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Gyrokinetic simulation of a fast L-H like bifurcation dynamics in a realistic diverted tokamak edge geometry

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Different experimental observations in L-H transition

Two different types of experimental observations for the role of the sheared-ExB flow (V'_{ExB}) in edge-turbulence bifurcation:

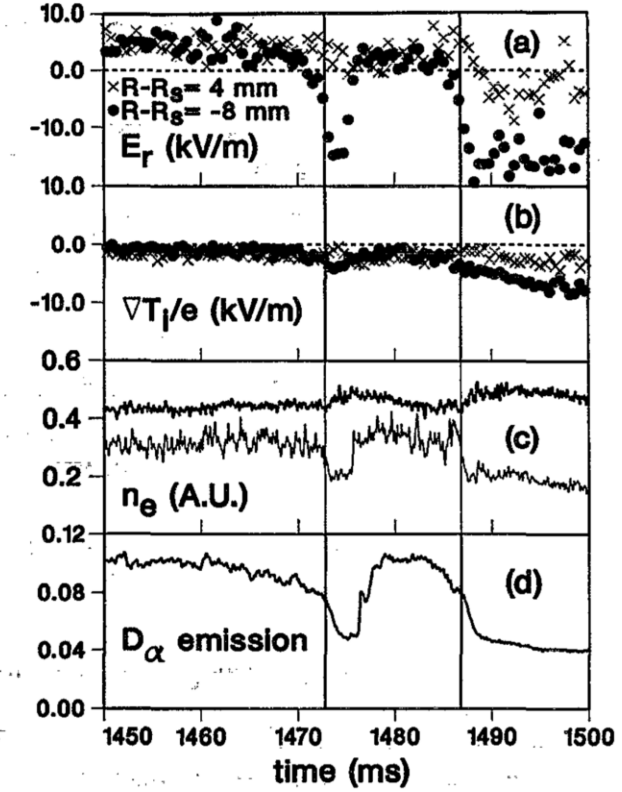
1. Turbulence generated zonal V'_{ExB}: *Reynolds stress*
   - Yan et al., IAEA16 & PRL14; Schmitz, IAEA16; Tynan, NF13; Istvan PPCF 14, and others]

2. Neoclassically generated V'_{ExB}: *X-point orbit-loss* [Chang et al, PoP02]
   - Kobayashi et al., PRL13, and others (X-point orbit-loss)
   - Cavedon, NF17 (Neoclassical)
   - NSTX finds that P_{L-H} is strongly correlated with orbit-loss V'_{ExB} [Kaye, NF11; Battaglia, NF13]

1. Turbulent zonal V'_{ExB} & L-H bifurcation in experiment

- $F_{\theta,Reynolds} = -d\langle\delta V_r \delta V_\theta\rangle/dr$
- Became basis for the predator-prey model [Kim-Diamond, PRL03, and others]
- When the turbulent Reynolds energy extraction ($\int dt\, F_{\theta,Reynolds}$) exceeds the turbulent kinetic energy, turbulence quenching can occur.

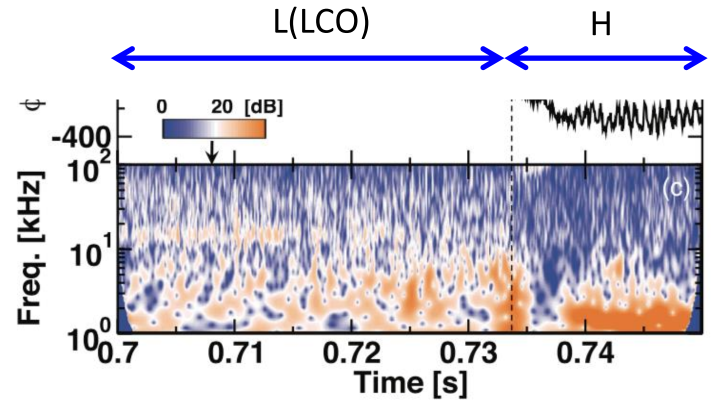
- **Unanswered questions if Reynolds stress is solely responsible for L-H**
  - Right after the turbulence quenching, what is supporting the strong V'_{ExB}?
    - Several experiments report that a strong ∇p (and its effect on V'_{ExB}) develops only well after a fast bifurcation event [Moyer et al., PoP1995; and others]
  - What breaks the symmetry in the $F_{Reynolds}$, thus the V'_{ExB}, direction?
  - Why some machines do not see much Reynolds work?



[Moyer et al., PoP1995]

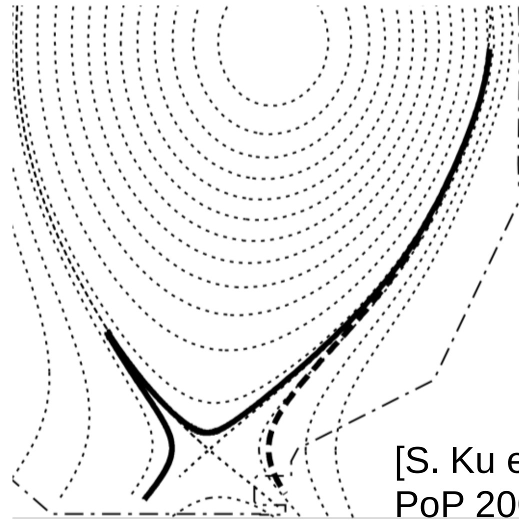
2. Neoclassically generated V'_{ExB} & L-H bifurcation in experiment, w/o seeing much Reynolds work

- V'_{ExB} is driven by∇p? [Cavedon et al., NF2017, ASDEX-U]
- Orbit-loss-driven V'_{ExB} [Kobayashi et al., PRL2013, and others]
- NSTX found $P_{L\text{-}H}$ is strongly correlated with orbit-loss V'_{ExB} [Kaye, NF2011; Battaglia, NF2013]



Zonal flow not seen as bifurcation driver
[Kobayashi., NF 2017]

- Could it be possible that the Reynolds stress and orbit loss mechanism work together, with one stronger than the other depending upon the plasma/geometry condition?
- Could the combined Reynolds and X-loss physics provide the missing puzzle pieces in L-H transition physics?

