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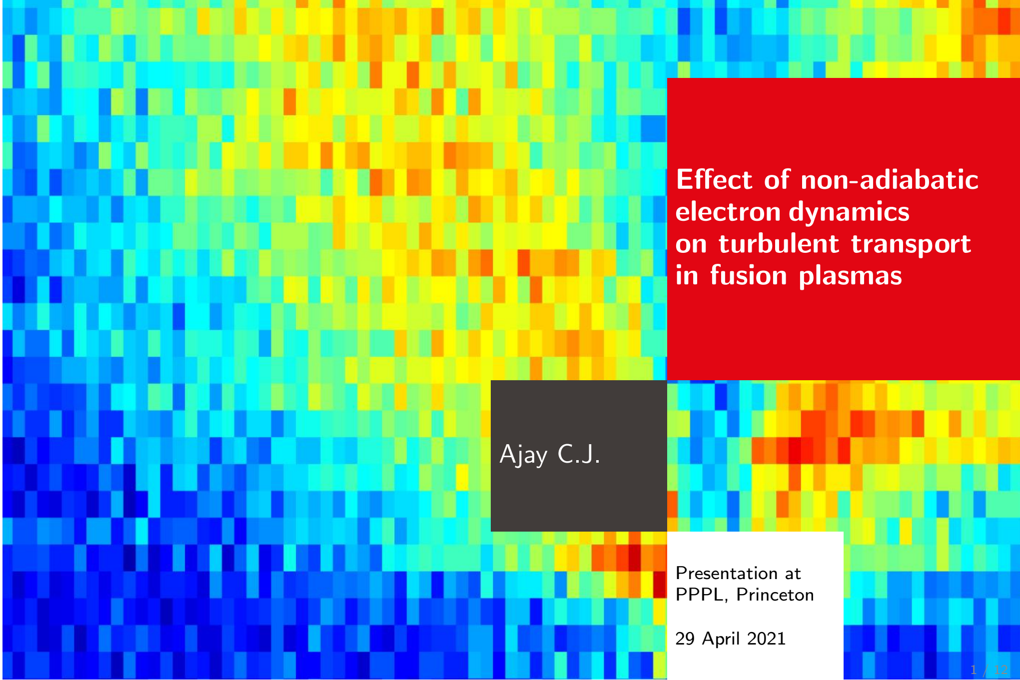

# Effect of non-adiabatic electron dynamics on turbulent transport in fusion plasmas

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Presentation at PPPL, Princeton

29 April 2021

Swiss Plasma Center

# Outline

- Introduction
  - Microturbulence in the tokamak core

- **How eigenmode self-interaction affects zonal flows** [Ajay C.J. et. al., JPP 86, 905860504 (2020)]

1. Zonal flow driving mechanisms:
   - Modulational instability, MI
   - Self-interaction, SI
2. Non-adiabatic electron response in ITG eigenmodes
3. Evidence of zonal flow drive by MI and SI in turbulence simulations
   - Non-adiabatic electron response amplifies SI
4. A system size effect resulting from SI

- **Effect of collisions on non-adiabatic electron response** [Ajay C.J. et. al., *submitted to* POP, arXiv:2104.12585 (2021)]

- $\delta T_e$ **measurement in TCV and verification with gyrokinetic simulations** [M. Fontana et al., NF 60, 016006 (2019)]

- Summary

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# Introduction

- Equilibrium pressure gradient can give rise to micro-instabilities

  $\rightarrow$ Turbulent transport of heat and particles

  $\rightarrow$ Loss of confinement

- Common microinstabilities in present day tokamaks
  1. **Ion Temperature Gradient (ITG)**
  2. Trapped Electron Mode (TEM)
  3. Electron Temperature Gradient (ETG), and more

- Turbulence saturation
  1. **Zonal flows**
  2. Collisions
  3. Damped eigenmodes, and more

