Impact of neoclassical viscosity and neutrals on radial electric field in SOLEDGE3X modelling

G. Falchetto

Acknowledgements to SOLEDGE Team:

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TSVV1 progress workshop 27-29-06-2023

OUTLINE

- SOLEDGE3X Task: explore the impact on the inverse radial electric field formation of
  - neoclassical friction
  - favorable versus unfavorable magnetic drift configuration in realistic X-point geometry
- SOLEDGE3X code status
- Progress report:
  - 3D turbulence simulations in limited circular geometry without and with neoclassical viscosity effects and fluid neutrals
- Next steps
  - Impact of current
  - Application to 3D turbulence in diverted geometry
- SOLEDGE3X TSVV1 deliverables review

Status of SOLEDGE3X code implementation

SOLEDGE3X code enables 2D/3D transport and 3D turbulence simulations for multi-species plasma.

H Bufferand NF 2021, H Bufferand PPCF 2022

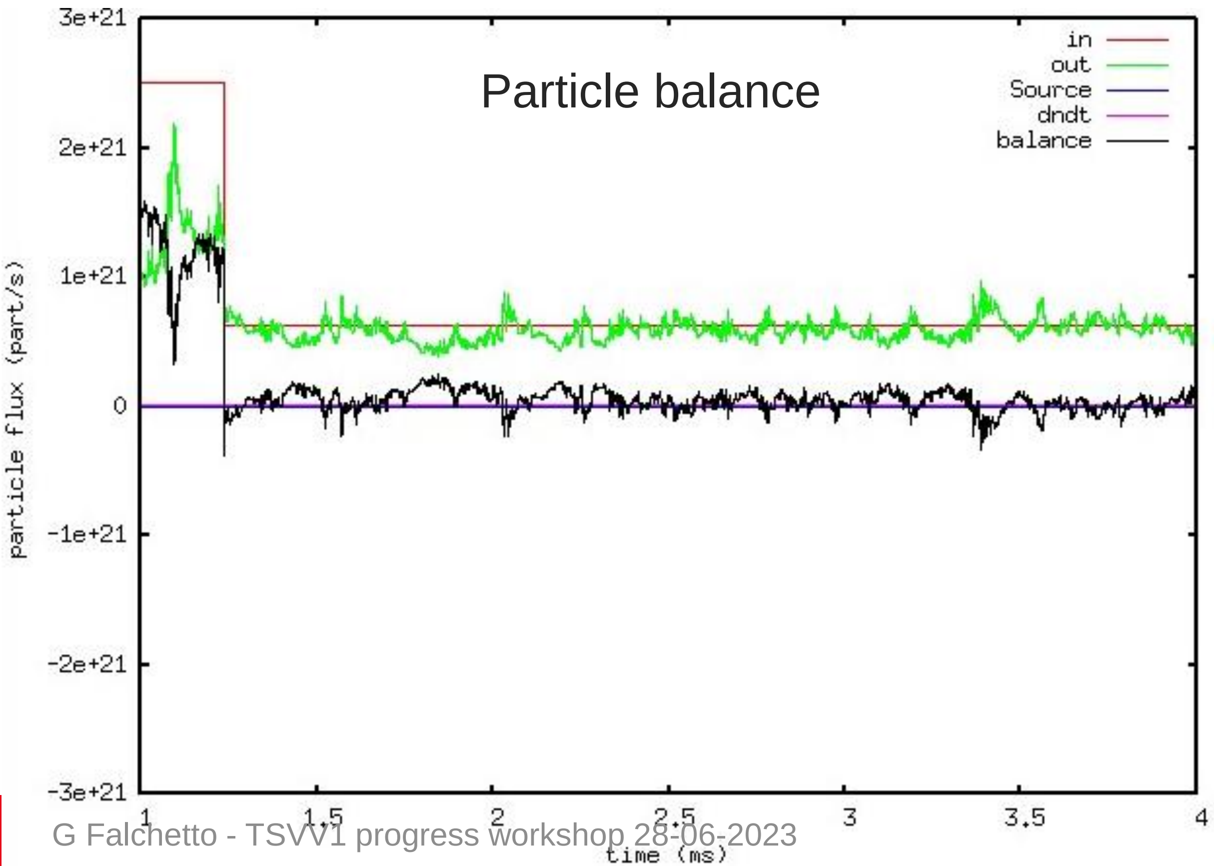
- ✓ Code runs routinely in 2D transport mode with drifts (tested on WEST/TCV/ITER cases) and 3D turbulent mode in limited and divertor geometry (WEST/TCV)
  - ✓ Drift and current associated to the stress tensor divergence, including parallel ion viscosity implemented.
  - ✓ Parallel friction force between ions and electrons : electron velocity computed without ambipolar assumption to properly compute ion-electron friction forces in presence of parallel currents.

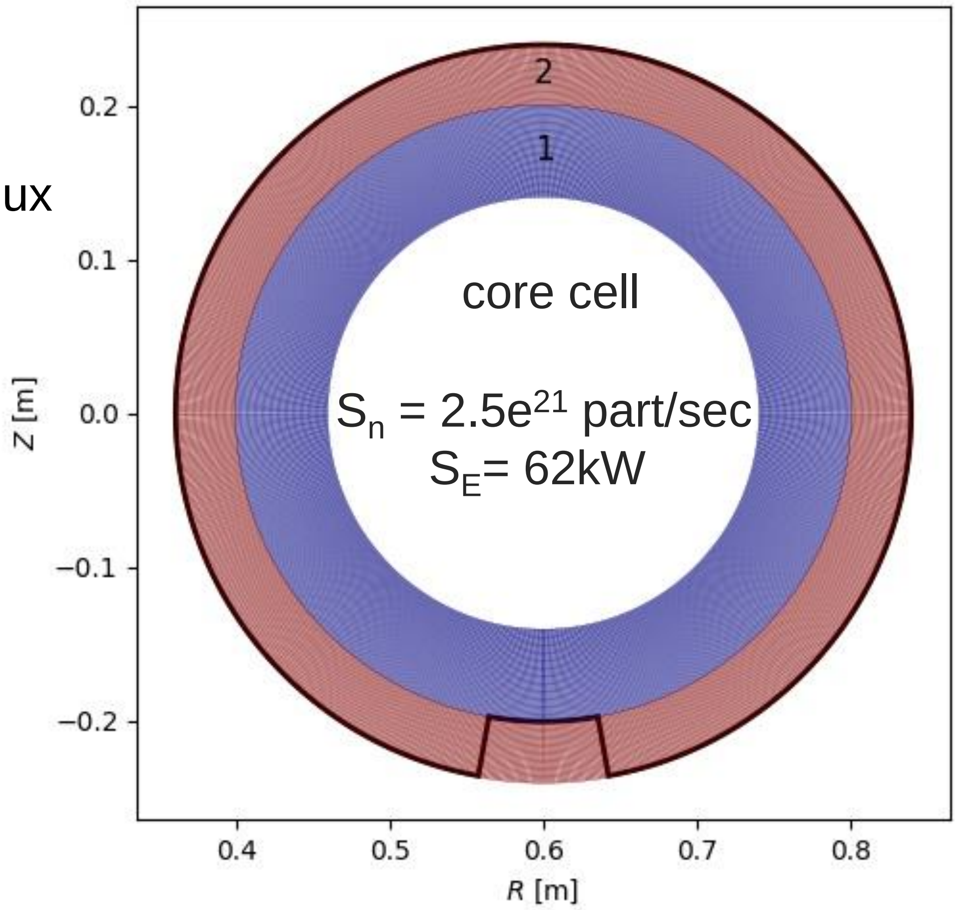
    ! polarization velocity not included in parallel momentum and energy transport
  - ✓ **Neutrals**: coupling to EIRENE for 2D transport + advanced A&M model (from Kotov PPCF 2008 w/o n-n collisions) [Bufferand PET 2021, N Rivals PET 2021, N Rivals Contrib. to Plasma Physics, 62, 2022]
  - ✓ coupling to hierarchy of fluid models in 2D and 3D turbulence simulations
    - ✓ **NEW: pressure diffusion fluid neutrals model** (TSVV3) V Quadri Invited PET 2023
  - ✓ **Release v1.2 20 June 2023**
  - ❖ **Electromagnetic** [R Düll EPS 2023 TSVV3] and non-axysimmetric [K Galakza TSVV6] versions under development

