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TRANSP tests of TGLF and predictions for ITER

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1. Introduction. Gyro kinetic simulations of turbulence capture some of the features observed in transport, fluctuations, and correlations measured in tokamak plasmas. These codes calculations are CPU intensive, and are not practical for incorporation in present time-dependant transport codes, so reduced models based on these gyro kinetic codes are being used. An example is the TGLF model [1] which is a quasilinear gyrofluid model calibrated to nonlinear results from the GYRO code [2]. Recently TGLF has been incorporated into TRANSP [3].

Analysis of experimental data using TRANSP with such models provides fundamental understanding of turbulent transport. Predictions of ITER performance with various plasma scenarios using such models are useful for optimizing design and for exposing issues that can be addressed in present experiments and theory. For instance, which combinations of heating, torquing, and current drive are optimal. Another application is for nuclear licensing (e.g. system integrity, neutron rates). Others are generating inputs for design of diagnostic systems and for theoretical studies. An example of the later is Alfvén Eigenmode and AE-induced loss of fast ions. The beam ion distribution can either enhance or reduce the alpha pressure drive of the AE instability. The AE instability can cause dangerous amounts of fast ion losses, as was seen in TFTR.

The TRANSP code is being used for self-consistent predictive modeling for ITER [4-6]. The time evolution of profiles of temperatures and toroidal rotation ω_ϕ have been predicted assuming boundary values using the GLF23 model [7]. Time-dependent simulations are needed to study efficient startup, safe shutdown, and transients such as magnetic diffusion, sawteeth, and ash accumulation.

A new solver PT-SOLVER has been added to TRANSP for stiff transport models. It incorporates TGLF, which includes more physics than does GLF23, but which is much more challenging numerically. Benchmarking and testing of this solver have been reported [3]. Recently this solver is being used to predict densities, temperatures, and angular momentum. For predicting ITER prior to experimental results all of the fields need to be predicted. Here new results verifying, validating, and predicting using PT-SOLVER are presented.

2. PT-SOLVER. The new solver is modular, parallel, and multi-regional. PT-SOLVER integrates the highly nonlinear time-dependent equations for ion and electron temperatures, densities, and toroidal angular momentum with implicit Newton iteration methods. The user controls the choice of transport models attached to the solver, with a range of neoclassical and/or turbulent, or semi-empirical or data driven choices available. Besides TGLF, GLF23, and MMM [8], the neoclassical models NEO [9]and Chang-Hinton are included.

Two options are available in TGLF for accounting for the turbulence mitigation form E×B flow shearing. One is the "quench rule" which compares the local magnitudes of the maximum growth and E×B flow shearing rates. The other is a new "spectral shift" rule [10]. E×B flow shearing rate induced by the NB torques is calculated by TRANSP using the self-consistent pressure and magnetic fields. Comparable predictions result from either.

3. Verification. To asses if TGLF is correctly installed in PT-SOLVER, it is being verified by comparing with the TGLF implementations in the XPTOR and TGYRO codes. Since the numerical schemes are different in these codes, XPTOR and TGYRO modes have been built in PT-SOLVER for comparisons. The PT-SOLVER standalone runs are performed on 64 processors and take about 10-40 hours for numerically accurate solutions. The three codes give predictions for temperatures in approximate agreement.

4. Validation. To asses if TGLF in PT-SOLVER is a plausible candidate for ITER predictions, it is being tested by comparing with experimental results. Several issues make comparisons challenging. Accurate measurements are needed, including profiles of n_e, impurity and fast ion densities, T_i, v_{tor}, Z_{eff}, P_{rad}, and $P_{CX-loss}$. These are important for deducing profiles of the energy, angular momentum, and species flows. Plasma conditions with minimal effects on transport from MHD and anomalous fast ion losses are needed since these effects are not included in the transport modeling. PT-SOLVER with TGLF can predict n_e using measured Z_{eff} but the particle source rates are needed. Uncertainties in the particle source rates affect the simulations. Core fueling profiles from NB are calculated by NUBEAM in TRANSP. Wall fueling profiles from gas puffing and recycling are calculated by FRANTIC in TRANSP. The in-flows through the boundary can be estimated from H_α data [11]. Since there are large uncertainties in the in-flows, here they are scaled in PT-SOLVER to produce the measured average densities.

