Modelling of D/T ratio control experiments in JET

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Abstract: This study follows the work presented in [1], which demonstrated that JETTO simulations based on simplified Bohm–gyroBohm transport models can successfully reproduce key plasma parameters, including electron density, the steady-state deuterium–tritium (D/T) ratio, and neutron rate evolution for JET D/T ratio control experiments [2]. The modelling work was further extended through the first implementation of a full real-time (RT) D/T ratio controller using pellet injection within the JETTO workflow. In addition, a new controller for the line-integrated density, n_{eL}, was introduced. A novel investigation of the interaction between the two controllers, based on the analysis of three distinct network configurations with different priority assignments, is presented. It is shown that combining these controllers within a single network is not straightforward, as the corresponding actuators are intrinsically coupled and can influence each other. It is found that, while some networks perform reliably when controlling either n_{eL} or the D/T ratio individually, they fail to maintain effective control of both parameters simultaneously under varying operating conditions. This underlines the importance of systematic validation of RT controllers prior to deployment. The workflow proposed in this study provides a robust and reliable framework for such assessments and is therefore strongly recommended for the evaluation of future control schemes.

Introduction

Controlling the D/T ratio in future fusion experiments is crucial for optimising the fusion performance. The maximum thermonuclear fusion rate is achieved at a D/T ratio of 0.5/0.5. For D/T ratios in the range 0.4/0.6 to 0.6/0.4, the reduction in reaction rate is small; however, larger imbalances, such as a D/T ratio of 0.3/0.7, significantly degrade fusion performance [1]. This highlights the importance of maintaining the D/T ratio close to 0.5/0.5 in future thermonuclear fusion operations.

The JET DTE3 campaign [3] achieved the first successful RT feedback control of the D/T ratio [1], [2], while also highlighting practical challenges such as delays and nonlinearities in fuelling systems, pellet reliability, and sensitivity of NBI deposition to plasma conditions. These issues impact controller performance and are expected to be relevant for future devices such as ITER, SPARC, DEMO, and STEP. To address this, modelling efforts using the JETTO framework showed that simplified transport and source models can effectively reproduce and predict RT controller behaviour without requiring full SOL and core physics fidelity [1]. Following this, the present study extends previous work by implementing a full RT D/T ratio and density controller by means of pellet fuelling in JETTO, thus enabling analysis of combined control strategies. The results demonstrate the value of simulation-based validation workflows for developing and optimising control systems prior to experimental deployment.

Numerical analysis

The results presented in this paper are based on predictive JETTO simulations, validated against experimental data where possible. JETTO, recently upgraded to interface with the Integrated Modelling & Analysis Suite (IMAS), serves as the core numerical tool, with data exchange handled through the standardized Interface Data Structure (IDS). This framework enables coupling with external actors, independent computational modules that extend JETTO capabilities to include RT control functions and advanced workflows. Actors can interact with JETTO during simulations, allowing the implementation of feedback control strategies. In this study, dedicated actors were developed to regulate the D/T ratio and line-integrated density, n_{eL}, following a staged approach that included design, testing, and validation against JET DTE3 experiments. The Neutral Gas and Plasma Shielding (NGPS) pellet model was selected as a practical compromise between physical fidelity and computational efficiency.

The control strategy is based on dynamic pellet injection, with pellet requests updated at fixed time intervals of 0.025s (40 Hz), while their size, species, and composition are determined in real time by the control actors. Initially, the system controlled only the D/T ratio by injecting pure D or T pellets depending on the deviation of the volume-averaged T fraction, $<X[T]>=<n_T>/<n_D+n_T>$ from the target range (0.4–0.6). This was subsequently extended to include n_{eL} control via mixed D/T pellets when the density falls below a prescribed reference. After validating the individual controllers, combined control schemes were implemented to simultaneously regulate both parameters, with pellet type determined by deviations from reference values and assigned control priorities. This integrated approach enables systematic investigation of multi-variable control strategies within a predictive modelling framework.

Experimental data and workflow validation

A detailed description of the experimental data and diagnostics used for validating the numerical tools is given in [1], based on dedicated JET DTE3 campaign pulses where the D/T ratio controller was tested under fully operational conditions [2]. In these experiments, the D/T ratio was varied in real time from approximately 0.7/0.3 ($<X[T]>\approx0.3$) during 4.5–7.5 s to about 0.4/0.6 ($<X[T]>\approx0.6$) during 7.5–10 s, with pulse #104651 (1.4 MA/1.7 T) as the primary case, where an initially D-rich phase was established via pellet injection and later shifted using T gas injection under RT control.

