Impact of neutral atoms on plasma turbulence in the tokamak edge region

C. Wersal
P. Ricci, F.D. Halpern, R. Jorge, J. Morales, P. Paruta, F. Riva

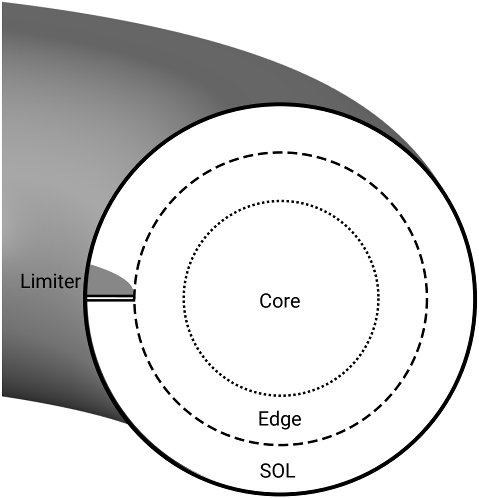
Theory of Fusion Plasmas
Joint Varenna-Lausanne International Workshop

29.08. - 02.09. 2016

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
SWISS PLASMA CENTER

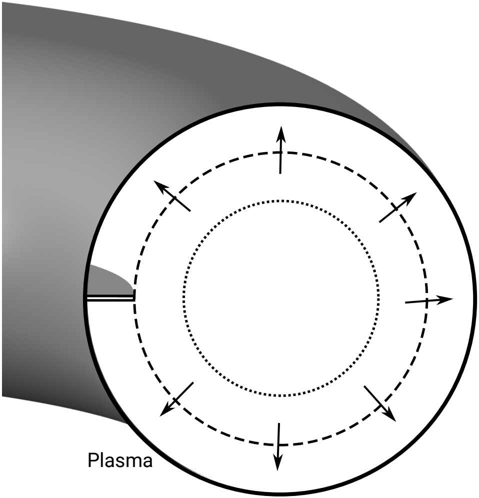
Physics at the periphery of a fusion plasma

- Toroidal limiter



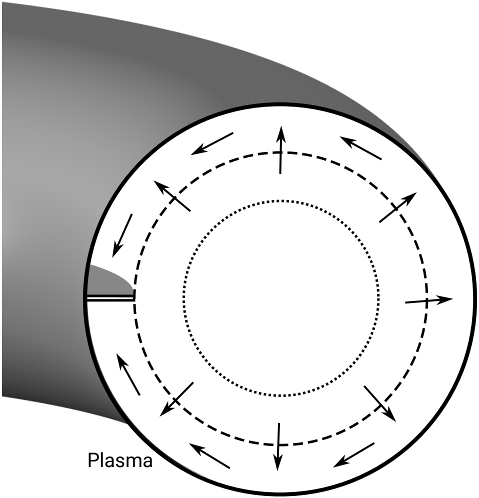
Physics at the periphery of a fusion plasma

- Toroidal limiter
- Radial transport due to turbulence



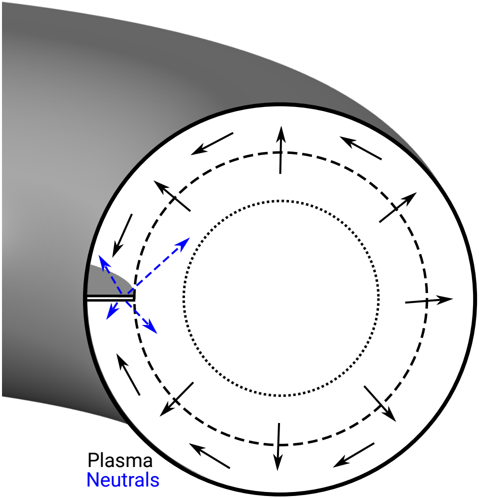
Physics at the periphery of a fusion plasma

- Toroidal limiter
- Radial transport due to turbulence
- Parallel flow in the SOL to the limiter



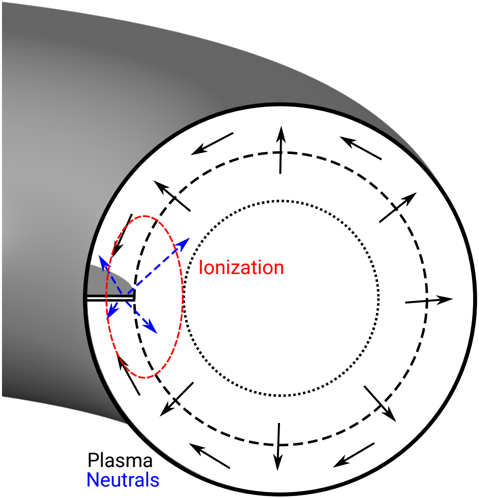
Physics at the periphery of a fusion plasma

- Toroidal limiter
- Radial transport due to turbulence
- Parallel flow in the SOL to the limiter
- Recombination on the limiter



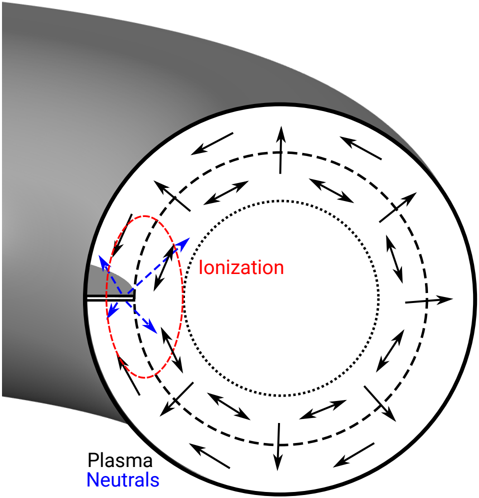
Physics at the periphery of a fusion plasma

- Toroidal limiter
- Radial transport due to turbulence
- Parallel flow in the SOL to the limiter
- Recombination on the limiter
- Ionization of neutrals
  - Density source
  - Energy sink



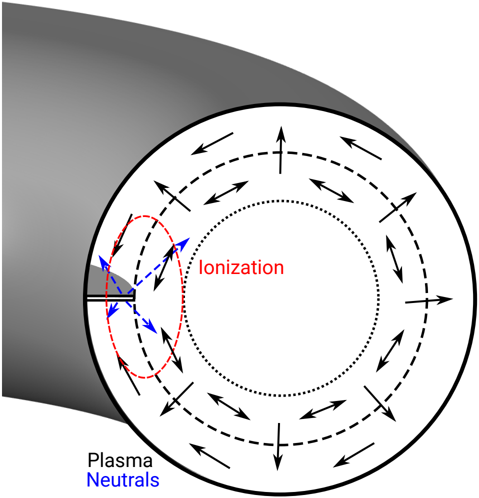
Physics at the periphery of a fusion plasma

- Toroidal limiter
- Radial transport due to turbulence
- Parallel flow in the SOL to the limiter
- Recombination on the limiter
- Ionization of neutrals
  - Density source
  - Energy sink



