The interaction between neutral particles and turbulent plasma in the tokamak SOL

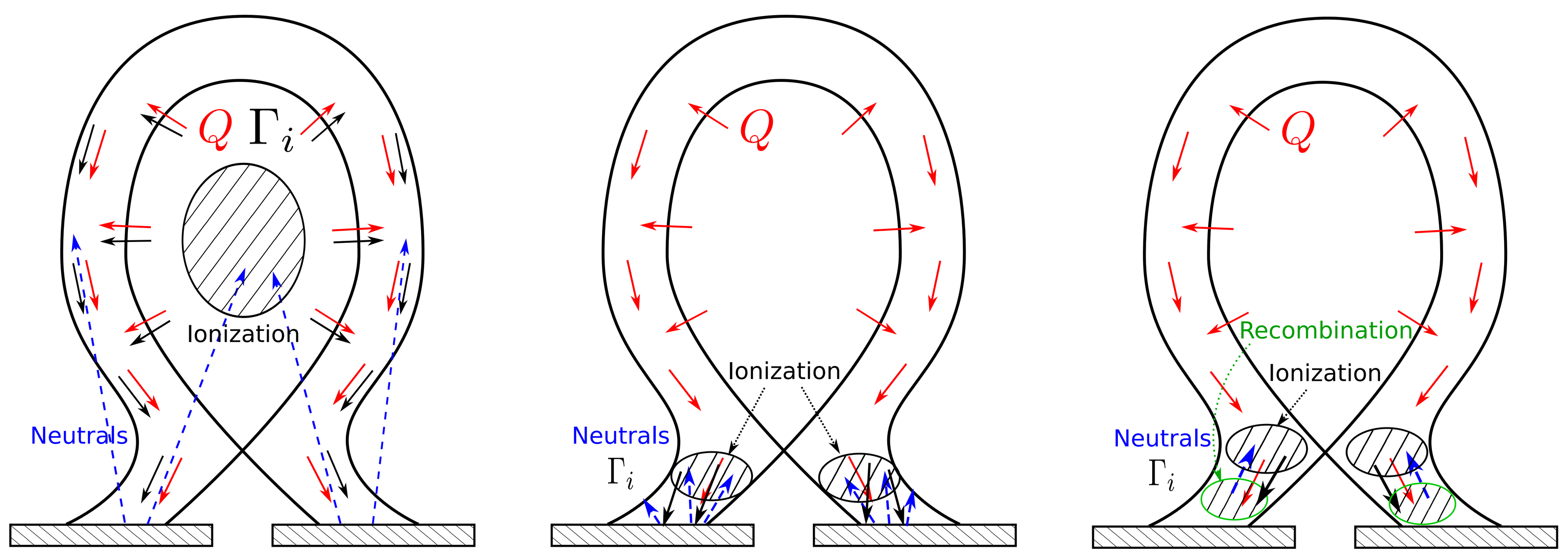
C. Wersal, P. Ricci, F.D. Halpern, F. Riva

École Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, CH-1015 Lausanne, Switzerland

Summary

- First fully turbulent SOL simulations self-consistently coupled to a neutral model.
- A kinetic equation with Krook operators for ionization, recombination and charge-exchange processes is solved for the neutral species.
- Two fluid drift-reduced Braginskii equations are solved for the plasma.
- First results from the GBS simulations show interesting interplay between neutral and plasma physics.
- The details of the model can be found in [C. Wersal and P. Ricci, submitted to NF 2015].

Complex interaction between neutrals and plasma



Convection limited regime
- Low plasma density
- Long λ_{mfp} for neutrals
- Ionization in the core
- Heat ≈ particle source
- Q is mainly convective

