EUROfusion

Introduction of the GBS plasma and neutrals multispecies model

D. Mancini

EPFL

- Swiss Plasma Center

Università degli Studi della Tuscia

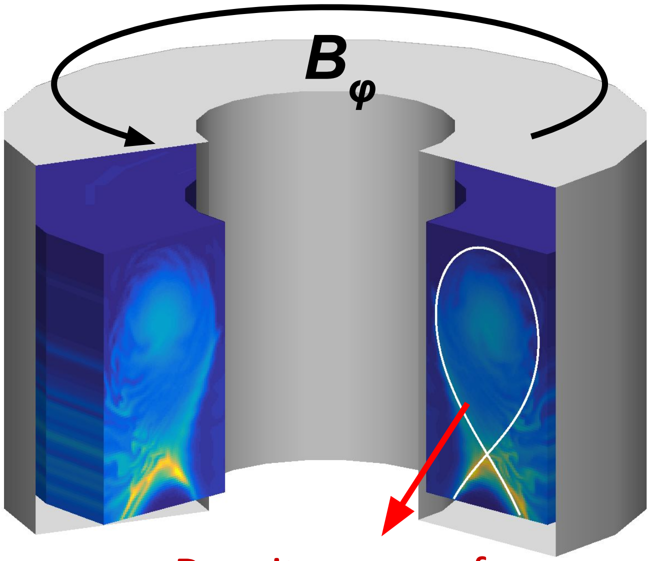
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The GBS code

The GBS code *[M. Giacomin et al 2021, JCP submitted]* is based on the drift-reduced Braginskii equations

- Magnetic pre-sheath boundary conditions
- Heating and fuelling modelled self consistently by <u>coupling with kinetic neutral model</u>

- TCV-like geometry with rectangular poloidal cross section
- Full-device modelling (core + edge + SOL)
- Arbitrary magnetic field



Plasma model and neutrals coupling

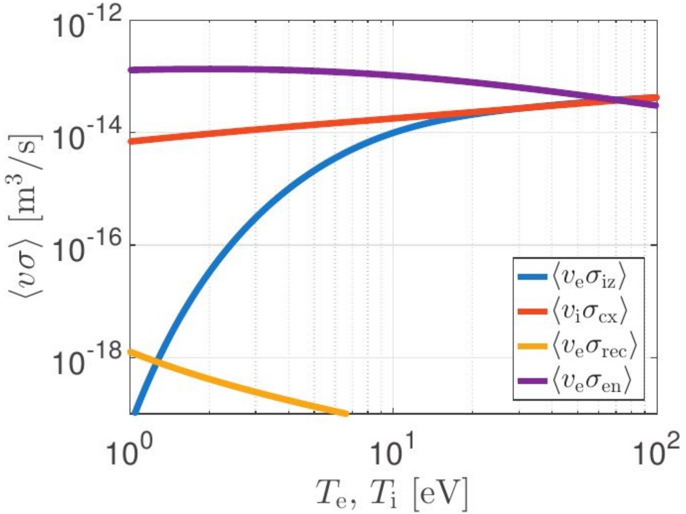
Plasma described by Braginskii drift-reduced equations:

$$\frac{\partial n}{\partial t} = -\frac{1}{B}[\phi, n] + \frac{2}{eB}\left[C(p_e) - enC(\phi)\right] - \nabla_\parallel (n v_{\parallel e}) + \nu_{\rm iz} n_{\rm n} - \nu_{\rm rec} n$$

ExB Convection | Compressibility due to curvature | Parallel flow | Neutrals interaction term

Similar equations for $T_e, T_i, v_{\parallel e}, v_{\parallel i}, \nabla^2\phi$

Reaction rates taken as functions of T_e, T_i, n



[M. Giacomin et al 2021, JCP submitted]

