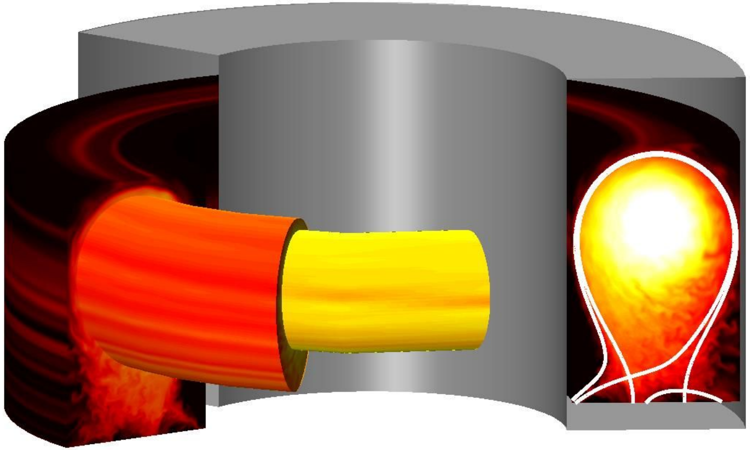

Self-consistent simulations of plasma turbulence and neutral dynamics in detachment regime

D. Mancini, P. Ricci and N. Vianello

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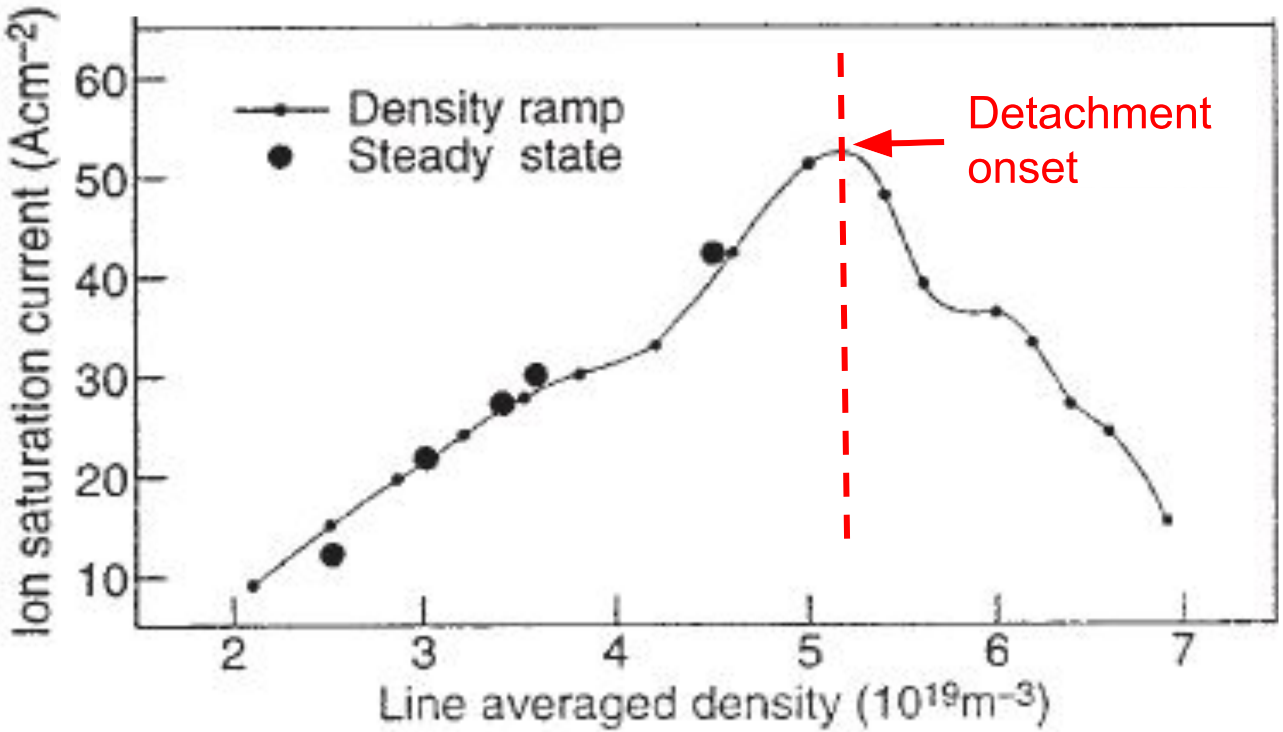
High density operation helps reducing divertor heat flux

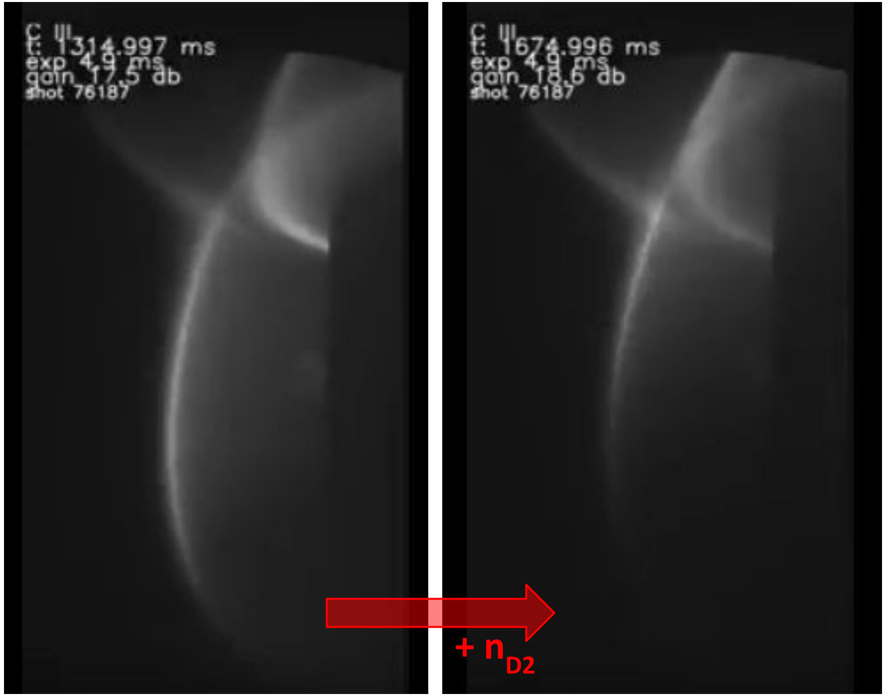


Detachment onset

[P.A. Loarte et al 1998 Nucl. Fus. 38]

Low target temperature in detachment conditions

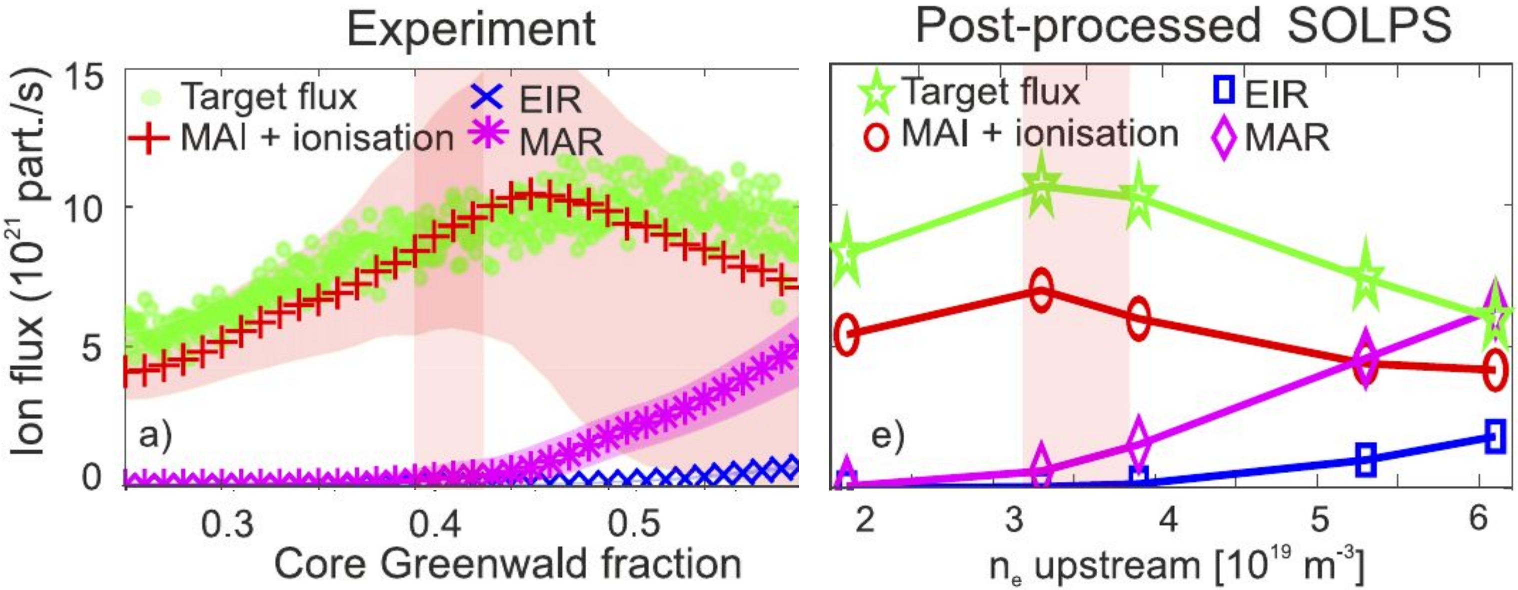
Low target temperature: volumetric recombination and ionization front away from the target



From a TCV discharge for WPTE RT22-05 campaign, proposal by D. Mancini et al

Role of molecular activated recombination in detachment

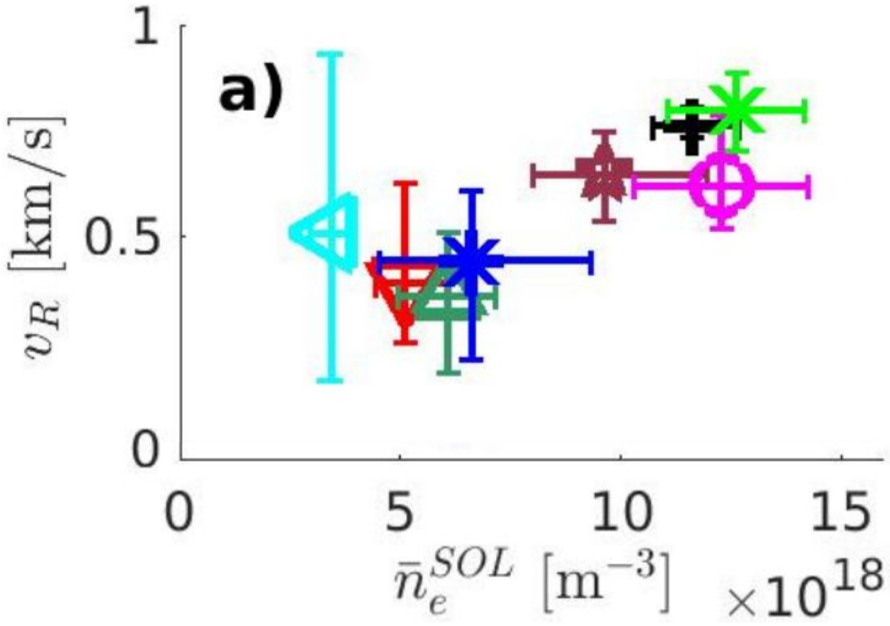
Experiments and SOLPS simulations show molecular activated recombination (MAR) in detachment conditions



[K. Verhaegh et al 2021 Nucl. Fusion 61]

Density increase affects turbulence properties

Increased density yields faster and larger filaments



[N. Offeddu et al 2022 Nucl. Fusion 62]

