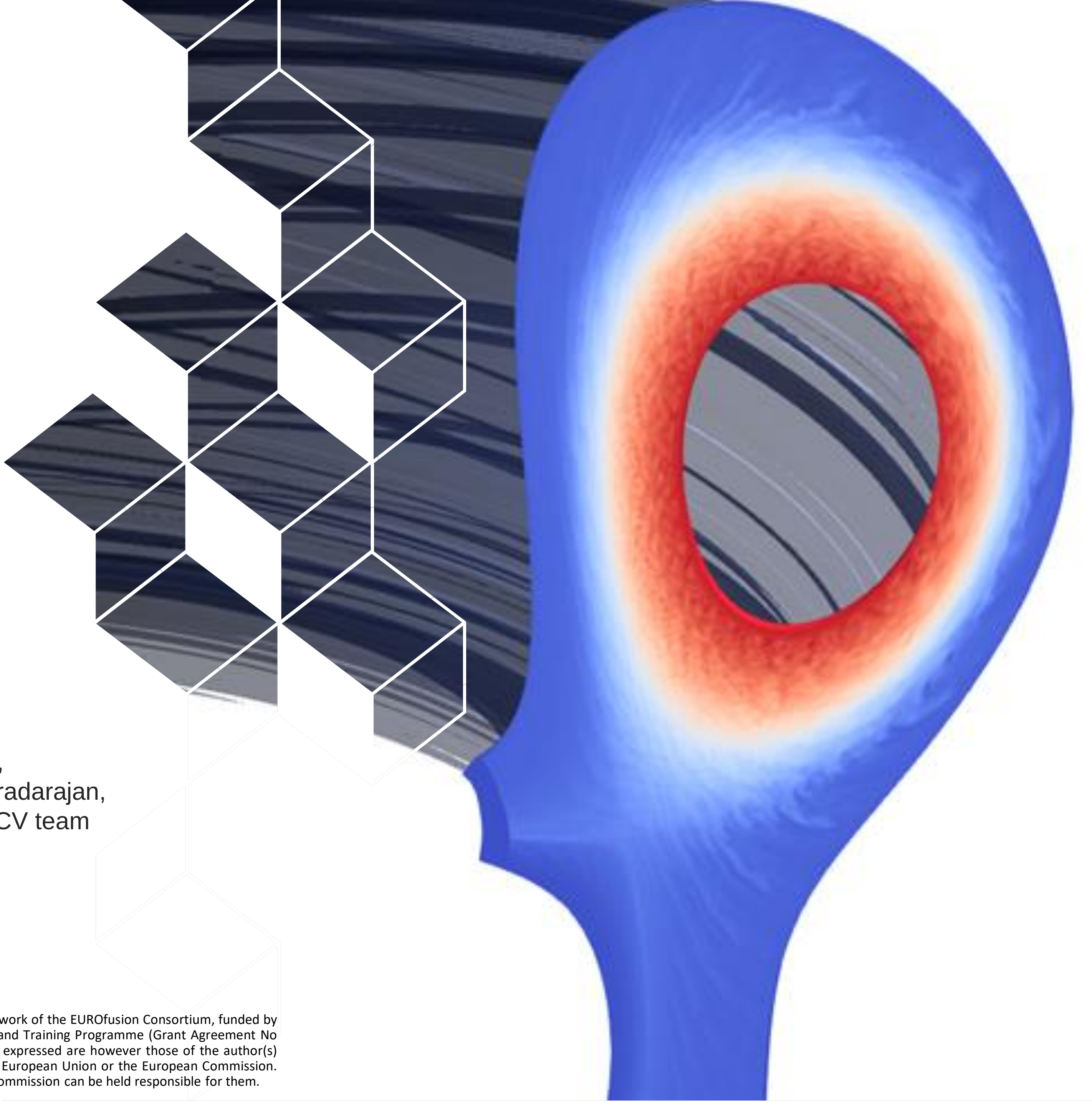
Hierarchy of turbulent transport models with the SOLEDGE3X code

H. Bufferand

M. Capasso, G. Ciraolo, H. Corvoysier, J. Denis, N. Fedorczak, Ph. Ghendrih,
E. Havlíčková, D. S. de Oliveira, N. Rivals, S. Sureshkumar, P. Tamain, N. Varadarajan,
Y. Marandet, R. Düll, I. Kudashev, F. Schwander, E. Serre, H. Yang and the TCV team



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.

Outline

1. **Introduction to the hierarchy of turbulence models**

2. **Implementation in the SOLEDGE3X code**

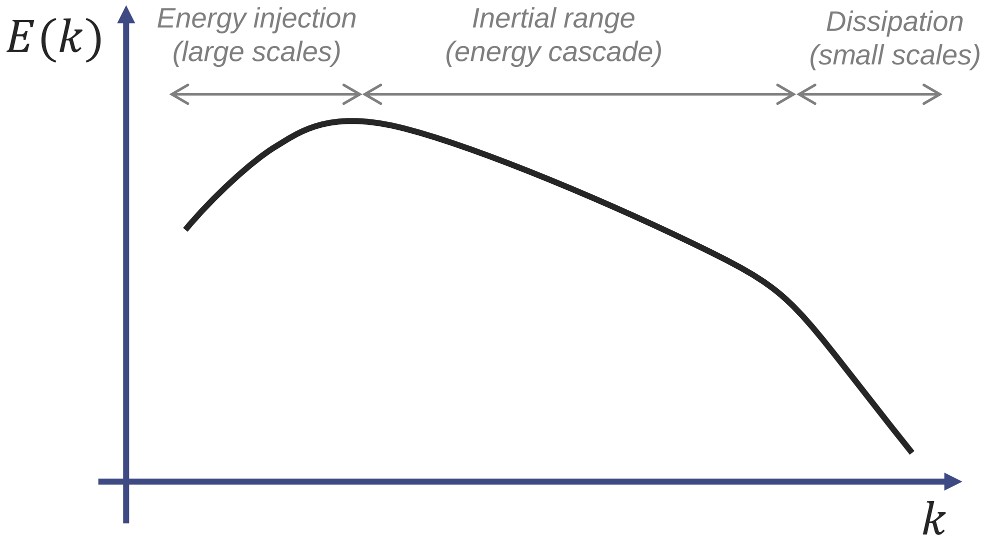
3. **Application to TCV-X21 reference scenario**

1. Introduction to the hierarchy of turbulence models

Example from the neutral fluid community

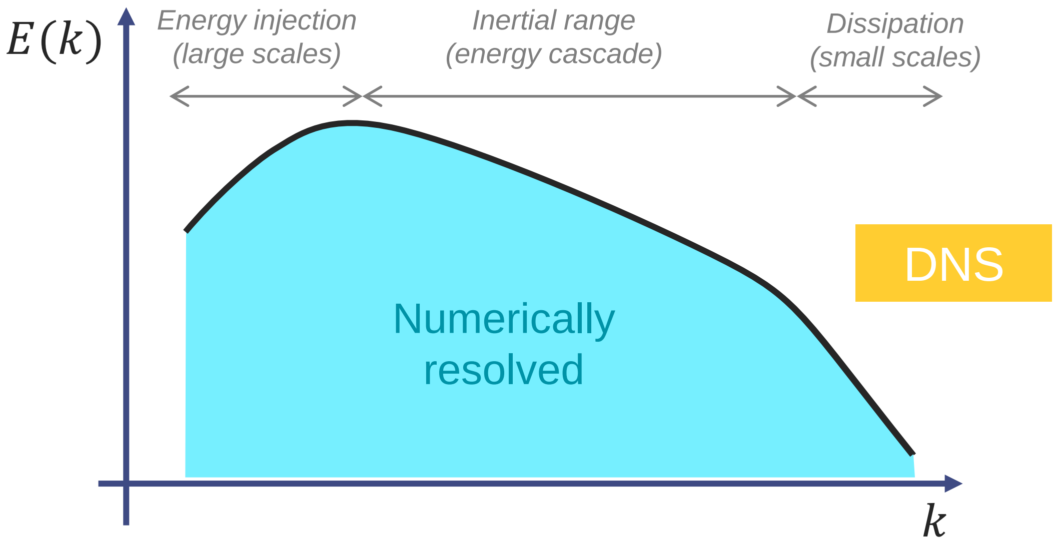
- Underlying model: **Navier-Stokes equations**
- Turbulence key properties (in 3D):
  - Mixing effect
  - Well characterized energy spectrum

- Turbulence numerical modelling hierarchy:



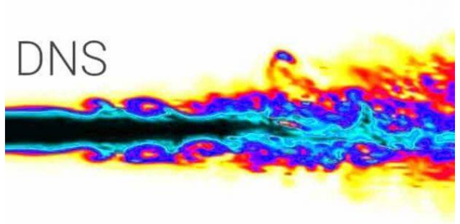
Example from the neutral fluid community

- Underlying model: **Navier-Stokes equations**
- Turbulence key properties (in 3D):
  - Mixing effect
  - Well characterized energy spectrum
- Turbulence numerical modelling hierarchy:



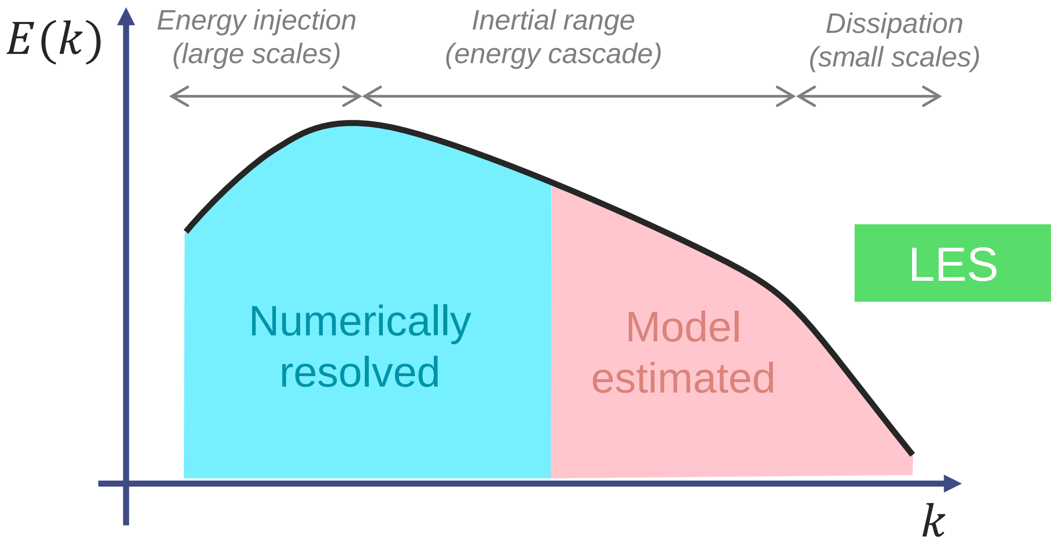
Fidelity

Direct Numerical Simulation



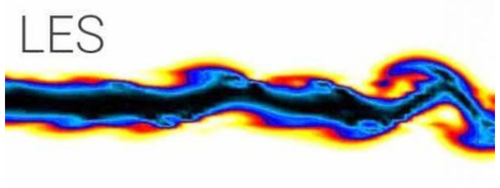
Example from the neutral fluid community

