A kinetic neutral atom model for tokamak scrape-off layer tubulence simulations

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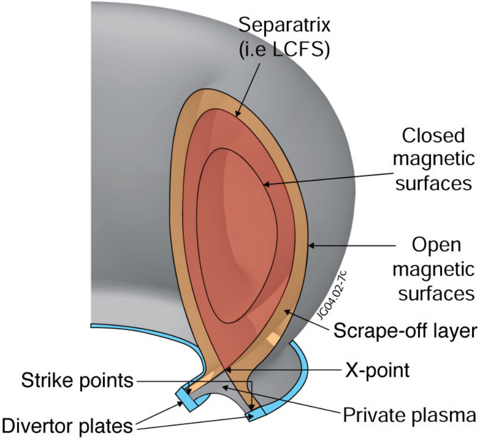
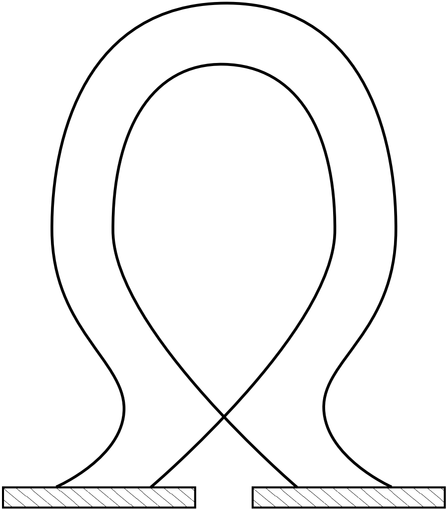
The tokamak scrape-off layer (SOL)

- Open field lines
- Heat exhaust
- Confinement
- Impurities
- Fusion ashes removal
- Fueling the plasma (recycling)
- Three regimes
  - Convection limited
  - Conduction limited
  - Detached



Convection limited regime



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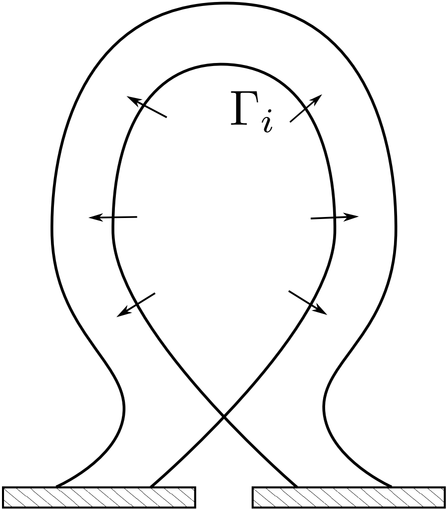

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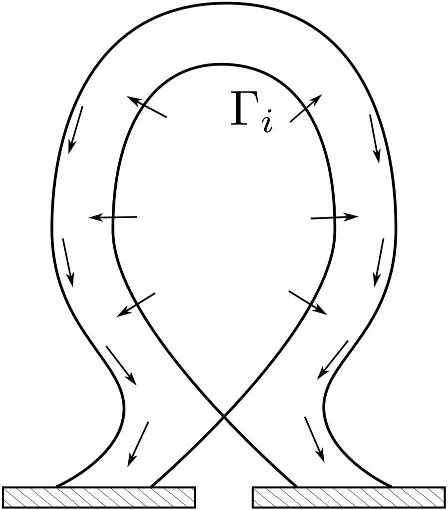
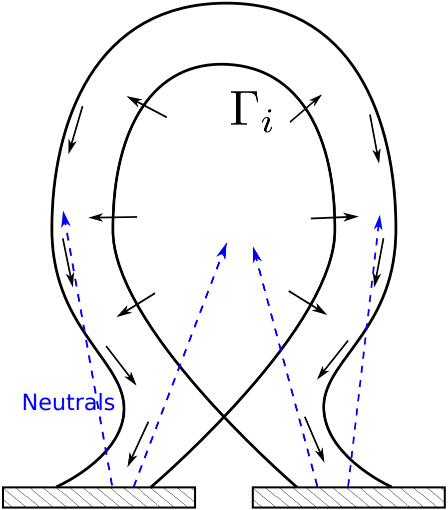


