A gyrokinetic discovery of fast L-H bifurcation physics in a realistic diverted tokamak edge geometry

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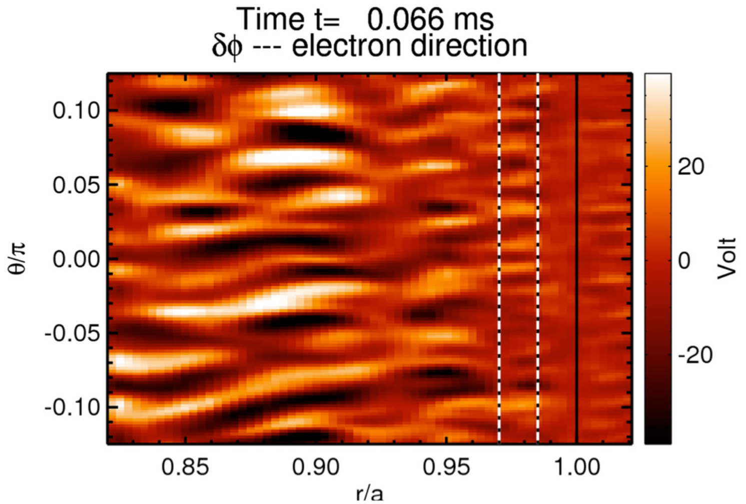
*Computing resources provided by OLCF at ORNL and ALCF at ANL

Rapid suppression electron direction turbulence in the edge bifurcation layer



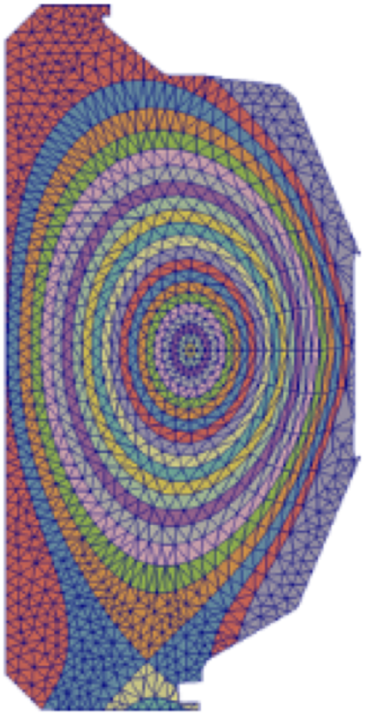
27th IAEA Fusion Energy Conference, 22 – 27 October 2018, Ahmedabad, India

Outline

- Introduction to XGC and the edge timescale
- Simulation setup
- XGC sees two turbulence suppression mechanisms by ExB shearing
  - Reynolds stress
  - Neoclassical (X-loss)
- Different suppression time-scale between electron and ion modes
  - Fast suppression of electron modes
  - Slow suppression of ion modes
- Conclusion and discussion

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

- XGC: X-point Gyrokinetic Code
- Steep electrostatic pedestal ordering [Hahm PoP 2009]
- **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



Capabilities

- ES with GK ions + drift-kinetic electrons [C.S. Chang TH/P7-22, R.M. Churchill TH/P7-26, J. Chowdhury TH/P8-7]
- Impurity ions [J. Dominski TH/P6-20]
- RMP or 3D B-field [J.M. Kwon TH/8-1, R. Hager TH/P5-9, G. Park TH/P5-26]
- Stellarator [M. Cole TH/P6-21, T. Moritaka TH/P5-5]
- EM with **fully implicit** drift-kinetic electrons (partially verified)
- Gyrokinetic electrons for ETG

Different timescales between core and edge

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

$$\frac{\partial f}{\partial t} + (v_{||} + v_d) \cdot \nabla f + \frac{e}{m} E_{||} v_{||} \frac{\partial f}{\partial w} = C(f, f) + \text{Sources/Sinks}$$

Core *f* evolves slowly: τ > 1ms

– Near-thermal equilibrium: $f = f_M + \delta f$;

$$C(\delta f), v_{||}/L_{||}, v_d/L_r, ev_{||}E_{||}/T, = O(\rho_* \omega_{bi})$$

