Collisional transport of impurity in global simulations

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Gyrokinetics

Particle transport in global simulations

Thermal screening

Incompressibility of the flows

Summary

Section outline

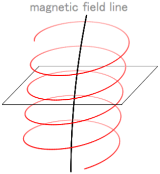
There are 2 major frameworks used when describing fusion plasmas:

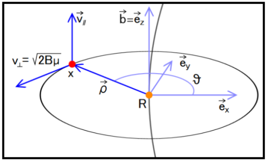
MagnetoHydroDynamics (MHD) → Coupling of Navier-Stokes + Maxwell equations.

Gyrokinetic (GK) → Kinetic approach following the time evolution of the distribution of particles in 6-dimensional phase space $f(\boldsymbol{r},\ \boldsymbol{v})$.

The dynamics is reduced to 5D by averaging over the particles' helicoilal motion around magnetic field lines

- $\boldsymbol{R}$: location of the gyro-center,
- $v_{/\!/}$: velocity along the magnetic field line,
- $\mu = \frac{m_s v_\perp^2}{2B}$: related to the gyration speed.





The equation system for species s is:

Vlasov equation
$$\frac{\partial f_s}{\partial t} + \frac{\partial \boldsymbol{R}}{\partial t} \cdot \frac{\partial f_s}{\partial \boldsymbol{R}} + \frac{\partial v_{/\!/}}{\partial t} \cdot \frac{\partial f_s}{\partial v_{/\!/}} = 0$$

Quasi-neutrality condition
$$-\sum_s \boldsymbol{\nabla}_\perp \cdot \left(\frac{\rho_{ts}^2}{\lambda_{Ds}^2} \boldsymbol{\nabla}_\perp \phi \right) = 4\pi \sum_s e_s n_s$$

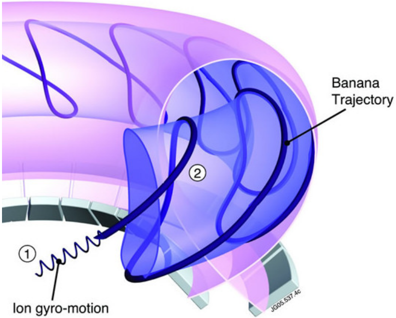
In addition to turbulence, the transport of particles, momentum and heat in a plasma can be driven by Coulombian collisions:

Boltzmann equation
$$\frac{\partial f_s}{\partial t} + \frac{\partial \boldsymbol{R}}{\partial t} \cdot \frac{\partial f_s}{\partial \boldsymbol{R}} + \frac{\partial v_{/\!/}}{\partial t} \cdot \frac{\partial f_s}{\partial v_{/\!/}} = \underbrace{\sum_{s'} C_{ss'}(f_s,\ f_{s'})}_{\text{collisions}}$$

This collisional transport is described by the **necoclassical transport theory**.

↪ The toroidal geometry of the magnetic field gives rise to complex "banana" orbits.

In this presentation, we will focus in part on particle flux predictions based on the Hirshman-Sigmar (HS) moments approach [Hirshman, NF 1981].



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High-Z materials (esp. Tungsten $Z_W = 74$) are now common elements for plasma facing components of fusion reactors:

- already in JET (UK), ASDEX-U (Germany)...
- will be used in ITER.

However, impurities which penetrate the plasma can be transported in- or outwards depending on species.

$\hookrightarrow$ Accumulation at the core is detrimental for fusion efficiency.

Most numerical studies of transport are performed using (stacks of) dedicated codes to treat various aspect of the dynamics separately.

$\hookrightarrow$ This assumes that turbulent and collisional transport are additive without synergistic effects.

Can those results be recovered in more general, **full-f global** codes?

The simulation code GT5D [Idomura, JCP 2016], which will be used for our simulations is:

- Eulerian 5D gyrokinetic,
- **global** $=$ all the 3D core plasma is simulated,
- **full-f** $=$ distribution functions f_s considered (instead of the more common decomposition $f_s = f_{0s} + \delta f$ with a fixed background equilibrium f_{0s}),

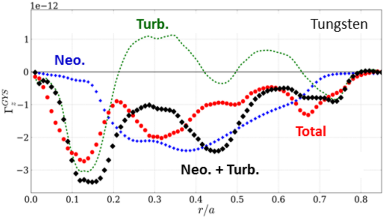
Those last 2 properties not being verified in the HS moment approach leads to complications:

- profile relaxation,
- evolution towards non-Maxwellian distribution,
- collisions at different temperatures.

(As well as the numerical issues arising from the wide range of masses at play.)

The recent paper [Estève, NF 2018] exhibited synergies between turbulent and collisional transport.

↪ This would suggest the 2 types of transport should not be computed separately, as is commonly done.



However, GYSELA results yielded much lower thermal screening factor than expected.

↪ Objective to verify invesrtigate that discrepency in thermal screening factor.

Section outline

- Gyrokinetics
- Particle transport in global simulations
- Thermal screening
- Incompressibility of the flows
- Summary

The particle flux Γ_z of a trace impurity z depends on:

- the radial density gradient $\frac{\partial(\ln n_s)}{\partial r} = -1/L_{ns}$ of all the species,
  $\hookrightarrow$ inward flux of particles,
- the common radial temperature gradient $\frac{\partial(\ln T)}{\partial r} = -1/L_T$,
  $\hookrightarrow$ outward flux of particles.

The temperature gradient dependence is modulated by the **thermal screening factor** $H_z \in [-1/2,\ 0]$.

