Validating reduced turbulence model predictions of Electron Temperature Gradient transport on a JET improved-confinement scenario

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Introduction

Accurate predictive modelling of tokamak core turbulent transport is a vital component of integrated tokamak simulation. The contribution of Electron Temperature Gradient (ETG) driven turbulence to electron heat transport in various operational regimes is an open question with extensive recent investigations [1], [2]. This paper focuses on validation of striking recent predictions [3] of anti-GyroBohm isotope scaling of core transport, mediated by ETG turbulence. The previous modelling was of the JET hybrid scenario #92398, with JINTRAC [4], [5] using QuaLiKiz v2.6.1 [6], [7] as the turbulent transport model. There, the T_e profile was pinned to near the ETG critical threshold, regardless of main ion isotope. Then, with increasing isotope mass, the decreasing ion-electron heat exchange enabled T_i to increase, sustaining larger T_i/T_e and hence a increased ITG instability threshold, improving confinement and increasing T_i further, leading to an anti-GyroBohm ion mass confinement scaling. Without ETG, T_i/T_e is predicted closer to 1, with higher T_e and lower T_i, and the mass scaling of the ion-electron heat exchange does not significantly impact the predicted confinement. This potential benefit of ETG turbulence for DT scenario extrapolations strongly motivates deeper validation of these predictions. This is the focus of the present paper. Since the JET discharge in Ref.[3] did not have core T_i measurements, a more recent hybrid scenario #94875 was selected for analysis, with T_i measurements available through trace Ne seeding. The discharge basic parameters are listed in Table 1.

Table 1: Basic parameters of JET hybrid discharge #94875, within the flattop time window $t = 8.25 - 8.55$ analyzed. $\beta_N \equiv \langle\beta\rangle \frac{aB_T}{I_p}$, where a is the minor radius.

B_T [T]	I_p [MA]	$P_{NBI}[MW]$	$P_{ICRH}[MW]$	β_N
2.8	2.2	27	6.1	2.3

The analysis plan and research questions are as follows.

- Does integrated modelling of #94875 with QuaLiKiz (v2.6.1), reproduce the trend seen in Ref. [3] of ETG-induced anti-GyroBohm isotope scaling?
- Is this same effect predicted with the recent release QuaLiKiz 2.8.1? Modifications include an improved collisionality model [8], leading to an increased impact of Trapped Electron Modes (TEM), and more electron heat flux on ion scales
- Validate QuaLiKiz ETG predictions against high-fidelity linear and nonlinear gyrokinetics at ion-scales and multi-scale. Use parameters from #94875 integrated modelling at $\rho \sim 0.65$, aiming to avoid electromagnetic stabilization effects since these are too expensive too include in multiscale gyrokinetic simulations,

Integrated modelling of JET hybrid scenario #94875 with QuaLiKiz

JINTRAC-QuaLiKiz core simulations of JET hybrid discharge #94875 were carried out with both QuaLiKiz 2.6.1 and 2.8.1. Taking an initial condition at flat-top with profiles fitted from a $t = 8.25-8.55$ time window, heat and particle transport was simulated until stationary state was reached. The core boundary condition was taken at $\rho = 0.85$. The simulations agree with experimental measurements, as shown in Figure 1. QuaLiKiz 2.6.1 reproduces the phenomenology reported in Ref [3] regarding the importance of ETG turbulence and a mechanism for anti-GyroBohm isotope scaling. However, comparisons with QuaLiKiz 2.8.1, which has increased TEM drive, shows a decreased importance of ETG while still maintaining agreement with the experimental measurements within 1σ of the Gaussian Process Regression fit envelope. With 2.8.1, the anti-GyroBohm isotope scaling predictions are significantly diminished.

