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Momentum Transport and Zonal Flow Generation in Magnetized Plasmas

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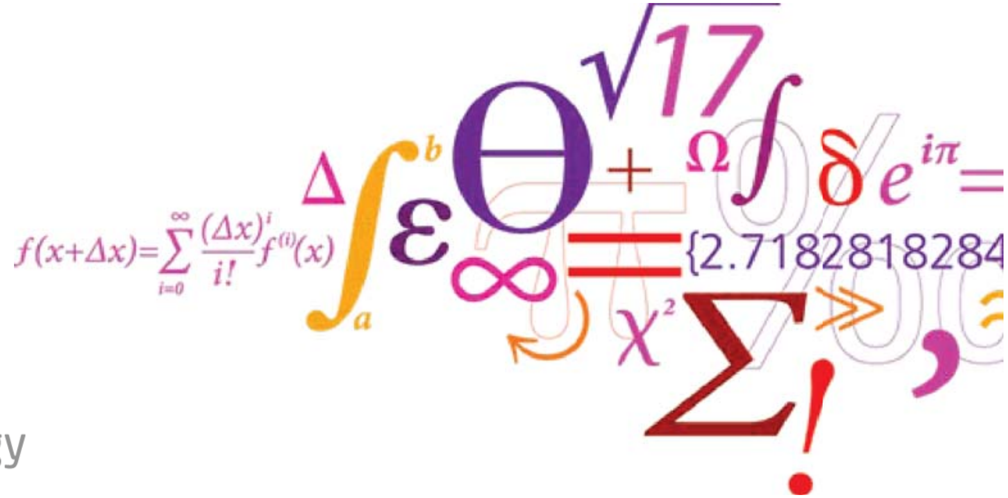

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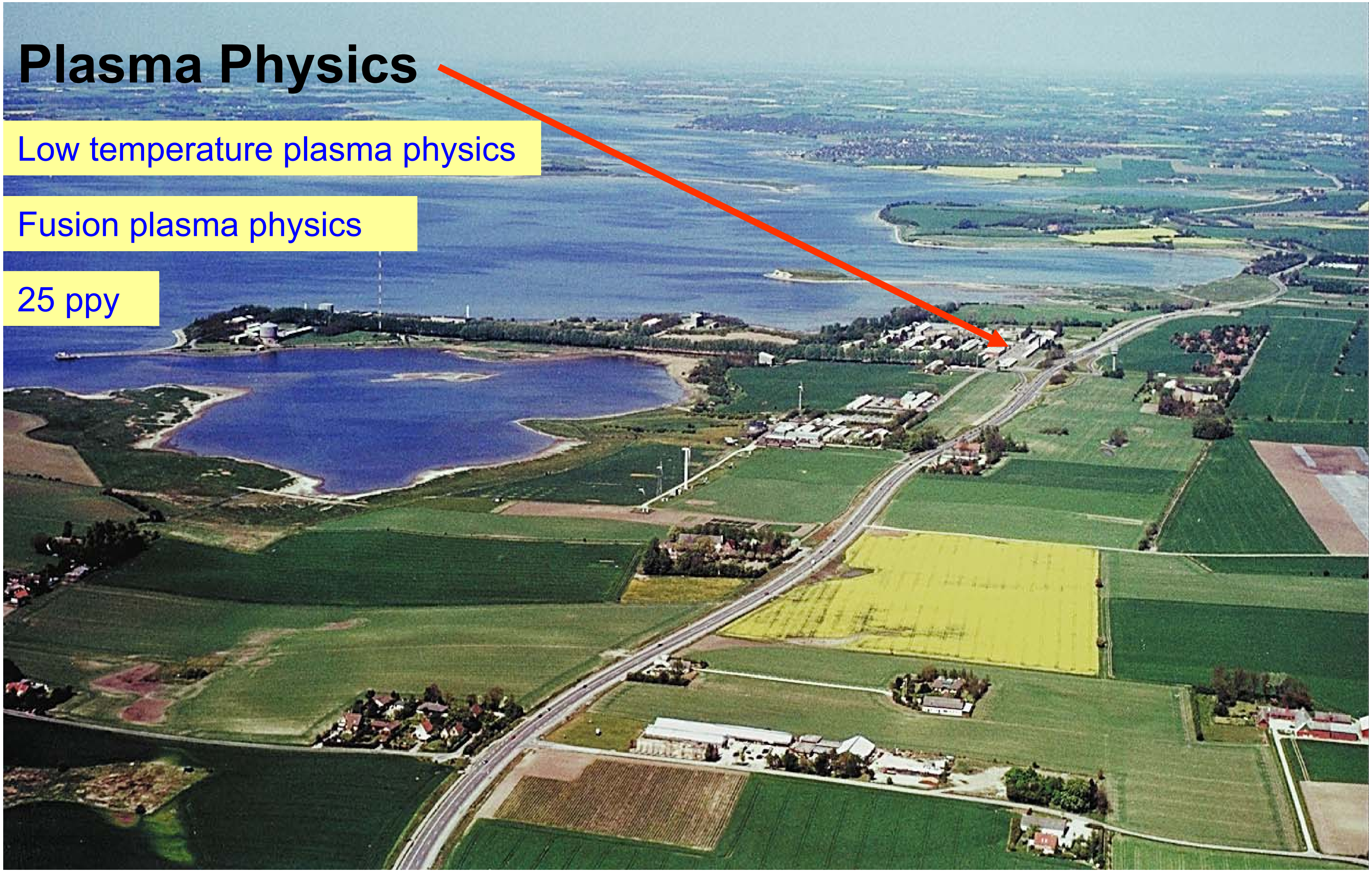
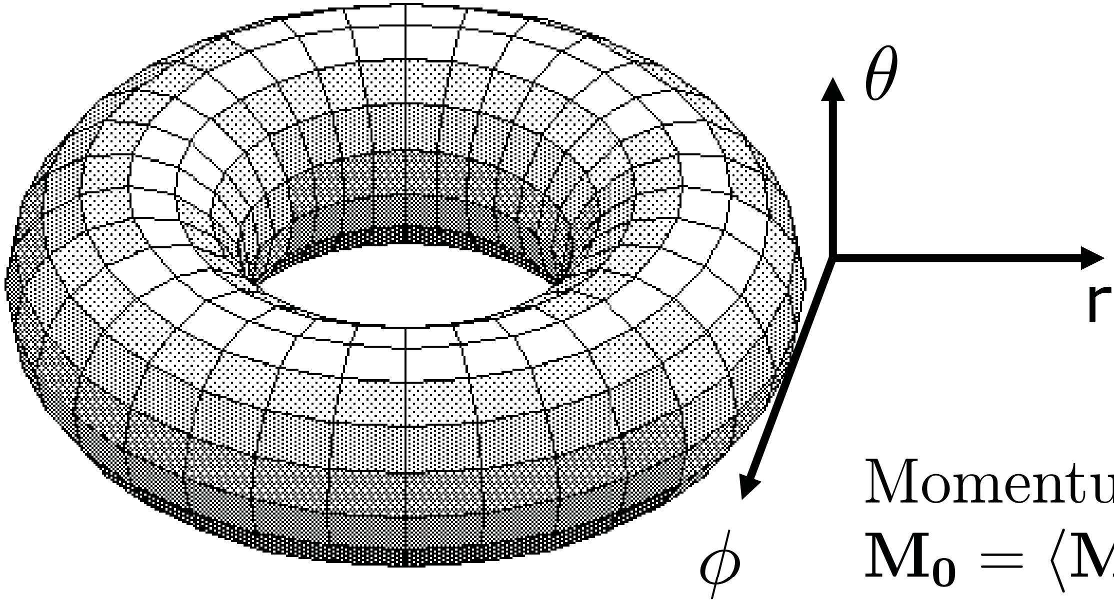


