Integrated modelling of multiple isotope pellet cycles at JET

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Experimental results

In future power plants, a 50%D - 50%T ratio will be needed in the core. In present tokamaks the plasma is usually fuelled through gas puffing, but such a method will not be efficient in future machines. A viable alternative is the use of frozen pellets. It is therefore important to understand the dynamics of a pellet injection, for example regarding the timescale for the penetration of the different isotopes. An experiment, pulse #91393, was performed at JET with the aim of using pure Deuterium pellets to reach a 50%D - 50%H ratio, starting from a pure hydrogen plasma [1]. The discharge had plasma current $I_p = 1.4MA$, toroidal field $B_T = 1.7T$, NBI and ICRH heating for a total power of $P_{aux} = 9.6MW$. The Hydrogen gas was puffed with a rate of $\Phi_{H2,gas} = 6.7 \times 10^{21} at/s$, while the deuterium pellets were injected with a frequency of $f_{pel} = 9.7Hz$, corresponding to a pellet fuelling rate of $\Phi_{pel} = 8.2 \times 10^{21} at/s$. In this experiment the size of the pellets, scaled to the plasma volume, leads to shallow deposition and transient inverted density profile, similarly to what is expected in ITER. The experiment managed to reach the desired core isotope composition, measured by Charge Exchange and neutron rate. The isotope particle transport coefficients were determined by interpretative modelling using the semi-empirical Bohm-Gyrobohm anomalous transport model [1], with the particle diffusivity calculated as $D = C_D \times \chi_{BgB}$. An anomalous pinch was included as $v/D = -C_v r/a^2$. These coefficients were varied between $2 < C_D < 7$ and $0.2 < C_v < 0.6$ and fitted to reproduce the electron and Deuterium density evolution. The results indicate $D_D \sim \chi_{eff}$, in line with previous experimental observation of fast isotope mixing with T-trace [2] and mixed H-D [3]. Theoretical analysis explained the fast isotope mixing by $D_i \gg D_e$ and $V_i \gg V_e$ in ITG dominated plasmas [4]. Integrated modelling was performed on stationary state, multiple isotope discharges, where the NBI and gas puff were varied to study the effect of the particle sources on the isotope profiles [5]. The successful comparison of the integrated modelling with the experimental data validated the anomalous transport model QuaLiKiz [6] for this effect.

Integrated modelling

The integrated modelling was performed within the JETTO [7] framework, with NCLASS [8] as the neoclassical transport model, QuaLiKiz [5] as the anomalous transport model, PENCIL [9] and PION [10] for NBI and ICRH heating, SANCO [11] for the impurity transport, FRANTIC [12] for the neutral source and HPI2 [13] for the pellets. Four pellets were modelled, from $t = 10.1$ to $t = 10.7$. The equilibrium was evolved self-consistently, starting from a q-profile obtained from constrained EFIT [14] and then evolved using ESCO [7]. The initial profiles were obtained through Gaussian Process Regression [15] on the experimental data, averaged for 200ms just before the first pellet. The pedestal, $0.94 < \rho < 1$, was evolved using a "continuous ELM model", which parameters were adjusted to match the experimental stationary state and evolution of the pedestal. First principle modelling was performed for $0.2 < \rho < 0.94$, while for $\rho < 0.2$ modest ad-hoc transport was artificially added. Outward particle convection was added as $v = v_0 \times exp\{-(t - t_{pel})/\tau + (r/a - 1)/\Delta\}$ where v_0, τ and Δ are parameters fitted to match the final total density. The need for this term was recognized in previous works [16].

