



**HAL**  
open science

# A self-consistent cross-field transport model for edge tokamak plasma simulations: SOLEDGE modelling and comparison with experiments

G Ciraolo, S Baschetti, H Bufferand, G Falchetto, Ph Ghendrih, H Yang, N Rivals, P Tamain, E Serre

## ► To cite this version:

G Ciraolo, S Baschetti, H Bufferand, G Falchetto, Ph Ghendrih, et al.. A self-consistent cross-field transport model for edge tokamak plasma simulations: SOLEDGE modelling and comparison with experiments. 48th EPS conference on plasma physics, Jun 2022, Videoconference, Netherlands. cea-03766468

**HAL Id: cea-03766468**

**<https://cea.hal.science/cea-03766468>**

Submitted on 1 Sep 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



# A self-consistent cross-field transport model for edge tokamak plasma simulations: SOLEDGE modelling and comparison with experiments

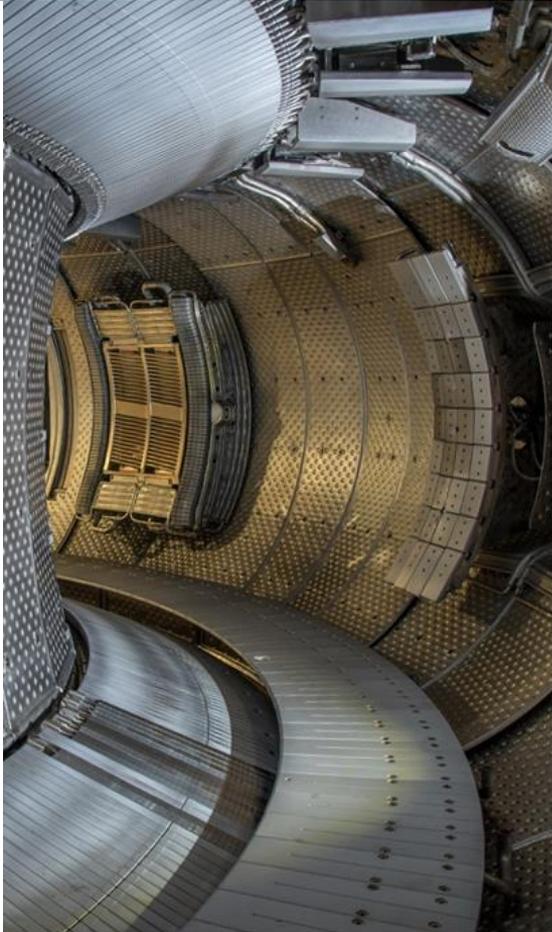
DE LA RECHERCHE À L'INDUSTRIE

G. Ciraolo<sup>1</sup>, S. Baschetti<sup>1</sup>, H. Bufferand<sup>1</sup>, G. Falchetto<sup>1</sup>, Ph. Ghendrih<sup>1</sup>,  
H. Yang<sup>1</sup>, N. Rivals<sup>1</sup>, P. Tamain<sup>1</sup>, E. Serre<sup>2</sup> and the WEST team<sup>3</sup>

*1 IRFM, CEA-Cadarache, 13108 Saint-Paul-lez-Durance, France*

*2 M2P2, Aix-Marseille Univ, CNRS, Centrale Marseille, 13013 Marseille, France*

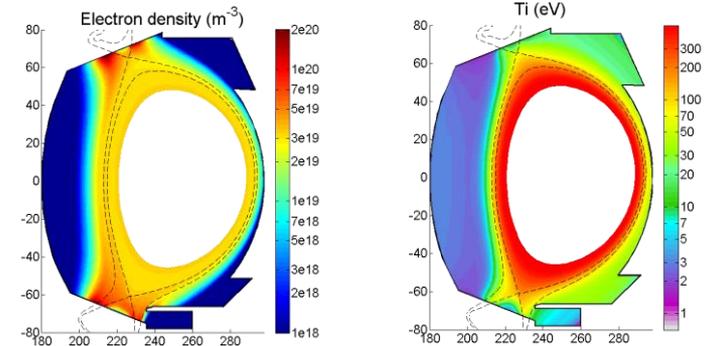
*3 <http://west.cea.fr/WESTteam>*



- Brief recall on transport codes and their applications
- Introducing turbulence in mean flow equations
  - The ideas from Computational Fluid Dynamics
  - The derivation for edge plasma transport codes
- Implementation in SOLEDGE code and application to modelling TCV and WEST experiments
- Summary and conclusions



