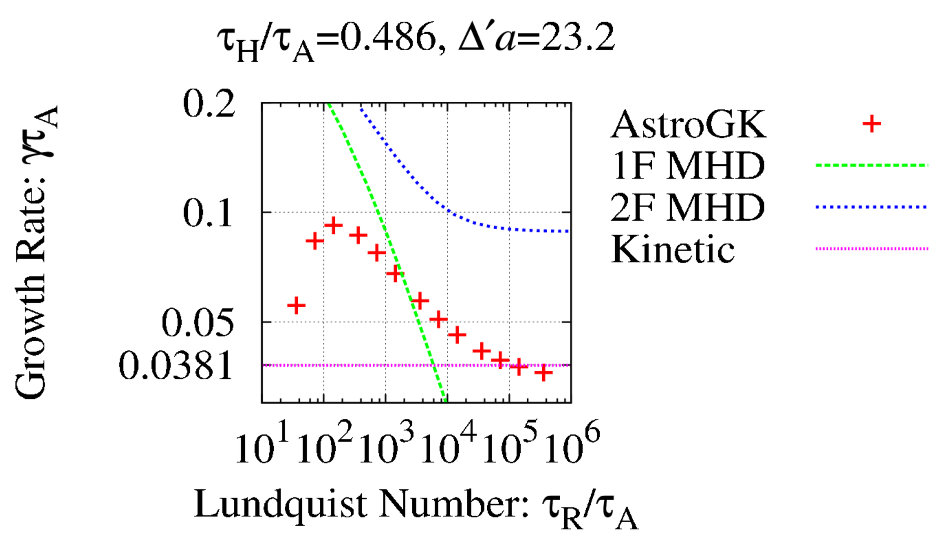
resistivity: Spitzer's formula relates the collision frequency and the resistivity $\eta/\mu_0=0.380\,\nu_e d_e^2$

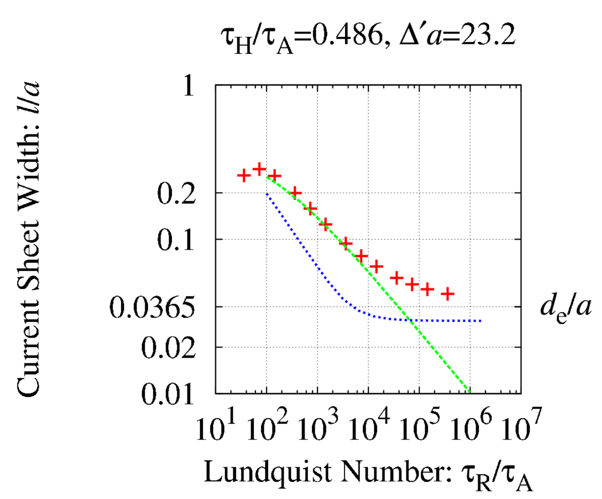


Simulation Result

$\sigma=0.01,\ \tau=1,\ \beta_e=0.3,\ r=0.2$







•Figures show the growth rate and the current layer width scalings against the Lundquist number.

•Red crosses are obtained from GK. Green and blue lines are numerically calculated growth rate using the single-fluid [1F] reduced MHD and the two-fluid [2F] reduced MHD[2]. (1F MHD result (asymptotes to FKR[3] for high-S regime) is *not relevant* to the present case, but is just shown for reference.) Growth rate for collisionless limit based on a kinetic model[4] is also shown.