Motivation

- Turbulence and the associated transport is known to be the most important transport channel for degrading confinement of hot plasmas
- Increasing interest in understanding the momentum generation and transport in magnetized plasmas : importance for confinement scenarios
- Momentum is now measurable in Tokamak devices and results on momentum transport are becoming available, understanding is still lacking
- Discussion of momentum transport in simple models, with illustrations from simulations and experiments

Momentum density

Toroidal magnetized plasma



Momentum density (mass = 1) :
$$\mathbf{M_0} = \langle \mathbf{M} \rangle = \langle n\mathbf{v} \rangle$$

$\langle \cdot \rangle$ averaging over ° ux surface

Toroidal momentum density : $M_{\phi 0} = \langle M_\phi \rangle = \langle n v_\phi \rangle$

Poloidal momentum density : $M_{\theta 0} = \langle M_\theta \rangle = \langle n v_\theta \rangle$ ➔

Consider here the B-perp momentum density and flux

Anomalous transport in turbulent plasmas

Radial transport across confining magnetic field

Particle density flux :

$$\Gamma_0 = \langle \Gamma \rangle = \langle n v_r \rangle = \langle \tilde{n} \tilde{v}_r \rangle$$

Energy density flux :

$$Q_0 = \langle Q \rangle = \langle n T v_r \rangle = n_0 \langle \tilde{T} \tilde{v}_r \rangle + T_0 \langle \tilde{n} \tilde{v}_r \rangle + \langle \tilde{n} \tilde{T} \tilde{v}_r \rangle$$

Momentum density flux (poloidal momentum):

$$\Pi_0 = \langle \Pi \rangle = \langle n v_\theta v_r \rangle = n_0 \langle \tilde{v}_\theta \tilde{v}_r \rangle + v_{\theta 0} \langle \tilde{n} \tilde{v}_r \rangle + \langle \tilde{n} \tilde{v}_\theta \tilde{v}_r \rangle$$

Reynolds stress term:
turbulence ⇨ flows

Passive convection

$$n = n_0 + \tilde{n},\ T = T_0 + \tilde{T},\ v = v_0 + \tilde{v},\ (v_{r0} = 0)$$

Myra *et al* Phys. Plasma 15, 032304 (2008)

Impact of fluxes

- Particle and energy flux degrade confinement and provide hazards to plasma facing components
- Momentum flux is not directly harmful in the same manner, but momentum flux sets up plasma rotation and zonal flows that control turbulence and transport
- Momentum flux is thought to be instrumental in the L-H transition in Tokamak plasmas
- In absence of sources and sinks:

$$\text{Global momentum is conserved}: \partial_t M_0 + v_r \partial_r M_0 = 0$$

No global spin up! Bi-polar flows excited

Example: Turbulence – flow interplay

Turbulence model: ESEL – 2D interchange dynamics

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:

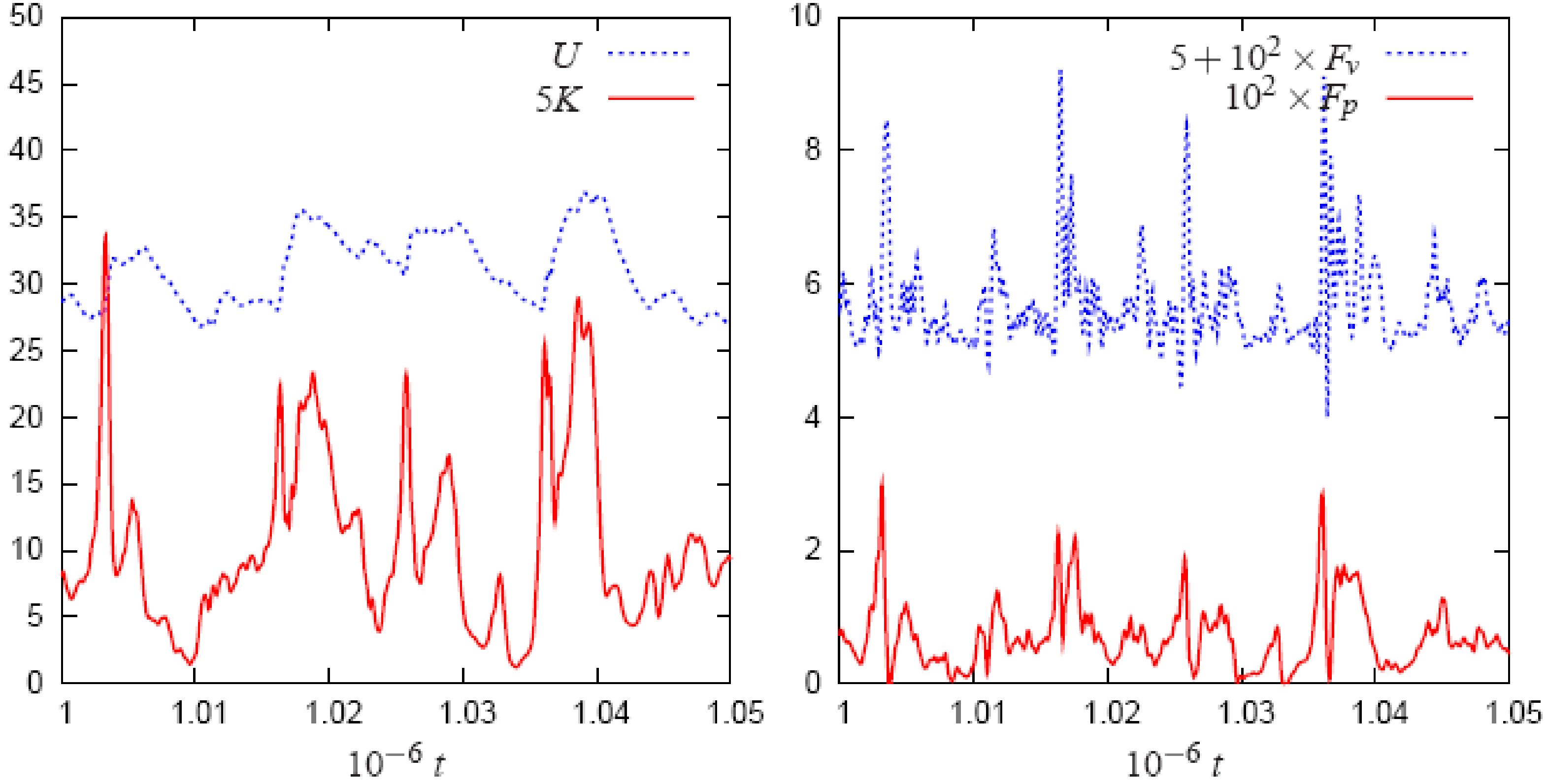
- include separate plasma production ``edge'' and loss region ``SOL'',
- allow self-consistent flows and profile relaxations,
- profiles and fluctuations are **NOT** separated,
- conserve particles and energy in collective dynamics.

Results agree well with experimental observations!

E.g., TCV, Lausanne (Garcia *et al*. PPCF **48**, L1 (2006)) and JET (Naulin *et al* IAEA-2006))

Garcia, Naulin, Nielsen, Rasmussen, PRL **92** 165003 (2004); Phys. Plasmas **12**, 090701 (2005); Physica Scripta**T122**, 89 (2006); Fundamenski *et al.,* Nucl. Fusion **47**, 417 (2007).

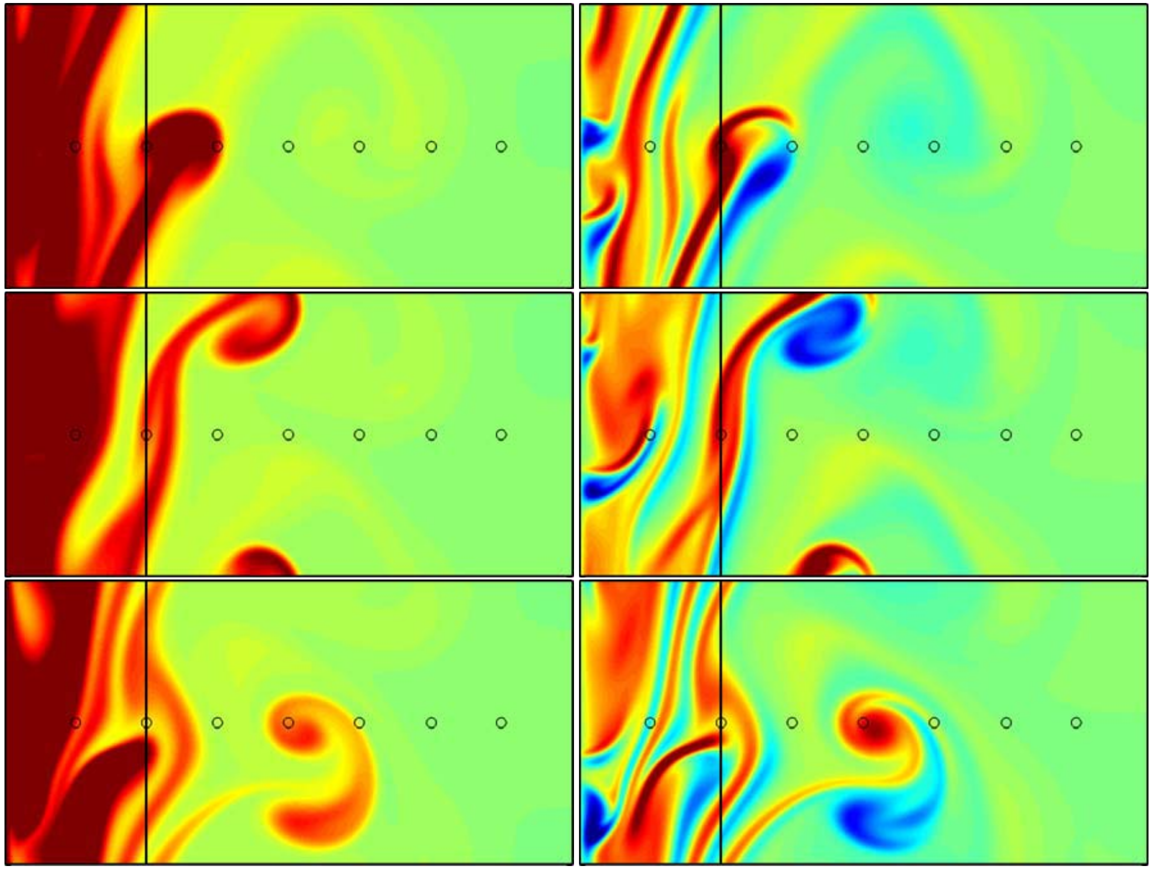
Energetics and Energy Transfer



Bursting : Kinetic energy contained in the mean ("zonal flow"), U, and in fluctuating motions K.

