Integrated modelling of ITER scenarios with D-T Mix control

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Abstract

An analysis of D and T fuelling requirements for DT mix control for ITER H-mode plasmas is performed including the use of pellet injection for core plasma fuelling and ELM pacing with gas fuelling for edge density and divertor power load control based on the ITER fuelling and pumping systems capabilities [1]. Simulations are carried out by 1.5D core transport modelling with individual treatment of D and T ions and discrete pellet modelling [2] with ASTRA suite of codes [3]. Plasma parameters at the separatrix and particle sources from gas puffing are derived from scalings based on SOLPS simulations [4]. The width and height of the pedestal were fitted following EPED1+SOLPS scaling prediction [5]. The anomalous transport was calculated by the TGLF model [6]. The TGLF model is benchmarked against the GLF23 model [8] predictions for a comparable case of DD ITER operation. The studies of sensitivity of the DT mix and density control to pellet injection parameters is carried out.

Transport model description

The simulations carried out by 1.5D core transport modelling with ASTRA suite of codes [3] comprise self-consistent modelling of 2D equilibrium and 1D transport for densities of the charged particle species, electron and ion temperatures T_e, T_i, and poloidal magnetic flux, ψ. Particle transport solver was modified to calculate 4 individual ion species, n_D, n_T, n_{He}, n_{Ne}, including individual treatment of D and T ions and calculation of the electron density from the quasi-neutrality condition: $n_e = \Sigma Z_k n_{i,k}$, i,k = D, T, He, Ne. Boundary conditions at the separatrix and particle sources from gas puffing are derived as functions of the particle and power fluxes to the SOL based on the SOLPS simulations [4]. The anomalous diffusivities in the edge transport barrier additional to the neoclassical transport are tuned to provide the time averaged pedestal pressure following EPED1+SOLPS scaling prediction [5]. Additionally to the neoclassical transport coefficients [7] we used the anomalous coefficients calculated by multi-ion version of the TGLF module [6], which takes into account nonlinear interaction between D and T main ion species and applicable to the reverses density gradients. Continuous pellet fuelling approximation used earlier [1], [5] is replaced by more realistic discrete pellet approximation [2]. Particle and energy loss with ELMs are simulated in the continuous ELM approximation [1]. We restrict our consideration to the H-mode operation.

DT operation with discrete D, T and DT pellets

As the initial target plasma for simulation with discrete D,T pellets we use the relaxed profiles, T_e, T_i, n_e, n_D, n_T, predicted by TGLF for continuous particle source at $n/n_{GW} \sim 0.5$, $n_T/n_D < 1$ (see solid red lines in figures 2a,b; 3a,b). All DT cases are simulated with the same averaged particle source from High Field Side (HFS) pellets, $S_{HFS} \sim 2\ 10^{22}\ s^{-1}$, and varying combinations of the pellet size, V_p= 50 mm^3, 90 mm^3, frequency, f_p = 2, 4, 8 Hz, composition, DT, D+T and order of pellet injection D+T, T+D.

For 15 MA DT H-mode operation with discrete D, T and DT pellets particles the behaviour predicted by TGLF is strongly nonlinear. Evolution depends on the pellet size, order of D and T injection and initial D:T ratio (figures 1, 3). The difference between n_T and n_D profiles has the major impact on transport of these components. Fast penetration of the tritium to the core, Δt_{elaps}~ 5 s, does not cool plasma (figure 1c). For the same fuelling rate, $S_{HFS} \sim 2\ 10^{22}\ s^{-1}$, the injection of 50 mm^3 HFS pellets in different order and combinations causes the oscillations of n_T/n_D and Q, or the saturation for D+T simultaneous injection with f_p = 4 Hz, but seems to be not sufficient for the density ramp up (figure 3). The ramp-up of plasma density with 50 mm^3 HFS pellets requires higher fuelling rates with increased pellet frequency, $f_p > 4$ Hz.

For DT full field operation in ITER TGLF predicts relaxation of n_D, n_T, T_e, T_i to the rigid rather than stiff profiles (for radial derivative of each profile A: A'= const, rather than $\ln'(A)$= const) (figures 2,3). The central n_0, T_0 values with profile rigidness (01) are less sensitive to the changes in pedestal values n_p, T_p than those with profile stiffness (02): $\Delta T_{01} \sim T_p\, \Delta n_p/n_p$ v.s. $\Delta T_{02} \sim T_0\, \Delta n_p/n_p$, thus, $\Delta T_{01}/\Delta T_{02} \sim T_p/T_0 << 1$.

