Transport hysteresis in electromagnetic microturbulence caused by mesoscale zonal flow pattern-induced mitigation of high β turbulence runaways

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... by **mesoscale zonal flow pattern** induced ...

Grown evidence of mesoscale zonal flow pattern formation in ...

- electrostatic ITG turbulence with adiabatic electrons.

  [G. Dif-Pradalier, *et al.*, Phys. Rev. E **82**, 025401(R) (2010); F. Rath, *et al.*, Phys. Plasmas **23**, 052309 (2016); A. G. Peeters, *et al.*, Phys. Plasmas **23** 082517 (2016)]

- electrostatic ITG turbulence with kinetic electrons.

  [F. Rath, *et al.*, Phys. Plasmas **28**, 072305 (2021)]

- electrostatic ETG turbulence with adiabatic ions.

  [G. J. Colyer, *et al.*, Plasma Phys. Controlled Fusion **59**, 055002 (2017)]

- tokamak experiments.

  [J.C. Hillesheim, *et al.*, Phys. Rev. Lett. **116**, 065002 (2016); G. Hornung, *et al.*, Nucl. Fusion **57**, 014006 (2017)]

... by **mesoscale zonal flow pattern** induced ...

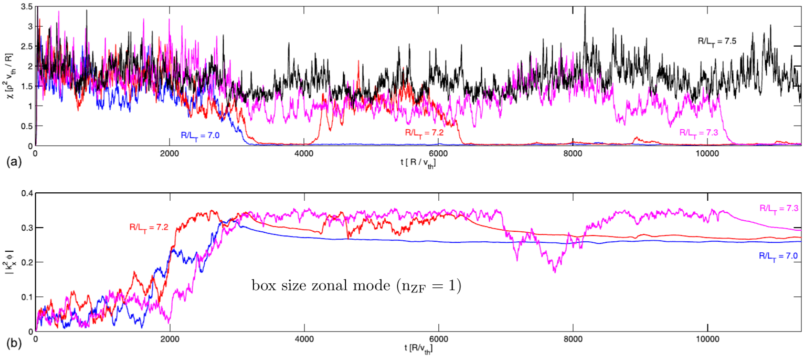
Properties:

- mesoscale $\rho < L_{\rm ZF} < R_{\rm ref}$
- long-term dynamics $10^2 R_{\rm ref}/v_{\rm th} < t_{\rm ZF} < 10^3 R_{\rm ref}/v_{\rm th}$
- temporal persistence
- near marginal stability phenomenon
- typical $E \times B$ shearing rate $\omega_{\rm ExB} \sim \gamma$

Example —adiabatic ITG

Gyrokinetic set-up:

- Cyclone Base Case + s-α-geometry + adiabatic electrons

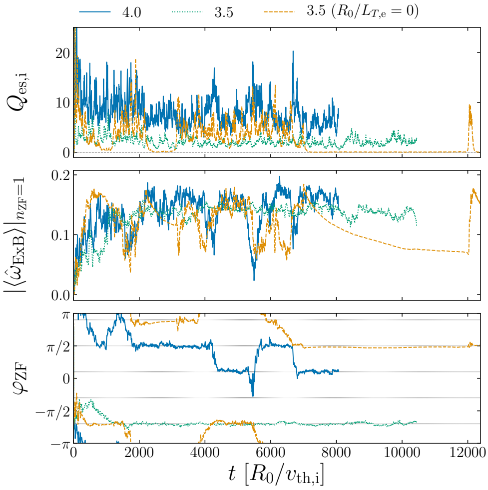


A. G. Peeters, *et al.*, Phys. Plasmas **23** 082517 (2016)

Example —kinetic ITG

Gyrokinetic set-up:

- Cyclone Base Case
- circular geometry
- kinetic electrons



F. Rath, *et al.*, Phys. Plasmas **28**, 072305 (2021)

... in **electromagnetic microturbulence** caused ...

Additional phenomena in electromagnetic ITG microturbulence:

- Magnetic stochasticity induced by nonlinear excitation of subdominant microtearing modes
  [W. M. Nevins, *et al.*, Phys. Rev. Lett. **106**, 065003 (2011); D. R. Hatch, *et al.*, PRL **108**, 235002 (2012)]

- Damping of zonal flows through magnetic stochasticity
  [P. W. Terry, *et al.*, Phys. Plasmas **20**, 112502 (2013)]

