Anomalous transport

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Introduction

(i) The topic of transport is dedicated to the physical processes by which, particles momentum and energy are moved in real (or in phase space) domain

(ii) The goal of transport theory is to identify the relationship between the thermodynamic fluxes and the thermodynamics forces

(iii) Thermodynamic fluxes are particle, momentum and energy (heat) presently driven mainly by external sources (particle sources, torques or heating power)

(iv) Thermodynamics forces are the spatial gradients, i.e. of density, temperature or momentum density

(v) Transport determines plasma reaction to imposed gradients and subsequent relaxing to final thermodynamics fluxes gradients.

- In tokamak plasmas collisional transport produced a level of minimum (unavoidable) level of transport $\chi_i^{CL} \sim 10^{-3}\mathrm{m}^2/\mathrm{s}$

$$\chi_i \approx \nu_{ii} r_{L,i}^2 \qquad \chi_e \approx \nu_{ee} r_{L,e}^2 \qquad \chi_i \sim \sqrt{\frac{M}{m}}\chi_e$$

- Neoclassical correction due to toroidicity increase the level of observed transport but still lower then observed:

$$\chi_{i,p}^{NC} \sim q^2 \chi_i^{CL} \sim 10^{-2}\mathrm{m}^2/s \qquad \chi_{i,t}^{NC} \sim q^2 \left(\frac{R_0}{r}\right)^{3/2} \chi_i^{CL} \sim 1\mathrm{m}^2/s$$

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- Apart from improved confinement regimes where thermal conductivity approaches values close to NC transport is higher and can only be explained by turbulence

Turbulent or anomalous transport

Transport relevant scales

- Although the most conspicuous instabilities observed in tokamaks are long-wavelength low-m MHD modes, their contributions to particle and heat trasnport is general low away from their resonant surface
- Microturbulence then main player contributing to transport through:
  (i) $\mathbf{E} \times \mathbf{B}$ drift across the confining lines resulting from fluctuating electric fields
  (ii) Motion along magnetic field lines with a fluctuating radial component

- We try to derive the influence of perturbation on particle transport directly from the equation Vlasov equation neglecting the collisional operator, which we already observed is unable to describe the level of transport observed.
- We will assume to be in the condition:

$$f = f_0 + \tilde{f} \qquad \mathbf{E} = \mathbf{E}_0 + \tilde{\mathbf{E}} \qquad \mathbf{B} = \mathbf{B}_0 + \tilde{\mathbf{B}}.$$

  where average is defined in term of ensemble average and fluctuating component is defined as the deviation from the ensemble average.
- For the average quantities we will consider the following spatial dependence

$$f_0 = f_0(x) \qquad \mathbf{E}_0 = \mathbf{E}_0(x) \qquad \mathbf{B} = B_0(x)\hat{\mathbf{z}} \tag{1}$$

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- Thus taking the average of the Vlasov with perturbation kept at first order one obtain:

$$\frac{\partial f_0}{\partial t} + \frac{\partial}{\partial x}(v_x f_0) + \frac{\partial}{\partial \mathbf{v}} \cdot \left[\frac{q}{m}(\mathbf{E}_0 + \mathbf{v} \times \mathbf{B}_0) f_0\right] + \frac{\partial}{\partial \mathbf{v}} \cdot \left[\frac{q}{m} \langle \tilde{\mathbf{E}} \tilde{f} \rangle + \frac{q}{m} \langle (\mathbf{v} \times \tilde{\mathbf{B}}) \tilde{f} \rangle \right] = 0 \tag{1}$$

where the highlighted quantities are responsible for turbulent transport

- Following what is customary done for average quantities we can derive the various moments also for fluctuating components

$$n_0 = \int f_0 \mathrm{d}\mathbf{v} \qquad \tilde{n} = \int \tilde{f} \mathrm{d}\mathbf{v} \tag{2}$$

$$\mathbf{\Gamma}_0 = \int \mathbf{v} f_0 \mathrm{d}\mathbf{v} \qquad \tilde{\mathbf{\Gamma}} = \int \mathbf{v}\tilde{f} \mathrm{d}\mathbf{v} \tag{3}$$

$$\mathbf{u}_0 = \frac{1}{n_0}\int \mathbf{v} f_0 \mathrm{d}\mathbf{v} \quad \tilde{\mathbf{u}} = \frac{1}{n_0}\int \tilde{\mathbf{v}} f_0 \mathrm{d}\mathbf{v} \tag{4}$$

