

First-Principle-Based integrated modelling of multiple isotope pellet cycles at JET

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Due to edge opacity, future tokamaks will rely on injection of cryogenic pellets for plasma fuelling. Maintaining the desired density and isotope composition crucially depends on the transient plasma response to pellet injection, motivating dedicated studies for increased understanding and predictive capabilities. In a recent experiment at the Joint European Torus (JET), Deuterium pellets were injected in a pure Hydrogen plasma, allowing multi-isotope transport analysis. The size of the pellets, scaled to the plasma volume, lead to shallow deposition and transient inverted density profile, similarly to what is expected in the International Thermonuclear Experimental Reactor (ITER).

The desired isotope composition was reached and the isotope particle transport coefficients were determined by interpretative modelling [1], using the semi-empirical Bohm-Gyrobohm anomalous transport model, and matching the transient response of the D-D neutron rates. The rapid increase in the neutron rate during the pellet train, particularly following the initial injection, led to an inference of relatively large D_D/χ_i values, and isotope mixing timescales faster than the energy confinement time. Such findings are consistent with previous experimental observations of fast isotope mixing, attributed to large ($D_i/D_e > 1$, $|V_i| > |V_e|$) ion particle transport coefficients due to Ion Temperature Gradient (ITG) modes [2]. While in a pure plasma this phenomena is impossible to observe due to ambipolarity, in a multi-ion plasma the different ions can interchange at different timescales to the electron particle transport. This is most prevalent during transient, non-stationary states, such as during pellet injections due to the significant modifications of the local density gradients. Modifying the pellet isotope ratio compared to the background isotope ratio leads to rapid mixing of ions, significantly modifying the core isotope mix without affecting the time averaged electron profile.

This contribution applies the JINTRAC [3] integrated modelling framework, already proven to be effective in capturing the fast isotope mixing effect in experiments with NBI and gas-puff fuelling [4]. The use of the quasilinear gyrokinetic model QuaLiKiz [5, 6] for turbulent transport ensures a first-principle-based approach, taken here for the first time in the modelling of pellet cycles. It is however crucial to stress that the predictive capabilities of this approach are limited to the core, while the transport in the pedestal region had to be prescribed. Specifically, the particle and heat transport coefficients in the pedestal region were adjusted to match the interferometer measurements. Given this constraint, the modelled and experimental pre-pellet T_i , T_e and n_e are well reproduced, as well as the neutron rate evolution. The deuterium transport timescale following D pellet injection was found to be on the order of the energy confinement time. In particular, the rapid evolution of the neutron rate after the first pellet was correctly reproduced in the model (Figure 1). This timescale depends on the turbulent regime and the agreement is a validation of the fast isotope mixing and of both QuaLiKiz and the pellet ablation model, HPI2 [7].

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The identification of the correct turbulent regime by QuaLiKiz underlines the results. Depending on the radial position and on the phase of the pellet cycle, different modes are excited. TEM was found by QuaLiKiz to be the dominant instability after the pellets for $\rho > 0.8$, in conjunction with a very large negative density gradient. This causes a large particle flux directed outwards, in line with expectations from previous works [8]. Both ITG and ETG are stable between $0.5 < \rho < 0.8$, where the density gradient is positive, for $\sim 4ms$ following each pellet injection. Immediately after, the cooling caused by the adiabatic ablation of the pellets results in a locally steeper R/L_T gradient, balancing the stabilizing impact of negative R/L_n which occurs for ITG modes with kinetic electrons. This is key since the fast mixing of the deuterium depends on the ITG drive. To verify this important observation, QuaLiKiz was compared with the higher fidelity code GENE [9] using as an input the parameters encountered in the integrated modelling simulation. Good agreement was observed between the two codes. Since the fast isotope mixing depends crucially on ITG turbulence, additional simulations were carried out with artificially reduced collisionality by a factor 10, consistent with ITER and reactor collisionality regimes, to gain insight on whether ITG is maintained at lower collisionality when Trapped Electron Modes (TEM) are further destabilized. In these simulations the turbulent regime changes, as expected for future reactors [10], to a mixed ITG-TEM regime and the density peaking increases. However, ITG at lower wave numbers is still destabilized by the pellet and the timescale for the deuterium penetration is almost unchanged.

These results are promising with regard to reactor fuelling capability and burn control.

References

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