In fusion plasmas, D and T sources arise from gas injection/recycling, NBI fast ion thermalisation, and pellets, the latter being central to this study's RT control implementation. Simulations use initial conditions from #104651 at 7.2s, core particle transport, known from extensive JET and literature studies to be predominantly anomalous and Ion-Temperature-Gradient (ITG)-driven, is modelled using Bohm/gyro-Bohm formulations, with coefficients A1=8 and A2=4 chosen to match experimental behaviour [1]. Compared to earlier work using continuous pellet model in JETTO code, the present NGPS-based model reproduces key observables well, including core and pedestal densities, line-integrated density, neutron rates, and $<X[T]>$ evolution, as well as density profiles, showing good agreement with measurements.

Modelling of D/T ratio and n_{eL} controllers

The RT control of the actuators was carried out in three stages. The initial phase focused on the development of a D/T ratio controller based on the injection of pure D or T pellets. At this stage, no real-time feedback on density was implemented. The results from this test demonstrated the capability of the proposed control scheme. The next stage in the development of the density and D/T mixture control actors focused on pure density regulation using mixed pellets with a composition of D/T = 0.5/0.5. In this phase, no real-time feedback on the D/T ratio was implemented. A strong agreement was observed between the predicted density evolution for the requested n_{eL}=8.5e19 m^{-2} and the experimentally measured profiles from discharge #104651, in which D pellet injection with the prescribed parameters was applied. The agreement remained reasonably good beyond t=7.5s, during which, in discharge #104651, D pellets were replaced by T gas injection. Effective control of n_{eL} was achieved with the selected pellet size. This indicated that, for the pellet size considered, injection frequencies at or below 40 Hz are adequate to maintain the density within

The ultimate objective of this study is to demonstrate a control network capable of simultaneously regulating both the electron density and D/T ratio with pellet injection. However, combining these two control schemes within a single network is not straightforward as the corresponding actuators are intrinsically coupled and can influence each other. For this reason, control strategies that impose a prioritisation between the two objectives are considered.

Results from a particular network, which prioritises D/T ratio control are presented here. It first evaluates the D/T ratio and, if <X[T]> lies outside the target range [0.4, 0.6], acts by injecting homogeneous D or T pellets as required. Once this condition is satisfied, the network shifts priority to the control of n_{eL} through the injection of mixed D/T pellets. A block diagram of this network is shown in figure 1 a). This configuration was tested for two reference density values, n_{eL} req#1=8.5e19 m−2 and n_{eL} req#2=1e20m−2. The corresponding results are presented in figure 1 b).

