Turbulence and intermittent transport in edge/SOL of a toroidal plasmas

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Motivation

Cross field transport of particles and heat in the edge/scrape-off-layer (SOL) region of a magnetically confined plasma is strongly intermittent and characterized by:

- large-amplitude, radially propagating blob-like structures of particles and heat,
- generated close to the last closed flux surface (LCFS),
- resulting in asymmetric conditional wave forms, and skewed and flattened PDFs,

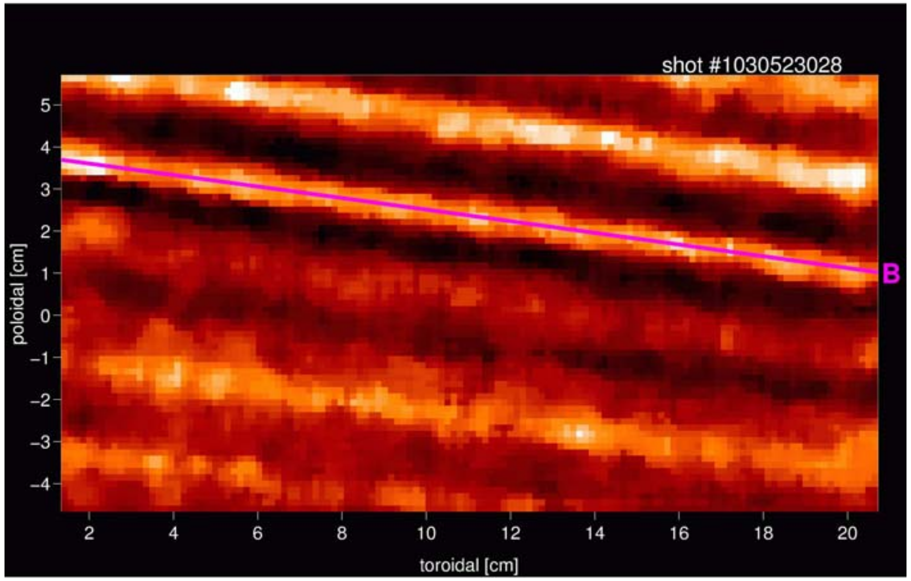
Observed under a variety of conditions:

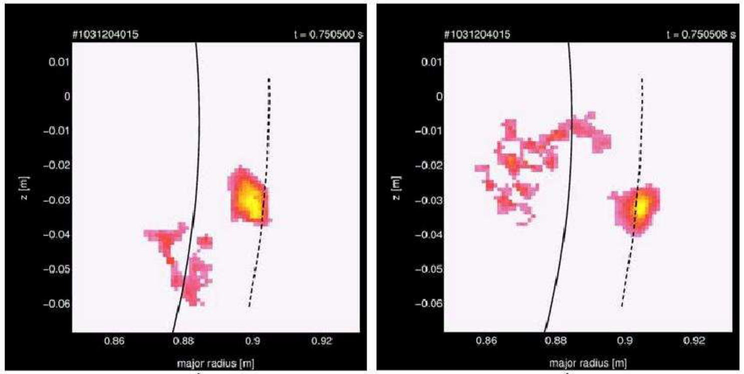
see, e.g., Zweben Phys. Fluids **28** 974 (1985) Antar *et al*, PoP **10** 419 (2003); Boedo *et al*, PoP **10**, 1670 (2003); Zweben *et al*, Nucl. Fus. **44**, 134 (2004); Grulke *et al* PSI-2004

Density blob observations

Observations of density blobs at the outboard midplane of ALCATOR C-mod (D_α - light)

O. Grulke *et al.* PSI-2004.





Structure along B.

Radial propagation, $V \approx 0.05 c_s$.

Density blobs theory

Several recent works:

Krasheninnikov PLA **283**, 268 (2001)

Curvature drift: charging of a density blob → radial propagation, velocity fraction of c_s, linear model, no self-consistent blob formation

D'Ippolito *et al*, PoP **9**, 222 (2002)

Bian *et al*, PoP **10**, 671 (2003)

D'Ippolito *et al*, CPP **44**, 205 (2004)

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Similar mechanism for uprising density bubbles in ionospheric E-F layer – inverse stratification in a gravitational field.

e.g. Kelley and Ott, JGR **83**, 4369 (1978).

Overview

A self-consistent description of fluctuations and intermittent transport in the edge/SOL by employing the RISØ ESEL (Edge SOL Electrostatic) model for interchange dynamics that:

- include separate plasma production "edge" and loss region "SOL",
- allow self-consistent flows and profile relaxations,
- conserve particles and energy in collective dynamics.

Results are in good agreement with experimental observations

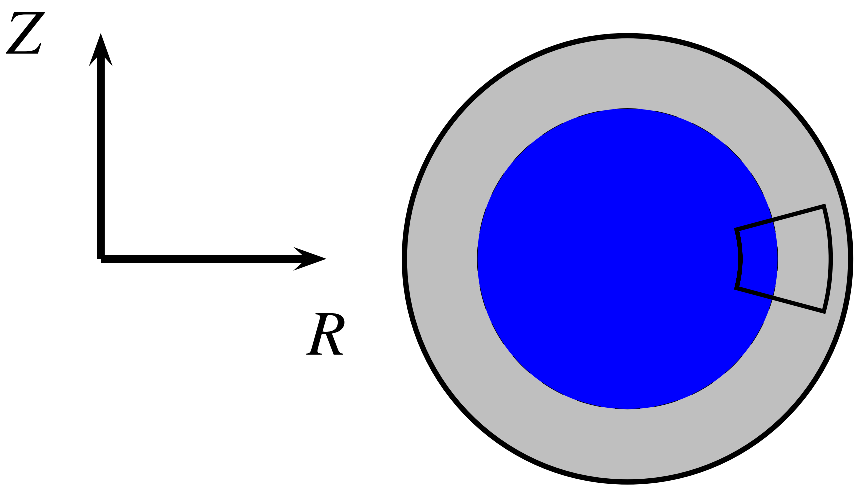
Garcia, Naulin, Nielsen, Rasmussen, PRL **92** 165003 (2004); PoP 2005 submitted.

Geometry and Coordinates

We consider the outboard midplane of a toroidal plasma

The non-uniform magnetic field is $\mathbf{B} = -(B_0 R_0/R)\widehat{\Theta}$, described in elementary cylindrical coordinates (R, Θ, Z).

Applying a local slab approximation: $x = R - R_a$, $y = Z$, $z = -\Theta$.



Model Equations

Fluid model cold ions and quasi-neutrality

$$\frac{dn}{dt} + nC(\phi) - C(nT) = \nu_n \nabla_\perp^2 n - \sigma_n (n-1) + S_n,$$

$$\frac{dT}{dt} + \frac{2T}{3} C(\phi) - \frac{7T}{3} C(T) - \frac{2T^2}{3n} C(n) = \nu_T \nabla_\perp^2 T - \sigma_T (T-1) + S_T,$$

$$\frac{d\Omega}{dt} - C(nT) = \nu_\Omega \nabla_\perp^2 \Omega - \sigma_\Omega \Omega, \quad \Omega = \nabla_\perp^2 \phi.$$

Advective derivative and curvature operators defined by

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{1}{B} \widehat{\mathbf{z}} \times \nabla\phi \cdot \nabla, \quad C = \nabla \left(\frac{1}{B} \right) \cdot \widehat{\mathbf{z}} \times \nabla, \quad B(x) = \frac{1}{1 + \varepsilon + \zeta x}.$$

Conservation of particles and global energy (lowest order in ζ)

$$E(t) = \int d\mathbf{x} \left[\frac{1}{2} (\nabla_\perp \phi)^2 + \frac{3}{2} nT \right].$$

RISØ Instability, Energy Integrals

Interchange instability: $N = -B'(p_0' - \frac{5}{3}B') \leq 0$ instability at low field side.

Naulin et al. PRL **81**, 4148 (1998); PoP **10**, 1075 (2003)

Define the kinetic energy of the fluctuating and poloidal mean motions,

$v_0(x,t) = \frac{1}{L_y}\int_0^{L_y} v_y(\mathbf{x},t)dy = \partial\phi_0/\partial x$:

$$K(t) = \int \frac{1}{2}\left(\nabla_\perp\widetilde{\phi}\right)^2 d\mathbf{x}, \qquad U(t) = \int \frac{1}{2} v_0^2 \, d\mathbf{x} \,.$$

Energy Transfer, Transport

Define the kinetic energy of the fluctuating and poloidal mean motions,
$v_0(x,t) = \frac{1}{L_y}\int_0^{L_y} v_y(\mathbf{x},t)dy = \partial\phi_0/\partial x$:

