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

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DE LA RECHERCHE À L'INDUSTRIE

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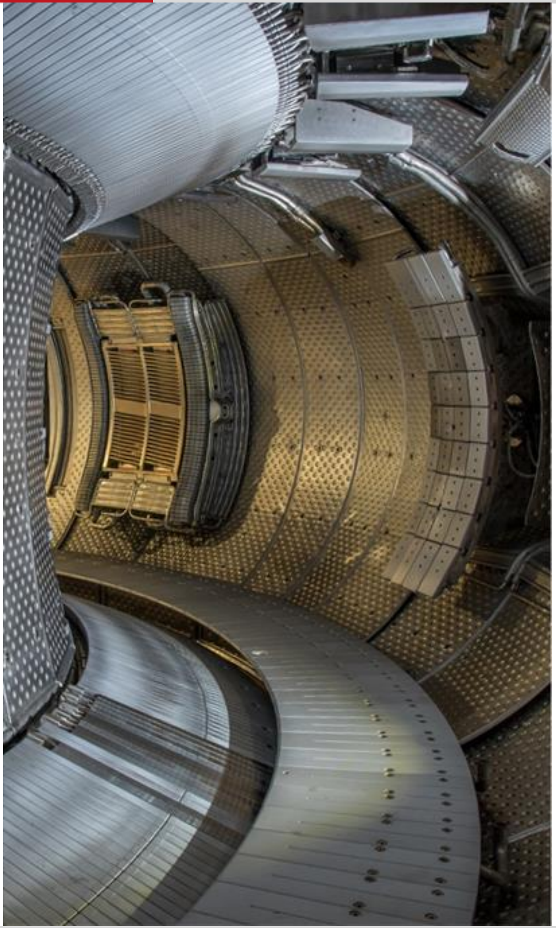
Outline

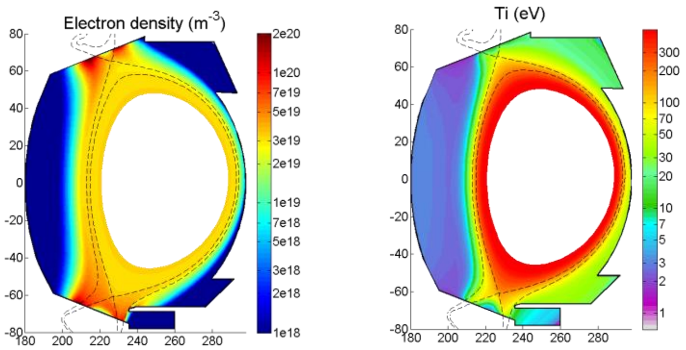


- Brief recall on transport codes and their applications
- Introducing turbulence in mean flow equations
  - The ideas from Computational Fluid Dynamics
  - The derivation for edge plasma transport codes
- Implementation in SOLEDGE code and application to modelling TCV and WEST experiments
- Summary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

Tokamak edge plasma modelling with fluid transport codes

- **<u>Transport codes</u>** provide a coarse grained picture of edge plasma properties integrating the many actors at play: main plasma, neutrals, impurities, wall properties

- **<u>Architecture</u>**:
  - 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

- **<u>Reduction</u>**: Radial turbulent transport treated with <u>empirical diffusion coefficients</u>

- **Non-exhaustive list of transport codes**: SOLEDGE-EIRENE, SOLPS-ITER, EDGE2D-EIRENE, EMC3-EIRENE, COREDIV, SONIC, UEDGE, …

Plasma mean–field transport solver

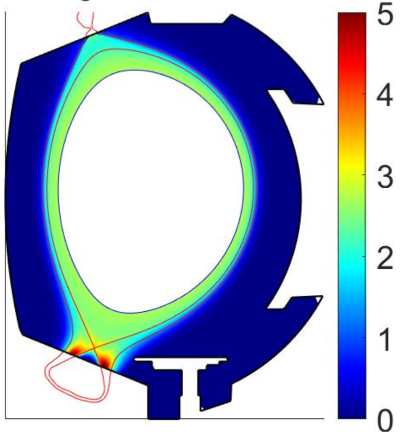
$$\frac{\partial n}{\partial t} + \boldsymbol{\nabla}.(n\boldsymbol{u}) = S(n, \boldsymbol{u}, \dots)$$