Physics at the periphery of a fusion plasma

- Toroidal limiter
- Radial transport due to turbulence
- Parallel flow in the SOL to the limiter
- Recombination on the limiter
- Ionization of neutrals
    - Density source
    - Energy sink
- Recycling



Movie

The tokamak scrape-off layer (SOL)

- Heat exhaust
- Confinement
- Impurities
- Fusion ash removal
- Fueling the plasma (recycling)

1. Modeling the periphery
2. A refined two-point model with neutrals
3. Gas puff fueling simulations

Modeling the periphery

Modeling the periphery

- High plasma collisionality, local Maxwellian

Modeling the periphery

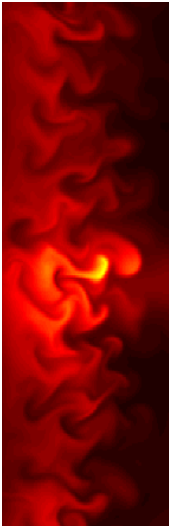
- High plasma collisionality, local Maxwellian
- $d/dt \ll \omega_{ci}, k_\perp^2 \gg k_\parallel^2$

Modeling the periphery

- High plasma collisionality, local Maxwellian
- $d/dt \ll \omega_{ci}, k_\perp^2 \gg k_\parallel^2$
- Drift-reduced Braginskii equations $n, \Omega, v_{\parallel e}, v_{\parallel,i}, T_e, T_i$

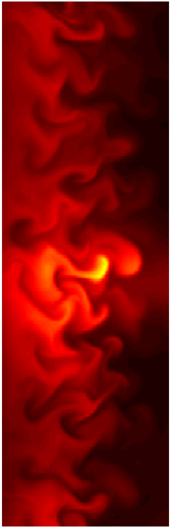
Modeling the periphery

- High plasma collisionality, local Maxwellian
- $d/dt \ll \omega_{ci}, k_\perp^2 \gg k_\parallel^2$
- Drift-reduced Braginskii equations $n, \Omega, v_{\parallel e}, v_{\parallel,i}, T_e, T_i$
- Flux-driven, no separation between equilibrium and fluctuations



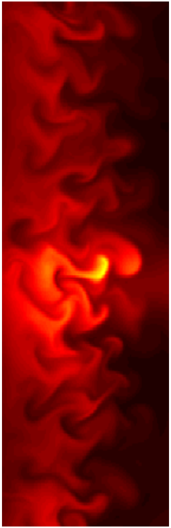
Modeling the periphery

- High plasma collisionality, local Maxwellian
- $d/dt \ll \omega_{ci}, k_\perp^2 \gg k_\parallel^2$
- Drift-reduced Braginskii equations $n, \Omega, v_{\parallel e}, v_{\parallel, i}, T_e, T_i$
- Flux-driven, no separation between equilibrium and fluctuations
- Kinetic neutral equation



Modeling the periphery

- High plasma collisionality, local Maxwellian
- $d/dt \ll \omega_{ci}, k_\perp^2 \gg k_\parallel^2$
- Drift-reduced Braginskii equations $n, \Omega, v_{\parallel e}, v_{\parallel, i}, T_e, T_i$
- Flux-driven, no separation between equilibrium and fluctuations
- Kinetic neutral equation
- Interplay between plasma outflow from the core, turbulent transport, sheath losses, and recycling



Fluid plasma model and interaction with neutrals

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi,n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel(n v_{\parallel e}) + \mathscr{D}_n(n) + S_n + n_n \nu_{iz} - n\nu_{rec} \quad (1)$$

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

$$\frac{\partial v_{\parallel e}}{\partial t} = -\rho_\star^{-1}[\phi,v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\left(\nu\frac{j_\parallel}{n} + \nabla_\parallel\phi - \frac{1}{n}\nabla_\parallel p_e - 0.71\nabla_\parallel T_e\right) + \mathscr{D}_{v_{\parallel e}}(v_{\parallel e}) + \frac{n_n}{n}(\nu_{en} + 2\nu_{iz})(v_{\parallel n} - v_{\parallel e}) \quad (3)$$

$$\frac{\partial v_{\parallel i}}{\partial t} = -\rho_\star^{-1}[\phi,v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel p + \mathscr{D}_{v_{\parallel i}}(v_{\parallel i}) + \frac{n_n}{n}(\nu_{iz} + \nu_{cx})(v_{\parallel n} - v_{\parallel i}) \quad (4)$$

$$\frac{\partial T_e}{\partial t} = -\rho_\star^{-1}[\phi,T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4T_e}{3B}\left[\frac{1}{n}C(p_e) + \frac{5}{2}C(T_e) - C(\phi)\right] + \frac{2T_e}{3}\left[\frac{0.71}{n}\nabla_\parallel j_\parallel - \nabla_\parallel v_{\parallel e}\right] \quad (5)$$

$$+ \mathscr{D}_{T_e}(T_e) + \mathscr{D}_{T_e}^{\parallel}(T_e) + S_{T_e} + \frac{n_n}{n}\nu_{iz}\left(-\frac{2}{3}E_{iz} - T_e + \frac{m_e}{m_i}v_{\parallel e}\left(v_{\parallel e} - \frac{4}{3}v_{\parallel n}\right)\right) + \frac{n_n}{n}\nu_{en}\frac{m_e}{m_i}\frac{2}{3}v_{\parallel e}(v_{\parallel n} - v_{\parallel e})$$

$$\frac{\partial T_i}{\partial t} = -\rho_\star^{-1}[\phi,T_i] - v_{\parallel i}\nabla_\parallel T_i + \frac{4T_i}{3B}\left[\frac{1}{n}C(p_e) - \tau\frac{5}{2}C(T_i) - C(\phi)\right] + \frac{2T_i}{3}\left[(v_{\parallel i} - v_{\parallel e})\frac{\nabla_\parallel n}{n} - \nabla_\parallel v_{\parallel e}\right] \quad (6)$$

$$+ \mathscr{D}_{T_i}(T_i) + \mathscr{D}_{T_i}^{\parallel}(T_i) + S_{T_i} + \frac{n_n}{n}(\nu_{iz} + \nu_{cx})\left(T_n - T_i + \frac{1}{3}(v_{\parallel n} - v_{\parallel i})^2\right)$$

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

+ boundary conditions

+ kinetic neutral equation

The density equation

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel (n v_{\parallel e}) + S_n + n_n \nu_{iz} - n\nu_{rec} + \mathscr{D}_{\perp n}(n) \quad (7)$$

- ExB drift
- Curvature terms
- Parallel advection
- Plasma source from core
- Interaction with neutrals
- Perpendicular diffusion

The density equation

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel(n v_{\parallel e}) + S_n + n_n \nu_{iz} - n\nu_{rec} + \mathscr{D}_{\perp n}(n) \quad (7)$$

- ExB drift
- Curvature terms
- Parallel advection
- Plasma source from core
- Interaction with neutrals
- Perpendicular diffusion

