A gyrokinetic discovery of fast L-H bifurcation physics in a realistic diverted tokamak edge geometry

Seung-Hoe Ku\textsuperscript{1}, C.S. Chang\textsuperscript{1}, R.M. Churchill\textsuperscript{1}, I. Cziegler\textsuperscript{2}, M. Greenwald\textsuperscript{3}, R. Hager\textsuperscript{1}, J. Hughes\textsuperscript{3}, G.R. Tynan\textsuperscript{4}

\textsuperscript{1}Princeton Plasma Physics Laboratory, USA, \textsuperscript{2}Univ. York, UK, \textsuperscript{3}PSFC, MIT, USA, \textsuperscript{4}UC San Diego, USA

*Computing resources provided by OLCF at ORNL and ALCF at ANL

27th IAEA Fusion Energy Conference, 22 – 27 October 2018, Ahmedabad, India
Outline

- Introduction to XGC and the edge timescale
- Simulation setup
- XGC sees two turbulence suppression mechanisms by ExB shearing
  - Reynolds stress
  - Neoclassical (X-loss)
- Different suppression time-scale between electron and ion modes
  - Fast suppression of electron modes
  - Slow suppression of ion modes
- Conclusion and discussion
XGC gyrokinetic PIC codes (V&V summary at hbps.pppl.gov)

- XGC: X-point Gyrokinetic Code
- Steep electrostatic pedestal ordering [Hahm PoP 2009]
- Heat and momentum source in core
- Monte Carlo neutrals with wall recycling
- Fully nonlinear Fokker-Planck Coulomb collision operation
- Logical wall-sheath
- Unstructured triangular mesh

Capabilities
- ES with GK ions + drift-kinetic electrons [C.S. Chang TH/P7-22, R.M. Churchill TH/P7-26, J. Chowdhury TH/P8-7]
- Impurity ions [J. Dominski TH/P6-20]
- RMP or 3D B-field [J.M. Kwon TH/8-1, R. Hager TH/P5-9, G. Park TH/P5-26]
- Stellarator [M. Cole TH/P6-21, T. Moritaka TH/P5-5]
- EM with fully implicit drift-kinetic electrons (partially verified)
- Gyrokinetic electrons for ETG
Different timescales between core and edge

For simplicity, let’s use the drift kinetic equation for this argument

\[
\frac{\partial f}{\partial t} + (v_{\parallel} + v_d) \cdot \nabla f + \frac{e}{m} E_{\parallel} v_{\parallel} \frac{\partial f}{\partial w} = C(f, f) + \text{Sources/Sinks}
\]

**Core \( f \) evolves slowly: \( \tau > 1\text{ms} \)**

- Near-thermal equilibrium: \( f = f_M + \delta f \);
  \[
  C(\delta f), v_{\parallel}/L_{\parallel}, v_d/L_r, ev_{\parallel}E_{\parallel}/T, = O(\rho \omega_{bi})
  \]
  \[\partial \delta f/\partial t=O(\rho \omega_{bi})\]

**Edge \( f \) evolves fast: \( \tau < 0.1\text{ms} \)**

- Non-Maxwellian: \( f \neq f_M \);
  \[
  C(f), v_{\parallel}/L_{\parallel}, v_d/L_r, ev_{\parallel}E_{\parallel}/T, S= O(\omega_{bi})
  \]
  \[\partial f/\partial t=O(\omega_{bi})\]
Why has a gyrokinetic L-H study not been done previously?

- Scale-inseparable, nonlocal multiscale in space and time
  - Edge turbulence including large-amplitude blobs
  - Neoclassical with X-loss
  - Neutral particle recycling with ionization and charge exchange
  - Overlapping space-time scale: e.g., turbulence correl. width ~ plasma gradient scale length ~ orbit width ~ ExB shearing width ~ neutral penetration length

- Magnetic separatrix interfacing two different magnetic topologies

- Non-Maxwellian plasma, requiring nonlinear Fokker-Planck collision

- Long global transport equilibrium time >> GK simulation time

→ We thought it would require exascale computer; non-existent yet.
A new strategy for GK simulation of L-H transition to make the bifurcation study possible on present HPCs

• Bifurcation may not be a global transport-equilibrium phenomenon
  – But, an edge localized phenomenon [Yan, PRL14; Cziegler, PPCF14, …]
  – May not need to wait until GAMs die out [Conway, PRL11; …]

• Study only the edge bifurcation itself, as soon as the L-mode edge turbulence establishes, without waiting for the pedestal buildup.
  – We want to force the bifurcation by having $P_{\text{edge}} / P_{\text{LH}} \gtrsim 2$
  – A forced L-H bifurcation action could be completed in $\lesssim 0.1\text{ms}$ (Cziegler PPCF14, Yan, PRL14, and others).
  – Take advantage of $\approx 0.1\text{ms}$ establishment of the nonlinear edge turbulence.