DD operation with gas fuelling

The GLF23 model is valid for a single main ion and a single impurity species. For this reason we chose the DD ITER operation for benchmarking of the TGLF vs the GLF23 predictions. To exclude the impact of the suprathermal ions on the anomalous transport we made simulations for the case B/I_p = 1.8T/5MA with the central EC heating, $P_{EC}(X=0.2)$= 20 MW, (here and in the figures X is a square root of the normalized toroidal flux). For such low magnetic field this power is sufficient for the H-mode operation at low density, $n_e \sim 2\ 10^{19}m^{-3}$. For 5 MA DD H-mode operation the HFS pellet fuelling appeared to be not required. The Low Field Side (LFS) pellet injection was assumed for ELM pacing. For 20 MW of central EC heating the TGLF predicts T_i, n_e profiles similar to GLF23 due to similar χ_i and D_e in the gradient zone and low equipartition, $P_{ei} \sim (T_e-T_i)/T_e^{3/2}$, and high ion heat diffusivity, $\chi_{0i,TGLF} >> \chi_{0i,GLF23}$, predicted by TFLF in the heating zone, X <0.2. For the electrons TGLF predicts $\chi_{e,TGLF} \approx 0.5\ \chi_{e,GLF23}$, in the gradient zone and therefore higher central electron temperature $T_{e0,TGLF}/T_{e0,GLF} \sim 1.5$.

Discussion

Note that our simulations for DT operation were carried out for $n_D \sim n_T$. It is necessary to study the possibility to control the fuel mix from $n_D >> n_T$ to $n_D \sim n_T$ operation. Dependence of the ramp-up speed on the initial n_T, n_D ratio should be studied. Predicted mutual impact of the fuel components on their transport can make fusion power and density control rather challenging. Such predictions require experimental verification.

The TGLF model predicts strong modification of the density, temperature and current profiles in the region of the edge pedestal for the HFS pellet fuelling. It would be necessary to analyse how such modification affects the screening of plasma against the tungsten accumulation as well as the effect on the stability of peeling-ballooning, kink and other MHD modes and their potential impact on the plasma performance.

It would be useful to analyse the ranges of plasma parameters where the anomalous transport keeps stiff or rigid plasma profiles and check it experimentally.

The discrepancy between GLF23 and TGLF predictions is of interest for further investigation for better assessment of the ITER and DEMO plasma performance.

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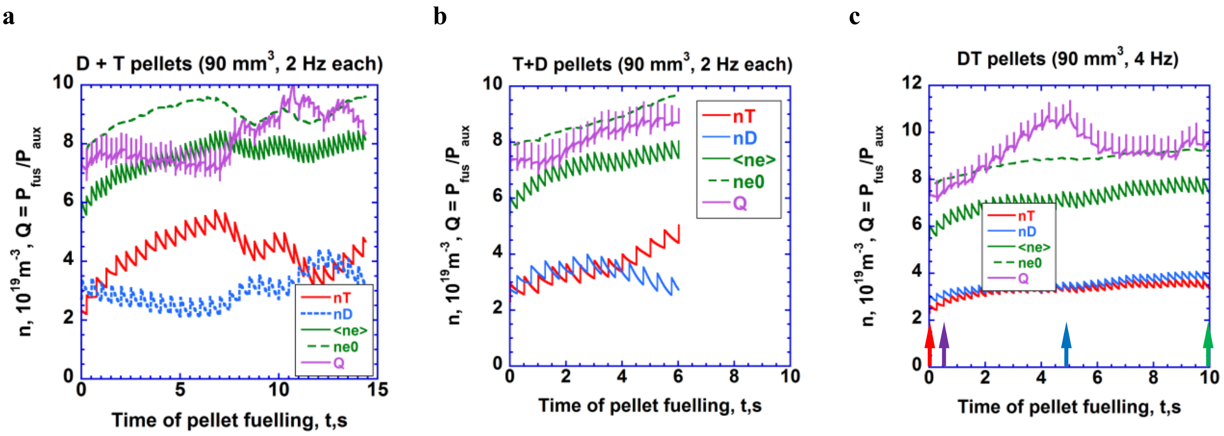
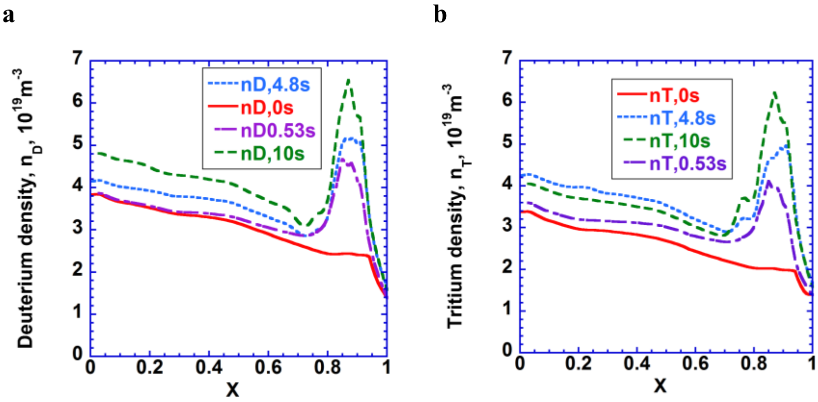


