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## Self-organization of plasma edge turbulence in interaction with neutrals recycling

Virginia Quadri, P Tamain, Y Marandet, H Bufferand, N Rivals, R Düll, G  
Ciraolo, H Yang, K Galazka, G Falchetto

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# Self-organization of plasma edge turbulence in interaction with neutrals recycling

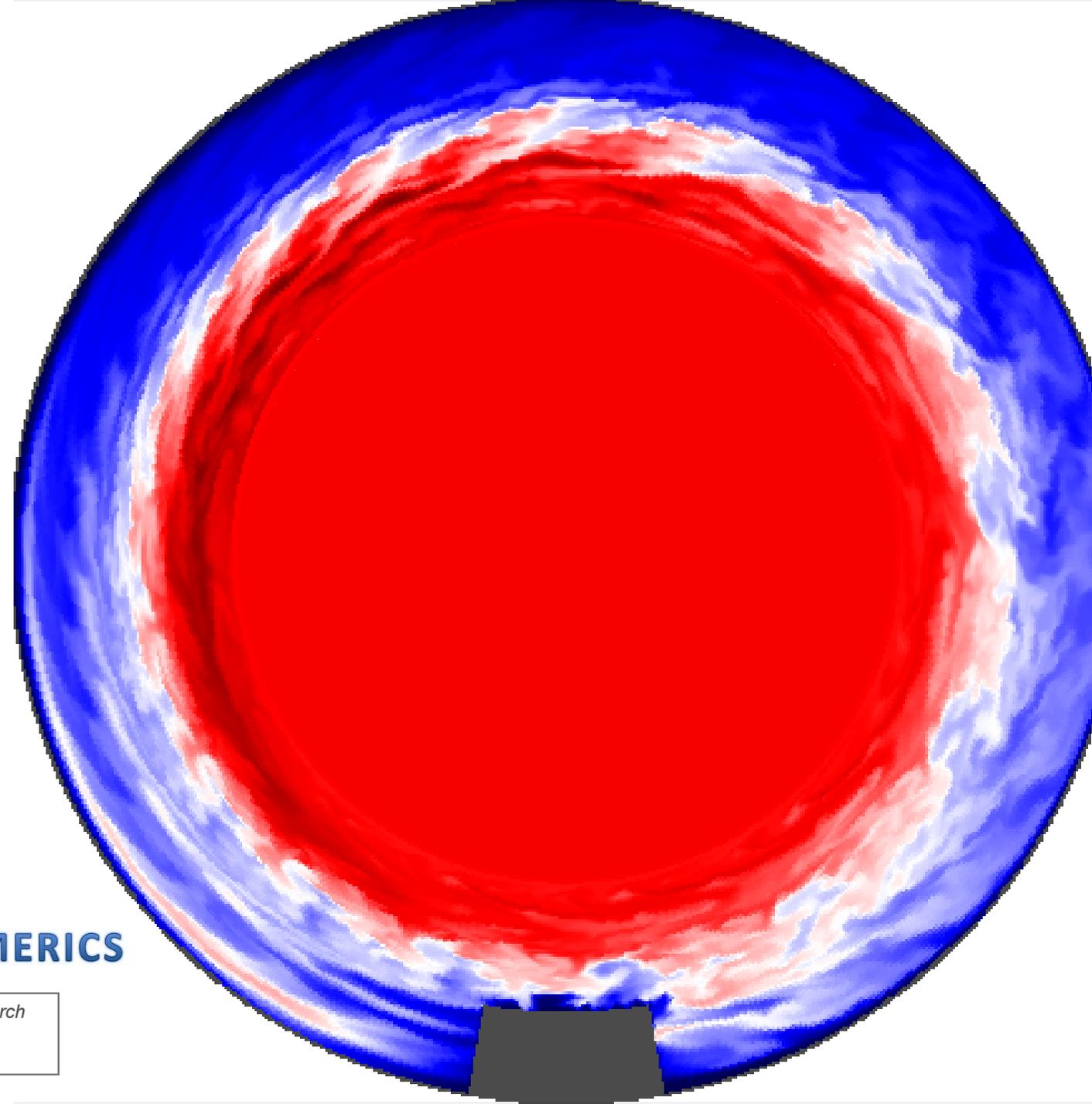
Virginia Quadri\*, P. Tamain, Y. Marandet, H. Bufferand, N. Rivals, R. Düll, G. Ciraolo, H. Yang, K. Galazka, G. Falchetto, and the SOLEDGE3X team all.



EUROfusion NUMERICS

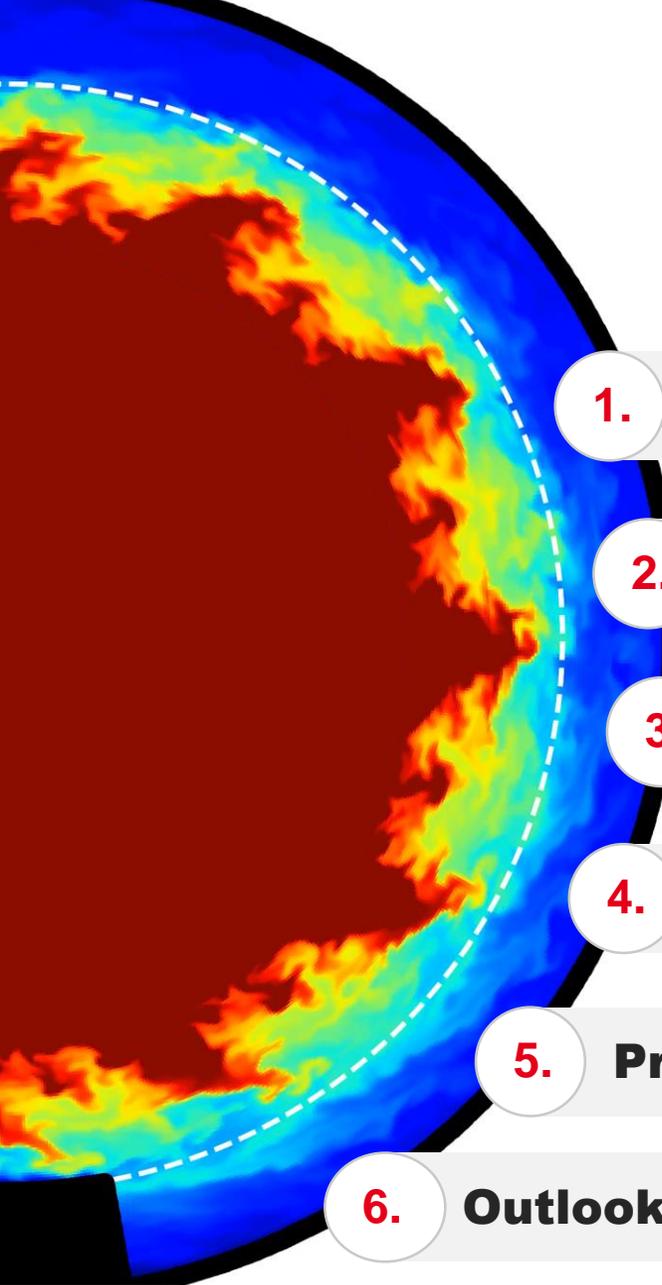


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# Content

*How neutrals fueling does impact turbulence  
The way for running these cases, the difficulties and their solutions*



**1. Transverse transport organization in the edge of tokamaks**

**2. Turbulence-neutrals modeling in Soledge3X-EIRENE**

**3. Impact of localized gas puff on toroidal symmetry**

**4. Self organization of turbulence w/ respect recycling**

**5. Preliminary study in diverted configuration**

**6. Outlooks and conclusions**



1

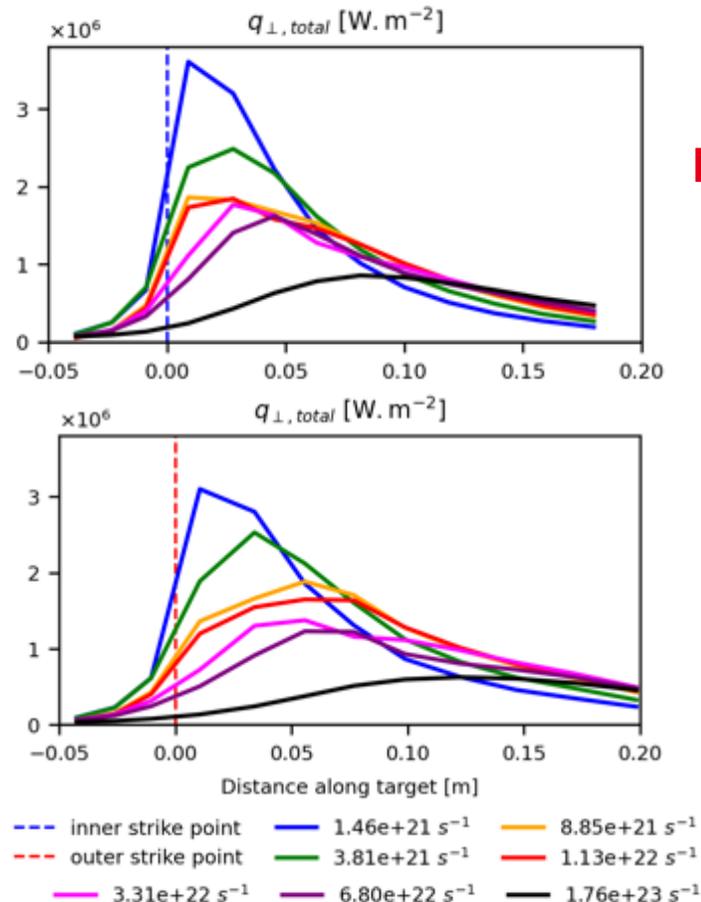


# Transverse transport organization in the edge of tokamaks

*The key-players, the need of modeling the edge for getting the relevant reactors operating regimes.*

# High recycling and detachment as relevant reactors operating regimes.

**Framework:** Dissipating the heat exhaust flowing through the SOL + dealing with the local density and energy fluxes, which determine the temperature at the wall.



*No future fusion devices with solid divertor will operate in attached conditions!*

The relevant reactors operating regimes are **detached regimes** where **plasma neutrals interactions** play a fundamental role for the edge plasma equilibrium.

Crucial modeling properly the SOL.

# The state of the art: the use of mean field code for modeling the SOL

Modeling of the detachment condition → **2D mean field codes** ( $\lambda_q$  and level of turbulent transport as an inputs).

- Transport locked for different densities;
- $\lambda_q$  is not calculated self-consistently: **ad hoc parameter** (*interpretative modeling*).
- Turbulence not included.



*...the reason why:*

There is **no multi-machines scaling law** for this level of transport at high density regimes

**The transport is not evaluated self consistently.**

To look at the strong interactions with neutrals,  $\lambda_q$  **has to be predictive** and **turbulence** has to be included.

# The exigence of having turbulence code including neutrals recycling

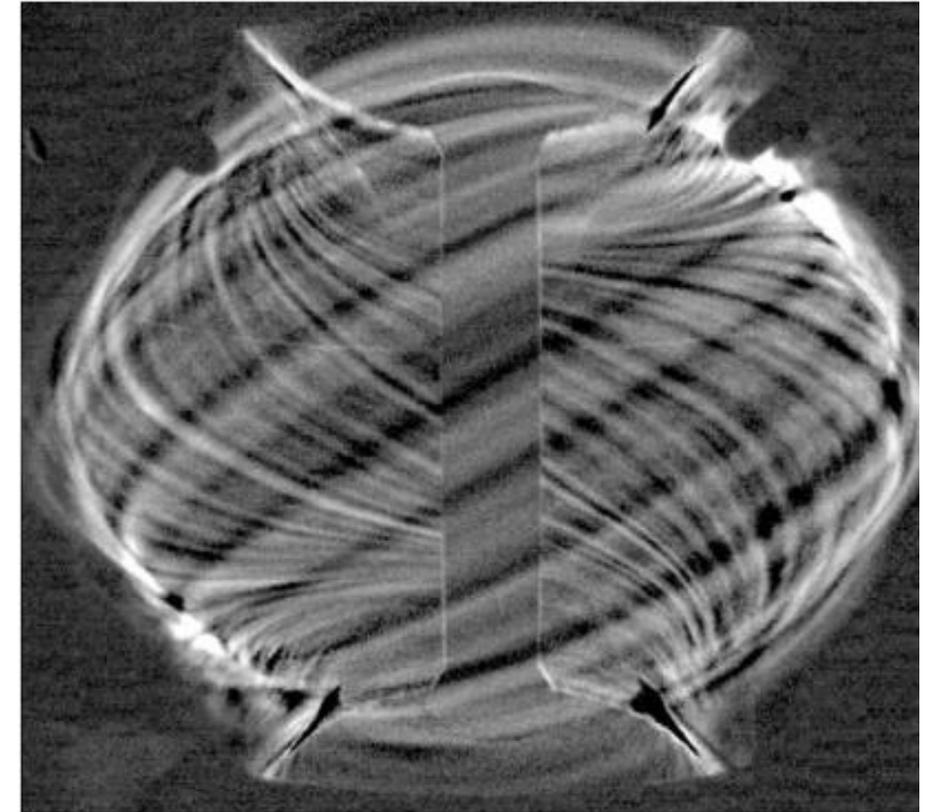
## Why turbulence?

- major actor for the radial transport in the edge.
- Influence the level of interactions between plasma and the wall.
- Experimental evidences show how turbulent transport is likely to depend on density regimes [[Eich et al, NF 2020](#)].



**Turbulence and neutrals physics are interconnected:**  
mandatory to model them at the same time.

Tools like Soledge3X-EIRENE are attempting an important step towards *predictive* modelling.



Visible light image of filaments in Ohmic L-mode on MAST. [[B. D. Dudson](#)]



# **2 ■ Turbulence-neutrals modeling in Soledge3X**

*The challenges of modeling the SOL and possible ways out.*

# The Soledge3X-EIRENE tool: state of the art

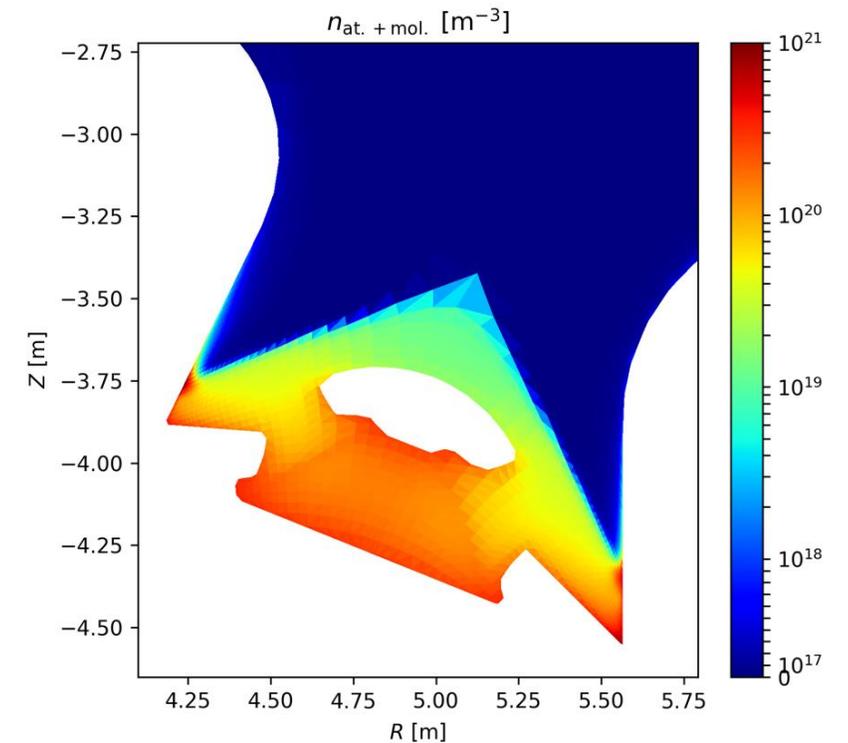
**Soledge3X** is an edge multi fluid code, implementing the mass, momentum and energy balance for an arbitrary number of plasma species.

It is coupled with **EIRENE** for a kinetic description of neutrals

The coupling has successfully made for the 2D mean field transport and running routinely for ITER cases.

## Capabilities:

|                           | Soledge3X | EIRENE |
|---------------------------|-----------|--------|
| Mean Field Transport      | ✓         |        |
| Turbulence                | ✓         |        |
| 3D                        | ✓         |        |
| Realistic plasma geometry | ✓         |        |
| Realistic wall geometry   | ✓         |        |
| Multi-species             | ✓         |        |
| Drifts                    | ✓         |        |
| Embedded fluid neutrals   | ✓         |        |
| Kinetic neutrals          |           | ✓      |



[N. Rivals, 2023, PhD thesis]

# Experiencing limitations in EIRENE coupling for 3D turbulent cases

The coupling works in 3D with reduced mesh (i.e. *low resolutions*) for any kind of geometry.