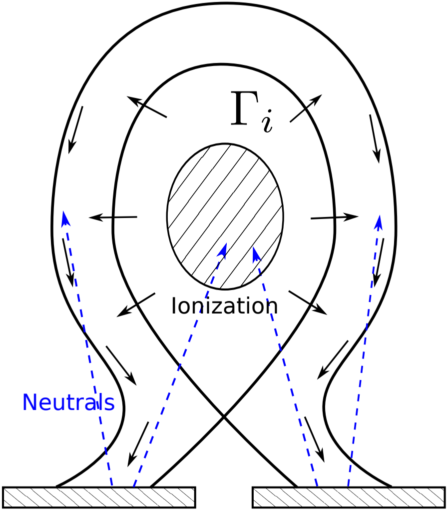
Convection limited regime

- Low plasma density
- Long λ_{mfp} for neutrals



Convection limited regime

- Low plasma density
- Long λ_{mfp} for neutrals
- Ionization in the core



Convection limited regime

- Low plasma density
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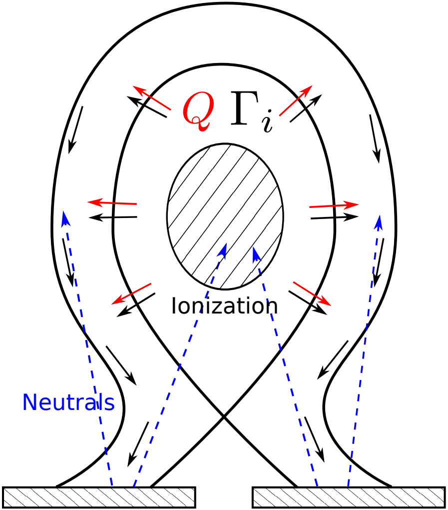
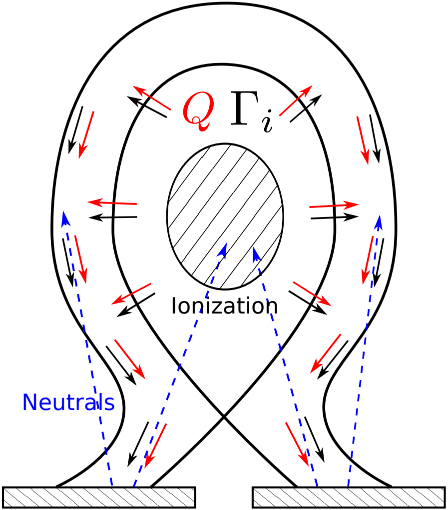
- Ionization in the core
- Heat $\approx$ particle source



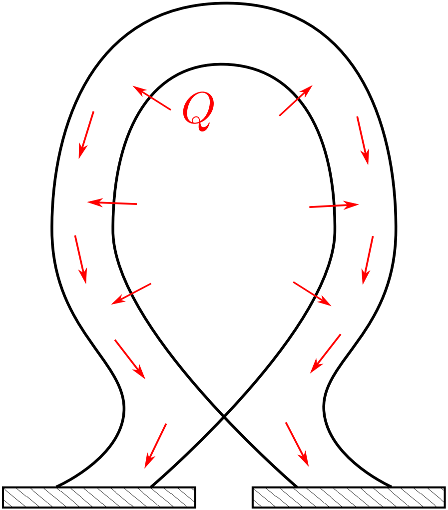
Convection limited regime

- Low plasma density
- Long λ_{mfp} for neutrals
- Ionization in the core
- Heat $\approx$ particle source
- Q is mainly convective



