~~The~~ Some physics of shear flows A personal view (no review)

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Contents

Turbulence and flows

Definitions: G. Falkovich:

Turbulence is a state of a nonlinear physical system that has energy distribution over many degrees of freedom strongly deviated from equilibrium.
Turbulence is irregular both in time and in space.
Turbulence can be maintained by some ..... influence or it can decay on the way to relaxation to equilibrium.
The term first appeared in fluid mechanics and was later generalized to include far-from-equilibrium states in solids and plasmas.

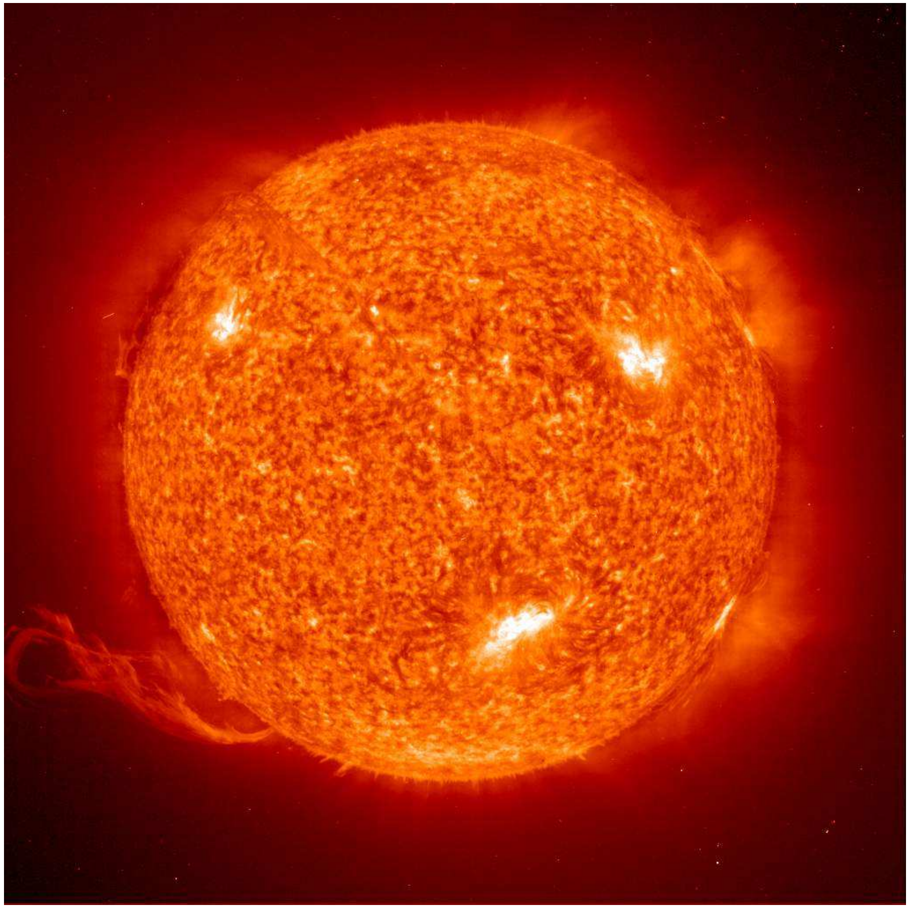
Turbulence and flows

Laminar flow with low level of mixing.

Turbulence and flows

Turbulence mixes fast (Chimneys, milk in the coffee).

Turbulence and flows

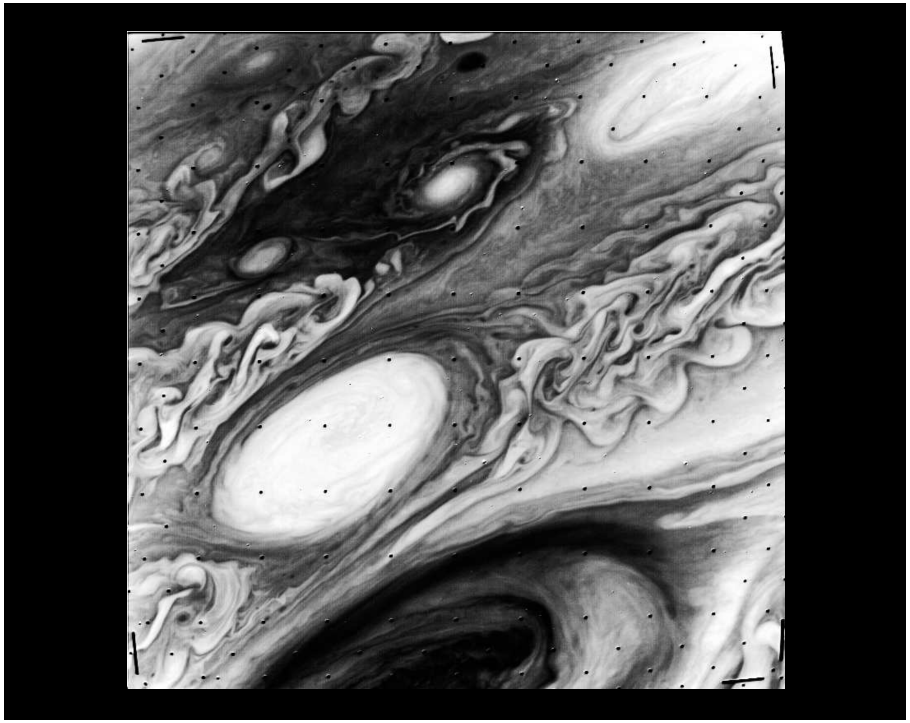


Turbulence in a working fusion reactor nearby

Turbulence and flows

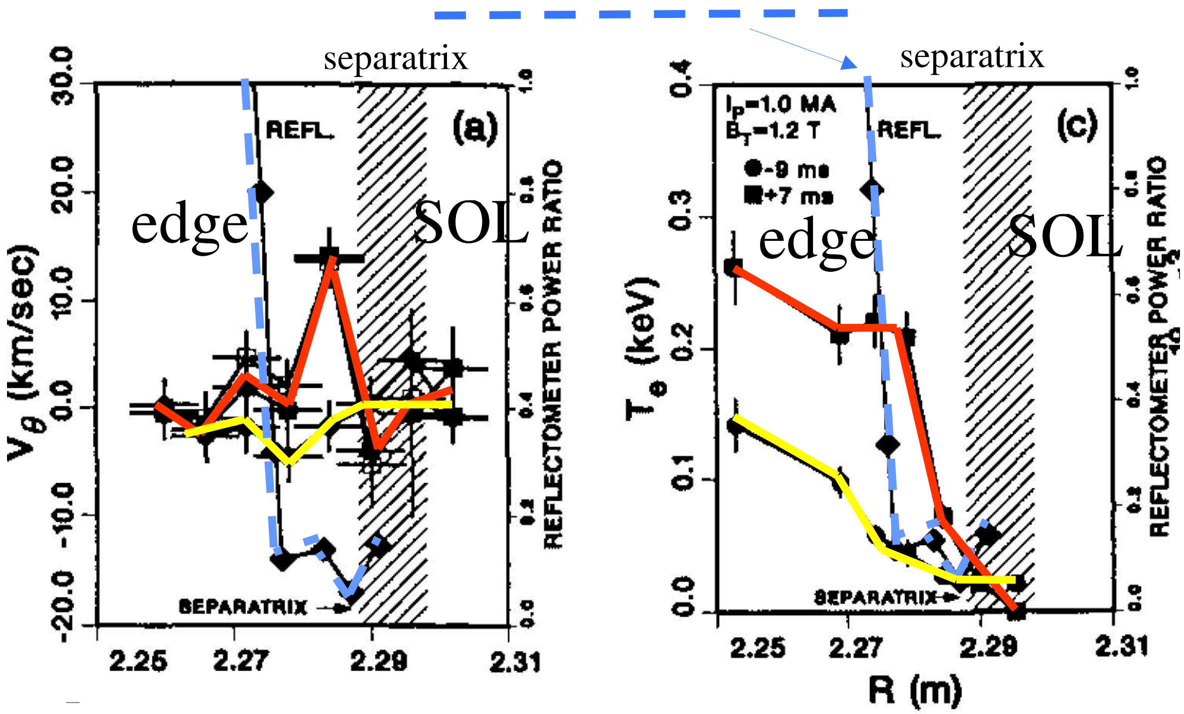
Turbulence in soapfilms

Turbulence and flows



Plasma turbulence is mainly 2D turbulence, perpendicular to magnetic field. Structures evolve: vortices, eddies and flows

Turbulence and flows



DIIID

K H Burrell
PFCF 34, 1859
(I992)

H-mode (Wagner, Asdex 1992) is essential to modern tokamak (stellarator) operation and connected to edge shear flows.

What do shear flows do?

Consider the standard advection-diffusion equation

$$\partial_t \Theta + v_0(x,t)\partial_y \Theta = \mu \nabla_\perp^2 \Theta$$

For a uniformly sheared flow, $v_0(x) = v_0 x$, a formal spectral transformation yields

$$\partial_t \hat{\Theta}_k + V_0' k_y \partial_{k_x} = -\mu k_\perp^2 \hat{\Theta}_k$$

indicating a spectral expulsion of the scalar field fluctuations towards large absolute value radial wave numbers.

What do shear flows do?

The sheared plane wave for $\mu = 0$.
The evolution of the initial plane wave $\exp(ik_x x + ik_y y)$ is

$$\exp[i(k_x - v_0 k_y t)x + ik_y y] = \exp[i(1 - t/t)k_x x + ik_y y]$$

with the *tilting time* $T = k_x / k_y v_0$.
Two cases may take place:

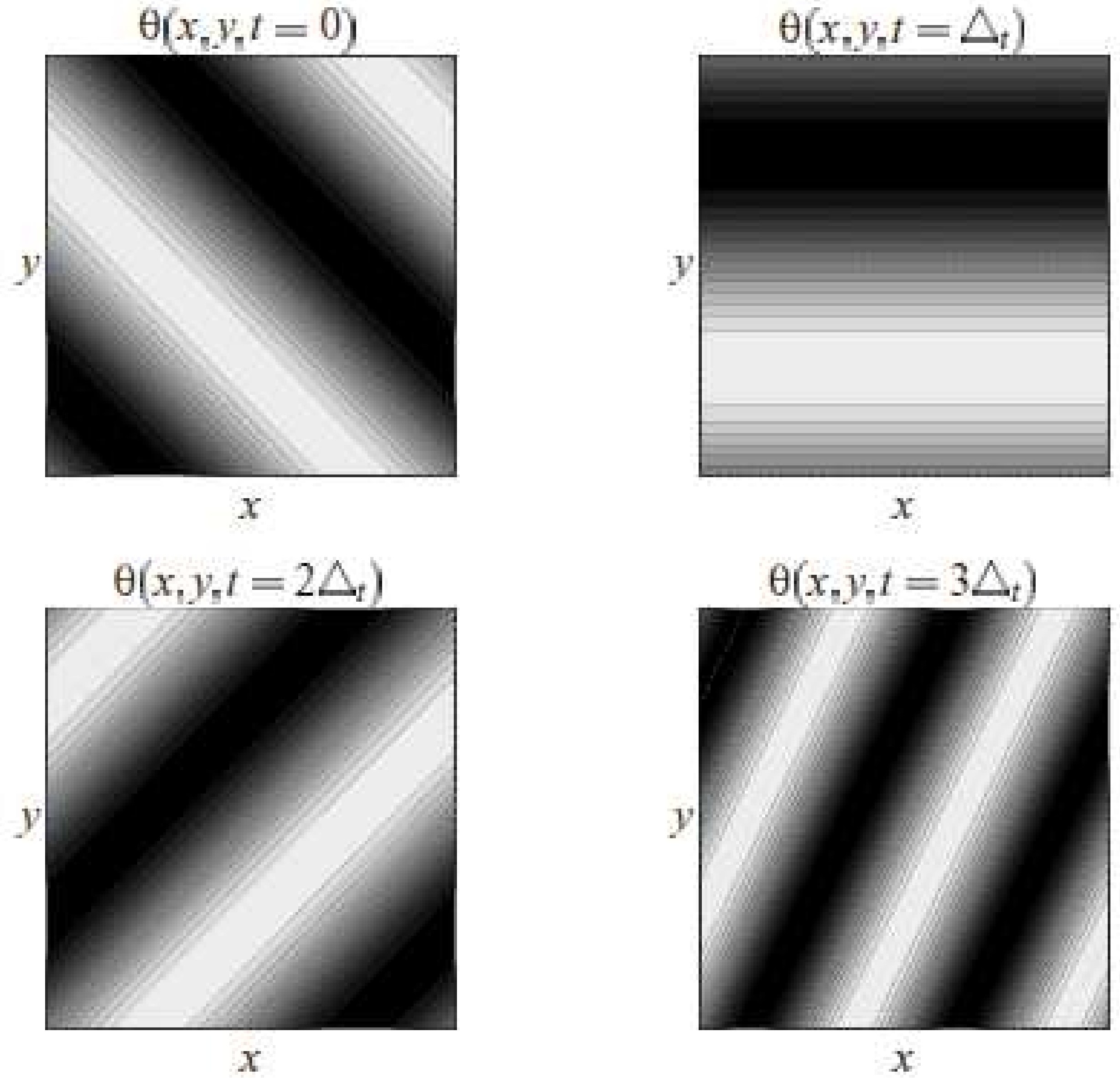
$T > 0$: plane wave is tilted against the flow
$T < 0$: plane wave is tilted with the flow

The radial wave number is

$$k_x(1 - t/T) = 0$$

at the tilting time $t = T$.