BTW, turbulence transport required mesh at Larmor radius resolutions.

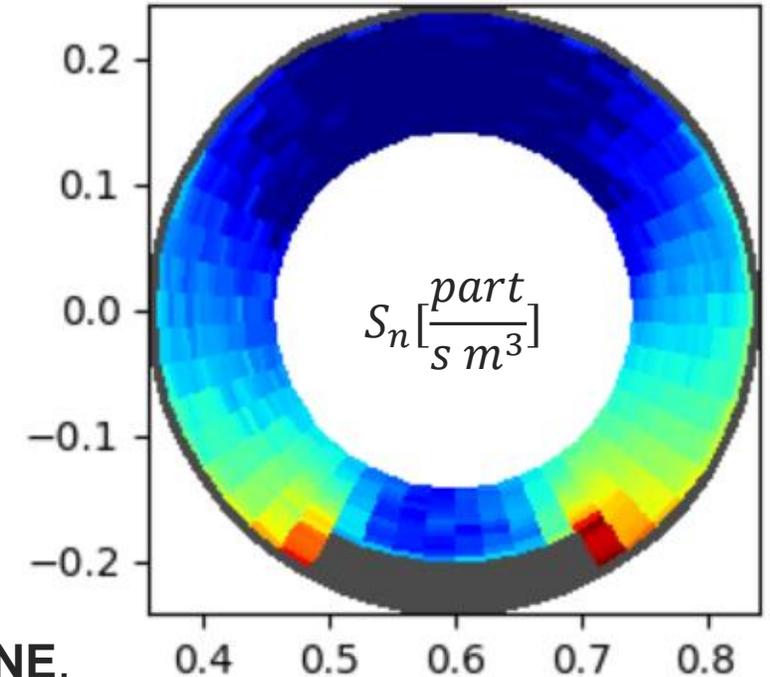
High resolution + 3D = much more points in the grid!

Too large memory consumption for EIRENE parallelized in MPI mode

Impossibility in running production cases with turbulence and EIRENE.

There are two main options taken into account:

1. Run with the newly available OpenMP version of EIRENE.
2. Change the way the couple is made, considering a coarser mesh for EIRENE respect with the one of Soledge3X.



*In the meantime, upgrading the fluid neutrals model in Soledge3X to stick with EIRENE.*

# The exigence of switching to a fluid description: the embedded fluid neutrals model in SOLEDGE3X.

The limit:

kinetic description  $\rightarrow$  fluid model = missing information

The goal: providing a qualitative interpretation of the physics as close as possible to EIRENE, by having a **realistic localization of the recycling source** and **consistent momentum and energy sources**.

*Convection – pressure diffusion*

$$\partial_t \mathbf{n}_n + \vec{\nabla} \cdot \vec{\Gamma}_n = S_{n_n} \text{ where } S_{n_n} = n_i n_e K_r - n_n n_e K_i$$

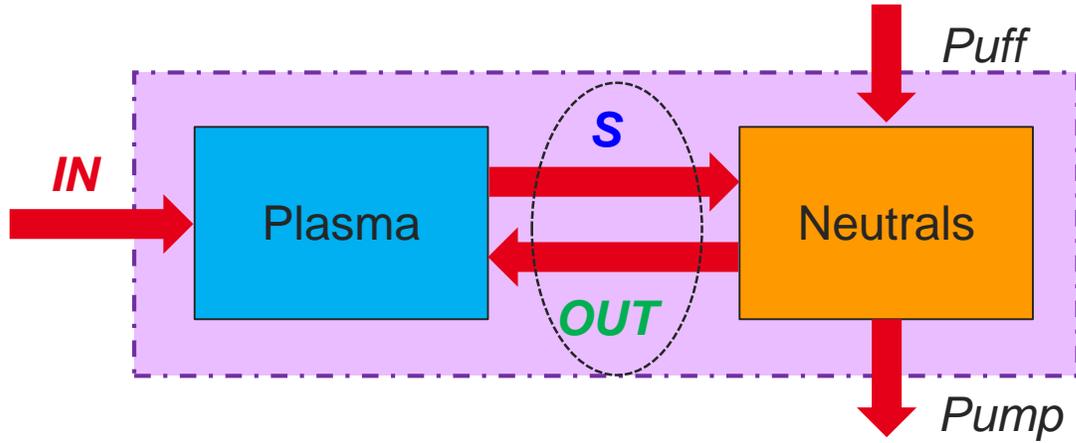
$$\vec{\Gamma}_n = n_{n,eq} \vec{u}_i - D_p^n \vec{\nabla} p_n$$
$$D_n^p = \frac{1}{m(n_i K_{cx,m} + n_e K_i)}$$

*hp*: referred to **charge exchange-dominated region** ( $T_n = T_i$ )  
(ref. Horsten et al, 2017, Nuclear Fusion 57, 116043)

*How do embedded neutrals impact the convergence and the solution in Soledge3x?*

# Particle balance and particle conservation

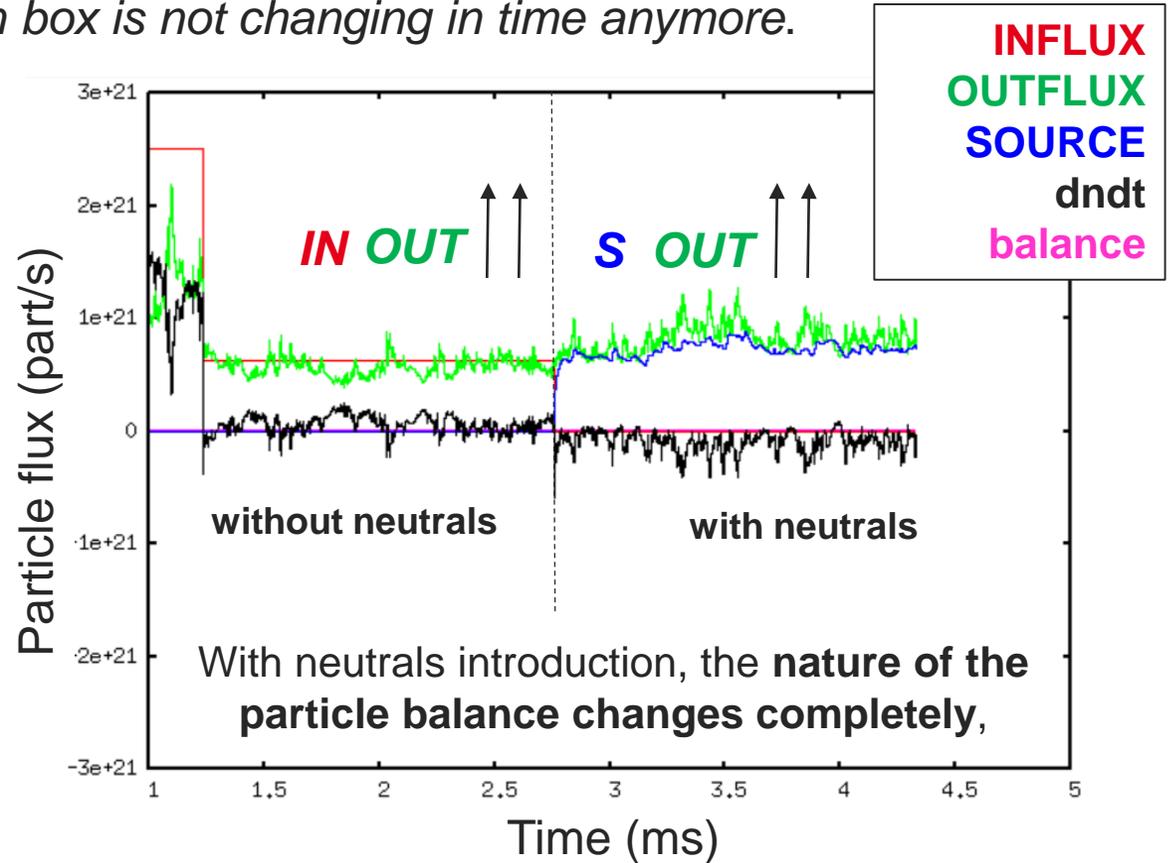
Particle balance = the amount of particle in the simulation box is not changing in time anymore.



**Global:** 
$$\frac{\partial \int N + N_n}{\partial t} = \Gamma_{IN} + \Gamma_{puff} - (1 - R)\Gamma_{out}$$

**Neutrals:** 
$$\frac{\partial \int N_n}{\partial t} = \Gamma_{puff} + \Gamma_{out} - \Gamma_{PUMP} - S$$

**Plasma:** 
$$\frac{\partial \int N}{\partial t} = \Gamma_{IN} + S - \Gamma_{out}$$



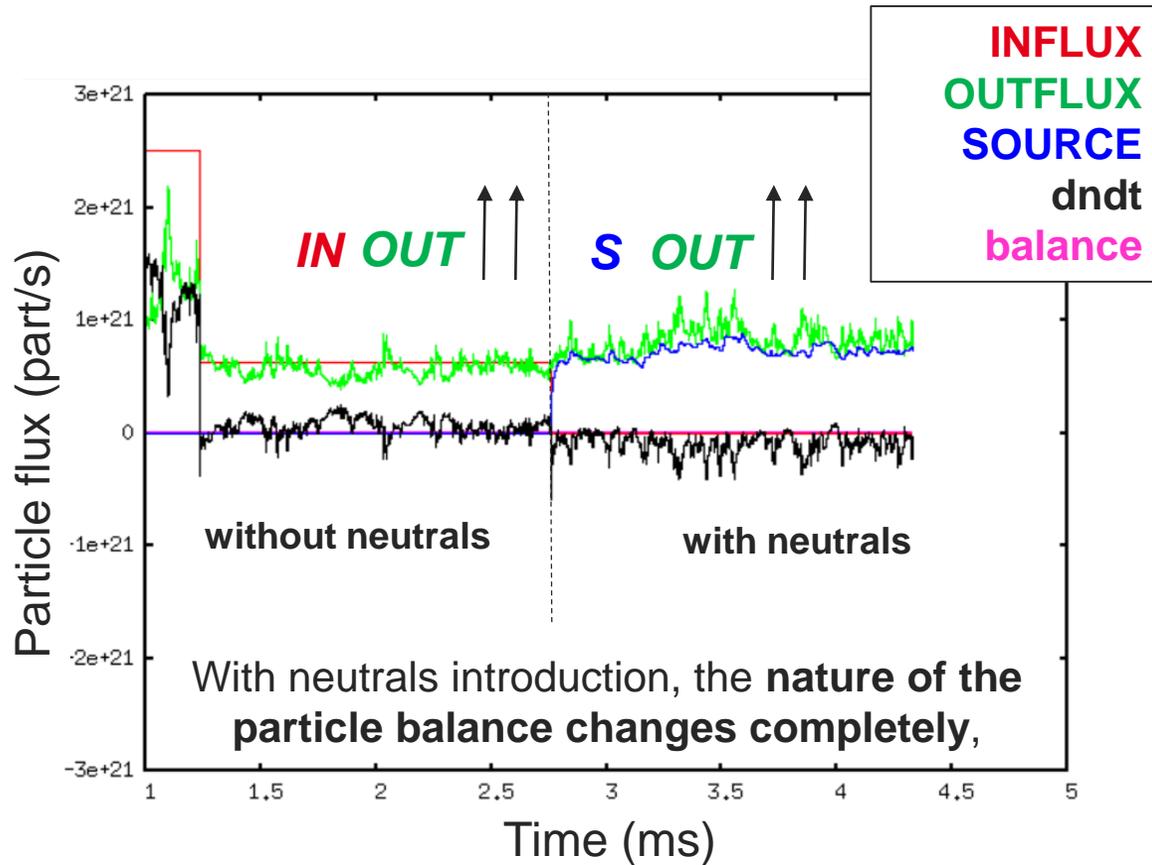
Conservation is a critical point for simulations with neutrals

- sanity check (**balance**)
- shows dominant terms (they change respect with driven mechanism)



Particle conservation perfectly maintained: **machine precision**

# Particle convergence: reaching the steady state



To reach steady state:  $\left\langle \frac{\partial \int N + N_n}{\partial t} \right\rangle_{tts} \rightarrow 0$ , and so

$$\left\langle \Gamma_{IN} + \Gamma_{puff} - (1 - R)\Gamma_{out} \right\rangle_{tts} \rightarrow 0$$

Convergence ratio:  $CR = \frac{\left\langle \frac{\partial \int N + N_n}{\partial t} \right\rangle_{tts}}{\Gamma_{IN} + \Gamma_{puff}} \sim 1 - 2\%$

*Plot CR as function of time  
(negative in this case, still not steady state!)*

# The convergence issue for turbulent – neutral cases

Different time scales interplay among them; **global convergence takes long** [H. Bufferand, PET-19, 18/09/23]

$$\tau_{eq} \sim 100 \text{ ms}$$

*Does it really matter being in steady state for investigating the properties of turbulence w/ recycling?*

**NO**



It depends on how the simulations are driven



**YES**

**A theoretical exercise in circular geometry**

- Fixed plasma conditions
1. *Does the gas puff break the axis-symmetry?*
  2. *How do the fluxes change at the poloidal direction?*
  3. *How do the turbulence properties change?*

**Divertor simulations matching the experiments**

- Plasma conditions corresponding to throughputs

# The circular cases: a theoretical exercise for understanding the neutrals impact on turbulence.

## Set-Up

3D Toroidal geometry –  $r \sim \rho_L, \theta \sim 2\rho_L$   
 ( $\phi = 128, \theta = 1024, r = 100 \sim 10^7$  points)

1/4 torus

Poloidal bottom extended *limiter*

Pure D plasma, two species  $e^-, D^+$

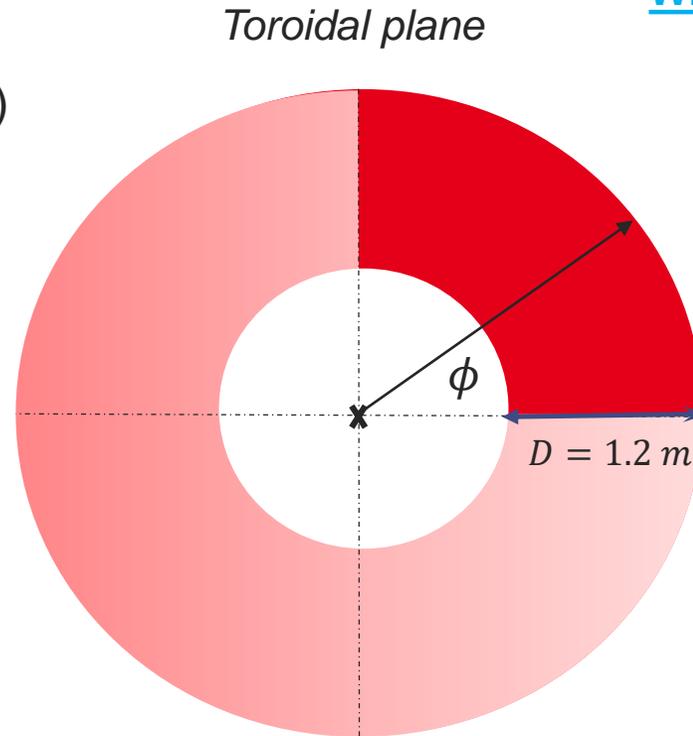
Drifts:  $E \times B, \nabla B$

Turbulence triggered by initial perturbation on the influx.

