Gyrokinetic Particle Simulations of Kinetic Ballooning Mode in DIII-D Tokamak Pedestal

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Outline

- Objectives
- Electrostatic turbulence in DIII-D pedestal
- Electromagnetic instabilities
- Towards simulation of RMP effects
Objectives of GTC simulations

► What is turbulent transport in tokamak H-mode pedestal?
► Does KBM exist in the pedestal and what role it plays?
  • Existence of KBM in DIII-D pedestal is not conclusively established by recent simulations [E. Wang, et. al. NF 52, 103015 (2012)]
Gyrokinetic Toroidal Code (GTC)

- GTC provides first-principles, integrated simulation capability for nonlinear interactions of kinetic-MHD processes, i.e., microturbulence, EP, MHD, and neoclassical transport

- GTC current capability for kinetic-MHD simulation:
  - General global 3D toroidal geometry and experimental profiles
  - Microturbulence and EP: gyrokinetic thermal/fast ions, drift-kinetic electrons and electromagnetic fluctuations
  - MHD: kink, resistive and collisionless tearing modes
  - Neoclassical transport: momentum/energy conserving collision operators
  - RF: fully kinetic (Vlasov) ions
  - Excellent scalability. Ported to GPU (Titan) & MIC (Tianhe-2)

http://phoenix.ps.uci.edu/GTC
Global gyrokinetic simulations of DIII-D shot #131997 at time 3011 ms (DOE Joint Research Target FY2011) using GTC code

Realistic magnetic equilibrium and profiles from EFIT and VMEC
Simulation profiles

- Temperature and density gradients from the maximum gradient region at $\psi_N = 0.98$ and pedestal top region $\psi_N = 0.95$ extended throughout simulation domain ($\psi_N = 0.9-1.0$)
Electrostatic instability

- Peak gradient region ($\psi_N=0.98$): **Trapped Electron Mode** instability with unusual mode structure peaked at $\theta=\pm\pi/2$ off the outer midplane [D. Fulton, et al., PoP’14)]
  - Linear growth rate monotonically increases with toroidal mode number $n$
  - Electron collisions decrease the growth rate by $\sim50$
- Pedestal top region ($\psi_N=0.95$): **Ion Temperature Gradient** instability
- Similar results from GTC simulation of HL-2A and EAST pedestal
Electrostatic turbulence

- Peak gradient region ($\psi_N = 0.98$)
  - Heat flux dominated by electrons
  - Turbulence saturation level is regulated by GAMs
  - Ion-ion collisions damp GAM

- Pedestal top region ($\psi_N = 0.95$)
  - Heat flux dominated by ions
Nonlinear turbulent spectrum is peaked around $k_\theta \rho_i \sim 0.15$ (TEM) and 0.25 (ITG) corresponding to $n \sim 20$ toroidal mode number.
Electromagnetic instability: peak gradient region

- **Kinetic Ballooning Mode** (KBM) is dominant
  - Ballooning structure
  - Mode is rotating in the ion diamagnetic direction
  - Instability exists with or without kinetic electron effect
Linear properties of KBM

- Linear growth rate increases at $\beta_e > 0.15\%$
- $n=20$ KBM instability barely exceeds TEM growth rate at $\beta_e \approx 0.15\%$ (experimental value)
- Maximum growth rate at toroidal mode number $n=20-30$ ($k_\theta \rho_i \sim 0.15-0.25$)
Electromagnetic instability: pedestal top region

- **Ion Temperature Gradient (ITG)?**
  - Ballooning structure rotating in the ion diamagnetic direction
  - Kinetic electrons significantly affect linear growth rate
Mode identification (pedestal top)

- ITG $\beta_e$-stabilization
- ITG-KBM transition at $\beta_e \approx 0.7\%$ above experimental value $\beta_e \approx 0.4\%$
Summary of microturbulence studies

► Electrostatic results:
  ● Peak gradient: trapped electron mode; Electron dominated transport
  ● Pedestal top: ion temperature gradient mode; Ion dominated transport

► Electromagnetic results:
  ● Peak gradient: kinetic ballooning mode is dominant for $\beta_e > 0.15$
  ● Pedestal top: finite-$\beta$ ion temperature gradient mode
RMP Effects on Pedestal Turbulence

- Resonant magnetic perturbation (RMP) is applied to control edge-localized mode (ELM) in DIII-D H-mode plasmas
- RMP significantly increases microturbulence in outer regions, and leads to particle pump out and change in toroidal rotation
- How does RMP affect microturbulence?
- We will use gyrokinetic particle simulation to investigate possible direct effect of RMP on microturbulence
Why RMP enhance microturbulence?

- A conjecture: Stochastic magnetic fields of RMP could suppress zonal flow generation due to increase of zonal flow dielectric constant by electron adiabatic response to zonal flow

What is the mechanism for particle pump out and change in rotation?

