EUROfusion

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GBS simulations of TCV-X23

D. Mancini, P. Ricci

EPFL Swiss Plasma Center

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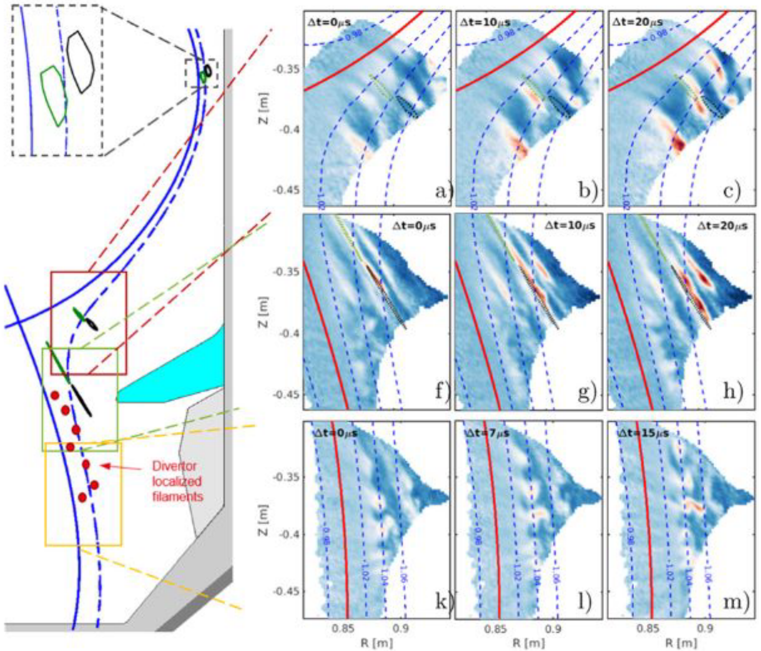
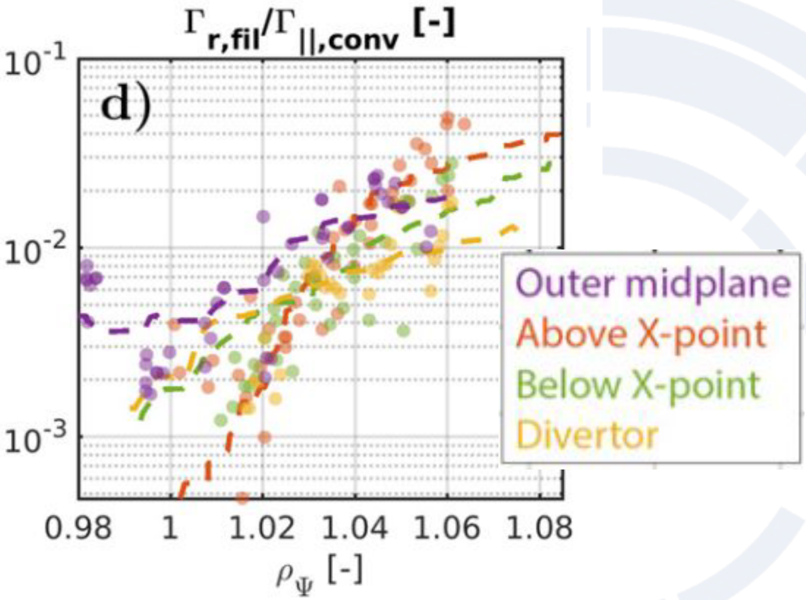
Complex interplay of turbulence and detachment





[C. Wüthrich et al, 2022 Nucl. Fus. 62]

- What is the role of molecular reactions in detachment and for turbulence?
- What is the estimate of radial to parallel flux in detachment conditions?