$$P_{TOT} = 62.5 \text{ MW}$$

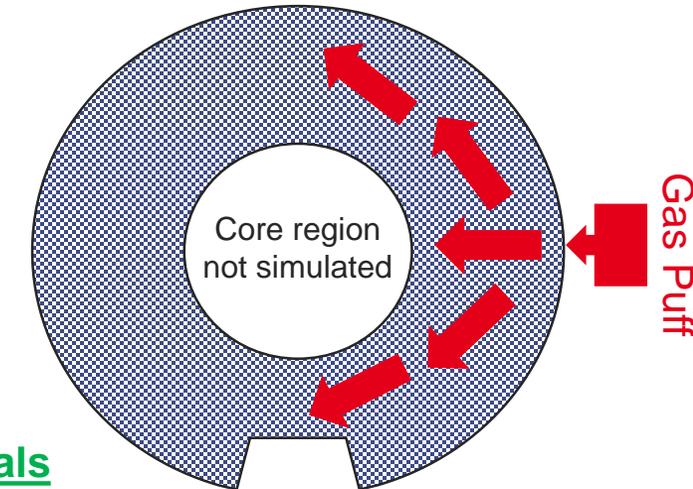
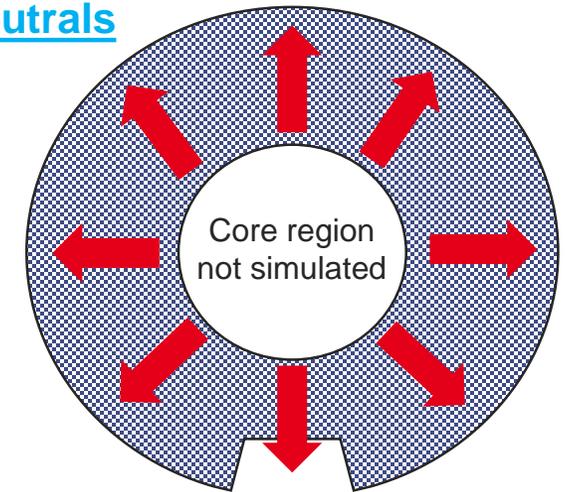
$$n_{BC} = 2.5 \times 10^{21} \text{ m}^{-3}$$

$$\text{Puff} = 2.15 \times 10^{20} \text{ m}^{-3} \text{ s}^{-1}$$



Without neutrals  
(NN)

Poloidal plane



With neutrals  
(WN)



# **3 ■ Impact of localized gas puff on toroidal symmetry**

- 1. Does the gas puff break the axis-symmetry?**

# The gas puff does impact the toroidal symmetry

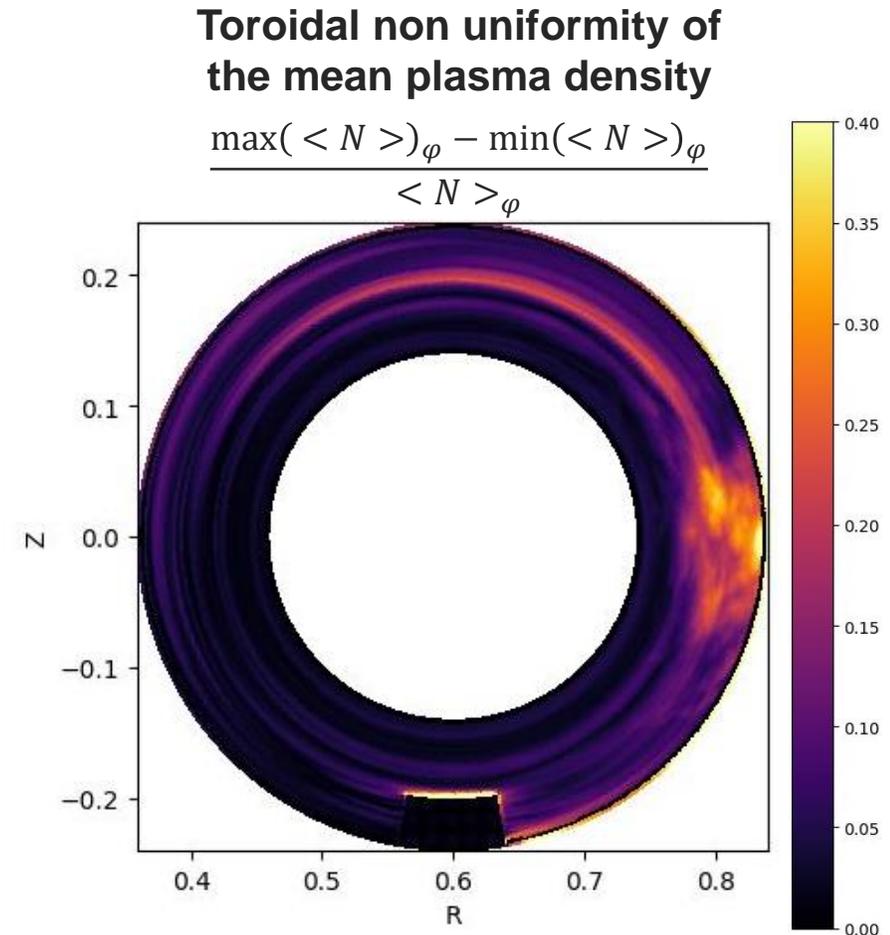
The gas puff introduces a **non-axis-symmetry** perturbation in the system along the toroidal direction.

*The effect of the perturbation is strongly **localized**.*

*The **entity** of the perturbation can be huge: **up to 40%** for some field (i.e. mean density)*

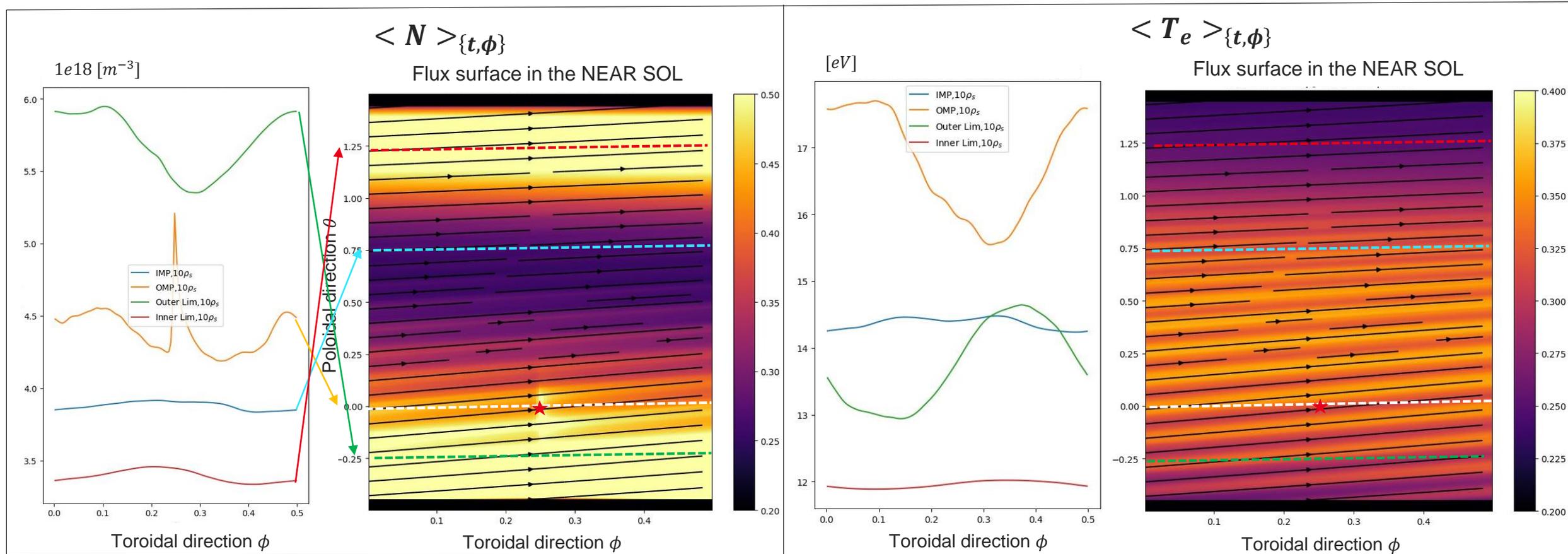
## Consequences on

- the **physics** (locally and not)
- the way in which simulations are **analyzed**.



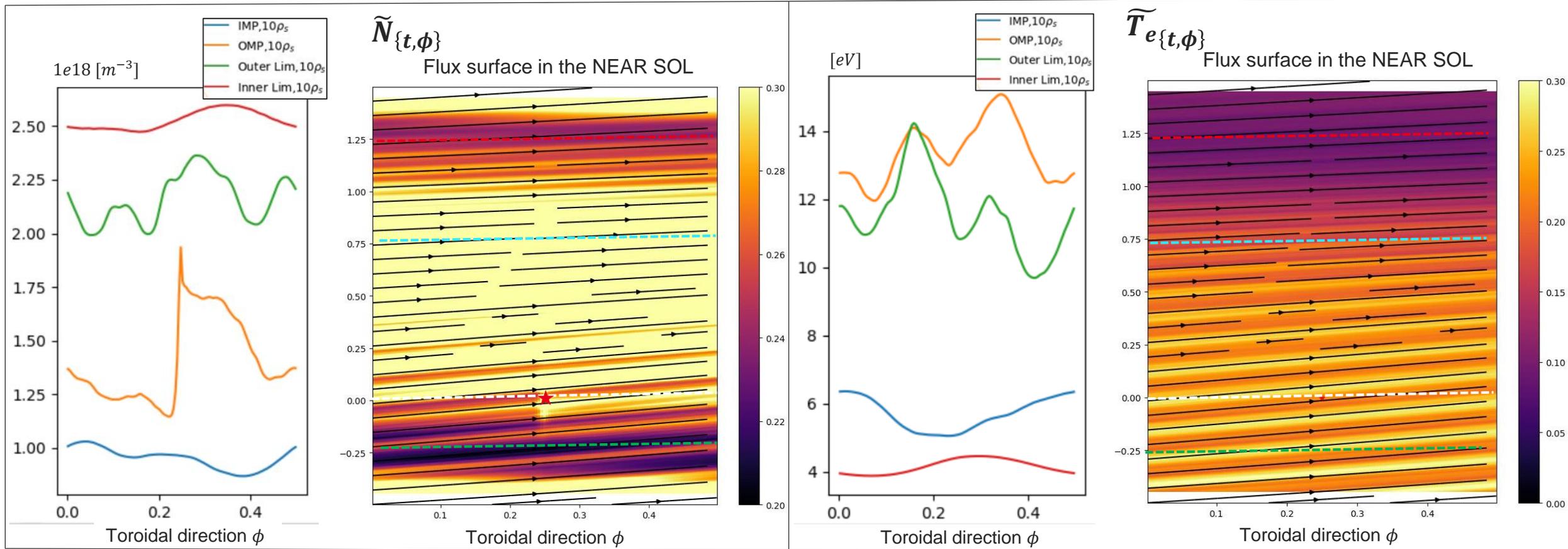
# Local & non local effects of the gas puff

- The non-axisymmetric perturbation driven by the puff has an impact on the mean plasma quantities.
- The impact of the puff is **flux tube localized**, the entity is more than 40% for some fields.
- **Not all the fields** are impacted in the **same way**.



# Local & non local effects of the gas puff

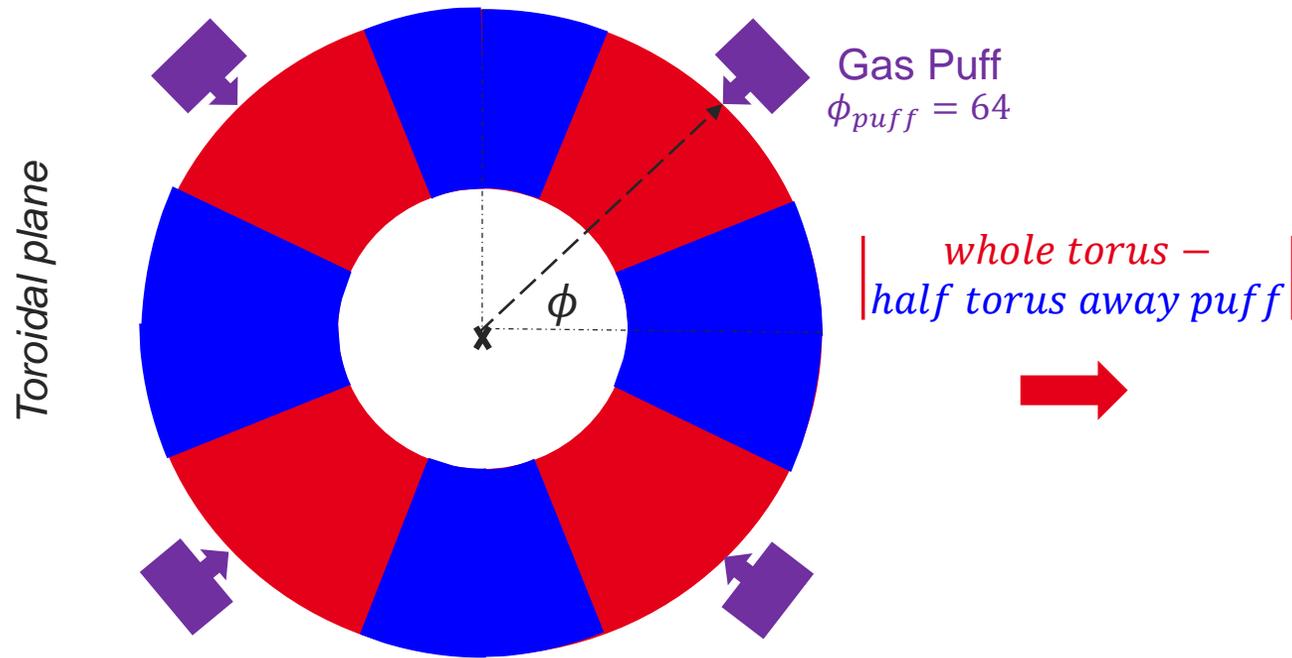
- The non-axisymmetric perturbation driven by the puff has an impact on turbulent transport.
- The impact of the puff is **flux tube localized**, the **change in local fluctuation rates is up to 20%**.
- This may be worrying for the **gas puff imagining** through diagnostics.



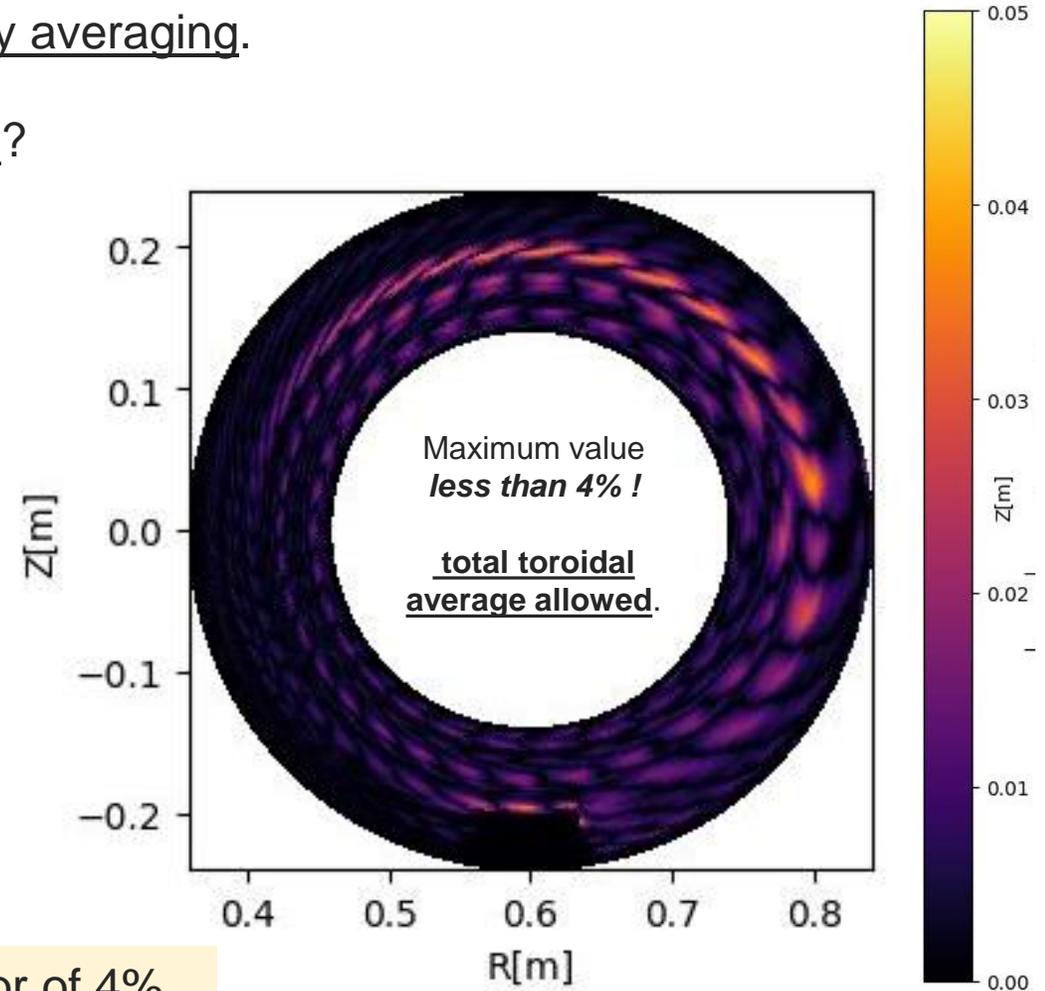
# Consequences on performing the analysis

The system is strongly axis-asymmetric due to the puff.  
Statistical analysis on turbulence are usually made by toroidally averaging.