Sheared wave



Sheared wave

Adding diffusion, the solution for any spectral component is

$$\hat{\theta}_k(t) = \exp\left[-\mu k_x^2 t\left(1 - \frac{t}{T} + \frac{t^2}{3T^2}\right) - \mu k_y^2 t\right]$$

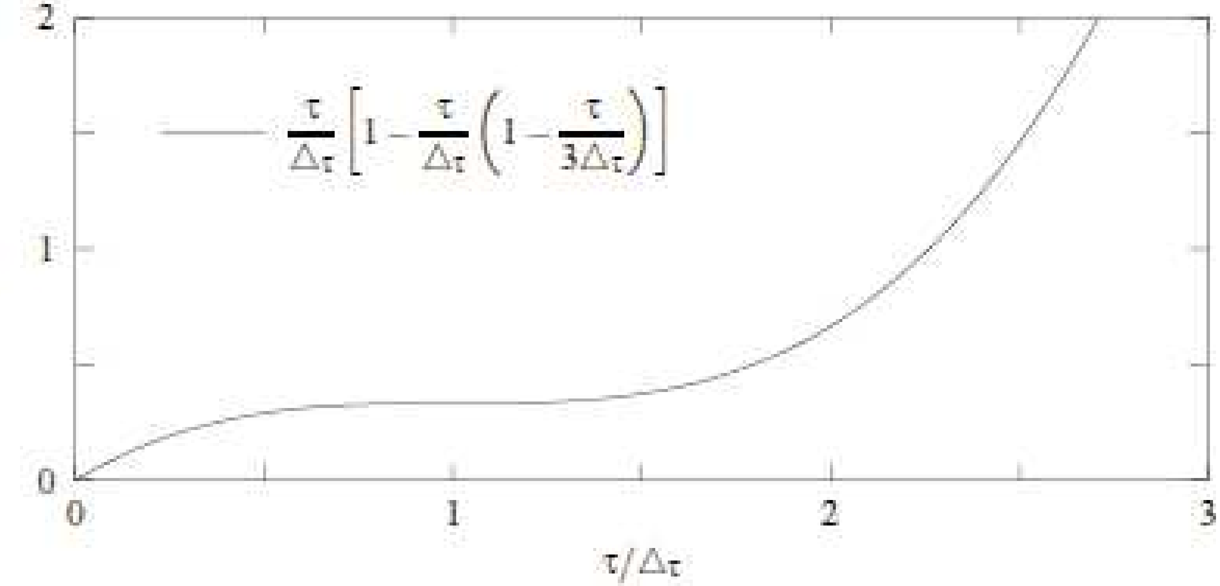
There are three phases of evolution:

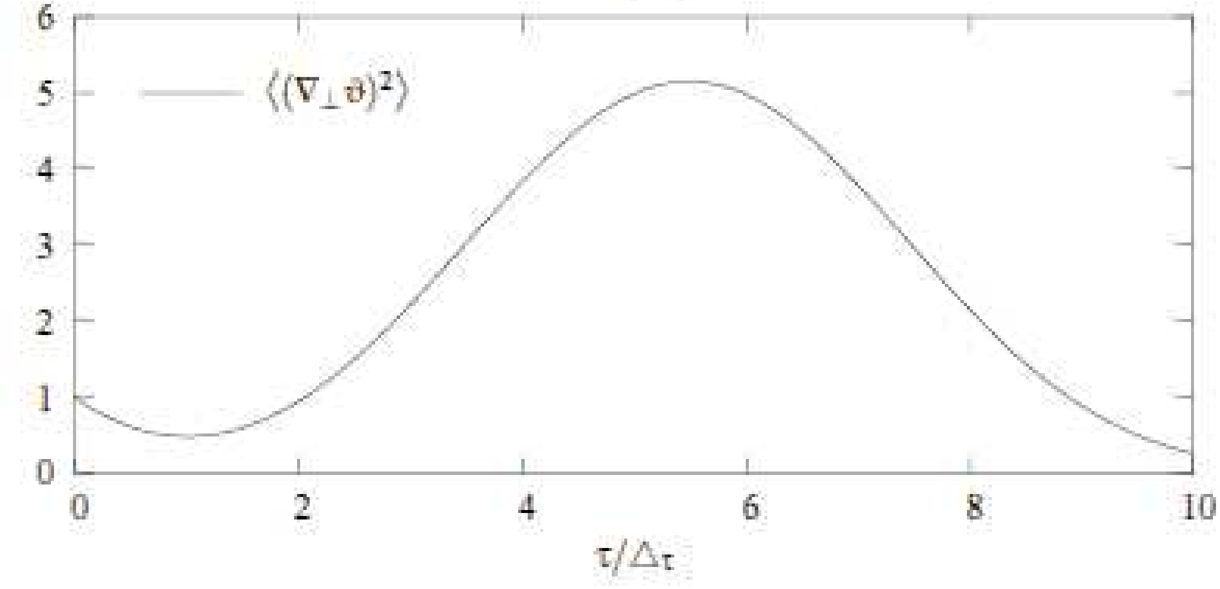
- exponential decay on the diffusive time scale $\tau_\mu = 1/\mu k_x^2$
- For $t > 0$ the decay rate is transiently halted at the T (structure aligned).
- for long times increase of damping rate

$$\exp(-\frac{\mu t^3}{3T^2})$$

These effects are known as:
reduced radial correlation length
turbulence decorrelation time

Sheared wave





Basic concepts

Prototype Equation:
Charney-Obukov-Hasegawa-Mima Equation:

$$\partial_t \left(1-\nabla_\perp^2\right)\phi + J(\phi,\nabla_\perp^2\phi) + \kappa_n\partial_y\phi = 0$$

Scaling:
Crossover from linear to non-linear regime:

$$\omega_{turb} = k^4\phi/(1+k^2)$$

$$\omega_{wave} = \kappa_n k_y/(1+k^2)$$

Use average Velocity $U = k\phi$ to equate the *isotropic* **Rhines length** (1975) [a]

$$k_R = \sqrt{\kappa_n/U}$$

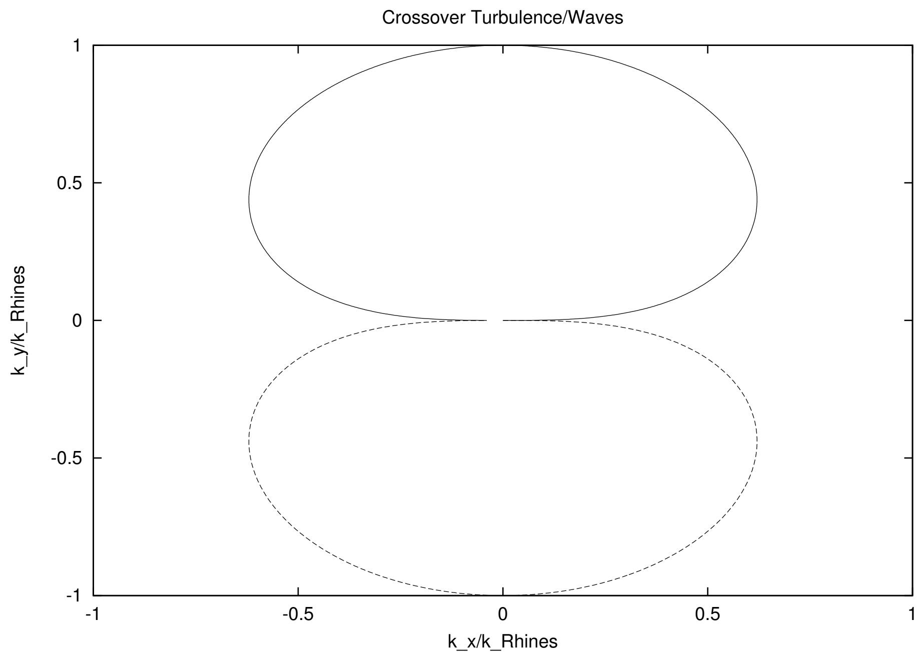
[a] Rhines, J. Fluid Mech. **69**, 691, 1975

Basic concepts

Anisotropic Rhines length:

$$k_{Rx} = \sqrt{\kappa_n/U}\sqrt{\sin(\theta)}\cos(\theta)$$

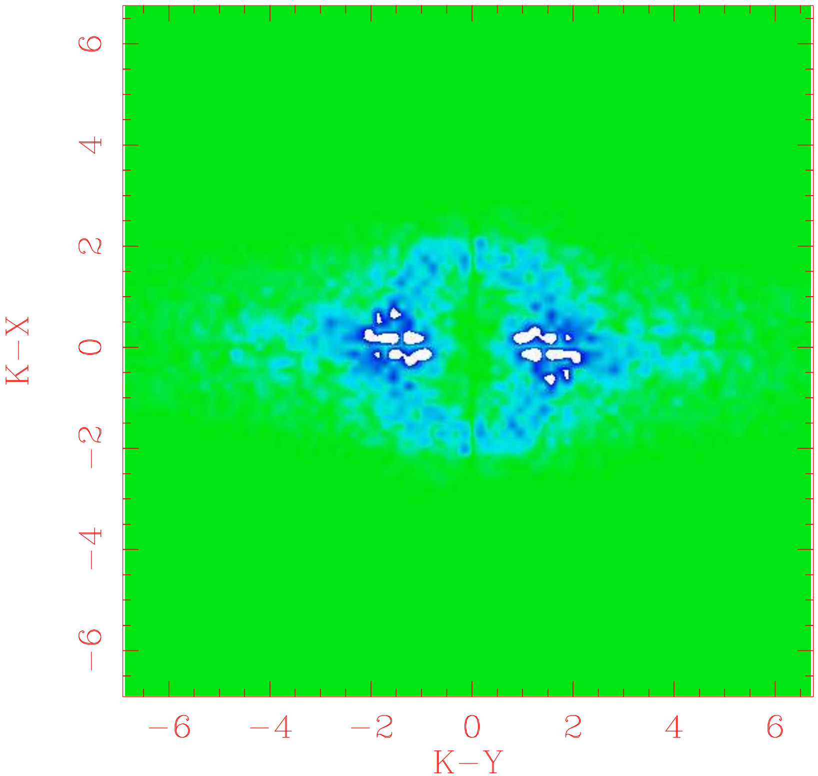
$$k_{Ry} = \sqrt{\kappa_n/U}\sqrt{\sin(\theta)}\sin(\theta)$$

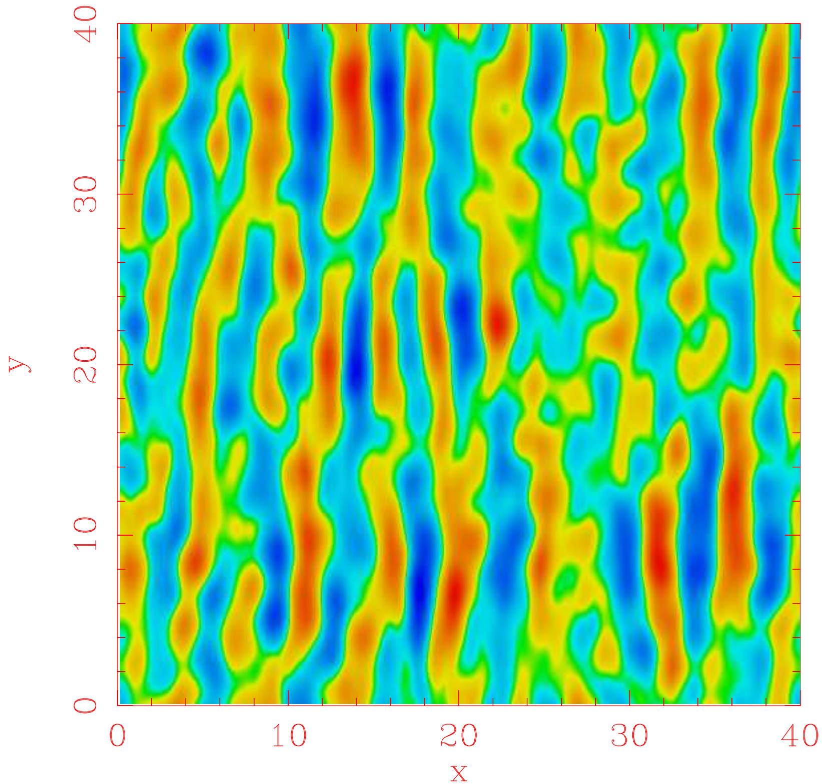


Formation of elongated structures with $k_y \rightarrow 0$ is favoured.