The collective energy transfer terms F_p (from potential energy in gradients to fluctuations) and F_v (from fluctuation to flows)

Spatial structure during a burst



Particle density (left) and vorticity (right) during a burst (Δt = 500)

Blob like-structure in plasma density and dipole structure in vorticity

Potential Vorticity, PV

PV – originating from geophysical fluid dynamics – is a quantity conserved on a fluid element along the Lagrangian trajectory.

Rhines Annual Rev. Fluid Mech 11 401 (1979)

Plasma case: ion momentum equation for cold ions: PV similar to fluid PV.

$$\Omega = \frac{\omega + \omega_c}{n}$$

Intrinsically 2-Dim equation, ion vorticity ω (∇ xv)

$$\frac{d\Omega}{dt} = (\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla)\Omega = 0$$

Conservation of PV dictates the dynamics

Effective mixing homogenisation of Ω**;** provide zonal flow < ω >

Rasmussen *et al* Physica Scripta T122, 44, (2006);
Basu *et al.* Phys Plasma 10, 2696 (2003)

Recently, applied to momentum transport in magnetized plasma by Diamond *et al* (**PPCF 50, 124018 (2008)**).

Potential Enstrophy Evolution I

Applying the drift wave scaling: fluctuations around a background density, PV expands:

$\Omega \approx \omega - n, \quad \Omega = \Omega_0 + \tilde{\Omega}$ $\qquad$ $\mathbf{v}$ is the $E \times B$ velocity

(convection velocity)

$$\frac{d\Omega}{dt} = \frac{\partial \tilde{\Omega}}{\partial t} + v_r \frac{\partial \Omega_0}{\partial r} + \mathbf{v} \cdot \nabla \tilde{\Omega} = 0$$

Conservation equation for potential enstrophy, $\langle \tilde{\Omega}^2 \rangle$:

$$\partial_t \langle \tilde{\Omega}^2 \rangle + \partial_r \langle v_r \tilde{\Omega}^2 \rangle + \langle v_r \tilde{\Omega} \rangle 2 \partial_r \Omega_0 = 0$$

The poloidally averaged flow

$$\partial_t v_{\theta 0} + \partial_r \langle v_r \tilde{v}_\theta \rangle = \mu \partial_r^2 v_{\theta 0} - \nu v_{\theta 0}$$

Diamond *et al* PPCF 50, 124018 (2008)

Potential Enstrophy Evolution II

Applying: $\partial_r \langle v_r \tilde{v}_\theta \rangle = \langle v_r \tilde{\omega} \rangle, \quad \langle v_r \tilde{\Omega} \rangle = \langle v_r \tilde{\omega} \rangle - \langle v_r \tilde{n} \rangle$

to obtain the zonal momentum conservation:

$$\frac{\partial}{\partial t}\left(v_{\theta 0} - \frac{\langle \tilde{\Omega}^2 \rangle}{2\partial_r \Omega_0} \right) = \frac{\partial_r \langle v_r \tilde{\Omega}^2 \rangle}{2\partial_r \Omega_0} - \langle v_r \tilde{n} \rangle + \mu \partial_r^2 v_{\theta 0} - \nu v_{\theta 0}$$

