joint presentation:

Turbulent Eddy-Mediated Particle, Momentum and Vorticity Transport in the Edge of HL-2A Tokamak Plasmas

Micro-Macro connection for shear flow generation

Sawteeth trigger limit cycle oscillations and I-phase in the HL-2A tokamak

Temporal structure of shear flow

→ L-H transition!!!

details: Poster Session, Fri 8:30-12:30

P.H. Diamond et al, TH/P4-02, Wed 2:00PM-6:45PM
G.R. Tynan et al, EX/10-3, Sat 9:50AM

Turbulent Eddy-Mediated Particle, Momentum and Vorticity Transport in the Edge of HL-2A Tokamak Plasmas

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24th IAEA Fusion Energy Conference, October 8-13, 2012, San Diego, USA

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Outline (for Part I)

- **Motivation**
- **Frequency-domain nonlinear energy transfer**
- **Real space counterpart of frequency-domain energy transfer -> vortex dynamics & vorticity flux**
- **Summary**

Motivation

- **Low-frequency sheared flows play a key role in L-H transition (T. Estrada, 11’ PRL, G.D. Conway, 11’ PRL, L. Schmitz, 12’ PRL)**

Q1: Does turbulence drive the low-frequency shear flow?

- **Ensemble averaged stresses associated with vortex propagation can drive sheared flows (M. Xu, 11’ PRL, M. Xu, 12’ PRL, G.S. Xu 09’ NF)**

Q2: HOW does turbulence drive shear flow in configuration space? LINK B/W MICRO & MACRO!!!

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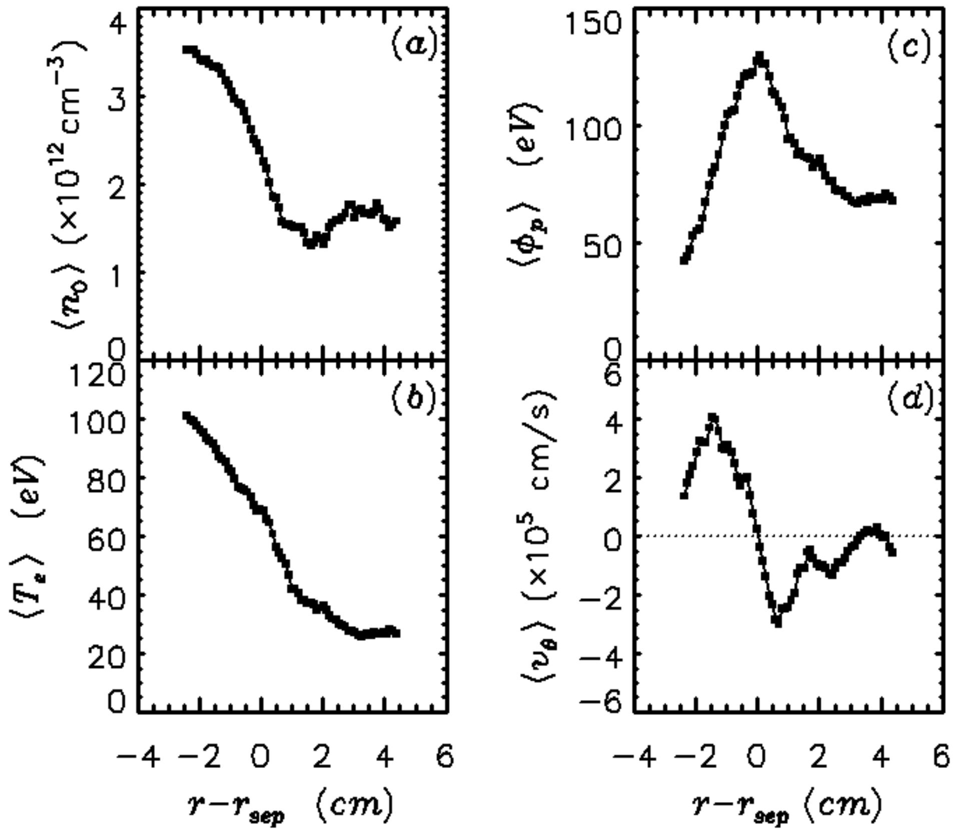
Profiles of time-averaged statistics



WHERE does the ZF energy come from?

→ direct measurement of energy transfer rate

- ✓ Strong shear flow exists near LCFS
- ✓ Driven by turbulence through Reynolds stress?

M. Xu et al., Turbulent eddy-mediated vorticity, momentum and partcle transport, IAEA, Oct. 8-13, 2012, San Diego, USA

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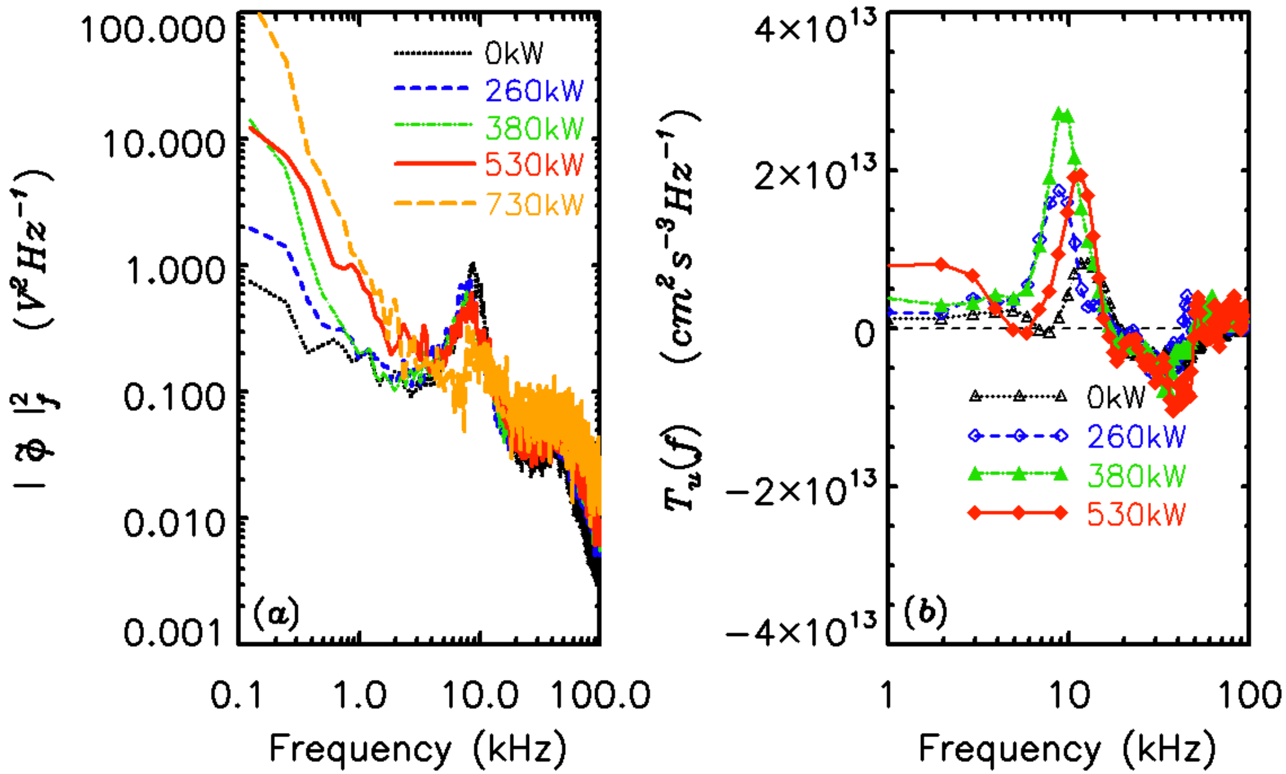
NL Energy Transferred into ZF/GAM; Stronger with Higher P_{ECH}



K. J. Zhao et al., PRL 06'

M. Xu et al., PRL 12'

✓ ***Turbulent energy is transferred into ZFs and GAMs***

Q: WHAT causes the energy transfer microscopically?

