TESTS OF 1-D TRANSPORT MODELS, AND THEIR PREDICTIONS FOR ITER

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Abstract

A number of proposed tokamak thermal transport models are tested by comparing their predictions with measurements from several tokamaks. The necessary data have been provided for a total of 75 discharges from C-mod, DIII-D, JET, JT-60U, T10, and TFTR. A standard prediction methodology has been developed, and three codes have been benchmarked; these 'standard' codes have been relied on for testing most of the transport models. While a wide range of physical transport processes has been tested, no single model has emerged as clearly superior to all competitors for simulating H-mode discharges. In order to winnow the field, further tests of the effect of sheared flows and of the 'stiffness' of transport are planned. Several of the models have been used to predict ITER performance, with widely varying results. With some transport models ITER's predicted fusion power depends strongly on the 'pedestal' temperature, but ~ 1GW (Q=10) is predicted for most models if the pedestal temperature is at least 4 keV.

1. INTRODUCTION

Predictions of ITER based on validated 1-D transport models would provide: 1) a physical foundation for extrapolations of energy confinement scalings to the ITER 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 last IAEA meeting [3] the database has expanded by 50%, and we have benchmarked three 'standard' simulation codes.

Standardized 'figures of merit' have been defined [3] to quantify each model's 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 as the others.

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 . The root mean square error in predicting W_{inc} is shown in Figure 1 for each model.

The L-mode results exhibit more variation from model to model, with the best models being Mixed-shear [4] and Weiland-Nordman [5]. For ITER the H-mode is of primary interest, and the best simulations are given by Multi-mode [6] and T11/SET [7], but the T11/SET simulations are not made with a 'standard' code. We note that, as a class, the 'theory based' models (Weiland through IFS/PPPL in the figures) 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.

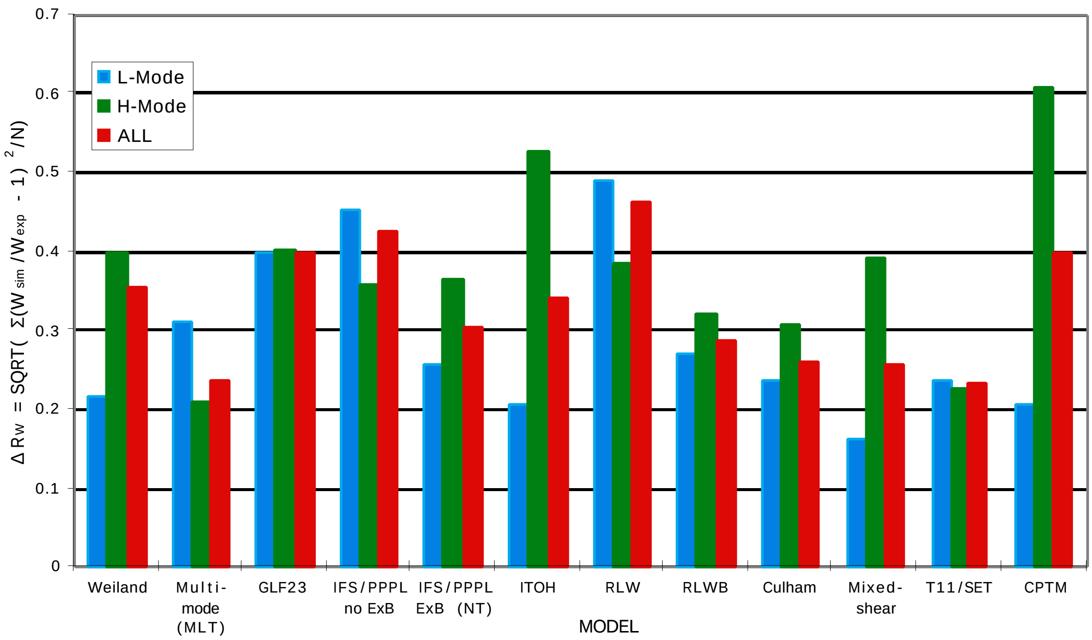

Figure 1: RMS of error in incremental stored energy, W_{inc}, simulated by the 12 transport models for the subset of 55 discharges which have measured ion temperature.

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, close examination of these models reveals that superficially related models sometimes approach the problem from very different theoretical directions, and even the most closely related models treat some 'details' differently [8].

We have looked for correlations between goodness of fit and many parameters, including ρ , ν , β $Z_{eff,}$ elongation, $I_{p,}$ 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. 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] are thought to be due to differences in the density and Z_{eff} profiles.

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 ρ 'dependence' 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 ITER. Secondly, while there is no evidence of