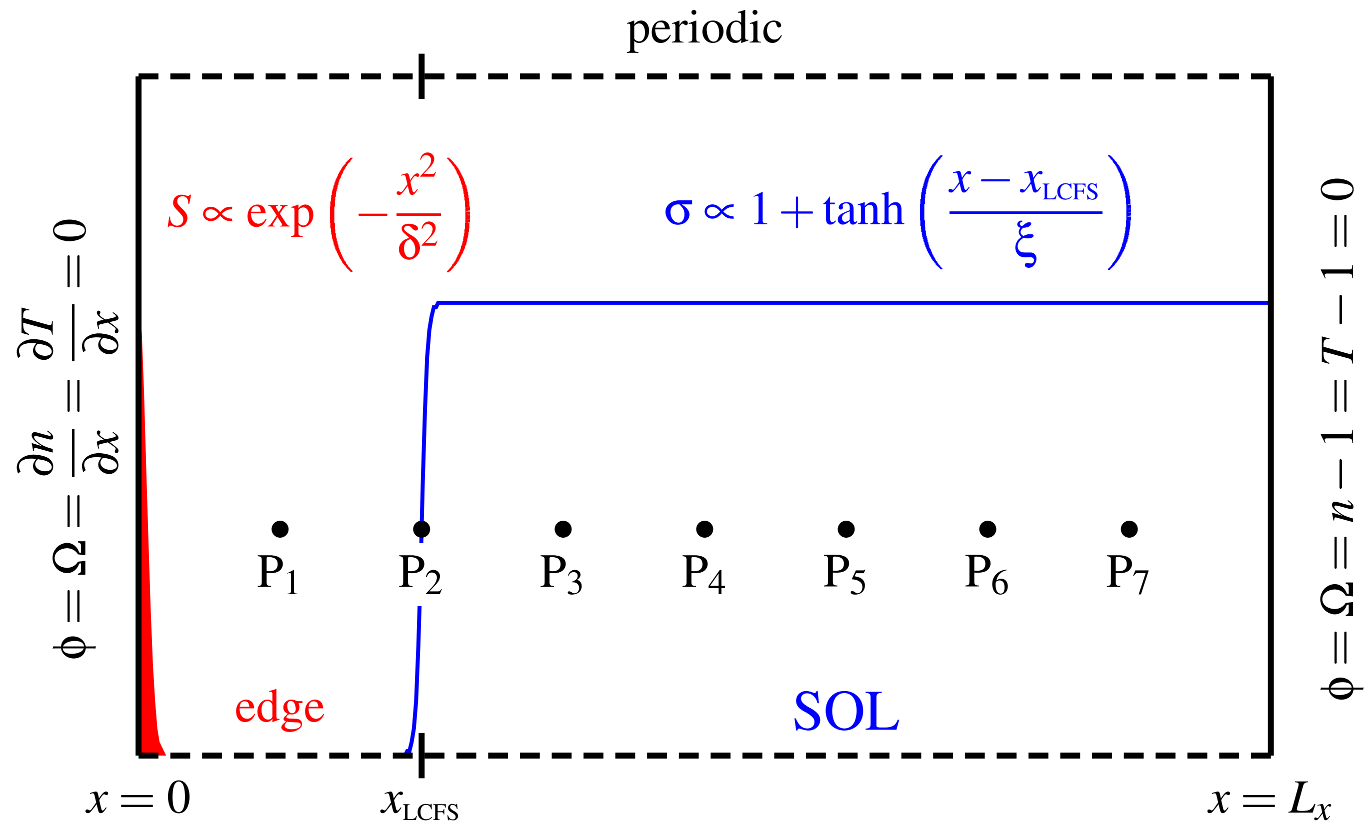
$$K(t) = \int \frac{1}{2}\left(\nabla_\perp\widetilde{\phi}\right)^2 d\mathbf{x}, \qquad U(t) = \int \frac{1}{2} v_0^2\, d\mathbf{x}\ .$$

Energy transfer rates from thermal energy to the fluctuating motions, and from the fluctuating to the poloidal mean flow:

$$F_p(t) = \int pC(\phi)\, d\mathbf{x}, \qquad F_v(t) = \int \widetilde{v}_x\widetilde{v}_y \frac{\partial v_0}{\partial x}\, d\mathbf{x}.$$

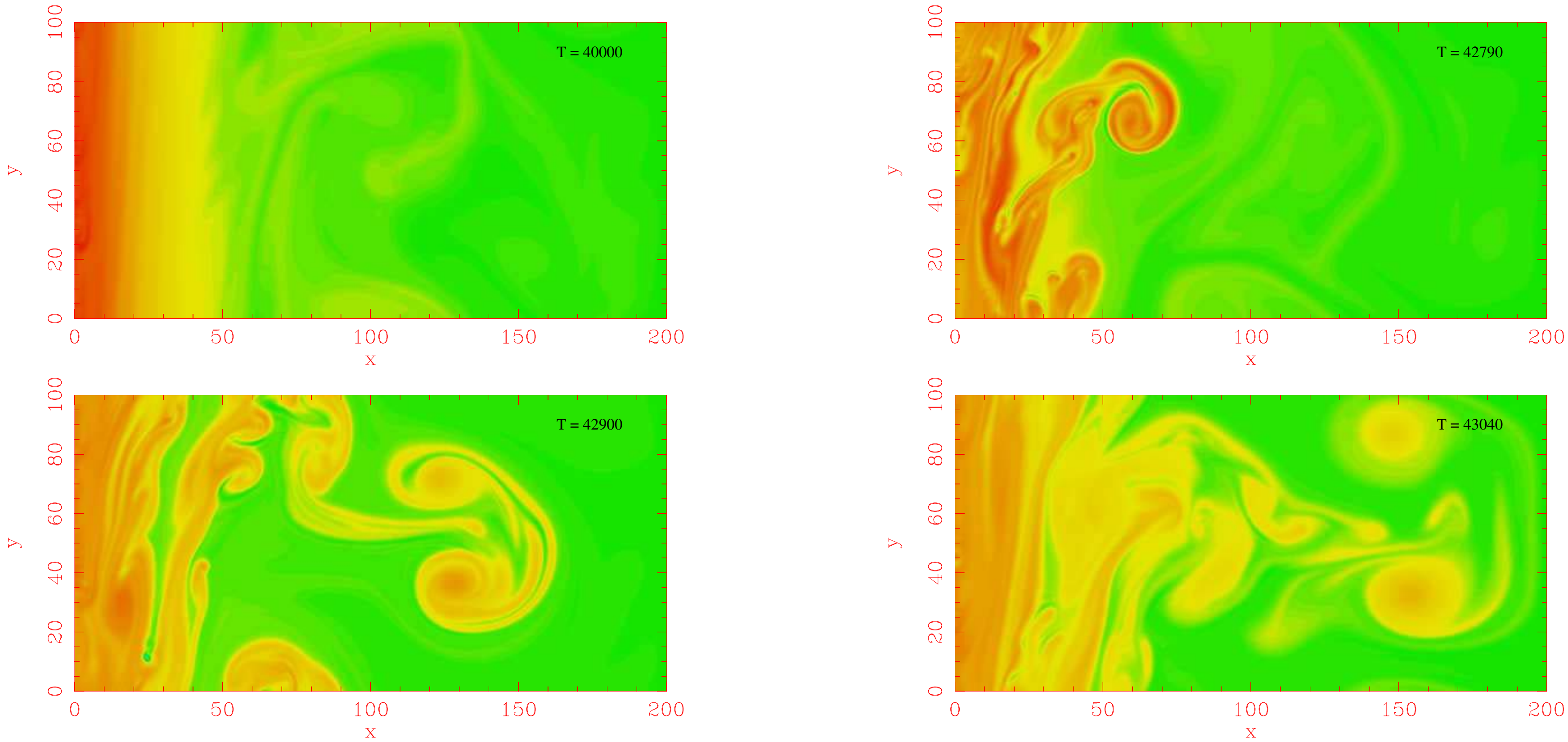
F_p is also a measure of the turbulent energy transport.

Simulation Geometry



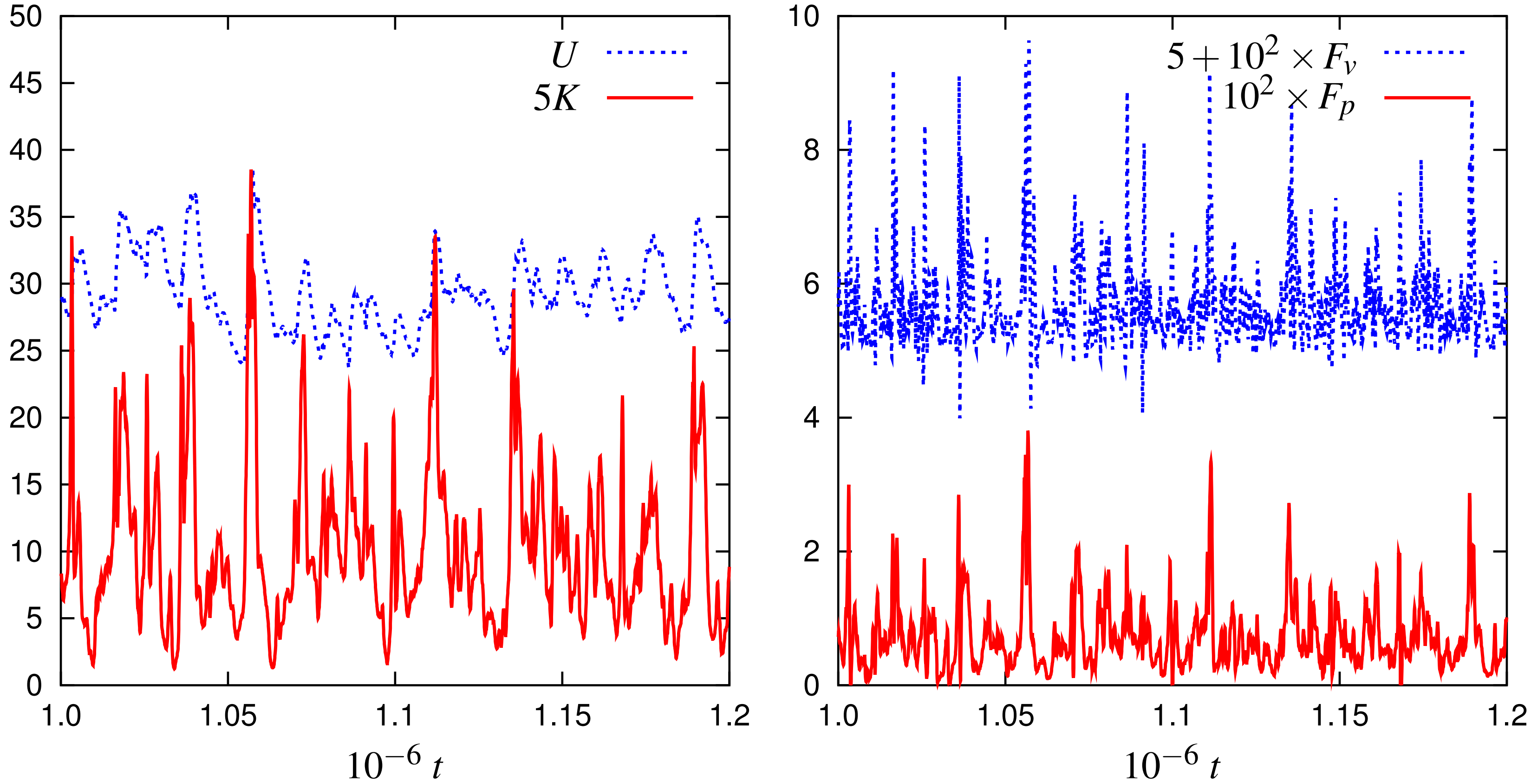
Domain $L_x = 2L_y = 200$, resolution 512×256, $x_{\mathrm{LCFS}} = 50$. SOL damping rates $\sigma_n = \sigma_\Omega = \sigma_T/5 = 3\zeta/2\pi q$ with $q = 3$; magnetic curvature $\varepsilon = 0.25$, $\zeta = 5 \times 10^{-4}$; collisional diffusion $\nu = 10^{-2}$; timespan 4×10^6