- **Transport codes** provide a coarse grained picture of edge plasma properties integrating the many actors at play: main plasma, neutrals, impurities, wall properties
- **Architecture:**
  - Fluid solver for the quasi-neutral plasma (main species + impurities)
  - Model to describe the plasma sheath
  - Databases or specific model to describe wall properties (recycling properties, sputtering...)
  - Solver for neutrals (fluid or kinetic)



*Example of SOLEDGE-EIRENE simulations for WEST geometry*

- **Reduction:** Radial turbulent transport treated with empirical diffusion coefficients
- **Non-exhaustive list of transport codes:** SOLEDGE-EIRENE, SOLPS-ITER, EDGE2D-EIRENE, EMC3-EIRENE, COREDIV, SONIC, UEDGE, ...

## ■ Plasma mean-field transport solver

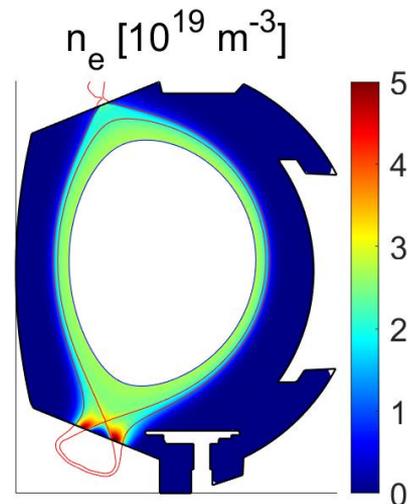
$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = S(n, \mathbf{u}, \dots)$$

- Scale separation  $n = \bar{n} + \tilde{n}$   
 $\mathbf{u} = \bar{\mathbf{u}} + \tilde{\mathbf{u}}$

$$\frac{\partial \bar{n}}{\partial t} + \nabla \cdot (\bar{n}\bar{\mathbf{u}} + \langle \tilde{n}\tilde{\mathbf{u}} \rangle_{t,r}) = S(\bar{n}, \bar{\mathbf{u}}, \dots) + \langle S(\tilde{n}, \tilde{\mathbf{u}}, \dots) \rangle_{t,r} + \dots$$

~~$$\frac{\partial \tilde{n}}{\partial t} + \nabla \cdot (\tilde{n}\bar{\mathbf{u}} + \bar{n}\tilde{\mathbf{u}}) = \tilde{S}$$~~

- gradient-diffusion closure  $\langle \tilde{n}\tilde{\mathbf{u}} \rangle_{t,r} = -Dn\nabla\langle n \rangle$
- Solves only the fluctuation averaged fluid equations
- Diffusion coefficient is chosen to reproduce outer midplane profiles from experiments



$$\frac{\partial \langle n \rangle}{\partial t} + \nabla \cdot (\langle n \rangle \mathbf{v}_{\parallel} - D_n \nabla \langle n \rangle) = S_n$$

- Taking inspiration from the  $\kappa - \varepsilon$  model for neutral fluids ([Jones, Launder 1971]) and prey-predator models [Miki, Diamond 2013]

- Transport equation for turbulent intensity  $\kappa = \frac{1}{2} \langle \tilde{u}^2 \rangle$  H. Bufferand et al, CPP 2016

$$\frac{\partial \kappa}{\partial t} + \nabla \cdot \mathbf{K} = S_{\kappa} - \varepsilon \quad \longrightarrow \quad \frac{\partial \kappa}{\partial t} + \nabla \cdot \mathbf{K} = \gamma_{int} \kappa - \Delta \omega k^2$$

