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PLASMA CONTROL EXPERIMENTS IN JET DEUTERIUM-TRITIUM PLASMAS

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Abstract

1. The Joint European Torus (JET) has the unique capability of operating with Deuterium-Tritium (DT) fuel mixture, as required in nuclear fusion power plants. A 3rd experimental campaign (DTE3) using a DT fuel mixture, and building on the experience from the two previous DT campaigns (DTE1 (1997)[1] and DTE2 (2021)[2-3]), was executed in the autumn of 2023. In this campaign a series of advanced real time controllers, which are likely to be essential in nuclear fusion reactors, have been exploited. The operational issues that these controllers addressed were the entry into and exit from burn, the entry into and exit from H-mode, the control of the plasma exhaust during the H-mode phases of a plasma discharge, and the identification of under-performing plasma discharges (dud). In this contribution, the key role of JET in developing burning plasma control will be presented including the challenges encountered, the lessons learned and the main control achievements

2. INTRODUCTION

The Joint European Torus (JET) has the unique capability of operating with Deuterium-Tritium (DT) fuel mixture, as required in nuclear fusion power plants. A 3rd experimental campaign (DTE3) using a DT fuel mixture [1], and building on the experience from the two previous DT campaigns (DTE1 (1997)[2] and DTE2 (2021)[3-5]), was executed in the autumn of 2023. In this campaign a series of advanced real time controllers, which are likely to be essential in nuclear fusion reactors, have been developed in dedicated experiments. The operational issues that these controllers addressed were the entry into and exit from burn, the entry into and exit from H-mode, the control of the plasma exhaust during the H-mode phases of a plasma discharge, and the identification of under-performing plasma discharges (dud). Several other active control schemes have been exploited in DTE2 and DTE3, although these were not specifically developed for Tritium, nor were they tested in dedicated experiments. Therefore these will not be discussed in this paper.

3. ISOTOPE CONTROL IN D/T EXPERIMENTS AND MODELLING

Controlling the D/T fuel ratio in a reactor could be an ideal tool to assure that the transition to and from burn occurs as desired. Hence demonstrating active D/T ratio control in the plasma core is of great importance. Fig. 1 b) shows one example of successful, closed loop control of the D/T ratio on JET [6]. In this discharge, the Tritium and the Deuterium were injected via gas valves. The D/T ratio was calculated using the ratio of D and T visible spectroscopy lines measured in the outer divertor lines of sight, as shown in Fig 1 a). The D/T ratio has also been calculated using mass spectrometry of the exhausted gas, but due to its delayed response to plasma composition, it has been used as second measurement in order to validate the real-time spectroscopy. The real-time algorithm controls at the same time the isotope ratio and the total injected gas rate, in order to avoid altering other plasma physics quantities while executing isotope control. Each pulse consisted of two distinct phases, as illustrated by the time traces of the injected gas in the Figure 1 b). In phase #1, Deuterium-rich plasma (4.5s–7.5s), the objective was to achieve a deuterium-rich plasma through real-time (RT) control of injected deuterium and tritium gases. During phase #2, equipartition (7.5s-10s), the RT controller was programmed to adjust the D/T ratio to a more favourable mixture, specifically D/T = 0.4/0.6. The response of DT neutron rate to the D/T ratio change, at constant injected power and plasma condition, is a demonstration of the effectiveness of this controller. Similar results have been obtained injecting Deuterium via cryogenic pellets, in order to demonstrate control using a more ITER-relevant fuelling actuator. Several discharges have been carried out in order to test the controller, making use of gas injection for Tritium, and both gas and pellet injection for Deuterium.

For the future development of real-time D/T ratio controllers, it is essential to test, train, and validate them through a robust workflow. This involves modelling D/T ratio control experiments and comparing simulation results with experimental data. Demonstrating that the model can accurately reproduce key measurements—such as electron density, D/T ratio, and neutron yield—will build confidence in its use for optimizing and testing controllers under various conditions. These include determining the required gas injection rates, pellet sizes, and selecting the most suitable actuator for specific operational scenarios. The experiments were simulated using the TRANSP and JETTO codes [7]. In these simulations, sources from NBI, pellet injection, and gas puffing were treated self-consistently, while particle transport was modelled using a simplified Bohm-gyroBohm approach. JETTO was run predictively for D, T densities, while electron and ion temperatures were prescribed as taken from measurements. Particle sources in JETTO were modelled with FRANTIC for gas injection and recycling neutrals, HPI2/continuous pellets for pellet source and PENCIL for ion source due to NBI. Impurities and Zeff were modelled with SANCO code with Be, Ni and W.