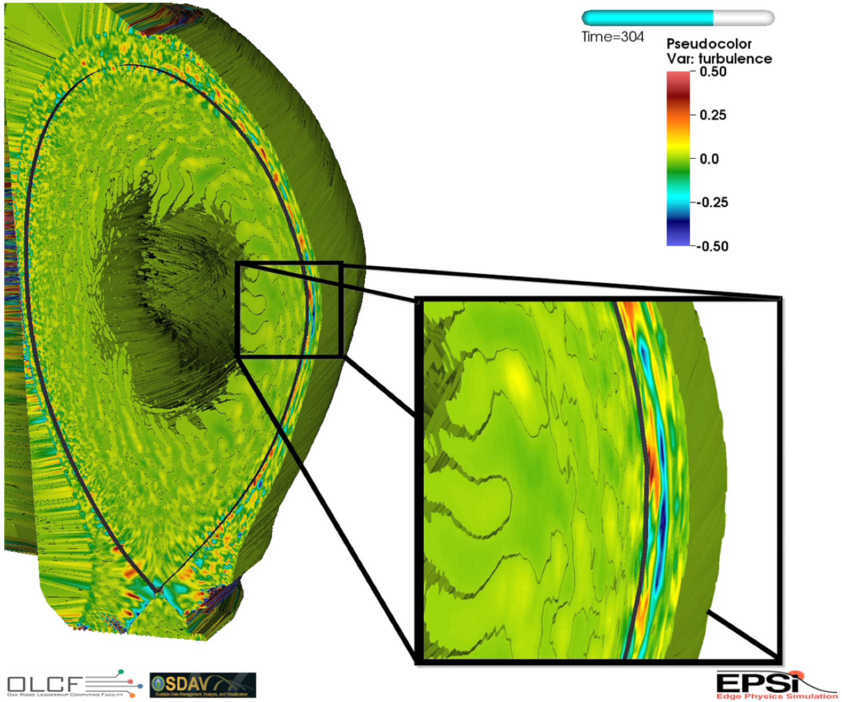
– $\partial \delta f / \partial t = O(\rho_* \omega_{bi})$

Edge *f* evolves fast: τ < 0.1ms

– Non-Maxwellian: $f \neq f_M$;

$$C(f), v_{||}/L_{||}, v_d/L_r, ev_{||}E_{||}/T, S = O(\omega_{bi})$$

– $\partial f / \partial t = O(\omega_{bi})$



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

- **Scale-inseparable, nonlocal multiscale in space and time**
  - Edge turbulence including large-amplitude blobs
  - Neoclassical with X-loss
  - Neutral particle recycing with ionization and charge exchange
  - Overlapping space-time scale: e.g., turbulence correl. width ~ plasma gradient scale length ~ orbit width ~ ExB shearing width ~ neutral penetration length
- **Magnetic separatrix interfacing two different magnetic topologies**
- **Non-Maxwellian plasma, requiring nonlinear Fokker-Planck collision**
- **Long global transport equilibrium time >> GK simulation time**

→ We thought it would require exascale computer; non-existent yet.

A new strategy for GK simulation of L-H transition to make the bifurcation study possible on present HPCs

- **Bifurcation may not be a global transport-equilibrium phenomenon**
  - But, an edge localized phenomenon [Yan, PRL14; Cziegler, PPFC14, …]
  - May not need to wait until GAMs die out [Conway, PRL11; …]
- **Study only the edge bifurcation itself, as soon as the L-mode edge turbulence establishes, without waiting for the pedestal buildup.**
  - We want to force the bifurcation by having $P_{edge} / P_{LH} \gtrsim 2$
  - A forced L-H bifurcation action could be completed in $\lesssim$ 0.1ms (Cziegler PPCF14, Yan, PRL14, and others).
  - Take advantage of $\lesssim$0.1ms establishment of the nonlinear edge turbulence.
- **Low beta electrostatic simulation: EM simulation in near future**

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For the present L-H bifurcation study in XGC, we use a low-beta electrostatic edge plasma