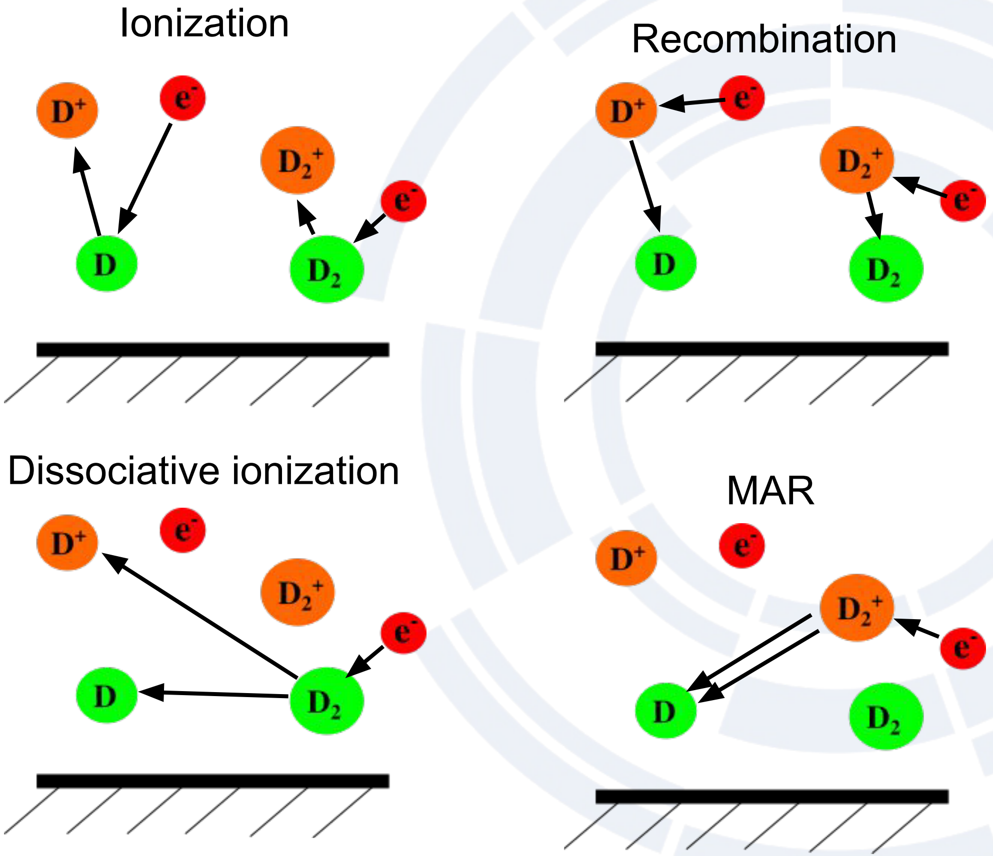
Outline

- Overview of GBS 5 species model
- Comparison of TCV-X21 and TCV-X23 simulations:
  - Average profiles of plasma and neutrals
  - Detachment characterization
  - First analysis of turbulence properties

Five species (D^+, D_2^+, e^-, D, D_2) and minimal interactions set

Detachment studied through simulations of tokamak plasma and neutrals, modelling:

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



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:

$$\frac{\partial n_e}{\partial t} = -\nabla \cdot [n_e(\mathbf{b}v_{\parallel e} + \mathbf{v}_{E\times B} + \mathbf{v}_{de})] + \int (I_{e,D} + I_{e,D_2}) d\mathbf{v}$$

$$I_{e,D} = n_D \langle v\sigma_{e,D}^{el}\rangle (n_e \Phi_{[\mathbf{v}_D, T_{e,D}^{el}]} - f_e) + n_D \langle v\sigma_{e,D}^{iz}\rangle (2n_e \Phi_{[\mathbf{v}_D, T_D^{iz}]} - f_e) - n_{D^+}\langle v\sigma_{e,D^+}^{rec}\rangle f_e$$

Where : $\Phi_{[\mathbf{v},T]}$ is a Maxwellian centered at velocity **v** , with temperature T , distribution of emitted electrons

With:

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

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

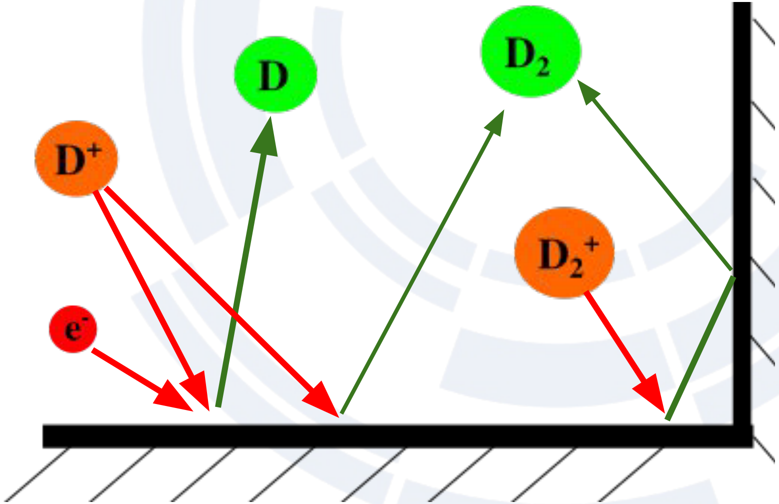
Kinetic neutral model - distribution functions evolved avoiding statistical noise of Monte Carlo methods

Boltzmann equation for f_D and f_{D_2}

$$\frac{\partial f_D}{\partial t} + \mathbf{v} \cdot \frac{\partial f_D}{\partial \mathbf{x}} = -n_e \langle v\sigma_{e,D}^{iz} \rangle f_D + n_e \langle v\sigma_{e,D+}^{rec} \rangle f_{D+} + \langle v\sigma_{D,D+}^{cx} \rangle (n_{D^+} f_D - n_D f_{D^+}) + \ldots$$

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



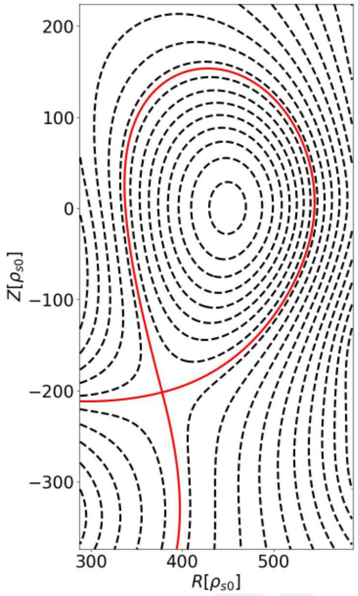
Goal: detachment with longer leg and compare with X21

For each configuration:

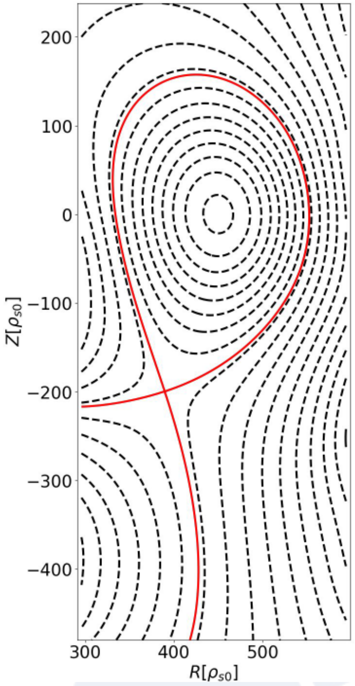
- Half TCV size
- 2 simulations, low and high density (GP D_2)
- e^-, D^+ and D_2^+ dynamics
  with D and D_2 interactions

Shape	B_t direction	Convergence
TCV-X21	FF	Yes*
TCV-X21	RF	Yes**
TCV-X23	FF	Almost

