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Nonlinear effects produced by the ExB drift on transport and structure generation in turbulent tokamak plasmas

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The milestones for 2010 are

- ***Density evolution of impurities and particles in turbulent tokamak plasmas***
- ***Zonal flow generation and particle trapping in the structure of the turbulent potential***

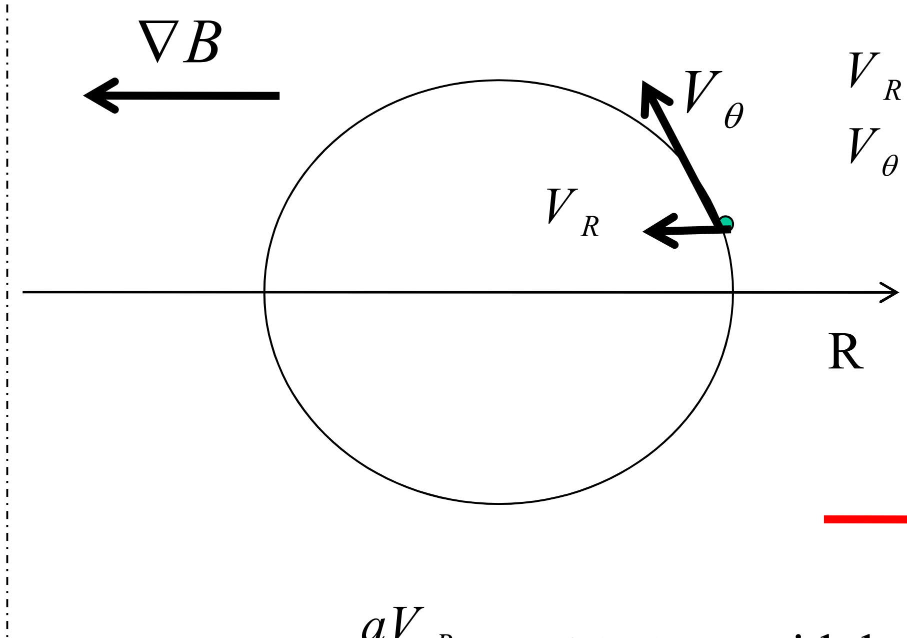
A part of the research proposed in this project represents our Association contributions to EFDA Work Programme for the Transport Task Group at the following topics:

- WP10-TRA-01: Physics of L-H transition, WP10-TRA-01-02: Role of the multi-scale mechanism in the L-H transition
- WP10-TRA-05: Statistical properties of the edge turbulent transport, WP10-TRA-05-01: Turbulent structures and intermittency

1. *Density evolution of impurities and particles in turbulent tokamak plasmas*

A new mechanism of impurity accumulation/loss was found in 2009.

It is a nonlinear affect determined by the ***ratchet pinch velocity*** in toroidal geometry due to the poloidal motion of the impurity ions induced by the motion along magnetic lines and by the flows generated by the moving potential.



V_R - The ratchet pinch

V_θ - Projection of the parallel motion + ion flow velocity generated by the moving potential of the turbulence

- Diffusion

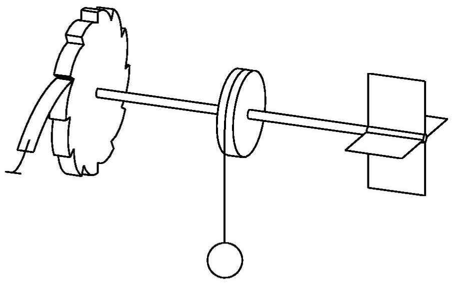
→ ***Oscillation of the peaking factor***

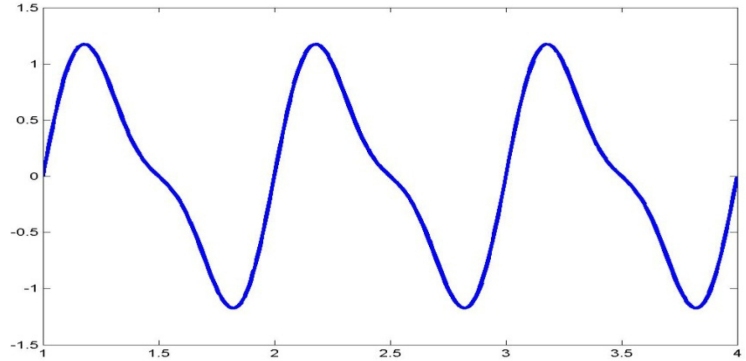
$$p = \frac{aV_R}{D} = f(R)$$ with large variation over poloidal rotation

Direct transport (pinch) from a ratchet type process

• ***Ratchet effects or Brownian motors***

Smoluchowski-Feynman Gedankenexperiment for converting Brownian motion into work





Minimal model:

V(x) is a periodic potential with ***broken symmetry***

$$\frac{dx}{dt} = V(x) + \eta(t) \longrightarrow \frac{d}{dt}\langle x(t)\rangle = 0 \quad for\ t \to \infty$$

<u>But,</u> if the system is not in equilibrium (due to a drive, another noise with different temperature, a variable amplitude of the noise, a time variation of the periodic potential, …),

an average velocity appears.

There are many types of ratchet models in all fields **(physics, biology, ingineering, …)**

See the review paper P. Reimann, Phys. Reports 361 (2002) 57-265 and the **784 references** therein !