Plasma input condition

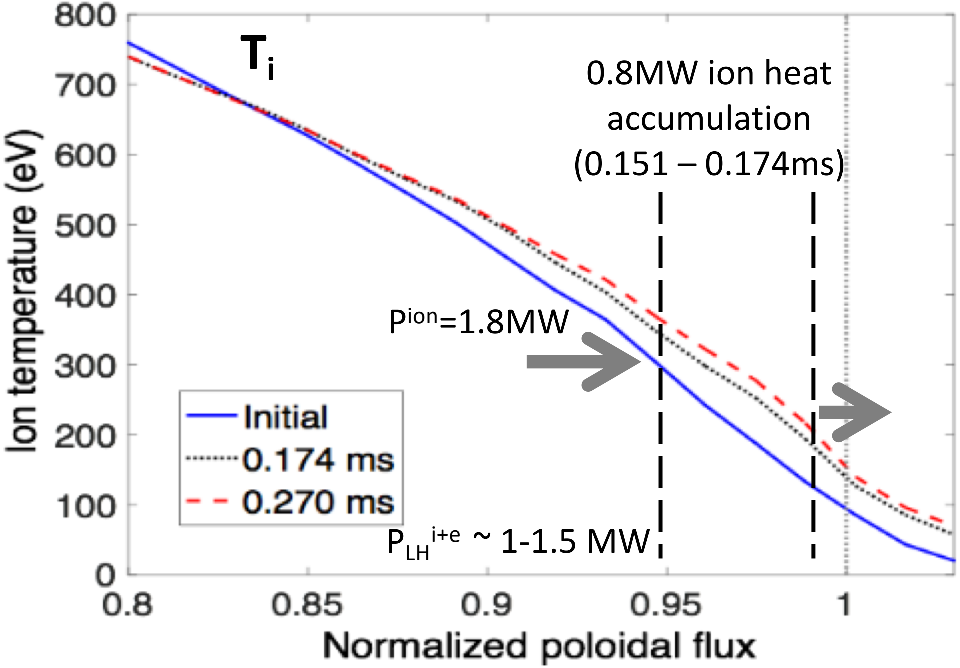
- C-Mod #1140613017 in L-mode, single-null, ∇B-drift away from X-point
- $\beta_e \approx 0.01\% < m_e/m_i$ in the bifurcation layer
- ∇B-drift has been flipped to be into the divertor for this presentation

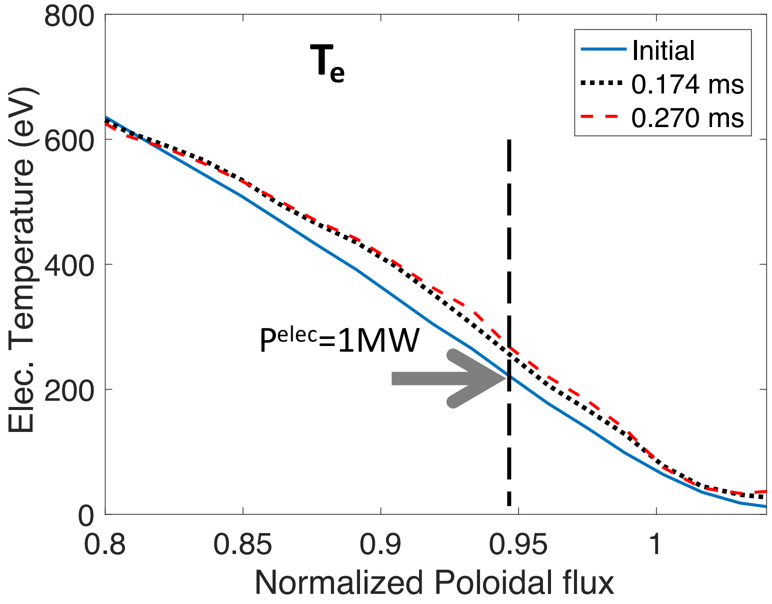
Include the most important multi physics

- 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.

An L-mode plasma from C-Mod (beta-edge~0.01%)





- Ion heat flux across $\Psi_N \simeq 0.95$ is ~1.8MW and well above P_{LH}^{i+e} ~ 1-1.5 MW.
- Edge temperature increases from heat accumulation.
- Transition layer is at $0.96<\Psi_N<0.98$, agreeing with C-Mod, DIII-D [Cziegler PPCF14, Yan PRL 14] and other devices.