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

$$\boldsymbol{u} = \bar{\boldsymbol{u}} + \tilde{\boldsymbol{u}}$$

$$\frac{\partial \bar{n}}{\partial t} + \boldsymbol{\nabla}.\left(\bar{n}\bar{\boldsymbol{u}} + \boxed{\langle \tilde{n}\tilde{\boldsymbol{u}} \rangle_{t,\boldsymbol{r}}}\right) = S(\bar{n}, \bar{\boldsymbol{u}}, \dots) + \boxed{\langle S(\tilde{n}, \tilde{\boldsymbol{u}}, \dots) \rangle_{t,\boldsymbol{r}} + \cdots}$$

$$\xcancel{\frac{\partial \tilde{n}}{\partial t} + \boldsymbol{\nabla}.(\tilde{n}\bar{\boldsymbol{u}} + \bar{n}\tilde{\boldsymbol{u}}) = \tilde{S}}$$



- <u>gradient-diffusion closure</u> $\boxed{\langle \tilde{n}\tilde{\boldsymbol{u}} \rangle_{t,\boldsymbol{r}} = -Dn\boldsymbol{\nabla}\langle n \rangle}$

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

- Solves only the fluctuation averaged fluid equations
- Diffusion coefficient is chosen to reproduce outer midplane profiles <u>from experiments</u>

DERIVATION OF A SEMI-EMPIRICAL MODEL FOR TURBULENT INTENSITY IN EDGE TOKAMAK PLASMA

- Taking inspiration from the $\boldsymbol{\kappa} - \boldsymbol{\varepsilon}$ **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

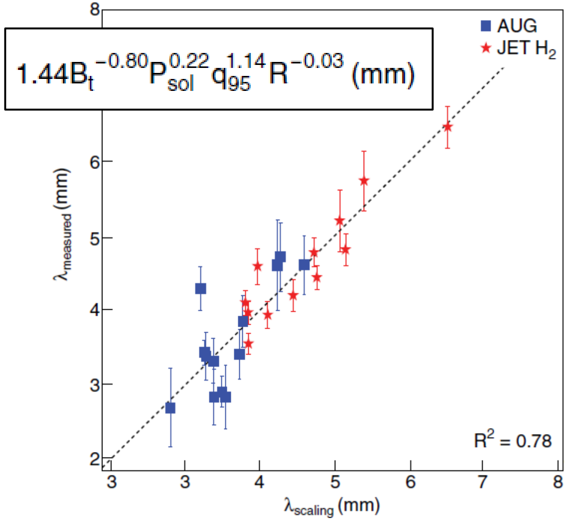
$$\frac{\partial \kappa}{\partial t} + \nabla . \boldsymbol{K} = S_\kappa - \boldsymbol{\varepsilon} \quad \Rightarrow \quad \frac{\partial \kappa}{\partial t} + \nabla . \boldsymbol{K} = \boldsymbol{\gamma_{int}} \kappa - \boldsymbol{\Delta\omega} k^2$$

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

DERIVATION OF A **SEMI-EMPIRICAL MODEL** FOR TURBULENT INTENSITY IN EDGE TOKAMAK PLASMA

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

[Scarabosio et al JNM 2013]



- The free parameter $\Delta\omega$ is determined using the scaling law for $\boldsymbol{\lambda_{SOL}}$

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

[R.J. Goldston Nucl. Fusion 2012]

$$\rho_i = \frac{m_i c_s}{q_i B_{tot}} \qquad q_{95} = \frac{aB_\varphi}{RB_\theta}$$

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

IMPLEMENTATION IN SOLEDGE AND APPLICATION TO TCV EXPERIMENT

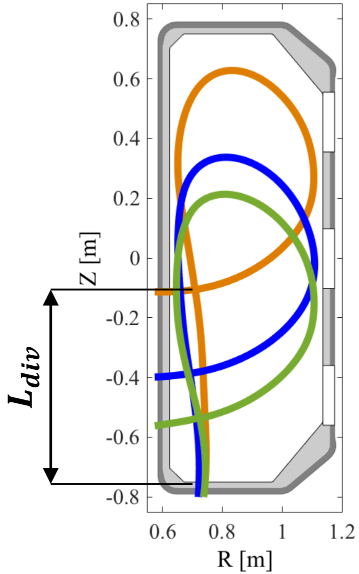
- **One-equation model** implemented in SOLEDGE tested vs very well diagnosed TCV experiment (*[Maurizio et al., NF, 58 (2018); Gallo et al., PPCF, 60 (2018)]*)