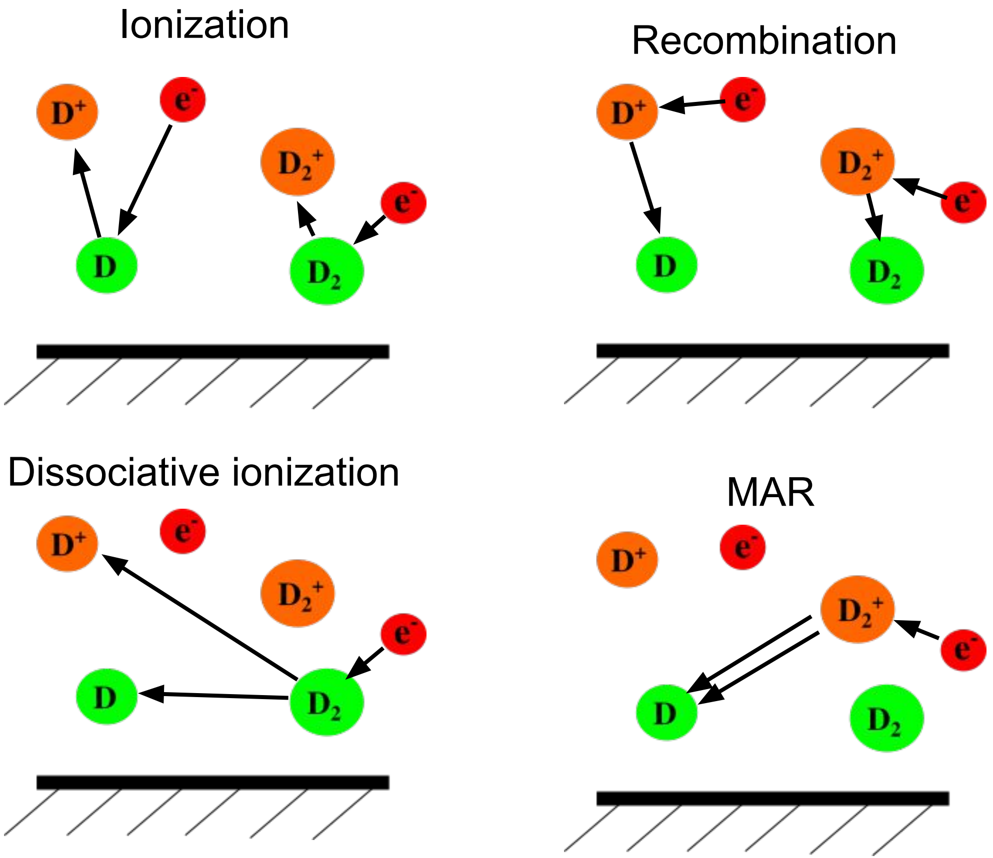
Outline

- The multispecies plasma and kinetic neutral implemented in GBS
- High density turbulent simulations
- First simulations showing features of detachment
- The role of the ExB drift with forward and reversed toroidal field

Five species model (D^+, D_2^+, e^-, D, D_2)

Total of 15 reactions, modelling:

- Ionization (atomic + MAI)
- Recombination (EIR + MAR)
- Charge exchange
- e-n collisions



Ionization

Recombination

Dissociative ionization

MAR

Plasma model: drift-reduced Braginskii equations

Plasma described by Braginskii equations with neutrals interactions
We evolve density, parallel velocity and temperatures of all charged species.
Example:

$$\frac{\partial n_e}{\partial t} = \boxed{-\nabla \cdot \left[n_e\left(\mathbf{b}v_{\parallel e} + \mathbf{v}_{E\times B} + \mathbf{v}_{de}\right)\right]}$$

$$\boxed{\begin{aligned} &+\nu_{\text{iz},D} n_D - \nu_{\text{rec},D^+} n_{D^+} \\ &+\nu_{\text{iz},D_2} n_{D_2} - \nu_{\text{rec},D_2^+} n_{D_2^+} \\ &+\nu_{\text{diss-iz},D_2} n_{D_2} + \nu_{\text{diss-iz},D_2^+} n_{D_2^+} - \nu_{\text{diss-rec},D_2^+} n_{D_2^+} \end{aligned}}$$

With:

- quasi neutrality $n_{D^+} = n_e - n_{D_2^+}$
- Zdhanov closure $\begin{bmatrix} q_{\parallel\alpha} \\ R_{\parallel\alpha} \end{bmatrix} = \sum_\beta Z_{\alpha\beta} \begin{bmatrix} \nabla_\parallel T_\beta \\ w_{\parallel\beta} \end{bmatrix}$
- Pre-sheath boundary conditions

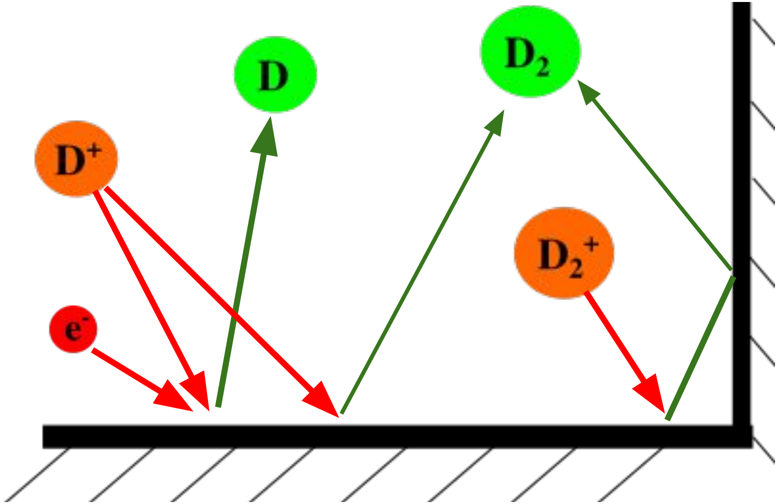
[A. Coroado and P. Ricci 2022 Nucl. Fusion 62]

Kinetic neutral model - distribution functions evolved avoiding statistical noise of Monte Carlo methods

Boltzmann equation for f_D and f_{D_2} solved with method of characteristics.

Boundary conditions reproduce:

- Neutral recycling due to ion flux to wall (including **parallel** and **drift velocity**)
- Reflection, re-emission, and association with probability from experimental measurements



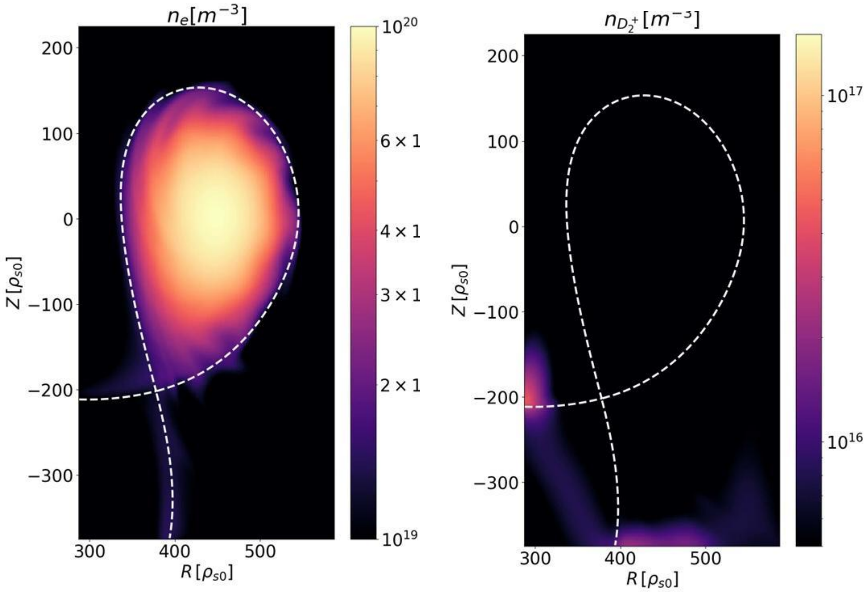
Density, flux and temperature profiles from f_D and f_{D_2}

Two TCV simulations: low and high density

Half-TCV size, explorative study with TCV-X21 equilibrium

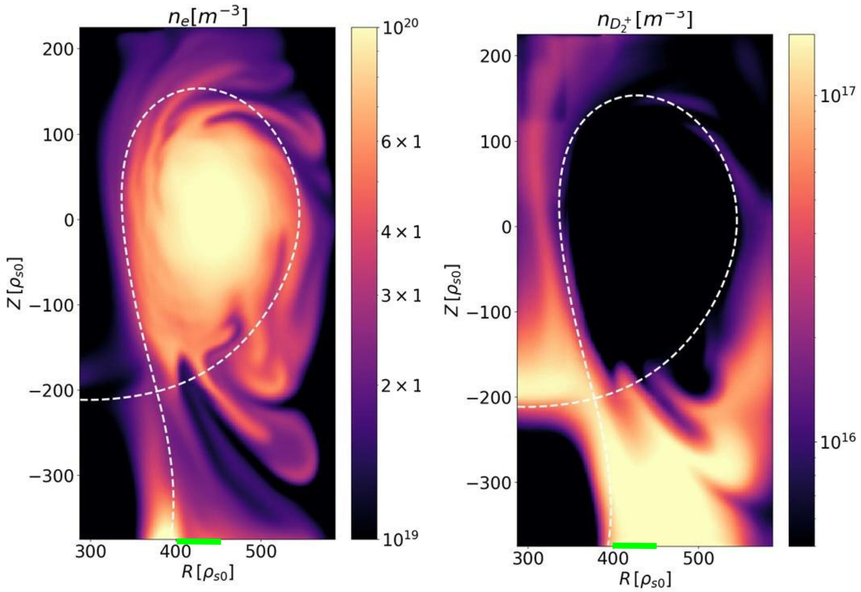
Low density
No puffing

$n_{e,sep}$ = 1.62 x 10^{19} m^{-3}
P_{SOL} = 165.3 kW
$p_{D,div}$ = 0.07 Pa



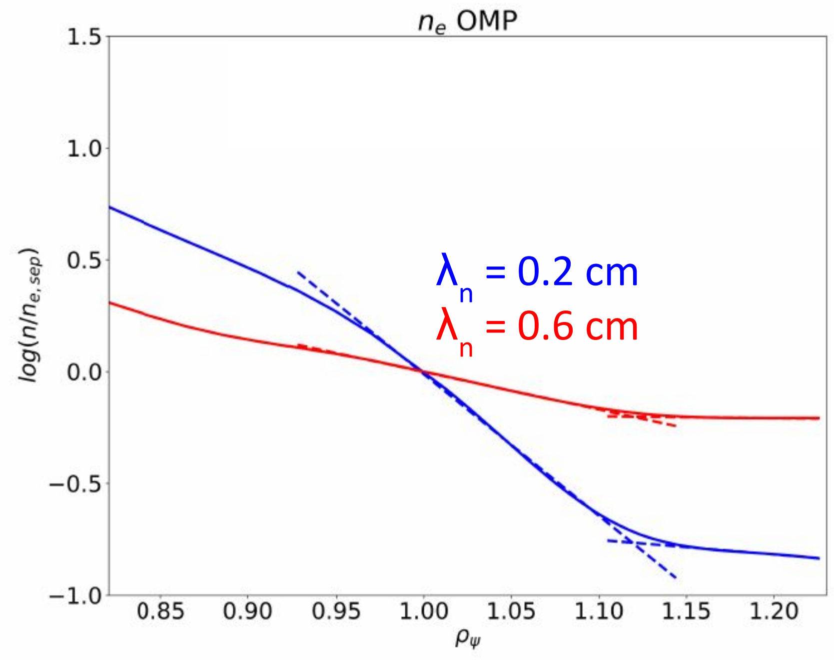
High density
Puffing of D_2

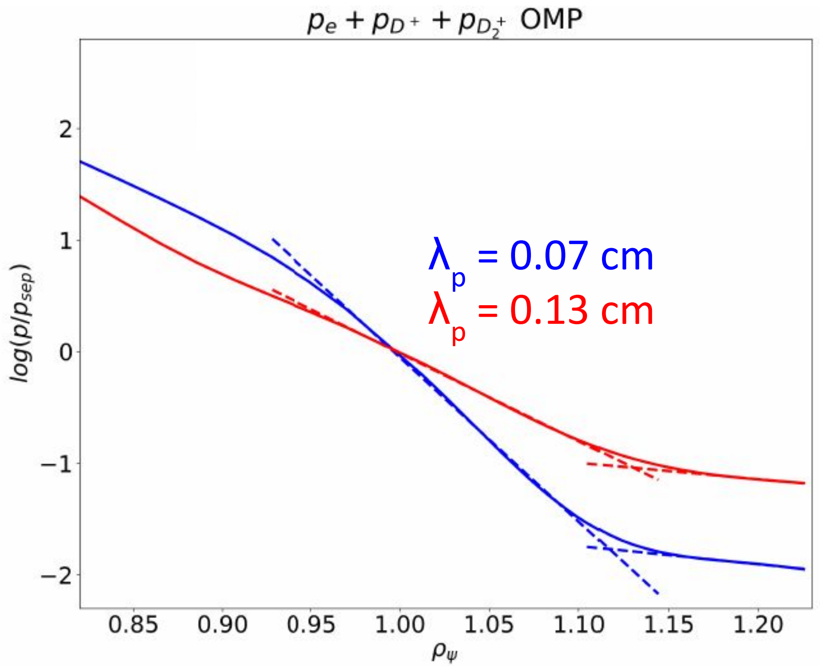
$n_{e,sep}$ = 3.42 x 10^{19} m^{-3}
P_{SOL} = 143.4 kW
$p_{D,div}$ = 0.32 Pa