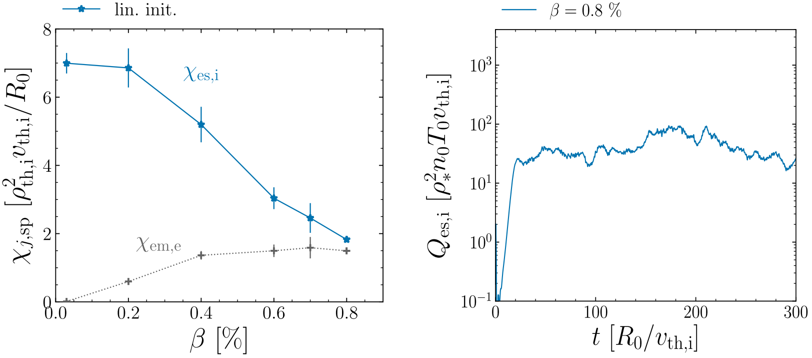
- High β turbulence runaways or non-zonal transition
  [R. E. Waltz, *et al.*, Phys. Plasmas **17**, 072501 (2010); M. J. Pueschel, *et al.*, PRL **110**, 155005 (2013)]

- Electromagnetic stabilization
  [G. G. Whelan, *et al.*, PRL **120**, 175002 (2018)]

… mitigation of **high β turbulence runaways.**

Gyrokinetic set-up:

- Cyclone Base Case + s-α-geometry + $A_{1\|}$ perturbations



- $\beta_{\mathrm{KBM}} \approx 1.2$ % [M. J. Pueschel, *et al.*, Phys. Plasmas **15**, 102310 (2008)]

... mitigation of **high β turbulence runaways.**

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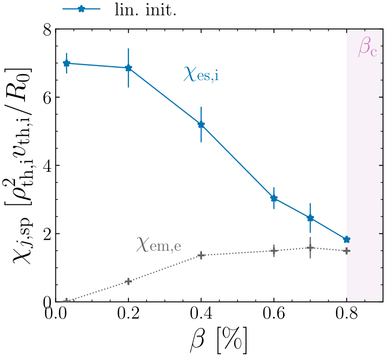

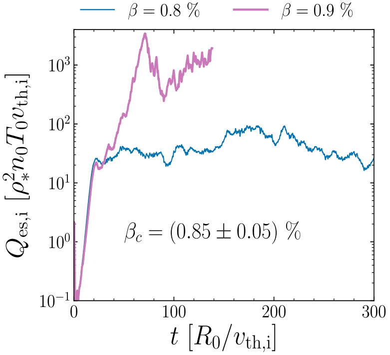

- $\beta_{KBM} \approx 1.2$ % [M. J. Pueschel, *et al.*, Phys. Plasmas **15**, 102310 (2008)]

... mitigation of **high β turbulence runaways.**

Current understanding of high β turbulence runaway:

1. Nonlinear saturation of electromagnetic ITG turbulence is caused by zonal flows.
   [G. G. Whelan, *et al.*, PRL **120**, 175002 (2018)]
2. Zonal flows are damped through magnetic stochasticity.
   [P. W. Terry, *et al.*, Phys. Plasmas **20**, 112502 (2013)]

- Sufficiently strong depletion of zonal flows through magnetic stochasticiy (supported by field line decorrelation).

  $\rightarrow$ Lack of zonal flow mediated turbulence saturation.
  [M. J. Pueschel, *et al.*, PRL **110**, 155005 (2013); M. J. Pueschel, *et al.*, Phys. Plasmas **20**, 102301 (2013)]

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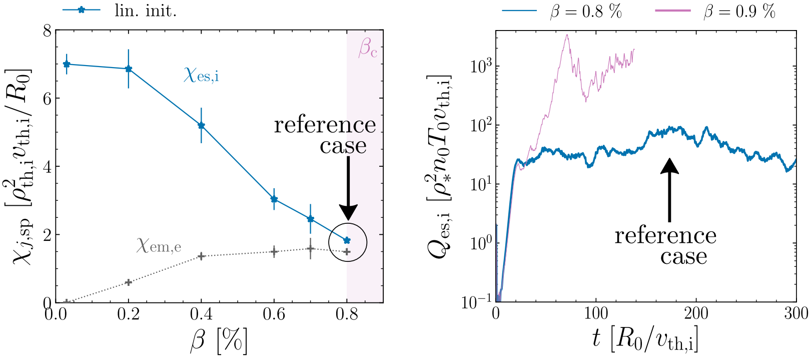
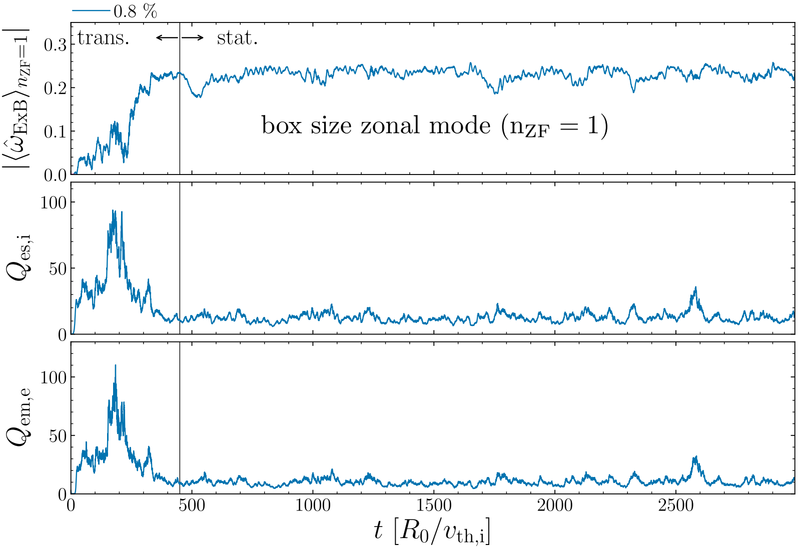
Question:

Does mesoscale zonal flow pattern formation occur also in electromagnetic ITG turbulence?