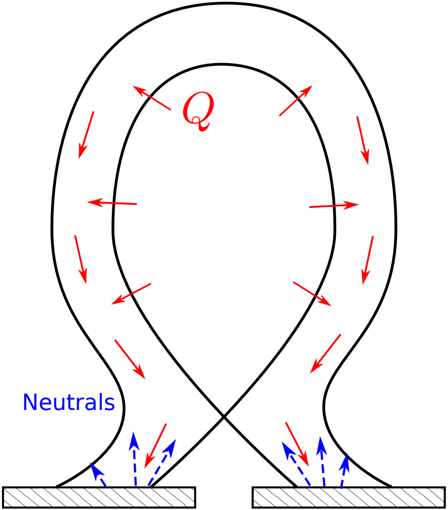
Conduction limited regime

- High plasma density



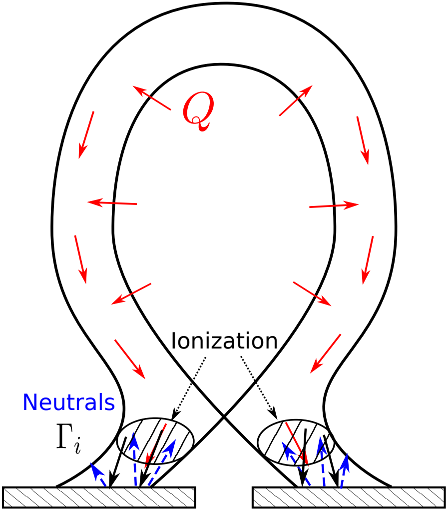
Conduction limited regime

- High plasma density
- Short λ_{mfp}



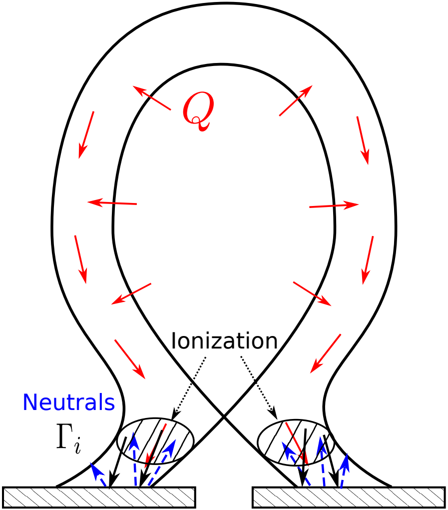
Conduction limited regime

- High plasma density
- Short λ_{mfp}
- Ionization close to targets



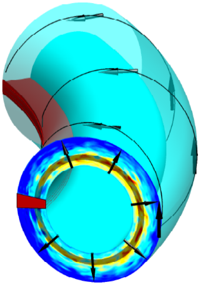
Conduction limited regime

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



The GBS code, a tool to simulate SOL turbulence

- Drift-reduced Braginskii equations
  $d/dt \ll \omega_{ci}, k_\perp^2 \gg k_\parallel^2$
- Evolves scalar fields in 3D geometry
  $n, \Omega, v_{\parallel e}, v_{\parallel,i}, T_e, T_i$
- Flux-driven, no separation between equilibrium and fluctuations
- Power balance between plasma outflow from the core, turbulent transport, and sheath losses [Ricci et al., PPCF, 2012]
- No divertor geometry
- No neutral physics



The model

Kinetic model for the neutral atoms with Krook operators

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

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

Boundary conditions

($v_\perp$ in respect to the surface; θ between $\vec{v}$ and normal vector to the surface)

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

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

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The model in steady state

Steady state, $\frac{\partial f_n}{\partial t} = 0$, first approach

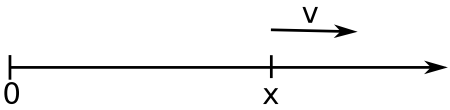
- Valid if $\tau_{neutral\ losses} < \tau_{turbulence}$
- e.g. $T_e = 20\text{eV}$, $n_0 = 5 \cdot 10^{19}\text{m}^{-3}$

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

- Otherwise: time dependent model

The method of characteristics

Example in 1D, no recombination, $v > 0$ and a wall at $x = 0$



The method of characteristics

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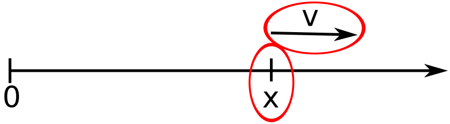

$f_n(x, v)$

(3)

The method of characteristics

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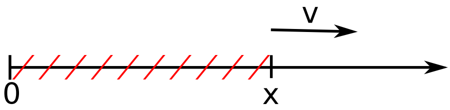

$$f_n(x, v) = \int_0^x dx' \tag{3}$$

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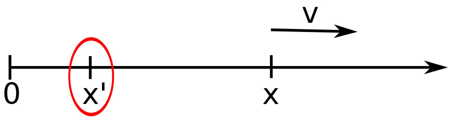

$$f_n(x, v) = \int_0^x dx' \, \frac{\nu_{cx}(x') n_n(x') \Phi_i(x', v)}{v} \tag{3}$$