Calculated electron density, neutrons, D/T ratio and Zeff validated versus measurements are shown in Figure 2. Modelled data are in agreement with the measurements, meaning the model can be used to study numerically the behaviour of the controller in different scenario, e.g. transition from T-rich plasma into D/T~0.5/0.5. This demonstrates that simple models and assumptions for D/T transport can be successfully used to predictively model the behaviour of RT controllers for D/T ratio control. This approach was able to reproduce the experimental data for the density, DT ratio and neutrons and therefore can be used to simulate the behaviour of future RT controllers in conditions at different scenario, particle sources and plasma parameters; this statement is supported by the fact that simulations using different particle transport coefficients did not change substantially the predicted quantities. For future D/T ratio RT controller development, the models presented here would serve as a foundation for extrapolation and application to future devices.

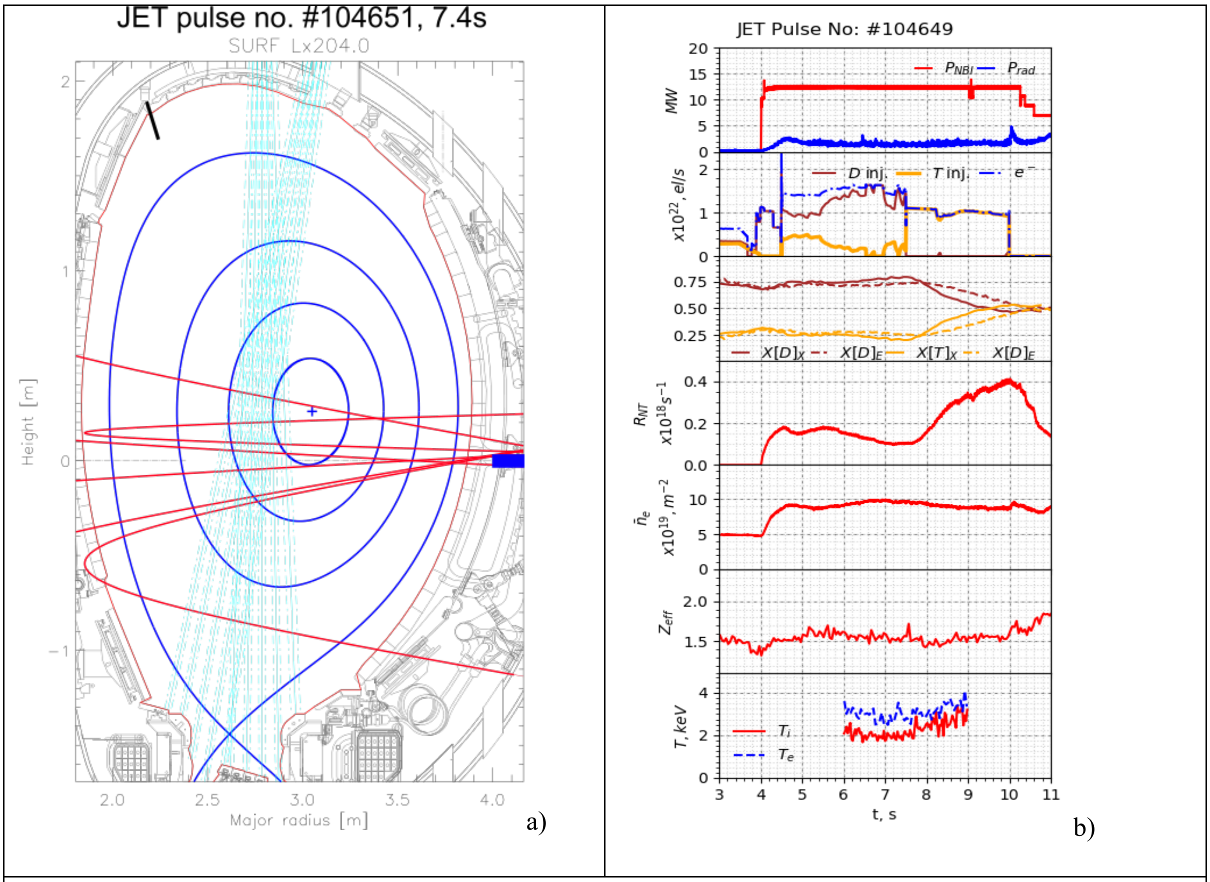

Figure 1: a) Plasma cross-section of 1.4MA/1.7T JET pulse #104651 at 7.4s. NBI injectors LOS projected on the poloidal plane, sources 1 to 6 used in this experiment are shown in red, while the pellet VHFS injection line is indicated in black. The LOS of HRS diagnostic providing the data for D/T ratio is shown in cyan. Gas injection modules approximate location is shown by a blue rectangle.