The density equation

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}\left[C(p_e) - nC(\phi)\right] - \nabla_\parallel(n v_{\parallel e}) + S_n + n_n \nu_{iz} - n\nu_{rec} + \mathscr{D}_{\perp n}(n) \quad (7)$$

- ExB drift
- Curvature terms
- Parallel advection
- Plasma source from core
- Interaction with neutrals
- Perpendicular diffusion

The density equation

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel(n v_{\parallel e}) + S_n + n_n \nu_{iz} - n\nu_{rec} + \mathscr{D}_{\perp n}(n) \tag{7}$$

- ExB drift
- Curvature terms
- Parallel advection
- Plasma source from core
- Interaction with neutrals
- Perpendicular diffusion

The density equation

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel(n v_{\parallel e}) + S_n + n_n \nu_{iz} - n\nu_{rec} + \mathscr{D}_{\perp n}(n) \quad (7)$$

- ExB drift
- Curvature terms
- Parallel advection
- Plasma source from core
- Interaction with neutrals
- Perpendicular diffusion

The density equation

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel(n v_{\parallel e}) + S_n + n_n \nu_{iz} - n \nu_{rec} + \mathscr{D}_{\perp n}(n) \quad (7)$$

- ExB drift
- Curvature terms
- Parallel advection
- Plasma source from core
- Interaction with neutrals
- Perpendicular diffusion

The density equation

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel(nv_{\parallel e}) + S_n + n_n\nu_{iz} - n\nu_{rec} + \mathscr{D}_{\perp n}(n) \quad (7)$$

- ExB drift
- Curvature terms
- Parallel advection
- Plasma source from core
- Interaction with neutrals
- Perpendicular diffusion

The kinetic model of the neutrals

- One mono-atomic neutral species
- Krook operators for ionization, charge-exchange, and recombination
- C. Wersal and P. Ricci 2015 *Nucl. Fusion* **55** 123014

The neutral model

$$\frac{\partial f_n}{\partial t} + \vec{v} \cdot \frac{\partial f_n}{\partial \vec{x}} = -\nu_{iz} f_n - \nu_{cx}(f_n - n_n \Phi_i) + \nu_{rec} n_i \Phi_i \qquad (8)$$

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

The neutral model

$$\frac{\partial f_n}{\partial t} + \vec{v} \cdot \frac{\partial f_n}{\partial \vec{x}} = -\nu_{iz} f_n - \nu_{cx}(f_n - n_n \Phi_i) + \nu_{rec} n_i \Phi_i \tag{8}$$

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

The neutral model

$$\frac{\partial f_n}{\partial t} + \vec{v} \cdot \frac{\partial f_n}{\partial \vec{x}} = -\nu_{iz} f_n - \nu_{cx}(f_n - n_n \Phi_i) + \nu_{rec} n_i \Phi_i \tag{8}$$

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

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

The neutral model

$$\frac{\partial f_n}{\partial t} + \vec{v} \cdot \frac{\partial f_n}{\partial \vec{x}} = -\nu_{iz} f_n - \nu_{cx}(f_n - n_n \Phi_i) + \nu_{rec} n_i \Phi_i \tag{8}$$

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

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

The neutral model

$$\frac{\partial f_n}{\partial t} + \vec{v} \cdot \frac{\partial f_n}{\partial \vec{x}} = -\nu_{iz} f_n - \nu_{cx}(f_n - n_n \Phi_i) + \nu_{rec} n_i \Phi_i \qquad (8)$$

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

Boundary conditions

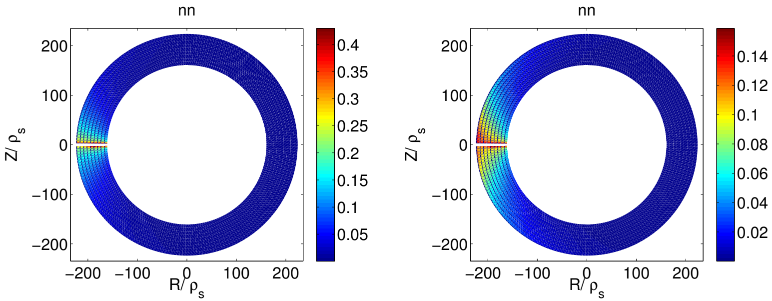
($v_\perp$ in respect to the surface; θ between $\vec{v}$ and normal vector to the surface)

$$\int d\vec{v} \; v_\perp f_n(\vec{x}_w, \vec{v}) + u_{i\perp} n_i = 0 \qquad (9)$$

$$f_n(\vec{x}_w, \vec{v}) \propto cos(\theta) e^{mv^2/2T_w} \quad \text{for} \;\; v_\perp > 0 \qquad (10)$$

Boundary conditions for the neutrals

- Partial reflection at the limiters
- Window averaged particle flux conservation at the outer boundary



- Gas puffs and neutral background

Further simplifications

- Separation of time scales
  - The neutrals' time of life is typically shorter than the turbulent time scale
  - $T_e = 20\text{eV}$, $n_0 = 5 \cdot 10^{13}\text{cm}^{-3}$
    $\rightarrow \tau_{neutral\,losses} \approx \nu_{eff}^{-1} \approx 5 \cdot 10^{-7} s$
    $\rightarrow \tau_{turbulence} \approx \sqrt{R_0 L_p}/c_{s0} \approx 2 \cdot 10^{-6} s$
  - Assume $\partial f_n / \partial t \approx 0$

Further simplifications

- Separation of time scales
  - The neutrals' time of life is typically shorter than the turbulent time scale
  - $T_e = 20\text{eV}$, $n_0 = 5 \cdot 10^{13}\text{cm}^{-3}$
    $\rightarrow \tau_{neutral\,losses} \approx \nu_{eff}^{-1} \approx 5 \cdot 10^{-7} s$
    $\rightarrow \tau_{turbulence} \approx \sqrt{R_0 L_p}/c_{s0} \approx 2 \cdot 10^{-6} s$
  - Assume $\partial f_n / \partial t \approx 0$
- Plasma anitrosopy
  - The plasma elongation along the field lines is much longer than the typical neutral mean free path
  - Assume $\nabla_{\parallel} f_n \approx 0$

Solution of neutral eq. with method of characteristics

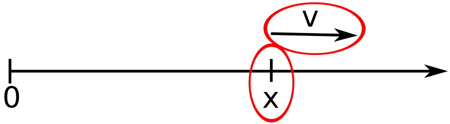
Example in 1D, no recombination, $v > 0$ and a wall at $x = 0$

$$v\frac{\partial f_n}{\partial x} = \nu_{cx} n_n \Phi_i - (\nu_{iz} + \nu_{cx}) f_n \tag{11}$$

Solution of neutral eq. with method of characteristics

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

$$v\frac{\partial f_n}{\partial x} = v_{cx} n_n \Phi_i - (v_{iz} + v_{cx}) f_n \qquad (11)$$



