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Spatiotemporal and spectral structure of the turbulence-flow interaction at the L-H transition in TJ-II plasmas

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Introduction

In the **TJ-II stellarator L-H transitions** are achieved in pure NBI heated plasmas

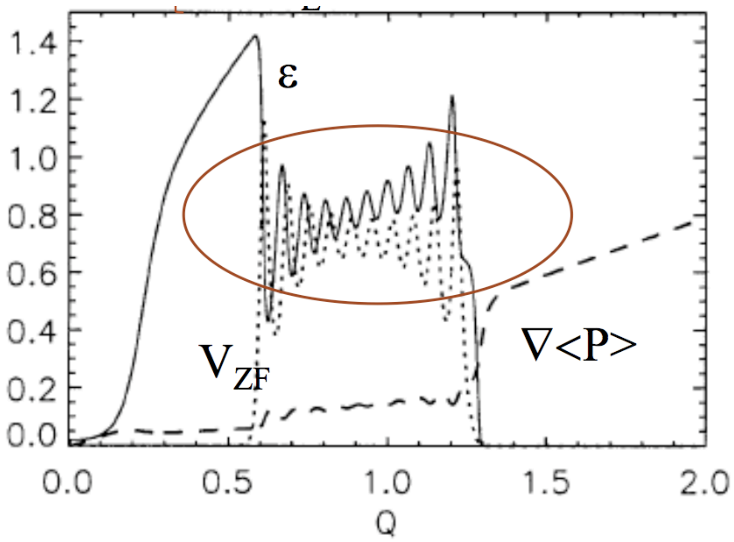
Close to the L-H transition threshold conditions the so-called **Intermediate phase (I-phase)** is observed: a coupling between turbulence and flows following a predator-prey relationship

This coupling is the basis for L-H transition models based on turbulence induced zonal flows:

E.-J. Kim and P.H. Diamond. PoP **10**,1698 (2003)

Zonal flows trigger the transition until the mean shear flow is high enough to suppress turbulence effectively

Due to the self-regulation between turbulence and zonal flows, the transition is marked by an oscillatory behaviour with a predator-prey relationship between turbulence and zonal flows

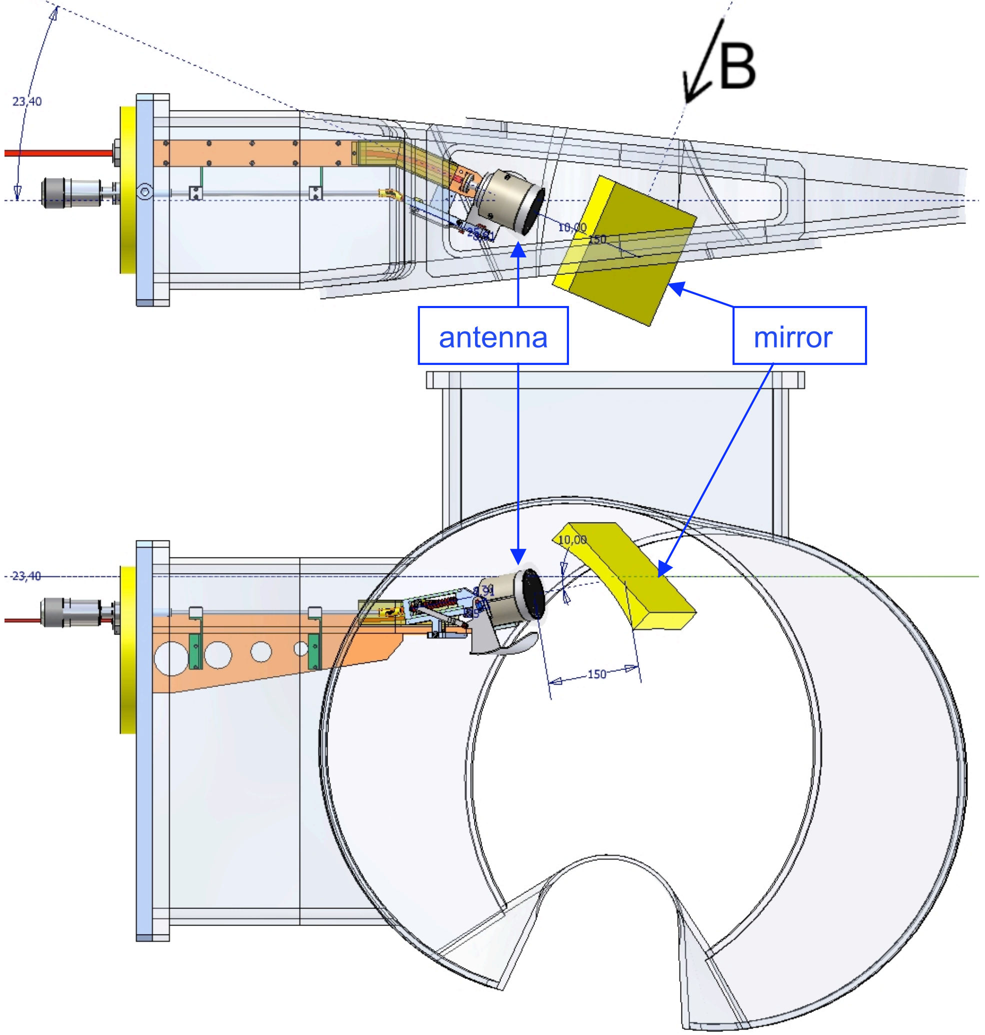


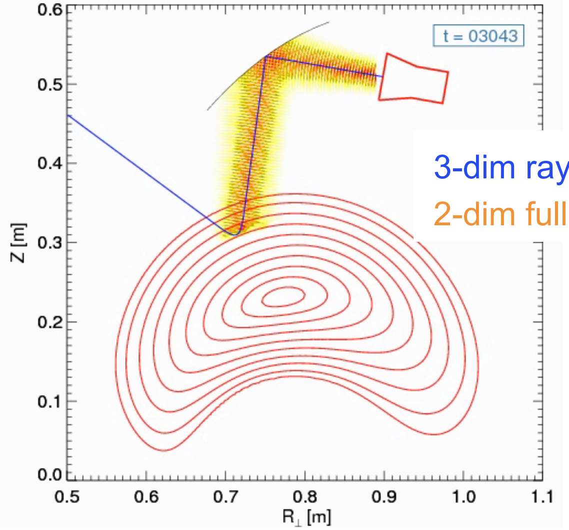
TJ-II **Doppler reflectometer** allows the measurement of turbulence and flows with very good spatial and temporal resolution [T. Happel *et al.*, RSI **80**, 073502 (2009)]

Experimental characterization of turbulence-flow interaction during the I-phase: temporal dynamics, spatial evolution and spectral structure

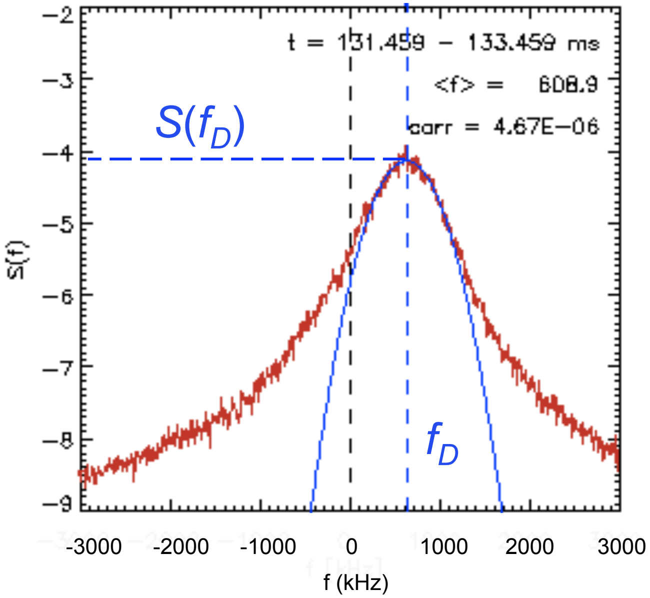
TJ-II Doppler reflectometer

T. Happel *et al*., RSI **80**, 073502 (2009)





3-dim ray-tracing and
2-dim full-wave codes



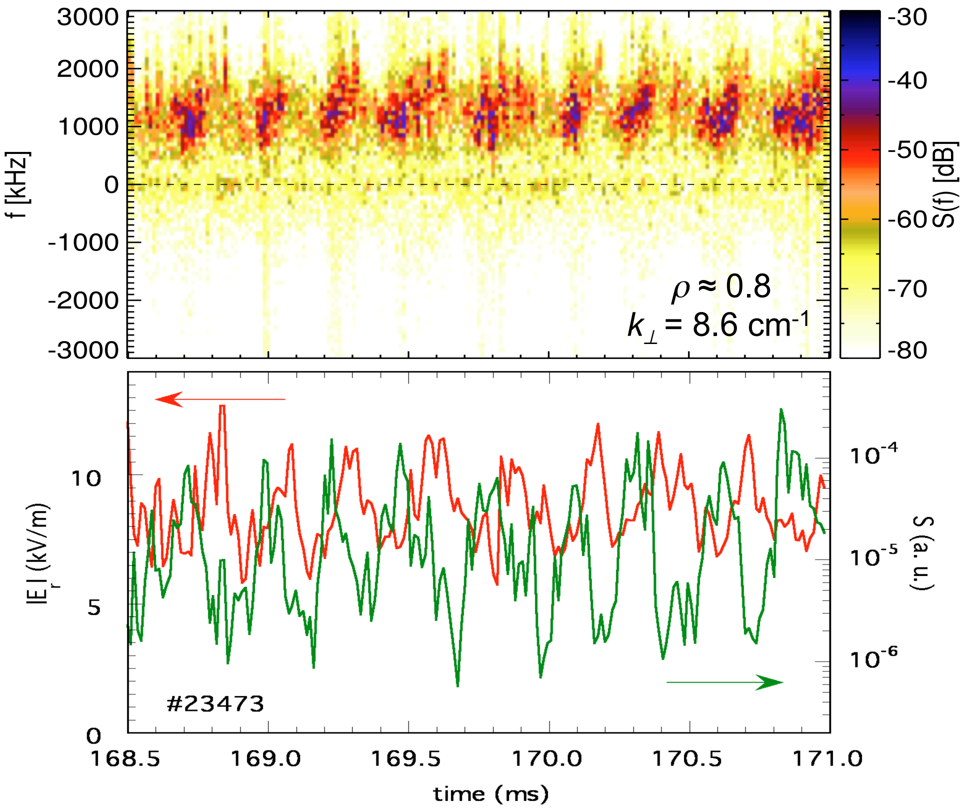
Two frequency hopping systems: f: 33 – 50 GHz, X–mode