We have shown that the ExB drift determines an average velocity of ratchet type *if the magnetic field is space dependent*

$$\frac{dx}{dt} = V(x) + \eta(t)$$

$$\frac{d\vec{x}(t)}{dt} = -\frac{\nabla\phi(\vec{x},t)\times\vec{B}}{B^2}, \quad B = B_0 \frac{x_1}{R}\vec{e}_z$$

1. Periodic non-symmetric velocity → Periodic Lagrangian velocity with symmetry braking due to space dependence of B
2. Noise → Random dynamics produced by the stochastic potential
3. Element that drives the system out of equilibrium → The time dependence of the stohastic potential

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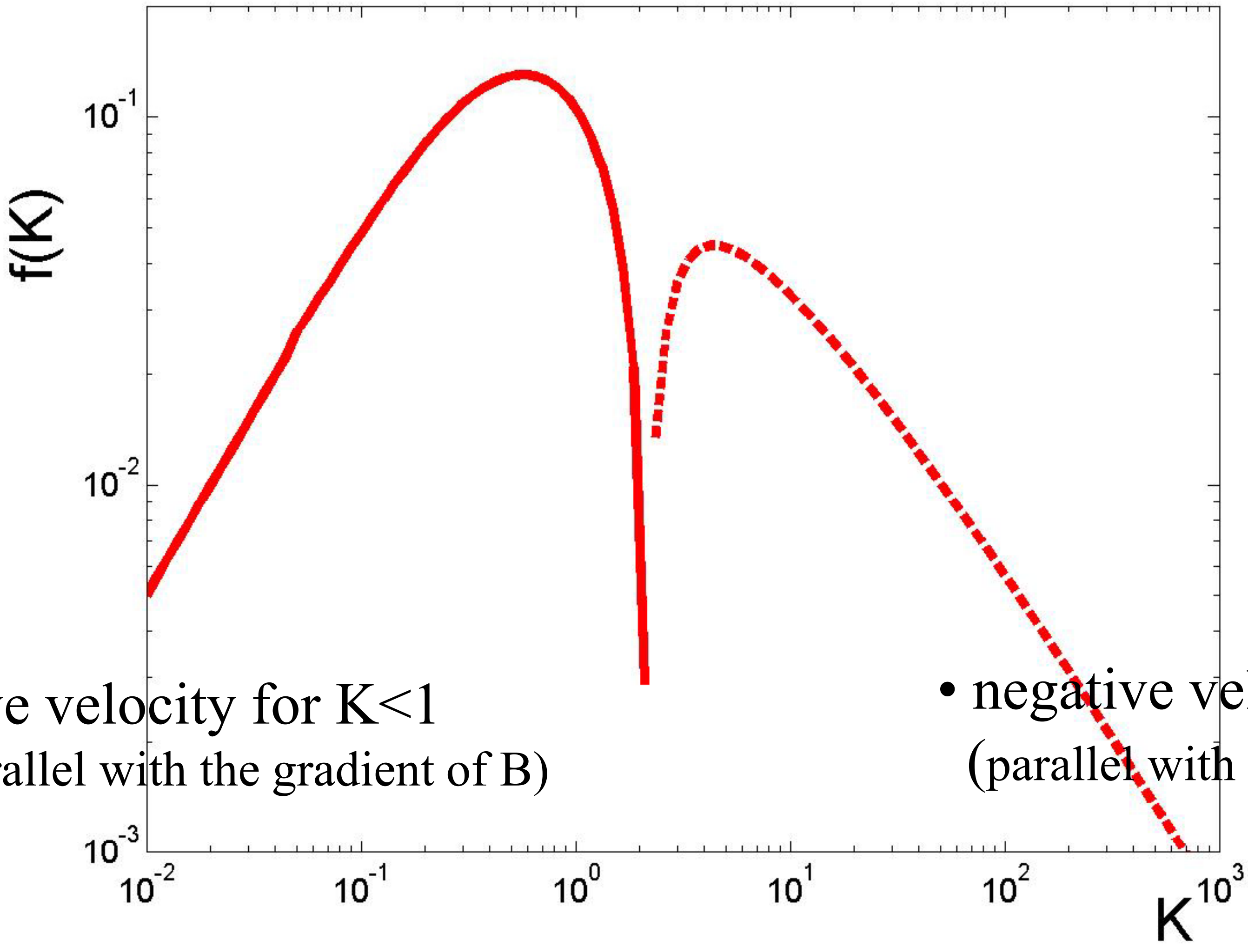
- The average velocity is obtained semianalytically using the ***decorrelation trajectory method***
- New type of ratchet: ***two-dimensional Hamiltonian stochastic ratchet***
- This mechanism is different from the turbulence equipartition model based on density compressibility (Yankov, Rasmunssen, Isichenko, …) also produced by space dependence of B.