PSI 2024



TCV-X21



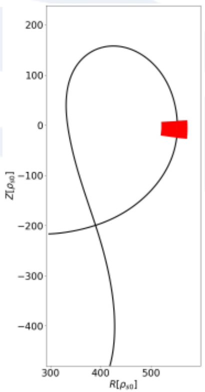
TCV-X23

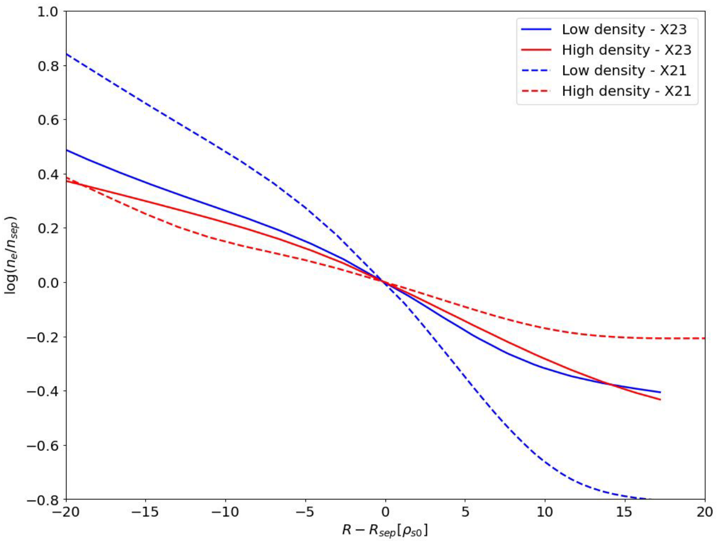
*D. Mancini et al, 2024, Nucl. Fusion 64 016012
** D.Mancini et al, 2024, PSI poster

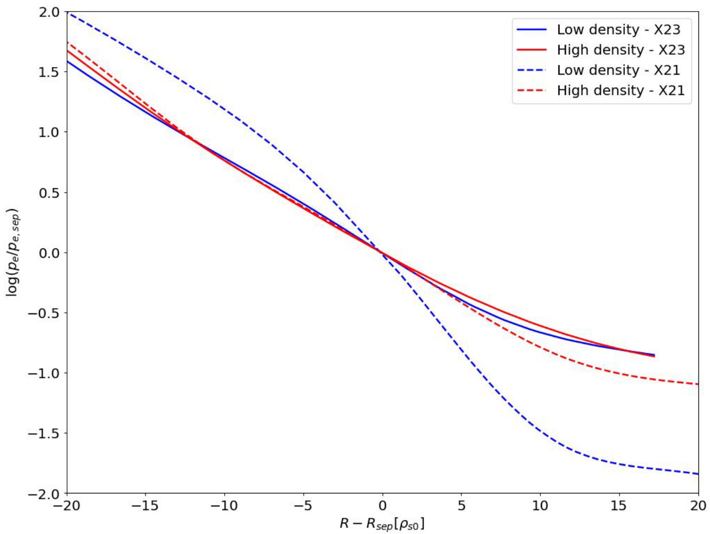
No changes in the OMP profile through puffing

Increased puff simulations show same density profile in low and high density TCV-X23:

- Density shoulder "between" the low and high density TCV-X21
- λ_p higher in TCV-X23