- **Source term:**  $S_{\kappa} = \gamma_{int} \kappa$  with  $\gamma_{int}$  is the **interchange growth rate**  $\gamma_{int}^2 = c_s^2 \left( \frac{\vec{\nabla}_B \cdot \vec{\nabla} p_i}{B p_i} - \frac{\Theta}{R^2} \right)$  with  $\Theta$  the interchange threshold so that interchange develops for  $\frac{R}{\lambda_p} > \Theta$  [X. Garbet et al., *Nucl. Fusion* **32** (1992)]
- $\gamma_{int}$  : **linear growth rate of the interchange instability** (governs a ballooning of the local drive)
- **Sink term:**  $\varepsilon = \Delta \omega k^2$  represents turbulence non-linear saturation
- $\Delta \omega$  is the **free parameter**  $\rightarrow$  **model closure:** tuning with **scaling law** to **improve predictive capabilities**
- Assuming transport coefficient proportional to turbulent intensity ( $D \propto \kappa$ )

- Neglecting transport, steady-state is reached when  $\gamma_{int}k = \Delta\omega k^2$  that is  $k = 0$  or  $k = \frac{\gamma_{int}}{\Delta\omega}$
- The SOL balance gives  $\frac{c_s}{L_{||}} \approx \frac{D}{\lambda_{SOL}^2}$  hence, recalling that  $D = kt_{||}$  and  $k = \frac{\gamma_{int}}{\Delta\omega}$
- $\Delta\omega = \frac{L_{||}\gamma_{int}}{c_s\lambda_{SOL}^2}$
- The free parameter  $\Delta\omega$  is determined using the scaling law for  $\lambda_{SOL}$

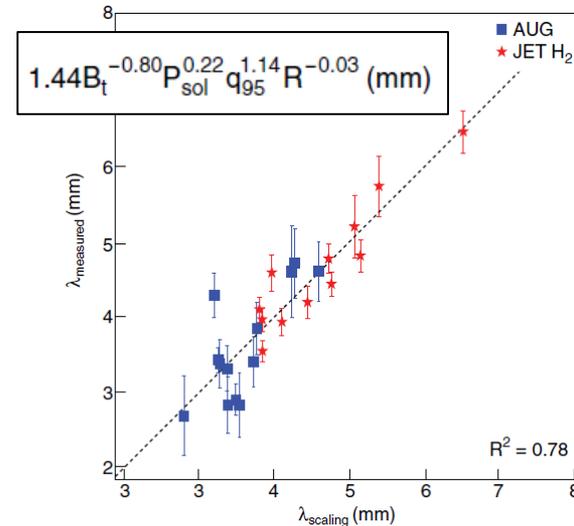
$$\lambda_{SOL} = \lambda_{SOL}^{scaling} \sim 4\rho_i q_{95}$$

[R.J. Goldston Nucl. Fusion 2012]

$$\rho_i = \frac{m_i c_s}{q_i B_{tot}} \quad q_{95} = \frac{a B_\phi}{R B_\theta}$$

$$\frac{\partial \kappa}{\partial t} + \nabla \cdot \mathbf{K} = \gamma_{int} \kappa - \Delta\omega k^2$$

[Scarabosio et al JNM 2013]

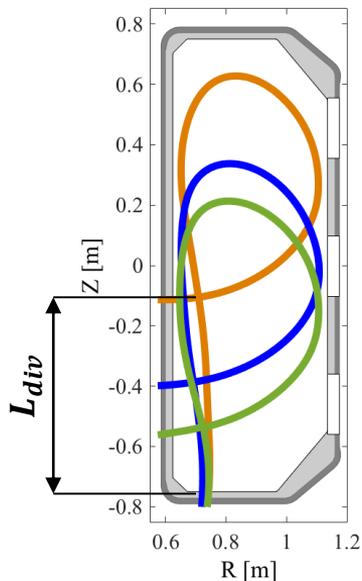


- ❑ **One-equation model** implemented in SOLEDGE tested vs very well diagnosed TCV experiment ([Maurizio et al., NF, 58 (2018); Gallo et al., PPCF, 60 (2018)])
- ❑ This experiment consists in **L-mode, LSN discharges** with **same main plasma parameters** and **varying magnetic divertor geometry ( $L_{div}$ )**.