➔ Can we drop the information along the toroidal direction?



*whole torus –  
half torus away puff*



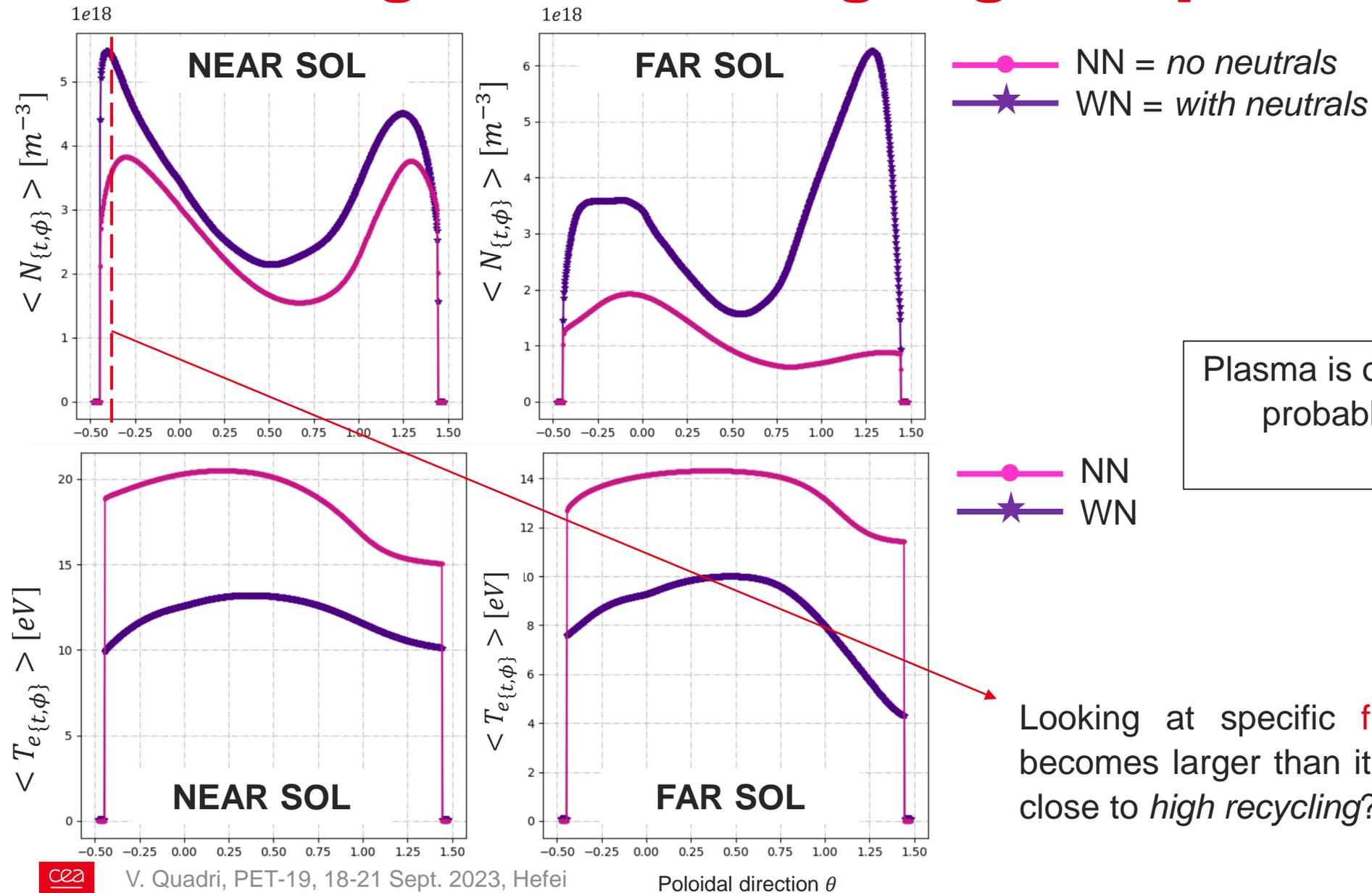
**Yes**, the following statistical analysis will be affected by an error of 4%.



# **4. Self organization of turbulence with respect neutrals recycling**

- 2. How do the fluxes change at the poloidal direction?**
- 3. How do the turbulence properties change?**

# Identifying the recycling regime: poloidal profiles

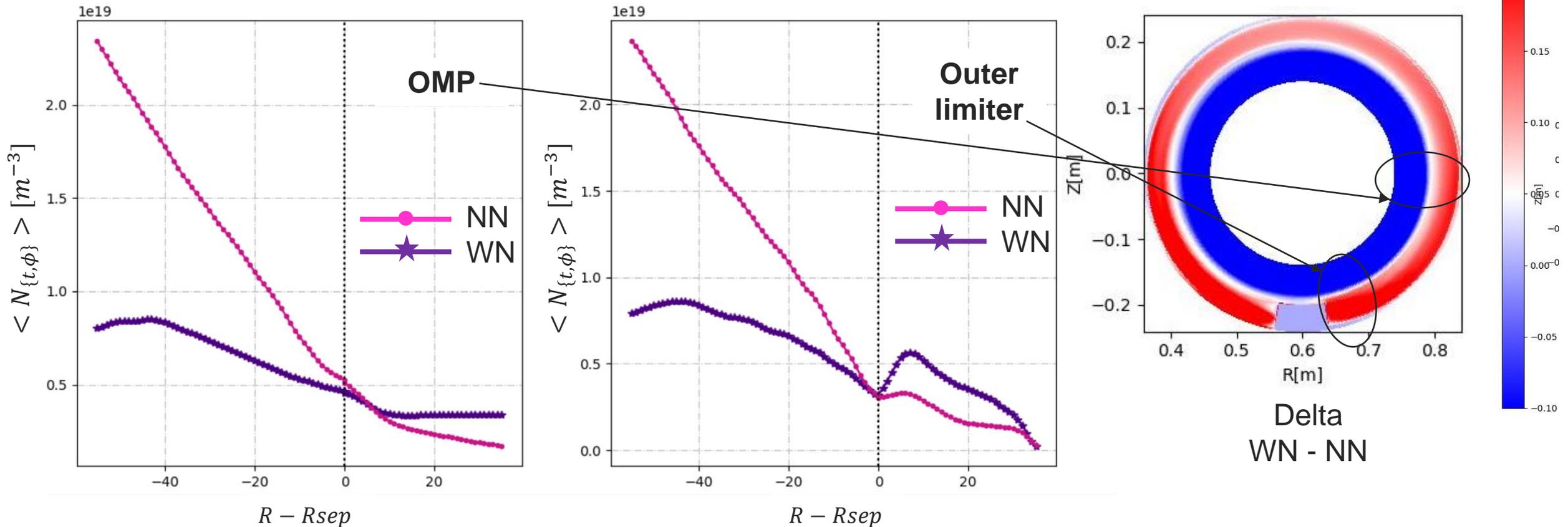


Plasma is overall denser and cooler but probably still in a **low recycling regime.**

Looking at specific **flux surfaces** the density becomes larger than it is in absence of neutrals: close to *high recycling*?

# Impact of neutrals on plasma overall equilibrium

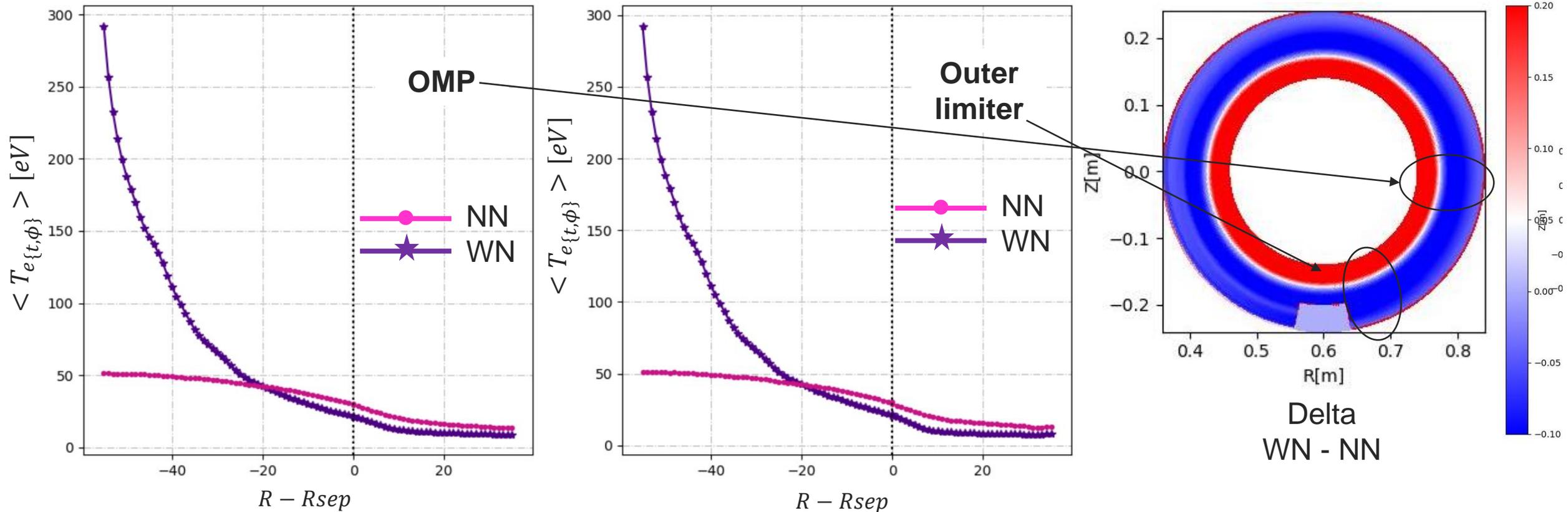
Changing in the radial profiles for density due to a flux re-organization after the puffing of neutrals.



- **Poloidal asymmetries** do appear, much marked with FN that without.
  - Strong **density accumulation** close to the limiter.
  - **Flattening** of the profiles in the core, and in the SOL.

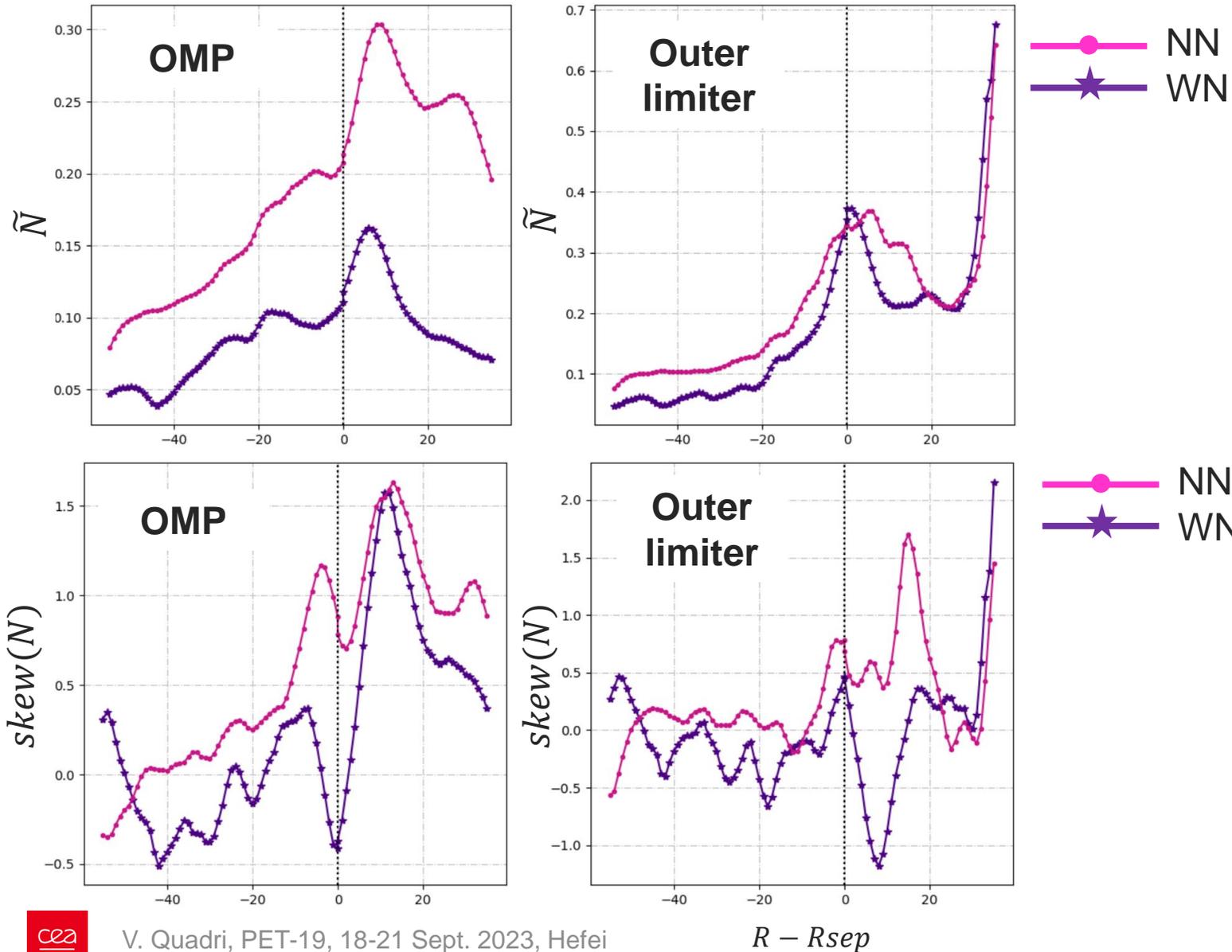
# Impact of neutrals on plasma overall equilibrium

Changing in the radial profiles for e- temperature due to a flux re-organization after the puffing of neutrals.



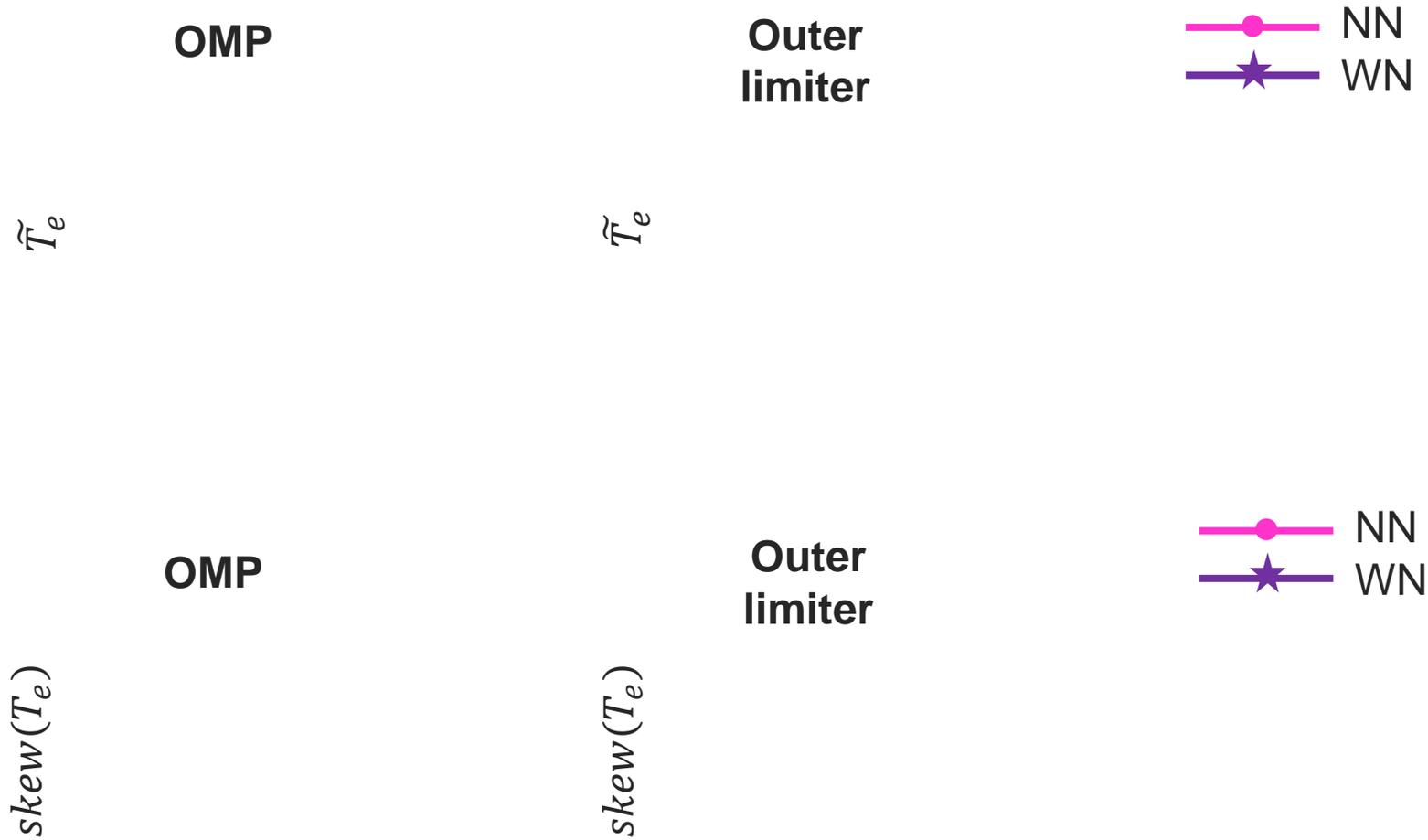
- Steepening of the profiles.
- Poloidal asymmetries not so strong as for the density

# Impact of neutrals on turbulent properties



- Sensitive differences w/ ancestor TOKAM3X.
- Global **change in the level of the fluctuations** for density, up to 20% at the midplane less at the target.
- The **general trend** is conserved.
- The skewness does not change so much.
- More negative events at the outer target where the recycling occurs.

