Sensitivity studies on the TRANSP particle balance equation for JET deuterium and hydrogen-deuterium plasma discharges

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Predictive simulations of mixed plasma discharges, like DT plasmas, rely on validated and self-consistent models for particle transport. Such models have to be validated with interpretive analysis of existing experiments. JET DD and mixed HD plasma discharges with D-NBI heating have been chosen for analysis with the TRANSP code [1]. We quantitatively assess influence of TRANSP input parameters and terms entering into the particle balance equation on the computed plasma parameters, in particular on the neutron rate. Uncertainties in particle balance are particularly important for modelling of mixed-plasma discharges, for which the plasma composition can significantly modify simulation results.

There are three essential equations to compute the plasma composition. The particle balance equation Eq. (1) in TRANSP is solved for electrons and ions (for the ion fluid as a whole and individual species). Here n_s is the density of individual ion species, S_{bs} represents the NBI thermalisation source, G_{0s} and R_{0s} are the gas and the plasma recycling sources respectively, $F_s = -D_s \cdot \nabla n_s + V_s \cdot n_s$ implies the ion outflux. The plasma quasi-neutrality Eq. (2) and the plasma effective charge Z_{eff} Eq. (3) are the additional constraints.

$$\frac{\partial n_s}{\partial t} = S_{bs} + G_{0s} + R_{0s} - F_s \quad (1) \qquad n_e Z_{eff} = \sum_j n_j Z_j^2 \quad (2) \qquad n_e = \sum_j n_j Z_j \quad (3)$$

Uncertainties in prescribed parameters, like temperature profiles and Z_{eff}, or the thermal ion transport model in the ion outflux term affect the simulation results through the terms entering the particle balance equation.

Uncertainties in the prescribed profiles and parameters

Sensitivity studies are performed first for DD plasmas to eliminate effects related to calculation of transport coefficients in multi-ion species plasmas. JET #94612 DD plasma discharge, which overview is shown in Figure 1.(a)-(d), features NBI heating up to 3.8 MW. Plasma equilibrium and q profiles are provided by the equilibrium reconstruction code EFIT++. T_e and n_e fitted

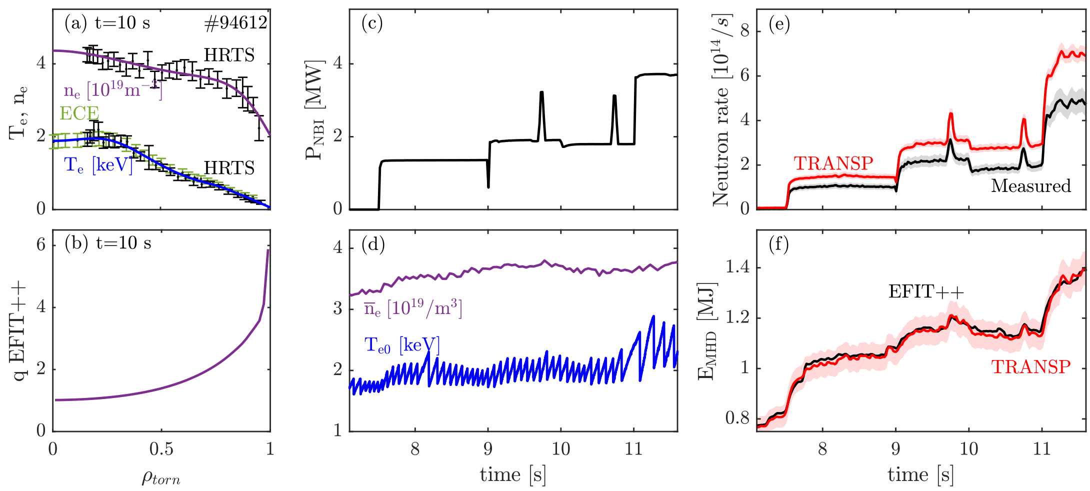

Figure 1. JET #94612 overview: (a) T_e and n_e profiles at 10 s; (b) EFIT++ q profile at 10 s; (c) NBI heating; (d) time traces of line averaged e^- density $\bar{n}_e$ and central temperature T_{e0}; (e) the neutron rate measured and computed by TRANSP; (f) the plasma energy computed by EFIT++ and TRANSP.

