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Impact of temperature flattening on microtearing turbulence

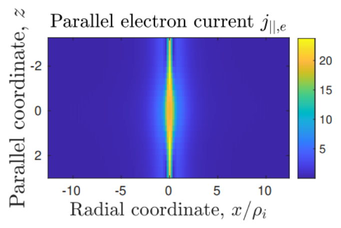
Zonal flow drive via turbulent self-interaction

Impact of collisions on ITG transport

Gyrokinetic study of Toroidal Alfven Eigenmode (TAE) turbulence

Motivation for microtearing study

- Microtearing modes are characterized by
    - Radially-narrow parallel electron current layers driven resonantly at the rational surfaces
    - Associated magnetic islands
- Perpendicular magnetic field perturbations can lead to transport loss
- A cause for concern in large high-beta spherical tokamaks like STEP
- Identifying saturation mechanisms is therefore crucial
- Start with a simple microtearing set-up



Temperature flattening in microtearing turbulence

[Ajay C. J. et al, Nucl. Fusion, 2023]

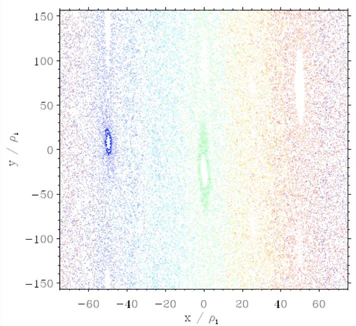
- Stationary magnetic islands persist near low-order rational surfaces
- Swift motion of electrons along the perturbed (magnetic island) field lines

→ periodic radial excursions

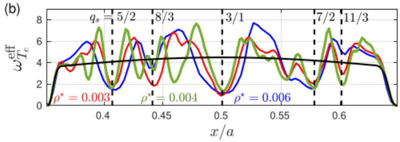
→ ‘short-circuit’ of the perturbed Te profile

→ T_e flattening at rational surfaces.

$$\frac{\partial \langle \delta T_{e,\parallel} \rangle y}{\partial t} \approx - \frac{m_e}{n_0} \frac{1}{\mathscr{C}} \frac{\partial}{\partial x} \sum_{k_y} i k_y \hat{q}_{e,\parallel,k_y} \hat{A}^*_{\parallel,k_y}$$



(a) Poincare plot of magnetic field lines intersecting outboard midplane.



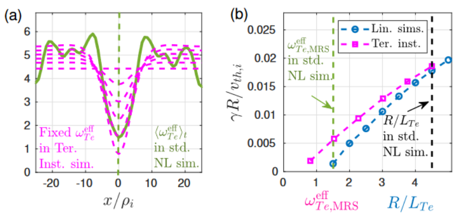
(b) Effective T_e gradient plotted vs radial coordinate in global simulations.

Local Te flattening decreases microtearing drive

- Extremely thin current layer → very localised Te flattening

- The drive mechanism for microtearing is also localised at the rational surfaces

- Perform a 'tertiary-instability-like' analysis with a fixed corrugated background Te gradient mimicking the nonlinear simulation.



- As T_e gradient falls below the critical gradient locally near rationals, the linear mode stabilises ⇒ Saturation mechanism.

System size scaling

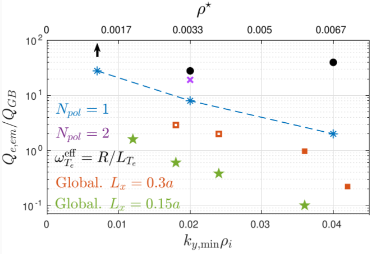
[Ajay C. J. et al, Nucl. Fusion, 2023]

- Increasing system size → increasing toroidal number density
- A model for heat flux-scaling

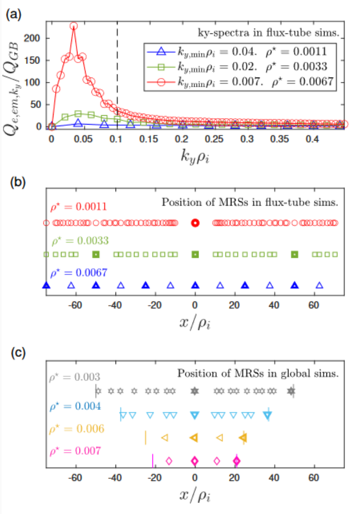
  ⇒ MRSs where microtearing diffusivity are localised becomes radially dense.

  ⇒ Lower flux

  $$Q_e \propto 1/(1 - w/\rho^\star).$$



Microtearing heat flux plotted vs $\rho^\star$.



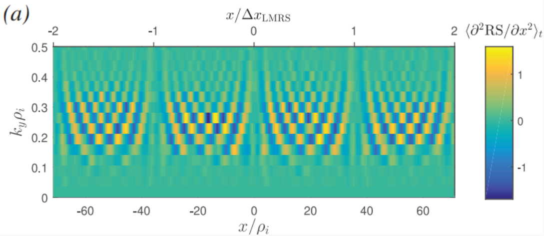
(a) ky spectra of heat flux for the flux-tube simulations. Radial position of MRSs for all $k_y\rho_i \leq 0.1$ for (b) flux-tube and (c) global simulations.