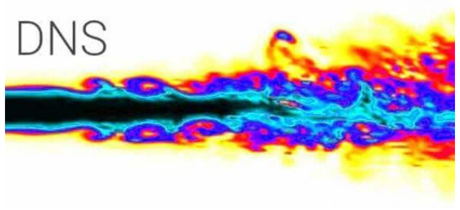
- Underlying model: **Navier-Stokes equations**
- Turbulence key properties (in 3D):
  - Mixing effect
  - Well characterized energy spectrum
- Turbulence numerical modelling hierarchy:



Fidelity

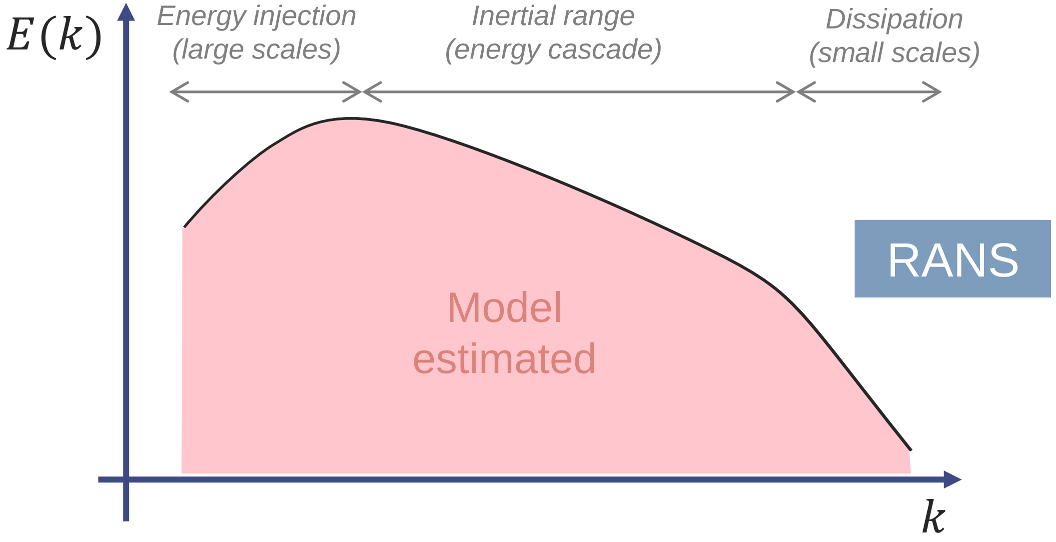
Large Eddy Simulation → Direct Numerical Simulation





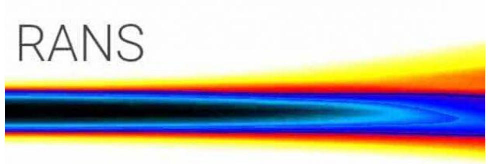
Example from the neutral fluid community

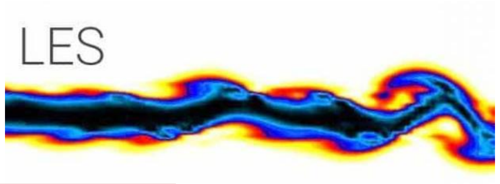
- Underlying model: **Navier-Stokes equations**
- Turbulence key properties (in 3D):
  - Mixing effect
  - Well characterized energy spectrum
- Turbulence numerical modelling hierarchy:

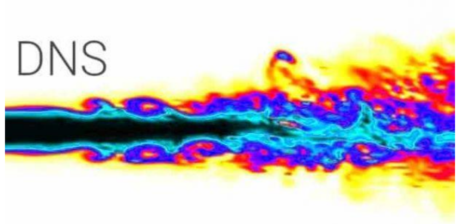


Efficiency *Fidelity*

Reynolds-Averaged Navier-Stokes → Large Eddy Simulation → Direct Numerical Simulation







Mean-field simulations

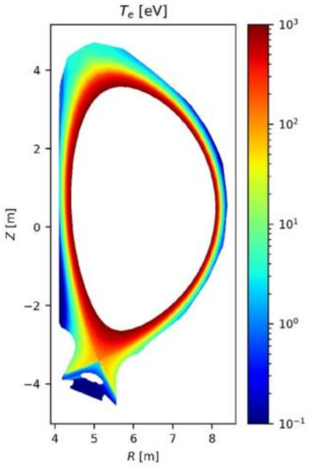
Model used:
- Empirical effective turbulent viscosity
- Semi-empirical: $k-\varepsilon$, $k-\omega$, RSM

Turbulence simulations

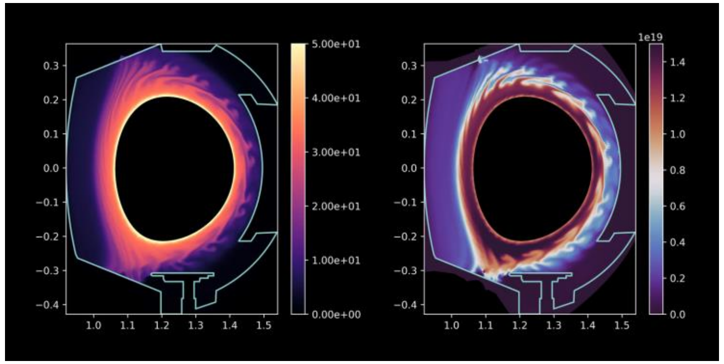
Hierarchy of models in edge plasma community

- Underlying model: **Braginskii's equations**
- Complex turbulence properties in strongly magnetized plasma
  - **Mixing effect** (enhanced transport)
  - Strong interaction between large scale flows and turbulent structures → **transport barrier**
- Hierarchy of models for turbulence:
- Models for effective turbulent diffusivities:
  - **Empirical**: ad-hoc diffusivities to match experimental profiles
  - Semi-empirical **reduced models** for turbulence:
    - Two equations models:
      - $k-\varepsilon$ [Baschetti et al., Nucl. Fusion 61(2021)]
      - $k-\zeta$ [Coosemans et al., Contrib. Plasma Phys. 60 (2020)]
    - Predator-Prey models [Miki et al., Phys. Plasmas 19 (2012)]
    - …

	Transport codes	Turbulence codes
Physical model	• Mean-field (2D or 3D) • Empirical or semi-empirical • Multi-physics (neutrals, impurities…)	• First principle modelling
Purposes	• Experiment interpretation • Plasma scenario design (exhaust)	• Predictive modelling (λ_q, $L-H$ threshold…)
Examples	SOLPS-ITER, EDGE2D, EMC3, SONIC, SOLEDGE3X…	GBS, GRILLIX, HERMES-3, SOLEDGE3X…



SOLEDGE3X ITER transport simulation
[Rivals et al., Nucl. Fusion 65, 2025]



SOLEDGE3X WEST turbulent simulation
[Bufferand et al. Nucl. Fusion 61, 2021]

2. Implementation in the SOLEDGE3X code

SOLEDGE3X: a versatile fluid code for edge plasma modelling

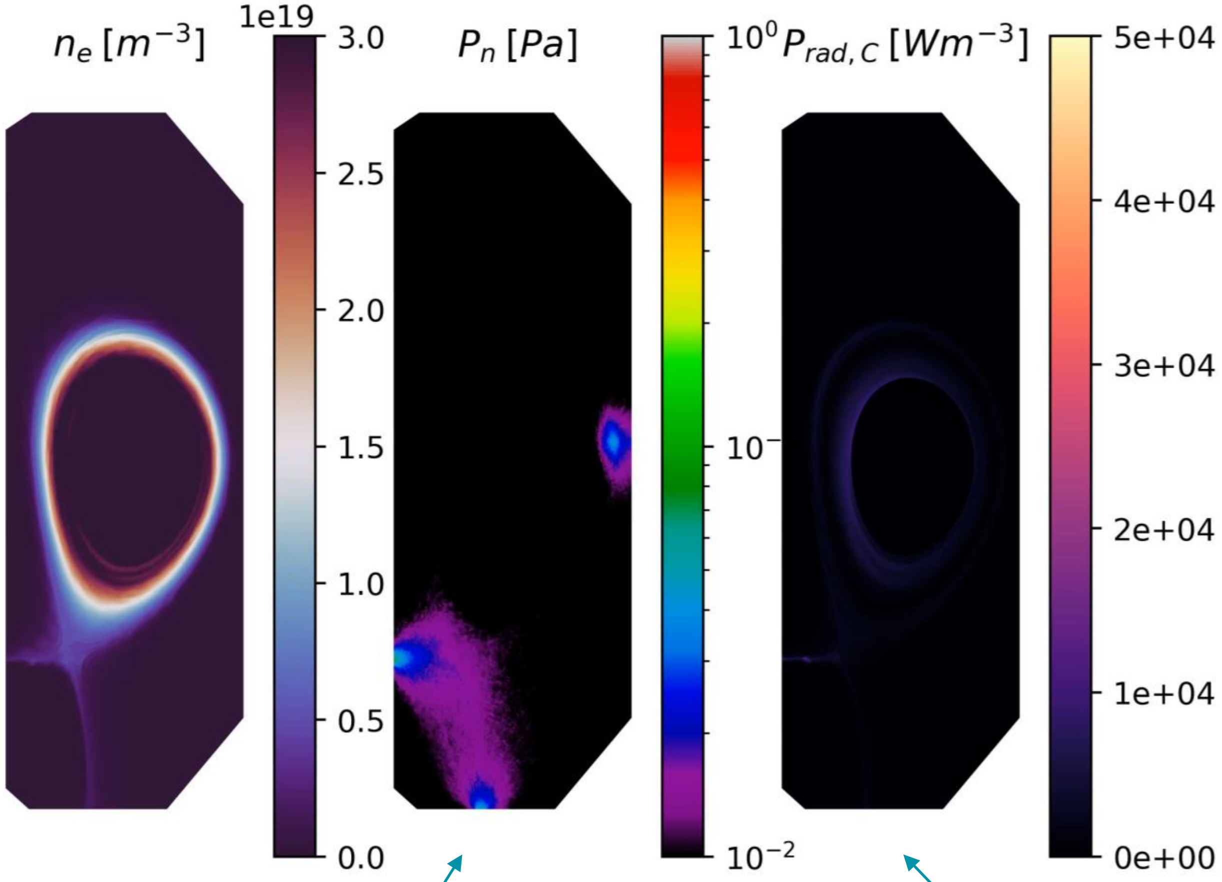
- **Drift-fluid code** based on Braginskii’s equations with Zhdanov closure terms for multi-component plasma

