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Transport modelling of Hybrid discharges from the ITPA Profile Database

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1. Introduction

The "hybrid" regime is a candidate scenario for ITER, with a potential for longer inductive pulse at high fusion gain [1,2]. Compared to conventional H-mode, these "hybrid" discharges feature improved confinement and beta, an improved long-pulse capability (additional non-inductive current drive, higher q95 ~ 4-5), as well as q_{min} maintained at or slightly above 1 (i.e. generally sawtooth-free). This particular shape of the q-profile has been attributed to a specific MHD activity [3], though this explanation is still controversed. In this work, we discuss the results of resistive current diffusion applied to those regimes. We also address the heat transport in the Hybrid regime, in order to investigate the origin of its improved confinement properties. Transport modelling of such discharges is a just starting activity, and remains a challenge for the models available today. A multi-machine comparison is carried out here, in order to test the commonality of the transport physics.

A few hybrid discharges have been submitted recently to the ITPA Profile Database, which offers a unique opportunity to access data from various tokamaks in the same format. In this work, predictive current and heat transport modelling of hybrid discharges from Asdex Upgrade (AUG), DIII-D, and JET is carried out using the CRONOS integrated modelling code [4]. We also model a high β_p Elmy H-mode discharge from JT-60U, as an example of high confinement (H_H >1) and high beta (β_N >~ 2.5) plasma with a flat central q profile and with q_{95} ~ 4 [5]. This JT-60U discharge has higher q_0 (~ 1.5) and higher bootstrap current fraction (~50%) than others, and may be regarded as closer to a steady-state scenario than to a hybrid scenario. Plasma geometry and profiles of effective charge, electron density, heat and current drive sources, and toroidal rotation are taken from the ITPA database. Three different heat transport models are used : the empirical mixed Bohm-gyroBohm (BgB) model [6], and the so-called “first principles” GLF23 [7] and Weiland models [8]. The pedestal is not modelled (use of ad hoc coefficients in the region ρ = 0.8-1), and we focus our attention on transport inside ρ = 0.8. All profiles are shown as a function of ρ, the normalised toroidal flux coordinate.

2. Resistive current diffusion

The current diffusion is first addressed, all the other fields being treated in interpretive way. In all pure "hybrid" cases (JET, AUG, and DIII-D), the flattening of the q-profile in the plasma core is reproduced by the modelling, and q has also a value close to 1. This is due to the non-inductive current drive (bootstrap and neutral beam injection), which represents of the order of 30-50 % of the total plasma current for the JET, AUG, and DIII-D cases. The non-inductive current drive sources have a rather broad profile (actually very similar among all the machines) which replaces partially the ohmic current, flattening its otherwise peaked shape in the core. It is actually not possible to state whether q is just above or just below 1, because of the uncertainties on the estimation of neutral beam current drive (Fig. 1). However, in some cases, q > 1 everywhere is obtained without involving specific MHD activity.

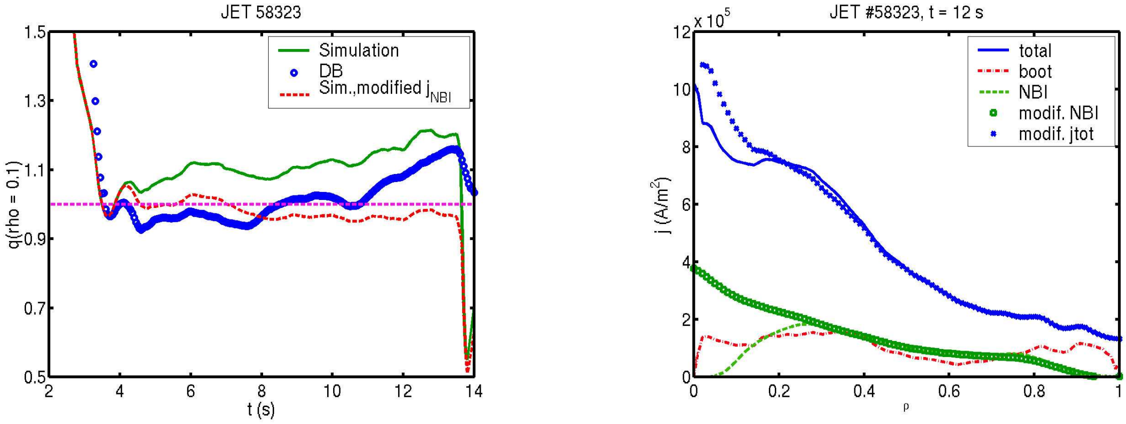

Fig. 1 : Time evolution of q(r = 0.1) for the JET case (left), and current density profiles (right). In order to quantify the uncertainty of the result, a simulation has been done also with a modified NBI current drive profile (green circles on the right, result in dash red on the left).