M. Vlad, F. Spineanu, S. Benkadda, "*Impurity pinch from a ratchet process*", **Physical Reviews Letters 96** (2006) 085001

Ratchet velocity

$$E(x,t) = \xi(\vec{x})\,h(t), \quad \xi(\vec{x}) = \frac{1}{\left(1 + x^2/\lambda_c^{\ 2}\right)}$$

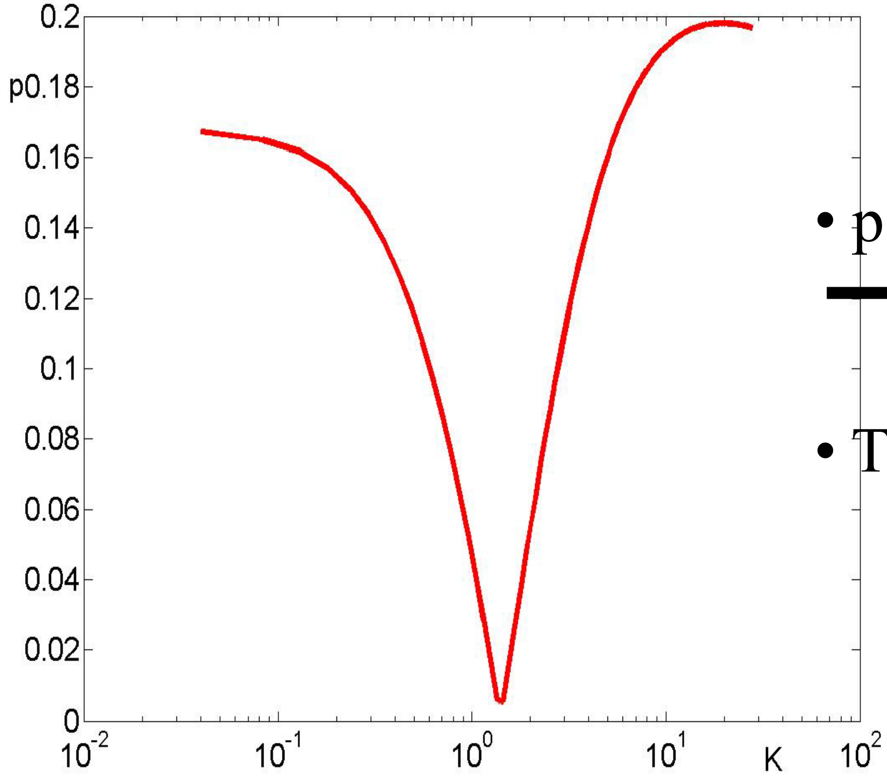
$$V_1^R = V\frac{1}{\overline{R}}f(K) = \frac{\beta}{B_0 R}f(K), \quad \overline{R} = R/\lambda_c > 10$$



- positive velocity for K<1
  (anti-parallel with the gradient of B)
- negative velocity for K>1
  (parallel with the gradient of B)

- for typical JET plasmas $V^R \leq 1\, m/\sec$ (as in experiments)

But the density peaking factor $p \equiv \frac{aV^R}{D}$ is much smaller than in experiments.



