Turbulent Transport of Plasma Edge Impurities

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Statement of Problem

Impurity profiles in fusion devices are often peaked. They are a limiting factor to achieve fusion and cw operation.

- How do impurities enter the confinement region ?
- Can we assess diffusion coefficients ?
- Are there anomalous pinches ?
- Relationship of anomalous transport to pinch velocity?

This investigation is restricted to the edge, understood as the gradient region (closed magnetic field lines)

Passive scalar approach

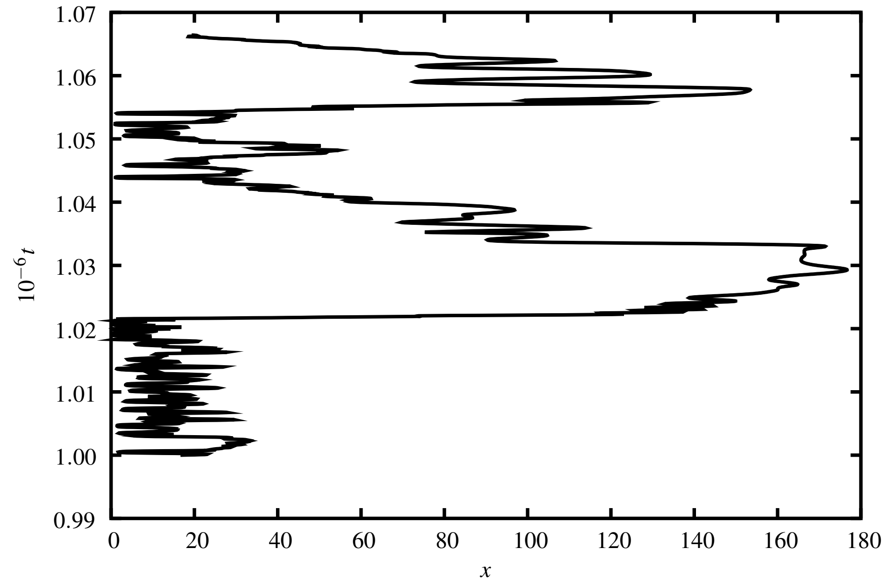
- assume impurity is rare
- $n_{imp}/n_{e,i} \ll 1$ is not enough
- impurity density should not enter quasi-neutrality condition
- $n_{imp} \ll \tilde{n}$
- this is possibly never really fulfilled
- **but** previous investigations have shown agreement between bulk transport and passive particle diffusion (Basu et al. , Phys. Plasmas **10**, 2696 (2003))

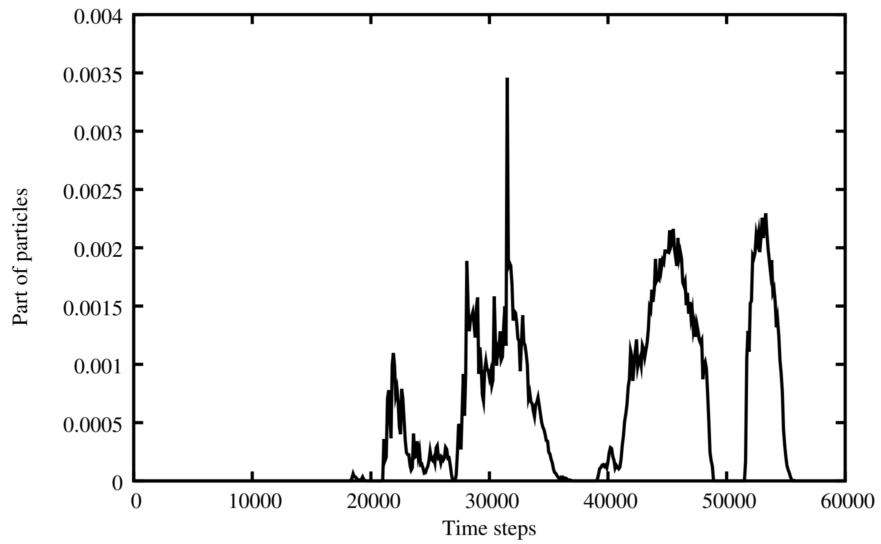
Thus we assume passive tracer transport to be a good proxy to impurity transport.

