ITG heat flux reduction in JETTO-TGLF modelling of high current high performance JET pulses

G. Szepesi[1], C.M. Roach[1], F.J. Casson[1], C.D. Challis[1], J. Garcia[2], L. Garzotti[1], Hyun-Tae K.[3], L. Irvine[1,4], E. Lerche[1,5], F. Rimini[1], J. Candy[6], G. Staebler[6] and JET contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1]CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[2]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[3]EUROfusion Programme Management Unit, Culham Science Centre, Abingdon, OX14 3DB, UK
[4]University of Bath, Claverton Down, Bath BA2 7AY, UK
[5]LPP-ERM/KMS, EUROfusion Consortium Member - Trilateral Euregio Cluster, Brussels, Belgium
[6]General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
(*)See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016)

Introduction

In the 2016 JET experimental campaign the highest D-D fusion neutron yield has been achieved under steady-state conditions since the installation of the ITER-Like-Wall (ILW), with both high current and high beta scenarios producing ~2.8e16 n/s. This value is about a factor of ~2 higher than the previous maximum neutron rate produced in ILW fpr the high current scenario, while in high beta scenario similar but slightly lower neutron rates were achieved before. The ILW high current scenario will be used in the upcoming JET D-T campaign, and in order to maximize the fusion power it is crucial to understand what leads to the increased performance.

In this paper we are comparing the recent record performance ILW high current pulse 92436 with the previous record high current ILW shot 87412 from the core transport point of view. We perform predictive transport simulations with the JETTO transport code [1] using TGLF [2] as the model for the turbulent fluxes. The main parameters of the two pulses are summarized in table 1. The high performance pulse is characterized by lower current, lower total fuelling rate (gas injection and pellets) and similar total heating power compared to the lower performance pulse. This leads to a lower average density (by ~20%) and higher pedestal temperature, enabling lower thermalization power due to reduced collisionality, and consequently an elevated T_i/T_e~1.23 in the centre [3]. Note that in previous high current pulses typically T_i/T_e~1. Another consequence of the lower gas fuelling in the high performance pulse is the higher influx of mid-Z metallic impurities from the vessel and less regular ELM-activity meaning that these impurities remain in the core plasma in larger concentration, leading to high Z_{eff}~1.75. The presence of mid-Z impurities (typically Ni) has been confirmed by VUV spectroscopy analysis. Good agreement between measured and modelled neutron rates could be obtained by assuming that Ni is the main contributor to Z_{eff}.

	I_p (MA)	B_{vac} (T)	P_{tot} (MW)	Fuelling (1e22 e/s)	n_e dl (1e20 m^{-2})	Z_{eff}	$T_{i,0}/T_{e,0}$	β_N	R_{NT} (1e16 n/s)
87412 (LP)	3.5	3.3	27 + 4	9.7	2.14	1.15	1	1.4	1.3
92436 (HP)	3	2.8	27 + 6	0.8 + 0.8	1.8	1.75	1.23	2.3	2.8

Table 1: Main engineering and plasma parameters of the high performance (HP) pulse 92436 and the reference lower performance (LP) pulse 87412.P_{tot} shows NBI and ICRH power terms, the fuelling rate shows gas injection and pellet ablation sources, respectively.

The goal of this work is to explore how the differences between the two pulses affect core transport, whether it plays a significant role in achieving improved performance, and if we can capture the change of performance with the JETTO-TGLF model. The latter point is particularly important since JETTO-TGLF is one of the tools being used to predict performance of scenarios in the upcoming D-T campaign.

Integrated modelling with JETTO-TGLF

Simulations predicting profiles of T_e, T_i and n_e have been performed using the JETTO integrated modelling code with the state-of-the-art quasi-linear gyro-fluid transport model TGLF. In each case, JETTO was run from an initial condition based on processed diagnostic data corresponding to a single time point until convergence was reached. That is, the outcome of the simulation is a set of plasma profiles that are consistent with energy and particle balance. For both pulses the initial profiles were taken during the steady-state phase of the plasma. Therefore, if the model is describing the system accurately, the predicted profiles are expected to remain close to the experimental data. This method of predictive modelling is used to evaluate the validity of the model (defined by all physical and numerical assumptions), rather than to follow the evolution of the plasma during transients.

Initial profiles of n_e and T_e were taken from the High Resolution Thomson Scattering (HRTS) measurement. T_i and v_{tor} are coming from the Charge Exchange (CX) spectroscopy diagnostic. The experimental data were averaged over 10.35-10.45s, and data consistency checks were performed by the TRANSP code [4]. The toroidal rotation velocity v_{tor}, current profile j, magnetic equilibrium and ICRH heating deposition profiles were kept fixed during the simulations. The magnetic equilibrium is from an EFIT reconstruction, and the ICRH heating is from TORIC (via TRANSP). The NBI deposition profiles were computed self-consistently with the Pencil code coupled to JETTO. The radiation profile was taken from bolometry tomography reconstruction. For both pulses only one impurity type was included in the simulations with radially constant Z_{eff}: Be in 87412, Ni in 92436.