Density shoulder formation at OMP

- Strong increase in density with puff ~4x in absolute value
- Strong increase in near SOL decay length *[D. Mancini et al 2021 Nucl. Fusion 61]*





Fluctuations amplitude increases in high density

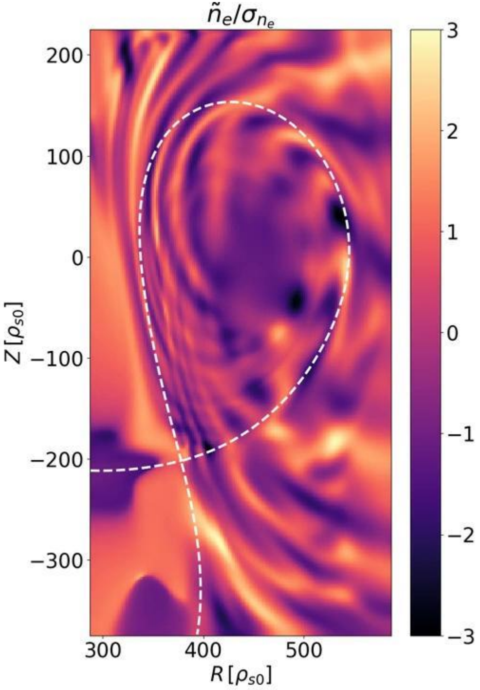
- Detection routines to reconstruct 3D structure of filaments

  [G. Van Parys, EPFL Master thesis (2022)]

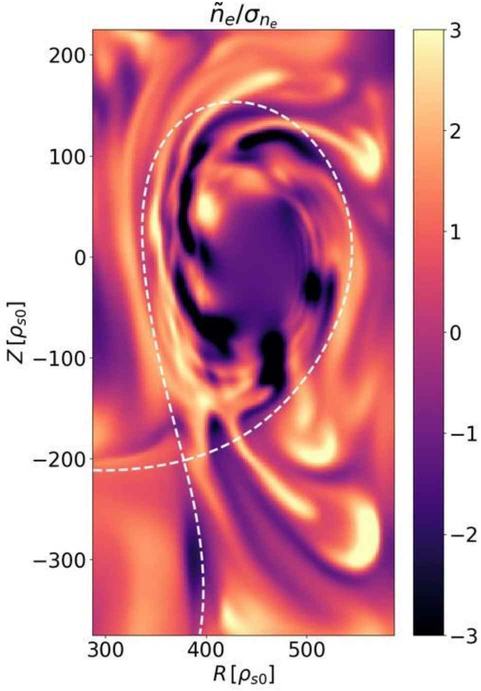
- Blob definition: $n - \langle n \rangle_{\varphi t} > 2.5\ \sigma_n$

- Amplitude of fluctuations increases with density

Low density



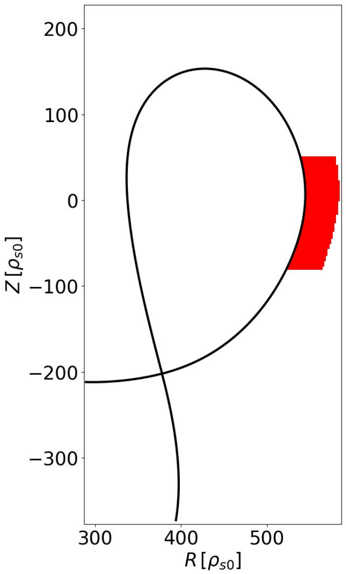
High density

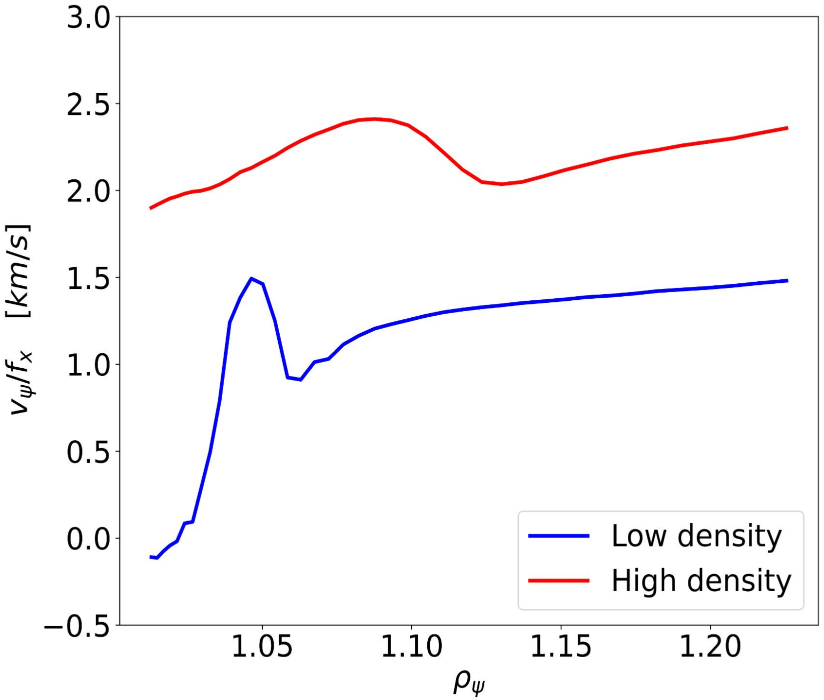


Filaments radial velocity increases

$\mathbf{v}_{\mathbf{CM}}$ radial profile at OMP with higher density:

- Higher radial velocity in all SOL
- Flat profile in near SOL

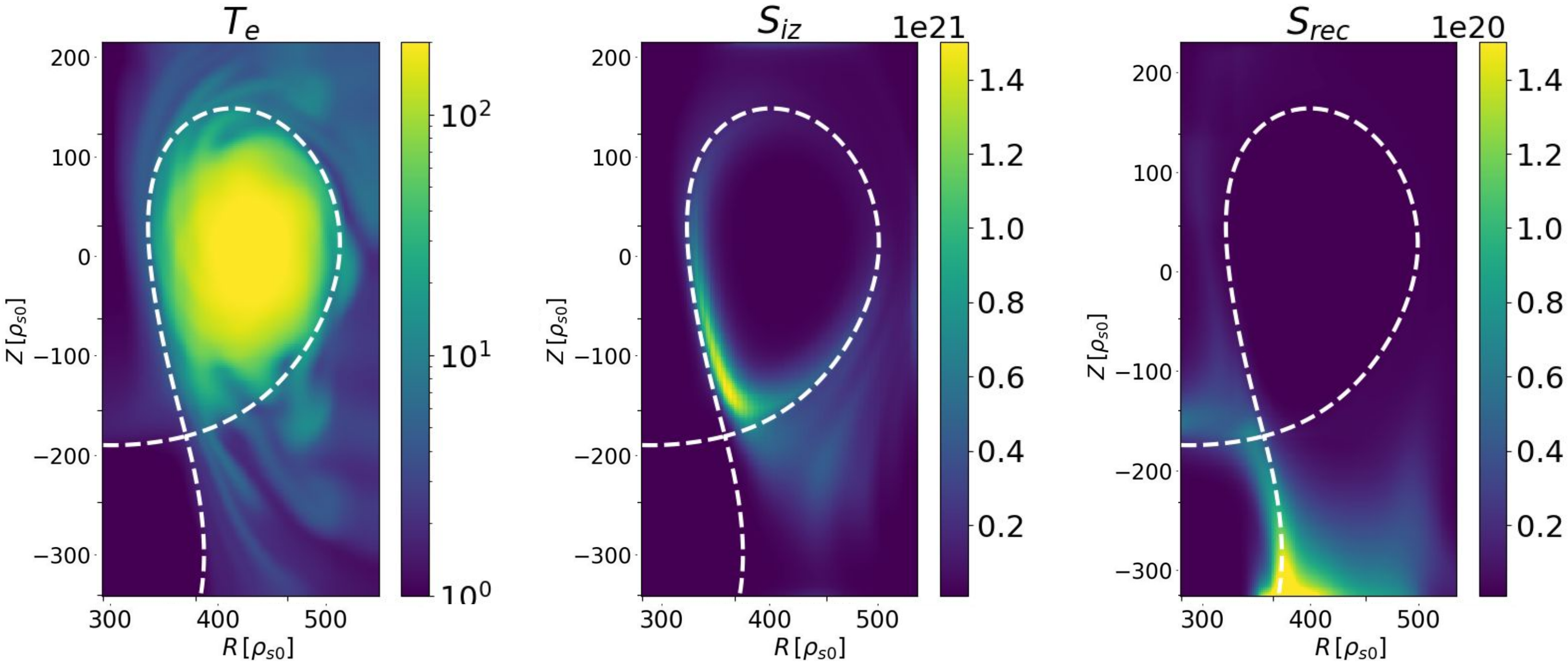




Better comparison with experiments in poster by
D.S. de Oliveira, "Progress in understanding the impact of the magnetic geometry on divertor turbulence" (12/09)

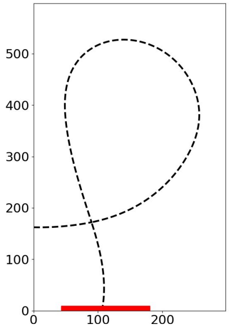
High-density simulation with molecular dynamics shows typical detachment conditions

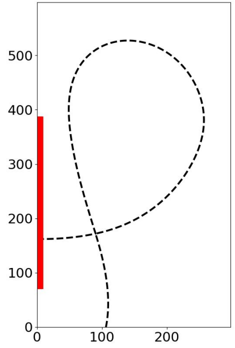
- T_e < 3eV in divertor volume leads to recombination, absent without molecules
- Ionization mainly inside core