LONG LEG #51325

MEDIUM LEG #51333

SHORT LEG #51262



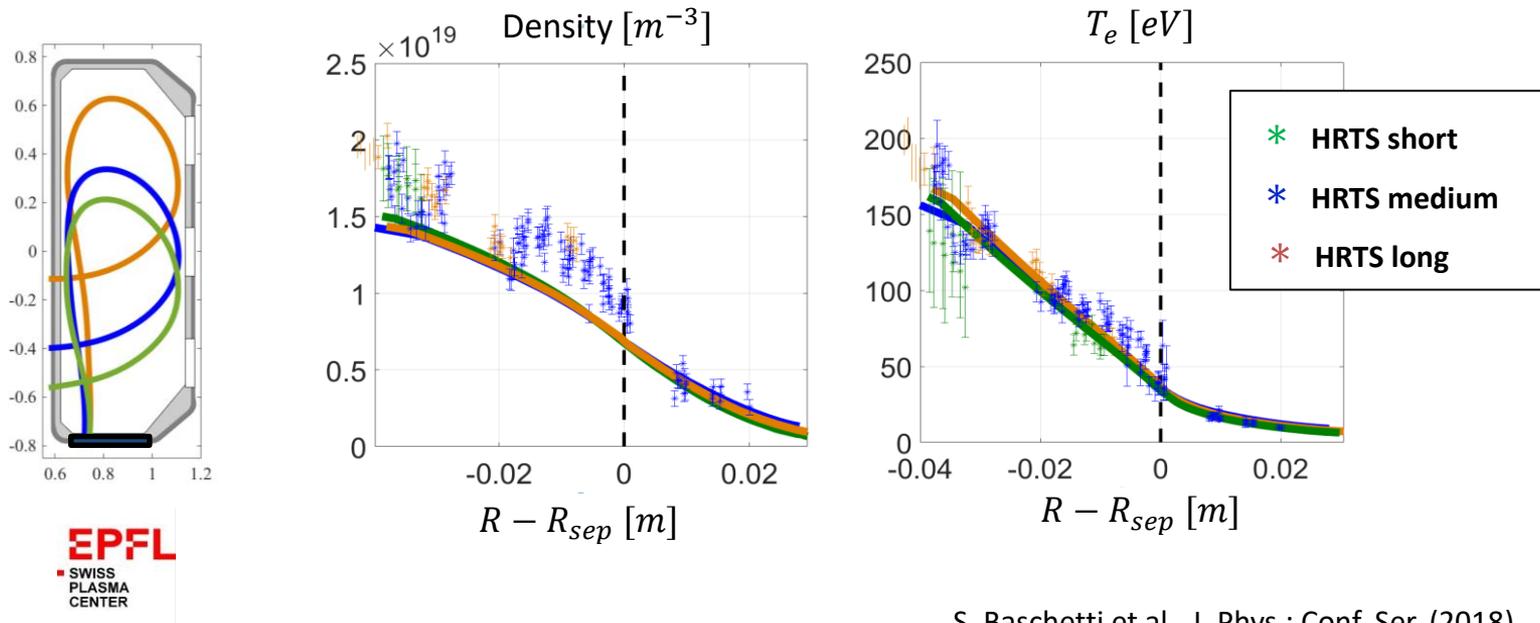
$R$ [m]	0.89
$a$ [m]	0.22
$k$	1.44
$I_p$ [kA]	210
$B_t$ [T]	1.4