b) Time traces of investigated 1.4MA/1.7T JET pulse #104649 in which D/T ratio was varied by means of D/T gas injection. Injected gas and species are shown in the second panel from the top, isotope concentration measured by spectroscopy (solid) and mass spectrometry (dashed) is shown in the third panel. R_{nt} is the neutron rate, n_e is the line averaged electron density, Z_{eff} is the effective mass, Ti and Te are ion and electron temperatures measured in the plasma center. In phase #1, Deuterium-rich plasma (4.5s–7.5s) was programmed. During phase #2 (7.5s-10s), a D/T ratio of 0.4/0.6 was programmed.

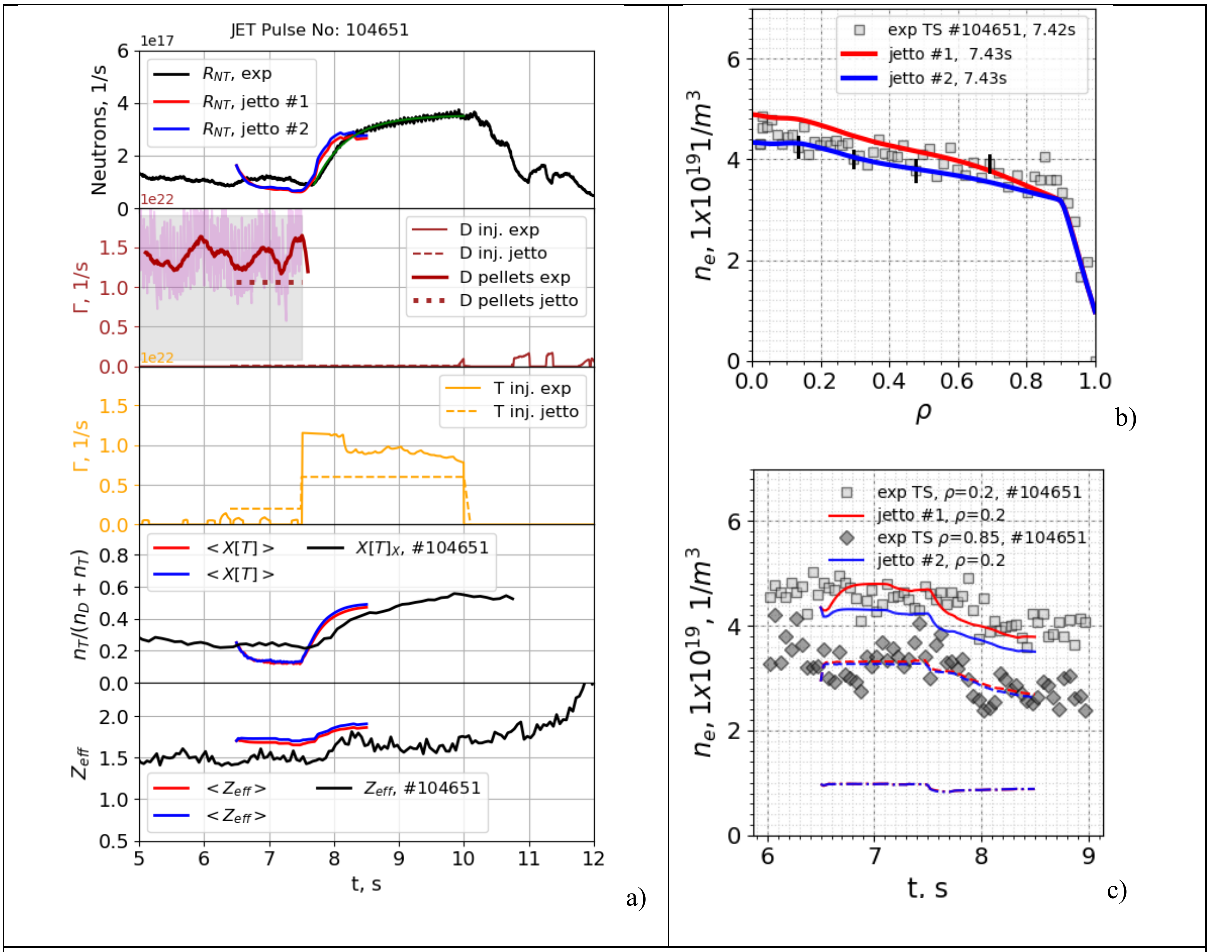

Figure 2. a) Results of two JETTO simulations of #104651 with Bohm-gyroBohm model and particle diffusion coefficients A_1=4, A_2=2 (jetto #1 red) and A_1=8, A_2=4 (jetto #2 blue). Time traces of R_{NT}, D and T gas injection rates, measured $X[T]_X$ (black) and calculated <X[T]> (red and blue) and Z_{eff} are shown from top to bottom in a). (b) Calculated and measured n_e for time slice at 7.43s while (c) shows measured and calculated n_e time traces in the core, for ρ=0.2 (squares and solid red and blue lines), and at the pedestal, at ρ=0.85 (diamonds and dashed red and blue lines), together with JETTO boundary condition at ρ=1 (dash-dotted lines).

4. CONTROL OF H-MODE EXIT