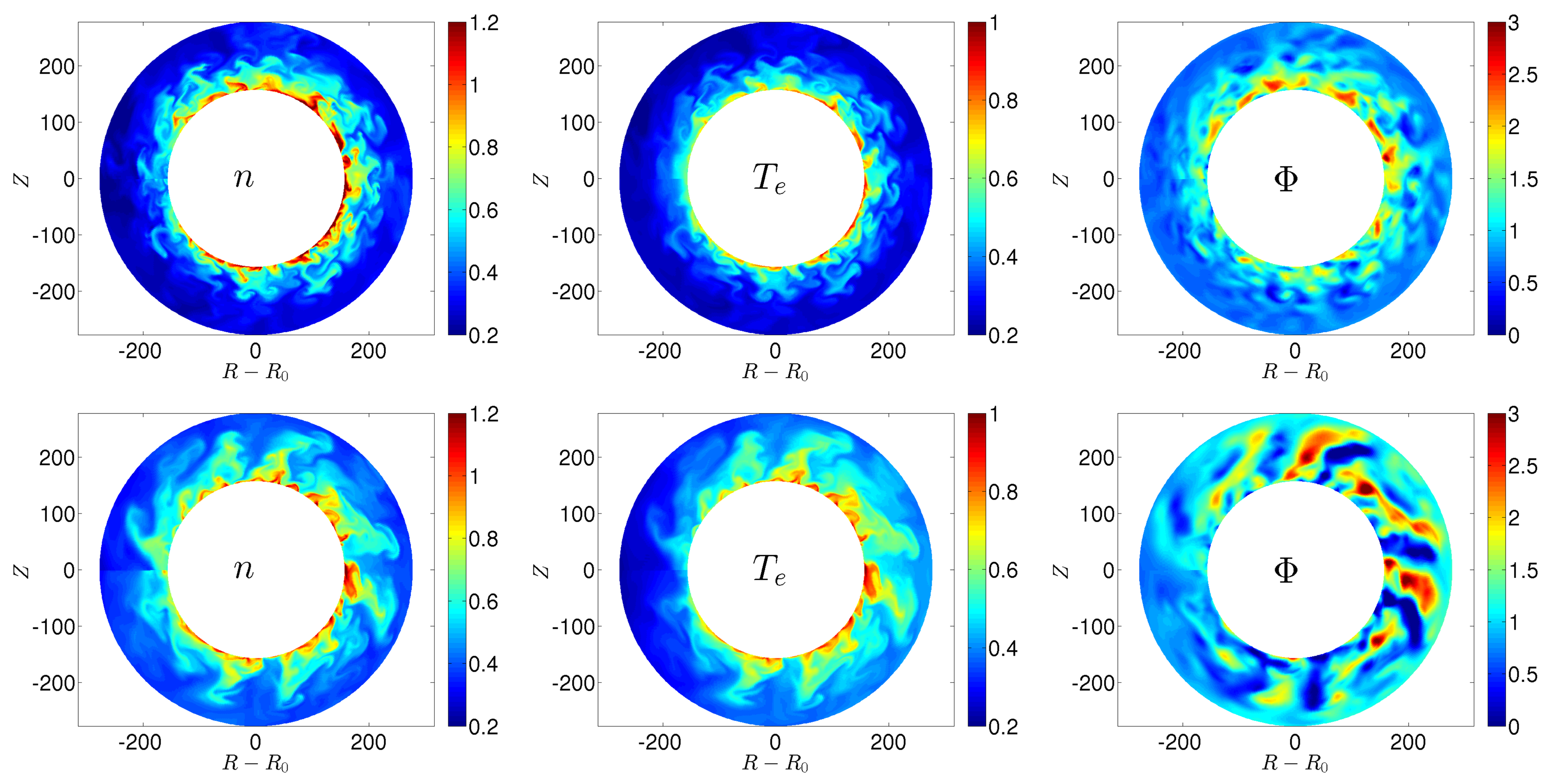
Conduction limited regime
- High plasma density
- Short λ_{mfp}
- Ionization close to targets
- ∥ Temperature gradients form
- Q is mainly conductive

Detached regime
- Very high plasma density
- Friction drag important
- Volumetric recombination
- Very low ion and energy flux to the target