Basic concepts

Numerical simulation of **decaying** turbulence:



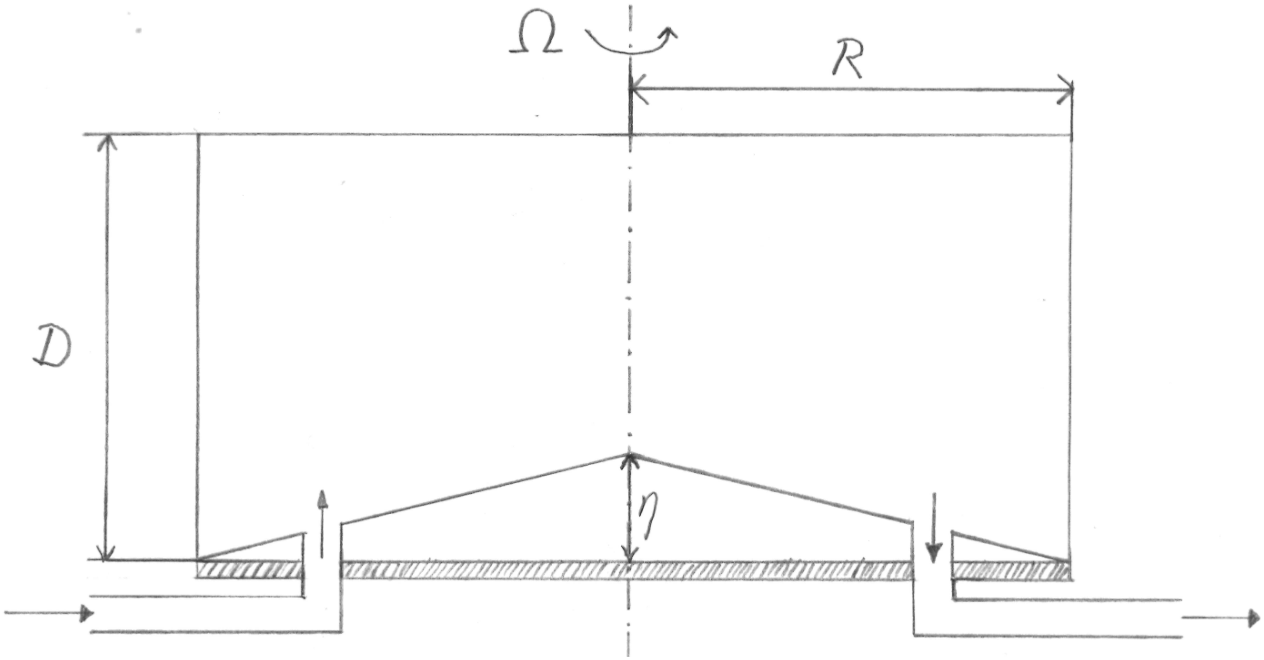


Driver in this case: density inhomogeneity.

Note: Density and *Potential* (e.g. momentum) transport are coupled!!!

Source: Nonlinearity: Polarization drift.

ZF: rotating tank

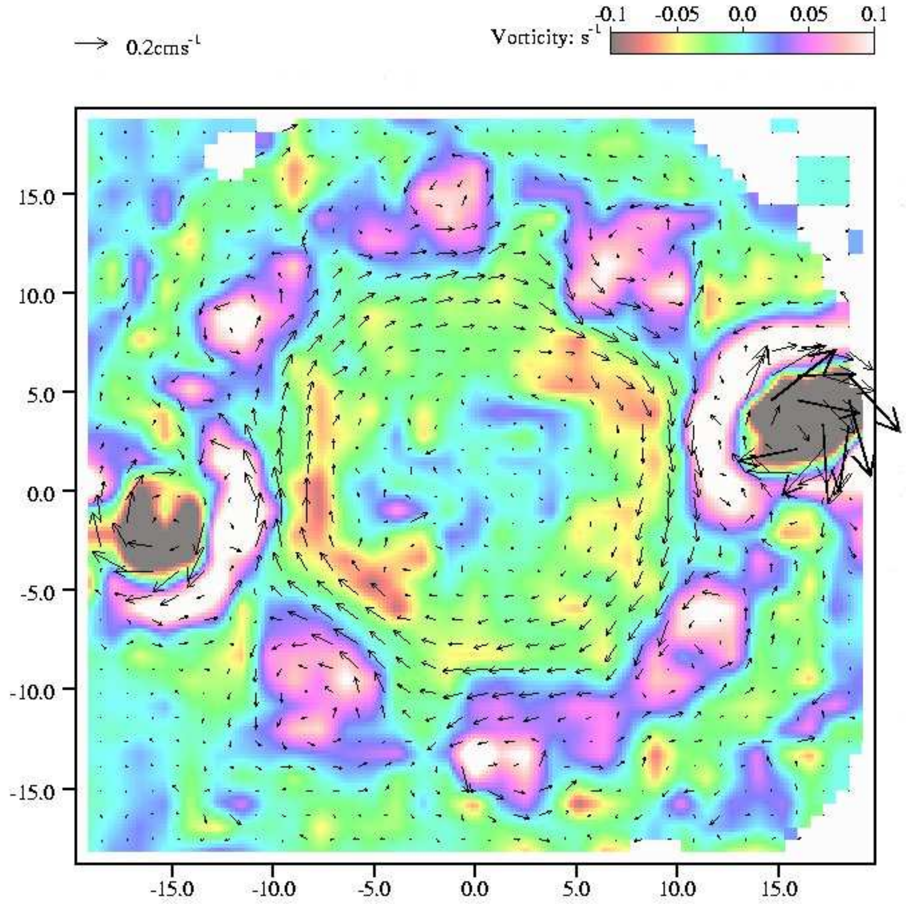


Experimental setup, rotating tank with a rigid lid. R = 19.4 cm, D = 20 cm, $\eta = 5$ cm, rotation rate 12 rpm.

$\Pi = \omega + \beta r$ (expansion $H(r) = 1 - \beta r$)

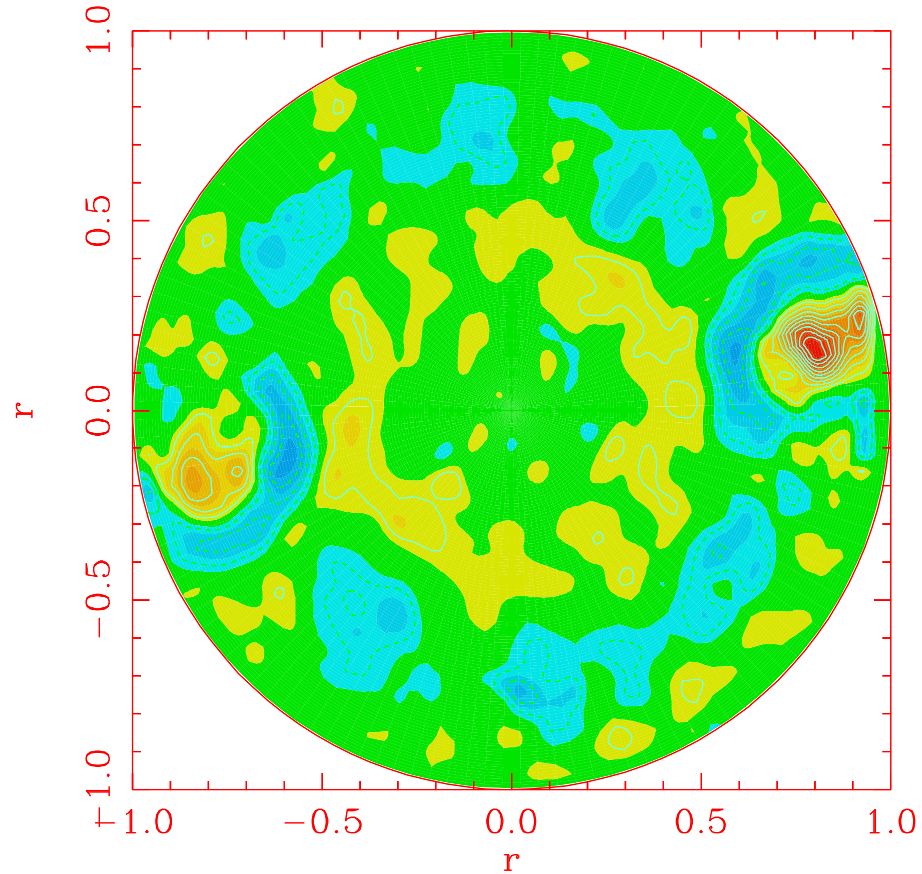
Mixing: periodically pumping water in and out of two holes (diameter $2\,cm$). Forcing period: T_F ($T_F = 6.6\,s$) Diagnostics: particle tracking: instantaneous velocity field

Vorticity field



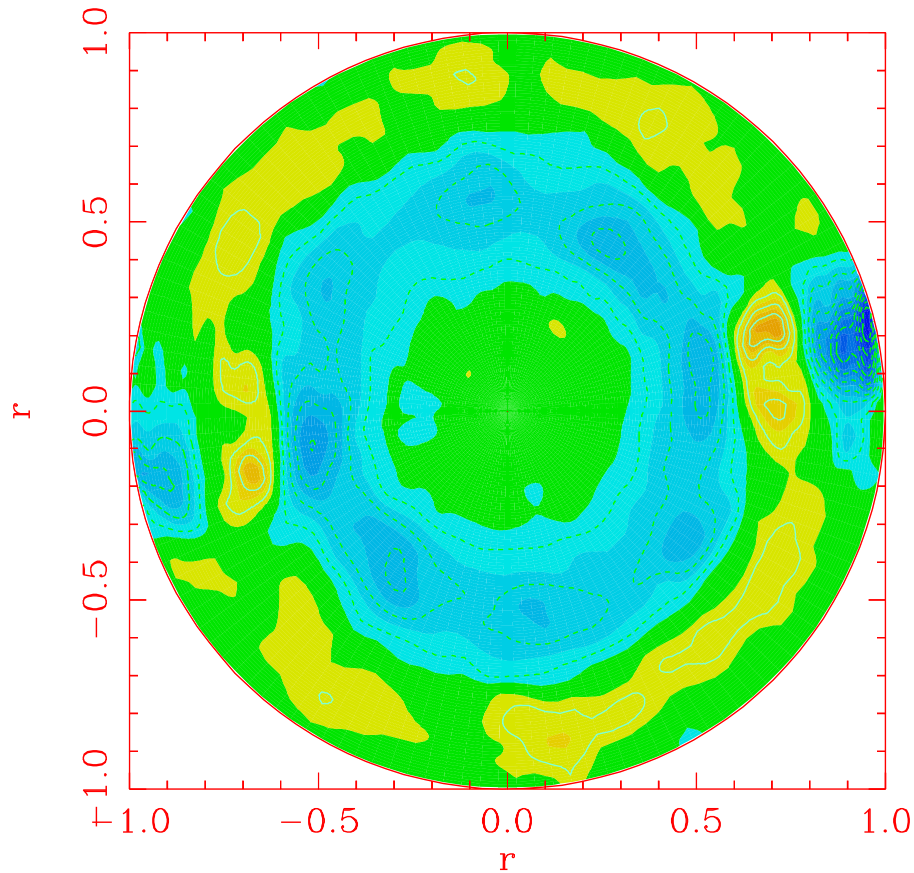
Velocity field shown by arrows and vorticity contours averaged over 10 forcing periods. An anticyclonic circulation is observed

Vorticity



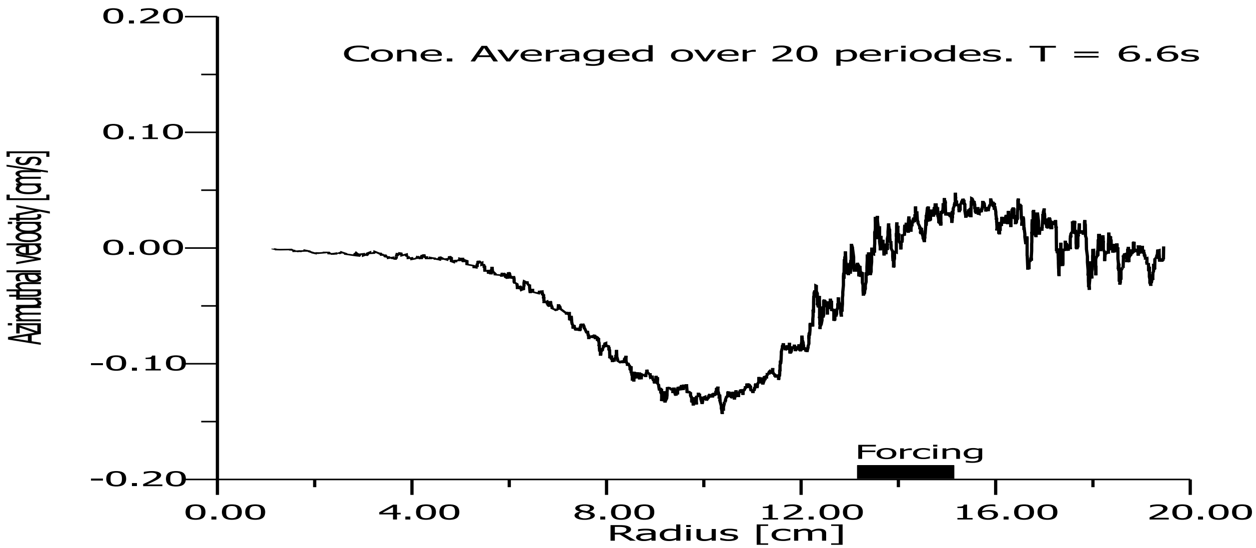
Vorticity field averaged over 20 forcing periods. Red designates negative vorticity and blue positive

