Real-time multichannel tokamak plasma profile simulations using the RAPTOR code and the QLKNN first-principle transport model

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Introduction

Real-time capable yet accurate simulators for the plasma (1D) profile evolution in a tokamak are important for discharge preparation and optimization, controller validation, as well as real-time profile reconstruction and control. The RAPTOR code, a transport code capable of simulating the plasma profile time-evolution in real-time, has been used for this purpose on TCV, AUG and RFX [1, 2, 3]. The code has recently undergone improvements and upgrades to improve its physics fidelity, while maintaining the real-time capabilities. In this work we present the recent addition of ion temperature and particle transport equations in RAPTOR, as well as the use of first-principle-based QLKNN code, a neural-network emulation of the quasi-linear gyrokinetic code QuaLiKiz [4], to provide accurate transport coefficients. As a result, for the first time, real-time-capable coupled simulations of the kinetic profiles T_e, T_i and n_e and q profile have been obtained that agree well with experimental data for JET.

The RAPTOR code and its recent upgrades

In order to be fast enough for routine use for control purposes, the RAPTOR code circumvents common bottlenecks in tokamak transport simulations. For example, the Grad-Shafranov equilibrium is not self-consistently evolved, but geometric properties of the equilibrium are taken from pre-computed equilibria. Similarly, deposition profiles from auxiliary heating and current drive sources are implemented as parametrizations of results from heavier codes, and transport coefficients are calculated using ad-hoc, analytical transport models. First versions of the RAPTOR code, aimed primarily at predicting the time-evolution of the q profile, solved only the poloidal flux diffusion and electron energy transport equations. In order to extend the predictive capabilities of the code, the ion energy transport equation was added, as well as the possibility to take into account a time-varying geometry [5]. Most recently, particle transport equations for ions, electrons and impurity species have been implemented as well. The particle

*See the author list of X. Litaudon et al 2017 *Nucl. Fusion* **57** 102001

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transport equation for a generic species s is implemented in RAPTOR as:

$$\frac{1}{V'_{\hat{\rho}}}\left(\frac{\partial}{\partial t}\bigg|_{\hat{\rho}} - \frac{\dot{\Phi}_b}{2\Phi_b}\frac{\partial}{\partial\hat{\rho}}\hat{\rho}\right)\left[(V'_{\hat{\rho}})n_s\right] + \frac{1}{V'_{\hat{\rho}}}\frac{\partial}{\partial\hat{\rho}}\Gamma_s = S_s \tag{1}$$

with

$$\Gamma_s = -\frac{g_1}{V'_{\hat{\rho}}}D_s\frac{\partial n_s}{\partial\hat{\rho}} + g_0 V_s n_s \tag{2}$$

Here, $n_s(\rho,t)$ is the particle density of the species of interest, Γ_s is the particle flux, $\hat{\rho}$ is the normalized toroidal flux, Φ_b is the toroidal flux enclosed by the last closed flux surface, $V' = \partial V/\partial\hat{\rho}$, $g_0 = \langle|\nabla V|\rangle$ and $g_1 = \langle|\nabla V|^2\rangle$ depend on the magnetic equilibrium geometry and are externally prescribed.

To test the correctness of the implementation, a 4-channel RAPTOR simulation (ψ, T_e, T_i, n_e) was compared to a CRONOS simulation using the same QLKNN-4Dkin transport model (discussed below). The results agree well, with small differences that can be explained by differing details of the numerics, treatment of boundary conditions, and smoothing in the two cases [6].

Profile simulations using the QLKNN transport model

In recent years, tokamak transport coefficient estimates that agree well with experimental results have been obtained from physics-based codes such as QuaLiKiz. QuaLiKiz solves the quasilinear gyrokinetic equation to calculate the linear stability of modes in the the plasma that drive turbulent fluxes, and uses a nonlinear saturation rule to calculate the dependence between these linear growth rates and the resulting fluxes once the turbulent modes have reached saturation [4]. As such, QuaLiKiz is already several orders of magnitude faster than local nonlinear delta-f gyrokinetic codes, while providing comparable accuracy, typically returning the values of turbulent flux (or transport coefficients) in 10CPUs per radial position per time step. A further speed-up can be obtained by creating a surrogate model, or emulation, of the input-output behaviour or QuaLiKiz via neural-networks. Since the neural network is an analytic function, the resulting QLK-NN transport model takes only $\sim$1CPUms per radial position per time step, a speedup of 4 orders of magnitude compared to full QuaLiKiz. Crucially, also the Jacobians of the outputs with respect to the input parameters can be returned, which is useful for implicit PDE transport solvers (allowing large simulation time steps) and for control and optimization purposes.

Depending on the amount of inputs into QuaLiKiz that are varied during training of the neural network, various versions of QLKNN are obtained. A proof-of-principle version, named QLKNN-4D, uses four inputs: the normalised logarithmic ion temperature gradient R/L_{T_i}, the ion to electron temperature ratio T_i/T_e, the safety factor q, and magnetic shear s and returns only electron and ion heat diffusion coefficients [7]. More recently, this has been extended to the QLKNN-4Dkin transport model featuring kinetic electrons and to returning also the particle diffusion and pinch coefficients D_e and V_e. This model was trained in the regime where turbulence drive is dominated by ITG modes and has proven successful in reproducing kinetic profiles from the well-studied JET 73342 discharge, while setting only the value of the profiles at the top of the pedestal as a boundary condition. Comparisons of experimental data to predicted profiles, as well as comparison of fluxes obtained from QLKNN-4Dkin versus full QuaLiKiz are presented in detail in [6]. In Figure 1 the main result is shown: the core profiles are well-approximated in the region $0.4 < \rho < 0.85$ with slight underestimation in the core. This simulation used a source profiles parametrization, as well as equilibrium data, from a previous CRONOS simulation. In the future, real-time capable heating and current drive source codes such as RT-TORBEAM for Electron Cyclotron heating and current drive [8] and the RABBIT code for Neutral Beam deposition calculations [9] can be used. Adding the effect of sawteeth, radiation losses and ICRH heating improves the result further.