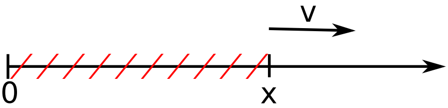
$f_n(x, v)$

(12)

Solution of neutral eq. with method of characteristics

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

$$v \frac{\partial f_n}{\partial x} = \nu_{cx} n_n \Phi_i - (\nu_{iz} + \nu_{cx}) f_n \tag{11}$$

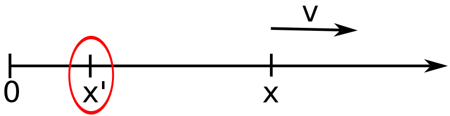


$$f_n(x, v) = \int_0^x dx' \tag{12}$$

Solution of neutral eq. with method of characteristics

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

$$v \frac{\partial f_n}{\partial x} = \nu_{cx} n_n \Phi_i - (\nu_{iz} + \nu_{cx}) f_n \quad (11)$$

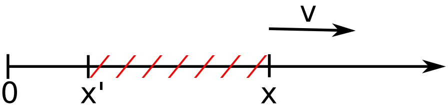


$$f_n(x, v) = \int_0^x dx' \, \frac{\nu_{cx}(x') n_n(x') \Phi_i(x', v)}{v} \quad (12)$$

Solution of neutral eq. with method of characteristics

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

$$v\frac{\partial f_n}{\partial x} = \nu_{cx} n_n \Phi_i - (\nu_{iz} + \nu_{cx}) f_n \tag{11}$$

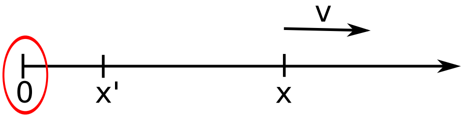


$$f_n(x, v) = \int_0^x dx' \, \frac{\nu_{cx}(x') n_n(x') \Phi_i(x', v)}{v} e^{-\frac{1}{v}\int_{x'}^{x} dx'' \, (\nu_{cx}(x'') + \nu_{iz}(x''))} \tag{12}$$

Solution of neutral eq. with method of characteristics

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

$$v\frac{\partial f_n}{\partial x} = \nu_{cx} n_n \Phi_i - (\nu_{iz} + \nu_{cx}) f_n \tag{11}$$

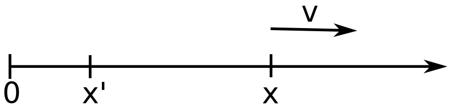


$$f_n(x,v) = \int_0^x dx' \, \frac{\nu_{cx}(x') n_n(x') \Phi_i(x',v)}{v} e^{-\frac{1}{v}\int_{x'}^{x} dx'' \, (\nu_{cx}(x'')+\nu_{iz}(x''))} + f_w(v) e^{-\frac{1}{v}\int_0^x dx'' \, (\nu_{cx}(x'')+\nu_{iz}(x''))} \tag{12}$$

Solution of neutral eq. with method of characteristics

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

$$v\frac{\partial f_n}{\partial x} = \nu_{cx} n_n \Phi_i - (\nu_{iz} + \nu_{cx}) f_n \tag{11}$$



$$f_n(x,v) = \int_0^x dx' \, \frac{\nu_{cx}(x') n_n(x') \Phi_i(x',v)}{v} e^{-\frac{1}{v}\int_{x'}^{x} dx'' \, (\nu_{cx}(x'')+\nu_{iz}(x''))} + f_w(v) e^{-\frac{1}{v}\int_0^x dx'' \, (\nu_{cx}(x'')+\nu_{iz}(x''))} \tag{12}$$

An equation for the density distribution

By imposing

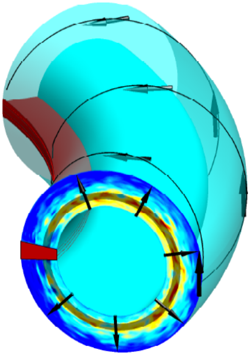
$$\int f_n \, dv = n_n \tag{13}$$

we get a linear integral equation for $n_n(x)$

$$\begin{aligned} n_n(x) = & \int_0^x dx' \; n_n(x') \int_0^\infty dv \; \frac{\nu_{cx}(x')\Phi_i(x',v)}{v} e^{-\frac{d_{eff}\nu_{eff}(x-x')}{v}} \\ & + \textit{contribution by } v < 0 \\ & + n_w(x) \end{aligned} \tag{14}$$

The GBS code, a tool to simulate SOL turbulence

- Evolves scalar fields in 3D geometry $n, \Omega, v_{\parallel e}, v_{\parallel,i}, T_e, T_i$
- Kinetic neutral physics
- Limiter geometry
- Open and closed field-line region
- Sources S_n and S_T mimic plasma outflow from the core
- (Divertor geometry)



Questions that we can address

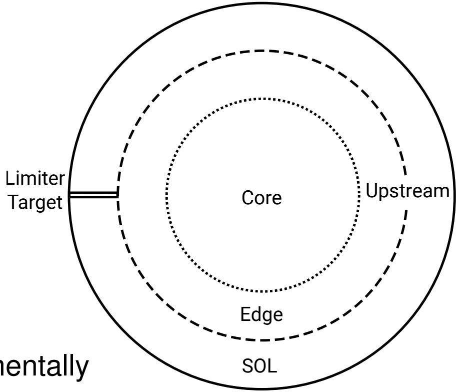
- How is the temperature at the limiter related to main plasma parameters?
- How is the plasma fueled?
- How do neutrals affect plasma turbulence?
  SOL width? Heat flux?
- How do diagnostic gas puffs affect the SOL?

Questions that we can address

- How is the temperature at the limiter related to main plasma parameters?
- How is the plasma fueled?
- How do neutrals affect plasma turbulence?
  SOL width? Heat flux?
- How do diagnostic gas puffs affect the SOL?

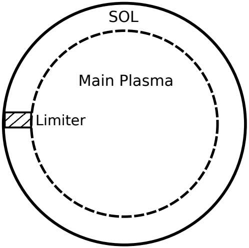
1. Modeling the periphery
2. A refined two-point model with neutrals
3. Gas puff fueling simulations

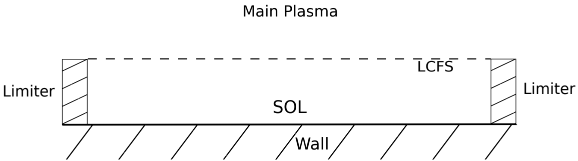
The two-point model



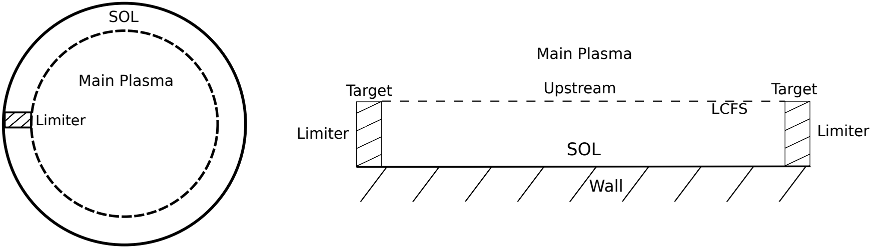
- Relation between upstream and target plasma properties
- Widely used experimentally for a quick estimate
- Derived from 1D model along field lines

