Predictive transport analysis of JET and AUG hybrid scenarios

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Introduction

Hybrid scenarios in present machines are characterized by improved confinement compared to the IPB98(y,2) empirical scaling law expectations. A number of possibilities explaining this improvement have been proposed: reduction in deleterious MHD, pedestal confinement improvement, rotational shear turbulence suppression, increased turbulent thresholds due to q-profile shaping, and stiffness reduction at low magnetic shear [1, 2, 3]. This work concentrates on isolating the impact of increased s/q at outer radii (where s is the magnetic shear) on core confinement in *low-triangularity* JET and ASDEX Upgrade (AUG) experiments. This is carried out by predictive heat and particle transport modelling using the integrated modelling code CRONOS [4] coupled to the GLF23 turbulent transport model [5]. This work aims to validate recent predictions of the ITER hybrid scenario also employing CRONOS/GLF23, where a high level of confinement and resultant fusion power sensitivity to the s/q profile was found [6].

Experimental discharges

For both machines, discharge pairs were analyzed displaying similar pedestal confinement yet significant differences in core confinement. A variation in q-profile was experimentally achieved in each pair, via the 'current-overshoot' method for the JET case (79626/79630, with $B_T = 2T$, $I_p = 1.7MA$ and $\beta_N(W_{th}) = 1.9/2.1,\ \beta_N(W_{dia}) = 2.6/2.8$) [7, 1], and by varying the auxiliary heating timing in the AUG case (20993/20995, with $B_T = 2.4T$, $I_p = 1MA$, and $\beta_N(W_{th}) = 1.6/1.9, \beta_N(W_{dia}) = 1.9/2.3$) [8]. Temporal evolution of the total plasma current, heating powers and confinement factors ($H_{98} \equiv \tau_{th}/IPB98(y,2)$) can be seen in figure 1. The s/q and rotation profiles used throughout this analysis can be seen in figure 2. For the JET pair, the interpretative q-profiles were used since the transient effect of the current overshoot may in certain cases be within the error bars of the MSE measurements. For the AUG pair, the measured q-profiles were used since the interpretative q-profiles failed to reproduce the measured relaxed q-profiles within experimental error, and MHD activity may be redistributing the current, clamping the q-profile to 1. The rotation profiles for the JET case are similar. For the AUG case, the 20993 (lower confinement) case has a significantly flatter rotation profile in the low magnetic shear region x<0.4. Finally, all discharges are devoid of NTMs in the temporal periods studied, apart from AUG 20993, which has a 3/2 NTM in the vicinity of $x = 0.5$.

Modelling tools and techniques

The core of CRONOS is a 1.5D transport solver, whereby 1D current diffusion, particle and energy equations are solved up to the separatrix, self consistently with 2D magnetic equilibrium.

*See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA Fusion Energy Conference 2010, Daejeon, Korea

The NBI heat and current sources are calculated by NEMO/SPOT [9, 10]. In all simulations, GLF23 is employed within the region x=0-0.83, where x is the normalized toroidal flux coordinate. For each discharge, comparison simulations were carried out substituting the q-profile input with the q-profile from the other member of each pair. In such a manner GLF23 predicts the confinement difference solely due to the q-profile. Further linear threshold analysis examining the effect of s/q is also carried out with the quasilinear gyrokinetic transport model QuaLiKiz [11].

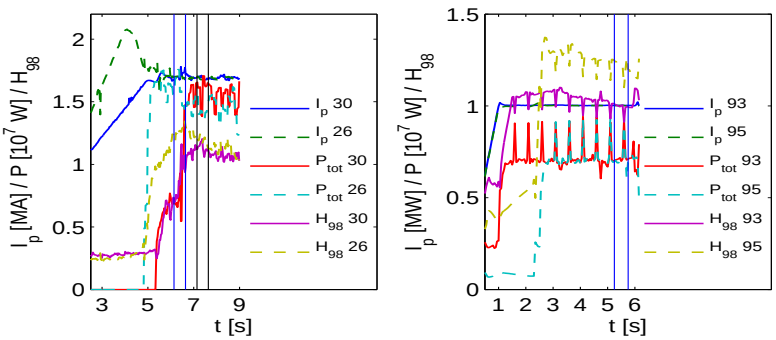

Figure 1: Evolution of $I_p[MA]$, $P_{tot}[10^7 W]$ and H_{98} for the JET (left panel) and the AUG (l panel) pairs

Results

Figure 3 shows the T_i predictions for JET 79630. These simulations include *heat transport only*, and runs were carried out both with and without ExB suppression. 79630 simulations with the substituted q-profile from 79626 (the improved confinement case) are also shown.