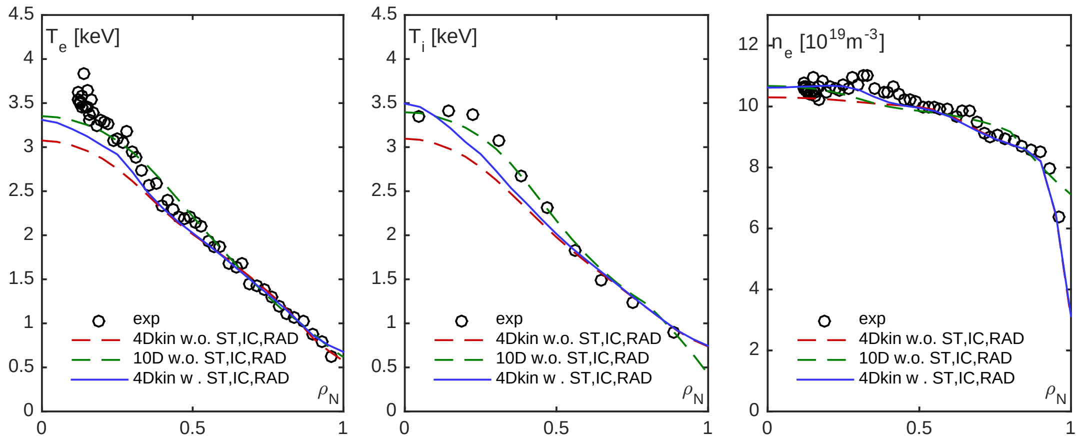

Figure 1: RAPTOR prediction of T_e, T_i and n_e profiles with QLKANN-4D (with and without including sawteeth, radiation sinks and ICRH heating), as well as first predictions with QLKANN-10D.

Time-varying simulations were also carried out in order to test the speed of the code towards entire-discharge simulations. Using a simulation time step of $0.25s$, which is comparable to the JET energy confinement time, one second of JET plasma could be simulated in less than $0.2s$ on a standard laptop with an i5 processor, showing the potential for accurate faster-than-real-time simulations.

We show here for the first time the most recent results using RAPTOR with an even more advanced version of the neural network transport model, QLKNN-10D [10]. This model is trained on an extended parameter space including further dependence on the electron temperature gradient R/L_{T_e}, the density gradient R/L_{n_e}, local aspect ratio ε, normalised collisionality ν^*, effective charge Z_{eff}, and perpendicular flow shear $\Gamma_E \sim \frac{\partial v_{tor}}{\partial \rho}$, and covers ITG/TEM/ETG turbulence regimes. In order to account for known limitations in the QuaLiKiz predictions at high collisionality, the training range was purposely restricted to $\nu^* < 0.05$ and the inputs into the transport model are clipped to that maximum. Results with this transport model are also shown in Figure 1 (green curve), showing that the simulation approaches the experimental measurements even more closely than the QLKNN-4Dkin results.

Conclusions and Outlook

Multichannel (ψ, T_e, T_i, n_e) core profile simulations using the fast RAPTOR transport model with the fast-yet-accurate physics-based QLKNN-4Dkin transport model has shown to be able to reproduce core profiles from a JET discharge, with simulation times satisfying the requirements for real-time simulations. First tests of the more complete transport model, QLKNN-10D, point towards further improvements of accuracy. Development and integration of real-time capable particle, heating and current drive source codes will reduce the dependency on parametrized actuator models. More tests of RAPTOR using this transport model are underway towards showing entire-discharge simulations for various shots in different scenarios on various tokamaks. Real-time implementations of multichannel simulations for plasma monotiring, profile estimation and control are foreseen on JET and MST1 devices in the near future.

References

[1] Felici, F. *et al.* 2012 *Plasma Physics and Controlled Fusion* **54** 025002

[2] Felici, F. *et al.* 2016 in *26th IAEA Fusion Energy Conference, Kyoto, Japan* EX/P8–33

[3] Piron, C. *et al.* 2016 in *Proceedings of the 29th Symposium On Fusion Technology*

[4] Bourdelle, C. *et al.* 2016 *Plasma Physics and Controlled Fusion* **58** 014036

[5] Teplukhina, A.A. *et al.* 2017 *Plasma Physics and Controlled Fusion* **59** 124004

[6] Felici, F. *et al.* 2018 *Nuclear Fusion* To be published

[7] Citrin, J. *et al.* 2015 *Nuclear Fusion* **55** 092001

[8] Poli, E. *et al.* 2018 *Computer Physics Communications* **225** 36

[9] Weiland, M. *et al.* 2018 *Nuclear Fusion* to be published

[10] van de Plassche, K. *et al.* in *This conference, P2.1086*

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This project is also sponsored in part by the Swiss National Science foundation.