- We can also derive the first order momentum of equation:

$$\frac{\partial \mathbf{\Gamma}_0}{\partial t} + \frac{\partial}{\partial x}\int v_x \mathbf{v} f_0 \mathrm{d}\mathbf{v} - \frac{q}{m}\int (\mathbf{E}_0 + \mathbf{v}\times\mathbf{B}_0) f_0 \mathrm{d}\mathbf{v} - \frac{q}{m}\int \langle \tilde{\mathbf{E}}\tilde{f}\rangle \mathrm{d}\mathbf{v} - \frac{q}{m}\int \langle (\mathbf{v}\times\tilde{\mathbf{B}})\tilde{f}\rangle \mathrm{d}\mathbf{v} = 0 \tag{5}$$

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- Particle flux along the x direction can be computed considering the evolution along the y direction:

$$\frac{\partial \Gamma_{0y}}{\partial t} + \frac{\partial}{\partial x}\int v_x v_y f_0 \mathrm{d}\mathbf{v} + \frac{q}{m}\Gamma_{0x}B_0 + \frac{q}{m}E_{0y}n_0 - \frac{q}{m}\langle \tilde{E}_y \tilde{n}\rangle - \frac{q}{m}\langle \tilde{\mathbf{\Gamma}} \times \tilde{\mathbf{B}}\rangle_y = 0$$

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- With the defined ordering we have

$$\frac{\partial v_y f_0}{\partial t} \sim \frac{v_y f_0}{T} \ll \frac{q}{m}\Gamma_{0x}B_0 \sim v f_0 \omega_c$$
$$\frac{\partial v_x v_y f_0}{\partial x} \sim v^2 f_0/L \ll \frac{q}{m}\Gamma_{0x}B_0 \sim v^2 f_0/r_L$$

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- Thus neglecting the pinch effects proportional to E_0 the particle flux induced by turbulent effects may be written:

$$\Gamma_{0x} = \frac{\langle \tilde{E}_y \tilde{n} \rangle}{B_0} + \frac{\langle \tilde{\mathbf{\Gamma}} \times \tilde{\mathbf{B}} \rangle_y}{B_0} = \frac{\langle \tilde{E}_y \tilde{n} \rangle}{B_0} + \frac{n}{B} \langle \tilde{\mathbf{u}}_z \tilde{\mathbf{b}}_x \rangle$$

Random walk estimate of turbulent diffusion

- In the case of electrostatic turbulence we can suppose fluctuation in electrostatic potential to be written in the form $\delta\phi = \sum_k \delta\phi_k e^{\mathbf{k}\cdot\mathbf{x}}$ so that $\delta\mathbf{v}_k = -i\frac{\mathbf{k}\times\mathbf{B}}{B^2}\delta\phi_k$ (see (Wesson 2004))

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- If the particle velocity persists for a correlation time τ_k causes a displacement $\delta r_k \sim \delta v_k \tau_k \implies$

$$D = \sum_k \frac{(\delta r_k)^2}{\tau_k} = \sum_k \left(\frac{k_\perp \delta\phi_k}{B}\right)^2 \tau_k \tag{6}$$

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    - The time variation of the fluctuations $\tau_k \sim 1/\omega_K$

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    - The effect of the linear motion of the particle as the parallel transit $1/k_{\|} v_T$

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    - The time $1/\nu_{eff}$ for collisions to change the particle orbit