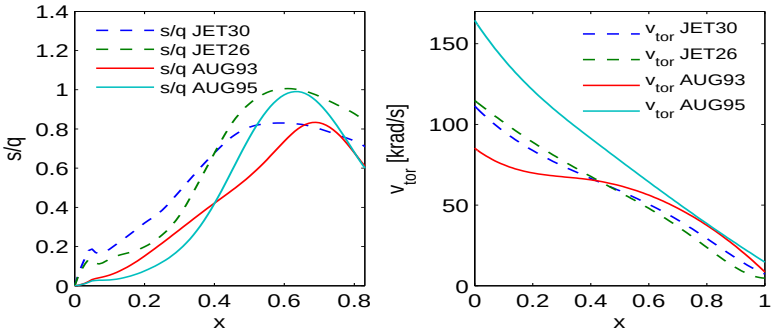

Figure 2: s/q (left) and rotation (right) profiles for all analysed discharges

The inclusion of ExB suppression leads to overprediction of T_i. This overprediction is also seen in JETTO [12] simulations of the same discharge, displayed in the same figure. However, independently of the degree of prescribed ExB suppression, the q-profile substitution leads to a degree of T_i increase comparable to the experimentally observed difference. A more quantitative analysis of these differences, and of all subsequent simulations discussed below, can be found in table 1. This pattern is replicated in the AUG simulations, displayed in figure 4 for a heat transport simulation of shot 20995. In the AUG case the degree of T_i overprediction is more severe. However, regardless of the ExB suppression assumption, the q-profile substitution leads to a T_i difference consistent with

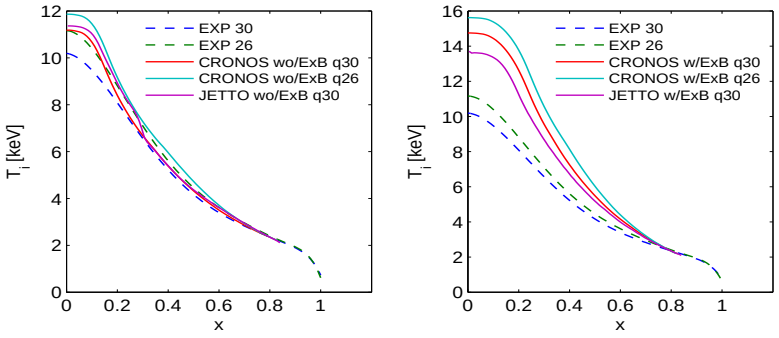

Figure 3: Heat transport only GLF23 predictions for ion temperatures in JET 79630, excluding ExB suppression (left panel) and including ExB suppression (right panel), and with the substituted q-profile from 79626

observations.

In figure 5, the results of *combined heat and particle transport* simulations for JET 79630 are shown. The pattern remains similar to the heat transport only cases, although the primary effect on confinement improvement following the q-profile substitution is now in the particle channel. The reduction of the T_i gradient increase in comparison to the heat transport only case, is due to positive correlation in GLF23 between density gradients and transport, interpreted as the destabilization of TEM modes. Similar results are shown for AUG 20995 in figure 6. For the AUG case, the degree of improved particle transport is consistent with observation, although when ExB suppression is included the n_e profiles are significantly overpredicted. In table 1 the simulation results are summarized in terms of the predicted core thermal energy content: $W_{core} = \int_0^{x_{ped}} (P_{th}(x) - P_{th}(x_{ped}))Jdx$, where x_{ped} is taken at the GLF23 operational zone boundary at x=0.83, and J the Jacobian corresponding to the volume element. The table summarizes - according to GLF23 - the extent of the s/q effect *alone* in explaining the core confinement *differences* between each pair, both including and excluding ExB shear stabilization. Finally, additional analysis was carried out for the JET case with QuaLiKiz, where we assess the sensitivity of the instability linear thresholds to the q-profile, at $x = 0.65$. The experimental R/L_{Ti} is 5.9 ± 0.5 and 6.3 ± 0.3 for 79630 and 79626 respectively, calculated with respect to a radial coordinate defined as $(R_{in} - R_{out})/2$, where $R_{in,out}$ are the radii to the high field and low field side flux surfaces on the midplane. If we take R_{out} as the radial coordinate, the gradients rise to 7.5 ± 0.6 and 8.1 ± 0.4. QuaLiKiz predicts $R/L_{Ti} = 7.32$ for 79630, and $R/L_{Ti} = 8.08$ for the same input apart from the substitution of the 79626 q-profile and magnetic shear values. The experimental $R/L_{n(e,i)}$ values were 2.6/2.9, and R/L_{Te} was kept at the observed ratio to R/L_{Ti} throughout the R/L_T scan.