zonal velocity — enstrophy transport — particle flux — dissipation

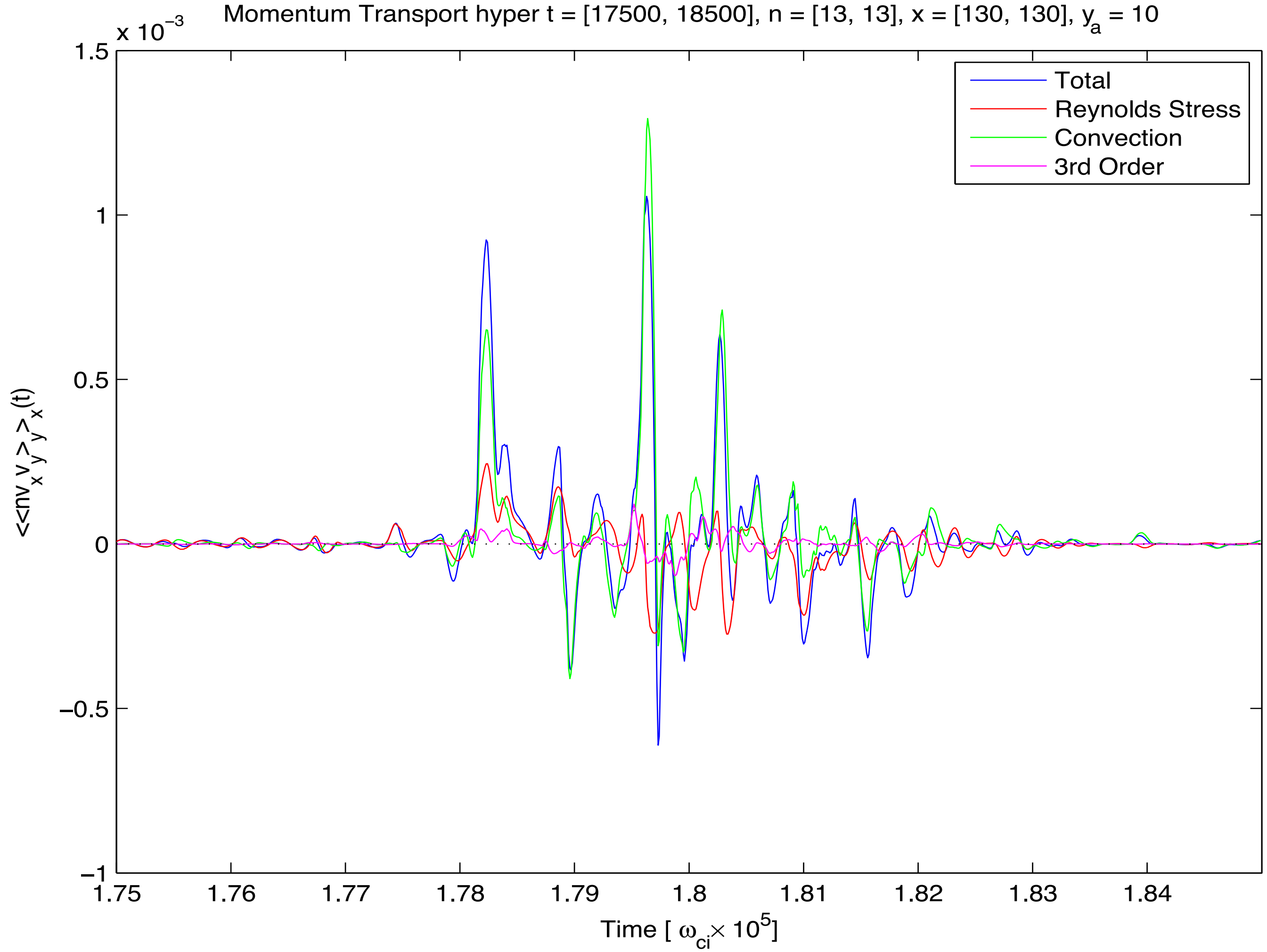
wave momentum density

Poloidal flow connected to particle flux

Flow structures regulated by dissipation profiles

Stationary turbulence cannot excite zonal flow in absence of “RHS”