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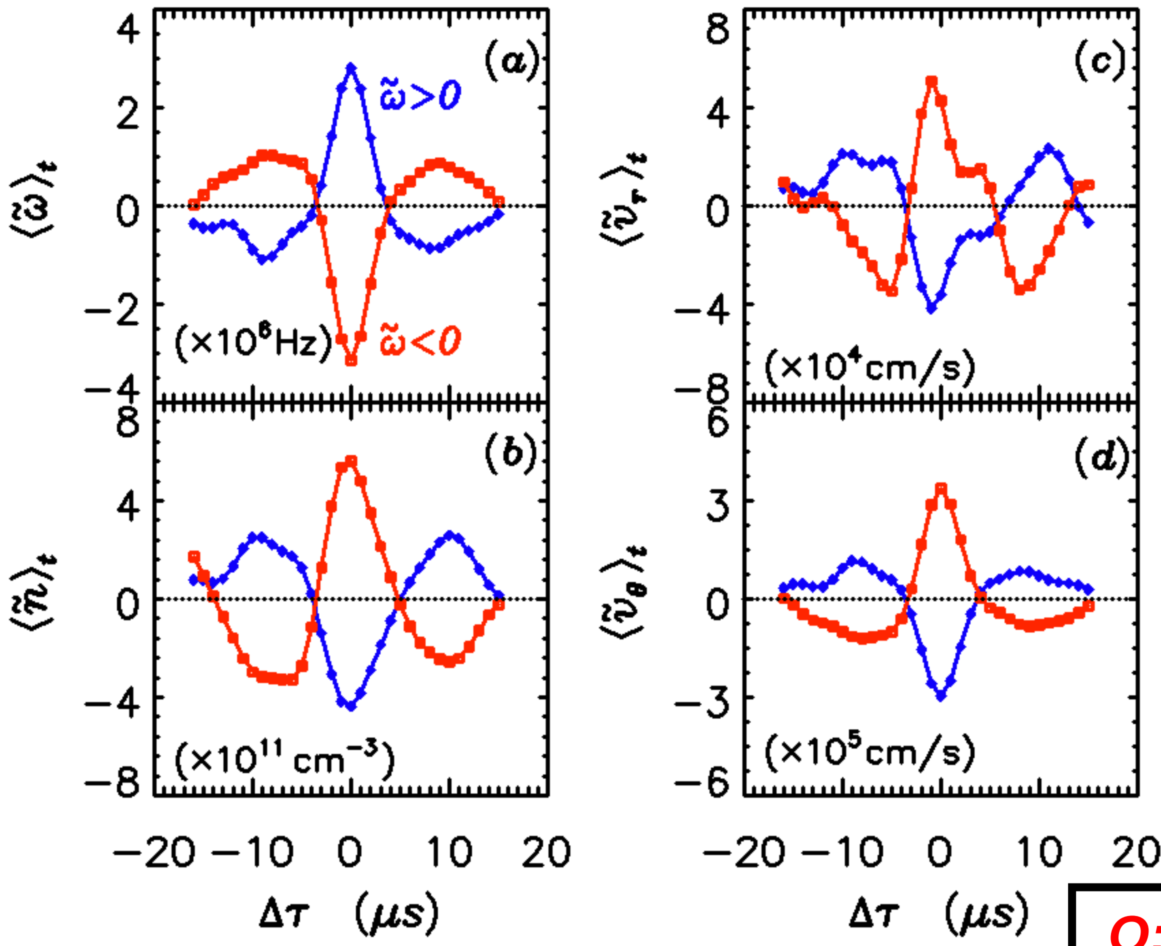
- ✓ Motivation
- ✓ Frequency-domain nonlinear energy transfer
- ➢ **Real space counterpart of frequency-domain energy transfer -> vortex dynamics & vorticity flux**
- ➢ Summary

Vortices mediate particle, momentum & vorticity transport



G. S. Xu et al., NF, 09'

Y. Kosuga et al., TH/P7-02

C. Hidalgo et al., EX/P3-22

Q: other locations?

M. Xu et al., Turbulent eddy-mediated vorticity, momentum and partcle transport, IAEA, Oct. 8-13, 2012, San Diego, USA

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Vortices propagation naturally leads to L-H

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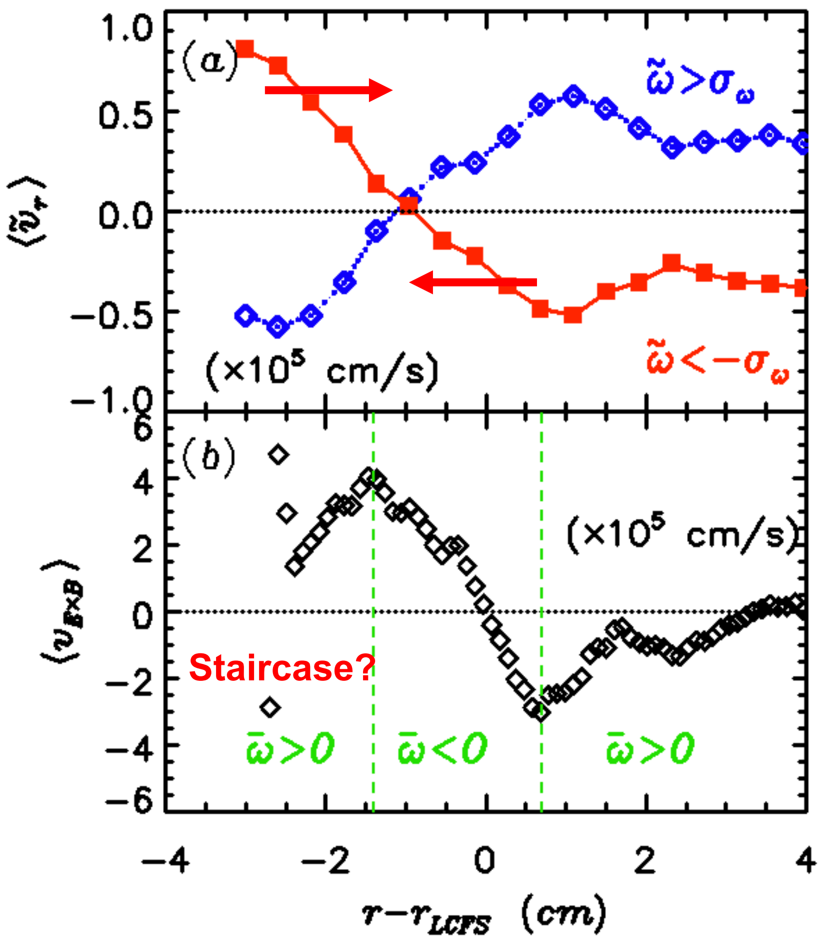

- **Negative vortices (i-diamagnetic) carry excessive POSITIVE momentum and concentrate around LCFS**
- **Positive vortices (e-diamagnetic) carry excessive NEGATIVE momentum and diverge away from around LCFS**
- **INFLUX OF POSITIVE MOMENTUM → strong ExB shear flow**
- **Voriticity drive gets stronger as heating increases**

→ L-H WITH SUFFICIENT HEATING!

Interaction b/w large-scale shear layer and vortices leads to the propagation of vortices.

P.H. Diamond et al, OV/P-03, Mon 2:00PM
P.H. Diamond et al., PPCF, 11'
G. Dif-Pradalier, et al., PRE 10'

