GOBIERNO DE ESPAÑA

MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Laboratorio Nacional Fusión

Dynamics of flows and confinement in the TJ-II stellarator

presented by E. Ascasíbar
on behalf of the TJ-II Team

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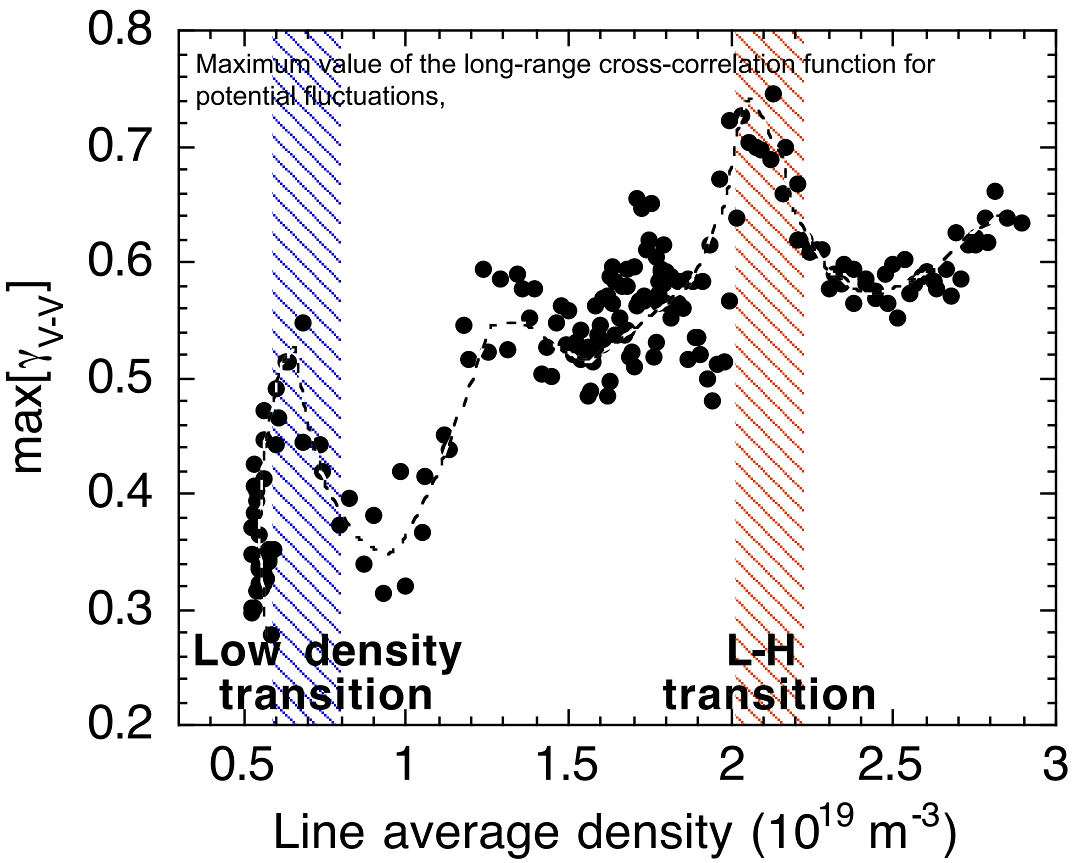
Introduction

- Confinement transitions have been studied in TJ-II since many years ago:
  - Low-density transition in ECH plasmas (Tabares PPCF 2001; Hidalgo Phys. Rev. E 2004; van Milligen NF 2011).
  - L-H transition (high density) in NBI Li-coated plasmas (Sanchez NF2009; Estrada PPCF 2009).

- Both types of transitions involve the formation of shear flow layers.

- Long-range correlations in plasma potential, that can be associated with ZFs, have been measured in TJ-II (Pedrosa PRL 2008, Hidalgo PPCF 2011, Xu NF2011).



The degree of long range toroidal correlations (zonal flows) increases as approaching the low-density and the L-H transitions.

[C. Hidalgo et al., EPL-2009].

- In the last two years, the TJ-II team has deepened in the physics of both transitions:

1. Both the mean and the fluctuating radial electric field have been studied for the low-density transition from the neoclassical point of view (Velasco PRL 2012).
2. The spatio-temporal characteristics of the global, fluctuating, zonal flow-like floating potential structures in the plasma edge has been experimentally studied (Alonso NF 2012).
3. The evolution of zonal flows in the TJ-II geometry has been investigated by means of linear gyrokinetic simulations (E. Sánchez PPCF 2012, in press).
4. The spatial, temporal and spectral structure of the interaction between turbulence and flows has been studied close to the L-H transition threshold conditions (Estrada PRL 2011).

- These topics are the guiding thread of this presentation.

Outline

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- TJ-II characteristics
  - Plasma-lithium interaction: Li coated walls
- Low-density transition
  - Shear layer formation
  - Vanishing neoclassical viscosity
  - Long-range correlations
- Zonal flow-like dynamics and transport
  - What drives ZFs?
  - Collisionless relaxation of ZFs
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TJ-II characteristics

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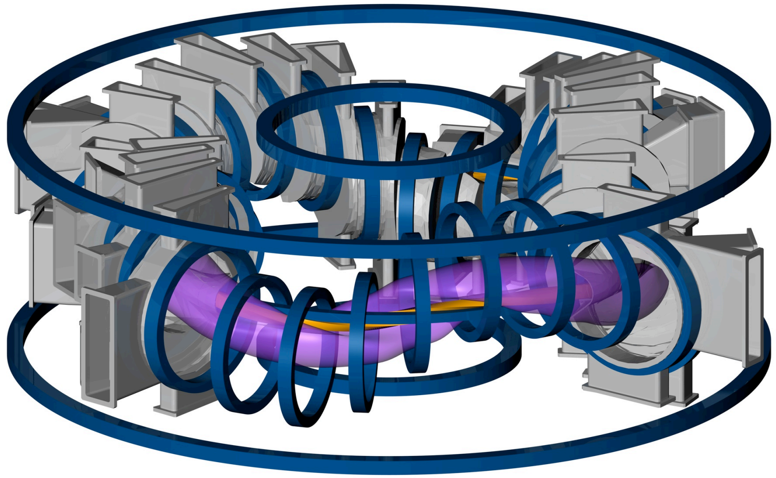
- TJ-II heliac is characterized by a high magnetic configuration flexibility and a complex 3D magnetic field geometry:
    - R=1.5 m
    - a ≤ 0.22 m
    - B ≈ 1 T
    - High rotational transform: $1 \leq \text{iota}/2\pi \leq 2.2$
    - Low magnetic shear
    - Advanced diagnostic set: Two HIBP, Doppler Reflectometer, multiple arrays of Langmuir, magnetic probes, bolometers, atomic beams...
    - Li wall coating: Density control and access to H mode in NBI plasmas.