# Impact of neutrals on turbulent properties





# **5. Preliminary study in diverted configuration**

# Matching experiments and more



**Goal:** Performing the same studies and answering the same question as the theoretical exercise.

Moreover:

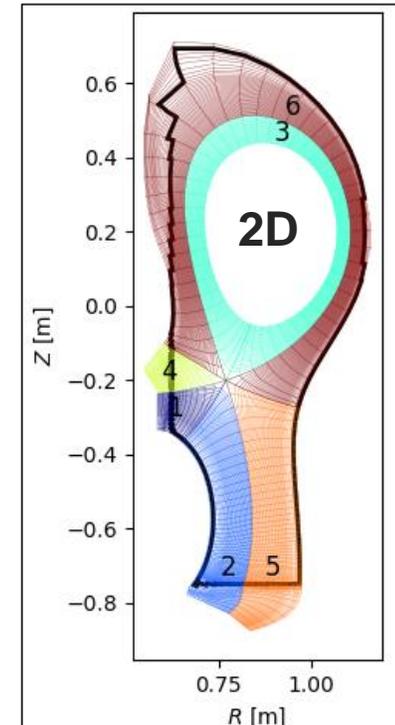
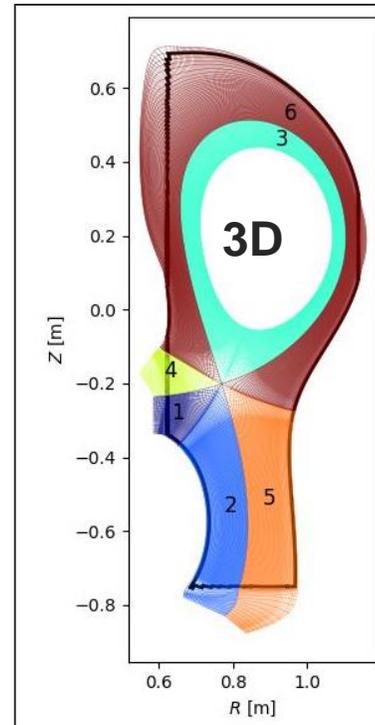
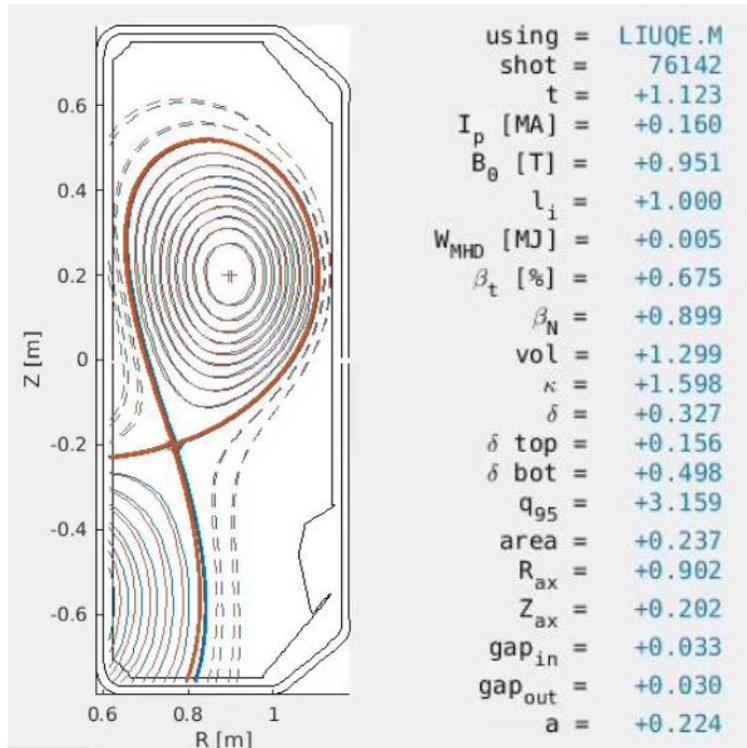
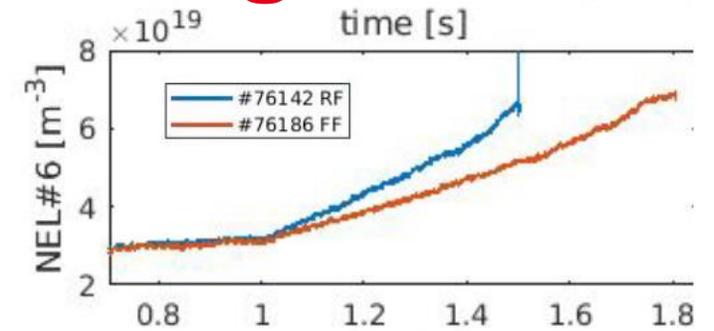
- Comparison to experiments
- Targeting different density regimes
- Benchmarking fluid neutrals model with respect EIRENE

# Modeling TCV experiments with Soledge3x

TCVX23 = Extension of TCVX21 experiment up to density regimes.

Long leg stable configuration at low field (RF #76142)

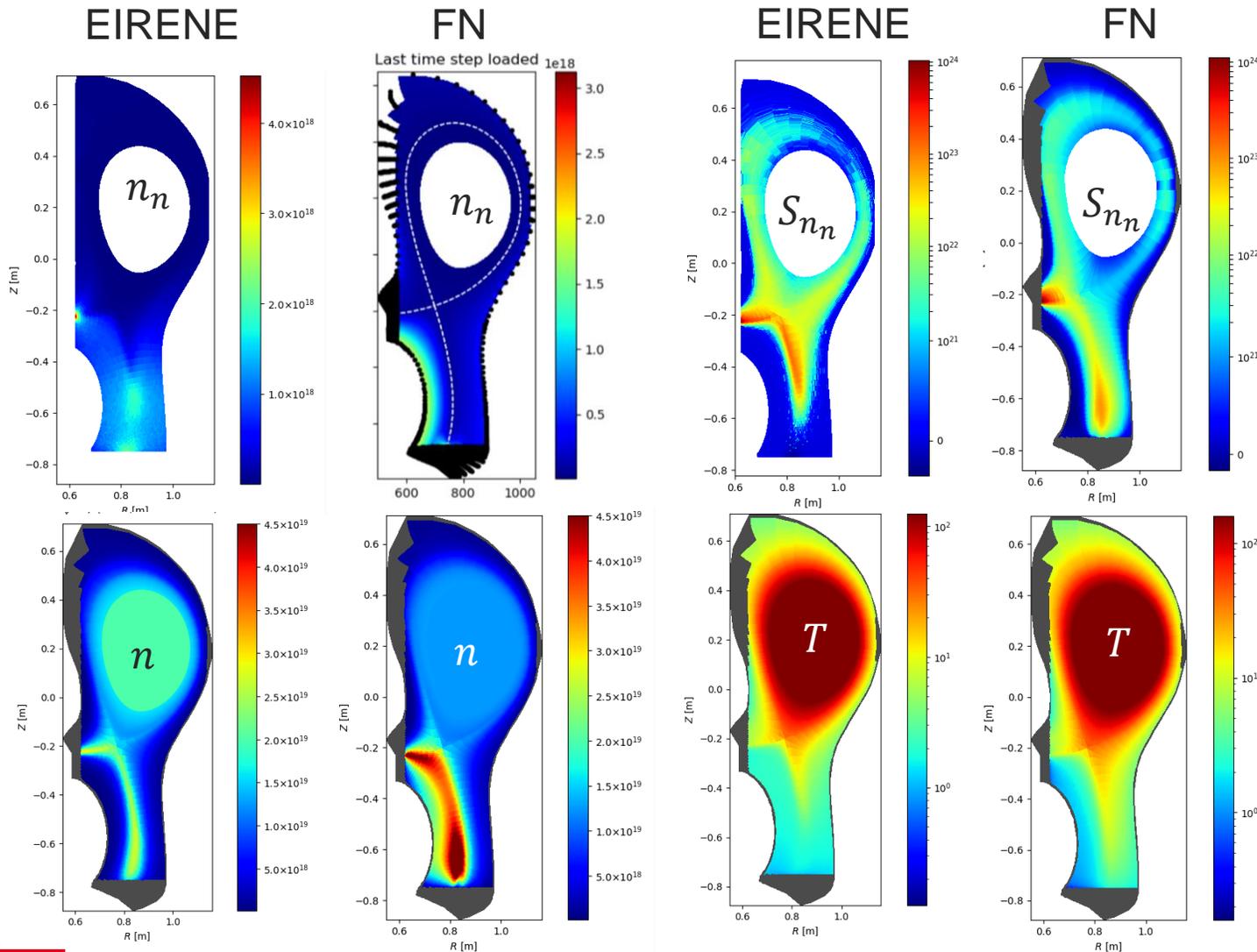
Initial density  $n_{sep} \approx 5E18$ , detachment at  $n_{sep} \approx 1E19$ ,  $P_{sep} = 160$  kW



[D. Sales de Oliveira et SPC team a]

[P. Tamain]

# 2D mean field case ( $n_{sep} = 1E19$ ): quality of FN compared with EIRENE.



- The neutrals density distribution not realistic

Still:

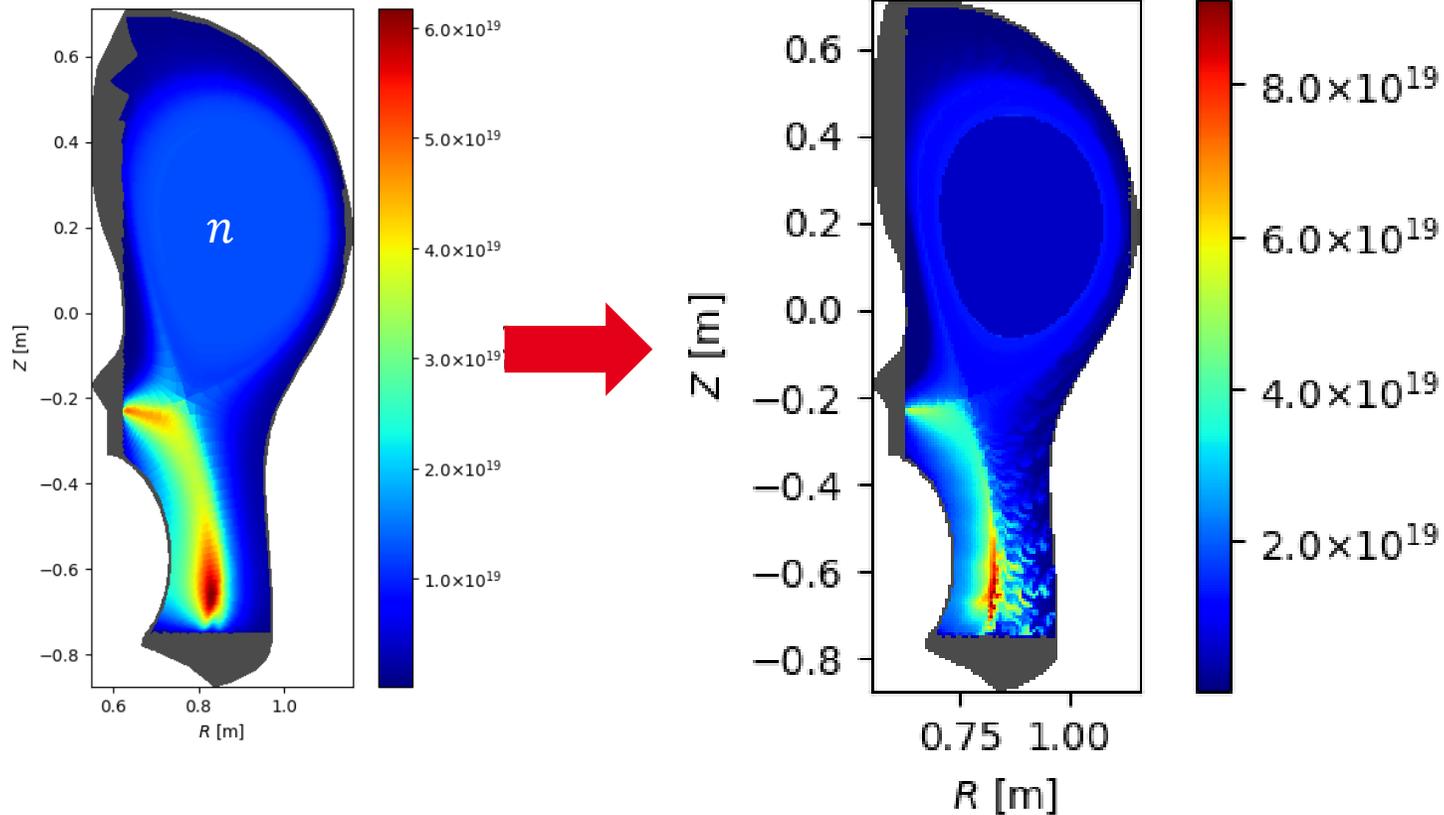
- Realistic localization of the ionization source

- FN is able to emulate a sort of detachment, at the condition of the experiments (TCVX23 does detach at  $n_{sep} = 1E19$ )

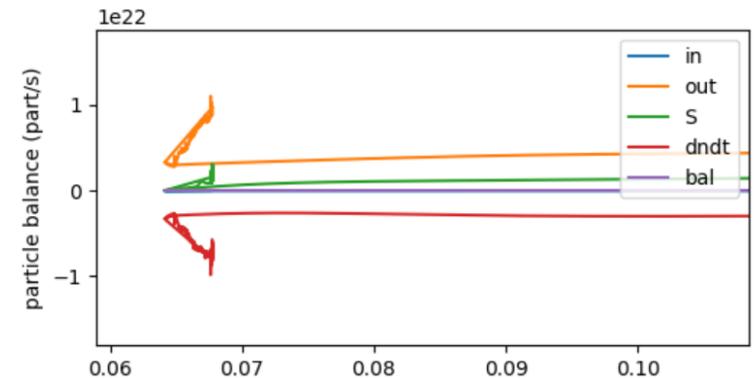
**Density regimes qualitatively captured:  
Good enough for turbulence modeling.**

# From 2D to 3D: the transition to turbulence.

- Restarting from 2D might help to have a proper plasma background in 3D!



- Specific **turbulent activity in the divertor region** under detachment conditions: may affect gas puff imagining?
- Turbulent activity in the **main SOL**
- Turbulence arises **quickly** ( $\sim 20K$  time steps), still not in steady state.



- W/ turbulence, particle balance is not broken dramatically!  
→ 2D mean field cases are promising in terms of convergence  
[\[H. Bufferand, PET-19, 18/09/23\]](#)



# **6** ■ **Outlooks and conclusions**

# Outcomes and conclusions



The **gas puff** introduces a **breaking** in the **toroidal asymmetry**.

- Consequences for divertor physics, due to the flux tube propagation.
- Consequences for gas puff diagnostics.

The **basic features of turbulence are conserved** whether neutrals or not.

- Filamentary/blobby transport
- Intermittency
- Ballooning in the LFS.

The **detailed properties of turbulence change due to the recycling**.

- Variations in **poloidal equilibrium**
- Reorganization of the **transverse transport**.

Changes even more marked when dealing with higher density regimes.