The SOL unrolled

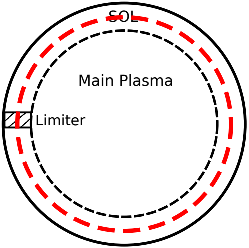


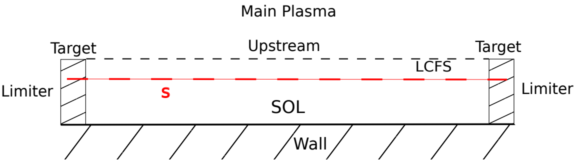


The SOL unrolled



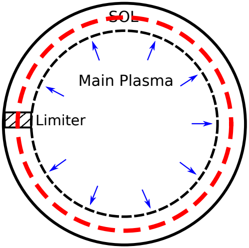
The SOL unrolled

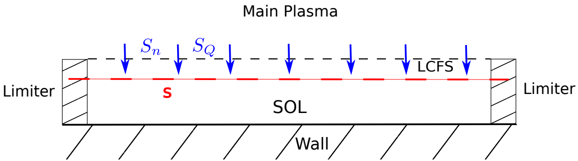




- Parallel plasma dynamics projected along poloidal coordinate

The SOL unrolled





- Parallel plasma dynamics projected along poloidal coordinate
- Plasma and energy outflowing from the core are modeled with prescribed S_n and S_Q

The basic two-point model

$$Q = \int S_Q ds = Q_{cond} + Q_{conv} \qquad (15)$$

The basic two-point model

$$Q = \int S_Q ds = Q_{cond} + Q_{conv} \qquad (15)$$

$$Q_{cond} = -\chi_{e0} T_e^{5/2} \frac{dT_e}{dz} \qquad (16)$$

The basic two-point model

$$Q = \int S_Q ds = Q_{cond} + Q_{conv} \quad (15)$$

$$Q_{cond} = -\chi_{e0} T_e^{5/2} \frac{dT_e}{dz} \quad (16)$$

$$Q_{conv} = c_{e0} \Gamma T_e \quad (17)$$

$$\Gamma = n v_{\parallel} = \int S_n ds \quad (18)$$

The basic two-point model

$$Q = \int S_Q ds = Q_{cond} + Q_{conv} \quad (15)$$

$$Q_{cond} = -\chi_{e0} T_e^{5/2} \frac{dT_e}{dz} \quad (16)$$

$$Q_{conv} = c_{e0} \Gamma T_e \quad (17)$$

$$\Gamma = n v_{\parallel} = \int S_n ds \quad (18)$$

Boundary conditions

- Upstream: $dT_e / ds = 0$
- At the limiter: $Q_L = \gamma_e \Gamma_L T_{eL}$, $\gamma_e \approx 5$

The basic two-point model

$$Q = \int S_Q ds = Q_{cond} + Q_{conv} \quad (15)$$

$$Q_{cond} = -\chi_{e0} T_e^{5/2} \frac{dT_e}{dz} \quad (16)$$

$$Q_{conv} = c_{e0} \Gamma T_e \quad (17)$$

$$\Gamma = n v_{\parallel} = \int S_n ds \quad (18)$$

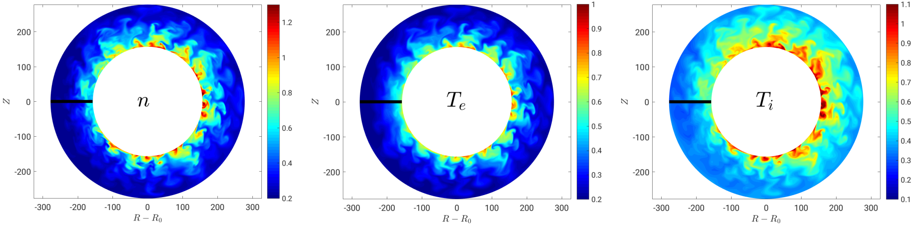
$$S_Q, S_n \Downarrow \frac{T_{e,u}}{T_{e,t}}$$

Boundary conditions

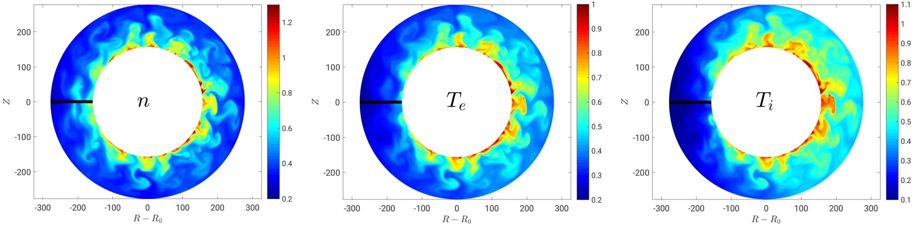
- Upstream: $dT_e/ds = 0$
- At the limiter: $Q_L = \gamma_e \Gamma_L T_{eL}$, $\gamma_e \approx 5$