Require turbulence simulation with 3D equilibrium and stochastic magnetic field
3D capability in GTC

- GTC has recently been adapted to 3D equilibriums
  - VMEC MHD equilibrium (Cylindrical) => GTC input file (Boozer)
  - New capability is tested by simulating ITG and TAE in LHD stellarator

n=10 ITG mode structure at $\zeta=0$, $\pi/20$, $\pi/10$

n = 3 TAE eigenmode structure for $T_{\text{fast}}=180$ keV
Toward First-Principles Integrated Simulation of Kinetic-MHD

- Kinetic effects at microscopic scales and coupling of multiple physical processes are crucial for excitation and evolution of macroscopic MHD modes, e.g., NTM.
- GTC extended for *current-driven* MHD instabilities and verified for kink mode [J. McClanehan, PoP 2014] and *resistive tearing mode* [D. Liu, PoP 2014].
- GTC simulation finds depression of bootstrap current and suppression of ITG due to flattening of pressure profile in the island center [Jiang, PoP 2014].
Fluid-kinetic hybrid electron model I

- Parallel electric field

\[ E_{\parallel} = -\hat{b}_0 \cdot \nabla \phi - \frac{1}{c} \frac{\partial A_{\parallel}}{\partial t} = \hat{b}_0 \cdot \nabla \phi_{\text{eff}} \]

- Lowest order (adiabatic) solution of electron DKE expansion in \( \varepsilon = \omega / k_{\parallel} v_{\parallel} \)

\[ \frac{\delta f_e^{(0)}}{f_0} = \frac{e \phi_{\text{eff}}^{(0)}}{T_e} + \frac{\partial \ln f_0}{\partial \psi} \delta \psi \]

\[ \begin{align*}
\frac{e \phi_{\text{eff}}^{(h)}}{T_e} &= \frac{\delta n_e}{n_0} - \frac{\delta n_e^{(h-1)}}{n_0} - \frac{\partial \ln n_0}{\partial \psi} \delta \psi
\end{align*} \]

- Faraday’s law

\[ \frac{1}{c} \frac{\partial A_{\parallel}}{\partial t} = \hat{b}_0 \cdot \nabla (\phi_{\text{eff}} - \delta \phi) \]

\[ \frac{\partial \delta \psi}{\partial t} = -\frac{1}{q} \frac{\partial}{\partial \theta} (\phi_{\text{eff}} - \phi) \]

- Contravariant representation of the magnetic field

\[ \mathbf{B} = \nabla \psi \times \nabla (q \theta - \zeta) = \nabla \psi \times \nabla \alpha \]

\[ \delta \mathbf{B}_{\perp} = \nabla \delta \psi \times \nabla \alpha + \nabla \psi \times \nabla \delta \alpha \]

\[ \delta \mathbf{B}_{\perp} = \nabla \times A_{\parallel} \mathbf{b}_0 \]
Fluid-kinetic hybrid electron model II

- Electron continuity equation

\[
\frac{\partial \delta n_e}{\partial t} + B_0 \mathbf{b}_0 \cdot \nabla \left( \frac{n_0 \delta u_{||e}}{B_0} \right) + B_0 \mathbf{v}_E \cdot \nabla \left( \frac{n_0}{B_0} \right) - n_0 (\mathbf{v}_* + \mathbf{v}_E) \nabla \ln B_0 = 0
\]

- Perturbed diamagnetic drift velocity

\[
\mathbf{v}_* = \frac{1}{n_0 m_e \Omega_e} \mathbf{b}_0 \times \nabla (\delta p_{||} + \delta p_{\perp})
\]

- Inversed gyrokinetic Ampere’s law for current

\[
\frac{4 \pi}{c} e n_e u_{||e} = \nabla^2 A_{||} + \frac{4 \pi}{c} Z_i n_i u_{||i}
\]

- High-order electron kinetic response

\[
\frac{d}{dt} \frac{\delta f_e}{f_0} = \left( 1 - \frac{\delta f_e^{(0)}}{f_0} - w_e \right) \left[ -\mathbf{v}_E \cdot \nabla \ln f_0e - \frac{\partial}{\partial t} \frac{\delta f_e^{(0)}}{f_0} - \mathbf{v}_d \cdot \nabla \left( \frac{\delta f_e^{(0)}}{f_0} - \frac{e \phi}{T_e} \right) - \langle \mathbf{v}_E \rangle \cdot \nabla \frac{\delta f_e^{(0)}}{f_0} \right]
\]

- Perturbed pressure

\[
\delta p_{\perp} = \frac{\pi B_0}{m} \int d\mathbf{v}_{||} d\mu \mu B_0 \delta f_e
\]

\[
\delta p_{||} = \frac{\pi B_0}{m} \int d\mathbf{v}_{||} d\mu m v_{||}^2 \delta f_e
\]
Validity of gyrokinetic theory


\[
\frac{V_E}{v_{th}} \approx k_{\perp} \rho_i \frac{e \Phi}{T} \sim \frac{\omega}{\Omega} \sim \frac{\rho_i}{L_p} \sim \frac{L_p}{R} << 1
\]

- Simulation parameters

\[
\begin{align*}
\rho_i/L_n &= 6.67 \times 10^{-2} & \rho_i/L_{Te} &= 1.37 \times 10^{-1} & \rho_i/L_{Ti} &= 4.48 \times 10^{-2} \\
L_n/R_0 &= 7.69 \times 10^{-3} & L_{Te}/R_0 &= 3.64 \times 10^{-3} & L_{Ti}/R_0 &= 1.1 \times 10^{-2} \\
\omega/\Omega &\sim 1 \times 10^{-3} & k_{\perp} \rho_i e \Phi/T_e &\sim 1 \times 10^{-2}
\end{align*}
\]