# Perspectives and future work



The logo for CEA (Commissariat à l'énergie atomique et aux énergies alternatives) features the lowercase letters 'cea' in a red, sans-serif font. A horizontal red line is positioned directly beneath the letters.The logo for IRFM (Institut de Recherches sur les Fusibles Magnétiques) consists of the lowercase letters 'irfm' in a red, sans-serif font.

## Contacts

**Virginia QUADRI**

**[virginia.quadri@cea.fr](mailto:virginia.quadri@cea.fr)**

**+33 4 42 25 5705**

**CEA Cadarache/IRFM/SPPF/GTSN (Office : 513/135)**

**Saint Paul Lez Durance, 13108, France**



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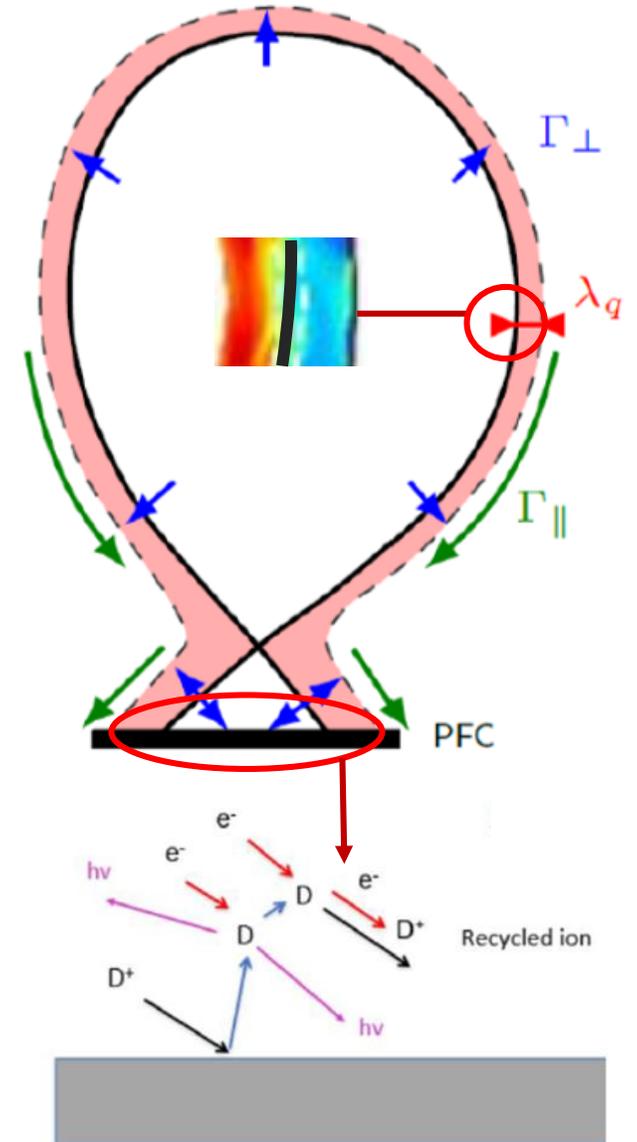
# Turbulence and neutrals: key players to edge plasma physics issues

Understanding the interactions among turbulence and neutrals is crucial for nuclear fusion and the challenge of handling the heat fluxes deposition at the target plates.

➔ Way out: **Spreading the power radially outwards.**

- Transfer the energy, feeding complex mechanism such as recycling of neutrals, leading to different plasma density states called **density or diverted regimes**.
- Broaden the width of the Scrape Off Layer (SOL),  $\lambda_q$ , which is (partly?) determined by turbulence, since it influences the level of interactions between plasma and the wall.

In this way, an investigation on the consequences of wall erosion due to particle flux and thermal stress is mandatory to model properly the SOL, taking into account both the two physics.



# The need of a predictive model

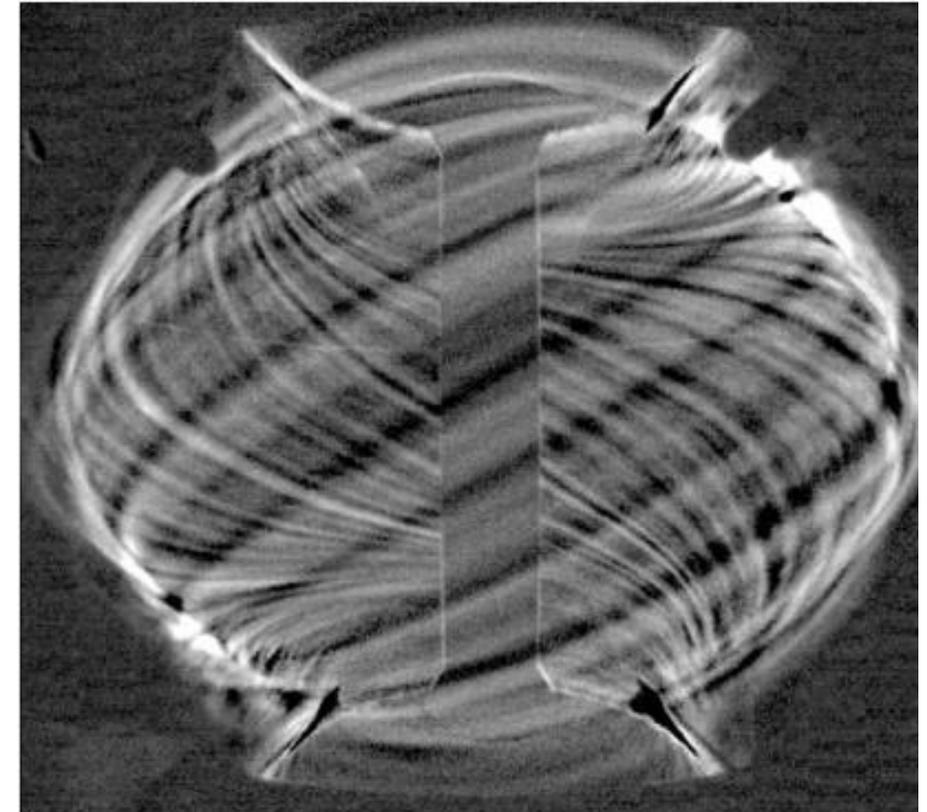
*Where were the interpretative models failing until now?*

There is **NO** multi-machine scaling law for high-recycling and detached plasmas in terms of  $\lambda_q$ .



*dynamics of*

Being interpretative means failing to capture some phenomena (like the formation of density shoulders) where the two physics, turbulence and recycling, are interconnected.



*Visible light image of filaments in Ohmic L-mode on MAST. [B. D. Dudson]*

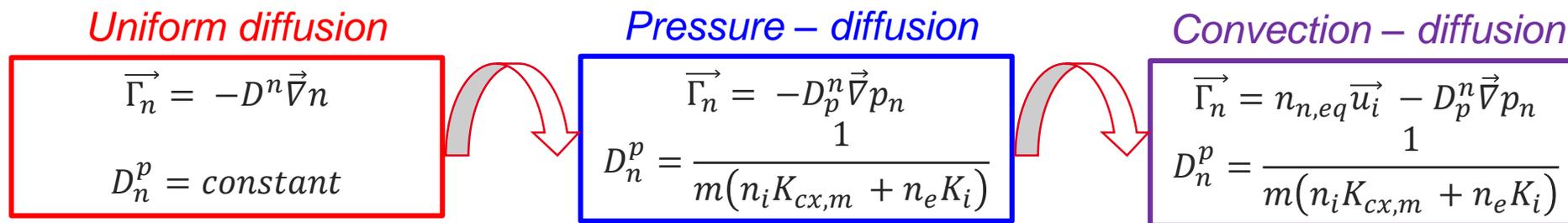
# The exigence of switching to a fluid description: the hierarchy of models in SOLEDGE3X.

Moving from a kinetic description to a fluid model entails missing information (i.e. molecular and atomic dynamics). The goal is indeed providing a qualitative interpretation of the physics as close as possible to EIRENE, by having a realistic localization of the recycling source and consistent momentum and energy sources.

A hierarchy of fluid neutrals model is currently available in Soledge3X: the common starting point is the mass balance equation

$$\partial_t \mathbf{n}_n + \vec{\nabla} \cdot \vec{\Gamma}_n = S_{n_n} \text{ where } S_{n_n} = n_i n_e K_r - n_n n_e K_i$$

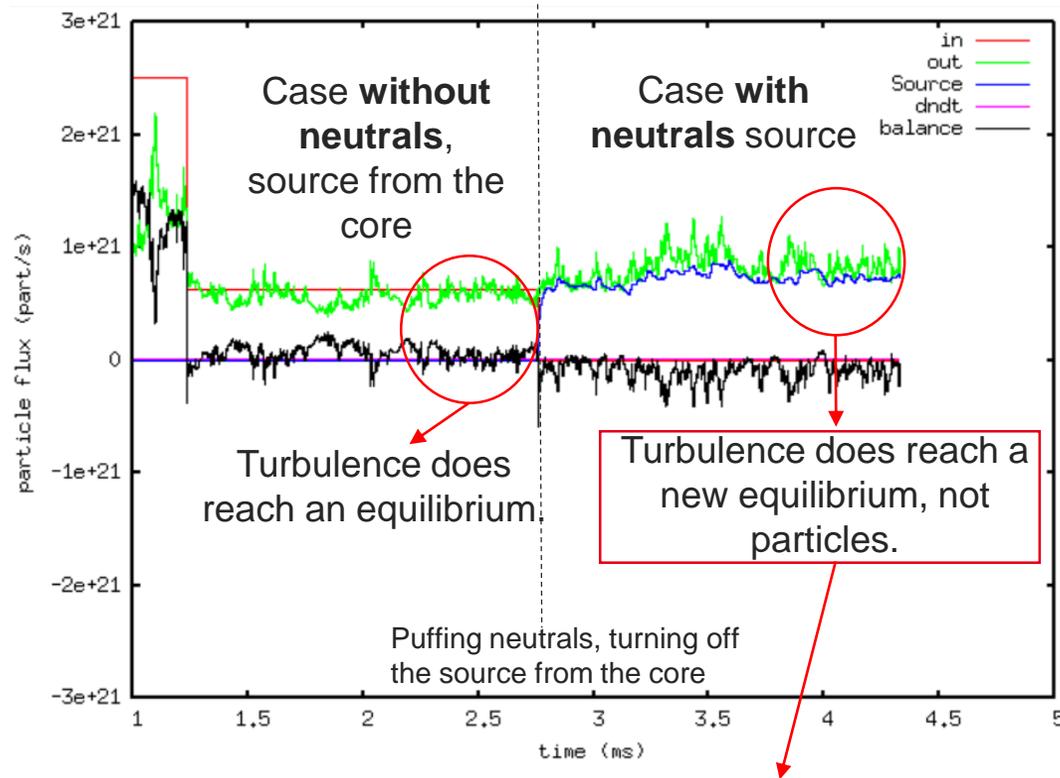
What makes the difference is the way in which  $\vec{\Gamma}_n$  and the **diffusion coefficients** (constant or based on a polynomial fit including cx and ionization) are computed.



*hp*: referred to **charge exchange-dominated region** ( $T_n = T_i$ )  
(ref. *Horsten et al, 2017, Nuclear Fusion 57, 116043*)

# The convergence issue for turbulent – neutral cases

Different time scales interplay among them



The reason depends on the  $(1-R)$  factor appearing in the total balance equation

1. Fast scale: typical of *turbulence*, which reacts very quickly to a new equilibrium after the breaking (i.e. injection of neutrals) of the previous one.
2. Slow scale: it concerns the global *particle balance*, in terms of equilibrium between the level of gas puff and the plasma density.

The reaching of particle convergence for these kind of simulations requires ages of computation: the response of the balances is very slow and the transient extremely costly in terms of computational resources.

**This absolutely does not prevent us to look at the impact of neutrals on turbulence through a snapshot of it at a given plasma density.**

The **turbulence** lays on a total different time scale: it reaches **steady state** for a given plasma density very **quick**.

# The convergence issue for turbulent – neutral cases

Different time scales interplay among them

$$\tau_{eq} = \frac{1}{1-R} \tau \sim 100 \text{ ms}$$

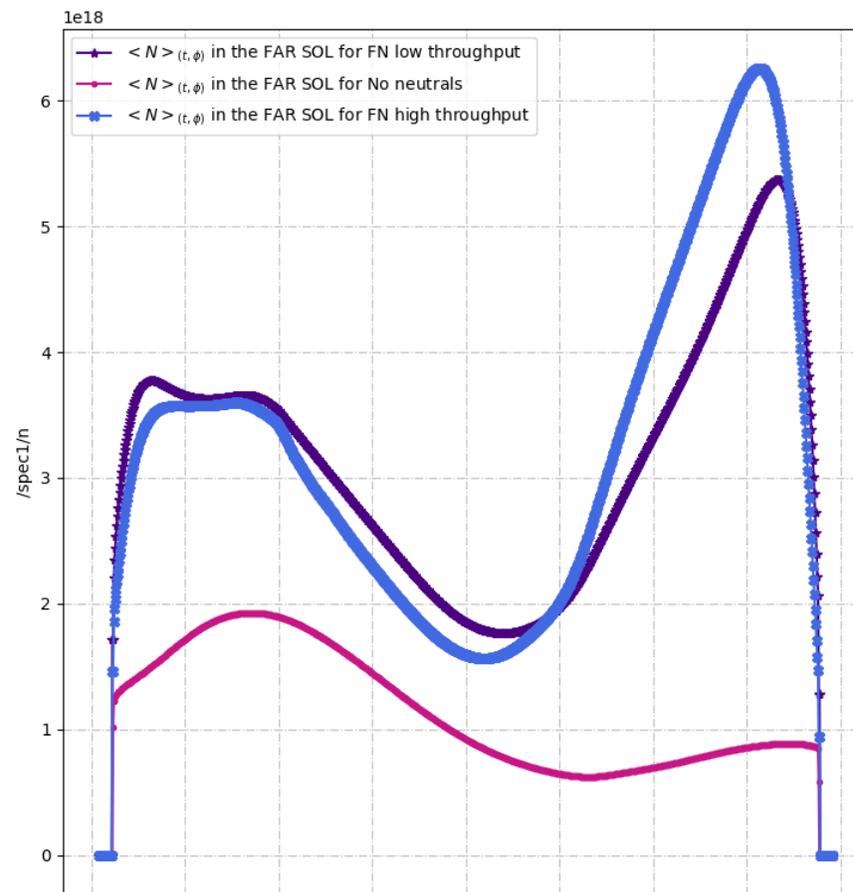
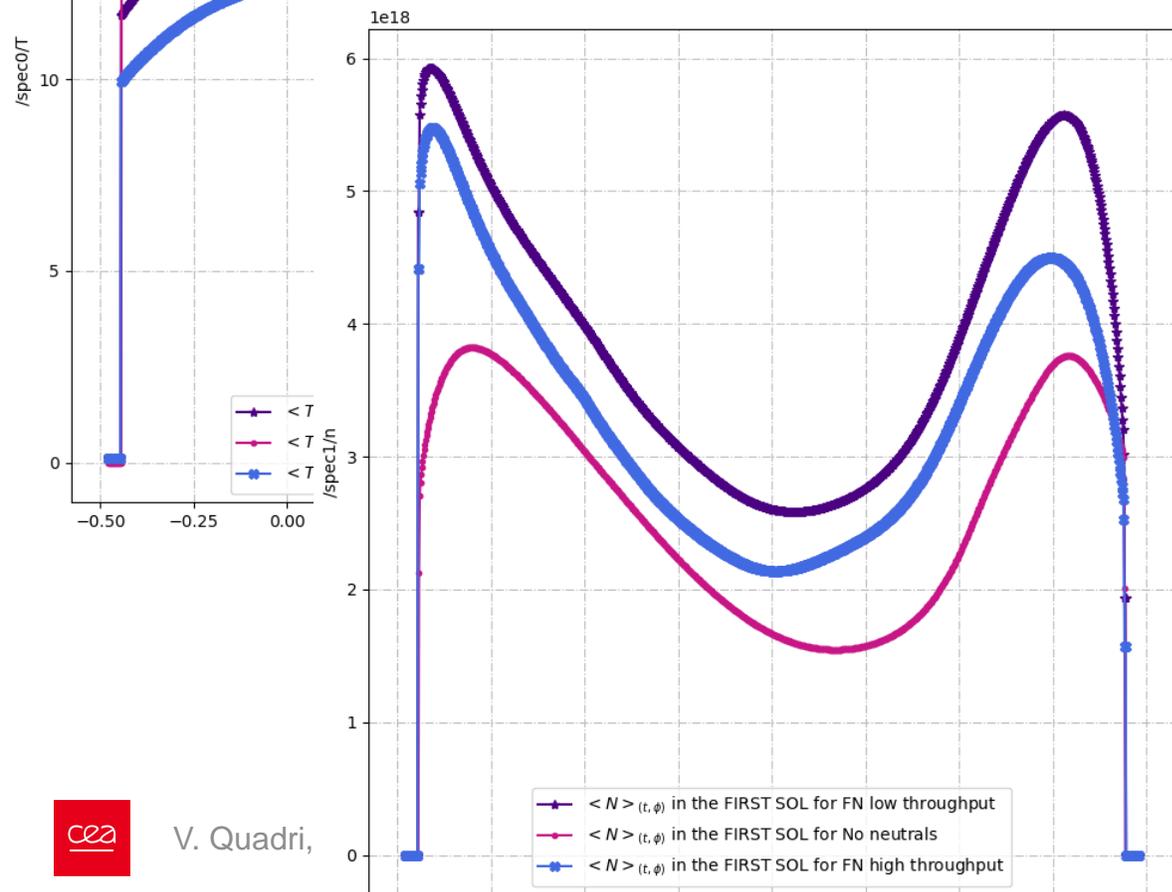
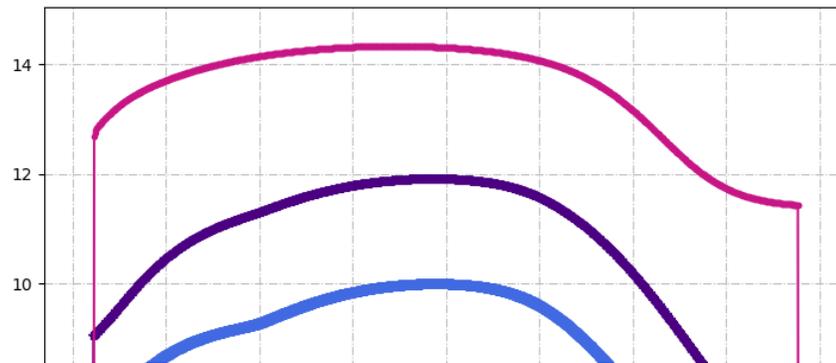
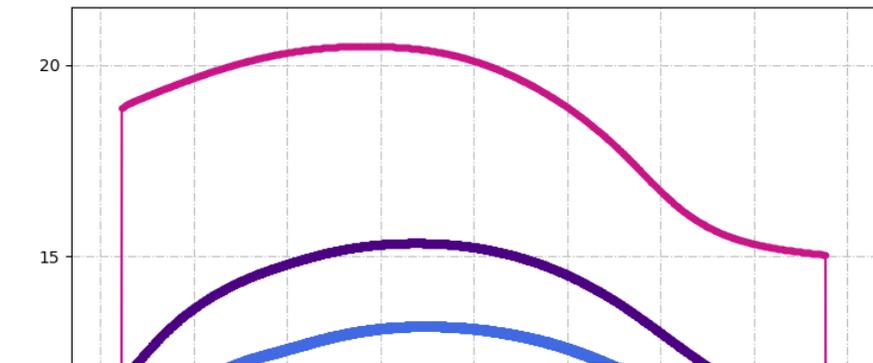
1. Fast scale: typical of *turbulence*, which reacts very quickly to a new equilibrium (i.e. injection of neutrals).
2. Slow scale: it concerns the transport and the plasma *particle balance*.
3. Global scale ( $\tau_{eq}$ ): for the whole system, with a very slow response and a long transient, costly in terms of computational resources