- 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

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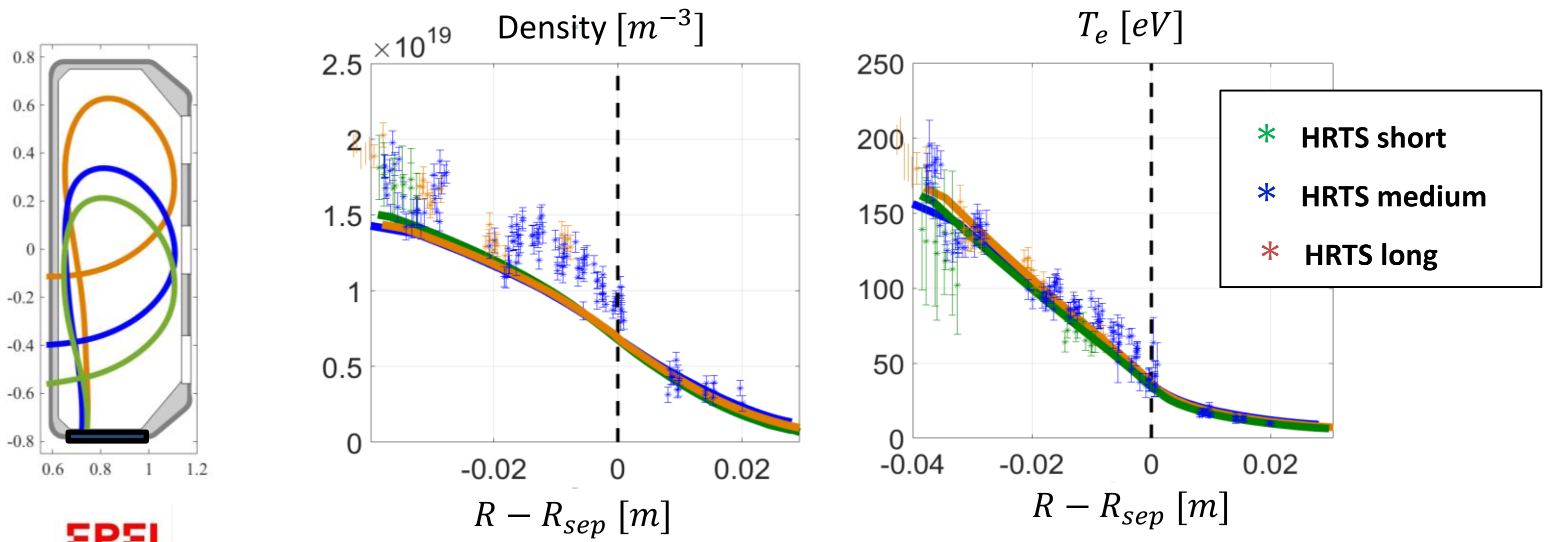
S. Baschetti et al., J. Phys.: Conf. Ser. (2018)

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

IMPLEMENTATION IN SOLEDGE AND APPLICATION TO TCV EXPERIMENT

- **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.