- p < 1 for all values of K

→ no density peaking due to ratchet velocity

- The reason: too large diffusion coefficient

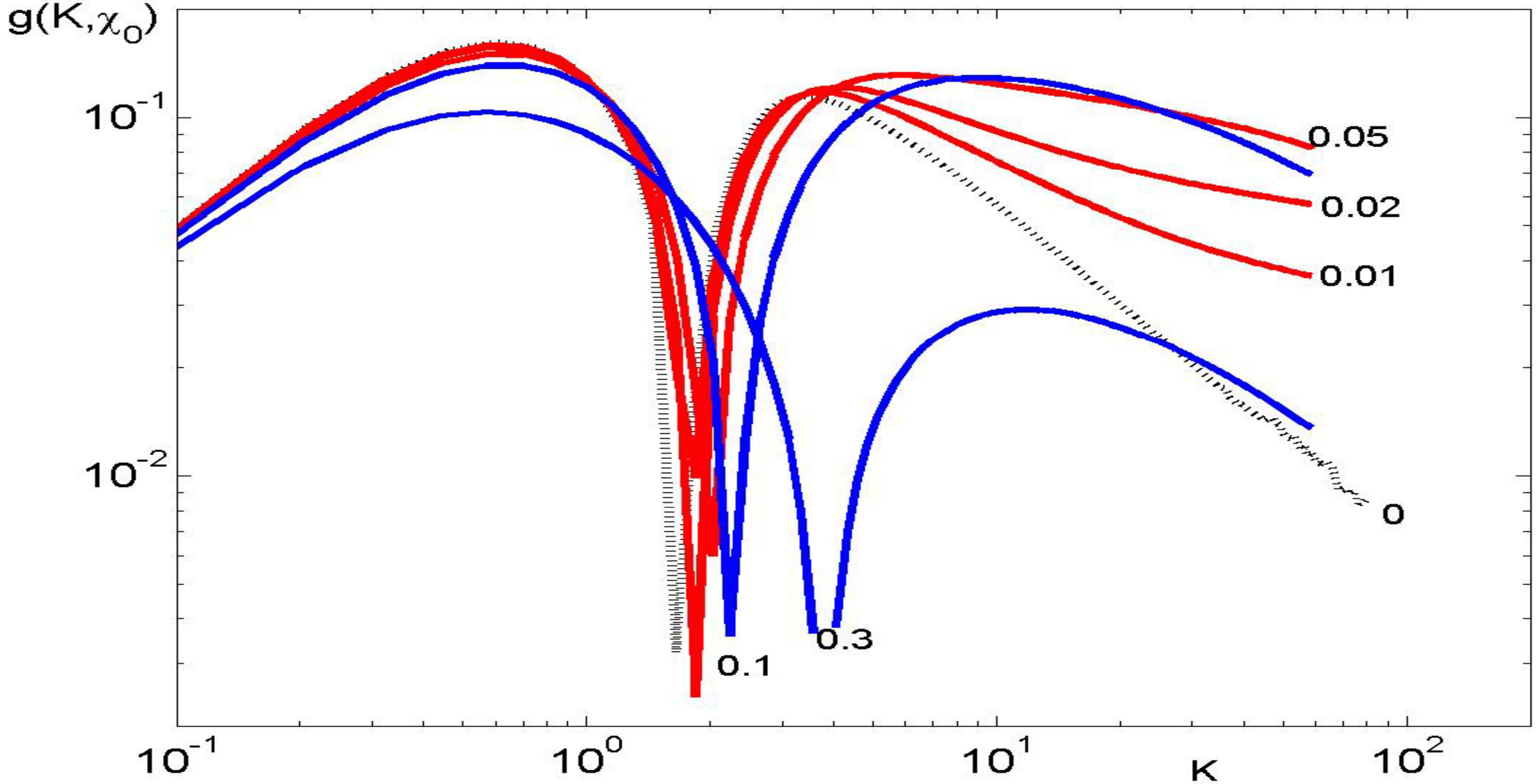
$$D \approx 10\ m^2 / \sec$$

We have show that a weak collisionality of the plasma combined with poloidal rotation determines peaking factors in the range [1, 2] as in H-mode JET plasmas

The effect of collisions

$$D = \beta\left(g(K,\chi_0) + \chi_0\right)$$

- The ratchet pinch is increased by collisions in the nonlinear regime (K>1).
- It is not influenced in the quasilinear turbulence (K<<1).



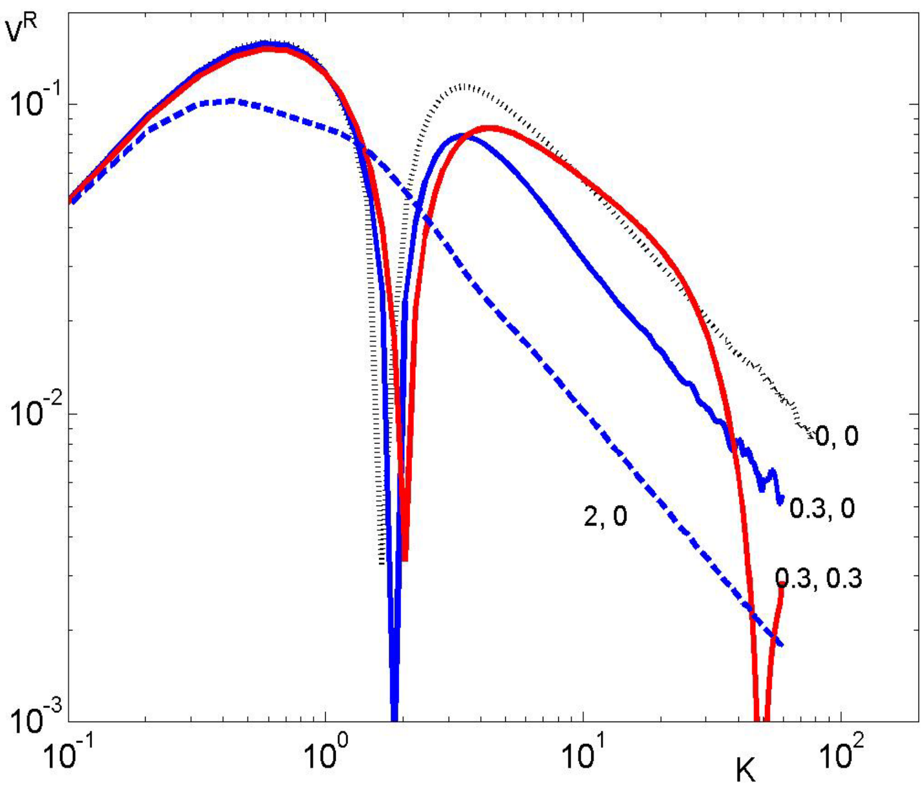
The collisional diffusion is represented by $\chi_0 = \dfrac{D_{coll}}{\beta}, \quad \beta = \dfrac{\Phi}{B_0}$