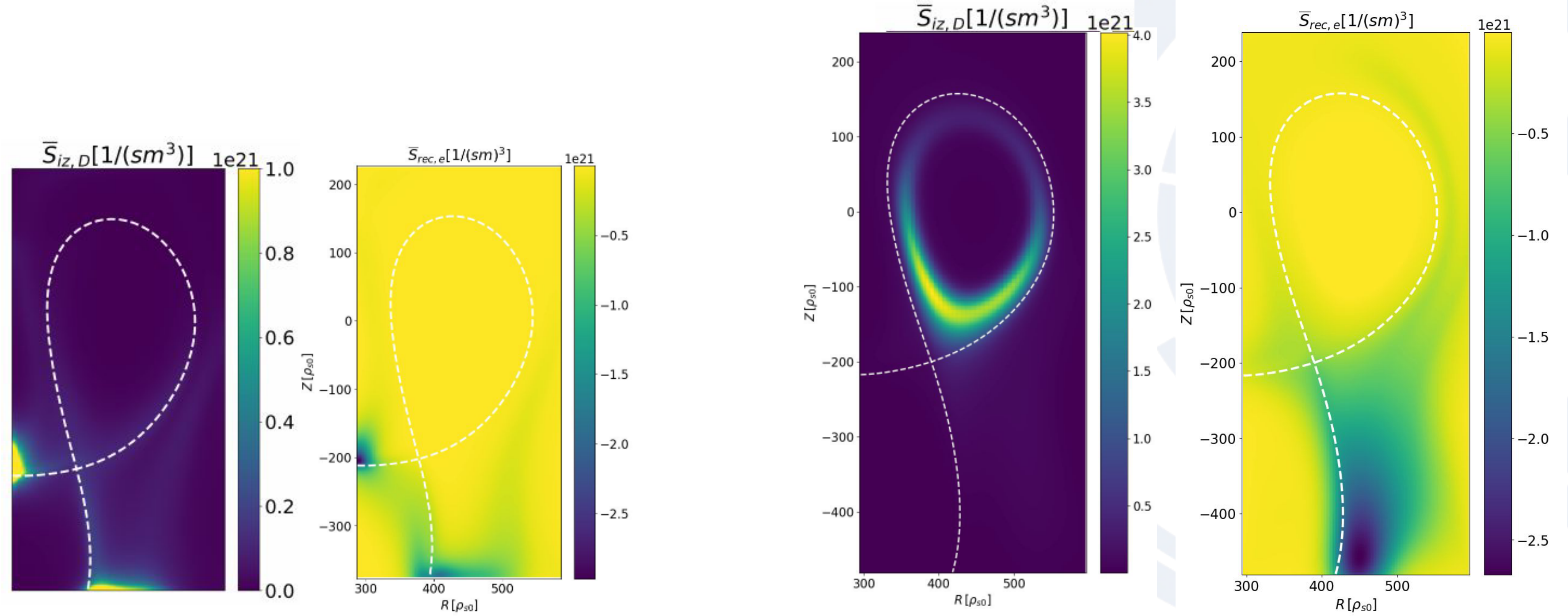






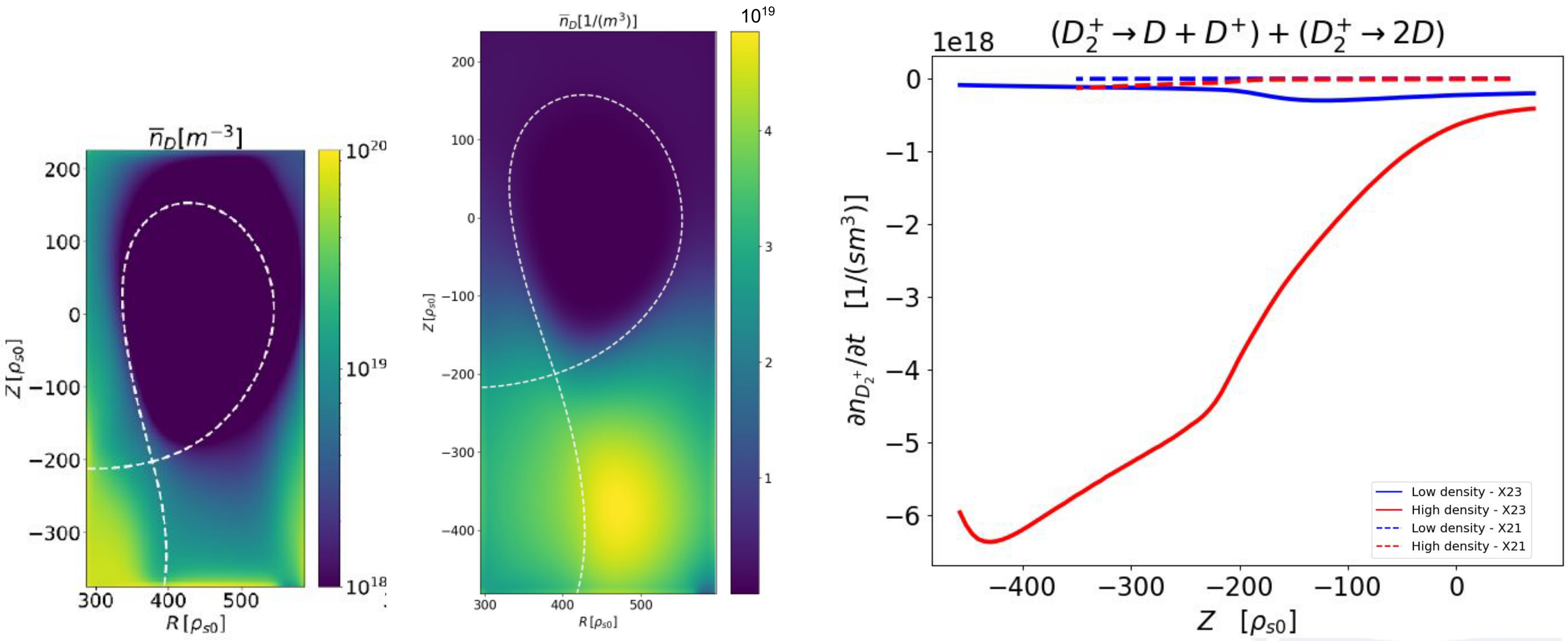
Ionization source detached from the target in X23

- Low temperature in TCV-X23 leads to ionization far from target even in low density
- Strong recombination in SOL for TCV-X23



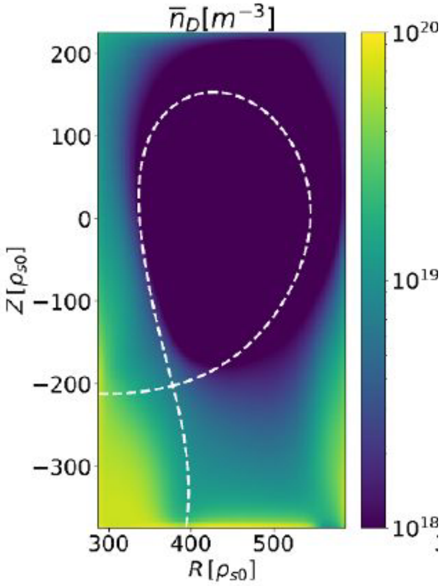
High D_2 density even with lower density

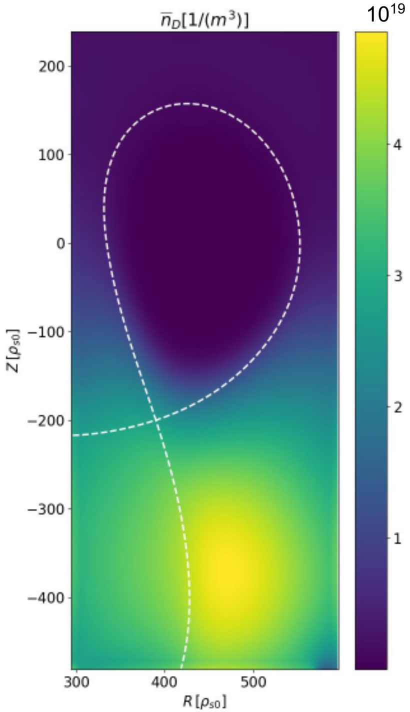
Higher D penetration due to higher D_2 dissociation