The boundary condition for the predicted profiles were set at the top of the pedestal at ρ_{JETTO}=0.8 (ρ_{JETTO} is the square root of the normalized toroidal flux). The profiles are fixed outside this value. The pedestals are different in the two pulses and this also contributes to the different performance, but pedestal modelling is not included in the analysis.

Both JETTO and TGLF are actively developed, hence the simulation results might change depending on which code version is used. For this analysis a recent version of both codes were used: JETTO based on the official release on 17/05/2017 (j170517), TGLF from GACODE GitHub repository commit cb720b3ee on 15/06/2017. TGLF was used with the new saturation rule SAT1 including zonal flow mixing effects [5].

Figure 1 shows the predictive simulation results for T_i, T_e and n_e for the high performance pulse 92436. On each subplot the errorbars show the raw experimental data, the dashed line indicates the initial profile, the solid line is the predicted steady-state profile, and the feint horizontal and vertical lines highlight the location of the boundary condition. The predicted profiles are in very good agreement with the experimental data for all three channels. It should be noted that the prediction is very sensitive to the choice of saturation rule in TGLF: using the previous SAT0 saturation rule (not including zonal flow effects) leads to significant overprediction of all profiles in this case. On the other hand, simulations with SAT1 (including zonal flow effects) are found to be much more sensitive to the boundary conditions.

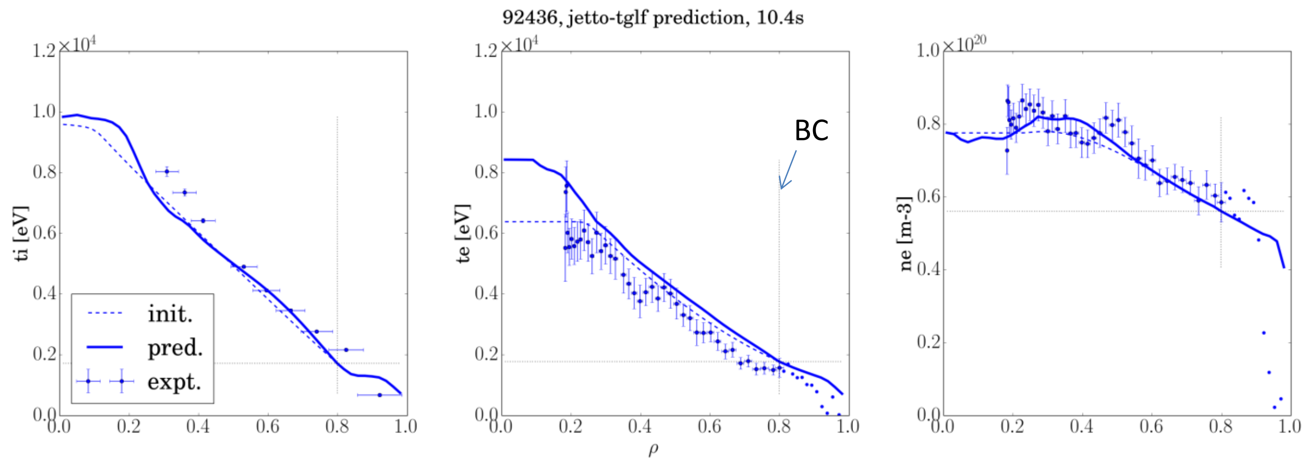

Figure 1: JETTO-TGLF prediction of T_i, T_e and n_e profiles for high performance pulse 92436.

On Figure 2 the result of a similar simulation for the lower performance pulse 87412 are plotted, with the solid blue line showing the 92436 predictions for reference. For this pulse T_i=T_e was assumed for the initial condition, supported by the CX data points in the centre. The agreement is not so good as for the high performance pulse with the gradients of both temperature profiles being reasonable but underpredicted and the density slightly overpredicted. It is nevertheless impressive that the model captures the main difference in performance between these two discharges.