Another uncertainty is transport near the magnetic axis. Many plasmas of interest for ITER have sawteeth. An interchange instability criterion is computed in TGLF and the model is not valid for radii within the flux surface of the instability. A method is needed to match the heat flows or transport coefficients at this boundary. Otherwise unphysical kinks are predicted for profiles of temperatures, densities, and the energy, momentum, and particle flows through the instability region. Here this is accomplished by scaling the neoclassical predictions of NEO in the core.

Results presented here use three kinetic species: electrons, bulk D ions, and a second species averaging impurity, beam, and minority ions. Runs with more than three kinetic species have been performed, and results will be reported elsewhere. Comparisons of simulated and TRANSP-mapped measured profiles for a JET hybrid shot [12] with good confinement are shown in FIG. 1. Comparisons of simulated and TRANSP-mapped measured profiles for a JET H-mode shot with high I_p [13] are shown in FIG. 2. Approximate agreement for n_e, T_e, T_i, and ω_{tor} are found in the regions between the interchange instability and assumed boundaries. These agreements motivate using the same methods for predicting ITER performance.

5. Predictions for ITER. The ITER predictions are performed using a boundary at either x (square-root of normalized toroidal flux) = 0.8 for comparison with results from previous TRANSP-GLF23 predictions (used as the initial conditions in PT-SOLVER), or at x=0.9 or 0.94 (to test the capability of predictions over a larger range). The TGLF momentum predictions are not valid past the pedestal due to the high rotation ordering that neglects diamagnetic flows which are critical for the formation of the H-mode barrier region. The TRANSP-GLF23 predictions assumed a flat n_e profile and angular momentum derived from the beam torque using $\chi_\phi = 0.5\chi_i$. Pedestal values of T_e, T_i, and ω_{tor} at the boundary were assumed. There are considerable uncertainties for these pedestal values in ITER.

Results for an ITER hybrid are shown in FIG. 3 and an H-mode in FIG. 4 [6]. The TGLF-predicted T_e, T_i, and ω_{tor} are low compared with the previous TRANSP-GLF23 results. The larger difference between GLF23 and TGLF found here compared with in previous simulations without momentum transport is due to the stronger toroidal velocity shear in the GLF23 case with momentum transport. The values of the Prandtl number χ_ϕ / χ_i from the TGLF validations and predictions are relatively low. The TGLF-predicted n_e is affected by adjusting the wall rate profiles. Slight peaking is predicted. Increases of n_e as the wall source rate increases correlate with reduces in T_e, T_i, and ω_{tor}. The heating and torquing profiles change as T_e, T_i, and ω_{tor} profiles change. These are not computed by PT-SOLVER in standalone mode. Time-dependent TRANSP runs update the heating and torquing profiles self-consistently. These are being performed.

6. Prospects. The approximate agreement predicting n_e, T_e, T_i, and v_{tor} (but over a limited range) suggests that TGLF can offer insights into the nature of the turbulent transport, such as which modes dominate the flows. Software for visualizing these results is being implemented. Runs with more kinetic species will elucidate details of particle pinches. TGLF running in TRANSP will be able to provide self-consistent time-dependent, physics-based predictions for ITER and beyond. More development is needed to make TGLF in TRANSP production ready.