SWIP HL-2A

M. Xu et al., Turbulent eddy-mediated vorticity, momentum and partcle transport, IAEA, Oct. 8-13, 2012, San Diego, USA

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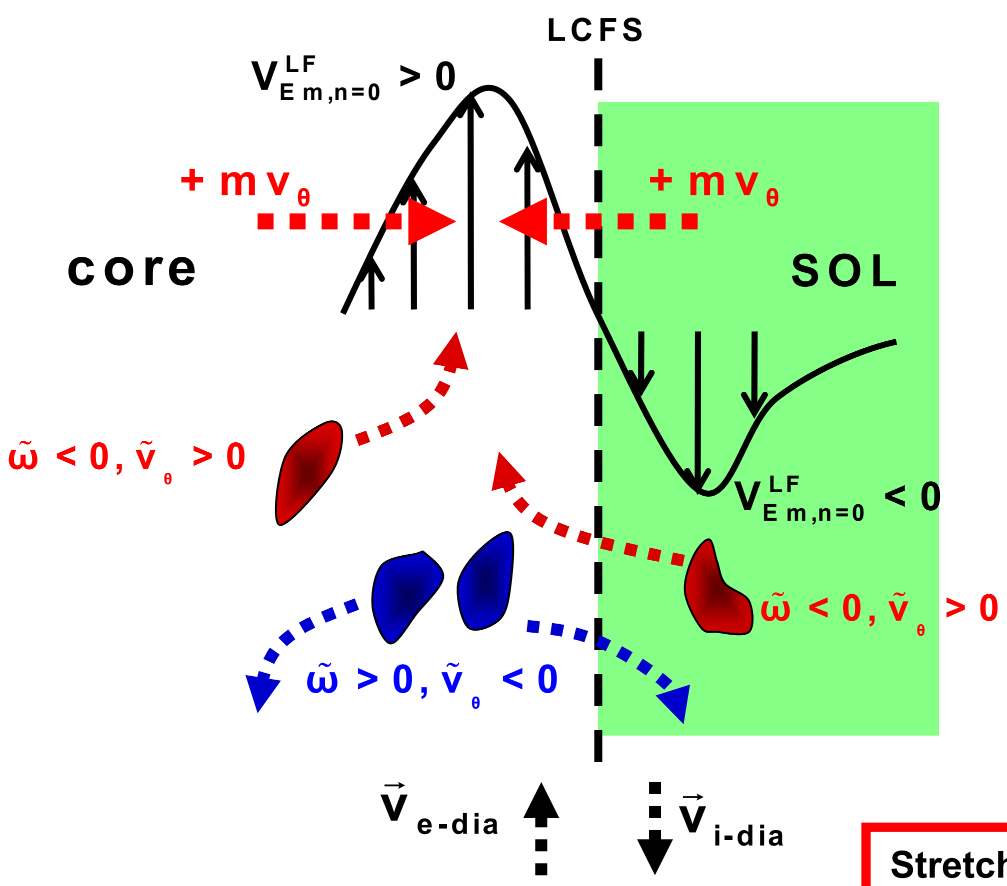
Message to take home



- ✓ Negative vortices (e-diamagnetic) carry excessive **POSITIVE** momentum and concentrate around LCFS
- ✓ Positive vortices (i-diamagnetic) carry excessive **NEGATIVE** momentum and diverge away from around LCFS
- ✓ **INFLUX OF POSITIVE MOMENTUM** → strong ExB shear flow
- ✓ Voriticity drive gets stronger as heating increases

→ **W/ SUFFICIENT HEATING!** → **stronger enough shear flow** → **L-H !!!**

Stretching process of eddies by shear flow is the same process that transfers energy from turbulence into shear flow.

M. Xu et al., Turbulent eddy-mediated vorticity, momentum and partcle transport, IAEA, Oct. 8-13, 2012, San Diego, USA

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Summary

✓ **Turbulence energy is transferred into both ZFs and GAMs. (Q1)**

✓ **Vortices propagation naturally drives shear flow and leads to L-H transition with sufficient heating. (Q2)**

✓ **Seems to be consistent w/ the model: turbulence drives shear flow → shear flow leads to L-H transition**

Solely based on statistics… robust?

TEST: Kick the ZF-turbulence system using heat pulse and see how it evolves over time.

Sawteeth trigger limit cycle oscillations and I-phase in the HL-2A tokamak

K. J. Zhao[1,2,3], P. H. Diamond [2,4], J. Q. Dong[1,8], L. W. Yan[1], M. Xu[4], G. Tynan[4], K. Miki[2], K. Itoh[5], S. I. Itoh[6], A. Fujisawa[6], Y. Nagashima[6], S. Inagaki[6], Z. X. Wang[7], L. Wei[7], W. Y. Hong[1], J. Cheng[1], Z. H. Huang[1], Q. Li[1], X. Q. Ji[1], Y. Huang[1], Yi. Liu[1], Q. W. Yang[1], X. T. Ding[1], X. R. Duan[1] and HL-2A team

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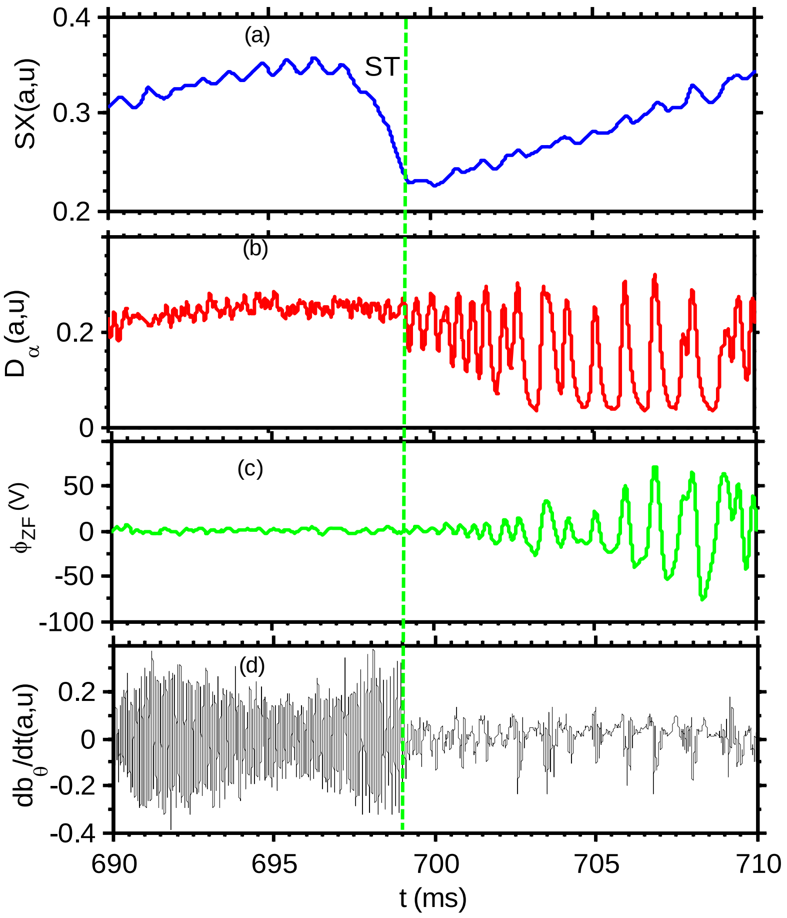
Motivation: Impulse respond of Turbulence-ZF System

✓The transition from low (L-mode) to high (H-mode) state occurs in various magnetic confinement fusion devices. [*F. Wagner et al., Phys. Rev. Lett,* ***49****, 1408(1982)].*

✓ The L-H transition and phenomenology for input power slowly increasing shows that there is an intermediate, quasi-periodic process, called the I-phase or the limit cycle oscillation (LCO). Here, turbulence, zonal flows, mean flows couple with the pressure gradient. The zonal flow, even being a single burst, can trigger the transition by regulating turbulence level and associated transport until the mean flow is high enough to suppress the remaining turbulence and sustain the steep pressure gradient. [*E.-J. Kim and P.H. Diamond, Phys. Rev. Lett , 90, 185006 (2003); P. Manz, et al., PoP 19 072311 (2012)].*

✓ The trigger physics, which are crucial for International Tokamak Experimental Reactor (ITER) to access the H-mode, are still not understood. A key point is clear that the I-phase power threshold controls to access H-mode

Limit cycle oscillations are triggered by Sawtooth heat pulses

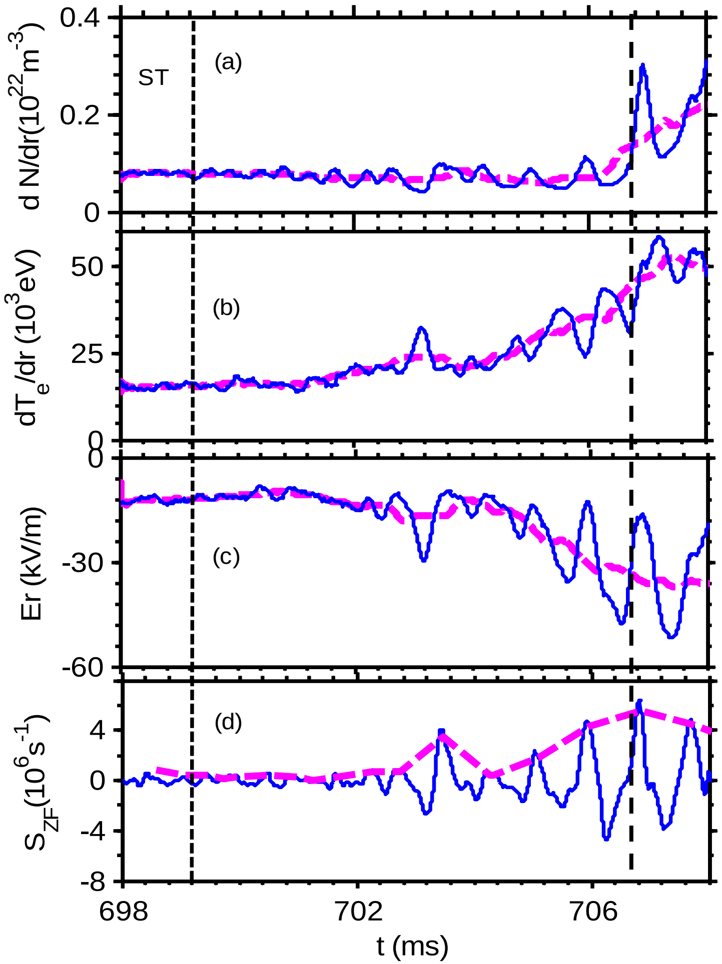


✓ **Following sawtooth crash, heat pulse propagate to the edge and modulate the gradient, first the MHD drops sharply, then Dą signals and zonal flows oscillate at the same frequency.**

