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Fast ion driven drift wave instability in reversed shear plasmas

B. J. Kang and T. S. Hahm
Seoul National University, Seoul, Korea
tshahm@snu.ac.kr

ABSTRACT

- It is shown that trapped fast ions can destabilize the electron drift wave because fast ions reverse their precession direction in RS plasmas to electron diamagnetic direction and can resonate with electron drift wave.
- The new instability occurs when temperature gradient of fast ions peaks sufficiently compared to the density profile and the linear growth rate is linearly proportional to the temperature gradient length of fast ions.
- Strongly negative shear plasmas are more favorable for the new instability.
- Resulting quasi-linear particle flux of fast ions is outward while particle flux of main hydrogenic ions is inward.

BACKGROUND

- In future devices, many fast ions are generated by heating or fusion reaction.
- Since most previous works focus on electromagnetic Alfvenic instabilities driven by fast ions, we look for possibilities of electrostatic drift wave destabilized by fast ions in RS plasmas with fusion reactor conditions.
- In RS plasmas, many fast ions reverse their precession direction so their precession direction becomes the same with electron drift wave. Thus, toroidal precession of fast ions can resonate with electron drift wave in RS plasmas.

THEORITECAL RESEARCH

Local dispersion relation : with Maxwellian distribution function

- For $\omega \sim \omega_{*e} \ll \omega_{bf}, k_\parallel v_{Ti} \ll \omega \ll k_\parallel v_{Te}$ and $k_\perp \rho_i \ll 1$,

linear growth rate with an equilibrium Maxwellian distribution function is calculated as [B.J.Kang and T.S.Hahm, PoP '19].

$$\frac{\gamma_{lin}}{\omega_{*e}} \simeq -2\sqrt{2\pi\epsilon} Z_f^2 \frac{T_e}{T_f}\frac{n_{f0}}{n_{e0}}\frac{\omega_{*e}R}{\omega_{*f}L_{nf}}\left\langle \frac{1}{G(\hat{s},\kappa)}\sqrt{\hat{E}_0(\hat{s},\kappa)}e^{-\hat{E}_0(\hat{s},\kappa)}\left[1-\frac{\omega_{*f}}{\omega_{*e}}\left\{1+\eta_f\left(\hat{E}_0(\hat{s},\kappa)-\frac{3}{2}\right)\right\}\right]J_0^2\right\rangle_\kappa$$

- For normal density profiles, employ $\bar{G}(\hat{s}) = 0.64\hat{s} + 0.57$ [J.Li and Y.Kishimoto, PPCF '02] to simplify the pitch-angle integration. Assuming $\bar{G}(\hat{s}) < 0$ and $|\bar{G}(\hat{s})| \sim 1$, we get the instability condition,

$$\eta_f = \frac{L_{nf}}{L_{Tf}} > \frac{1-\dfrac{\omega_{*e}}{\omega_{*f}}}{\dfrac{3}{2}-\dfrac{\omega_{*e}R}{\omega_{*f}L_{nf}\bar{G}(\hat{s})}} \simeq \frac{2}{3}$$

Local dispersion relation : with Slowing down distribution function

- Consider an equilibrium distribution function of fusion α particles as given by a slowing down distribution function [J.D.Gaffey Jr., Journal of Plasma Physics '76]
- Then linear growth rate is calculated as

$$\frac{\gamma_{lin}}{\omega_{*e}} \simeq -\frac{\sqrt{2\epsilon}}{3A_2}\frac{\omega_{*e}R}{\omega_{*\alpha}L_{n\alpha}}\left[\left\langle\frac{H_s(\hat{E}_0(\hat{s},\kappa))J_0^2}{G(\hat{s},\kappa)}\left[H_s(\hat{E}_0(\hat{s},\kappa))-\frac{\omega_{*\alpha}}{\omega_{*e}}\left\{1+\frac{L_{n\alpha}}{L_{E_c}}K_s(\hat{E}_0(\hat{s},\kappa))\right\}\right]\right\rangle_\kappa + H\left(\kappa_1-\sin\frac{\theta}{2}\right)\frac{\kappa_1}{\sqrt{\kappa_1^2-\sin^2\frac{\theta}{2}}}\frac{H_s(1)J_0^2}{G'(\hat{s},\kappa_1)}\right]$$

