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Flux-driven multi-channel simulations with the quasilinear gyrokinetic transport model QuaLiKiz

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An accurate predictive model for turbulent transport fluxes driven by microinstabilities is vital. This is a critical component in the interpretation and optimization of present-day experiments. Validated predictions are needed for extrapolation to future machines and design of control systems. However, the computational cost of direct numerical simulation with massively parallel nonlinear gyrokinetic codes, 10^4-10^5 CPUh for fluxes at a single radius, precludes their use for routine integrated tokamak transport simulations.

Increased tractability is gained by applying the quasilinear approximation. This has proven to be a successful tool for model reduction in tokamak and stellarator turbulence modelling. A $\sim$6 order of magnitude computional speedup is gained compared to nonlinear gyrokinetics. It is valid in the plasma confinement zone where the density fluctuations are small - $\delta n/n{\sim}O(\%)$. Their success hinges on the reproduction of local nonlinear gyrokinetic fluxes [1].

We focus on significant progress made in the quasilinear gyrokinetic transport model QuaLiKiz [2, 3]. Optimization of the numerics has accelerated the calculation time by a factor $\sim 20-50$ compared to Ref [2]. The dispersion relation for a single wavenumber is now solved within $\sim$1 s. This allows tractable simulation of flux-driven dynamic profile evolution including all transport channels: ion and electron heat, main particles, impurities, and momentum. Furthermore, additional physics has been added, widening the applicability of the model. All numerical and physial improvements are listed below:

- Plasma dispersion functions calculated with Weidman method [4, 5]. Speedup $\times \sim 2$
- Contour path optimization in dispersion relation root solver. Speedup $\times \sim 5$
- In integrated modelling: use previous solution for next timestep initial guess. Speedup $\times \sim 5$
- Allow an arbitrary number of active or tracer ion species
- Impact of rotation and temperature anistropy induced poloidal asymmetry on heavy impurity transport. This is critical for W-transport applications [6, 7].
- ETG saturation rule based on JET single-scale nonlinear gyrokinetic simulations [8]

QuaLiKiz is coupled to both the CRONOS integrated modelling suite [9], and more recently to JETTO-SANCO [10, 11] through the Transport Code Interface (TCI). Applying QuaLiKiz in JETTO-SANCO, 1 s of JET plasma simulation costs 10 hours walltime using 10 CPUs. We present QuaLiKiz validation within JETTO-SANCO, through simulations of both JET hybrid and baseline discharges. These include the first QuaLiKiz integrated modelling simulations with rotation and momentum transport, as originally developed in Ref [12]. All source calculations are from PENCIL (NBI) and PION (ICRH). The current profile is either prescribed from constrained EFIT or from predictive current profile modelling depending on the case.

In figure 1 we display a JETTO/QuaLiKiz simulation of JET C-wall hybrid discharge 75225. A stationary state corresponding to an averaging between 6-7s seconds is modelled. The boundary condition is at normalized toroidal flux coordinate $\rho = 0.8$. The modelling includes heat, particle, impurity, and momentum transport simultaneously. The C-impurity is evolved separately within SANCO. The predicted effective Prandtl number is ~ 0.5.

Good multi-channel agreement is achieved, particularly for $\rho > 0.5$. ETG scales improves agreement with experiment. At $\rho < 0.5$, QuaLiKiz underpredicts the value of T_i. This is expected, since QuaLiKiz does not include nonlinearly enhanced electromagnetic stabilization of ITG, shown to be important for this discharge [13].

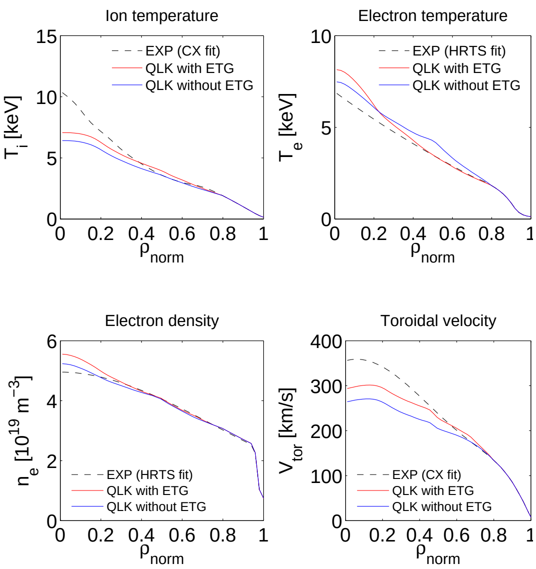

Figure 1: *Comparison of JETTO/QuaLikiz predictions and measured profiles for JET hybrid scenario 75225*

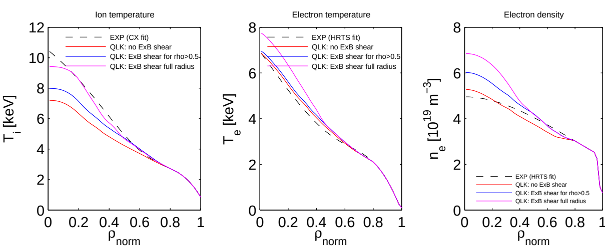

Figure 2: *Comparison of different rotation settings in the 75225 JETTO/QuaLikiz simulations*

Due to its ballooned eigenfunction ansatz, QuaLiKiz tends of overpredict the impact of α_{MHD}-stabilization at low magnetic shear. QuaLiKiz also likely underestimates the impact of parallel velocity shear stabilization. Thus, in integrated modelling applications, the $E\times B$ shear and α-stabilization models are not activated for $\rho < 0.5$. The generalization of the model is under development. The impact of this choice for the rotation is seen in figure 2. The $E\times B$ shear is important for reaching agreement in the outer half-radius, but would lead to a spurious T_i increase in the inner half. This is not in agreement with full nonlinear modelling, where the $E\times B$ impact is weak in the inner core [13].