Case 1 –TURBULENCE CIRCULAR LIMITED CASE REFERENCE SIMULATION

SOLEDGE3X reference circular bottom limiter case
– COMPASS like size ¼ torus
D plasma
a=0.2m R=0.6m B_0=1T
T_0=50eV
$D = \nu_\perp = \chi = 1\ e^{-2}\ m^2/s$

particle flux
driven by constant in-flux
from the core region

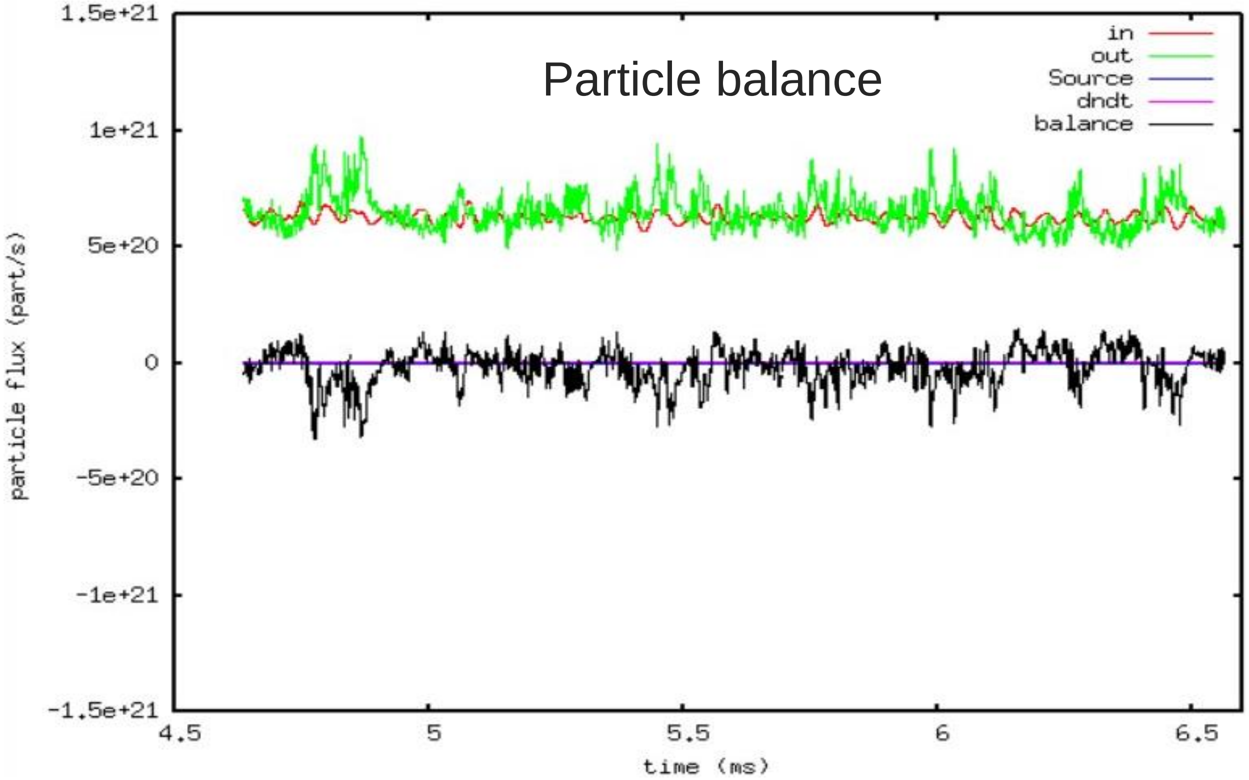




Very fine mesh (~10^7 **points**)
Npsi = 100
Ntheta = 1024
Nphi = 128

Case 2 - TURBULENCE CIRCULAR LIMITED CASE – including $\eta_{//}$

$$\pi_{\parallel} = -3\eta_{\parallel}\left(\nabla_{\parallel} v_{\parallel} - \vec{\kappa}\cdot\vec{v} - \frac{1}{3}\vec{\nabla}\cdot\vec{v}\right)$$



Simulation extended up to 6.5 msecs of plasma

statistical analysis on the plasma fields performed over the quasi-stationary turbulence state of about 2msec

The pressure diffusion fluid neutrals model

SOLEDGE3X coupled to a hierarchy of fluid models of increasing fidelity, based on the mass balance equation

$$\partial_t n_n + \vec{\nabla} \cdot \vec{\Gamma_n} = S_{n_n}$$

$$S_{n_n} = n_i n_e K_r - n_n n_e K_i$$

recombination + ionization processes

differing in the computation of $\vec{\Gamma_n}$:

diffusion coefficients either constant
or including charge exchange and ionization rates $K_{cx,m}$ K_i based on polynomial fit from ADAS/EIRENE

New: advanced fluid neutrals model based on **assumption of a charge-exchange dominated plasma-neutral interaction**

Pressure – diffusion

$$\vec{\Gamma_n} = -D_p^n \vec{\nabla} p_n$$

$$D_p^n = \frac{1}{m\left(n_i K_{cx,m} + n_e K_i\right)}$$

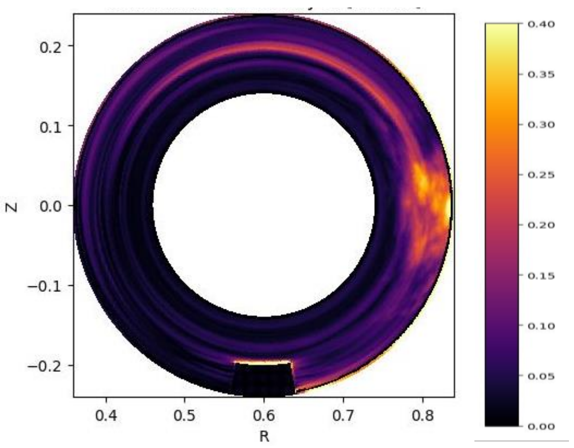
charge exchange-dominated region $(T_n = T_i)$
Horsten et al, NF 2017

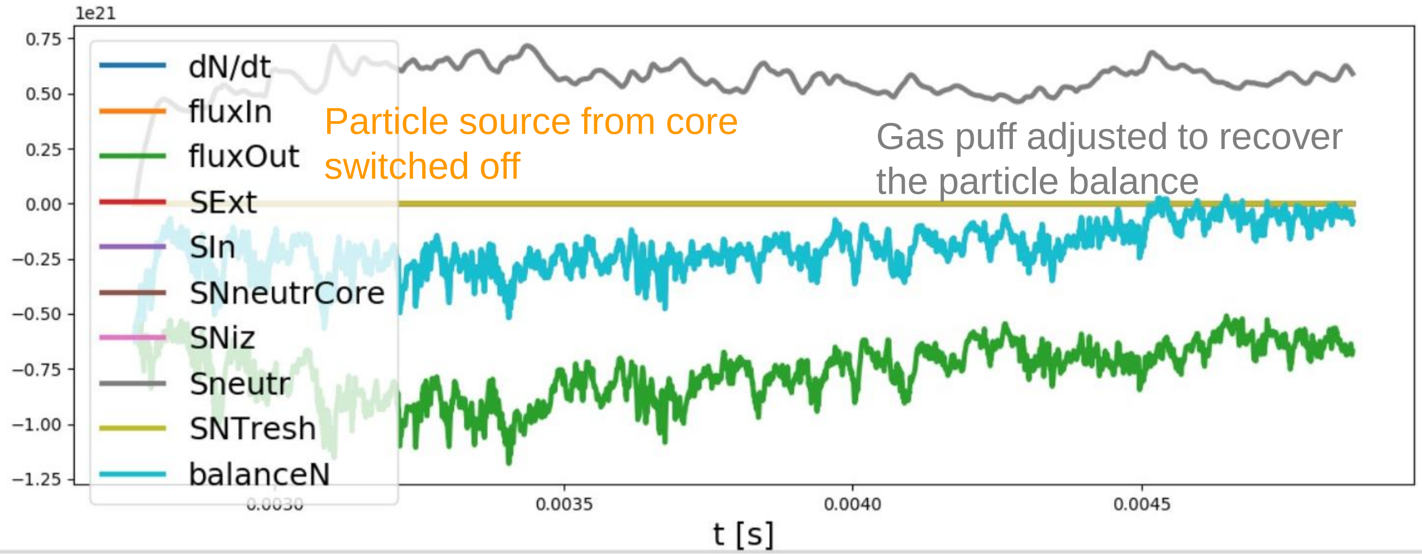
Case 3 - TURBULENCE CIRCULAR LIMITED CASE with FLUID NEUTRALS

