Gyrokinetic Simulations of Microtearing Instability

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Introduction

•Tearing mode can be driven unstable by electron temperature gradient with current density gradient [Hazeltine *et al.* (1975)].

•High k modes (Microtearing [MT] mode) can be unstable even in the regime where normal tearing mode is stable ($\Delta'<0$).

•MT is collisional mode ($\nu_e/\omega_n \gg 1$). Energy dependence of collision frequency is important.

•Nonlinear theory by Drake et al (1980) predicts saturation level of magnetic fluctuations scales like ρ_e/L_T .

•MT may account for anomalous electron transport in fusion experiments, but may not in (conventional) takamaks because of low collisionality.

•Trapped particle effect may enhance the instability [Catto and Rosenbluth (1981), Conner (1990)].

•MT may be relevant in Spherical Tokamaks (ST); Redi et al (2003) – NSTX, Applegate (2004) – MAST.

•In this study, we perform gyrokinetic simulations of MT mode using AstroGK in a simplified geometry to study fundamental properties of the instability. We don't consider curvature, trapped particles.

Problem Setup

We perform gyrokinetic simulations for both ions and electrons in purely two-dimensional $(\partial/\partial z=0)$ doubly-periodic slab domain.

We initialize the simulation by putting a sheared equilibrium magnetic field,

$$\boldsymbol{B_0}=B_{z0}\hat{z}+B_{y0}(x)\hat{y}$$

where $\epsilon\equiv|B_{y0}|/B_{z0}\ll 1$. B_{y0} is generated by electron distribution function perturbation $\propto 2(v_\parallel/v_{\mathrm{th,e}})f_{0\mathrm{e}}$ ($f_{0\mathrm{e}}$ is a Maxwellian) to satisfy parallel Ampère's law.

We consider sinusoidal profile, $B_{y0}(x)=B_{y00}\sin(x/a)$, which gives the standard stability index,

$$\Delta' a=\begin{cases} 2\sqrt{1-(k_y a)^2}\tan\left(\frac{\pi}{2}\sqrt{1-(k_y a)^2}\right) & 0<k_y a<1 \\ -2\sqrt{(k_y a)^2-1} & k_y a>1. \end{cases}$$

Magnetic shear length is often defined by $L_s\equiv(1/B_{z0})(d\,B_{y0}/dx)=a/\epsilon$.

Density and temperature gradients of electrons, $L_{n_{0e}}^{-1}\equiv-\partial(\ln n_{0\mathrm{e}})/\partial x$, $L_{T_{0e}}^{-1}\equiv-\partial(\ln T_{0\mathrm{e}})/\partial x$, ($\eta_e=L_{n_{0e}}/L_{T_{0e}}$) drive diamagnetic drift $U_{n,T}^d=-T_0/(q B_{z0} L_{n_0,T_0})$.
We also define the drift frequencies, $\omega_{n,T}=k_y U_{n,T}^d$.

Other free parameters are:

$$\sigma=m_e/m_i,\quad \tau=T_{0i}/T_{0e},\quad \beta_e=n_0 T_{0e}/(B_{z0}^2/2\mu_0),\quad r=\sqrt{2}\rho_{Se}/a,$$

where $\rho_{Se}=\sqrt{T_{0e}/m_i}/\Omega_{ci}$ is the ion sound Larmor radius. Given these parameters, physical length scales are calculated as follows:

$$\rho_i/a=\tau^{1/2}r,\quad d_i/a=\beta_e^{-1/2}r,\quad \rho_e/a=\sigma^{1/2}r,\quad d_e/a=\beta_e^{-1/2}\sigma^{1/2}r.$$

Linear Theory

Drake & Lee (1977), Gladd et al (1980)

Drift kinetic electron + Kinetic ions (low β): quasi-neutrality $\frac{q_i n_0}{T_{0i}}\left(\langle\langle\phi\rangle_{\boldsymbol{R}}\rangle_r-\phi\right)=\frac{k_\parallel}{\omega q_e}J_{\parallel e}$

parallel Ampère $-\nabla^2 A_\parallel=\mu_0 J_{\parallel e}$

Electron parallel current (or parallel conductivity $\sigma=J_{\parallel e}/E_\parallel$) can be directly calculated from the distribution function, which closes the system of equations.