- **Up to the first wall** modelling thanks to immersed boundary conditions

- Kinetic neutrals via coupling with **EIRENE**

- Applications: 2D/3D transport AND 3D turbulent simulations

- More info: www.soledge3x.com



Neutrals simulated with EIRENE

Radiation by sputtered carbon

Example of application to turbulent simulation of a Deuterium & Carbon plasma on TCV

Reduced k-equation turbulence model for mean-field simulations

- One equation model based on estimating **turbulent kinetic energy** $k = \frac{1}{2}\langle \tilde{v}^2 \rangle$
- Effective turbulent diffusivity proportional to k : $D = \tau k$

$$\partial_t k + \vec{\nabla} \cdot (k\vec{v}) = \gamma_I k(1 - \beta k)$$

linear drive

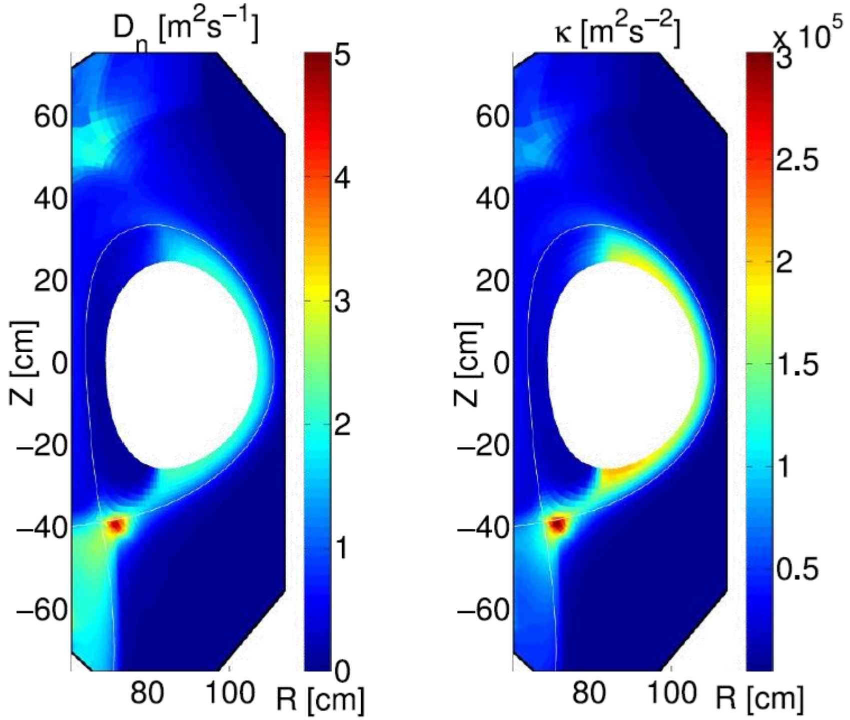
non-linear saturation

- Drive governed by **interchange growth rate**: $\gamma_i = c_s \sqrt{\frac{\vec{\nabla} B}{B} \cdot \frac{\vec{\nabla} p}{p}}$
- Saturation set empirically with **scaling law**:
  - D at fixed point: $D = \tau \beta^{-1}$
  - SOL width by ⊥ vs ∥ balance: $\lambda_{scaling}^2 = D \frac{L_\parallel}{c_s}$

$$\beta = \tau \frac{L_\parallel}{c_s \lambda_{scaling}^2}$$

D and k for a TCV case from

[Baschetti et al., NME 19 (2019)]



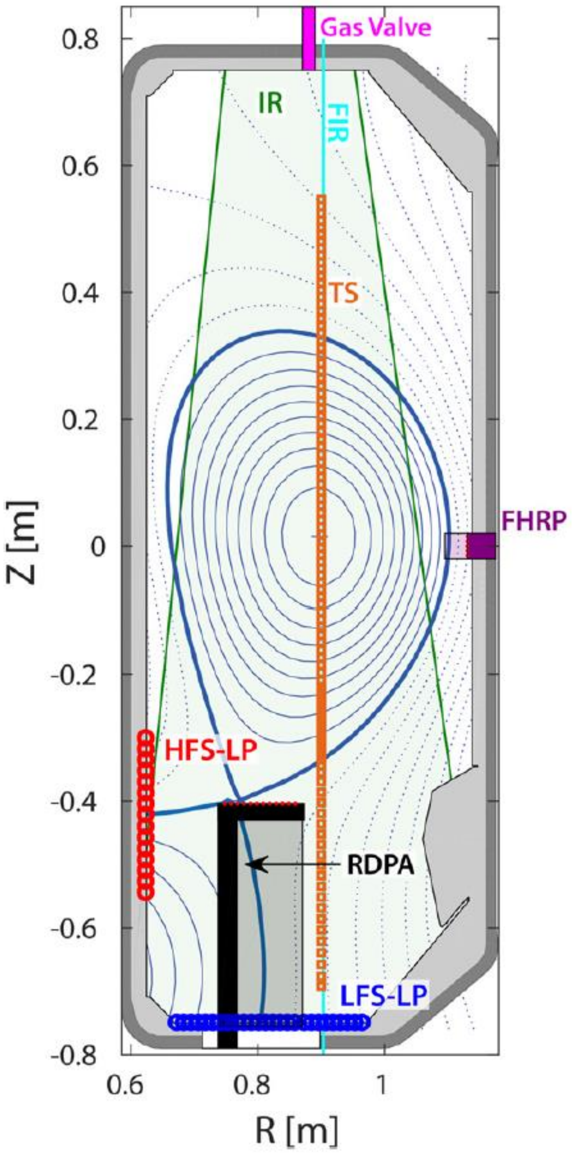
3. Application to the TCV-X21 reference scenario

The TCV-X21 experiment

- TCV-X21 = set of shots on TCV for edge turbulence codes confrontation
  - Deuterium Ohmic L-mode, lower single-null
  - Low magnetic field for lower $\rho^\star = \rho_L/a$
  - Low density, targeting sheath-limited regime

Parameter	Value
R	$0.88\ m$
a	$0.25\ m$
B_ϕ	$0.95\ T$
I_p	$165\ kA$
q_{95}	3.2
f_{GW}	0.25
P_{Ohm}	$150\ kW$

- Main results in [D.S Oliveira, T. Body et al., Nucl. Fusion 62 (2022)]
  - Public experimental dataset on https://github.com/SPCData/TCV-X21



TCV-X21 magnetic configuration and main edge diagnostics.

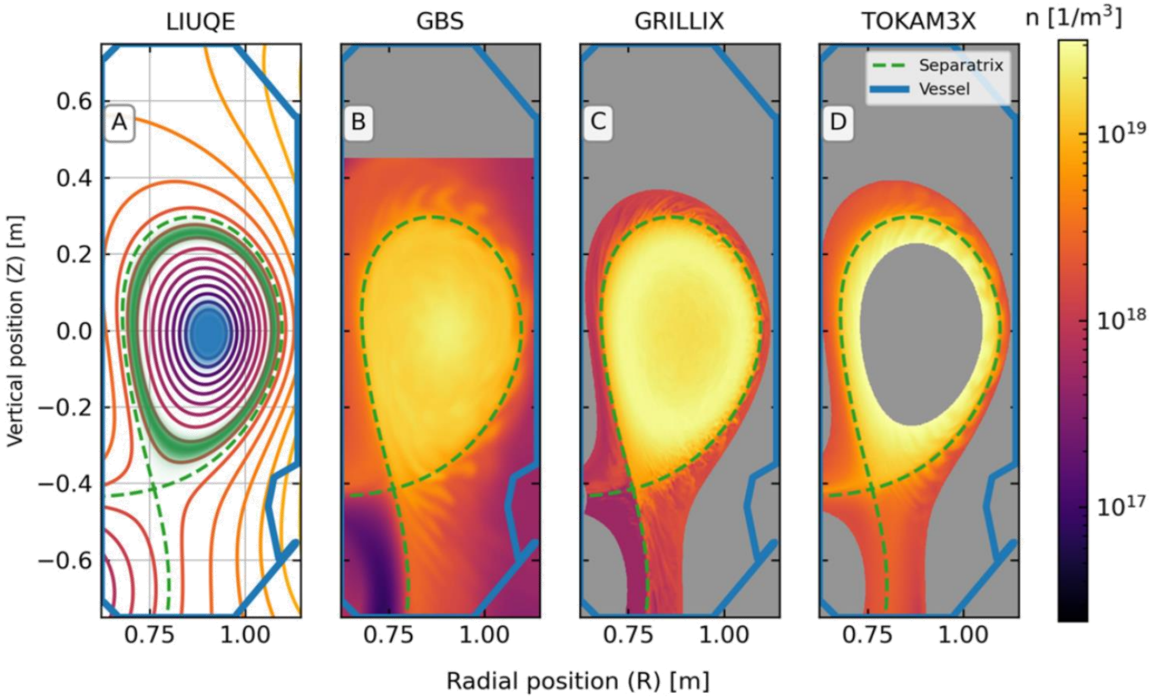
The TCV-X21 benchmark

- Experimental dataset used to benchmark edge turbulence codes [D.S Oliveira, T. Body et al., Nucl. Fusion 62 (2022) & pre-print arXiv:2506.12180]
  - GBS EPFL
  - GRILLIX MAX PLANCK INSTITUTE FOR PLASMA PHYSICS
  - TOMAK3X cea irfm
  - HERMES-3 Lawrence Livermore National Laboratory

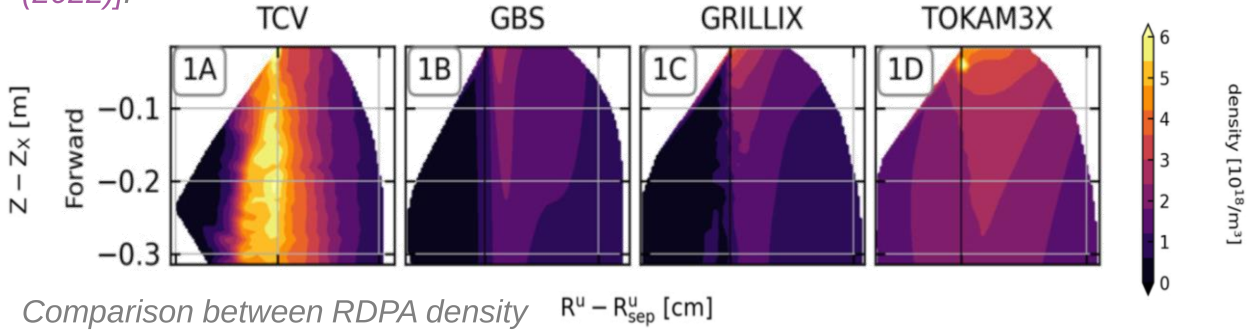
→ Rather good agreement with mid-plane profile measurements – discrepancies in the divertor

✖ No Neutrals !