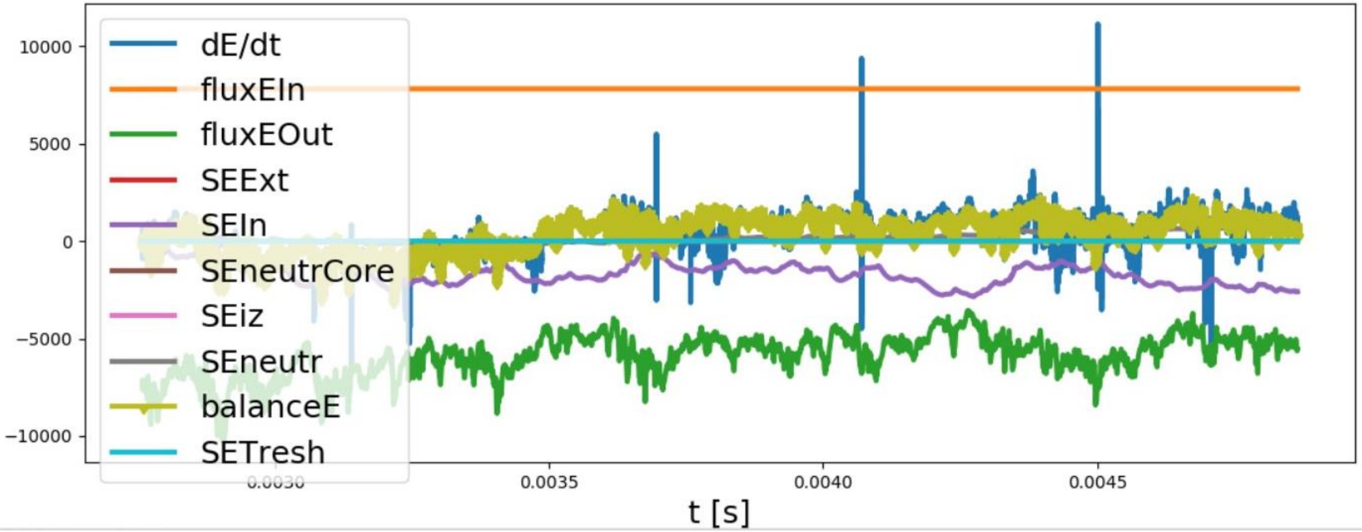
Simulation including neutrals recycling : particle input to the system self-consistently injected by a gas-puff from the outer mid-plane

High puffing:
GasPuffRate = 2.15 e20 part/sec
Rn = 0.98 recycling coeff.

$$\frac{\max(<N>)_\varphi - \min(<N>)_\varphi}{<N>_\varphi}$$







No pumping
! Energy balance not closed for neutrals

TURBULENCE CIRCULAR LIMITED CASES : generation of inversed Er

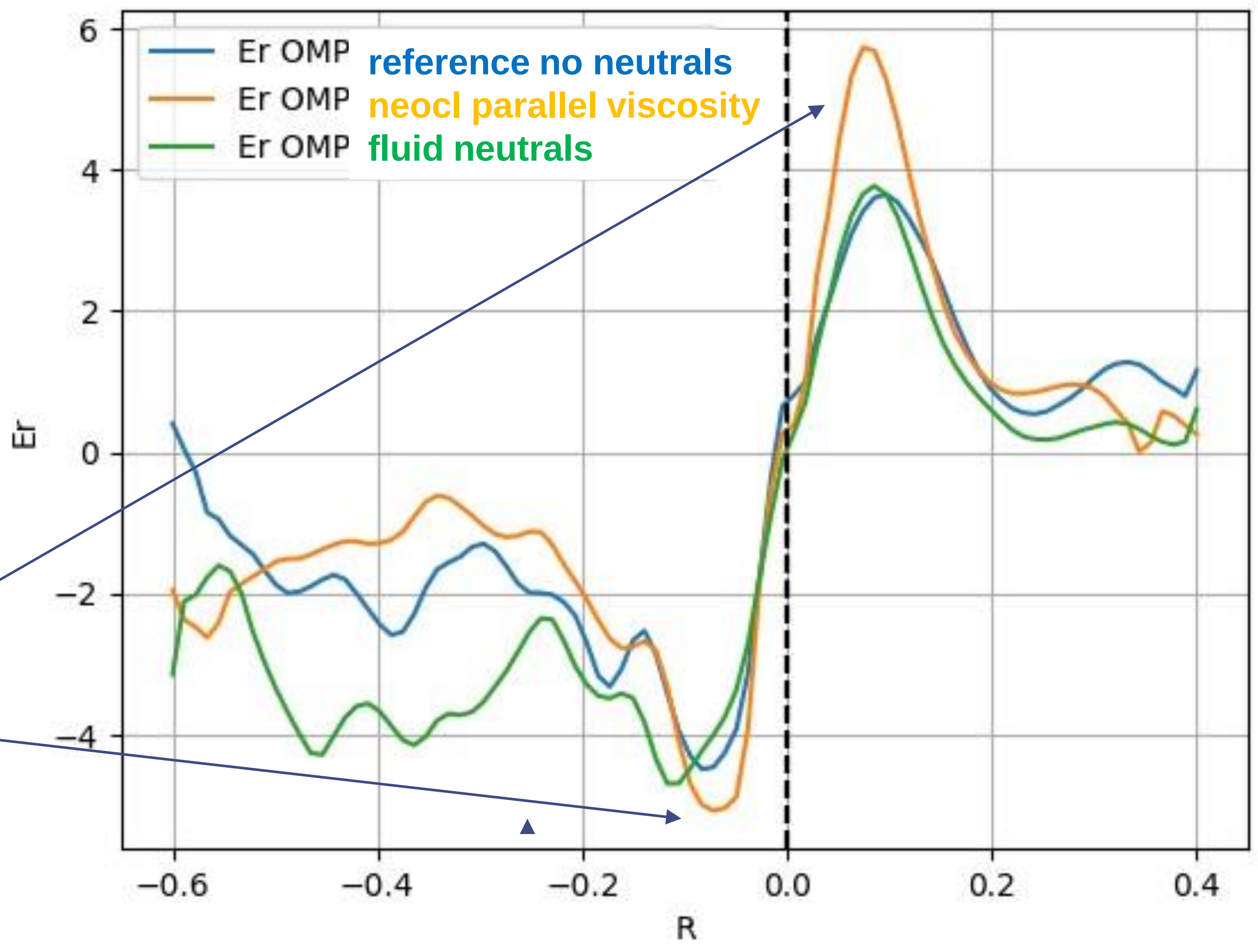
Spontaneous generation of inversed E_r around the separatix always occurring in SOLEDGE3X simulations

E_r constrained by
- Force balance in the core
  $E_r \sim \nabla Pi/n$
- Sheath BC in the SOL
  $\Phi \sim Te$

Er well peaks inside the separatrix as exp. observed

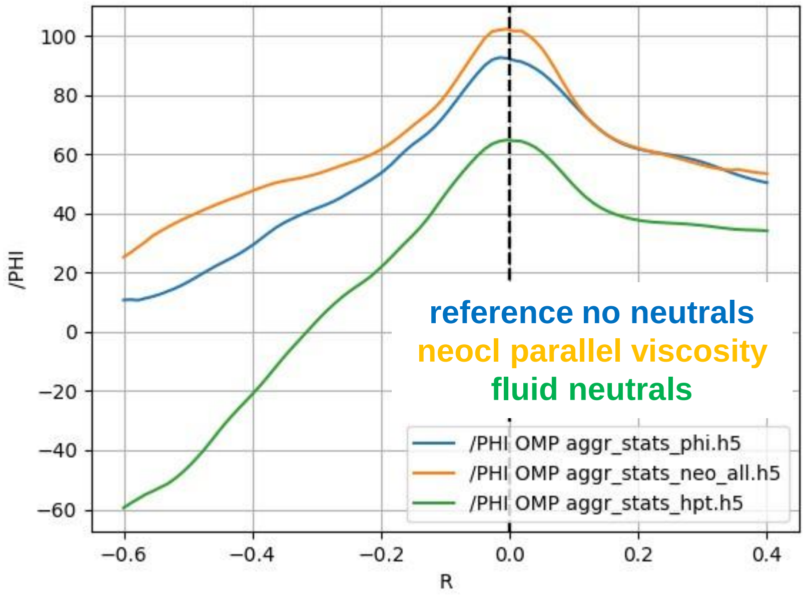
Inclusion of **full neoclassic effects** slightly enhances E_r peaking at OMP neutrals flatten core profile