While controlling the isotope ratio, it has been important to ensure that the total plasma radiation remained at low level. At JET, this radiation was dominated by the influx of heavy impurities, and avoiding this influx has been of key importance to remaining in a good quality H-mode with regular ELMs. This can be achieved controlling the entry into and exit from H-mode [8]. The exit from H-mode has been particularly difficult to handle, as reducing the input power, while the plasma radiation or density was too high, can lead to a radiative collapse. In order to address this problem, a real time algorithm has been used at JET in D and DT plasmas, which modified heating power and fuelling to assure that the plasma remained in H-mode as long as required, before executing a controlled exit from H-mode.

In Fig. 3, two DT discharges with 1.4 MA plasma current, 1.8 T toroidal magnetic field are reported. In the experiment on the left, the plasma terminated because of a MHD event which has been triggered at t=50.2 s. On the other hand, in the experiment on the right, the P_{LH} controller [9] has been activated from t=50 s and a prescribed trajectory of the f^{Net}_{LH} indicator, defined as the ratio between the power across the separatrix and the P_{LH} from Martin's scaling law, has been requested. The NBI power and the flow rate from gas injector GIM11, as shown in panels (g) and (h), respectively, have been used to tailor the f^{Net}_{LH} trajectory, avoiding the MHD onset while guaranteeing a good ELM behavior and a safe plasma termination.