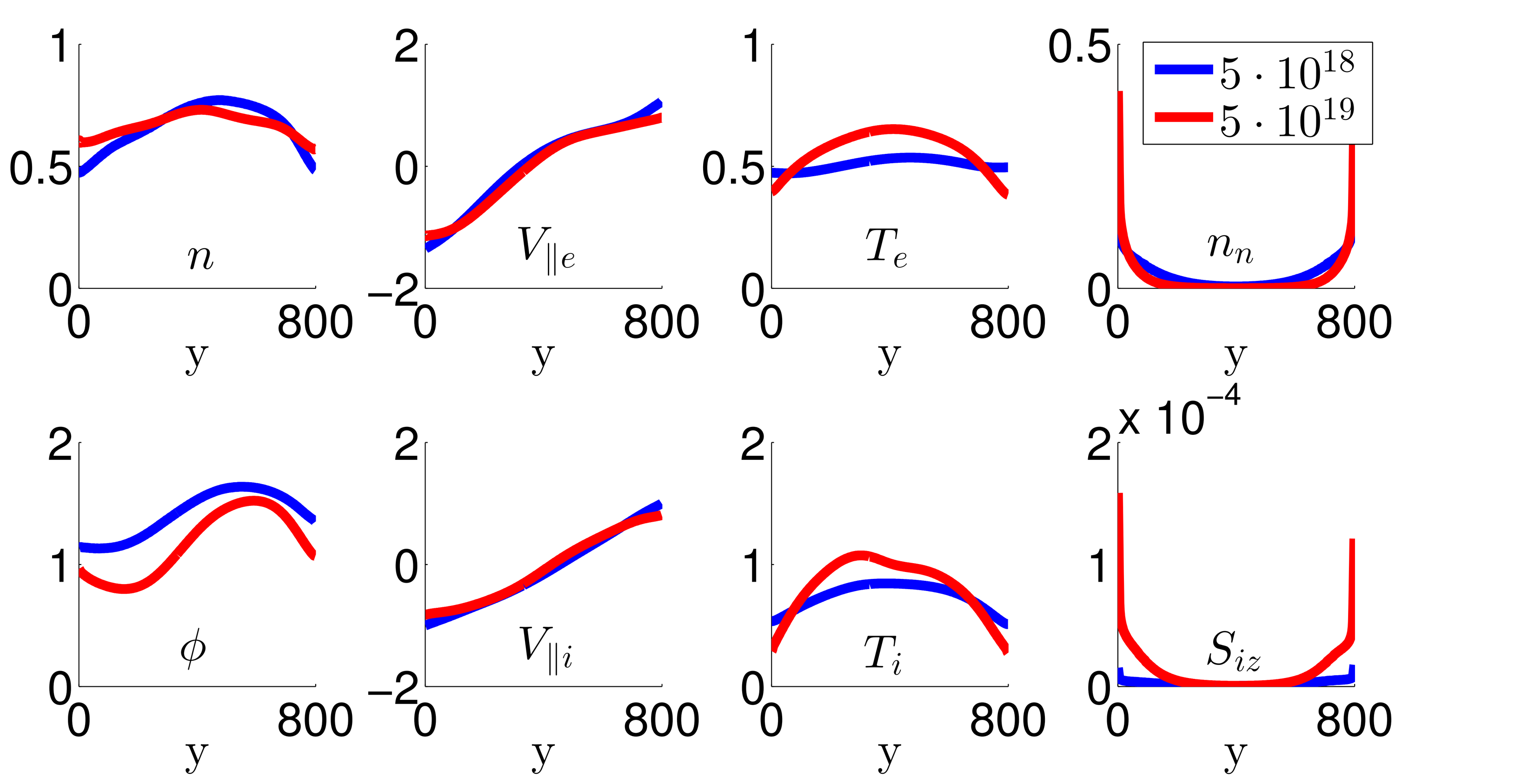
Turbulent simulations of the SOL including neutrals

- Two fully consistent simulations with the code GBS and the neutral model have been performed with two different densities ($n_0 = 5 \times 10^{18} m^{-3}$ and $n_0 = 5 \times 10^{19} m^{-3}$).

  Normalization: $v_0 = c_s$, $T_0 = 10eV$, $L_\perp = \rho_s$, $\rho_\star^{-1} = 500$



- The top row shows snapshots of plasma density, electron temperature, and the electric potential for the low density simulation, while the lower row shows the same plots for the high density simulation.
- Time- and space-averaged poloidal profiles during the quasi-steady-state phase of the two simulations:



- The simulations show clear changes in behavior of plasma density, electron and ion parallel velocities, and electron and ion temperatures.
- The high density simulation shows properties of the conduction limited regime (e.g., parallel temperature gradient).