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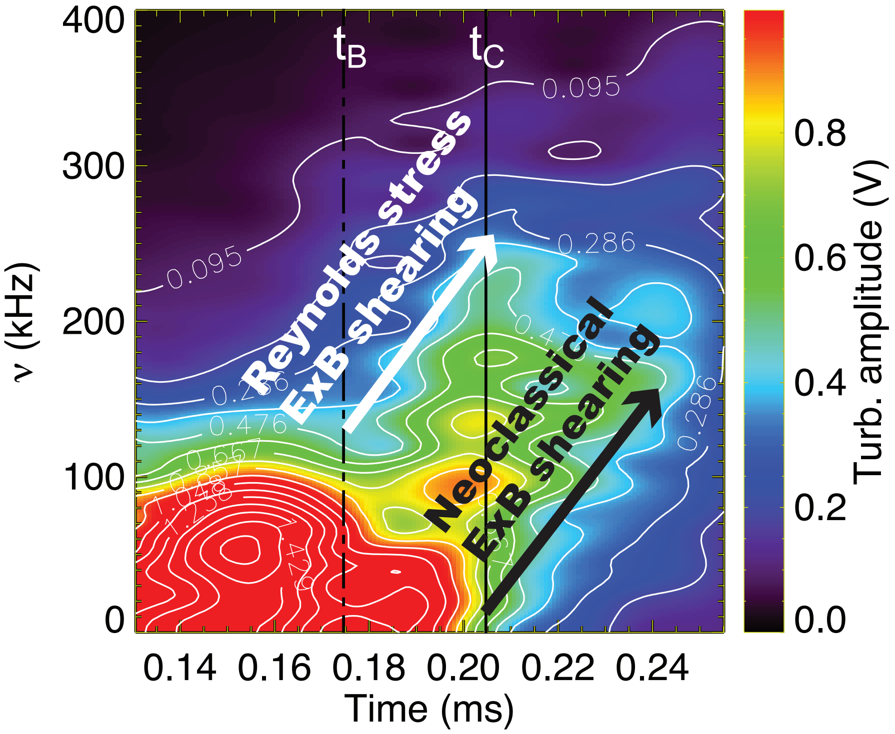
Overview of the turbulence behavior at bifurcation