Azimuthal velocity



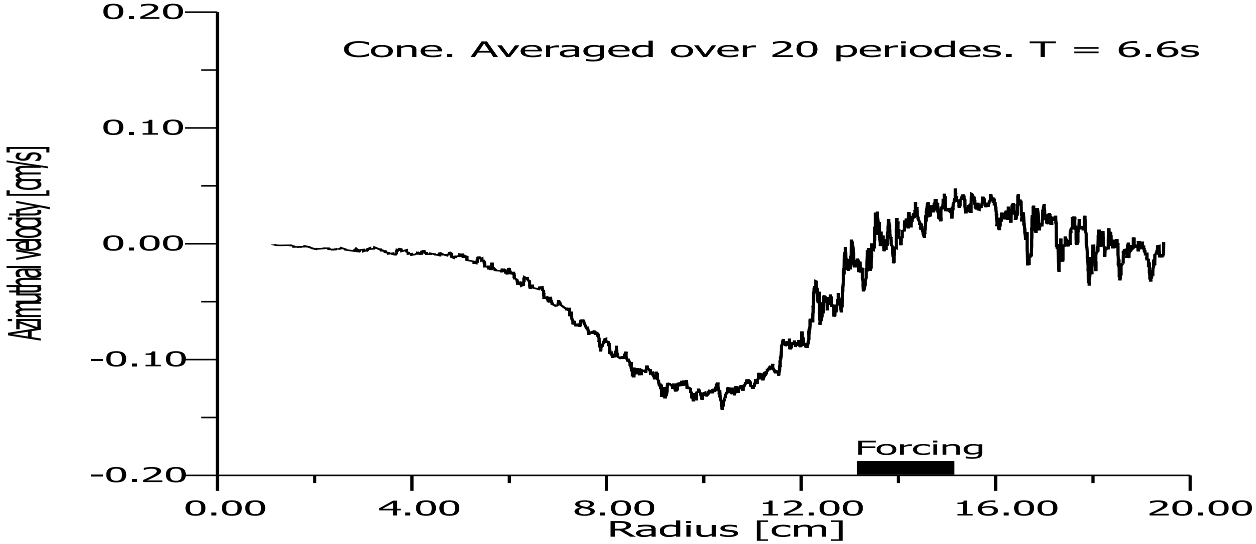
The azimuthal velocity component averaged over 20 forcing periods. Blue designates negative velocity, i.e. anti-cyclonic motion and red designates positive velocity

Averaged flow

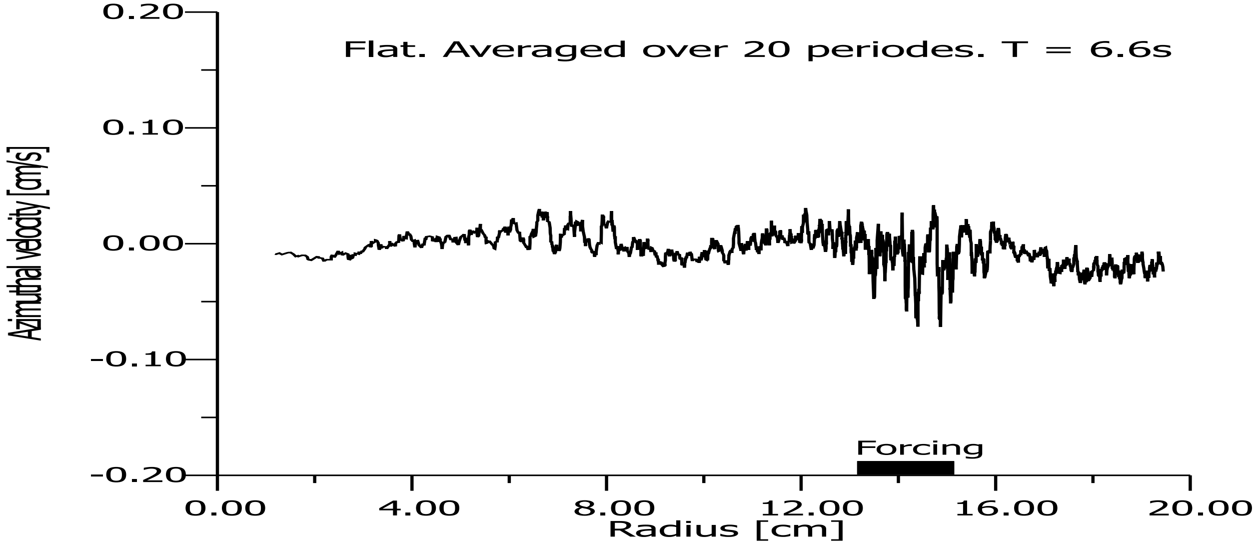


Cone

Averaged flow



Cone



Flat

Numerical results

The forced quasi-geostrophic vorticity equation on a disk with no-slip boundary conditions at the walls.

$$\frac{\partial\omega}{\partial t} + \frac{1}{r}[\phi,\omega] - \frac{\beta}{r}\frac{\partial\phi}{\partial\theta} = -\nu\omega + \frac{1}{Re}\nabla^2\omega + F \quad , \qquad (1)$$

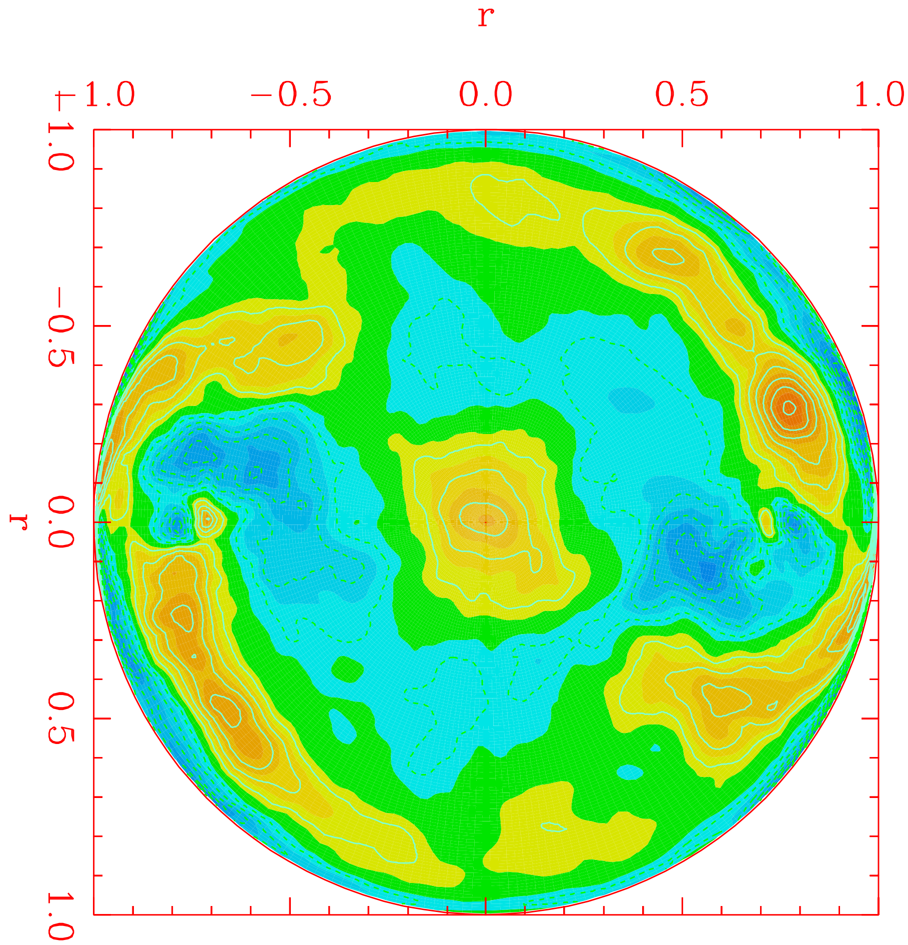
Length is scaled as R, time as f^{-1}, and β by f/R. $\nu = \sqrt{E}$, Ekman number $E = \mu/D^2\Omega$ with a spin down time $\tau_E \approx 90\,s$.

The forcing is modeled by localized vorticity sources with alternating positive and negative vorticity:

$F = A_0[G(x,y;r_1)\sin(\sigma_F t) + G(x,y;r_2)\sin(\sigma_F t + \pi)]$, $G(x,y,r_{1,2})$ localized at the positions of the two holes.

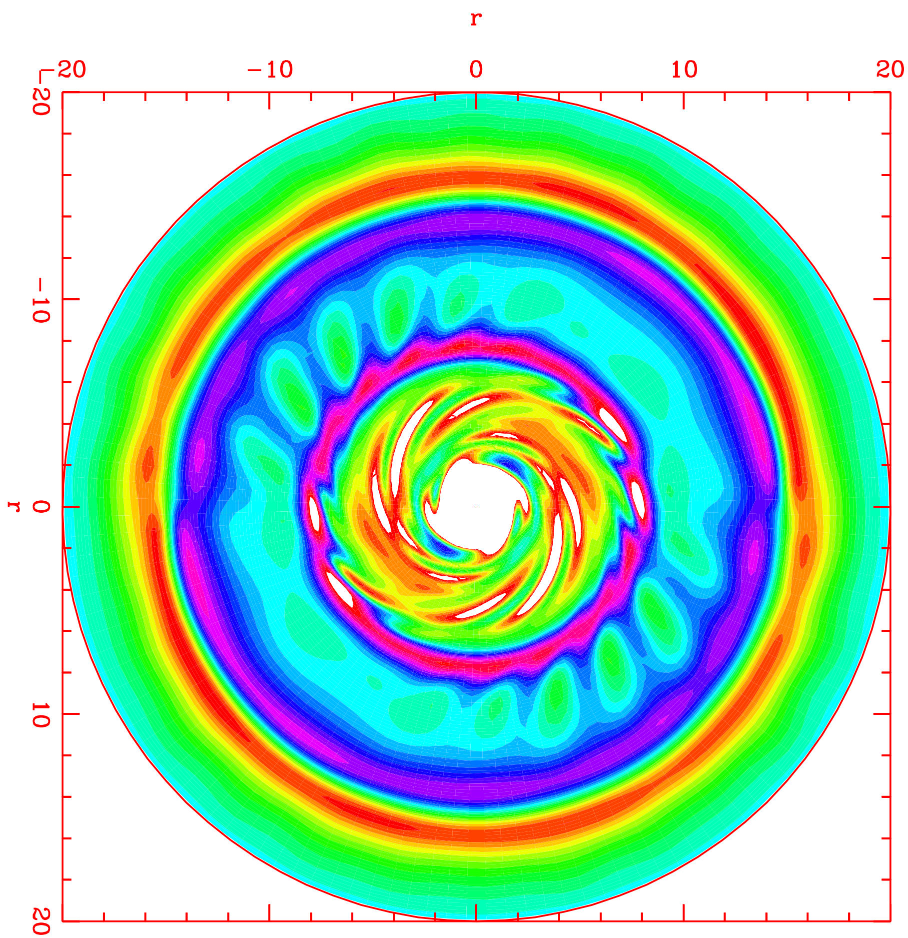
For the experimental condition the scaled values of $\beta = 0.256$ and $E = 4.55\times 10^{-4}$. While $Re \approx 80.000$ and volume viscosity is negligible.

Vorticity field



Numerical solution for the same parameters as in the experiment. Vorticity field averaged over 20 forcing periods for the case of a conical bottom. Red: negative vorticity and blue positive.

Zonal bands



Finite Rossby radius $\rho_s = 1$

The number of bands and their width depends on many parameters:

β, strength of forcing

Is this a case for turbulence spreading??

ZF: rotating fluid

Homogenization of potential vorticity (PV) in quasi 2-D flows (geophysical flows)

P. Rhines *The Sea* (1977); (1979) Ann. Rev. Fluid Mech. **11**, 401 (1979)

$$\frac{D\Pi}{Dt} = \frac{D}{Dt}\left(\frac{\omega + f}{H(r)}\right) = 0$$

$D/Dt \equiv \partial/\partial t + \mathbf{v}\cdot\nabla\mathbf{v}$, ω is the relative vorticity of a fluid element, f is background vorticity, $H(r)$ is the depth of the fluid layer.

Movement towards deeper regions stretch the vortices and enhance ω; towards shallower regions compress the vortices and decrease ω.

Mixing of $\Pi \rightarrow$ low relative vorticity over shallow regions and higher relative vorticity over deeper regions.

Plasma case: Ion vorticity equation (cold ions):

$$\frac{D\Pi_i}{Dt} = \frac{D}{Dt}\left(\frac{\omega + \omega_{ci}}{n(r)}\right) = 0$$

Flows: Reynolds stress

Momentum equation/vorticity equation:

$$\frac{\partial \omega}{\partial t} + \{\phi, \omega\} = \mu \nabla^2 \omega \, .$$

Flows: Reynolds stress

$$\frac{\partial\omega}{\partial t} + \{\phi, \omega\} = \mu\nabla^2\omega\,.$$

Reynolds decomposition (Reynolds (1894)):

$$\omega = \Omega + \widetilde{\omega},\ \phi = \Phi + \widetilde{\phi},\ \mathbf{v} = \mathbf{V} + \widetilde{\mathbf{v}}$$

$$\Omega = \langle\omega\rangle \equiv \frac{1}{L_y}\int_0^{L_y} \omega dy$$

Zonal velocity $V = \langle v \rangle$; $U = 0$

Flows: Reynolds stress

$$\frac{\partial \omega}{\partial t} + \{\phi, \omega\} = \mu \nabla^2 \omega .$$

$$\Omega = \langle \omega \rangle \equiv \frac{1}{L_y} \int_0^{L_y} \omega dy$$

Zonal velocity $V = \langle v \rangle$; $U = 0$

Flow evolution:

$$\frac{\partial V}{\partial t} = - \frac{\partial}{\partial x} \langle uv \rangle + \mu \frac{\partial^2}{\partial x^2} V$$

Flows: Reynolds stress

$$\frac{\partial \omega}{\partial t} + \{\phi, \omega\} = \mu \nabla^2 \omega .$$

$$\Omega = \langle \omega \rangle \equiv \frac{1}{L_y} \int_0^{L_y} \omega dy$$

Zonal velocity $V = \langle v \rangle$; $U = 0$

$$\frac{\partial V}{\partial t} = -\frac{\partial}{\partial x} \langle uv \rangle + \mu \frac{\partial^2}{\partial x^2} V$$

Quasilinear approximation: Contribution from the k'te wave-component:

$$\partial_x \langle uv \rangle = -2k \partial_x (|\psi_k|^2 \partial_x \theta_k)$$

θ_k is the phase of ψ_k.

