Progress in Gyrokinetic Simulations of Microtearing Turbulence

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A brief history of microtearing research

- **1968**: Tearing instability (Furth, Killeen, Rosenbluth)
- **1975**: Instability due to $\nabla T_e$: $\mu$-tearing (Hazeltine et al.)
- **1980**: Model for saturation (Drake et al.)
- **1990**: $\mu$-tearing should be stable for realistic tokamak scenarios (Connor et al.)
- **1999**: Focus on $\mu$-tearing in plasma edge (Kesner et al.)
- **2003**: Linear gyrokinetic simulations (Redi et al., Applegate et al.); Large electron heat transport in spherical tokamaks caused by $\mu$-tearing?
- **2008**: $\mu$-tearing modes also found in conventional tokamaks (linear GK, Vermare et al., Told et al.)
Scope of this work

Problems

- **Existence** of microtearing instability in Tokamak geometry
- Electromagnetic **heat transport** caused by microtearing
- **Nonlinear saturation** of microtearing turbulence

Strategy

- Linear and nonlinear **simulations** using GENE
- Examine impact of steeper gradients, collisional effects...
- Comparison to **analytical models**
The GENE code
Gyrokinetic Electromagnetic Numerical Experiment

Solves gyrokinetic equations on fixed grid in 5D phase space
(⇒ continuum code)

- Comprehensive physics
- Massively parallel
- Open source

http://www.ipp.mpg.de/~fsj/gene/
Characteristics of $\mu$-tearing modes

Balooning representation

- Fluctuating **electrostatic potential** $\tilde{\phi}$ extends along field line
- **Vector potential** $\tilde{A}_\parallel$ is strongly localized around $\theta = 0$

$\mu$-tearing modes found in

- Spherical tokamaks (NSTX, MAST)
- Conventional tokamaks (ASDEX Upgrade)
- Model geometry: *Circular* (Lapillonne et al. 2009)
Influence of collisions

- Growth rate depends on collisionality $\nu_c$ only moderately
- Agreement with Applegate 2007

Microtearing modes exist in the weakly collisional regime!
Influence of temperature gradients

**Ions**
- \( R/L_{Ti} \) not important

**Electrons**
- \( \frac{R}{L_{Te}} = -\frac{R}{T_e} \frac{\partial T_e}{\partial x} \) crucial
- \( \left( \frac{R}{L_{Te}} \right)_{crit} \sim 1.5 \)

Existence of a critical electron temperature gradient confirmed
Nonlinear microtearing simulations are challenging to perform.
Magnetic field fluctuations of microtearing turbulence leads to field stochastization.
Heat Transport in Stochastic Magnetic Fields

\[ \chi_{em} = v_{te} D_M \]
\[ D_M = L_0 \left( \frac{\delta B}{B_0} \right)^2 \]

- Collisionless case
  \[ L_0 = q_0 R \]
- Collisional case
  \[ L_0 = \lambda_{mfp} = \frac{v_{te}}{\nu_e} \]
  \[(Wong \text{ et al., PRL 2007)}\]

Simple model (e.g. Liever 1985) confirmed in collisionless case
Nonlinear Behavior of Microtearing Turbulence

Model by Drake ’80

- \( \gamma_L \sim v_t e \lambda_{mfp} (\rho_e/L_{Te})^2 k_{\perp}^2 \)
- \( \gamma_{NL} \sim -D_M k_{\perp}^2 \)
- \( \Rightarrow \delta B/B_0 \sim \rho_e/L_{Te} \)

Gyrokinetic simulations

- Relevant low \( k \) regime:
  \( \gamma_L \sim 0.18 \frac{R}{L_{Te}} k_y \)
- Robust to changes in \( \beta, \nu_c, (R/L_n), q_0, \hat{s} \)

Nonlinear saturation mechanism is an open issue
Problems of Microtearing Simulation

sometimes...

- Peak at lowest $k_y$
- No saturation of heat flux

Solution

- Larger box?
- Higher resolution?
- Some Physics missing?

Nonlinear microtearing simulations are very challenging to perform
Conclusions

- Microtearing modes can be unstable in conventional tokamaks
- **Heat transport** can be substantial
- Nonlinear **saturation mechanism** is an open issue
- Further simulations:
  - System size: global microtearing + ITG
  - ...

Microtearing modes may play a role in future tokamak experiments like ITER
Thank you for your attention!
Nonlinear results adiabatic ions

Magnetic fluctuations

- Magnitude
  \[ \frac{\delta B}{B_0} \times \left( \frac{L_{Te}}{\rho_e} \right) \sim 1 \]  
  (Drake)
- **Stronger scaling** with \( R/L_{Te} \)

Heat diffusivity

- Rapidly increases with \( R/L_{Te} \)
- Nonlinear upshift of the **Critical gradient** \( \left( \frac{R}{L_{Te}} \right)_{\text{crit}} \)