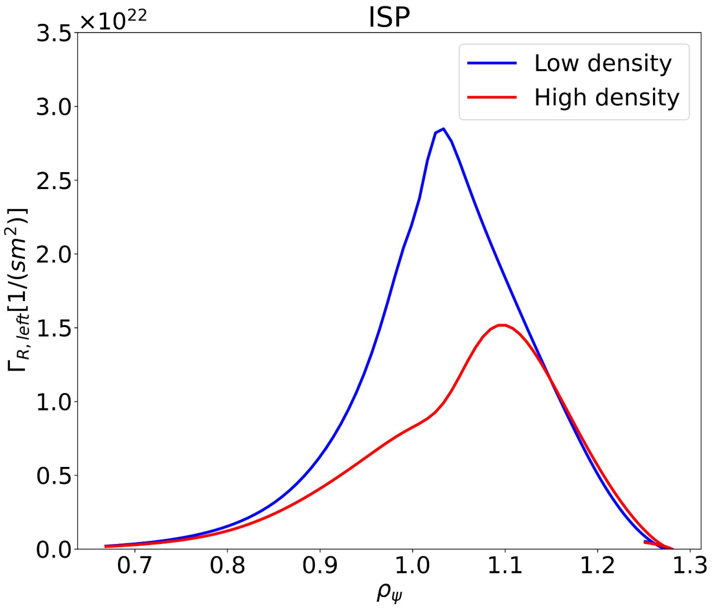


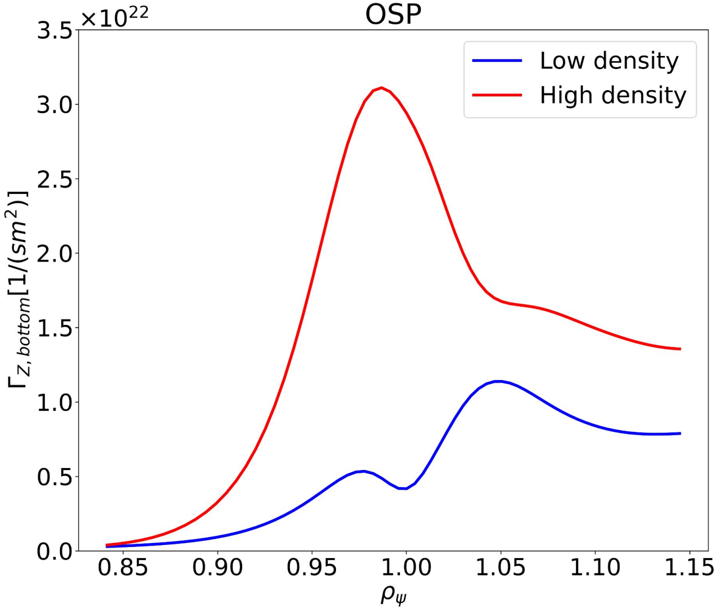
High-density simulation: reduced particle flux at ISP

- Ion flux to target decreases at ISP
- Ion flux peak moves away from separatrix



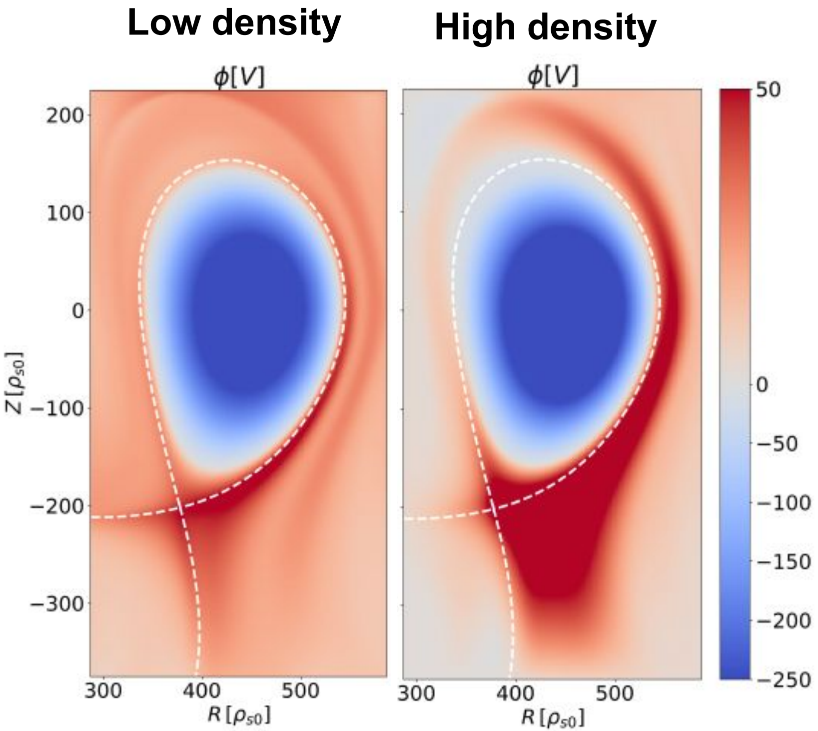


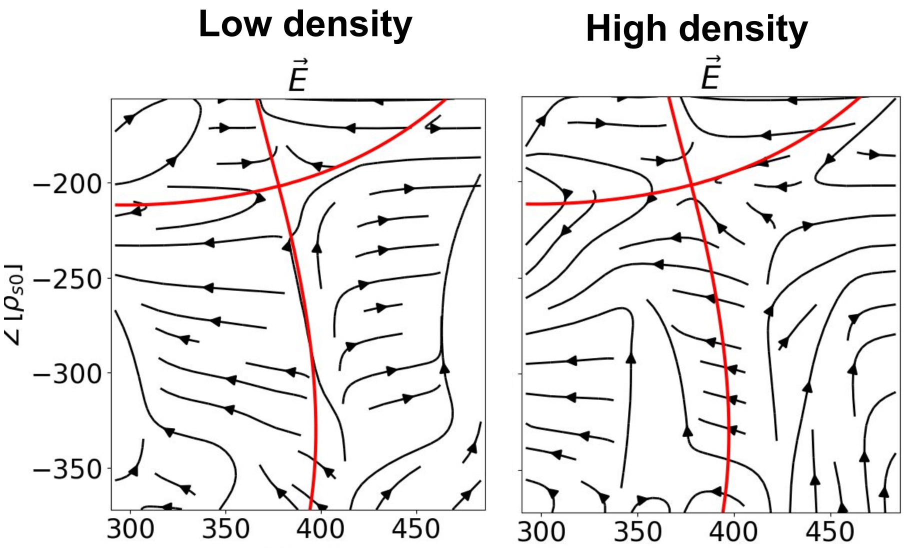




High-density simulation: strong electric field at outer leg

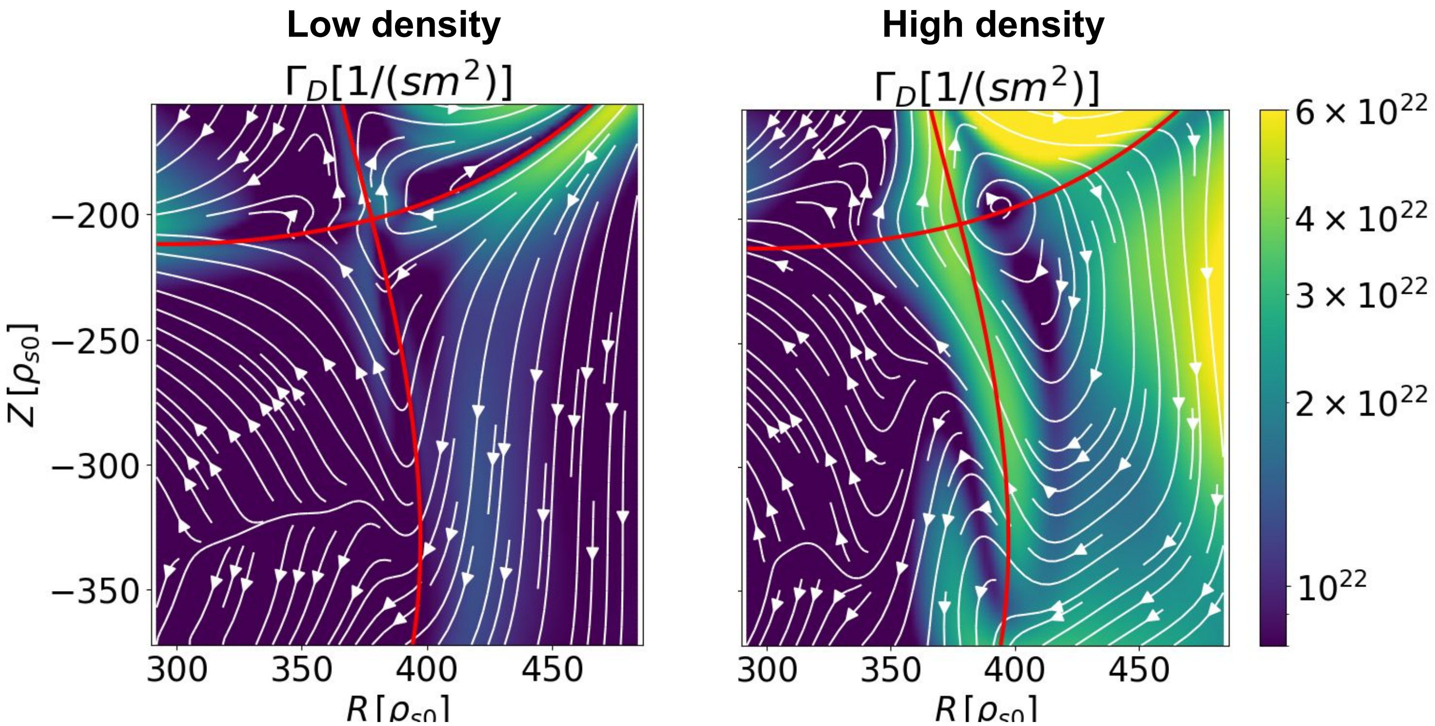
Strong gradients of plasma potential at SOL boundary





ExB increases with density

Large ExB convective cell appears at high density



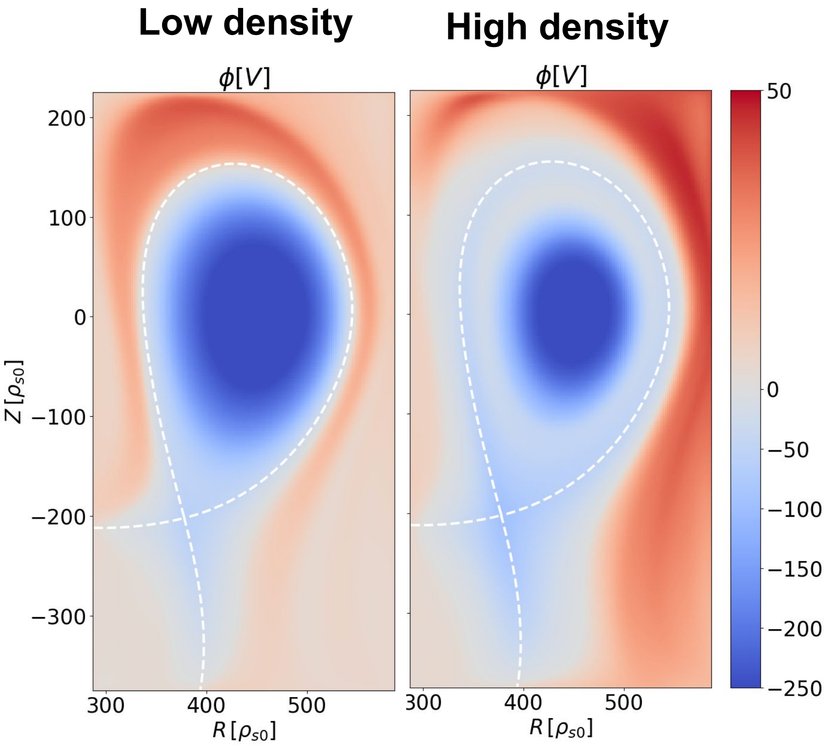
Low density

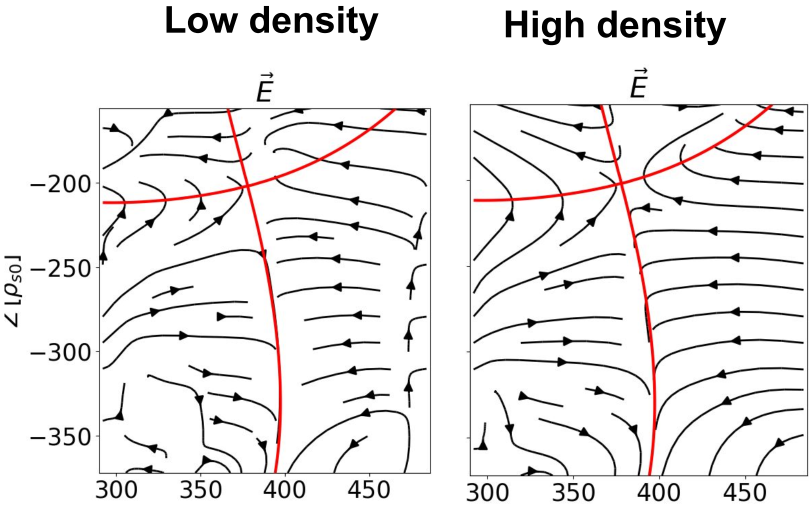
High density

The ExB drift moves the particle and heat flux inside the separatrix

First results in RF: negative potential at X-point

Reversing toroidal field sign leads to negative potential in SOL *[M. Wensing et al 2020 Nucl. Fusion* ***60*** *054005]*