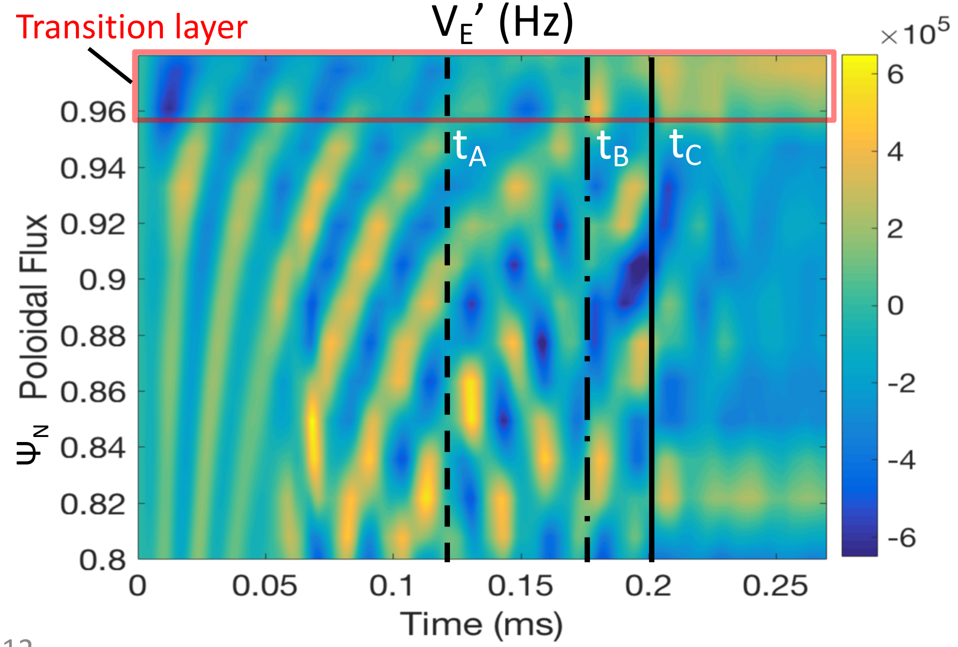
Two different shearing actions noticed

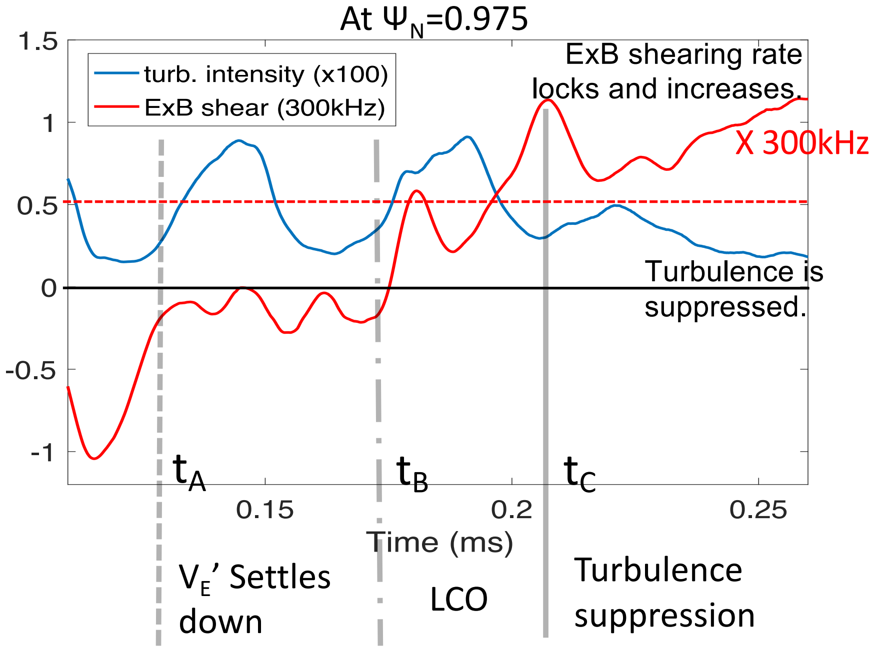
1. At t~0.175-0.21ms, lower frequency turbulence is sheared to higher frequency turbulence (by Reynolds-stress ExB shearing, to be shown).
2. At t>0.21ms, shearing and suppression of all frequency turbulence (neoclassical ExB shearing, to be shown, Biglari-Diamond PoF1990)



Time-radius behavior of the sheared ExB flow, V_E'

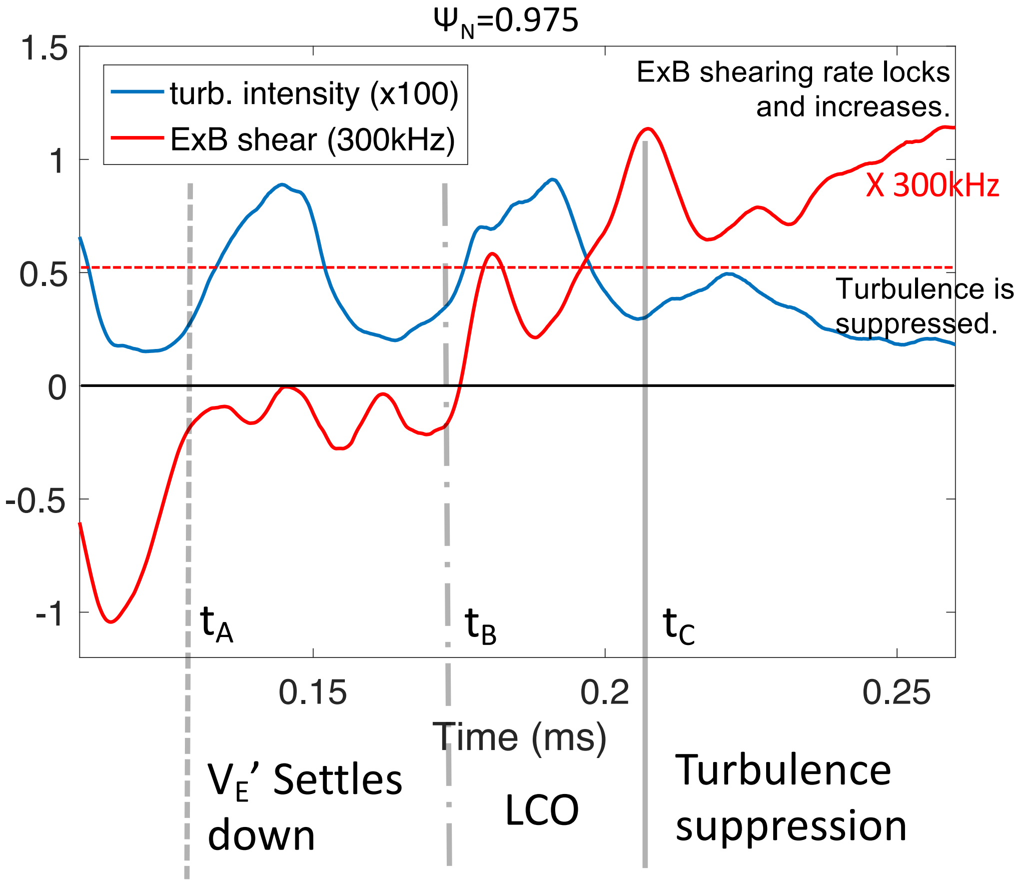
1. t_A=0.12ms, V_E' and L-mode turbulence settle down in edge layer
2. t< t_B =0.175ms, L-mode V_E' remains negative in the edge layer (ρ>0)
3. t~ t_B, something pushes the V_E' to >0 in the edge layer (ρ<0): Reynolds
4. t > t_C =0.2ms, V_E' locks into mean ExB shearing in the bifurcation layer: neoclassial