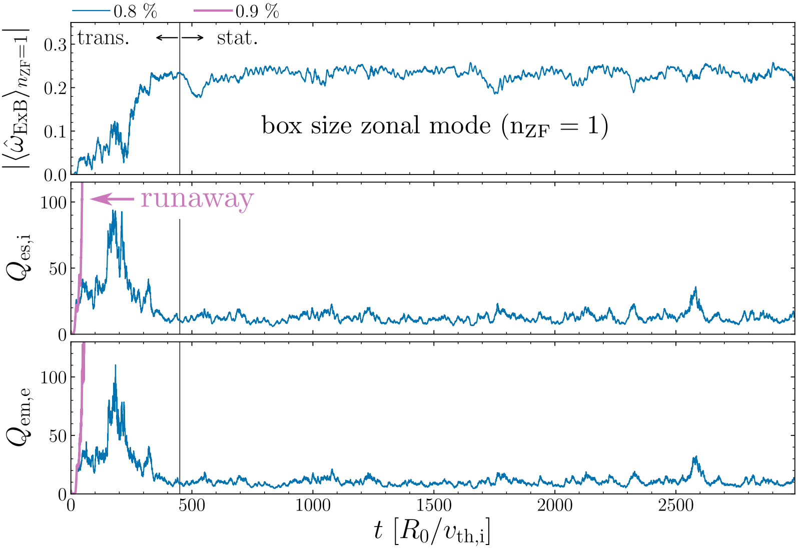
High β reference case



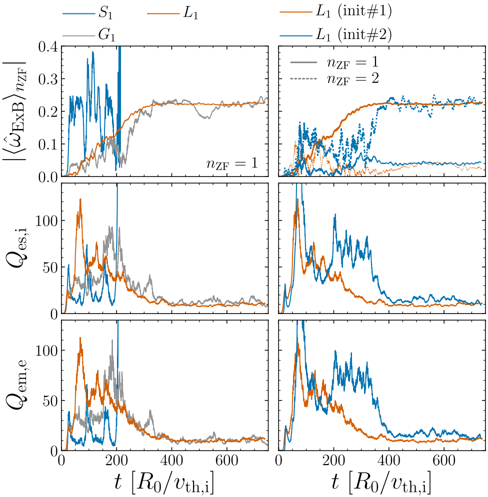
Long-term evolution of mesoscale zonal flows



Long-term evolution of mesoscale zonal flows

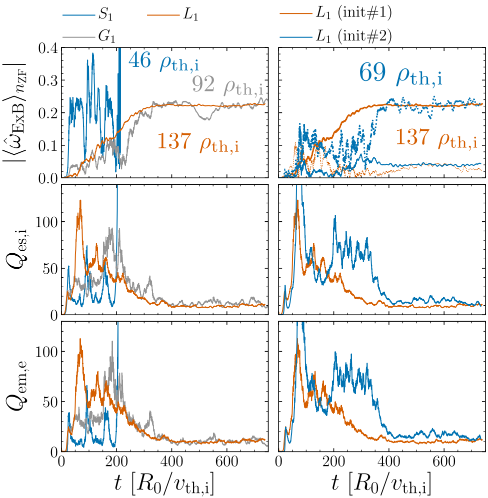


Box size convergence study at $\beta = 0.8$ %



- S_1: 1/2 std. box size
- G_1: std. box size
- L_1: 3/2 std. box size

Box size convergence study at $\beta = 0.8$ %

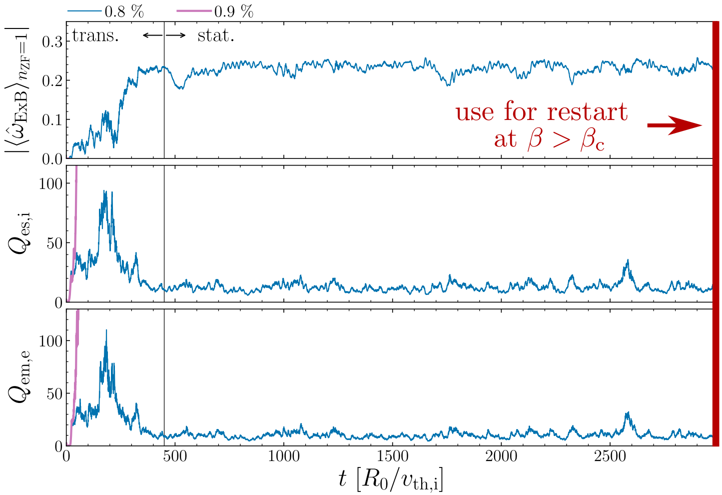


- S_1: 1/2 std. box size
- G_1: std. box size
- L_1: 3/2 std. box size

Question:

