Global Gyrokinetic Simulations of Electromagnetic Instabilities in Magnetically Confined Plasmas

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Outline

• Gyrokinetic simulations of DIII-D plasma pedestal
  – Electrostatic instabilities
  – Turbulent Transport
  – Electromagnetic instabilities
• Extension of GTC for treating non-axisymmetric equilibrium
• Gyrokinetic simulations of current-driven instabilities
  – Internal kink mode
  – Resistive tearing mode
  – Collisionless tearing mode
GTC simulation of DIII-D plasma pedestal

- Global gyrokinetic simulations of DIII-D shot #131997 at time 3011
- Realistic magnetic equilibrium reconstructed by EFIT and VMEC
- Temperature and density profiles from the top of the pedestal $\psi_N = 0.95$ and from the maximum gradient region at $\psi_N = 0.98$
Electrostatic instability ($\psi_N = 0.98$)

- Electrostatic simulations recover trapped electron driven instability with unusual mode structure peaked at $\theta = \pm \pi/2$ [D. Fulton, et al., Phys. Plasmas 21, 042110 (2014)]
- Turbulent spectrum is peaked at $m = 60-80$ ($n = 20-30$)
Turbulent transport

- Pedestal top ($\psi_N=0.95$):

- Peak gradient region ($\psi_N=0.98$):
Electromagnetic instability

- Peak gradient region ($\psi_N=0.98$) is considered
- Kinetic ballooning instability (KBM) is observed at $\beta_e>0.15\%$
- Mode is rotating in ion diamagnetic direction
- Instability exists with or without kinetic electrons

![Graphs showing the behavior at $n=20$, $\beta_e=0.15\%$ and $\beta_e=0.75\%$](image)
Linear properties of KBM

- Maximum growth rate at toroidal mode number $n=20$
- Linear growth rate increases with $\beta_e$
- $n=20$ instability exceeds electrostatic threshold at $\beta_e \approx 0.15\%$

![Graph 1: Growth rate vs. $n$](image1)

![Graph 2: Growth rate vs. $\beta_e$](image2)
3D capability in GTC

- GTC is extended to treat non-axisymmetric magnetic equilibrium
- Equilibrium input data provided as Fourier coefficients for cylindrical coordinates of flux surfaces and magnetic field strength B
- Spline interpolation in $\zeta$ is made, with spline coefficients stored by corresponding toroidal parallel process for efficiency
- New capability is tested by simulating ITG and TAE in LHD stellarator
- Will be applied for simulation of microturbulence with RMP in DIII-D tokamak

Mode structure of electrostatic potential for $n=3$ EP driven TAE mode in LHD stellarator

Poloidal snapshot of electrostatic potential for $n=10$ ITG mode in LHD at $\zeta=0$
GTC for current-driven instability

- Faraday’s law is replaced with parallel force balance in fluid-kinetic hybrid electron model

- Continuity equation

\[
\frac{\partial \delta n_e}{\partial t} + \mathbf{B} \cdot \nabla \left( \frac{n_0 u_{||e}}{B_0} \right) + B_0 \mathbf{v}_E \cdot \nabla \left( \frac{n_0}{B_0} \right) - n_0 \left( \mathbf{v}_* + \mathbf{v}_E \right) \cdot \frac{\nabla B_0}{B_0} + \frac{\nabla \times B_0}{B_0^2} \left( - \nabla \delta p_{||e} + n_0 \nabla \phi \right) = 0
\]

- Ampere’s law

\[
n_0 e \delta u_{||e} = \frac{c}{4\pi} \nabla^2 \delta A_{||} + \sum_{\alpha \neq e} n_\alpha Z_\alpha \delta u_{||\alpha}
\]

- Parallel force balance

\[
\frac{\partial A_{||}}{\partial t} = -\nabla_{||} \phi + \frac{1}{n_0} \nabla_{||} \delta p_e + \mathbf{v}_e \cdot \delta u_{||e}
\]

\[
\delta p_{||} = \int d\mathbf{v} \mu B_0 \delta f
\]

\[
\delta p_{\perp} = \int d\mathbf{v} mv_{\perp}^2 \delta f
\]

- Poisson’s equation

\[
\sum_{\alpha \neq e} \left( \tilde{\phi} - \phi \right) \frac{n_0 \alpha Z_\alpha^2}{T_\alpha} = -\sum_{\alpha} n_\alpha Z_\alpha
\]
GTC simulation of internal kink mode

- Good agreement with MHD theory in cylindrical geometry
- Internal kink in toroidal geometry
- Stabilization by kinetic effects
GTC simulation of resistive tearing mode

- (2,1) Resistive Tearing mode in cylinder

- (2,1) Resistive Tearing mode in tokamak with kinetic effects

- Poloidal symmetry breaking of mode structure and stabilization of the mode due to the magnetic field toroidal curvature
GTC simulation of collisionless tearing mode

- Resolving electron skin-depth
- Electron inertia
  \[ n_0 \frac{\partial \delta u_{\text{ec}}}{\partial t} = n_0 \nabla || \phi - \nabla || \delta P_e \]
- Microscopic Ampere’s law
  \[ \frac{1}{4\pi n_0} \left( \nabla^2 - \frac{1}{D_e^2} \right) \delta A_{\parallel} = \delta u_{\text{ec}} \]
- Verification of (1,1) collisionless TM in cylindrical geometry
(2,1) Double collisionless tearing mode in cylinder
Conclusions

- Gyrokinetic simulations of plasma edge region have been done using realistic DIII-D equilibrium and profiles.
  - The electrostatic simulations in the peak gradient region recover a trapped electron mode instability with a mode structure peaked at $\theta = \pm \pi/2$ rotating in the electron diamagnetic direction.
  - Turbulent transport is dominated by ion contribution in the top of pedestal and electron contribution in the peak gradient region.
  - Electromagnetic simulations recover instability with properties of kinetic-ballooning mode.
- General magnetic geometry used in GTC has been recently extended to treat non-axisymmetric equilibriums for simulating stellarators and resonant magnetic perturbation in tokamak. This new capability has been tested by simulating ITG and TAE modes in LHD stellarator.
- Tearing physics and equilibrium current included in GTC formulation.
  - Simulation of internal kink mode is verified against MHD theory. Effect of kinetic stabilization of internal kink in tokamak is observed.
  - Simulation of resistive tearing mode is verified in cylindrical geometry. Stabilization of resistive tearing mode due to magnetic toroidal curvature is observed.
  - Simulation of collisionless tearing mode is verified in cylindrical geometry.