- The mode becomes unstable when the temperature profile is more peaked than density profile and becomes more easily unstable in strongly negative shear plasmas but the critical value shows saturation (Fig.1).
- Since the barely trapped particles can reverse precession direction more easily, the high field side region can be more unstable than the low field side (Fig. 2). This will influence the eigenmode structure along the magnetic field line.
- Linear growth rate is linearly proportional to ${}^{L_{n\alpha}}/_{L_{E_c}}$ which is a free energy source of instability.

Instability driven particle flux

The quasi-linear particle fluxes of fast ions and ions are calculated as

$$\Gamma_f = \sum_{\vec{k}} \Gamma_{f,\vec{k}} = \sum_{\vec{k}} \frac{1}{Z_f}\frac{\gamma_{lin}}{\omega_{*e}} k_\theta \rho_s C_s \frac{|e|^2\left\langle|\delta\phi_{\vec{k}}|^2\right\rangle}{T_e^2} n_{e0}$$

$$\Gamma_i = \langle \delta n_i \delta v_r \rangle = \langle (\delta n_e - Z_f \delta n_f)\delta v_r \rangle = -Z_f \Gamma_f$$

When instability occurs, $\Gamma_\alpha > 0$ and $\Gamma_i < 0$ i.e. outward α-particle flux and inward main ion flux. It can expel relatively low energy He ions preferentially while keeping the ion working gas inside.

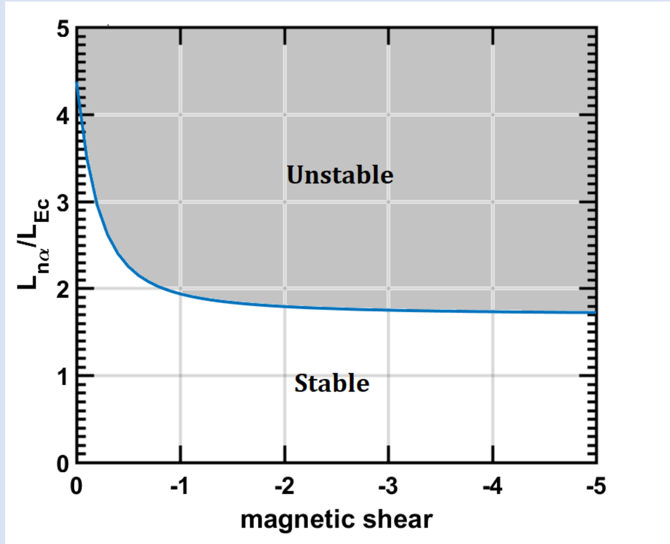

Fig.1
For a D-T plasma with $T_e = T_i = 10keV$, ${}^{L_{ne}}/_R = {}^{L_{n\alpha}}/_R = {}^1/_3$, $k_\perp \rho_i = 0.2$ and $\theta = 0$.