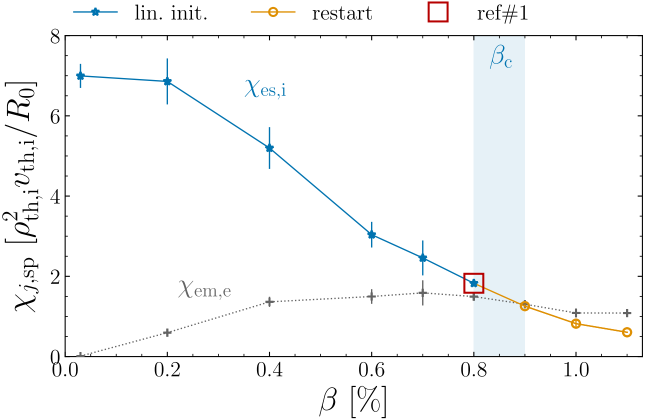
What is the role of mesoscale zonal flow patterns for high β turbulence runaways?

Restart method



transit time $\sim 10^{-5}\ s$ $\leftrightarrow$ confinement time $\sim 10^{0}\ s$

Transport hysteresis



Questions:

Is it the mesoscale zonal flow that allows for mitigation of turbulence runaways?

How resilient is the zonal flow pattern against turbulence runaways?

Stability constraints for $\beta > \beta_c$

Zonal flow stability study:

- Restart late stationary state of cases with $\beta > \beta_c$
- Scale the mesoscale zonal flow amplitude by $0 \leq \alpha \leq 1$
- Does runaway occur?

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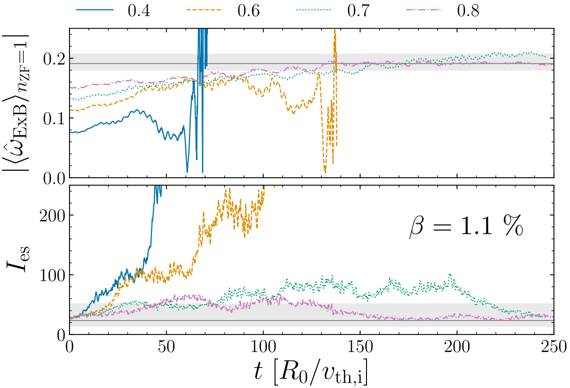
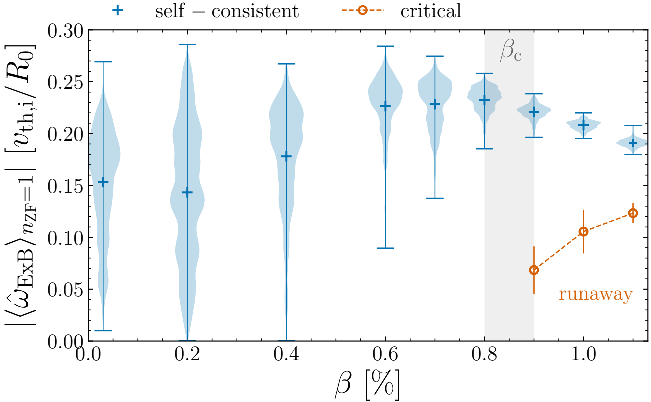


Stability constraints for $\beta > \beta_c$



Question:

What is the reason for the mitigation of turbulence runaways?

Zonal flow intensity equation

Evolution equation for zonal flow intensity $\mathcal{E}_Z = k_{\mathrm{ZF}}^2 |\langle \hat{\phi}_{\mathbf{k}} \rangle|^2$:

$$\frac{\partial \mathcal{E}_Z}{\partial t} = \underbrace{\mathcal{R}}_{E\times B-\text{nonlin.}} + \underbrace{\mathcal{M}}_{\text{magn. flutter nonlin.}} + \underbrace{\mathcal{L}}_{\text{linear terms}}$$

- electrostatic "Reynolds stress" $\mathcal{R}$
- electromagnetic "Maxwell stress" $\mathcal{M}$