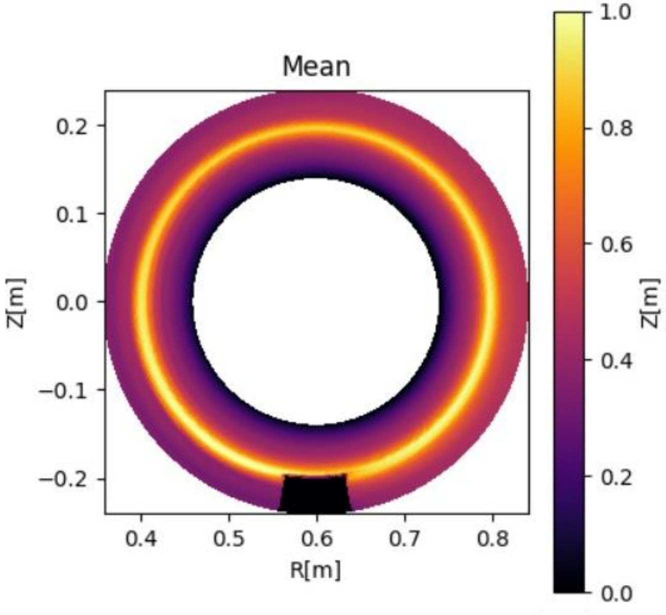
<mean E_r >$_{phi}$ [kV/m]

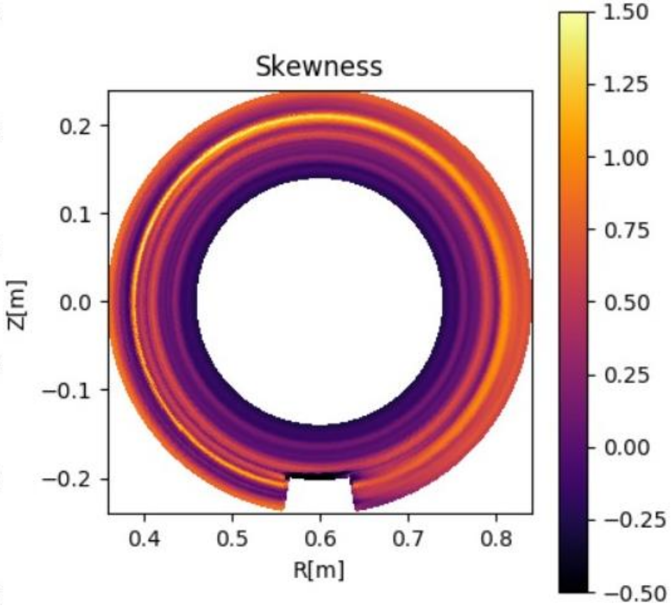


 L Vermare NF22

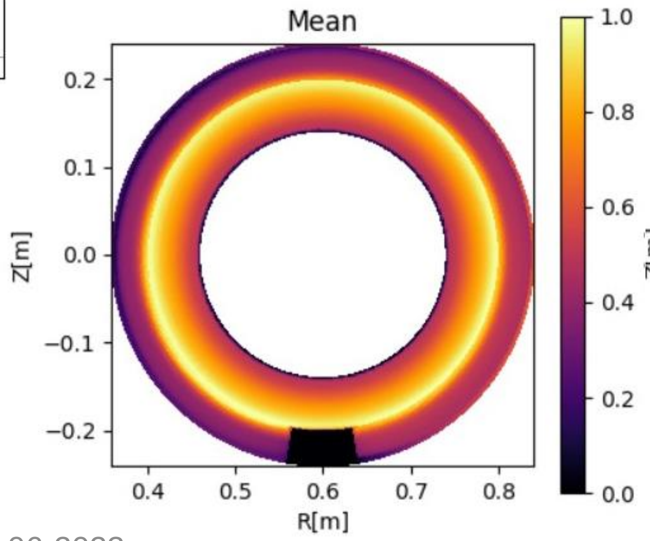
IMPACT of NEUTRALS on PHI – poloidal plane

