A kinetic neutral atom model for tokamak SOL turbulence simulations

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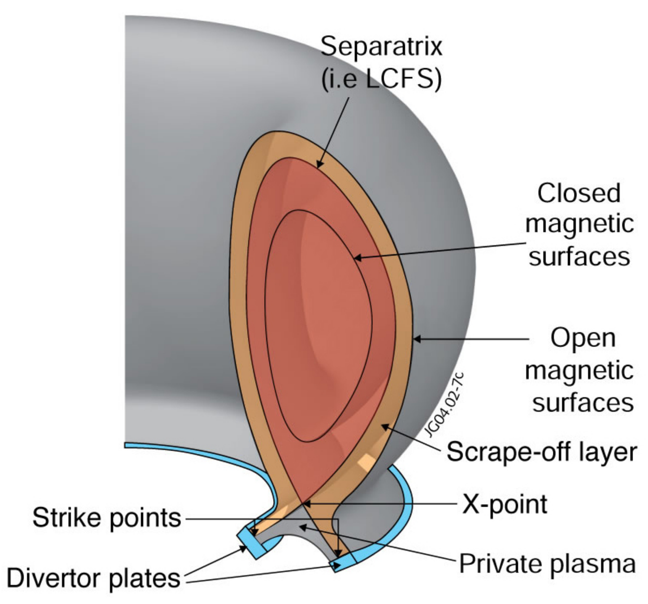
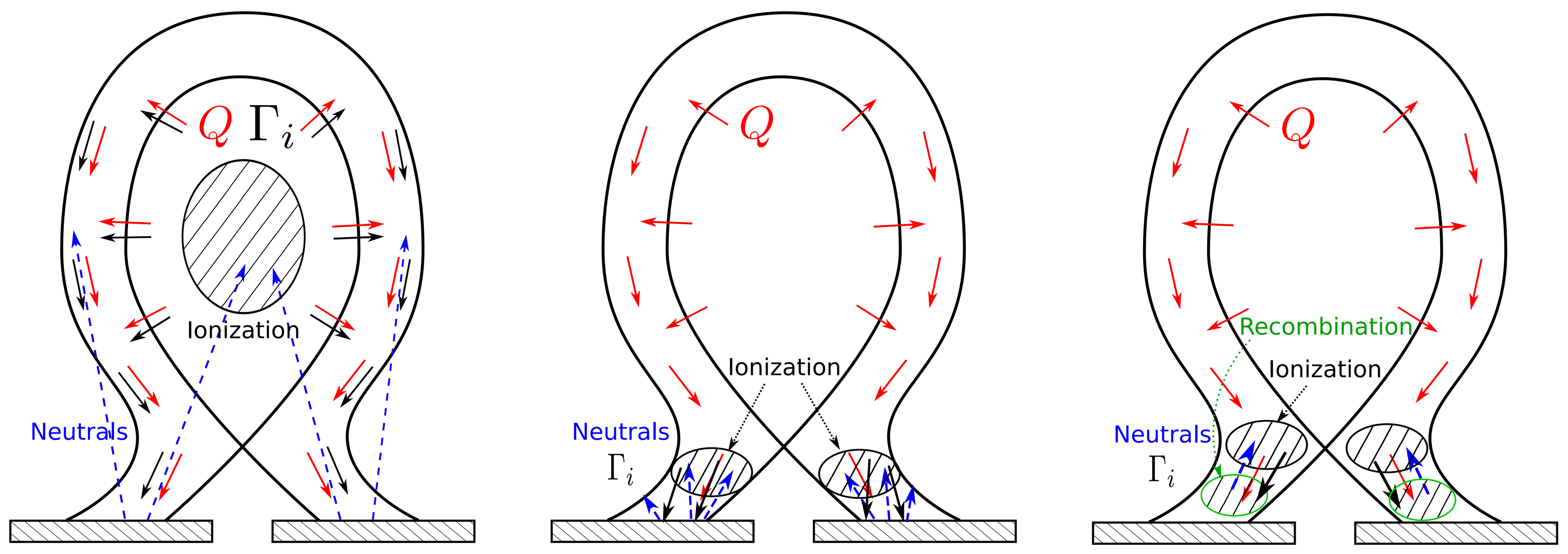
SOL operating regimes



