Overview of multi-scale turbulence studies covering ion to electron scales in magnetically confined fusion plasma

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Purpose of this overview

Multi-scale turbulence covering ion to electron scales is studied.

- When are they important?
- What happens as cross-scale interactions?
- Should we consider them for ITER?

- Establish understanding from the experiments, theories and simulations.
- Clarify related issues to be solved for future burning plasmas.
Outline

- Experimental evidences
- Theoretical understanding and modeling
- Prediction for burning plasmas
- Summary and future perspectives
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Terminology

Ion-scale eddy (large)

Electron-scale eddy (small)

Ion-scale (low-k) fluctuations
- \(k_\perp \sim \rho_{ti}^{-1}\)
- ITG, TEM, KBM, MTM

Electron-scale (high-k) fluctuations
- \(k_\perp \sim \rho_{te}^{-1}\)
- ETG

Cross-scale interactions
Importance of electron scales in experiments

- Electron heat flux in multi-channel transport [Howard (2016), Holland (2017), Howard (2021)]
  Multi-scale turbulence can explain ion and electron heat fluxes in experiment.

- Electron temperature stiffness [Mariani (2021); Nasu, EX/3-3 (Thu.)]
  ETG can limit the electron temperature peaking.

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**Graphs:**

1. **A:** Ion heat flux ($Q_i$) vs. $a/L_{T_i}$
2. **B:** Electron heat flux ($Q_e$) vs. $a/L_{T_i}$
3. **C:** Electron heat flux ($q_{e,gb}$) vs. $R/L_{Te}$

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**Legend:**

- **A:** Ion-Scale Simulation, Multi-Scale Simulation, Multi-Scale Components, High-$k$ (ETG) Contributions, Low-$k$ (ITG) Contributions
- **B:** Experimental Level
- **C:** GENE (Zeff=1): multi-scale ion-scale
Electron-scale effects appear not only in tokamak core.

✓ ETG turbulence contributes to the heat flux in the H-mode pedestal and in the core/pedestal of spherical tokamaks.
Simultaneous measurement of multi-scale fluctuations is done.

✓ Simultaneous measurement of electron and ion-scale fluctuations reveals the nonlinear interplay, not explained only by single-scale physics. [Nasu, EX/3-3 (Thu.)]

Electron and ion-scale fluctuations at the same location measured by DBS and millimeter-wave BS
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Criteria for the impact of electron scales

✓ Cross-scale interactions significantly affect turbulent transport when ion scales are close to marginal stability.

• Rule of thumb: \( \gamma_{\text{high-k}}/\gamma_{\text{low-k}} > \sqrt{m_i/m_e} \)
• Zonal flow mixing [Staebler (2016), Creely (2019)]: \((\gamma/k_\theta)_{\text{high-k}} > (\gamma/k_\theta)_{\text{low-k}}\)
• Parallel-to-the-field shear [Hardman (2020)]: \(\gamma_{\text{high-k}} > k_{\text{high-k}} \partial_\theta v_{\text{low-k}}\)

☐ Even when \((\gamma/k_\theta)_{\text{high-k}} > (\gamma/k_\theta)_{\text{low-k}}\), however, strong suppression of ETG is reported, e.g., DIII-D L-mode near edge [Neiser (2019)] and JET hybrid H-mode [Citrin (2022)].
**Ion-scale effects on electron-scale turbulence**

- **Suppression of electron-scale turbulence by ion-scale turbulence** is ubiquitous.

(i) **Perpendicular shearing by sub-ion-scale flows**

[Maeyama (2015); (2017)]

(ii) **Parallel-to-the-field shear of ion-scale fluctuations** [Hardman (2020)]

- **Perpendicular shearing analyzed by the gyrokinetic triad transfer**

- **Reduction of ETG growth by parallel-to-the-field shearing**

- **PDF of ETG growth rate w/ ion-scale fluc.**
Electron-scale effects on ion-scale turbulence

Electron-scale turbulence has dissipative effects on ion-scale structures.

Electron-scale effects analyzed by the gyrokinetic subspace transfer in a variety of multi-scale turbulence

- ITG/ETG [Maeyama (2015)]
- MTM/ETG [Maeyama (2017)]
- TEM/ETG [Maeyama (2022)]

An effective diffusion model of the electron-scale effects on the ion-scale fluctuation is proposed. [Watanabe, Poster 2 (Tue.)]  

\[ D\bar{f} = \tau_{ac} \nabla_{\perp} \cdot (\bar{\nu}_E \bar{\nu}_E \cdot \nabla_{\perp} \bar{f}) \]
Electron-scale turbulent transport are partially included into quasilinear transport models.

