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Tests of Tokamak Transport Models

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1. Introduction

Predictions of tokamak reactors based on validated 1-D transport models would provide: 1) a physical foundation for extrapolations of energy confinement scalings to the reactor regime, 2) a means for optimizing the tokamak design and operational scenarios, 3) profiles required for MHD stability analyses, 4) clarification of the outstanding confinement issues which should be addressed in current tokamak confinement research programs.

Many transport models have been partially tested against tokamak data [1]. In order to establish how well each model represents the wide range of existing tokamak data we have developed the ITER Profile Database [2] which contains fully analyzed profile data, readily accessible, specified in a standardized manner, from many tokamaks and covering a variety of confinement modes. Presently 209 discharges from 12 tokamaks are available, including series of discharges over which various parameters were individually varied: scans over current, shaping, isotope (H/D and D/T), ρ , ν and β . Energy and particle sources are given as a function of radius and time to allow detailed transport analysis. By defining each transport model in a standard form, using the same variables as defined in the Profile Database, and using transport codes which are also written in a standardized form and benchmarked against each other, it is possible to carry out reliable and verifiable testing of transport models. Since the 1996 IAEA meeting [3] the database has expanded by 50%, and we have benchmarked three 'standard' simulation codes.

Standardized 'figures of merit' have been defined [2] to quantify model performance. Predictions are compared to electron temperatures in a standard dataset of 75 L- and H-mode discharges from C-mod, DIII-D, JET, JT-60U, T10, and TFTR. A subset of 55 discharges which have measured ion temperatures were used in the comparisons with incremental stored thermal energy, W_{inc}, and with the ion temperature profiles. All models were tested with benchmarked 'standard' codes except the Weiland-Nordman, IFS/PPPL with **ExB**, T11/SET, and CPTM; these models have only been used to simulate about half as many discharges.

All of the models were developed without direct reference to data in the ITER Profile Database (but there is some overlap between discharges in the database and those used to calibrate some models). We found that some models tended to systematically over- or under-predict the temperatures, and their performance could be significantly improved by renormalization. For example, after recalibration the GLF23 model achieved a reduction in the mean square deviation of W_{inc} (on a 46 discharge subset) from 43% to 32% (the original model is shown in the Figures). Both the magnitude of χ (the stiffness) and the **ExB** stabilization were reduced by 50% to achieve this improved fit; the first change improves predicted reactor performance, while the latter has little effect on it[8]. Finally, renormalization of the CDBM model could clearly improve its performance.

It is important to test models of the stabilizing effect of sheared flows because some tokamaks (DIII-D and JET) have uni-directional neutral beam injection, and this may lead to an improvement in confinement which may not be available in reactors. We have used the IFS/PPPL model (with and without **ExB**) to estimate that the size of this effect for DIII-D and JET is typically 10-30% (see also Ref. [8]). However, the flow shear corrections in the IFS/PPPL **ExB** model frequently (but not always) appear to be too strong (this was also noted above in the recalibration of the GLF23 model), and study of this issue continues.

2. Tests Of Transport Models

There are currently several transport models which are successful in reproducing core temperature profiles. Our figure of merit is the incremental thermal stored energy, W_{inc}, which is the energy above the 'pedestal' energy (see [2] for details); this takes no credit for the pedestal energy which is input to the simulations through the temperature boundary condition at ρ=0.9a . Figure 1 shows the root mean square error in predicting W_{inc}.