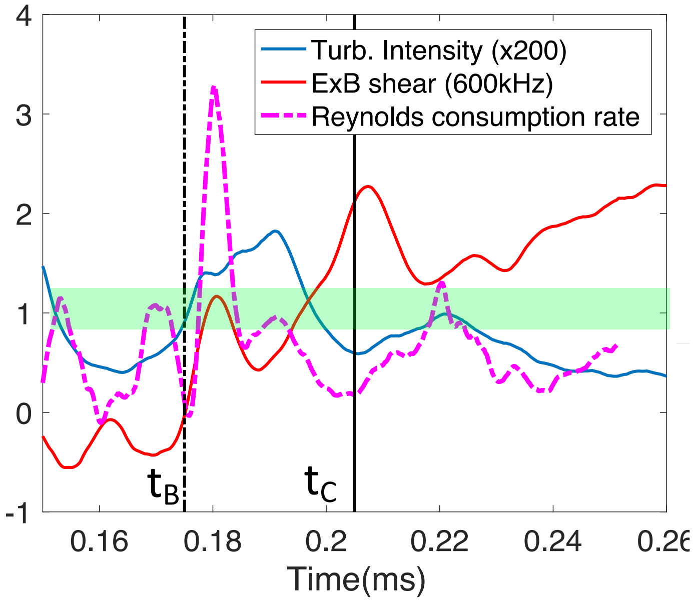
The bifurcation criterion is identified to be $V_E' > 150$ kHz

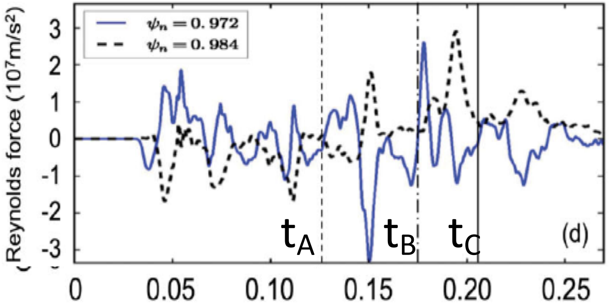
(Growth rate of dissipative TEMs [Romanelli PoP 2007]).

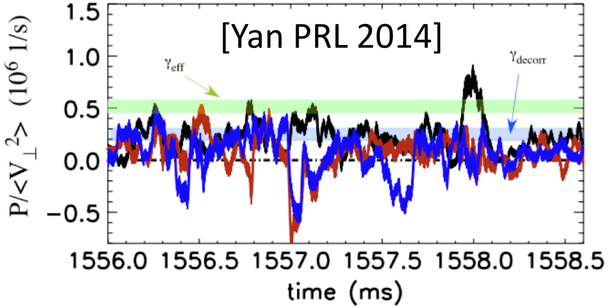


Reynolds stress induces the jump in ExB shearing at t_B

- **The normalized, turbulence Reynolds consumption rate $P = \langle\tilde{v}_r\tilde{v}_\theta\rangle V_E'/(\gamma_{\text{eff}}\tilde{v}_\perp^2/2)$ becomes peaked (> 3) in the beginning of the bifurcation action, but becomes ≤ 1 after that; and dies out eventually.**
- **What is then keeping the turbulence suppressed?**