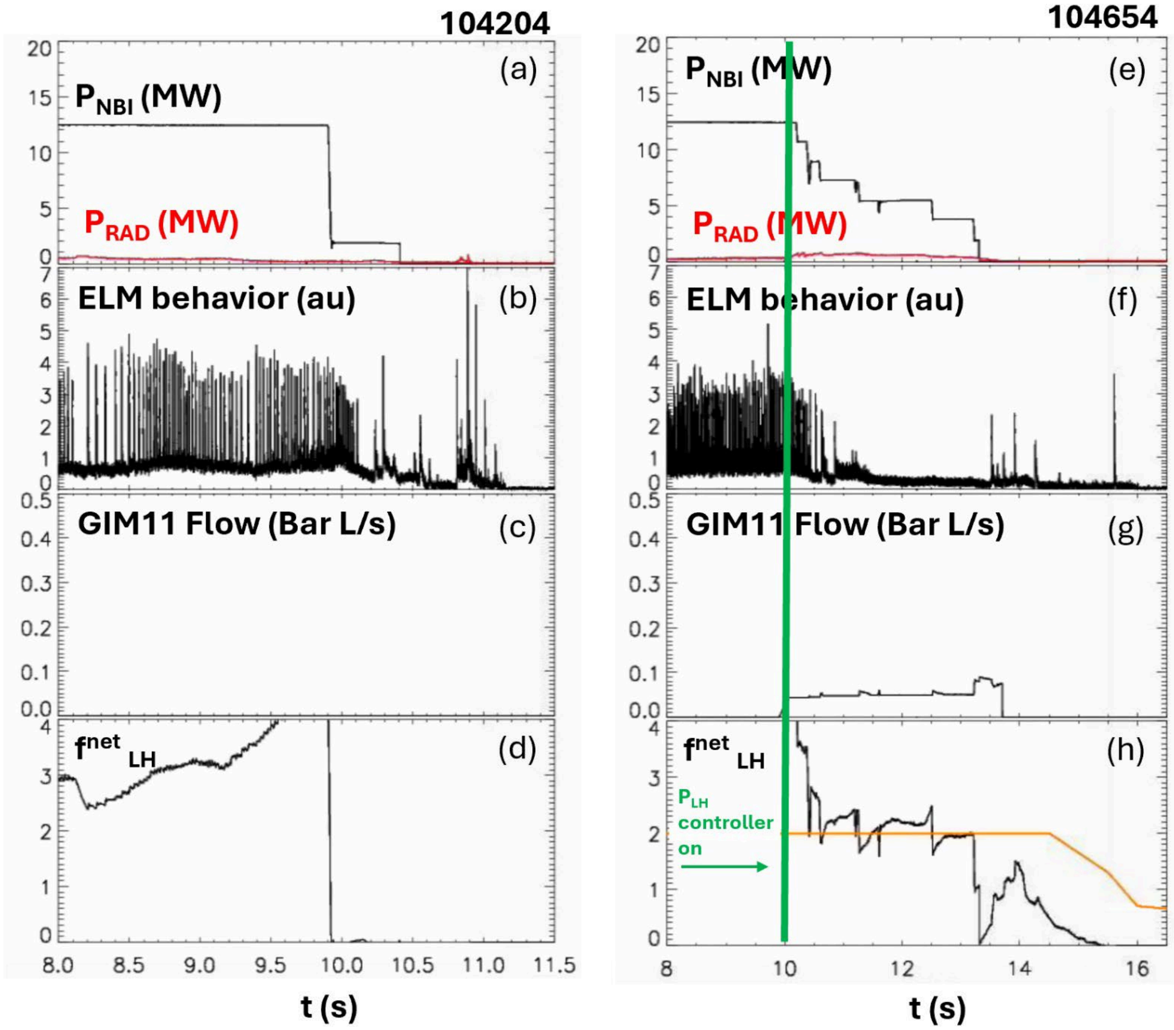

Fig. 3 Time behavior of NBI injected power, radiated power (in red) (a,e), ELMs signature as measured in Be emission in the divertor (b,f), Injected gas controlled in realtime with GIM11 (c,g), the f^{Net}_{LH} calculated as the ratio of the power across the separatrix and the P_{LH} from Martin's scaling law (in black) and the reference controller value in orange (d,h).

5. DETACHMENT CONTROL

For tokamak fusion reactors, acceptable divertor target conditions can be achieved by maintaining a detached divertor plasma. In this regime, there is significant mitigation of power and particle fluxes impacting the divertor targets. Given varying plasma conditions during the discharge, real-time control algorithms that actively assess the exhaust plasma state are required to adjust actuator actions in response to evolving reactor conditions and disturbances. The X-point radiator (XPR) [11] regime in JET was successfully controlled in both DD and DT operation. The experiments were performed in a low-triangularity, 2.5 MA, −2.7 T H-mode scenario with input power of 20–30 MW. The impurity seeding used is a combination of argon and neon, with only one species applied in feedback while the other was preprogrammed in feedforward. Results showed that argon injection as feedback actuator enabled effective XPR control, whereas neon could not actively influence the radiator position, although it was necessary in order to achieve the XPR configuration. The controller is systematically designed with a local control-oriented model identified from perturbative experiments measuring the XPR response to impurity seeding [12], similar to earlier work in TCV [13,14,15], AUG [16], and MAST-U [17]. These perturbative studies, carried out in both DD and DT plasmas, demonstrated that the XPR response to impurity seeding are independent of isotope mixture, meaning a controller designed for DD could be directly transferred to DT with robust stability and performance. Interestingly, these dynamics show similar properties as that of other detachment regimes [18]. Based on the identified control-oriented model, a PI controller was designed and implemented, achieving the first successful XPR position control in JET for both DD and DT operation. The results are shown in Figure 4, where in JET pulse 104294 an XPR scenario is established in DT experiments, using gas injection of Ar and Ne. At 50s the XPR is started with seeding Ar and Ne in the JET H-mode discharge, causing the disappearance of ELMs. At 51s the Ne injection continues in feed-forward, while the Ar injection is prescribed by the feedback algorithm, which controls the vertical position of the XPR and keeps it constant up to 58s, when the discharge has been already ramped down to L-mode.