A similar validation was carried out for JET ILW baseline discharge 87412. The comparison is seen in figure 3. The boundary condition in this case was at $\rho = 0.85$. Apart from V_{tor}, the agreement is good. Due to poor CX measurements in the inner core, the assumption $T_i = T_e$ was made for the measured profiles. The peaking at $rho < 0.2$ may be alleviated by including a sawtooth model. The mismatch of V_{tor} may also be affected by NTV torque from magnetic islands. 3/2 and 4/3 modes are present during the studied time window. Their impact is not taken into account.

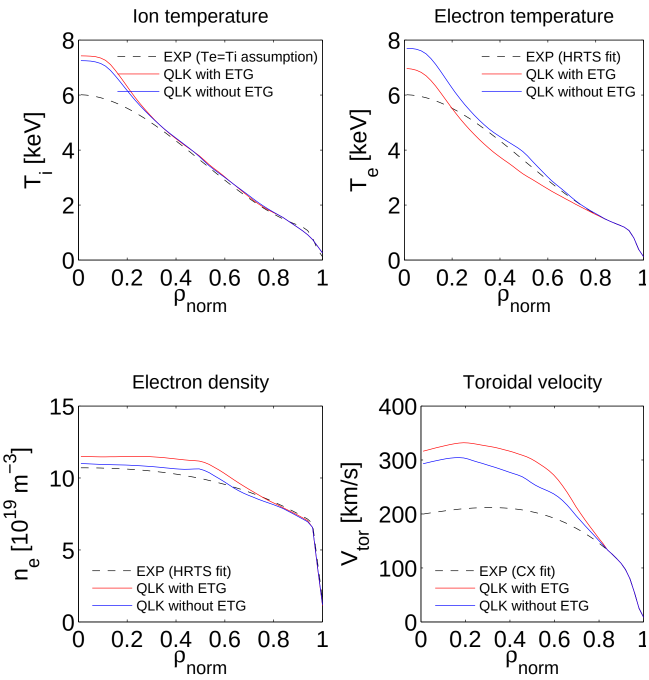

Figure 3: *Comparison of JETTO/QuaLikiz predictions and measured profiles for JET ILW baseline 87412*

An important application for integrated modelling is profile dynamics. This was examined for the 87412 density rise following the L-H transition. As seen in figure 4, the hollow density profile in the initial condition transitions to peaked during the subsequent ~1.5 s of evolution. This behaviour was reproduced by QuaLiKiz. However, the degree of the fast observed rise during 9-9.5 s was not reproduced.

Finally, we present a proof-of-principle of a realtime capable emulation of QuaLiKiz using neural networks. The adiabatic electron emulation presented in Ref. [14] has been extended to kinetic electrons, by nonlinear regression of a 4D

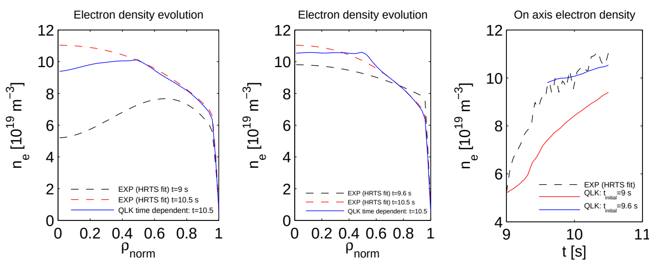

Figure 4: *Central n_e evolution in JETTO/QuaLiKiz 87412 simulations, with varying initial conditions*

input dimensionality QuaLiKiz database (R/L_{Ti}, T_i/T_e, q, $\hat{s}$). Simultaneous heat and particle transport was then predicted with the neural network transport model inside CRONOS, for JET C-wall baseline case 73342 [15]. The neural network model reproduces the same results as full QuaLiKiz, and agrees with the measurements. Furthermore, the neural network transport model is ∼6 orders of magnitude faster than QuaLiKiz itself, and is capable of faster-than-realtime tokamak modelling in the control-oriented tokamak simualtion code RAPTOR [16].

To conclude: the first-principle-based quasilinear gyrokinetic transport code QuaLiKiz has been optimized and generalized. Successful validation was carried out within the JETTO modelling suite. QuaLiKiz is now ready for extensive integrated modelling applications, including for W-transport. In parallel, a neural network emulation of QuaLiKiz is validated, and work is ongoing to extend the input dimensionality of the neural networks. This opens the path towards control room applications of realtime capable, validated, first-principle-based quasilinear gyrokinetic transport modelling. This would allow fast discharge preparation, realtime supervision, and model-based predictive control.

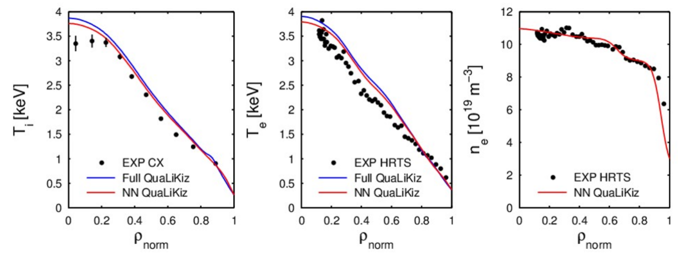

Figure 5: *Comparison of full QuaLiKiz and its neural network emulation in CRONOS simulations of JET C-wall baseline 73342*

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