By assuming the electrostatic effect is negligible ($E_\parallel=\mathrm{i}\omega A_\parallel$), analytical dispersion relation is obtained:

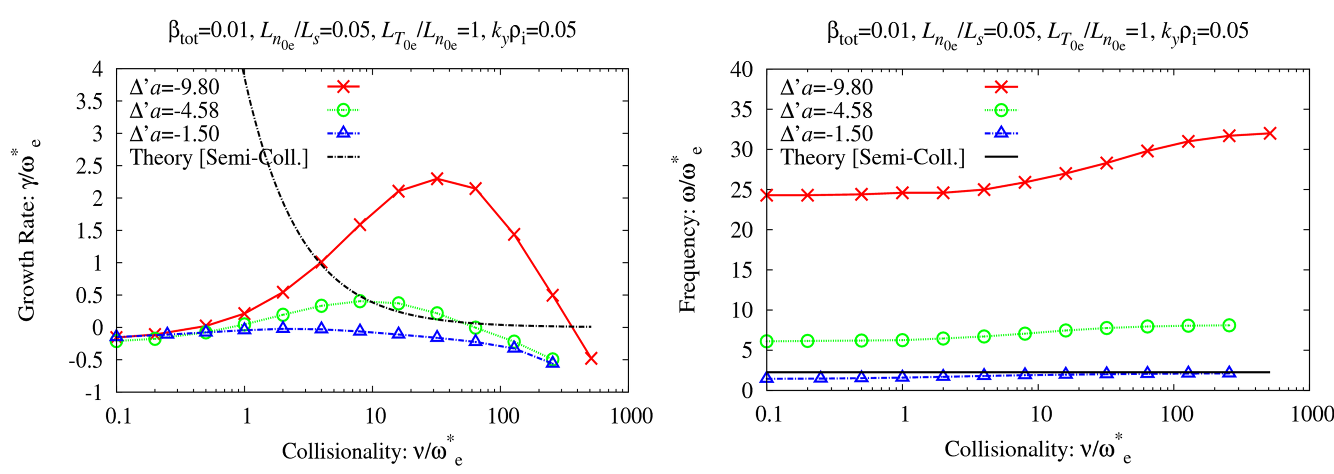
Collisionless
$$\frac{\gamma_1}{\omega_n}=\frac{1}{\sqrt{\pi}}\frac{L_{n_{0e}}}{L_s}\Delta'\rho_e \qquad \frac{\omega_1}{\omega_n}=1+\frac{1}{2}\eta_e$$

Semi-Collisional $(\delta\ll\rho_i)$
$$\frac{\gamma_2}{\omega_n}=\frac{3\pi^{1/4}}{\sqrt{2}4\Gamma(11/4)}\frac{\gamma_1}{\omega_n}\left(\frac{\omega_2}{\omega_n}\right)^{-1/2}\left(\frac{\nu_e}{\omega_n}\right)^{1/2}+\frac{2\Gamma(17/4)}{\sqrt{\pi}\Gamma(1/4)}\frac{\omega_2}{\omega_n}\frac{\omega_T}{\omega_n}\left(\frac{\nu_e}{\omega_n}\right)^{-1} \qquad \frac{\omega_2}{\omega_n}=1+\frac{5}{4}\eta_e$$

The assumption is too restrictive, and in general, the eigenvalue problem is solved numerically with appropriate boundary conditions.