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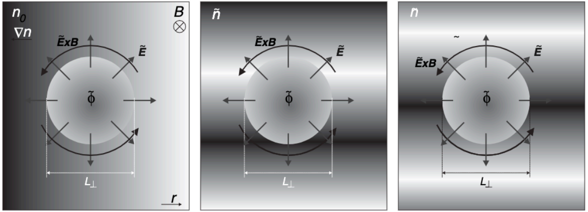
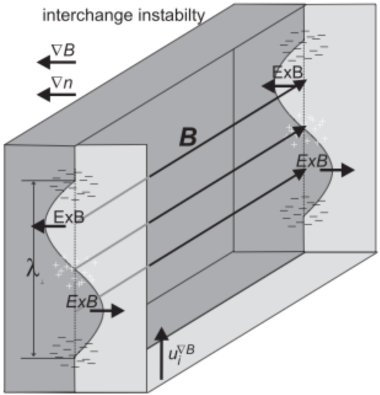
- The correlation time is determined by the process which limits more rapidly the $\mathbf{E}\times\mathbf{B}$ drift. Among these:
- At high level of fluctuations the fastest limiting process is the turbulent velocity δv_k carrying a particle a perpendicular wavelength $\tau_k = \Omega_k^{-1}$ with $\Omega_k = k_\perp \delta v_k = \frac{k_\perp^2 \delta\phi_k}{B}$. Thus if $\Omega_k \ll \omega_{eff} = \max(\omega_k, k_{\|} v_T, \nu_{eff}) \rightarrow D = \sum_k \frac{1}{\omega_{eff}}\left(\frac{k_\perp \delta\phi_k}{B}\right)^2$ otherwise for $\Omega_k \gtrsim \omega_{eff,k}, D = \sum_k \frac{\delta\phi_k}{B}$

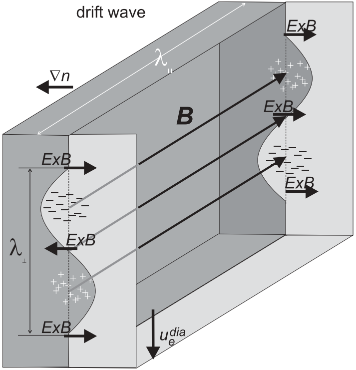
- Net advected transport requires both density and electrostatic potential perturbation
- These perturbation needs to be out of phase



- Interchange instability intrinsically 2D with $k_{\|} = 0$ and dynamics restricted to the plane perpendicular to $\mathbf{B}$
- Occurring in the region of bad-curvature
- In the figure instability driven by the charge-dependent curvature drift. Given the different motions of $\mathrm{e}^{-}/\mathrm{i}$ w.r.t. the density perturbation a potential perturbation with $\pi/2$ phase difference with density builds up.
- The resulting $\mathbf{E} \times \mathbf{B}$ drift amplifies the original density perturbations.



- Three dimensional perturbation of the pressure equilibrium with $k_{\|} \neq 0, k_{\perp} \gg k_{\|}$
- Electron faster response create positive charges in the region of positive density and vice versa. Creates and electric field and an advective $E \times B$ drift



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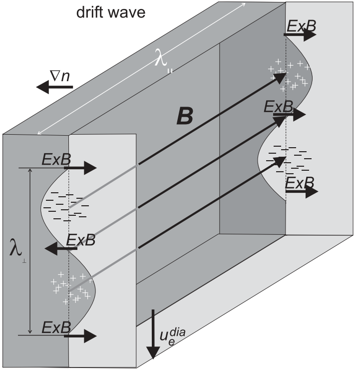
- With adiabatic electrons ($\frac{\tilde{n}}{n} \simeq \frac{e\phi}{T_e}$)(instantaneous response) only a displacement of the perturbation which moves in the e-diamagnetic direction $\omega_{*,e} = -\frac{k_y T_e}{eBn}\frac{\mathrm{d}n}{\mathrm{d}x}$