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*See appendix of F.Romanelli et al., Proceedings of the 24^{rd} IAEA Fusion Energy Conference 2012, San Diego

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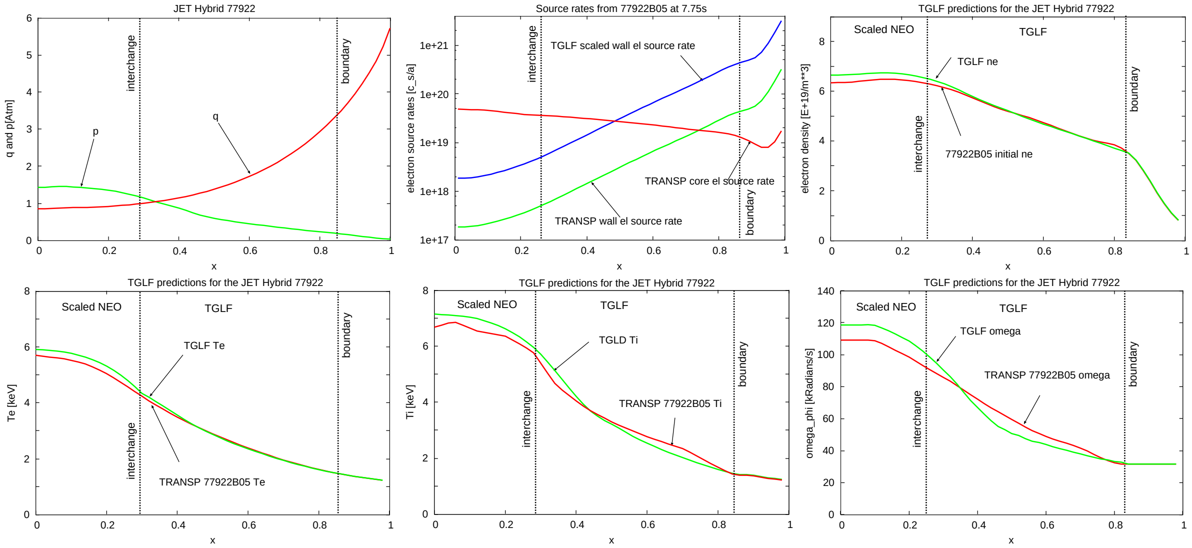

FIG. 1: Simulation of the JET Hybrid 77922 with P_{NB} = 17MW, I_p = rampdown from 2.5 to 1.7MA, B_{tor} = 2.4T, and high confinement at 7.75s. The outer boundary for the PT-Solver simulation is set at x=0.84. The inner boundary is the start of the interchange instability. TGLF is not valid further inboard. The wall source and beam source rates from a TRANSP analysis run are shown in the top middle panel. The wall source needed to be scaled up by a factor of 10.0 to predict n_e in approximate agreement with the high resolution Thomson measurement. The predicted and measured T_e, T_i, and ω_{tor} profiles are shown in the lower panels. in the core.