- TJ-II is a non-quasisymmetric stellarator with a large fraction of trapped particles. Therefore, it is expected that zonal flows be strongly damped.

Plasma-lithium interaction: Li coated walls

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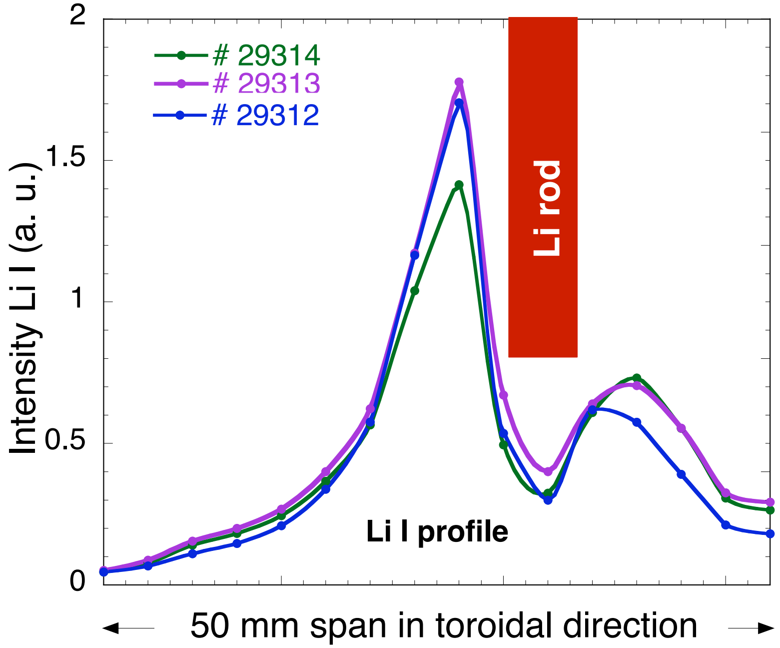
- Li coating has produced crucial benefits for TJ-II plasma operation:
  - important reduction in sputtering and recycling.
  - density control in NBI plasmas-> Access to H mode.

- Liquid metals (Li) as an alternative to solid plasma facing materials for future Fusion devices.
  - Recent experiments:
    - Plasmas with Liquid Lithium Limiter (Vertkov FST 2012)
    - Lithium rod insertion in the LCFS: Indications of a local denser plasma surrounding the rod (Apicella PPCF 2012).

Toroidal profile of neutral LiI emission near a solid Li rod inserted into the LCFS of TJ-II.



Tabarés, poster EX/P5-36 (Thursday morning)

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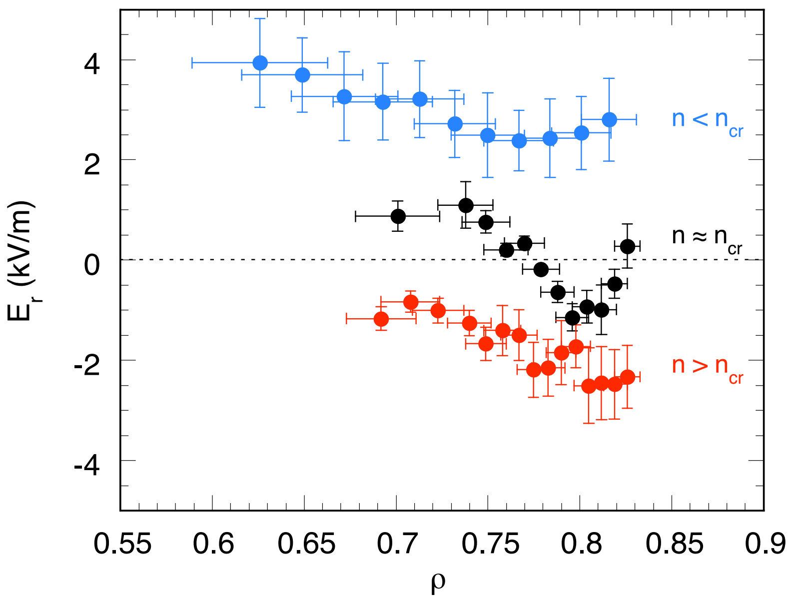
Low-density transition: shear layer formation

Experiment:

- Confinement improvement occurs spontaneously as the line-averaged density reaches a certain threshold density.

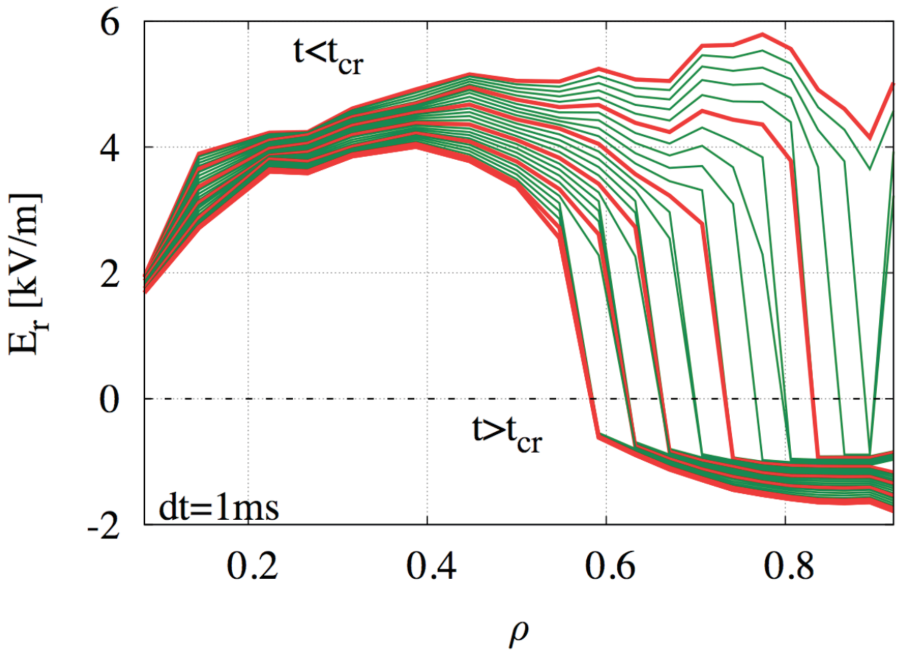
- At this critical density the radial electric field reverses from positive (electron root) to negative (ion root) (Estrada PPCF 2009).



Neoclassical calculation:

•Drift kinetic equation solved with slowly varying plasma profiles which mimic a density ramp-up. [Velasco et al., PRL 2012].