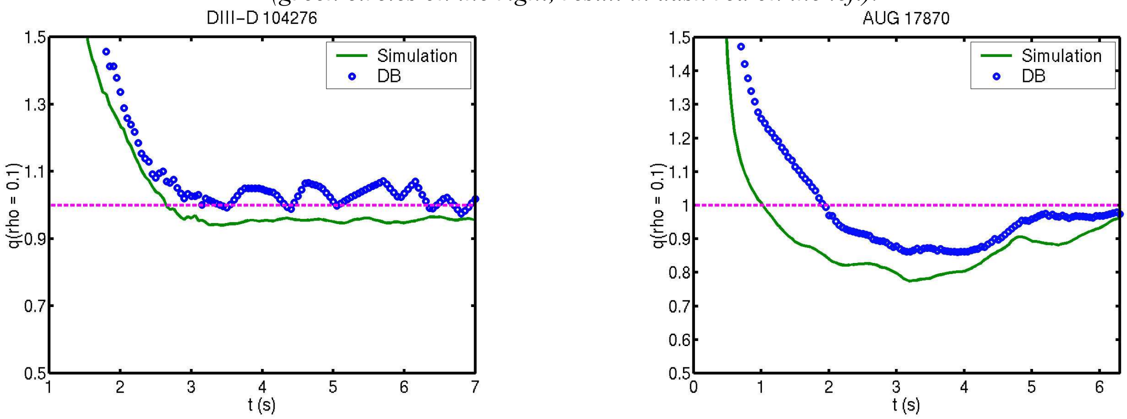

Fig. 2 : Time evolution of q(r = 0.1) for the DIII-D case (left) and AUG case (right). The database (DB) values correspond to MSE measurement (DIII-D) or to current diffusion simulations by local codes (AUG, JET).

3. Heat transport simulations

The mixed Bohm/gyro-Bohm model is a two-term empirical model. Turbulence suppression by magnetic and/or ExB shear is taken into account by a smoothed Heaviside function with reduces the Bohm term when the stabilisation criterion is locally met, of the form : $F = \dfrac{1}{1+\exp\left(20(0.05+\alpha_E\omega_{E\times B}/\gamma_{ITG}-s)\right)}$. The Bohm term has a non-local scaling, being inversely proportional to the electron temperature at the top of the pedestal, in order to reproduce the reduced core heat diffusivity in the H-mode regimes [9]. The prediction is strongly influenced by this scaling, with very different accuracy from one particular case to the other : very good agreement with experiment in the AUG case, completely wrong for the JET case. In the DIII-D case, this scaling provides a good prediction of the electron temperature profile, but in addition a strong influence of the ExB shear is needed ($\alpha_E = 2$) in order to produce an acceptable prediction of the ion temperature profile (Fig. 3). Since the magnetic shear is positive outside ρ = 0.1, only the ExB shearing rate is able to enhance the core confinement, using the above stabilisation criterion.

The GLF23 model performs rather well on most test cases (except JT-60U), describing quite accurately the temperature profile in the region ρ = 0.3 - 0.7. The ExB shearing rate plays also an important role in this result, the prediction being less accurate if it is not taken into account in the simulation. The model predicts full turbulence stabilisation in the ion channel inside ρ < 0.2, while the experimental ion heat transport level remains a few times larger than the neoclassical value in DIII-D and JET. This small but still above neoclassical transport level is not well described by GLF23 in the cases presented here.

