Predictive modelling of D-T fuel mix control with gas puff and pellets for JET 3.5 MA baseline scenario

V. K. Zotta[1], L. Garzotti[2], F. J. Casson[2], D. Frigione[3], S. Gabriellini[1], R. Gatto[1], E. Giovannozzi[4], T. T. C. Jones[2], H.-T. Kim[2], F. Koechl[2], P. Lomas[2], G. Pucella[4], F. Rimini[2], Z. Stancar[5], M. Valovic[2], D. Van Eester[6], J. Mailloux[2], E. de la Luna[7], J. Bernardo[8], C. Reux[2] and JET Contributors*

[1] *Sapienza University of Rome, Rome, Italy*
[2] *CCFE, Culham Science Centre, Abingdon, UK*
[3] *University of Tor Vergata, Rome, Italy*
[4] *ENEA C. R. Frascati, Frascati, Italy*
[5] *Slovenian Fusion Association (SFA), Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*
[6] *Laboratory for Plasma Physics, LPP-ERK/KMS, Bruxelles BE*
[7] *Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain*
[8] *IPFN, Institute for Plasma and Nuclear Fusion, Lisboa, Portugal*
* *See the author list of Mailloux J. et al. 2022 Nucl. Fusion* ***62*** *042026*

1. Introduction Fuel mix control is a relevant problem in present experiments featuring mixed isotope fusion plasmas, and it will be crucial in future fusion reactors operating with a D-T plasma mixture. To maximise the deuterium-tritium (D-T) thermal reactions the plasma mixture has to be close to 50-50. However, the fusion power can be maximised in presence of D neutral beam injection (NBI) in a T rich plasma, so to favour the beam target component of fusion reactions. Integrated modelling can help explore and compare different fuelling schemes and provide guidance to arrive to a suitable recipe that leads to the desired experimental condition. The starting point for this paper is the wide database of fully predictive simulations carried out in preparation to the D-T operations of the JET baseline scenario [1]. The baseline and hybrid are two ELMy H-mode scenarios envisaged for high fusion performance at JET. In the baseline, featuring low β_N, good confinement is achieved at high plasma current [2]. The simulations in this work are performed using the JINTRAC [3] suite of codes using QuaLiKiz [4, 5] as first-principle transport model to predict the plasma current density, the electron density, the D, T ion densities, the electron and ion temperatures, self-consistently with the equilibrium computed by ESCO [6]. The heating deposition profiles are computed by PENCIL for the NBI [7] and PION for the ICRH [8], taking into account the synergy between them [9]. The impurity transport and the evolution of the impurity density profiles is predicted by SANCO [10]. The impurity mix composition is determined by matching the nickel content required to radiate the power estimated by spectroscopy [11], tungsten is adjusted to match the total radiation from the plasma bulk, and the beryllium content is obtained from experimental measurements of the effective charge Z_{eff}. The ionization sources (not measured at JET) are computed by FRANTIC [12]. The boundary conditions of the simulations are imposed at the separatrix, which is assumed to be located at the position where $T_e = T_i = 100$ eV. Modelling up to the separatrix allows us to investigate the effects of the imbalanced gas puff and the effects on the plasma composition of pure D ELM pacing pellets. The edge transport barrier is modelled assuming $\chi/D = 4$ in the pedestal region, the electron density at the top of the pedestal is imposed with a feedback loop on the gas puff to match the experimental measurements, and the thermal heat diffusivity is tuned to match the experimental electron temperature. Thus, the pedestal is modelled *ad hoc* with an effective ELM averaged diffusivity and conductivity to reproduce the experiment. It has been shown in [1] that this approach allows for proper modelling of the pedestal and of the external particle source required to sustain the pedestal density. In next sections we will show a first group of simulations done before the D-T experimental campaign (Sec. 2), the validation done on the D-T baseline discharge, chosen as a reference in this work, modelling gas puff and pellets as gas puff (Sec. 3), and a final simulation where D pellets are modelled with T gas puff (Sec. 4).