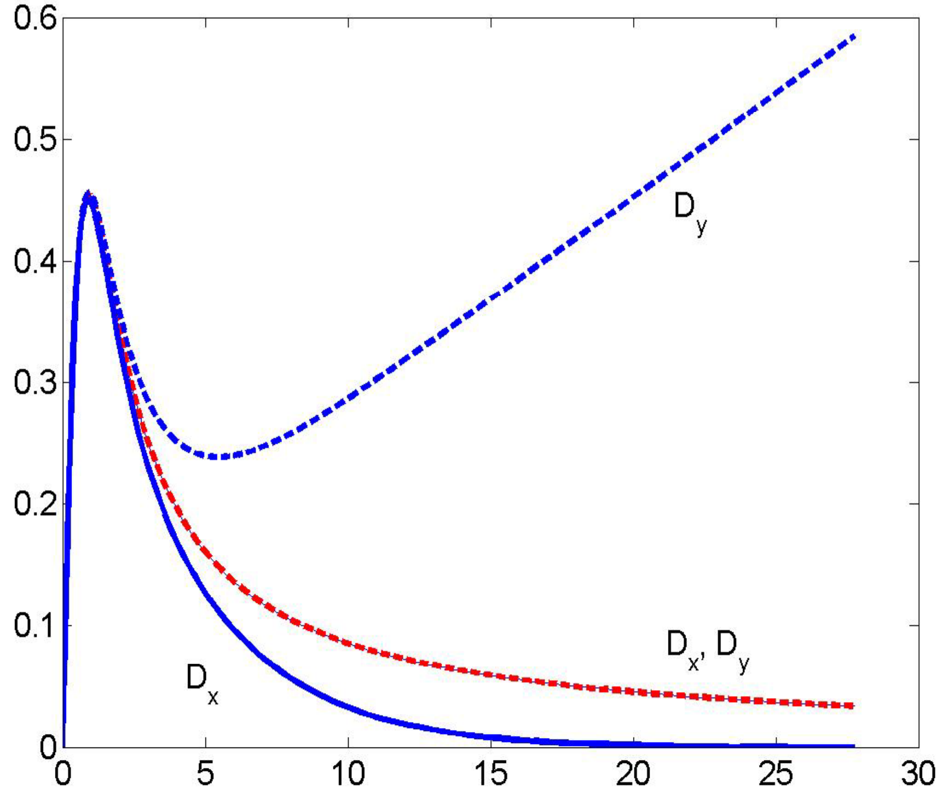
→ ***The peaking factor is not much changed by collisions***

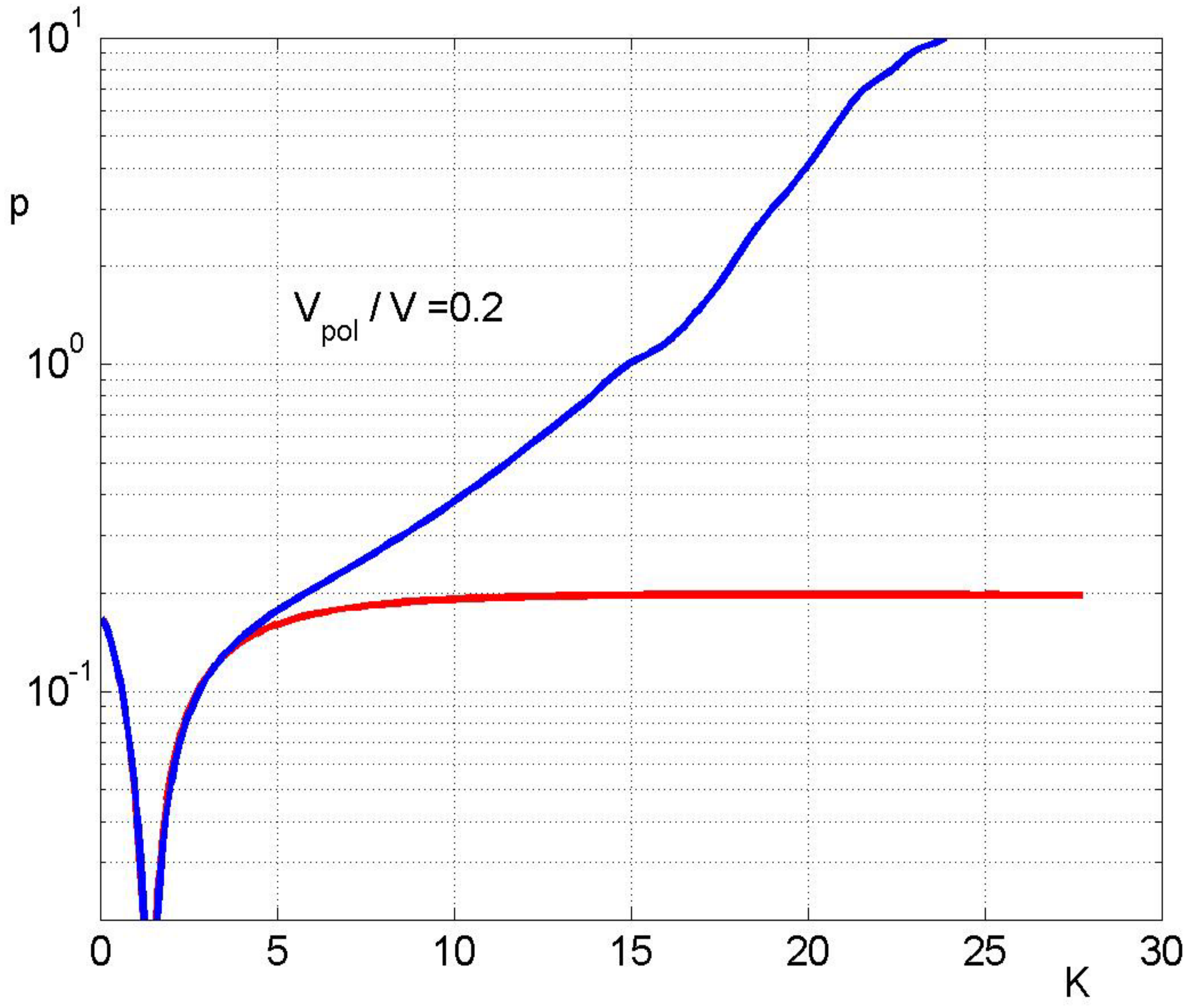
Effects of poloidal rotation:

• Moderate decrease of the ratchet velocity at K>1

• Strong decrease of the radial diffusion coefficient and very large amplification of the poloidal diffusion coefficient



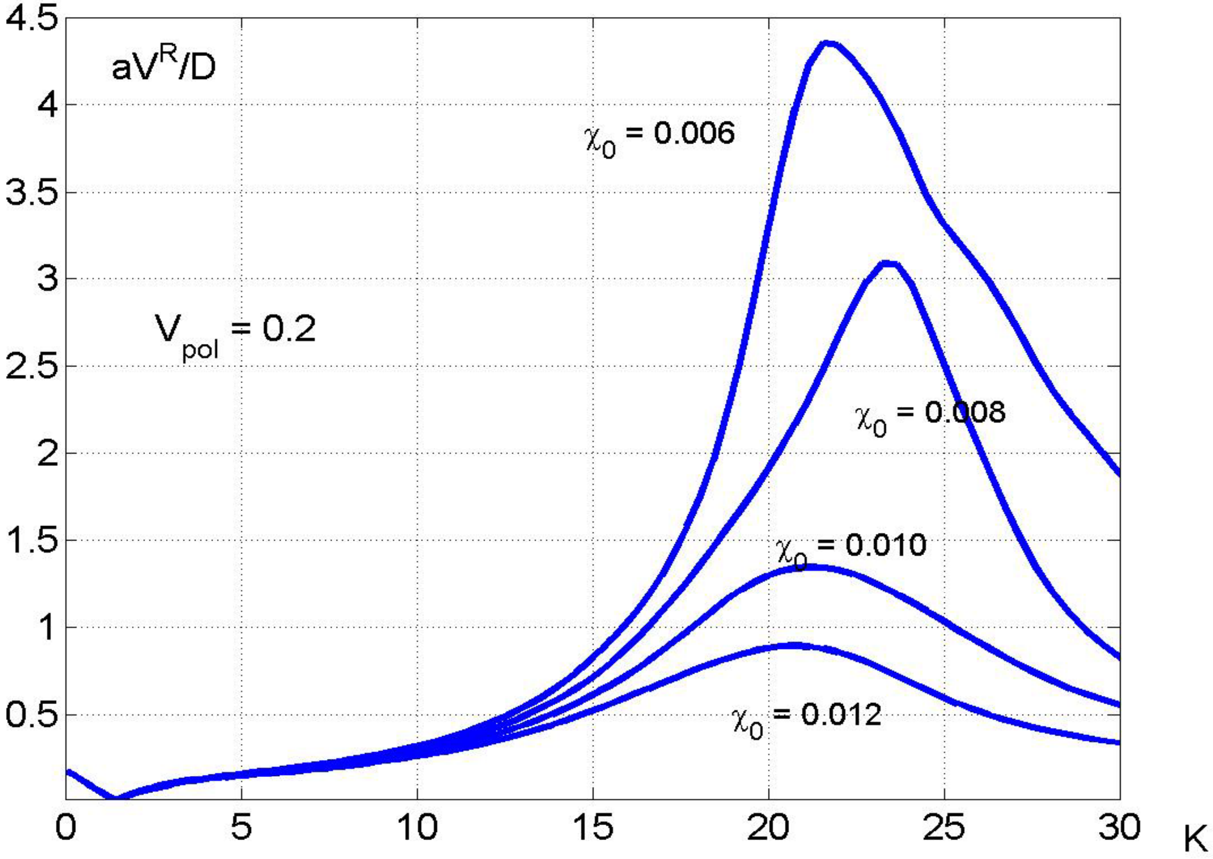




The peaking factor strongly increases at $K > 1$ due to poloidal rotation

The peaking factor p is larger than 1

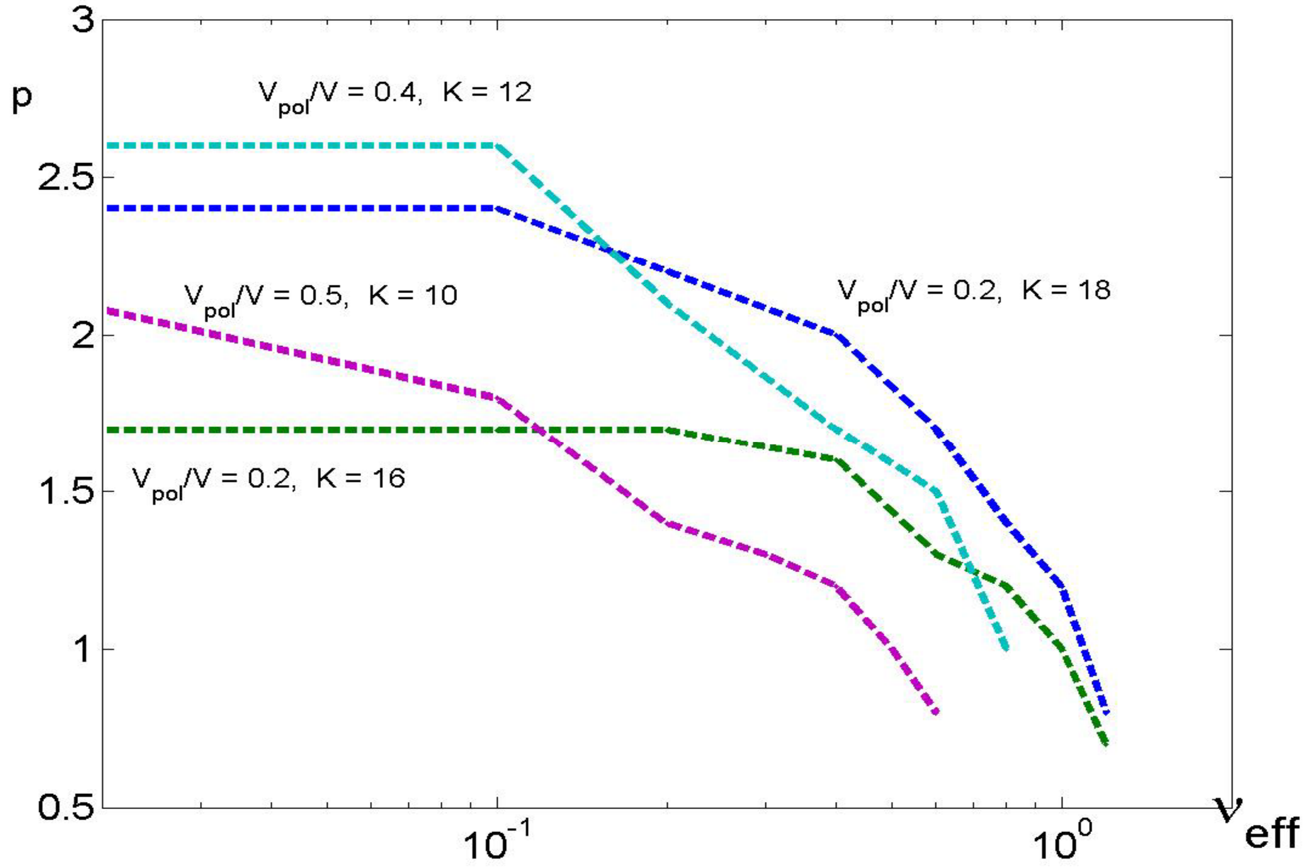
<u>only in the nonlinear regime and in the presence of a weak poloidal rotation</u>



The peaking factor is large for $V_{pol} / V = 0.2 - 0.4, \quad V_{pol} \leq 1000 \;\; m/s$

The peaking factor is a complicated function $p = F(K, V_{pol}, \nu_{eff})$

that also depends on plasma parameters through ν_{eff}



Plasma parameters at r=a/2:

$T_e = T_i = 2 KeV,$

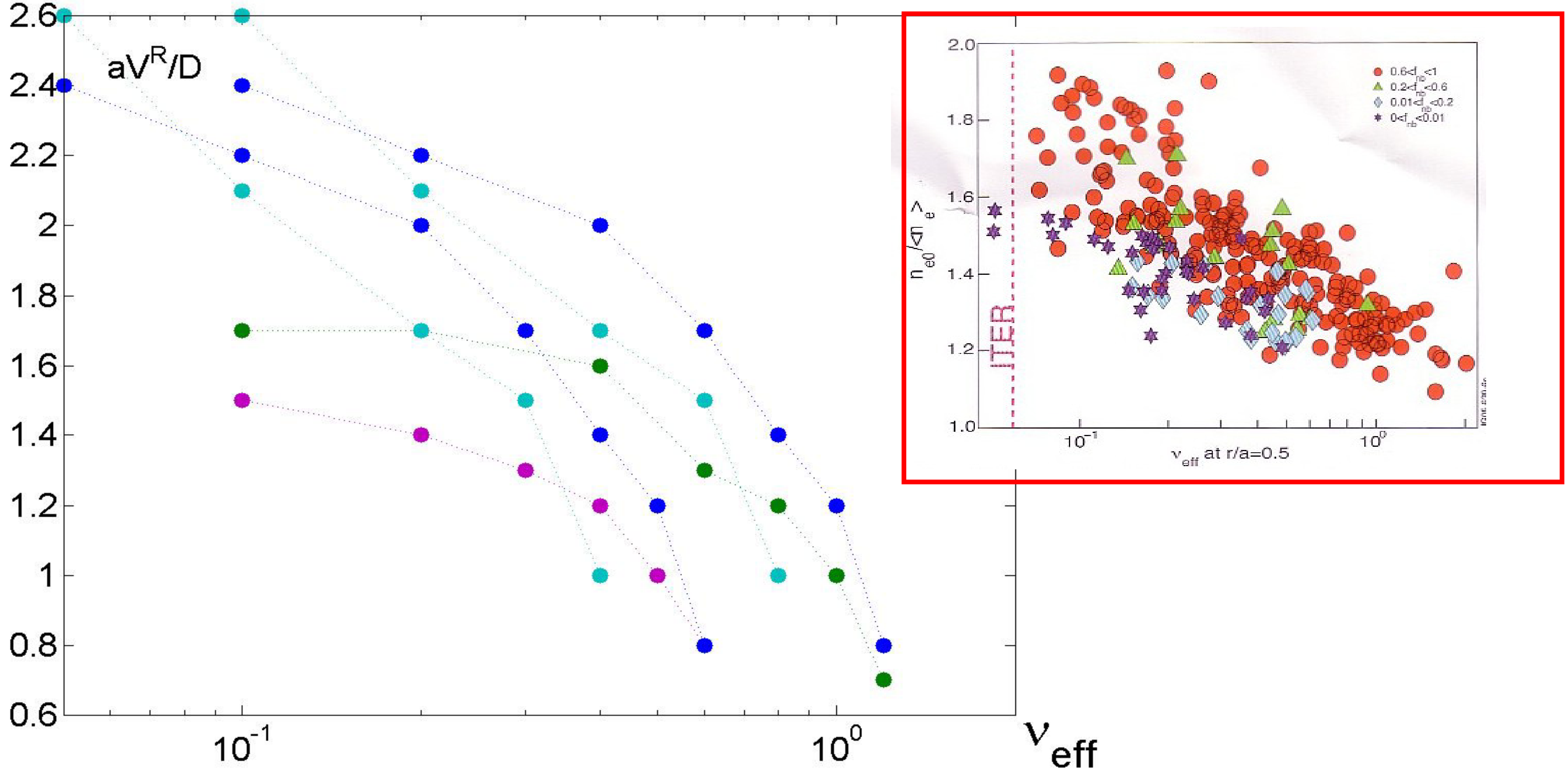
$n = 2 10^{19} m^{-3},$

$\beta = 25 V/T$

p decays with the increase of ν_{eff}, but faster than the scaling of JET H-mode data

p In all cases it is much faster than the slow decay as 1/log(ν) extracted from JET data.

But, ***choosing points corresponding to diffusion coefficients of the order of the experimental ones, a plot in qualitative agreement with JET H-mode data is obtained***



This suggest that scaling of the data does not necesarly describe the physical mechanism of peaking, but the statistical consequence of the dependence of p on some other parameters.

Density pinch in QL and NL conditions

$$\partial_t (n/B) + \vec{v} \cdot \nabla (n/B) = 0$$

The solution obtained with the characteristics method for the average density (that has space-time scales much larger than the stochastic potential):

$$n_0(x,t) = \int dx' N(x') P(x - x', t) \exp\left(- \frac{x - x'}{R} \right)$$

where *N(x)* is the initial density and *P(x,t)* is the probability of displacements.
The density pinch velocity is determined from the average displacement:

$$\left\langle x(t) \right\rangle_n \equiv \frac{\int n_0(x,t) x dx}{\int n_0(x,t) dx}$$

The particle pinch velocity is obtained from $\left\langle x(t) \right\rangle_p \equiv \int P(x,t) x dx$

$P(x,t)$ is determined starting from $P_1(x,\tau_c)$, the probability of the displacements in τ_c, using the convolution equation.

$P_1(x,\tau_c)$ is obtained with the ***decorrelation trajectory method:***

- analytic solution for the decorrelation trajectories in the QL case (K<1);
- numerical solution for the NL case (K>1)

QL: $P(x,t) \cong \left(2\pi D_{QL} t\right)^{-1/2} \left(1 + \frac{x}{2R}\right) \exp\left(-\frac{x^2}{2D_{QL} t}\right)$

Distorted Gaussian;
non-Gaussian
(all odd cumulants non zero)

$$\langle x(t) \rangle_p = \frac{D_{QL}}{2R} t, \quad V_R = \frac{D_{QL}}{2R}$$