Density Evolution



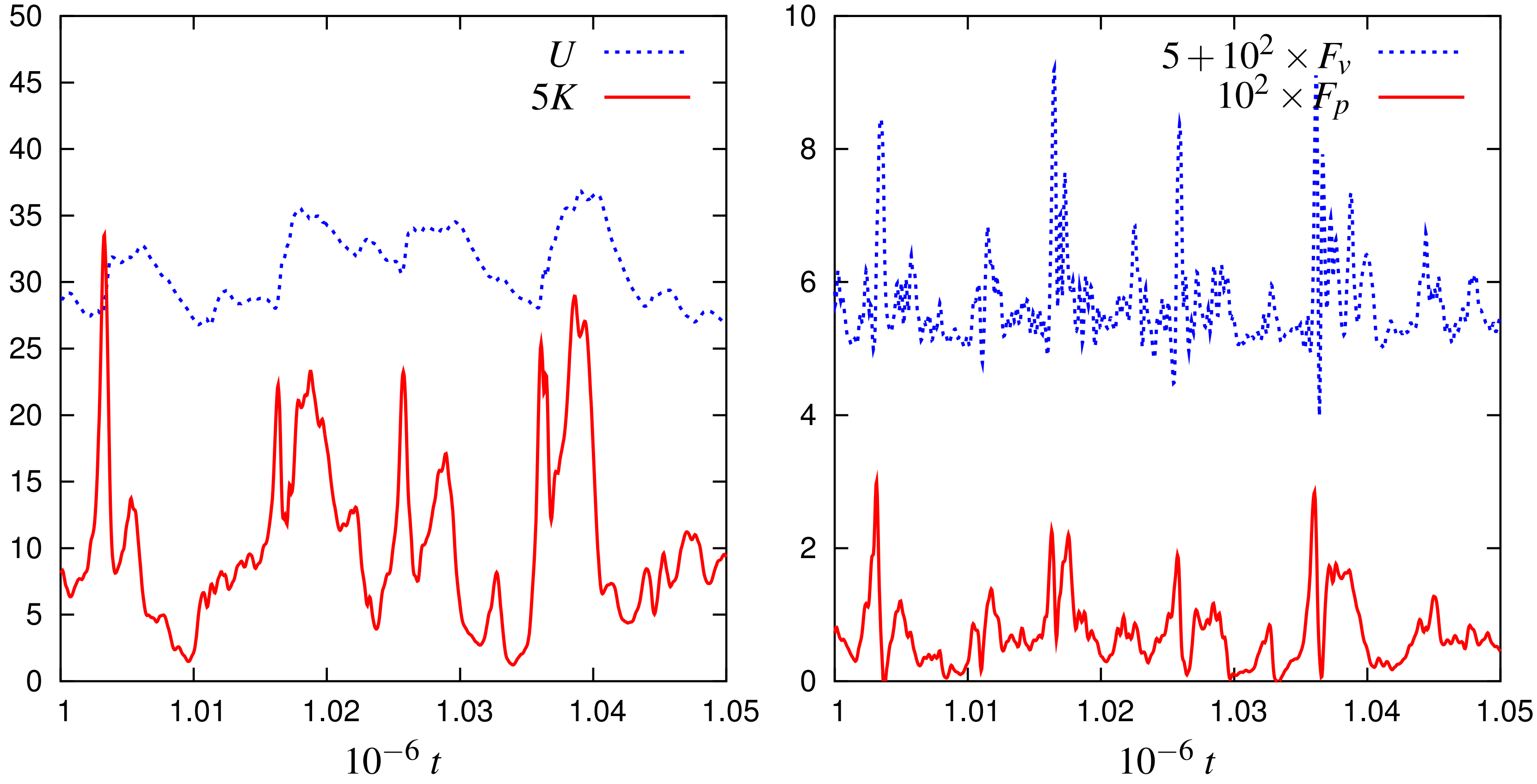
Density blob propagation: The blob is generated inside LCFS ($x_{LCFS} = 50$). Radial propagation velocity of the structures is estimated to $\approx 0.05c_s$; but with large variance. Envisage the density blob as a filament elongated along the magnetic field with a ballooning structure.

Energy Transfer



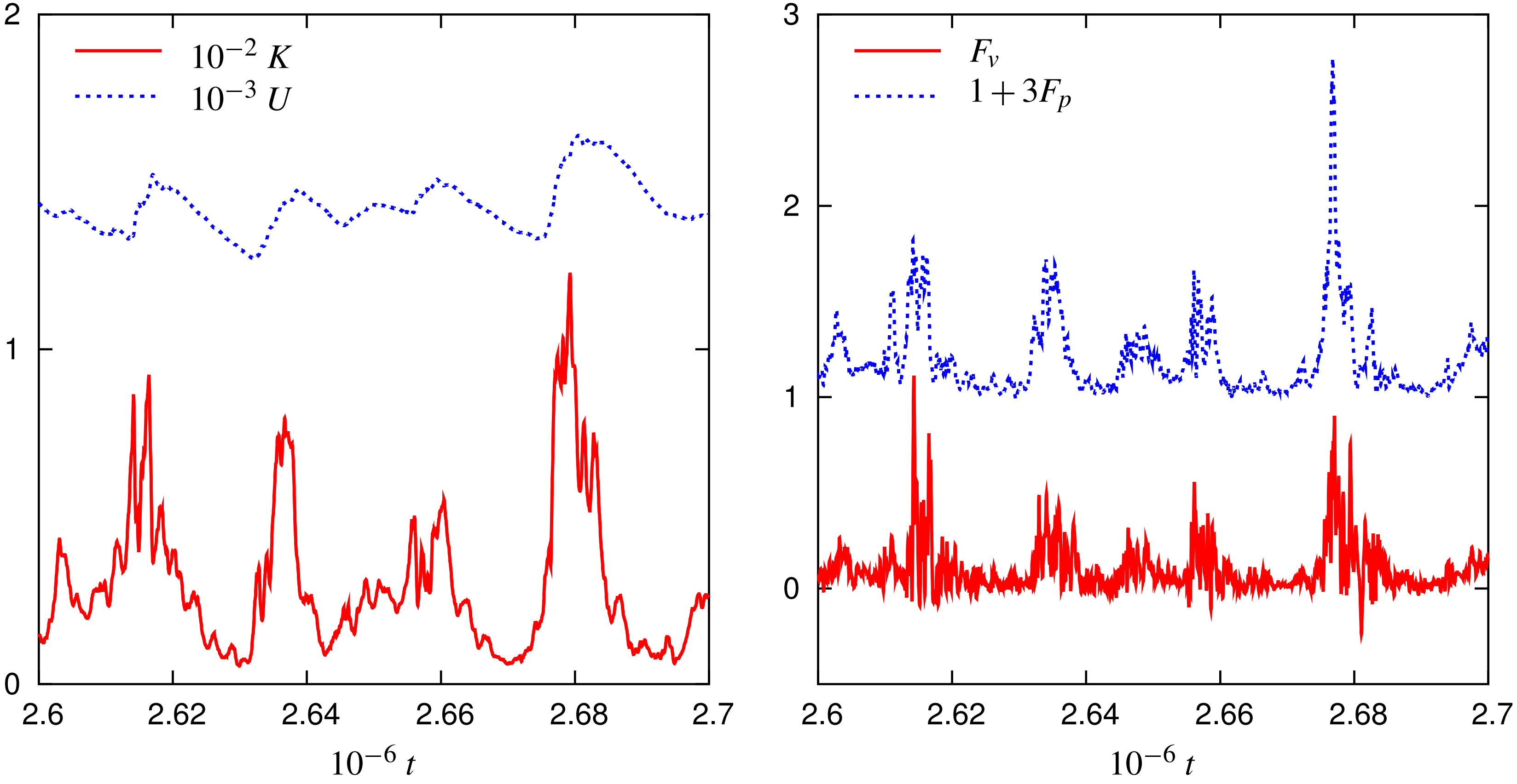
Bursting : Kinetic energy contained by the mean U *and fluctuating* K *motions and the collective energy transfer terms* F_p *and* F_v *.*

Energy Transfer



Bursting : Expanded time scale, ($\nu = 10^{-2}$) .

