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First full-scale TCV L-mode edge turbulent simulation including neutral recycling with the SOLEDGE3X code

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► To cite this version:

Bufferand H., Ciraolo G., Düll R., Falchetto G., Fedorczak N., et al.. First full-scale TCV L-mode edge turbulent simulation including neutral recycling with the SOLEDGE3X code. EPS 2023 - 49th Plasma Physics Conference, Jul 2023, Bordeaux, France. . cea-04203326

HAL Id: cea-04203326

<https://cea.hal.science/cea-04203326>

Submitted on 11 Sep 2023

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Introduction

Accurate modelling of cross-field turbulent transport in tokamak's edge plasma remains a challenge, many key experimental features such as edge transport barriers formation being still hard to simulate, especially for ITER size tokamaks. Being able to predict the SOL width or the power load imbalance between inner and outer divertor legs even for today's JET size tokamaks is still an open issue. First principle modelling of edge plasma turbulence is thus today a very active topic in the fusion community.

The edge plasma code SOLEDGE3X [H. Bufferand et al., Nucl. Fusion 61 (2021), 116052] aims at simulating plasma transport and plasma turbulence in the edge plasma based on a fluid description. In this poster, we present first SOLEDGE3X simulation results of the so-called TCV-X21 case [D.S. Oliveira et al., Nucl. Fusion 62 (2022), 096001], a series of diverted ohmic L-mode discharges on TCV designed as a dataset for edge turbulence codes validation. The simulation includes plasma recycling and impact of neutrals on edge plasma turbulence.

The SOLEDGE3X code

SOLEDGE3X solves Braginskii/Zhdanov equations for a multi-species plasma in 2D or 3D geometry. SOLEDGE3X is coupled to several neutral models : fluid neutrals or kinetic neutrals via coupling with EIRENE.

Recall on the model (simplified):

- Mass balance: $\partial_t n + \vec{\nabla} \cdot (n\vec{v}) = S_n$

- Parallel momentum balance

$$\partial_t (mnv_{\parallel}) + \vec{\nabla} \cdot (mnv_{\parallel}\vec{v}) = -\nabla_{\parallel} p + ZneE_{\parallel} + \vec{b} \cdot (\vec{\nabla} \cdot \vec{\Pi}) + R_{\parallel} + S_p$$

- Perpendicular momentum balance (drifts – zeroth order): $\vec{v}_{\perp} = \frac{\vec{E} \times \vec{B}}{B^2} + \frac{\vec{B} \times \vec{\nabla} p}{q n B^2}$

- Energy balance: $\partial_t \varepsilon + \vec{\nabla} \cdot (\varepsilon \vec{v} + p v_{\parallel} \vec{b} + \vec{\Pi} \cdot \vec{v} + \vec{q}) = (ZneE_{\parallel} + R_{\parallel}) v_{\parallel} + S_{\varepsilon}$

- Current balance (vorticity equation): $\vec{\nabla} \cdot (\vec{j}_{\text{pola}} + \vec{j}^* + j_{\parallel} \vec{b}) = 0$

Ongoing implementation of electromagnetic effects (see R. Düll poster)

Numerical Aspects

The code is based on a 2D/3D finite volumes numerical scheme. One uses structured grid aligned on magnetic flux surfaces + domain decomposition to treat X-points. A mask function χ is used to define the wall location. Boundary conditions are imposed at the interface $\chi=1$ | $\chi=0$.

The parallelization is hybrid MPI/OpenMP + ongoing porting to GPU architectures. More details on www.soledge3x.com.