**EPFL**  
 SWISS  
 PLASMA  
 CENTER

S. Baschetti et al., J. Phys.: Conf. Ser. (2018)

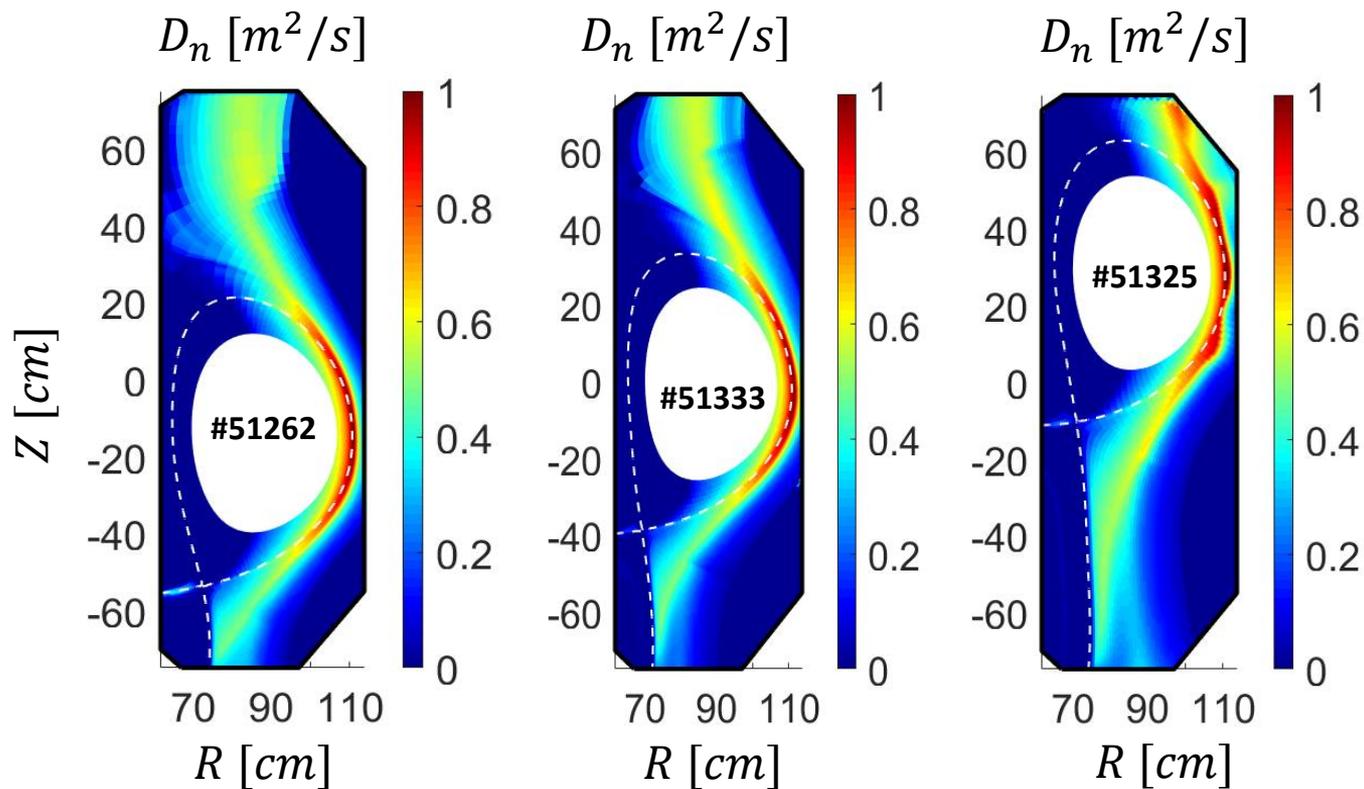
S. Baschetti, PhD manuscript, Aix-Marseille University, 2019

- ❑ **Simulation parameters:** pure deuterium,  $n_{sep,OMP} = 0.7 \cdot 10^{19} m^{-3}$  and  $P_{in} = 100 kW$ ;
- ❑ By changing the magnetic equilibrium, the **main plasma is not affected**;
- ❑ **Very good agreement** between simulation results (—) with HRTS data (\*) in the SOL.



S. Baschetti et al., J. Phys.: Conf. Ser. (2018)

S. Baschetti, PhD manuscript, Aix-Marseille University, 2019



- **Two transport equations on turbulent intensity and its dissipation rate from a heuristic approach** (Baschetti *et al.* NF 2021):

$$\frac{\partial \kappa}{\partial t} + \nabla \cdot \mathbf{K} = \gamma_{\kappa} \kappa - \varepsilon$$

$$\kappa \equiv \frac{1}{2} \langle \tilde{v}_{\perp}^2 \rangle$$

Kinetic energy per unit mass of the fluctuating transverse velocity

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \mathbf{E} = \gamma_{\varepsilon} \varepsilon - \beta_{\varepsilon} \varepsilon^2$$

$$\varepsilon \equiv \kappa / \tau_{\kappa \varepsilon}$$

Rate of turbulent energy dissipation (drive the damping of the fluctuations) with  $\tau_{\kappa \varepsilon}$  characteristic time of turbulence