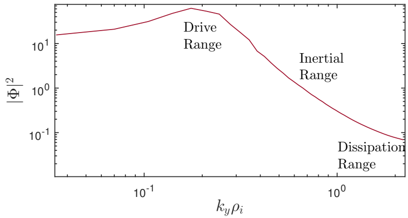
- Gyrokinetic codes are used to simulate turbulence
  $\rightarrow$ GENE code [F. Jenko, et al., Phys. Plasmas 7, 1904 (2000)]

- Field aligned coordinate system:

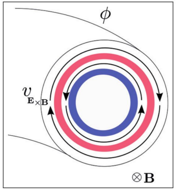
$$x = \mathrm{fct}(\psi) \quad : \text{radial}$$
$$y = \frac{r_0}{q_0}\left[q(\psi)\chi - \varphi\right] \quad : \text{binormal}$$
$$z = \chi \quad : \text{parallel}$$

$(\psi, \chi, \varphi)$ : straight field line magnetic coordinates

Microturbulence energy spectrum




Zonal flow shearing




[G. Merlo, PhD Thesis (2016)]

# Zonal flow driving mechanisms

## Modulational Instability

- **In a Shearless Slab**:

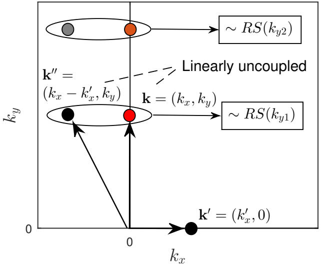
  Eigenmodes = Fourier modes $\mathbf{k} = (k_x, k_y)$.

- **Resonant decay** mechanism $\mathbf{k} \to \mathbf{k}', \mathbf{k}''$ involving 3 linearly decoupled modes with $\mathbf{k} = \mathbf{k}' + \mathbf{k}''$ and **frequency matching** $\omega_{\mathbf{k}} \simeq \omega_{\mathbf{k}'} + \omega_{\mathbf{k}''}$.

  [A. Hasegawa, et al., Phys. Fluids 22, p2122 (1979)]

- **Modulational Instability (MI)** = two coupled resonant interactions: $\mathbf{k} \to \mp\mathbf{k}', \mathbf{k}_{\pm}; \mathbf{k}_{\pm} = \mathbf{k} \pm \mathbf{k}'$.

  $\Rightarrow$ A finite amplitude zonal mode $\mathbf{k}'$ can stimulate the **coherent decay** of multiple $\mathbf{k}$ modes.




## Self-interaction

- **In a Sheared Torus**:

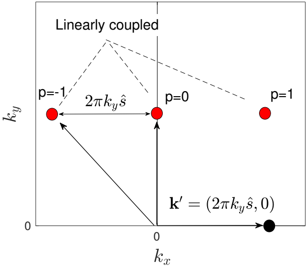
  Eigenmodes of the form:

$$\Phi(x, y, z) = e^{ik_y y} \sum_{\substack{p=-\infty \\ k_x = k_{x0} + p2\pi k_y \hat{s}}}^{\infty} \hat{\Phi}_{k_x, k_y}(z) e^{ik_x x}$$

- **Self-Interaction (SI)**: Fixed relative phases between the linearly coupled Fourier modes $k_x = k_{x0} + p2\pi k_y \hat{s}$

  $\Rightarrow$ zonal modes $(p2\pi k_y \hat{s}, k_y = 0)$ driven with **fixed phases**

  $\Rightarrow$ stationary $\omega_{E\times B}$ structures localized at MRSs $x = p/k_y \hat{s}$.