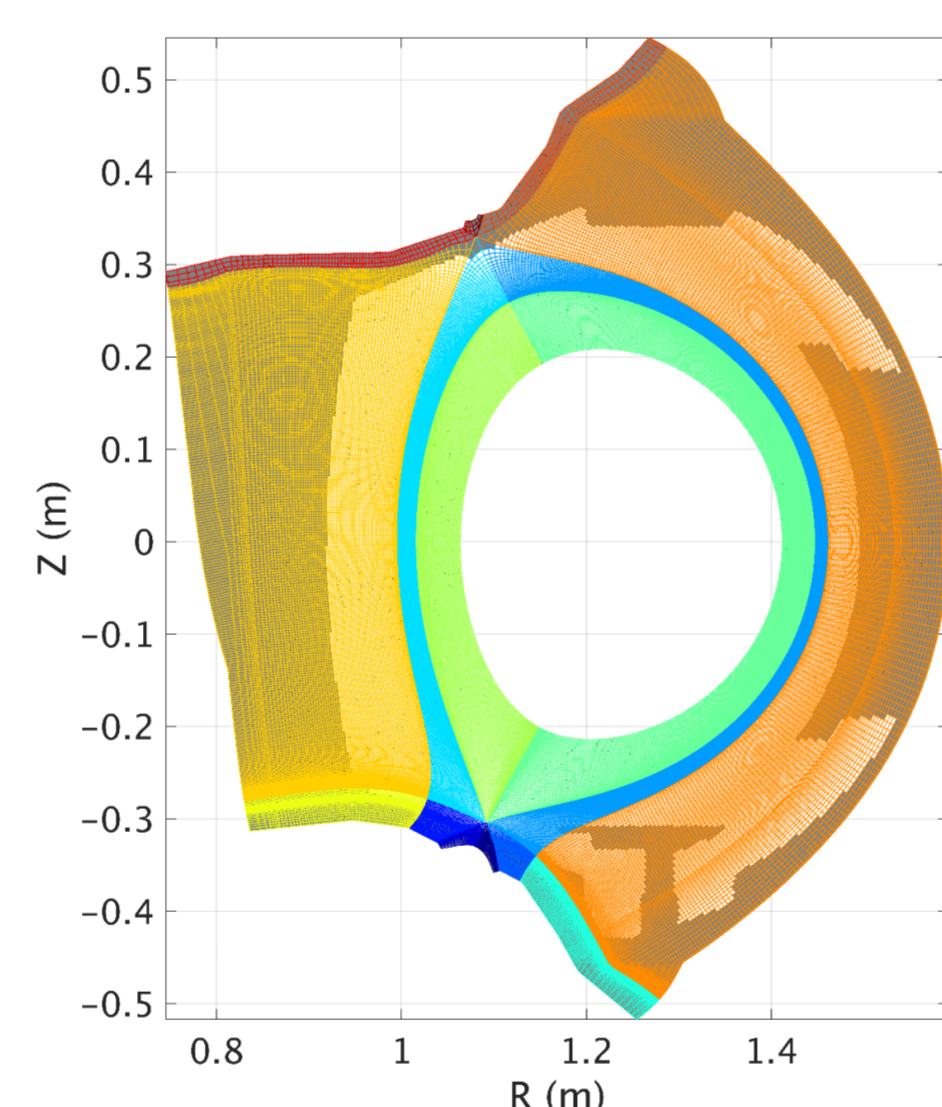
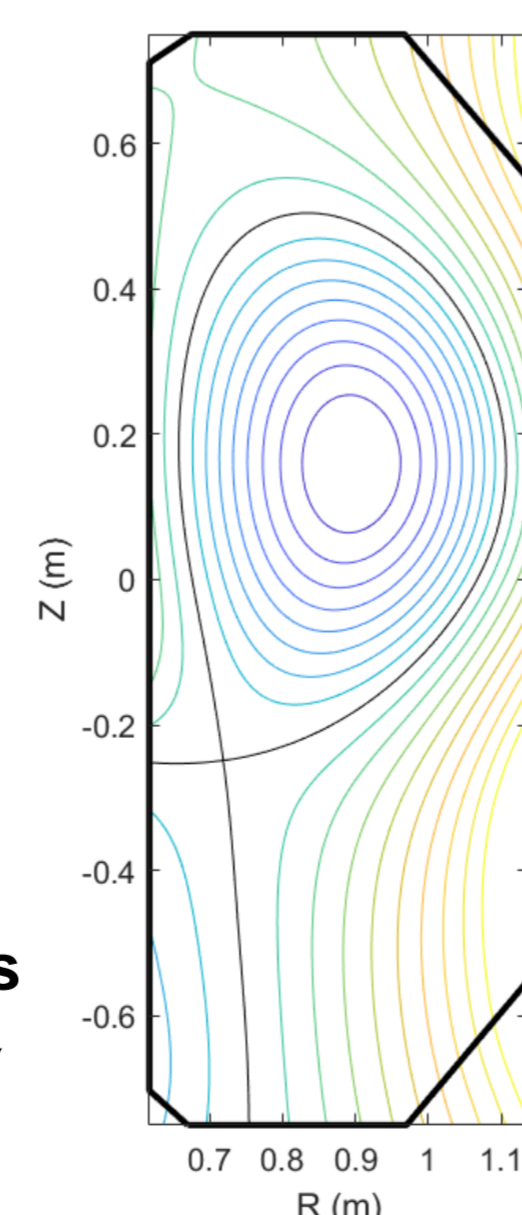


