GA–A27861

IMPROVED ITER PERFORMANCE MODELING VIA ZONAL-FLOW STABILIZATION

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GENERAL ATOMICS

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This is a preprint of a paper to be presented at the Forty-First European Physical Society Conf. on Plasma Physics, June 23–27, 2014 in Berlin, Germany and to be published in the *Proceedings.*

*Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA.

Work supported by
the U.S. Department of Energy under
DE-FG02-95ER54309 and DE-AC05-00OR22725

GENERAL ATOMICS PROJECT 03726
JULY 2014

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Improved ITER performance modeling via zonal-flow stabilization

J. Candy[1], R. Budny[2], G. Staebler[1], E. Belli[1]

[1]*General Atomics, San Diego, California, USA*

[2]*Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA*

In this work, we show that improvements in predicted ITER performance may be realized by accounting for stabilization from self-generated zonal flows. Prior transport modeling [1] has shown that acceptable ITER confinement requires core ion/electron energy fluxes to be on the order of a single gyroBohm; that is, $Q_e/Q_{\rm GB}, Q_i/Q_{\rm GB} \simeq 1$, where $Q_{\rm GB} \doteq \rho_s^2 c_s/a$ is the gyroBohm energy flux, ρ_s is the ion-sound gyroradius, and a is the midplane minor radius of the last closed flux surface. This implies proximity to the linear threshold, and GYRO [2] simulations show that nonlinearly-generated zonal flows may reduce the steady-state flux – in comparison with TGLF [3] levels – in the core plasma where the safety factor is low enough to allow appreciable zonal flow activity [4]. This effect is expected to be more important for reactor-scale devices where turbulence stabilization via driven rotation is weaker than in present experiments. Indeed, we observe that for steady-state ITER profiles predicted by TGLF, GYRO simulations typically exhibit turbulence quenching at radii inside about $r/a = 0.6$. This observation suggests that accounting for zonal-flow stabilization (not presently treated in the TGLF model) may lead to improved ITER performance estimates.

All profile predictions herein are made using TGYRO [5], based on an ITER hybrid DT scenario with approximately 45 MW of auxiliary power, hollow q-profile, equal D/T fractions, and ^{4}He ash. Impurity ions (Ar, Be, W) and fast-ion populations are also retained in the most complete scenario definition, but we have established that neglect of these species during TGYRO simulation leads to only small errors in profile prediction. For this reason, we consider only three gyrokinetic ions (D, T, ^{4}He) in the subsequent modeling. In TGYRO, Alpha heating to electrons and ions, collisional exchange, and electron radiation are computed self-consistently. Neoclassical transport for all species is computed by NEO [6] without approximation. Using 8 TGYRO simulation radii (plus a point on the magnetic axis at which fluxes approach zero linearly), we compute steady-state temperature profiles as shown in Fig. 1. The total alpha (fusion) power for this case, inside $r/a = 0.8$, is 102 (510) MW. This prediction uses unmodified TGLF as the transport model, with no direct reference to GYRO simulations. In what follows we denote $z_i \doteq -(a/T_i)dT_i/dr$ and $z_e \doteq -(a/T_e)dT_e/dr$. At this point, we emphasize that gyrokinetic simulation of ITER is challenging because the turbulence is highly-intermittent – a consequence of the closeness to linear threshold. Fluxes do not reach clear statistical steady