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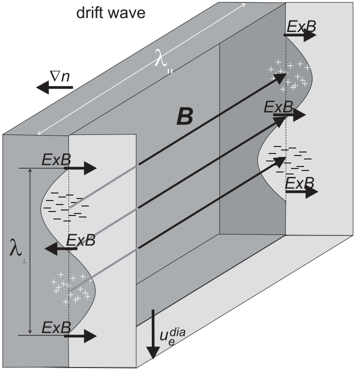
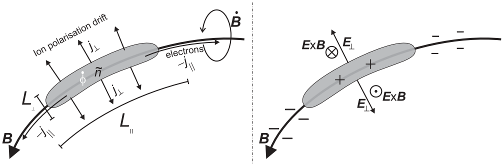
- Electron dissipation through collisions or geometry effects break adiabatic response. With a small lag or delayed electron response the drift-wave is unstable. $E \times B$ amplifies the initial perturbation.





- We start from an elongated positive density perturbation
- Due to their smaller inertia electrons respond faster and creates a positive potential inside the positive density
- Time constant defined by the polarization drift which drives ions in the perpendicular direction counteracting the charging building up
- The resulting $E_\perp$ causes the density perturbation advection driving transport
- The perturbation is intrinsically 3D. Parallel dynamics sets by electrons, perpendicular one by the ion drifting.
- Consider the simplest case with cold ions $T_i = 0$ and a density gradient with decay length $L_n = -n_0/\nabla n_0$

- A simplified model for drift-wave turbulence may be built starting from the Generalized Ohm's law and Parallel Electric field equation

$$\frac{m_e}{e}\frac{\partial j_\parallel}{\partial t} = enE_\parallel + \nabla_\parallel p - en\frac{j_\parallel}{\sigma} \qquad \text{Generalized Ohm's law}$$

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- The two previous equations may be combined in the following

$$en\frac{\partial A_\parallel}{\partial t} + \frac{m}{e}\frac{\partial j_\parallel}{\partial t} = -en\nabla_\parallel \phi + \nabla_\parallel p_e - 0.511\frac{m_e \nu}{e} j_\parallel$$

- The previous equation may be considered together with the Perpendicular ion drift

$$\mathbf{u}_{i\perp} = \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{m_i}{eB^2}\left(\frac{\partial \mathbf{E}_\perp}{\partial t} + \mathbf{u}^{\mathbf{E}\times\mathbf{B}} \cdot \nabla \mathbf{E}_\perp\right)$$

- Where we have recognize that the only ion contribution to the electric current come from the ion polarization current

$$\mathbf{j}_\perp = \frac{m_i n}{B^2}\left(\frac{\partial \mathbf{E}_\perp}{\partial t} + \mathbf{u}^{\mathbf{E}\times\mathbf{B}} \cdot \nabla \mathbf{E}_\perp\right)$$

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- From the quasi-neutrality condition $\boldsymbol{\nabla}_\perp \mathbf{j}_\perp + \nabla_\parallel j_\parallel = 0$ and with $E_\perp = -\nabla_\perp \phi$ we derive the vorticity equation

$$\frac{m_i n}{B^2}\left(\frac{\partial}{\partial t} + \mathbf{u}^{\mathbf{E}\times\mathbf{B}} \cdot \boldsymbol{\nabla}\right) \nabla_\perp^2 \phi = \nabla_\parallel j_\parallel$$

