AND THEIR PREDICTIONS FOR ITER

D. R. MIKKELSEN[1], G. BATEMAN[2], D. BOUCHER[3], J. W. CONNOR[4],
YU. N. DNESTROVSKIJ[5], W. DORLAND[6], A. FUKUYAMA[7], M. J. GREENWALD[8],
W.A. HOULBERG[9], S.M. KAYE[1], J. E. KINSEY[10], A. H KRITZ[2], M. MARINUCCI[11],
Y. OGAWA[12], D. SCHISSEL[10], H. SHIRAI[13], P. M. STUBBERFIELD[14],
M. F. TURNER[4], G. VLAD[11], R. E. WALTZ[10], J. WEILAND[15]

1) PPPL, Princeton, USA
2) Lehigh University, Lehigh, USA
3) ITER San Diego JWS, USA
4) UKAEA, Culham, UK
5) Kurchatov Institute, Moscow, Russian Federation
6) U. Maryland, College Park, USA
7) Kyoto University, Kyoto, Japan
8) MIT, Cambridge, USA
9) ORNL, Oak Ridge, USA
10) GA, San Diego, USA
11) Associazione Euratom/ENEA sulla Fusione, Frascati, Italy
12) U. Tokyo, Tokyo, Japan
13) JAERI, Naka, Japan
14) JET, Abingdon, UK
15) Chalmers University of Technology, Göteborg, Sweden

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 have 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

We seek predictions of ITER based on validated 1-D transport models for several reasons. Firstly, to enhance our confidence in extrapolations of energy confinement to the ITER regime by providing a theoretical foundation. Secondly, transport models provide a means for optimizing the tokamak design and operational scenarios. Thirdly, predictions of profiles are required for MHD stability analyses. Lastly, the process of testing transport models and comparing their predictions for ITER clarifies the outstanding physics issues which should be addressed in current tokamak confinement research programs.

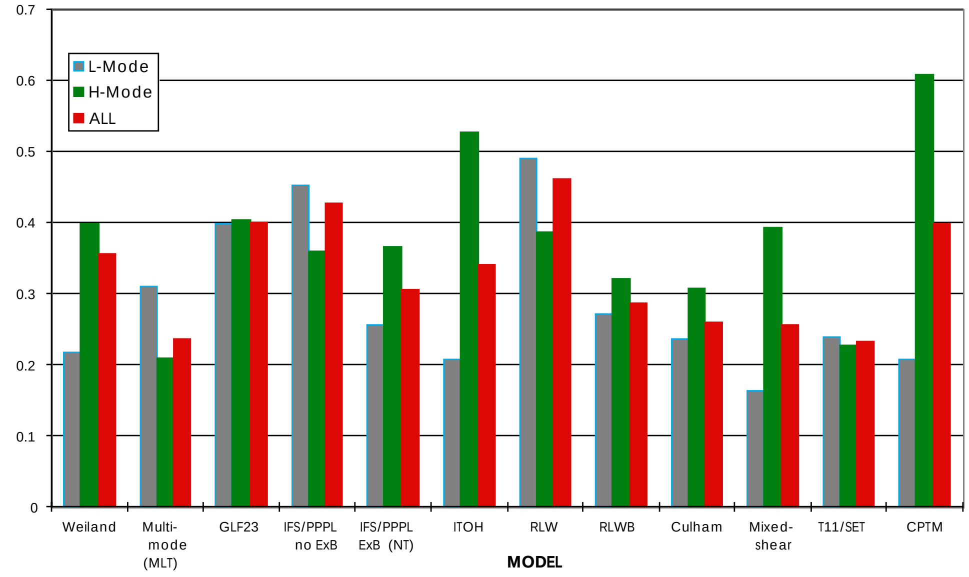
Historically, a range of transport models has been proposed and partially tested against various tokamaks [1]. Before predicting the performance of ITER, which is a considerable extrapolation from all existing devices, it is important to understand how well each model represents the wide range of existing tokamak data. This has led to the development of the ITER Profile Database [2] which contains fully analyzed profile data, readily accessible, specified in a standardized manner, from many are available, including series of discharges over which various parameters were individually varied: scans over current, shaping, isotope (H/D and D/T), $\rho*$,$\nu*$ 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 the database has expanded by 50%, and we have benchmarked three ’standard’ simulation codes.