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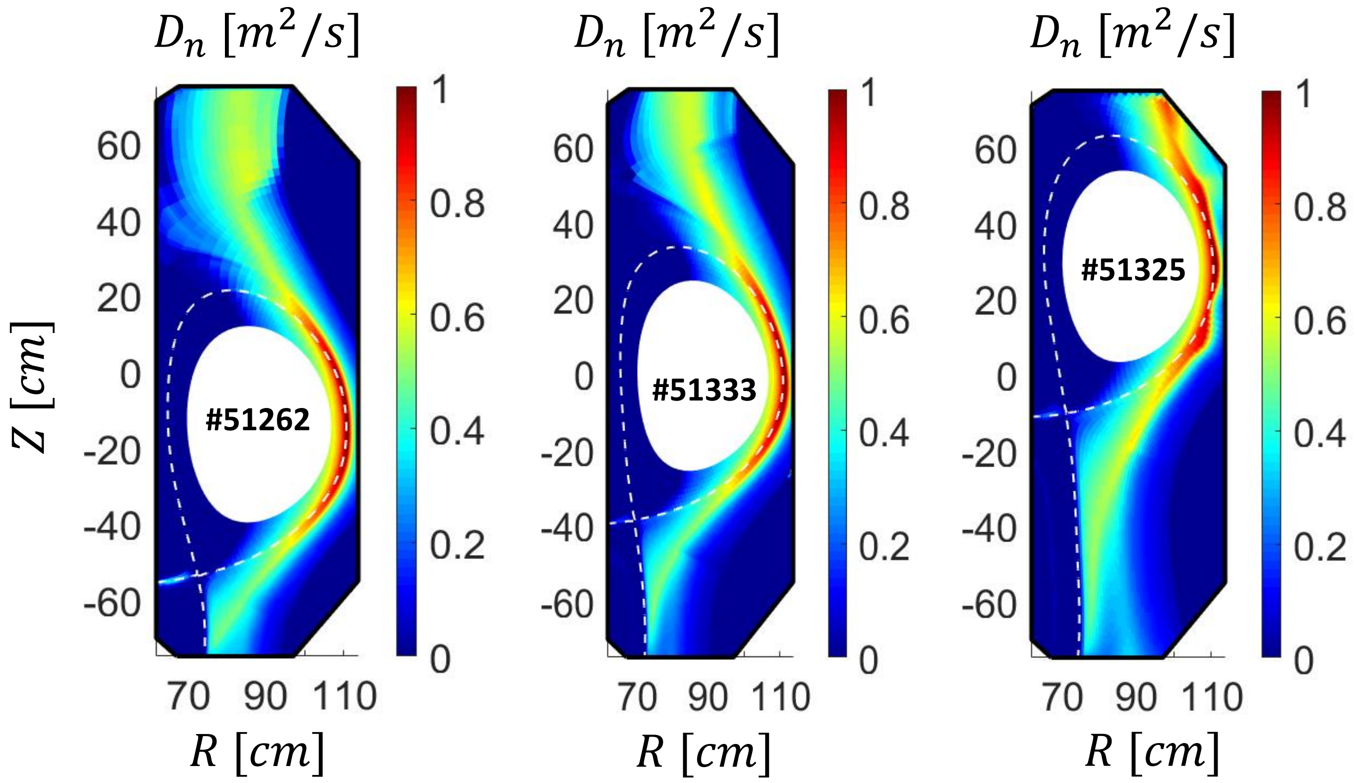
S. Baschetti et al., J. Phys.: Conf. Ser. (2018)
S. Baschetti, PhD manuscript, Aix-Marseille University, 2019

POLOIDAL MAP OF DIFFUSION COEFFICIENT OBTAINED FROM SOLEDGE COUPLED TO THE EQUATION ON TURBULENT INTENSITY



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

$$\frac{\partial \kappa}{\partial t} + \nabla . \boldsymbol{K} = \gamma_\kappa \kappa - \varepsilon$$

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

$\kappa \equiv \frac{1}{2}\langle \tilde{v}_\perp^2 \rangle$ Kinetic energy per unit mass of the fluctuating transverse velocity

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

- Quadratic saturation term for ε

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

- Linear driving terms

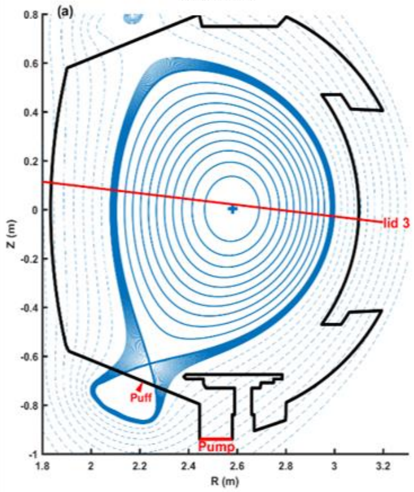
$$\gamma_\kappa = \gamma_\varepsilon = \gamma = \frac{c_S}{R}\sqrt{R^2 \frac{\nabla p . \nabla B_t}{p B_t}}$$