A model for neutral atoms in the SOL

Kinetic equation with Krook operators

$$\frac{\partial f_n}{\partial t} + \mathbf{v} \cdot \frac{\partial f_n}{\partial \mathbf{x}} = -\nu_{iz} f_n - \nu_{cx} n_n \left(\frac{f_n}{n_n} - \frac{f_i}{n_i} \right) + \nu_{rec} f_i \quad (1)$$

$$\nu_{iz} = n_e r_{iz} = n_e \langle v_e \sigma_{iz}(v_e) \rangle, \quad \nu_{cx} = n_i r_{cx} = n_i \langle v_{rel} \sigma_{cx}(v_{rel}) \rangle, \quad \nu_{rec} = n_e r_{rec} = n_e \langle v_e \sigma_{rec}(v_e) \rangle$$

Boundary conditions are particle conserving and are defined as

$$f_n(\mathbf{x}_b, \mathbf{v}) = (1 - \alpha_{refl}) \Gamma_{out}(\mathbf{x}_b) \chi_{in}(\mathbf{x}_b, \mathbf{v}) + \alpha_{refl} [f_n(\mathbf{x}_b, \mathbf{v} - 2\mathbf{v}_p) + f_i(\mathbf{x}_b, \mathbf{v} - 2\mathbf{v}_p)] \quad (2)$$

with Γ_{out} the ion and neutral particle outflow, α_{refl} the reflection coefficient, $\mathbf{v}_p$ the velocity perpendicular to the wall. The distribution function of absorbed and re-emitted particles is

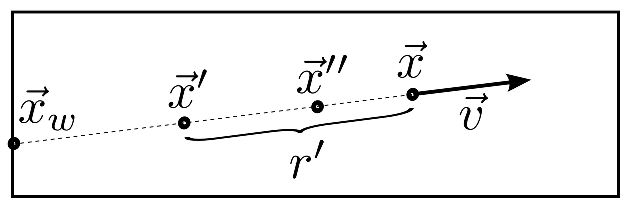
$$\chi_{in}(\mathbf{x}_b, \mathbf{v}) = \frac{3}{4\pi} \frac{m^2}{T_b^2} cos(\theta) \exp\left(-\frac{mv^2}{2T_b}\right) \quad (3)$$

with θ the angle between $\mathbf{v}$ and the normal vector to the surface, and T_b the temperature of the wall.

We apply **two assumptions** to simplify the model, namely $\tau_{\text{neutral losses}} < \tau_{\text{turbulence}}$ and $\lambda_{\text{mfp, neutrals}} \ll L_{\parallel,\text{plasma}}$.

The method of characteristics
The formal solution of equation (1) within these two approximations is

$$f_n(\mathbf{x}_\perp, \mathbf{v}) = \int_0^{r_{\perp b}} \left[\frac{S(\mathbf{x}'_\perp, \mathbf{v})}{v_\perp} + \delta(r'_\perp - r_{\perp b}) f_n(\mathbf{x}'_{\perp b}, \mathbf{v}) \right] \exp\left[-\frac{1}{v_\perp} \int_0^{r'_\perp} \nu_{eff}(\mathbf{x}''_\perp) dr''_\perp \right] dr'_\perp \quad (4)$$



$$S(\mathbf{x}, \mathbf{v}) = \nu_{cx}(\mathbf{x}) n_n(\mathbf{x}) \Phi_i(\mathbf{x}, \mathbf{v}) + \nu_{rec}(\mathbf{x}) f_i(\mathbf{x}, \mathbf{v})$$
$$\nu_{eff}(\mathbf{x}) = \nu_{iz}(\mathbf{x}) + \nu_{cx}(\mathbf{x})$$
$$r' = |\mathbf{x} - \mathbf{x}'|$$

A **linear integral equation** for the neutral density is obtained by integrating equation (4) over $\mathbf{v}$.