Kinetic mono atomic neutral species

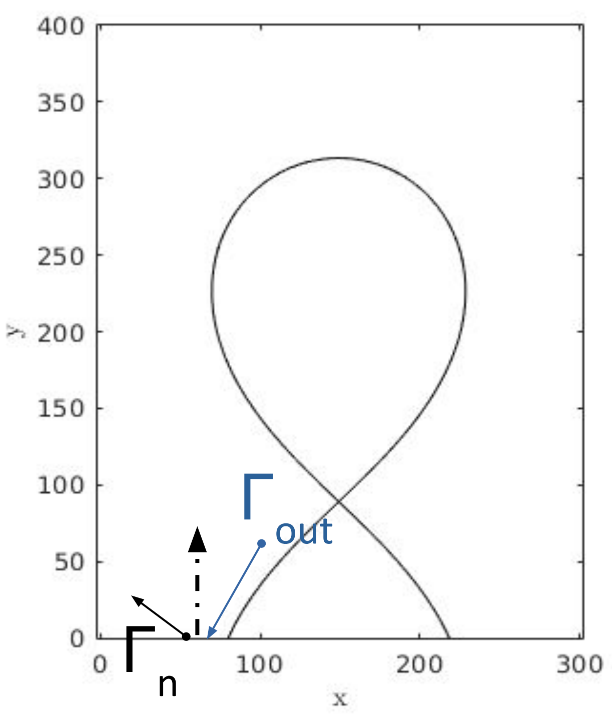
$$\frac{\partial f_n}{\partial t} + \mathbf{v} \cdot \frac{\partial f_n}{\partial \mathbf{x}} = -\nu_{iz} f_n - \nu_{cx}\left(f_n - \frac{n_n}{n_i} f_i\right) + \nu_{rec} f_n$$

with:

- Ionization $\nu_{\rm iz} = n_e \langle v_e \sigma_{\rm iz} \rangle_{v_e}$
- Charge exchange $\nu_{\rm cx} = n_i \langle v_i \sigma_{\rm cx} \rangle_{v_i}$
- Recombination $\nu_{\rm rec} = n_e \langle v_e \sigma_{\rm rec} \rangle_{v_e}$
- e-n collisions $\nu_{\rm en} = n_e \langle v_e \sigma_{\rm en} \rangle_{v_e}$

Boundary conditions : emission or reflection, one neutral for each particle, ion or neutral, impacting the wall

Ion out flux to wall include **parallel** and **drift velocity**



Two limits, valid in typical SOL conditions:

- Neutral adiabatic regime $\tau_n < \tau_{\rm turb}$
- Neutral lengths smaller than parallel lengths $\lambda_{{\rm mfp},n} << 1/k_\parallel$

A statistical noise free approach to the neutral model

Integral equation for the neutral distribution function:

$$f_n(\mathbf{x},\mathbf{v},t) = \int_0^{r_b'} \left[\frac{S(\mathbf{x}',\mathbf{v},t')}{v} + \delta(r - r_b') f_n(\mathbf{x}',\mathbf{v},t')\right] \exp\left(-\frac{1}{v}\int_0^{r'} \nu_{\mathrm{eff}}(\mathbf{x}'',t'')dr''\right) dr'$$

Integrate in velocity space and obtain discrete matrix system for neutral density:

$$\begin{bmatrix} n_{\mathrm{n}} \\ \Gamma_{\mathrm{out,n}} \end{bmatrix} = \begin{bmatrix} \nu_{\mathrm{cx}} K_{p\to p} & (1-\alpha_{\mathrm{refl}}) K_{b\to p} \\ \nu_{\mathrm{cx}} K_{p\to b} & (1-\alpha_{\mathrm{refl}}) K_{b\to b} \end{bmatrix} \begin{bmatrix} n_{\mathrm{n}} \\ \Gamma_{\mathrm{out,n}} \end{bmatrix} + \begin{bmatrix} n_{n,\mathrm{rec}} + n_{\mathrm{n[out,i]}} \\ \Gamma_{\mathrm{out,rec}} + \Gamma_{\mathrm{out,n[out,i]}} \end{bmatrix}$$