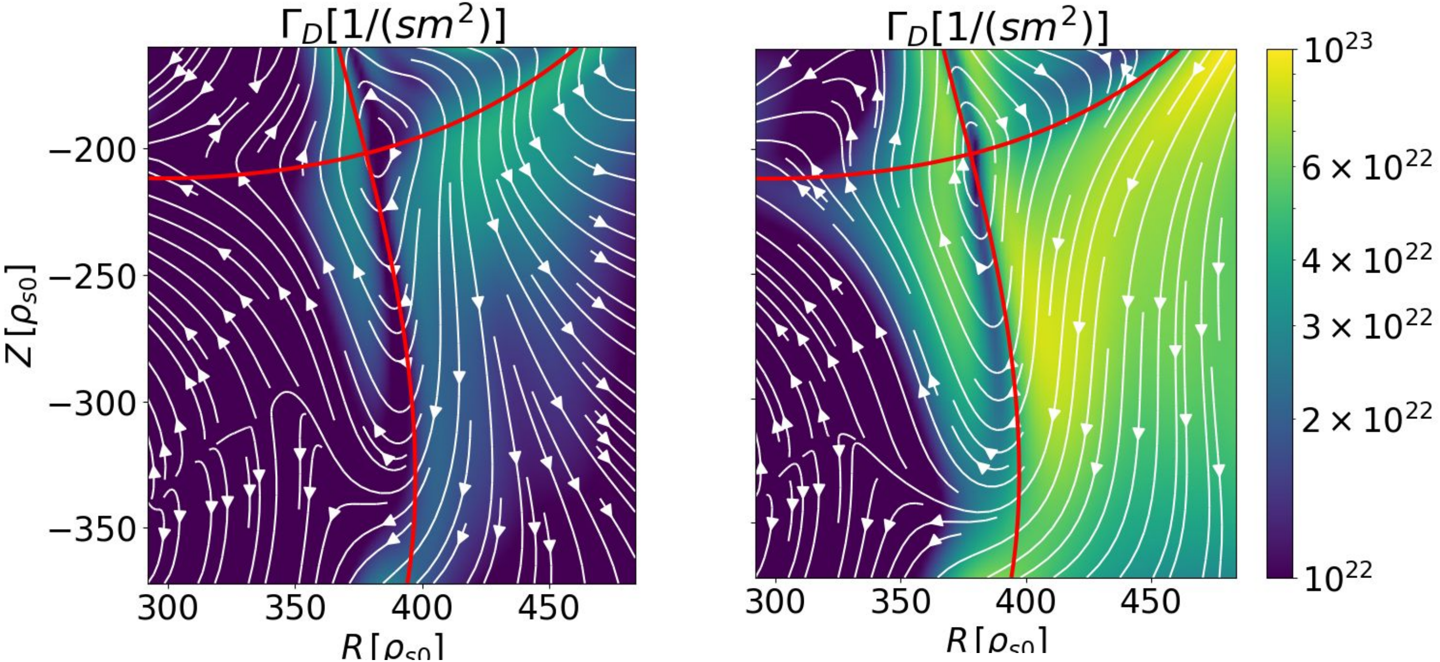




First results in RF: ExB above X-point increases SOL width

Opposite $\mathbf{B}_\varphi$ and $\mathbf{E}_r$ leads to same ExB convective cell as forward field in the divertor region

Low density **High density**



Conclusions

- The GBS code is able to simulate turbulent plasma with multiple ion and neutral species
- High-density diverted simulations show density shoulder and good agreement with experimental values in filament size and velocities, both increasing with higher density
- Diverted simulation with molecules shows hints of detachment, **DOD > 1 at ISP**
- **Temperature decreases due to strong penetration of neutrals**, where most of neutrals are produced in the volume by **D_2 dissociation** and **Molecular activated recombination**
- **ExB drift moves ion flux peak at both targets**, where electric field is set by resistivity
- **Reverse toroidal field** leads to wider SOL and potential well at X-point

Degree of Detachment

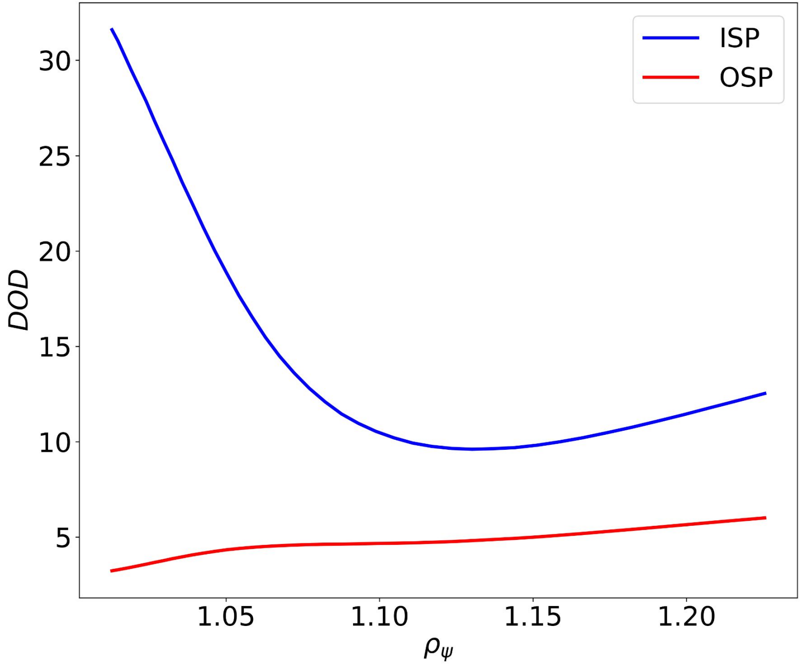
Degree of Detachment = (Expected flux) / (Measured flux)

$$DOD = C\frac{n_{up}^2}{\Gamma_{D+}}$$ Detached if >> 1

[A. Loarte et al 1998 Nucl. Fusion 38 331]

Values calibrated with low density simulation near separatrix

Both targets show DOD > 1

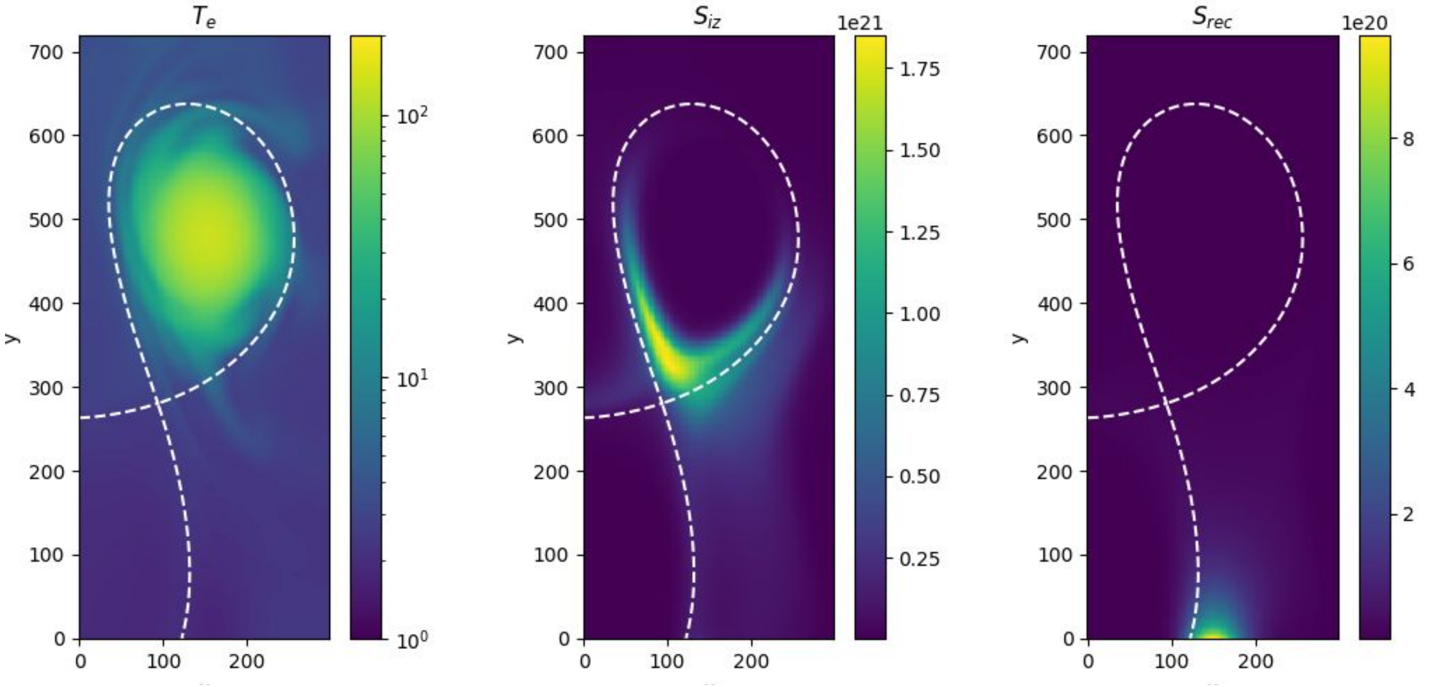


[D. Mancini et al, submitted to Nucl. Fusion]

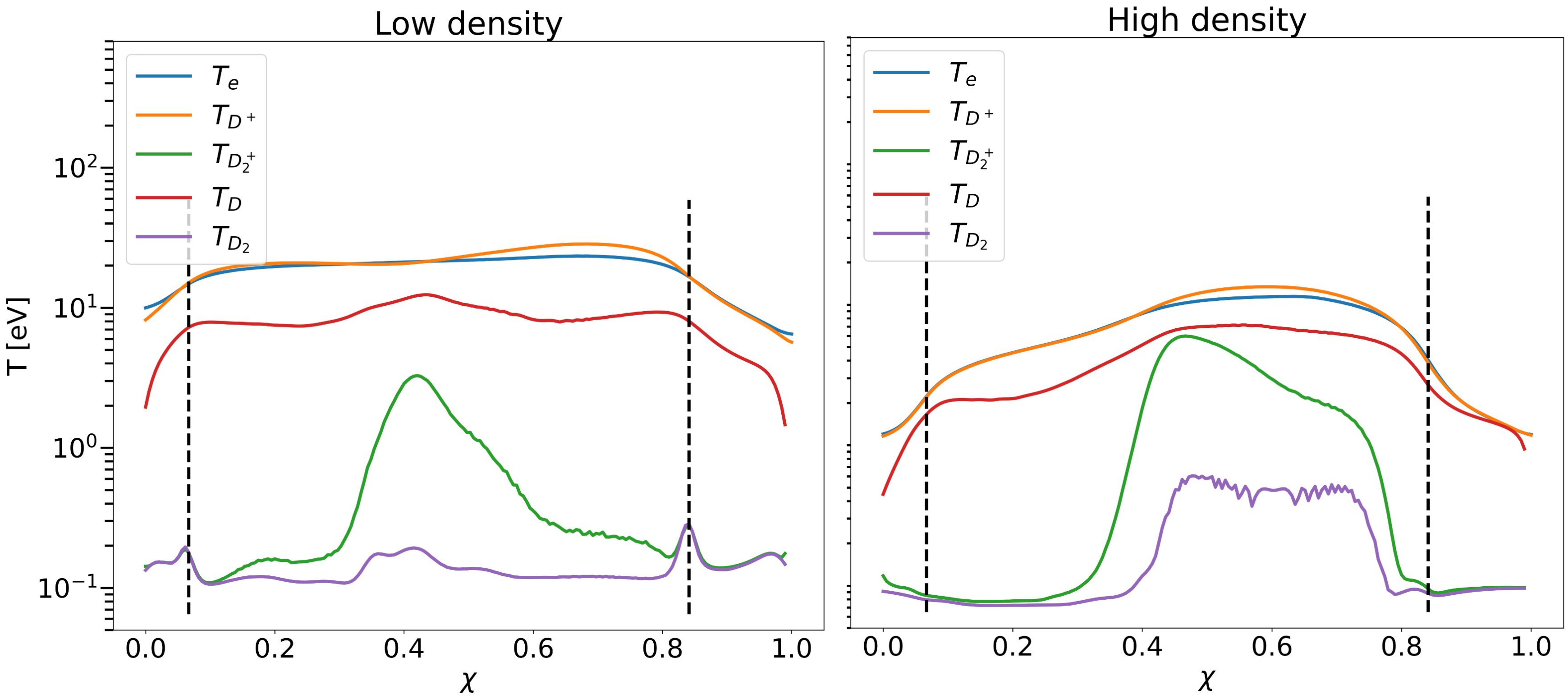
Outlook - Long outer leg

No steady state:

- Ionization moved inside the core
- Recombination low at the target, T_e still high



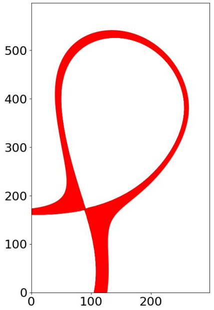
Temperature decrease in high-density

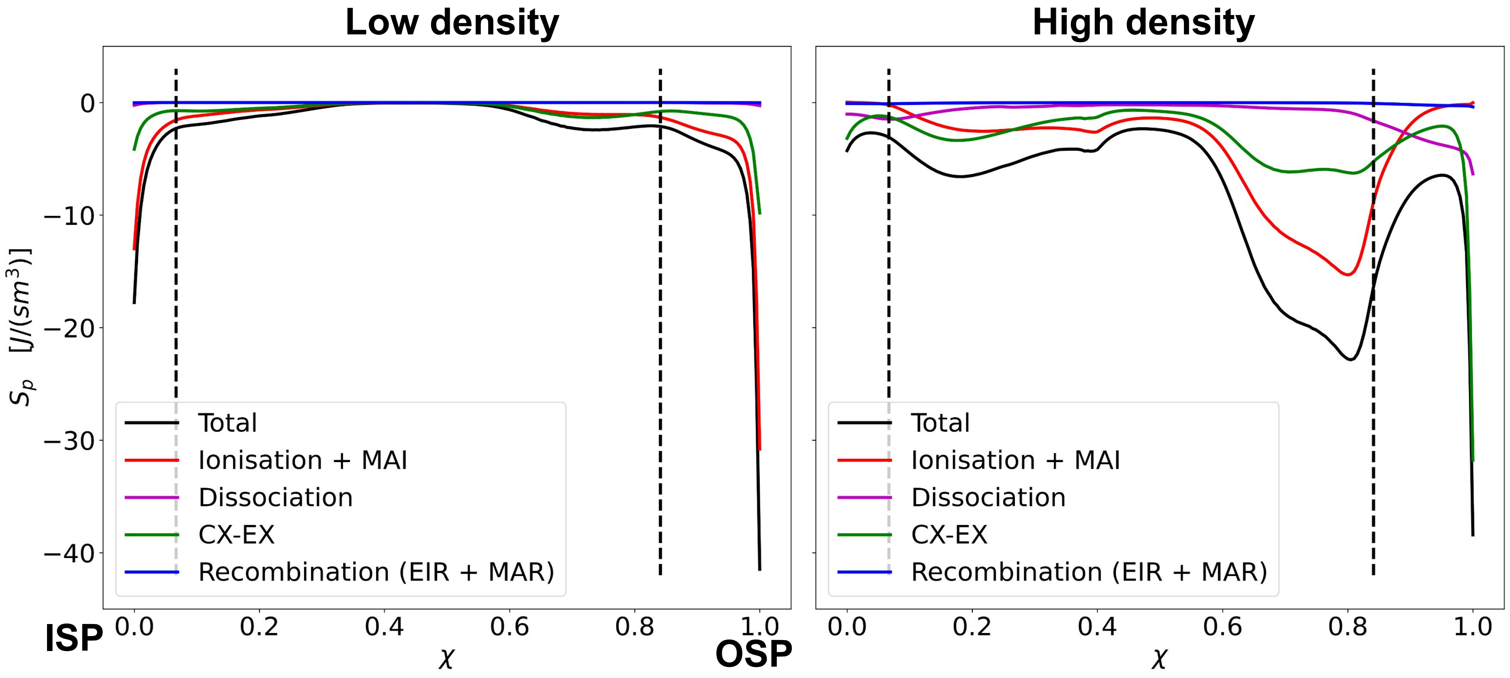


D_2 neutrals increase power losses from ionization and cx-ex

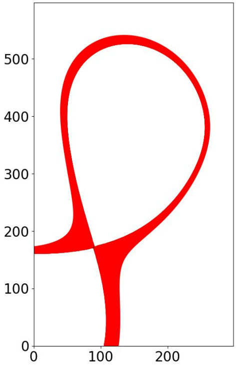
In high density:

- Ionization negligible close to ISP due to low T_e
- Charge-exchange and dissociation dominant close to targets





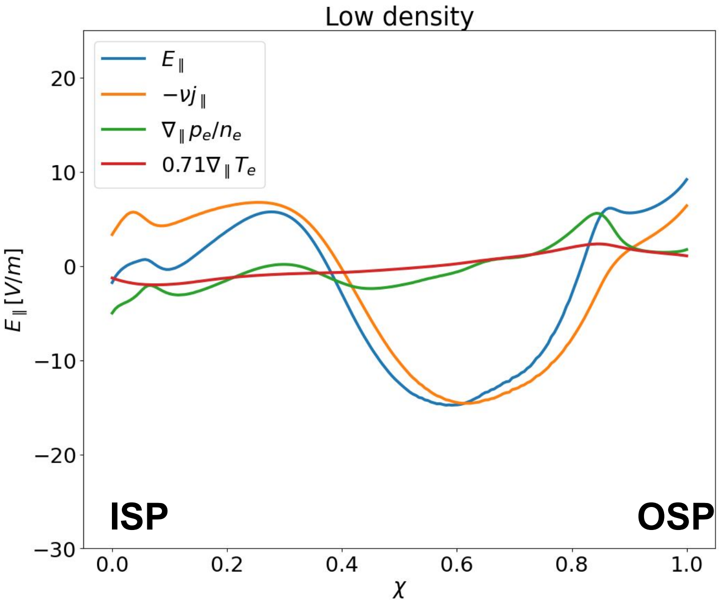
Strong $E_{||}$ due to high resistivity

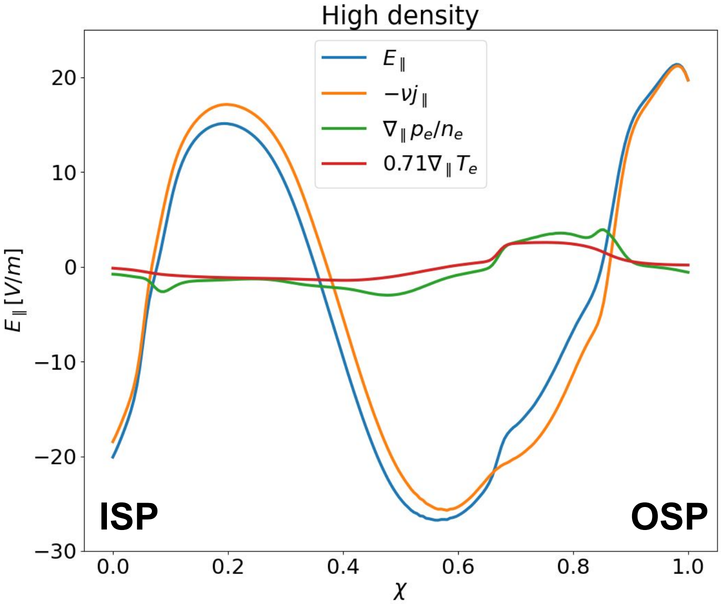


Plasma potential set by Ohm's law

$$E_{\|} = -\nabla_{\|}\phi \simeq \nabla_{\|}p_e/ne + 0.71\nabla_{\|}T_e/e - \nu j_{\|}$$

[D. Brida et al Nuclear Mat and Energy 33 (2022)]

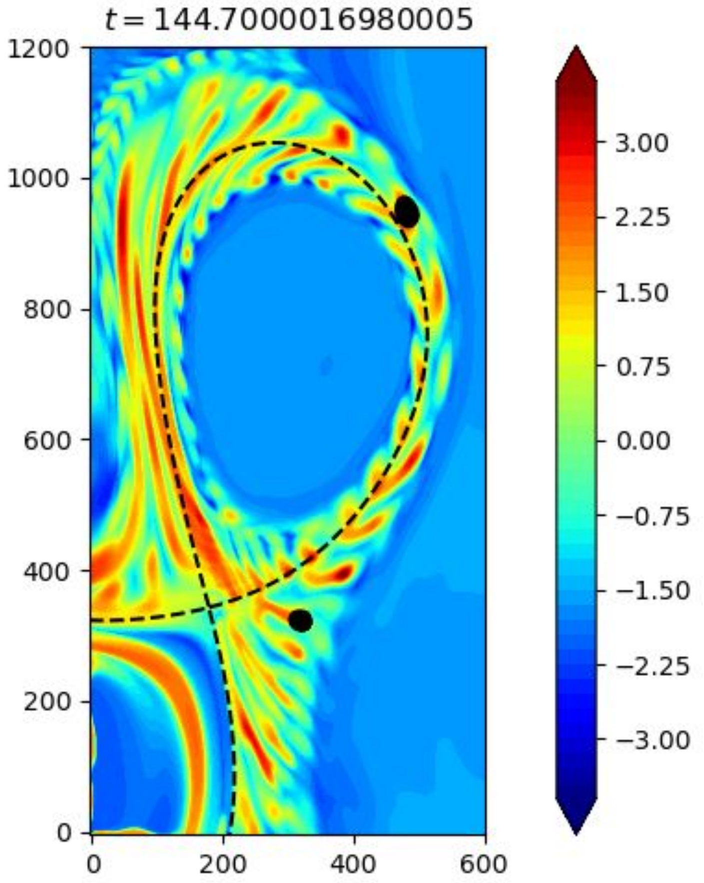


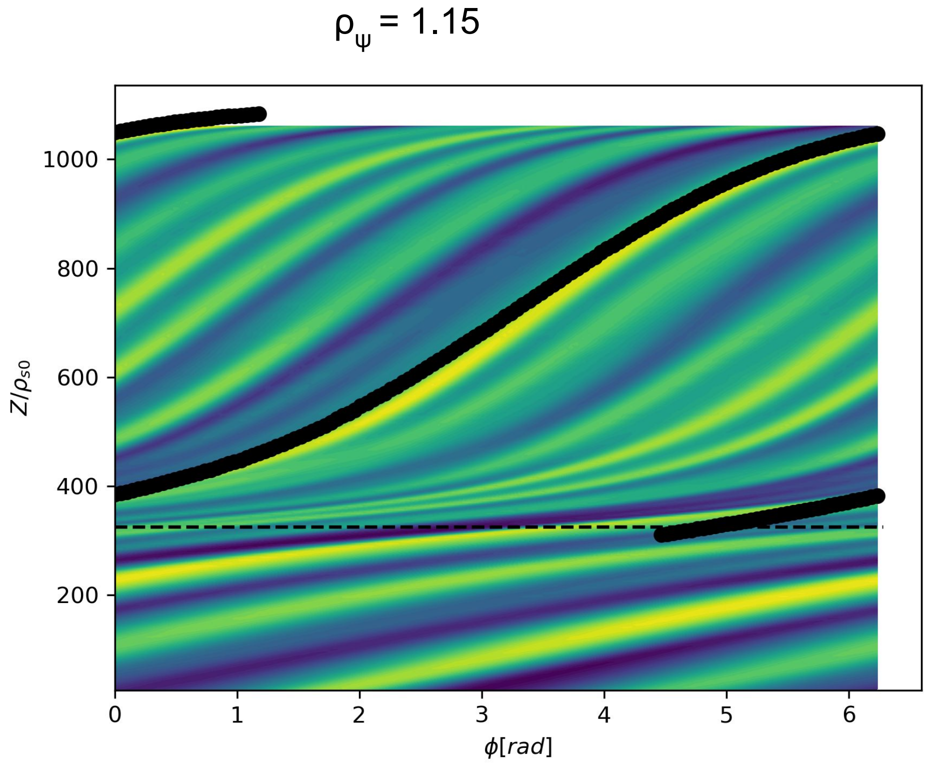


3D detection algorithm

Example: one poloidal plane (left), one surface along the torus (right) , blob CM in black