- TCV-X21 plasmas simulated with SOLPS-ITER [Wang et al., Nucl. Fusion 64 (2024)]



Comparison between turbulence code simulations of a TCV-X21 shot – poloidal map of the density. On the left panel, the green and blue shaded areas display the particle and energy source respectively. Figure from [Oliveira et al, Nucl Fusion 62 (2022)].

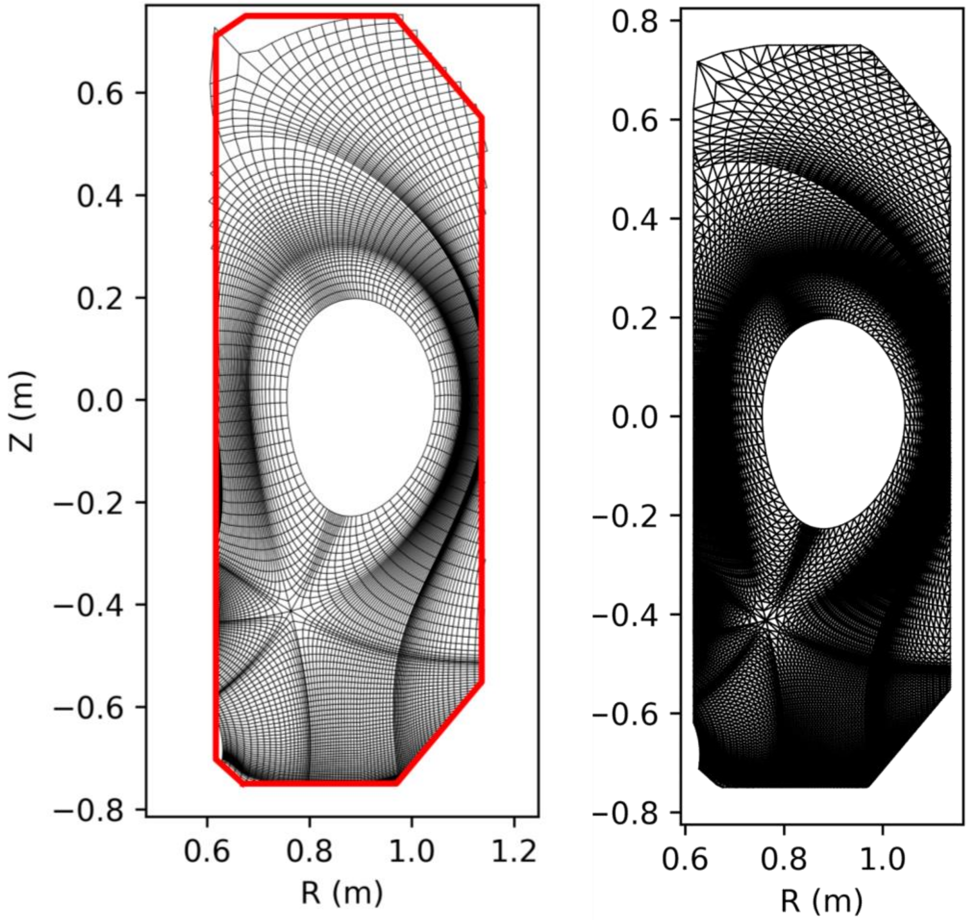


Comparison between RDPA density measurements and simulations

SOLEDGE3X turbulence models vs TCV-X21

- Simulation set-ups:
  - Grids based on TCV #51333
    - Coarse grid for mean-field simulation
    - Fine grid for turbulent simulation
  - EIRENE for neutrals
  - Gas puff feedback to get $n_{sep} \approx 8 \cdot 10^{19} m^{-3}$
  - Power source set to $P_{heat} = 170kW$

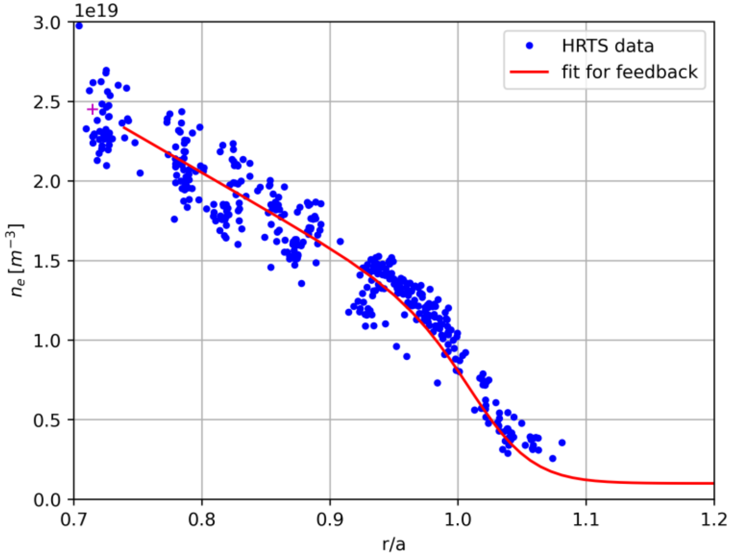
	Case 1		Case 2	Case 3
Type	2D transport		2D transport	3D turbulent
Turbulent model	Empirical		k-model	First-principle (ES)
Plasma composition	D	D+C	D	D
Grid points	8700		8700	60000×64
CPU time	1 day on 48 CPUs		1 day on 48 CPUs	2 month on 1024 CPUs

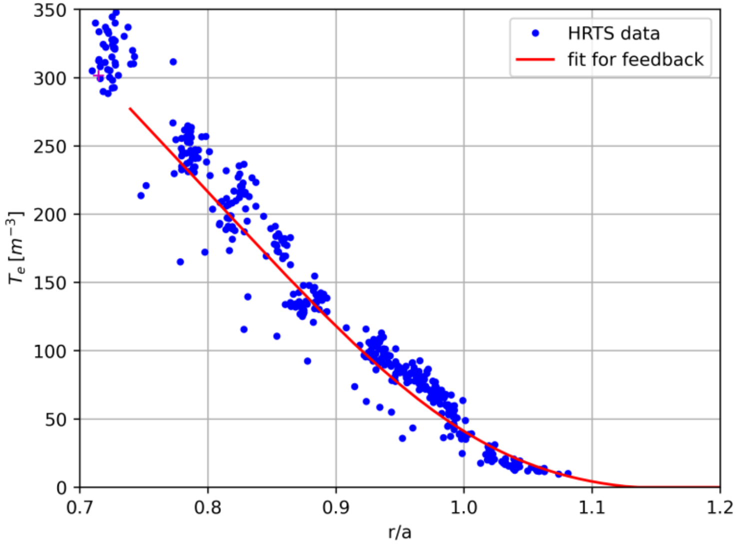


Coarse grid used for mean-field simulations. Left: quadrangles grid for SOLEDGE3X, right: triangles grid for EIRENE.

Case1: Empirical mean-field modelling

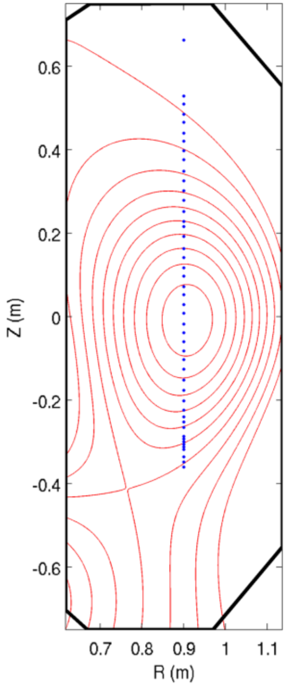
- **Inputs**: Thomson Scattering profiles (remapped at mid-plane)





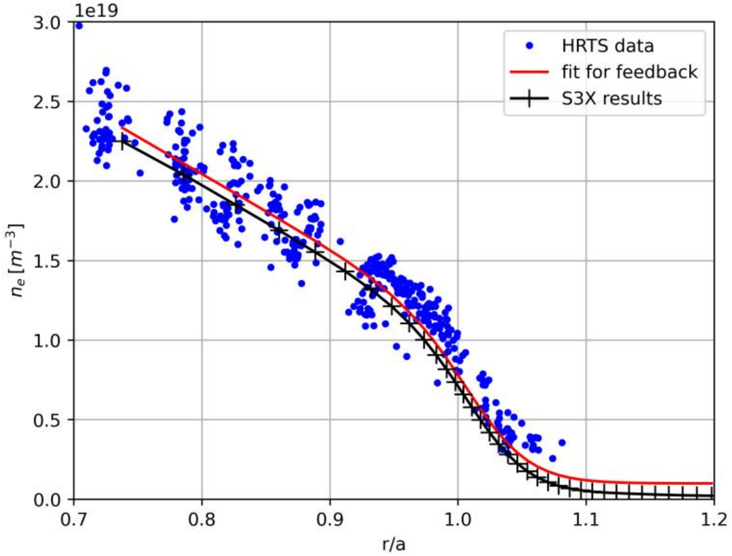
Estimations from HRTS mid-plane data

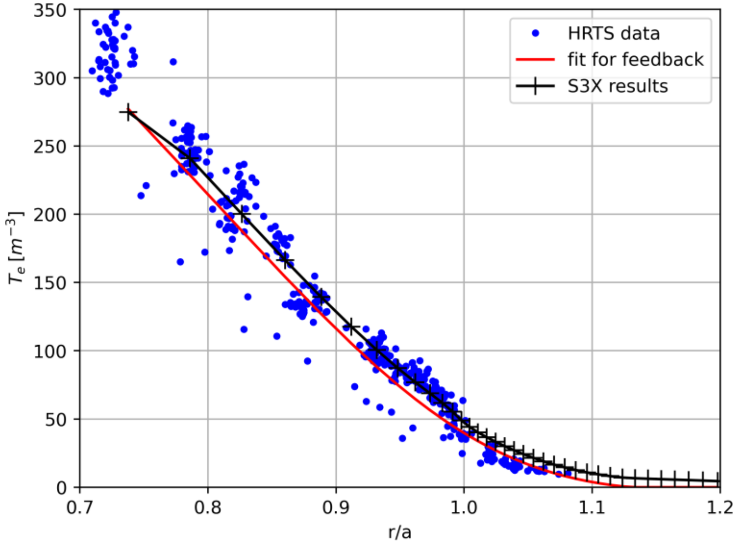
Quantity	Experimental Value
$\lambda_q\ [mm]$	4.1
$P_{div}\ [kW]$	104