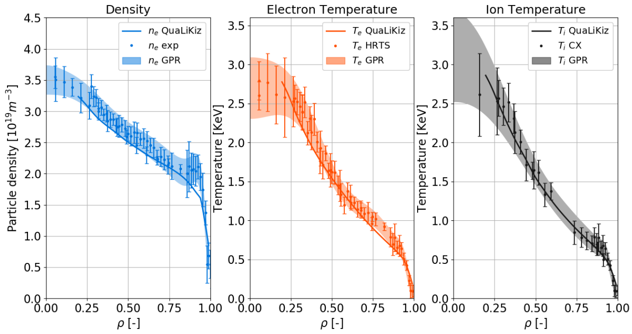


Figure 1: JETTO-QuaLiKiz prediction for density and temperature profiles before the first pellet ($t = 10.187s$). The shaded area represents the GPR confidence interval, with the experimental data averaged between $49.5s < t < 50.15s$. The solid line is the JETTO-QuaLiKiz prediction

The modelled n_e, T_e and T_i were found to be in agreement with the experimental values before the pellet train. This is shown in figure 1, while the modelled profiles just after the first pellet are shown in figure 2. The continuous ELM model coefficients were then modified in order to match the evolution of the density at the top of the pedestal.

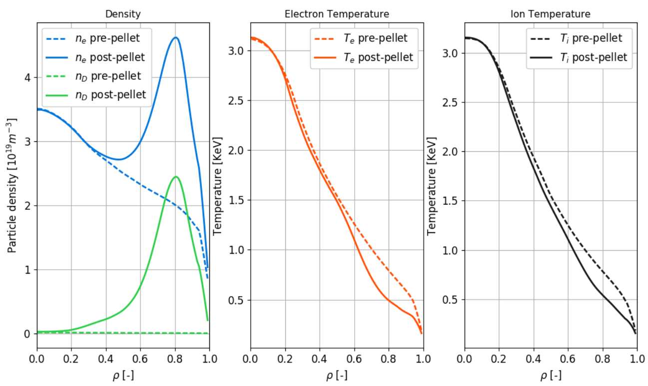


Figure 2: Modelled density and temperature profiles before ($t = 10.187s$) and 8ms after ($t = 10.192s$) the first pellet.

The measured interferometer lines of sight were compared with the modelled ones, reconstructed using a synthetic diagnostic within JETTO. Only the line of sight looking

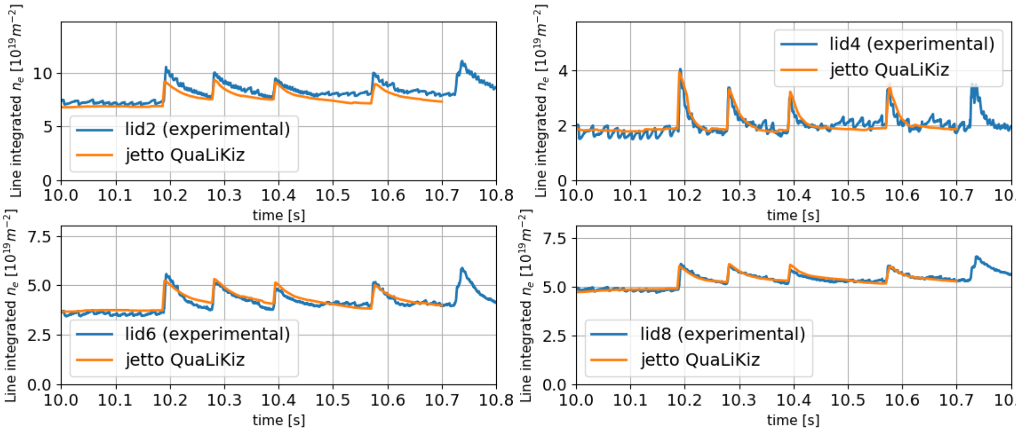


Figure 4: Four different experimental interferometer lines (solid blue lines), compared with a synthetic diagnostic in JINTRAC (solid orange lines). The pellets are injected at $t = 10.187, 10.278, 10.390, 10.572$.

at the edge, lid4, was matched, but good agreement was automatically found in all channels. The final total Deuterium concentration was matched adjusting the recycling coefficient for deuterium in FRANTIC. The evolution of the central deuterium density was then compared with the experimental measurements. This is shown in figure 3. Crucially, the fast timescale for the deuterium penetration after the first pellet is reproduced in the model. This timescale depends on the turbulent regime and the agreement is a validation of the fast isotope mixing and of the codes used.