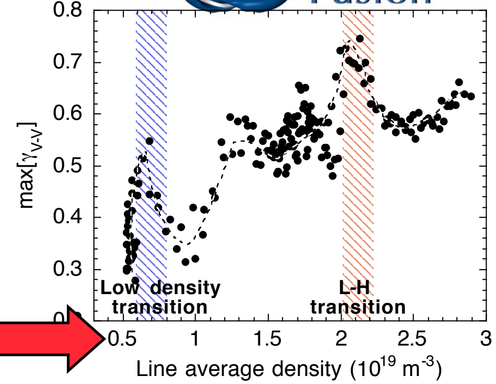
•E_r and its shear in very good agreement with experiment. The point with highest shear (root change) moves inwards [Happel EPL 2008].



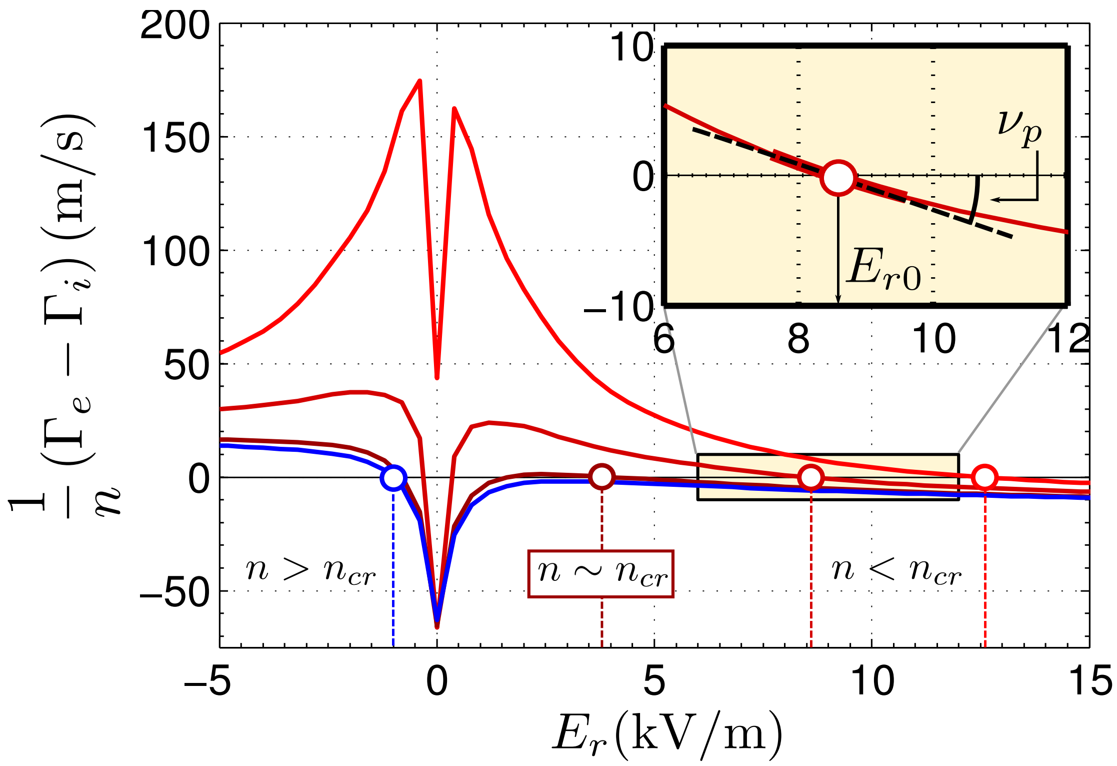
Similar observations in other non-quasisymmetric stellarators (CHS,W7-AS, LHD …).

Low-density transition: vanishing neoclassical viscosity

- This NC calculation provides interpretation of several additional experimental observations (amplitude in E_r low-frequency fluctuations, peaking of relaxation time and increase of the Er amplitude in biasing experiments) (Pedrosa PPCF 2007, Carralero PPCF 2012).



- **And, why do long-range correlations appear at the critical density?**



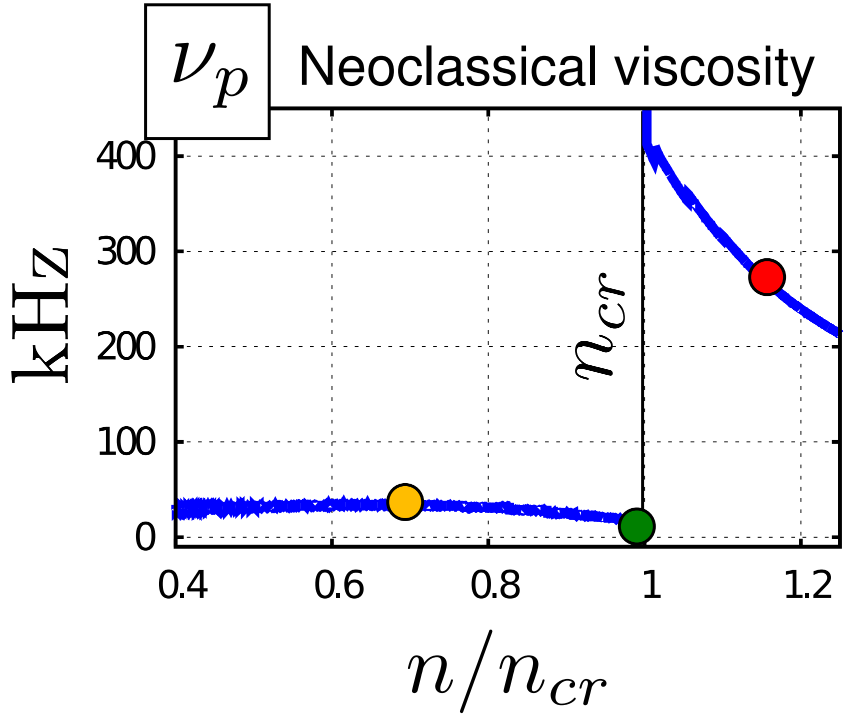
– Neoclassical viscosity interpreted as the restoring force that drives the system back to ambipolarity.