Momentum Transport by Blob

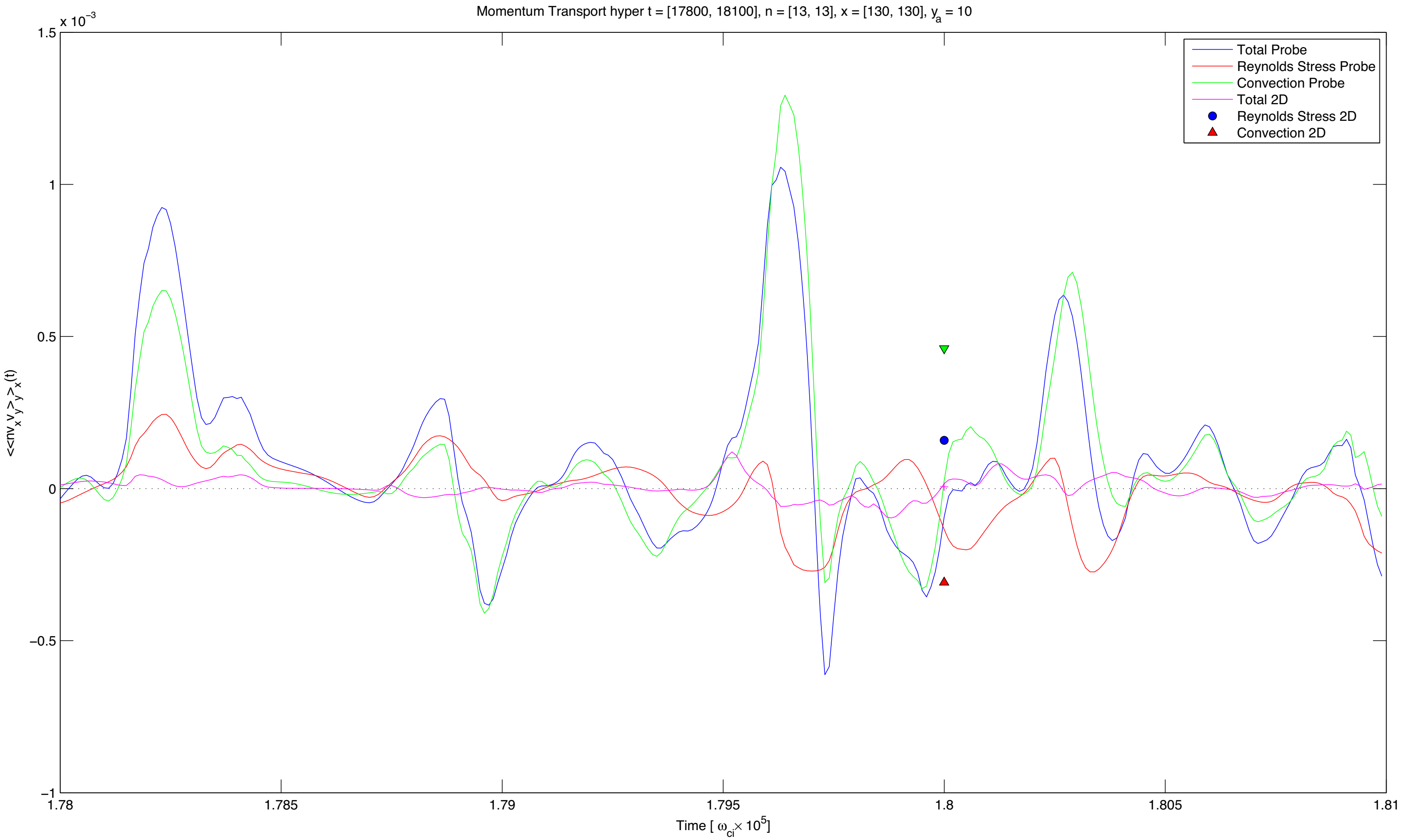


ESEL simulations, modelling probe measurements in the SOL

Components of momentum flux “measured” by probes in the SOL

Momentum Transport by Blobs

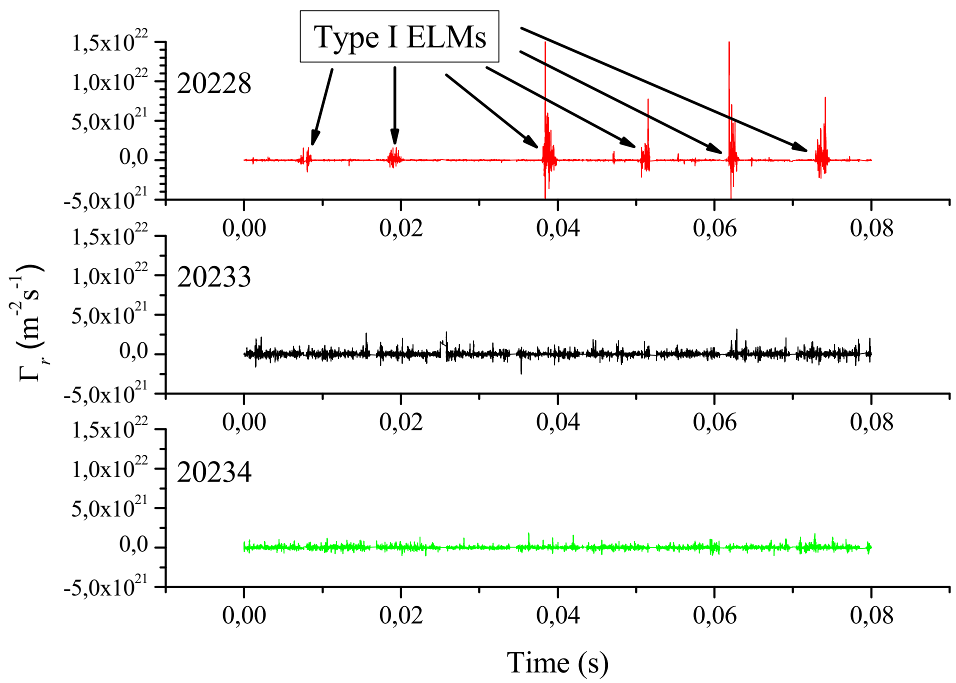
Expanded scale.



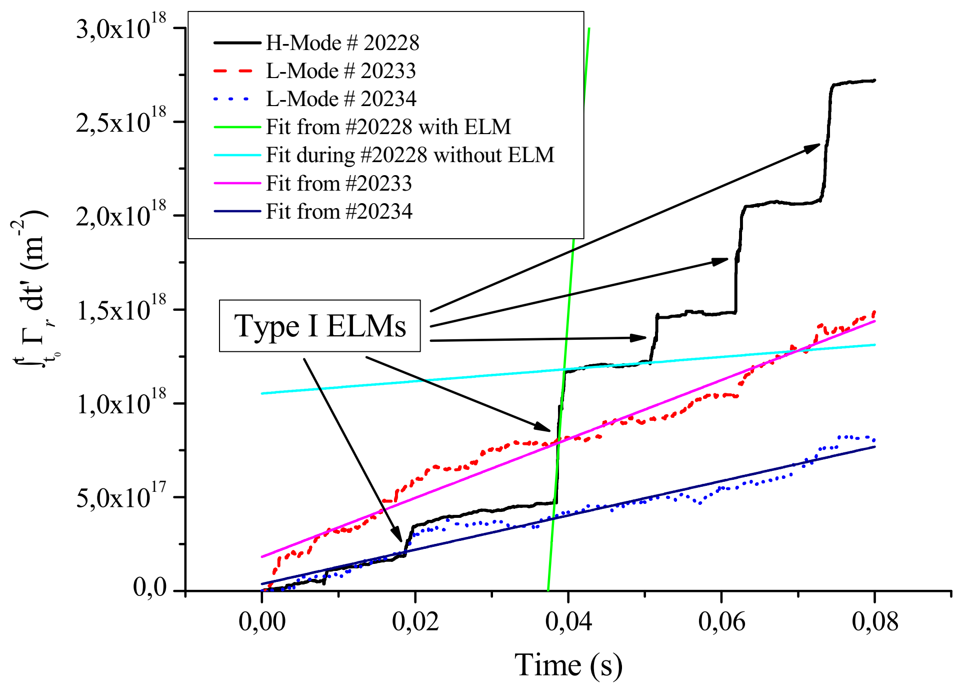
Blob carries its momentum along

Particle density flux in H- and L-mode in ASDEX UG

Particle density flux Γ



Integrated Γ



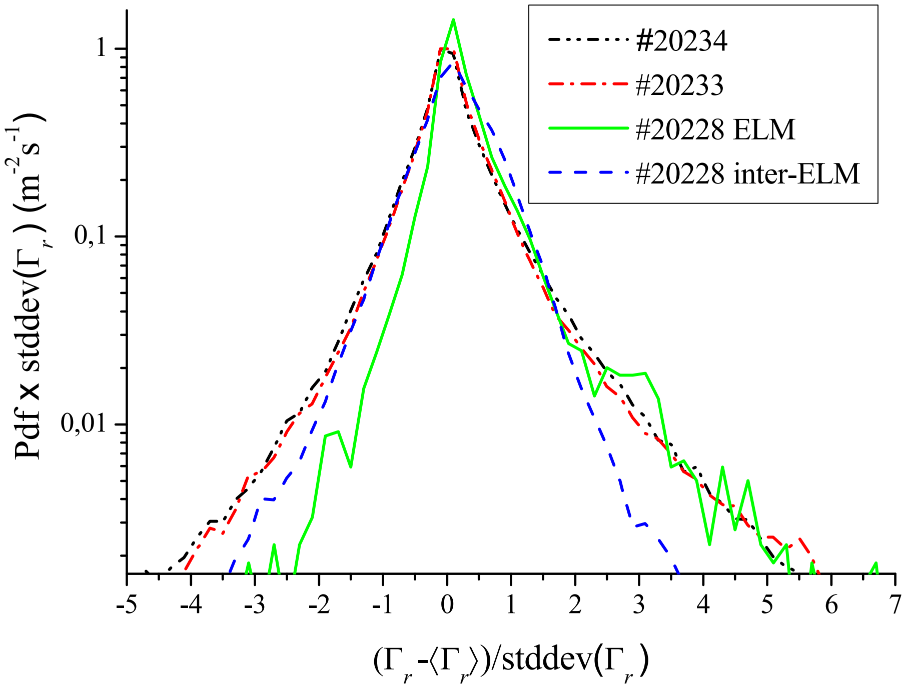
Probe measurements in the SOL of Asdex UG during ELMy H-mode and L-mode.