The tokamak scrape-off layer (SOL):

- Open field lines
- Heat exhaust from the main plasma
- Important for impurity transport and fusion ashes removal
- Fueling the plasma (recycling and gas puffing)

Three regimes



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

A model for neutral atoms in the SOL

Kinetic equation with Krook operators

$$\frac{\partial f_n}{\partial t} + \vec{v}\cdot\frac{\partial f_n}{\partial \vec{x}} = -\nu_{iz} f_n - \nu_{cx}(f_n - n_n\Phi_i) + \nu_{rec} n_i \Phi_i \qquad (1)$$

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

Boundary conditions conserve particles and respect the Knudsen Cosine Law.

$$\int d\vec{v}\; v_\perp f_n(\vec{x}_w,\vec{v}) + u_{i\perp} n_i = 0 \qquad (2)$$

$$f_w(\vec{x}_w,\vec{v}) \propto cos(\theta) e^{mv^2/2T_w} \quad \text{for} \;\; v_\perp > 0$$

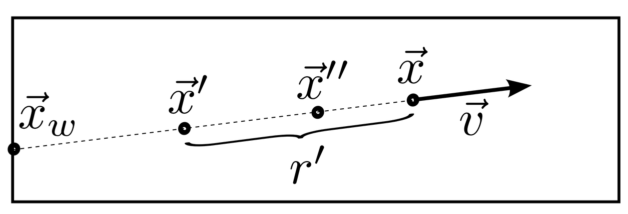
with $v_\perp$ the velocity component perpendicular to the surface, θ the angle between $\vec{v}$ and the normal vector to the surface, and T_w the temperature of the wall.

We consider the **steady state** solution, $\frac{\partial f_n}{\partial t} = 0$, which is valid if $\tau_{\text{neutral losses}} < \tau_{\text{turbulence}}$.
Typical SOL parameters: $T_e = 20\text{eV}$, $n_0 = 5\cdot 10^{19}\text{m}^{-3}$

$$\tau_{\text{neutral losses}} \approx \nu_{eff}^{-1} \approx 5\cdot 10^{-7}s$$
$$\tau_{\text{turbulence}} \approx \sqrt{R_0 L_p / c_{s0}} \approx 2\cdot 10^{-6}s$$

The method of characteristics
The formal solution of the kinetic equation is

$$f_n(\vec{x},\vec{v}) = \int_{x_w}^{x} dx' \frac{S(\vec{x}',\vec{v})}{v_x} e^{-\frac{1}{v_x}\int_{x'}^{x} dx''\,\nu_{eff}(\vec{x}'')} + f_w(\vec{x}_w,\vec{v}) e^{-\frac{1}{v_x}\int_{x_w}^{x} dx''\,\nu_{eff}(\vec{x}'')} \qquad (3)$$



$$S(\vec{x},\vec{v}) = \nu_{cx}(\vec{x}) n_n(\vec{x})\Phi_i(\vec{x},\vec{v}) + \nu_{rec}(\vec{x}) f_i(\vec{x},\vec{v})$$
$$\nu_{eff}(\vec{x}) = \nu_{iz}(\vec{x}) + \nu_{cx}(\vec{x})$$
$$\vec{x} = (x,y,z),\; \vec{v} = (v_x, v_y, v_z)$$

2D assumption
- $k_\parallel \ll k_\perp$ for plasma structures, but neutrals are not affected by B
- $\lambda_{mfp,neutrals} \ll L_{\parallel,plasma}$
- f_n is evaluated independently on each poloidal plane

An integral equation for the neutral density
The contribution to the neutral distribution function from recombination, as well as the contribution by recycling at the limiter, can be evaluated directly. The contribution by charge exchange and the one from neutrals that are absorbed and re-emitted from the walls can be calculated by imposing $n_n(\vec{x}) = \int d\vec{v}\; f_n$. A linear integral equation for the neutral density is obtained.

