Outline

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Motivation

Microinstabilities are known to make significant contributions to turbulence and transport in tokamaks.

In RFPs, the focus has been on large scale (global) tearing modes.

Key Question - Do microinstabilities exist in the RFP (particularly in the outer region), and if so, what are their characteristics?
microinstabilities - perpendicular wavelengths on the order of a gyroradius

- Electrostatic (Zero Beta)
  - ITG/ETG (Ion/Electron Temperature Gradient)
  - TEM (Trapped Electron Mode)
- Electromagnetic (Finite Beta)
  - KBM (Kinetic Ballooning Mode) - ion frequency mode
  - Microtearing Mode - electron frequency mode
    - $\Delta' < 0$ for $k_\theta$ large (no current gradient drive)
    - driven by electron temperature gradient
Gyrokinetics and the GYRO\(^1\) code

- GYRO solves the gyrokinetic-Maxwell system of equations in a flux-tube domain
- Kinetic equation reduced to 5D by averaging over the gyrophase angle
- Linear (growth rates) and nonlinear (transport levels)
- Poloidal wavenumber \( k_\theta = \frac{nq(r)}{r} \)

RFP Modifications

Equilibrium - Toroidal Bessel Function Model $^2$

$$ B_\theta(r) = B_0 J_1 \left( \frac{2\Theta r}{a} \right) \frac{1}{1+(r/R_0)\cos(\theta)}, \quad B_\phi(r) = B_0 J_0 \left( \frac{2\Theta r}{a} \right) \frac{1}{1+(r/R_0)\cos(\theta)} $$

$$ \Theta = \frac{\langle B_\theta \rangle_{\text{wall}}}{\langle B_\phi \rangle_{\text{vol}}}, \text{ pinch parameter} $$

Modifications are primarily due to geometric changes in operators - curvature, diamagnetic, parallel transit

$$ \hat{b} \cdot \nabla = \frac{1}{qR_0} \frac{\partial}{\partial \theta} \rightarrow \frac{z}{qR_0} \frac{\partial}{\partial \theta} $$

$$ z = \frac{1}{\sqrt{1+\left( \frac{\epsilon}{q} \right)^{1/2}}} $$

s-$\alpha$ equilibrium not adequate to describe RFP growth rates

$^2$V. Tangri, P.W. Terry, and R.E. Waltz (2011)
Tokamak Results - $\beta_e$ stabilizes ITG, destabilizes KBM

Candy and Waltz (2003)

$R_0/a = 3.0, R_0/L_n = 3.0$
$R_0/L_T = 9.0, q = 2.0, s = 1.0$

Pueschel, Kammerer, and Jenko (2008)

$R_0/a = 2.78, R_0/L_n = 2.22$
$R_0/L_T = 6.89, q = 1.4, s = 0.786$
$k_\theta \rho_s = 0.372$

$r/a = 0.5, \; T_e/T_i = 2.5, \; a/L_n = 0.58, \; a/L_T = 5.0, \; \Theta = 1.35$
Low $\beta_e$ modes show ITG eigenmode structure

$$k_\theta \rho_s = 0.372, \beta_e = 0$$
canonical ballooning parity
$\theta_*$: extended ballooning angle
**ITG beta suppression**

- Hirose (2000) did an analysis of finite beta ITG suppression in tokamak geometry
- Concluded that ITG is suppressed by \( \alpha_e = -q^2 R \frac{d\beta_e}{dr} \), the electron ballooning parameter
- Modifying these results yields an estimate of when to expect it in the RFP
- Important difference: \( L_B : qR(\text{tokamak}) \rightarrow a(\text{RFP}) \)

**Stabilization Criterion**

\[
\alpha_e \geq \frac{1+\eta_e}{3} \frac{\tau^2}{(\tau+2\bar{\varepsilon}_n)(\tau+1)+\tau^2\eta_e}
\]

\[
\eta_e = \frac{L_n}{L_{Te}} = 8, \quad \bar{\varepsilon}_n = \frac{L_n}{L_B} = 1, \quad \tau = \frac{T_e}{T_i} = 2.5, \quad \epsilon = 1/3, \quad q = 0.2
\]

Stabilization occurs above \( 0.285 \rightarrow \beta_{e,\text{crit}} \sim 0.07 \)
High $\beta_e$ modes show Microtearing eigenmode structure

$$k_\theta \rho_s = 0.372, \quad \beta_e = 0.09$$
Shifting peak of instability growth rate

Microtearing strong across range of scales at high beta.

Next: focus on microtearing at $\beta_e = 0.09$ and $k_\theta \rho_s = 1.488$
Parameter Dependence - Electron Temperature Gradient

\[ k_\theta \rho_s = 1.488, \quad \beta_e = 0.09 \]

threshold value is \( a/L_{Te} \sim 3.5 \)
Parameter Dependence - Collisionality

Pitch-angle-scattering Lorentz operator

\[ C(f_\sigma) = \frac{\nu_{\sigma}(\epsilon)}{2} \frac{\partial}{\partial \xi} (1 - \xi^2) \frac{\partial f_\sigma}{\partial \xi} \]

Previous analytic work (in tokamaks) suggested that microt earing should be stable for collisionless plasma.
Microtearing stability sensitive to sign of shear?

Connor, Cowley, and Hastie (1990) - "Micro-tearing stability in Tokamaks"

\[ \dot{\gamma} = -C_1 \lambda \ln(1/\lambda) \eta_e^2 + C_2 \eta_e \sqrt{\frac{\epsilon \nu_e}{\omega_e}} - C_3 \eta_e^2 \frac{\nu_e}{\omega_e} - C_4 \Lambda \left( \frac{\omega_e}{\nu_e} \right) \] (1)

\[ C_4 = \frac{1}{\sqrt{\pi}} \frac{(1 + \tau)(1 + \frac{\eta_e}{2})}{1 + (1 + \frac{\eta_e}{2}) \tau} \] (2)

\[ \Lambda = \frac{4 \epsilon^{3/2}}{\beta_e} \frac{L_n^2}{R^2 q^2} s \nu_e, \quad s = \frac{rq'}{q}, \quad \nu_e = \frac{\nu_e R q}{\epsilon^{3/2} v_{Te}} \] (3)

Role of negative shear in instability drive?

Caveat - microtearing sometimes observed in tokamak simulations at low collisionality
Linear gyrokinetic simulations were performed using RFP equilibrium. At low electron beta, ITG is the dominant mode for $k_\theta \rho_s < 1$. ITG is suppressed by finite beta, in agreement with expectations. Microtearing becomes dominant around $\beta_e \sim 4.5\%$. The microtearing mode is driven by electron temperature gradient and seems to persist even at low collisionality.
Future Work

- Continue analysis of collisionless microtearing mode
- Use the GENE code for cross-checking and comparisons
- Nonlinear simulations for turbulence and transport levels
- Comparison with measurements - HIBP, Fast Thomson, FIR, probes
- $\tilde{n}$, $\tilde{T}$, $\tilde{\phi}$, $\tilde{B}$ fluctuations and correlation functions