Transport via the SOL

using the ESEL code (see O4.004)

$$\partial_t n_{imp} + \vec{v}_{E\times B} \nabla n_{imp} = -n_{imp} \mathcal{K}(\phi)$$





Particle trace (left) and arrival times (right).
Blobs add to rapid inward flow of impurities (see P1.030).

The edge turbulence

- stationary edge turbulence at a fixed gradient
  $\longrightarrow$ fluctuation model is sufficient
  $\longrightarrow$ no interest in turbulence/gradient interaction
- no ion temperature effects
- no trapped particles
- includes: geometry, drift waves, Alfvén waves, interchange instability, electromagnetic effects....

TYR flux-tube drift-Alfvén code

The Impurity Density

$$d_t n_{imp} = M\nabla_\perp \cdot (n_{imp} d_t \nabla_\perp \phi) - n_{imp}\mathcal{K}(\phi) - \nabla_\parallel (n_{imp} u)$$

d_t includes full $E \times B$ advection.
Polarisation drift term includes relative mass and charge state of impurity

$$M = M_{imp}/(Zm_{ion})$$

parallel advection included
Initial conditions: drift-poloidally and parallel constant Gaussian

$$n_{imp}(t=0) \approx \exp(-r^2/\sigma_0)$$

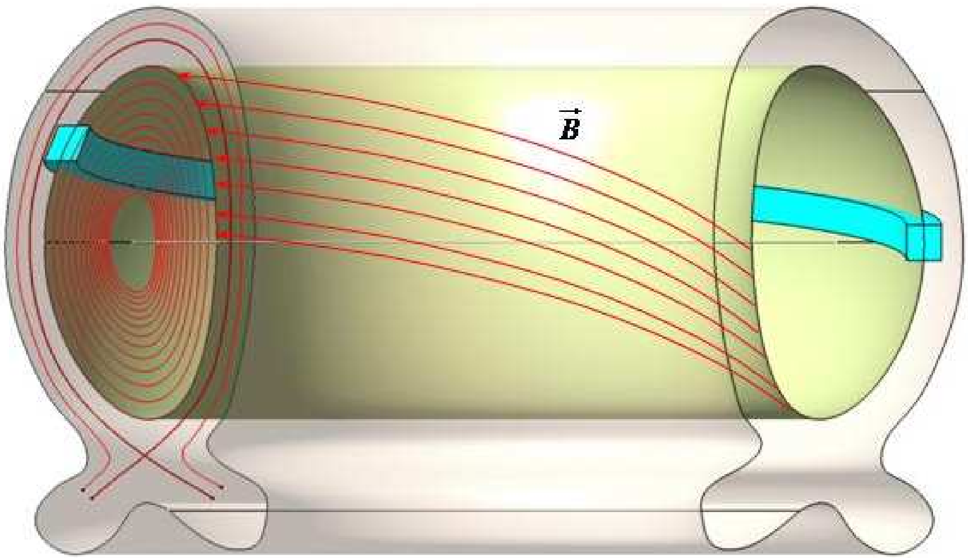
Parameters

Typical for edge plasma:

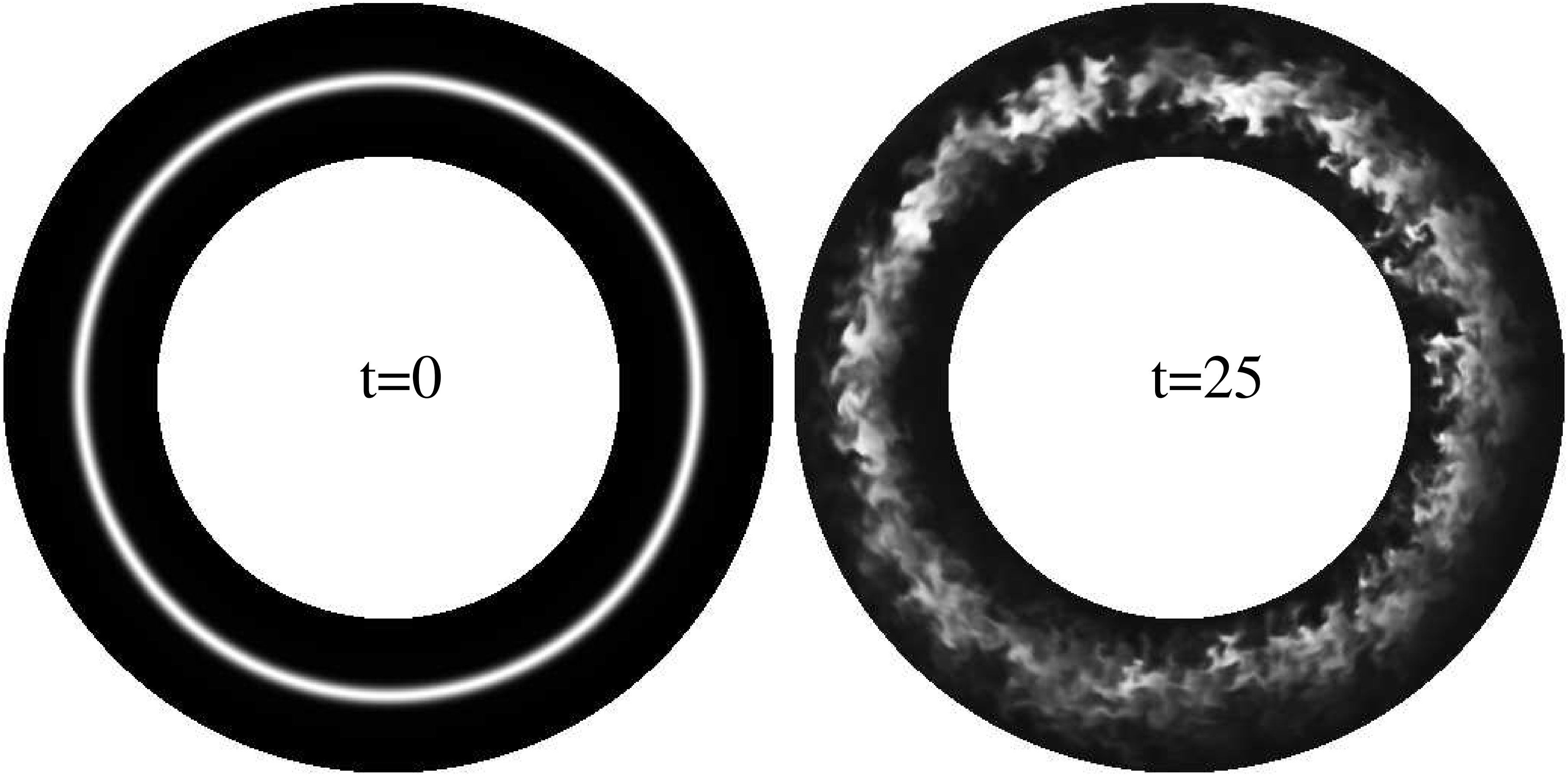
$$q = 3,\ \ n_e = 4 \times 10^{13}\text{cm}^-3,\ \ T_e = 150\text{eV},$$

$$M_i/m_e = 4000,\ \ B = 2\text{Tesla}.$$

Simulation domain: $2.5\text{cm} \times 10\text{cm}$
Time unit: $\sim 0.5\mu s$
Resolution:
$64 \times 256 \times 16$