where kernels ***K*** includes contribute from reflection on walls

Solve and evaluate higher moments: $\Gamma_{n,\perp}$, $\Gamma_{n,//}$, T_n

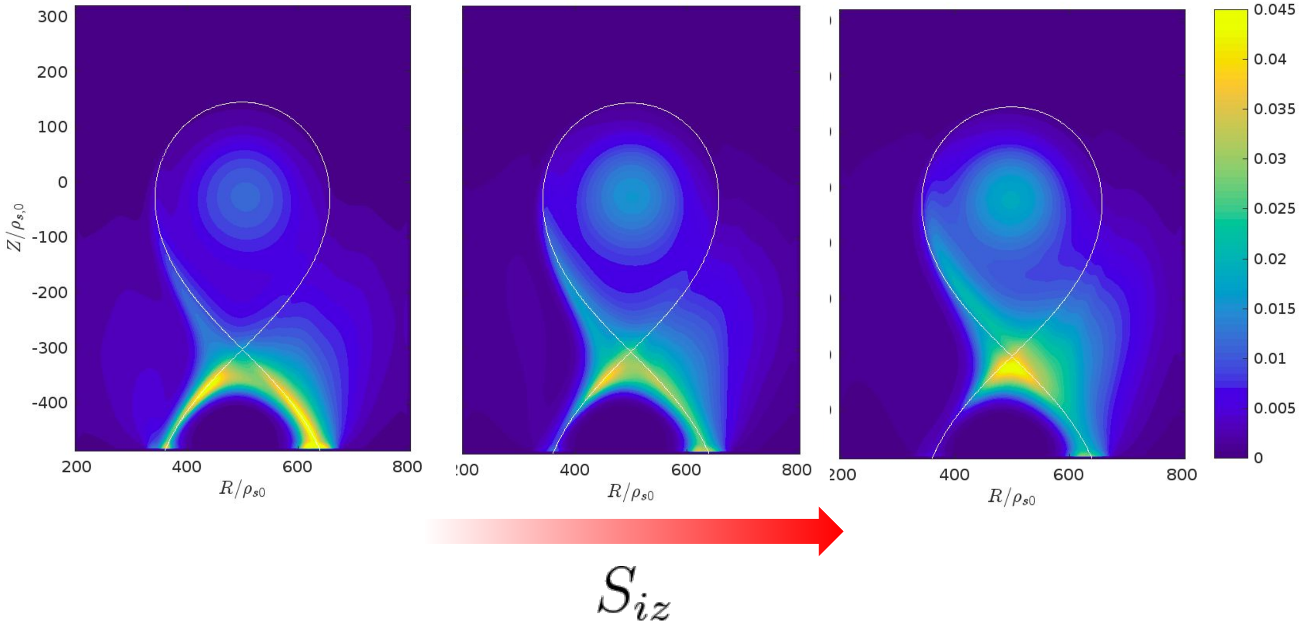
[C. Wersal and P. Ricci 2015 Nucl. Fusion]

First diverted turbulence simulations with neutrals

3 sim with increasing neutrals effects (same SOL input power):

- Higher ionization source in core
- Lower temperature and higher resistivity $\nu \propto T_e^{-3/2}$