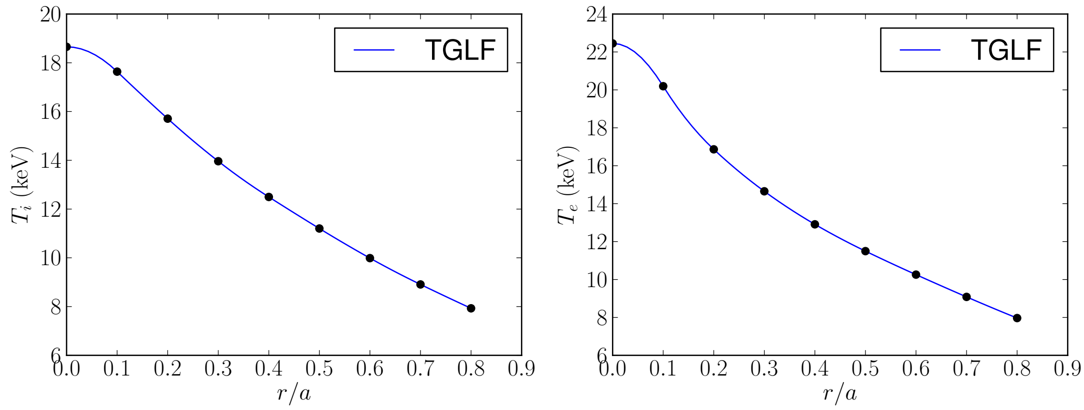

Figure 1: Baseline TGYRO-TGLF prediction of ITER profiles for hybrid DT scenario using current version of TGLF.

states even when simulation times are far in excess (say, 2000 a/c_s) of typical run times. This has the consequence of making profile prediction using direct gyrokinetic simulation highly impractical. Instead, our approach will be to carry out GYRO simulations and use the results to modify the TGLF calculation. So, we freeze the profiles shown in Fig. 1 and carry out flux-tube GYRO simulations at $r/a = 0.4$. For the GYRO simulations we use an $(L_r, L_\theta)/\rho_s = (96, 96)$ domain with 12 toroidal Fourier modes (resolving up to $k_\theta \rho_s = 0.72$) and 100 radial gridpoint (resolving up to $k_r \rho_s = 1.6$). Because of the relatively high plasma beta, we treat full electromagnetic fluctuations (both transverse and compressional). The results shown in Fig. 2a, carried out at $r/a = 0.4$ and for the nominal TGLF gradients, indicate that toward the end of the simulation the transport relaxes to a quasi-steady-state level well below the TGLF values. Even for the increased gradients (also shown in Fig. 2) the transport levels remain intermittent even as the gradients are increased by 20% to $(z_i, z_e) = (1.356, 1.471)$ as shown in Fig. 2c. Thus, we estimate that below the latter gradient values, the TGLF transport levels should be reduced such that they vanish at the nominal gradients $(z_i, z_e) = (1.130, 1.226)$. Calling this approach TGLF-ZF, Fig. 3 illustrates the modest performance improvement achieved by applying TGLF-ZF at $r/a = 0.4$ only. The alpha power for this case increases by 4MW to 106MW. Based on the simulation results in Fig. 4, we can again construct a TGLF-ZF model at $r/a = 0.5$ by reducing TGLF transport levels such that they are reduced linearly below $(z_i, z_e) = (1.366, 1.442)$ and made to vanish at $(z_i, z_e) = (1.138, 1.110)$. TGYRO simulation with TGLF-ZF at $r/a = 0.4$ and 0.5 yields another 4MW gain in alpha power in comparison with TGLF-ZF at $r/a = 0.4$ only (see Fig. 5). The core temperatures are actually slightly lower for the this case, but the alpha power has increased slightly due to higher temperature in the range $(0.1 \leq r/a \leq 0.5)$. Finally, at $r/a = 0.6$ the effect of zonal-flow stabilization appears to be small enough that it can be ignored in TGLF. In summary, by modifying the TGLF model at the radii $r/a = 0.4$ and 0.5 to