- **Quadratic saturation term for  $\varepsilon$**

$$\beta_{\varepsilon} = \frac{V}{\kappa^{3/2}} \quad \text{with} \quad V = \rho^* c_S$$

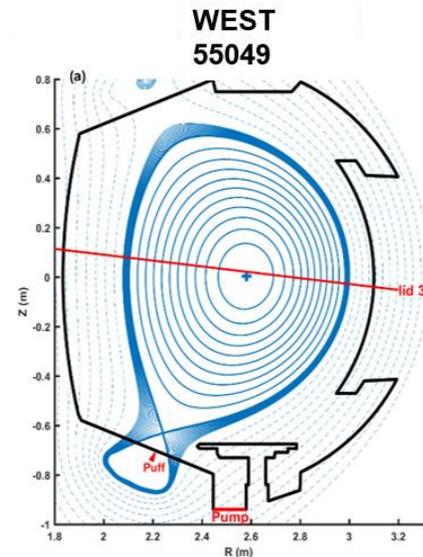
- **Linear driving terms**

$$\gamma_{\kappa} = \gamma_{\varepsilon} = \gamma = \frac{c_S}{R} \sqrt{R^2 \frac{\nabla p \cdot \nabla B_t}{p B_t}}$$



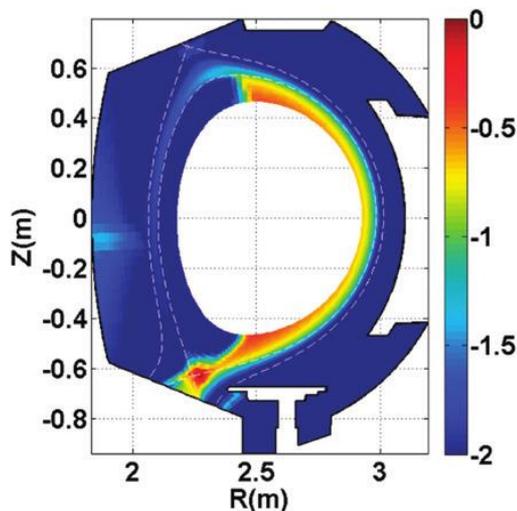
$$D_{\perp} = \frac{\kappa^2}{\varepsilon}$$

- **Plasma composition**
  - Pure Deuterium
- **Wall parameters**
  - Recycling coefficients of the wall is 0.99.
  - Red line on the wall represent the passive pumping with the recycling coefficient 0.9
- **Core boundary conditions**
  - $P_{in} = P_{tot} - P_{radiated,bulk} - P_{ripple} = 1 \text{ MW}$
  - Plasma density controlled by gas puff injection
- **Transport coefficients obtained from  $\kappa - \varepsilon$  model**

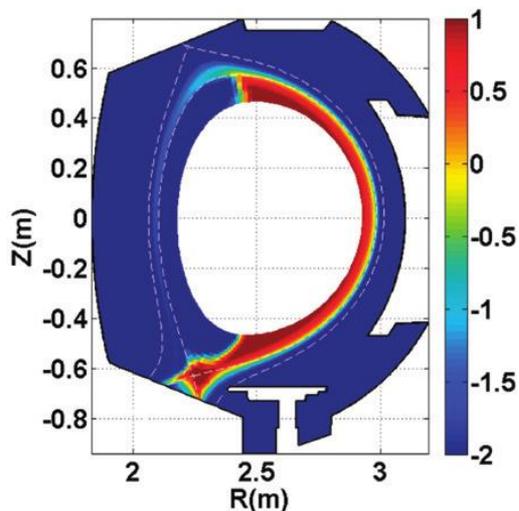


$I_p [kA]$	500
$\bar{n}_e [m^{-2}]$	$4 \cdot 10^{19}$
Bt(T)	3.6

Contour plot of  $k/k_{\max}$   
in the poloidal plan  
(logarithmic scale)