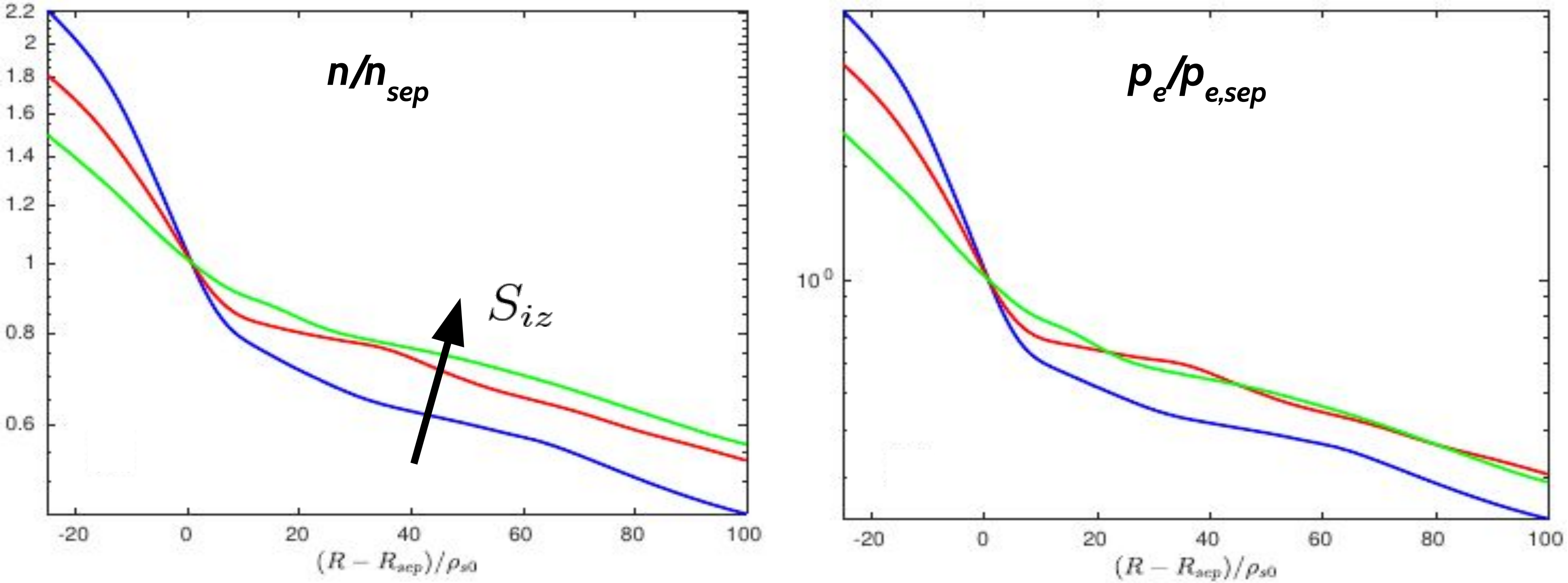
- Radius ~ 1/3 TCV
- Lower single null
- T_e source in core
- Recycling on bottom
- No recombination in volume



Density shoulder formation and neutrals contribute

With higher density source (and resistivity):

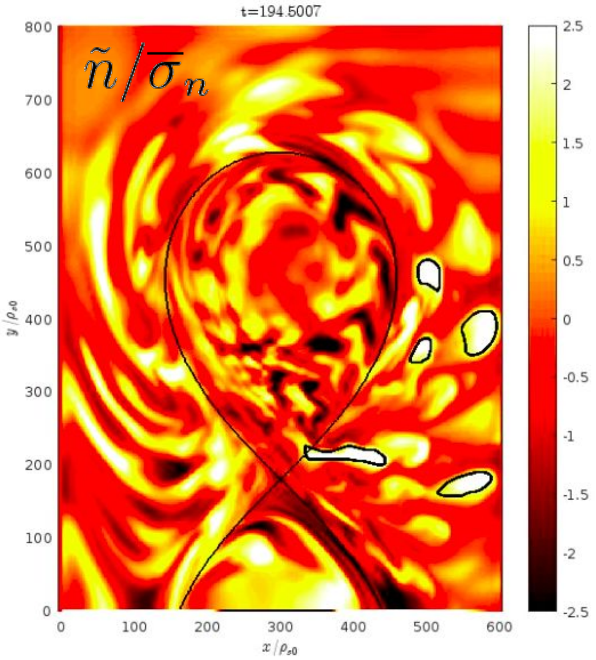
- Increasing near SOL e-folding lengths
- Increasing far SOL density and pressure