Case1: Empirical mean-field modelling

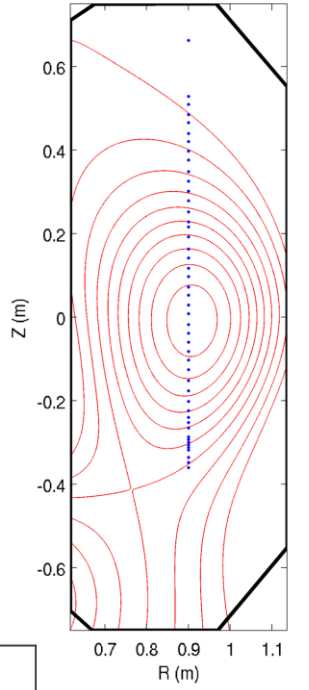
- **Inputs**: Thomson Scattering profiles (remapped at mid-plane)



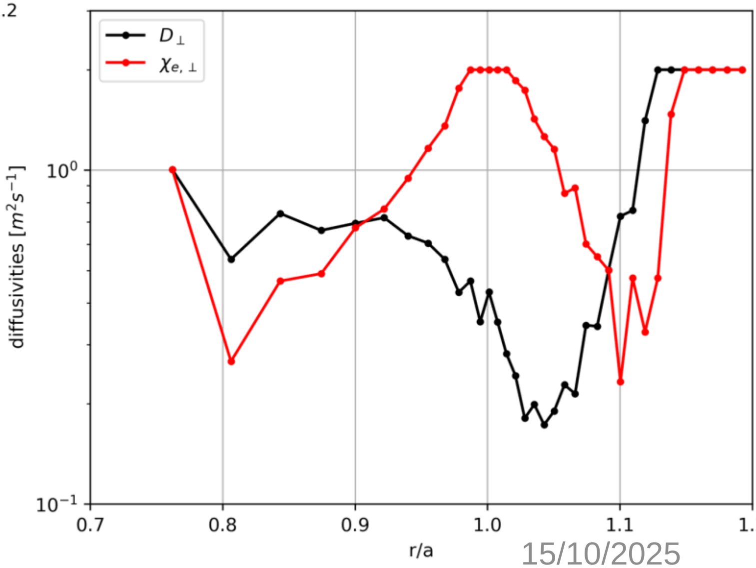


Estimations from HRTS mid-plane data

Quantity	Experimental Value
$\lambda_q\ [mm]$	4.1
$P_{div}\ [kW]$	104



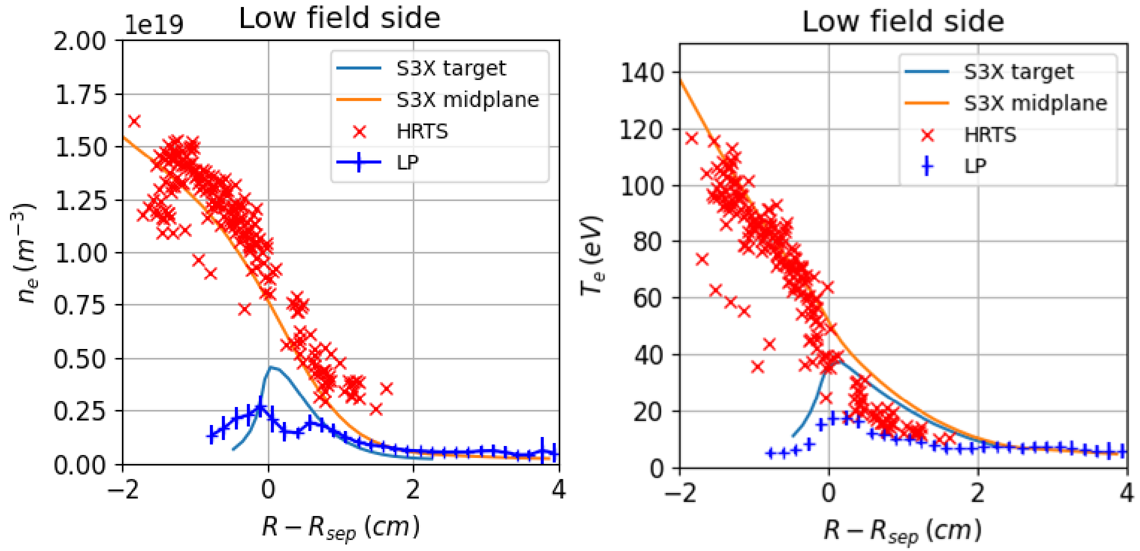
- **Outputs**: Ad-hoc **empirical diffusivities** found by the automated procedure **to fit experimental radial profiles** →
  - Quite complex radial variations with amplitude ranging over 1 order of magnitude, <u>hard to guess a priori!</u>



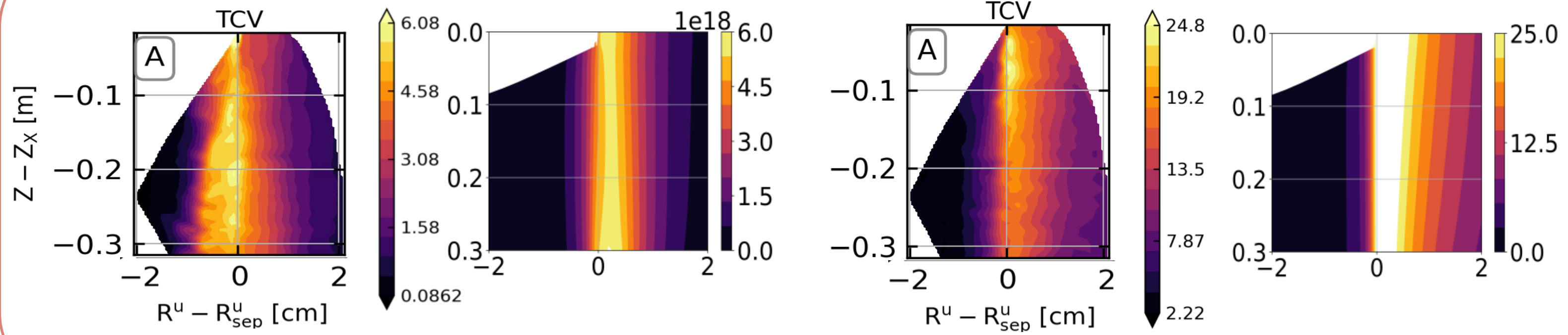
Case1: Empirical mean-field modelling

Pure D

- **Outputs**: target profiles, divertor plasma properties

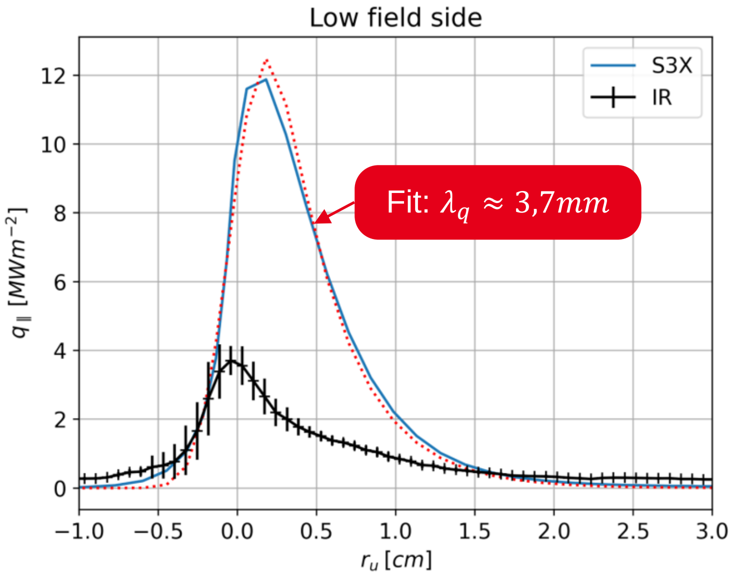


Quantity	Experimental Value	Simulation results	
		Pure D	With Carbon
$\lambda_q\ [mm]$	4.1	3.7	
$P_{div}\ [kW]$	104	162	