Flow generation for $\partial_x \theta_k \neq 0$ Radial propagation

Diamond and Kim, Phys. Fluids B **3**, 1626 (1991)

(equivalent to inhomogeneity)

Zonal flows

Facts and fiction:

Sheared flows influence the turbulent transport:

Example radial particle flux: $\Gamma = \langle nu \rangle$

Any poloidal flow does not contribute to Γ!

Flows are said to suppress turbulence!?

Popular: Turbulence shear decorrelation!
(Biglari *et al.* Phys. Fluids B **2**, 1 (1990))

$\omega_{shear} > \gamma_{inst}$

But (turbulence generated) flows are a part of the turbulence, generated by inverse cascade, $\rightarrow$ turbulent fluctuation energy

condensates into flow energy.
Energy transfer processes are crucial to understand.
Moreover: Turbulence not necessarily generated locally (see HM example and Turbulence spreading topic).

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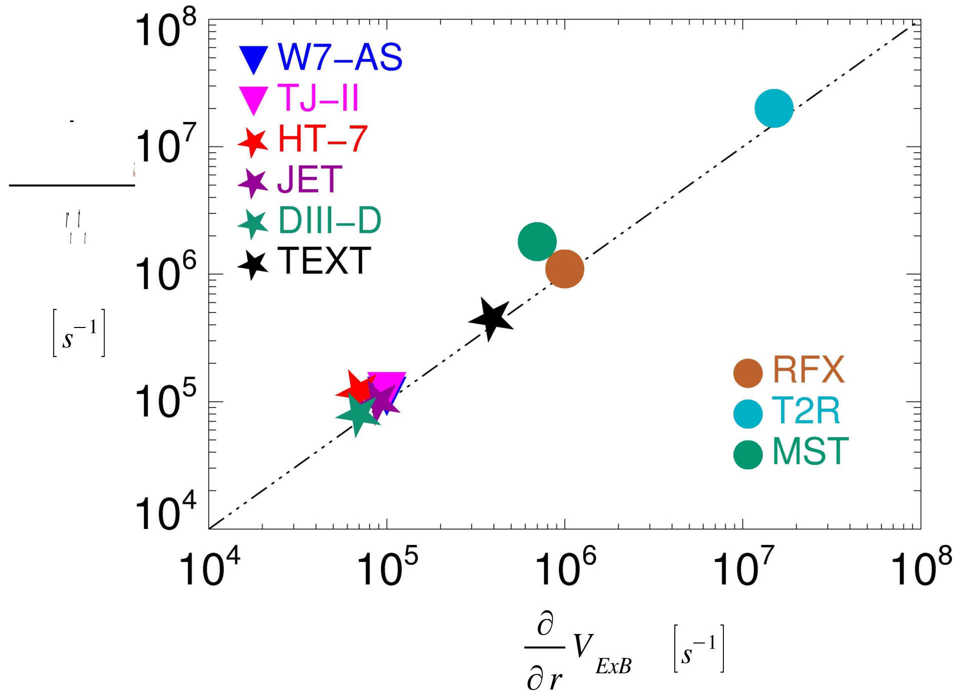
Flows: part of turbulence



Flow shear compared to turbulence scales (radial correlation, mean wavelength) and times (autocorrelation) (V. Antoni, EPS 2005). Suppression of instability is then marginal.

Stabilization?

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

$$\frac{d^2\Psi}{dx^2} + \left[-k_y^2 + \frac{V''}{c-V} + \frac{N}{(c-V)^2} \right] \Psi = 0$$

$N = -B'\left(n_0' - \frac{5}{3}B'\right)$ for $V = 0$: $N \geq 0$ sufficient for stability

Taylor-Goldstein Equation

Sufficient for stability

$$\frac{N}{(V')^2} > \frac{1}{4}$$

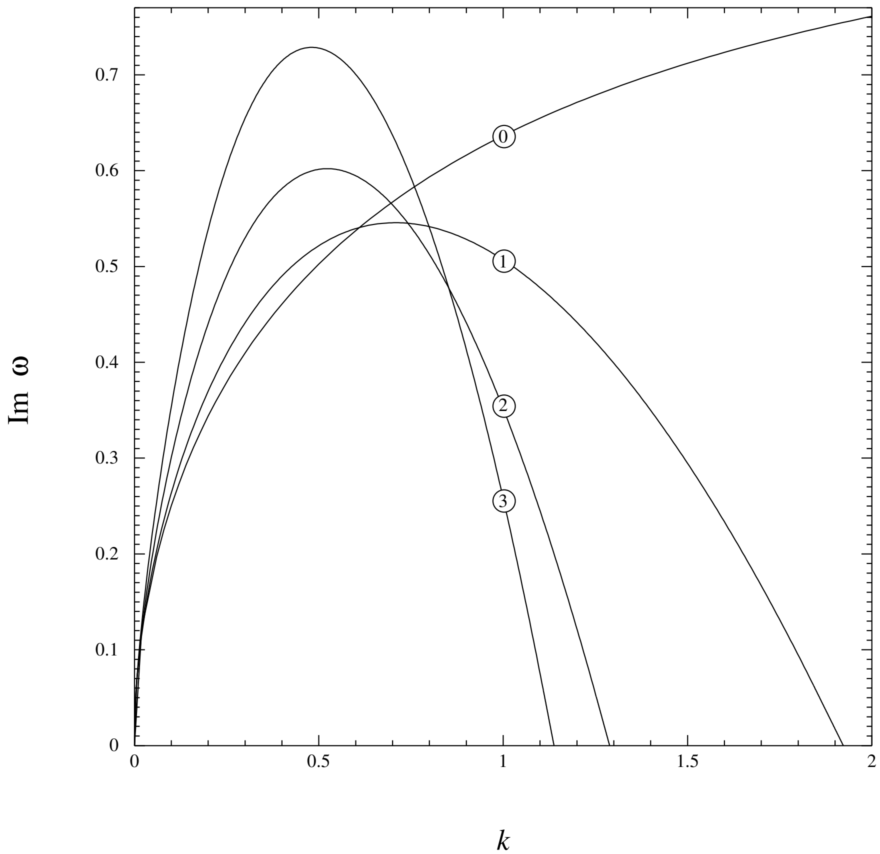
Miles-Howard, JFM **10**, 496 and 509 (1961))

$\longrightarrow$ Shear flow is destabilizing

BUT: stabilizing for a finite $\alpha = L_y/L_x$

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

Shear flow stabilization?



Numerical solution of Taylor-Goldstein eq.: $V(x) = V_0 \tanh x$, $V_0 = 0,\ 0.5,\ 1.0,\ 2.0$

Stability for $2\pi/L_y > k_c$

Drift-Alfvén System

Quasi neutrality

$$\partial_t w + \{\phi, w\} = \mathcal{K}(n+T) + \nabla_\parallel J + \mu_w \nabla_\perp^2 w \, .$$

Drift-Alfvén System

$$\partial_t w + \{\phi, w\} = \mathcal{K}(n+T) + \nabla_\| J + \mu_w \nabla_\perp^2 w\,.$$

Electron continuity

$$\partial_t n + \{\phi, n+n_0\} = \mathcal{K}(n+T-\phi) + \nabla_\| (J-u) + \mu_n \nabla_\perp^2 n\,.$$

Drift-Alfvén System

$$\partial_t w + \{\phi, w\} = \mathcal{K}(n+T) + \nabla_\| J + \mu_w \nabla_\perp^2 w \, .$$

$$\partial_t n + \{\phi, n + n_0\} = \mathcal{K}(n + T - \phi) + \nabla_\| (J - u) + \mu_n \nabla_\perp^2 n \, .$$

Electron temperature

$$\frac{3}{2}\partial_t T = \frac{3}{2}\{\phi, T \hat{+} T_0\} + \nabla_\| ((1+\alpha)J - u) + \frac{1.6}{\mu\nu}\nabla_\| \cdot \nabla_\| T + \hat{\mathcal{K}}\left(n + \frac{7}{2}T - \phi\right)$$

Drift-Alfvén System

$$\partial_t w + \{\phi, w\} = \mathcal{K}(n+T) + \nabla_\parallel J + \mu_w \nabla_\perp^2 w \, .$$

$$\partial_t n + \{\phi, n+n_0\} = \mathcal{K}(n+T-\phi) + \nabla_\parallel (J-u) + \mu_n \nabla_\perp^2 n \, .$$

$$\frac{3}{2}\partial_t T = \frac{3}{2}\{\phi, \hat{T} + T_0\} + \nabla_\parallel ((1+\alpha)J - u) + \frac{1.6}{\mu\nu}\nabla_\parallel \cdot \nabla_\parallel T + \hat{\mathcal{K}}\left(n + \frac{7}{2}T - \phi\right)$$

Ohms Law

$$\mu \partial_t J + \hat{\beta}\partial_t \Psi + \mu\{\phi, J\} = \nabla_\parallel (n + n_0 + (1+\alpha)(T+T_0) - \phi) - \mu\nu J \, .$$

Drift-Alfvén System

$$\partial_t w + \{\phi, w\} = \mathcal{K}(n+T) + \nabla_\parallel J + \mu_w \nabla_\perp^2 w \ .$$

$$\partial_t n + \{\phi, n + n_0\} = \mathcal{K}(n + T - \phi) + \nabla_\parallel (J - u) + \mu_n \nabla_\perp^2 n \ .$$

$$\frac{3}{2}\partial_t T = \frac{3}{2}\{\phi, T\hat{} + T_0\} + \nabla_\parallel ((1+\alpha)J - u) + \frac{1.6}{\mu\nu}\nabla_\parallel \cdot \nabla_\parallel T + \hat{\mathcal{K}}\left(n + \frac{7}{2}T - \phi\right)$$

$$\mu\partial_t J + \hat{\beta}\partial_t \Psi + \mu\{\phi, J\} = \nabla_\parallel (n + n_0 + (1+\alpha)(T + T_0) - \phi) - \mu\nu J \ .$$

Parallel Ion motion

$$\partial_t u + \{\phi, u\} = -1/\mu\nabla_\parallel (T + T_0 + n + n_0) \ .$$

Drift-Alfvén System

$$\partial_t w + \{\phi, w\} = \mathcal{K}(n+T) + \nabla_\| J + \mu_w \nabla_\perp^2 w \,.$$

$$\partial_t n + \{\phi, n+n_0\} = \mathcal{K}(n+T-\phi) + \nabla_\| (J-u) + \mu_n \nabla_\perp^2 n \,.$$

$$\frac{3}{2}\partial_t T = \frac{3}{2}\{\phi, T\hat{\ } + T_0\} + \nabla_\| ((1+\alpha)J - u) + \frac{1.6}{\mu\nu}\nabla_\| \cdot \nabla_\| T + \hat{\mathcal{K}}\left(n + \frac{7}{2}T - \phi\right)$$

$$\mu\partial_t J + \hat{\beta}\partial_t \Psi + \mu\{\phi, J\} = \nabla_\| (n + n_0 + (1+\alpha)(T+T_0) - \phi) - \mu\nu J \,.$$

$$\partial_t u + \{\phi, u\} = -1/\mu\nabla_\| (T + T_0 + n + n_0) \,.$$

Definitions: $\{\phi, \cdot\} = \vec{v}_{E\times B} \cdot \nabla\cdot \,, \quad J = -\nabla_\perp^2 \Psi \,, \quad w = \nabla_\perp^2 \phi \,.$

Drift-Alfvén System

$$\partial_t w + \{\phi, w\} = \mathcal{K}(n+T) + \nabla_{\|} J + \mu_w \nabla_{\perp}^2 w \,.$$

$$\partial_t n + \{\phi, n+n_0\} = \mathcal{K}(n+T-\phi) + \nabla_{\|}(J-u) + \mu_n \nabla_{\perp}^2 n \,.$$

$$\frac{3}{2}\partial_t T = \frac{3}{2}\{\phi, T\hat{} + T_0\} + \nabla_{\|}((1+\alpha)J - u) + \frac{1.6}{\mu\nu}\nabla_{\|}\cdot\nabla_{\|}T + \hat{\mathcal{K}}\left(n + \frac{7}{2}T - \phi\right)$$

$$\mu\partial_t J + \hat{\beta}\partial_t\Psi + \mu\{\phi, J\} = \nabla_{\|}(n + n_0 + (1+\alpha)(T+T_0) - \phi) - \mu\nu J \,.$$

$$\partial_t u + \{\phi, u\} = -1/\mu\nabla_{\|}(T + T_0 + n + n_0) \,.$$

Definitions: $\{\phi, \cdot\} = \vec{v}_{E\times B}\cdot\nabla\cdot\,, \quad J = -\nabla_{\perp}^2\Psi\,, \quad w = \nabla_{\perp}^2\phi\,.$
Parallel Gradient is non-linear operator.