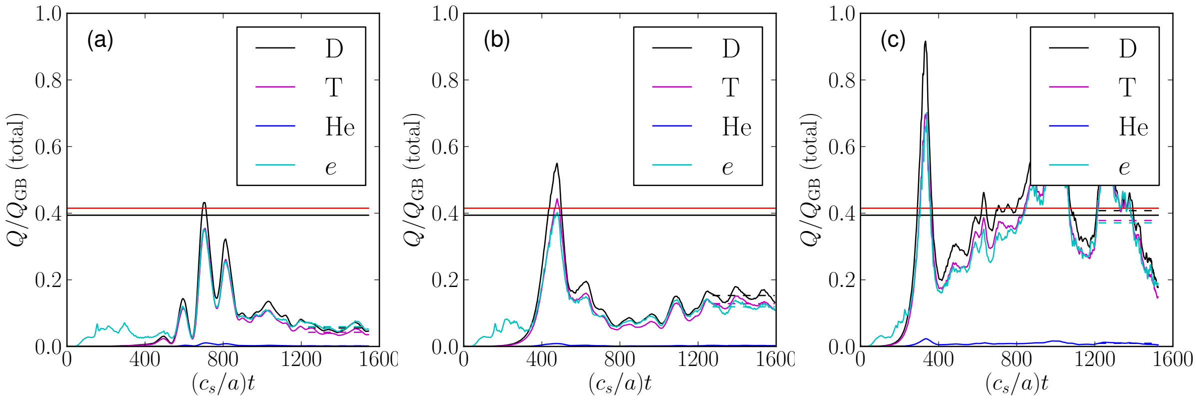

Figure 2: GYRO simulations at $r/a = 0.4$. Plot (a) shows simulation at nominal TGLF gradients $(z_i, z_e) = (1.130, 1.226)$, (b) at (1.243,1.349) and (c) at (1.356,1.471). Horizontal lines are nominal TGLF electron (red) and total ion (black) fluxes.

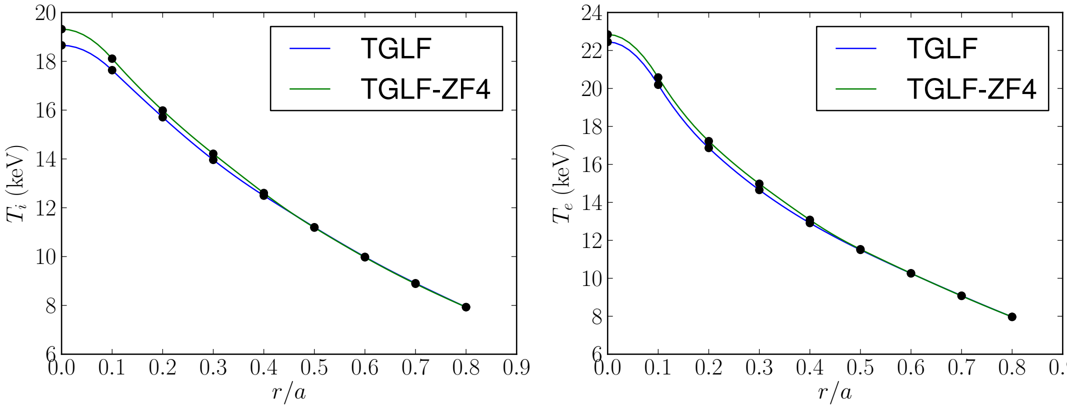

Figure 3: Profile modification using TGLF-ZF4 (i.e., zonal-flow effects added to TGLF at $r/a = 0.4$) compared with baseline TGLF prediction.

account for zonal flow stabilization, we have increased the core T_e by 0.2 keV and the core T_i by 0.6 keV, and the alpha power by 8 MW. Applying the zonal flow stabilization mechanism deeper inside the core is likely to lead to additional improvements, but we have not yet attempted to quantify this. We also remark that the hybrid case studied in this work had relatively low current and high q. Because the stabilization effect is stronger at lower q, performance improvements for the baseline ITER case are potentially even greater.

Work supported by the U.S. Department of Energy under Grant No. DE-FG03-95ER54309.