Electron density $[m^{-3}]$

Electron temperature $[m^{-3}]$

RDPA: Experiment vs SOLEDGE3X simulation

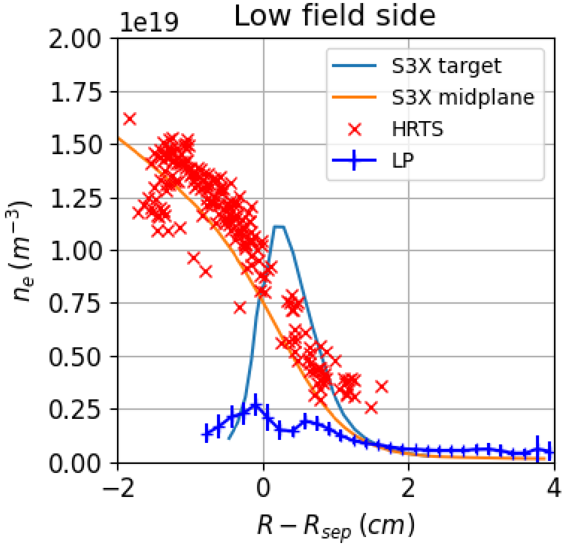


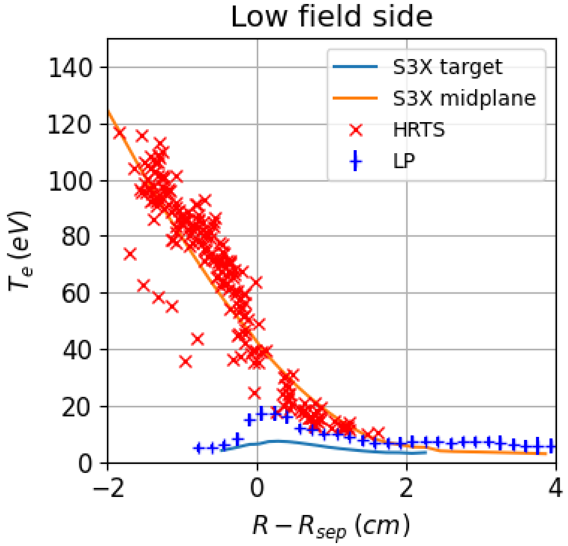
Fit: $\lambda_q \approx 3{,}7mm$

Case1: Empirical mean-field modelling

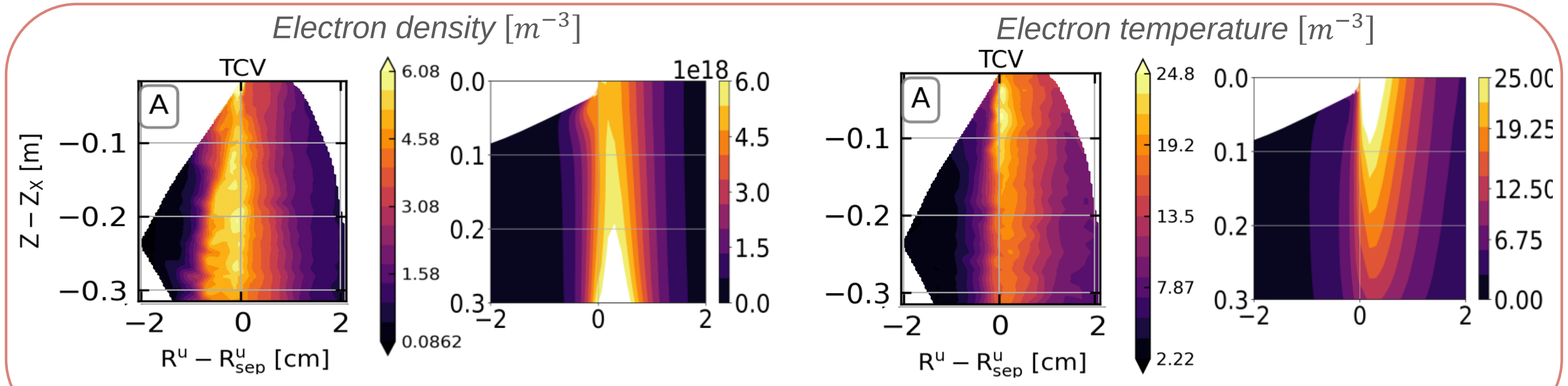
With Carbon

- **Outputs**: target profiles, divertor plasma properties



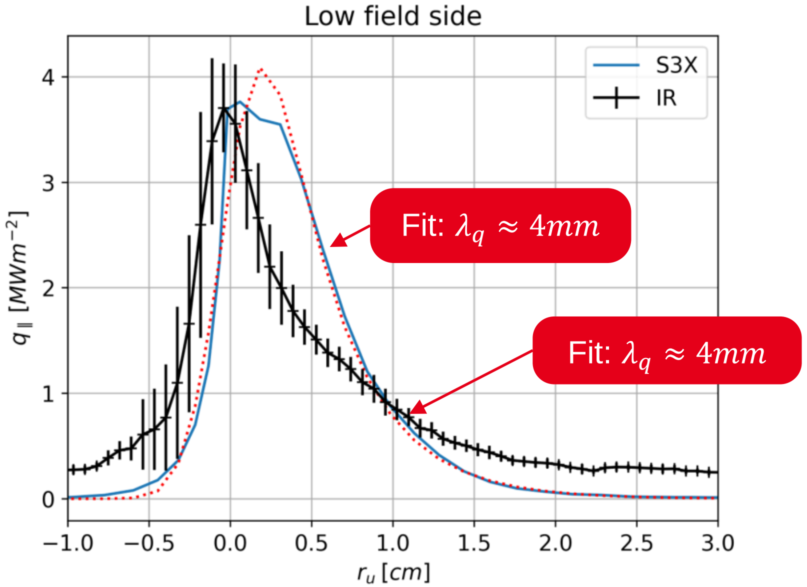


Quantity	Experimental Value	Simulation results	
		Pure D	With Carbon
$\lambda_q\ [mm]$	4.1	3.7	4.0
$P_{div}\ [kW]$	104	162	80


Electron density $[m^{-3}]$

Electron temperature $[m^{-3}]$

RDPA: Experiment vs SOLEDGE3X simulation



Fit: $\lambda_q \approx 4mm$

Fit: $\lambda_q \approx 4mm$

Case1: Empirical mean-field modelling

☹ **Predictability**

low – lot of free parameters

☺ **Experiment matching**

multi-physics + fitting procedure

☺ **Numerical cost**

cheap ~ 1 day on 48CPUs

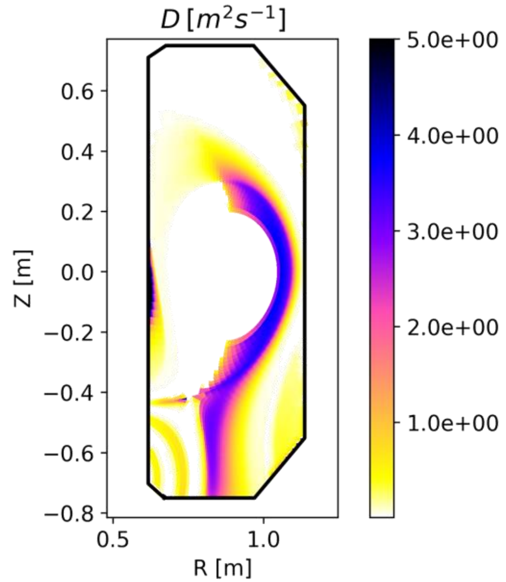
Case2: Semi-empirical mean-field modelling: k-model

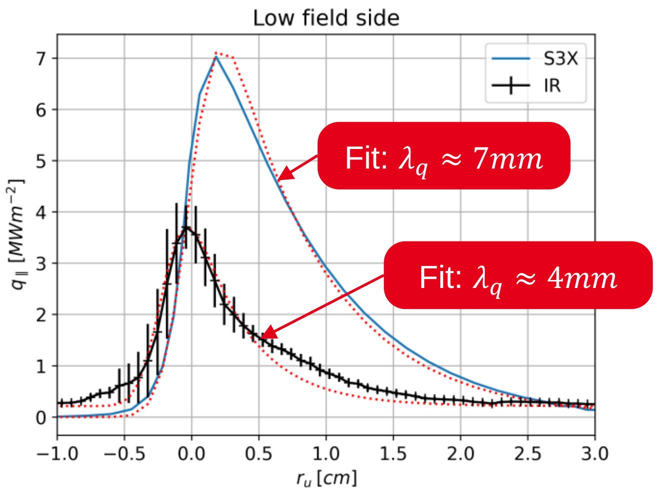
- **Inputs**:
  - Heating power [$170kW$ – 50/50 ion/electron channel]
  - $n_{sep} = 8 \times 10^{18} m^{-3}$ (used to tune gas puff rate)

- **Outputs**: Map of turbulent kinetic energy computed with the k-model:
  - Low field side ballooning
  - Turbulence along LFS divertor leg

- Profiles:
  - T_e profile OK but n_e profile too flat
  - λ_q overestimated → **TCV-X21 not on the scaling law** used to close the semi-empirical model!

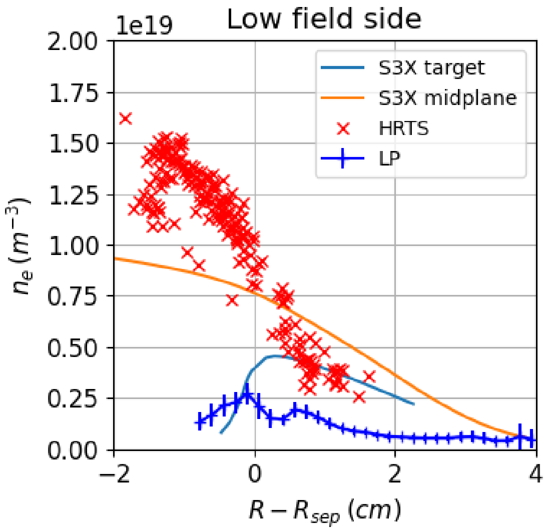
λ_q	TCV-X21	Scaling ($4q_{95}\rho_L$)	Simulation
Value (mm)	4.1	11	7.1