✓ **During the limit cycle oscillation, Dą signals drop, and zonal flow intensity increases and its frequency decreases.**

F. Wagner et al., Phys. Rev. Lett, 53, 1453(1984).

Time evolutions of gradients, Er, and zonal flow shear



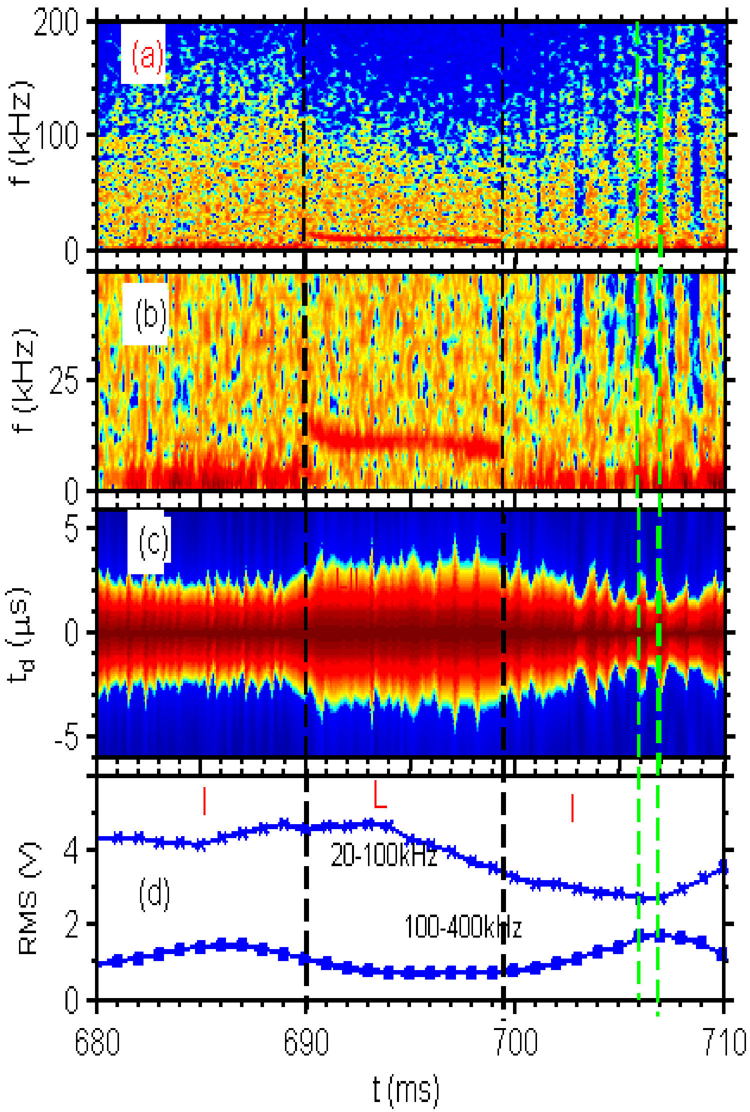
Following sawtooth crash, density gradient, electron temperature gradient, E_r, and zonal flow shearing rate all start to oscillate.

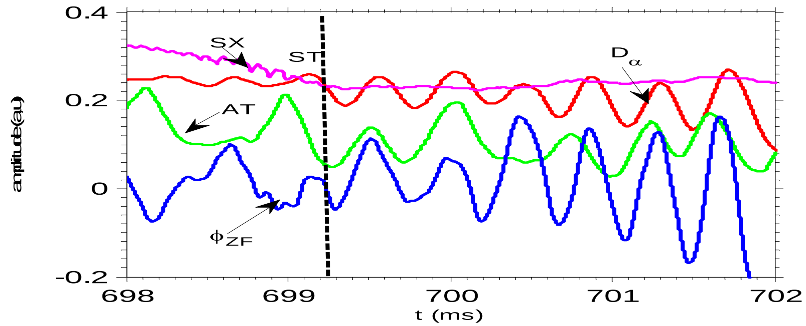
The E_r , temperature gradient firstly rise at ~701ms, then zonal flow shearing rate increase ~702.5ms. But the density gradient increases significantly at ~706.7ms.

The density gradient oscillations (m/n=1/0 mode number) are well anti-correlated with temperature gradient oscillations.

The larger flow oscillations result in more negative mean flow (pink dashed line).

Characteristics of turbulence during LCOs





The intensity of bursty turbulence in I-phase is significantly stronger than that of the L-mode. The result suggests that higher intensity of bursty turbulence drives larger zonal flows.

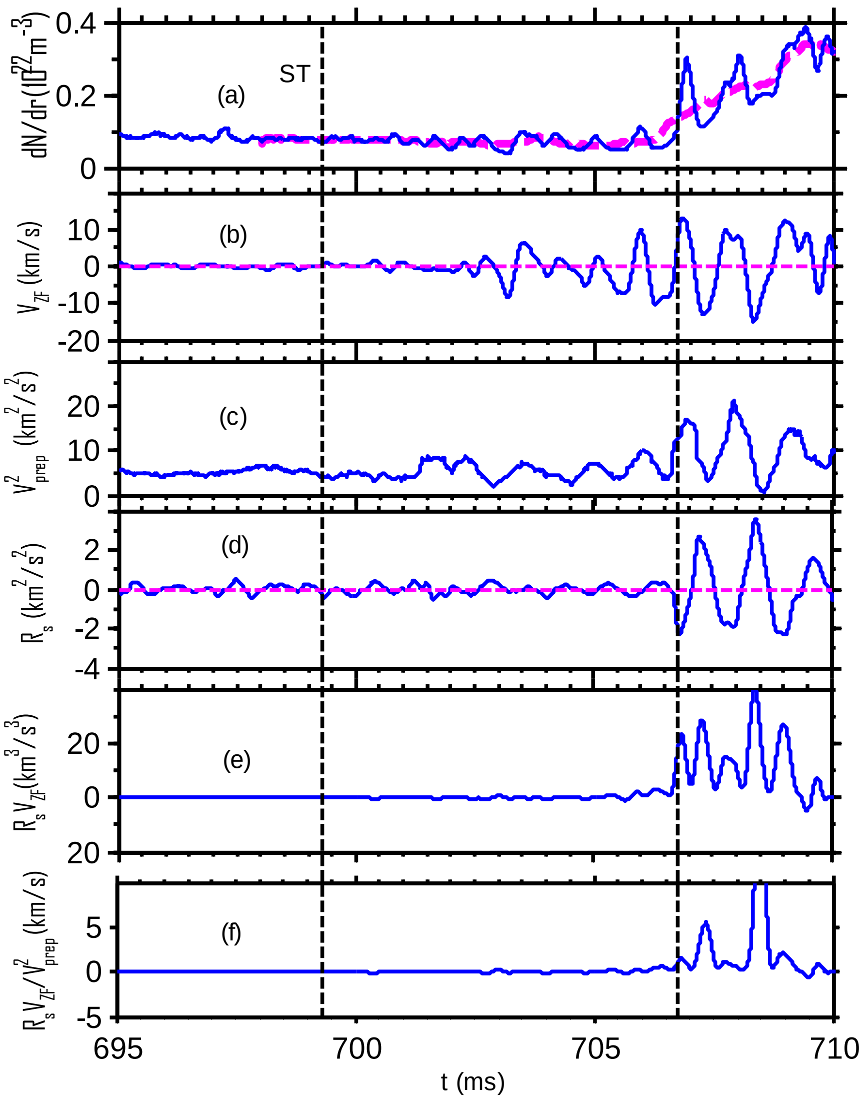
Zonal flows mainly modulate turbulence in the frequency band of ~20-100 kHz; but bursty turbulence with frequency more than 100 kHz has more power.