$$n_n(\mathbf{x}_\perp) = \int dv\, f_n(\mathbf{x}_\perp, \mathbf{v}) = \int_D n_n(\mathbf{x}'_\perp) \nu_{cx}(\mathbf{x}'_\perp) K_{p \to p}(\mathbf{x}_\perp, \mathbf{x}'_\perp) dA' + n_{n,rec}(\mathbf{x}_\perp) + n_{n,walls}(\mathbf{x}_\perp) \quad (5)$$

$$K_{p \to p}(\mathbf{x}_\perp, \mathbf{x}'_\perp) = \int_0^\infty \frac{1}{r'_\perp} \Phi_{\perp i}(\mathbf{x}'_\perp, \mathbf{v}_\perp) \exp\left[-\frac{1}{v_\perp} \int_0^{r'_\perp} \nu_{eff}(\mathbf{x}''_\perp) dr''_\perp \right] dv_\perp \quad (6)$$

The kernel $K_{p \to p}$ only depends on plasma quantities. Equation (5) together with the boundary conditions are spatially discretized, leading to a linear system of equations in the form

$$\begin{bmatrix} n_n \\ \Gamma_{out} \end{bmatrix} = \begin{bmatrix} K_{p \to p} & K_{b \to p} \\ K_{p \to b} & K_{b \to b} \end{bmatrix} \cdot \begin{bmatrix} n_n \\ \Gamma_{out} \end{bmatrix} + \begin{bmatrix} n_{n,rec} \\ \Gamma_{out,rec} + \Gamma_{out,i} \end{bmatrix} \quad (7)$$

which can be solved with standard methods. n_n can then be used to compute the distribution function and any of its moments using equation (4).

The Global Braginskii Solver (GBS) code

The drift-reduced two-fluid **plasma model** is derived from these kinetic equations for ions and electrons

$$\frac{\partial f_i}{\partial t} + \mathbf{v} \cdot \frac{\partial f_i}{\partial \mathbf{x}} + \mathbf{a} \cdot \frac{\partial f_i}{\partial \mathbf{v}} = \nu_{iz} f_n - \nu_{cx} n_n \left(\frac{f_i}{n_i} - \frac{f_n}{n_n} \right) - \nu_{rec} f_i + C(f_i) \quad (8)$$

$$\frac{\partial f_e}{\partial t} + \mathbf{v} \cdot \frac{\partial f_e}{\partial \mathbf{x}} + \mathbf{a} \cdot \frac{\partial f_e}{\partial \mathbf{v}} = \nu_{iz} n_n \left[2\Phi_e(\mathbf{v}_n, T_{e,iz}) - \frac{f_e}{n_e} \right] + \nu_{en} n_n \left[\Phi_e(\mathbf{v}_n, T_{e,en}) - \frac{f_e}{n_e} \right] - \nu_{rec} f_e + C(f_e), \quad (9)$$

with $\Phi_e(\mathbf{v}, T)$ a Maxwellian distribution, $T_{e,iz} = T_e/2 - E_{iz}/3 + m_e v_e^2/6 - m_e v_n^2/3$, and $T_{e,en} = T_e + m_e(v_e^2 - v_n^2)/3$.

Two fluid drift-reduced Braginskii equations [Ricci *et al.*, PPCF 2012], $k_\perp^2 \gg k_\parallel^2$, $d/dt \ll \omega_{ci}$

$$\frac{\partial n}{\partial t} = -\frac{1}{B}[\phi, n] + \frac{2}{eB}[C(p_e) - enC(\phi)] - \nabla_\parallel(n v_{\parallel e}) + \mathcal{D}_n(n) + S_n + n_n \nu_{iz} - n \nu_{rec} \quad (10)$$

$$\frac{\partial \tilde{\omega}}{\partial t} = -\frac{1}{B}[\phi, \tilde{\omega}] - v_{\parallel i} \nabla_\parallel \tilde{\omega} + \frac{B^2}{m_i n} \nabla_\parallel j_\parallel + \frac{2B}{m_i n} C(p) + \mathcal{D}_{\tilde{\omega}}(\tilde{\omega}) - \frac{n_n}{n} \nu_{cx} \tilde{\omega} \quad (11)$$