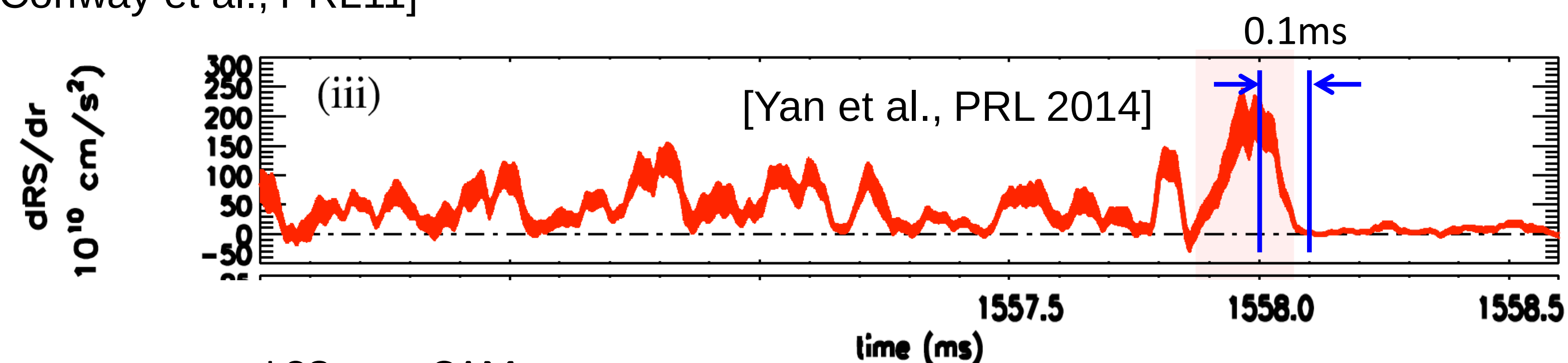


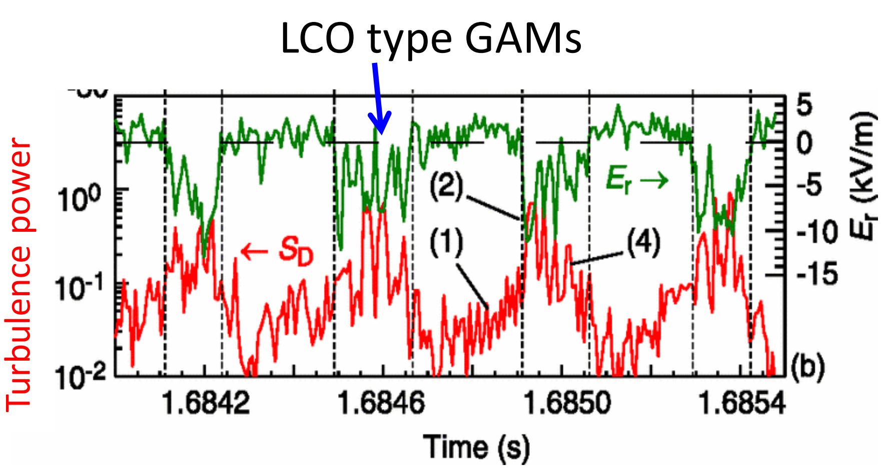
[S. Ku et al., PoP 2004]

Experimental observations of L-H bifurcation time scale, GAM, and LCO

- When the heating power is close to P_{LH}, the bifurcation is observed to be slow with many limit cycle oscillations (I-phase) [Schmitz et al. PRL12 and others]
- When the heating power is > P_{LH}, the bifurcation is (forced to be) fast (< 0.1 ms) with an abbreviated I-phase [Yan PRL14, and others]

GAM and Limit cycle oscillation observed as L-mode approaches L-H bifurcation [Conway et al., PRL11]





LCO-type GAMs can be part of the bifurcation physics.

[Conway, PRL 2011]

Why has a gyrokinetic L-H study not been done previously?

Difficulty

- Multiscale in space and time
  - Turbulence
  - Neoclassical with ion orbit loss
  - Neutral particles with ionization and charge exchange
- Magnetic separatrix ($q=\infty$), which interfaces two different magnetic topologies
- Nonlocal physics

  Radial turbulence correlation width ~ plasma gradient scale length ~ ExB shearing width ~ neutral penetration length
- Large amplitude nonlinear turbulence: $\delta n/n > 10\%$
- Non-Maxwellian plasma
  - Requires fully nonlinear and conserving Collisions

→ Total-f simulation with ~100X more number of marker particles than delta-f simulation in the complex edge geometry: XGC.

→ We thought it would require >100PF computer, non-existent in US yet.

Previously, compute resources discouraged us from studying the L-H transition physics

If we were to establish a global transport-equilibrium in an L-mode plasma, move toward the bifurcation by quasistatically increasing P_{heat}, go through the bifurcation, and build up pedestal, we would not have enough compute resources to study the transition.

→ Requires >10X faster computer than Titan at ORNL.

A new strategy to make the transition physics study possible on Titan:

- Bifurcation may not be a global transport-equilibrium phenomenon
  - But a localized phenomenon at edge
  - May not need to wait until the global non-transport-equilibrium GAMs die out
- Study only the edge bifurcation itself, as soon as the L-mode edge turbulence is established.
  - Force the bifurcation by having $P_{edge} >> P_{LH}$
  - Experimentally, a forced L-H bifurcation action could be completed in <0.1ms (Yan-McKee, PRL2014, and others).
  - Take advantage of the fast establishment of edge physics
- Low beta electrostatic simulation

In the core plasma, *f* evolves slowly

For this argument, let's use the drift kinetic equation

$\partial f/\partial t+(\mathbf{v}_{||}+\mathbf{v}_d)\cdot\nabla f + (e/m)E_{||}v_{||}\,\partial f/\partial w = C(f,f) + Sources/Sinks$

where w is the particle kinetic energy.