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

APPLICATION TO WEST EXPERIMENT #55049

- **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 MW
  - Plasma density controlled by gas puff injection
- **Transport coefficients obtained from $\kappa-\varepsilon$ model**

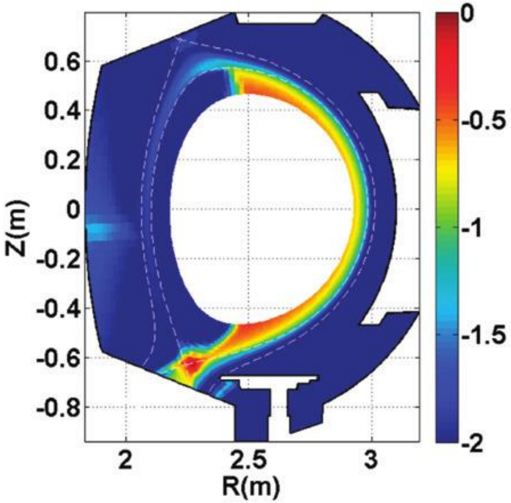
WEST
55049



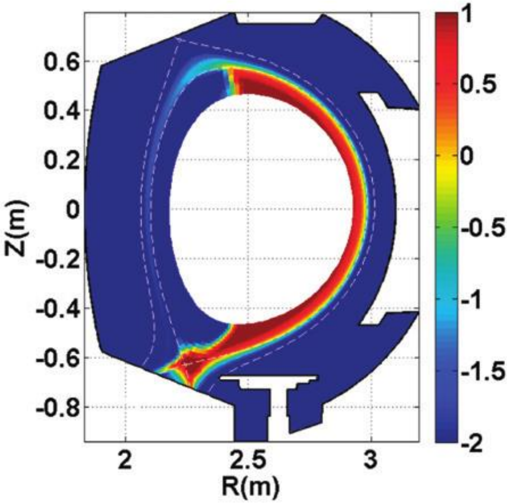
$I_p[kA]$	500
$\bar{n}_e[m^{-2}]$	$4\cdot10^{19}$
Bt(T)	3.6

APPLICATION TO WEST EXPERIMENT #55049

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



Diffusion coefficient D in the poloidal plan (logarithmic scale)

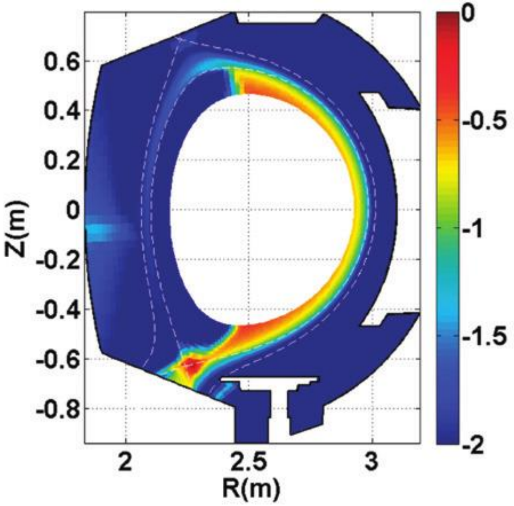


- Recovering the ballooned radial transport
- Spreading of κ and D governed by parallel transport in the near SOL region