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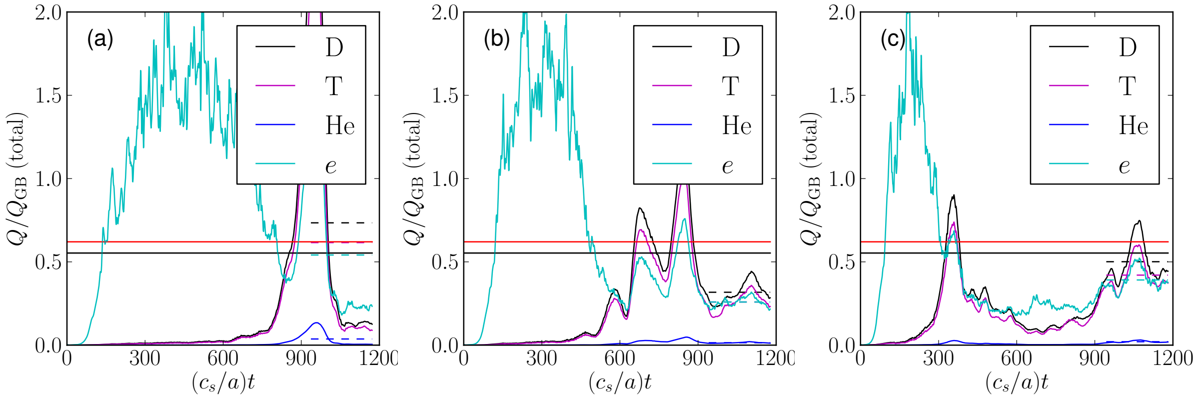

Figure 4: GYRO simulations at $r/a = 0.5$. Plot (a) shows simulation at nominal TGLF gradients $(z_i, z_e) = (1.138, 1.110)$, (b) at (1.252,1.221) and (c) at (1.366,1.442). Horizontal lines are nominal TGLF electron (red) and total ion (black) fluxes.

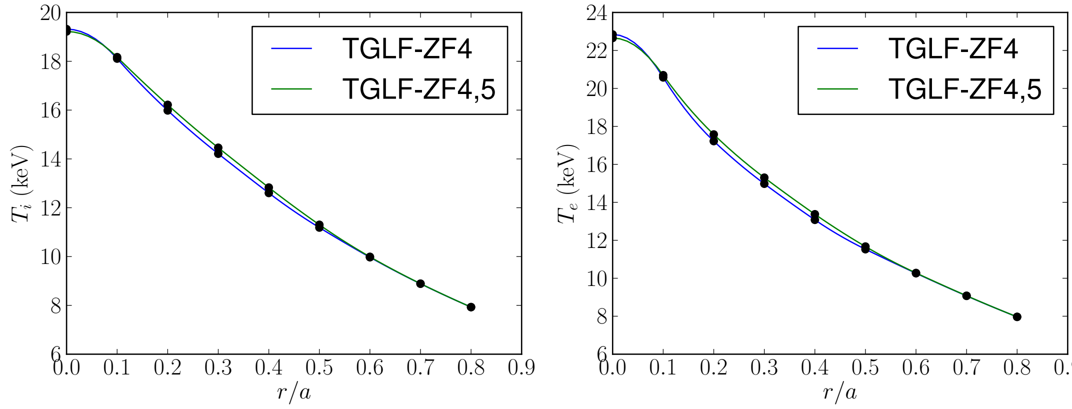

Figure 5: Improvement in performance using ZF-TGLF at $r = 0.4$ and $r = 0.5$ compared with $r = 0.4$ only.

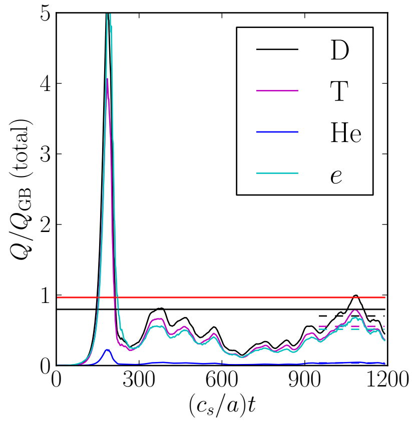

Figure 6: GYRO simulation at $r/a = 0.6$ showing turbulence level comparable to the TGLF result.