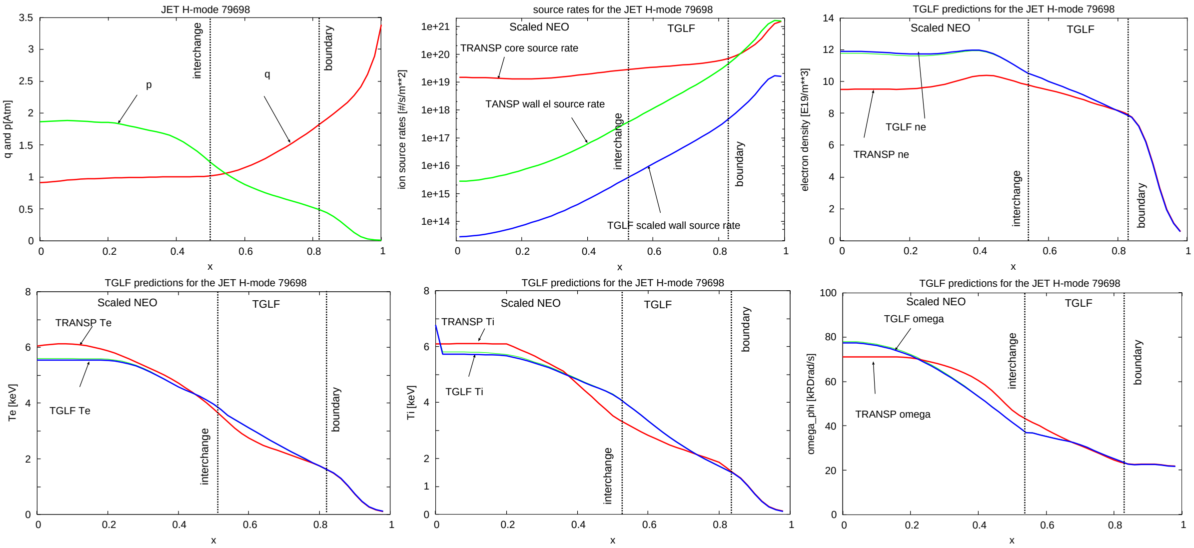

FIG. 2: Simulation of the JET H-mode 79698 with $P_{NB} = 23$MW, $P_{IC} = 3$MW, $I_p = 4.5$MA (nearly the highest), B_{tor} = 3.7T, and Greenwald fraction = 0.56 at 12.4s. The wall source profile needed to be scaled down from the TRANSP analysis run to a negligible value (here by a factor of 0.01) to approximate the average n_e. NEO predictions for $\chi_{e,nc}$, $\chi_{i,nc}$, and $\chi_{v,nc}$ are scaled up 150, 10, and 40 in the core. The large radius of the interchange instability leaves a small region where TGLF alone is tested.