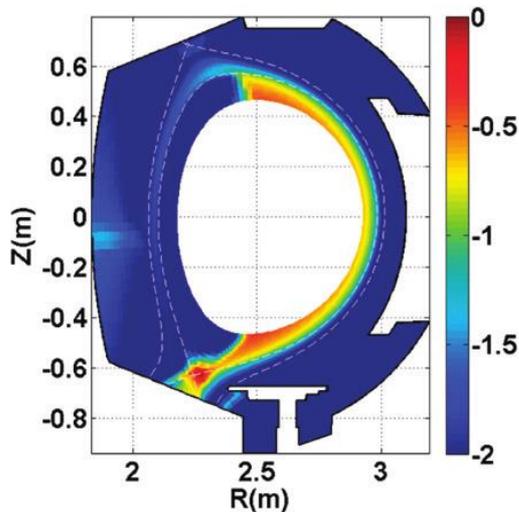
Diffusion coefficient  
 $D$  in the poloidal plan  
(logarithmic scale)



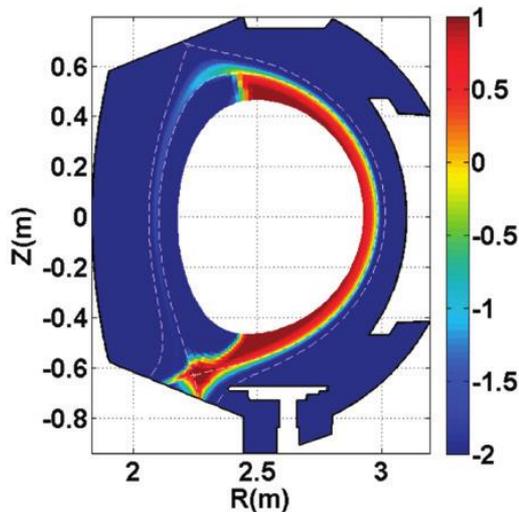
- Recovering the ballooned radial transport
- Spreading of  $\kappa$  and  $D$  governed by parallel transport in the near SOL region

Baschetti *et al.* NF 2021

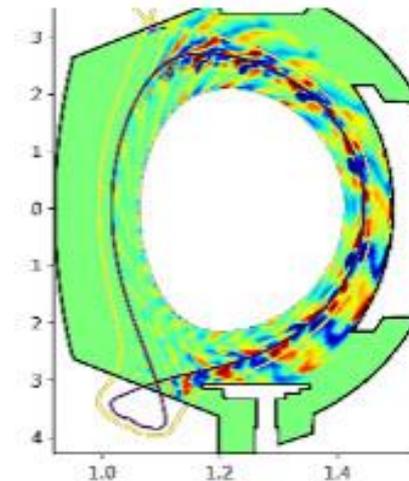
Contour plot of  $k/k_{\max}$  in the poloidal plan (logarithmic scale)



Diffusion coefficient  $D$  in the poloidal plan (logarithmic scale)

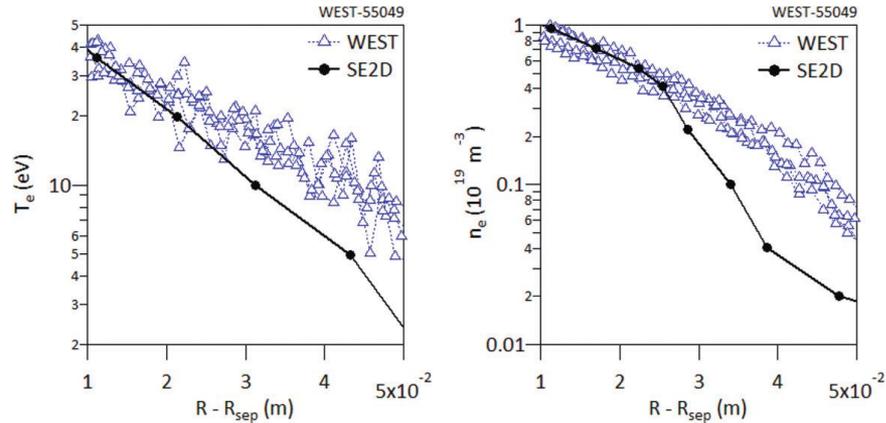


Poloidal map of density fluctuations obtained from 3D turbulence simulation performed with SOLEDGE3X.