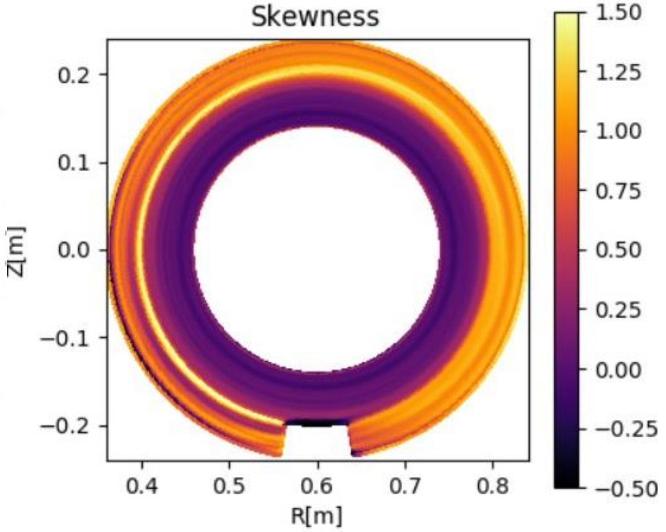






Full neoclassic effects





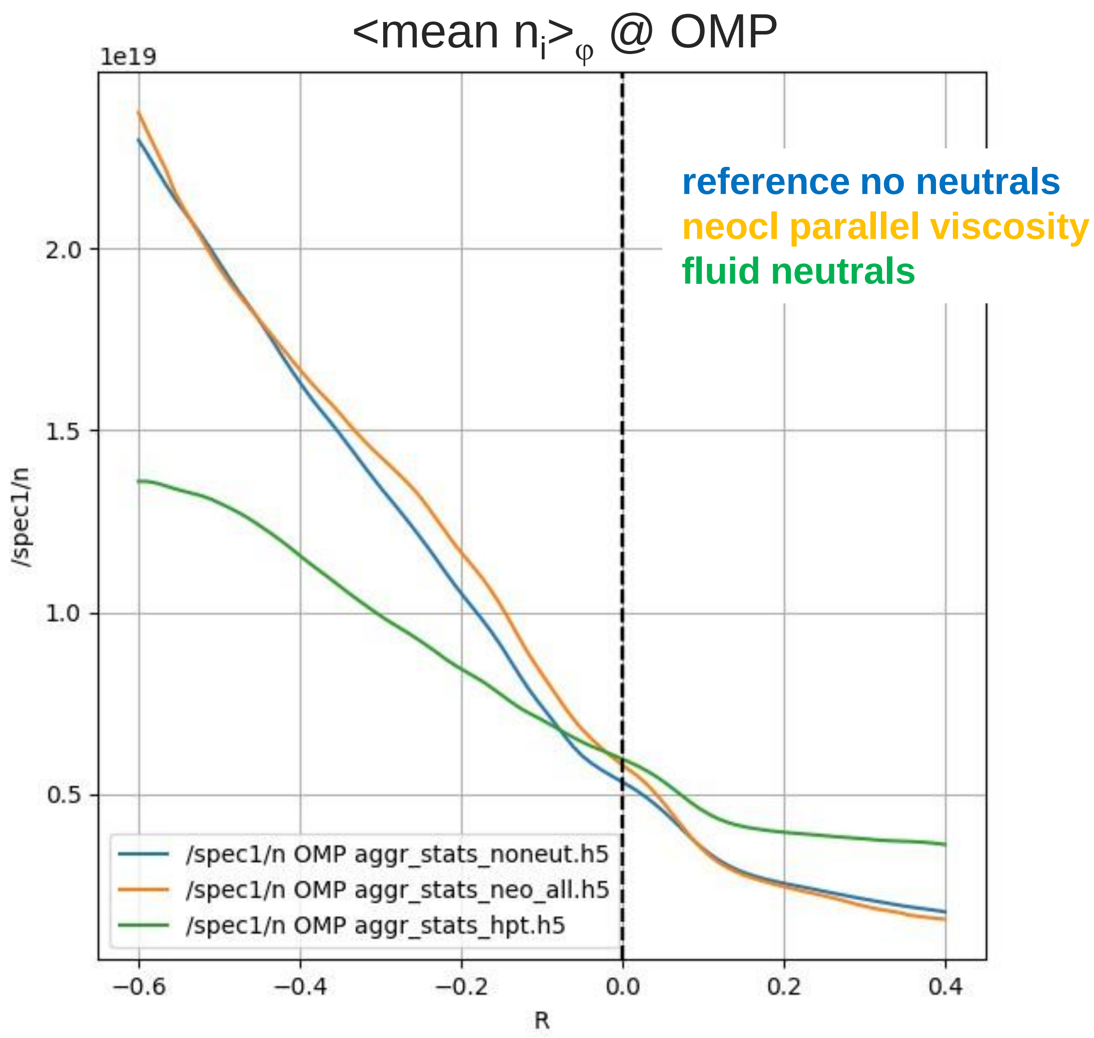
Fluid neutrals

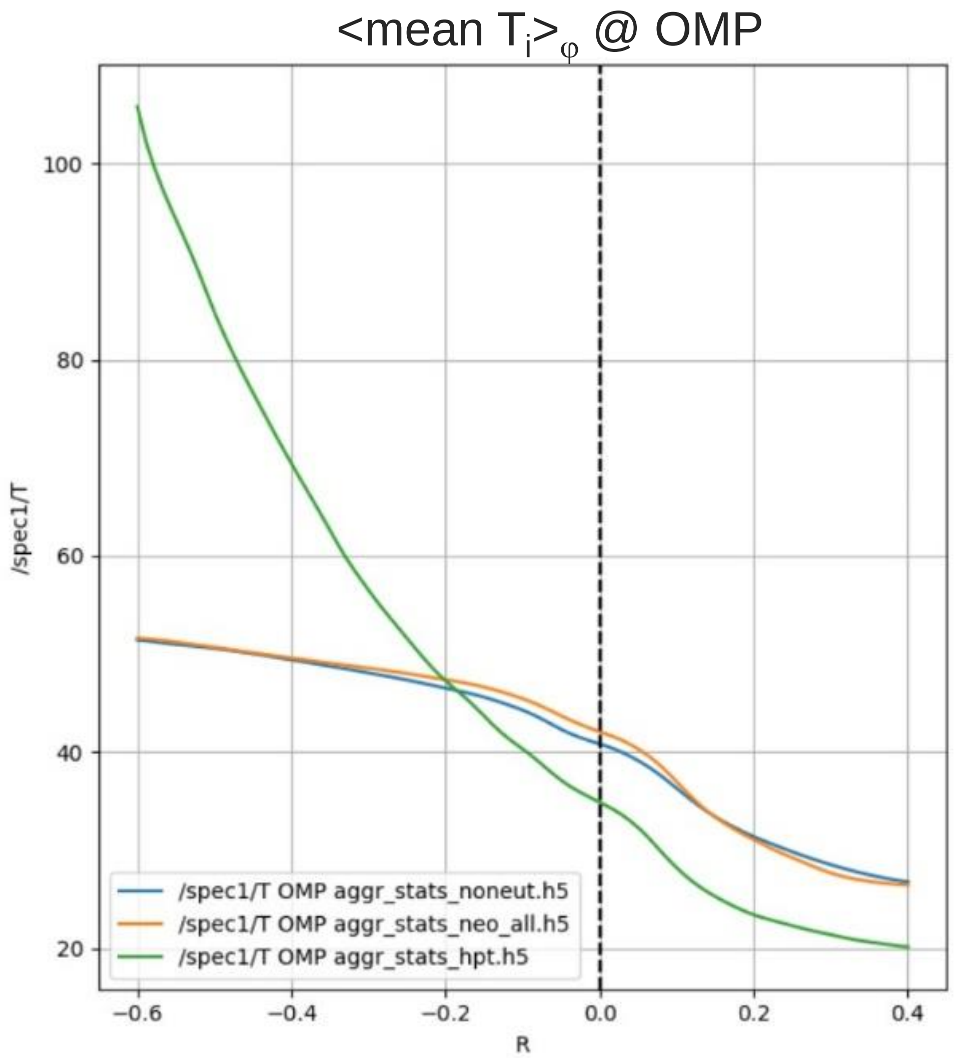
Impact of neutrals

- break toroidal axisymmetry

! impact toroidal average

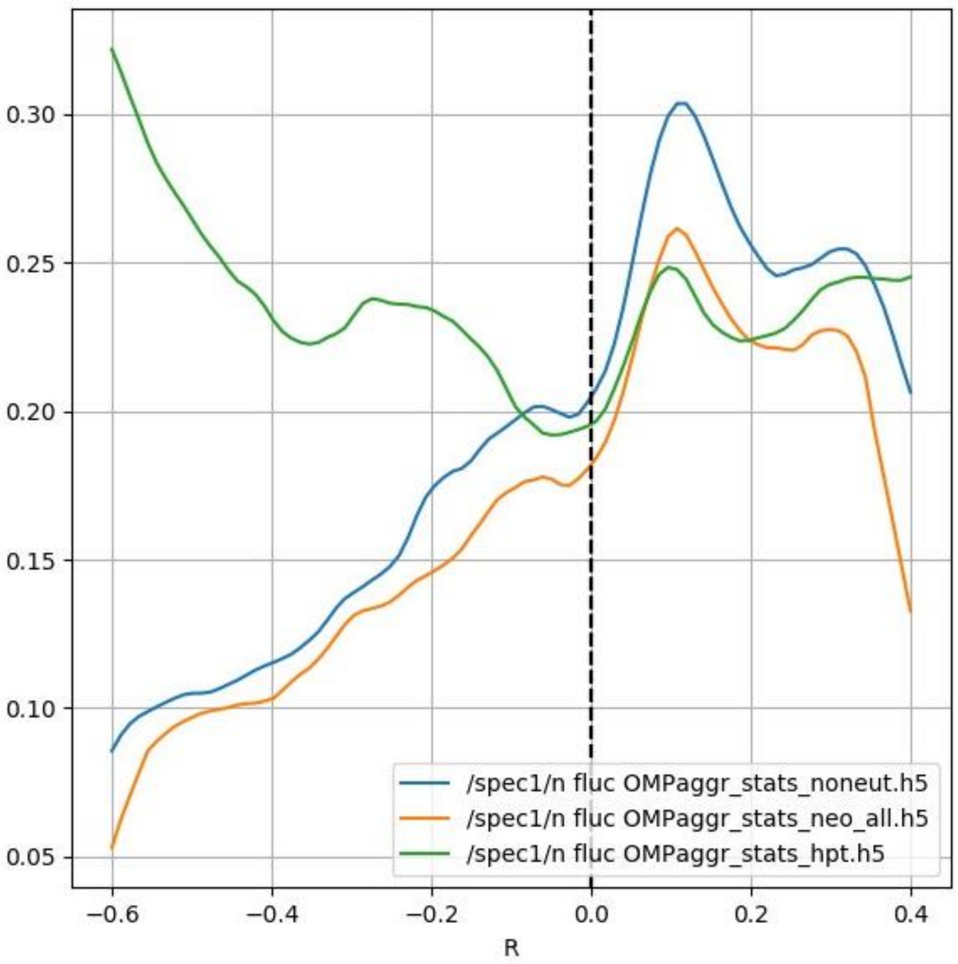
TURBULENCE CIRCULAR LIMITED CASES : plasma profiles