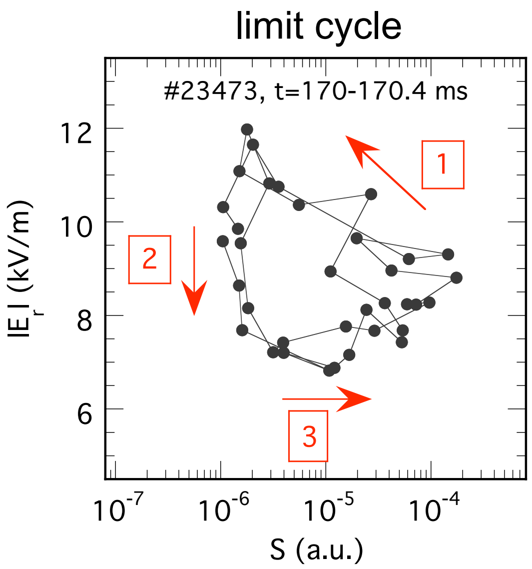
L. Cupido *et al* RSI **75**, 3865 (2004)

n_e: 0.3 – 1.4 10^{19} m^{-3}

$\tilde{n}_e$, *ExB* flow and *ExB* flow-shear can be measured with good spatiotemporal resolution at $k_\perp$: 3 – 15 cm^{-1}

Temporal dynamics of turbulence and flows at the I-phase





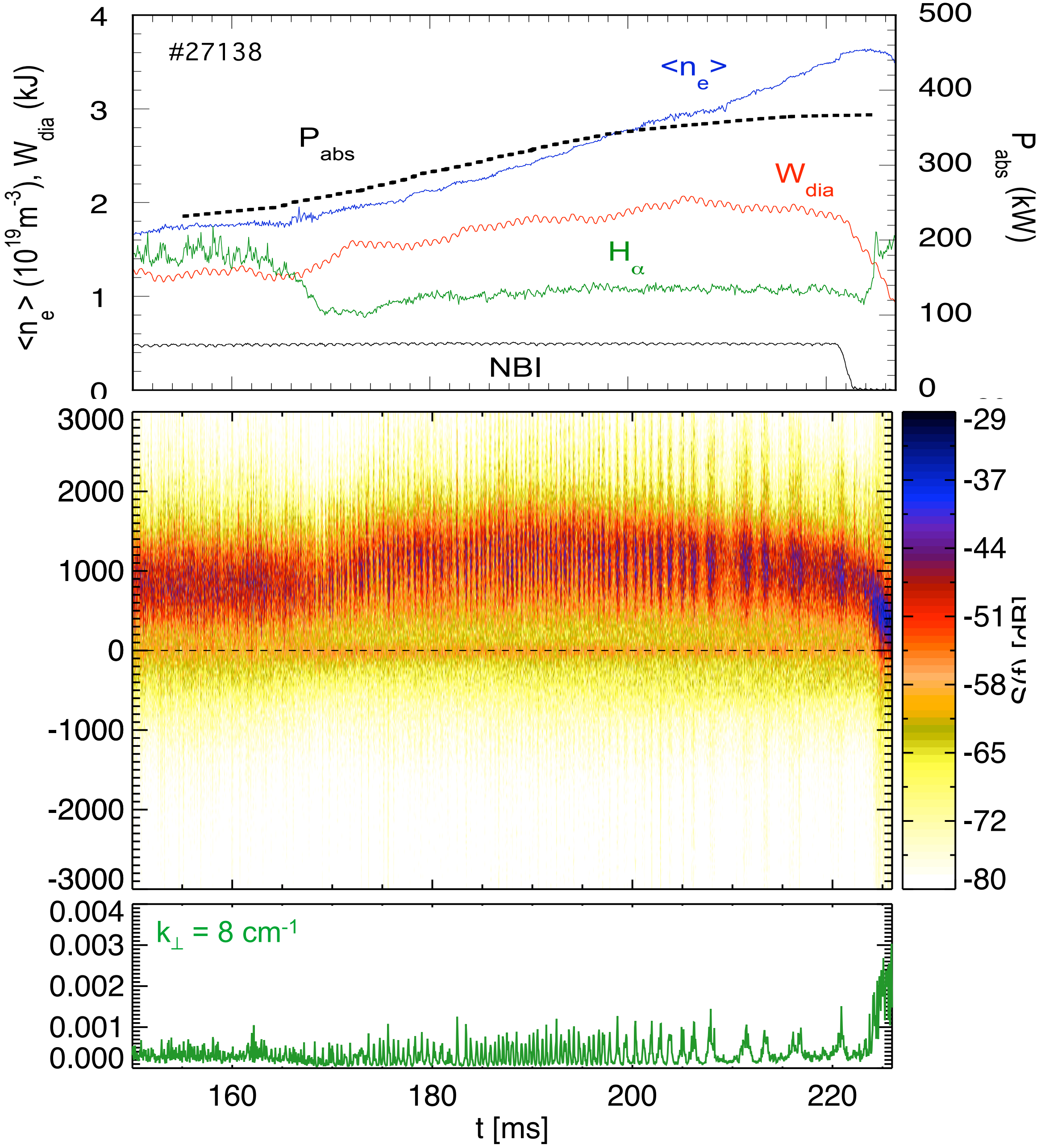
T. Estrada *et al.*, EPL **92**, 35001 (2010)

Similar/related results have been found in NSTX [Zweben PoP 2010], AUG [Conway PRL 2011], and EAST [Xu PRL 2011]. In these experiments, **the temporal dynamics of the turbulence-flow interaction** is reported

Recently, the **spatio-temporal evolution** of the turbulence-flow oscillation-pattern has been studied in TJ-II [Estrada PRL 2011] and DIII-D [Schmitz PRL 2012] and also in the L-I-H transition model [Miki PoP 2012, Diamond TH/P4-02]

Besides, its **spectral structure** has been measured in TJ-II [Estrada PPCF 2012]

L-I transition: turbulence and flows dynamics



co-NBI:

540 kW port-through

magnetic configuration:

$\iota/2\pi=1.53$

Doppler reflectometry spectrogram and density fluctuation level (green) measured at ρ: 0.75 → 0.80

As the density rises:

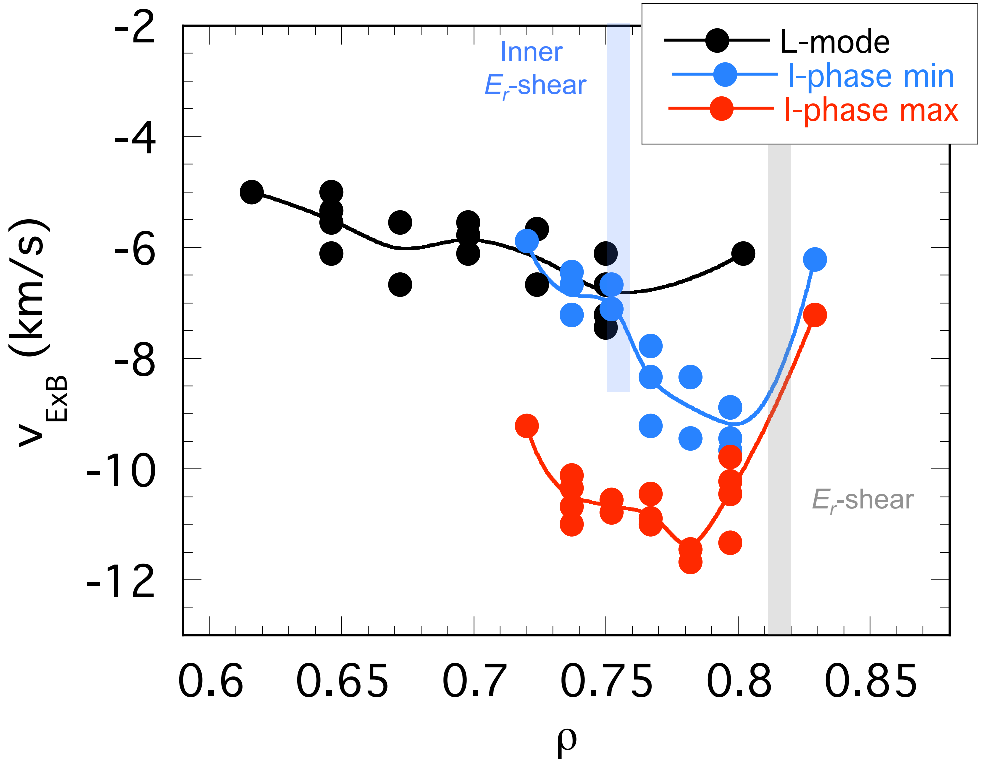
the repetition frequency of the turbulence-flow oscillation-pattern ↓

ΔE_r ↓

$\Delta rms(\tilde{n}_e)$ ↑

→ Can be explained based on the collisional damping of flows that eventually sets the turbulence level

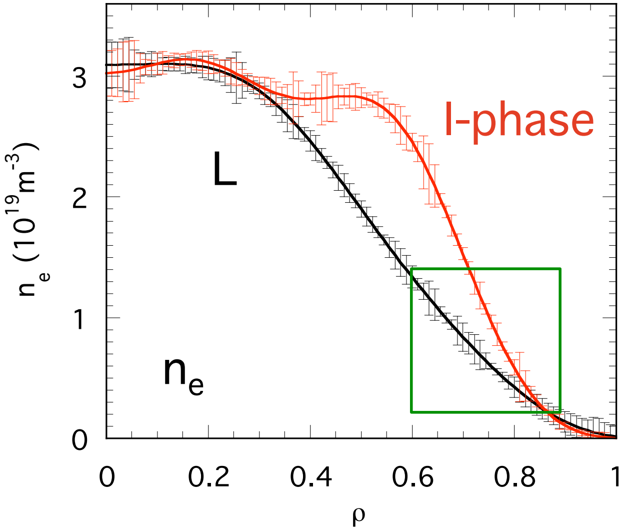
ExB flow radial profile evolution



L-mode v_{ExB} profile (black) and extreme values of the v_{ExB} oscillation at different radial positions @ $n_e \approx 2.0 - 2.5 \times 10^{19}$ m^{-3}