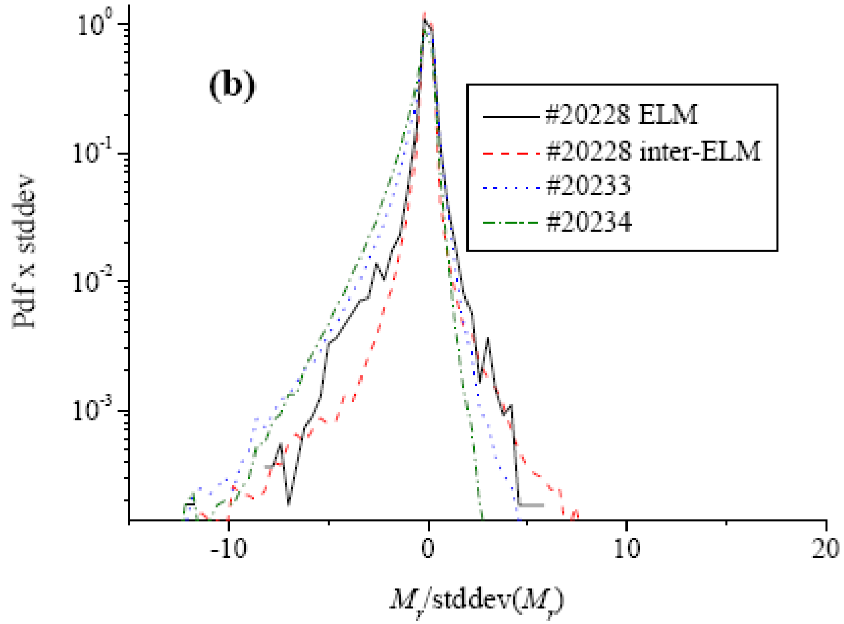
Ionita, Schrittwieser *et al* EPS 2008

PDF of the particle and momemtum density flux in the SOL

Similar statistics!

Ionita *et al* , ICPP - 2008 and to be published



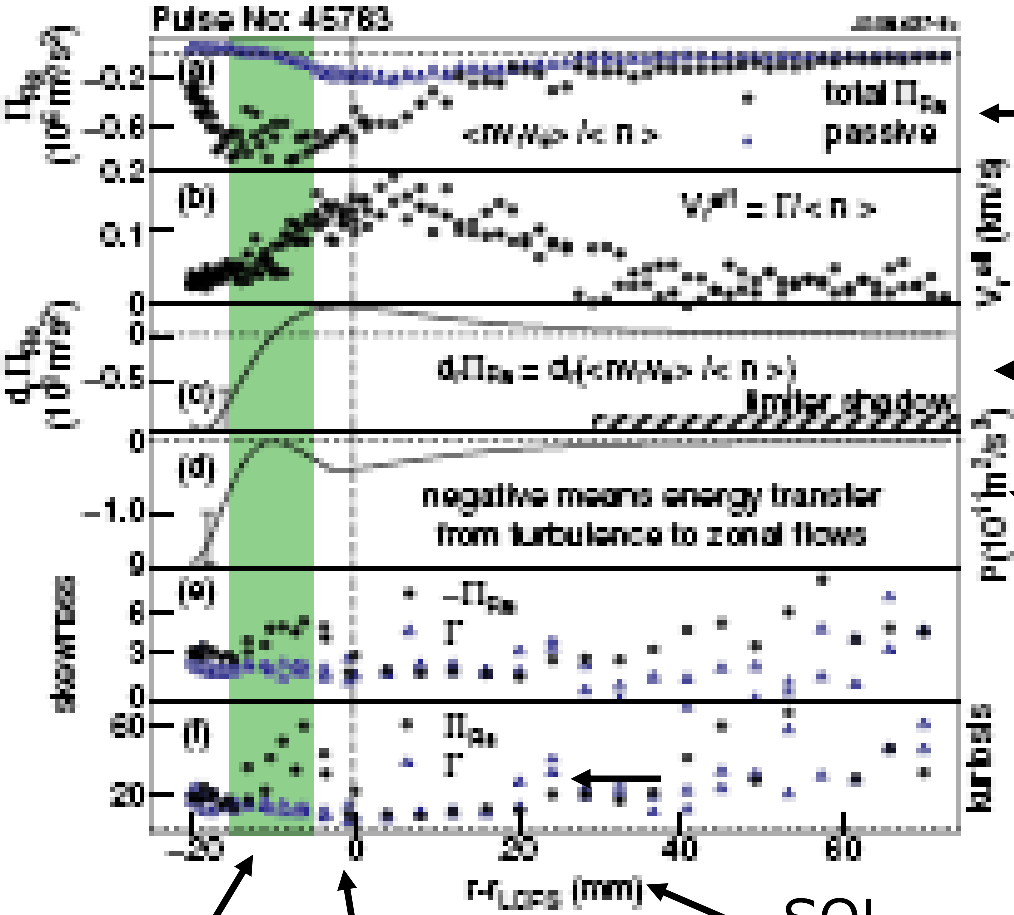


Renormalized PDF of Γ in H-mode during ELM activities, in between ELMs and in two L-mode cases.

Renormalized PDF of momentum density flux, π , in H-mode during ELM activities, in between ELMs and in two L-mode cases.

