Recent Developments in Gyrokinetic Understanding of Divertor Heat-Load Width

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The gyrokinetic code XGC tries to simulate plasma particle dynamics as in real experiment, according to Vlasov-Fokker Planck equation, below gyrofrequency

Mission: Use largest computers to perform first-principles-based studies
- Total-f particle-in-cell
- Neutral particle recycling with atomic cross-sections
- Logical sheath at material bd
- Non-Maxwellian plasma
- NL Fokker-Planck operator
- Heat, momentum & cooling source/sink
- > Trillion particles: Requires largest computers
- Attached plasma so far, moving toward detachment.

Free parameter: neutral particle recycling rate (R=0.99) & \( \Phi(\text{limiter}) = 0 \).
XGC outputs all the drift motions, including ExB around X-point

- **Forward Grad-B:**
  - Potential hill with higher plasma density around X-point
  - Lower $T_e$ around X-point (pressure equilibration)
  - Impurity particles from SOL tend to enter into core through the high-field side near X-point

- **Backward Grad-B** reverses the ExB drift direction

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[Chang et al., PoP 2019]
XGC automatically outputs the gyrokinetic heat-flux footprint consistently with neoclassical, turbulent and neutrals physics.
The edge gyrokinetic code XGC says

- Today’s conventional tokamaks and 5MA-ITER:
  - Transport in pedestal is at ion neoclassical level
  - Transport across separatrix is also at ion neoclassical level despite the ”blobby” turbulence.
  \[ \lambda_q \sim 0.63/B_{pol}^{1.19} \] [Eich (Goldston)]

- 15MA-ITER: Transport in pedestal and near-SOL is dominated by kinetic micro-turbulence
  - Weak neoclassical ExB shearing due to small \( \rho_{i,\text{pol}}/a \) cannot suppress turbulence [Kotchenreuther, Chang 2017]
  - This also includes the weak neoclassical X-point orbit-loss driven ExB shearing rate [Chang 2002, 2017]
  - XGC finds that \( \lambda_q^{\text{XGC}} \) is spread by kinetic trapped-electron turbulence by \( >6 \times \lambda_q^{\text{Eich}} \)

- Machine Learning and Regression reveal a hidden parameter \( a/\rho_{i,\text{pol}} \)
  - Consistently with the neoclassical ExB shearing physics

- A simple correction to Eich formula is identified (preliminary)
  - A manufactured JET plasma at higher \( I_p \) and ITER plasma at \( I_p\sim12\text{MA} \) are needed to refine the formula

- To validate the XGC findings – trapped-electron turbulence – on today’s tokamaks, a turbulence-dominant wide pedestal with high \( T_e(\text{sep}) \) may be used: \( \rho_{i,\text{pol}}/L_{\text{ped}}<<1 \) and weak \( \nu_e \) at separatrix
  - QH mode with edge ECH/LHH could be a good candidate?
  - \( \lambda_q \) measurements from EAST with edge LHH shows a significant \( \lambda_q \) broadening?
Kinetic effect: Neoclassical ion orbit excursion generates radial electric field

- Banana width
  \[ \rho_{ip} \propto \frac{1}{B_{pol}} \]
- Ion/electron banana width ratio is \( (m_i/m_e)^{1/2} \gg 1 \)
  \[ \Rightarrow \text{Radial charge separation} \]
  \[ \Rightarrow \text{(Sheared) radial electric field generation} \]
  [Chang, PoP2004]
  \[ \Rightarrow \text{Suppresses turbulence} \]
- If \( \rho_{ip}/L \rightarrow 0 \), neoclassical \( E_r \rightarrow 0 \)
Kinetic effect: Neoclassical X-point orbit loss generates $E_r$-layer and toroidal rotation in the edge, from ion orbit drift ($1/B_{pol}$)

- $B_p=0$ at magnetic X-point and is small around it.
  - Weak poloidal ion rotation
  - Confinement is lost $\rightarrow$ ion orbit loss
  - Negative charge within ion banana width $\Delta_b$ inside separatrix $\rightarrow$ strong $E_r<0$ in $\Delta_b$ layer

- Strong $E_r$ or toroidal rotation creates steep $\nabla p$ (force balance, electrostatic confinement) $\rightarrow$ pedestal

![Typical ion X-point loss orbits (XGC)](image)

![Buildup of $E_r$ in XGC1 (DIII-D)](image)

Grounded Wall

Buildup of $E_r$ in XGC1 (DIII-D)

Major contribution to outer divertor heat-load
XGC says: with $a/\rho_{i,\text{pol}}$ becoming very large, hence the neoclassical ExB shearing rate becoming weak, the 15MA ITER pedestal becomes turbulence-dominant.

- A new turbulence-dominant pedestal profile is established in XGC1 in the pedestal-turbulence self-organization time (~1ms): but only a “wiggly” energy balance has been achieved yet.
  - $n_e$ pedestal is ~2x milder than the MHD-limited profile.

- ITER at full-current may achieve a significant H-mode pedestal height that
  - Is only 10% lower than the operation design value,
  - But, mild enough not to provoke the usual ELMs from peeling-ballooning modes.

- More simulations will be performed on world #1 Summit, to confirm this important result further.
Predictions from gyrokinetic XGC agree with $\lambda_q^{14}(\text{Eich})$ on existing tokamaks, but not on 15MA ITER.