In a near-thermal equilibrium, we take the "transport ordering" (= diffusive ordering):

$$\partial f/\partial t=O(\delta^2),\ S=O(\delta^2),\ with\ \delta<<1$$

- Let $f=f_0+\delta f$, with $\delta f\,/\,f_o=O(\delta),\ \delta<<1,\ v_d/v_{||} = O(\delta),\ E_{||}/m = O(\delta\ or\ \delta^2)$

$O(\delta^0)$: $v_{||}\cdot\nabla f_0 = C(f_0,f_0) \rightarrow f_0=f_M$: H-theorem

$O(\delta^1)$: $\partial\delta f/\partial t + v_{||}\cdot\nabla\delta f + v_d\cdot\nabla f_0 + (e/m)\,E_{||}v_{||}\,\partial f_o/\partial w = C(\delta f)$

- ✧ Perturbative kinetic theories then yield transport coefficients $=O(\delta^2)$
- ✧ In this case, fluid transport equations ($f_o \rightarrow n,T$) can be used with the kinetically evaluated or ad hoc closures

→ **GK simulation is cheaper per physics time, but *δf* equilbrates on a slow time scale** $O(\delta^1\omega_{bi})$ ~ ms. **And, a meaningful time evolution of** f_0 **in** V_T **frame can only be obtained in a long "transport-time" scale** $O(\delta^2\omega_{bi})$. V_T **evolves on an even slower time scale.**

In edge plasma, *f* evolves fast

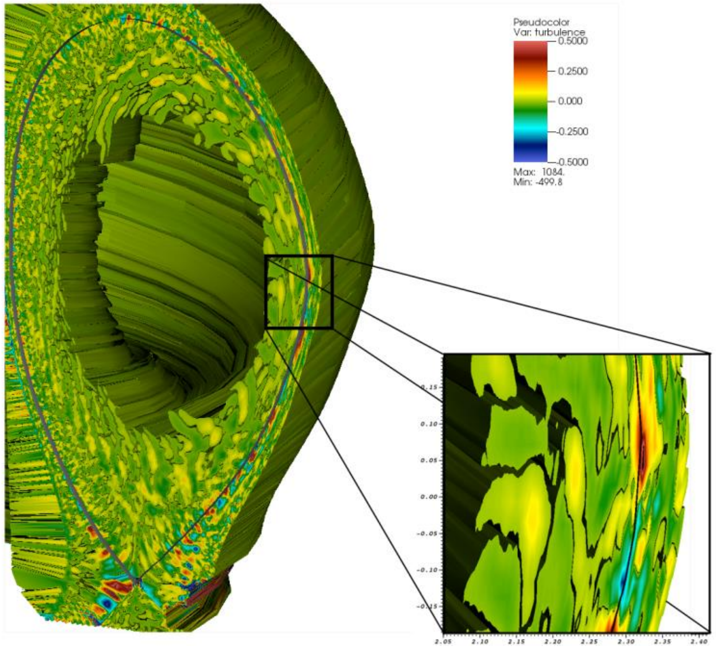
- Ion radial orbit excursion width ~ pedestal width & scrape-off layer width
- Orbit loss from $\psi_N<1$ and parallel particle loss to divertor

All terms can be large: ~ either $O(\omega_{bi})$ or $O(\nu_C)$

- $\mathbf{v}_{||}\cdot\nabla f \sim \mathbf{v}_d\cdot\nabla f \sim C(f,f) \sim eE_{||}v_{||}/m\, \partial f/\partial w \sim O(\omega_{bi})$ ~ 0.05 ms in DIII-D
- *f* equilibrates very fast: $\partial f/\partial t + (\mathbf{v}_{||}+\mathbf{v}_d)\cdot\nabla f\,(e/m) + E_{||}v_{||}\partial f/\partial w = C(f,f)+S$
- If $S_{neutral}$ is small, it does not affect the fundamental structure of *f.*

Fast-evolving nonthermal kinetic system: expensive per physics time → extreme scale computing. However, a short time simulation (~0.1X) can yield meaningful physics.

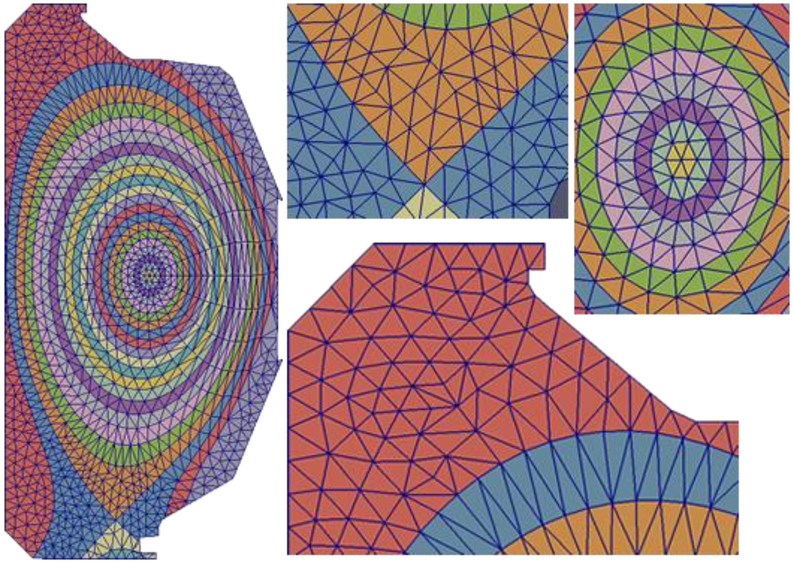
The edge turbulence around the separatrix saturated before the central core turbulence even started to form



XGC gyrokinetic codes (V&V summary at epsi.pppl.gov)

XGC1: **X**-point **G**yrokinetic **Code** 1

- Gyrokinetic ions and electrons
- Lagrangian PIC + Eulerian 5D grid
- Heat and momentum source in core
- Monte Carlo neutrals with wall recycling
- Fully nonlinear Fokker-Planck Coulomb collision operation
- Logical wall-sheath
- Unstructured triangular mesh
- EM with fully implicit drift-kinetic electrons (partially verified).