$$n_n(\vec{x}) = \int d\vec{v}\; f_n = \int_0^\infty v dv \int_0^{2\pi} d\varphi \int_{-\infty}^{\infty} dv_z\, f_n \qquad (4)$$
$$= \iint d\vec{x}'\; n_n(\vec{x}') \int_0^\infty dv\, \frac{1}{r'}\, \nu_{cx}(\vec{x}')\Phi_i^{2D}(\vec{x}',\vec{v}) e^{-\frac{1}{v}\int_0^{r'} dr''\,\nu_{eff}(\vec{x}'')} + n_{n,rec}(\vec{x}) + n_{n,walls}(\vec{x})$$

Integrating over v_z, we assume Φ_i Maxwellian, according to the use of a fluid model for the plasma. The discretized form can be solved with standard methods.

$$n_n(\vec{x}_i) = A_{i,j} n_n(\vec{x}_j) + n_{n,rec}(\vec{x}_i) + n_{n,wall}(\vec{x}_i) \qquad (5)$$
$$A_{i,j} = dxdy \frac{\nu_{cx}(\vec{x}_j)}{r} \int_0^\infty dv\; \Phi_i^{2D}(\vec{x}_j, v\hat{r}) e^{-\frac{1}{v}\int_0^{r} dr'\,\nu_{eff}(\vec{x}_j + r'\hat{r})}$$