The lifetime of turbulence during the I-phase is shorter than that of the L-mode and becomes intermittent.

During the I-phase, the MHD potentials drop, while MHD potentials came up again in the L-mode. The observation suggests that the MHDs compete with zonal flows, and possibly result in the L-I back transition.

Zonal flows lag relative to the turbulence about $\pi/2$ which differs from that observed in L-mode

Power transfer from turbulence into zonal flows

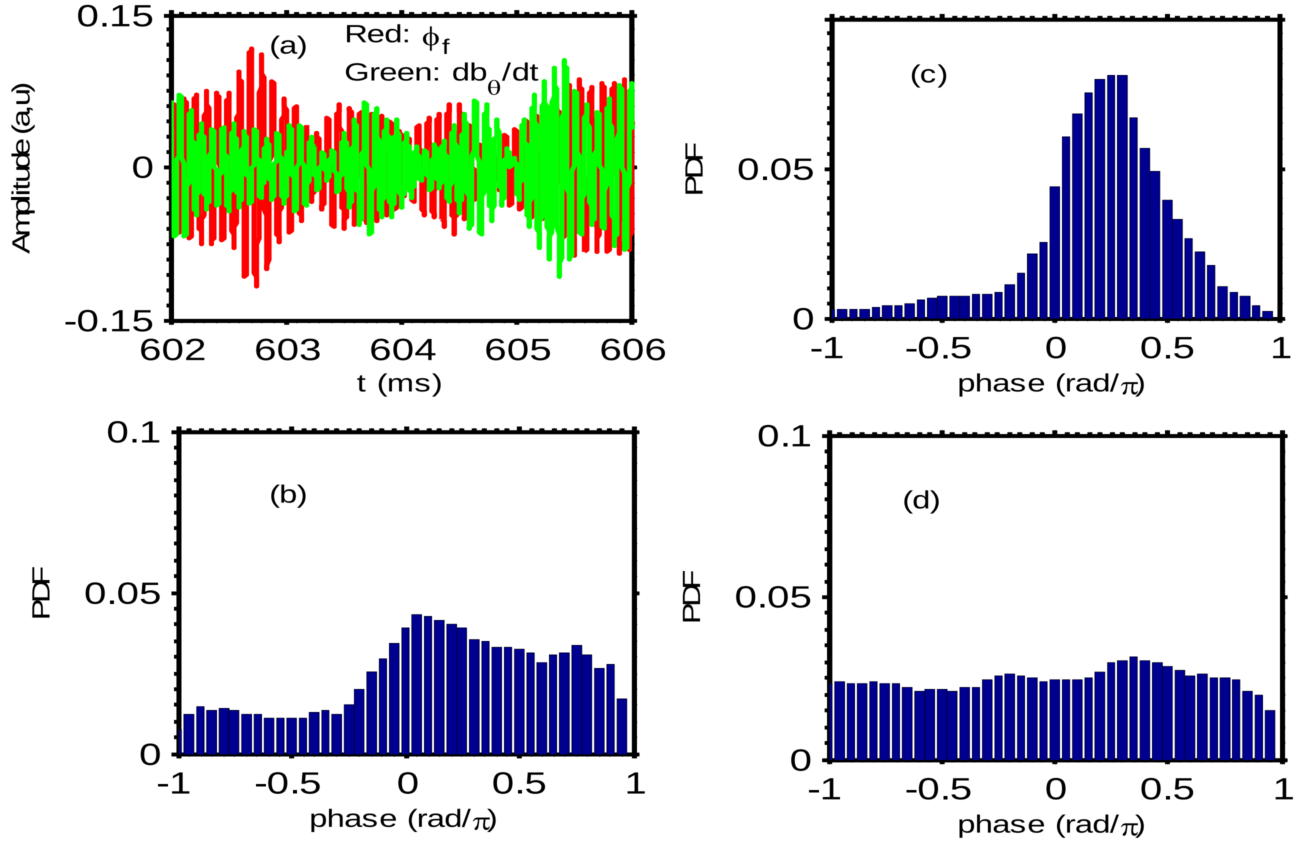


As the energy transfer production reaches its peak, the absolute amplitudes of zonal flows reach their maximum. And at the same time, the rates of energy transfer also peaks. The result suggests that the power transfer is from turbulence into zonal flows.

The more energy transfer production means that the stronger interaction between turbulence and zonal flows exists The stronger interaction drives the higher zonal flows, then mean flows become more negative and sustain steeper gradients. While, the zonal flow himself also modulates the oscillatory gradients.

Turbulent stresses also work on the GAM and the power transfer is from turbulence into the GAM.

MSEFs* are phase-locked with magnetic islands



The peak of PDF of relative phase shifts is located at 0.3 π .

No peak is observed without synchronization.

* MSEF = Meso-scale Electric Field fluctuation

Summary

Sawtooth heat pulses propagate to the plasma boundary and result in the modulation gradients, then the transition from L-mode to LCOs occurs. The zonal flow and Da signal oscillate at the same frequency.

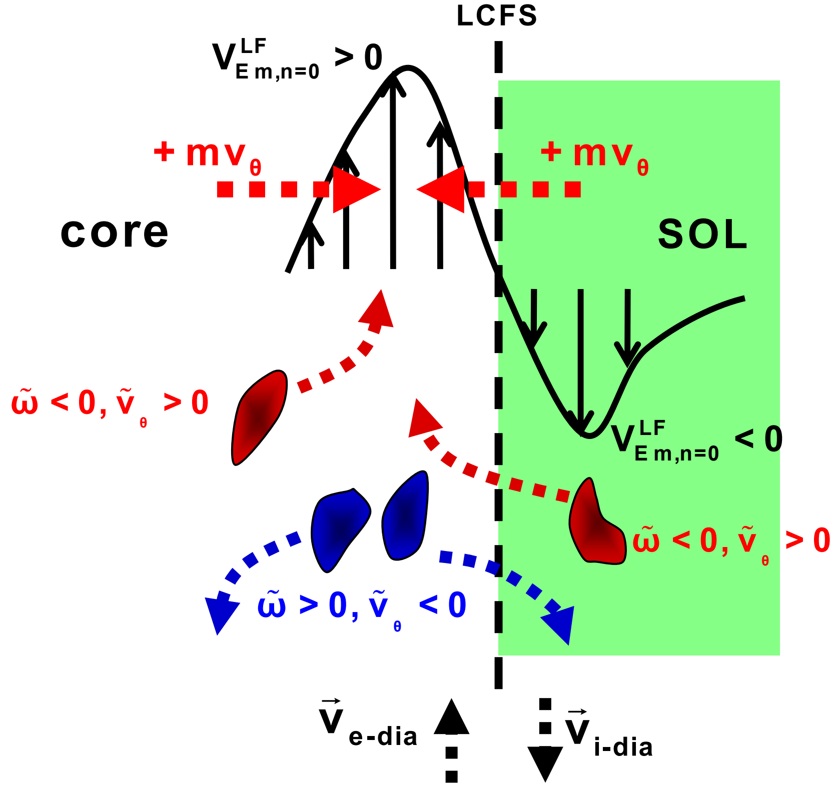
During I-phase, zonal flows and turbulence couple with the edge gradient oscillations and the structures of gradient oscillations are identified as the m/n=1/0 mode.