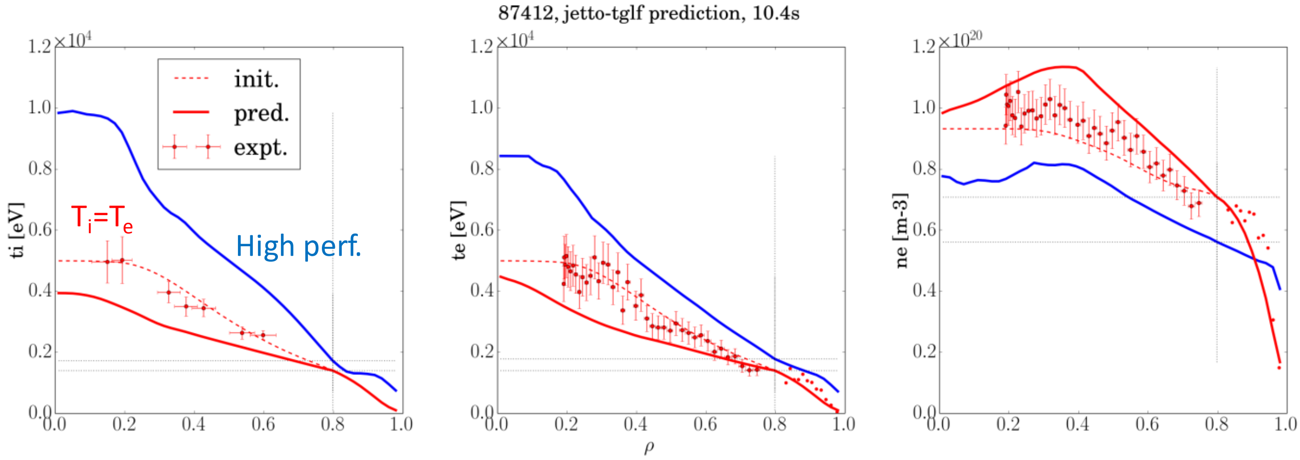

Figure 2: JETTO-TGLF prediction of T_i, T_e and n_e profiles for lower performance pulse 87412. The solid blue line shows the prediction for 92436 for reference.

Two significant differences between the two pulses are: lower density and higher Z_{eff} in the high performance pulse. If we modify the predictive simulation for the low performance pulse matching the density and temperature boundary conditions as well as the impurity content to the high performance pulse, we find that the high performance and the elevated T_i/T_e cannot be recovered. If all the other input physical parameters are matched to the high performance pulse, such as the NBI beam voltages and power fractions, magnetic equilibrium and ICRH heating, the prediction for 92436 is still not recovered. In fact, as shown on figure 3, in this "fully matched" case the only difference compared to the nominal simulation for 92436 is the shape of the initial profiles, showing that the *predicted profiles depend on the initial conditions not just the boundary conditions*.

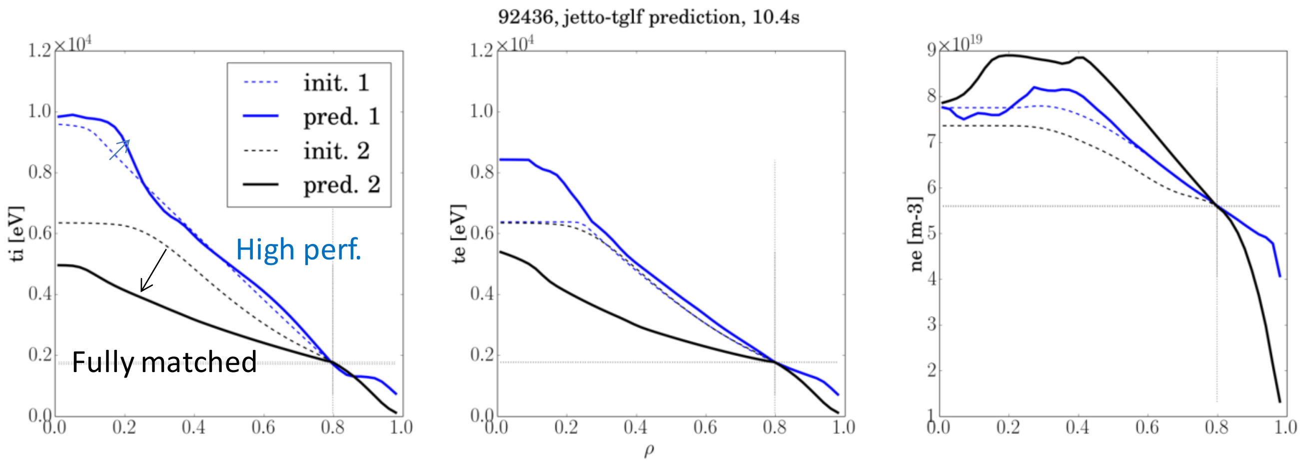

Figure 3: JETTO-TGLF prediction of T_i, T_e and n_e profiles for the high performance pulse 92436 starting from two different initial conditions.