- Vorticity equation is coupled with the continuity equation

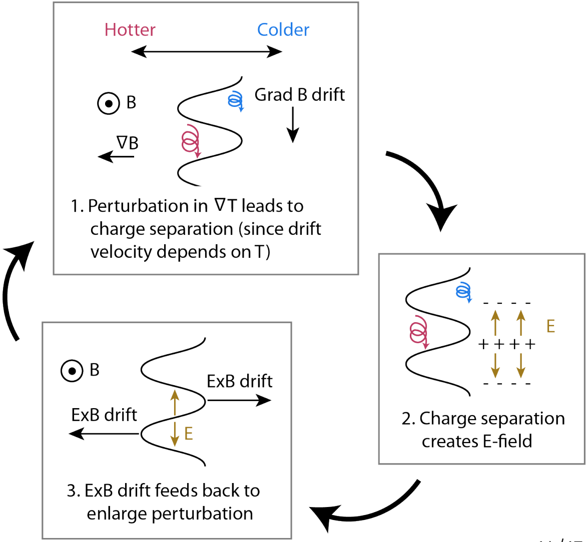
$$\left(\frac{\partial}{\partial t} + \mathbf{u}^{\mathsf{E}\times\mathsf{B}} \cdot \boldsymbol{\nabla}\right) n = -n\nabla_{\|} u_{e\|} \approx \nabla_{\|} j_{\|}/e$$

- In the electrostatic limit we have an explicit definition of $j_{\|}$. The two coupled equation are:

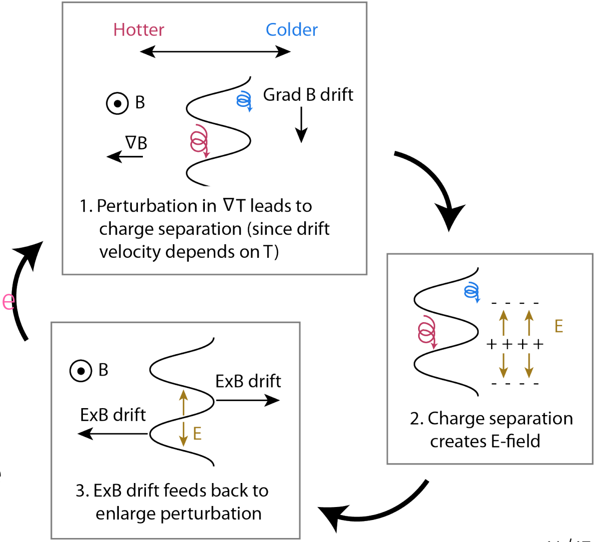
$$\begin{aligned} \left(\frac{\partial}{\partial t} + \mathbf{u}^{\mathsf{E}\times\mathsf{B}} \cdot \boldsymbol{\nabla}\right) n &= \frac{1}{m_e \nu_e} \nabla_{\|}(\nabla_{\|} p_e - en\nabla_{\|}\phi) \\ \frac{m_i n}{B^2}\left(\frac{\partial}{\partial t} + \mathbf{u}^{\mathsf{E}\times\mathsf{B}} \cdot \boldsymbol{\nabla}\right) \nabla_{\perp}^2 \phi &= \frac{e}{m_e \nu_e} \nabla_{\|}(\nabla_{\|} p_e - en\nabla_{\|}\phi) \end{aligned}$$

- The linearized normalized form of these two coupled equations is known as Hasegawa-Wakatani equations

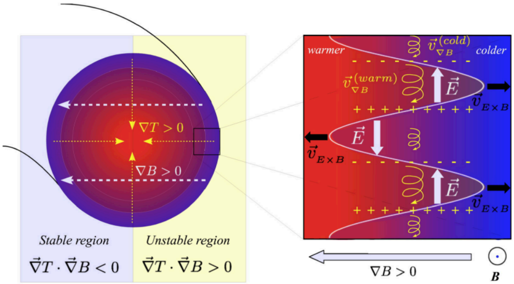
- Instability drive could arise as well from temperature gradients as the case of Ion Temperature Gradient (ITG) modes
- Assuming a temperature perturbation occurs on an isothermal flux surface



- The grad-B drift, $\mathbf{v}_{\nabla B} = \pm \frac{v_\perp^2}{\omega_c} \frac{\mathbf{B} \times \nabla \mathbf{B}}{B^2} \propto T$ is proportional to the temperature
- $\Longrightarrow$ Corresponding density perturbation builds up $\Longrightarrow$ *interchange like density perturbation*
- Assuming that $\omega \ll \omega_b$, and $\omega \ll k_{\|} v_{T_e}$, adiabatic response of the passing particle population
- Parallel force balance ensures the build up of a potential perturbation and corresponding $\mathbf{E} \times \mathbf{B}$ drift which enhance the perturbation