$$\frac{\partial v_{\parallel e}}{\partial t} + \frac{e}{m_e} \frac{\partial \Psi}{\partial t} = -\frac{1}{B}[\phi, v_{\parallel e}] - v_{\parallel e} \nabla_\parallel v_{\parallel e} + \frac{e}{\sigma_\parallel m_e} j_\parallel + \frac{e}{m_e} \nabla_\parallel \phi - \frac{T_e}{m_e n} \nabla_\parallel n - \frac{1.71}{m_e n} \nabla_\parallel T_e + \mathcal{D}_{v_{\parallel e}}(v_{\parallel e}) + \frac{n_n}{n}(\nu_{en} + 2\nu_{iz})(v_{\parallel n} - v_{\parallel e}) \quad (12)$$

$$\frac{\partial v_{\parallel i}}{\partial t} = -\frac{1}{B}[\phi, v_{\parallel i}] - v_{\parallel i} \nabla_\parallel v_{\parallel i} - \frac{1}{m_i n} \nabla_\parallel p + \mathcal{D}_{v_{\parallel i}}(v_{\parallel i}) + \frac{n_n}{n}(\nu_{iz} + \nu_{cx})(v_{\parallel n} - v_{\parallel i}) \quad (13)$$

$$\frac{\partial T_e}{\partial t} = -\frac{1}{B}[\phi, T_e] - v_{\parallel e} \nabla_\parallel T_e + \frac{4 T_e}{3eB} \left[\frac{T_e}{n} C(n) + \frac{7}{2} C(T_e) - eC(\phi) \right] + \frac{2 T_e}{3n} \left[\frac{0.71}{e} \nabla_\parallel j_\parallel - n \nabla_\parallel v_{\parallel e} \right] + \mathcal{D}_{T_e}(T_e) + \mathcal{D}^\parallel_{T_e}(T_e) + S_{T_e} + \frac{n_n}{n} \nu_{iz} \left[-\frac{2}{3} E_{iz} - T_e + m_e v_{\parallel e} \left(v_{\parallel e} - \frac{4}{3} v_{\parallel n} \right) \right] - \frac{n_n}{n} \nu_{en} m_e \frac{2}{3} v_{\parallel e}(v_{\parallel n} - v_{\parallel e}) \quad (14)$$

$$\frac{\partial T_i}{\partial t} = -\frac{1}{B}[\phi, T_i] - v_{\parallel i} \nabla_\parallel T_i + \frac{4 T_i}{3eB} \left[C(T_e) + \frac{T_e}{n} C(n) - \frac{5}{3} C(T_i) - eC(\phi) \right] + \frac{2 T_i}{3n} \left[\frac{1}{e} \nabla_\parallel j_\parallel - n \nabla_\parallel v_{\parallel i} \right] + \mathcal{D}_{T_i}(T_i) + \mathcal{D}^\parallel_{T_i}(T_i) + S_{T_i} + \frac{n_n}{n}(\nu_{iz} + \nu_{cx}) \left[T_n - T_i + \frac{1}{3}(v_{\parallel n} - v_{\parallel i})^2 \right] \quad (15)$$

$$\nabla_\perp^2 \phi = \omega, \ \rho_\star = \rho_s/R, \ \nabla_\parallel f = \mathbf{b}_0 \cdot \nabla f, \ \tilde{\omega} = \omega + \tau \nabla_\perp^2 T_i, \ p = n(T_e + \tau T_i)$$

- These equations are implemented in **GBS**, a **3D**, **flux-driven**, **global** turbulence code with circular geometry including electromagnetic effects
- A set of fluid boundary conditions applicable at the magnetic pre-sheath entrance where the magnetic field lines intersect the limiter is used [Loizu *et al.*, PoP 2012]

Some achievements of GBS (see also http://crpp.epfl.ch/research_theory_plasma_edge):
- SOL width scaling as a function of dimensionless/engineering plasma parameters
- Origin and nature of intrinsic toroidal plasma rotation
- Non-linear turbulent regimes in the SOL
- Mechanism regulating the equilibrium electrostatic potential

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.