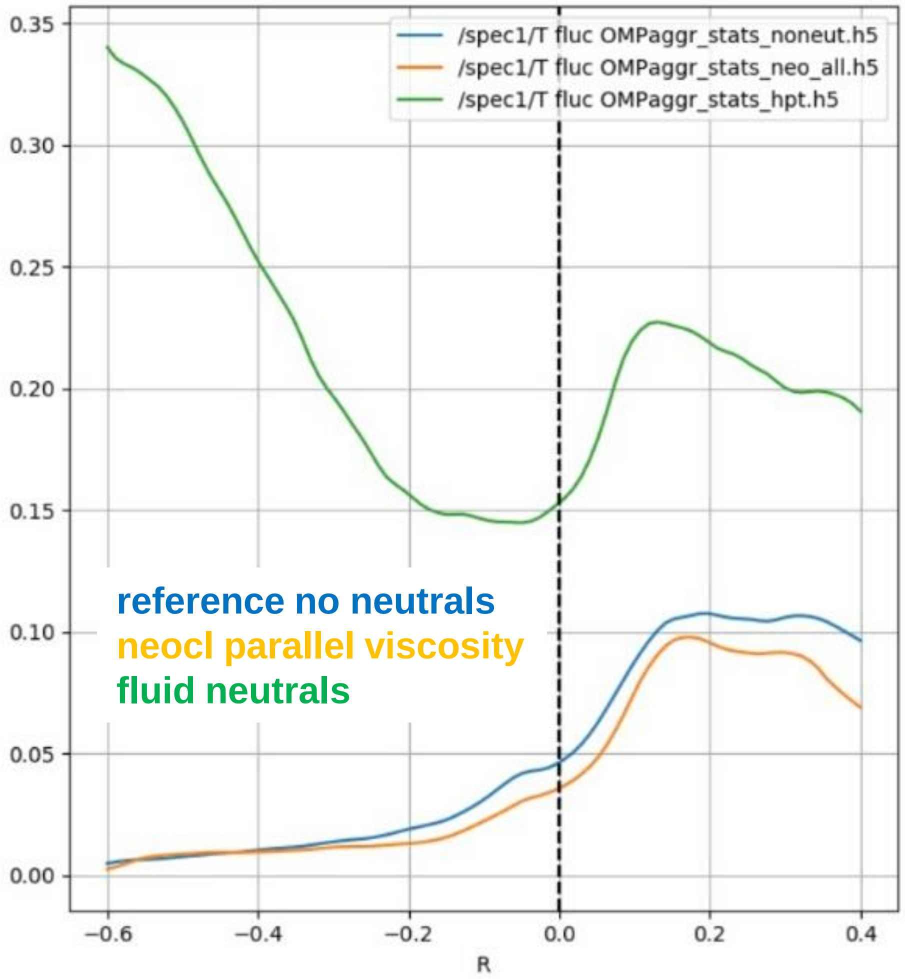


TURBULENCE CIRCULAR LIMITED CASES : fluctuation profiles

$<\sigma / \text{mean } n_i>_\varphi$ @ OMP

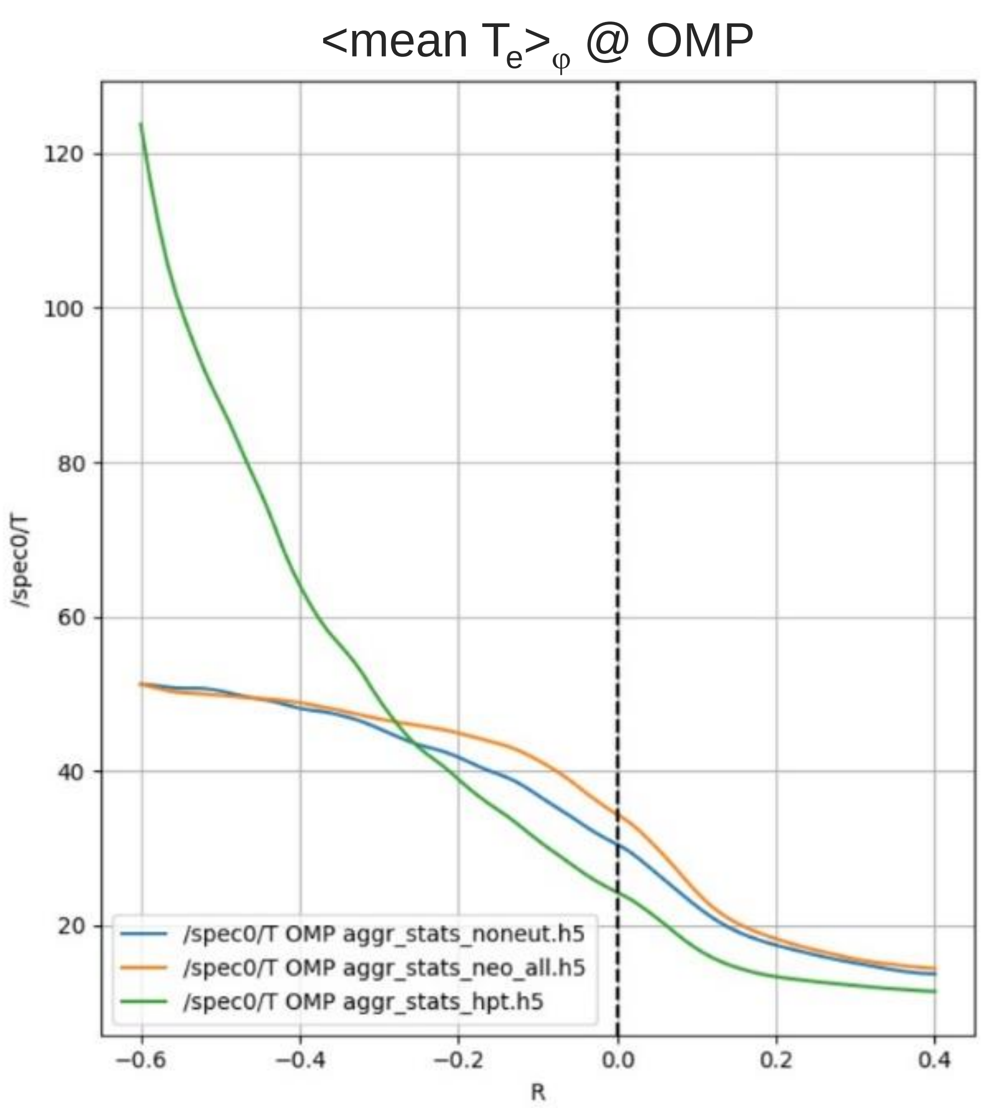


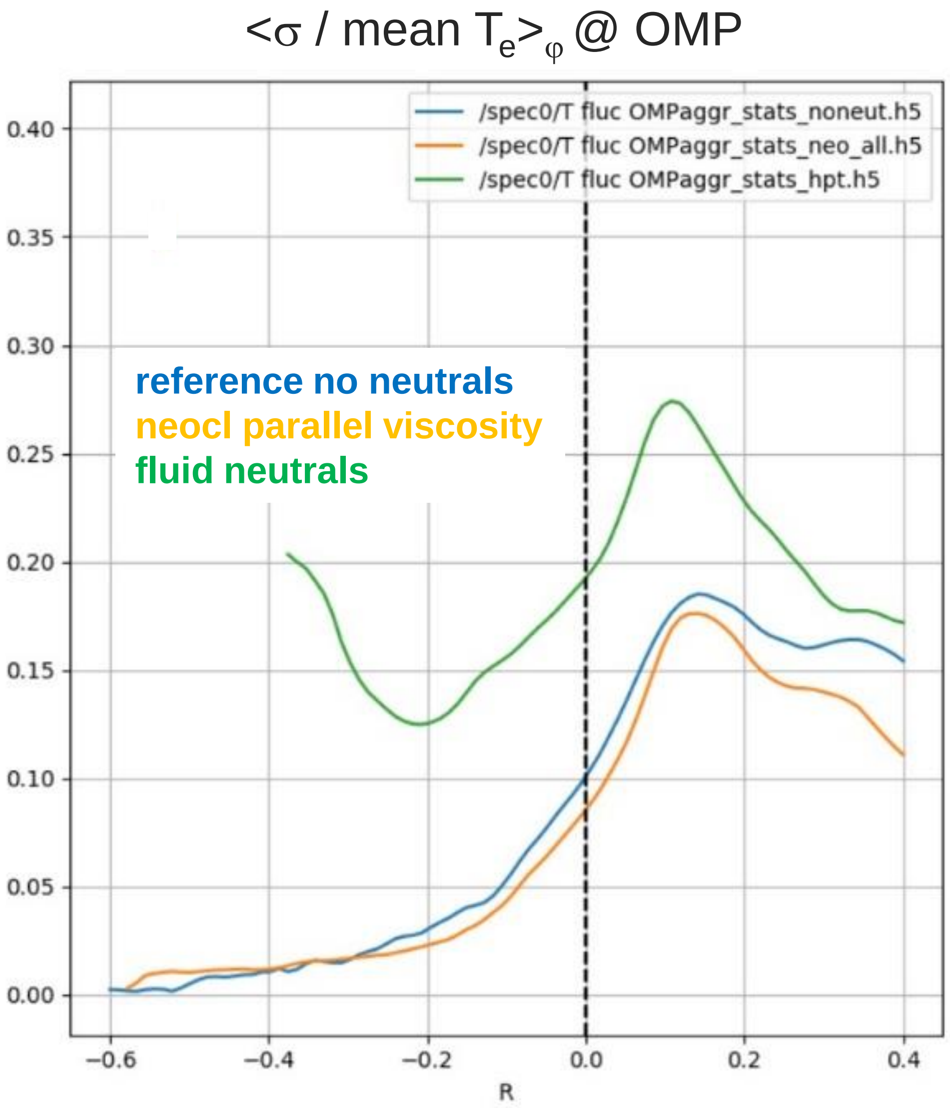
$<\sigma / \text{mean } T_i>_\varphi$ @ OMP