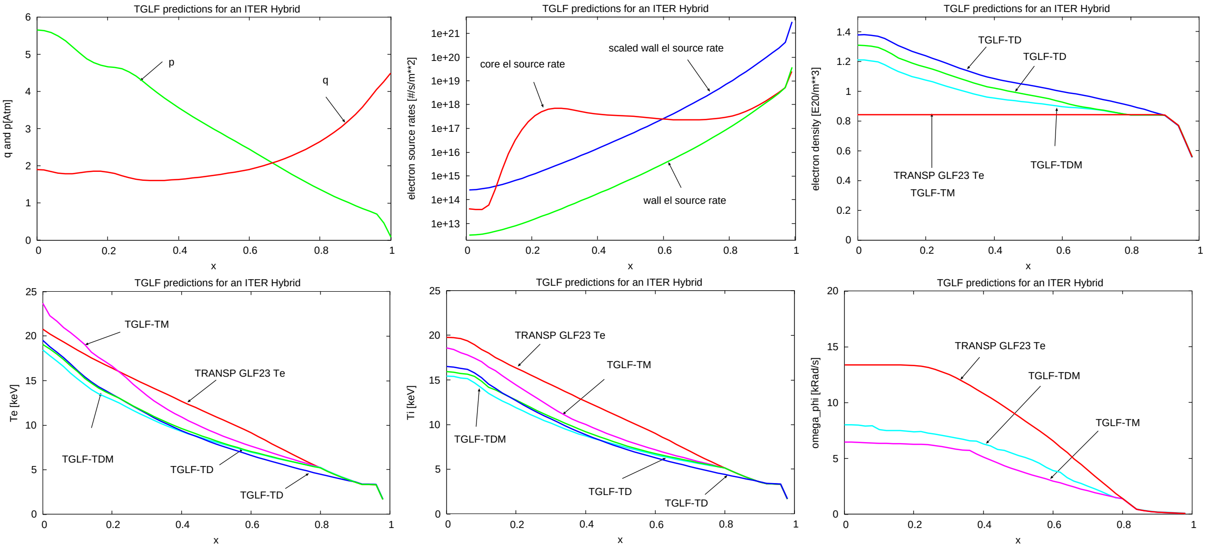

FIG. 3: Simulation of an ITER Hybrid with P_{NNBI}=33MW, P_{IC}=10MW, P_{EC}=7MW, Q_{DT}=9.4, I_p=12MA, B_{tor}=5.6T, and Greenwald fraction = 0.87 at 295s. The PT-SOLVER boundary was set at x=0.8 (for comparison with the TRANSP-GLF23 prediction 20102A06), and at x=0.9. The TRANSP-GLF23 prediction assumed a flat n_e and computed ω_{tor} from the NNB torque and $\chi_\phi = 0.5\chi_i$, which are shown for comparison. TGLF predictions for T_e, T_i, and n_e are labeled TGLF-TD; for T_e, T_i, and ω_{tor} are labeled TGLF-TM; and for T_e, T_i, n_e and ω_{tor} are labeled TGLF-TDM. The TGLF-predicted T_e, T_i and ω_{tor} are below the TRANSP-GLF23 predictions and decrease as the boundary is shifted outward. The TGLF-predicted n_e is more peaked that the flat profile assumed for the TRANSP-GLF23 predictions.

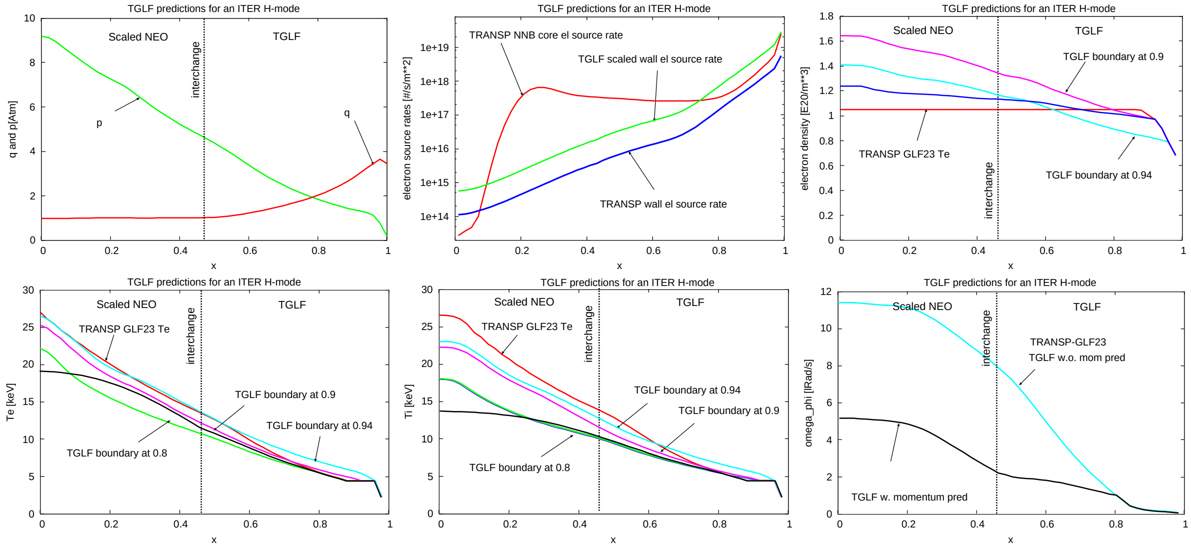

FIG. 4: Simulation of an ITER H-mode with P_{NNBI}=33MW, P_{IC}=17MW, Q_{DT}=9.4, I_p=15MA, B_{tor}=5.6T, and Greenwald fraction = 0.85 at 245s [6]. Kadomtsev-like sawteeth mixing was assumed with period 10s. These assumptions predict a very large sawtooth inversion radius. Results from a scan in the outer boundary is shown. TGLF runs with the boundary at x=0.8 were performed with and without momentum prediction. The TGLF T_e, T_i, and ω_{tor} are below the TRANSP-GLF23 prediction, and n_e is more peaked.

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