- Clear balloning character since favorable/unfavorable curvate in the HFS/LFS of the Torus



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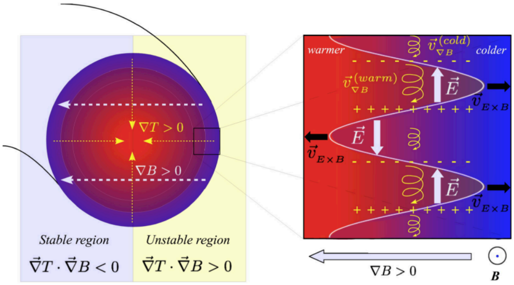
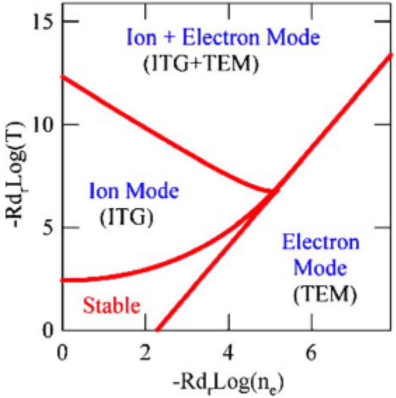
- ITG exhibit a critical threshold for R/L_{T_i}, being $L_{T_i} = |T_i/\nabla T_i|^{-1}$
- The threshold increases with increasing T_i/T_e and for adiabatic electrons increasing with increasing R/L_n
- For $\eta_i = L_n/L_{T_i} > \frac{2}{3}$ analytical formula found for critical gradient (Romanelli 1989)

$$\frac{R}{L_{T_i}} > \frac{4}{3}\left(1 + \frac{T_i}{T_e}\right)$$

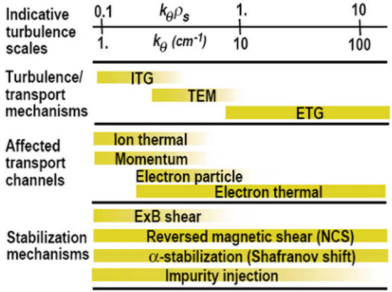


- So far we have explored the (electrostatic) ITG mode with adiabatic electrons
- The inclusion of the electron dynamics leads to several other modes as trapped electron mode (TEM) and the electron temperature gradient (ETG) mode
- Both the two instabilities exhibit still a critical electron temperature gradient
- The TEM , still at r_{L_i} scale include the effect of electron slower inertial along field line because of trapping
- The ETG is an analogous of ITG at electron larmor radius effects
- Plasma conditions determine the stability diagram

(Garbet *et al.* 2004)

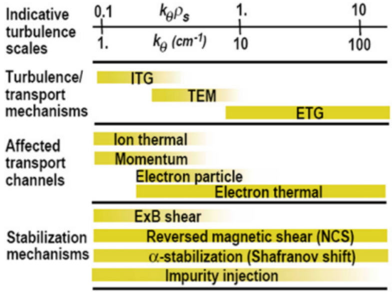


- Plasma turbulence is a multiscale process where different instabilities may coexist

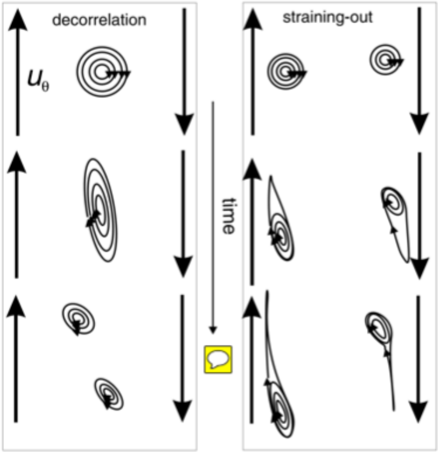


Other instabilities, corresponding scales and stabilizing mechanism

- Plasma turbulence is a multiscale process where different instabilities may coexist
- Main stabilizing mechanisms are the $\mathrm{E} \times \mathrm{B}$ shear and the magnetic shear