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# Non-adiabatic electron response

## Presence of fine structures with kinetic electron response

- Adiabatic electron response: $n_e(\mathbf{x}) = N(x)e^{e\Phi(\mathbf{x})/T_{0,e}(x)}$

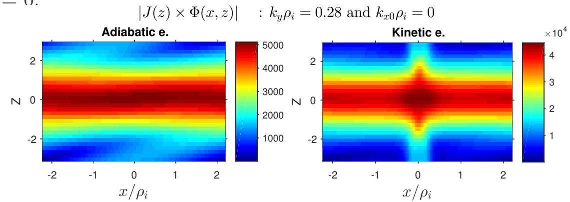
  Adiabatic condition $|\omega/k_{||}| \ll v_{th,e}$.

  Violated at MRS where $k_{||} \approx (nq+m)/Rq = 0$.

- Non-adiabatic passing electron response

  $\Rightarrow$ **Fine structures at Mode Rational Surface (MRS)**.

  [J.Dominski, et al., Phys.Plasmas 22, 062303(2015)]

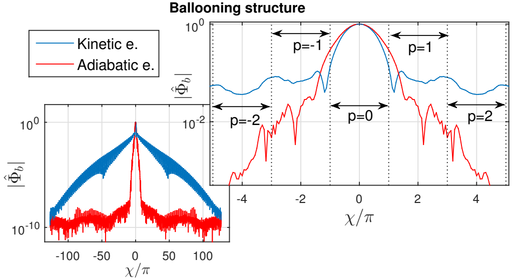



- An eigenmode takes the form:

$$\Phi(x,y,z) = e^{ik_y y} \sum_{\substack{p=-\infty \\ k_x = k_{x0} + p2\pi k_y \hat{s}}}^{\infty} \hat{\Phi}_{k_x,k_y}(z) e^{ik_x x}$$

  Parallel boundary condition:

$$\hat{\Phi}_{k_x,k_y}(z+2\pi) = \hat{\Phi}_{k_x+2\pi k_y \hat{s},k_y}(z)$$

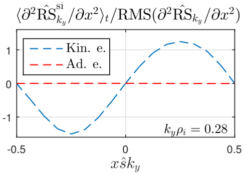


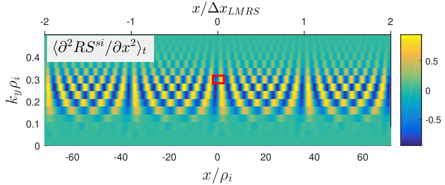
# Evidence of SI in nonlinear fully developed turbulence simulations

- $\mathrm{RS} \simeq \langle \tilde{V}_{E\times B,x} \tilde{V}_{E\times B,y} \rangle_{y,z}$ can be considered as a proxy to the drive of zonal flows: $\frac{\partial}{\partial t}\omega_{E\times B} \sim \frac{\partial^2}{\partial x^2}\mathrm{RS}$
- **SI contribution to Reynolds stress** $\hat{\mathrm{RS}}_{k_y}(x)$ given by:

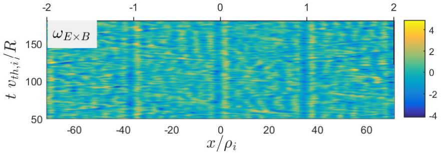
$$\hat{\mathrm{RS}}^{\mathrm{SI}}_{k_y}(x) = \mathrm{Real} \sum_{k_{x1}} \sum_{\substack{p=-\infty \\ k_{x2}=k_{x1}+p2\pi k_y \hat{s}}}^{\infty} \left\langle \frac{2}{B_0^2} \left( k_{x1} k_y g^{xx} + k_y^2 g^{xy} \right) \hat{\Phi}^\star_{k_{x1} k_y} \hat{\Phi}_{k_{x2} k_y} \right\rangle_z e^{i(k_{x2}-k_{x1})x}$$

- **With kinetic electrons**, self-interaction part of Reynolds Stress remains persistent (with same phase) and dominant.