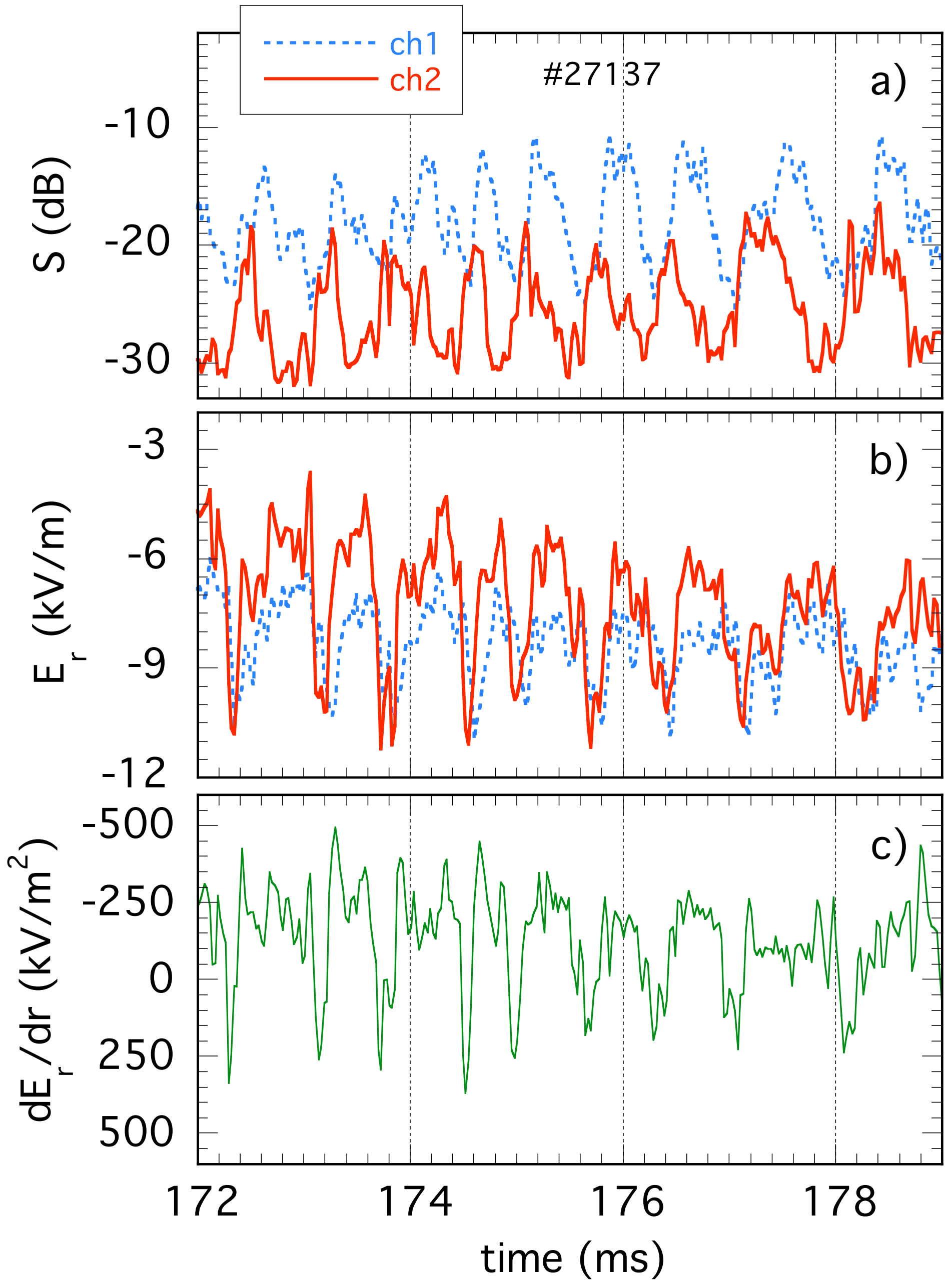
The oscillation amplitude is about 1 km/s close to the E_r-shear position (ρ ≈ 0.82) and increases gradually (up to ≈ 4 km/s) as inner positions are probed

The E_r-well shrinks in each cycle and an inner shear layer develops (at ρ ≈ 0.75)



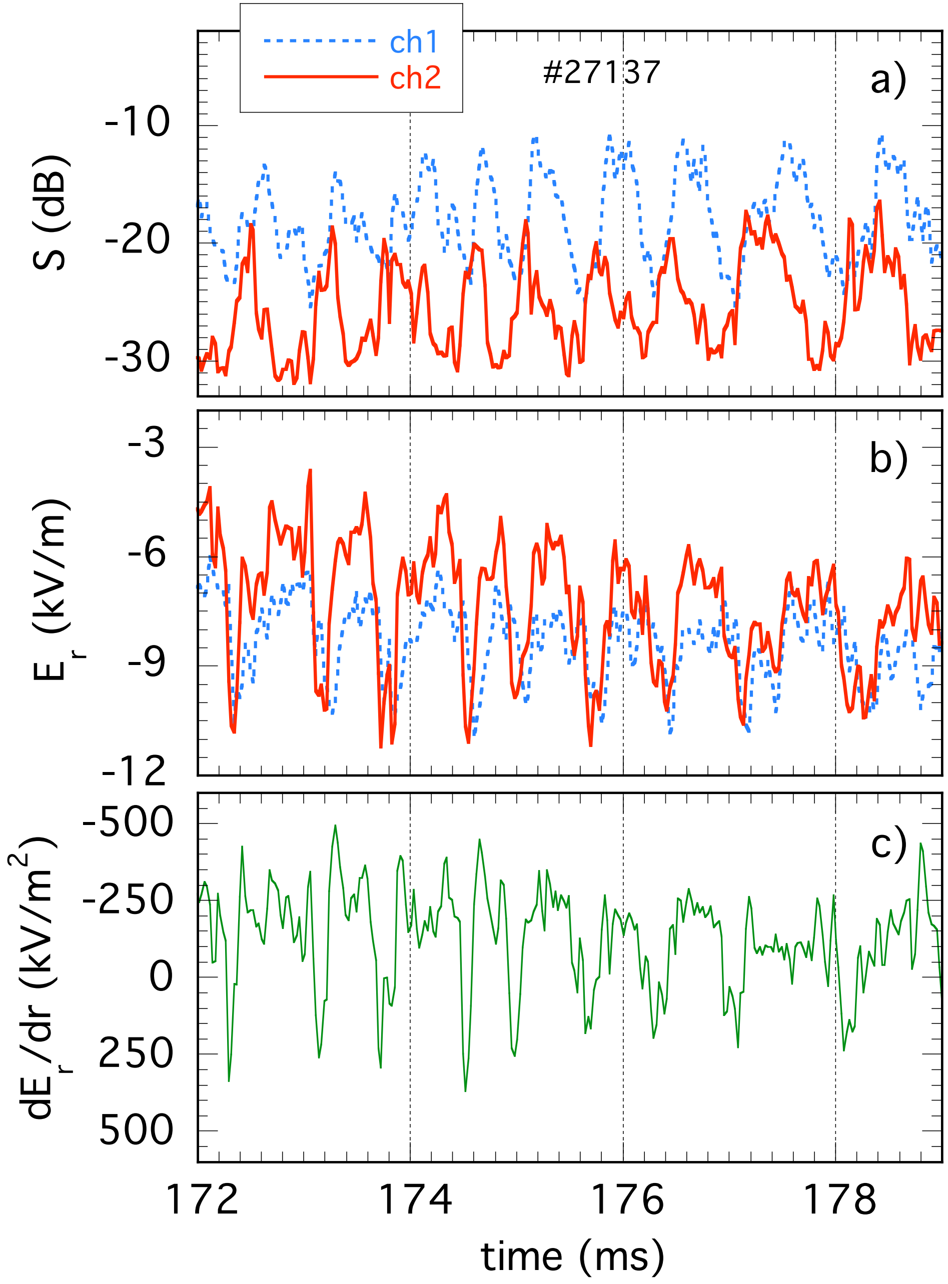
Oscillation-pattern spatiotemporal evolution