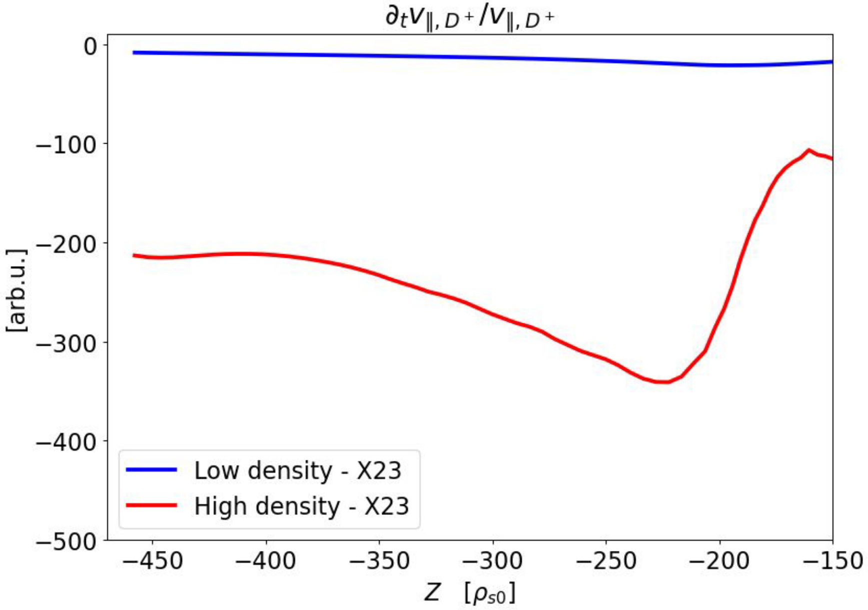


High D_2 density even with lower density

Higher D penetration due to higher D_2 dissociation → leads to momentum losses along leg





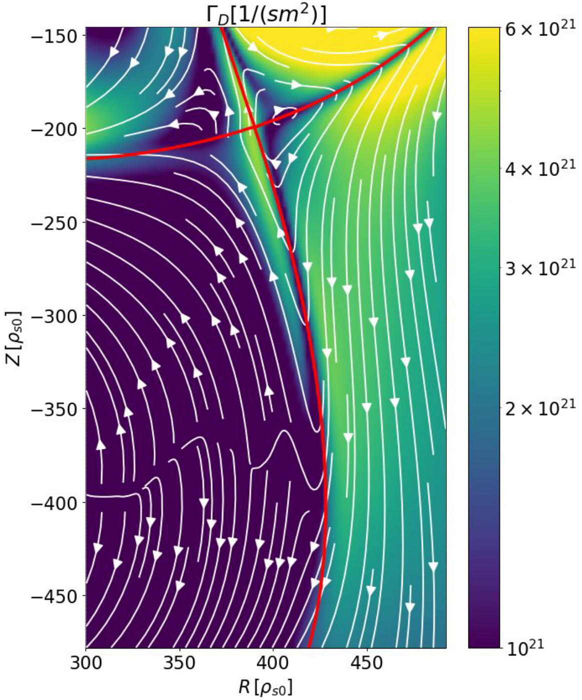


Decrease of particle flux localized along outer leg

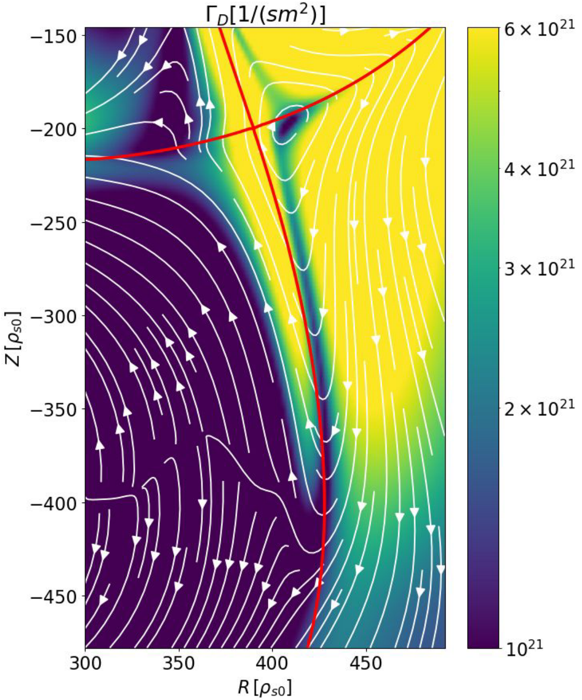
Low density: mostly parallel flow, small gradient along leg

High density: increased flow upstream, but strong gradient along leg → strong detachment