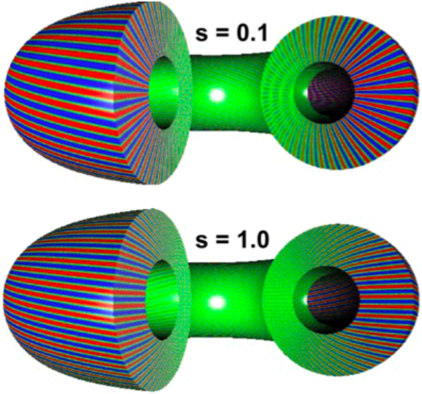


- Any sheared flow (gradient in rotation velocity) can produce a reduction of the turbulence and associated transport
- The mechanism is identified as the key player producing the transport barrier at the edge during the transition to H-Mode



Other instabilities, corresponding scales and stabilizing mechanism

- Magnetic shear is due to different winding numbers of the field lines (non constant safety factor)
- Since most of the instabilities are field aligned due to the strong anisotropy in velocity it has a strong stabilizing effect
- It basically lead to a deformation of the structures

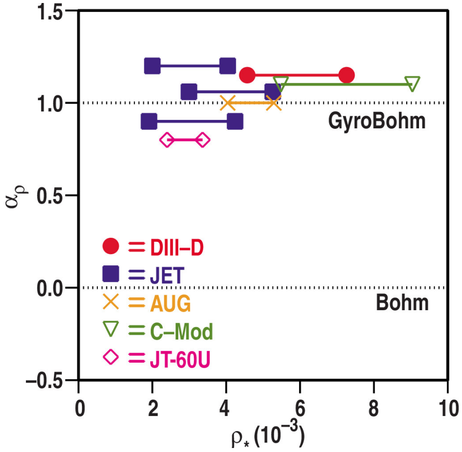


- Reference diffusivity is the Bohm like diffusion $D_B \propto \frac{T_e}{B}$ (Horton 1999) arising from mesoscale toroidal drift-wave structures near marginal stability
- Drift-wave diffusivity exhibit a gyro-Bohm scaling of the form

$$D_{dw} = \frac{\rho_s}{L_n}\frac{T_e}{B} \qquad \propto \rho^* D_b$$

being $\rho^* \approx \frac{\rho_s}{a}$

- However ρ^* scaling is more Bohm-like for
  - High $q_{95} > 4$
  - Heating power close to L-H power threshold
  - Low (L) confinement mode



(Petty 2008)

What we learned

(i) We introduce the concept of anomalous transport showing how a perturbation in the particle distribution function may contribute to particle and heat transport

(ii) We introduce two of the basic linear instabilities responsible for transport showing how collisionality and geometry could contribute to their non-linear evolution

(iii) We empirically describe one of the major player in the core transport as the ITG and as well the characteristic scale lengths for smaller scale turbulence

(iv) We provide proper scaling of turbulence induce diffusivities

(v) We introduce the basic mechanisms for turbulence suppression

(vi) Clearly all presented is just an attempt to scrap the surface and we are still far for a proper understanding of anomalous transport to provide adequate predictive capabilities

1. Garbet, X. *et al.* Physics of transport in tokamaks. *Plasma Physics and Controlled Fusion* **46,** B557 (2004).
2. Horton, W. Drift waves and transport. *Reviews of Modern Physics* **71,** 735 (1999).
3. Petty, C. C. Sizing up plasmas using dimensionless parameters. *Physics of Plasmas* **15,** 080501 (2008).
4. Romanelli, F. Ion temperature gradient driven modes and anomalous ion transport in tokamaks. *Physics of Fluids B: Plasma Physics* **1,** 1018 (1989).
5. Wesson, J. *Tokamaks.* ISBN: 0199592233 (Oxford University Press, 2004).