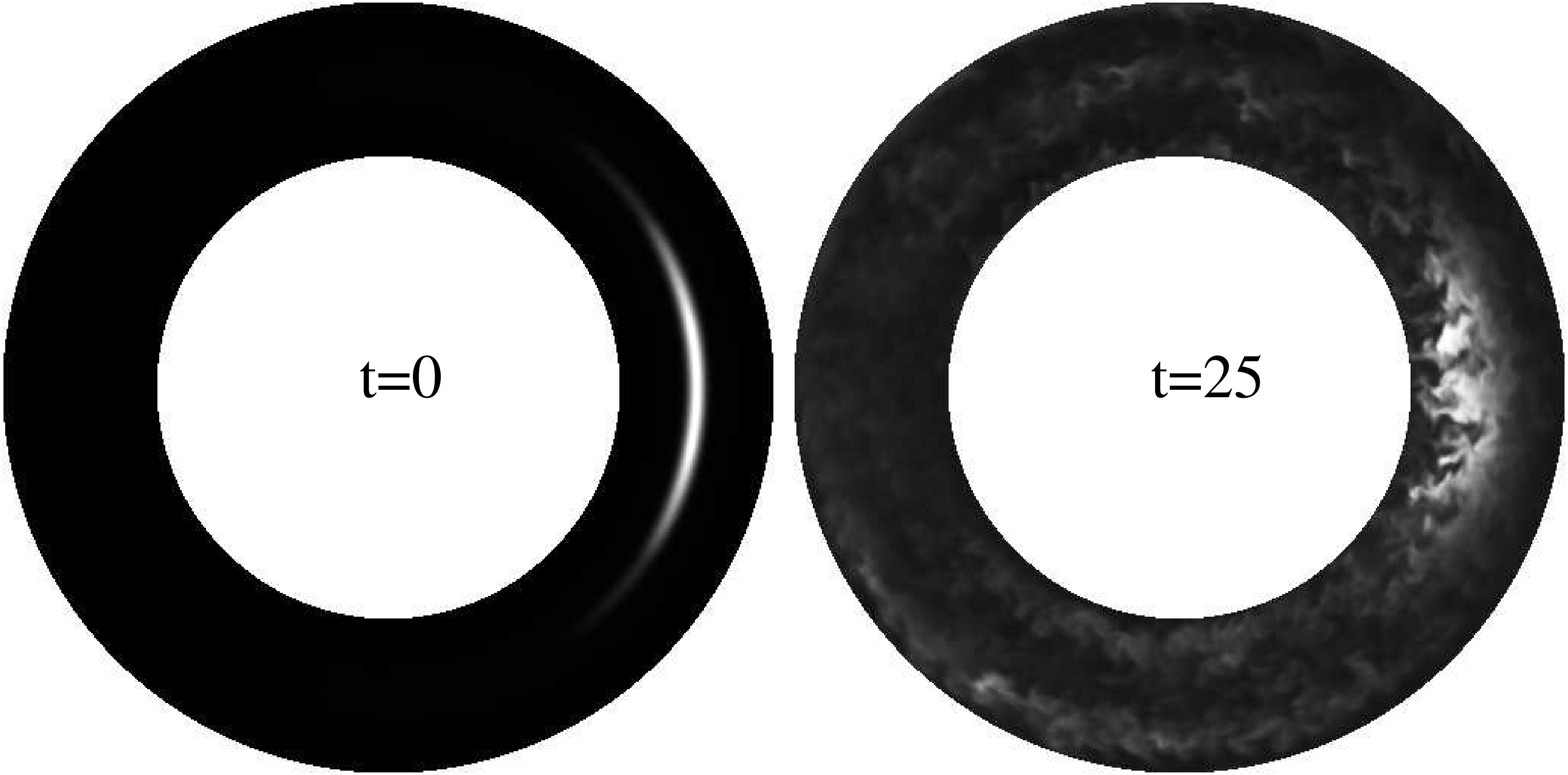
How does this look?



Fluxtube projected onto a geometrically poloidal cut.

How does this look?

Parallel advection not important.



Fluxtube projected onto a geometrically poloidal cut.