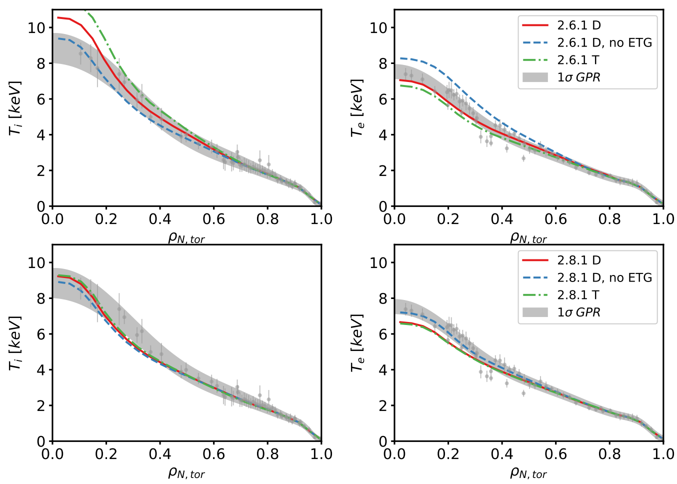

Figure 1: *JINTRAC-QuaLiKiz integrated modelling simulations of JET #94875 with version 2.6.1 (upper row) and 2.8.1 (lower row), and compared to measurement fits using Gaussian Process Regression. Particle transport was also simulated with good agreement with experiment, but not shown for brevity*

Validation against high-fidelity gyrokinetics: ion-scale

Nonlinear GENE [9] simulations were carried out and compared to QuaLiKiz (2.6.1 and 2.8.1) for #94875 parameters at $\rho = 0.65$. An R/L_{Ti} scan was carried out, with $\hat{s}-\alpha$ geometry, no rotation, and no electromagnetic (EM) effects. The modelled R/L_{Ti} is lower at inferred power balance levels compared to the measured R/L_{Ti}, since both EM effects and rotation shear are important stabilizing effects in this regime (not shown for brevity).

As shown in figure 2, at power balance levels, QuaLiKiz 2.8.1 is more accurate than 2.6.1 compared to GENE, with a similar $Q_i/Q_e \sim 2$ and subdominant TEM. Power balance in QuaLiKiz is reached with a minor upshift of $R/L_{Ti} \approx 0.5$ compared to GENE, reflecting relatively close correspondence At low R/L_{Ti} (Q_i much lower than inferred power balance), TEM is overpredicted in QuaLiKiz 2.8.1 compared to GENE.

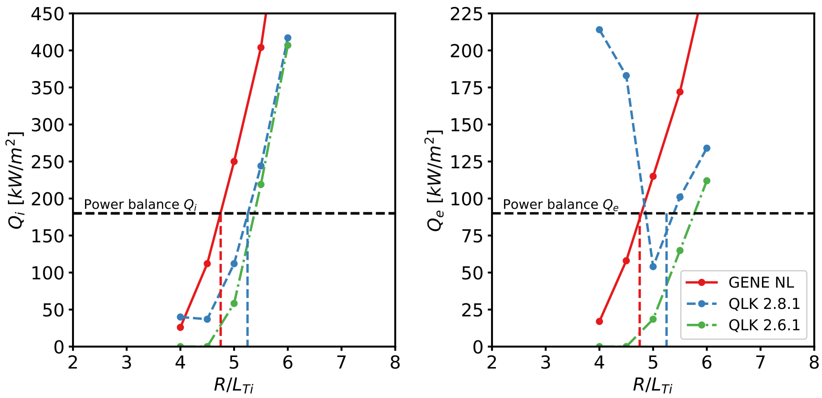

Figure 2: GENE *ion-scale simulations for JET #94875 at* $\rho = 0.65$ *compared to QuaLiKiz 2.6.1 and 2.8.1, for ion heat flux (left panel) and electron heat flux (right panel). Experimental power balance flux levels are portrayed by the horizontal dashed black line. The predicted* R/L_{Ti} *corresponding to* Q_i *power balance levels are shown as vertical dashed lines for* GENE *(red) and QuaLiKiz 2.8.1 (blue)*