Simulations with different densities

$n_0 = 5 \cdot 10^{12} \mathrm{cm}^{-3}$

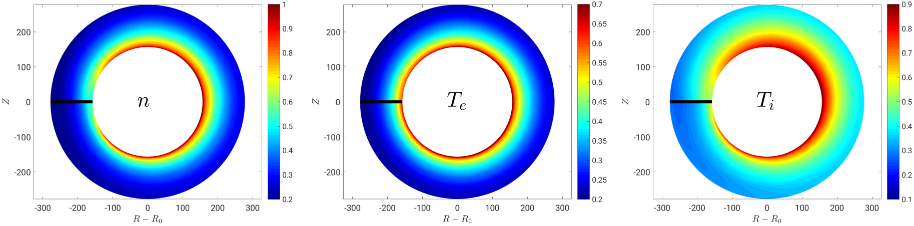


$n_0 = 5 \cdot 10^{13} \mathrm{cm}^{-3}$

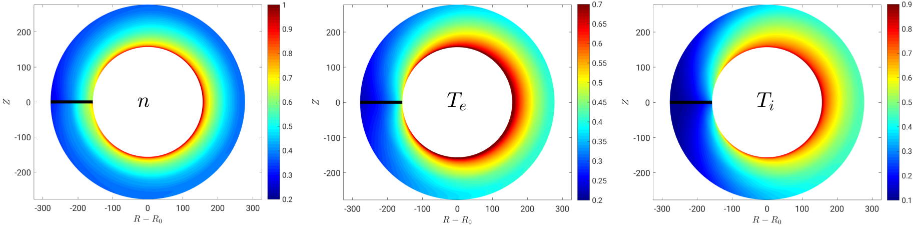


Simulations with different densities

$n_0 = 5 \cdot 10^{12} \mathrm{cm}^{-3}$

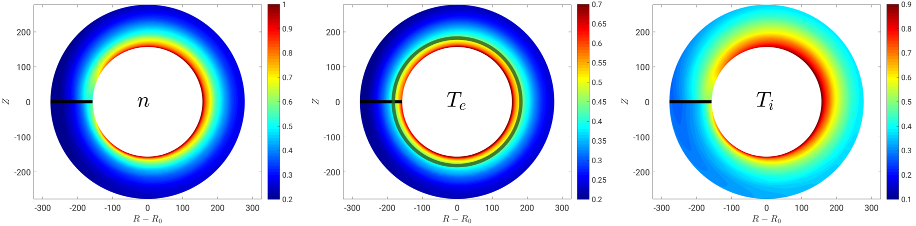


$n_0 = 5 \cdot 10^{13} \mathrm{cm}^{-3}$

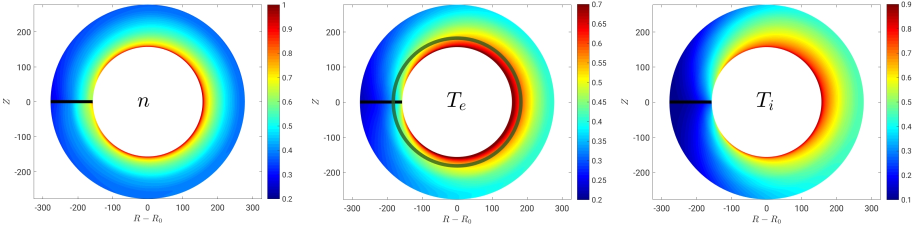


Simulations with different densities

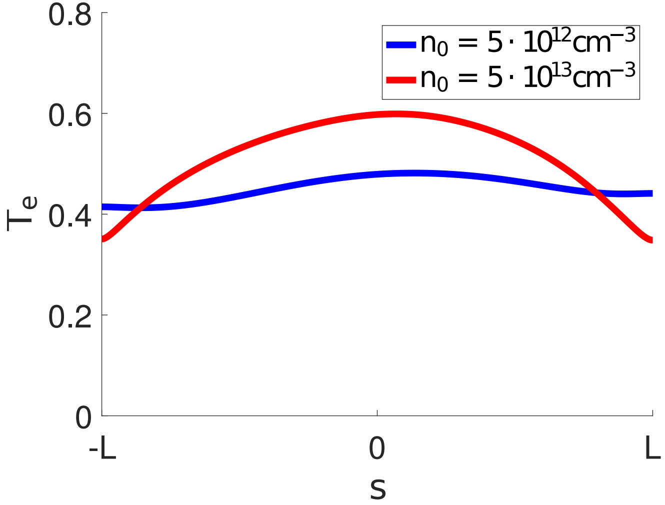
$n_0 = 5 \cdot 10^{12} \mathrm{cm}^{-3}$



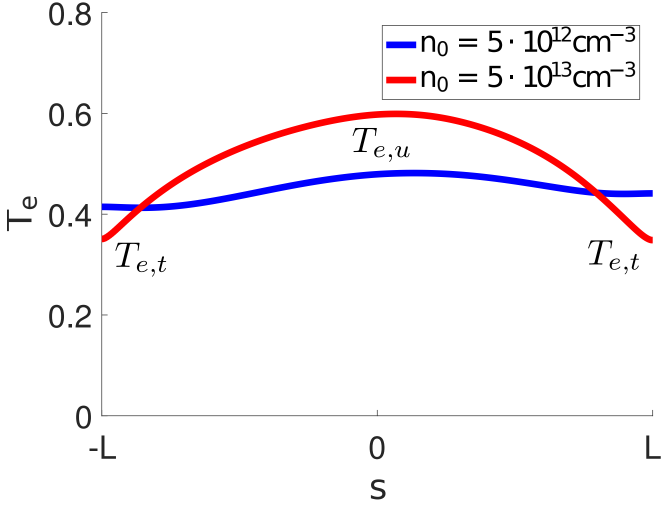
$n_0 = 5 \cdot 10^{13} \mathrm{cm}^{-3}$



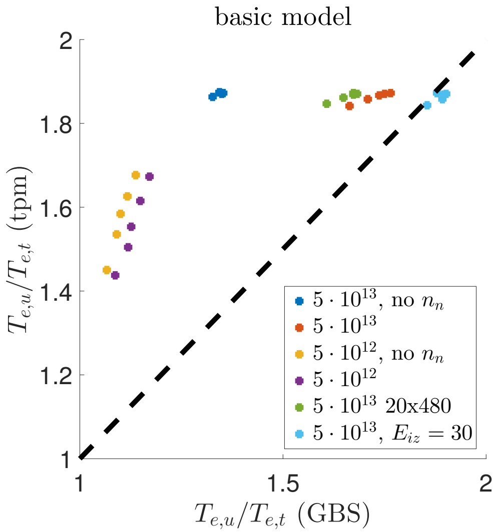
Poloidal profiles of electron temperature



Poloidal profiles of electron temperature



Temperature ratio upstream to target



A more refined two-point model

- Obtain an electron heat equation in quasi-steady state

$$\frac{3}{2} T_e \frac{\partial n}{\partial t} + \frac{3}{2} n \frac{\partial T_e}{\partial t} \approx 0 \qquad (19)$$

- Assume $v_{e,\parallel} \approx v_{i,\parallel}$ and neglect small terms (e.g., $\mathscr{D}_{\perp T_e}$)
- Combine perpendicular transport terms into S_Q

$$\nabla_\parallel \left(\frac{5}{2} n v_\parallel T_e \right) - \chi_{e0} \nabla_\parallel \left(T_e^{5/2} \nabla_\parallel T_e \right) - v_\parallel \nabla_\parallel (n T_e) = \langle S_Q \rangle + S_{\mathrm{neutrals}} \qquad (20)$$

with $S_{\mathrm{neutrals}} = -n_n v_{iz}(T_e) E_{iz}$ and $\chi_{e0} = 3/2 \bar{n} \kappa_{e\parallel}$

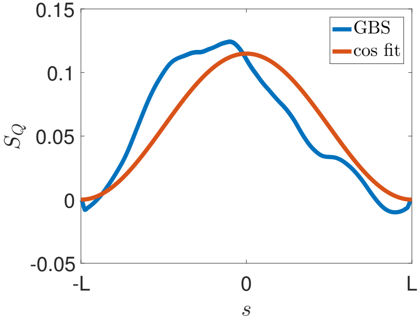
Further assumptions and relations

- $v_{\parallel}$ is linear from $-c_s$ to c_s
- $c_s = \sqrt{T_{e,t} + T_{i,t}} \approx \sqrt{2T_{e,t}}$
- $nv_{\parallel} = \int [S_n + n_n \nu_{iz}(T_e)]\, ds$
- n_n is decaying exponentially from limiter with λ_{mfp}