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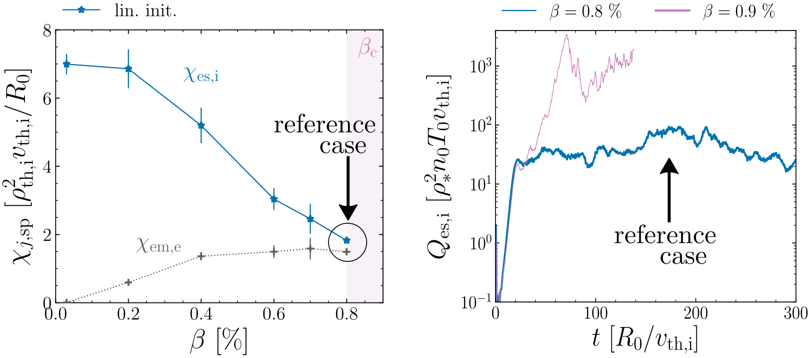
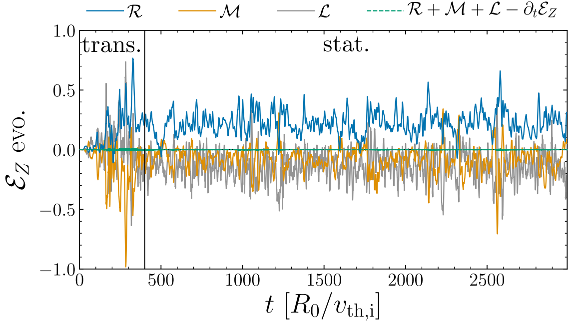
- electrostatic "Reynolds stress" $\mathcal{R}$
- electromagnetic "Maxwell stress" $\mathcal{M}$ $\leftarrow$ zonal flow damping!

Zonal flow transfer study



Zonal flow transfer study

Mesoscale ($n_{\mathrm{ZF}} = 1$) zonal flow intensity evolution:



Zonal flow transfer study

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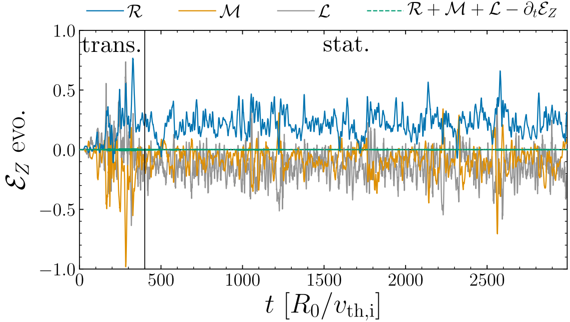

	trans.	stat.
$\mathcal{R}$	0.149	0.223
$\mathcal{M}$	-0.148	-0.084
$\mathcal{L}$	0.032	-0.138
$\lvert\mathcal{R}/\mathcal{M}\rvert$	**1.007**	

Zonal flow transfer study

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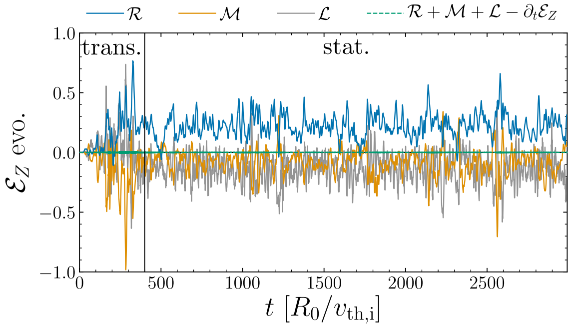
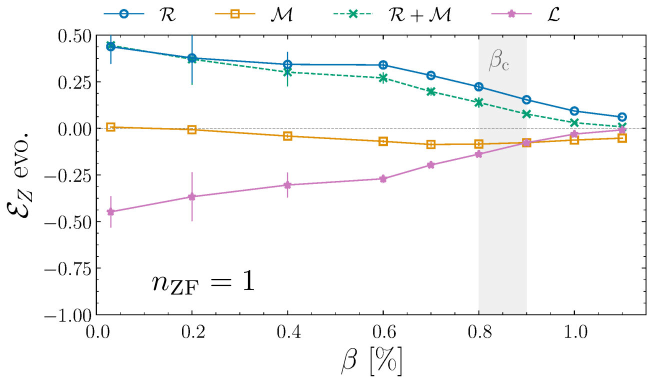


	trans.	stat.
$\mathcal{R}$	0.149	0.223
$\mathcal{M}$	−0.148	−0.084
$\mathcal{L}$	0.032	−0.138
$\lvert\mathcal{R}/\mathcal{M}\rvert$	**1.007**	**1.616**

$\Rightarrow$ **positive feedback effect**

Zonal flow transfer study



- positive feedback effect:

  $\Rightarrow$ **nonlinear sustain** of mesoscale zonal flows beyond β_c

Summary

- Mesoscale zonal flow patterns do develop in electromagnetic near marginal ITG driven turbulence.
- Zonal flow patterns allow for the access of an improved regime with $\beta > \beta_{\mathrm{c}}$.
- Positive feedback effect allows for the nonlinear sustain of mesoscale zonal flows in the improved β-regime.

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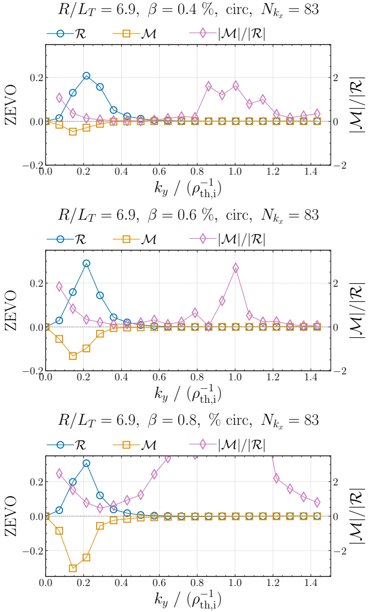
Questions:

What is the reason for the positive feedback effect?