Figure 1. Sensitivity to the order of the D&T pellets with $S_{HFS} \sim 2\ 10^{22}\ s^{-1}$, $V_p = 90\ mm^3$(a)D then T pellet, (b)T then D pellet, (c)50:50DT pellet predicted by TGLF for $B/I_p = 5.3T/15MA$ DT ITER operation.



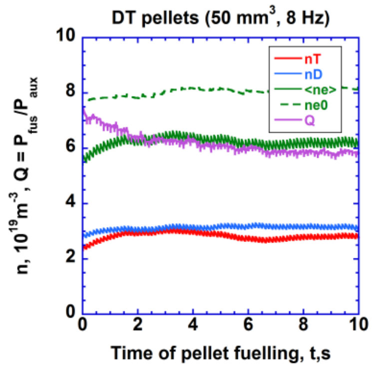
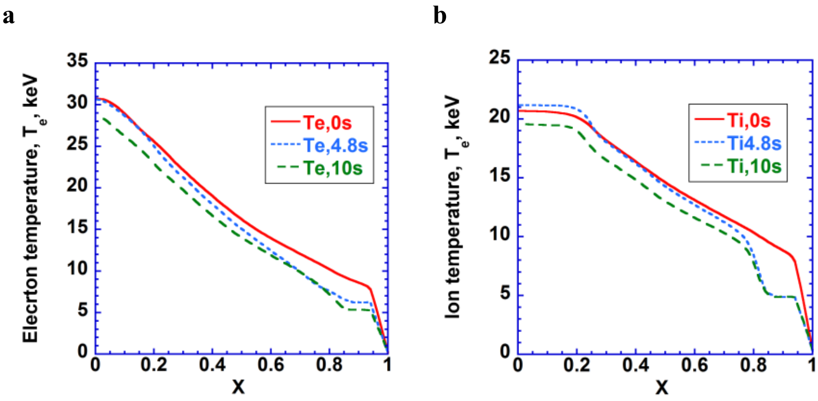


Figure 2. Density profiles of deuterium (a), tritium (b) predicted by TGLF for the case from figure 1c with DT pellet fuelling

Figure 3. Same as in figure 1c with $V_p = 50\ mm^3$, fp=8 Hz



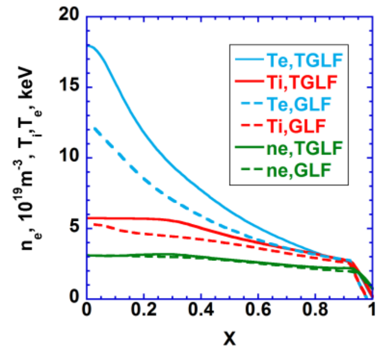


Figure 4. Electron (a) and ion (b) temperature profiles predicted by TGLF for the case from figure 1c with DT pellet fuelling

Figure 5. DD operation in ITER for $B/I_p = 1.8T/5\ MA$