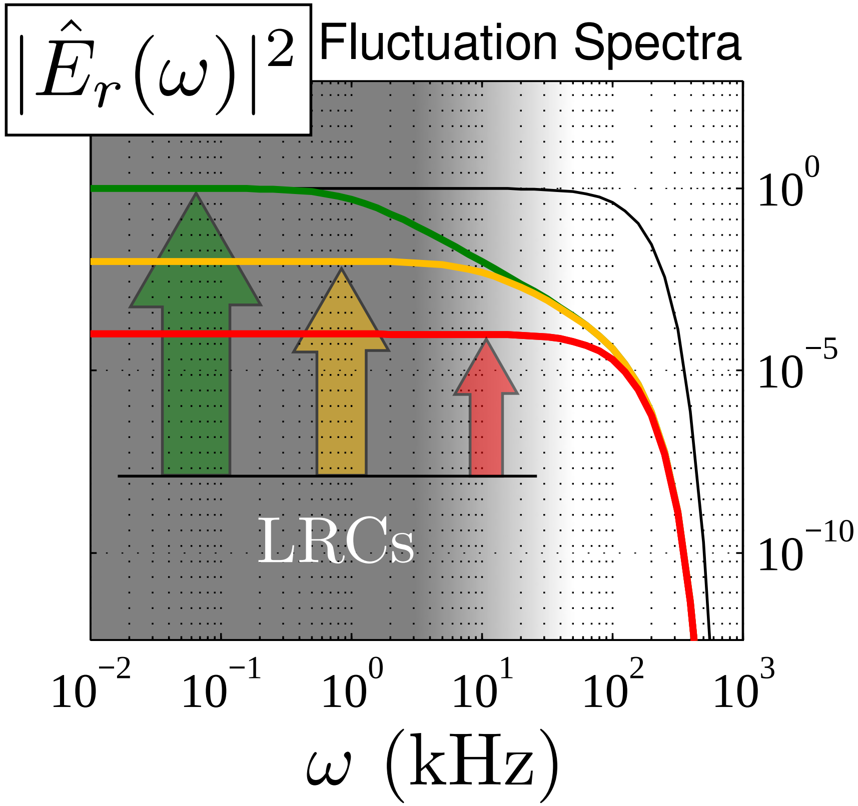
$$[\Gamma_e - \Gamma_i](E_r) \propto -\nu_p(E_r - E_r^0) + \ldots$$

– It vanishes as the critical density is approached from below. This allows large deviations of E_r from NC ambipolarity. [Velasco et al., PRL 2012].

Direct evidence of ZF regulation by NC viscosity

$$|\hat{E}_r(\omega)|^2 \propto \frac{1}{\nu_p^2 + \omega^2}$$





Long-range toroidal correlations (zonal flows), strongly damped before and after the transition, become undamped at the transition, as a consequence of the reduction of the neoclassical viscosity. [Velasco et al., PRL 2012].

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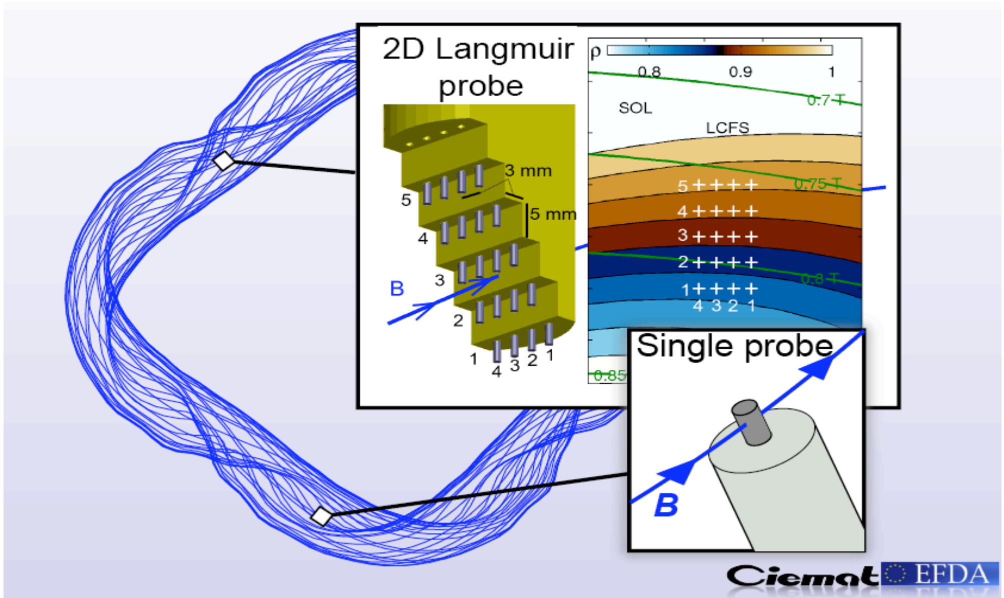
Zonal flow dynamics and transport

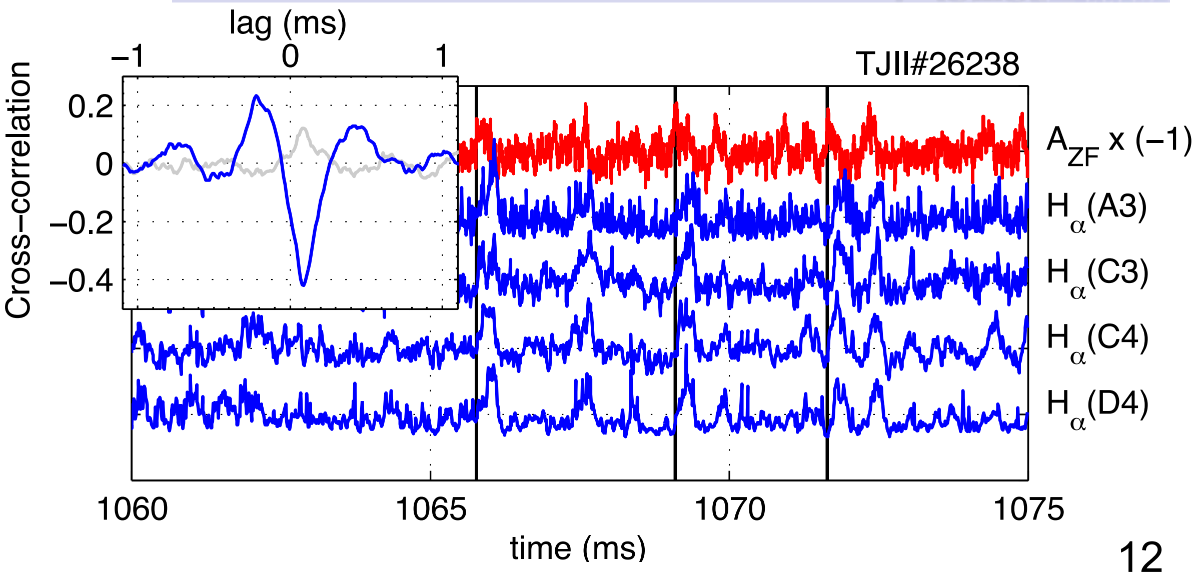
- ZF-like structures are diagnosed with simultaneous electric potential measurement with two toroidally separated Langmuir probes.

- The ZF component is extracted by means of Singular Value Decomposition.



- Dynamic modulation of global particle transport by the ZF component.

- All Hα monitors respond (anti-correlation) to changes in the amplitude of the ZF component, some 100 μs afterwards.