XGC1-hybrid: GK ions + fluid electrons

- Implicit fluid electrons (Hager PoP17)

XGCa: Axisymmetric gyrokinetic version of XGC1

XGC0: Axisymmetric and flux surface averaged drift-kinetic version

Full-f + Neutral particles + Unstructured triangular grid
→ **Expensive to simulate**
→ **Requires extreme scale HPCs**

For the present L-H bifurcation study, we have performed a low-beta electrostatic edge simulation using XGC1

Plasma input condition

- C-Mod #1140613017 in L-mode, single-null
- $\beta_e \approx 0.01\% < m_e/m_i$ in the bifurcation layer
- ∇B-drift direction has been flipped to be into the divertor

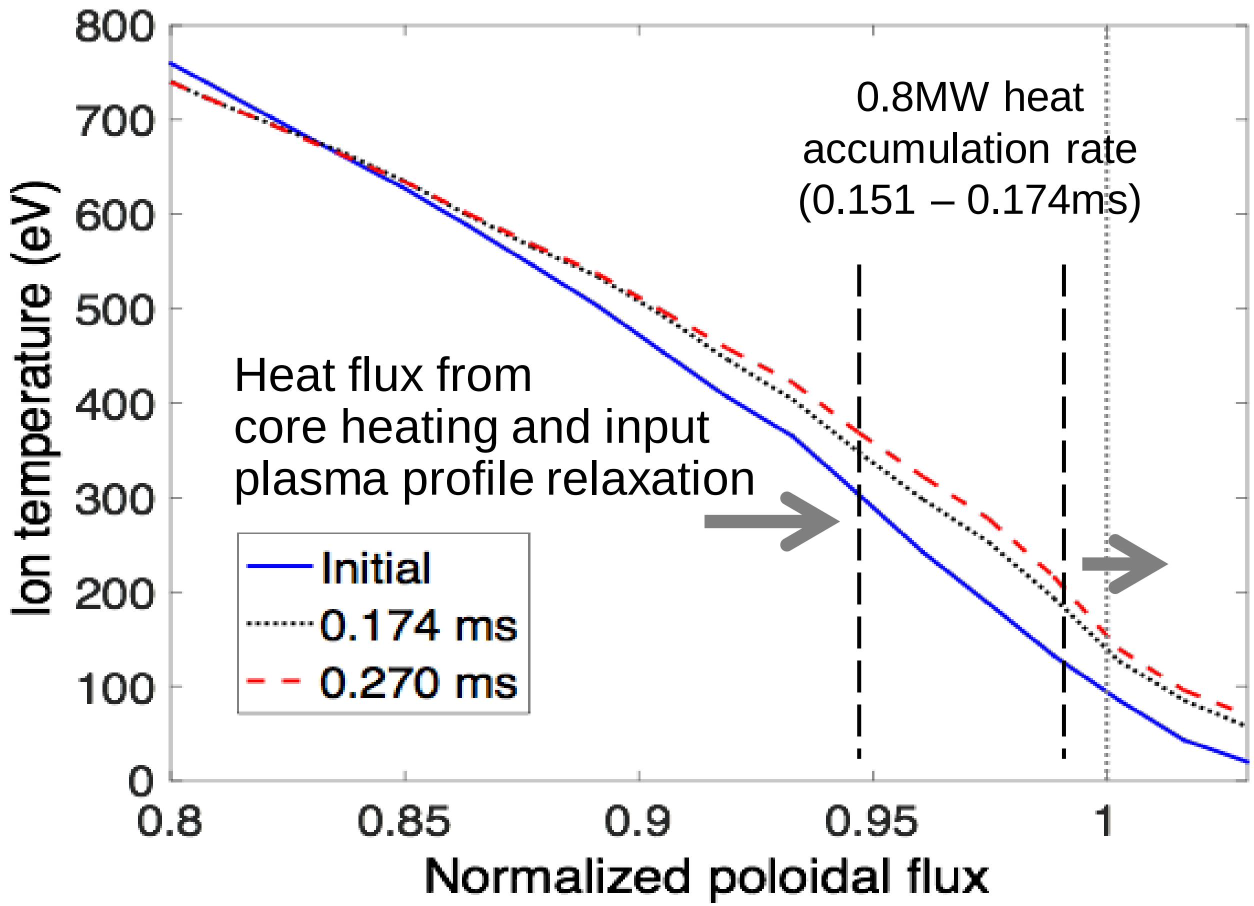
Include the most important multiscale physics

- Neoclassical kinetic physics
- Nonlinear electrostatic turbulence
  - ITG, TEM, Resistive ballooning, Kelvin-Helmholtz, other drift waves
- Neutral particle recycling with CX and ionization
- Realistic diverted geometry

Electromagnetic correction to the present result is left for a future work.

Use a L-mode plasma from C-Mod (beta~0.01%)

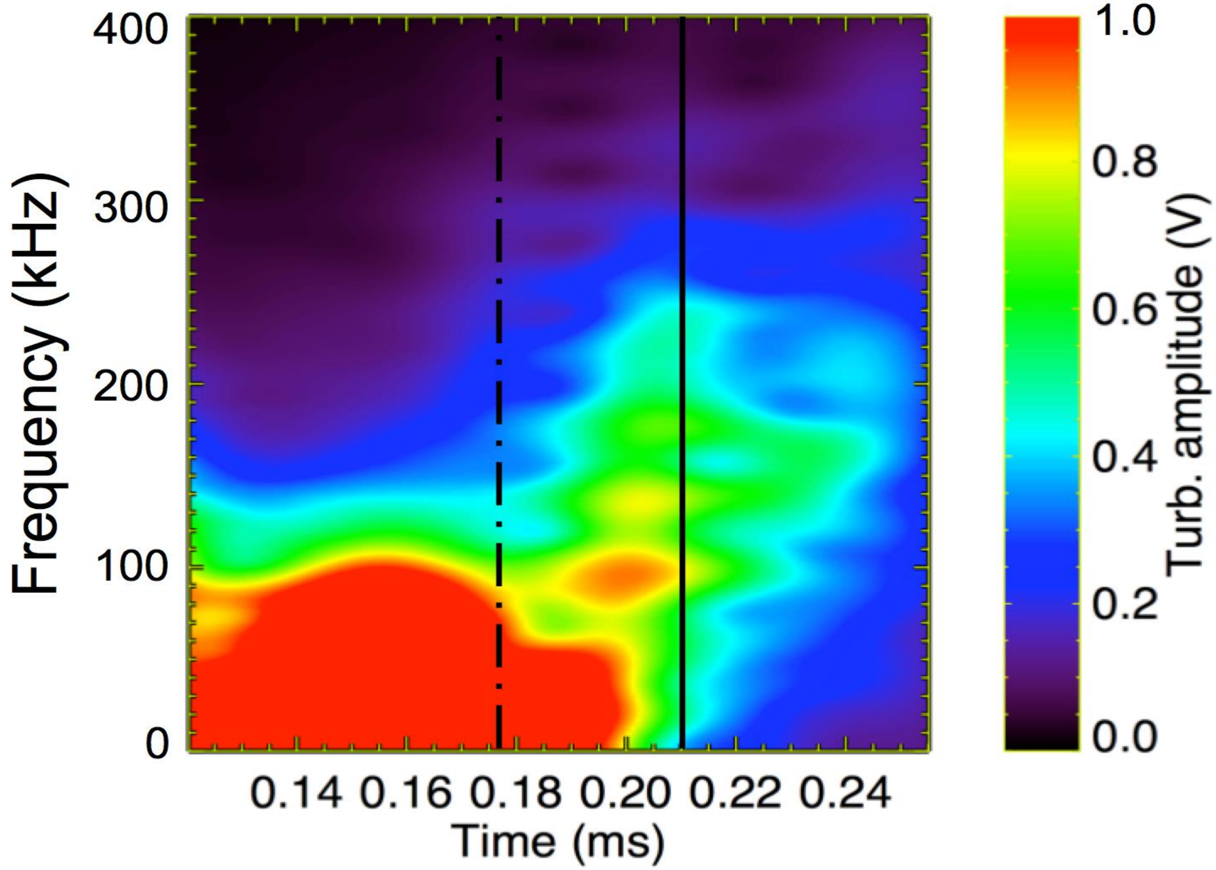
Edge temperature increases from heat accumulation