$$\langle x(t) \rangle_n = -\frac{D_{QL}}{2R} t$$

$$V_n = -\frac{D_{QL}}{2R} = \frac{V_c}{2} = -V_R$$

Flater asymptotic profiles of the density due to trajectory modification (a)

$$t \to \infty \quad n_0(x,t) \to \sqrt{B(x)} \left(i.e.\, L_n = 2R\right)$$

NL: P(x,t) is ***strongly non-Gaussian***

(narrow peak in x=0, almost Gaussian for large x, complicated distorsion factor)

The transport coefficients can be determined without explicite calculation of P(x,t):

$$\langle x(t)\rangle_p = V_R t, \quad \langle x^2(t)\rangle_p = 2D_{NL}t, \quad V_R = \frac{V}{R} f(K), \quad D_{NL} = V\lambda_c K^{-\gamma}, 0<\gamma<1$$

The density pinch velocity obtained from $n_0(x,t) = \int dx' N(x') P(x-x',t) \exp\left(-\frac{x-x'}{R}\right)$

$$V_n = -\frac{D_{NL}}{R} + V_R = V_c + V_R$$

The curvature (TEP) pinch velocity for the NL case has the same structure as in the QL case $V_c^{NL} = -\frac{D_{NL}}{R}$

Preliminary results:

-The “macroscopic” motion (particle orbits in tokamak configuration) introduce can amplify or reduce the effect of density peaking

- dependence on particle charge and mass through the parallel motion and through collisions
- dependence on the characteristics of turbulence
- dependence on the geometrycal aspects (toroidal effects, cross section, size)

Stage

-***Construction and testing of a Monte Carco code***

- ***Extension of the Decorelation Trajectory Method to the toroidal configuration***

- ***Zonal flow generation and particle trapping in the structure of the turbulent potential***

Important theoretical results for the nonlinear evolution of drift type turbulene

- large scale correlation generated by trajectory trapping

- zonal flows and turbulence damping induced by trapping and potential drift

Next period:

Study of instabilities relevant for tokamak : ITG, TEM

Need for integration of the toroidal geometry in the decorrelation trajectory method.