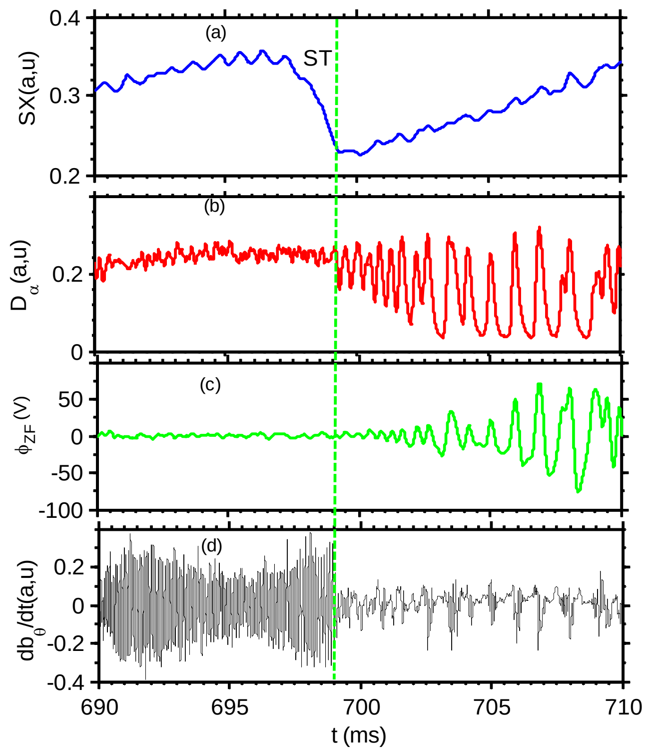
The intensity of turbulence bursts in the I-phase is stronger than those observed in L-mode plasmas. The statistical characteristics of turbulence show that the zonal flow mainly regulates turbulence in the frequency band of ~20-100 kHz, and the high frequency turbulence (>100 kHz) has more power than that in the L-mode. The estimated lifetime of turbulent eddies in the LCO is shorter than that of the L-mode and also becomes bursty.

The analyses of the time resolved power transfers between turbulence and zonal flows clearly show that power is transferred from turbulence into zonal flows during the I-phase and from turbulence into geodesic acoustic modes in ohmic plasmas.

Stronger nonlinear interaction drives the higher zonal flows, so mean flows become more negative and sustain steeper gradients. The zonal flow himself also modulates the oscillatory gradients.

Summary of the joint presentation





- ✓ **Vortices propagation naturally drives shear flow and leads to L-H transition with sufficient heating**
- ✓ **Sawtooth heat pulse can enhance zonal flow → triggers L-I transition**

P.H. Diamond et al, TH/P4-02, Wed 2:00PM-6:45PM
Y. Kosuga et al., TH/P7-02, Fri 8:30AM-12:30PM

T. Estrada, et al., EX/10-2, Sat 8:50AM
G.R. Tynan et al, EX/10-3, Sat 9:50AM
G.S. Xu et al., EX/11-1, Sat 10:45AM

backups

Vorticity drive gets stronger as heating increases

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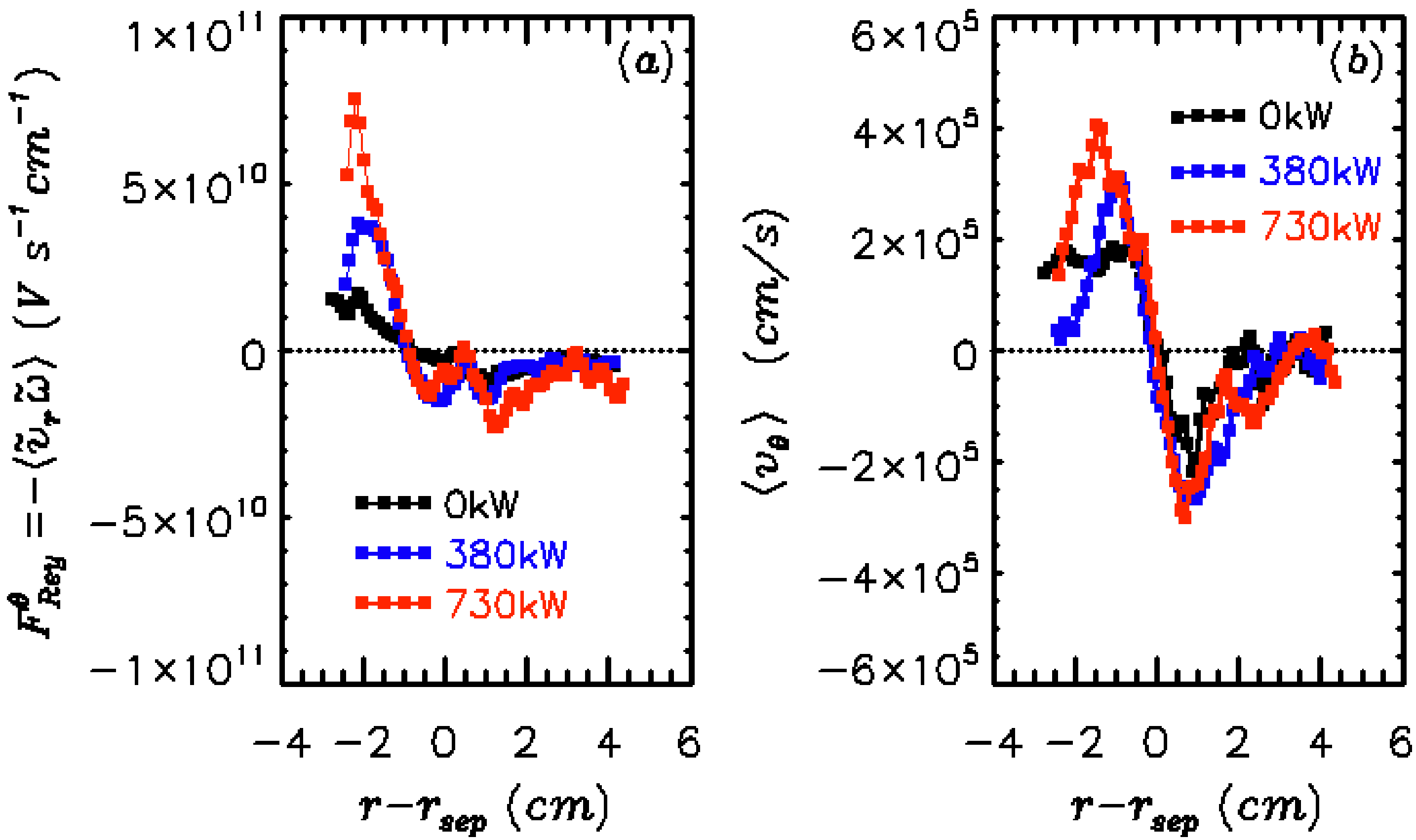
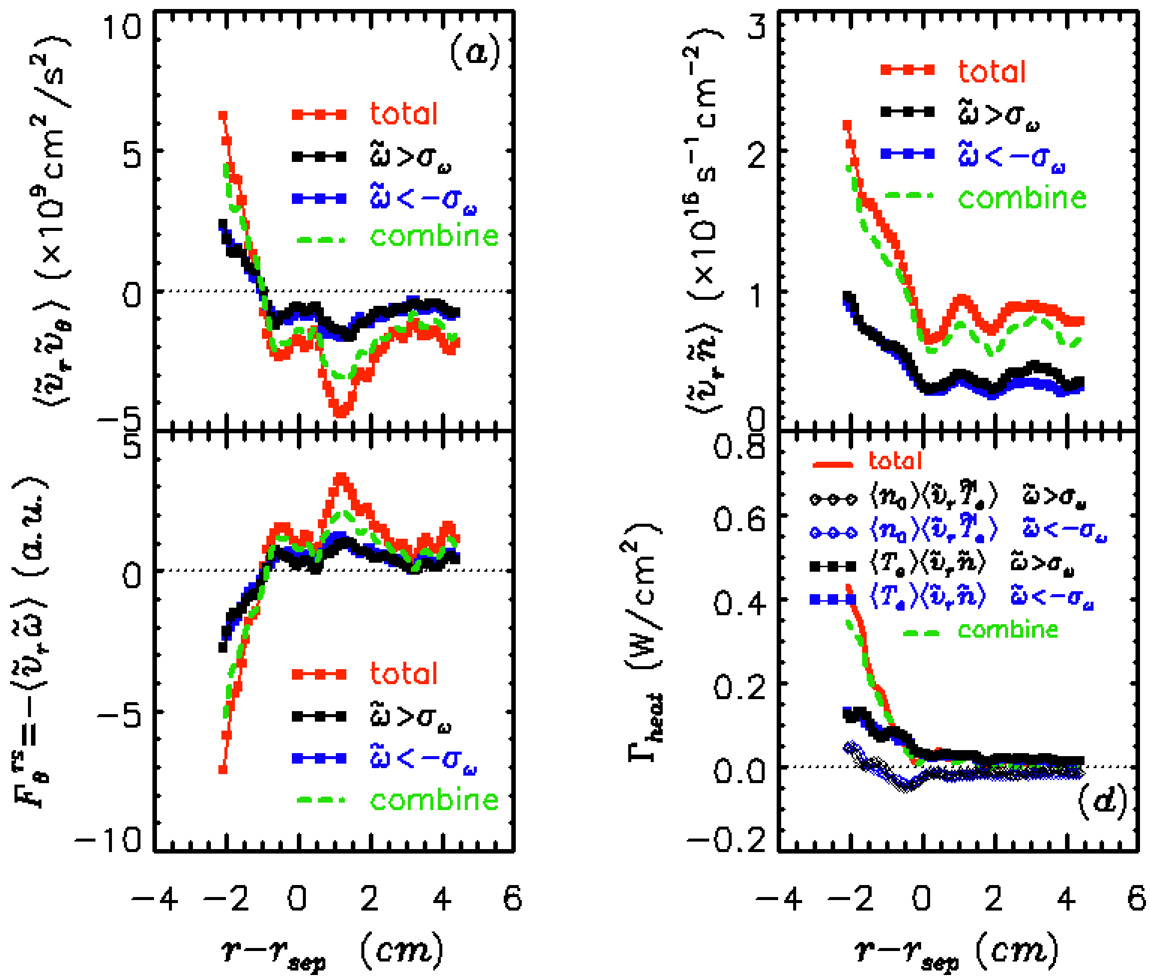