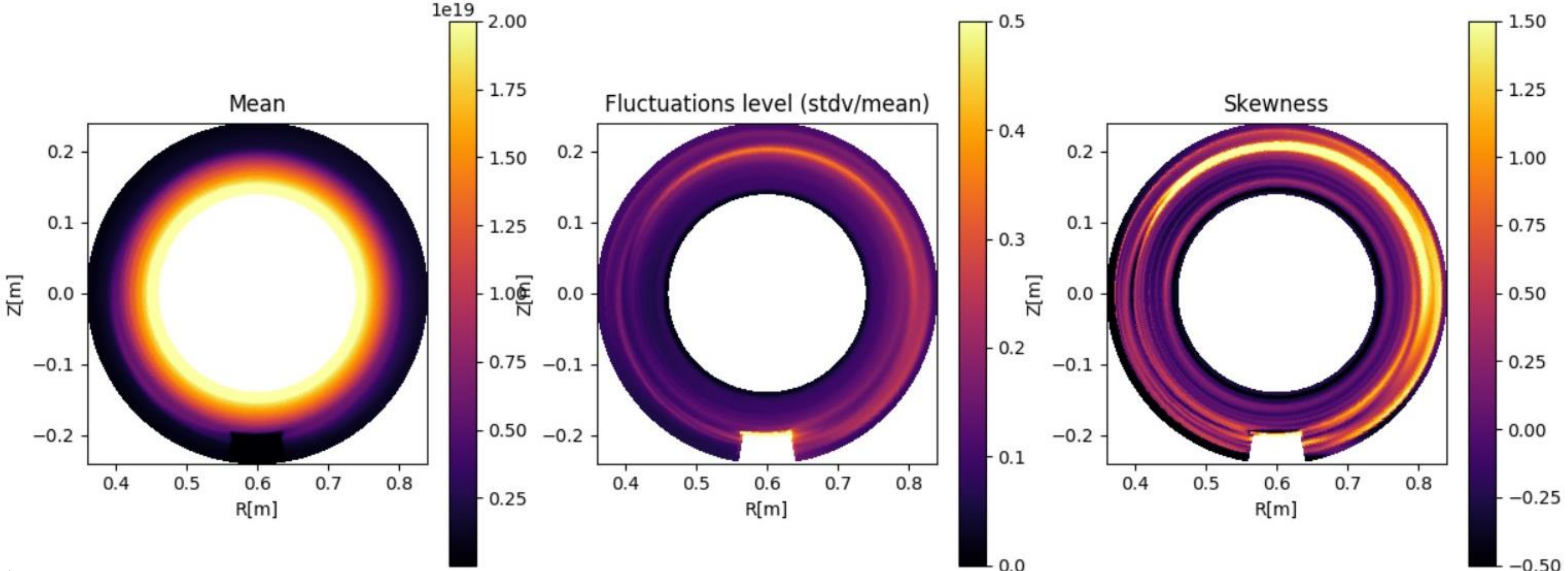
! $T_i = T_n$

TURBULENCE CIRCULAR LIMITED CASES : T electron



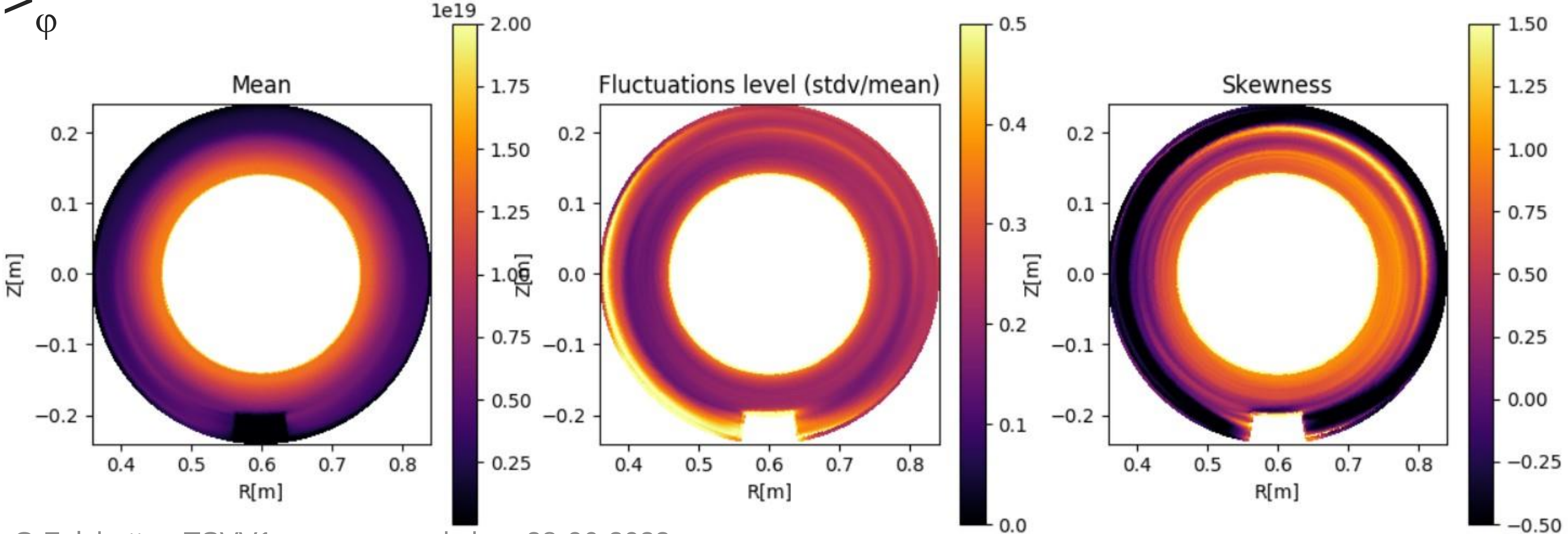


IMPACT of NEUTRALS on turbulence characteristics – poloidal asymmetry



Full neoclassic effects

$\langle n_i \rangle_\varphi$



fluid neutrals

Next steps

- **Analyses of fluxes ExB etc..**
- **Investigate the impact of neoclassical parallel viscosity in the case with fluid neutrals**
- **Investigate impact of q profile –** reproduce the effect observed experimentally - R Varennes, L Vermare
- ✓ Ongoing in the team:

  3D turbulence simulations in real size TCV geometry (TCV23 validation case within TSVV3)

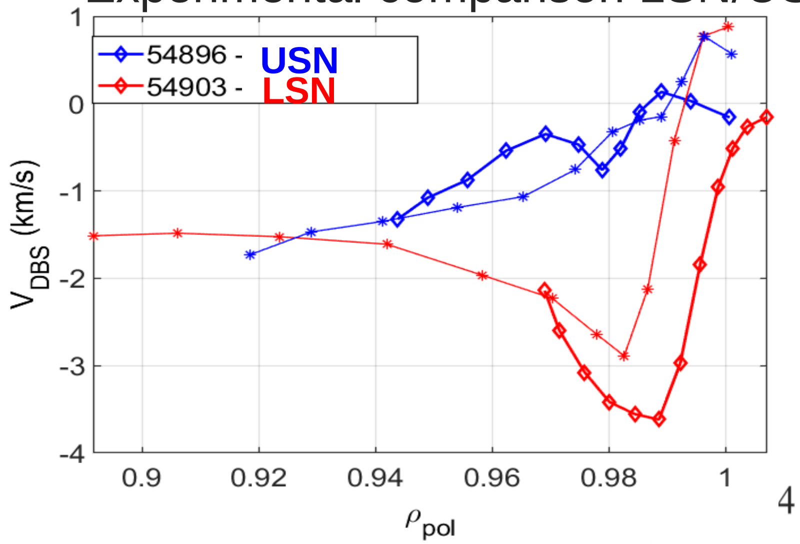
  with different models of fluid neutrals H Bufferand Invited @PET2023; V Quadri Invited @PET2023