Analysis of the roles of: perpendicular flux, parallel flux, ionization source

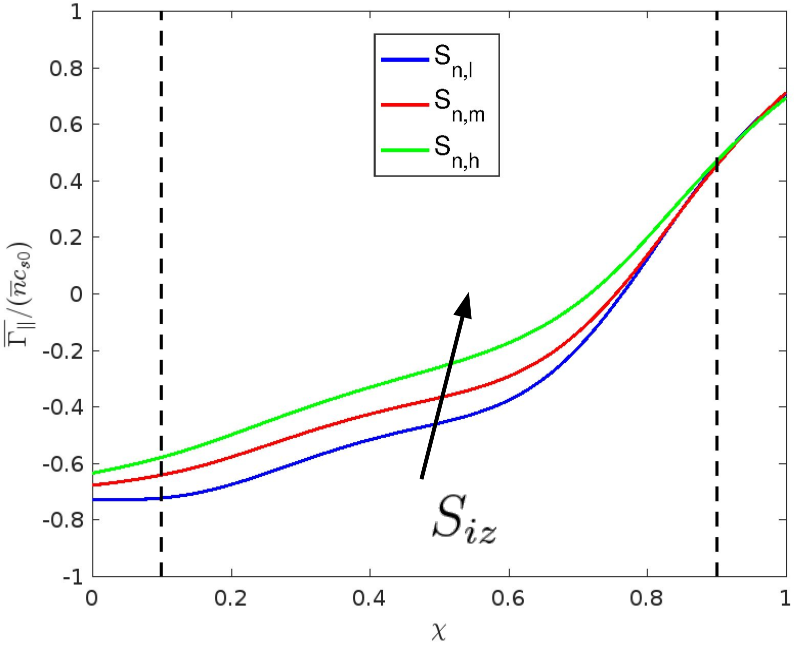
Higher density due to lower parallel transport

$$\overline{\Gamma}_{\perp} \simeq \overline{\Gamma}_{E\times B} \simeq \overline{\tilde{n}\partial_{\chi}\tilde{\phi}}$$



Detailed analysis of blobs:
constant perpendicular transport

$$\overline{\Gamma}_{\parallel} \simeq \overline{n}\,\overline{v}_{\parallel}$$



With higher density source:
Lower T_e along flux line → Decrease in $\Gamma_{//}/\Gamma_{\perp}$
→ <u>increase in far SOL density</u>

[D. Mancini et al 2021, Nucl. Fusion]

New plasma model: molecular species

Plasma described by density, velocity and temperatures of electrons, atomic ions and molecular ions :

$$\frac{\partial n_e}{\partial t} = -\frac{1}{B}[\phi, n_e] + \frac{2}{eB}[C(p_e) - enC(\phi)] - \nabla_{\parallel}(n_e v_{\parallel e}) + \nu_{\text{iz},D} n_D - \nu_{\text{rec},D^+} n_{D^+}$$
$$+\nu_{\text{iz},D_2} n_{D_2} - \nu_{\text{rec},D_2^+} n_{D_2^+} + \nu_{\text{diss-iz},D_2} n_{D_2} + \nu_{\text{diss-iz},D_2^+} n_{D_2^+} - \nu_{\text{diss-rec},D_2^+} n_{D_2^+}$$

$$\frac{\partial n_{D_2^+}}{\partial t} = -\frac{1}{B}[\phi, n_{D_2^+}] + \frac{2}{eB}[C(p_{D_2^+}) - en_{D_2^+} C(\phi)] - \nabla_{\parallel}(n_{D_2^+} v_{\parallel, D_2^+}) + \nu_{\text{iz},D_2} n_{D_2} - \nu_{\text{rec},D_2^+} n_{D_2^+}$$
$$+\nu_{\text{cx},D_2-D^+} n_{D_2} + n_D \nu_{\text{cx},D-D^+} + n_{D_2^+}(\nu_{\text{diss-iz},D_2^+} + \nu_{\text{diss},D_2^+} + \nu_{\text{diss-rec},D_2^+})$$

\+ quasi neutrality: $n_{D^+} = n_e - n_{D_2^+}$

- Zdhanov closure
- Low molecules density $n_{D_2^+} << n_{D^+}$
- Magnetic boundary conditions

[A. Coroado et al 2021, Nuclear Fusion, accepted manuscript]