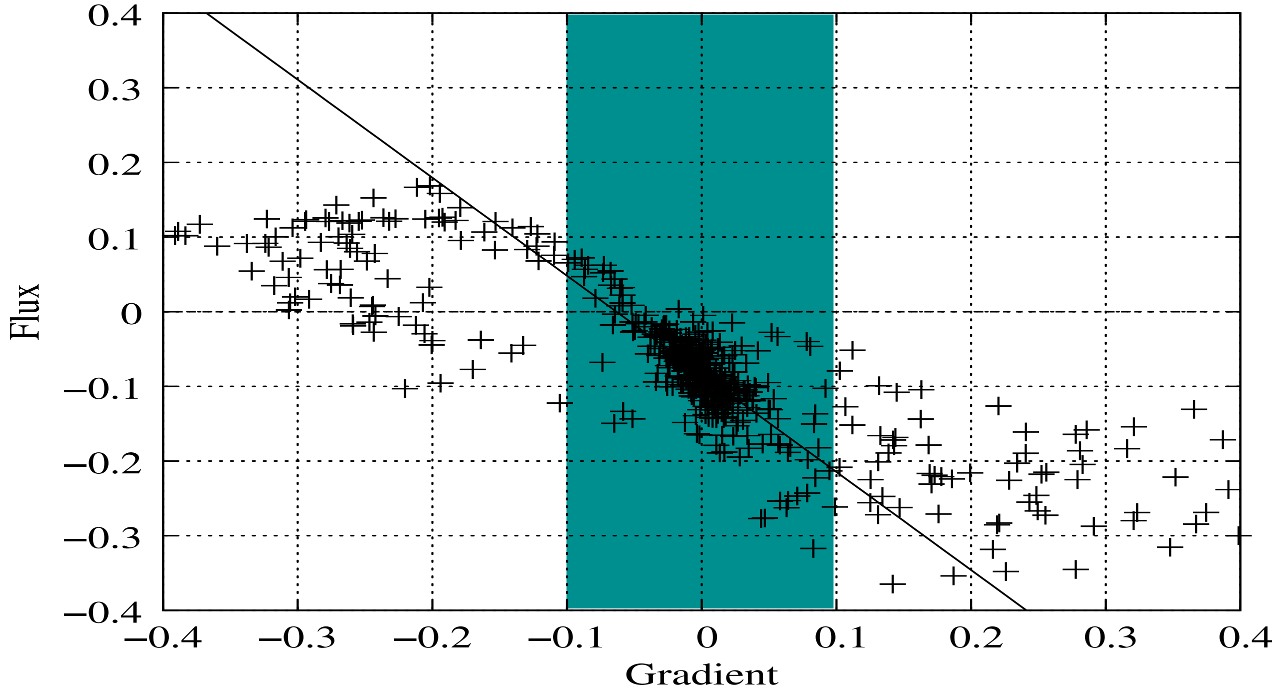
Analysis

Diffusion $D(s)$ constant on a drift plane, but varies along B. Assume transport can be expressed by a diffusion coefficient and a pinch velocity:

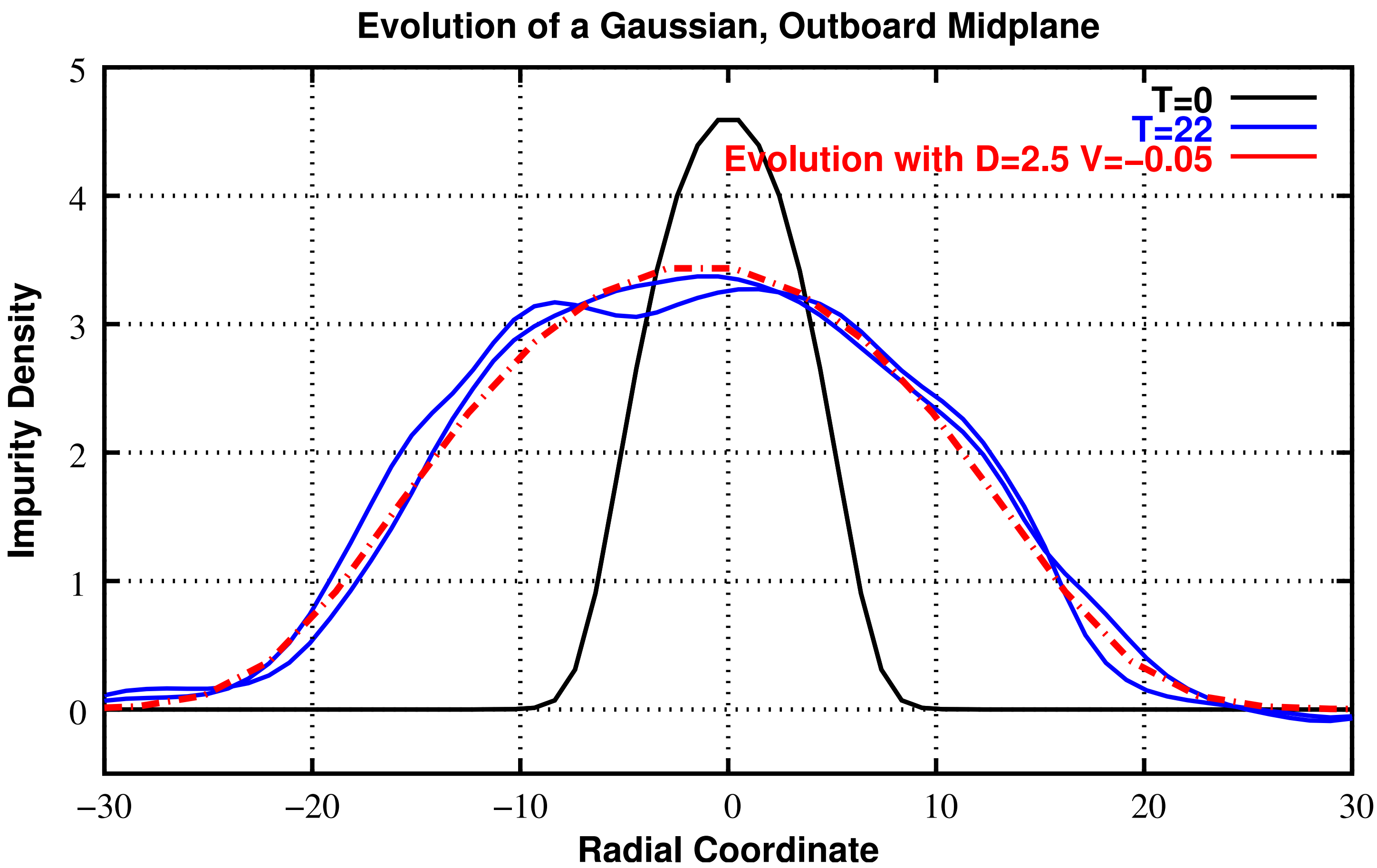
$$\Gamma(r) = -D\nabla < n >_y + V < n >_y$$

Scatter plot of $\Gamma(r)/ < n >_y$ versus $\nabla < \ln n >_y$:

HFS
D=1.25
V=-0.08



Analysis



Initial impurity density profile and profile after $\Delta t = 22$ overlayed with analytical evolution of the profile following a diffusion and pinch velocity.

Dimensional Parameters

- local pinch velocity
  - $V_p \approx 60$m/s outward velocity at highfield side.
  - $V_p \approx -80$ m/s inward pinch velocity at outboard midplane.
- local diffusion:
  - $D_T \approx 2$ m$^{-}2/$s at highfield side
  - $D_T \approx 1.5$ m$^{-}2/$s at outboard midplane.

Averaged pinch effect: $< V_p >_{FS} \approx -0.4$m/s
Gradient in stationary situation:
$V(s=0)/D(s=0) \sim -40$m^{-1} similar to result by (Dux:2003)

Interpretation

absence of parallel advection, finite mass effects and classical diffusion
approximate Lagrangian invariant