What mechanism causes a change in the relative importance of $\mathcal{R}$ and $\mathcal{M}$?

Spectral decomposition of $\mathcal{R}$ and $\mathcal{M}$



Observation:

- $\mathcal{R}(k_y)$ and $\mathcal{M}(k_y)$ peak at different k_y
- $|\mathcal{M}(k_y)|/|\mathcal{R}(k_y)|$ increases with decreasing k_y

A shift of the turbulence spectrum to ...

- ... smaller k_y

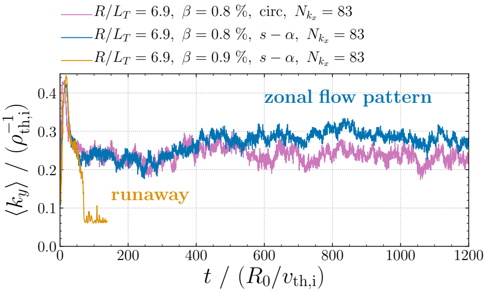
  $\Rightarrow$ net zonal flow damping

- ... larger k_y

  $\Rightarrow$ net zonal flow drive

Turbulence k_y-centroid

Realizations around β_c:



Turbulence k_y-centroid:

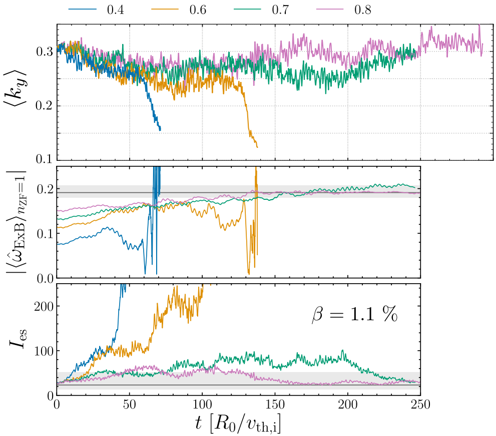
$$\langle k_y \rangle = \frac{\sum_{k_y>0} k_y |\hat{\phi}_{\mathbf{k}}|^2}{\sum_{k_y>0} |\hat{\phi}_{\mathbf{k}}|^2}$$

Observation:

- runaway $\rightarrow \langle k_y \rangle$ decreases
- mesoscale zonal flow pattern development $\rightarrow \langle k_y \rangle$ increases

Turbulence k_y-centroid

Zonal flow stability study at $\beta = 1.1$ %:



Turbulence k_y-centroid:

$$\langle k_y \rangle = \frac{\sum_{k_y>0} k_y |\hat{\phi}_{\mathbf{k}}|^2}{\sum_{k_y>0} |\hat{\phi}_{\mathbf{k}}|^2}$$

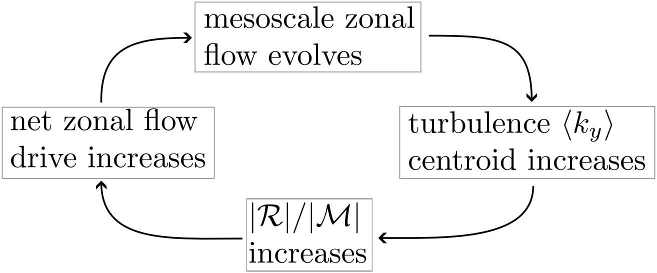
Observation:

- reduction of mesoscale zonal flow $\rightarrow$ reduction of $\langle k_y \rangle$
- recovering of mesoscale zonal flow $\rightarrow$ increase of $\langle k_y \rangle$

Reason for positive feedback effect

Hypothesis:

- Mesoscale zonal flow patterns control the turbulence spectral centroid $\langle k_y \rangle$ and thereby the net nonlinear zonal flow drive in electromagnetic ITG turbulence (with CBC parameters) in a favorable way.



Open questions:

Why do $\mathcal{R}$ and $\mathcal{M}$ peak at different k_y and is this universal?

$\rightarrow$ Nonlinear excitation of subdominant microtearing modes might be more efficient at small ky (MTM growth rate spectrum often peaks at smaller k_y compared to ITG).

What is the mechanism behind the $\langle k_y \rangle$ evolution?

$\rightarrow$ Inverse energy cascade might become important at small zonal flow level (and comparably large turbulence level).