- Time-averaged contributions to $\partial^2 RS^{si}/\partial x^2$ from different $k_y$s aligned near Low(est) order MRSs $\Rightarrow$ non-zero $\langle \omega_{E\times B} \rangle_t$ structures.
- Away from LMRSs, time-averaged contributions from different $k_y$s cancel $\Rightarrow \langle \omega_{E\times B} \rangle_t \simeq 0$. But, fluctuating contributions are present everywhere in x $\Rightarrow SD_{x,t}(\omega_{E\times B}) \neq 0$.

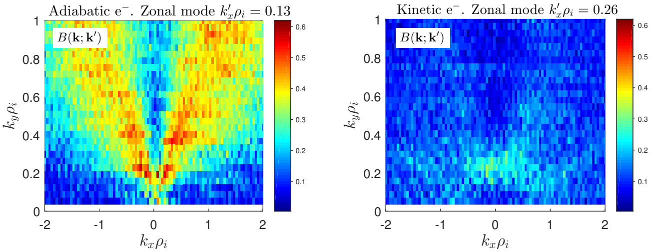


- **Bicoherence analysis** measures level of phase matching in 3 Fourier mode interactions, characteristic of MI.
- Bicoherence for Fourier mode triplet $(\mathbf{k}, \mathbf{k}', \mathbf{k}'')$, such that $\mathbf{k} = \mathbf{k}' + \mathbf{k}''$, is defined here as:

$$b(\mathbf{k};\mathbf{k}') = \frac{|\langle \hat{\Phi}^\star_{\mathbf{k}}\, \hat{\Phi}_{\mathbf{k}'}\, \hat{\Phi}_{\mathbf{k}''} \rangle_t|}{\langle |\hat{\Phi}^\star_{\mathbf{k}}\, \hat{\Phi}_{\mathbf{k}'}\, \hat{\Phi}_{\mathbf{k}''}| \rangle_t}$$

$$B(\mathbf{k};\mathbf{k}') = \frac{b(\mathbf{k};+\mathbf{k}') + b(\mathbf{k};-\mathbf{k}')}{2}$$

$B(\mathbf{k};\mathbf{k}')$ as a function of $\mathbf{k} = (k_x, k_y)$ for given zonal mode $\mathbf{k}' = (k'_x, 0)$.

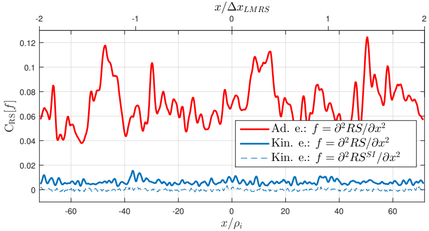



⇒ **Adiabatic electrons:** Coherent (and thus correlated) contributions from different $k_y \neq 0$ modes to drive of a given zonal mode. Evidence of strong MI.

⇒ **Kinetic electrons:** Less coherent contributions to drive of zonal modes. MI mechanism is weakened.

- Considering average correlation estimate:

$$\mathrm{C_{RS}}[f] = \sum_{\substack{k_{y,i},\, k_{y,j} \\ k_{y,j} > k_{y,i}}} \frac{\mathrm{Cov}[\hat{f}_{k_{y,i}}, \hat{f}_{k_{y,j}}]}{\sigma[\hat{f}_{k_{y,i}}]\sigma[\hat{f}_{k_{y,j}}]} \Bigg/ \sum_{\substack{k_{y,i},\, k_{y,j} \\ k_{y,j} > k_{y,i}}} 1$$




- Contributions from SI are fully decorrelated, reflecting that they essentially act as **independent random kicks** when driving ZFs.

# A system size effect resulting from SI

## Significance of fluctuating zonal flows

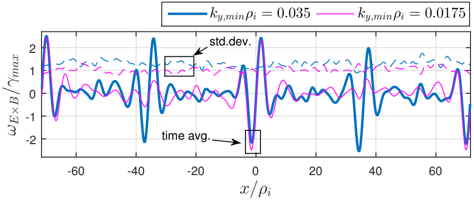
- $k_{y,\min}\rho_i = (n_{\min} q_0 a/r_0)\rho^\star$, with $\rho^\star = \rho_i/a$

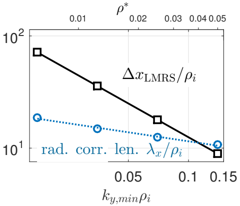
  $\Longrightarrow$ scan in $k_{y,\min}\,\rho_i$ addresses a particular system size effect.