Vortices propagation naturally leads to a strong shear flow → L-H transition!

Transport is dominated by large eddies



M. Xu et al., Turbulent eddy-mediated vorticity, momentum and partcle transport, IAEA, Oct. 8-13, 2012, San Diego, USA

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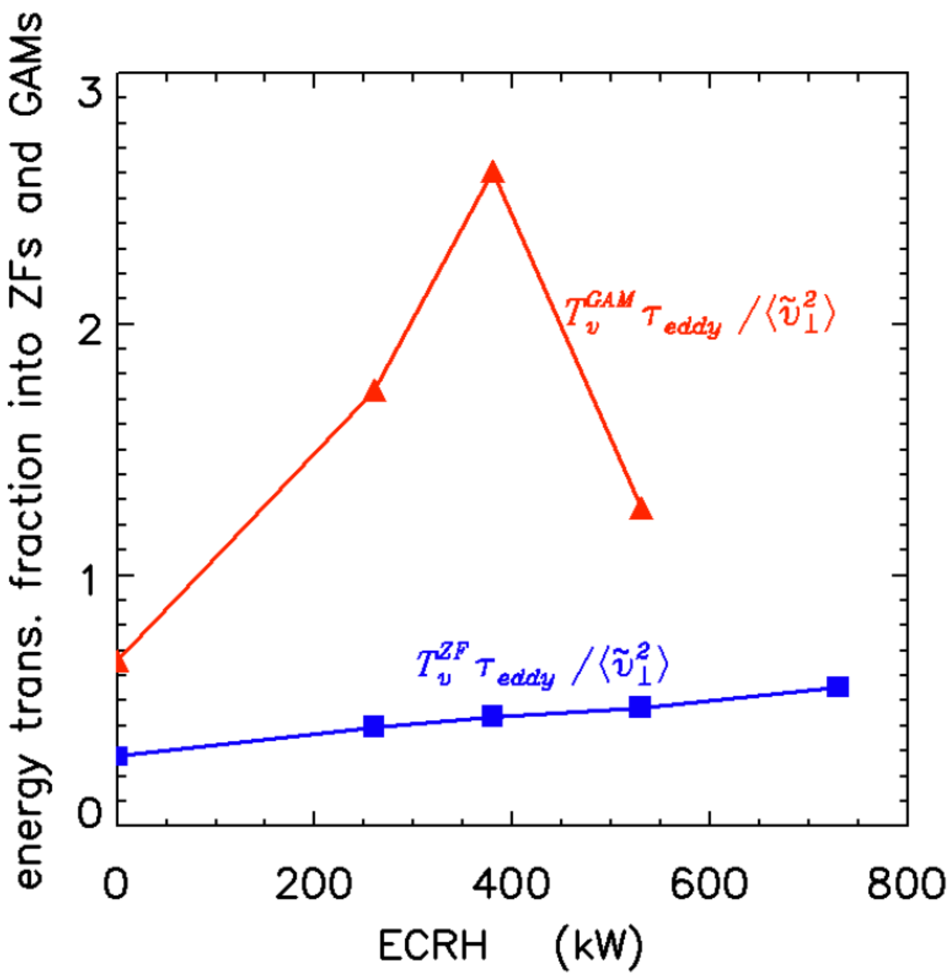
ZF and GAM competes for extracting energy out of turbulence

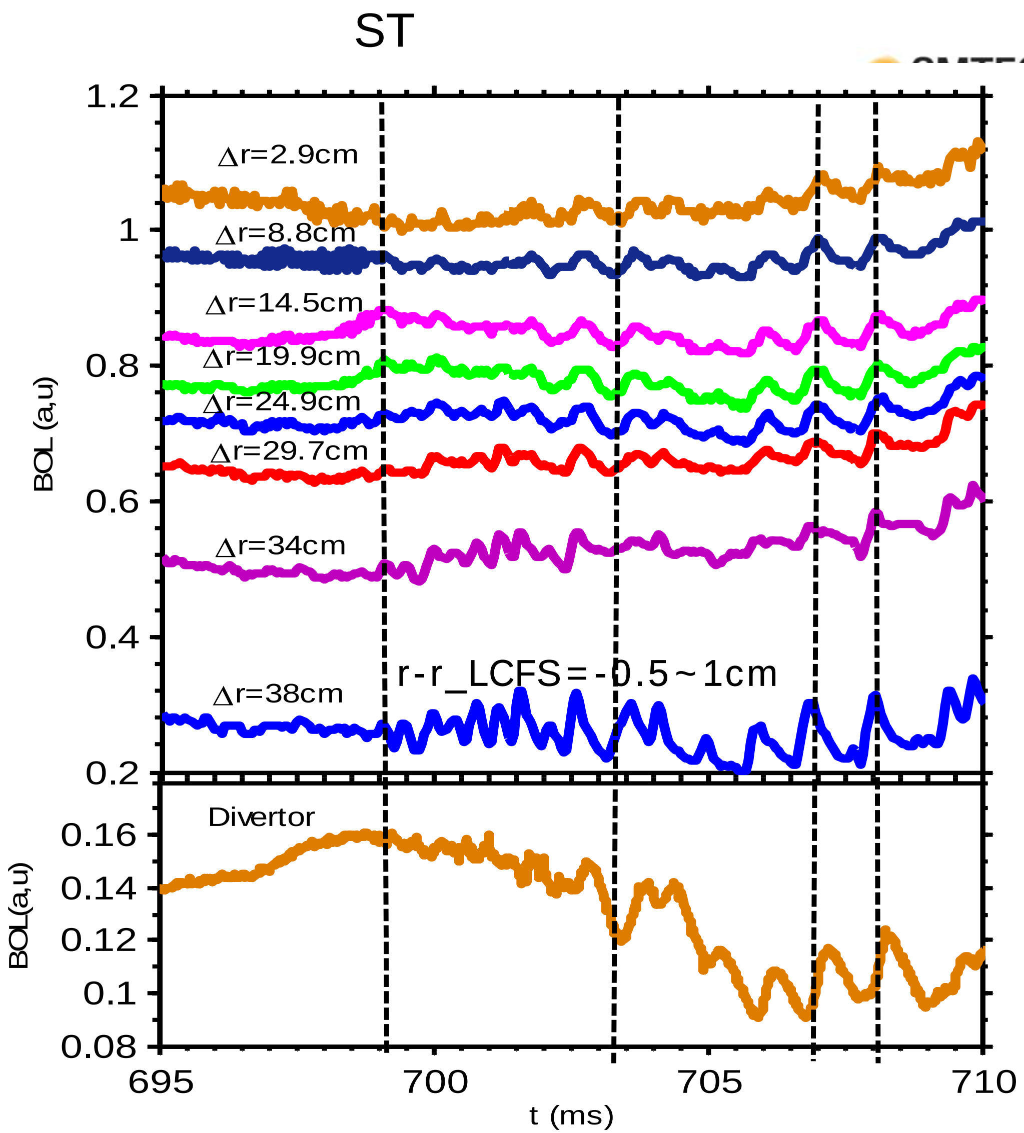


Total energy transferred within a turbulence characteristic time (25 microsecond was used) normalized by total turbulent energy.