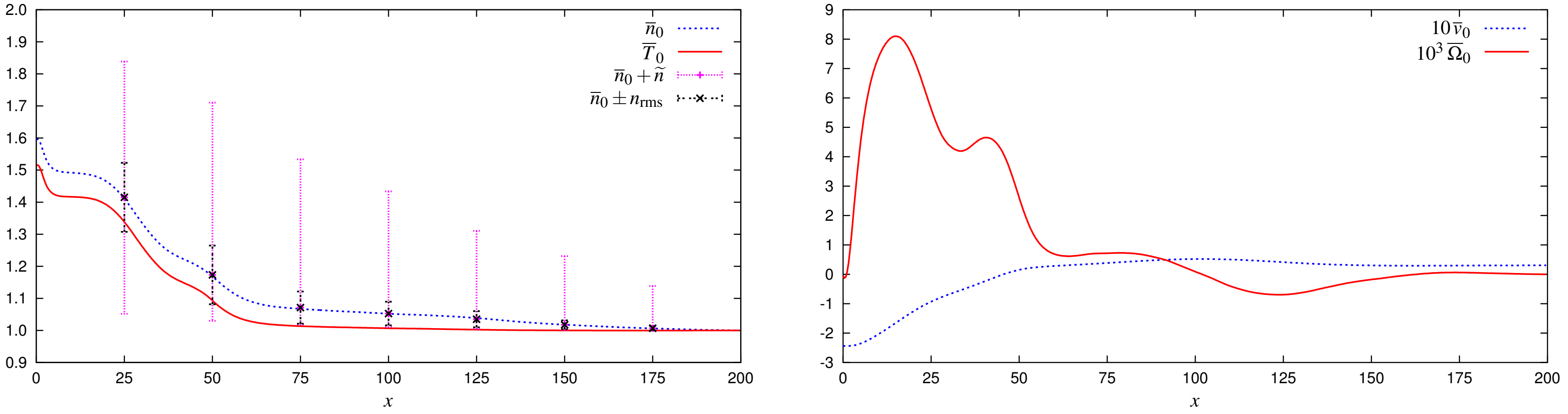
Energy Transfer



Bursting : Half viscosity $\nu = 5 \times 10^{-3} \rightarrow$ *double time span*

Robust behavior

Profiles



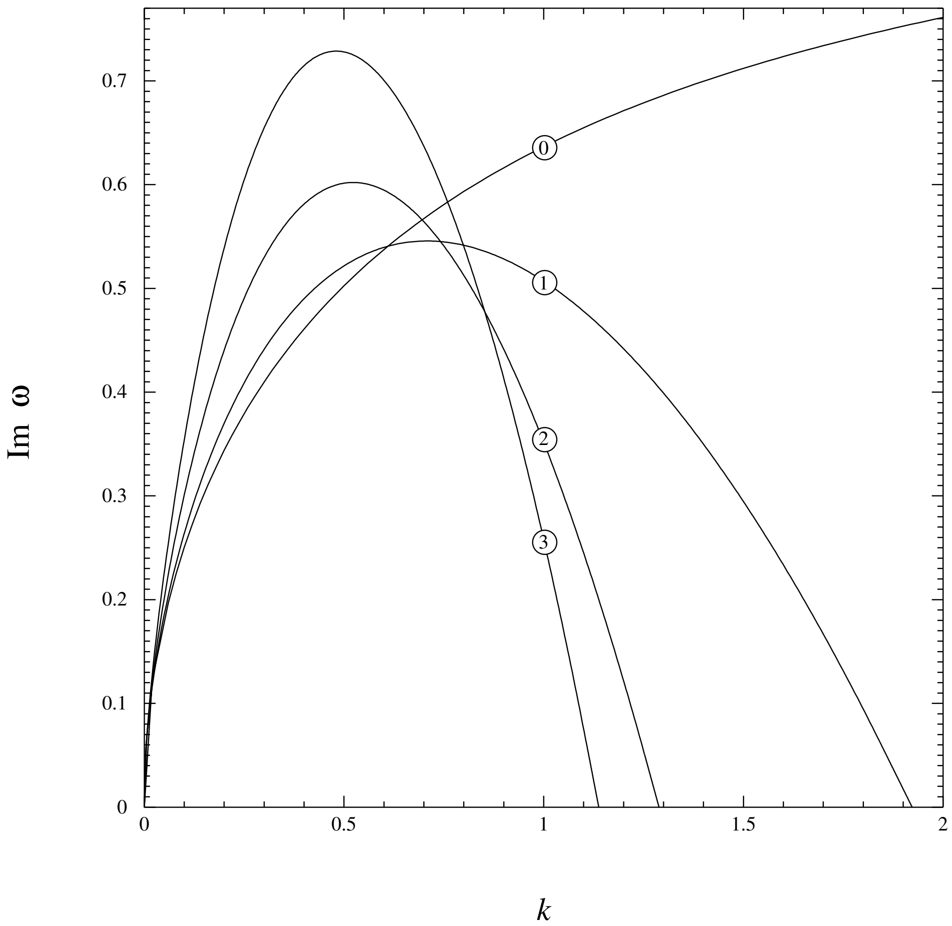
Time averaged profile of density, $\bar{n}_0$ *and temperature,* $\bar{T}_0$*: Strong gradients in the edge region* ($x < x_{LCFS} = 50$) *and flat profiles in the SOL.*

Time averaged profile of the poloidal flow, $\bar{v}_0$*, and vorticity,* $\bar{\Omega}_0$ ($\nu = 10^{-2}$)

Shear flow stabilization?

Influence of a background shear flow $V(x)\hat{y}$ on the classical interchange instability

Benilov *et al* Phys. Fluids **14** 1674 (2002)



Numerical solution of linear dispersion relation: $V(x) = V_0 \tanh x$, $V_0 = 0,\ 0.5,\ 1.0,\ 2.0$

NOTE: Stability for $2\pi/L_y > k_c$

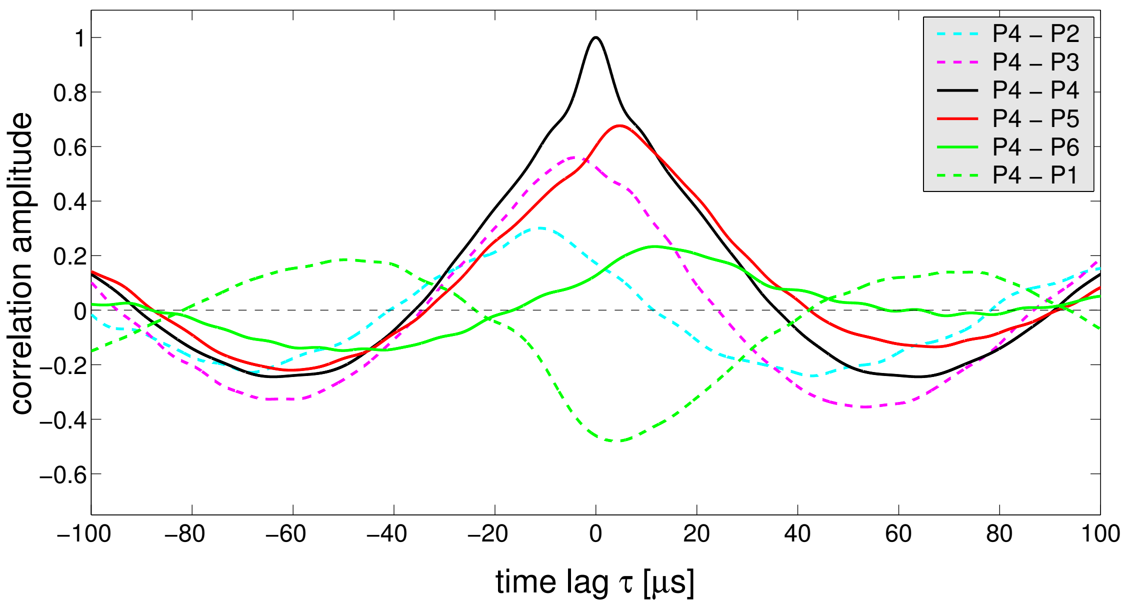
Energy flow

- Instability drive in the edge
- Turbulence propagating into the SOL
- Saturates and via particle and momentum fluxes
- Profile modification and flow generation; weak transport
- Profile steepening, flow damping (viscous timescale)
- Instability drive

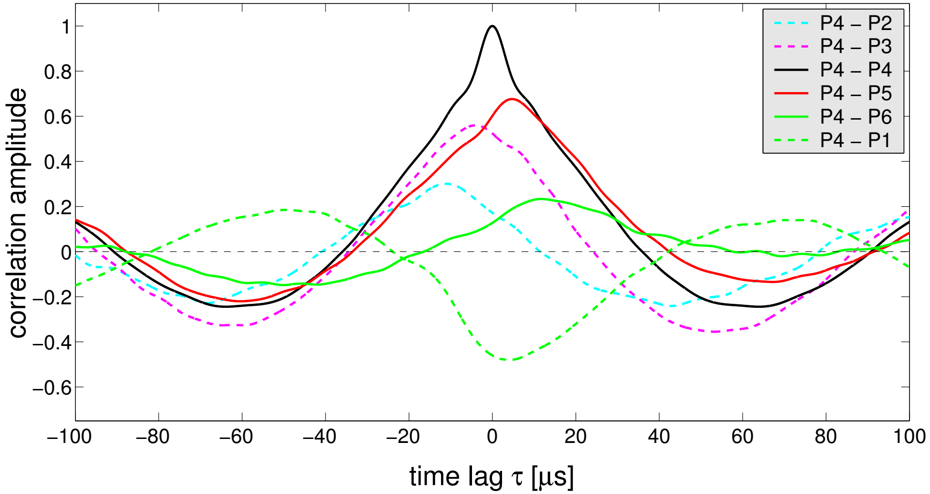
Bursting period related to viscous timescale.