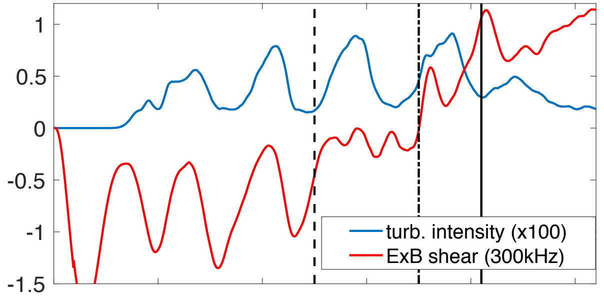


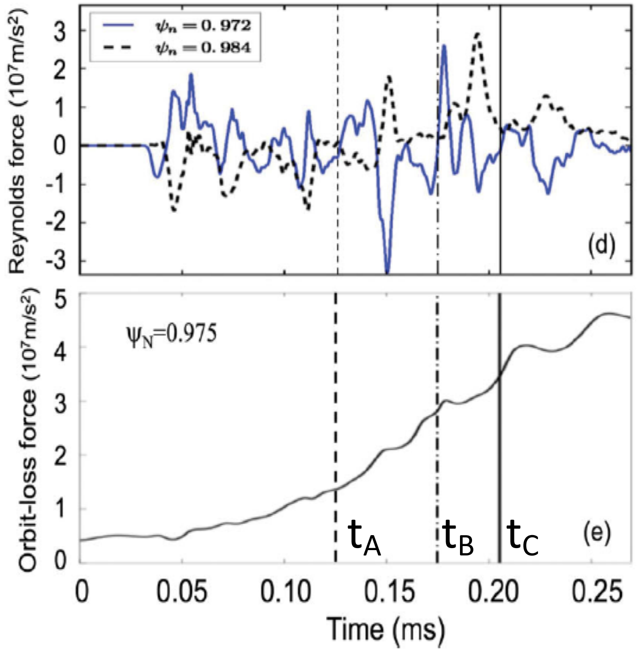
Various opinions exist on the role of Reynolds consumption:
- Kobayashi PRL13, Cavedon NF17, Stoltzfus-Dueck PoP16, Diallo NF17
- Yan PRL14, Schmidt NF17, Tynan NF13, Istvan PPCF14, papers by Diamond

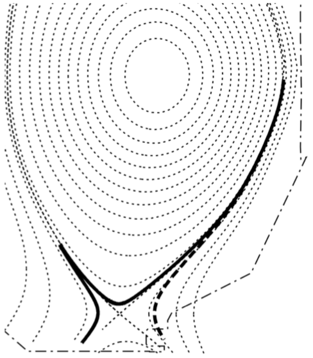
Similar behaviors of Reynolds consumption rate has been reported in EAST, C-Mod, and DIII-D experiments. [Manz PoP12, Tynan NF13, Yan PRL14]

The X-point orbit-loss [Chang PoP02, Ku PoP04] provides the answer

- The negative Reynolds force is canceled by orbit-loss force, and not effective.
- Orbit-loss force is pushing V'_{ExB} further to positive direction after 0.175 ms.
- This V'_{ExB} is keeping the turbulence suppressed after the bifurcation.

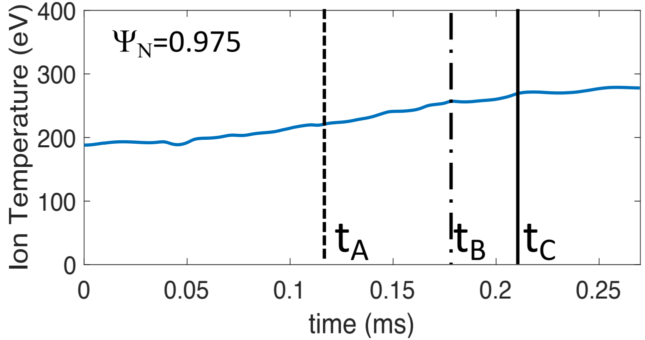






[S. Ku et al., PoP 2004]