[Alonso et al., NF 2012]

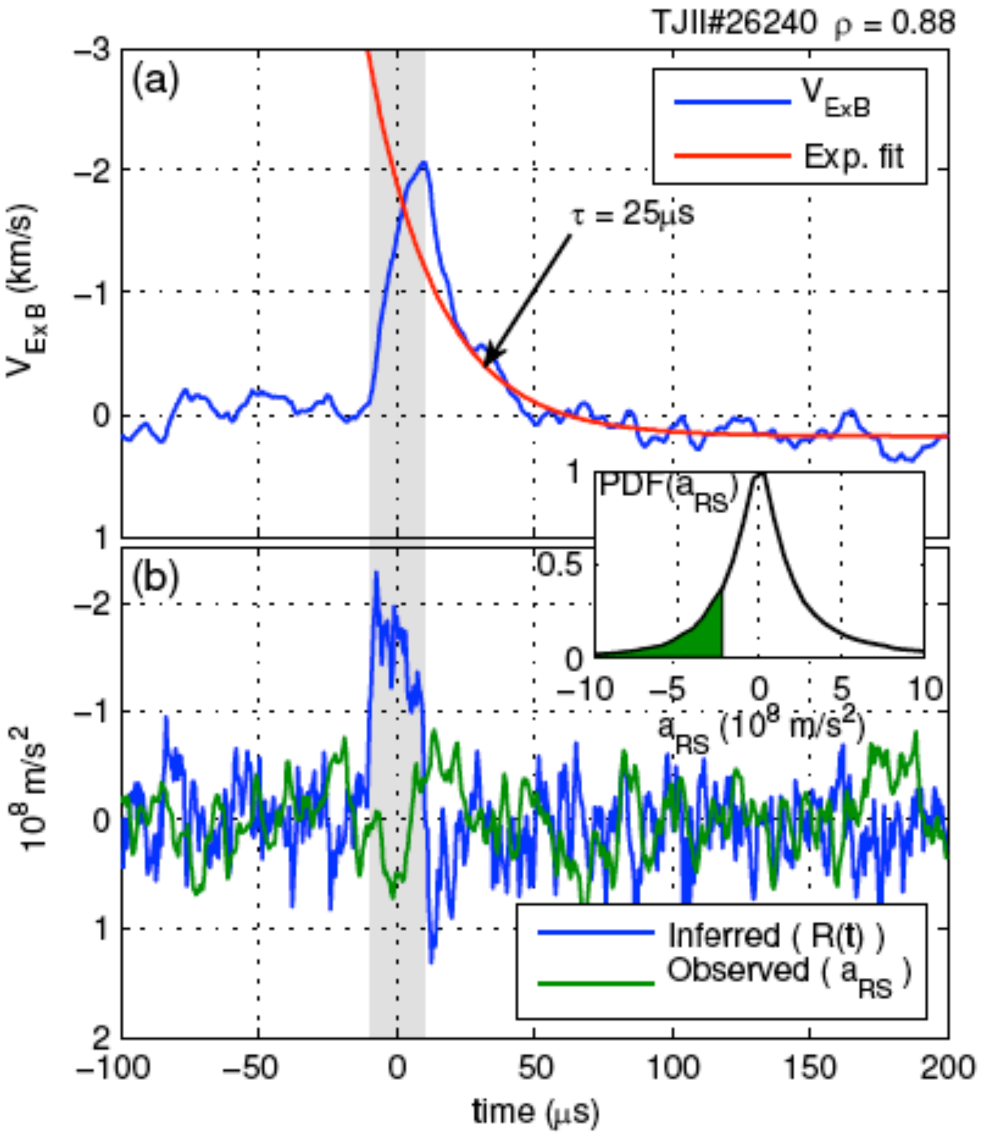
What drives ZFs?

- A typical (conditionally averaged) ZF evolution shows accerations of 10^8 m/s^2 and decay times of 25 μs.
- The 2D array of Langmuir probes allow to extract the (local) electrostatic turbulent momentum flux or Reynolds stress (RS).
- The PDF of RS acceleration shows events capable of producing the observed electric field excursions.
- However, no causal relationship could be established between those excursions and the locally measured RS.

Alonso PPCF 2012 (in press)

And, what damps ZFs? …

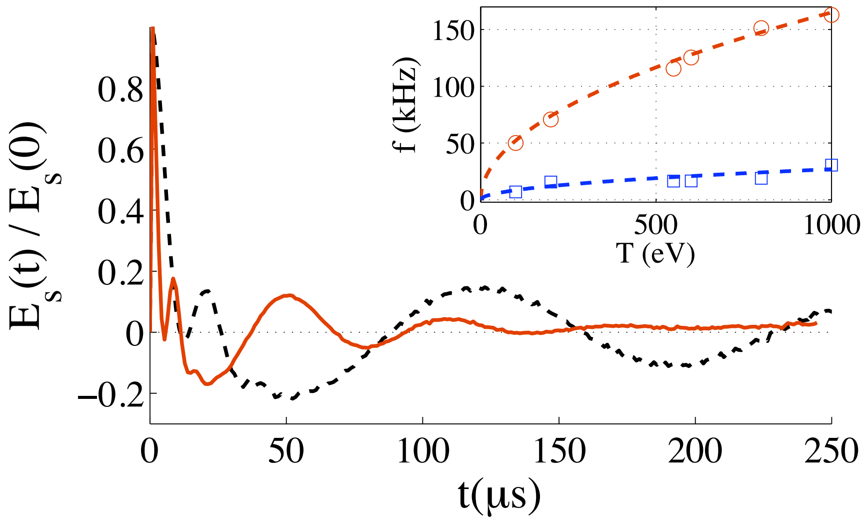
Typical ExB velocity excursion at rho= 0.88