$$\nabla_{\|}\cdot = \partial_s\cdot + \hat{\beta}\{\Psi, \cdot\} \,.$$

Drift-Alfvén System

$$\partial_t w + \{\phi, w\} = \mathcal{K}(n+T) + \nabla_\parallel J + \mu_w \nabla_\perp^2 w \; .$$

$$\partial_t n + \{\phi, n+n_0\} = \mathcal{K}(n+T-\phi) + \nabla_\parallel (J-u) + \mu_n \nabla_\perp^2 n \; .$$

$$\frac{3}{2}\partial_t T = \frac{3}{2}\{\phi, T \hat{+} T_0\} + \nabla_\parallel ((1+\alpha)J - u) + \frac{1.6}{\mu\nu}\nabla_\parallel \cdot \nabla_\parallel T + \hat{\mathcal{K}}\left(n + \frac{7}{2}T - \phi\right)$$

$$\mu\partial_t J + \hat{\beta}\partial_t \Psi + \mu\{\phi, J\} = \nabla_\parallel (n + n_0 + (1+\alpha)(T+T_0) - \phi) - \mu\nu J \; .$$

$$\partial_t u + \{\phi, u\} = -1/\mu \nabla_\parallel (T + T_0 + n + n_0) \; .$$

Definitions: $\{\phi, \cdot\} = \vec{v}_{E\times B} \cdot \nabla \cdot \; , \quad J = -\nabla_\perp^2 \Psi \; , \quad w = \nabla_\perp^2 \phi \; .$

$$\nabla_\parallel \cdot = \partial_s \cdot + \hat{\beta}\{\Psi, \cdot\} \; .$$

$$\mathcal{K} = \omega_B(\sin(z)\partial_x + cos(z)\partial_y) \; .$$

$$\hat{\beta} = \frac{4\pi p_e}{B^2}\left(\frac{qR}{L_\perp}\right)^2, \quad \mu = \frac{m}{M}\left(\frac{qR}{L_\perp}\right)^2, \quad \nu = 0.51\frac{L_\perp}{\tau_e c_s} \, ,$$

Flow generation

Start from the vorticity equation

$$\partial_t w + \{\phi, w\} = \mathcal{K}(n+T) + \nabla_\parallel J + \mu_w \nabla_\perp^2 w \,.$$

Flow generation

multiply by V_0, average .

$$\frac{d}{dt}U = \frac{1}{2}\frac{\partial \int V_0^2}{\partial t}dx =$$

$$\int \langle uv \rangle \frac{\partial V_0}{\partial x}dx - \hat{\beta} \int \langle \widetilde{B}_x \widetilde{B}_y \rangle \frac{\partial V_0}{\partial x}dx$$

$$-\omega_B \int \langle n \sin s \rangle V_0 dx - \nu_\omega \int (\frac{\partial V_0}{\partial x})^2 dx.$$

Flow generation

multiply by V_0, average .

$$\frac{dU}{dt} = T_{\mathsf{RS}} + T_{\mathsf{MS}} + T_{\mathsf{GAM}} + \Delta,$$

kinetic energy transfer terms due to Reynolds stress (RS), Maxwell stress (MS) and geodesic acoustic modes (GAM):

$$T_{\mathsf{RS}} = \int d\mathbf{x}\, \widetilde{v}_x \widetilde{v}_y \frac{\partial v_0}{\partial x},$$

$$T_{\mathsf{MS}} = -\widehat{\beta} \int d\mathbf{x}\, \widetilde{B}_x \widetilde{B}_y \frac{\partial v_0}{\partial x}, \qquad T_{\mathsf{GAM}} = -\omega_B \int d\mathbf{x}\, v_0 n \sin s.$$

and dissipation Δ (*we know how that works*).

β effects

In pure MHD turbulence there is a balance between Maxwell and Reynolds stress. (Kim, Hahm, Diamond 2001). Functional relationship between the fluctuations in magnetic potential and electrostatic potential:

$$A_\| = \frac{(\omega_B k_y)/(k_\| k_\perp^2) + c}{[\omega_B k_y c(\hat{\beta} - \hat{\mu} k_\perp^2)]/[k_\| k_\perp^2] + 1} \phi \, ,$$

with $c = \omega / k_\|$.

In the limit of high $\hat{\beta}$ use Alfvén branch of the dispersion relation $v_A = \hat{\beta}^{-1/2}$:

$$A_\| = \phi / \sqrt{\hat{\beta}} \, .$$

Reynolds- and Maxwellstress cancel.

Toroidal effects

GAM arises from coupling of density sidebands with geodesic curvature

$$\frac{\partial}{\partial t}\langle n \sin z\rangle + \frac{\partial}{\partial x}\langle \sin z\, n \frac{\partial \phi}{\partial y}\rangle + \omega_B \langle \sin^2 z \frac{\partial n}{\partial x}\rangle$$

$$= \omega_B \langle \sin^2 z \frac{\partial \phi}{\partial x}\rangle - \langle \sin z \frac{\partial u}{\partial z}\rangle .$$

Frequency of oszillation

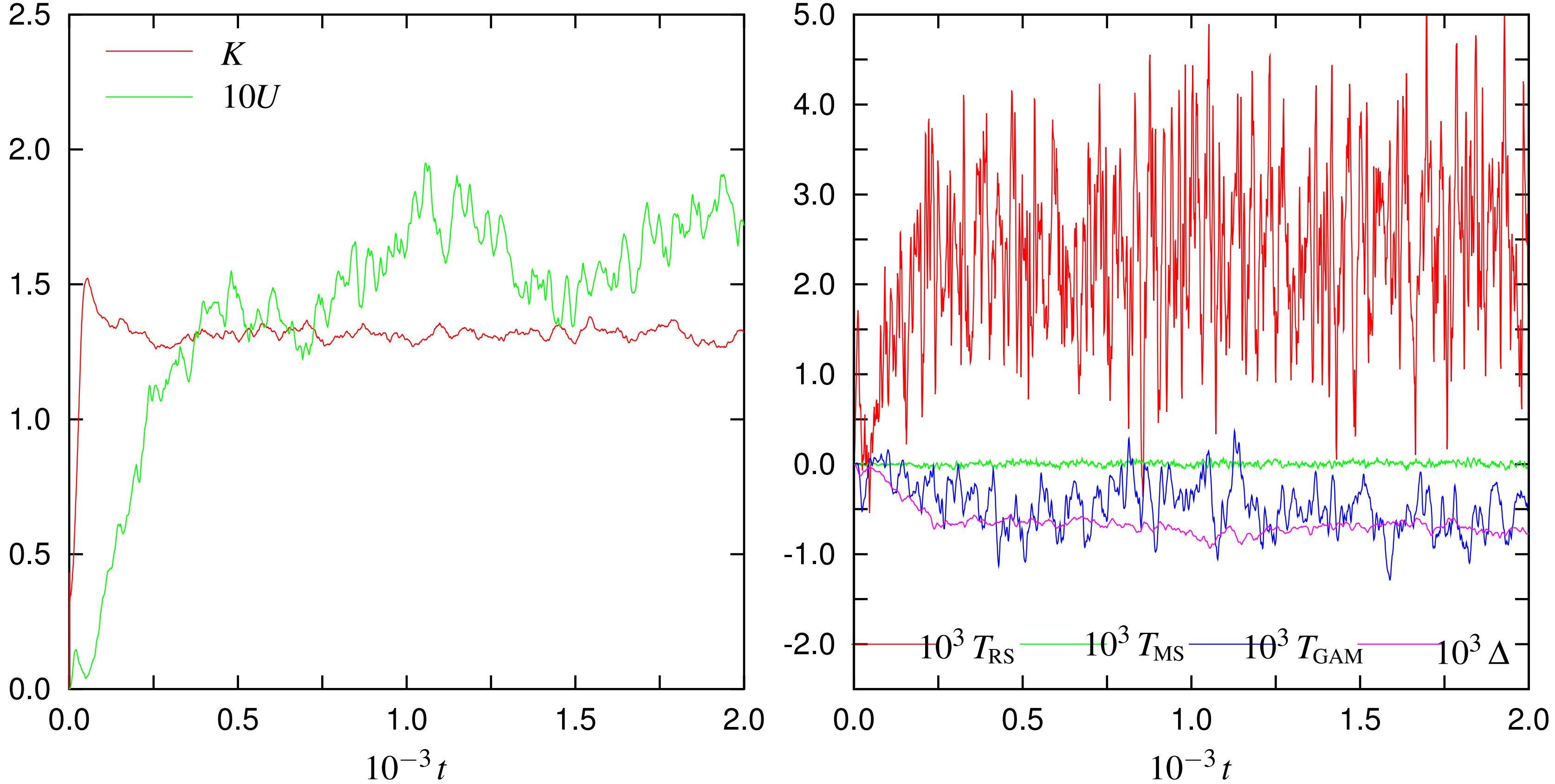
$$\omega_B \langle \sin^2 z \frac{\partial \phi}{\partial x}\rangle = \frac{1}{2}\omega_B \langle [1 - \cos(2z)] \frac{\partial \phi}{\partial x}\rangle \approx \frac{1}{2}\omega_B V_0$$

If fluctuations show ballooning GAM frequency is shifted from ω_{GAM}. For our parameters we experience a downshift by an additional factor of approximately $\sqrt{1/2}$.

flows (low $\hat{\beta}$)

Variation with collisionality $\widehat{\nu}$

$$\widehat{\beta} = 1.0, \widehat{\nu} = 2.0$$

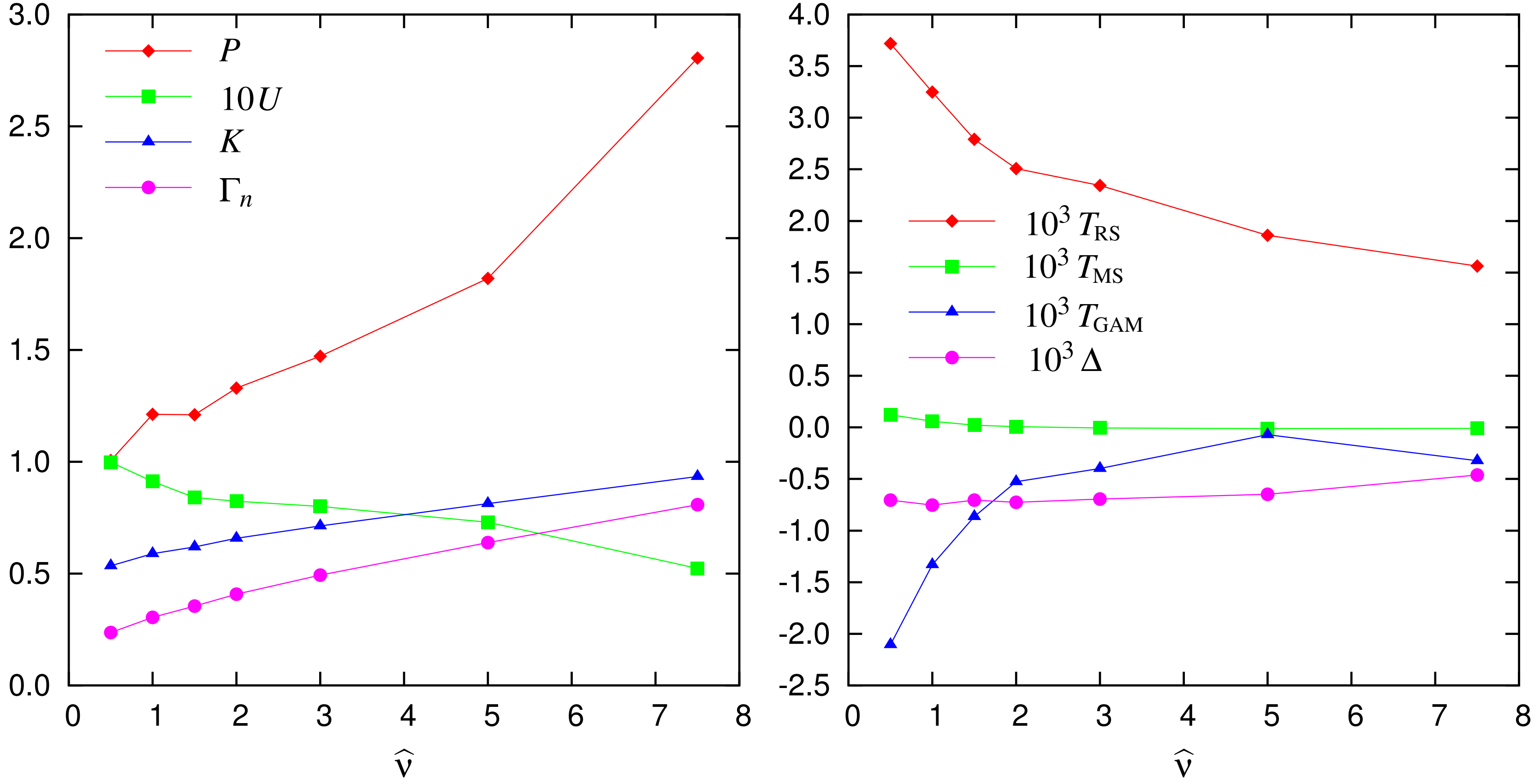


Kinetic energy and flow energy (left), transfer terms (right)

flows (low $\hat{\beta}$)