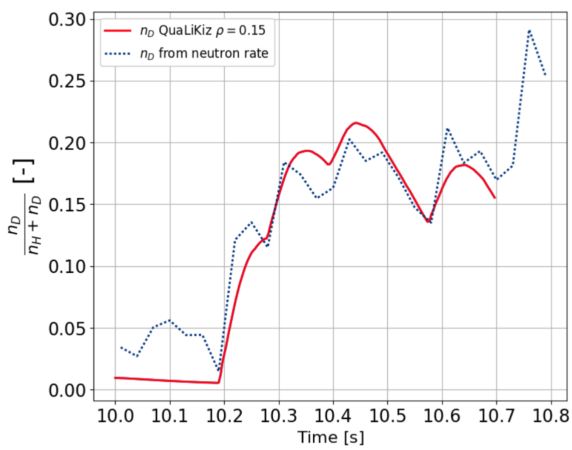
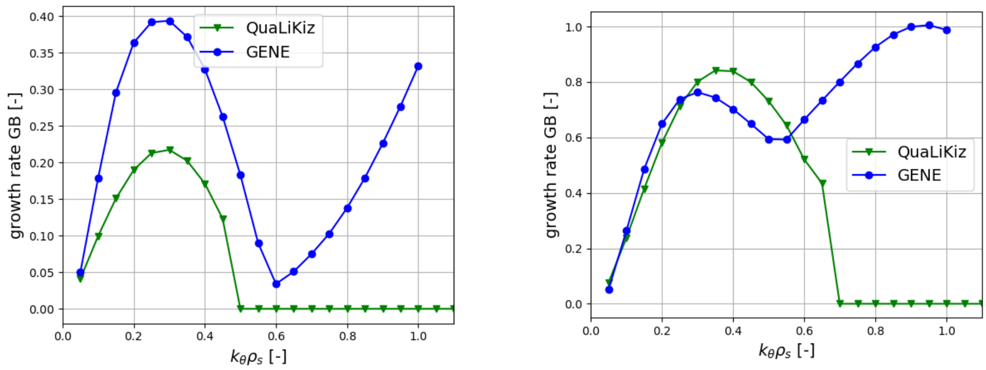


Figure 3: Central n_D inferred from the neutron rate (blue dashed line) compared with n_D content calculated by JETTO-QuaLiKiz at $\rho = 0.15$

Gyrokinetic analysis pre and post pellet phases

TEM was found to be the dominant instability by QuaLiKiz after the pellets for $\rho > 0.8$, in conjunction with a very large negative density gradient. This causes a large particle flux directed outwards. On the other hand, ITG was not completely stabilized by the strong positive density gradient that develops between $0.6 < \rho < 0.8$ after the pellets, as found in previous studies [17]. The cooling caused by the adiabatic ablation of the pellets, in fact, results in a locally steeper R/L_T gradient, which balances the stabilizing impact of negative R/L_n, which occurs for ITG modes with kinetic electrons. This is key since the fast Deuterium penetration depends on the ITG drive. To verify this important observation, QuaLiKiz was compared



(a) (b)

Figure 5: Comparison between the normalized growthrates from QuaLiKiz (green triangles) and growthrates from GENE (blue circles). The parameters for both simulations are taken from the JETTO simulation at $\rho = 0.68$ just before (a) and 5ms after (b) the first pellet

with the higher fidelity code GENE for the parameters encountered in the integrated modelling simulation. The comparison was between linear GENE and QuaLiKiz growth rates, since comparison of fluxes would require nonlinear GENE and would be more computationally expensive. The comparison between the two codes is shown in figure 5a and 5b respectively before and 5ms after the pellet. TEM is found by GENE for $k_\theta \rho_s > 0.6$ and is absent in QuaLiKiz, but ITG is responsible for most of the transport in both cases, thus validating the integrated modelling findings.

Conclusions

Despite the absence of predictive capabilities for $\rho > 0.94$, the JETTO integrated modelling framework with QuaLiKiz as the anomalous transport model and HPI2 as the pellet deposition model proved to be suitable in simulating multiple pellet injections. The experimentally observed [3] and theoretically expected [4] fast transport mixes of isotopes was further validated, now including the dynamics of the process. The compensation between R/L_n stabilization and R/L_T destabilization is shown to lead to ITG drive and isotope mixing after the pellets.

References

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