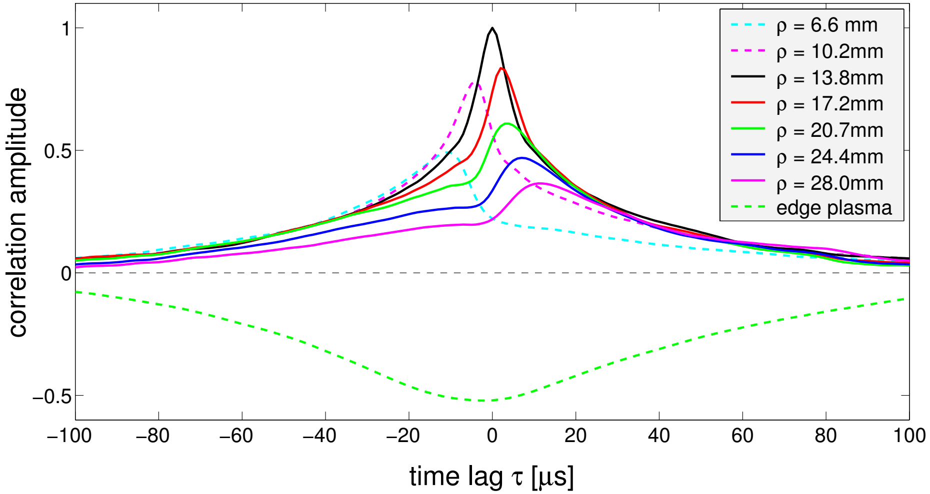
Cross-correlations

Cross-correlations of density fluctuations between probe P_4 *and the other probes* P_i *in the simulations:*



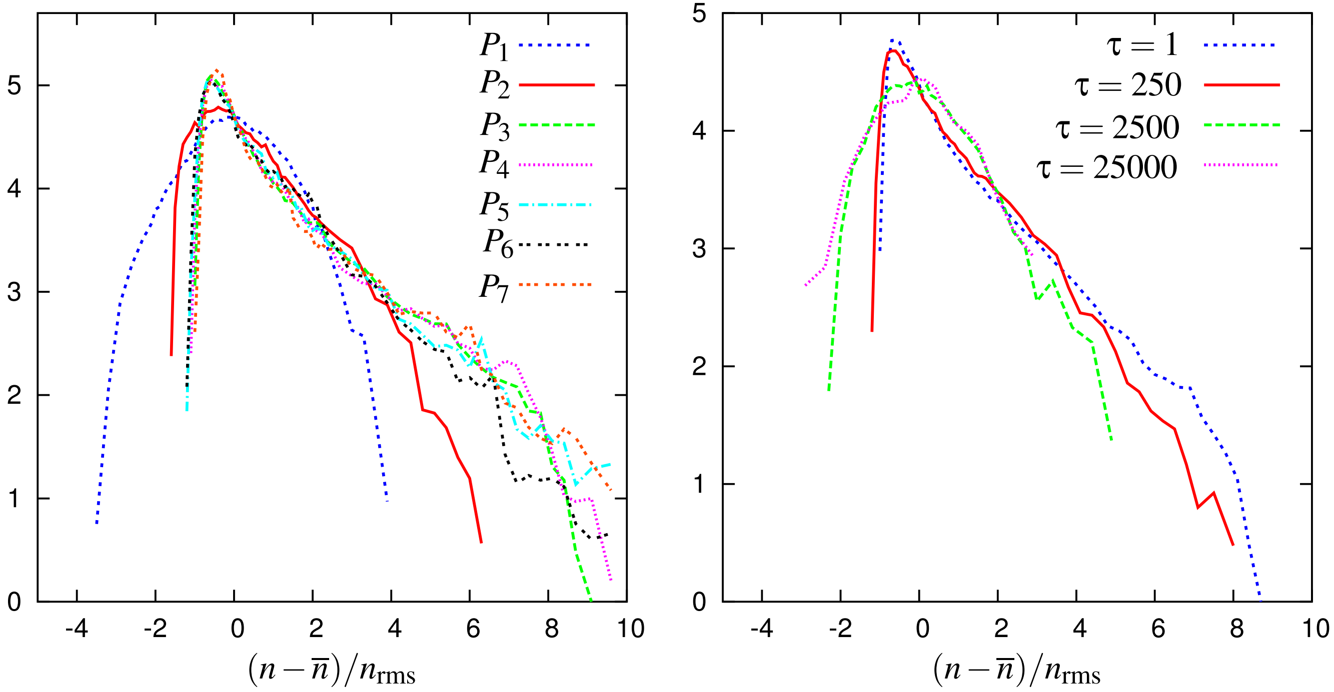
..Comparison Experiment





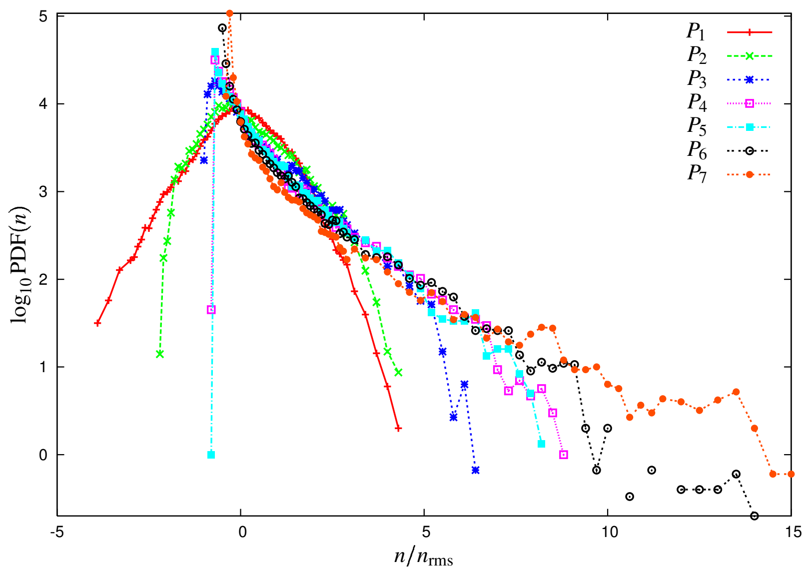
Cross-correlations between probe at $\rho = 13.8mm$ and the other probes in ALCATOR C-Mod (Grulke et al)

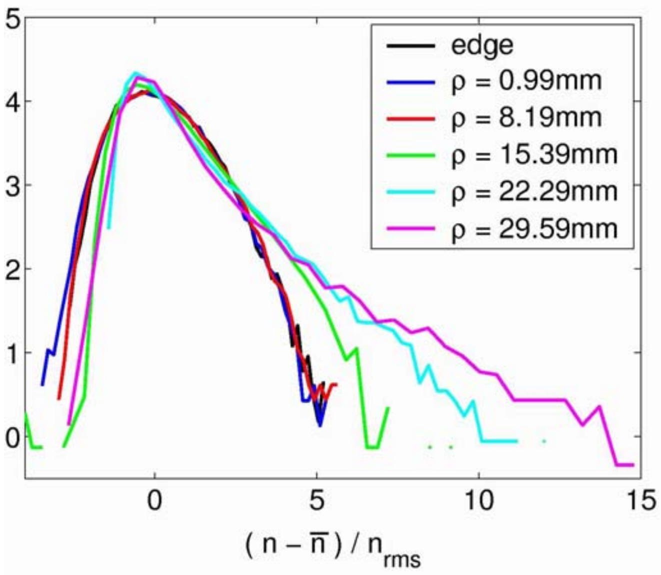
Single-Point PDFs



Probability distribution functions (count number) of density at P_i.
$i > 2$ exponential tails, indicating strong blob structures.
Coarse grained PDF at P_3. Time intervals τ. Increasing τ: skewness decreases: 2.6 $\rightarrow$ 0.06, flatness factor decreases: 12.0 $\rightarrow$ 3.1. Absence of self-similarity for all scales ($\tau > 10^4$): intermittency

..Comparison Experiment





Probability distribution functions (count number) of density at P_i.

