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Developing reduced turbulence transport models for the tokamak scrape-off layer

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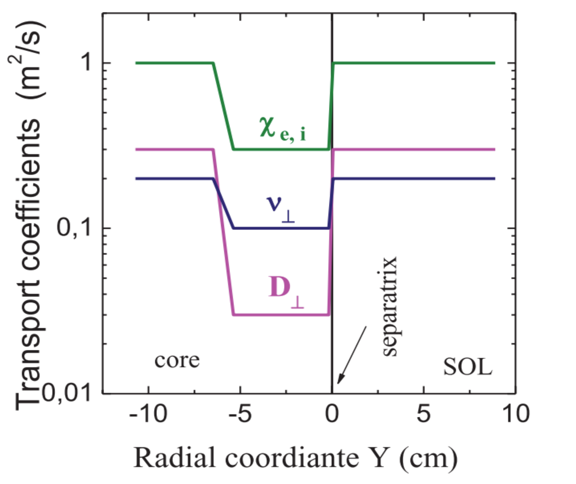
Introduction and motivation

- The design and operation of magnetic confinement fusion devices requires predicting plasma profiles over a wide range of parameters.
- Turbulence simulations provide accurate turbulent transport predictions, but they are very expensive and (currently) not suitable for wide parameter space exploration.
- Validated reduced transport models are commonly applied in the tokamak core for profile predictions [1, 2].
- Ongoing work to develop reliable reduced transport models in the pedestal region [3, 4].
- Reduced transport models in the scrape-off layer (SOL) are at much less mature stage and integrated modelling tools often use simplified semi-empirical models that provide the boundary conditions at the separatrix [5].
- Uncertainties on the SOL profiles translates into uncertainties in the design of future devices, with substantial consequences on costs and feasibility [6].
- Developing fast and accurate SOL reduced transport model is pivotal for the design of the next-generation magnetic confinement fusion devices.

State of the art

Ad-hoc, semi-empirical and surrogate models

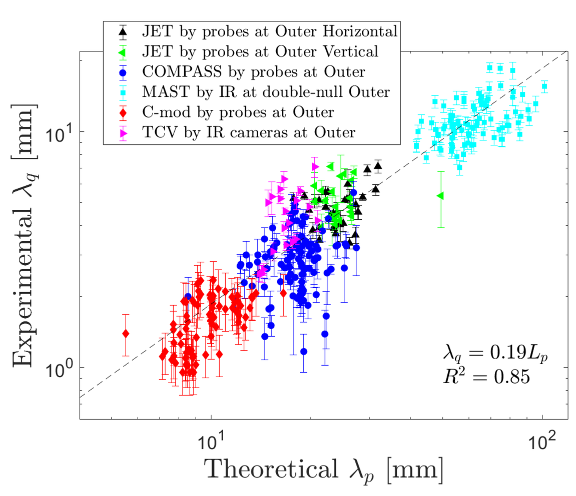
- Most of the two-dimensional transport simulations make use of ad-hoc cross-field diffusion coefficients.
- Full-radius integrated modeling relies on semi-empirical models (with machine specific parameters).
- Surrogate models have been developed for parallel transport, improving model fidelity in integrated tools [7].



Ad-hoc cross-field diffusion coefficients in a SOLPS-ITER simulation [8].

Reynolds-Averaged Navier-Stokes models

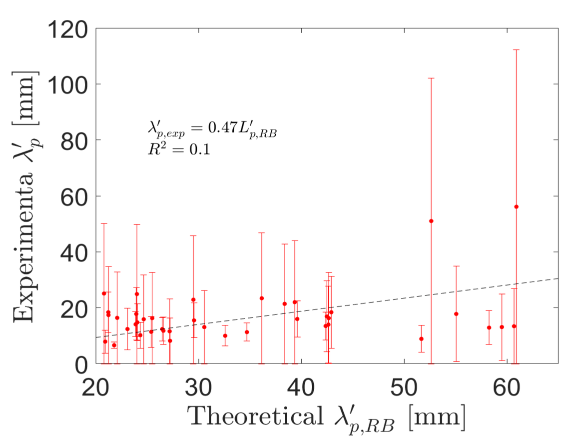
- $\kappa - \epsilon$ model based on fluctuating transverse velocity κ and the damping energy ϵ, similar to the predator-prey model [8, 9].
- KU Leuven model based on the evolution of the turbulent kinetic energy [10].
- These models are promising, but with some limitations due to the closure [11].



Validation of near SOL width derived from a quasi-linear theory [14].