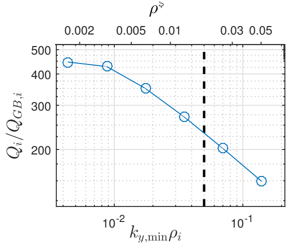
- As $k_{y,\min} \to 0$

  $\Rightarrow$ distance $\Delta x_{LMRS} = 1/k_{y,\min}\hat{s}$ between LMRSs where $\langle\omega_{E\times B}\rangle_t \neq 0$ increases

  $\Rightarrow$ Higher fluxes ?... Not the full picture!



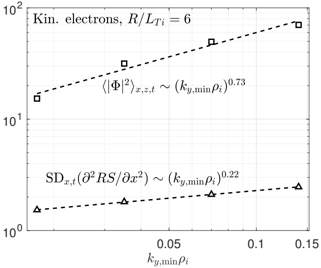

[J. Ball et al., JPP 86, 905860207 (2020)]

- As $k_{y,\min}\rho_i \to 0$, the radial extent $\lambda_x$ of turbulent eddies becomes smaller than $\Delta x_{LMRS}$.

  $\Rightarrow$ *Fluctuating component* of ZFs are actively shearing turbulent eddies *in between* LMRSs.

- SI explains the system size effect:

  Using a statistical scaling argument, one gets, $\mathrm{SD}_{x,t}(\partial^2 RS/\partial x^2) \sim (k_{y,\min}\rho_i)^{0.23}$.



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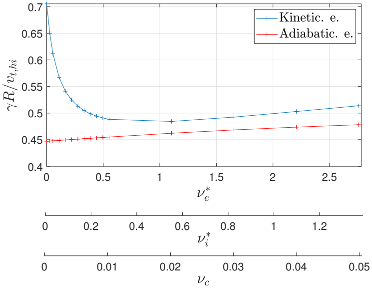
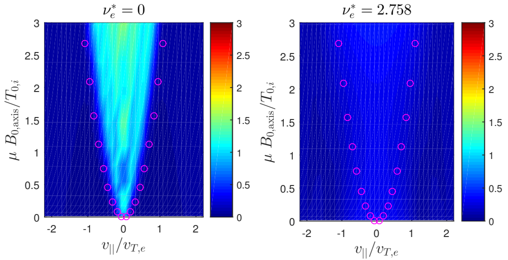
# Effect of collisionality on non-adiabatic electron dynamics

[Ajay C. J., S. Brunner, J. Ball, *in preparation* (2021)]

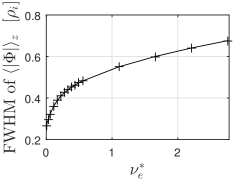
- With increasing collisionality, growth rate decreases [D. Mikkelsen et al., PRL 101, 135003 (2008)]
- Increased trapped-detrapped electron mixing $\rightarrow$ Increased adiabatic-like electron response

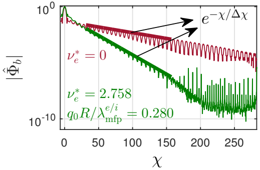


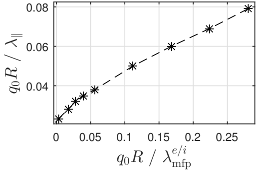

$|f_{1,e,\mathrm{na}}/f_{1,e,\mathrm{ad}}|$ at $z=0$, $x=-L_x/2$




- Increase in radial width of fine-structures $\Longleftrightarrow$ parallel length scale ($\lambda_{||} = Rq_0\Delta\chi$) associated with the tail of the ballooning structure scales with electron-ion mean free path.