Local transport analysis with standalone TGLF

In order to understand how turbulent transport differs in the two discharges, TGLF was run standalone as a local transport code at mid radius (r/a~0.5 in the high gradient region) with the input parameters taken from fits to the experimental profiles that were also used as initial profiles of the JETTO simulations. Figure 4 shows the spectra of deuterium heat flux in Gyro-Bohm units as a function of the perpendicular wavenumber normalized to the reference ion Larmor radius $k_y\rho_s$. The part of the spectrum included in these plots is typically occupied by the Ion Temeprature Gradient driven (ITG) modes. The total ion heat flux in the high performance pulse 92436 is more than a factor of 4 lower than in 87412 allowing a higher temperature gradient in the core. There are several differences between the two pulses causing this difference: higher T_i/T_e ratio, higher plasma beta, toroidal rotation and Z_{eff} in 92436 are all known to stabilize ITG modes and independently contribute to the reduction of the ion heat flux. It is important to note that these parameters are indeed identical in the integrated JETTO simulations in the nominal 92436 and the "fully matched" cases except for the initial T_i/T_e ratio. Lower T_i/T_e in the "fully matched" case reduces the critical ion temperature gradient needed to de-stabilize ITG modes [6], and increases the total ion heat flux by a factor of ~2 compared to the nominal high performance case (figure 4b).

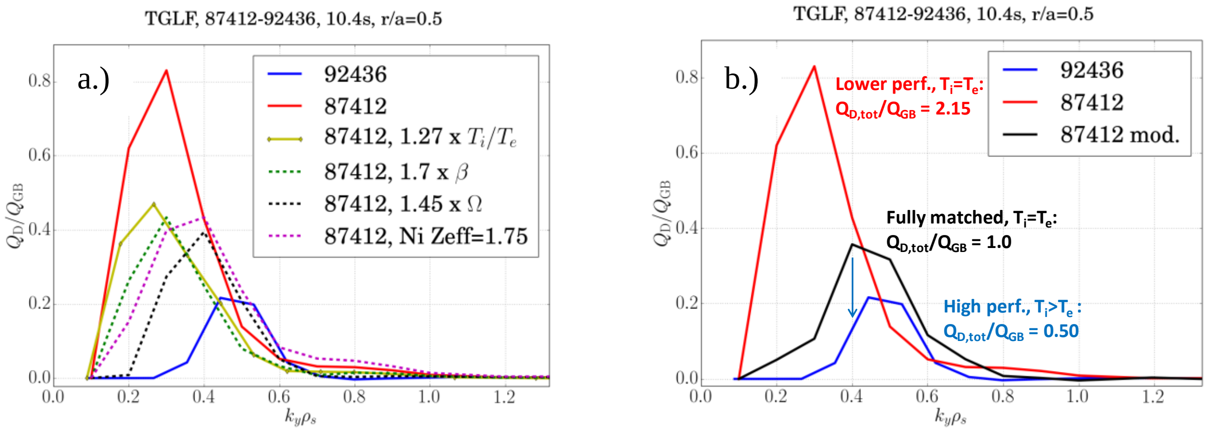

Figure 4: Ion heat flux spectrum in Gyro-Bohm units from standalone TGLF simulations for 92436 and 87412 matching individual parameters (a) or all parameters except the initial conditions (b).

Summary and conclusions

A comparative transport analysis has been presented between two high current ILW JET pulses: the recent high performance pulse 92436 achieving record neutron rate and the previous record pulse 87412. JETTO-TGLF simulations predicting n_e, T_e, and T_i are able to capture the major difference in performance between the two pulses. For 92436 a very good agreement between input experimental data and predicted profiles has been achieved, while for 87412 using the same modelling assumptions the discrepancy is higher. In our attempt to find the critical parameters that separate the high and lower performance simulations, it was discovered that the predictive JETTO-TGLF simulations depend on the initial conditions. This is completely reasonable in pulses where the turbulent transport is dominated by ITG modes considering the stabilizing effect of T_i/T_e on ITG growth rates and ion heat flux. However, it implies that extrapolating simulations to different scenarios, such as those planned for the D-T campaign, may not be reliable without predicting the evolution of the plasma from the beginning of the discharge.

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[1] M. Romanelli et. al., Plasma and Fusion Research **9**, 3403023 (2014)
[2] G.M. Staebler et al., Phys. Plasmas **12**, 102508 (2005)
[3] H-T Kim et al., at this conference
[4] http://w3.pppl.gov/transp/refs
[5] G.M Staebler et al., Phys. Plasmas **23**, 062518 (2016)
[6] S.C. Guo, F. Romanelli, Physics of Fluids B: Plasma Physics (1989-1993) **5**, 520 (1993)