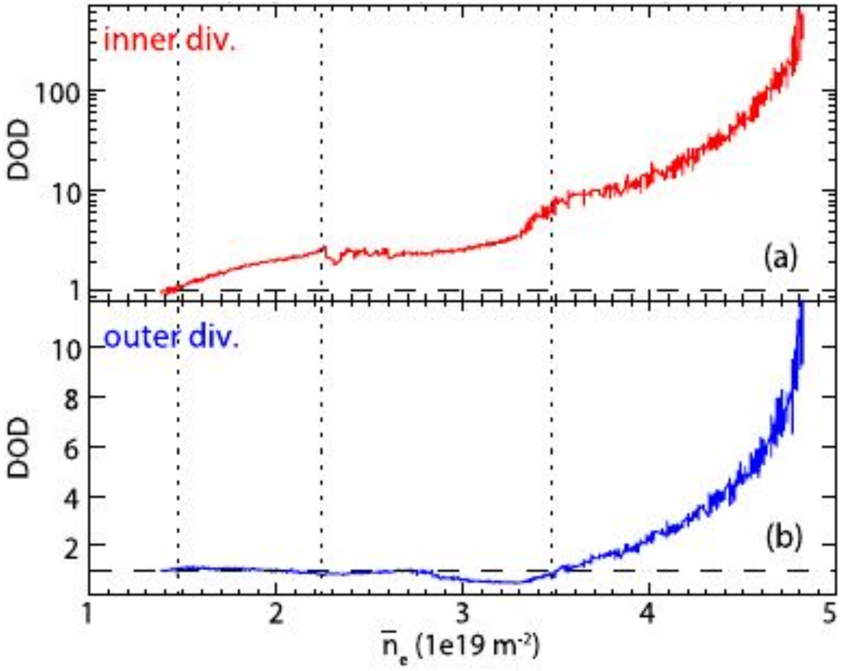
$\varphi = 4.9$





Phenomenology of detachment

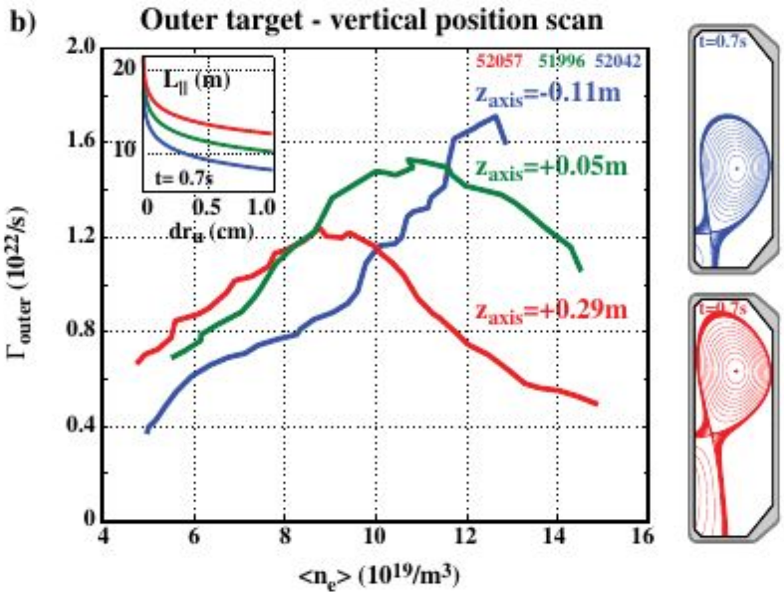
Asymmetries inner/outer strike points (ISP/OSP) depends on B_t direction



[S. Potzel et al 2014 Nucl. Fusion 54]

Phenomenology of detachment

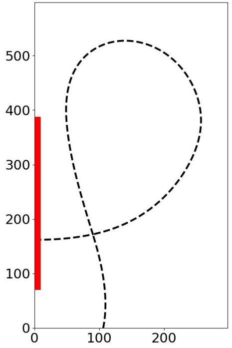
- Strong role of molecular activated recombination (MAR)
- Increased turbulent filament velocity and size with increasing density
- Dependence on magnetic geometry (e.g. leg length or B_φ sign)

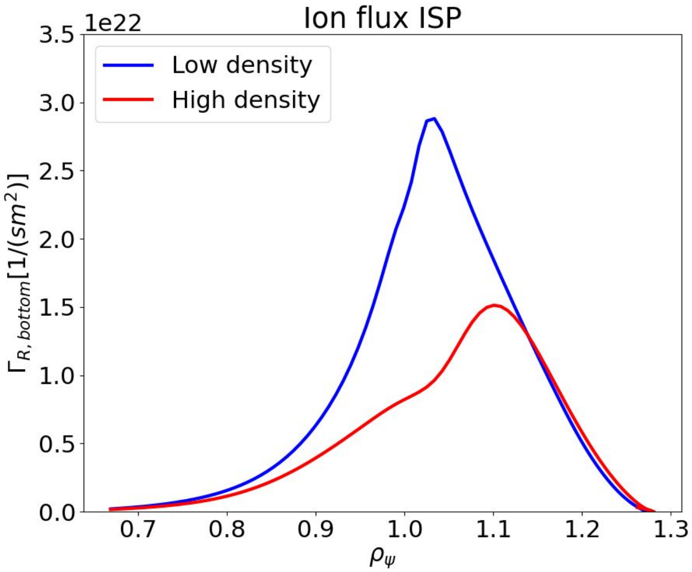


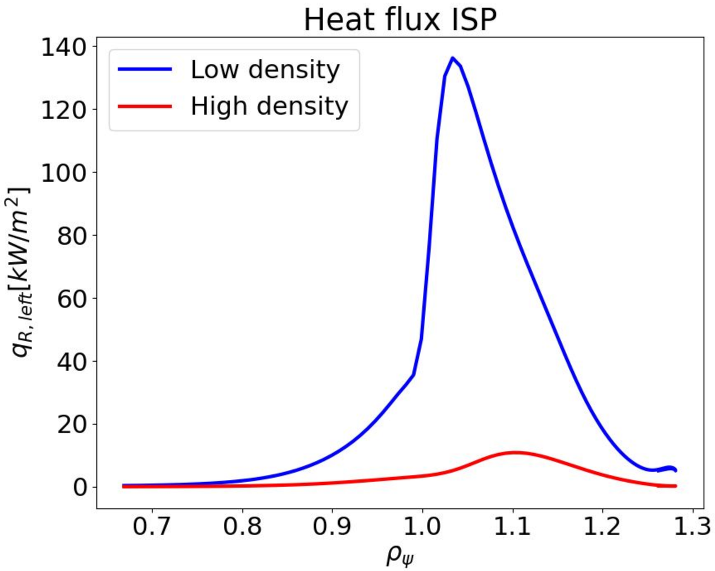
[H. Reimerdes et al 2017 Nucl. Fusion 57]

High-density simulation: reduced particle and heat flux at ISP

- Ion flux to target peak moves away from separatrix and decreases
- Flat heat flux

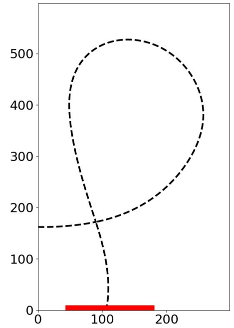


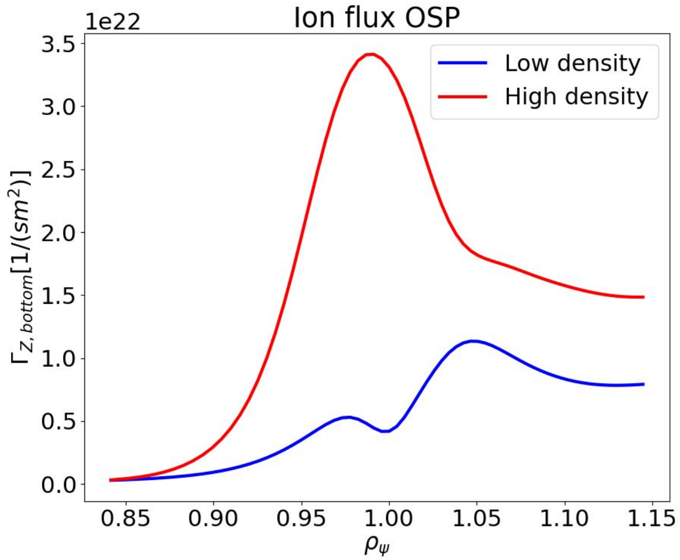


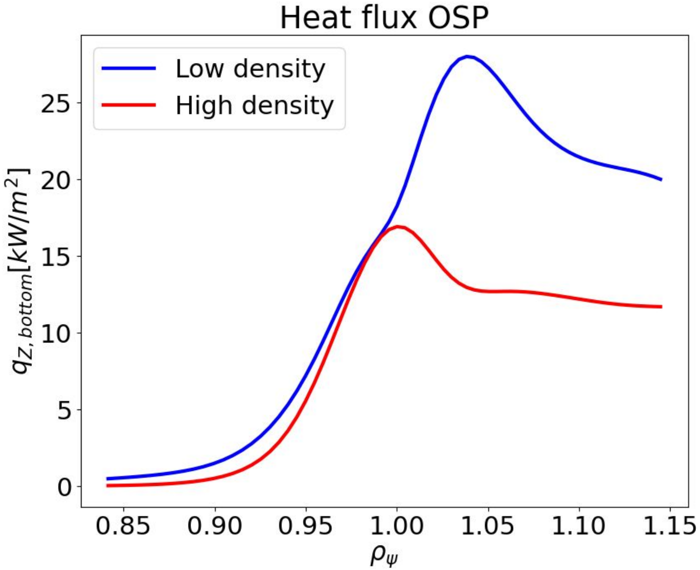


High-density simulation: increased particle flux at OSP

- Ion flux increases, peak in private flux region
- Heat flux decreased







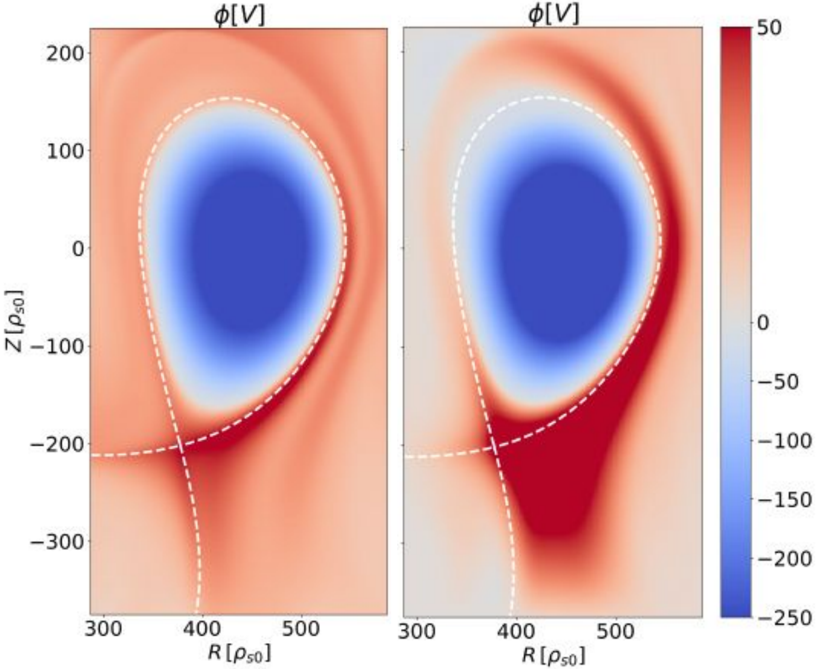
Reduced radial electric field in near SOL