ch1: ρ = 0.80 ch2: ρ = 0.75

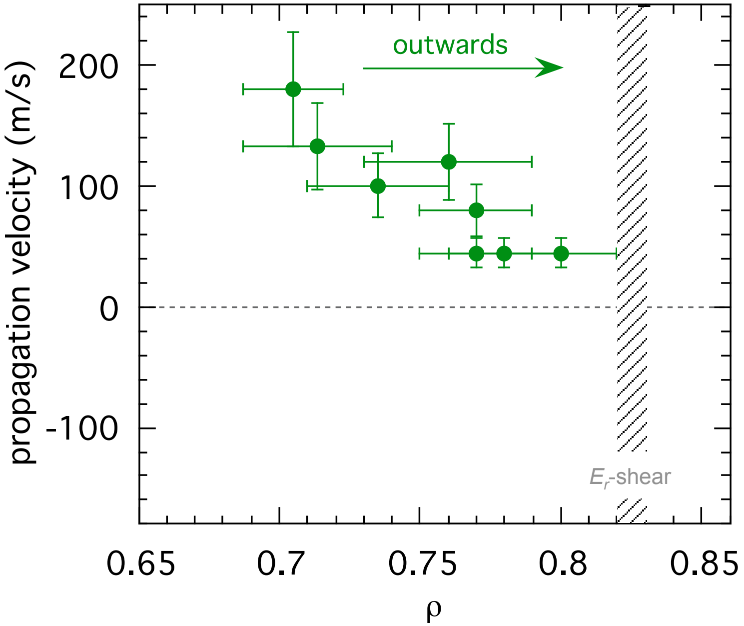


Oscillation-pattern spatiotemporal evolution

ch1: ρ = 0.80 ch2: ρ = 0.75

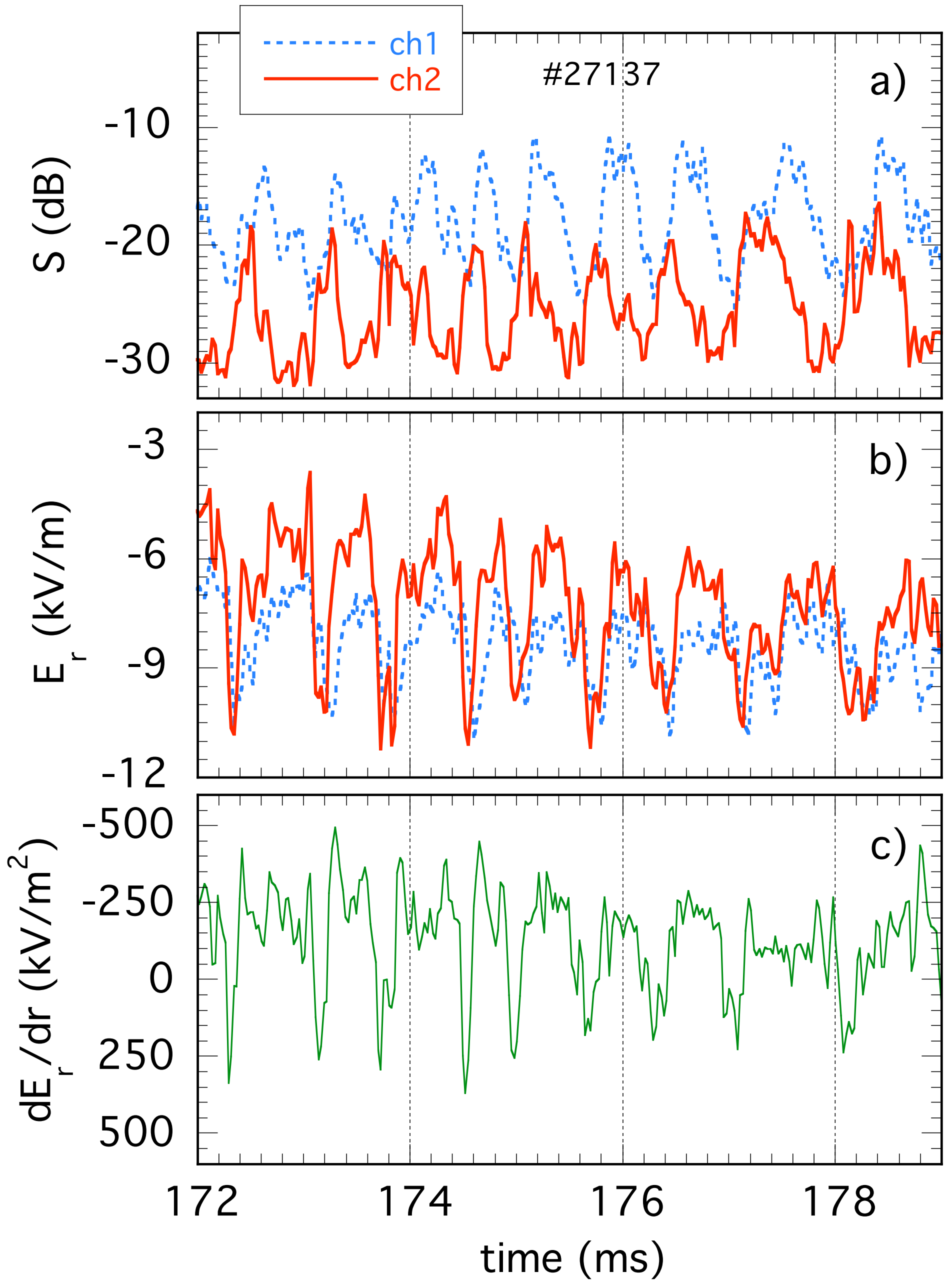


The delay shows a radial propagation from inner to outer channel (at densities $2 – 2.5 \times 10^{19}$ m^{-3})

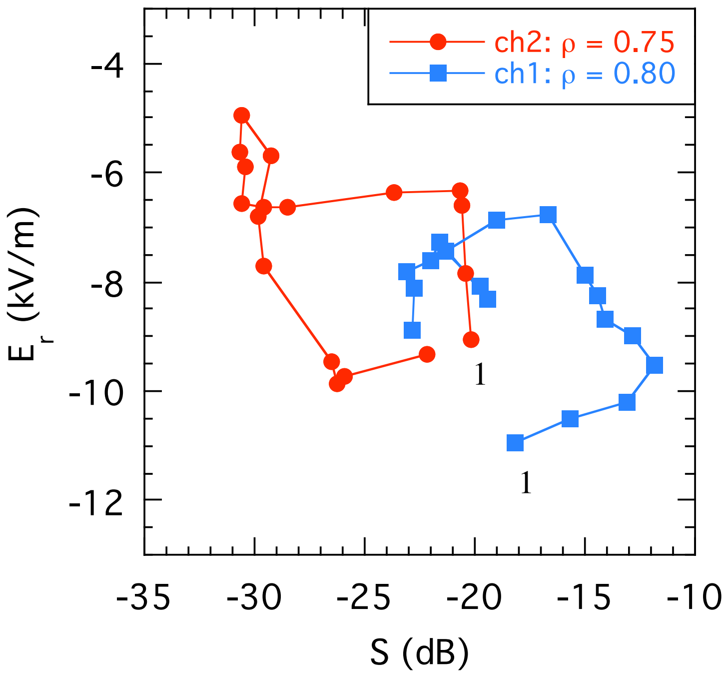


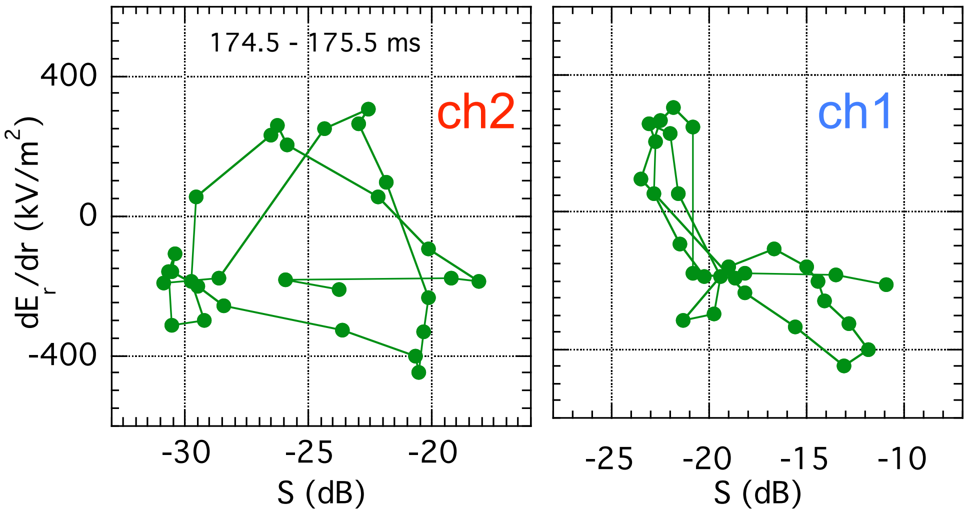
Oscillation-pattern spatiotemporal evolution

ch1: ρ = 0.80 ch2: ρ = 0.75

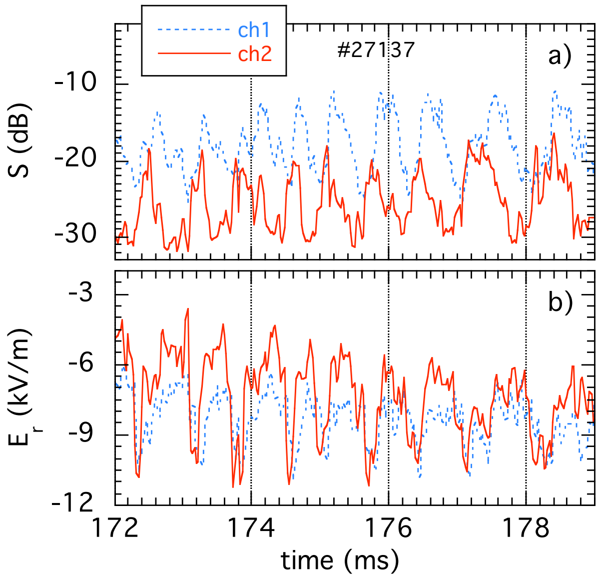


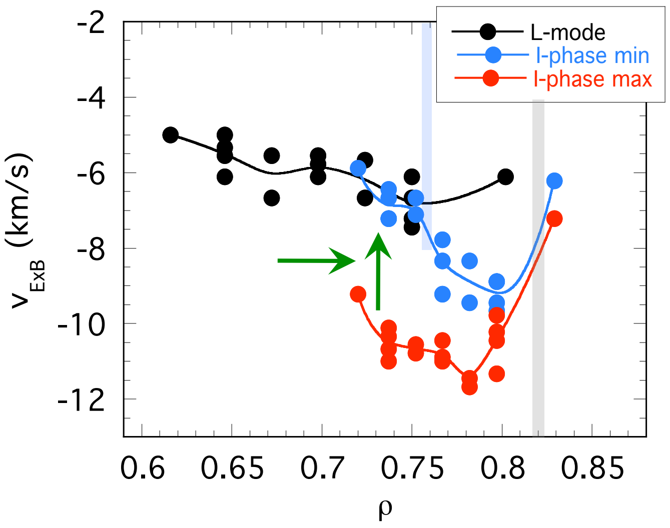
174.6-175.04 ms
δt = 25 µs

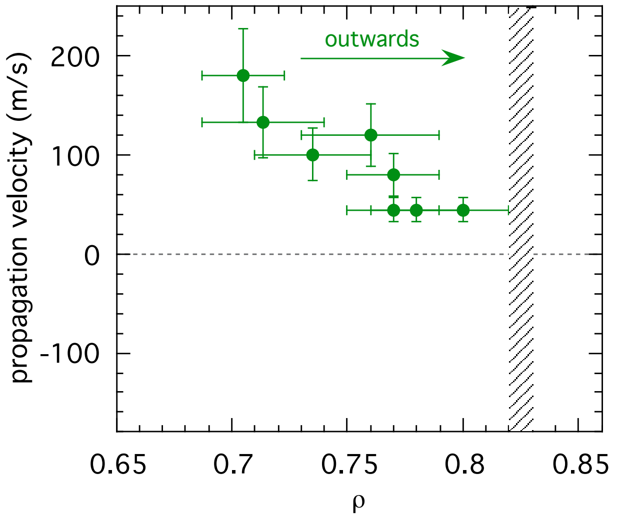




Outward propagating turbulence-flow oscillating structures







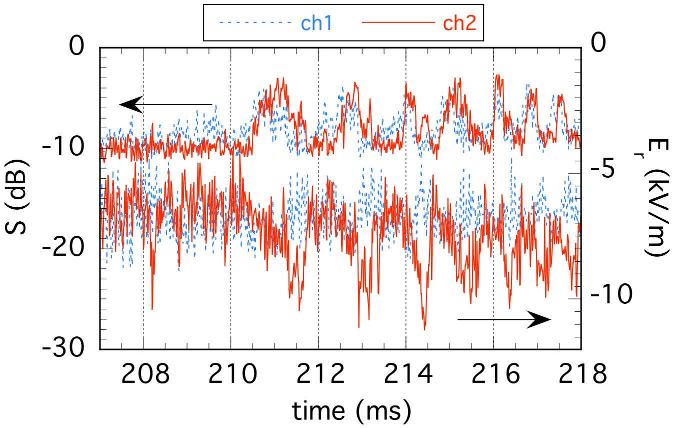
Turbulence spreading / turbulent bursts: as the turbulence propagates to the barrier the associated turbulence driven flow generates the inner shear layer which in turn regulates the turbulence level