In a developed H-mode pedestal, $dV_E/dr > 0$ at Ψ_N~0.97.
Any bifurcation mechanism needs to lead to this sign.

Overview of the turbulence behavior at bifurcation

1. t~0.175-0.21ms, suppression of lower frequency, higher amplitude turbulence occurs, and higher frequency, lower amplitude turbulence is generated (shades of green, eddy tearing by ExB shearing, to be shown).
2. t>0.21ms, suppression of the lower amplitude turbulence follows.

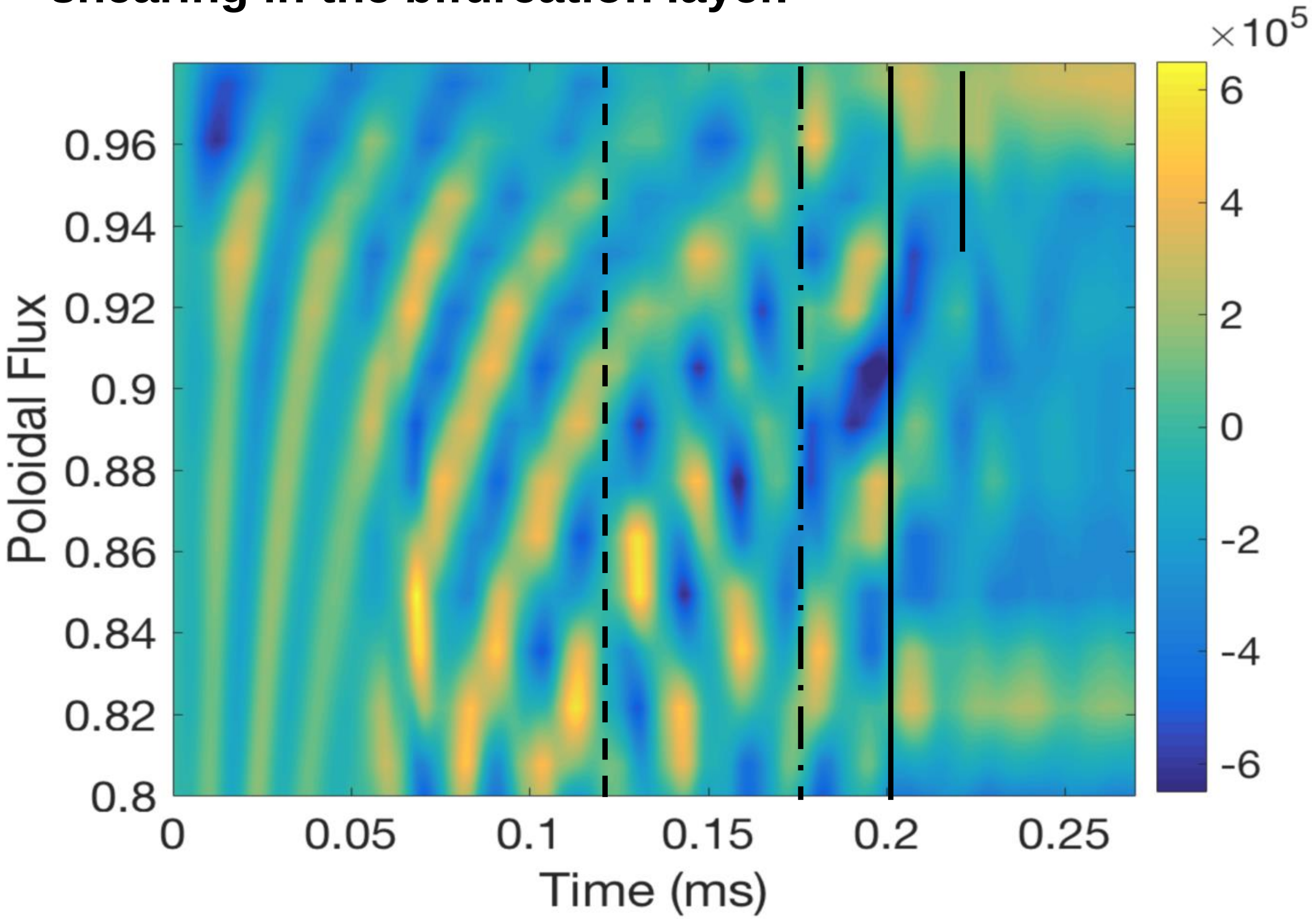


Time-radius behavior of the sheared ExB flow V_E'

1. t=0.12ms, V_E' settles down in Ψ_N~0.97-98
2. t<0.17ms, positive part of V_E' does not penetrate into the edge layer (ρ>0)

Gyrokinetic Poisson Eq. $(\rho_i^2/\lambda_D^2)\epsilon_0 B\ V_E' \simeq e(n_e - n_{i,gc})$

1. t~0.175ms, something pushes the V_E' to be >0 in the edge layer (ρ<0)
2. t >0.2ms, something then locks the sheared ExB flow into the mean ExB shearing in the bifurcation layer.