Three external input quantities

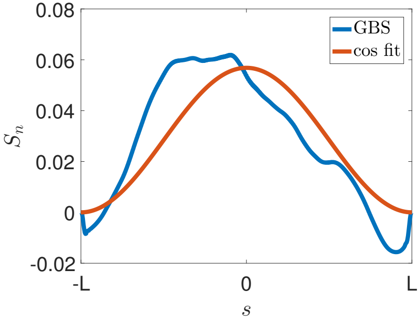
Three external input quantities

- Perpendicular heat source, S_Q



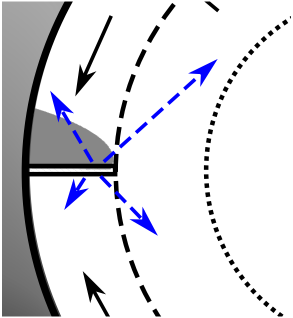
Three external input quantities

- Perpendicular heat source, S_Q
- Perpendicular particle source, S_n



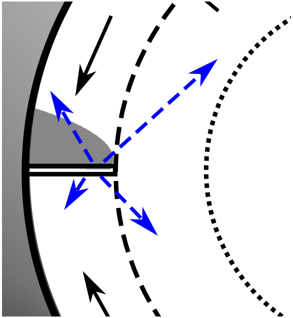
Three external input quantities

- Perpendicular heat source, S_Q
- Perpendicular particle source, S_n
- Ionization particle source, S_{iz}



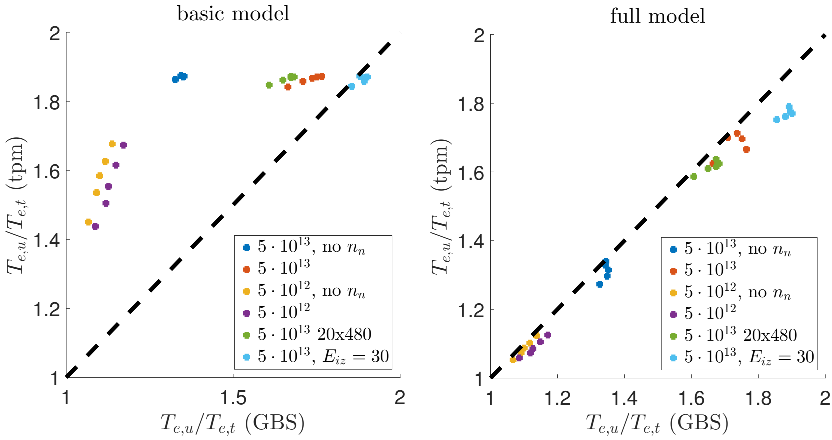
Three external input quantities

- Perpendicular heat source, S_Q
- Perpendicular particle source, S_n
- Ionization particle source, S_{iz}



$$S_Q, S_n, S_{iz}$$
$$\Downarrow$$
$$\frac{T_{e,u}}{T_{e,t}}$$

Temperature ratio upstream to target



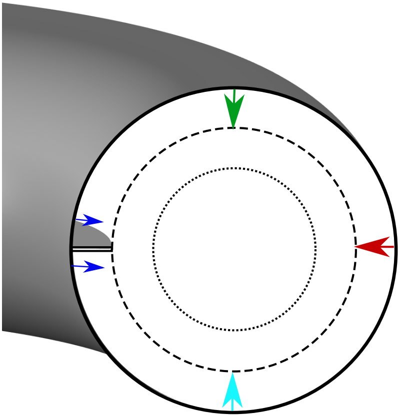
Questions that we can address

- How is the temperature at the limiter related to main plasma parameters?
- How is the plasma fueled?
- How do neutrals affect plasma turbulence?
  SOL width? Heat flux?
- How do diagnostic gas puffs affect the SOL?

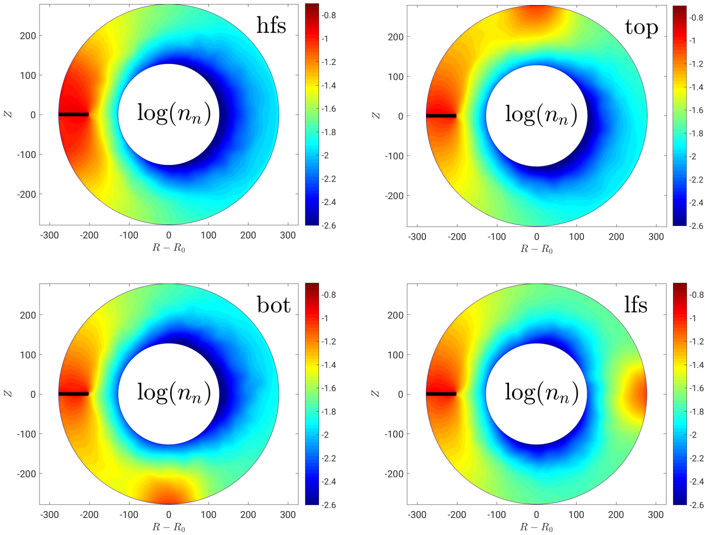
1. Modeling the periphery
2. A refined two-point model with neutrals
3. Gas puff fueling simulations

Gas puff/fueling simulations

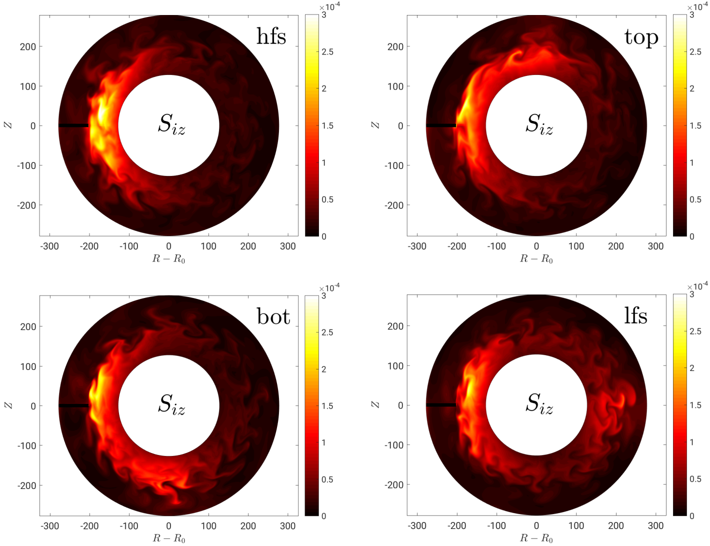
- Open and closed field lines
- Various gas puff locations (hfs, bot, lfs, top)
- Small constant main wall recycling
- $n_0 = 10^{13}\mathrm{cm}^{-3}$, $T_0 = 20\mathrm{eV}$, $q = 3.87$, $\rho_\star^{-1} = 500$, $a_0 = 200\rho_s$