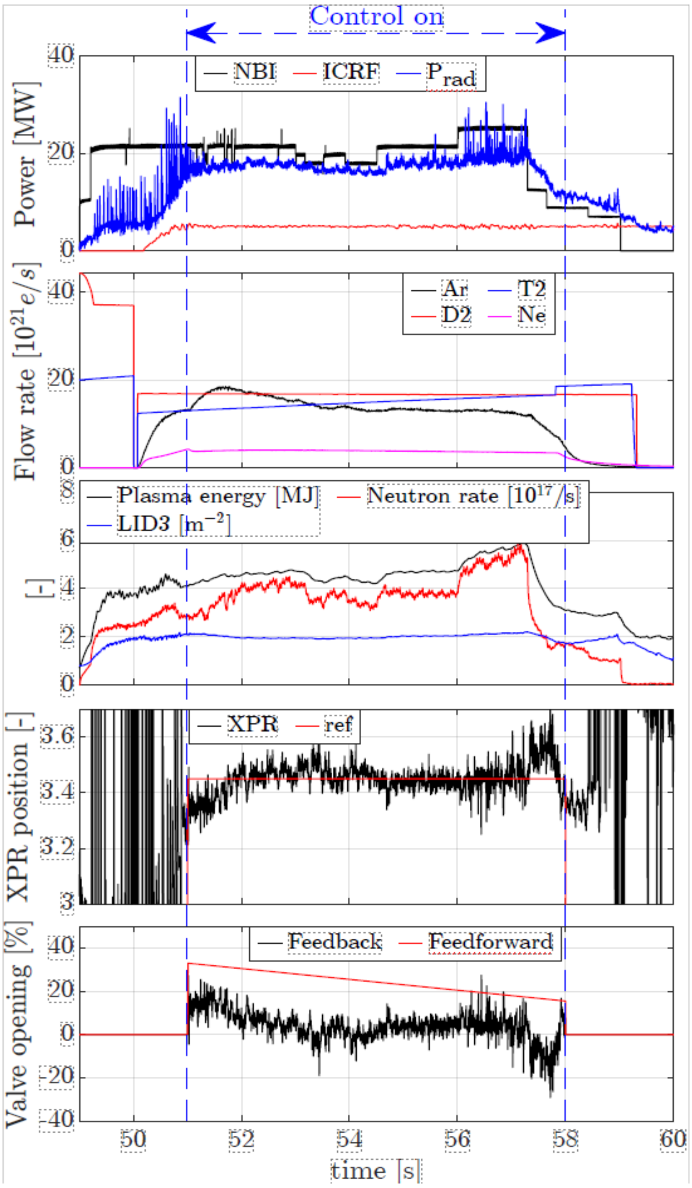

Fig. 4: Overview of JET #104294 where the position of the X-point radiator is controlled using the Argon seeding during DT operation. The input powers and total radiated power are displayed in (a). The flow rates for all the gas species are shown in (b). The plasma energy and neutron rate and line-integrated density are depicted in (c). The vertical position of the X-point radiator and the control reference (d), the feedback and feedforward control actions (e).

6. NON-PERFORMING PULSE DETECTION AND TERMINATION

In JET DT pulses, dud detector has been extensively used to terminate scenario development pulses that were not reaching the expected plasma performance. Metrics based on the value of H_{98} and on the ratio between fusion neutron rate over the plasma stored energy squared (Rnt/Wp^2) have been monitored during the plasma evolution of baseline plasmas. If their values were below certain thresholds, empirically identified, the plasma was terminated safely. This has allowed the optimal use of the limited tritium and neutron budget.

On the other side, for hybrid plasmas, the dud detection was based on different metrics: the electron temperature hollowness indicator [19, 20], which is an indication of heavy impurity accumulation in the plasma center, and the evolution of the diamagnetic energy, which has been seen as a proxy of the neutron rate. An example of the dud detection behaviour in hybrid plasma scenario is shown in Fig.5, where four DT JET pulses with 2.5 MA plasma current, 3.5 T toroidal magnetic field are depicted. Note that the T_e hollowness indicator, reported in panel (b), stayed above the prescribed value indicated with an orange dashed line, while in the discharges 99527 and 99866, reported in red and in blue respectively, the diamagnetic energy has fallen below the prescribed thresholds at t=49s and t=49.55s, respectively, triggering the emergency plasma shut down procedure named jump to termination (JTT).