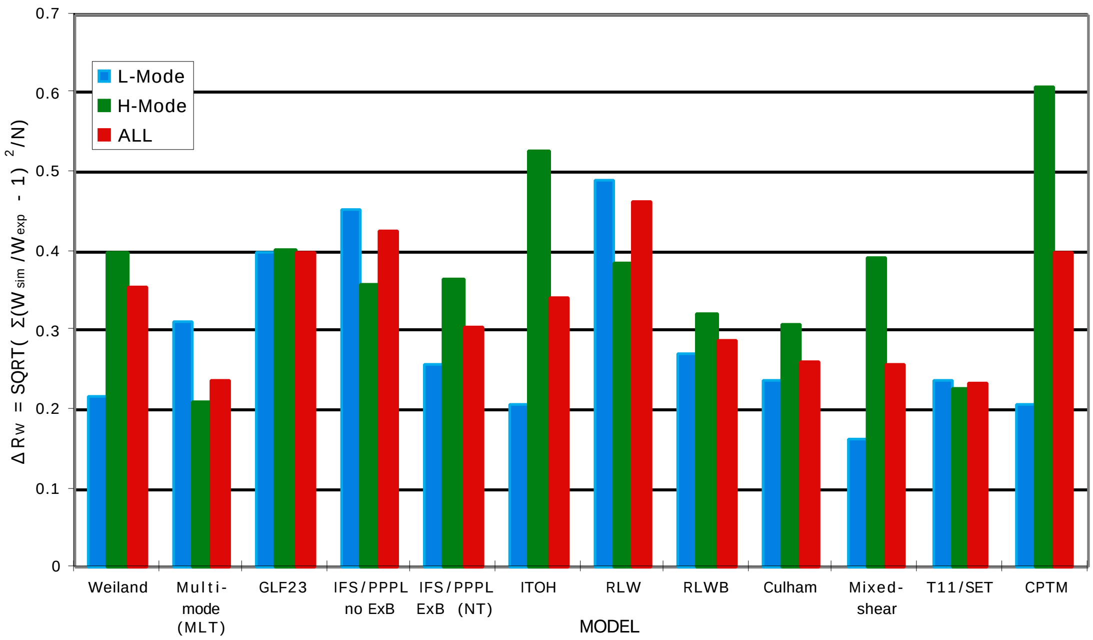

Figure 1: RMS of error in incremental stored energy, W_{inc}, simulated by the 12 transport models for the subset of 55 discharges which have measured ion temperature.

The L-mode results exhibit more variation from model to model, with the best models being Mixed-shear [4] and Current Diffusive Ballooning Mode (Itoh in Fig. 1) [5]. For reactors the H-mode is of more interest, and the best simulations are given by Multi-mode [6] and T11/SET [7] (not from a 'standard' code). We note that, as a class, the 'theory based' models (Weiland through Itoh in the figure) are not notably more successful that the 'empirical' models, and that the models which best simulate the L- and H-modes are drawn from both categories.

It may seem surprising that models which are based on the same physical process (e.g., ion temperature gradient modes) should give results as dissimilar as models which are based on entirely different processes. However, a detailed examination reveals that models which appear to be closely related approach the problem from very different theoretical directions, and even the most closely related models treat some 'details' differently [8]. No pair of the four models based on ion temperature gradient turbulence (Weiland, Multi-mode, GLF23, and IFS/PPPL) exhibit any clear correlation between their goodness of fit. However, predictions of some physically unrelated models (e.g., Culham and Multi-mode) do exhibit a rough correlation, but this may simply reflect their mutual success in simulating these discharges since model predictions which closely resemble the data are likely to closely resemble each other.

We have looked for correlations between goodness of fit and many physics parameters, including η_i, η_e, ρ , ν , T_i/T_e, R/L_n, R/L_{Te}, R/L_{Ti}, β, β/β_n, q, magnetic shear, v_φ/c_s, Z_{eff}, elongation, triangularity, $n_{eo}/\bar{n}_e$, n_e, P_b, I_p, and B_{tor}. In most cases there is no correlation, indicating that the models' predictions do not depart from measurements in a systematic way as the parameter in question varies. Prominent exceptions are the correlations between goodness of fit and ρ for several models, and some weaker correlations with β (or β/β_n, which is correlated with β over much of the data set). Figure 2 shows the Multi-mode model's ratio of predicted to measured W_{inc} as a function of ρ at mid-radius. Different results from fully predictive simulations [6] is likely due to differences in the neutral beam deposition, density and Z_{eff} profiiles.