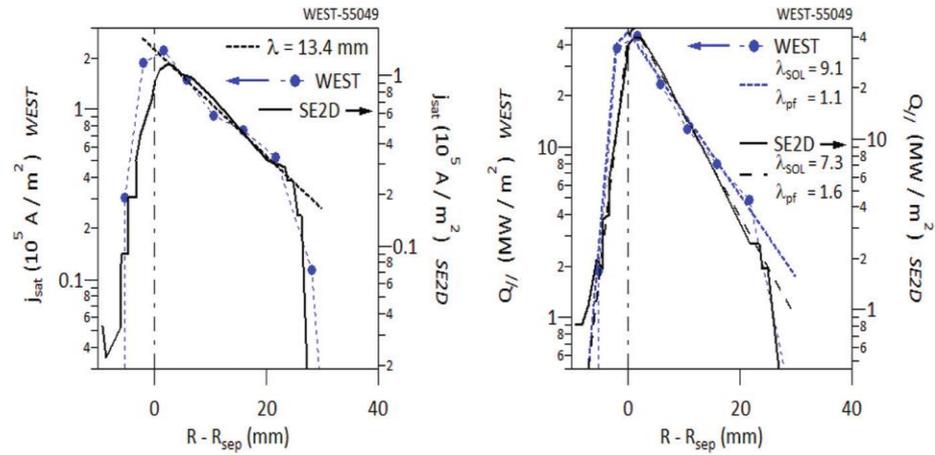
Baschetti *et al.* NF 2021  
H. Bufferand *et al.*, NF 2022

## outer midplane profiles



$T_e$  and  $n_e$  radial profiles at the outer midplane  
(radial extension where experimental data are available)

## outer target profiles



Ion saturation current and parallel heat flux at the  
outer strike point

- Agreement in the near SOL region ( $0.01\text{m} \leq R - R_{sep} \leq 0.03\text{m}$ )
- Too strong numerical gradients in the far SOL ( $0.03\text{m} < R - R_{sep} \leq 0.05\text{m}$ )

Baschetti *et al.* NF 2021

- We address the issue of modelling radial transport in edge plasma transport codes
- **Taking inspiration from what have been done in CFD community** we introduced a self-consistent approach for turbulent intensity from which one can derive the radial transport coefficients
  - a single scalar to be fixed
  - 2D map of radial transport obtained with this approach (recovering the ballooning feature)
- **Results from SOLEDGE simulations in L-mode plasma** coupling transport equations with  $\kappa$ - $\varepsilon$  model for radial transport: good match with the experimental profiles, both at the divertor and at the midplane is found for TCV and WEST experiments
- **Increasing the database** and comparison with turbulent 3D simulations
- Generalization to transport simulations **with impurities**
- Ongoing work for introducing in the  $\kappa$ - $\varepsilon$  model the dependence of the radial coefficients on ExB shear flow intensity in order to address the **L-H transition**

- H. Bufferand et al, “Interchange Turbulence Model for the Edge Plasma in SOLEDGE2D-EIRENE” Contrib. Plasma Phys.56, No. 6-8, 555 – 562 (2016) /DOI10.1002/ctpp.201610033
- S. Baschetti et al., Optimization of turbulence reduced model free parameters based on L-mode experiments and 2D transport simulations, Contributions to Plasma Physics 58(6-8), 2017
- S. Baschetti et al., Study of the role of the magnetic configuration in a  $k - \epsilon$  model for anomalous transport in tokamaks, Journal of Physics Conference Series 1125(1):012001, 2018
- H. Bufferand et al., Three-dimensional modelling of edge multi-component plasma taking into account realistic wall geometry, Nuclear Materials and Energy Volume 18 , Pages 82-86, 2019
- S. Baschetti et al., A  $\kappa - \epsilon$  model for plasma anomalous transport in tokamaks: closure via the scaling of the global confinement, Nuclear Materials and Energy, Volume 19 , Pages 200-204, 2019
- S. Baschetti et al, Self-consistent cross-field transport model for core and edge plasma transport, Nucl. Fusion 61, 106020, 2021
- H. Bufferand et al, Progress in edge plasma turbulence modelling—hierarchy of models from 2D transport application to 3D fluid simulations in realistic tokamak geometry, Nucl. Fusion 61, 116052 (2021)
- N.B. In the framework of the ETASC TSVV 3 project, a similar approach has been recently proposed by Coosemans et al., CPP 2022, e202100193