profiles are based on HRTS and ECE (for T_e) diagnostic measurements. NUBEAM [2] is used for fast ion tracking and provides the thermalisation source to the particle balance equation. Due to a lack of experimental data, impurity ions are assumed to be beryllium Be9 only, ion temperature T_i equals to T_e, and there is no plasma rotation. The plasma effective charge Z_{eff} is fixed at 1.2. TRANSP interpretive simulation results are in good agreement with experimental data for the plasma energy, however there is up to 40% discrepancy in the neutron rate as shown in Figure 1.(e)-(f). If there is good agreement in the computed and experimental plasma energy but not in the neutron rate, then it might indicate large uncertainties in T_i, Z_{eff} or plasma rotation profiles. Propagation of uncertainties in the prescribed profiles to the computed parameters is assessed in terms of the D line averaged density $\bar{n}_D$, the neutron rate and the plasma energy. The results of sensitivity studies are reported in Table 1. Electron temperature and density affect both the neutron rate and the plasma energy. However, the plasma energy is less sensitive to T_i, Z_{eff} and plasma rotation. Uncertainties in the prescribed profiles contribute to the neutron rate through beam-target and beam-beam fusion reactions whose cross-sections increase with T_i. Higher Z_{eff} results in lower D thermal ion density and a fewer number of beam-target fusion reactions. If the plasma rotation is included, the beam ion relative velocity is reduced and NBI deposition profiles are broadened, thus the neutron rate is decreased. In the numerical test with combined uncertainties

Parameter	$\bar{n}_D$, %	Neutron rate, %	Plasma energy, %
$T_e \pm 5\%$	-	±5	±3
$n_e \pm 5\%$	±5	<1	±5
$T_i \pm 10\%$	-	±6	±5
$Z_{eff} \mp 5\%$	±4	±4	<2
$\Omega_0 = 20\ krad/s$	-	-5	-
Combined	-9	-18	-12

Table 1. Sensitivity of $\bar{n}_D$, the neutron rate, the plasma energy on the uncertainties in the prescribed parameters.

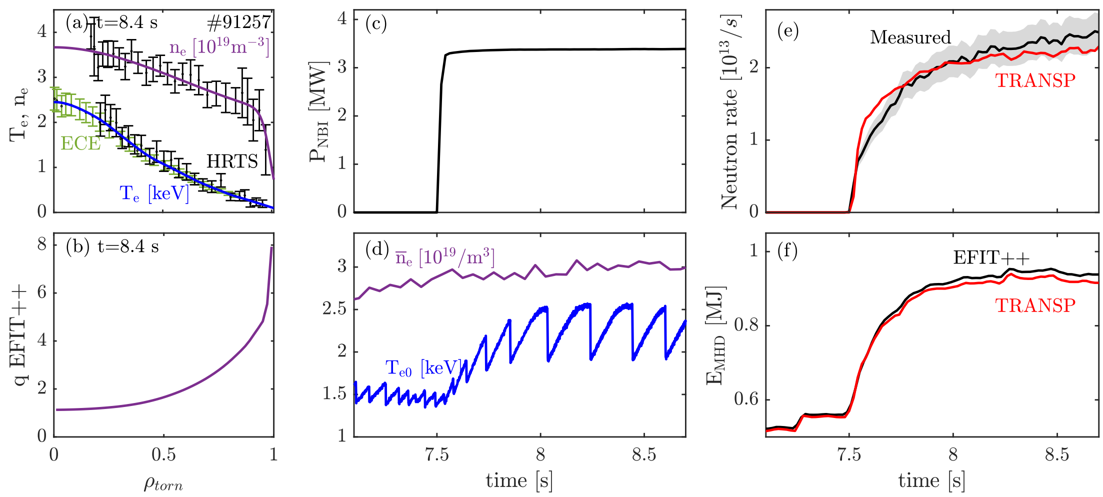

Figure 2. JET #91257 overview: (a) T_e and n_e profiles at 8.4 s; (b) EFIT++ q profile at 8.4 s; (c) NBI heating; (d) time traces of line averaged e^- density $\bar{n}_e$ and central temperature T_{e0}; (e) the neutron rate measured and computed by TRANSP; (f) the plasma energy computed by EFIT++ and TRANSP.

(T_e-5%, n_e-5%, T_i-10%, Z_{eff}+10%, Ω_0=20 krad/s), the neutron rate is reduced up to 18%. Uncertainties in the impurity content, T_i and plasma rotation can noticeably affect the assessment of plasma performance.