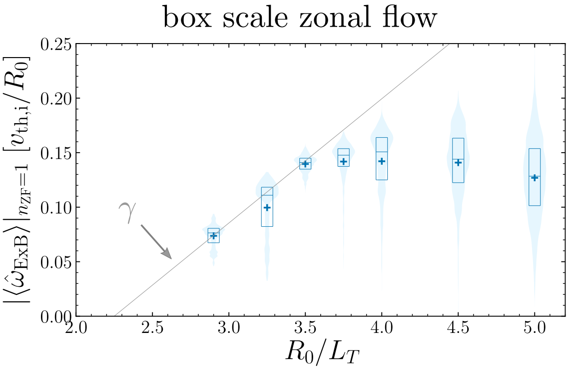
$\rightarrow$ Zonal flows transfer energy to high k_x at fixed k_y; Isotropization through isotropic $E \times B$-nonlinearity might cause transfer to high k_y.

$\rightarrow$ Simply a consequence of saturation rule $\propto \gamma / k_\perp^2$ with varying level of zonal flow.

Is the change in the turbulence spectral properties the dominant mechanism behind the positive feedback process?

Supplemental material

Results —Mesoscale zonal flow properties

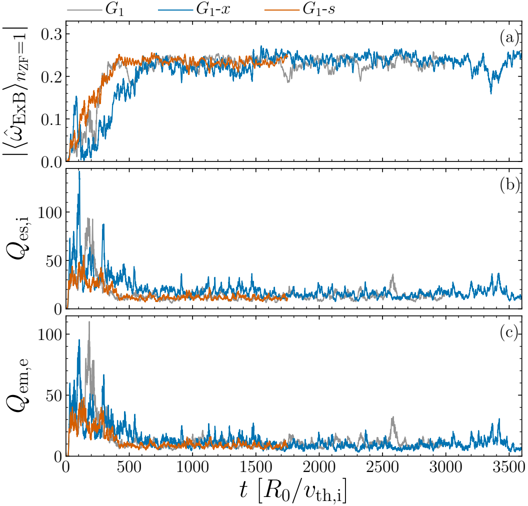


Waltz rule:

$$\omega_{\mathrm{ExB}} \sim \gamma$$

Convergence study —zonal flow evolution

Reference case $\beta = 0.8$ %:

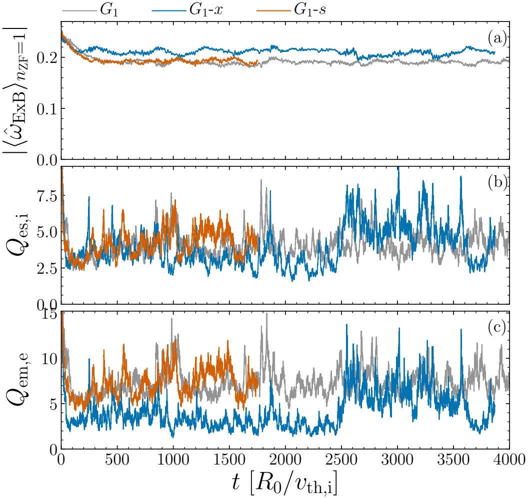


G_1-x: double x-resolution

G_1-s: double s-resolution

Convergence study —improved β-regime

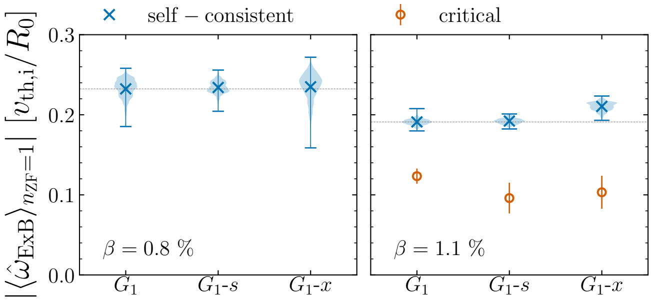
Improved regime $\beta = 1.1$ %:



G_1-x: double x-resolution

G_1-s: double s-resolution

Convergence study —saturated and critical zonal flow level



G_1-x: double x-resolution

G_1-s: double s-resolution

Field line tracing —equations

Field line equations:

$$\frac{\partial y}{\partial s} = \frac{(\nabla y \times \nabla x) \cdot \mathbf{b}}{\nabla s \cdot \mathbf{B}} \frac{\partial A_{\parallel}}{\partial y} \tag{1}$$

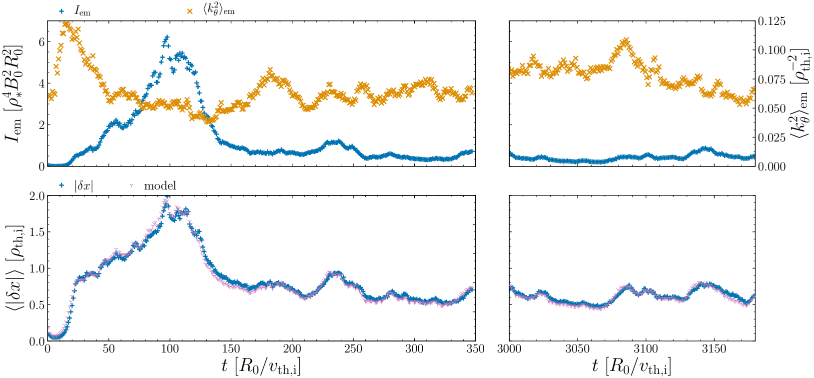
$$\frac{\partial x}{\partial s} = - \frac{(\nabla y \times \nabla x) \cdot \mathbf{b}}{\nabla s \cdot \mathbf{B}} \frac{\partial A_{\parallel}}{\partial x} \tag{2}$$