2. Predictive modelling before D-T campaign

Before the last D-T campaign at JET, we have studied the sensitivity of plasma composition to different fuelling schemes for the (3.5 MA / 3.3 T) baseline scenario, extrapolating to D-T plasma mixture the JPN 96482 shown in [13]. As shown in Fig. 1, the predicted performance of the JINTRAC – QuaLiKiz simulations follow the trend of the TRANSP interpretative runs done with the experimental profiles of the flat-top phase of the JPN 96482 imposing different plasma mixtures. It has been shown that a balanced D-T plasma mixture can be obtained by an appropriate balance of the external particle sources. The T concentration profile predicted in QuaLiKiz simulations is flat with respect to the radial coordinate, leading to core T concentration almost equal to the volume average T concentration. The main insight from this work has been the baseline discharges fuelling recipe, accomplished with a balanced D-T gas puff and, during the flat-top phase of the discharge, with pure T gas puff with the injection of D pacing pellets (nominal source rate S_{pel} = 0.8 10^{22} s^{-1}). Pacing pellets are required in the baseline scenario for ELM triggering, high/medium-Z impuritiy influx control and density control [2]. Since JET pellet injector is not compatible with T, the D pellets used in JET D-T baseline experiments are the first cause of imbalance in the external particle source and eventually of the plasma mixture. In the next sections we will present the results of the D-T predictive modelling done on actual D-T data.

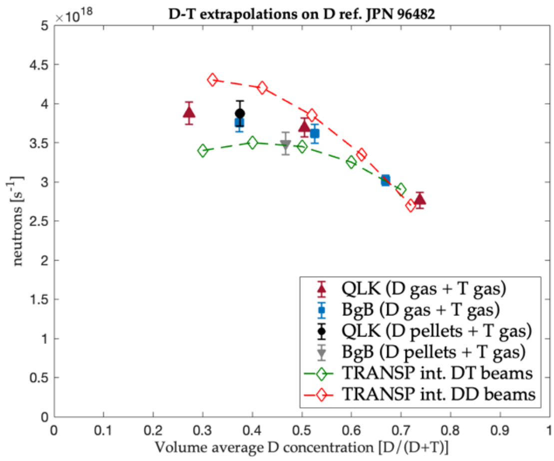

Figure 1. Sensitivity of the (3.5 MA / 3.3 T) baseline scenario to the plasma composition, comparing the results of fully predictive simulations done with QuaLiKiz or Bohm gyro-Bohm transport model in presence of D-T balanced beams (full markers) to TRANSP interpretative analysis (open markers) with D-T balanced beams or D-D beams.

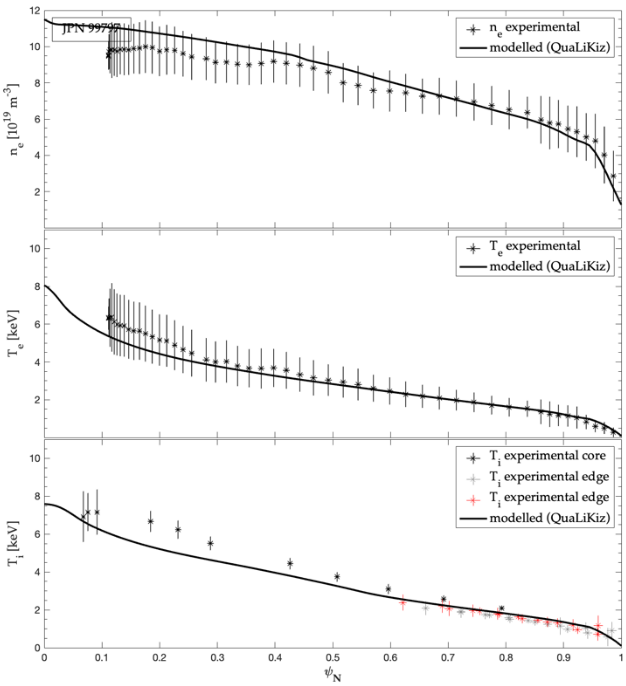

Figure 2. Comparison between experimental and modelled profiles, with electron density and temperature measured by the high-resolution Thompson scattering and ion temperature measured by charge exchange spectroscopy.