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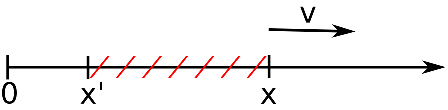

$$f_n(x, v) = \int_0^x dx' \; \frac{\nu_{cx}(x')n_n(x')\Phi_i(x', v)}{v} e^{\frac{1}{v}\int_{x'}^{x} dx'' \; (\nu_{cx}(x'')+\nu_{ion}(x''))} \tag{3}$$

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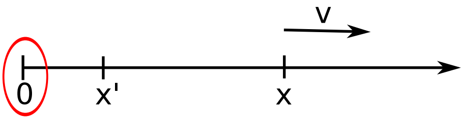

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$$+ f_w(v) e^{\frac{1}{v}\int_0^x dx'' \, (\nu_{cx}(x'')+\nu_{ion}(x''))} \tag{3}$$

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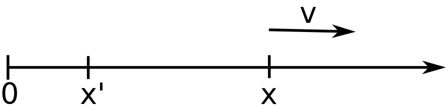

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An equation for the density distribution

By imposing $\int dv\ f_n = n_n$

$$n_n(x) = \int_0^x dx'\ n_n(x') \int_0^\infty dv\ \frac{\nu_{cx}(x')\Phi_i(x', v)}{v} e^{\frac{\nu_{eff}(x-x')}{v}} \qquad (4)$$
$$+ contribution\ by\ v < 0$$
$$+ n_w(x)$$

we get an integral equation for $n_n(x)$.

Discretized equations

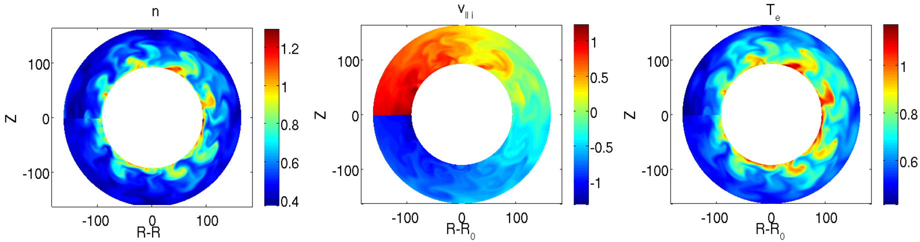
Discretize the spatial direction in $x \to x_i$ and $n_n(x_i) \to n_n^i$

$$n_n^i = \sum_{j \leq i} n_n^j \int_0^\infty dv \, \frac{\nu_{cx}(x_j)\Phi_i(x_j, v)}{v} e^{\frac{\nu_{eff}(x_i - x_j)}{v}} \qquad (5)$$
$$+ \, contribution \; by \; v < 0$$
$$+ \, n_w(x_i)$$

System of linear equations, solved with standard methods

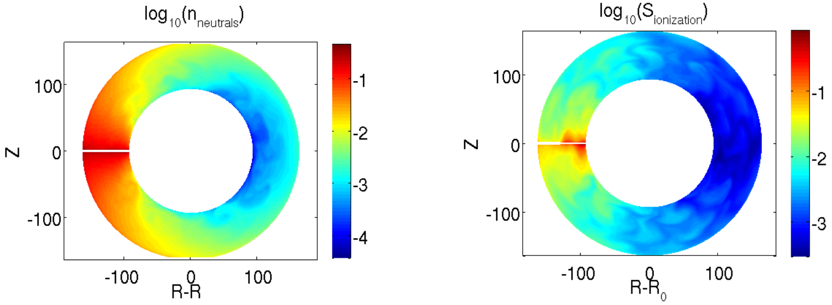
Self-consistent simulation with GBS and neutrals model

Plasma: snapshot of density, parallel ion velocity and electron temperature from GBS



Self-consistent simulation with GBS and neutrals model

Neutral density distribution and ionization rate ($n_n n_e \langle v_e \sigma_{ion} \rangle$) from the simple neutral model, $n_0 = 5 \cdot 10^{19}\mathrm{m}^{-3}$, $T_0 = 10\mathrm{eV}$



Conclusions

- Developement of a neutral model for GBS
- Kinetic equation with Krook operators for ion, rec and cx
- 2D evaluation of the neutral density shows its proximity to the limiter

Outlook

- Find the transition from convection to conduction limited regime
- Relax the steady state assumption
- Adding density source, drag force, and temperature source/sink to the equations in GBS
- Move towards detachment
  - Divertor geometry
  - Radiative detachment in limited geometry
  - Mimic the geometry of one divertor leg