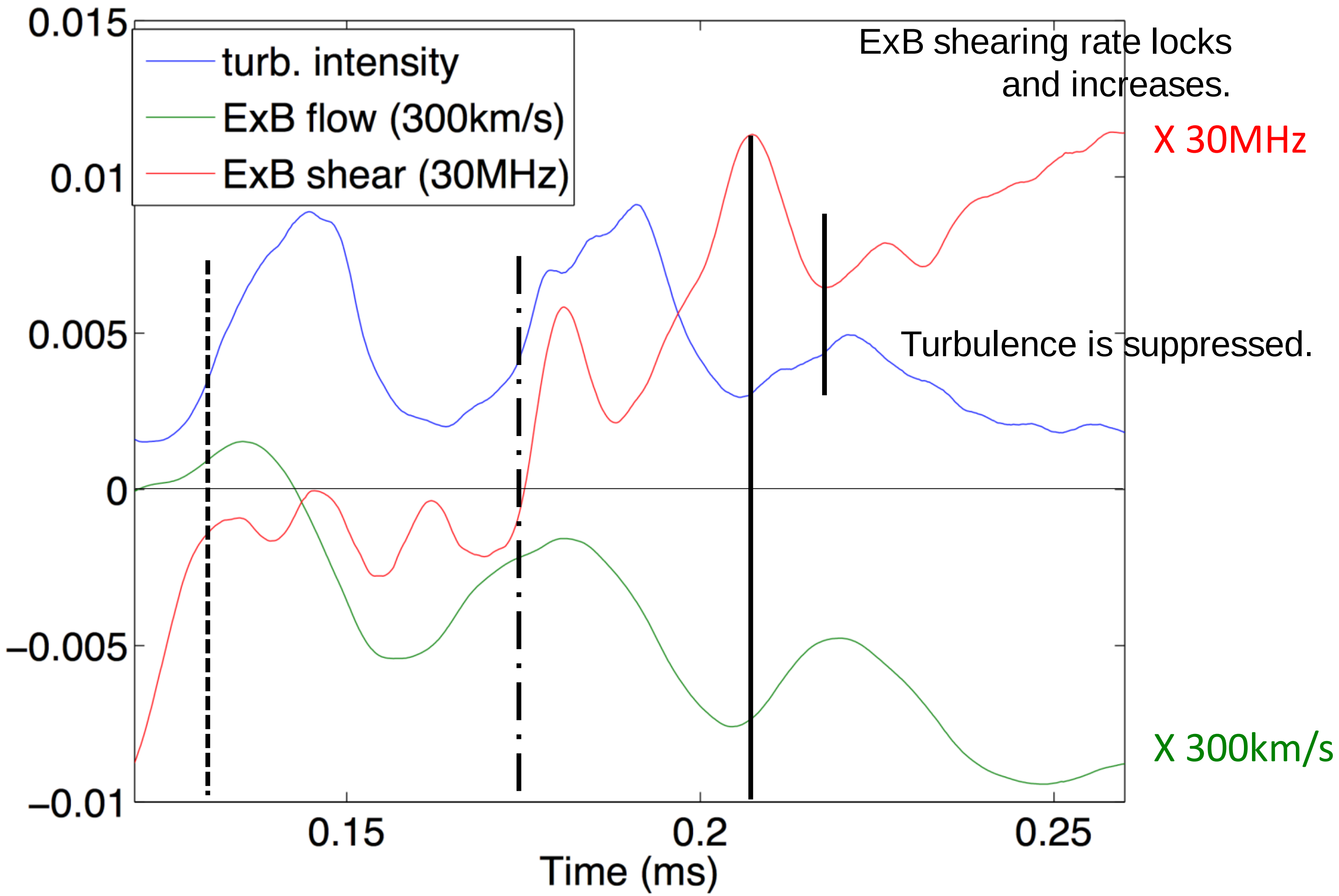


Transition layer is at 0.96<Ψ_N<0.98, agreeing with C-Mod [Cziegler PPCF2014] and other devices.

[Titan, ALCC 2016]

Detailed local analysis at Ψ_N=0.975:

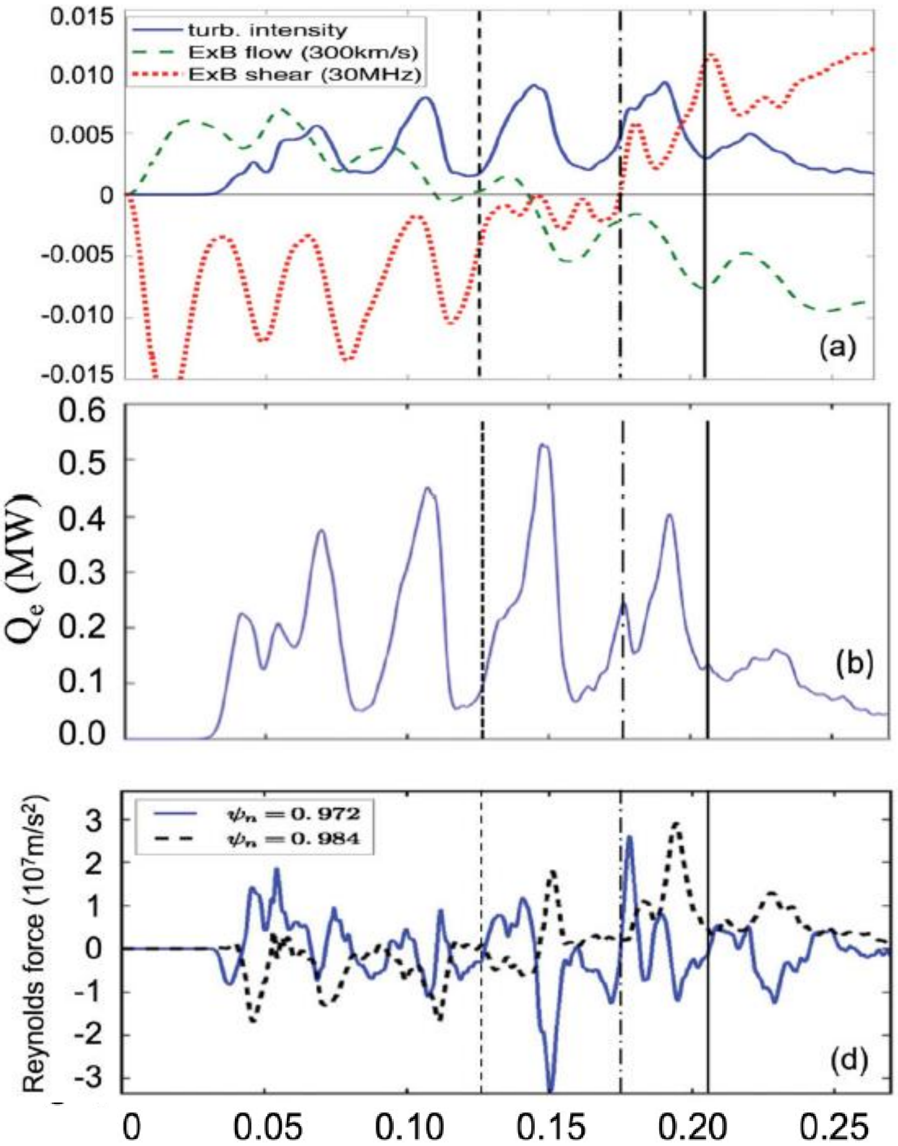
Important physics quantity is the ExB shearing rate, V_E', not V_E.
The bifurcation criterion is identified to be $V_E' > 300$ kHz
(Maximum growth rate of dissipative TEMs [Romanelli PoP 2007]).



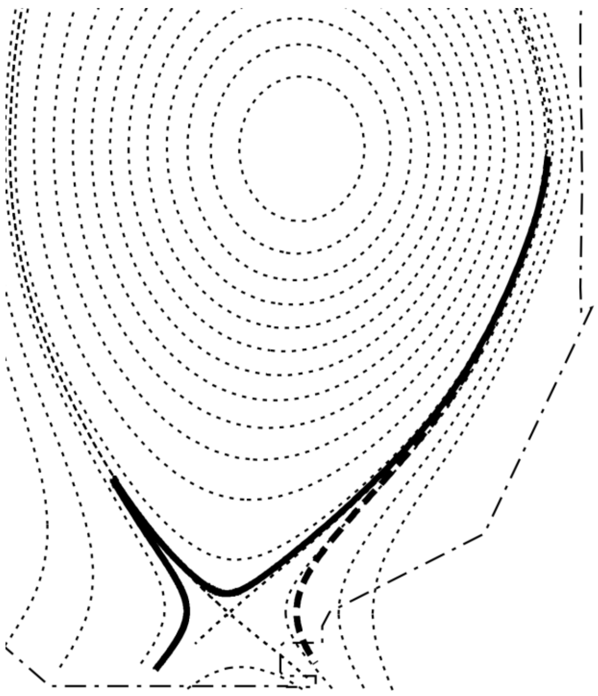
(0.96<Ψ_N<0.98, per Cziegler PPCF 2014)

Transport fluxes and Reynolds force

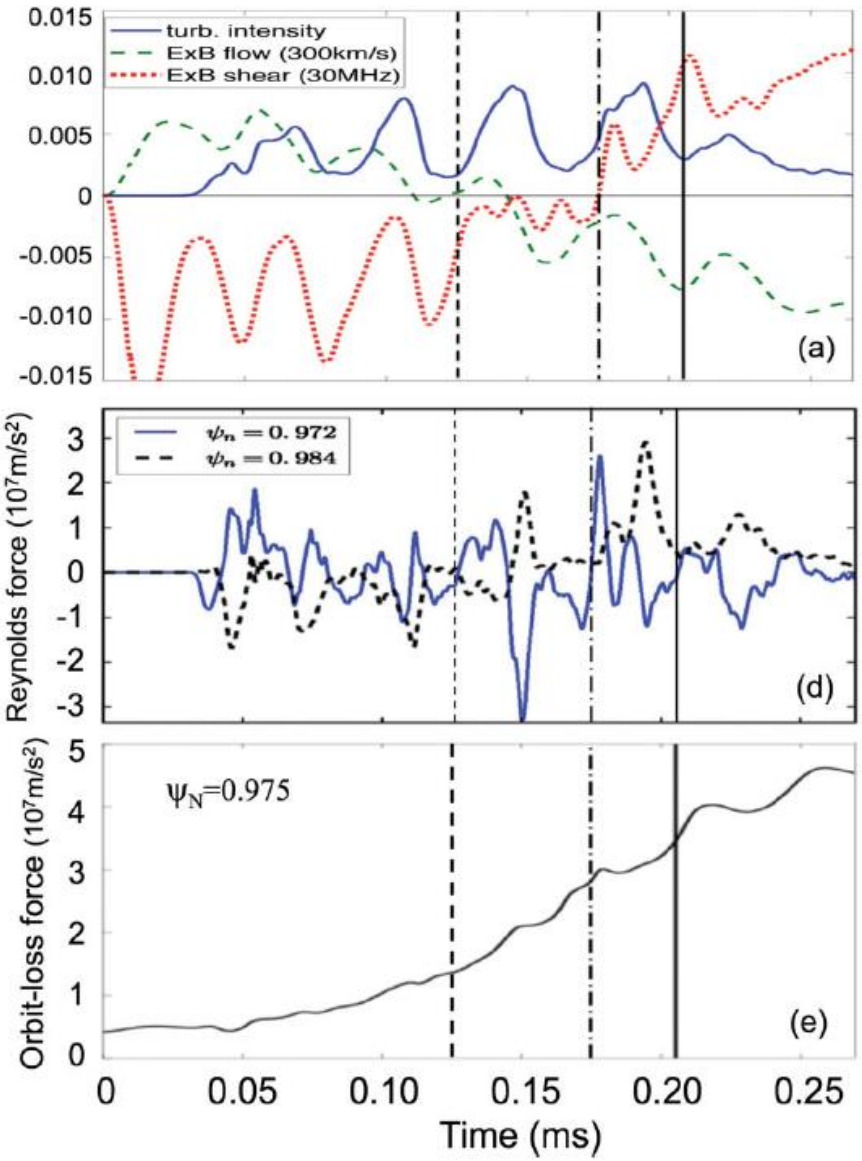
- Edge transport fluxes are non-local and follow the GAM behavior, with suppression at the "critical" time.
- The Reynolds force from turbulence $F_{\theta,\mathrm{Reynolds}} = -d\langle\delta V_r \delta V_\theta\rangle/dr$ fluctuates in both directions, and exhibits shearing
- However, the Reynolds force is a non-player after the bifurcation.
- **Questions:**
  - What is keeping the turbulence suppressed after the bifurcation?
  - Why is the negative Reynolds force not effective
  - What is pushing V'_{ExB} further to positive after 0.175 ms?
- It is reasonable to conjecture that there is another force in the positive $\mathbf{V_E}'$ direction