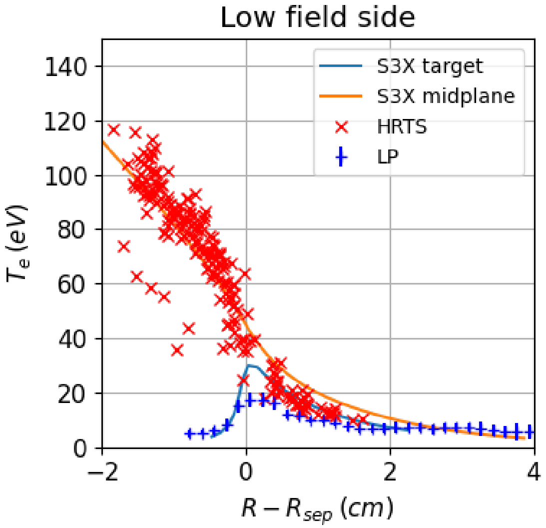




Fit: $\lambda_q \approx 7mm$

Fit: $\lambda_q \approx 4mm$





Case2: Semi-empirical mean-field modelling: k-model

😐 **Predictability**

improved – less free parameters

😐 **Experiment matching**

decent / rely on model hypothesis

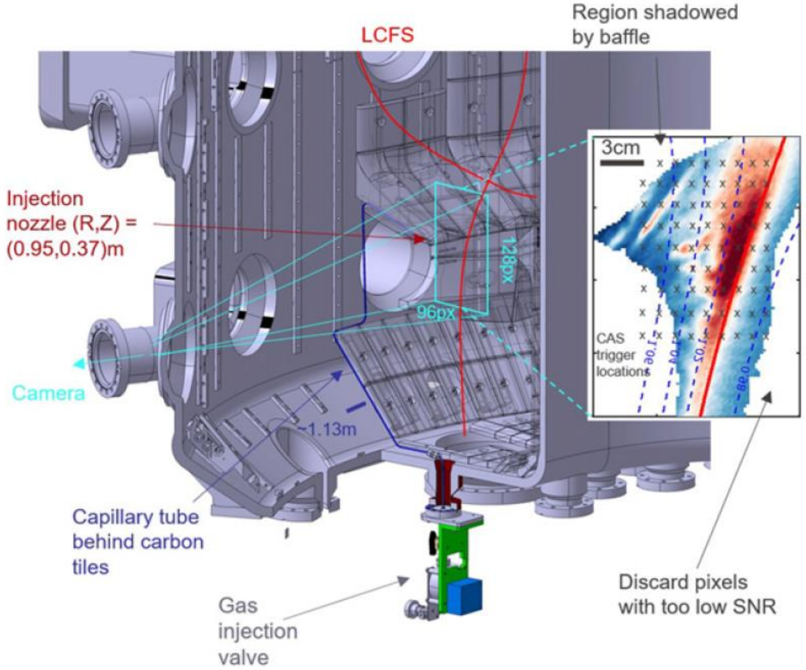
🙂 **Numerical cost**

cheap ~ 1 day on 48CPUs

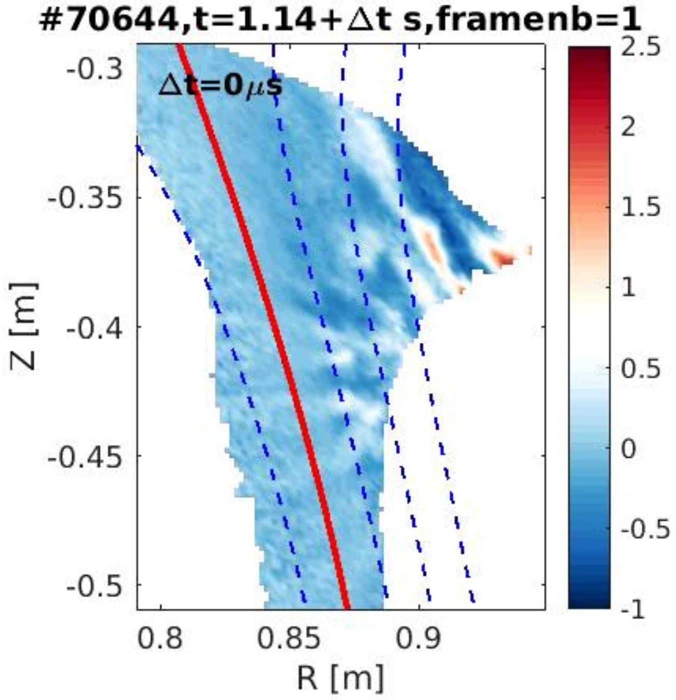
Case3: First principle simulations

- Enable direct comparison with turbulence measurements

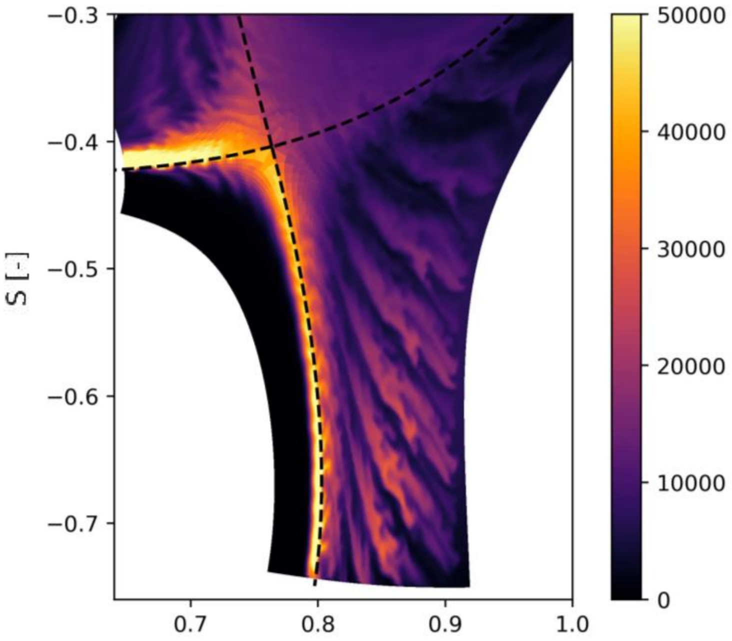
→ e.g.: Characterization of **divertor localised filaments**



Sketch of the gas puff imaging diagnostic on TCV. Figure from [Wütrich et al., Nucl. Fusion 62 (2022)]



Experimental data:
Normalized brightness
Video from [Wütrich et al., Nucl. Fusion 62 (2022)]

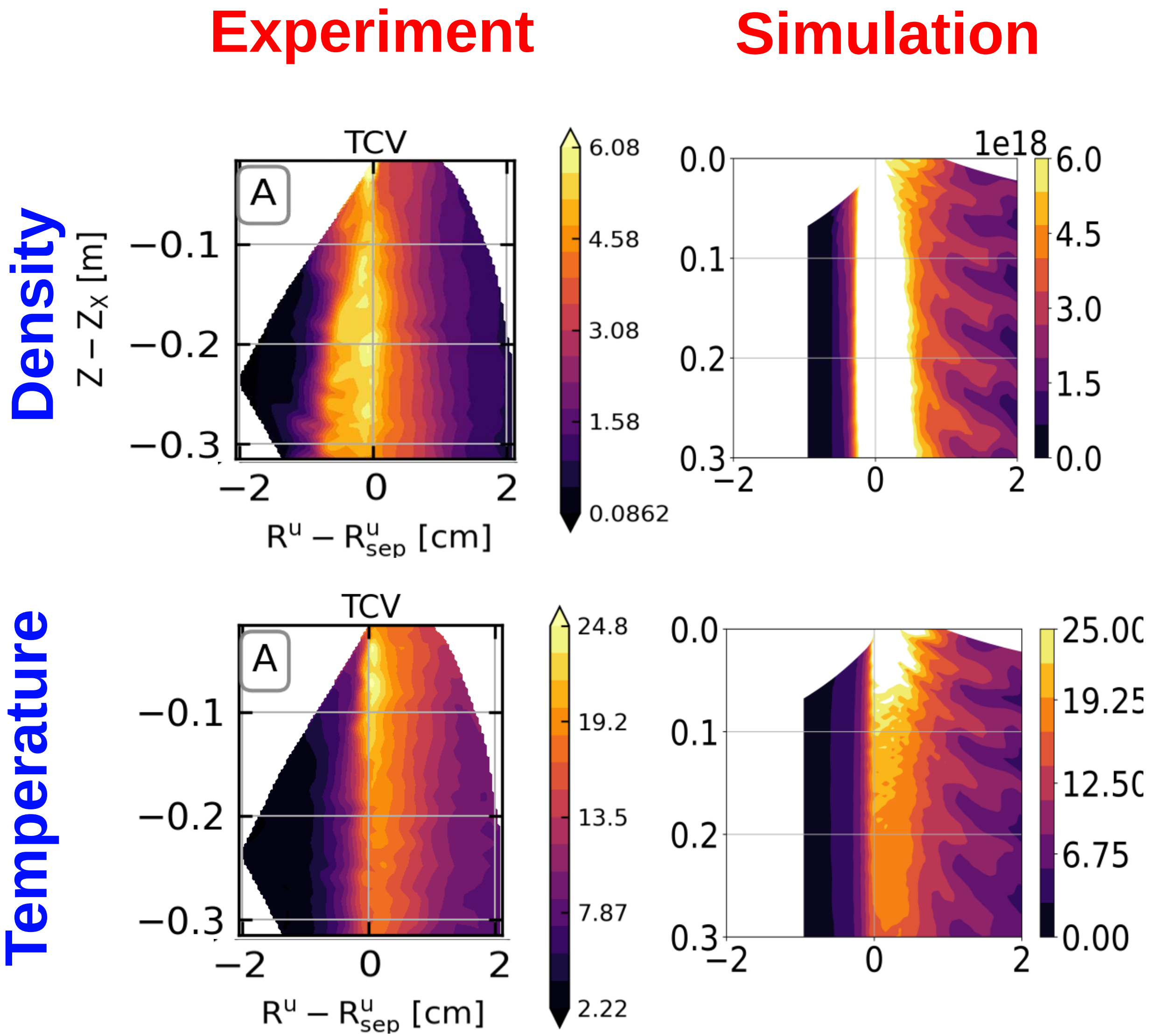


Simulation data:
Deuterium atom radiation (W/m3)
[Bufferand et al., NME 41 (2024)]

Case3: First principle simulations

- **Inputs**:
  - Heating power [$170kW$ – 50/50 ion/electron channel]
  - $n_{sep} = 8 \times 10^{18} m^{-3}$ (used to tune gas puff rate)

- **Outputs**:
  - SOL profiles
  - Turbulence pdf, filament size and velocity…
  - λ_q prediction (OK w.r.t. experiment)



Case3: First principle simulations

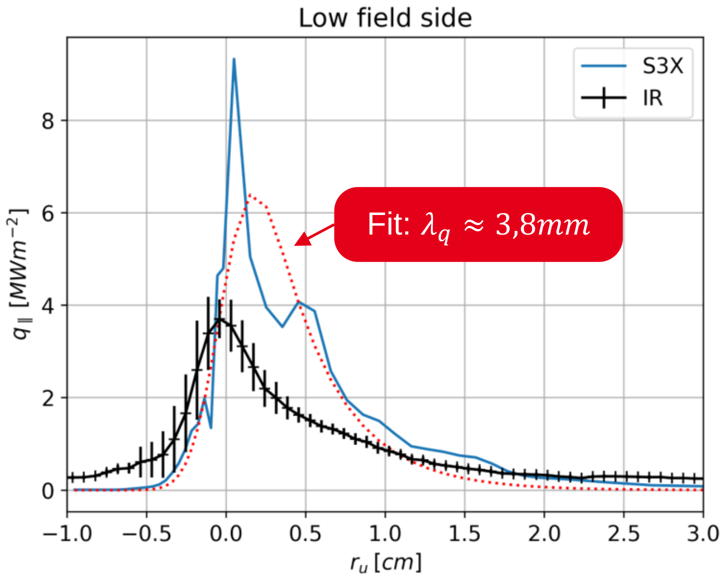
- **Inputs**:
  - Heating power [$170kW$ – 50/50 ion/electron channel]
  - $n_{sep} = 8 \times 10^{18} m^{-3}$ (used to tune gas puff rate)

- **Outputs**:
  - SOL profiles
  - Turbulence pdf, filament size and velocity…
  - λ_q prediction (OK w.r.t. experiment)