Standardized ’figures of merit’ have been defined [3] to quantify how well each model predicts a standard data set 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 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 1-D models which are successful in reproducing core temperature profiles. The first figure of merit to be discussed is the incremental thermal stored energy, W^{inc}, which is the energy above the ’pedestal’ energy (see [2] for details); we take 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.

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 it should be remembered that the T11/SET simulations are not made with a ’standard’ code and the number of simulated discharges is smaller. 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.



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].

generally reflect the results in Figure 1: the best models do well for both species. The overall performance in these Figures is better than in Fig. 1 because these figures of merit use the local temperature rather than an incremental temperature above the pedestal temperature.

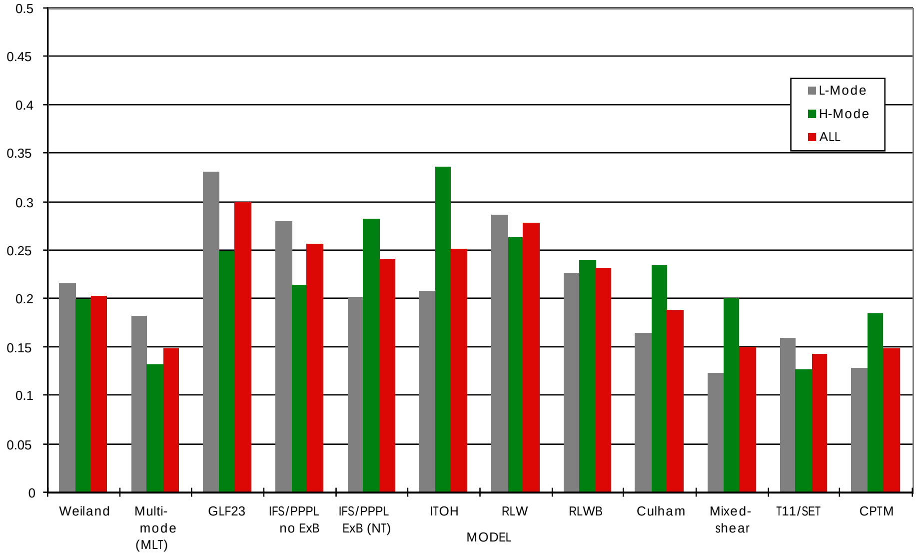


Figure 2: RMS error in simulated electron temperature profile for each of the 12 transport models, averaged over the standard set of 75 discharges

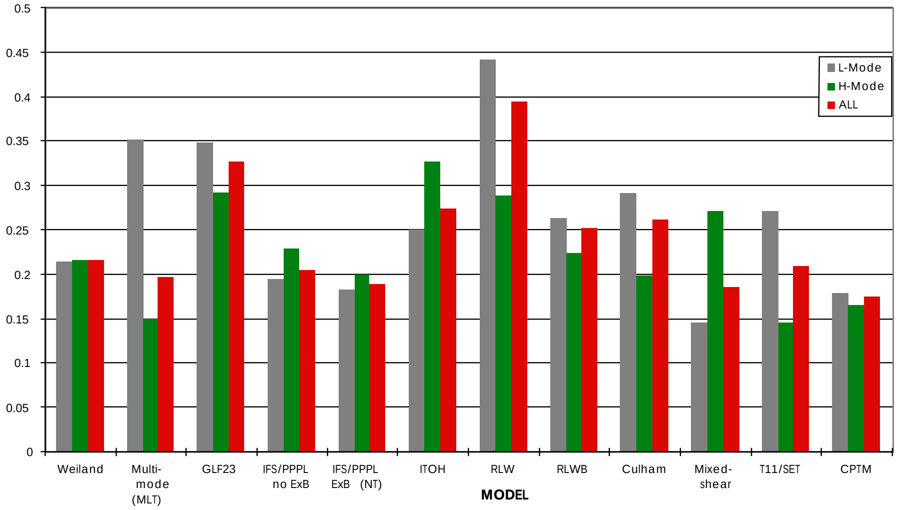


Figure 3: RMS error in simulated ion temperature profile for each of the 12 transport models, averaged over the subset of 55 discharges with measured Ti.

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).

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 so called '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., $\rho*$). 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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