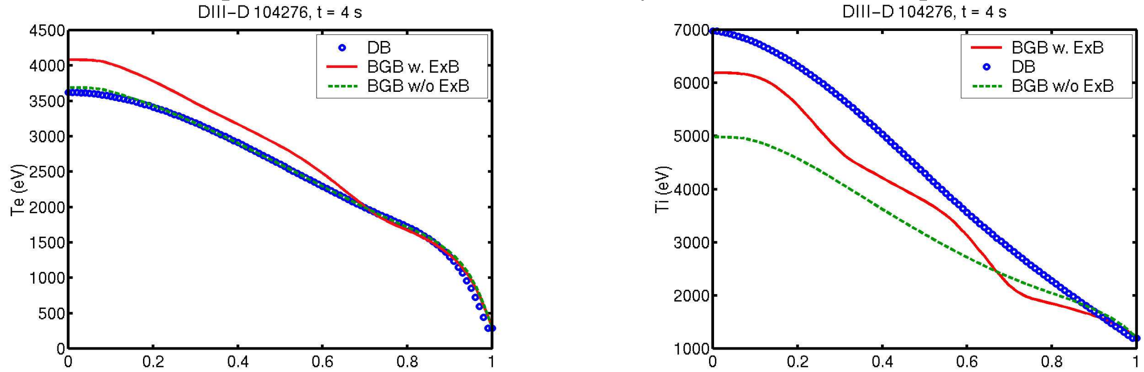

Fig. 3 : Bohm/gyro-Bohm prediction for the DIII-D case, t = 4 s, with and without ExB shear.

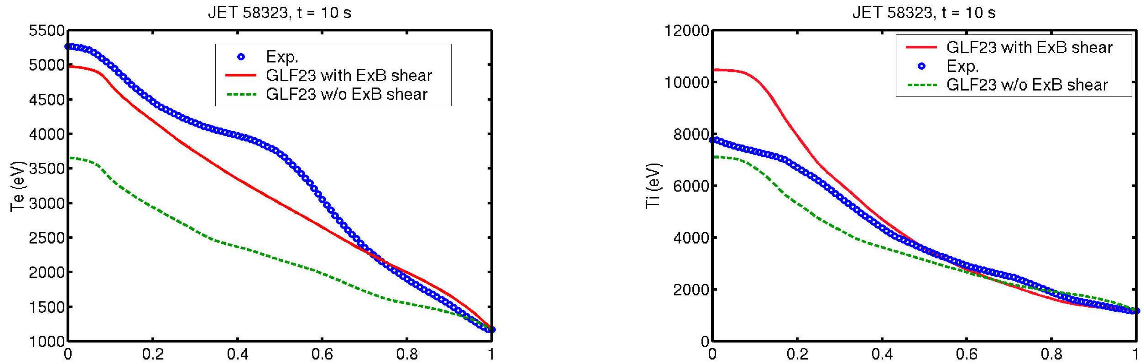

Fig. 4 : GLF23 prediction for the JET case, t = 10 s,with and without ExB shear

Both BgB (Fig. 5) and GLF23 fail in reproducing the strong slope of Te and Ti profiles observed in JT-60U, even when the ExB shearing rate is taken into account. It should be noted that for the JT-60 case, the q-profile in the simulation is less flat than the one deduced from MSE measurement. If the BgB model were forced to use the flat experimental MSE q-profile, the predicted temperature profiles would be much higher.

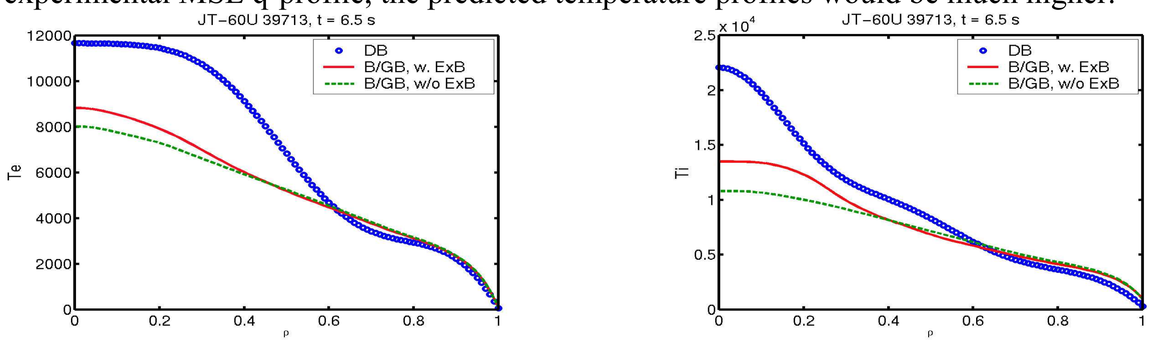

Fig. 5 : Bohm/gyro-Bohm prediction for the JT-60U case, t = 6.5 s, with and without ExB shear.

