Synergetic effects of collisions, turbulence and sawtooth crashes on impurity transport.

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Motivation: impurity transport

- Tungsten plasma facing components → impurity accumulation in the core?

- Neoclassical and turbulence transport processes compete
  Casson 13, Angioni 14

- Interplay with MHD events: tearing modes, ELMs, sawtooth crashes
  Hender 16, Sertoli 15

**Asdex Upgrade – tungsten density**

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1) Interaction between turbulent and neoclassical transport.

2) Interaction between sawtooth cycles and neoclassical transport.

Punchline: interplay between different contributions to impurity transport are mediated by large scale flows.
Impurity transport modelled with gyrokinetics or MHD with closure

- Gyrokinetic description (GYSELA code): \( \frac{d}{dt}F = C(F) + \) Poisson equation → neoclassical and turbulent transport Grandgirard 16
- MHD equations (XTOR code) + impurity density and momentum equations Lütjens 10

\[
\frac{\partial N}{\partial t} + \nabla \cdot (NV) = \nabla \cdot \left( DN - \nabla N \right) = \left\langle N \nabla V \right\rangle_{turb}
\]

\[
Nm \left( \frac{\partial}{\partial t} + V \cdot \nabla \right)V = Ne \left( E + V \times B \right) - \nabla \cdot \Pi + R
\]

→ Pfirsch-Schlüter transport included in the fluid dynamics
→ neoclassical and MHD transport
Impurity neoclassical flux is related to parallel friction force

- Neoclassical flux

\[ \Gamma^\psi = -\frac{B_T R}{Z e} \left\langle \frac{R_{||}}{B} \right\rangle \]

- Pfirsch-Schlüter convection cell due to perpendicular compressibility Hinton & Hazeltine 76

- controls \( \Gamma^\psi \) at high collisionality \( \nu^*_Z > 1 \)
Neoclassical thermal screening works against accumulation

- General form of the impurity flux \( \Gamma_{Z\psi} \):
  \[
  \frac{\Gamma_{Z\psi}}{D_{\text{neo}} N_Z} = -\frac{\partial \ln N_i}{\partial r} + Z \frac{\partial \ln N_i}{\partial r} + H Z \frac{\partial \ln T_i}{\partial r}
  \]

  - Accumulation
  - Thermal screening

- Impurity collisional, ions weakly collisional \( H = -1/2 \)

- GYSELA benchmarked against theory and NEO code

Neoclassical and turbulent transport processes are synergetic

- Neoclassical and turbulent contributions isolated by playing with collisionality and symmetries
- Total flux ≠ neoclassical + turbulent

**Turbulent**, friction force $R_{\parallel Z} = 0$

**Neoclassical** $R_{\parallel Z} \neq 0$, axisymmetric $n=0$ modes only

**Self-consistent** $R_{\parallel Z} \neq 0$, all modes

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Interplay is mediated by poloidal convective cells

- Turbulent Reynolds stress $\rightarrow$ poloidal convective cells
- Poloidal asymmetries $\rightarrow$ change neoclassical impurity flux
- // momentum transport, turbulence self-regulation

Diamond 05

![Graphs showing impurity density](image)
Curvature and ExB fluxes are anticorrelated

- Anti-correlation due to poloidal convective cells
- Thermal screening factor $H > -1/2$: consequence of static density poloidal asymmetries? Romanelli 98, Fülöp 99, Angioni 14, Breton 16
Fast relaxation of the impurity density profile during a sawtooth crash

- $\nabla N_i = 0$, $\nabla T_i \neq 0 \rightarrow$ screening
- Crash time $<<$ collision time $\rightarrow$ neoclassical transport processes inefficient during crash
- Post-crash profile consistent with Kadomtsev model Kadomtsev 75, Porcelli 96, Nicolas 15

\[ \frac{\langle N_z \rangle}{(\text{XTOR unit})} \]

\[ \psi^{1/2} \]

Normalized minor radius

Ahn 16

+ before ST crash
- after ST crash
- Kadomtsev model

Before crash

After crash

$N_z(r)$

$\psi^{1/2}$

$r = r_{\text{inv}}$ $\rightarrow$

$r = r_{\text{mix}}$
ExB drift is the main cause of impurity transport during a sawtooth crash.

Poincaré map of magnetic field lines

Impurity density and stream function
ExB drift is the main cause of impurity transport during a sawtooth crash (cont.)

- ExB impurity flux $\sim 10$ flux due to magnetic flutter
- Consistent with SXR measurements on TFTR Nagayama 91
Sawteeth change the impurity profile on long time scales

- Neoclassical transport dominant during recovery phase, but ion temperature gradient is lower → weaker thermal screening effect
- Overall temperature profile flatter with sawteeth

![Impurity density profile - Ahn 16](chart.png)

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Interplay between turbulent and neoclassical transport processes:

- Poloidal convective cells generated by turbulence → poloidal asymmetries – total flux ≠ turbulent + neoclassical calculated separately. Should play at low rotation speed (e.g. EAST, WEST, ITER)

- Thermal screening gets weaker

Sawteeth cycles affect neoclassical transport

- Crashes flatten impurity density profile + lower main ion temperature gradient → thermal screening less efficient