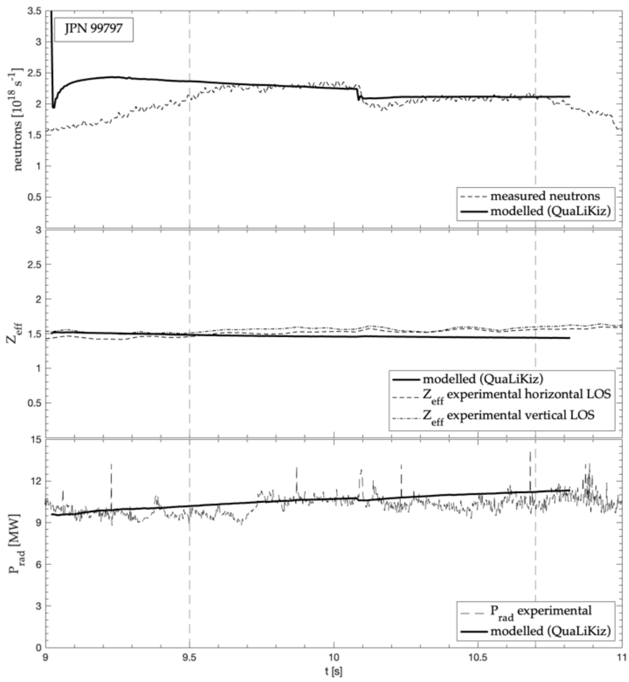

Figure 3. Comparison between experimental and modelled neutron rate, effective charge, and bulk radiative power for the JPN 99797 in the flat-top phase.

3. Validation with predictive modelling of the D-T data The pulse chosen as reference in this work is the JPN 99797, an H-mode in D-T plasma mixture with plasma current I_p = 3.5 MA, toroidal magnetic field B_T = 3.3 T, and heating power P_{aux} = 29.5 MW, 25.7 MW from the neutral beam injection (NBI) and 3.8 MW from the ion cyclotron resonance heating (ICRH) in H minority (4%) heating scheme. The flat-top time interval chosen to be compared with the predictive simulations is 1.2 s long, starting from 9.5 s, when the T concentration, measured by the Balmer-alpha spectrum form the subdivertor pressure gauge, is around 53%. We model starting from 9 s in order to relax the initial conditions taken from measurements and compare the experimental profiles with the modelled quantities computed self-consistently. The results of the predictive modelling on the reference pulse are shown in Fig. 2 averaging the experimental and simulated profiles in the selected time interval. In Fig. 3 the relevant experimental time traces are compared with the modelled ones, showing a good agreement within the uncertainties both in the kinetic profiles and in the time traces.

4. Modelling pellets, balancing particle sources to reproduce the experimental T concentration

While in a first set of simulations we have modelled both gas puff and pellets as D-T gas puff in order to determine the total particle source required to sustain the experimental pedestal density, in the second set of predictive simulations, presented in this section, we consider D pellet modelling in presence of T gas puff. We unbalance the main ion mixture by means of unbalancing the D-T fuelling sources modelled as gas puff ("gas only"), and then, modelling separately D pellets and T gas puff. The different fuelling sources such as NBI, gas puff and pellets are dominant particle sources in different regions of the plasma. In the inner core region

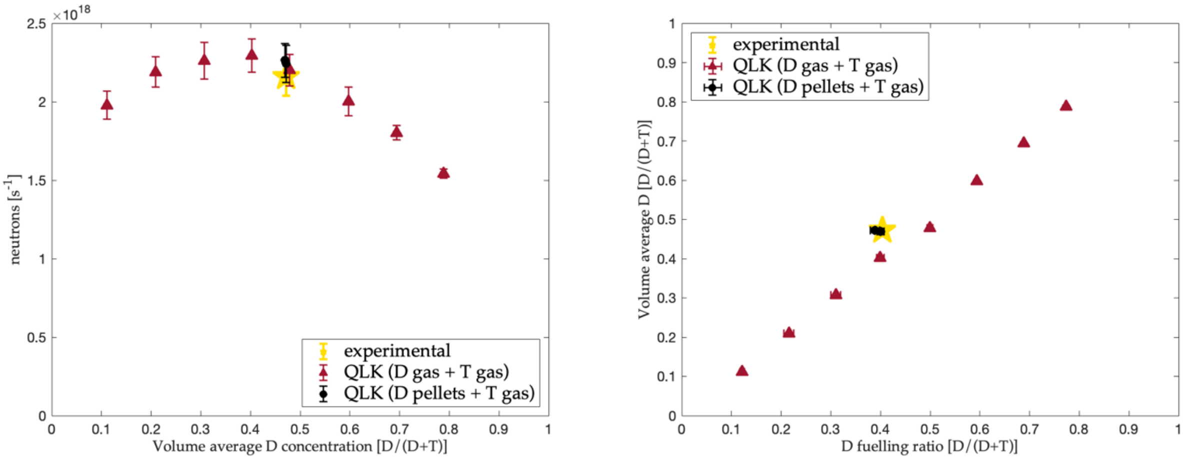

Figure 4. Comparison between experimental and modelled plasma mixtures, the dependence of neutron yield (left) and the fuelling ratio required to achieve the desired plasma composition (right).