The Weiland model has also been tested in the JET and AUG cases, with contrasted results : very good agreement is obtained on Ti for AUG, but Te is strongly overestimated inside ρ = 0.5. A poor agreement is found for JET, during the highest heating phase : the model is prone to trigger an internal transport barrier in the ion channel, due to a sensitivity to the smoothing used for the experimental density profile, and overestimates Te strongly. The ExB shearing rate is not taken into account in the simulations with the Weiland model.

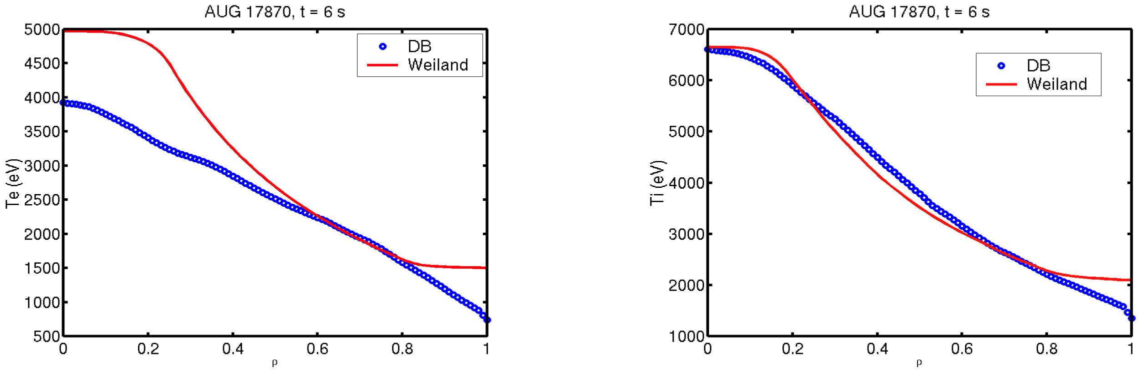

Fig. 6 : Weiland model prediction for the AUG case, t = 6s, without ExB shear

4. Conclusion

Resistive current diffusion, in the AUG, JET, and DIII-D cases, provides a flat q-profile in the plasma core, with a value very close to 1. No specific MHD activity has to be involved in order to account for this. However, because only resistive diffusion is involved in our simulations, q may fall a bit below 1 near the plasma center, depending on the estimations of the neutral beam current drive. A careful assessment of the uncertainties on the NBCD calculations on one side, and on the q-profile measurements on the other side, is needed in order to conclude whether another mechanism is needed to account for the q-profile shape in the hybrid regime. Moreover, from the experimental point of view, longer discharges are needed in order to assess the characteristics of the fully relaxed current profile (only the DIII-D case has reached a true stationary current profile).

Both the BgB and GLF23 models indicate that the ExB shearing rate must be taken into account in order to predict the correct transport level, especially in the ion channel. The ExB shear is due partly to the toroidal rotation induced by neutral beams, but the contributions of ion pressure gradient and poloidal velocity are also significant. The ExB shearing rate stabilises marginally the turbulence in the gradient region (ρ = 0.3 - 0.7). However, it is not clear whether this represents an enhancement of the core confinement with respect to the standard H-mode, which might also feature this effect. Comparisons of core and pedestal energy content with respect to 2-term scaling laws are therefore needed,in order to determine whether the improved confinement of the hybrid regime has its origin in the plasma core or in the pedestal. The GLF23 model can be regarded as an efficient tool for predicting the heat transport in the region ρ = 0.3 - 0.7. Nevertheless, the lack of reliable 1D transport models for the edge region and the pedestal is a strong drawback for the overall prediction capability of H-mode discharges.

5. References

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