Quasi-linear models based on the gradient removal

- Quasi-linear non-local models based on a simplified drift-reduced Braginskii model [12] and spectral filament analysis [13].
- SOL width predictions based on these quasi-linear models agree well with experimental measurements, but limited to interchange-driven turbulence [14].
- Recent work on extending these models to drift-wave turbulence [15], but validation to experimental data has not been carried out yet.



Two-region model (for blob transport in the far SOL)

- Two-region model provides analytical dependence of the blob velocity on its size [16, 17].
- Reduced models based on blob transport predict far SOL widths that are consistent with the experiments, but the agreement is poor [14].

Validation of near SOL width from a two-region model of blob transport [14].

Project objectives

- Identification of the key parameters that control turbulence dynamics in various confinement regimes, including L-mode and **small/no-ELM H-mode regimes**, and derivation of quasi-linear models for turbulence dynamics in the near SOL.
- Development of reduced transport models able to capture the **non-diffusive, non-local** nature of turbulent transport in the far SOL and in the divertor region.
- Characterization of the **main effects of neutrals and impurities dynamics on SOL turbulence**, with the aim of deriving approximated analytical or semi-analytical sources to be included in reduced physical models for turbulence dynamics in the SOL.
- **Experimental validation** of the profile predictions obtained from the reduced SOL transport models developed during the project.

Project milestones and current status

#	Task / Milestone	Assignees	Exp. Date
1	Derivation of quasi-linear particle and heat turbulent flux models for interchange, drift-waves and other turbulence regimes that are relevant to small/no-ELM plasmas in the near SOL.	M. Giacomin	30/09/2026
2	Comparison of quasi-linear particle and heat turbulent flux prediction in the near SOL to experimental data.	M. Giacomin M. La Matina N. Vianello	31/12/2026
3	Development of a reduced transport model for the far SOL and divertor regions.	S. Garcia Herreros	30/06/2026
4	Comparison of the reduced transport model prediction in the far SOL and divertor regions to experimental data.	S. Garcia Herreros A. Khan N. Vianello	31/12/2026
5	Exploring data-driven approaches for developing reduced transport models in the near and far SOL.	F. Auriemma R. van Schaik	31/03/2027
6	Development of reduced physical models (effective sources) to account for neutrals and impurities in the SOL and implementation in transport solvers of the reduced turbulent transport models developed in the project.	S. Garcia Herreros M. Giacomin R. van Schaik	30/09/2027
7	Experimental validation of the profile predictions obtained by performing transport simulations with the reduced models developed during the project.	F. Auriemma A. Khan M. La Matina N. Vianello	31/12/2027

Current status and near-future next steps

Quasi-linear heat flux in the near SOL (tasks 1 and 2)

- The analytical work in Ref. [18] provides an estimate of the heat flux from resistive ballooning mode turbulence.
- Next steps:
  - Implementation of the heat flux (and particle flux) scaling in a two-dimensional transport code.
  - Validation of near SOL profile predictions against experimental data on multiple machines.

Two-region heat flux in the far SOL (tasks 3 and 4)

- The particle flux from a two-region model can be written as $\Gamma_{\perp b} \simeq f_b\, n_b v_b$, where f_b is the blob packing fraction, n_b is the blob peaking density and v_b is the blob average velocity (see, e.g., Ref. [17]).
- Next step:
  - Experimental comparison between the measured particle flux and the measured $\Gamma_{\perp b} \simeq f_b\, n_b v_b$ in TCV is ongoing using the GPI and the RPTCV diagnostics.
  - Validation of the heat and particle fluxes provided by the two-region model.

Collaboration with WPTE/TSVV work packages

- TSVV-A: Interface with core and pedestal turbulent transport.
- TSVV-B: Comparison of reduced model predictions against the high-fidelity models developed and cooperation for improving RANS-like models.
- TSVV-D: Reduced models of the cross-field transport near the first wall may be required to provide fast yet accurate evaluation of wall erosion.
- TSVV-H: The activity of core and pedestal integrated modelling is complemented with reduced transport models in the SOL that will be developed here.
- WPTE: The cooperation with WPTE will be fundamental for validating reduced transport model in the SOL. The validation is a pilar of the present project.

Expected outcomes by the end of 2027

- A set of reduced transport models in the near SOL, covering various turbulence regimes and potentially including the main effects of neutrals on turbulence.
- Improved two-region model or similar reduced models for far SOL and divertor transport.
- Transport code(s) implementing the newly derived reduced transport models for profile predictions in the SOL.

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