Uncertainties in the thermal ion transport model

In mixed plasma discharges with prescribed profiles based on diagnostic measurements of high quality, one still can expect some uncertainties coming from a thermal ion transport model. JET mixed plasma discharge #91257 has been chosen for TRANSP interpretive analysis. HD thermal ion ratio is known at the plasma edge by isotopic measurements: 96% H, 4% D at 7 s with a 2% increase in D thermal ion density n_D at 9 s. As shown in Figure 2.(a)-(d) there is D-NBI heating up to 3.2 MW. Similar to #94612, plasma equilibrium and q-profiles are computed by EFIT++, Be9 is the only impurity ions, Z_{eff} = 1.2, T_i=T_e, plasma rotation is not included. T_e and n_e profiles are fitted from HRTS and ECE. Sawtooth crashes are present in plasma starting 7.5 s, however their modelling is not included to analysis. Using isotopic measurements at the plasma edge, one can prescribe n_D as a fraction of electron density n_e as n_D=0.03 – 0.047·n_e. In this case good agreement is observed for the measured and computed neutron rate (within 10%) and the plasma energy (Figure 2). Since the HD density ratio is measured at the edge, for the core plasma it should be taken with some level of uncertainty. Note that if n_D is prescribed then its time evolution is not computed consistently with the NBI thermalisation source. Uncertainties in T_i, Z_{eff} and plasma rotation are contributing to the computed neutron rate too.

In the absence of isotopic measurements, for example in case of predictive studies, one has to choose a transport model for each individual ion species to solve the particle balance equation Eq. (3). One of the natural assumptions is to assume the same diffusivity for electrons

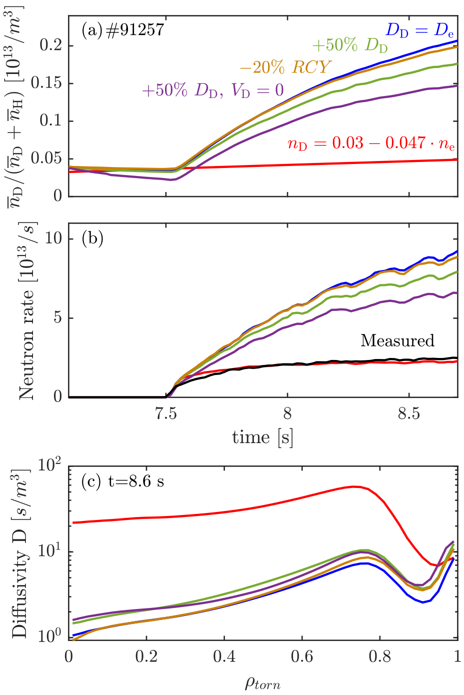

Figure 3. JET #91257 transport model tests (a) the D relative fraction; (b) the neutron rate; (c) diffusivity D_D profile at 8.6 s.

and thermal ions D_D=D_e. In this case, as shown in Figure 3, a significant difference between the time evolution of the measured neutron rate and the neutron rate computed by TRANSP is observed. Increased diffusivity D_D results in reduced D thermal ion density, thus the neutron rate. Excluding the convection V_D term from the ion outflux F_D leads to even lower n_D. The plasma recycling affects not only transport of thermal ions at the plasma edge but in the core region too. Diffusivity D_D computed from prescribed n_D significantly exceeds electron diffusivity D_e. Therefore, the assumption on the similar transport of e^- and ions is not accurate and results in accumulation of thermal D ions near the plasma axis. To assess influence of the ion outflux term F_D and recycling R_D on the computed $\bar{n}_D$ multiple sensitivity tests have been performed. An 8% increase in F_D results in a 30% decrease in $\bar{n}_D$, whereas plasma recycling has much less influence. The ion outflux has strong impact on the computed $\bar{n}_D$ and, consequently, the neutron rate.

Conclusion

Uncertainties in prescribed profiles can propagate to simulation results and significantly affect them, in particular the neutron rate, the plasma energy and densities of individual ion species. With profiles prescribed from high quality measurements there are uncertainties coming from the ion transport models. Decoupling measurements and model contribution to the simulation results is not a straightforward task. It has been found that assuming similar transport properties for electrons and thermal ions might not be correct in certain cases of mixed plasma discharges with on-axis NBI heating. Increased transport of thermal D ions is expected according to sensitivity studies on the computed plasma composition and comparison of the computed and measured neutron rates. The thermal ion transport model used for the ion outflux has a large effect on the calculated ion densities when multiple background species are present.

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