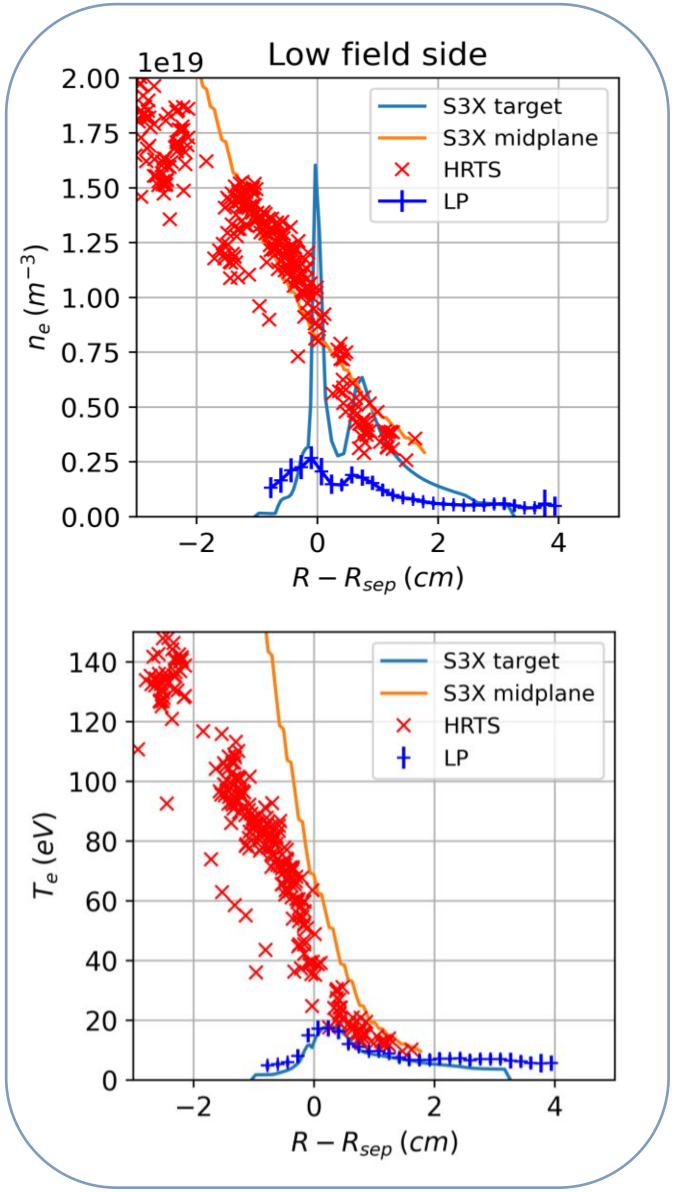
Quantity	Experimental Value	Simulation results
$\lambda_q\ [mm]$	4.1	3.8
$P_{div}\ [kW]$	104	122

Good agreement on λ_n (midplane) – overestimation of n_e at the divertor targets

Rather good agreement on λ_T in the SOL but too hot – good agreement at the divertor targets



Fit: $\lambda_q \approx 3{,}8mm$



Case3: First principle simulations

🙂 **Predictability**

No free parameter

😐 **Experiment matching**

OK if multi-physics (neutrals, impurities…)

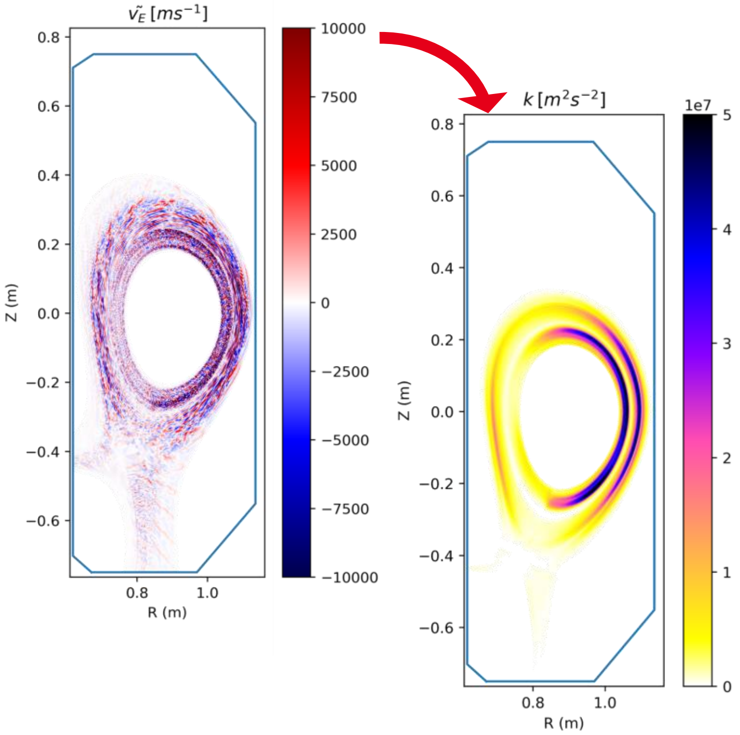
🙁 **Numerical cost**

Heavy ~ 2 months on 1024 CPUs

Conclusions and discussions

	Empirical	K-model	1st principles
Predictability	☹	😐	☺
Accuracy	☺	😐	😐
Cost	☺	☺	☹

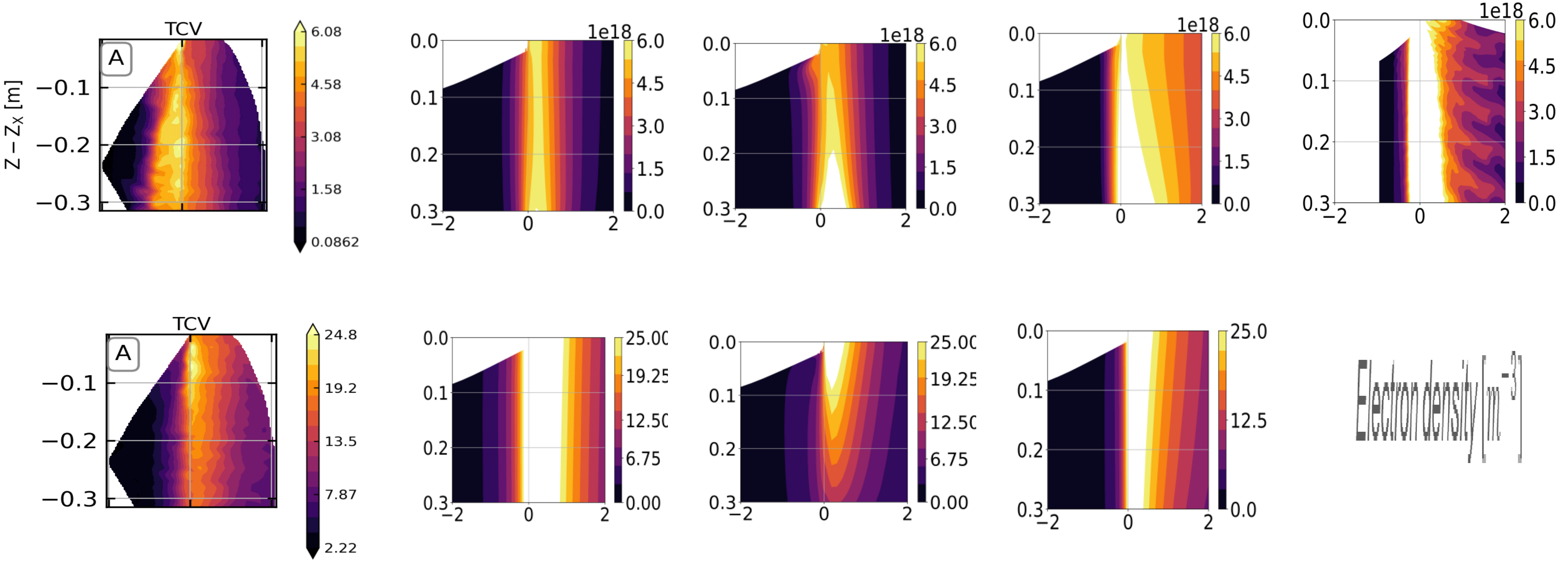
- Hierarchy of turbulence models required to address wide range of edge-plasma modelling application
  - **Pros and cons of each approach**
- **Cross-fertilization** between the different approaches:
  - 1st principles simulations → data for developing reduced models
  - Mean-field simulations → converge particle balance (long time scale): starting point for turbulent simulations / needed to address larger tokamaks
- Multiphysics necessary for detailed comparison with experiments (neutrals, impurities…)
- Push for increasing **open database** for benchmarking / code validation
  - Same exercise in detached conditions (TCV-X23 [V. Quadri et al., Nucl. Mat. Energy 41 (2024)])
  - H-mode plasmas



Backup

RDPA summary

Experiment	Case1 Empirical		Case2 k-model	Case3 1st principles
	D	D+C	D	D



Electron density $[m^{-3}]$

Electron temperature $[m^{-3}]$

Time scales of transport and turbulence simulations taking into account neutral physics

- **Challenge: Time scale to reach Quasi-Steady-State with neutrals**
- Time scales at play:
  - τ_{turb} = Turbulence time scale: time for turbulent structures to develop

    Interchange growth rate $\gamma_I \approx c_s\sqrt{\frac{\vec{\nabla}p\cdot\vec{\nabla}B}{pB}}$ ➔ $\tau_{turb} \sim \tau_I \approx \frac{\sqrt{aR}}{c_s} \sim 10\mu s$
  - τ_{transp} = Transport time: time for a plasma quantity (particle/energy) to travel from the source to the sink (wall): $\tau_{transp} \sim \frac{\delta r^2}{D} \sim \frac{L_\parallel}{c_s} \sim 1 - 10ms$
  - τ_{eq} = Particle and energy balance: time to equilibrate net sources with net sinks (e.g. energy injected = energy deposited / gas puff = pumped flow) → $\tau_{eq} > 100\ ms$

$$\tau_{eq,n} = \frac{\tau_{transp,n}}{1 - R_n}$$

$R_n > 95\%$ ☹

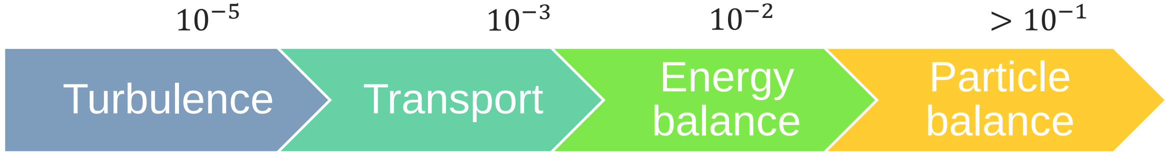
Recycling

Impurity content radiation balance

$$\tau_{eq,E} = \frac{\tau_{transp,E}}{1 - R_E}$$

$R_E \sim 25\%$

Time scales (s)



10^{-5} Turbulence

10^{-3} Transport

10^{-2} Energy balance

$> 10^{-1}$ Particle balance

Case	3D fine	2D transport	3D coarse
N_{points}	17 000 000	60 000	2 000 000
$t_{simu}\ (ms)$	0.8	30	20
$Cost\ (CPUh/ms)$	1 250 000	13	25 000