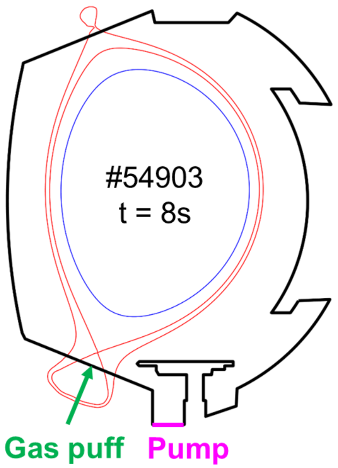
Magnetic drift impact was explored in SOLEDGE3X-EIRENE 2D transport simulations for WEST

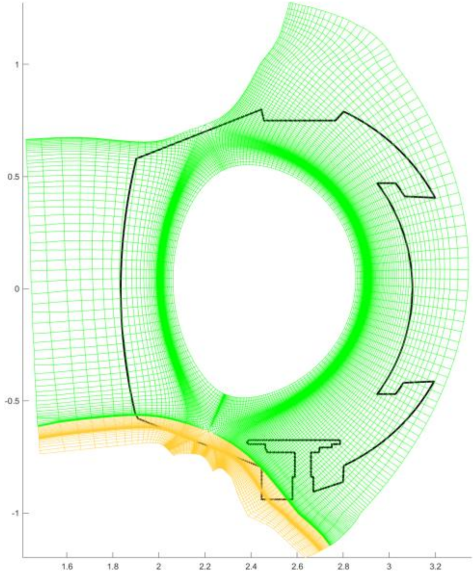
WEST #54903 LSN @t = 4.8s, compared to reversed B field case: USN
The converged transport cases could be used as starting point to speed up the turbulence simulations
– SE3X mesh generator allows to automatically create a refined mesh from a coarser
Initial plan:
- Higher q_{95}
- Increase power in USN case

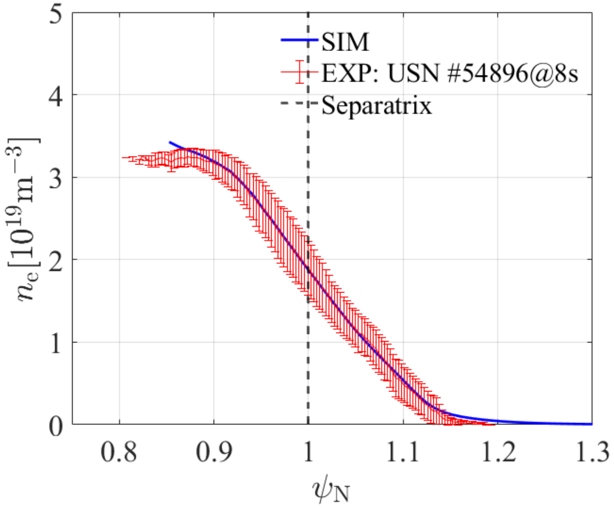
SOLEDGE3X-EIRENE 2D transport simulations of WEST

Experimental comparison LSN/USN



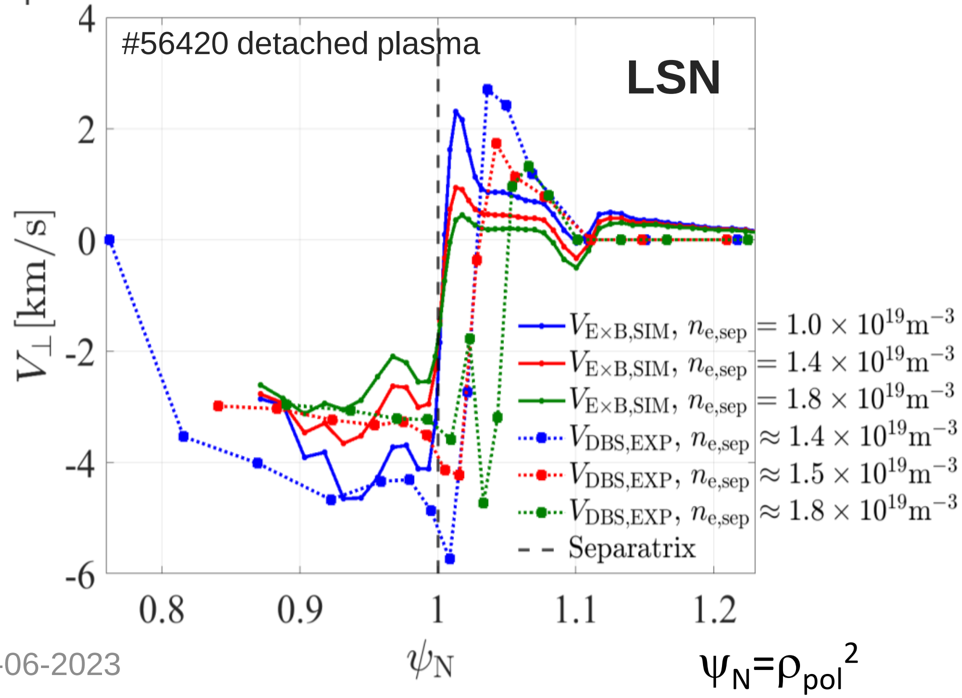


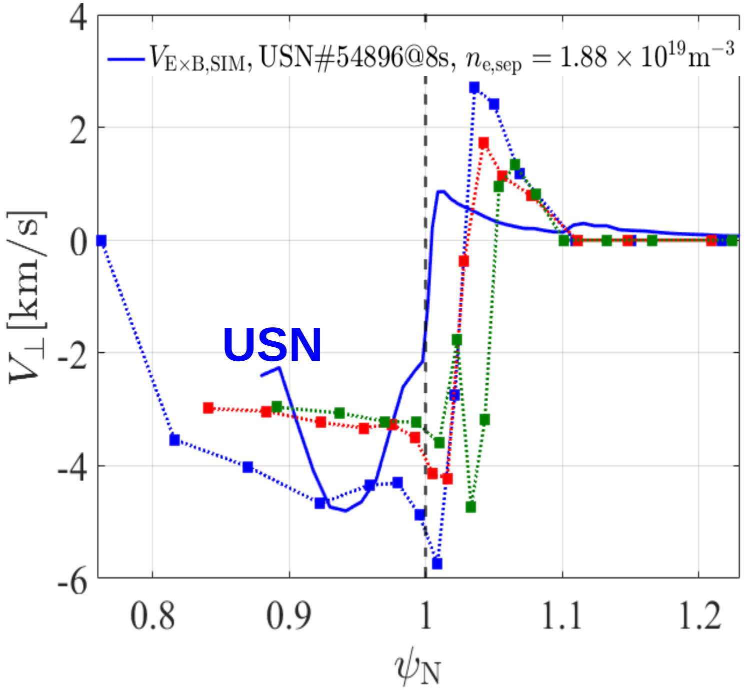




Inversed E_r near separatrix present in 2D transport simulation

comparable peak in USN vs LSN





$\psi_N=\rho_{pol}^2$

Courtesy H Yang, PhD

SOLEDGE3X related milestones/deliverables

- M2.7 Implement neoclassical friction in SOLEDGE3X fluid edge turbulence code. Investigate its impact on the generation and dynamics of the radial electric field well via a power scan in a limited case, in comparison to previous results without the friction (of TSVV1 pilot) and to GK results. Investigation of QH or I mode regime.

- ✓ D2.5 Report including statements on the relative impact of some separate ingredients playing a role in the radial electric field formation (orbit losses, **ripple, turbulence**, neutrals..)   Report or paper submitted, conference contribution X. Garbet, R. Varennes, L. Vermare, G. Falchetto 12/2022

- M4.2 Compare the generation of an inversed radial electric field in two magnetic configurations (favourable vs unfavourable magnetic drift direction) in SOLEDGE3X with realistic X-point geometry and neutrals, compare to experimental findings on one machine. G. Falchetto 06/2023

- **D4.2** Report on the study of the effect of the direction of the magnetic drift and the level of realism of the edge conditions, with respect to experimental measurements. Report, paper, or conference contribution G. Falchetto 12/2023

- **M2.18** Study the development of a radial electric field in response to further key parameters (injected power, **shaping**, etc) with SOLEDGE3X and GBS. Initial comparisons to GK and experimental findings. G. Falchetto, M. Giacomin 06/2024
- **M2.19** Extend above analysis to a larger number of scenarios / machines and by **realistic geometries and neutral particles**. G. Falchetto, M. Giacomin 12/2025
- **D2.9** Electromagnetic fluctuations and radial electric field development in response to key parameters (injected power, shaping, etc) studied with fluid codes. Comparisons to experimental findings and GK simulations, assessing the limits of fluid modelling.   Report, paper, or conference contribution M. Giacomin, G. Falchetto 12/2025