Variation with collisionality $\widehat{\nu}$

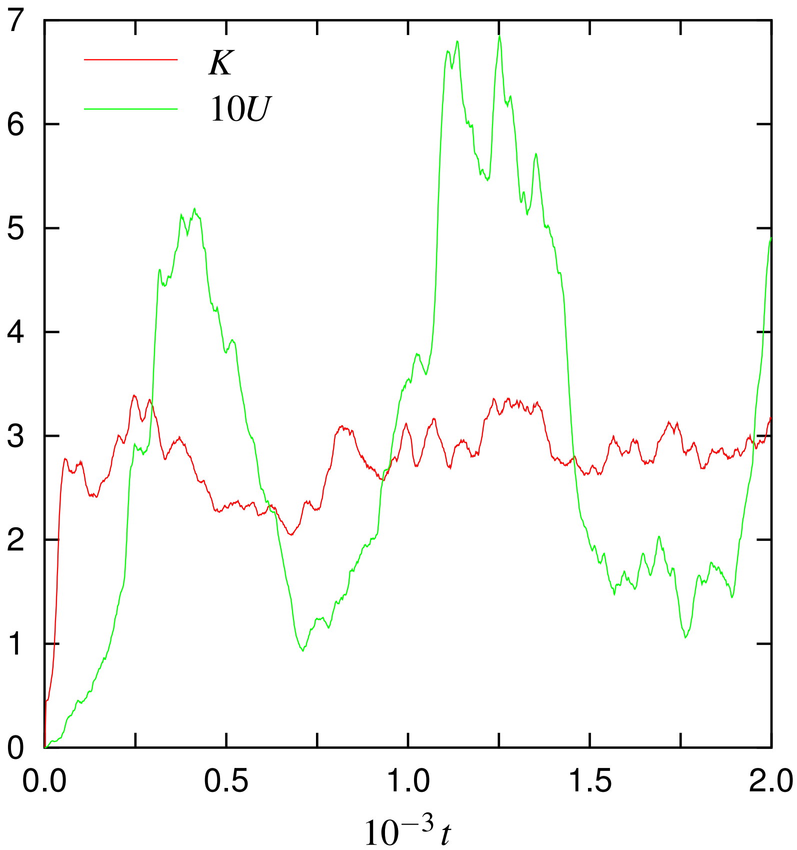
$$\widehat{\beta} = 1.0$$

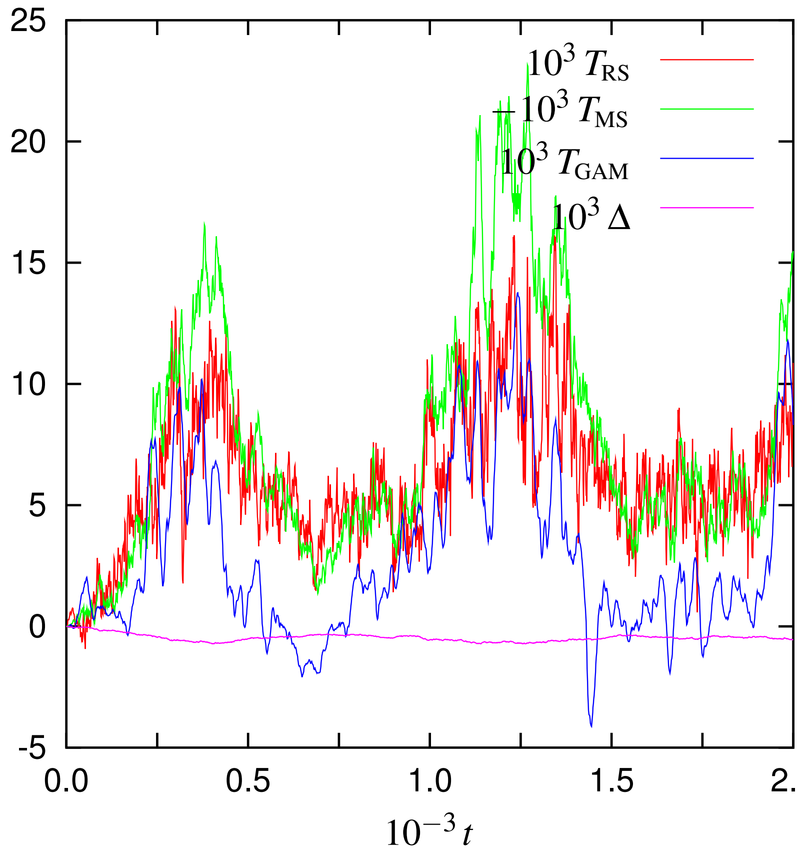


flows (high $\hat{\beta}$)

Variation with collisionality $\hat{\nu}$

$$\widehat{\beta} = 30.0,\ \widehat{\nu} = 5.0$$



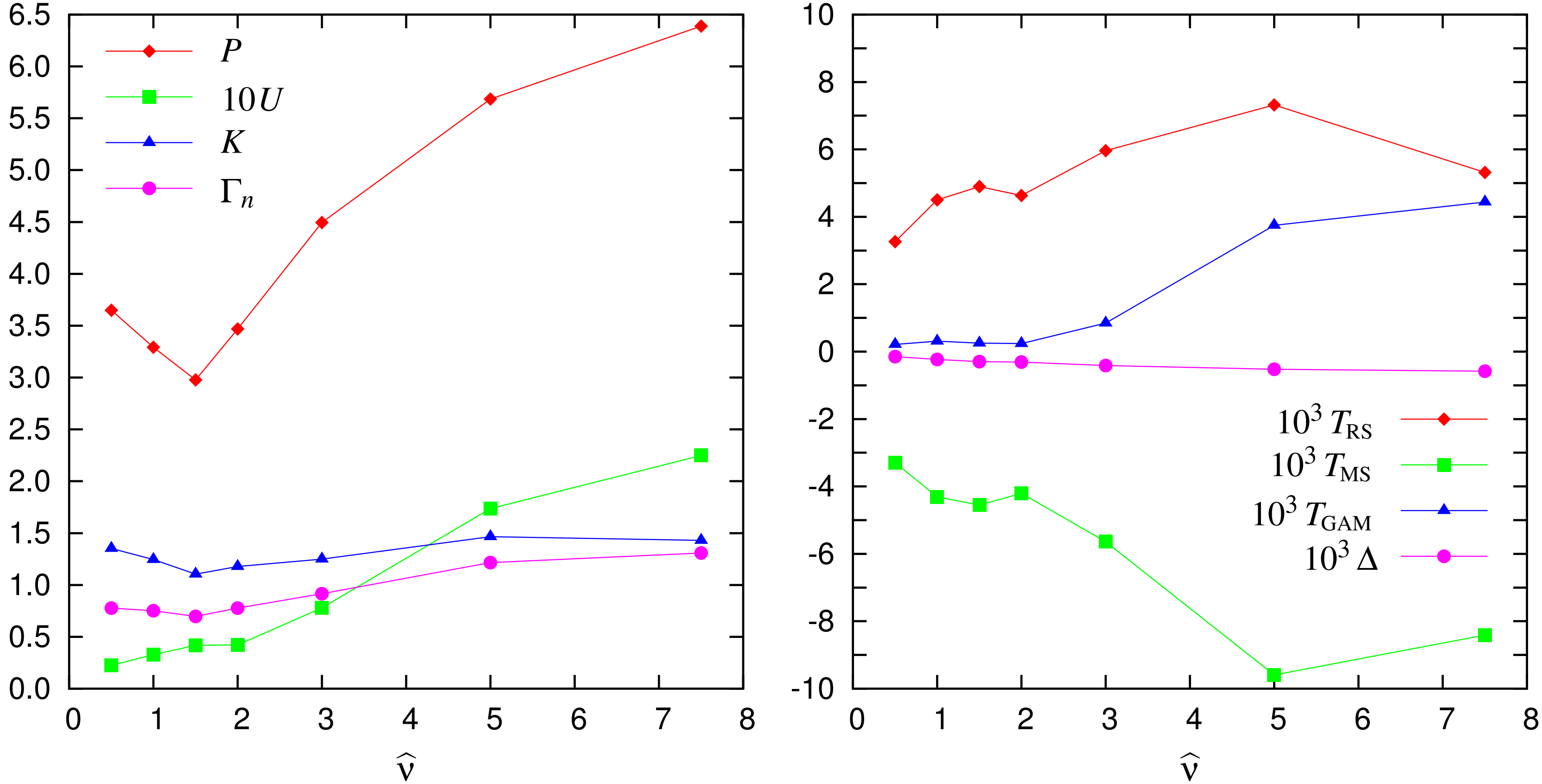


Kinetic energy and flow energy (left), transfer terms (right)

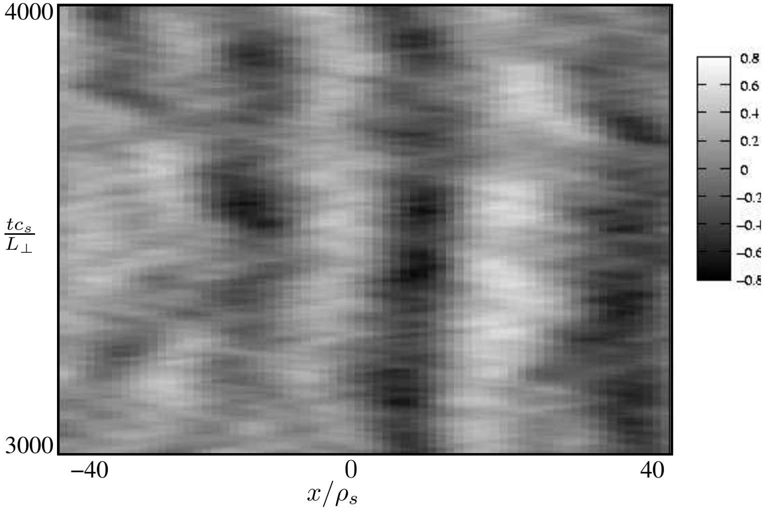
flows (high $\hat{\beta}$)

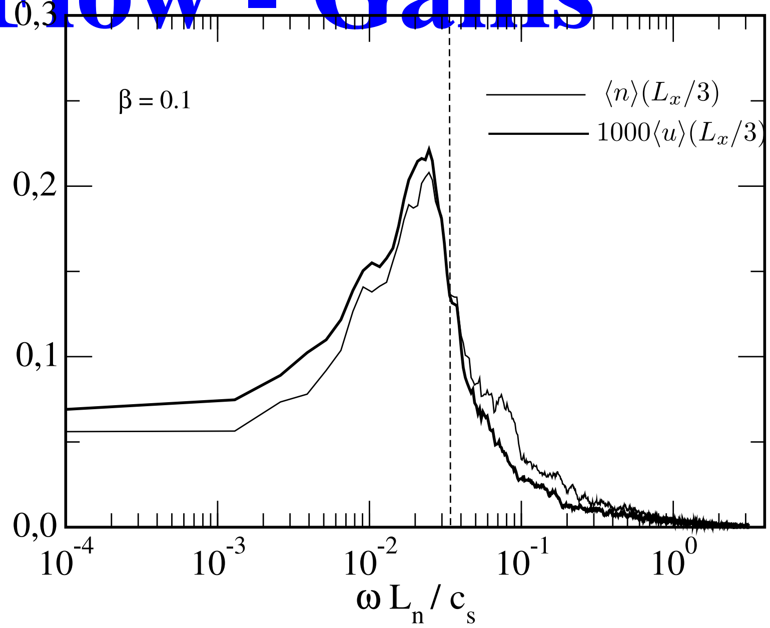
Variation with collisionality $\hat{\nu}$