$$L(s) = \ln n_{imp} + \omega_B cos(s) x - \omega_B sin(s) y \; .$$

Turbulent EquiPartition: spatial homogenization of L

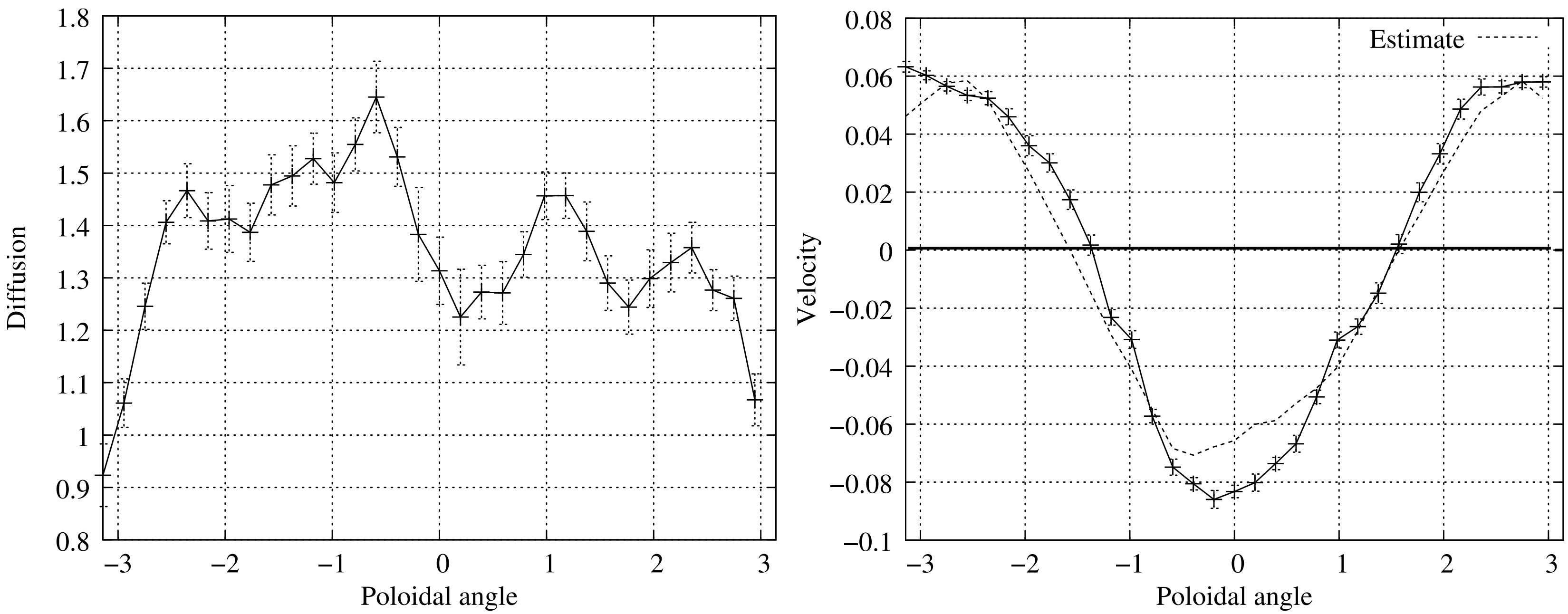
$$< L(s) >_y = const(s)$$

$$< \ln n_{imp} >_y = -x \omega_B cos(s)$$

Interpretation

Velocity V is proportional to anomalous diffusion D in "stationary" case: proportionality factor one.

$$V(s) = -\omega_B \cos(s) D(s) \, .$$



Pinch does not depend on gradient of D.

Conclusion

- scatter plots to derive v and D
- blobs add to rapid **inward** transport of impurities
- turbulent curvature pinch is recovered
- pinch velocity is proportional to diffusion
- interpretation in terms of Turbulent EquiPartition
- no divergence in D needed for pinch
- average pinch velocity depends on geometry and ballooning of the turbulence
- additional scaling and anomalous pinch with finite mass effects (see M. Priego P1.031)

Drift-Alfvén System

Quasi neutrality

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

Drift-Alfvén System

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

Electron continuity

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

Drift-Alfvén System

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

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

Ohms Law

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

Drift-Alfvén System

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

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

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

Parallel Ion motion

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

Drift-Alfvén System

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\mathcal{K} = \omega_B \left[\sin(s) \partial_x + \cos(s) \partial_y \right] \ .$$

$$\hat{\beta} = \frac{4\pi p_e}{B^2} \left(\frac{qR}{L_\perp}\right)^2, \quad \mu = \frac{m}{M} \left(\frac{qR}{L_\perp}\right)^2, \quad \nu = 0.51 \frac{L_\perp}{\tau_e c_s}, \quad \partial_x n_0 = 1$$