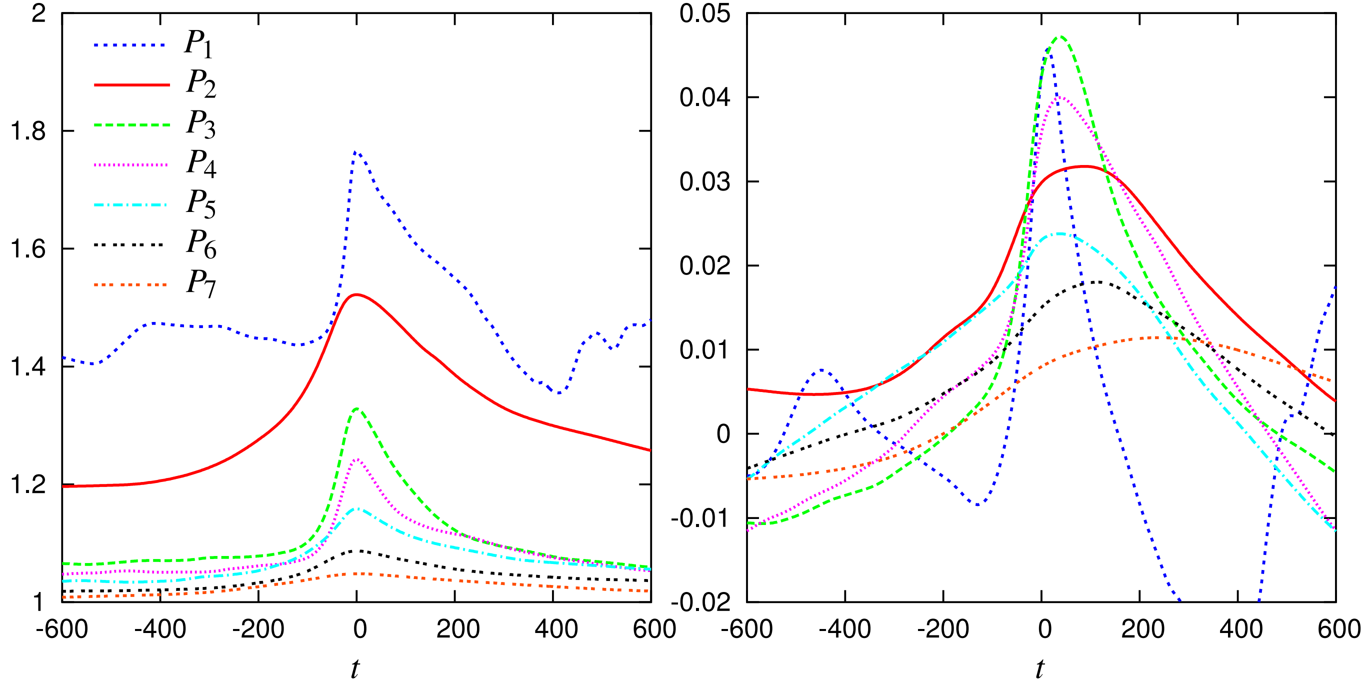
$i > 2$ *exponential tails, indicating strong blob structures.*

PDF from experiment in ALCATOR C-Mod (Grulke et al)

Detailed comparisons with density fluctuation PDFs at TCV are in progress. Universal PDF: One parameter Gamma-distribution.

Graves *et al*, PPCF **47**, L1 (2005)

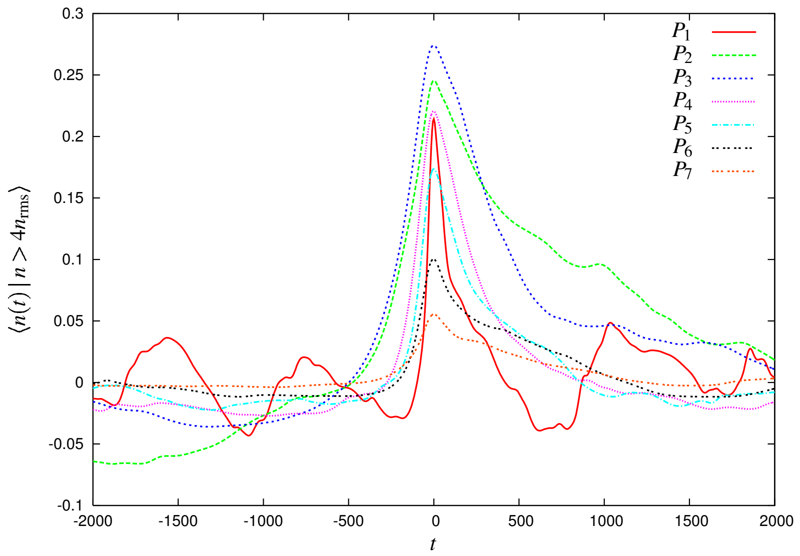
Conditionally Averaging

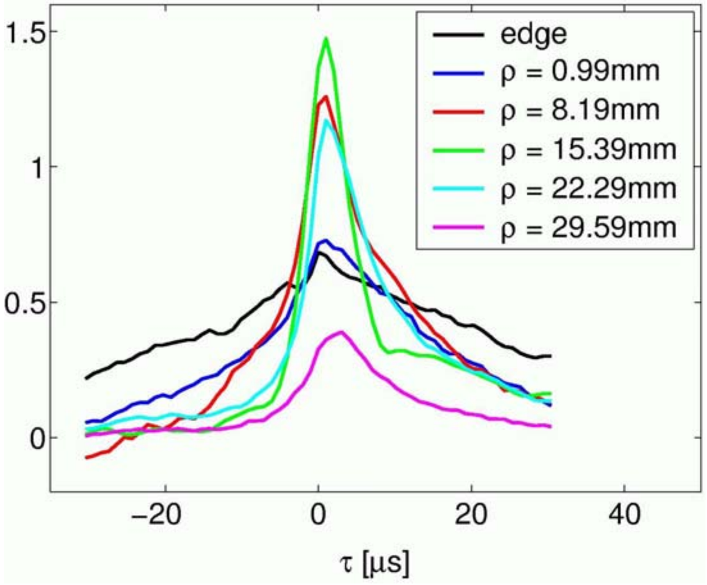


Conditional averaging of the density signal: asymmetric, large-amplitude wave forms significantly exceeding the back-ground levels; decaying outwards in the SOL. Condition $n(x_{P_i}) - \bar{n}(x_{P_i}) > 3n_{rms}(x_{P_i})$

Conditional averaging of radial velocity; maximum > 0 *in blob center.*

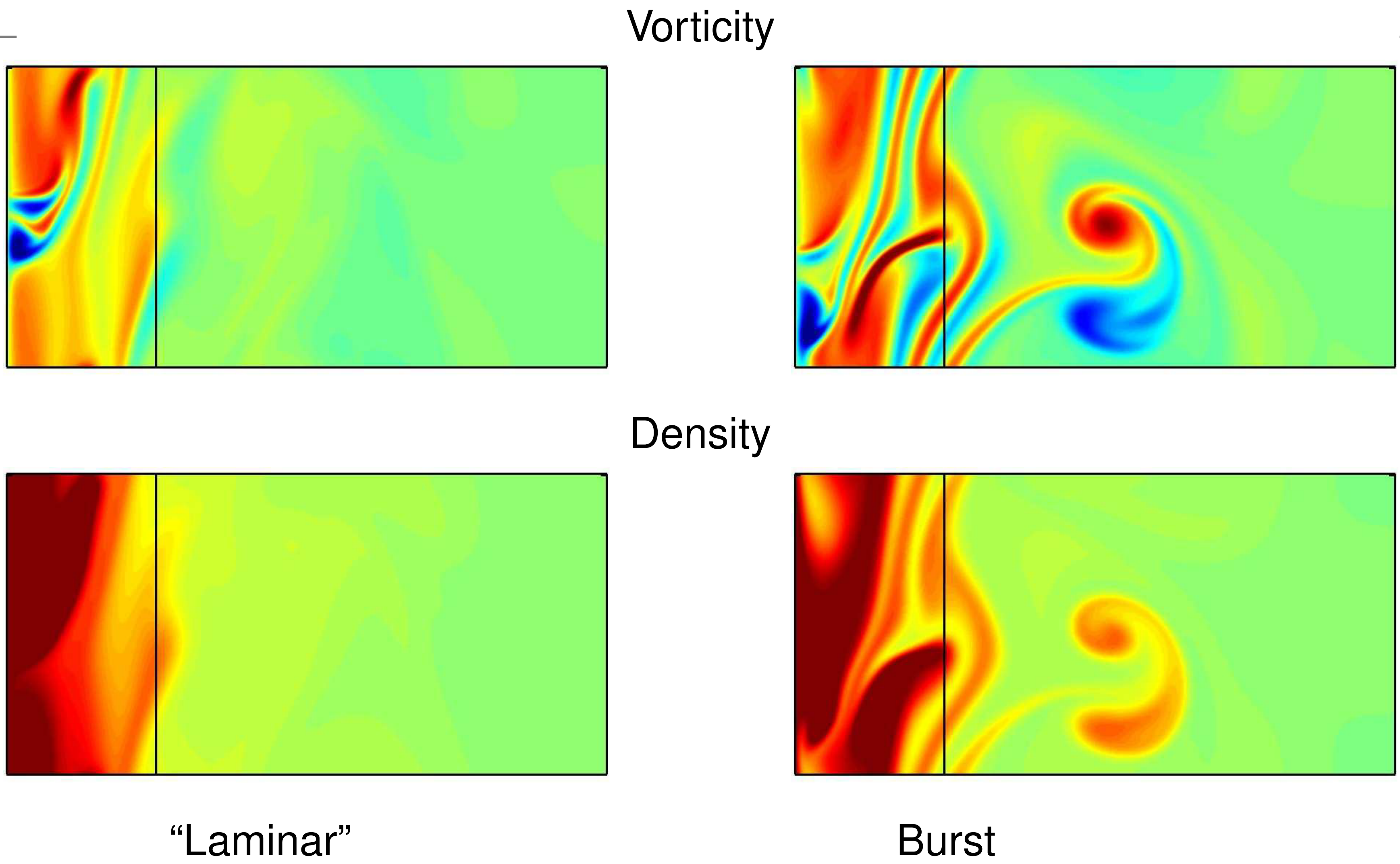
..Comparison Experiment





Conditional averaging of the density signal: compared with experimental results from the ALCATOR C-Mod (Grulke et al)

