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Introduction

Over the last few years, a significant part of the JET experimental programme has been dedicated to the development of the hybrid scenario, characterized, with respect to the standard H-mode scenario, by a flatter q profile in the plasma core, a value of q_0 greater than or approximately equal to 1, higher β and improved performances in terms of H98(y,2) factor. In support of the experiments, an extensive modelling activity has been carried out to interpret the results. The main focus of this activity has been the investigation of the evolution of the current profile and the study of thermal transport. This was achieved by means of semi-predictive transport simulations where the density behaviour was prescribed. However, since the shape of the density profile affects important plasma parameters, like the bootstrap current or the beam deposition, density should be modelled self-consistently to understand present day experiments and to extrapolate the results to future devices.

In this paper, we present the first results of fully predictive simulations of JET hybrid scenarios, performed in the framework of the ITM-TF ISM group. The behaviour of the density, temperature and current profiles is simulated self-consistently, although the rotation is not taken into account. The codes deployed to perform the simulations were JINTRAC, ASTRA and CRONOS, all equipped with the physics based GLF23 and the semi-empirical Bohm/gyro-Bohm transport models.

Simulations

For the simulations presented in this paper, four JET shots were selected. Of the four shots, two were high triangularity configurations and two were low triangularity configurations. For the high triangularity shots, one was done at high NBI power and the other at low NBI power and the same is true for the low triangularity shots. The parameters of the shots selected are summarized in table 1.

The majority of the simulations presented in the paper were performed with the JINTRAC

Shot	I_p [MA]	B_T [T]	P_{NBI} [MW]	β_N	δ	H_{98}
77922	1.7	2.3	17	3.1	high	1.37
75225	1.7	2.0	18	3.2	low	1.35
75590	1.3	1.7	10	2.9	high	1.38
74641	1.7	2.0	9.3	1.8	low	1.00

Table 1: main parameters of the shots selected for the simulations presented in the paper.

suite of codes available at JET. The initial conditions were taken from the experiment, the NBI particle and energy sources were calculated with PENCIL and the particle source due to the ionisation of the neutrals recycling at the wall was calculated by FRANTIC. The beam particle source was benchmarked against NUBEAM, the Monte Carlo code implemented in TRANSP to calculate the NBI particle and power deposition, and the two calculations were in good agreement with each other.

The transport model adopted in these simulations is the Bohm/gyro-Bohm transport model described in [1]. Since we are particularly concerned with the simulation of the density profile, it is worth noting that in this model the particle diffusivity D is given by the expression:

$$D(\rho) = S(\rho)\frac{\chi_i(\rho)\chi_e(\rho)}{\chi_i(\rho)+\chi_e(\rho)}$$

where ρ is the normalized toroidal flux, χ_i and χ_e are the ion end electron thermal diffusivities and S(ρ) is a linear weight function with S(0)=1.0 and S(1)=0.3. The radial shape of S was tuned on a variety of JET discharges.

The strategy for the simulations was the following. Firstly, to model the edge transport barrier (ETB) characteristic of H-mode plasmas, we adjusted the particle diffusivity D and the thermal conductivity χ inside this region to match the experimental height and width of the