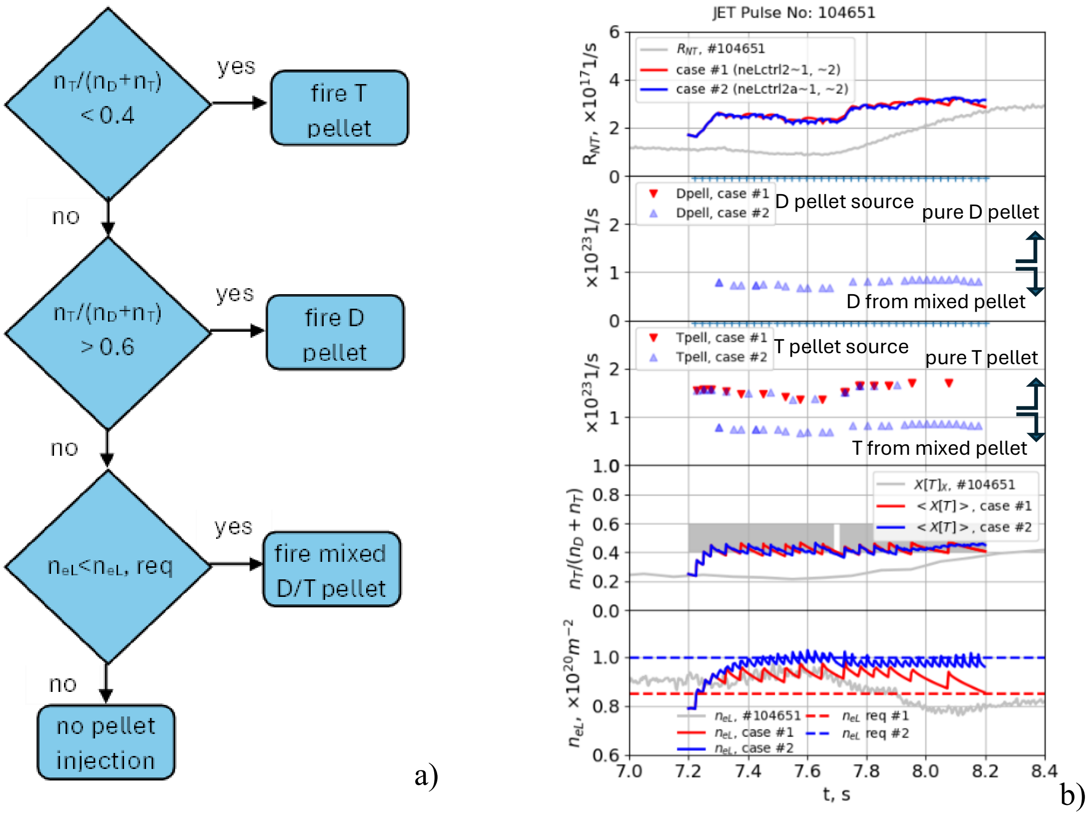

Figure 1: a) Proposed block-diagram for RT control network on D/T ratio and n_{eL}. b) Results of two JETTO simulations of RT network controlling D/T ratio and n_{eL}. Case #1 in red is for requested n_{eL}=8.5e19m^{-2}, while case #2 is for requested n_{eL}=1e20m^{-2}. Time traces from top to bottom provide calculated and measured (grey) neutron rates R_{NT}, D and T gas fuelling rates from the pellets, measured $X[T]_X$ (grey) and calculated <X[T]> and line integrated calculated and measured (grey) density, n_{eL}. D/T ratio was controlled for <X[T]> in the range [0.4, 0.6] (shaded area in X[T] graph in b)). The arrows shown in the pellet rate plots are approximate and are intended to distinguish between pellets originating from the mixed D/T source and those corresponding to pure D or T injections.

This network handles the case with the lower requested n_{eL}, case #1. In this regime, n_{eL} is sustained above n_{eL} req#1, while the D/T ratio is rapidly established within the target range and maintained throughout the simulation via the injection of pure tritium pellets. In general, of the networks investigated in this study, this one demonstrated the best performance in simultaneously controlling both the D/T ratio and n_{eL}. In this case, both the target density and the desired D/T ratio are rapidly achieved and maintained throughout the entire simulation. As a result, the network is able to sustain high fusion performance, as evidenced by the corresponding neutron production trends.

The analysis of the dynamic response of this network indicates that reducing the density presents a significant challenge. This outcome is not unexpected, given that in our case density reduction occurs naturally on the transport time scale, whereas all actuators available within the present control scheme — namely pellet injection — act in the opposite direction by increasing particle content. The network performs considerably better in controlling the D/T ratio.

Summary and conclusions

The RT controllers investigated in this study operate based on two control references, the line-integrated density n_{eL} and the D/T ratio, allowing for multiple possible configurations. A number of configurations were assessed, and the results demonstrate that not all provide effective RT control within the explored parameter space. This highlights the necessity of systematically validating RT controllers prior to deployment. The workflow proposed in this work provides a robust framework for such testing and is therefore strongly recommended for the evaluation of future control schemes.

The predictive modelling results for the RT D/T ratio and n_{eL} controllers are sensitive to both the chosen transport model and the pellet injection model. However, since in this work the RT controller is implemented through external actors, the framework is not constrained by the internal models or codes used within JETTO. This model-independent design represents a significant advantage over previous control implementations, which were tightly coupled to specific simulation modules.

Among the configurations studied, network prioritising n_{eL} control proves most effective for increasing and sustaining the line-integrated density. In contrast, the network prioritising D/T ratio control, performs best for reducing and regulating the D/T ratio and efficiently drives <X[T]> to the desired lower range without significantly compromising density.

When considering specific goals, networks were found to behave differently with regard to whether sustaining n_{eL} or maintaining D/T ratio is prioritised.

Overall, these findings reveal an inherent trade-off between density and mixture control when using pellet-based actuation. They emphasise the importance of aligning controller design and prioritisation with the specific operational goals of the plasma scenario.

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