Validation against high-fidelity gyrokinetics: multi-scale

A further test of previous QuaLiKiz predictions in this regime is direct comparison to nonlinear gyrokinetic multi-scale simulations. To save computing time, a simplified setup was modelled based on #94875 at $\rho = 0.65$: single ion, electrostatic, no rotation, and modified gradients for strongly driven ETG (linearly). Both GENE and GKV [10], [11] were applied, with a successful linear benchmark between them. QuaLiKiz predicted $Q_{e,ETG} \approx Q_{e,ITG}$ for these inputs. GENE and GKV linear predictions showed $\frac{\gamma_{ETG,max}}{\gamma_{ITG,max}} \approx 2\sqrt{\frac{m_i}{m_e}}$, which is expected to lead to strong ETG in multi-scale simulations according to the "rule of thumb" [12].

However, both GKV and GENE surprisingly predicted negligible ETG turbulence in this regime, as shown in figure 3, not in line with the "rule of thumb". QuaLiKiz overpredicts ETG here, motivating a revisitation of its multi-scale saturation rule.

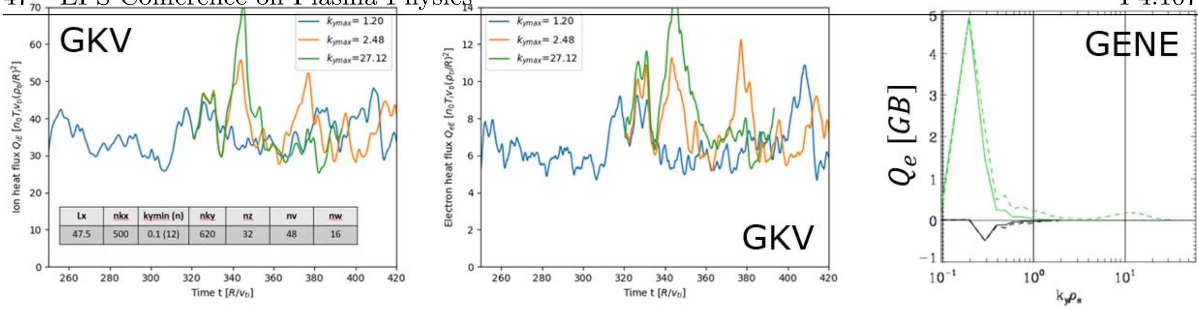

Figure 3: GENE *(right panel) and GKV (left panels) results from multi-scale simulations based on JET #94875 at* $\rho = 0.65$. *The* GENE *plot shows the electron heat flux* k_y *spectrum in a logx plot, with only an insignificant contribution from electron scales. The GKV plots show ion and electron heat flux from a simulation scan with increasing maximum* $k_y\rho_s$*, and no significant added contribution from electron scales even in the multi-scale (green) case. Numerical grid parameters are embedded in the left plot*

Conclusions

Previous predictions of the ETG impact in the JET hybrid scenario, leading to anti-GyroBohm isotope scaling, are reproduced with QuaLiKiz 2.6.1. However, this effect is much diminished when using the more accurate QuaLiKiz 2.8.1 with an improved collision operator and increased sub-dominant TEM. Nonlinear GENE simulations validated ion-scale QuaLiKiz 2.8.1 predictions at power-balance fluxes. When pushing system to a regime where strong ETG is expected, multi-scale GENE and GKV simulations did not predict significant ETG fluxes. This motivates a reexamination of the QuaLiKiz ETG saturation rule.

The expected role of ETG in the JET hybrid scenario is diminished following this analysis. However, we cannot rule out the importance of ETG at more inner radii $\rho < 0.4$ where QuaLiKiz 2.8.1 still predicts ETG, and high electron stiffness was previously reported [13]. However, NL GK multi-scale analysis hampered by dominant EM effects in that region [14]. Furthermore, we cannot rule out the importance of ETG in higher T_i/T_e scenarios.

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