Low density



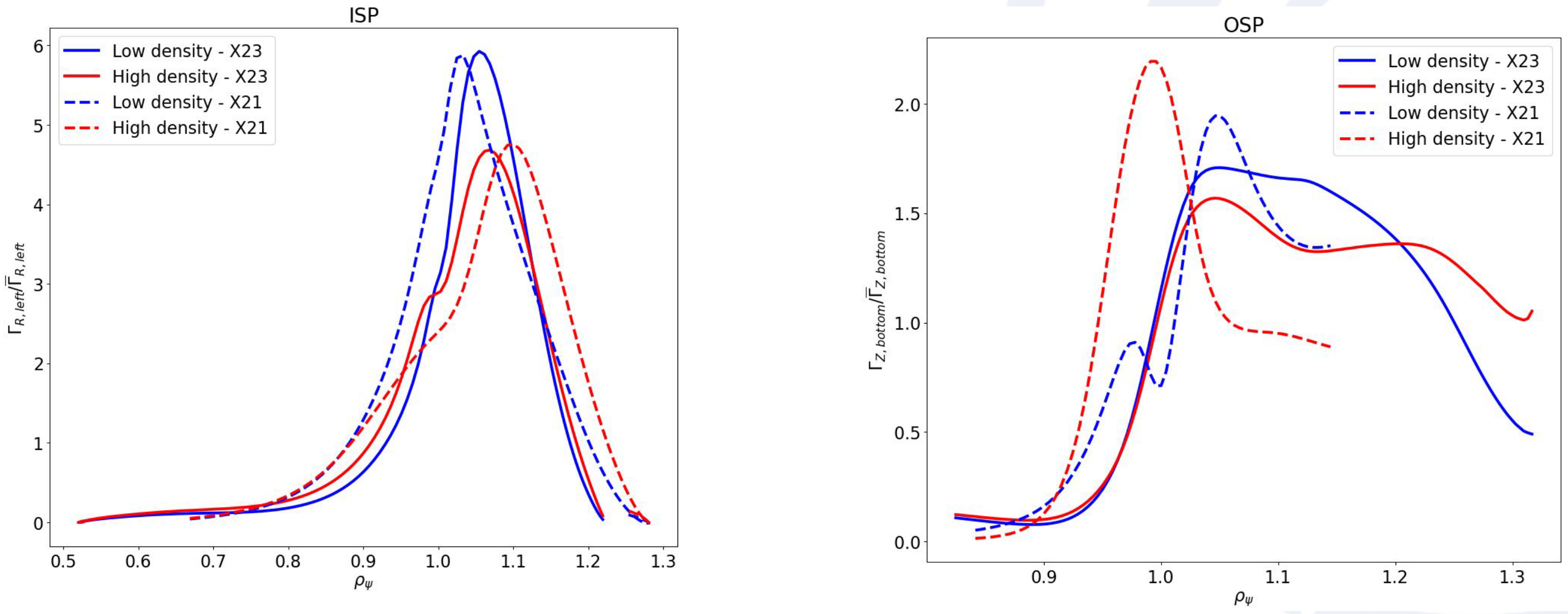
High density



Ion fluxes at target decreases

At both target decrease with increasing density:

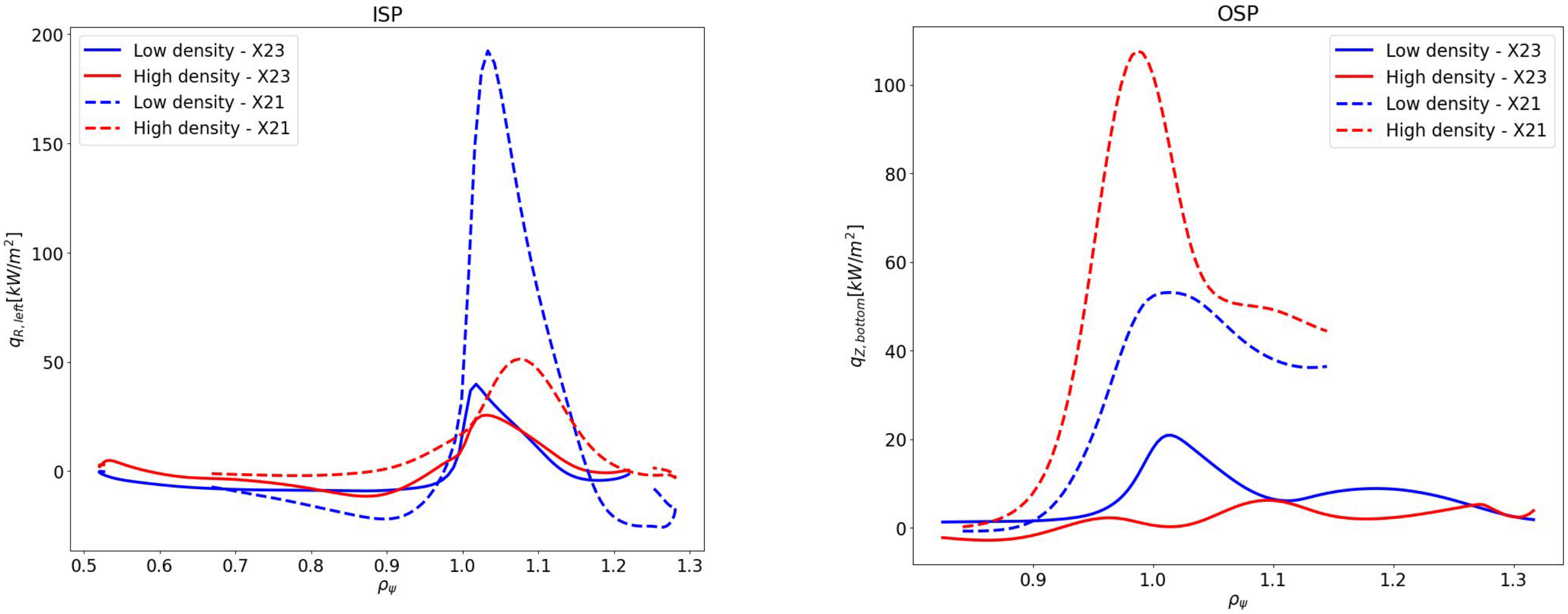
- At ISP same shape for TCV-X21 and TCV-X23 → detached in similar way
- At OSP broader peak in TCV-X23 even at low density → already quite detached