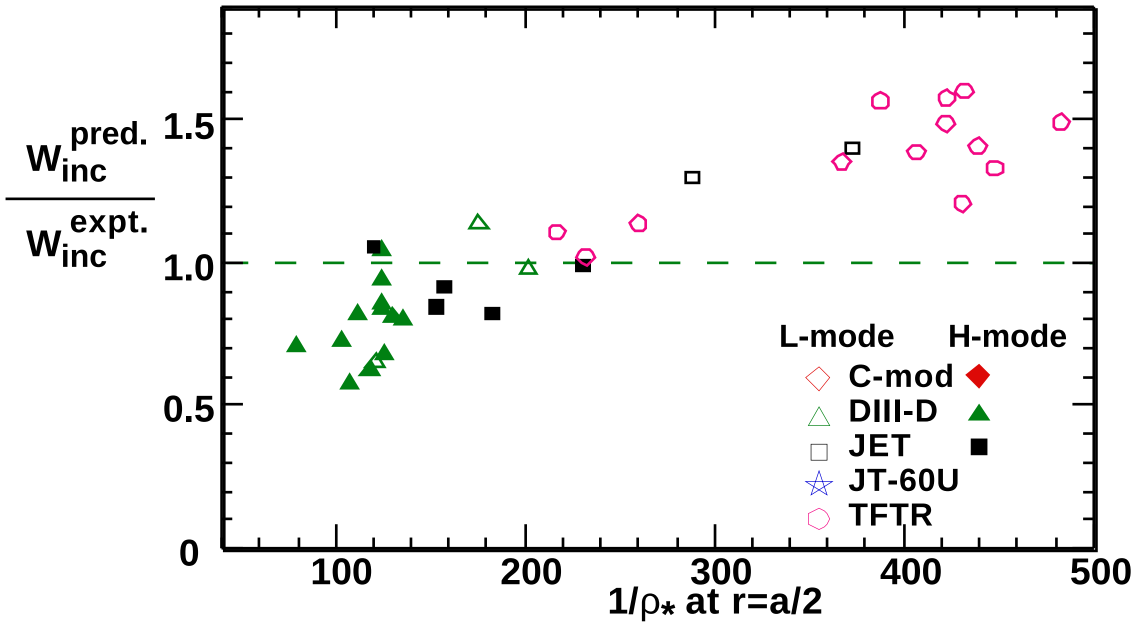

Figure 2: Ratio of predicted to measured W_{inc} as a function of ρ at mid-radius for Multi-mode.

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. Other limitations of the standard dataset are apparent in Fig. 3, which shows the experimental β and ρ at mid-radius. H-mode discharges produce most of the β variation; thus, apparent correlations with β arise from simulations of these discharges. There are no low β H-modes and, as noted above, H-modes are nearly absent with medium to relative small ρ (we expect to add discharges in this region).

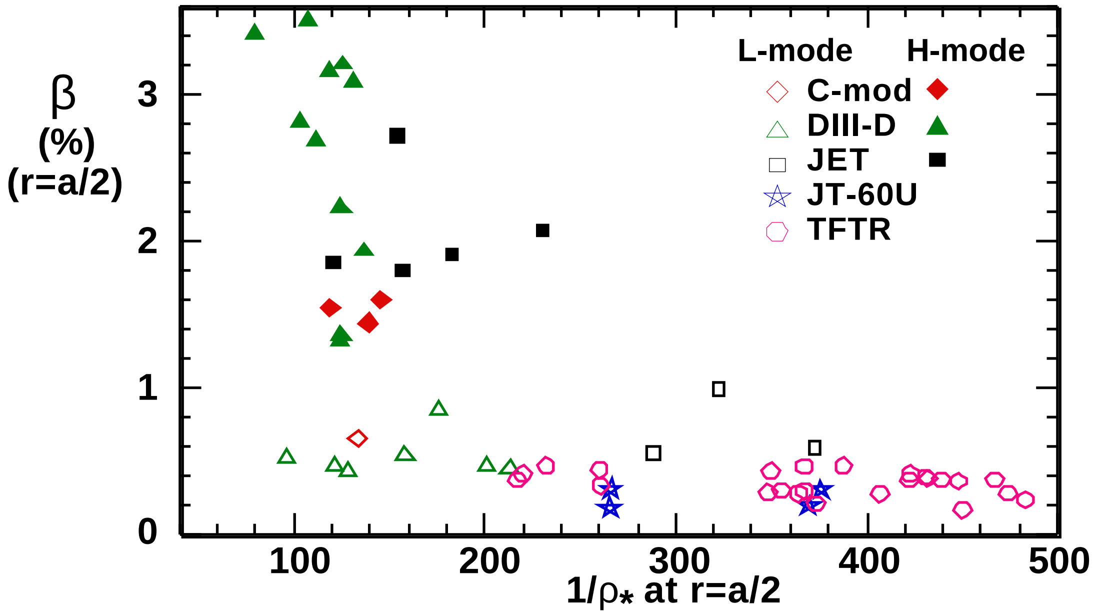

Figure 3: Thermal toroidal β vs. ρ at mid-radius for the standard dataset.

All of the models were developed without direct reference to the ITER Profile Database (but there is some overlap between the discharges in the database and those used to calibrate some models). We noted that some models tended to systematically over- or under-predict the temperatures, and their performance could be significantly improved by renormalization. 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 ITER 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 to ITER. 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%. However, the flow shear corrections in the IFS/PPPL **ExB** model frequently appear to be too strong (also noted above in the recalibration of the GLF23 model), and study of this issue continues.

3. ITER SIMULATIONS

To compare various models' predictions for ITER under uniform conditions, prescribed density and current profiles and boundary conditions were used. The boundary temperature plays an important role in some stiff models so it was varied from 1 to 5 keV**.** Not surprisingly, the range of predicted fusion power is large: about of factor of 6 between extremes. The Multi-mode model predictions are insensitive to pedestal temperature and are very close to the reference fusion power found independently using global scaling expressions for energy confinement time prediction. The models based on a gyro-fluid numerical simulation of electrostatic turbulence [8] are quite sensitive to the assumed edge temperature, and occupy the lower range of fusion power. Under simplified modeling assumptions (fixed τ^*_{He}/τ_E, density and auxiliary heating power) and despite the wide disparity between models, an edge temperature of 4 keV ensured at least 1.0 GW (Q = 10) from most models in these standard runs. An edge temperature up to 5 keV ensured 1.5 GW (Q = 15).

4. 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). 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 ITER performance predictions.

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