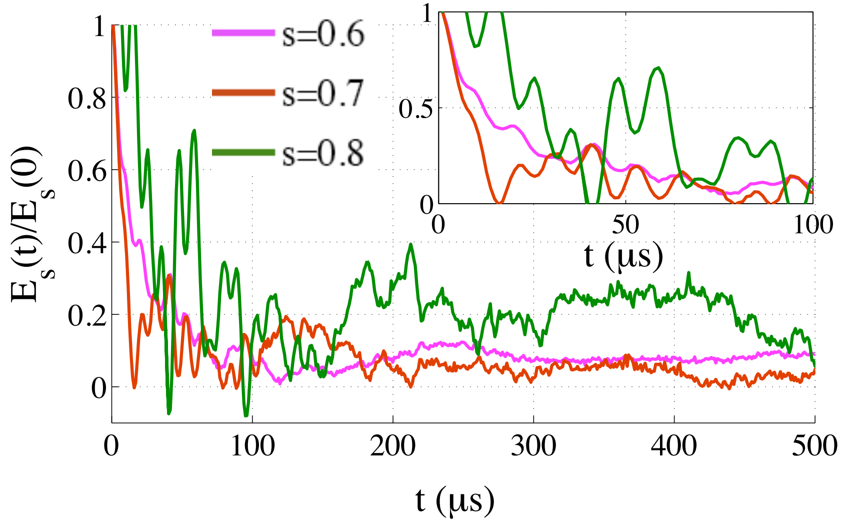
Collisionless relaxation of Zonal Flows

- Linear collisionless gyrokinetic simulations with the MC-PIC code EUTERPE [R. Kleiber CPC 2012, E. Sánchez PPCF 2012].
- The long-term evolution is dominated by slowly damped Low Frequency Oscillations (LFOs)
  - Temperature-dependence in qualitative agreement with theory [H. Sugama PoP 2005, Mishchenko PoP 2008].
- Typical frequencies of the edge LFO (<10 kHz) in agreement with the LRCs measured at the low-density transition and with the flow oscillations measured at the L-H transition [Pedrosa PRL 2008, Estrada NF 2012].
- Small residual ZF level is found, as expected for a non-quasisymmetric stellarator.
- A NC electric field increases residual level, in agreement with previous works.
- Typical relaxation times around the experimentally measured time for a perturbation with $k\rho \sim 0.1$.

WITHOUT ELECTRIC FIELD



WITH NC ELECTRIC FIELD



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L-H Transition Physics

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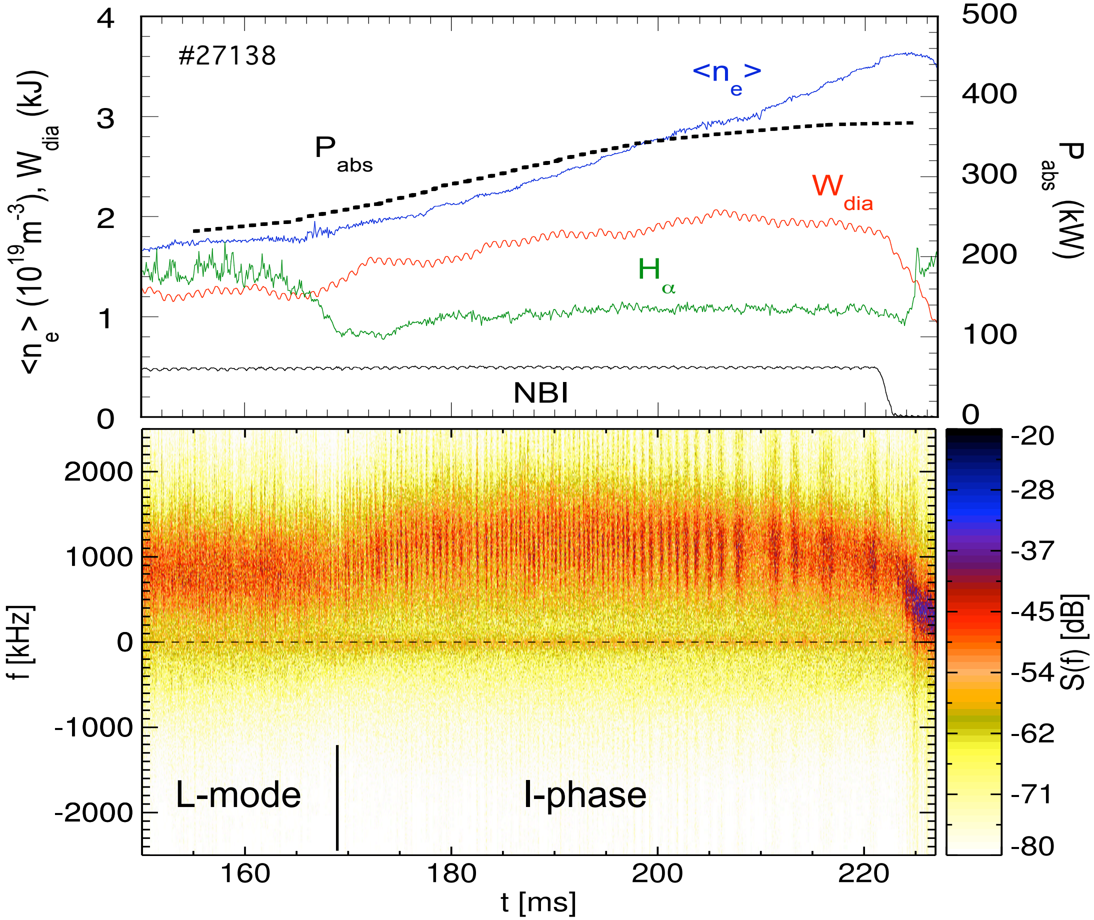
L-H transitions in TJ-II are achieved in pure NBI heated plasmas. In general, the plasma undergoes a *fast* direct transition from L to H-mode [Estrada PPCF 2009].

The magnetic configuration has a sensitive influence on H-mode realization and quality (Lopez-Bruna PPCF 2011)
(Lopez-Bruna, poster EX/P4-18, this afternoon)

Close to the transition threshold conditions at specific magnetic configurations, 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 [Kim & Diamond PRL 2003]