Self-interaction of microinstability eigenmodes and zonal flow drive

[Ajay C. J. et al, Journ. Plasma Phys., 2020]

- Self-interaction: Modes extended along the magnetic field lines can 'bite-their-tails' at mode rational surfaces and nonlinearly interact with themselves
- Leads to a zonal flow drive distinct from modulational instability.

$$\mathrm{ZF} \sim \Sigma_{\mathrm{ky}}\, \mathrm{RS}_{\mathrm{ky}}$$



(a) Time-averaged Reynolds stress on toroidal mode number - radial coordinate plane.

- Reynolds stress drive from each toroidal mode is temporally incoherent/decorrelated with each other
  ⇒ fluctuating zonal flow → plays an important role in ITG saturation.

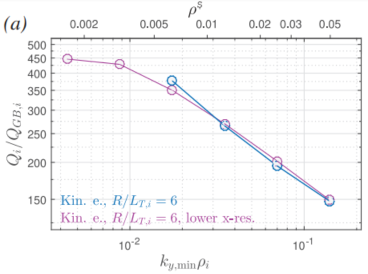
System size scaling in ITG turbulence

[Ajay C. J. et al, Journ. Plasma Phys., 2020]

- Incoherent decorrelated zonal flow drive from each toroidal mode.

$$\mathrm{ZF} \sim \Sigma_{\mathrm{ky}} \mathrm{RS}_{\mathrm{ky}}$$

- A statistical analysis shows decrease in zonal flow levels with increasing toroidal number density or an increase in system size
  ⇒ Increase in gyro-Bohm normalised flux-levels with increasing system size.

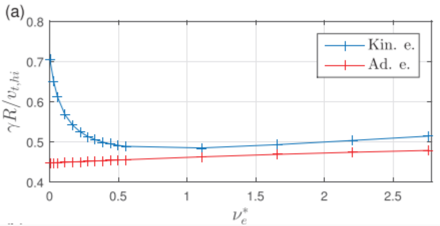


(a) ITG Heat flux plotted vs $\rho^{\star}$.

Effect of collisions on ITG

[Ajay C. J. et al, Phys. Plasmas, 2021]

- With kinetic electrons, ITG linear growth rate decreases with increasing collisionality.



(a) Linear growth rate of ITG vs collisionality

- Collisions increase the trap-pass conversion of electrons.
  ⇒ All electrons begin to respond adiabatically.
- Nonlinear heat flux decreases with collisionality.
  ⇒ A consequence of linear growth rate decrease as confirmed by a quasi-linear analysis.

Toroidal Alfven Eigenmode destabilisation by fast ions

[Ajay C.J. et al, AIP Advances 14, 075120 (2024)]

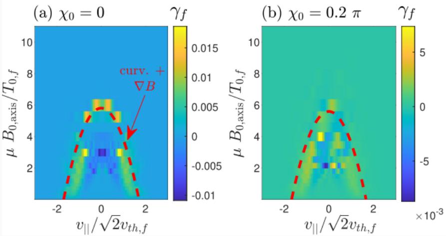
- Free-energy based growth rate γ_j for each species

$$\gamma = \sum_j \gamma_j = \frac{1}{E}\sum_j \frac{\partial E_j}{\partial t},$$

where

$$E = \sum_j \mathrm{Real}\left[\int dz d\mu dv_{\|} \frac{\pi B_0 n_0 T_0}{2 f_{0,j}} (\Phi^* + f^*_{1,j}) f_{1,j}\right].$$

- TAEs destabilised by the resonance of curvature and ∇B drift of fast-ions with the TAE.
- Resonance possible only where the curv+∇B drift direction and TAE phase fronts align (at outboard midlplane).
- Finite ballooning angle stabilises the mode
  → equilibrium flow-shear can be a possible saturation mechanism.

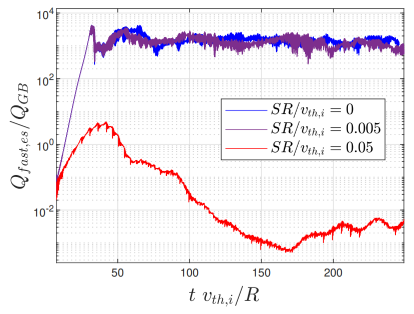


Fast-ion free energy growth rate for two values of ballooning angle χ_0

Toroidal Alfven Eigenmode saturation

- Flux-tube simulations of TAE turbulence give unphysically high values of heat flux.
- Equilibrium flow-shear (found in typical tokamaks) indeed suppresses TAE turbulence.
- No TAE self-saturation-mechanisms identified in the local gyrokinetic picture.
- A global treatment is necessary where profile flattening of fast-ion pressure helps in saturation.
- The nonlinear excitation of electron diamagnetic direction TAEs and their beating with the ion-diamagnetic TAEs

  → large oscillations in observable quantities.



TAE heat flux plotted vs time for various values of equilibrium flow-shear.

Ongoing work

- Integrated modelling of L-H transition and pedestal physics - Just started!

- Analyse gyrokinetic results to deduce basic physics
- Come up with reduced models
- Apply in an integrated modelling suite like JINTRAC.

Thanks!