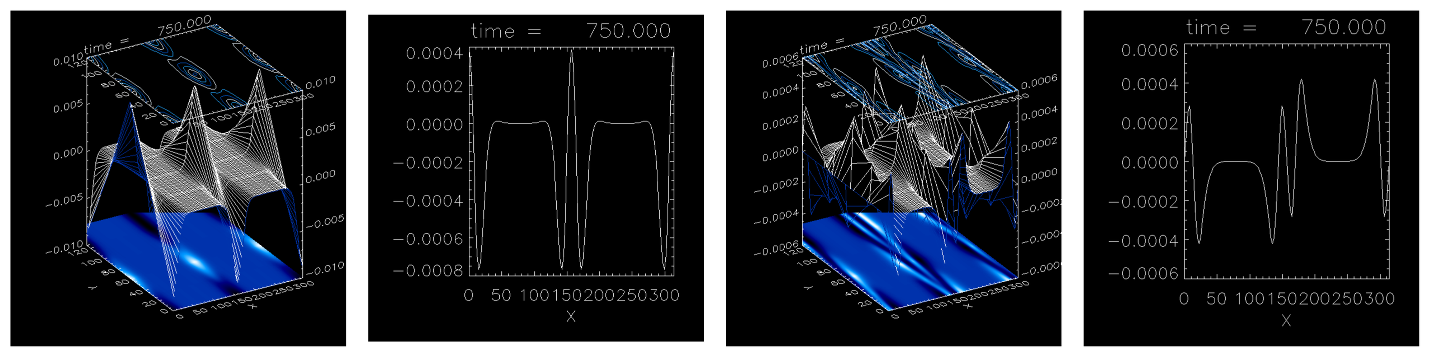
Simulation Result

Linear growth rate and frequency



•Growth rate scaling qualitatively fits with the theory only if the electrostatic effect is included.
– MT is unstable only if collisional ($\nu_e/\omega_n\sim 10$).
•Growth rate and frequency are strongly depends on $\Delta' a$ (or $\rho_{i,e}/a$).
– For given parameters, larger $|\Delta' a|$, smaller $\rho_{i,e}/a$ case is more unstable.
•Inconsistency with the theory
– it is said that MT growth rate is determined by competition between the destabilizing effect by temperature gradient and the stabilizing effect by the negative Δ' .

Eigenfunction $A_\parallel$ ϕ



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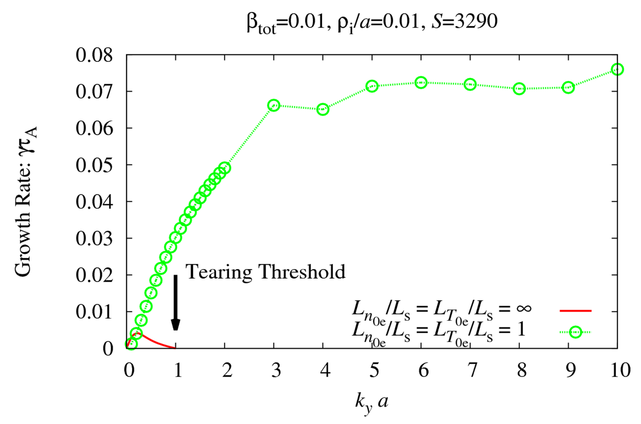

Same linear dispersion relation transformed into usual tearing mode terminology.

For the smallest ρ_i/a case, MT growth rate is much faster and has a broader spectrum (extending at least ρ_i/a scale) compared with the normal tearing mode.

Very preliminary nonlinear runs

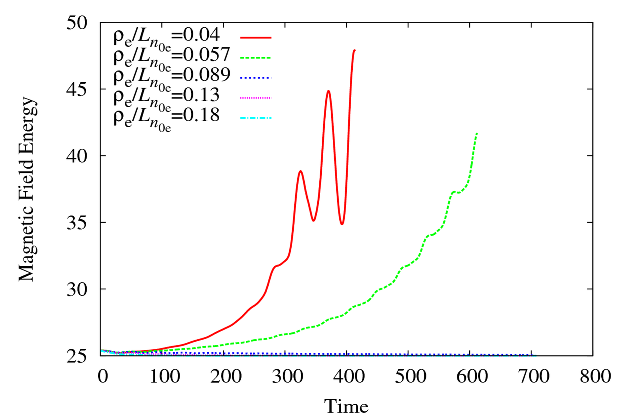

Figure shows time evolutions of magnetic field energy for different

Theory predicts magnetic perturbations saturate at $\tilde{B}/B_0\sim\rho_e/L_{T_{0e}}$ by balancing nonlinear and linear terms.

It seems smaller $\rho_e/L_{T_{0e}}$ case has higher saturation level.

Conclusions

•We have performed linear and nonlinear (only very preliminary) simulations of microtearing mode using gyrokinetic code, AstroGK.

•We have successfully demonstrated the code can capture the qualitative behavior of the instability.

•However, the theory only applicable to very restrictive situations. We even observe counter-theoretical behavior: small ion/electron gyroradius (less kinetic) cases are more dangerous (fast growth, high transport).

•Nature of the instability even in the linear regime is not well understood. Further intensive study is required.

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