Fig 1. SOLEDGE3X mesh
Example of mesh for a WEST case (double X-point) showing domain decomposition and wall mask function

The TCV-X21 case

In order to benchmark European turbulence codes (at that time GBS, GRILLIX and TOKAM3X), a dedicated set of discharges were performed on TCV. The magnetic field was chosen quite low to increase $\rho^* = \rho_L/a$ and be less demanding in term of grid resolution. The discharges were low power Ohmic L-mode plasmas.

Fig 2. TCV shot #51333 for X21 series
Magnetic equilibrium and wall geometry



Acknowledgements

This work was granted access to the HPC/AI resources of CINES/IDRIS/TGCC under the allocation 2022-A0120510482 made by GENCI and to the HPC resources of Aix-Marseille University financed by the project Equip@Meso (ANR-10-EQPX-29-01). This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Simulation setting

First attempt for full-scale TCV simulation with neutrals.

Simulation parameters:	Power	n_{sep}	B_t	I_p
	120 kW	$7 \cdot 10^{18} m^{-3}$	0.95 T	165 kA

- Recycling coefficient set to 90% (quite low to speedup convergence given $\tau \sim \frac{1}{1-R}$)
 - Fluid neutrals model based on [Horsten et al., Nucl. Fusion 57 (2017)]
 - Plasma density set at separatrix by feedback on gas puff (localized at the outboard mid-plane)
- Grid resolution: $N_{\psi} \sim 200$, $N_{\theta} \sim 1400$, $N_{\varphi} \sim 64$ [quarter torus]
CPU time: 800kCPUh on 3072 CPUs, not yet (at all) at quasi steady state.