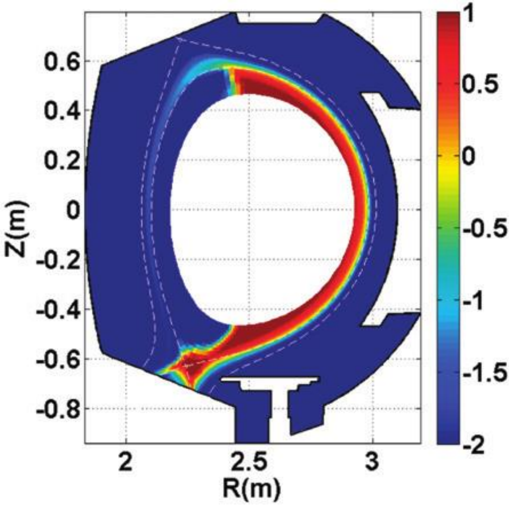
Baschetti *et al*. NF 2021

RADIAL TRANSPORT AND COMPARISON WITH 3D TURBULENT SIMULATIONS

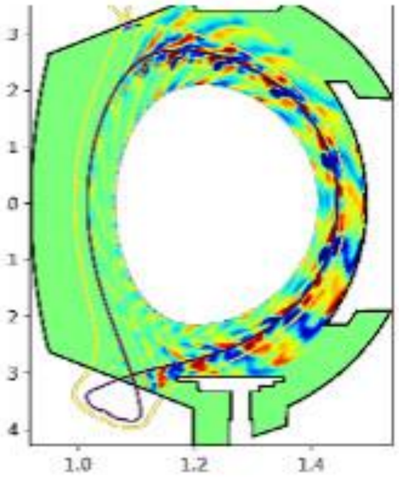
Contour plot of k/k_{max} in the poloidal plan (logarithmic scale)



Diffusion coefficient D in the poloidal plan (logarithmic scale)



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

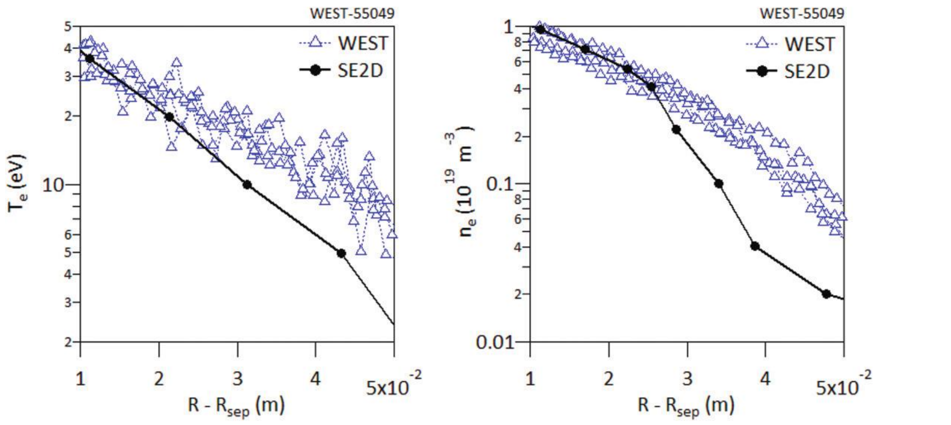


Baschetti *et al*. NF 2021

H. Bufferand et al, NF 2022

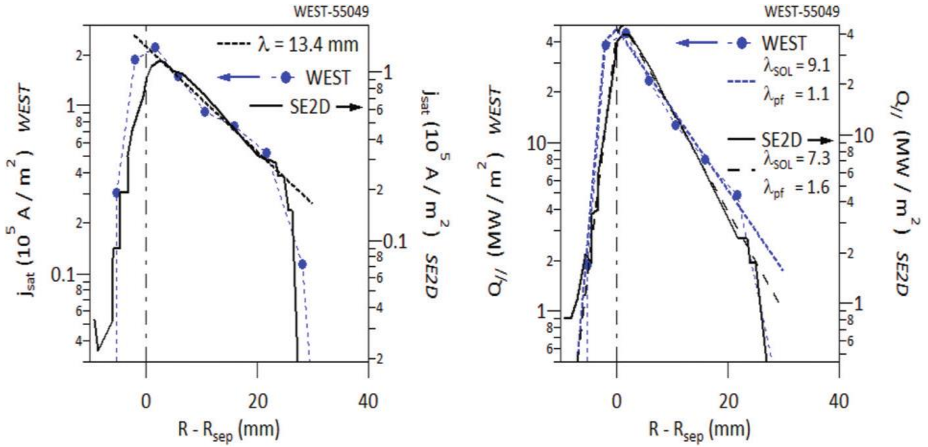
COMPARISON BETWEEN EXPERIMENTAL AND SIMULATION PROFILES (WEST #55049)

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

Baschetti *et al*. NF 2021

SUMMARY AND CONCLUSIONS

- 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 κ–ε 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 κ–ε model the dependence of the radial coefficients on ExB shear flow intensity in order to address the **L-H transition**

references

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- 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