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# Effect of collisionality on non-adiabatic electron dynamics

- Heat flux decreases with increasing collisionality.
  - A result of corresponding decrease in linear growth rate $\rightarrow$ Verified by a quasi-linear and zonal flow shearing rate analysis

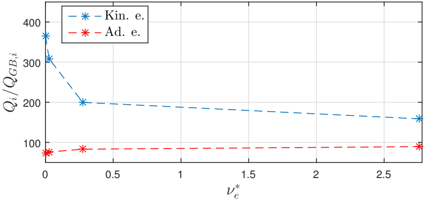
- Stationary fine structures remain significant with respect to their fluctuation levels.

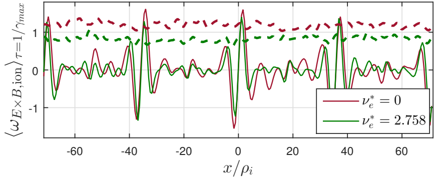
- Self-interaction measured by $\langle \partial^2 RS^{si}/\partial x^2 \rangle_t / \mathrm{RMS}(\partial^2 RS/\partial x^2)$ for a single $k_y$
$\rightarrow$ increases with increasing collisionality.

- Combined effect of self-interaction measured by the bicoherence and correlation analysis for multiple $k_y$s simultaneously
$\rightarrow$ decreases with increasing collisionality.

- Greater the number of $k_y$ modes contributing significantly to turbulence
$\rightarrow$ more the decorrelated drive from multiple $k_y$s.

- Parallel with increasing collisioanlity and decreasing $R/L_{T,i}$
$\rightarrow$ bicoherence and correlation levels indeed increases as one moves closer to marginal stability.



# Experimental measurement of electron temperature fluctuations in TCV

## and verification with linear gyrokinetic simulations

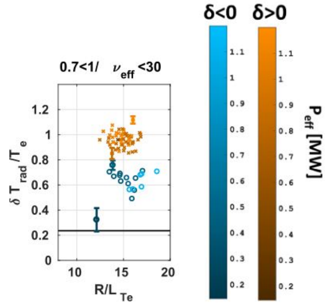
[M. Fontana et al., Nuclear Fusion, 60, 016006 (2019)]

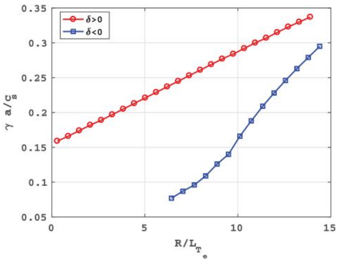
- Increased confinement in negative triangularity plasmas compared to postive triangularity.
  [Z. Huang et al., PPCF 61 014021 (2018)]
  [M. Fontana et al., NF 58 024002(2017)]

- Electron temperature fluctuations measured using Correlation Electron Cyclotron Emission (CECE) diagnostic.

- Extending electron temperature measurements to NBI heated plasmas with $T_e/T_i \sim 1$.

- Lower growth rate and higher critical gradients observed in linear GENE sims for negative triangularity.



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## Summary

- Non-adiabatic electron response amplifies zonal flow drive via the self-interaction mechanism.
- Self-interaction Reynolds stress contribution from each toroidal mode is uncorrelated with each-other, disrupts modulational instability mechanism, and can lead to a system size effect.
- Collisions affect non-adiabatic electron response and the self-interaction mechansim
- Experiment-gyrokinetic verification of improved confinement in negative $\delta$ plasma for $T_e/T_i \sim 1$ in TCV.
- A few additional comments:
  - Background flow shear study with non-adiabatic electrons similar to that with adiabatic electrons.
  - Attempt to measure the fine-structures at low order MRSs in TCV.

**Thanks!**

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