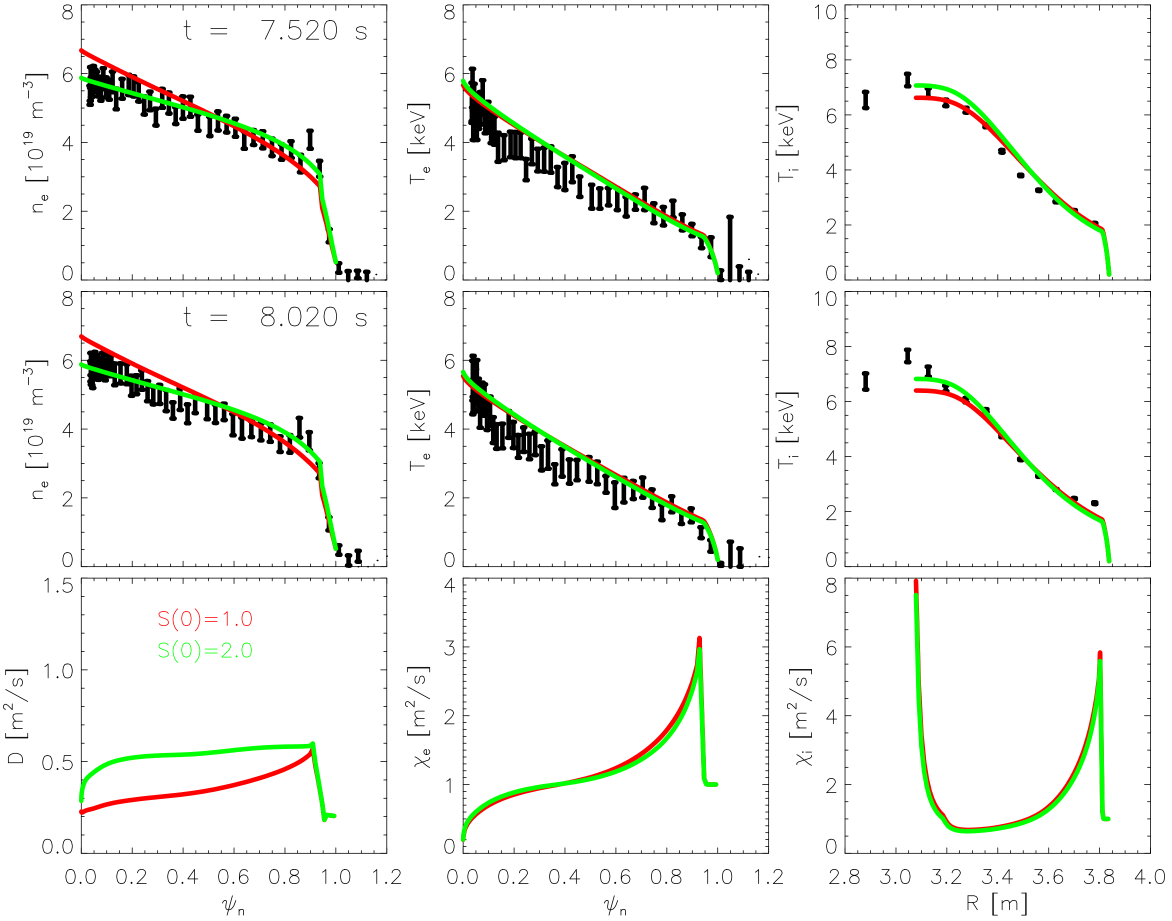

Figure 1: experimental and simulated electron density and electron and ion temperature profiles for JET shot 77922 (top and middle row) and particle diffusivity and electron and ion thermal conductivity (bottom row). Red curves: S(0)=1.0 in the Bohm/gyro-Bohm expression for the particle diffusivity; green curves: S(0)=2.0.

density and temperature pedestal. Then, we applied the Bohm/gyro-Bohm transport model in the plasma core to simulate the evolution of the density and temperature profiles and, at the same time, adjusted the recycling coefficient to match the evolution of the volume average plasma density. Finally, we compared the simulated peaking of the density profile with the experimental one and modified the particle diffusivity in the plasma core to match the experimental value. In fact, to increase D in the plasma centre, we increased the value of S(0).

An example of the results is given in figure 1, where, for shot 77922, the experimental profiles are compared with the simulations obtained with the Bohm/gyro-Bohm transport model with S(0)=1.0 and S(0)=2.0. It can be seen that S(0)=2.0 gives a better agreement with the experiment and simulates better the peaking of the density profile.

Results and discussion

A summary of the results for the shots analysed is presented in table 2. For each shot, we show the time interval analysed, the experimental value of the peaking factor γ (defined as $n_e(0)/\langle n_e \rangle$, where $n_e(0)$ and $\langle n_e \rangle$ are the on-axis and volume averaged electron density respectively), the simulated value of γ, the value of S(0) and the χ/D ratio in the ETB used in the simulation. For shot 77922 and 75225, the simulated values of γ corresponding to S(0)=1.0 are also shown. In all the shots simulated, the electron and ion temperature and q profiles were reproduced with good accuracy.