Neutral density

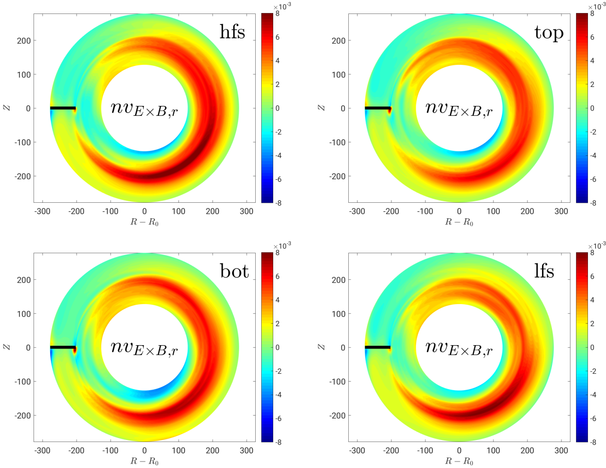


Ionization


hfs
top
bot
lfs
S_{iz}
Z
$R - R_0$
$\times 10^{-4}$
3
2.5
2
1.5
1
0.5
0
200
100
0
-100
-200
-300
-200
-100
0
100
200
300

Radial ExB flow

- outward/inward flow
- Ballooning outward transport at the low field side
- Inward fueling at the high field side
- Robust feature independent of gas puff location

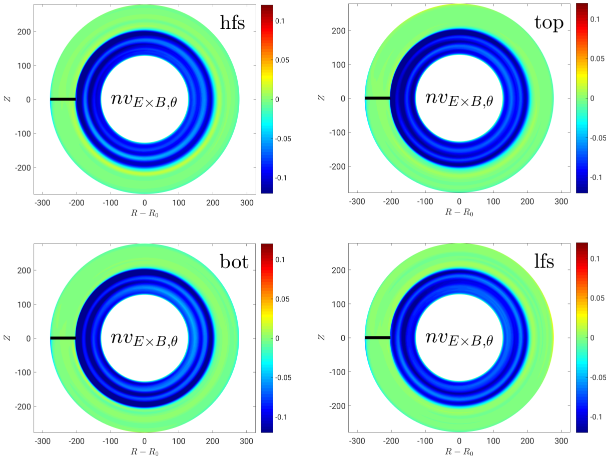


Questions that we can address

- How is the temperature at the limiter related to main plasma parameters?
- How is the plasma fueled?
- How do neutrals affect plasma turbulence?
  SOL width? Heat flux?
- How do diagnostic gas puffs affect the SOL?

Poloidal ExB flow

- Poloidal rotation due to radial electric field
- Shearing of the turbulent eddies



Conclusions

- Plasma turbulence at the periphery and interaction with neutrals are crucial issues on the way to fusion electricity
- GBS is now able to simulate this complex interplay self-consistently
- Development of a more refined two-point model, in agreement with GBS
- Initial study of plasma fueling due to ionization and radial flows, and of plasma poloidal rotation.

Reaction rates - Stangeby

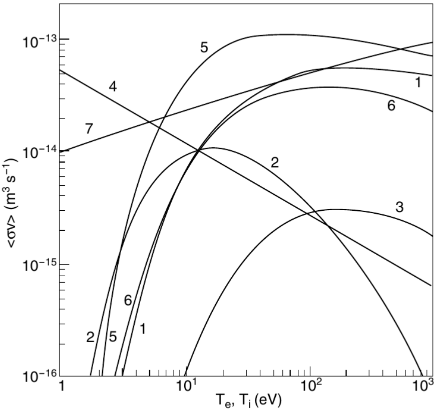
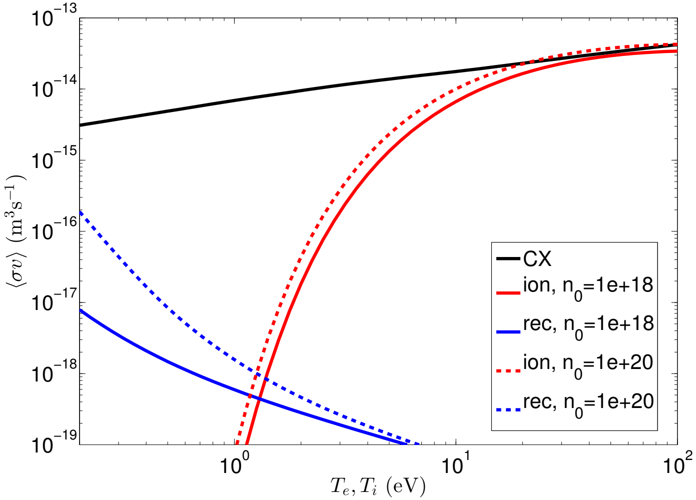


Figure 1.25. The rate coefficients for atomic and molecular hydrogen [1.23]. The numbered reactions are (1): $e + H_2 \rightarrow H_2^+ + 2e$, (2): $e + H_2 \rightarrow 2H^0 + e$, (3): $e + H_2 \rightarrow H^0 + H^+ + 2e$, (4): $e + H_2^+ \rightarrow 2H^0$, (5): $e + H_2^+ \rightarrow H^0 + H^+ + e$, (6): $e + H^0 \rightarrow H^+ + 2e$, and charge exchange (7): $H^0 + H^+ \rightarrow H^+ + H^0$.

Reaction rates - openADAS



Timescales

T_0(eV)	n_0(m^{-3})	$\tau_{turbulence}$(s)	τ_{nnloss}(s)	λ_{mfp}(m)
1	1e+17	1.0e-05	1.4e-03	2.5e+00
1	1e+18	1.0e-05	1.4e-04	2.5e-01
1	1e+19	1.0e-05	1.4e-05	2.5e-02
1	1e+20	1.0e-05	1.4e-06	2.5e-03
1	1e+21	1.0e-05	1.4e-07	2.5e-04
20	1e+17	2.3e-06	2.6e-04	4.4e-01
20	1e+18	2.3e-06	2.5e-05	4.3e-02
20	1e+19	2.3e-06	2.4e-06	4.1e-03
20	1e+20	2.3e-06	2.2e-07	3.7e-04
20	1e+21	2.3e-06	1.8e-08	3.1e-05
50	1e+17	1.4e-06	1.6e-04	2.8e-01
50	1e+18	1.4e-06	1.6e-05	2.7e-02
50	1e+19	1.4e-06	1.5e-06	2.6e-03
50	1e+20	1.4e-06	1.4e-07	2.4e-04
50	1e+21	1.4e-06	1.2e-08	2.0e-05

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. $T_e = 20\text{eV}$, $n_0 = 5 \cdot 10^{19}\text{m}^{-3}$

$$\tau_{neutral\,losses} \approx \nu_{eff}^{-1} \approx 5 \cdot 10^{-7} s$$

$$\tau_{turbulence} \approx \sqrt{R_0 L_p}/c_{s0} \approx 2 \cdot 10^{-6} s$$

- Otherwise: time dependent model