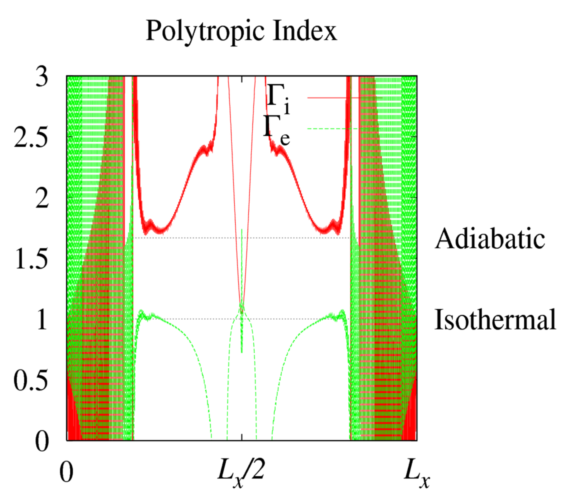
•Two-fluid model overestimates the growth rate

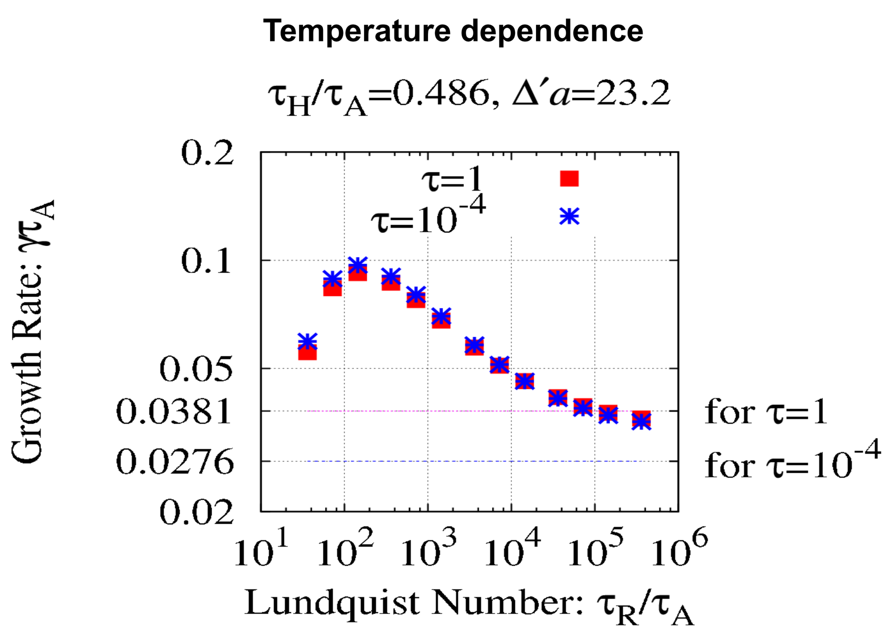
Temperature/Pressure effect

•Fluid models often assume polytropic equation of state $p/(mn)^{\Gamma}=\text{constant}$
Scaling laws given as $\gamma=\gamma(d_i,\rho_S,d_e)$ has ambiguity.
How to define ρ_S? It depends on τ, $\Gamma_{e,i}$.

•For high ion temperature, the ion finite Larmor radius (FLR) effect plays a role. Porcelli derived the growth rate including the FLR effect[4,5]:

$$\left(\frac{\gamma\tau_A}{k\rho_S}\right)^3=\hat{\gamma}^3=\frac{2}{\pi}\frac{d_e}{\rho_S}\left(1-\frac{\hat{\gamma}\pi}{d_e\Delta'}\right)\quad \text{where}\quad \rho_S=\sqrt{(T_{0e}+T_{0i})/m_i}/\Omega_{ci}$$





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Off-diagonal components of pressure have no effect