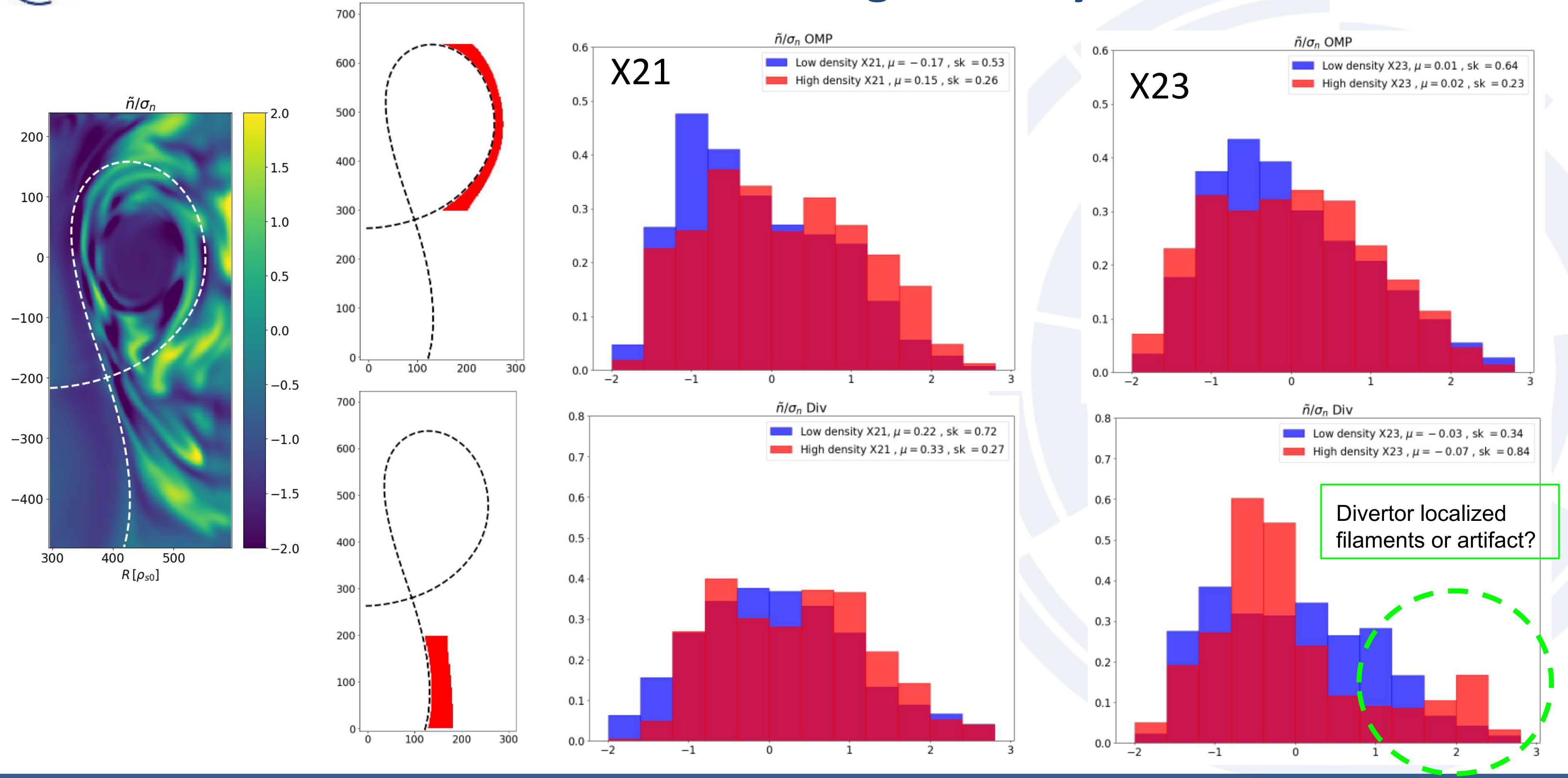
Heat fluxes at target decreases

Low heat flux at both targets:

- At ISP, TCV-X23 exhibits heat flux similar to high density TCV-X21
- At OSP strong decrease of heat flux and complete flattening for high density



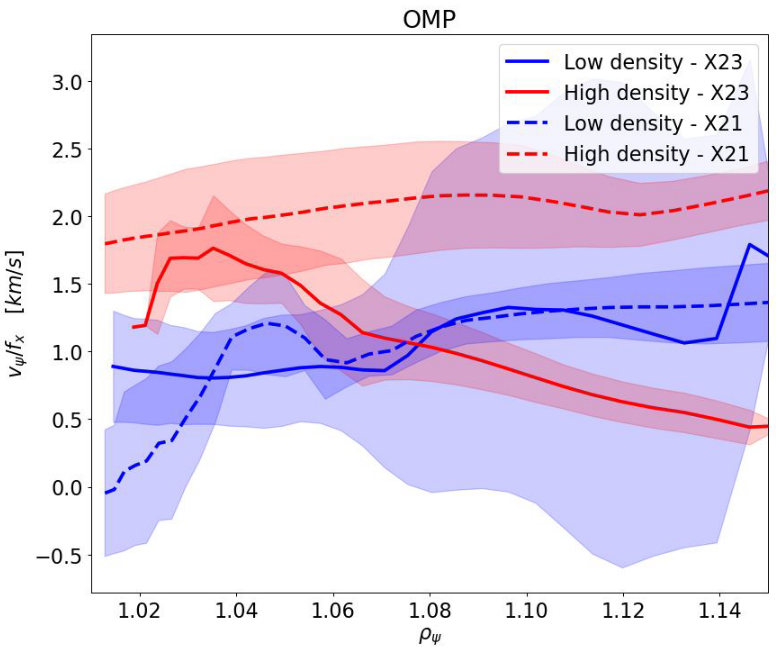
Positive fluctuations increase in high density