K. Miki and P. H. Diamond, Nucl. Fusion 51, 103003 (2011)

M. Xu et al, PRL 2012

Time evolutions of Bolometer signals



Following sawtooth crash, edge heat radiation gradient increases and becomes oscillatory.

The heat radiation intensity decreases in divertor chamber, indicating confinement improvement.

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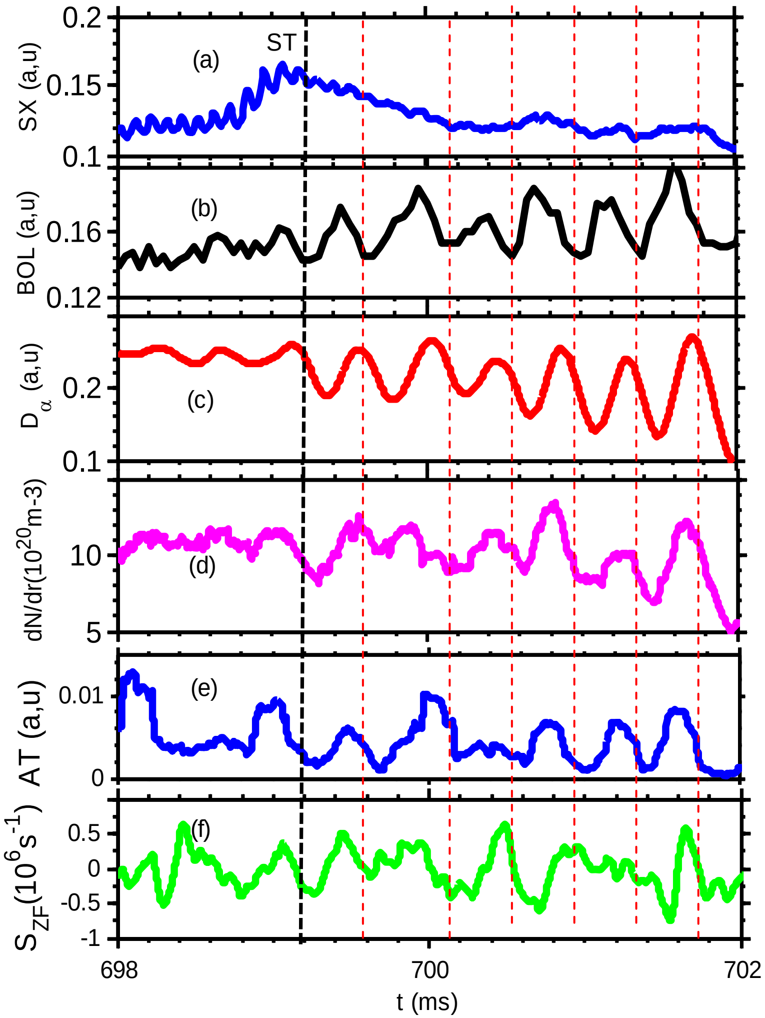
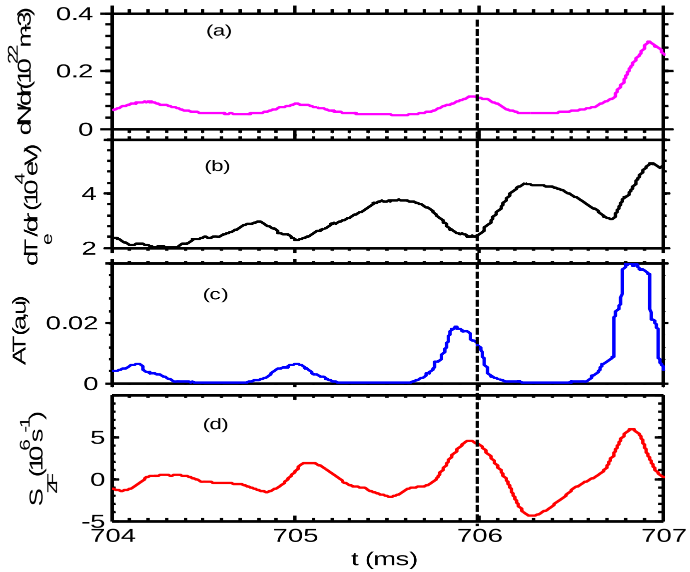
Time evolution of turbulence, density gradient, heat radiation, and zonal flow shearing rates

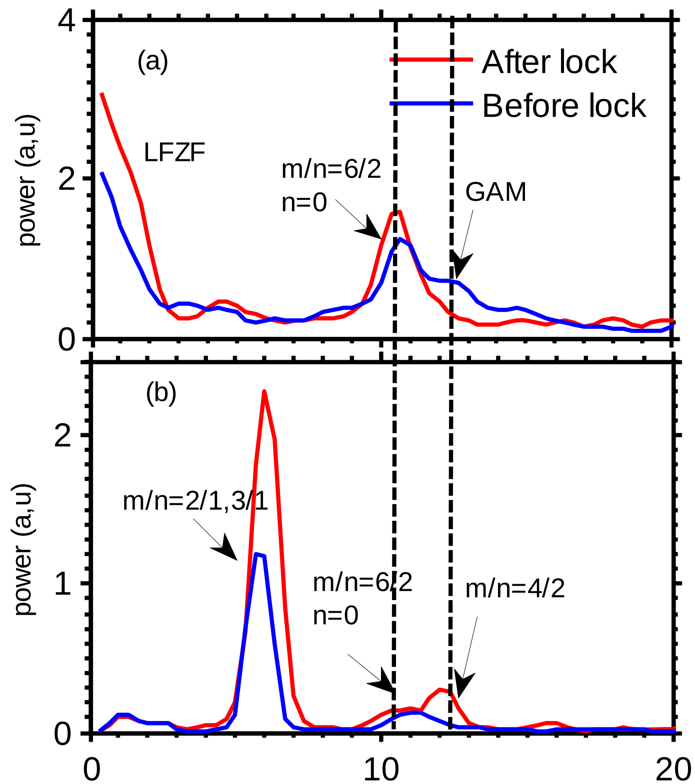


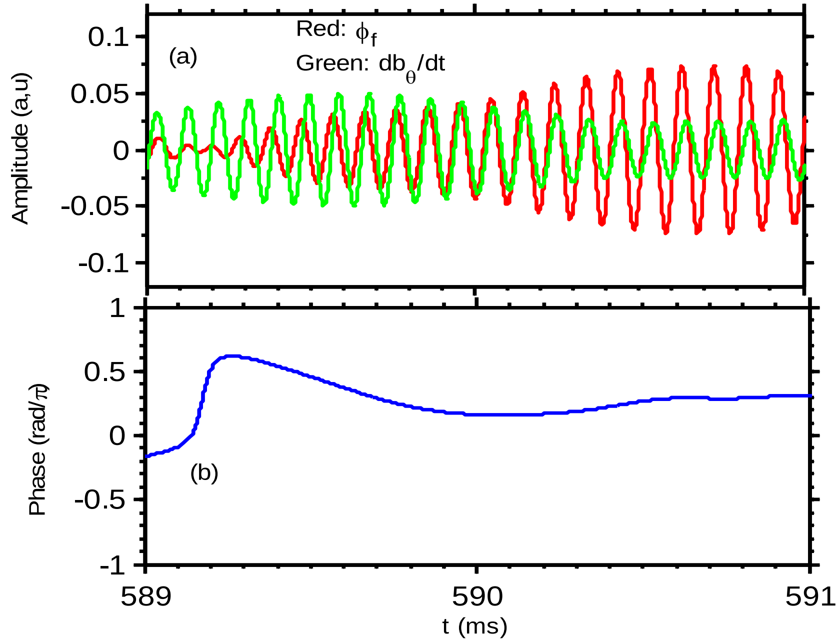


Following sawtooth crash, the density gradient collapses, turbulence intensity decreases and the zonal flow shearing rate increases; then turbulence and zonal flow shears all couple with gradient oscillations.

Turbulence feed zonal flow with energy, while zonal flow shear sustains the oscillatory gradients. Thus, the feedback loop for cycle exists among turbulence, zonal flows, and oscillatory gradients.

Synchronization of GAM and magnetic island





- GAM frequency gradually decreases and synchronizes with magnetic island.
- The phase lock between magnetic islands and GAM results in the generation of meso-scale electric fluctuation (MSEF), which peaks at q=3 and has both electric and magnetic field fluctuations at 10.5kHz.