($\psi_N < 0.4$) the fuelling injection associated to the NBI is dominant, while gas puffing is the dominant source from $\psi_N \geq 0.6$ to the edge. The effects of pellets depend on the injection parameters and can be used to control the plasma compositions as shown in [14]. Moreover, a different fuelling efficiency can be expected for different hydrogen isotopes. We use the continuous pellet model [15] with a gaussian source of D centred at the normalised toroidal flux coordinate ρ_n = 0.9 with a width equal to 0.15 for a total particle source (S_{pel} = 0.61 10^{22} s^{-1}) which matches the experimental data. In Fig. 4 we can compare the dependence of neutrons produced to the plasma composition and the agreement with the experimental data (left), while on Fig. 4 (right) the plasma composition as a function of the fuelling composition. It has to be noted that, thanks to the increased retention time of pellets with respect to the gas puff, it is possible to reproduce the experimental plasma mixture with a reduced D source with respect to the "gas only" cases. Despite the absence of D gas puff during the flat-top of the experiment, the main result of the pellet modelling is the need of a residual D source in the simulations to match the experimental plasma composition. Plasma main ion composition and sources are shown in Fig. 5. Under the assumption of D and T equivalent wall ionization source, we apply the estimate found in [16] to calculate the D wall ionization source $\phi^D \approx \phi^T = (\phi^D_{NBI} + \phi^T_{NBI})$. The residual D source obtained in this work is in agreement with the D wall ionization source calculated with [16] (c.f. Fig 5 – particle sources). This case corresponds to the lower limit of the pellet fuelling efficiency, by imposing the nominal pellet source (S_{pel} = 0.8 10^{22} s^{-1}) the residual D source required to match the experimental T concentration is reduced to around 1% of the total particle sources.

4. Conclusions

Before the JET D-T campaign we have studied the sensitivity of the baseline performance to the main ion plasma mixture obtaining the gas recipe required in the experiments.

We have validated JINTRAC – QuaLiKiz – SANCO simulations on actual D-T data modelling the particle sources as gas puff and modelling separately D pacing pellets and T gas puff, the simulations describe well the evolution of the experiment.

In the simulations we found a residual D source, which corresponds to a lower limit of the pellet fuelling, and it agrees with the D wall ionization source computed using the method described in [16].

Further work will investigate the sensitivity of these solutions to the assumptions done on the ETB, possibly using EIRENE for a more accurate estimate of the cold neutral sources (see for example the contribution [17] presented in this conference).

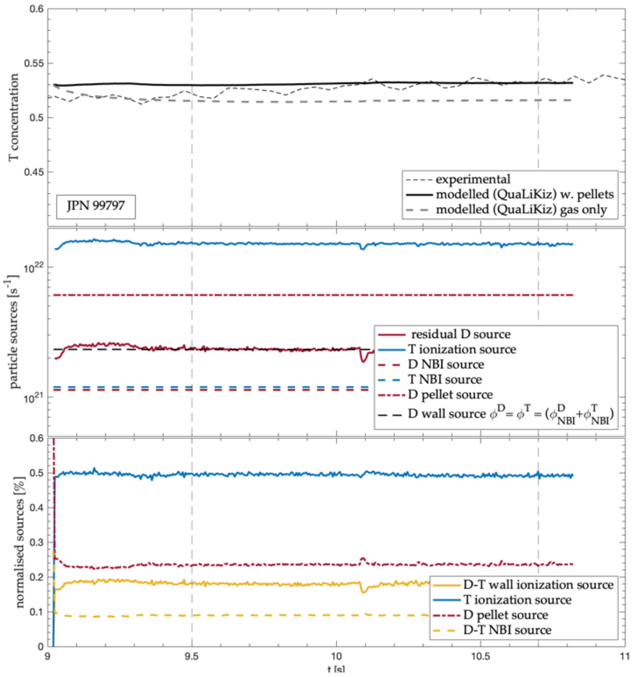

Figure 5.T concentration measured and simulated (top), simulated particle sources (middle), normalised particle sources with respect to the total particle sources (bottom).

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