L-H transition dynamics: predator-prey behaviour

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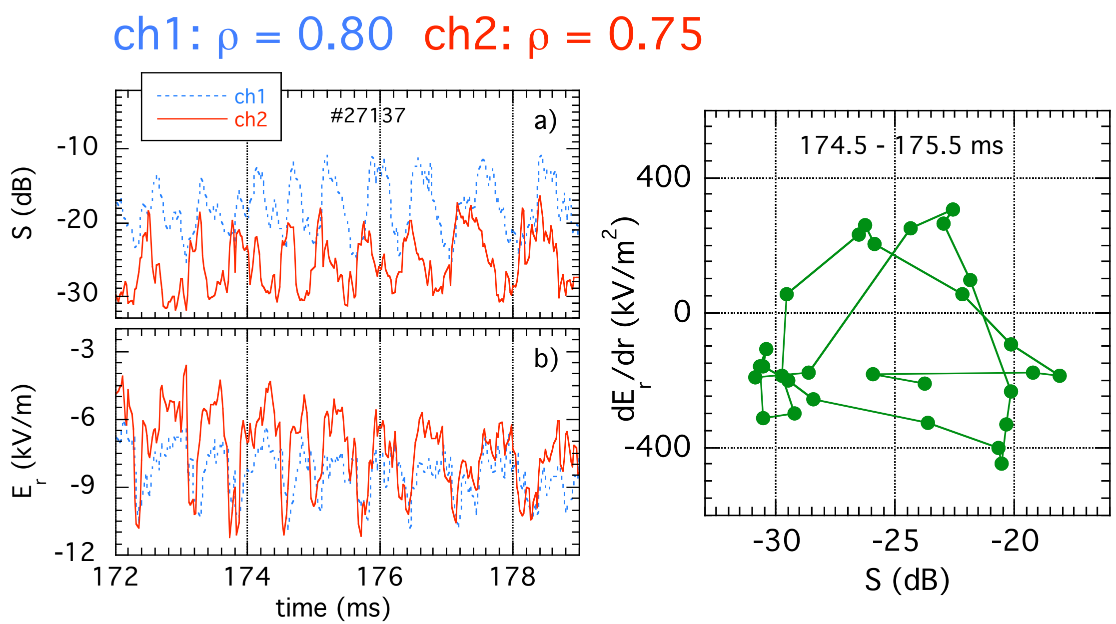
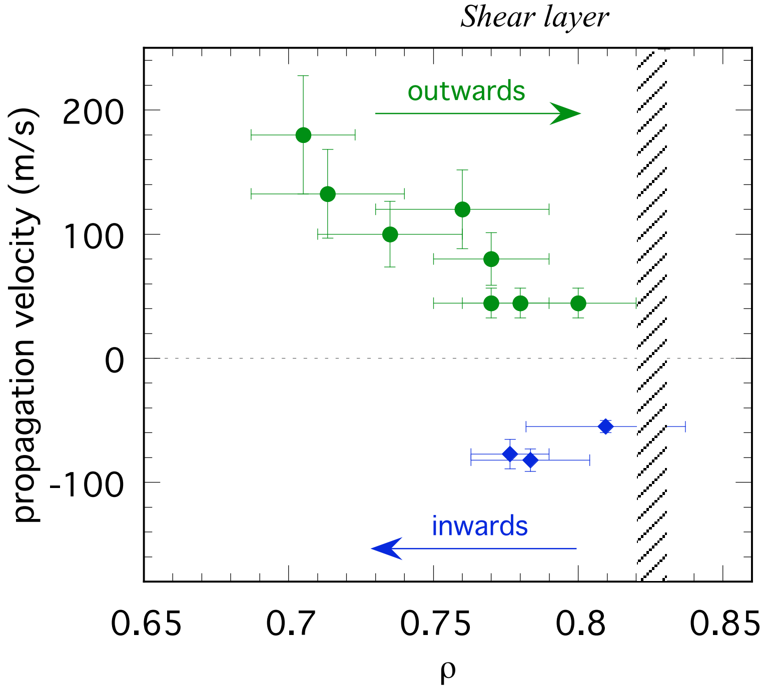
Predator-prey relationship between turbulence and flows: the flow -the predator- following the turbulence -the prey- with a phase delay of 90º as in a limit-cycle

The outward propagation velocity of the turbulence-flow front decreases as the E_r-shear location is approached



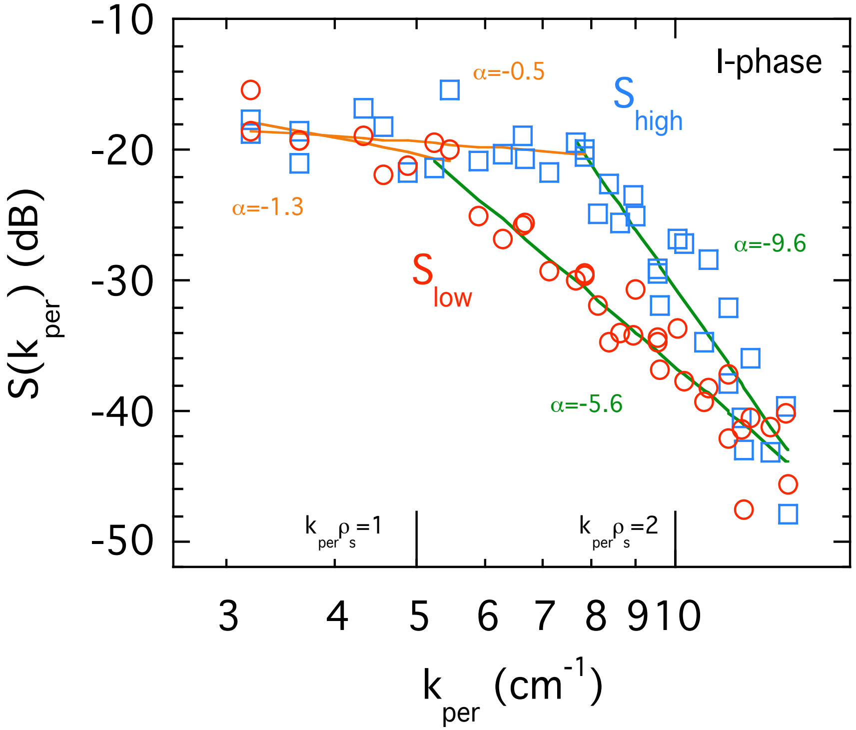


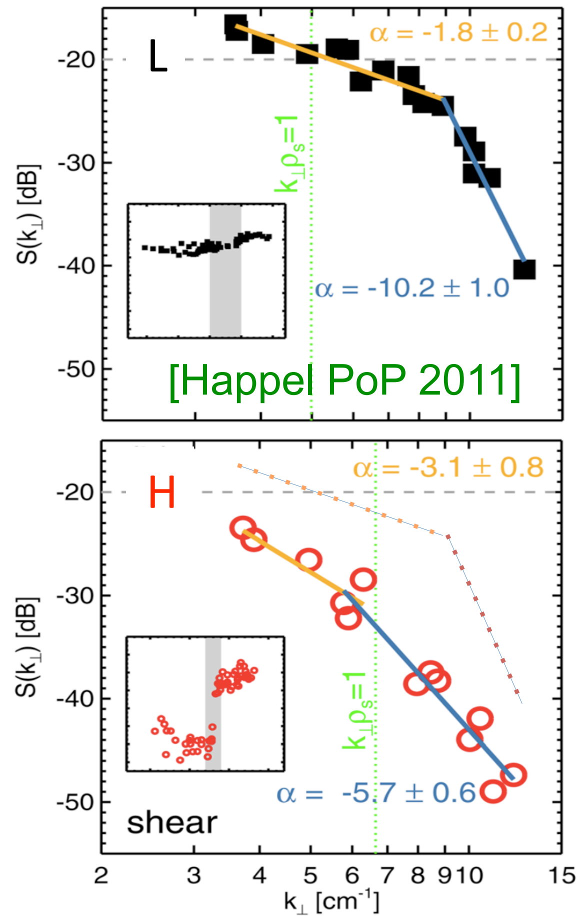
The **spatiotemporal evolution** of the oscillation-pattern shows **radial outward and inward propagation velocities of the turbulence-flow front.** [Estrada PRL 2011]

The results show the need of approaching L-H transition studies within a one-dimensional spatiotemporal framework [Miki PoP 2012 & Diamond TH/P4-02]

L-H transition : spectral structure of the turbulence-flow interaction

Turbulence wavenumber spectra in the **I-phase**: extreme values of the turbulence level [Estrada PPCF 2012]





I-phase: Intermediate turbulence scales, $k_{per} \approx 6 - 12$ cm^{-1}, dominate the energy transfer of the turbulence-flow prey-predator process. As the plasma enters into the **H-mode**, a turbulence reduction is measured in the whole wavenumber range.