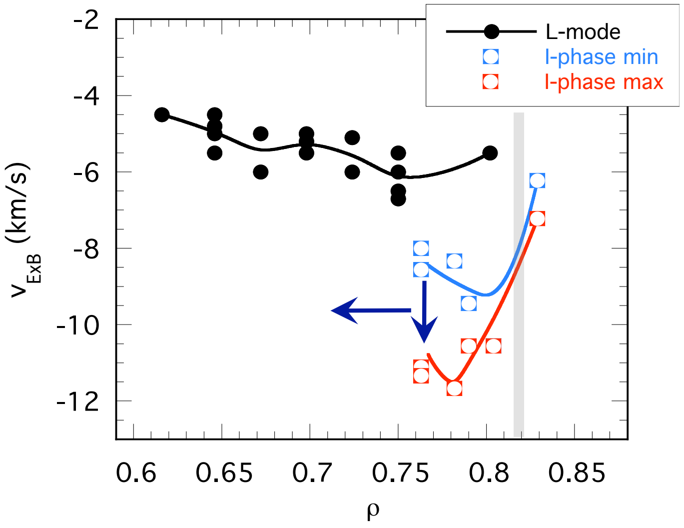
The deceleration of the turbulence-flow front as it approaches the edge shear layer together with its absence at outer radial positions suggest an absorption process at the shear layer

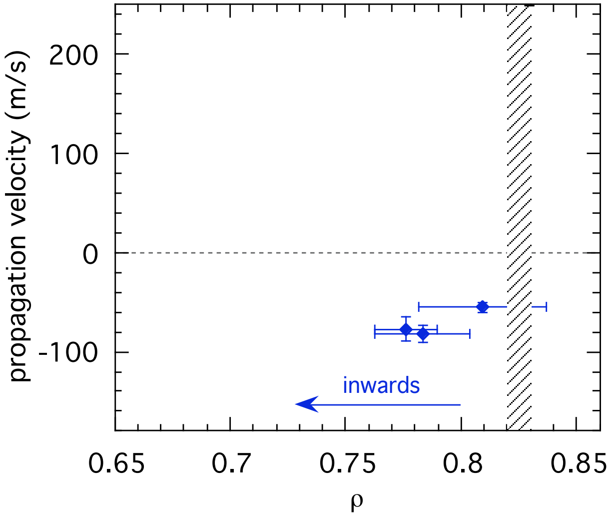
In this process, the turbulence driven flow generates a dual shear layer, and thus enhance the formation of the E_r-well

T. Estrada *et al*. PRL **107**, 245004 (2011)

Inward propagating turbulence-flow events







At higher densities, inward propagating turbulent-flow events eventually appear after a short time period without oscillations

Turbulence-flow events generated at the edge shear layer propagate towards the plasma centre. The turbulence-flow events enhance the edge shear layer

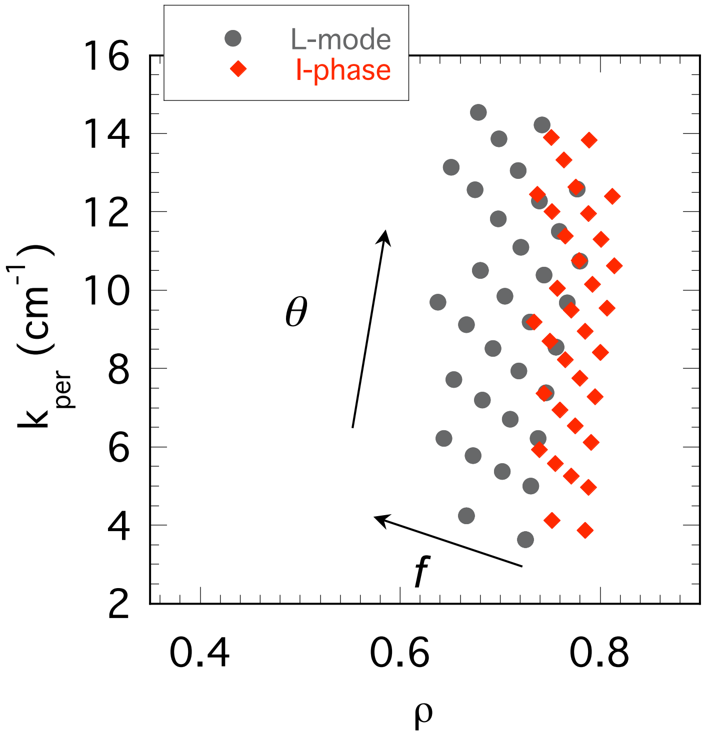
The results indicate that the **edge shear flow** linked to the L−H transition can behave **either as a slowing-down, damping mechanism** of outward propagating turbulent-flow oscillating structures, or as a **source** of inward propagating turbulence-flow events

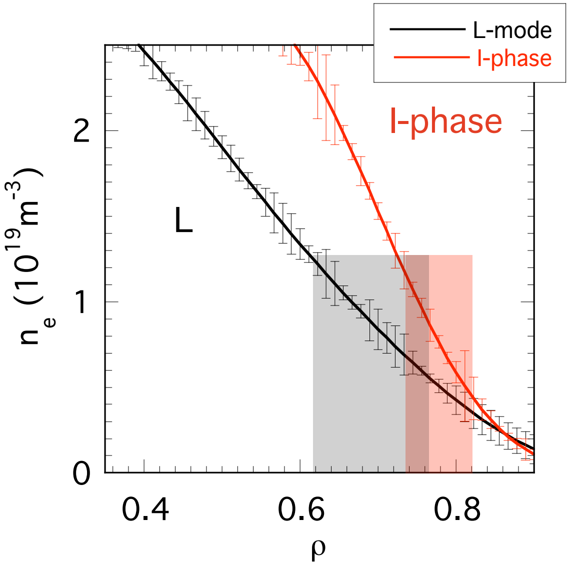
T. Estrada *et al*. PRL **107**, 245004 (2011)

Spectral structure of the turbulence-flow interaction

Turbulence wavenumber range: Scanning the Doppler reflectometer ellipsoidal mirror tilt angle and the probing frequency in a shot to shot basis, a rather broad perpendicular wavenumber range, $k_\perp$: 3 – 15 cm^{-1}, can be measured.

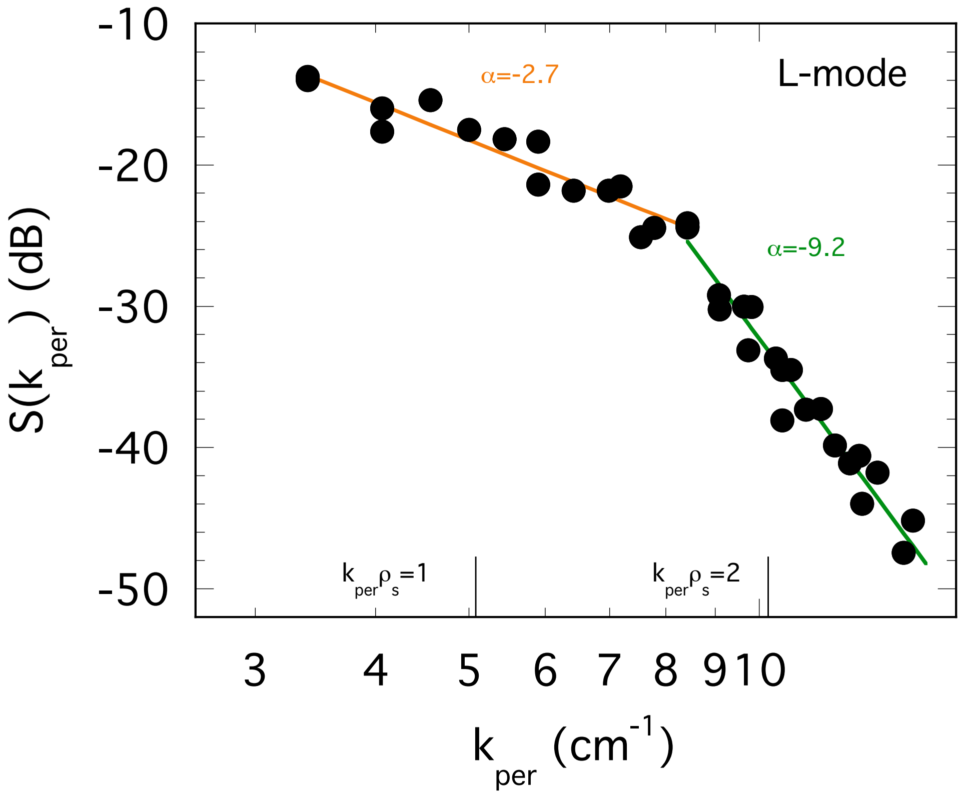
Perpendicular wavenumber-radius space covered by the Doppler reflectometer in L-mode and I-phase:





Turbulence wavenumber spectra

Turbulence wavenumber spectra measured during the L-mode ($n_e \approx 1.8\ 10^{19}\ m^{-3}$)

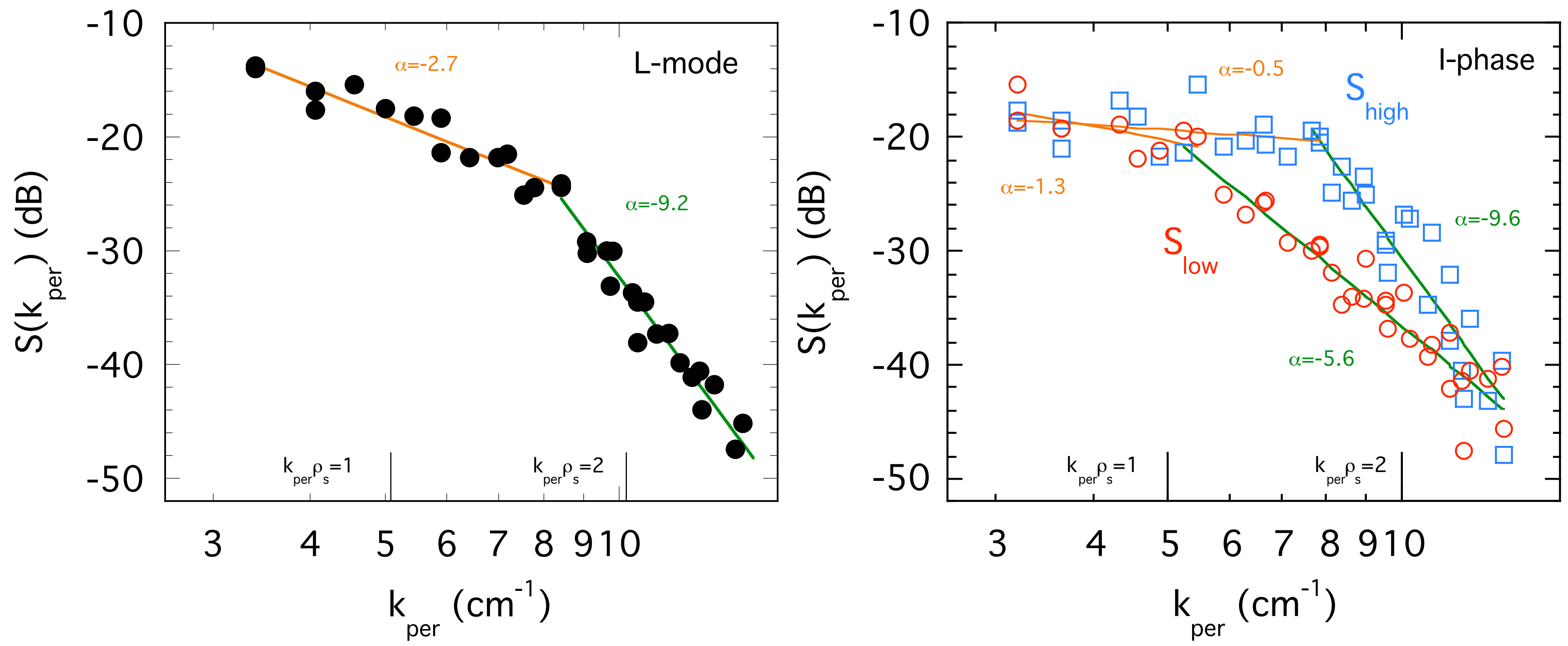


The turbulence level decreases as the wavenumber increases

Two wavenumber ranges: a flatter wavenumber region at large turbulence scales and a spectral fall-off at $k_{per} > k_{knee}$