Off-diagonal components are not negligibly small

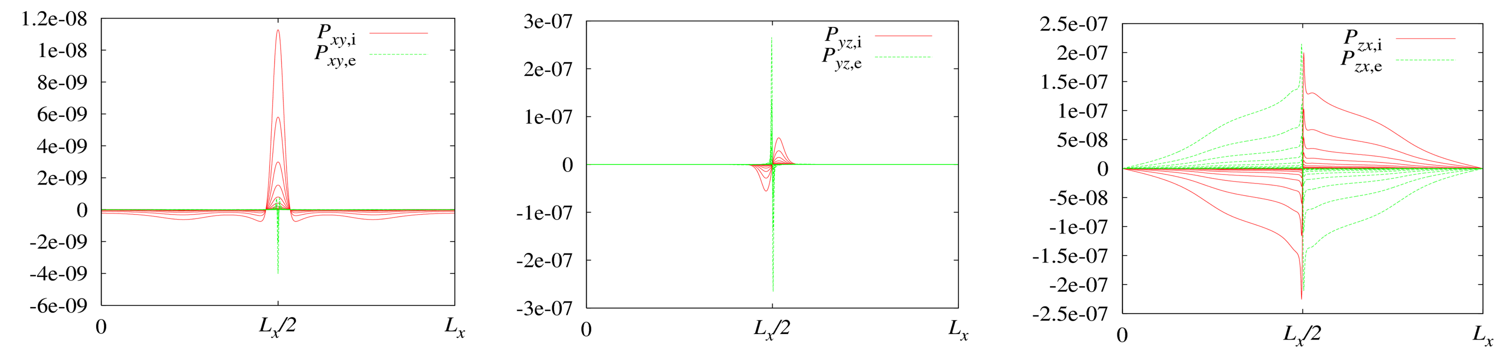
$$\begin{pmatrix}\boldsymbol{e}_x\\ \boldsymbol{e}_y\end{pmatrix}=\begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\boldsymbol{e}_{k_\perp}\\ \boldsymbol{e}_{k_\theta}\end{pmatrix}$$

$$\mathsf{P}_{\boldsymbol{k}}=P_{\perp\perp,\boldsymbol{k}}\boldsymbol{e}_{k_\perp}\boldsymbol{e}_{k_\perp}+P_{\theta\theta,\boldsymbol{k}}\boldsymbol{e}_{k_\theta}\boldsymbol{e}_{k_\theta}+P_{\theta\parallel,\boldsymbol{k}}\boldsymbol{e}_{k_\theta}\boldsymbol{b}_0+P_{\parallel\parallel,\boldsymbol{k}}\boldsymbol{b}_0\boldsymbol{b}_0$$

$$P_{\perp\perp,\boldsymbol{k}}=\int\frac{(J_0+J_2)}{2}h_{\boldsymbol{k}}mv_\perp^2\,\mathrm{d}\boldsymbol{v},\quad P_{\theta\theta,\boldsymbol{k}}=\int\frac{(J_0-J_2)}{2}h_{\boldsymbol{k}}mv_\perp^2\,\mathrm{d}\boldsymbol{v},$$

$$P_{\theta\parallel,\boldsymbol{k}}=\mathrm{i}\int J_1h_{\boldsymbol{k}}mv_\perp v_\parallel\,\mathrm{d}\boldsymbol{v},\quad P_{\parallel\parallel,\boldsymbol{k}}=\int J_0h_{\boldsymbol{k}}mv_\parallel^2\,\mathrm{d}\boldsymbol{v}$$

Only P_{xy} and P_{yz} are $\pi/2$ out-of-phase in the y direction with other components and have the same parity with $A_\parallel$



However, pressure tensor contributions in ion vorticity equation and Ohm's law are identically zero.

$$(\nabla\times\nabla\cdot\mathsf{P}_i)_\parallel=0\qquad(\nabla\cdot\mathsf{P}_e)_\parallel=0$$

Conclusions

•We have performed gyrokinetic tearing instability simulation using AstroGK for collisiionless case, and investigate kinetic effects.

•Gyrokinetic tearing growth rate is slower than the two-fluid MHD model (by factor of ~2) implying that the equation of state needs to be re-considred.

•Gyrokinetic result is also compared with the theory based on a kinetic model. Dependence on ion temperature seems much weaker than expected.

•If we assume polytropic equation of state, the indices are $\Gamma_i\approx5/3$, $\Gamma_e\approx1$. However, spatially varying indices suggests non-polytropicity.

•Off-diagonal components of pressure tensor do not affect the dynamics.

References

1) AstroGK Web Site: http://www.physics.uiowa.edu/~ghowes/astrogk/
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