Momentum Flux in the JET Edge Plasma

L-mode



Momentum flux

Gradient of momentum flux

Transfer from turbulence to flow

Edge

LCFS

SOL

Xu *et al.* Nucl. Fusion 49, 092002 (2009)

Summary

- Momentum transport and balance in magnetized plasmas are governed by the Potential Vorticity "conservation"
- Momentum transport is strongly related to particle and energy transport
- Transport events, blobs and ELM structures carry momentum along
- Momentum loss in the SOL important for flow generation in the plasma edge
- Full 3-D description needed for poloidal and toroidal momentum balance

Thank you for your attention

some details

Model Equations: ESEL

2D model for cold ions and quasi-neutrality $n_i \approx n_e = n$.
Vorticity $\Omega = \nabla \times \vec{u}_E \cdot \hat{z} = \nabla_\perp^2 \phi$

2D interchange dynamics

$$\frac{dn}{dt} + n\mathcal{C}(\phi) - \mathcal{C}(nT) = \nabla \cdot \left(\nu_e \rho_e^2 (\nabla n - \frac{n}{2T}\nabla T)\right) - \frac{n}{\tau_{\parallel n}}$$

$$\frac{dp}{dt} - \frac{5}{3}p\mathcal{C}(\phi) + \frac{5}{3}\mathcal{C}(pT) = \frac{3}{2}\nabla \cdot (\kappa_\perp \nabla T + \nu_e \rho_e^2 \nabla p) - \frac{p}{\tau_{\parallel p}}$$

$$\frac{d\Omega}{dt} - \mathcal{C}(nT) = \nu_\Omega \nabla_\perp^2 \Omega - \frac{\Omega}{\tau_{\parallel \Omega}} \quad (-\sigma\phi)$$

Sheath dissipation

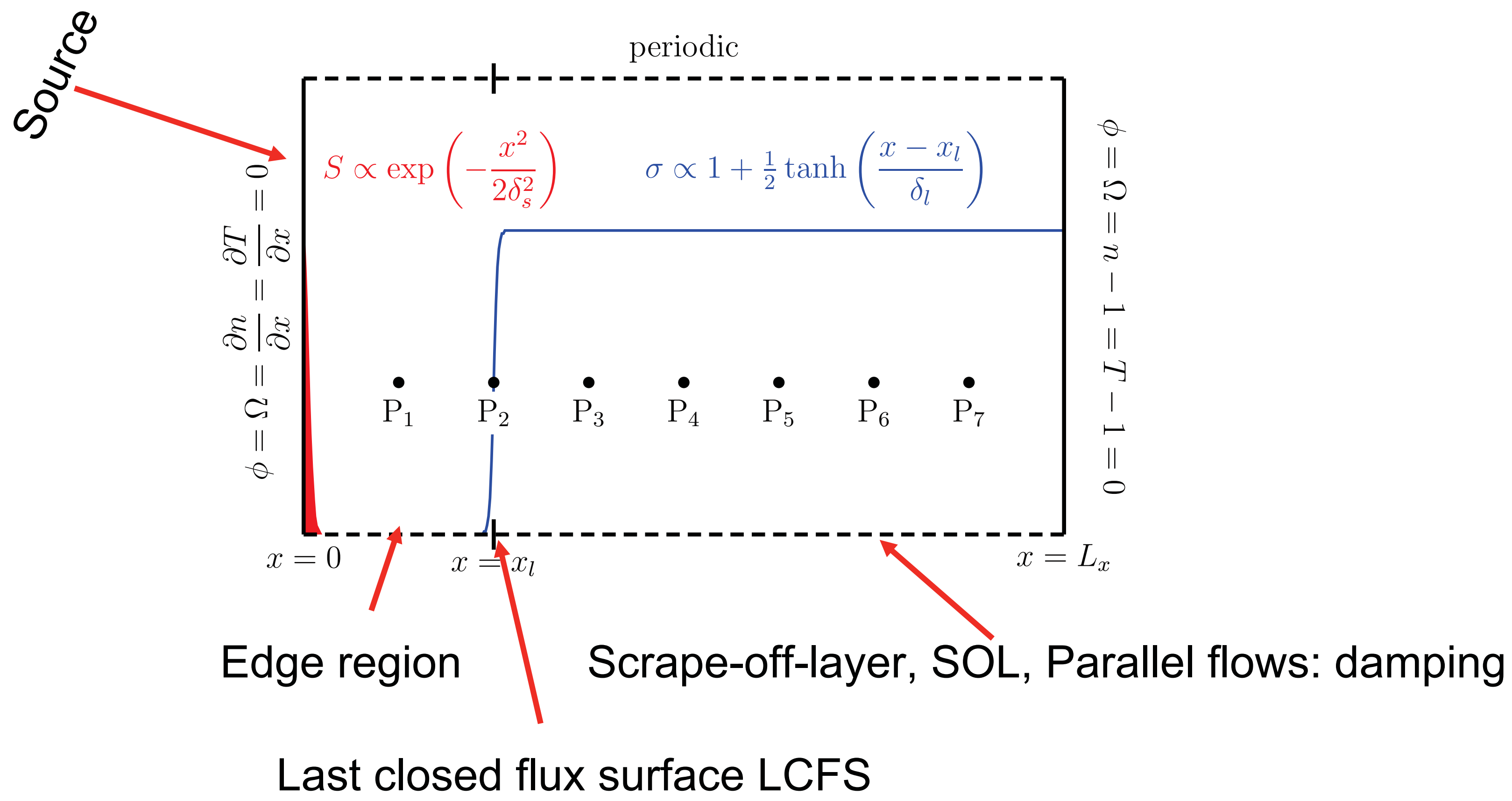
Advective derivative and curvature operators defined by

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

In SOL particle transport along open field lines: modelled by linear damping

Geometry in the Simulations

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



Instability, Energy Integrals

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

Naulin et al.; PoP **10**, 1075 (2003)

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

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

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

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

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

F_p is also a measure of the turbulent energy transport.