Additional force



[S. Ku et al., PoP 2004]

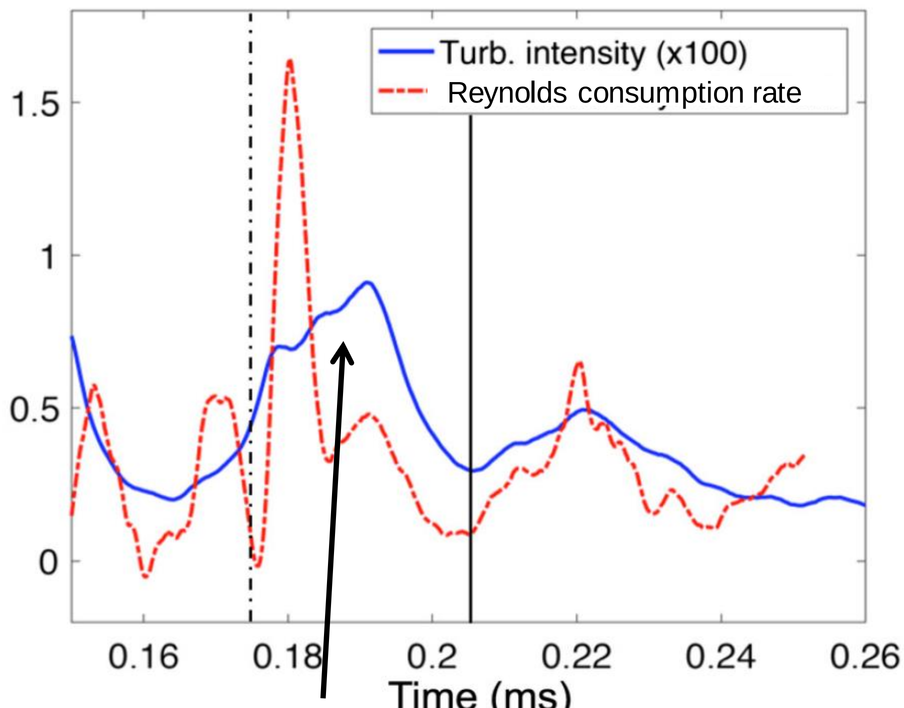


The orbit loss physics provides answers to all three questions.

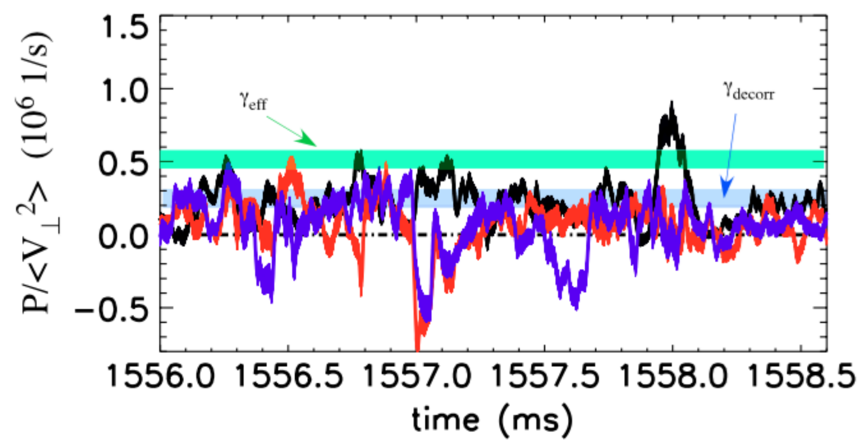
[Chang, PoP 2002]

Why does the turbulence get cut-off around 0.18ms? What triggers the bifurcation action?

The normalized, turbulence Reynolds consumption rate $P=\langle\tilde{v}_r\tilde{v}_\theta\rangle V_E' / (\gamma_{eff}\tilde{v}_\perp^2/2)$ becomes >1 in the beginning of the bifurcation action (I-phase), but becomes <1 after that → Zonal flows cannot be responsible for keeping the turbulence suppressed.



Relevance of the turbulence consumption rate? Eddie-tearing by ExB shearing could also be respnsible for this cut-off.



[Yan PRL 2014] reported a very similar behavior in the Reynolds consumption rate.

Summary and Discussions

- The total-f XGC family codes have been making important scientific discoveries on leadership class computers, which could not have been possible otherwise.
- A forced, fast L-H like bifurcation dynamics has been revealed, with transport suppresion in both the heat and particle channels.
- The turbulent Reynolds stress and the neoclassical X-loss physics work together in achieving the L-H bifurcation.
  - When combined together, the puzzle pieces appear to come together.
  - How will the geometry and plasma condition change their combination? → Neoclassical NSTX could be a good test bed.
  - How will this affect $P_{L\text{-}H}$ in ITER where the $E_{r,}'_{NEO}$ could be relatively weak?
- Isotope effects may be studied in the near future.
- EM correction to the present electrostatic result will be studied in the future.
- We will study the I-mode bifurcation in the near future.