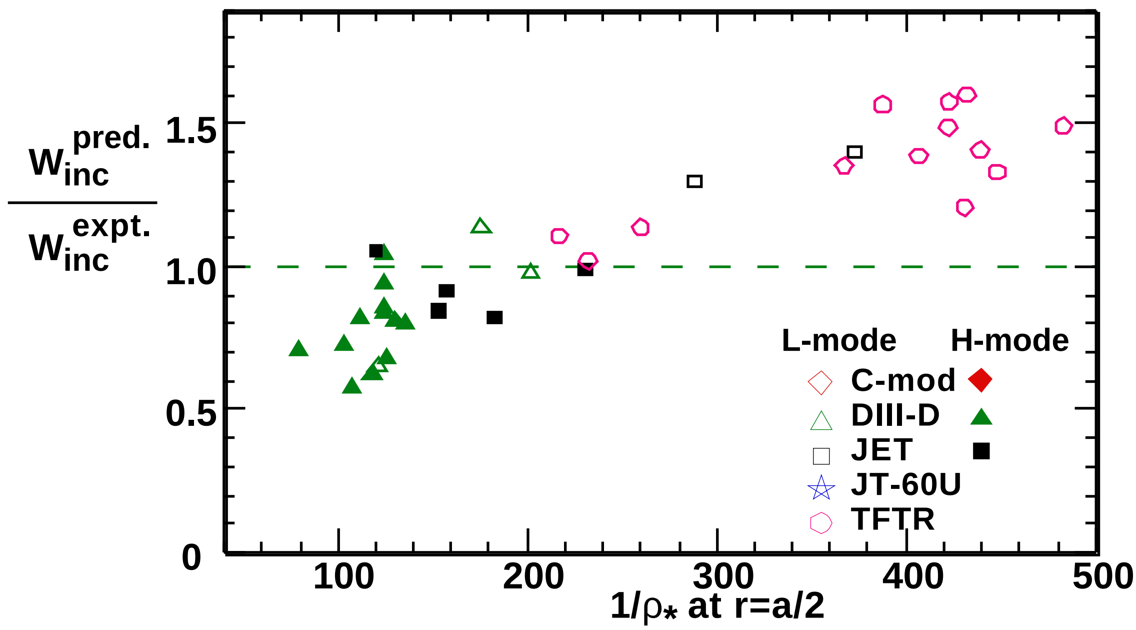

Figure 2: Multi-mode model: ratio of predicted to measured W_{inc} vs. ρ at mid-radius.

A correlation seems self-evident, but the discharge dataset is incomplete in important ways and has hidden correlations; as a result, the true cause may have nothing to do with the 'dependence on ρ ' of the model. Firstly, note that the limited ρ range of H-mode discharges alone does not support a strong correlation with ρ ; thus, there is no indication of incorrect ρ behaviour in the H-mode regime which is important to reactors. Secondly, while there is no evidence of machine to machine variability in the region of overlapping ρ , the bulk of the trend arises from simulations of a single tokamak, TFTR. Additional JET and JT-60U discharges with medium to low ρ are being sought to strengthen the dataset.

As shown in Fig. 3, the IFS/PPPL model's goodness of fit is not correlated with the degree to which measured ion temperature gradient scale lengths venture beyond the model's stability threshold for ITG turbulence. The figure also reflects the model's prediction that many discharges should lie well inside the unstable region.

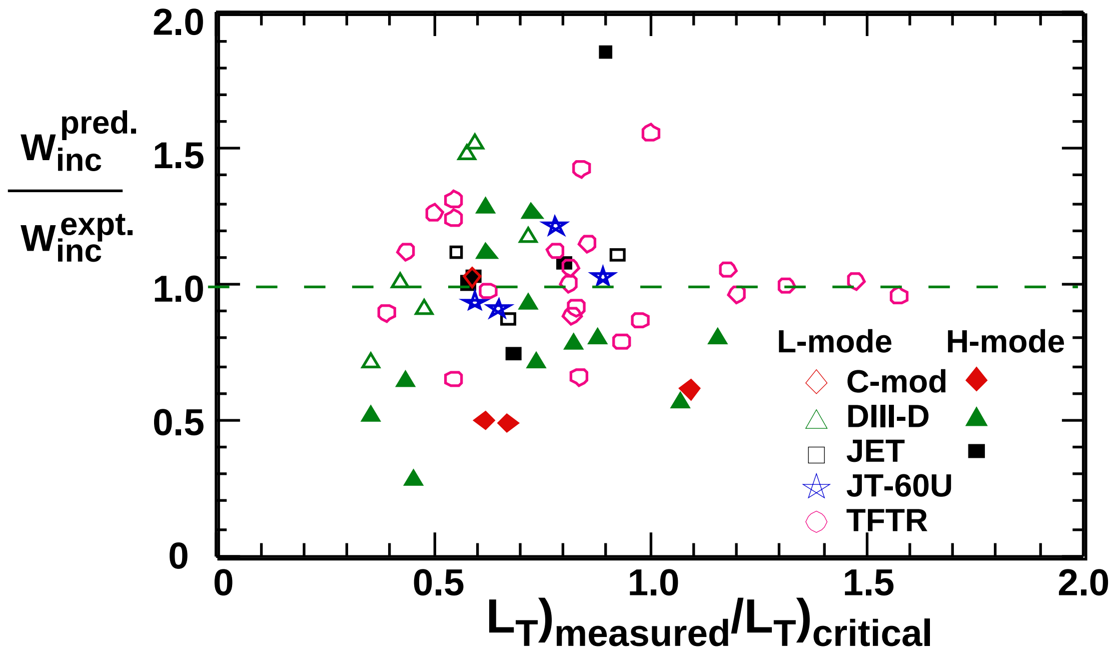

Figure 3: IFS/PPPL model: ratio of predicted to measured W_{inc} vs. ratio of measured and critical ion temperature gradient scale lengths at mid-radius.

3. Summary

Our work has identified several avenues for further research which may differentiate the currently successful transport models. We hope to discriminate between models with perturbative and transient experiments to test the "stiffness" of ion temperature profiles, tests of the effect of plasma elongation on thermal diffusivity, and close examination of controlled scans (of, e.g., ρ and T_{ped}). Characterization and testing of models for the effect of velocity shear on transport coefficients are also required. Finally, validated theoretical models for the edge pedestal, important for stiff transport models, are required for complete predictions of performance.

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