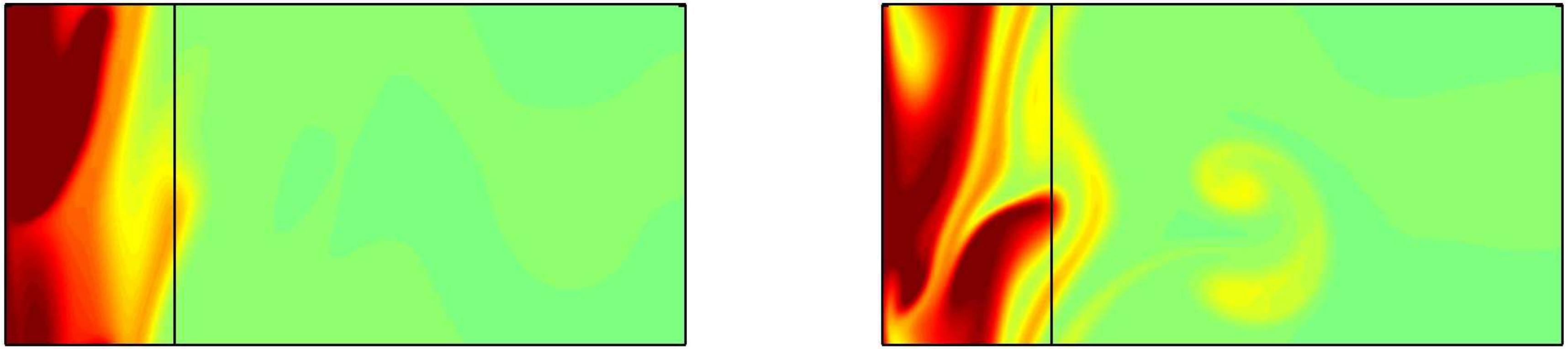
Spatial Structure



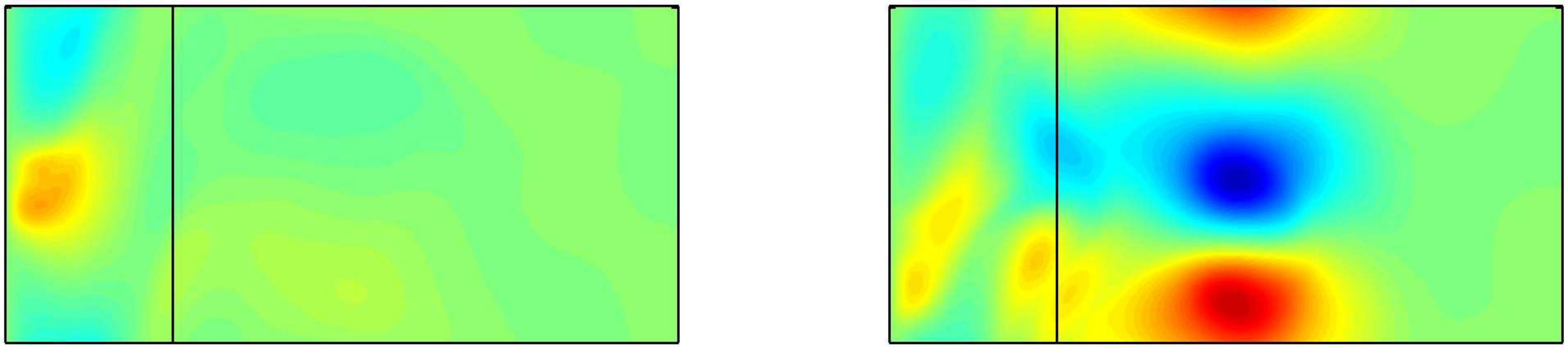
“Laminar” periods: dominated by poloidal flow. “Bursty” periods: blob propagating radially with dipolar vorticity structure.

Spatial Structure

Temperature



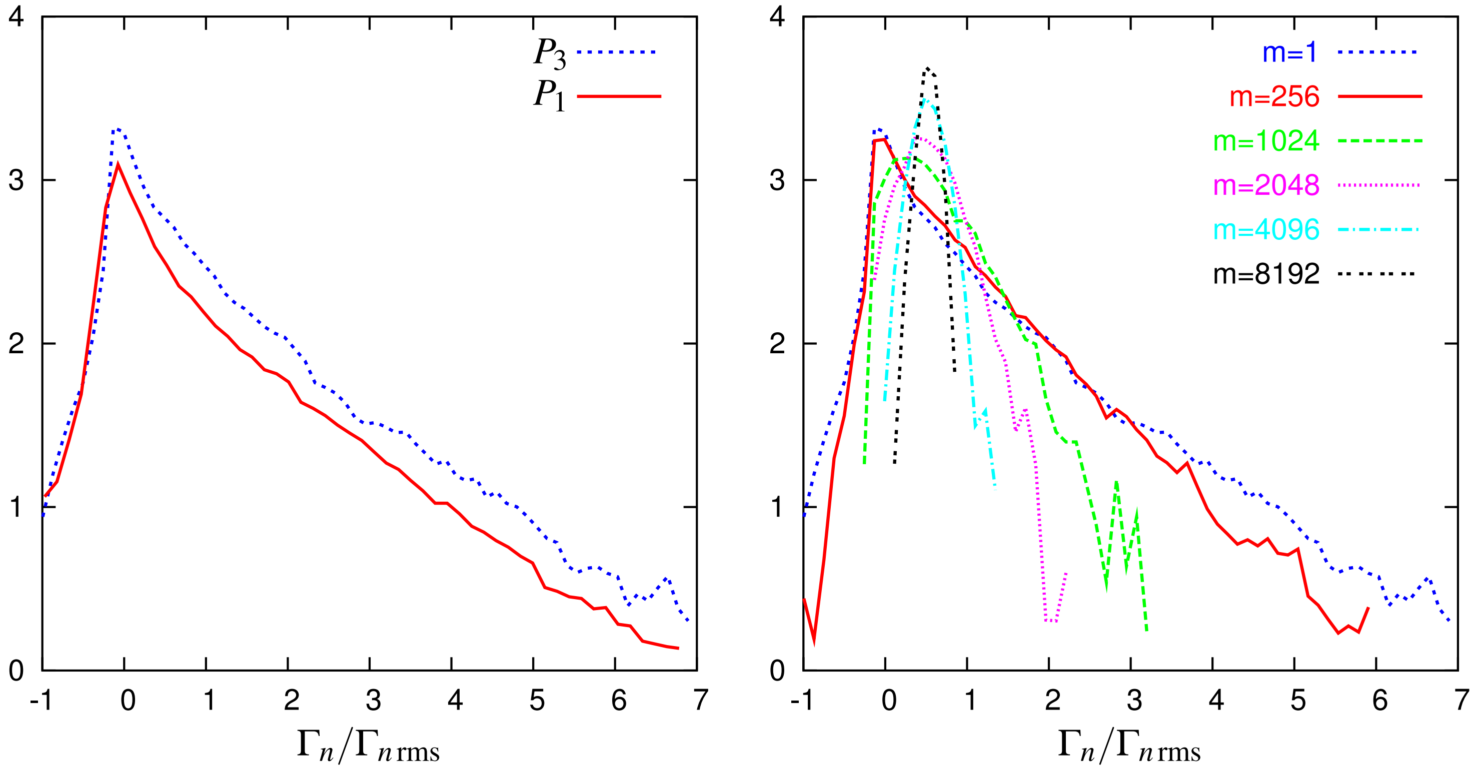
Potential



“Laminar” Burst

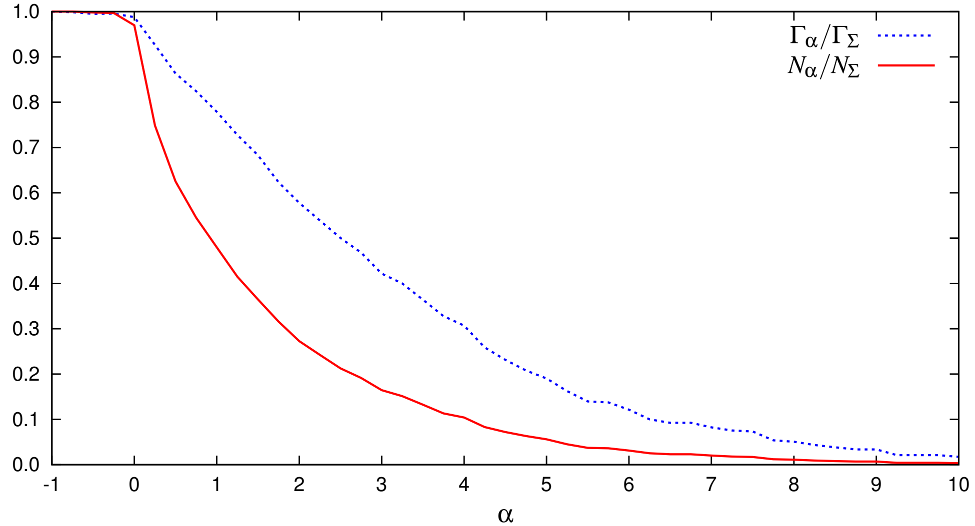
Temperature structure, faster decay (higher sheath transmissivity) than density structure; the potential is subtracted the poloidially averaged potential.