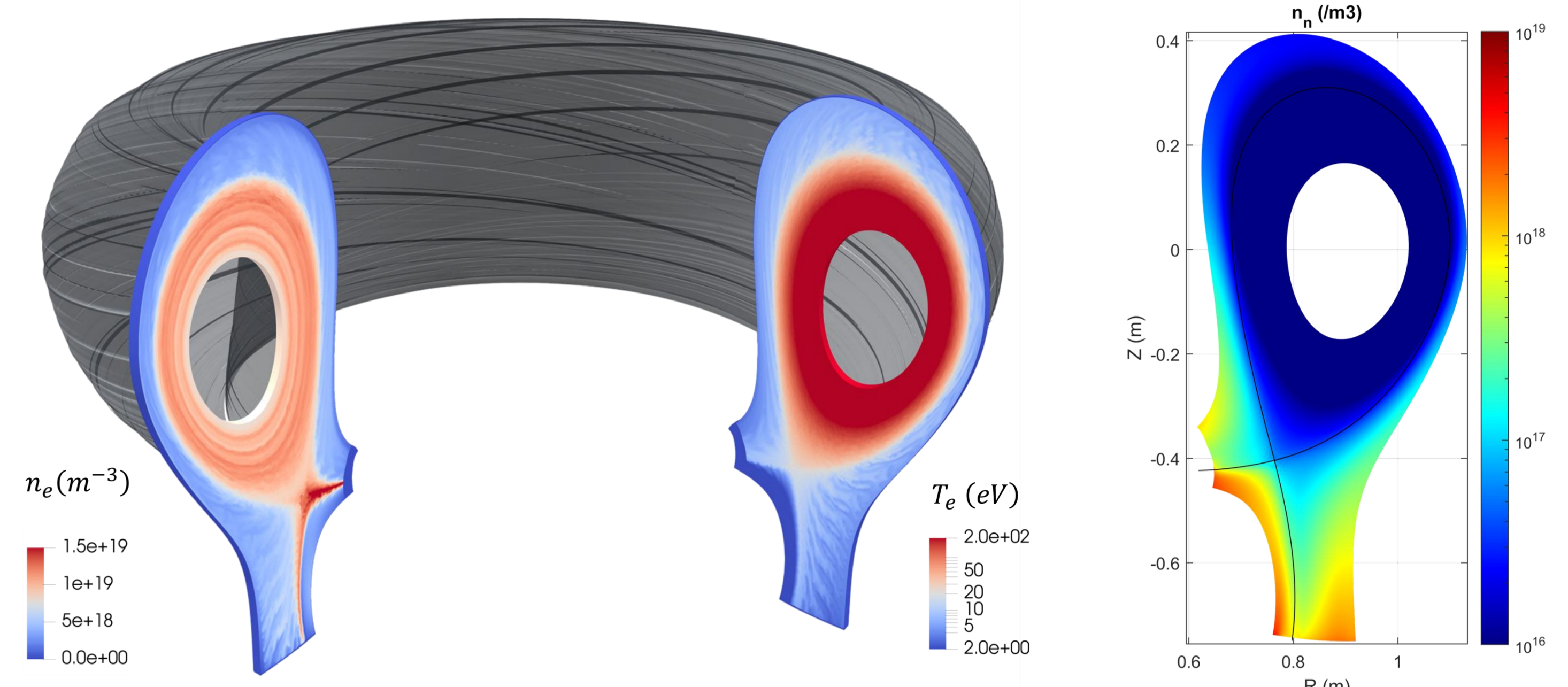


Fig 3. 3D snapshot of the TCV-X21 simulation
Left slice: density, Right slice: electron temperature

Fig 4. Atoms density

Turbulence in high recycling plasma

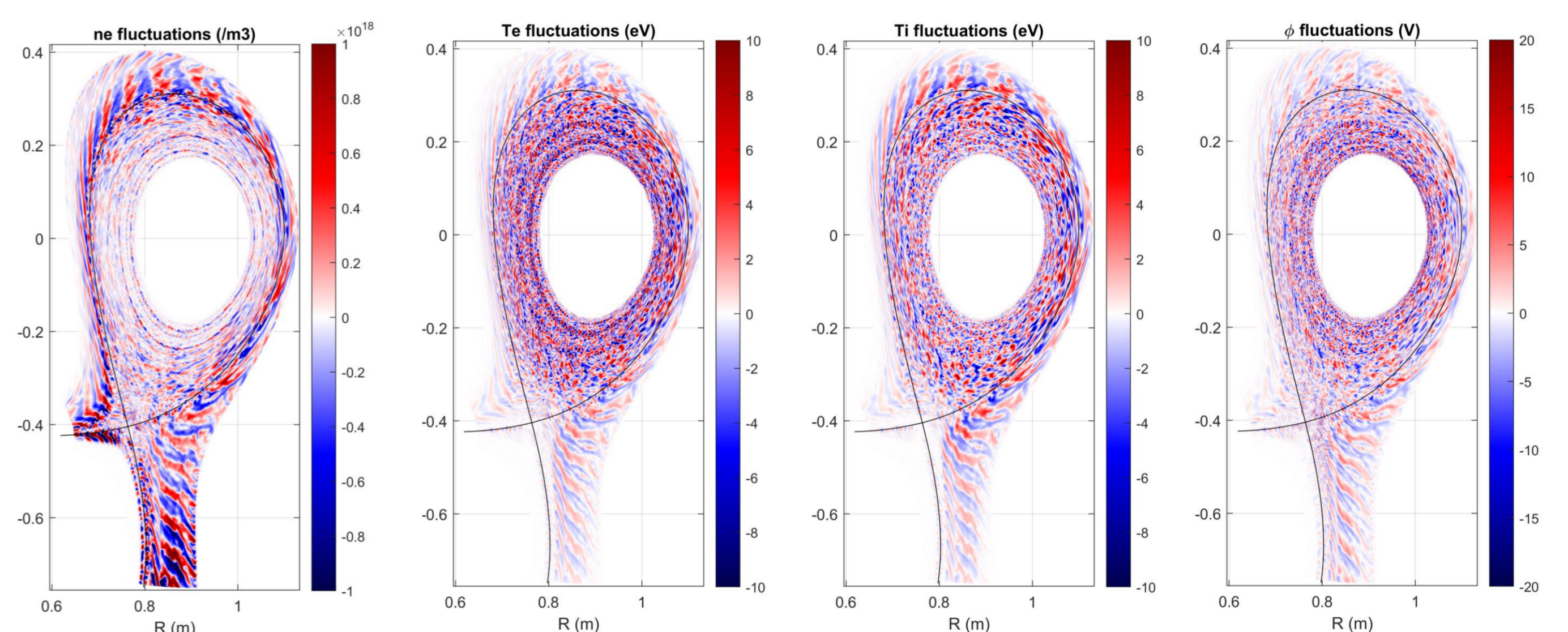


Fig 5. Snapshot of toroidal fluctuations

From left to right: density, electron temperature, ion temperature and electric potential