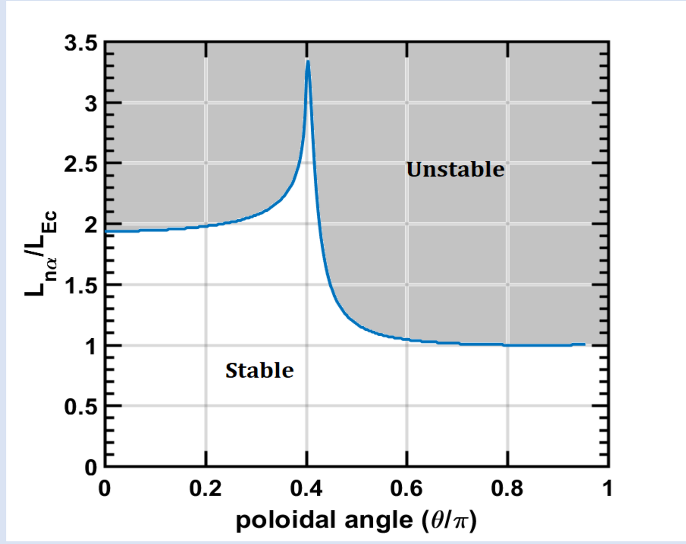

Fig.2
For a D-T plasma with $T_e = T_i = 10keV$, ${}^{L_{ne}}/_R = {}^{L_{n\alpha}}/_R = {}^1/_3$, $k_\perp \rho_i = 0.2$ and $\hat{s} = -1$.

GYROKINETIC SIMULATION RESEARCH

- GKW (Gyrokinetics Warwick) code [A.G.Peeters and D.Strinzi, Phys. Plasmas (2004)] is a nonlinear gyrokinetic delta-f and flux tube code.
- Electrostatic, collisionless, local and linear simulation.
- Adiabatic electron response, D-T plasma ($\frac{n_D}{n_e} = \frac{n_T}{n_e}$), cold ion (${}^{T_i}/_{T_e} = 0.1$) and Fusion alpha particles with Maxwellian distribution function.
- $r/a = 0.5$, R/a=3, $q = 1.4$, $\frac{R}{L_{Ti}} = \frac{R}{L_{Te}} = 0$, $\frac{R}{L_n} = 3$ and $k_\theta \rho_s = 0.2$
- Instabilities driven by alpha particles where $\omega_r \sim \omega_{*e}$ are found. Behavior of γ_{lin} and ω_r at $-2 \le \hat{s} \le -1$ can be explained by Y.J.Kim's work (Fig.3).
- γ_{lin} is linearly proportional to $R/L_{T\alpha}$. (Fig. 4)
- γ_{lin} is linearly proportional to n_α/n_e for $n_\alpha/n_e \ll 1$ regime. But it shows saturation for $n_\alpha/n_e > 0.1$ (Fig. 5).

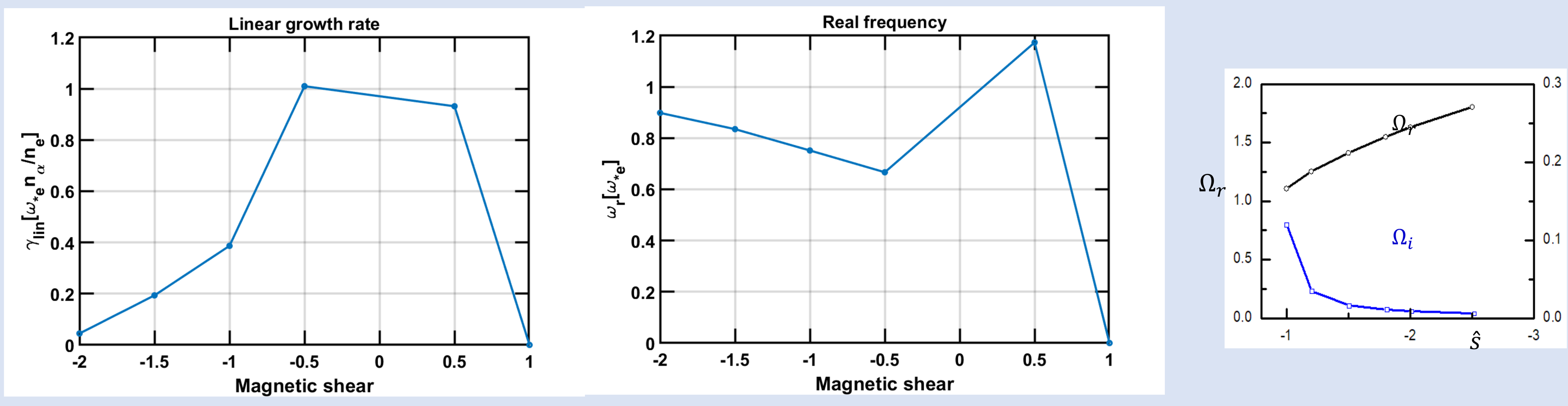

Fig.3 For ${}^R/_{L_{T\alpha}} = 30$, ${}^{T_\alpha}/_{T_e} = 50$ and $n_\alpha/n_e = 0.1$