Benchmark simulations were ran with our global full-f gyrokinetic code, GT5D, to be compared with the HS moment approach:

- CBC-like (L_n and L_T varied for scans), $\rho_* = \rho_{ti}/a_0 = 1/150$,
- trace impurities {**He**, **C**, **W**$^{40+}$, **W**$^{65+}$} spanning over the 3 collisional regimes (resp. banana, plateau and PS and deep PS).
- only one poloidal section simulated ($n = 0$),
- $\phi_{\{m>0\}}$ filtered out at each timestep (to prevent the onset of turbulence),
- kinetic electrons $m_e = m_D/100$.

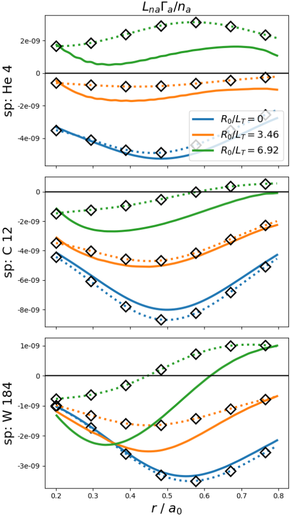
While the density gradient dependence was recovered, the **thermal screening factor** H_z was not.

Figures to the right:

- $R_0/L_T = 0,\ 3.46,\ 6.92,$
- solid lines = GT5D,
- $\cdots\ \diamond\ \cdots$ = HS estimate.

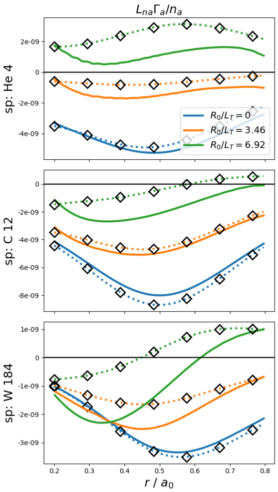
Similarly to GYSELA, $|H_z|$ is found to be $\sim 30\%$ smaller than predicted.

$\hookrightarrow$ If not a mistake, a model limitation?

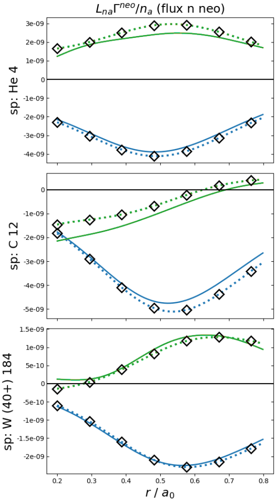


What model difference could cause these large differences?

↪ The HS moment approach is $O(\rho_*^0)$ ($\rho_* = \rho_i/a_0$, normalised gyroradius).



$\rho_* = 1/150$



$\rho_* = 1/600$

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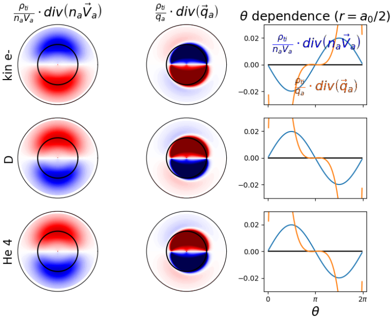
In the HS moment approach, the parallel flows are determined through the incompressibility condition for each flow:

$$\mathrm{div}\,(n_a\,\boldsymbol{V_a}) = 0, \qquad \mathrm{div}\,(\boldsymbol{q_a}) = 0, \qquad \cdots \qquad (\text{all is } + O(\rho_*))$$

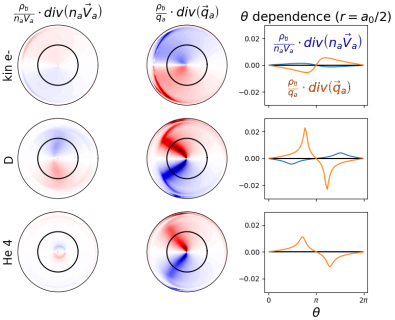
In the initial Maxwellian configuration used in simulations:

- local incompressibility is not verified,
- flux-averaged divergence is indeed 0.

$\hookrightarrow$ As required by HS theory.



Left two columns: divergence of the first 2 flows for electrons (top), Deuterium (middle) and Helium (bottom). Right column: poloidal dependence at mid-radius



However, as the simulations runs:

- local incompressibility diminishes,
- but its radial dependence on flux-surface does not cancel anymore.

↪ Small but non-zero flux-surface average, which decreases with ρ_*.

The violation of the incompressibility condition comes from the radial flow:

$$\boldsymbol{V_r} = \frac{1}{n_s} \iint m_s^2 B^*_{/\!/ s} \left(\dot{\boldsymbol{R}}_{\phi=0} \cdot \boldsymbol{e_r} \right) f \, dv_{/\!/} \, d\mu$$

↪ It can be traced back to the small poloidal asymmetries which grow in the temperature profile.

Section outline

We have compared trace impurity particle fluxes from full-f gyrokinetic simulations to the commonly used HS estimate:

- agreement recovered when the normalised gyroradius is reduced $\rho_* \rightarrow 0$,
- this ρ_* is in agreement with previous results from GYSELA,
- lower values of ρ_* also reduced the inward particle flux.

A likely explanation is the violation of the incompressibility of the flows:

- 0 in flux-surface average for the initial Maxwellian distribution,
- non-zero value set by asymmetries in the temperature T.

Thank you for your attention