Does it really matter for this cases being in steady state?

From theoretical to experimental relevant the point of view changes in terms of how the simulations are driven

1. A **theoretical exercise in circular geometry**, where plasma conditions are fixed and we study the behavior of turbulence in interactions with neutrals.
2. **Divertor simulations** matching the experiments: where the aim is getting both plasma conditions and turbulence corresponding to throughputs.

# Backup slides





$n_i [m^{-3}]$

$z [m]$



$R [m]$

Modify video by adding neutrals as well

# Importance of particle conservation



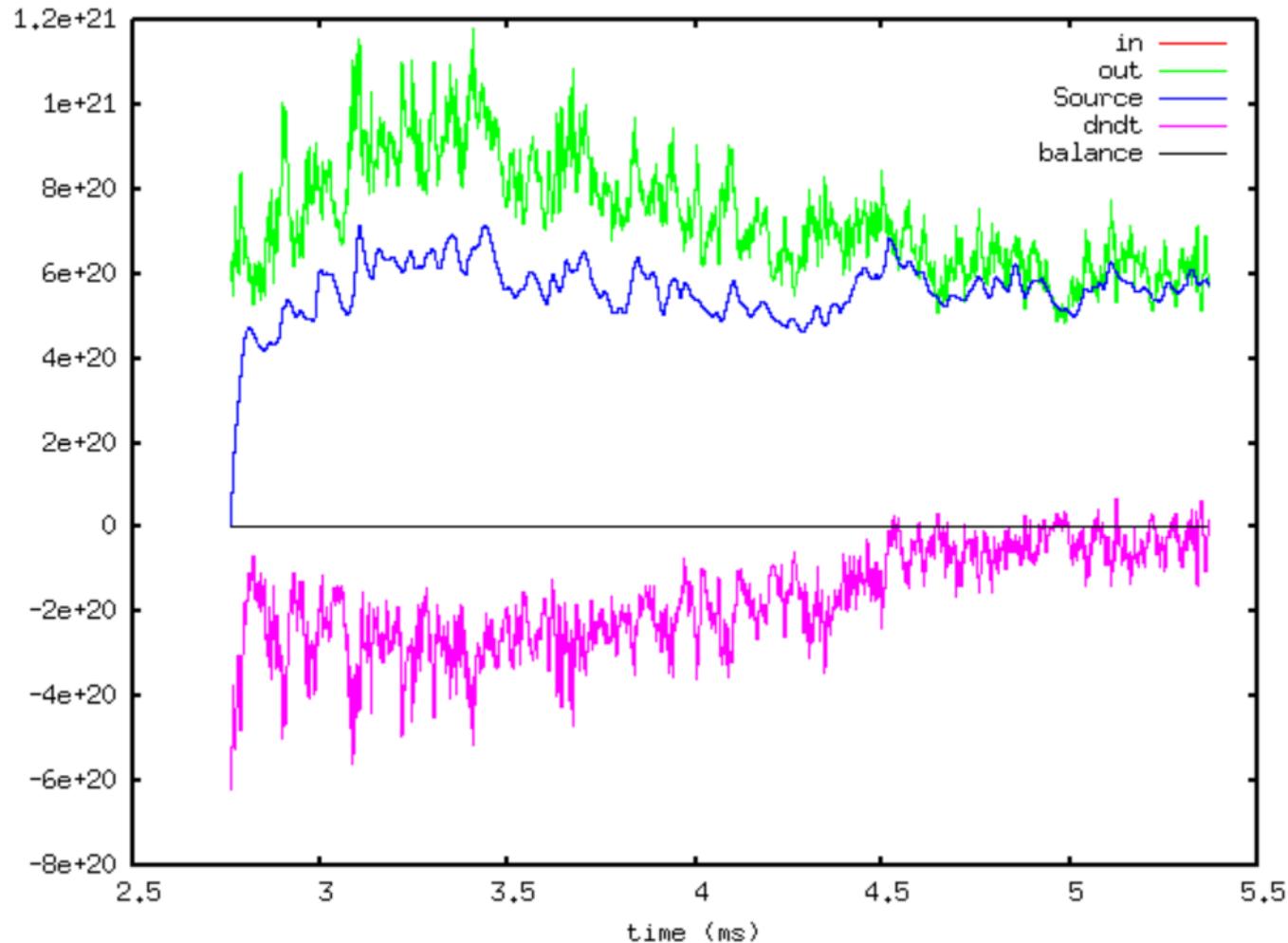
**Source** and **Out** are the larger terms: even small errors on them, will dramatically impact the balance

, due to numerical scheme suited.

With neutrals introduction, the **nature of the particle balance changes completely**, since the dominant fueling mechanism becomes different.

***A redistribution of the transport has started..***

# Reaching the steady state in theoretical exercise vs experimental matching



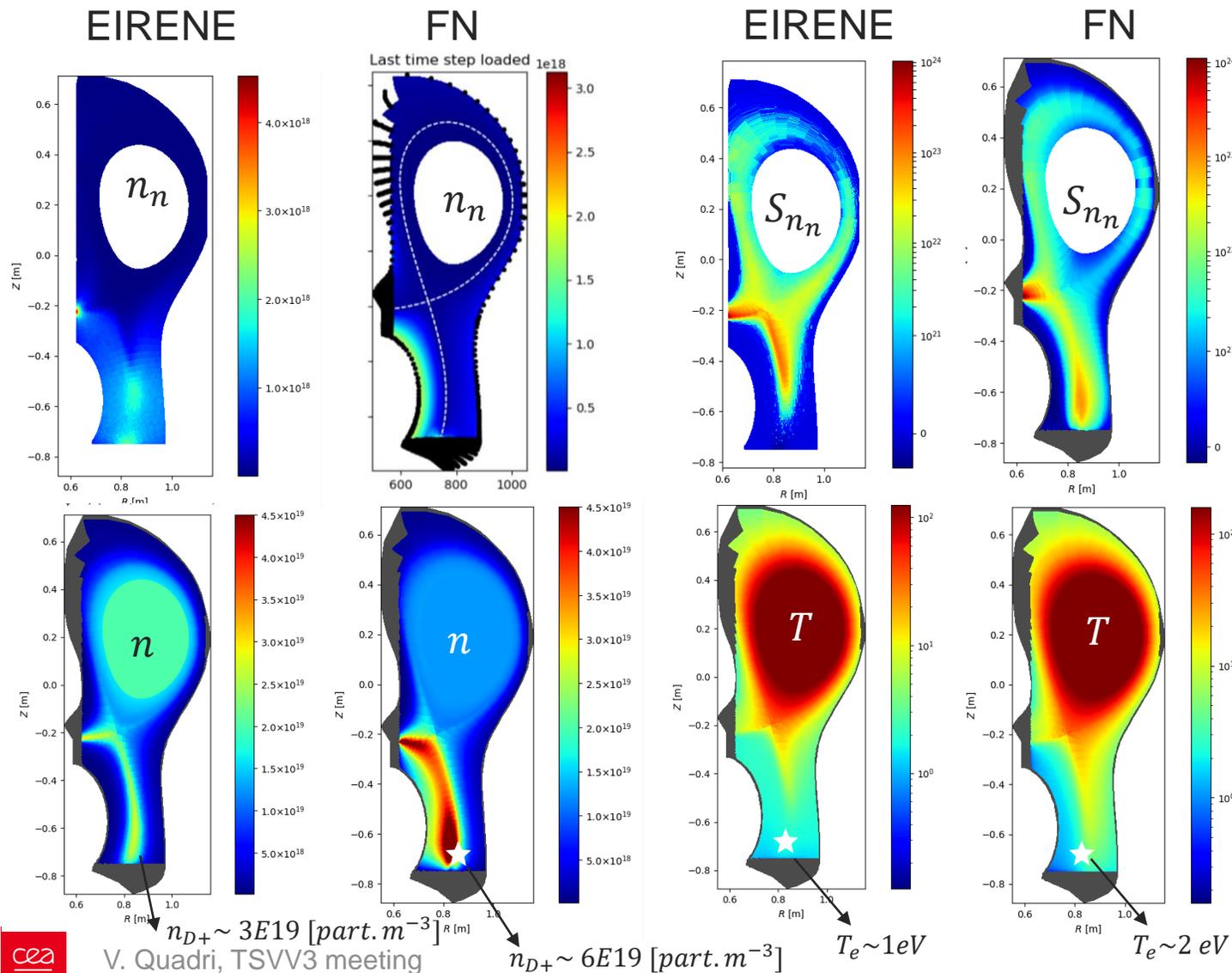
Respect to the given throughput, the circular case results to be in steady state. This has been possible by tuning the value of the puff: in order to do something predictive, the control parameter is no more the plasma, but the puff itself.

➔ **The simulation does reach the steady state with respect a given puff.**

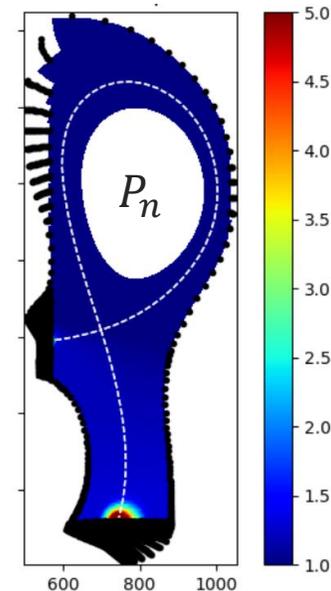
In order to be experimental relevant, both plasma conditions and turbulence have to match the throughputs:

➔ **Next step: full steady state for turbulence and particle balance**

# 2D mean field case ( $n_{sep} = 1E19$ ): quality of FN compared with EIRENE.



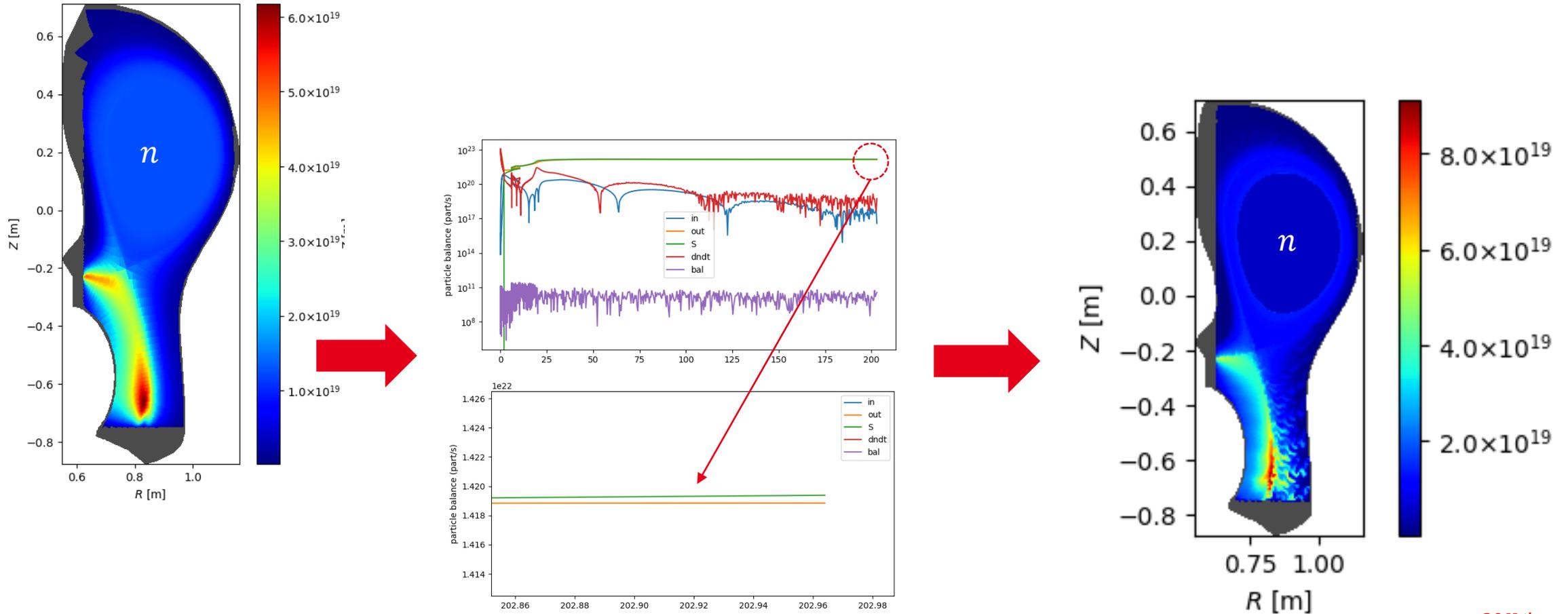
- the neutrals density distribution improved but still not realistic ( $n_n$  is not the diffusive quantity in the model -  $P_n$  does).
- Realistic localization of the ionization source (despite is a bit more elongated all along the legs)



- FN is able to emulate a sort of detachment, at the condition of the experiments (TCVX23 does detach at  $n_{sep} = 1E19$ ), with a plasma density and temperature higher with respect EIR

# From 2D to 3D: the transition to turbulence.

- Restarting from 2D might help to have a proper plasma background in 3D!



*~20K time steps*  
We are able to transit in 3D with turbulence very quick  
but still under investigation!