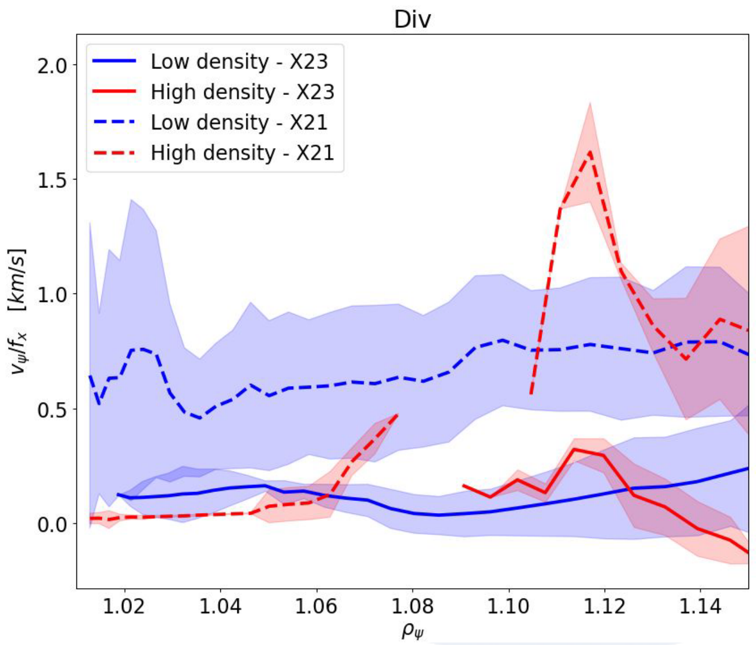


Slow or absent filaments when detached

First analysis of turbulence profiles:

- At OMP velocity ~ follows ordering shoulder profiles
- At divertor no filaments close to separatrix in high density → disconnected?

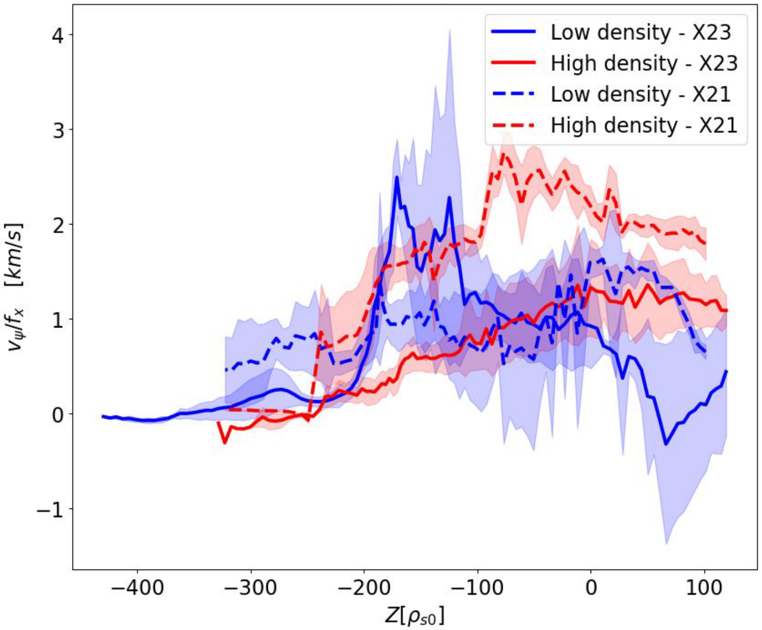


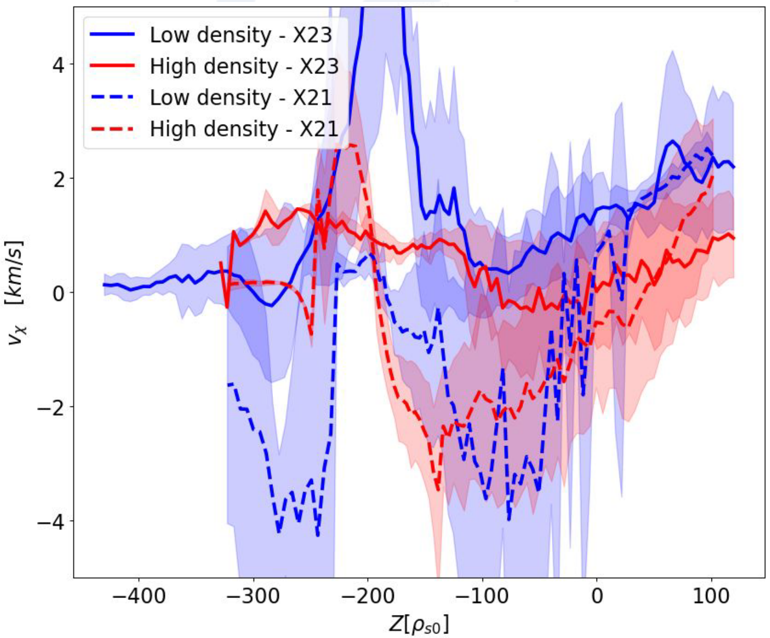


Decreasing velocity below X-point, steeper if detached

Analysis along SOL:

- Radial velocity decreases strongly when detaching
- Poloidal velocity decreases rapidly with longer leg and higher density below X-Point





Conclusions

GBS simulations to reproduce experimental results of TCV-X23 shots are almost converged

Preliminary analysis of comparison low vs high density in TCV-X23 shows:

- Similar profiles in the two cases (between TCV-X21 case) → low impact of puffing at OMP
- Low plasma temperature in TCV-X23
- Strong fluxes reduction with puffing → localized neutrals increase momentum losses
- Stronger detachment in TCV-X23 high density case (higher density with lower fluxes)
- Enhanced fluctuations level and OMP velocity for higher density
- No filaments in divertor region → disconnected filaments?

Next steps:

- Collect more turbulence statistics, verify disconnected filaments when detached
- Understand balance of neutrals along leg