- QuaLiKiz [Citrin (2017)] … ETG transport when \((\gamma/k_\theta)_{\text{high-k}} > (\gamma/k_\theta)_{\text{low-k}}\).
- TGLF (SAT1/SAT2) [Staebler (2016)]… Evaluation with zonal flow mixing.
- ETG saturation level is calibrated to multi-scale gyrokinetic simulations.

- **Stiff electron temperature response by ETG is validated** against JET, whilst the electron temperature gradient threshold is sensitive to effective charge and impurity mix. [Mantica (2021)]

- There are also modelling efforts on ETG transport in the H-mode pedestal: a simple \(\eta_e = L_{ne}/L_{Te} \) dependence. [Chapman-Oplopoiou, Poster 2 (Tue.); Guttenfelder, Poster 7 (Fri.)]
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Cross-scale interaction in electron heated plasma

- As $T_e/T_i$ increases, ETGs are stabilized, whereas TEMs are destabilized.
- Multi-scale interactions exist even at high $T_e/T_i$ and affect electron/fuel/ash transport.
- Stabilization by ETG has a significant impact near marginal TEM. (Cf. Dimits shift)
- The possibility of reduced $Q_e$ by cross-scale interactions [Maeyama (2022)]
Electron-scale turbulence will likely play a minor role in SPARC. [Howard (2021)]

Large $3 < Q_i/Q_e < 5$ (due to collisional coupling in high density and core radiative loss at high temperature) also indicates ion-scale dominance.

Nonlinear gyrokinetic profile prediction with a machine-learning surrogate based on ion-scale turbulence is utilized. [Rodriguez-Fernandez Poster 2 (Tue.); Howard, EX/3-4 (Thu.)]

Transport in electron-scale simulation is much smaller than ion-scale one.
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Summary – Physics

- The importance of electron scales is found in experiments.

- Electron-scale turbulence plays a role when the ion scale is close to marginal stability. An estimate \((\gamma/k_\theta)_{\text{high-}k} > (\gamma/k_\theta)_{\text{low-}k}\) should be improved further.

- Mutually exclusive nature of disparate-scale turbulence is emerged.
  - Ion-scale eddy distorts electron-scale modes.
    - Perpendicular and parallel-to-the-field shearing
  - Electron-scale turbulence dissipates ion-scale structures.
    - Anisotropic dissipation by electron-scale turbulence
Cross-scale interactions can enhance/reduce turbulent transport.

Low-\(k\) → high-\(k\) effect
- Reduction of high-\(k\) transport: \(Q_{\text{single high-}k} > Q_{\text{multi high-}k}\)
- When the ion scale is strongly unstable, ion-scale analyses reasonably agree with multi-scale ones: \(Q_{\text{total}} \sim Q_{\text{low-}k}^{\text{single}} \sim Q_{\text{low-}k}^{\text{multi}} \gg Q_{\text{high-}k}^{\text{multi}}\)

Low-\(k\) ← high-\(k\) effect
- High-\(k\) transport can survive: \(Q_{\text{high-}k}^{\text{multi}} > 0\)
- Low-\(k\) transport is enhanced when zonal flows are damped: \(Q_{\text{low-}k}^{\text{single}} < Q_{\text{low-}k}^{\text{multi}}\)
- Low-\(k\) transport is reduced when TEM or MTM are damped: \(Q_{\text{low-}k}^{\text{single}} > Q_{\text{low-}k}^{\text{multi}}\)

Quasi-linear transport models are extended to include finite electron-scale transport and its suppression by ion-scale turbulence.

Pedestal ETG turbulent transport could be described in a simple \(n_e\) dependence.
Future perspectives

- The impact of multi-scale turbulence in future burning plasma is under active investigation.
  - Recent multi-scale turbulence simulation suggests that
    - Electron-scale turbulence can exist even at high $T_e/T_i$.
    - Possibility of transport reduction by cross-scale interaction.
  - Gyrokinetic analysis of SPARC plasma
    - Electron-scale turbulence is likely to be minor in SPARC.
    - Ion-scale gyrokinetic surrogate is utilized for profile prediction.

- ETG turbulence in the H-mode pedestal attracts attention, while most of them are single-scale analyses. The number of multi-scale analyses is limited. [Pueschel (2020), Parisi (2022), Belli (2023)]

- Further modeling efforts on quasi-linear models are desired to include electron-scale effect on the ion scale.