Turbulence wavenumber spectra

Turbulence wavenumber spectra measured during the L-mode ($n_e \approx 1.8\ 10^{19}\ m^{-3}$) and during the I-phase: extreme values of the turbulence level ($n_e \approx 2.3\ 10^{19}\ m^{-3}$)



The turbulence level decreases as the wavenumber increases

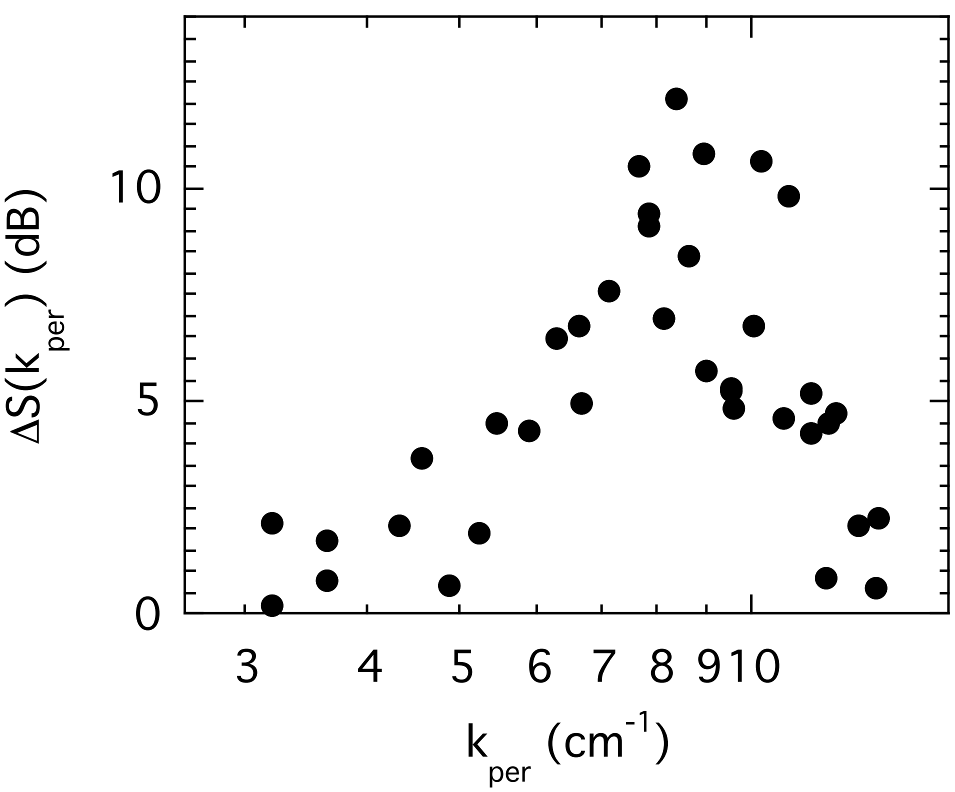
Two wavenumber ranges: a flatter wavenumber region at large turbulence scales and a spectral fall-off at $k_{per} > k_{knee}$

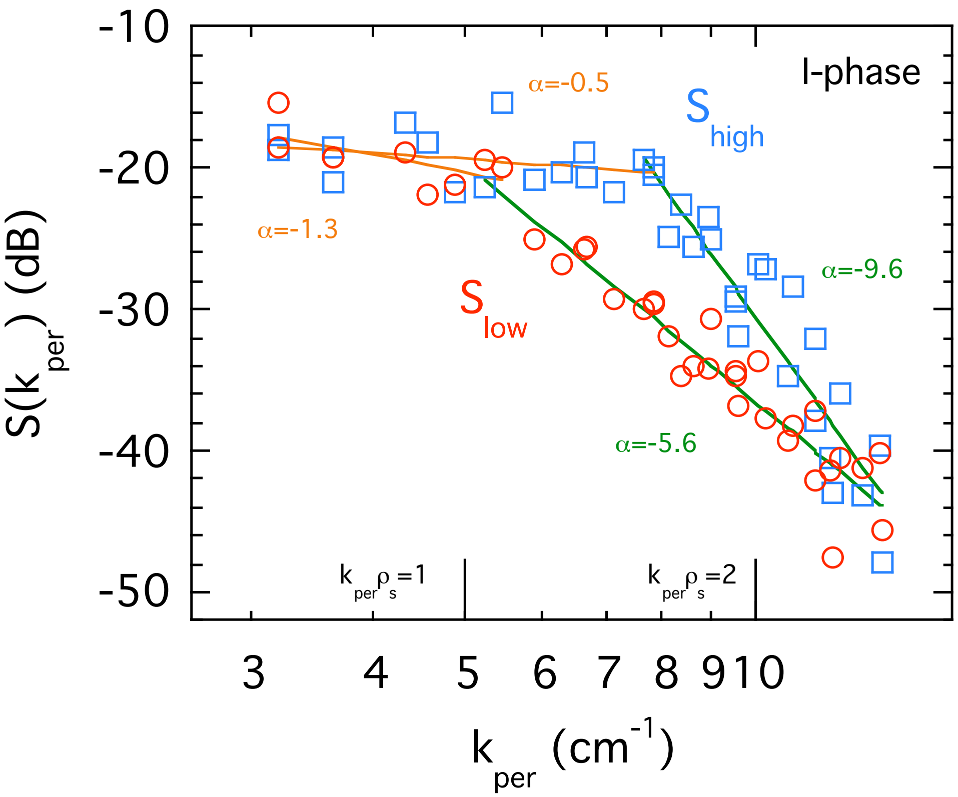
S_{high} vs S_{low}: a well defined wavenumber range where the turbulence level oscillation is maximum

T. Estrada *et al.* PPCF **54** (2012)

Spectral structure of the turbulence-flow interaction

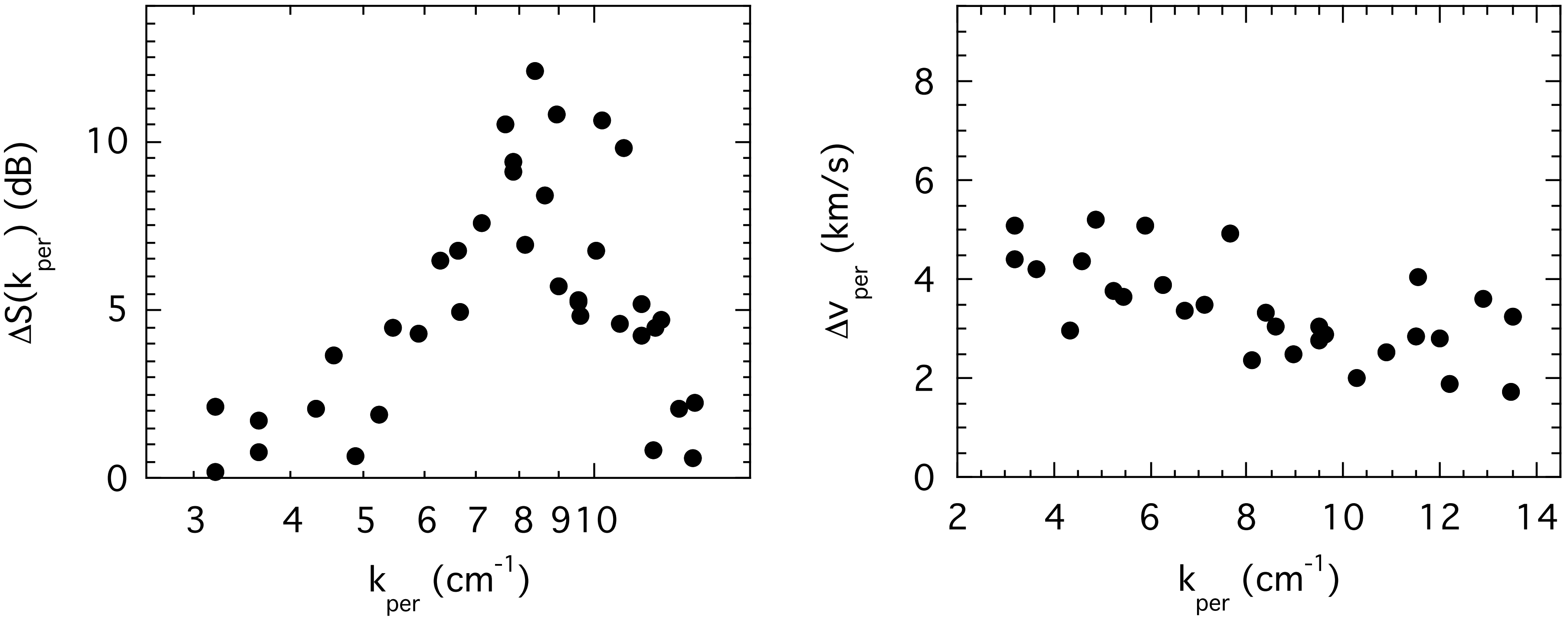
Intermediate turbulence scales, $k_{per} \approx 6 - 12\ cm^{-1}$, dominate the energy transfer of the turbulence-flow prey-predator process