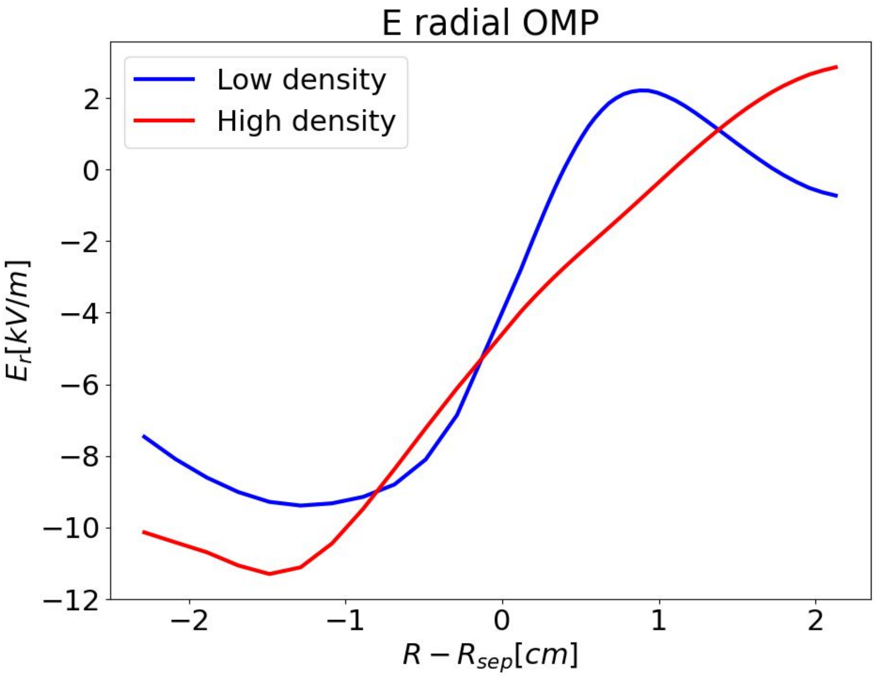
Increasing density:

- Lower radial electric field at separatrix (same as experiments)
- Higher electric field in far SOL (different from experiments)

[D. Brida et al Nuclear Mat and Energy 33 (2022)]

Low density **High density**

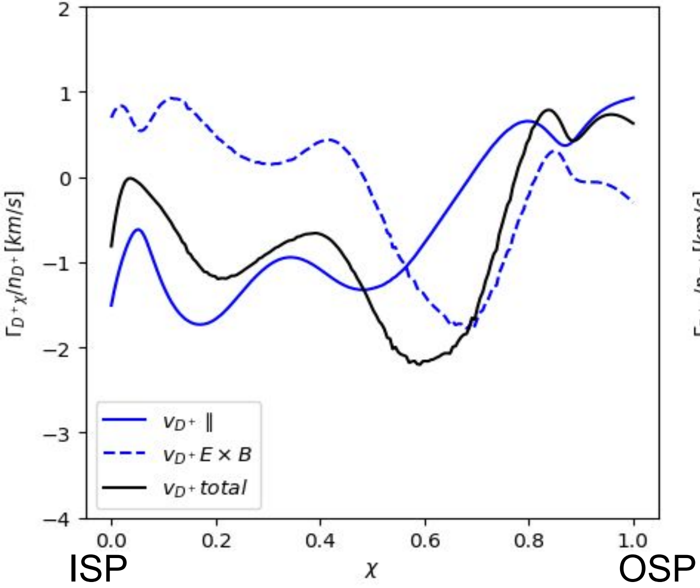




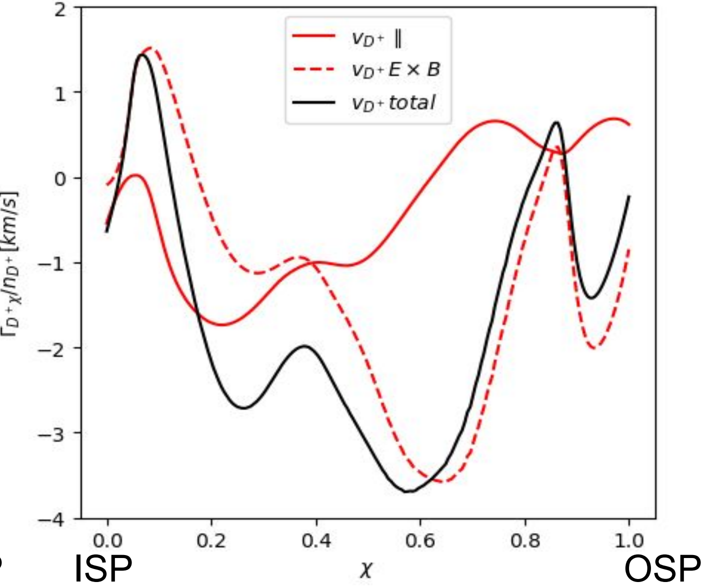
Target flux decreases with reduced T_e and increased ExB

In a flux tube near separatrix:

- Parallel flux decrease by 1/3 due to decreased temperature → decreased c_s
- Below Xpt flux dominated by ExB in high density

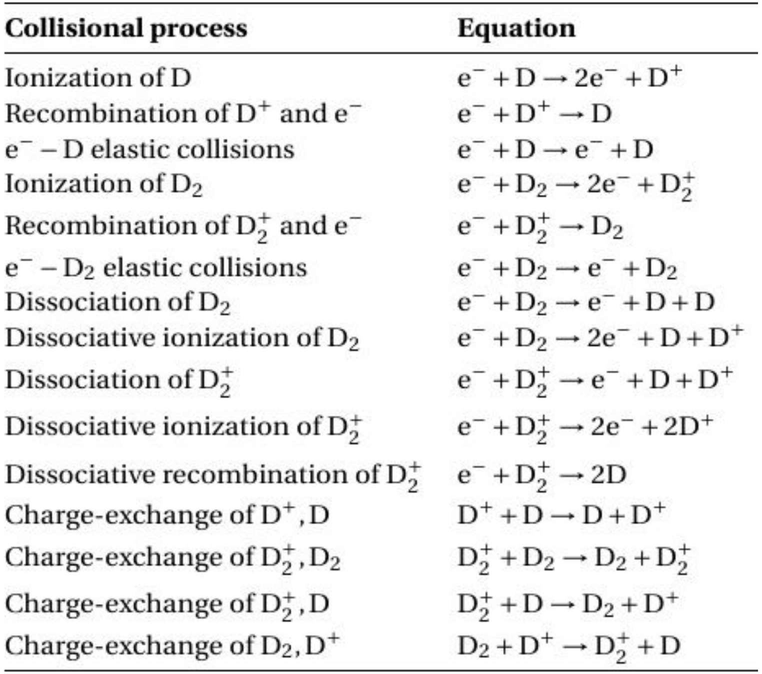


Low density



High density

GBS model - Simulations of atomic and molecular D plasma



	Collisional process	Equation
🟥	Ionization of D	$e^- + D \rightarrow 2e^- + D^+$
🟩	Recombination of D^+ and e^-	$e^- + D^+ \rightarrow D$
	$e^- - D$ elastic collisions	$e^- + D \rightarrow e^- + D$
🔴	Ionization of D_2	$e^- + D_2 \rightarrow 2e^- + D_2^+$
🟢	Recombination of D_2^+ and e^-	$e^- + D_2^+ \rightarrow D_2$
	$e^- - D_2$ elastic collisions	$e^- + D_2 \rightarrow e^- + D_2$
🟩	Dissociation of D_2	$e^- + D_2 \rightarrow e^- + D + D$
🟥	Dissociative ionization of D_2	$e^- + D_2 \rightarrow 2e^- + D + D^+$
🟩	Dissociation of D_2^+	$e^- + D_2^+ \rightarrow e^- + D + D^+$
🟥	Dissociative ionization of D_2^+	$e^- + D_2^+ \rightarrow 2e^- + 2D^+$
🟩	Dissociative recombination of D_2^+	$e^- + D_2^+ \rightarrow 2D$
	Charge-exchange of D^+, D	$D^+ + D \rightarrow D + D^+$
	Charge-exchange of D_2^+, D_2	$D_2^+ + D_2 \rightarrow D_2 + D_2^+$
	Charge-exchange of D_2^+, D	$D_2^+ + D \rightarrow D_2 + D^+$
	Charge-exchange of D_2, D^+	$D_2 + D^+ \rightarrow D_2^+ + D$

🟥 Production of D^+

🟩 Production of neutral D

🔴 Production of D_2^+

🟢 Production of neutral D_2

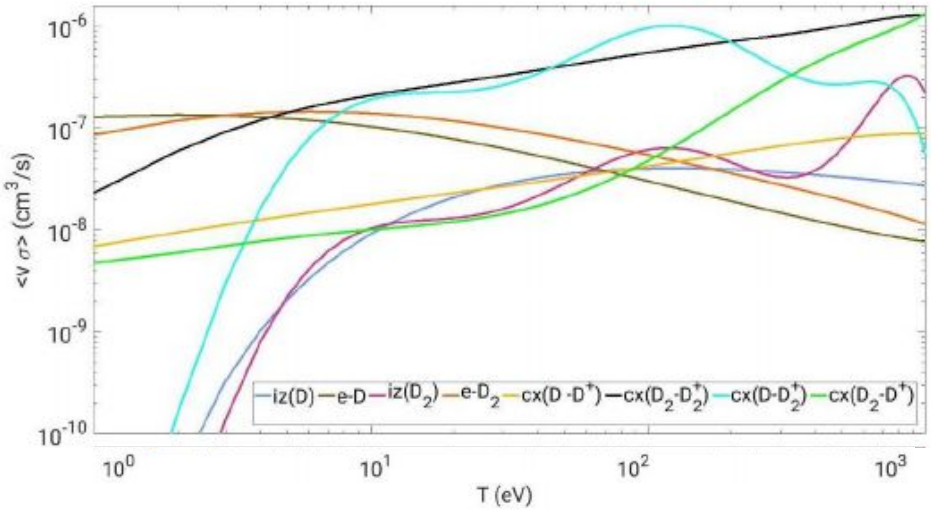
[A. Coroado and P. Ricci 2022 Nucl. Fusion 62]

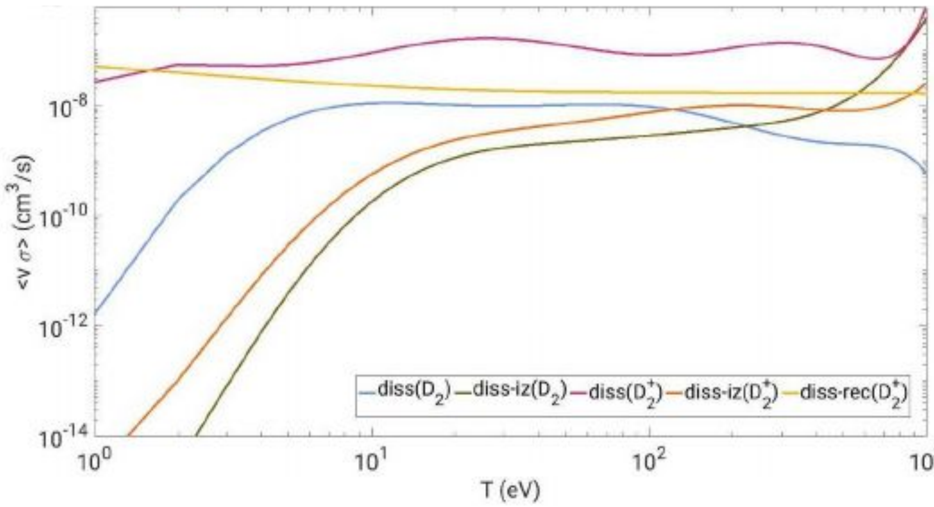
GBS model - Simulations of atomic and molecular D plasma

All reaction rates are taken as functions of T_e and n_e or n_{D+}

Detachment-relevant reactions at low temperature $T_e < 2$eV :

- Decrease in ionization
- Strong relevance of dissociations involving D_2^+





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