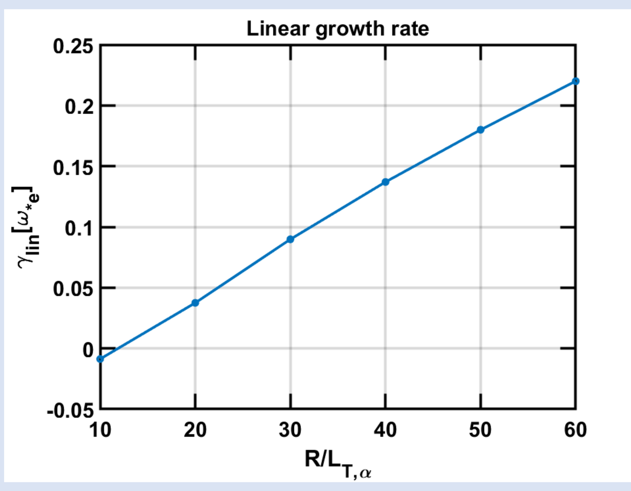

Fig.4 ,For $\hat{s} = -1$, ${}^{T_\alpha}/_{T_e} = 30$, $n_\alpha/n_e = 0.1$

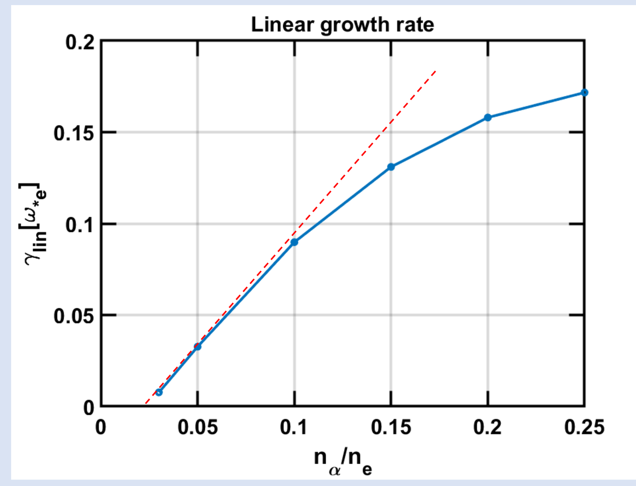

Fig.5 ,For ${}^R/_{L_{T\alpha}} = 30$, $\hat{s} = -1$ and ${}^{T_\alpha}/_{T_e} = 30$

CONCLUSION

- There exist drift instabilities propagating in electron diamagnetic direction driven by fast ions in reversed shear plasmas.
- Assuming an equilibrium Maxwellian distribution function, instability occurs when $\eta_f > \eta_{f,crit} \simeq \frac{2}{3}$.
- Considering the slowing down of fusion α-particles, instability occurs when $L_{n\alpha}/L_{E_c}$ is large which is similar to the Maxwellian case.
  - The mode becomes more easily unstable in strongly negative shear plasmas.
  - The high field side region can be more unstable than the low field side.
  - Linear growth rate is linearly proportional to ${}^{L_{n\alpha}}/_{L_{E_c}}$ which is a free energy source of instability.
- This instability might be even beneficial since it can expel lower energy fast ions (such as He-ash) preferentially while keeping the ion working gas inside.
- Using GKW code, instabilities driven by alpha particles at negative shear regime are found. But still we need to do more research to verify the new instability is driven by the resonance between precession reversal of trapped fast ions and the electron drift wave.

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