# The challenge and reward of predictive multi-channel modelling

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Predictive modelling capability for tokamak scenarios requires the self-consistent integration of models for plasma sources, transport, and magnetic equilibrium. This overview will review the state-of-the-art in integrated modelling, its successes and present limitations, and will identify areas where models must be improved in order to realise a predictive tokamak simulator which can extrapolate to future experiments and future devices with confidence.

For core plasma, the required integration framework for plasma sources, transport, and magnetic equilibrium has been in place for more than a decade, in a group of 1.5D transport solvers. The present state-of-the-art focuses on exploiting advanced first-principle-based models of transport and heating with increasing sophistication and predictive power. Advanced transport models improve upon the previous scaling based semi-empirical models (for heat transport only) in a variety of ways: a) In their ability to describe non-diffusive transport in the particle and momentum channels, b) in capturing the influence of the channels upon each other, c) in achieving a consistent description of transport across the channels derived from a physical description of the underlying turbulent instabilities. The additional physics of the advanced transport models allow multiple nonlinearities in multi-channel prediction by allowing interactions between the channels; various examples will be presented. These nonlinearities provide both the reward (in replicating the complex phenomenology of experiments) and the challenge (in creating sensitive feedback loops requiring both robust numerics and accurate models) for multi-channel prediction.

Despite this complexity, accurate core predictions can be achieved: Predictive integrated simulations, like tokamak experiments, are flux-driven, and allow transport models to evolve naturally to the turbulence regime consistent with all fluxes and sources (a constraint that can be challenging to satisfy in gradient-driven simulations). Heat transport is (often) stiff, so temperature predictions can be insensitive to model inaccuracies. The turbulent mode frequencies are determined by the ratio of ion and electron heat fluxes, so the secondary transport in the (non-stiff) density and momentum channels can be well predicted by models which capture the necessary off-diagonal transport mechanisms. Successful 4-channel core predictions (Ti, Te, j, Ni) with advanced transport models are becoming commonplace, and validated predictive capability also including the momentum and impurity channels are starting to being proven. In one example, the evolution of the JET high performance hybrid scenario, including central accumulation of the tungsten (W) impurity, is reproduced with 8 predictive channels ($T_i, T_e, j, V_{tor}, n_D, n_{Be}, n_{Ni}, n_W$) yielding a predictive system which reproduces observed radiative temperature collapse after several confinement times.

The remaining grand challenge of the numerical tokamak lies in building and integrating a predictive description of the pedestal and SOL. To predict the pre-ELM pedestal height, models based on MHD linear stability (EPED and similar) have been integrated, enabling synergy between core and pedestal pressures to be captured. In the integrated framework, ELMs can presently be modelled only with ad-hoc models, which can nevertheless capture some interactions of the ELM frequency with the core evolution. Multiple free parameters are still needed to describe the pedestal transport, both to determine inter-ELM evolution and to separate pedestal pressure predictions into individual channels. Also in the SOL region, the description of perpendicular transport (and some wall and pump interactions) still relies on free parameters which represent fundamental limitations of predictive capability. Despite these limitations, at least one core transport solver is coupled to a 2D Braginskii SOL solver, a coupling now routinely used to assess target heat loads, seeding, and fuelling requirements in ITER scenarios, and which has also been applied to model W flushing during kick-triggered ELMs during ramp-down in JET.