Procedure:

- generate $A_{\parallel}(x, y, s)$ data through gyrokinetic simulations
- seed N_{fl} field lines equidistantly in x at LFS midplane
- trace 3D field line trajectories by integrating Eqs. (1) and (2) with respect to s
- full-turn displacement δx: radial displacement of a field line after one poloidal turn $s = -0.5 \rightarrow +0.5$
- half-turn displacement $\delta x_{1/2}$ ($\delta x_{2/2}$): radial displacement of a field line after the poloidal half-turn $s = 0 \rightarrow +0.5$ ($s = -0.5 \rightarrow 0$)

Field line tracing —temporal behavior

Reference case $\beta = 0.8$ %:

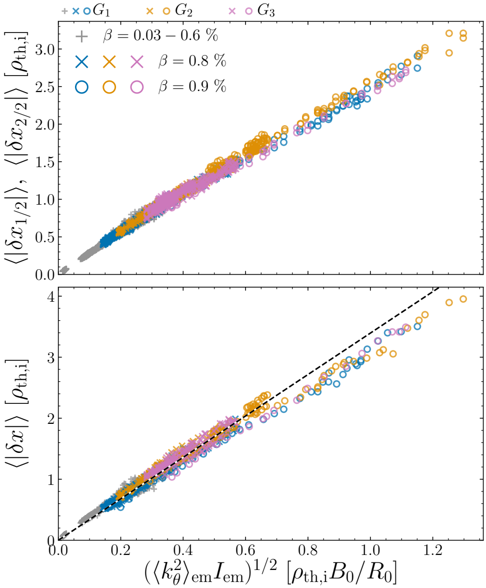


$$I_{\rm em} = \sum_{k_\theta > 0} |\hat{A}_{\parallel,\mathbf{k}}|^2 \qquad \langle k_\theta^2 \rangle_{\rm em} = \frac{\sum_{k_\theta > 0} k_\theta |\hat{A}_{\parallel,\mathbf{k}}|^2}{\sum_{k_\theta > 0} |\hat{A}_{\parallel,\mathbf{k}}|^2}$$

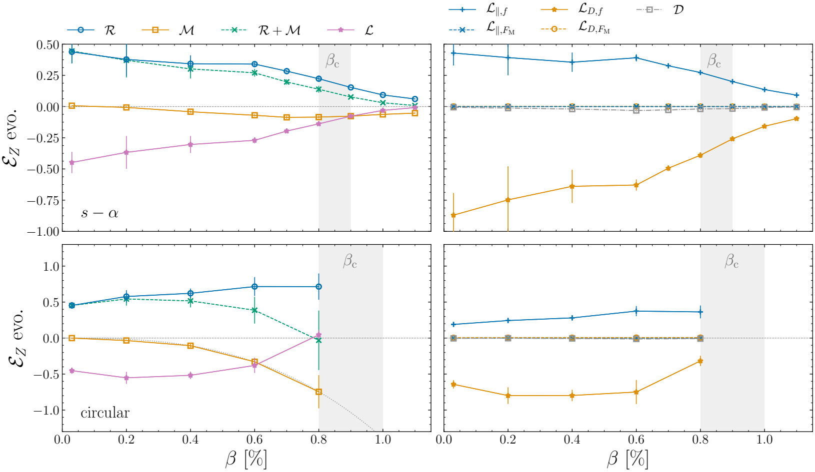
Model:

$$|\delta x| = m \times \underbrace{\left(\langle k_\theta^2 \rangle_{\rm em} I_{\rm em} \right)^{1/2}}_{\sim \delta B_x}$$

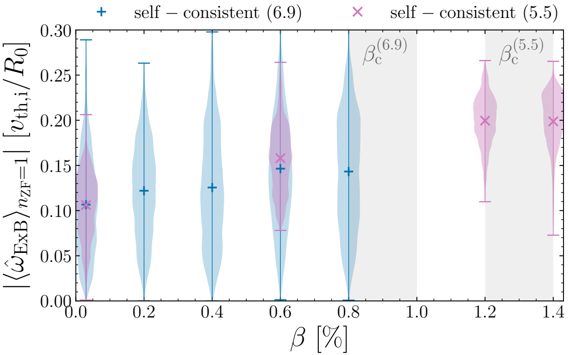
Field line tracing —radial displacement scaling



Zonal flow transfer study —β dependence



Mesoscale zonal flow —exact circular geometry



Transport hysteresis —exact circular geometry