L-H transition dynamics and ZFs

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- At the transition threshold conditions, the so-called intermediate phase starts in which the coupling between turbulence and flows takes place, following a predator-prey relationship.
- In this 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 sheared flows may become active affecting a broader range of turbulence scales.

T. Estrada, oral EX/10-2 (Saturday morning)

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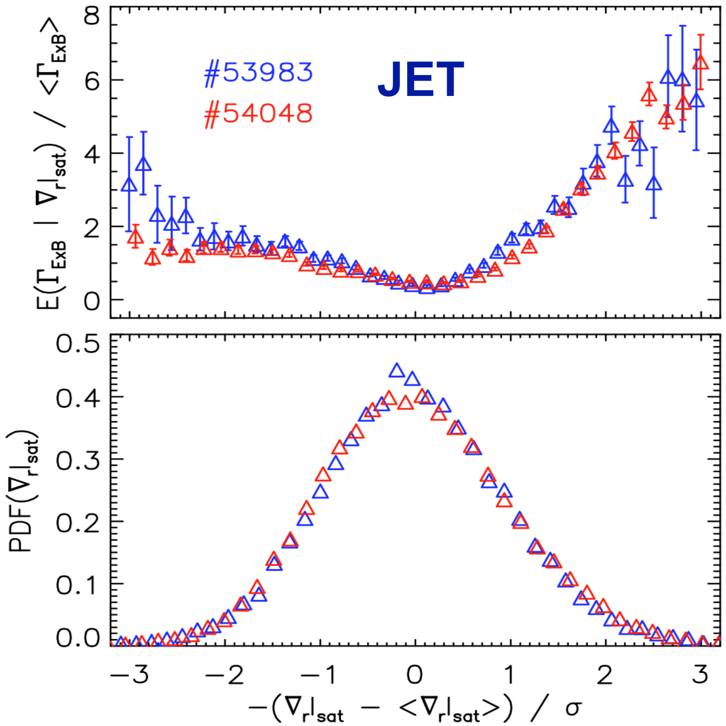
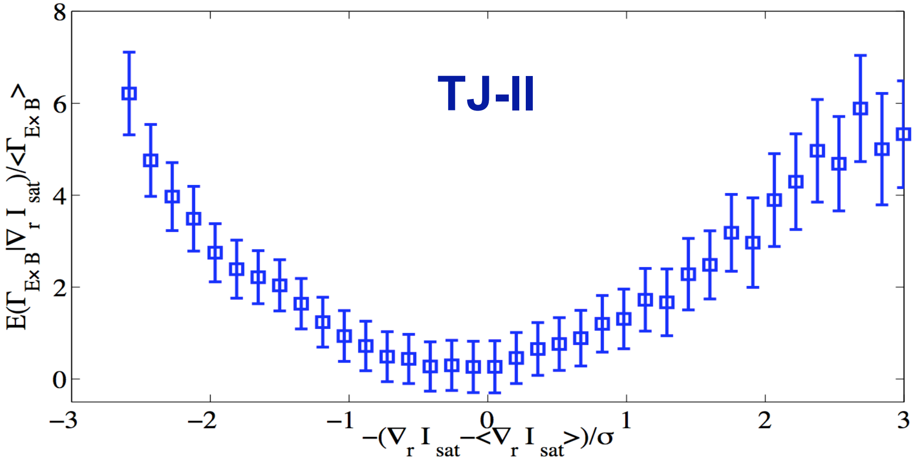
Relation between transport and gradients

Expected value of the turbulent flux



C. Hidalgo et al., Phys. Rev. Lett 2012



A non-linear coupling between fluxes and gradients is observed both in JET and TJ-II.

Measurements show that the size of turbulence transport events increases when plasma density gradient deviates from its most probable value:

-Fluctuations are self-regulated in such a way that the most probable density gradient minimizes the size of the radial turbulent transport events.

(C. Hidalgo, poster EX/P3-22 (this morning))

Conclusions

- The role of ZFs on plasma confinement in the TJ-II stellarator, under Li coated wall, has been studied.
- In the low density transition the NC viscosity vanishes. This may explain the observation of ZFs, which were shown to regulate transport.
- ZFs suffer collisionless damping but they can survive in the presence of the ambipolar NC field.
- Close to the L-H transition threshold conditions, ZFs regulate the turbulence, following a prey-predator behaviour. The spatiotemporal evolution of the oscillation-pattern and the relevant turbulence scales involved in the process have been identified.
- Gradients and fluxes are dynamically coupled: The most probable density gradient minimises the turbulent flux.

TJ-II results at this conference

- K. Ida et al. Towards an Emerging Understanding of Non-local Transport. OV/3-4 (Wednesday Morning)
- B. Zurro et al. Suprathermal Ion Studies in ECRH and NBI Phases of the TJ-II Stellarator. EX/P3-06 (Wednesday Morning)
- C. Hidalgo et al. Dynamical Coupling Between Gradients and Transport in Tokamaks and Stellarators. EX/P3-22 (Wednesday Morning)
- A. Dinklage et al. Inter.Machine Validation Study of NC Trasnport Mmodelling in Medium- to High-Density Stellarator Heliotron Plasmas. EX/P3-14 (Wednesday Morning)
- D. López-Bruna et al. MHD Events and Transport Barriers in TJ-II Plasmas. EX/P4-18 (Wednesday Afternoon)
- J.A. Romero et al. Current profile control using the ohmic heating coil in TCV". EX/P4-35 (Wednesday Afternoon)
- F. Tabarés et al. Studies of Plasma-Lithium Interactions in TJ-II. EX/P5-36 (Thursday Morning)
- S. Yamamoto et al. Studies of Energetic-ion-driven MHD Instabilities in Helical Plasmas with Low Magnetic Shear. EX/5-2 (Thursday morning)
- T. Estrada et al. Spatiotemporal and spectral structure of the turbulence-flow interaction at the L-H transition in TJ-II plasma. EX/10-2 (Saturday Morning)

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Back-up

$$|\hat{E}_r(\omega)|^2 \propto \frac{1}{\nu_p^2 + \omega^2}$$