with $\vec{r} = \vec{x}_i - \vec{x}_j$, $r = |\vec{r}|$, $\hat{r} = \vec{r}/r$

The Global Braginskii Solver (GBS) code

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

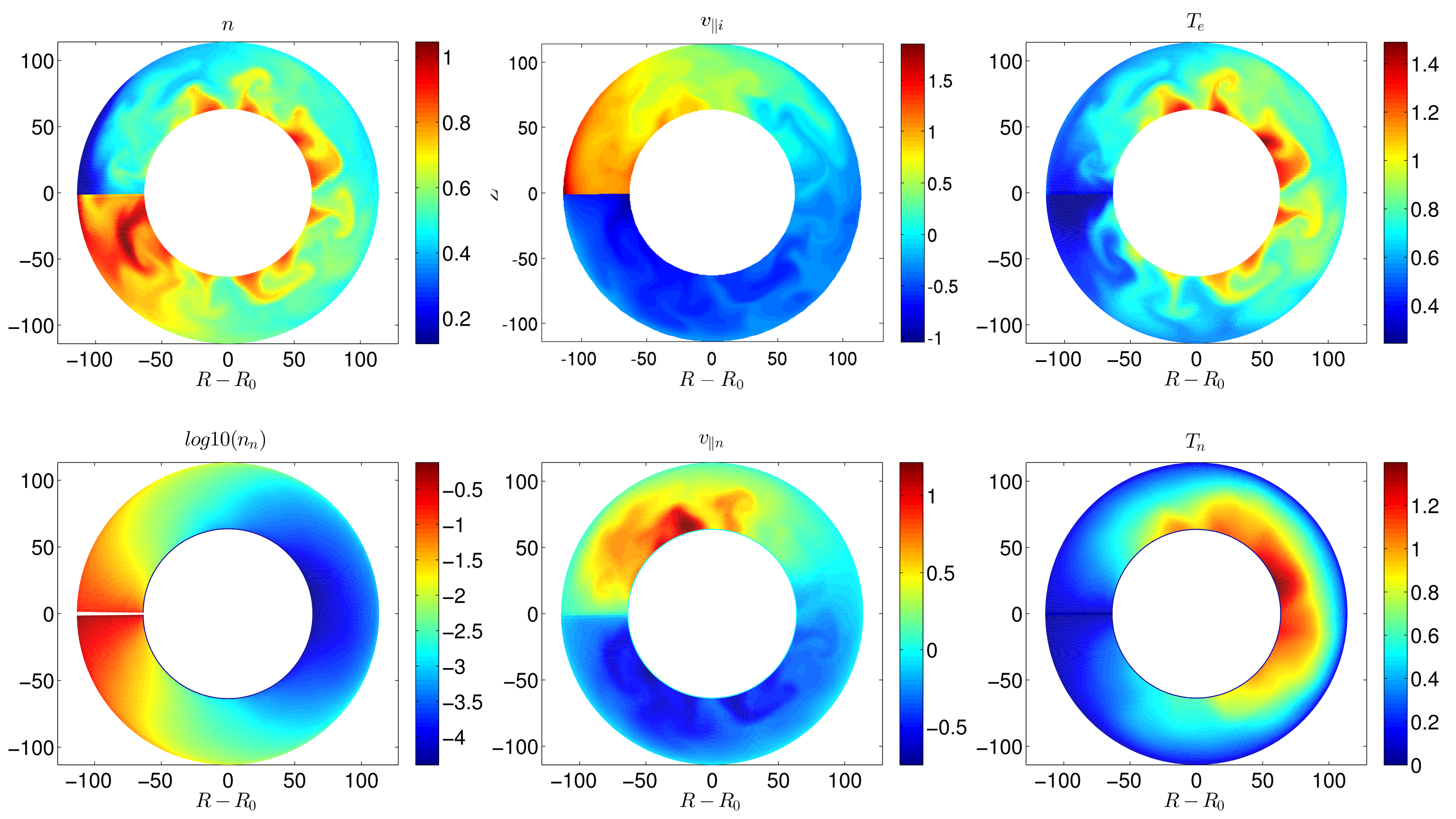
$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel(n v_{\parallel e}) + \mathcal{D}_n(n) + S_n + n_n n r_{iz} - n^2 r_{rec} \qquad (6)$$
$$\frac{\partial \tilde\omega}{\partial t} = -\rho_\star^{-1}[\phi, \tilde\omega] - v_{\parallel i}\nabla_\parallel\tilde\omega + \frac{B^2}{n}\nabla_\parallel j_\parallel + \frac{2B}{n}C(p) + \mathcal{D}_{\tilde\omega}(\tilde\omega) \qquad (7)$$
$$\frac{\partial v_{\parallel e}}{\partial t} = -\rho_\star^{-1}[\phi, v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\left(\nu\frac{j_\parallel}{n} + \nabla_\parallel\phi - \frac{1}{n}\nabla_\parallel p_e - 0.71\nabla_\parallel T_e\right) + \mathcal{D}_{v_{\parallel e}}(v_{\parallel e}) \qquad (8)$$
$$\frac{\partial v_{\parallel i}}{\partial t} = -\rho_\star^{-1}[\phi, v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel p + \mathcal{D}_{v_{\parallel i}}(v_{\parallel i}) + n_n(r_{iz} + r_{cx})(v_{\parallel n} - v_{\parallel i}) \qquad (9)$$
$$\frac{\partial T_e}{\partial t} = -\rho_\star^{-1}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4T_e}{3B}\left[\frac{1}{n}C(p_e) + \frac{5}{2}C(T_e) - C(\phi)\right] + \frac{2T_e}{3}\left[\frac{0.71}{n}\nabla_\parallel j_\parallel - \nabla_\parallel v_{\parallel e}\right]$$
$$+ \mathcal{D}_{T_e}(T_e) + \mathcal{D}^\parallel_{T_e}(T_e) + S_{T_e} - n_n r_{iz} E_{iz} \qquad (10)$$
$$\frac{\partial T_i}{\partial t} = -\rho_\star^{-1}[\phi, T_i] - v_{\parallel i}\nabla_\parallel T_i + \frac{4T_i}{3B}\left[\frac{1}{n}C(p_e) - \tau\frac{5}{2}C(T_i) - C(\phi)\right] + \frac{2T_i}{3}\left[(v_{\parallel i} - v_{\parallel e})\frac{\nabla_\parallel n}{n} - \nabla_\parallel v_{\parallel e}\right] \qquad (11)$$
$$+ \mathcal{D}_{T_i}(T_i) + \mathcal{D}^\parallel_{T_i}(T_i) + S_{T_i} + n_n(r_{iz} + r_{cx})(T_n - T_i + (v_{\parallel n} - v_{\parallel i})^2)$$