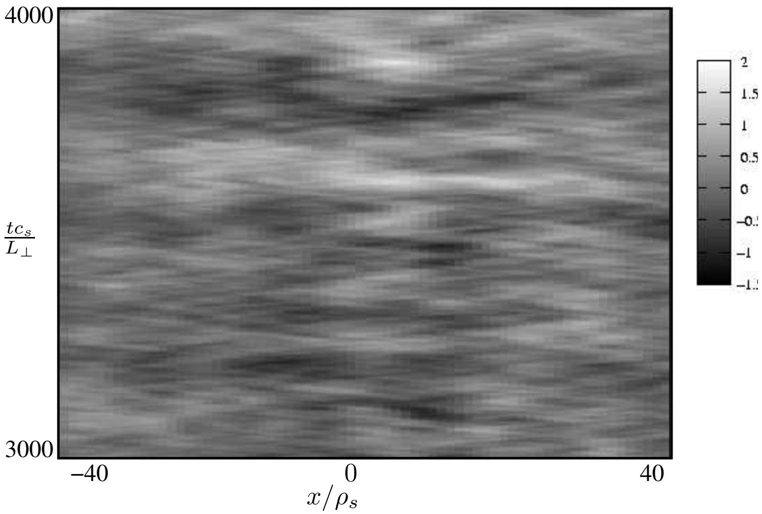
$$\hat{\beta} = 30.0$$

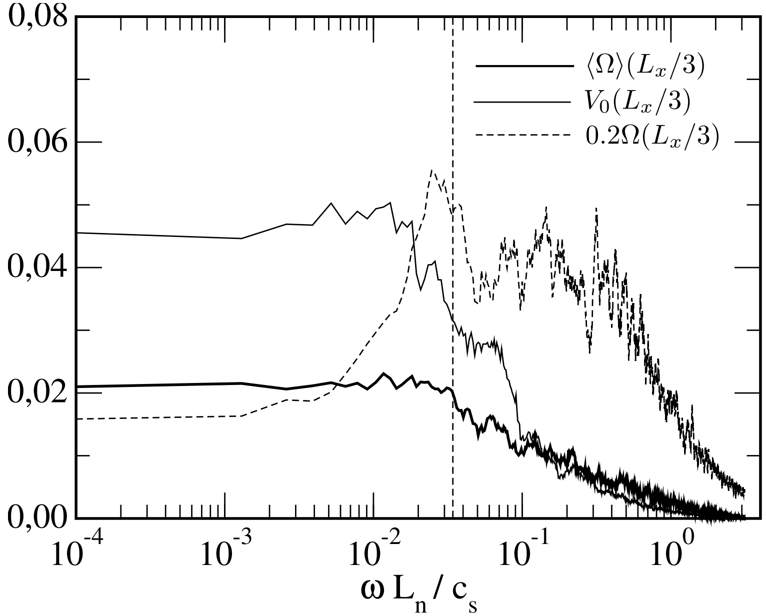


Zonal Flow - Gams

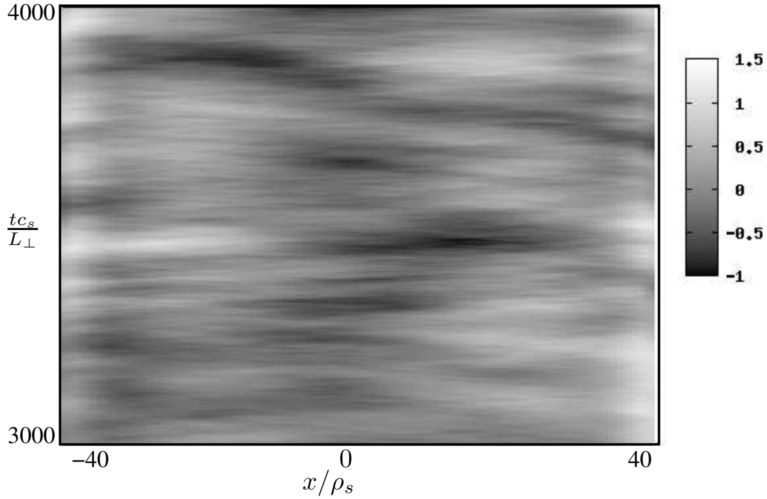


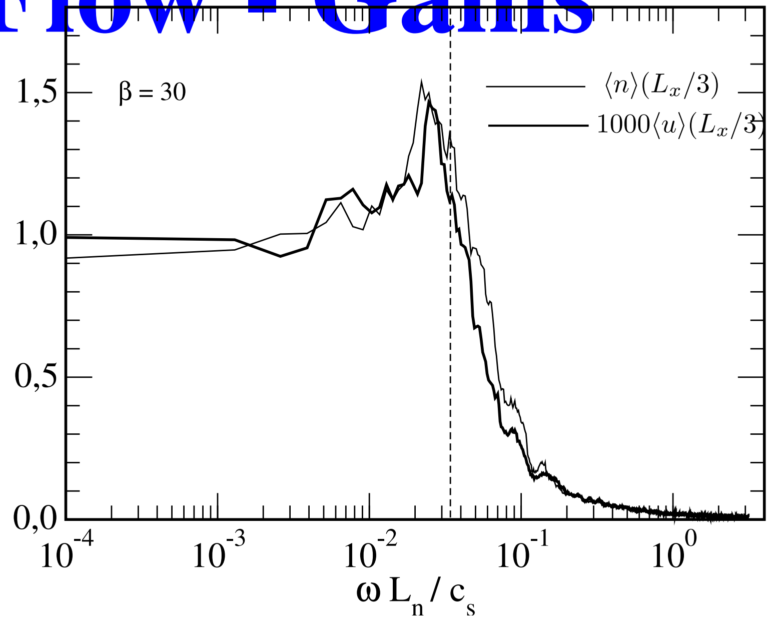


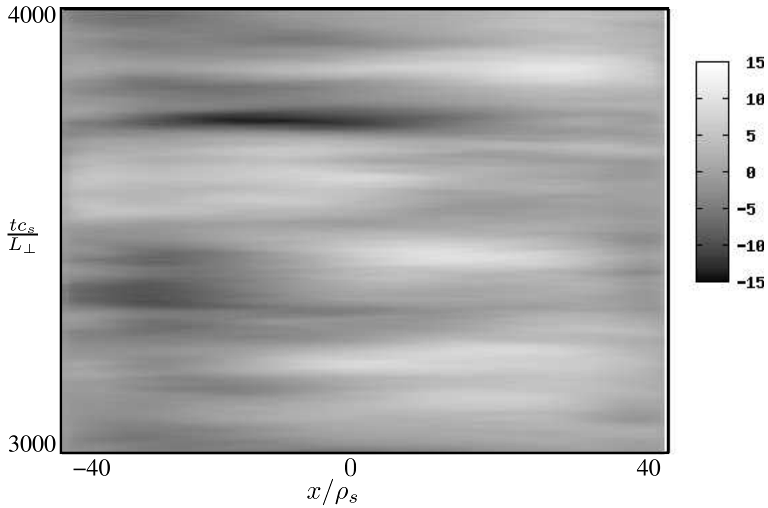


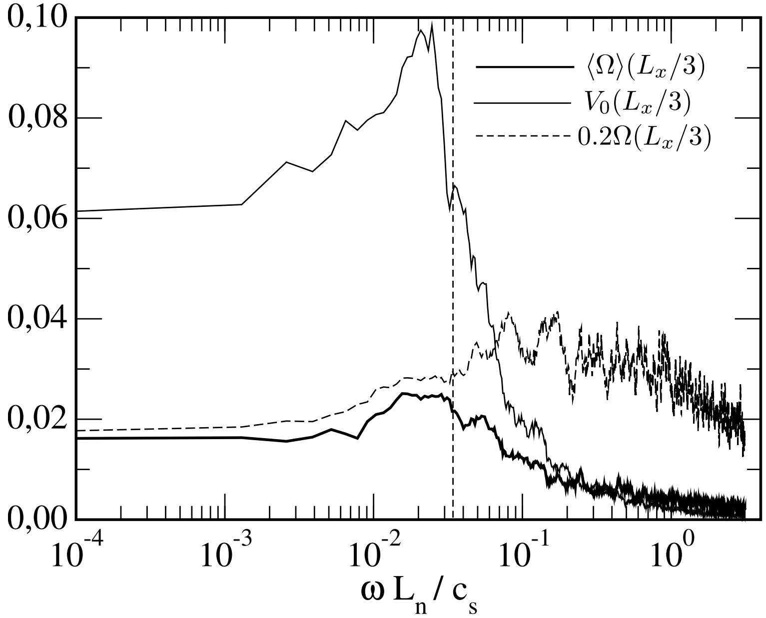


Zonal Flow - Gams

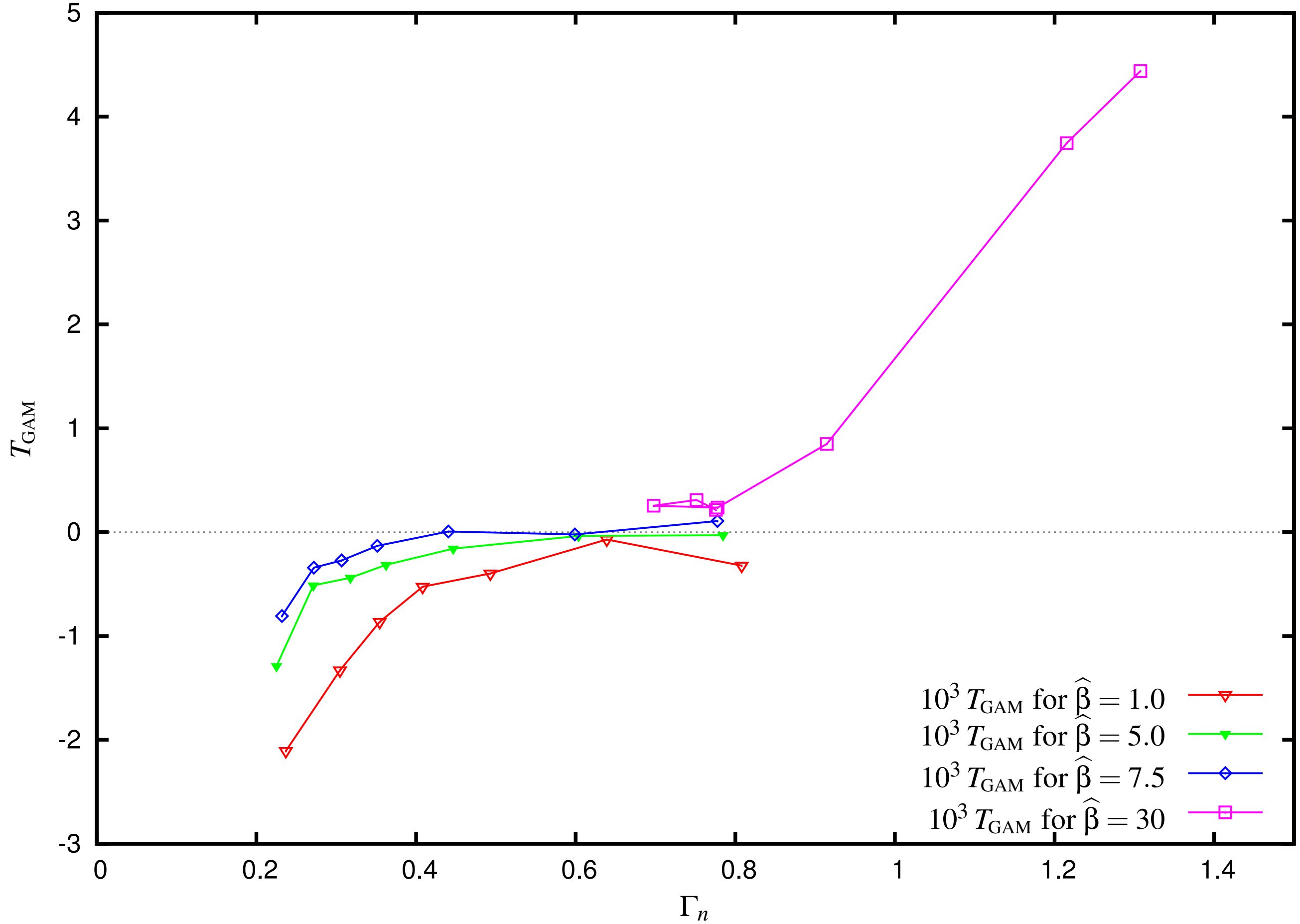






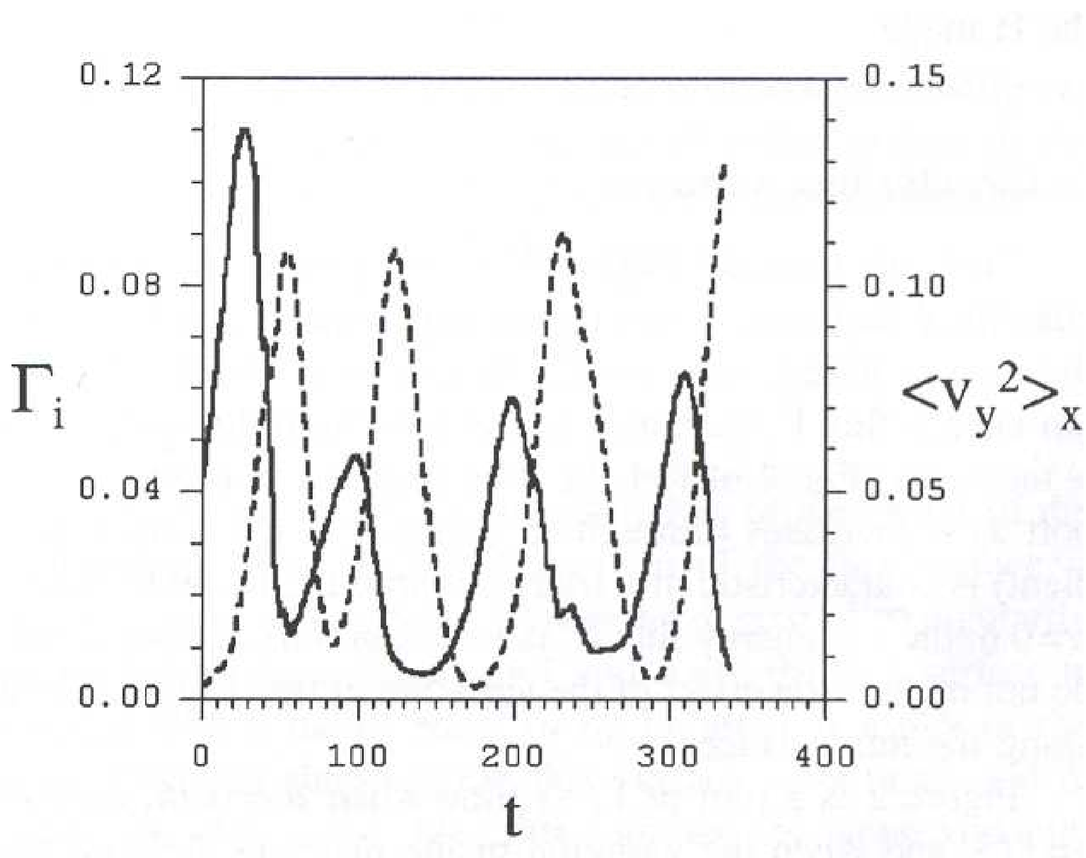


Gams and Transport



Gams transfer shows dependence on transport level and ballooning.

Edge transport model



Edge turbulence simulation in D-shaped Tokamak plasmas

R.G. Kleva *et al.* Phys. Plasma **11**, 4280 (2004)

Predator prey models, self-regulation ....

To many open questions to conclude...

Questions

- How do flows flow in Tokamak geometry?
- zonal flows vs. general sheared flows
- toroidal rotation
- perpendicular/parallel vs. poloidal/toroidal
- momentum transport, additional mechanisms
- expulsion of fast particles with preference parallel direction