Neutral species kinetic equations

Atomic and molecular neutrals considered:

$$\frac{\partial f_D}{\partial t}+\mathbf{v}\cdot\frac{\partial f_D}{\partial \mathbf{x}} = -\nu_{\text{iz},D} f_D - \nu_{\text{cx},D}\left(f_D - \frac{n_D}{n_{D^+}} f_{D^+}\right) + \nu_{\text{rec},D^+} f_D^+ + \nu_{\text{cx},D_2-D^+}\left(\frac{n_{D_2}}{n_{D^+}} f_{D^+}\right) - \nu_{\text{cx},D-D_2^+} f_D$$
$$+ f_{D_2}(2\nu_{\text{diss},D_2} + \nu_{\text{diss-iz},D_2}) + f_{D_2^+}(2\nu_{\text{diss-rec},D_2^+} + \nu_{\text{diss},D_2^+})$$

$$\frac{\partial f_{D_2}}{\partial t} + \mathbf{v}\cdot\frac{\partial f_{D_2}}{\partial \mathbf{x}} = -\nu_{\text{iz},D_2} f_{D_2} - \nu_{\text{cx},D_2}\left(f_{D_2} - \frac{n_{D_2}}{n_{D_2^+}} f_{D_2^+}\right) + \nu_{\text{rec},D_2^+} f_{D_2^+} + \nu_{\text{cx},D-D_2^+}\left(\frac{n_D}{n_{D_2^+}} f_{D_2^+}\right)$$
$$- \nu_{\text{cx},D_2-D^+} f_{D_2} - f_{D_2}(\nu_{\text{diss},D_2} - \nu_{\text{diss-iz},D_2})$$

Boundary conditions : emission or reflection for each particle impacting the wall, or association of atomic ions and neutrals in molecular neutrals

Same limits, valid in typical SOL conditions:

- Neutral adiabatic regime $\tau_n < \tau_{\text{turb}}$
- Neutral lengths smaller than parallel lengths $\lambda_{\text{mfp},n} << 1/k_{\|}$

Densities evaluated solving one linear system

Two coupled integral equations solved as a linear system:

$$
\begin{pmatrix} n_D \\ \Gamma_{\text{out},D} \\ n_{D_2} \\ \Gamma_{\text{out},D_2} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & 0 \\ M_{21} & M_{22} & M_{23} & 0 \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{pmatrix} n_D \\ \Gamma_{\text{out},D} \\ n_{D_2} \\ \Gamma_{\text{out},D_2} \end{pmatrix} + \begin{pmatrix} n_D^{\text{rec},D^+} + n_D^{\text{diss},D_2^+} \\ \Gamma_D^{\text{rec},D^+} + \Gamma_{\text{out},D}^{D^+} \Gamma_D^{\text{refl},D^+} \\ n_{D_2}^{\text{rec},D^+} \\ \Gamma_{D_2}^{\text{rec},D_2^+} + \Gamma_{D_2}^{\text{refl},D_2^+} \Gamma_{D_2}^{\text{refl},D^+} \end{pmatrix}
$$

- sub-matrices **M** include the different kernel functions **K**, considering also reflection and association on walls
- Known terms comes from recombination, reflection or dissociation of ions

<u>Possibility to extend the model to include any kind of species</u>

[A. Coroado et al 2021, Nuclear Fusion, accepted manuscript]

Densities evaluated solving one linear system

Two coupled integral equations solved as a linear system:

Old atomic neutrals matrix

$$\begin{pmatrix} n_D \\ \Gamma_{out,D} \\ n_{D_2} \\ \Gamma_{out,D} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & 0 \\ M_{21} & M_{22} & M_{23} & 0 \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{pmatrix} n_D \\ \Gamma_{out,D} \\ n_{D_2} \\ \Gamma_{out,D} \end{pmatrix} + \begin{pmatrix} n_D^{rec,D^+} + n_D^{diss,D_2^+} \\ \Gamma_D^{rec,D^+} + \Gamma_{out,D}^{D^+} \Gamma_D^{refl,D^+} \\ n_{D_2}^{rec,D^+} \\ \Gamma_{D_2}^{rec,D_2^+} + \Gamma_{D_2}^{refl,D_2^+} \Gamma_{D_2}^{refl,D^+} \end{pmatrix}$$

- sub-matrices **M** include the different kernel functions **K**, considering also reflection and association on walls
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<u>Possibility to extend the model to include any kind of species</u>