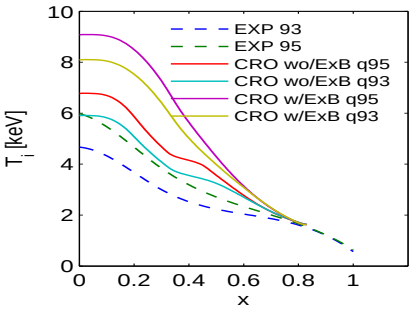

Figure 4: Heat transport only GLF23 predictions for ion temperatures in AUG 20995

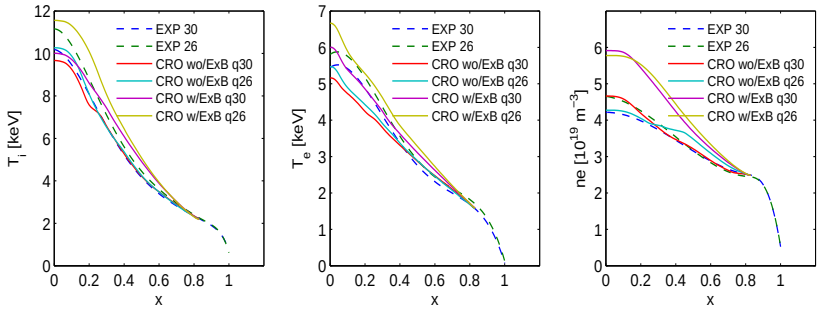

Figure 5: Heat and particle transport GLF23 predictions of T_i (left panel), T_e (center panel), and n_e (right panel) for JET 79630

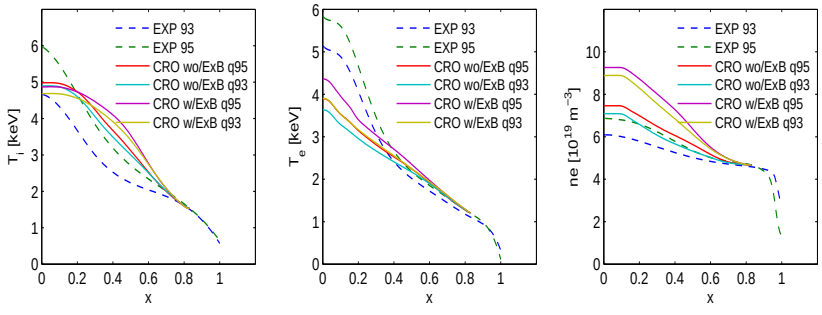

Figure 6: Heat and particle transport GLF23 predictions of T_i (left panel), T_e (center panel), and n_e (right panel) for AUG 20995

Table 1: Core thermal energy following GLF23 predictions for JET and AUG hybrids. Units are [MJ].

	EXP	Heat transport		Heat and particle			EXP	Heat transport		Heat and particle	
		no ExB	with ExB	no ExB	with ExB			no ExB	with ExB	no ExB	with ExB
79630 (q30)	1.67	1.71	2.37	1.71	2.68	20995 (q95)	0.33	0.36	0.48	0.34	0.47
79626 (q26)	1.97	1.9	2.62	1.83	3.03	20995 (q93)	0.22	0.3	0.43	0.29	0.41
Ratio	1.17	1.11	1.11	1.07	1.13	Ratio	1.5	1.2	1.12	1.17	1.15

Discussion and conclusions

A significant proportion of improved confinement in the JET and AUG hybrid scenarios analysed here is due to improved q-profile shaping in the high magnetic shear region, at $x > 0.4$, according to GLF23. A proportion of $\sim 60/30\%$ of the observed improvement in core thermal energy content within each JET/AUG pair respectively, is predicted through q-profile substitution alone (when averaging the ratios in the bottom line of table 1). In the heat transport simulations, differences in R/L_{Ti} are in the JET case only observed in the high shear region (x>0.4) and are correlated with differences in s/q. In the AUG case, the R/L_{Ti} differences occur both in the low and high magnetic shear regions within x=0.3-0.6. The R/L_{Ti} difference in the high shear region is correlated with a difference in s/q. However, the difference in the low shear region cannot be explained by s/q effects. Due to the difference in rotational shear for x<0.4 between the two discharges in the AUG case, it may be possible that reduced stiffness in the low shear region (not predicted by the stiff GLF23) may account for a further proportion of core confinement difference, as also observed in JET [3]. It is also possible that the 3/2 NTM observed in AUG 20093 is partially responsible for the apparent overprediction of the core confinement by GLF23, even when not including ExB shear suppression, and can thus explain a proportion of the core energy content difference between the pair. Including rotation in GLF23 leads to core energy content overprediction for all discharges, although it is not possible to verify whether this is due to the GLF23 ExB shearing model or to an intrinsic overprediction of the turbulent thresholds. Nevertheless, confinement improvement due to s/q is independent of the rotation assumption. The degree of improvement in the ITG/TEM linear thresholds in the JET pair is also well predicted by QuaLiKiz through the s/q effect. The overlap of the experimental error bars on R/L_{Ti} is however a caveat in such analysis.

Acknowledgements

This work, supported by the European Communities under the contract of Association between EURATOM/FOM and EURATOM/CEA, was carried out within the framework of the European Fusion Programme with financial support from NWO. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work is supported by NWO-RFBR Centre-of-Excellence on Fusion Physics and Technology (Grant nr. 047.018.002).

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