It can be seen that, irrespective of the triangularity, high power shots exhibit a core particle diffusivity higher by a factor 1.5-2.0 with respect to the standard Bohm/gyro-Bohm transport model. On the other hand, low power shots exhibit a higher value of the ratio χ/D inside the ETB with respect to high power shots. It is worth noting that in none of the cases analysed an anomalous inward particle pinch had to be invoked to explain the observed level of density peaking. This seems to be in contrast with simulation of standard JET H-mode plasmas, where an anomalous particle pinch had to be invoked to simulate the experimental peaking factor [2].

These results are consistent with fully predictive GLF23 simulations of the same JET shots performed with the ASTRA transport code and presented in [3], which also predict a density peaking higher than that observed experimentally. In those simulations, a better agreement with the experiment was achieved when the coefficient in front of the E×B stabilization term in the GLF23 transport model was reduced from the value of 1.35 in the retuned version of the model to 0.5. Moreover, fully predictive GLF23 simulations of a different set of JET and ASDEX-U hybrid scenarios presented in [4] show the same feature, namely a simulated density profile significantly more peaked than the experimental one when the retuned version of the GLF23 transport model is applied and a better agreement with the experiment if the E×B stabilization term is suppressed.

Shot	**Time (s)**	γ_{Exp}	γ_{Sim}	**S(0)**	**χ/D (ETB)**
77922	7.5-8.0	1.36	1.40 (1.60)	2.0 (1.0)	5.0
75225	6.0-6.5	1.59	1.58 (1.73)	1.5 (1.0)	7.5
75590	5.8-6.3	1.42	1.45	1.0	15.0
74641	6.0-6.5	1.52	1.51	1.0	15.0

Table 2: summary of the results for the simulations presented in the paper.

In terms of transport coefficients in the Bohm/gyro-Bohm transport model, the experimental density peaking can be recovered either with an increased core particle diffusivity (as done in the simulations presented in this paper) or by introducing an outward convective velocity in the plasma core.

The reasons for an increased core particle diffusivity are not clear yet. However, one could speculate that, at the lower shear and higher β characteristic of the hybrid scenario, ion temperature gradient (ITG) modes are stabilized and other modes become dominant, resulting in higher particle fluxes. Linear and non linear analysis with the GYRO gyrokinetic code [5] that can test this hypothesis is under way, but it is at a too early stage to draw conclusions on this point.

On the other hand, to investigate whether an outward convective velocity should be expected in the shots analysed, a quasi-linear microstability analysis of shot 77922 with the QuaLiKiZ code [6] has been performed. The analysis (which does not take into account E×B stabilization) shows that, in the shots considered, the dominant instability is the ITG mode and that an outward convective velocity could be expected. However, this velocity is the result of an outward contribution due to parallel compressibility and an inward contribution due to thermo-diffusion and the balance between these terms is extremely sensitive to the shape of the ion and electron temperature profiles. Therefore, this result should not be regarded as a clear cut prediction that an outward particle pinch, which would explain the extra flattening of the density profile, should always exist in hybrid discharges.

Conclusions

Fully predictive simulations of JET hybrid mode plasmas have been performed with JINTRAC and the Bohm/gyro-Bohm transport model and compared with similar fully predictive simulations performed with ASTRA and CRONOS and the GLF23 transport model. The results show that both transport models, which in the past were used to analyze the standard H-mode scenario and predicted correctly the peaking of the density profile, when applied to the analysis of the hybrid scenario, tend to over-estimate the density peaking. Good agreement with the experiment is recovered by either increasing the core particle diffusivity in the Bohm/gyro-Bohm transport model or reducing the coefficient in front of the E×B stabilization term in the GLF23 transport model. On the other hand, the behaviour of the temperature and q profile is in general correctly predicted by both transport models. The reason for the discrepancy is not clear at the moment, but the magnetic shear s and β and their effects on the plasma micro stability could be possible candidates.

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