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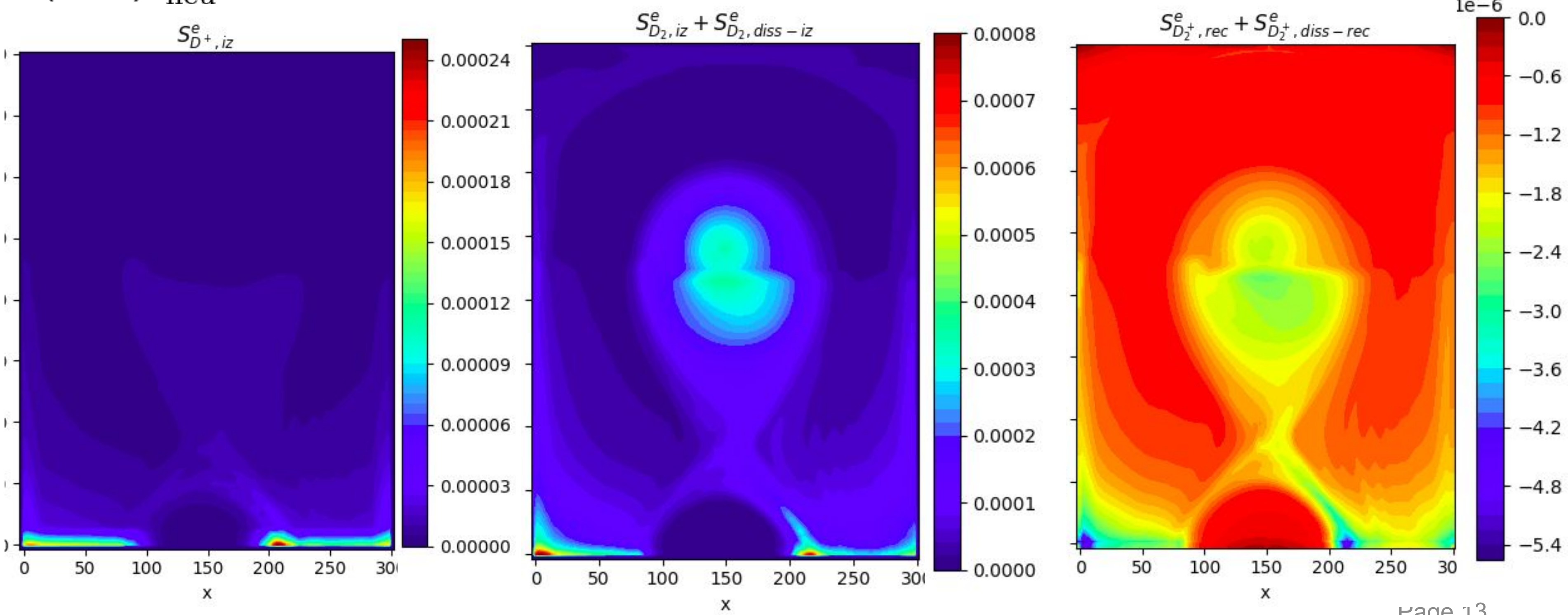
Test simulation with multispecies model

Small, lower single null configuration, as testbed:

$$\left(\frac{\partial n_e}{\partial t}\right)_{\text{neu}} = n_D \nu_{\text{iz},D} + n_{D_2}(\nu_{\text{diss},D_2} + \nu_{\text{iz},D_2}) - n_{D_2^+}(\nu_{\text{rec},D_2^+} + \nu_{\text{diss-rec},D_2^+})$$



Summary

- A neutral model coupled with the GBS plasma model is implemented
- The monoatomic neutral model is tested and used to investigate the role of neutrals in the shoulder formation, giving insights on the phenomenon

- A new framework for multispecies plasma and neutral is introduced:
  - Plasma model developed with Zdhanov closure and extended magnetic boundary conditions
  - Neutrals model developed with multiple neutral distribution functions and equations solved in a bigger linear system
- The framework is tested in a simulation with molecular and atomic ions and neutrals