- Ion drift-motion dominant $\propto 1/B_{\text{pol}}$
- But, the same code predicts $\lambda_q^{(XGC)} > 6\lambda_q^{(\text{Eich})}$ for 15MA ITER
  - Confirmed via multiple attempts
- High-current C-Mod experiments have $B_{\text{pol}}$ similar to 15MA ITER
  - Both experiment and XGC showed $\lambda_q \sim \lambda_q^{14}(\text{Eich})$: Is this a bifurcation?
    - Hidden parameters, or something is wrong: simulation has been confirmed multiple times
- XGC on NSTX-U at 2MA also produced a wider $\lambda_q$
  - But, not at 1.5MA
  - Hidden parameters, again?
XGC: Electron heatSpread by kinetic trapped electron modes is the suspect

- Fact: $\rho_{ip}/a \rightarrow 0$ in 15MA ITER yields little neoclassical ExB shearing,
- Fact: $(2a/R)^{1/2} \rightarrow 1$ in NSTX-U with warm $T_e$ yields TEM turbulence

TEM streamers are the suspect. ITGs do not penetrated into SOL [Chang, 2009].

XGC: Similar to blobs in today’s conventional aspect tokamaks

XGC found a mixed TEM-blob turbulence structure on 2MA NSTX-U

Isolated “blobby” turbulence (with strong sheared-ExB flow across separatrix)

Connected “streamer”-type turbulence (with weak sheared-ExB flow across separatrix)
Machine learning reveals trapped electron interaction with turbulence in the 15MA ITER edge (R.M. Churchill)

A strong non-adiabatic electron response found across the separatrix: characteristics of TEMs.

- K-means clustering, with K=6
- At a higher energy band, trapped electrons show correlated response to turbulence
  - Another sign of CTEM turbulence
- Because of the high $\omega_r\sim\nu(\rho/L)$ around the separatrix, $q$ needs to be high for precession resonance by trapped electrons:
  $$V_{\text{precess}}\sim\nu(\rho/R)(B/B_P)$$

→ easier excitation of Collisionless trapped electron modes (CTEMs) just inside the separatrix, $\psi_N=0.98-1$, where $\nabla P_e$ is high.
Looking for hidden parameters from CTEM physics understanding

• Large \( a/\rho_{i,pol} \) weakens the neoclassical ExB shearing rate \( \rightarrow \) stronger TEM

In the present conventional aspect-ratio tokamaks, \( \lambda_q(XGC) \) follows \( \lambda_q(Eich) \).

However, \( \lambda_q(XGC) \) shows a discontinuity (of multiple solutions) between high-\( Ip \) C-Mod and 15MA ITER.

When we use \( B_{pol} a/\rho_{i,pol} \) as the scaling variable,
- \( \lambda_q(XGC) \) in the present tokamaks still follows \( \lambda_q(Eich) \)
- and the discontinuity from high-\( Ip \) C-Mod to 15MA ITER disappears
Moving forward for a more accurate $\lambda_q$-scaling law towards ITER

Requires a large compute time on Summit

We need at least a couple more data points between the high-Ip JET and the full-B ITER
- Collaboration with JET and ITER teams needed to build some artificial plasma and B equilibriums

Further refinement using machine learning will be performed after more simulations.
How do we validate the TEM broadening of $\lambda_q$ in existing tokamaks?

Most of the NSTX-U edge electrons are in banana regimes $\rightarrow$ Strong CTEM drive if $\nu_e^* \approx \nu_e < 1 :$ validated

- $\lambda_q(\text{XGC})$ for 2MA NSTX-U shows $\sim 2 \times \lambda_q(\text{Eich})$
- $N_e^*,<1$ at $\Psi_N=0.99$, most of the electrons are banana trapped
- Edge turbulence across separatrix is mixture of blobs and streamers $\rightarrow$ TEM

• $\Theta$ represents CTEM threshold
• Assume CTEM threshold $\sim (a/R)^{1/2}/\nu_e^* > \eta$
• Fit $\alpha$ and $\eta$ to make $\Theta=1$ for NSTX-U 2MA, & 0 for 1.5MA $\rightarrow$ $\alpha=2$ and $\eta=1.75$ have been chosen
How do we validate the TEM broadening of $\lambda_q$ in existing tokamaks?

- Look for experiments with “ITER-similar” edge condition
  - Turbulence-limited pedestal: large $L/\rho_{pol}$
  - Low $\nu_e^* < 1$ around the magnetic separatrix (using $q_{95}$)
  - Low torque input
  → Can we study the QH mode edge plasma with low torque input?
    - Edge ECH/LHH can be helpful to reduce $\nu_e^*<1$, given the experimental observations that the pedestal $T_i$ increases more than $T_e$ does in QH.

- Could the broader $\lambda_q$ observed in EAST [Wan2016, Zhang 2016; Deng2018], with Lower Hybrid Heating in edge, be an example for the kinetic trapped-electron-mode broadening?
  - $T_e(sep) \sim 150$eV, $n_e(sep) \sim 1 \times 10^{19}$m$^{-3}$ → $\nu_e^* < 1$
  - $\lambda_q^{XGC} \sim 1.7 \lambda_q^{Eich}$: qualitatively agrees with experimental observation
  - Such a broadening was not seen without edge RF heating
XGC suggests that the wide $\lambda_q$ ITER is not from a turbulence bifurcation, but a gradual transition: supported by experimental measurement on EAST?

2MA NSTX-U, or EAST with edge LHH

(XGC: Figures not to scale)
Summary

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