T. Estrada *et al.* PPCF **54** (2012)

Spectral structure of the turbulence-flow interaction

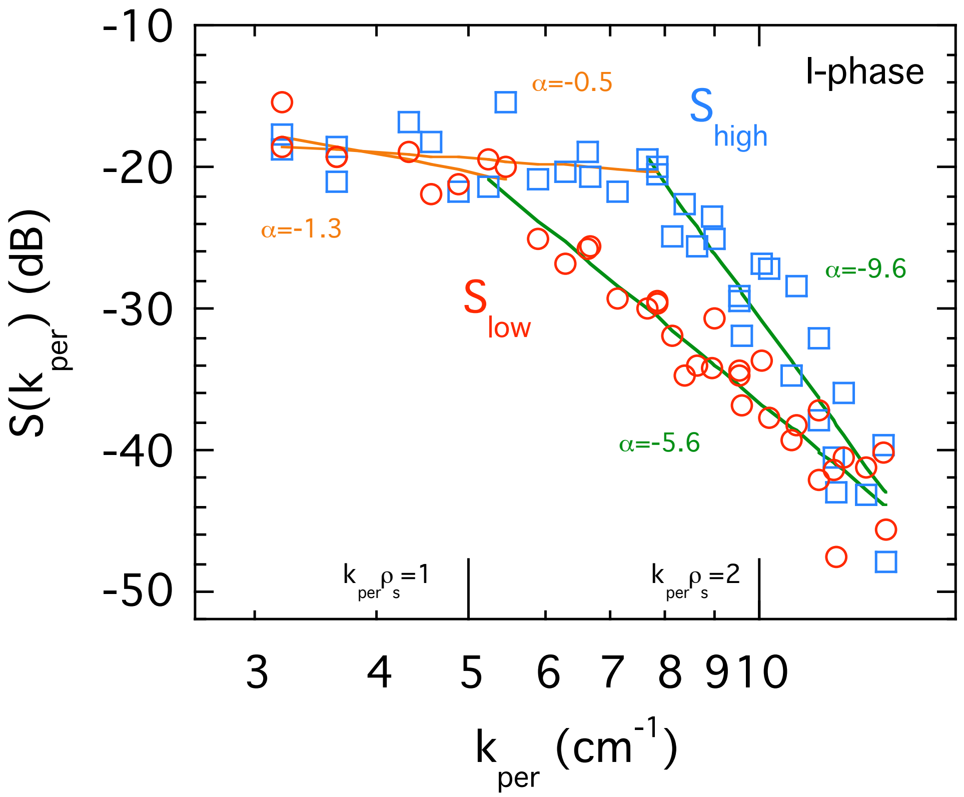


The flow oscillation amplitude depends slightly on the turbulence scale, indicating that all turbulence scales follow the flow oscillations although the scales involved in the predator-prey process are preferentially the intermediate ones

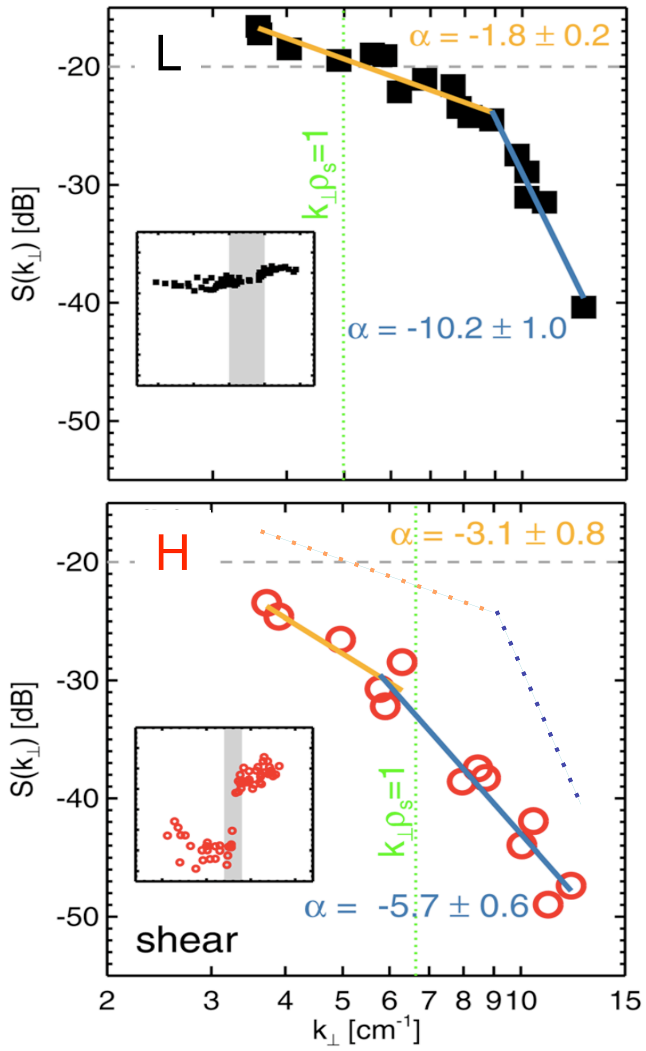
Intermediate turbulence scales: identified as the dominant player in the zonal flow generation by Reynolds stress both in simulations [Scott NJP 2005] and experiments [Manz PRL 209, Stroth PPCF 2011]

I-phase vs. H-mode

Turbulence wavenumber spectra at the I-phase and during the L and H modes



T. Happel *et al.*, PoP **18**, 102302 (2011)



In the **I-phase**, the turbulence is regulated mainly by the zonal-flow generation which effectively takes place at intermediate turbulence scales. No changes are measured at shorter and longer turbulence scales

As the plasma enters into the **H-mode**, additional mechanisms like turbulence decorrelation by mean sheared flow may become active affecting a broader range of turbulence scales

Conclusions

The **temporal dynamics** of the **turbulence-flow interaction** has been measured at the L-H transition in TJ-II plasmas. It displays an oscillatory behaviour with a characteristic **predator-prey relationship** supporting the *Kim & Diamond* predator-prey theory model of the L-I-H transition

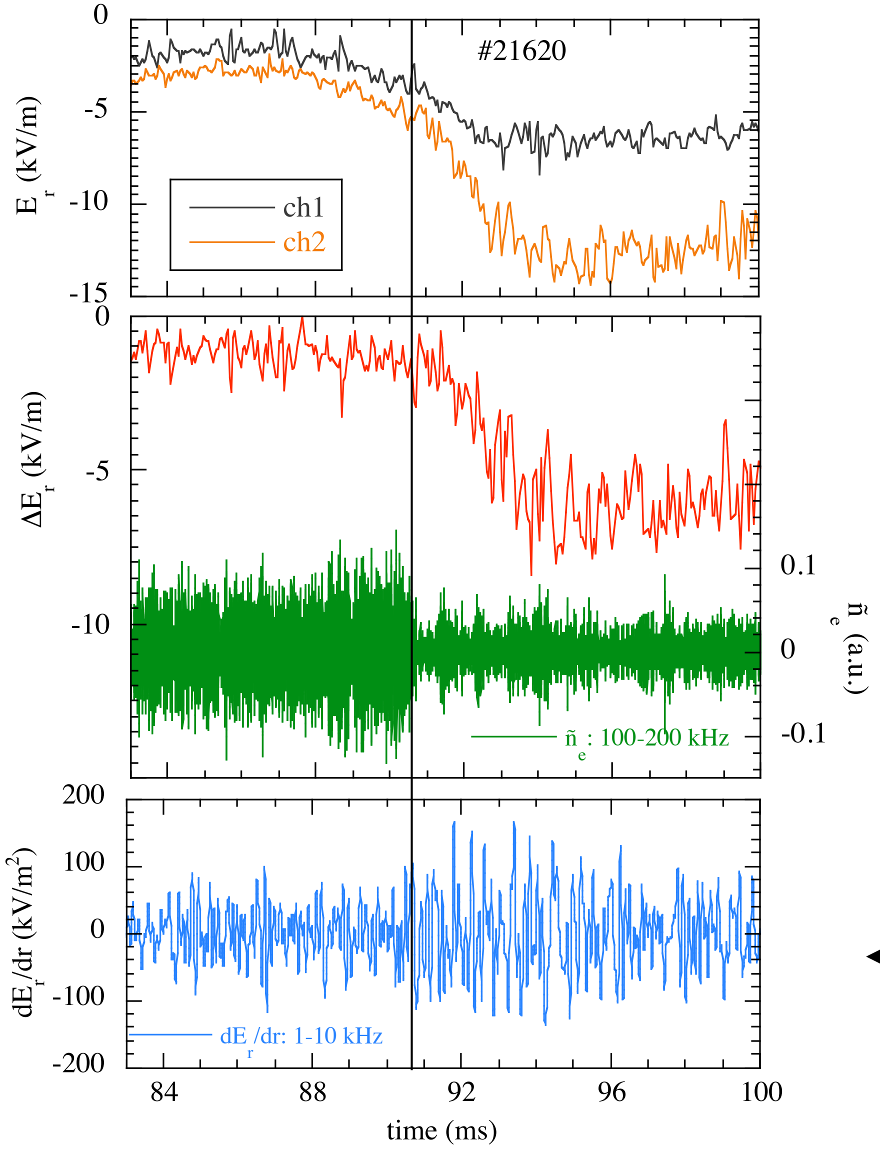
The **spatial evolution** of this oscillation-pattern has been measured, showing both, **radial outward and inward propagation velocities of the turbulence-flow front.** The results show the need of approaching L-H transition studies within a one-dimensional spatiotemporal framework [Miki PoP 2012, Diamond TH/P4-02]

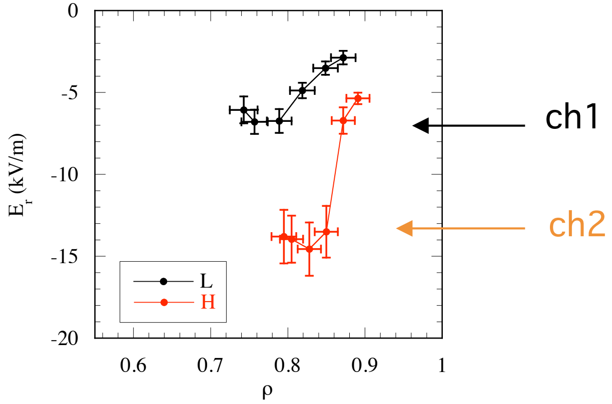
The **relevant turbulence scales** involved in the energy transfer of the predator-prey process have been identified. In the I-phase, the **turbulence is regulated mainly by the zonal-flow generation** which effectively takes place at intermediate turbulence scales

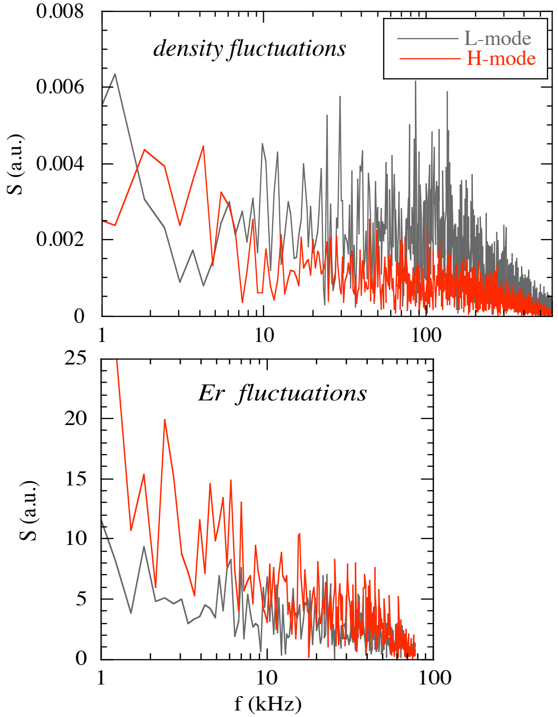
As the plasma enters into the **H-mode**, additional mechanisms like turbulence decorrelation by mean sheared flow may become active affecting a broader range of turbulence scales