# Conclusions and perspectives

*Turbulence* has found to globally conserve the same basic properties whether neutrals recycling is accounted for or not:

- Is driven by intermittent small-scale and field aligned fluctuations propagating outwards in the parallel direction by the ExB advection in the form of **filaments**.
- Shows a **marked ballooned character** on the Low Field Side (LFS).

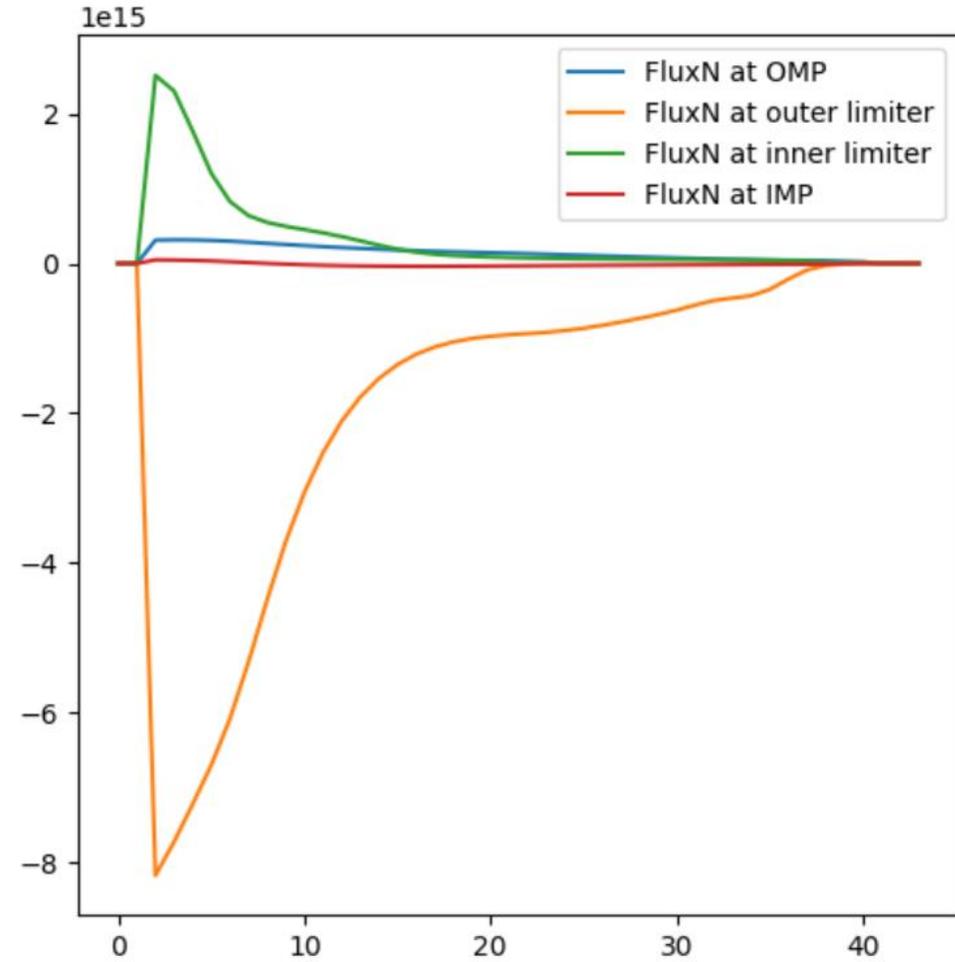
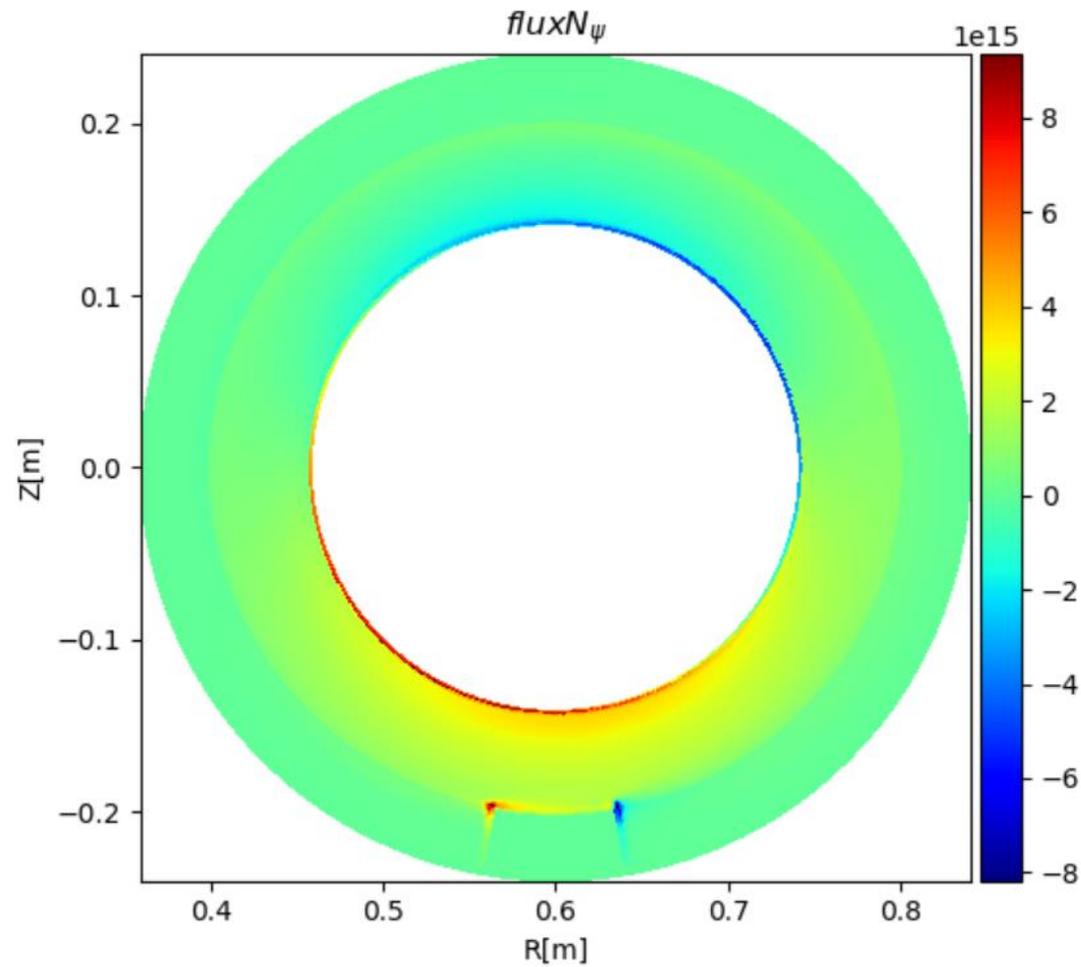
The presence of a localized neutral source strongly impacts the **poloidal equilibrium** of the plasma and the way the **transverse transport** is going to organize itself in the edge.

This impact is likely to become even more marked when dealing with higher density regimes in which the localization of the recycling source in the radial and poloidal directions is more pronounced.

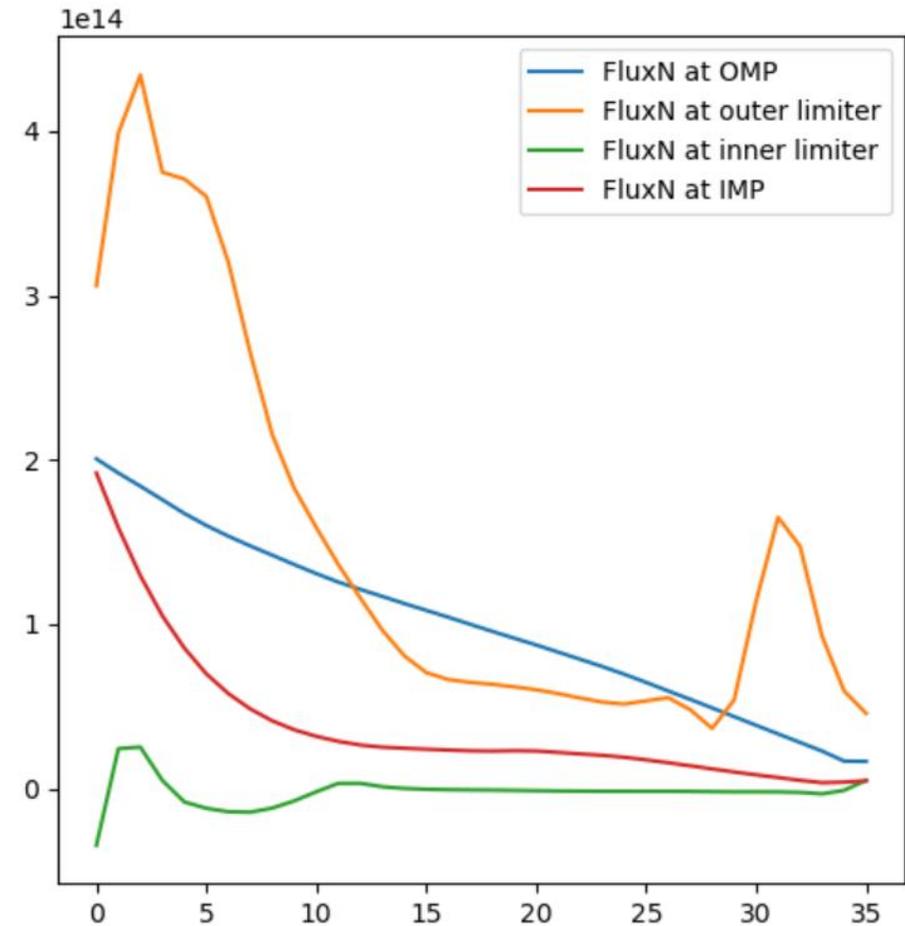
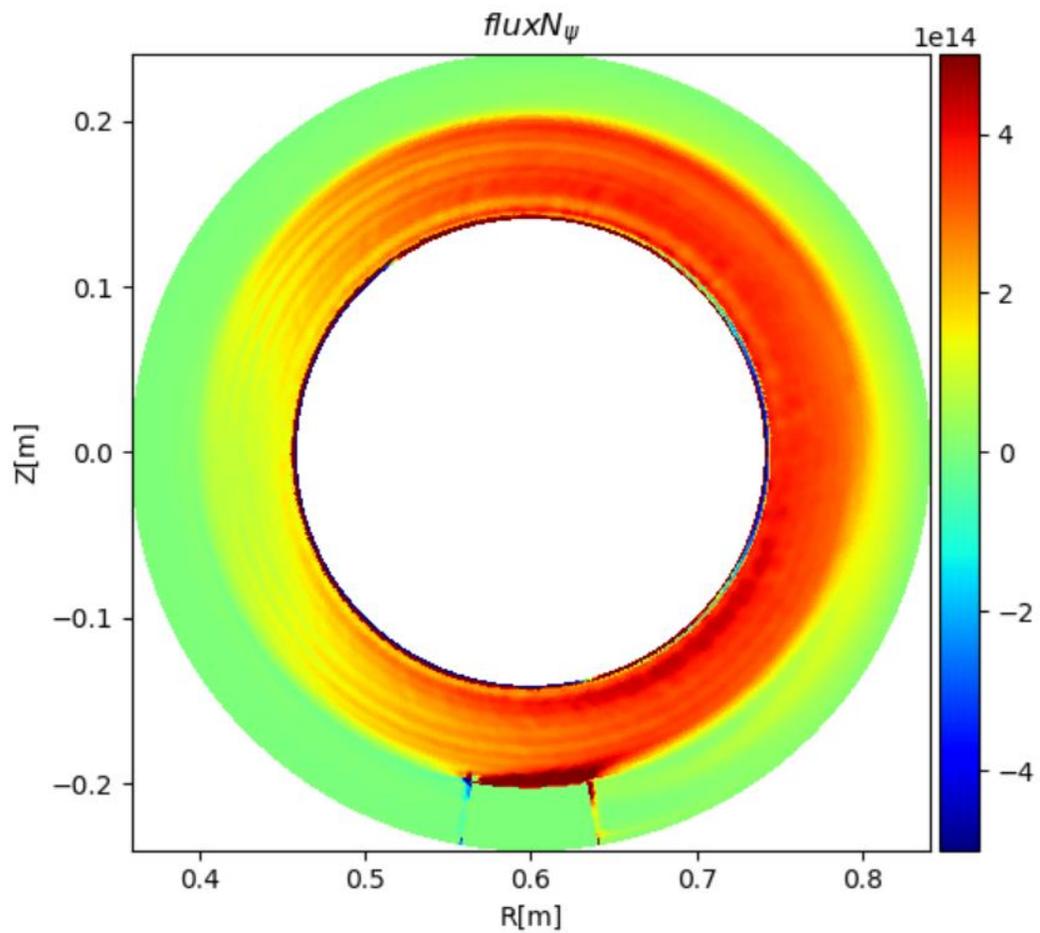
The gas puff provides a breaking in the toroidal asymmetry: it may have consequences for divertor physics, due to the flux tube propagation.

Getting the particle balance from the 2D mean fields with drifts might help to have a proper plasma background when transiting in 3D

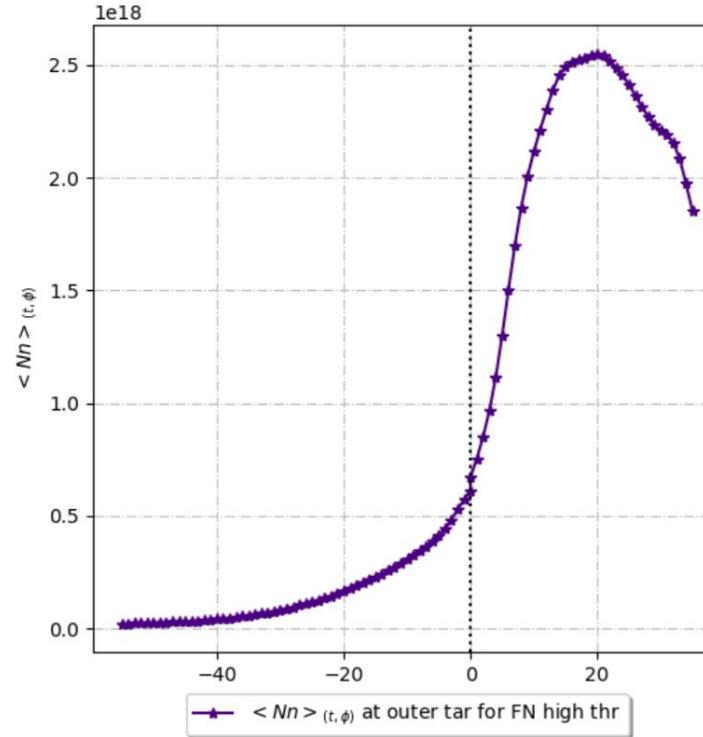
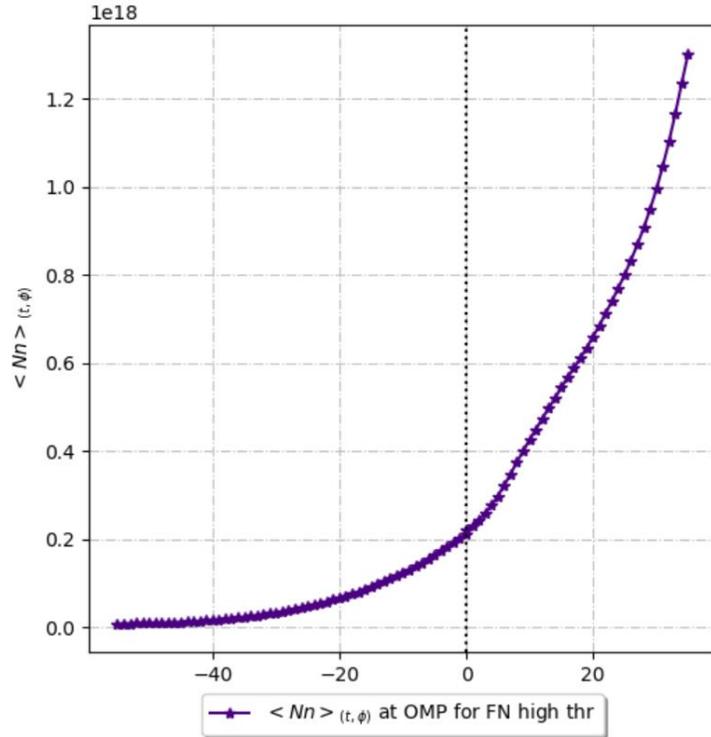
# Fluxes no neutrals case with drifts



# Fluxes no neutrals case



# Neutrals density average



# Neutrals density fluctuations +skew