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

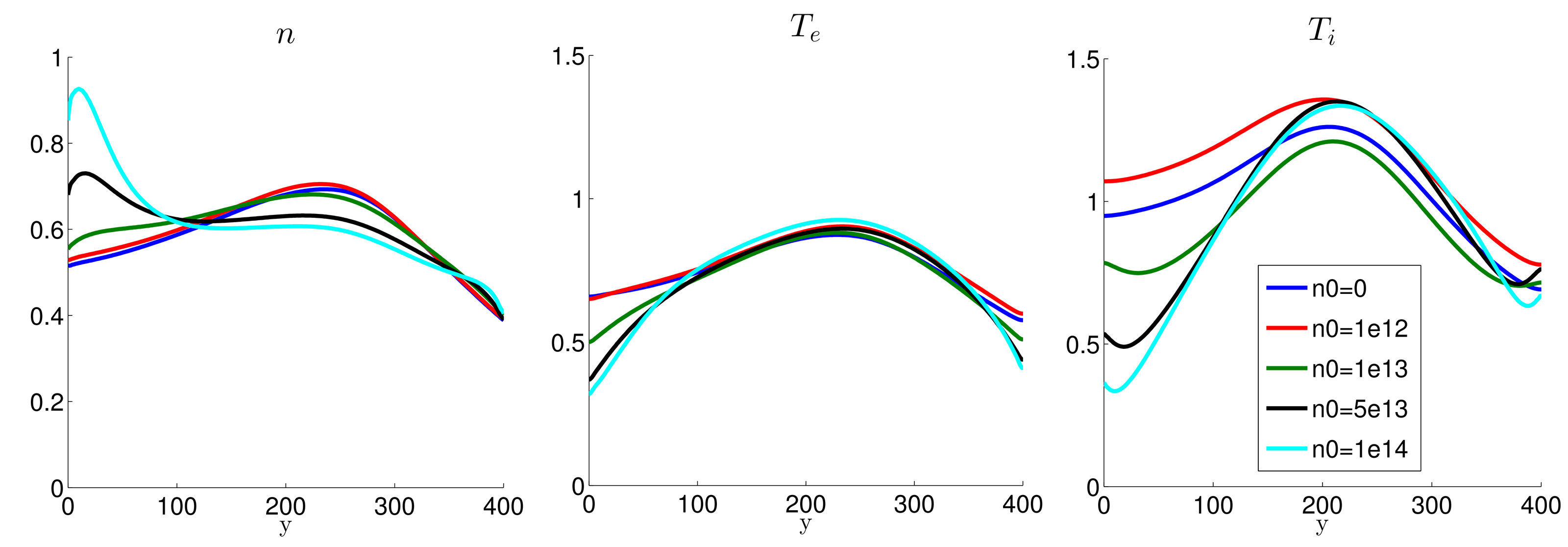
- These equations are implemented in **GBS**, a **3D**, **flux-driven**, **global** turbulence code with circular geometry including electromagnetic effects [presented by F.D. Halpern, Monday, I-3]
- System is closed with a set of fluid boundary conditions applicable at the magnetic pre-sheath entrance where the magnetic field lines intersect the limiter [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

Turbulent simulations of the SOL including neutrals

- First fully consistent simulations with the code GBS and the neutrals model have been performed. Parameters and normalization: $n_0 = 10^{14} cm^{-3}$, $v_0 = c_s$, $T_0 = 10eV$, $L_\perp = \rho_s$, $\rho_\star^{-1} = 500$



- A scan over different densities has been carried out to investigate the transition from convection to conduction limited regime.
- Time- and space-averaged poloidal profiles during the quasi-steady-state phase of the five density-scan simulations:



- The simulations show clear changes in behavior of plasma density, electron and ion temperatures.
- The underlying physical mechanisms behind these changes (e.g. temperature gradient mainly because of lack of convection or because of direct sink terms?) are still under investigation.

Future work

- Investigate the transition from convection to conduction limited regime
- Move towards detachment
  - Divertor geometry
  - Radiative detachment in limited geometry
  - Mimic the geometry of one divertor leg
- Relax the steady state assumption

Conclusions

- 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.
- First results from the GBS simulations show interesting interplay between neutral and plasma physics.

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