Oscillating sheared flow at the L-H transition

balanced-NBI: 900 kW port-through, standard configuration: $\iota(a)=1.65$; H_{ISS04}: 1.3 – 1.4







T. Estrada *et al.*, PPCF **51**, 124015 (2009)

Turbulence and flows dynamics close to the threshold

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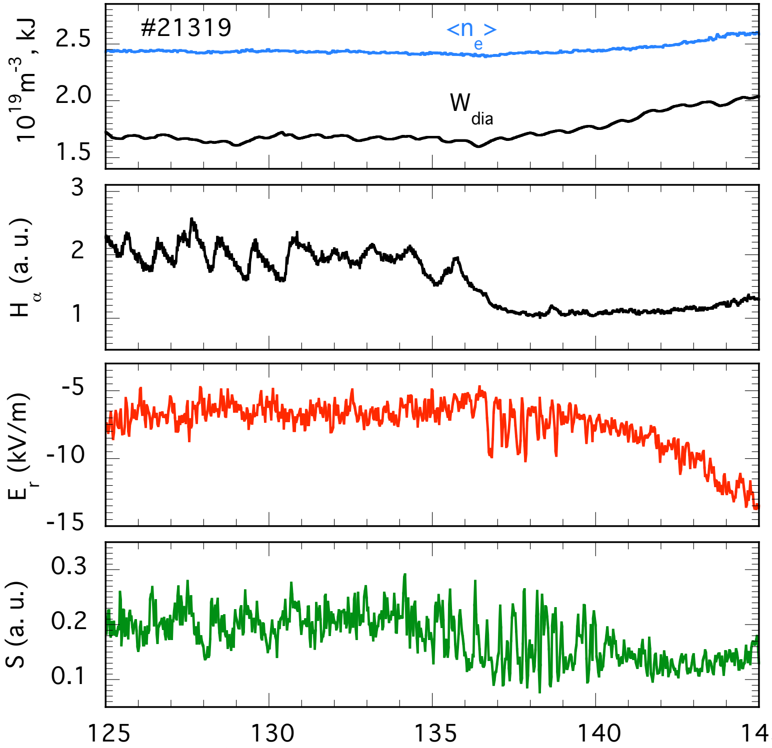
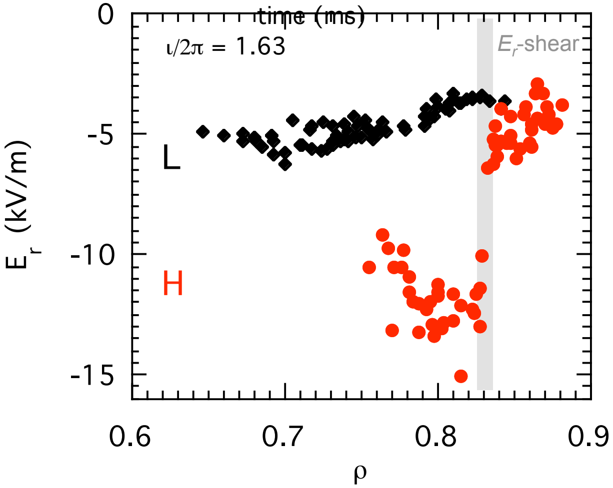
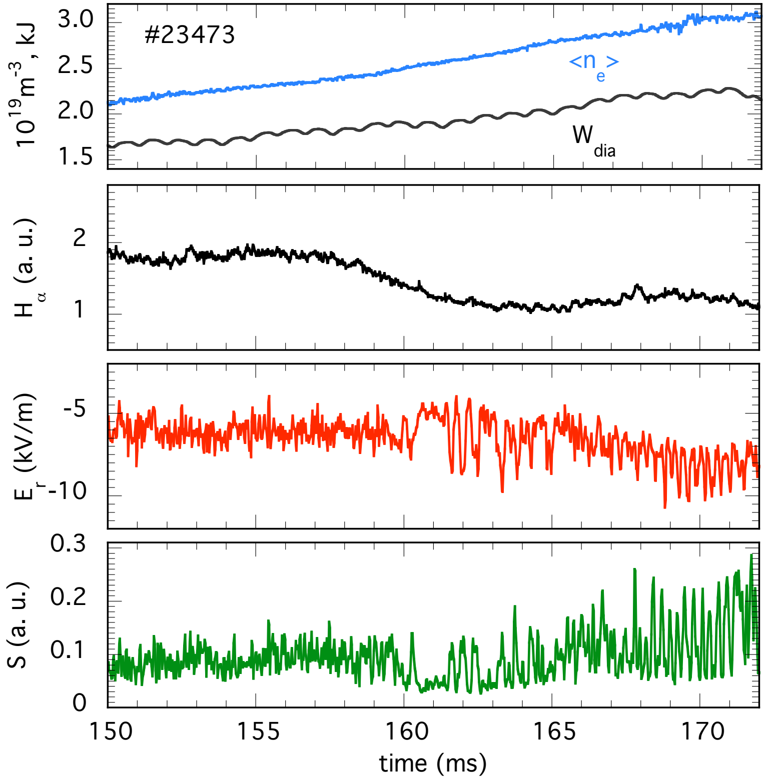
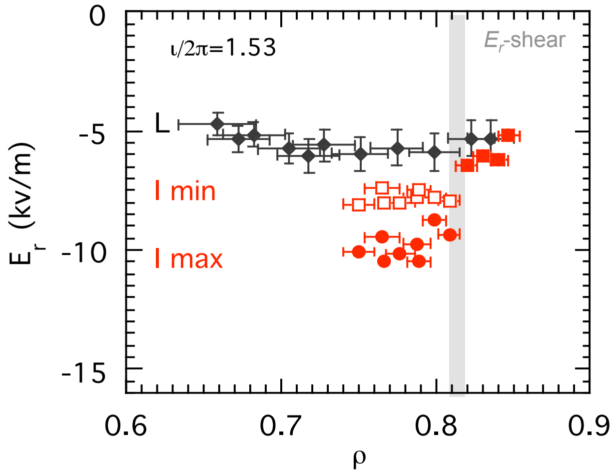
$\iota/2\pi$ = 1.63, co-NBI: 400 kW port-through



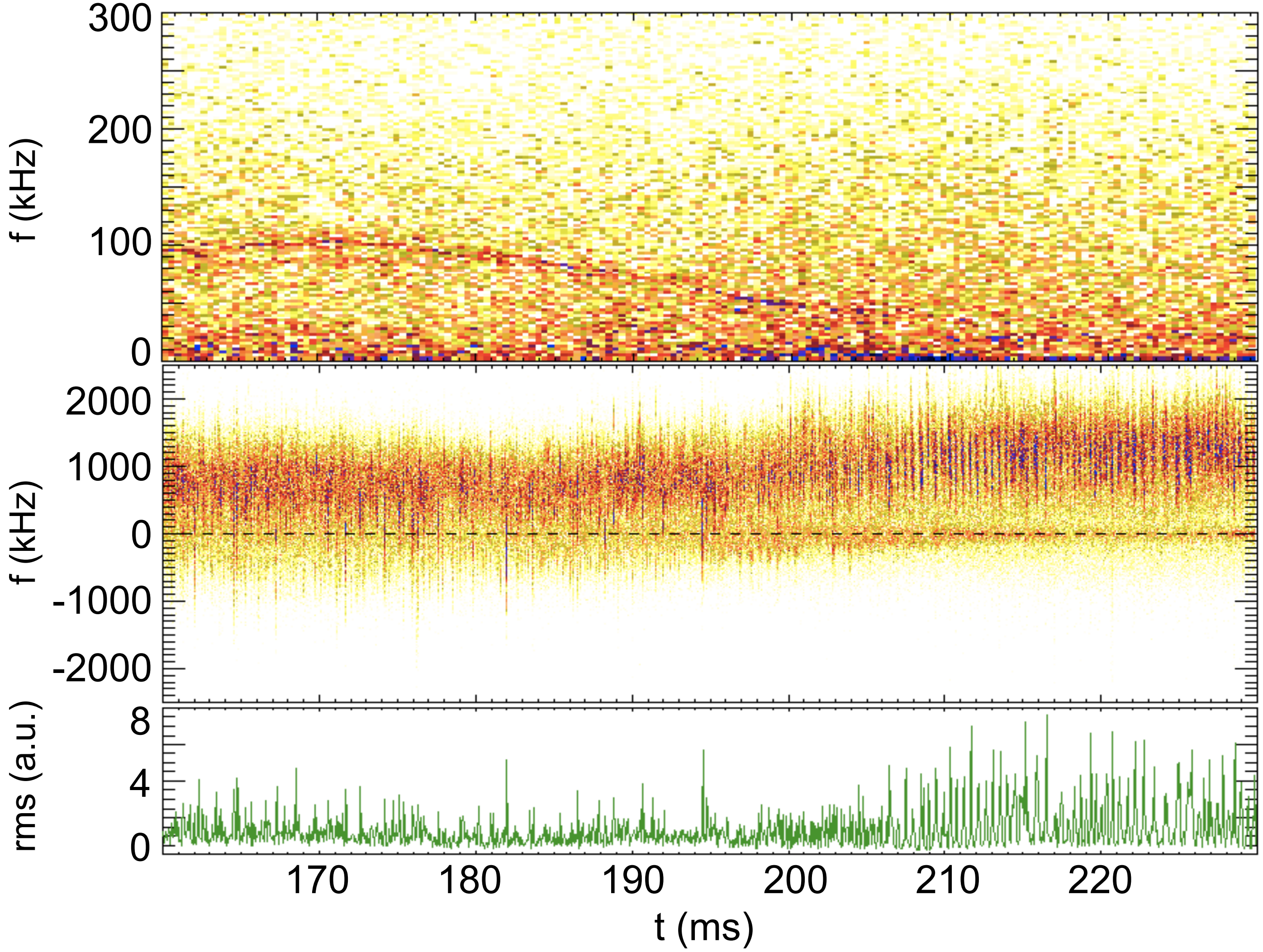


$\iota/2\pi$ = 1.53, co-NBI: 380 kW port-through





Triggering



The magnetic configuration has a sensitive influence on H-mode realization and quality, and also on **I-phase**

NBI driven modes are observed linked to low order rational surfaces (3/2, 5/3 or 8/5). The mode is measured at $\rho < 0.7$, its frequency decreases before the onset of the I-phase and the mode vanishes afterwards