Preliminary observation: Edge plasma turbulence characterized by temperature fluctuations in the confined region and density fluctuations in the Scrape-off layer. Properties of turbulence still to be investigated at quasi-steady-state based on statistics.

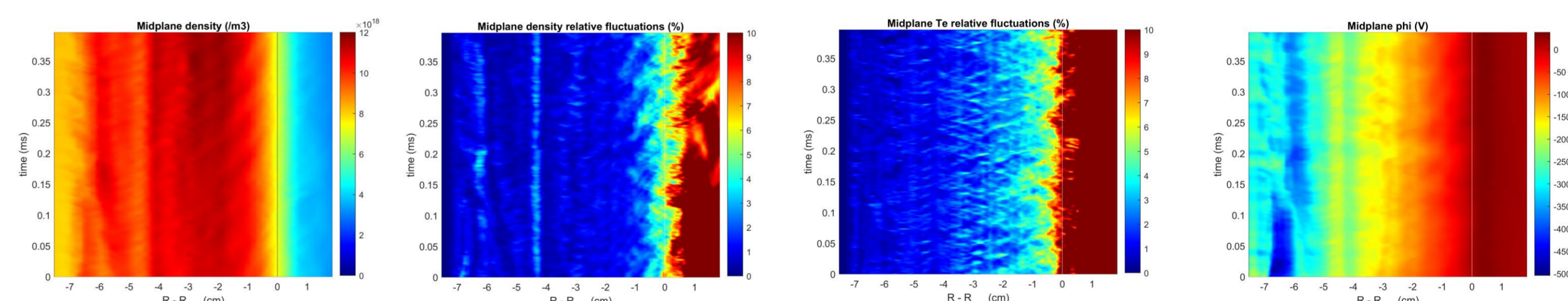


Fig 6. Spatio-temporal evolution of plasma at the outboard mid-plane

From left to right: density, density and electron temperature fluctuation level and electric potential

Avalanches clearly observed on electron temperature fluctuations. Zonal flows and staircases to be investigated. Influence of the "core" boundary condition to be assessed since grid do not extend to the magnetic axis. Confined plasma region still being fueled by the edge (reverse density profile)

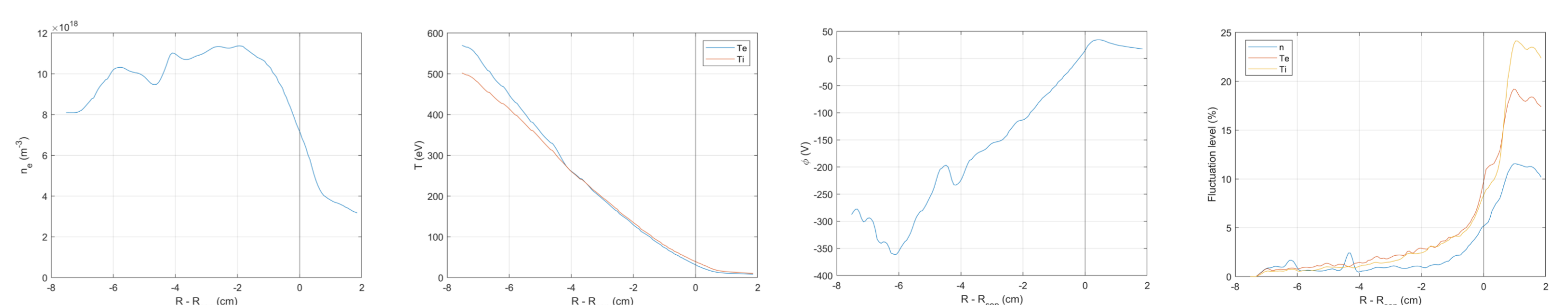


Fig 7. Time averaged radial profiles at the outboard mid-plane

From left to right: density, temperatures, electric potential and levels of fluctuations

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