Orbit loss force increases exponentially with T_i



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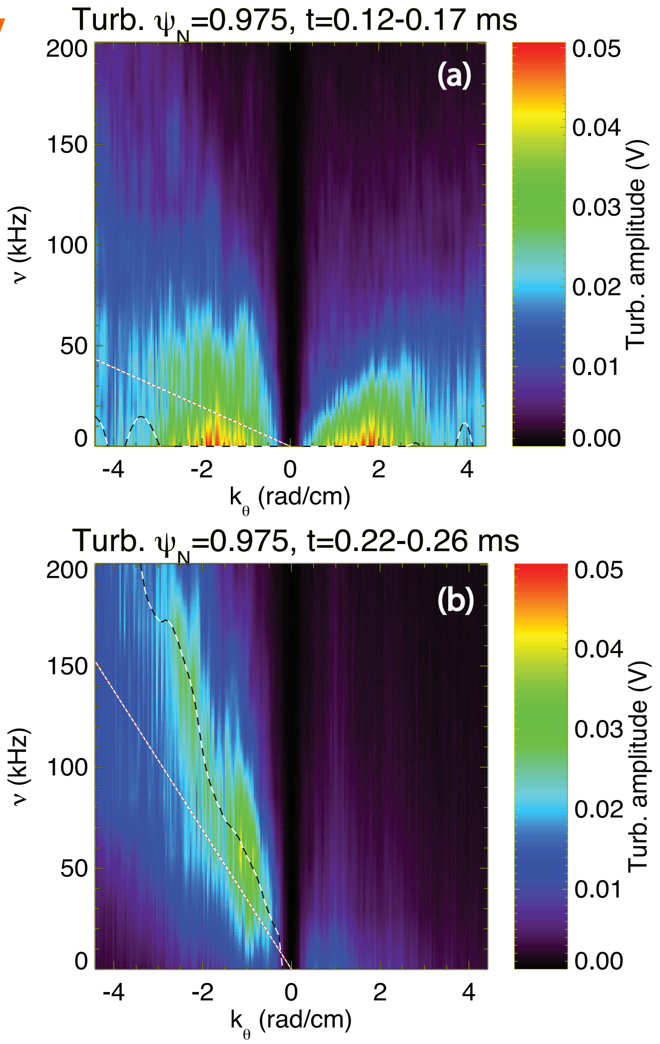
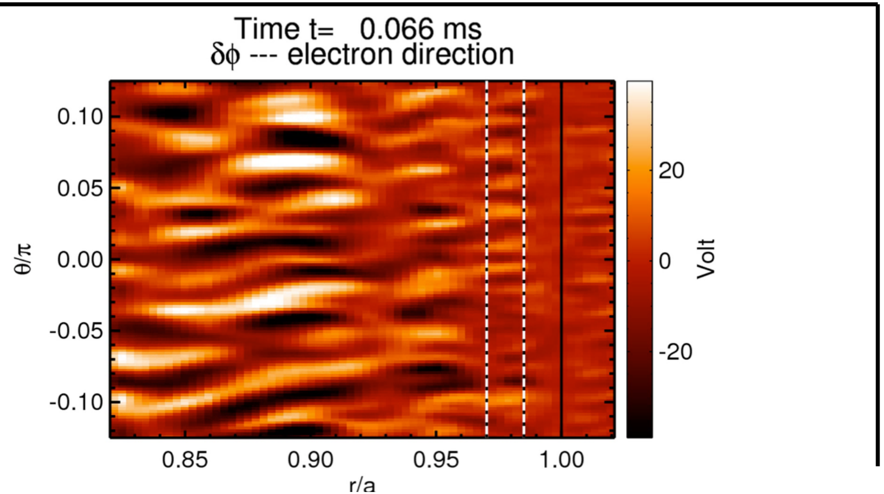
Electron modes disappeares immediately around the transition time

- Figures at right: Time-averaged wavenumber spectrum of the turbulence at Ψ_N=0.975
- Top: Before the first-phase $E\times B$ shearing starts (t=0.12 - 0.17 ms)
  - Both ion and electron modes exist
- Well into the second-phase shearing activities (t=0.22-0.26 ms)
  - Electron modes have disappeared
  - Ion modes are being sheared away to higher frequency
- Would be interesting to compare with experimental results.





Conclusion and Discussions

- A forced, fast L-H like bifurcation physics has been revealed under favorable magnetic drift condition, with transport suppression 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.
  - How will the geometry and plasma condition change their combination?
  - How will this affect $P_{L\text{-}H}$ in 15MA ITER that has small ρ_i/a?
- Fast suppression of electron modes by Reynolds-stress ExB shearing, followed by slower suppression of ion modes by neoclassical ExB shearing: experiments?

Not shown in this talk:

- Unfavorable ∇B case shows stronger GAMs. Weakly coherent modes appears during the bifurcation.
- Hydrogen isotope simulation gives higher GAM damping and weaker ExB shear