Particle Density Flux



Probability density functions of poloidially averaged particle density flux, $\Gamma_0 = \langle nv_x \rangle$ *at* P_1, P_3. *Exponential tails: flux dominated by strong bursts. Coarse grained PDF at* P_3. *Increasing* $\tau = 2.5m$*: skewness and flatness factor decreases* $\rightarrow$ *Gaussain for large* $\tau >$ *burst intervals. Absence of self-similarity for all scales: intermittency*

Particle Density Flux



Conditional particle flux $\Gamma_\alpha = \langle \Gamma_0 | \Gamma_0 - \bar{\Gamma}_0 > \alpha \Gamma_{0rms} \rangle$ *relative to total flux* Γ_Σ *at* P_3*.*

Relative count number N_α *of sub-records.*

Few events contain most of the flux. Burst rate $\propto$ *viscosity.*

Transport characterized by the Flux PDF; not diffusive: find the “unique PDF“

Prediction of loads to divertor plates and PFC.

Impurity dynamics

Impurity dynamics are modeled by tracing passive particles convected by the turbulent field.
Assumptions: Impurity density low, fully ionized, cold.

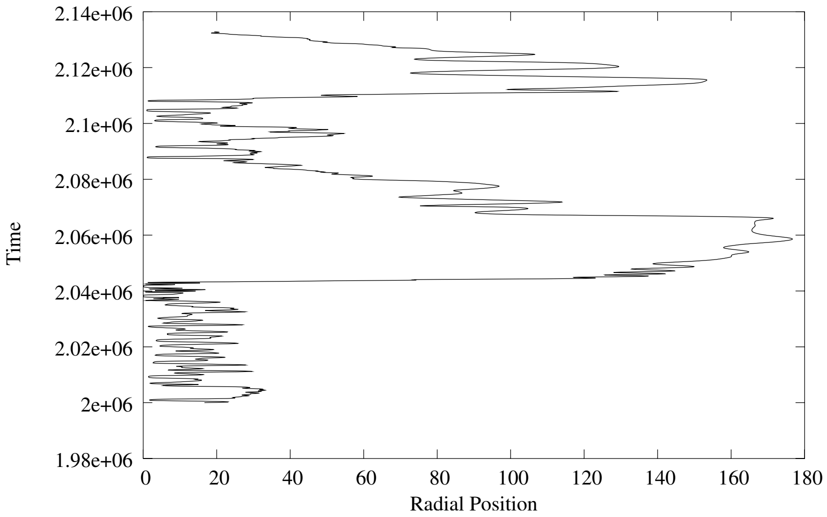
Impurity convection: $\frac{d\vec{x}}{dt} = \vec{v}_{part} = \frac{1}{B}\hat{z} \times \nabla\phi$ $\quad \nabla \cdot \vec{v}_{part} \neq 0$ due to curvature.

Neglecting inertia effects $\propto M_{imp}/Zm_i$: only lighter impurities.

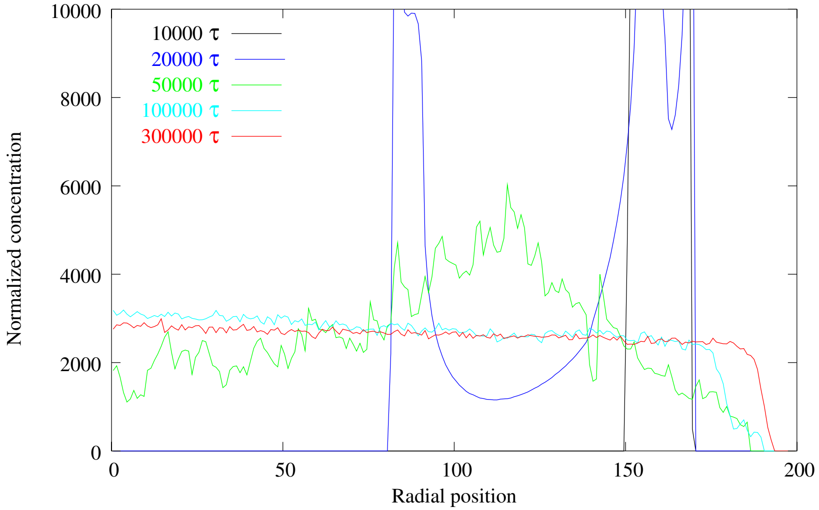
Impurity density: $D(n_{imp}/B)/Dt = 0$: Total mixing :: $n_{imp} \propto B$ :: Curvature pinch (Naulin, PRE **71**, 015402 (2005))

Impurity dynamics

Impurity density: $D(n_{imp}/B)/Dt = 0$: Total mixing :: $n_{imp} \propto B$ :: Curvature pinch (Naulin, PRE **71**, 015402 (2005))

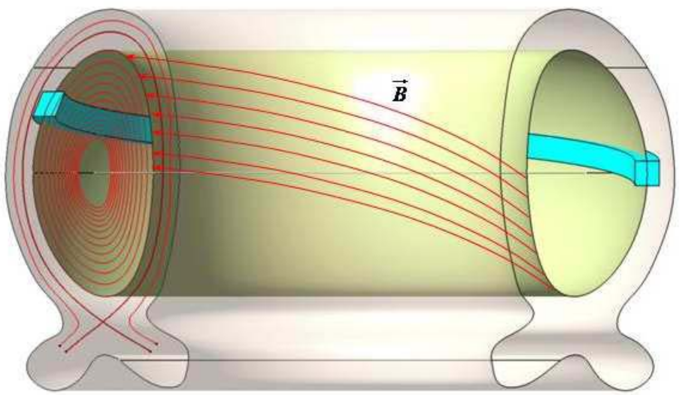


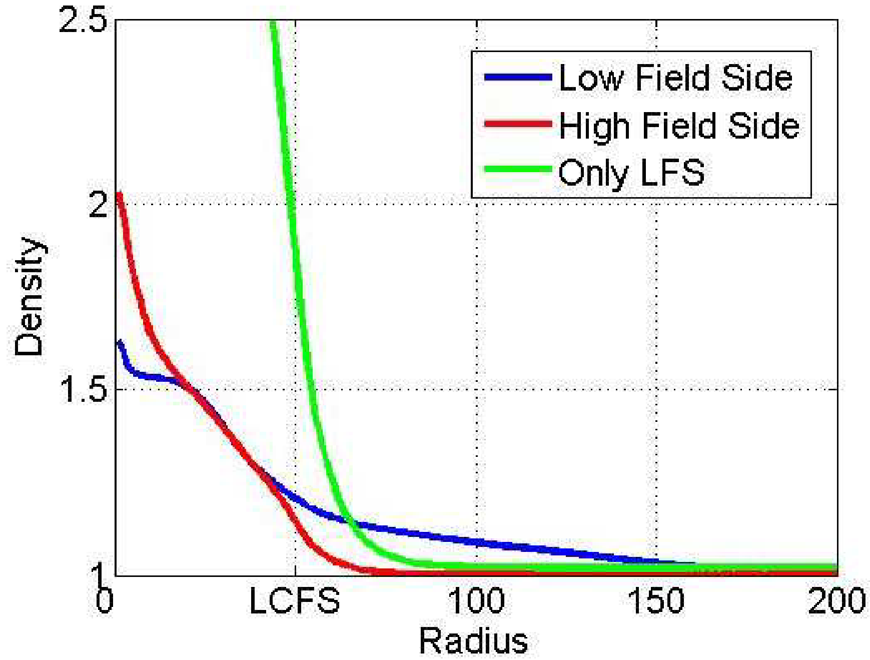
Trajectory of a test particle released inside LCFS



Distribution of impurities, that are initially released at x = 160: Turbulent mixing. Inward (curvature) pinch

Generalizations: 3D effects





Connect regions of good curvature (HFS) with outboard midplane (LFS) in the edge region to mimic the dynamics along the field lines.

First approach $\frac{dn_L}{dt}.. = ..\alpha(n_H - n_L),\ \frac{dn_H}{dt}.. = ..\alpha(n_L - n_H)$

Ballooning nature of fluctuations.

Conclusions and Outlook

The non-linear dynamics of interchange turbulence (2-D ESEL-code) yields very good agreement with experimental measurements:

- the formation of blobs due to profile relaxations,
- radial propagation velocities around 0.1 acoustic speed,
- asymmetric wave forms; skew and flat PDFs.
- intermittent transport.

More complete modelling of edge and SOL turbulence

- should be 3-D, non-local, and energy-conserving,
- with geometry effects and boundary conditions,
- address the relation to ELMs