• Low beta electrostatic simulation: EM simulation in near future
Outline

• Introduction to XGC and the edge timescale

• Simulation setup
  • XGC sees two turbulence suppression mechanisms by ExB shearing
    – Reynolds stress
    – Neoclassical (X-loss)
  • Different suppression time-scale between electron and ion modes
    – Fast suppression of electron modes
    – Slow suppression of ion modes

• Conclusion and discussion
For the present L-H bifurcation study in XGC, we use a low-beta electrostatic edge plasma

Plasma input condition
- C-Mod #1140613017 in L-mode, single-null, \( \nabla B \)-drift away from X-point
- \( \beta_e \approx 0.01\% < m_e/m_i \) in the bifurcation layer
- \( \nabla B \)-drift has been flipped to be into the divertor for this presentation

Include the most important multi physics
- Neoclassical kinetic physics
- Nonlinear electrostatic turbulence
  - ITG, TEM, Resistive ballooning, Kelvin-Helmholtz, other drift waves
- Neutral particle recycling with CX and ionization
- Realistic diverted geometry

Electromagnetic correction to the present result is left for a future work.
An L-mode plasma from C-Mod (beta-edge~0.01%)

- Ion heat flux across $\Psi_N \approx 0.95$ is $\sim 1.8$ MW and well above $P_{\text{LH}^{i+e}} \sim 1$-1.5 MW.
- Edge temperature increases from heat accumulation.
- Transition layer is at $0.96 < \Psi_N < 0.98$, agreeing with C-Mod, DIII-D [Cziegler PPCF14, Yan PRL 14] and other devices.
Outline

• Introduction to XGC and the edge timescale
• Simulation setup
• **XGC sees two turbulence suppression mechanisms by ExB shearing**
  – Reynolds stress
  – Neoclassical (X-loss)
• Different suppression time-scale between electron and ion modes
  – Fast suppression of electron modes
  – Slow suppression of ion modes
• Conclusion and discussion
Overview of the turbulence behavior at bifurcation

Two different shearing actions noticed

1. At $t \sim 0.175-0.21\,\text{ms}$, lower frequency turbulence is sheared to higher frequency turbulence (by Reynolds-stress $\text{ExB}$ shearing, to be shown).

2. At $t > 0.21\,\text{ms}$, shearing and suppression of all frequency turbulence (neoclassical $\text{ExB}$ shearing, to be shown, Biglari-Diamond PoF1990)
Time-radius behavior of the sheared ExB flow, $V_E'$

1. $t_A=0.12\text{ms}$, $V_E'$ and L-mode turbulence settle down in edge layer
2. $t< t_B=0.175\text{ms}$, L-mode $V_E'$ remains negative in the edge layer ($\rho>0$)
3. $t\sim t_B$, something pushes the $V_E'$ to $>0$ in the edge layer ($\rho<0$): Reynolds
4. $t> t_C=0.2\text{ms}$, $V_E'$ locks into mean ExB shearing in the bifurcation layer: neoclassial
The bifurcation criterion is identified to be \( V'_E > 150 \text{ kHz} \) (Growth rate of dissipative TEMs [Romanelli PoP 2007]).
Reynolds stress induces the jump in ExB shearing at $t_B$

- The normalized, turbulence Reynolds consumption rate $P = \langle \tilde{v}_r\tilde{v}_\theta \rangle V'/\langle \mathcal{V}_{\text{eff}}^2 \rangle /2$ becomes peaked ($> 3$) in the beginning of the bifurcation action, but becomes $\leq 1$ after that; and dies out eventually.

- What is then keeping the turbulence suppressed?

Various opinions exist on the role of Reynolds consumption:
- Kobayashi PRL13, Cavedon NF17, Stoltzfus-Dueck PoP16, Diallo NF17
- Yan PRL14, Schmidt NF17, Tynan NF13, Istvan PPCF14, papers by Diamond

Similar behaviors of Reynolds consumption rate has been reported in EAST, C-Mod, and DIII-D experiments. [Manz PoP12, Tynan NF13, Yan PRL14]
The X-point orbit-loss [Chang PoP02, Ku PoP04] provides the answer

- The negative Reynolds force is canceled by orbit-loss force, and not effective.
- Orbit-loss force is pushing $V'_{ExB}$ further to positive direction after 0.175 ms.
- This $V'_{ExB}$ is keeping the turbulence suppressed after the bifurcation.

[S. Ku et al., PoP 2004]
Outline

• Introduction to XGC and the edge timescale
• Simulation setup
• XGC sees two turbulence suppression mechanisms by ExB shearing
  – Reynolds stress
  – Neoclassical (X-loss)
• Different suppression time-scale between electron and ion modes
  – Fast suppression of electron modes
  – Slow suppression of ion modes
• Conclusion and discussion
Electron modes disappear immediately around the transition time

- Figures at right: Time-averaged wavenumber spectrum of the turbulence at $\Psi_n = 0.975$
- Top: Before the first-phase $E \times B$ shearing starts ($t = 0.12 - 0.17$ ms)
  - Both ion and electron modes exist
- Well into the second-phase shearing activities ($t = 0.22 - 0.26$ ms)
  - Electron modes have disappeared
  - Ion modes are being sheared away to higher frequency
- Would be interesting to compare with experimental results.
Conclusion and Discussions

• A forced, fast L-H like bifurcation physics has been revealed under favorable magnetic drift condition, with transport suppression in both the heat and particle channels.

• The turbulent Reynolds stress and the neoclassical X-loss physics work together in achieving the L-H bifurcation.
  – How will the geometry and plasma condition change their combination?
  – How will this affect $P_{L-H}$ in 15MA ITER that has small $\rho_i/a$?

• Fast suppression of electron modes by Reynolds-stress ExB shearing, followed by slower suppression of ion modes by neoclassical ExB shearing: experiments?

Not shown in this talk:

• Unfavorable $\nabla B$ case shows stronger GAMs. Weakly coherent modes appears during the bifurcation.

• Hydrogen isotope simulation gives higher GAM damping and weaker ExB shear