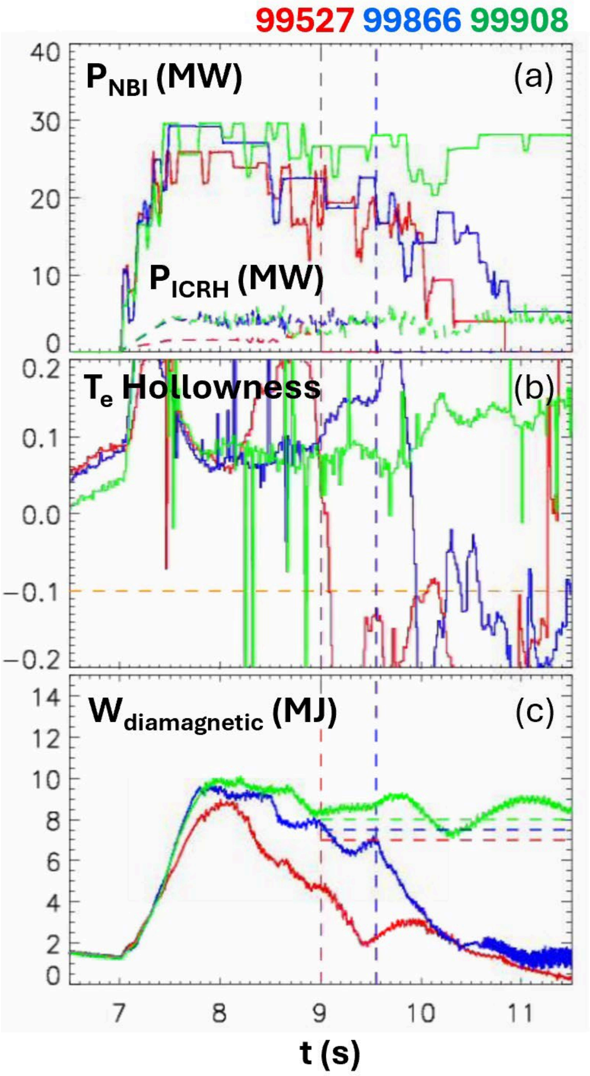

Fig 5. Time behavior of (a) NBI and ICRH power, (b) electron Temperature profiles hollowness (measured with Lidar Thompson Scattering), (c) NBI and ICRH power, (d) plasma diamagnetic energy. The dashed horizontal lines in (e) represent different thresholds set on magnetic energy, the dashed vertical lines show the triggering time of the algorithm

After DTE2 operation, the originally designed dud detector for JET baseline plasmas has been revisited in the so-called innovative dud detector [21,22], to include a metric on the power above the P_{LH} threshold. This has been motivated by the radiation runaway events that affected most of the baseline scenario plasmas. Novel dud detection algorithms, also based on machine learning methods have been recently proposed, as documented in [IAEA], in preparation for incoming DT experiments in BEST, ITER and SPARC.

6. CONCLUSIONS

In this paper an overview of real time controllers tailored to JET DT operation has been given. The development of these controllers constituted a long-standing effort carried out in multiple experimental campaigns, based on the testing and concept development in Deuterium operation or in Hydrogen/Deuterium at JET [20], and in other

WPTE tokamaks as well [16]. Control tools and simulation capabilities have been developed with Deuterium/Tritium operation in mind, and finally ported to DT with minimal optimization time required.
In future fusion devices several controllers will have to work simultaneously sharing the same actuators, with possible interaction between different controllers [23]. This increased interaction might complicate the integration of the controllers, and can result in a reduction in performance, or robustness.
While the controllers developed for DT operation were not generally developed for actuator sharing, this approach was followed in the case of the isotope ratio controller and ELM frequency controller. To sustain a stable type-I ELMy H-mode plasma, it is desirable to maintain a given edge localised mode (ELM) frequency. However, both the total fuelling rate and the D/T ratio influence this ELM frequency, with higher fuelling rates and higher D/T ratios both resulting in more frequent ELMs. For this reason, the D/T ratio controller was combined with an ELM frequency controller in a multi-input multi-output controller. The successful simultaneous decoupled control of the D/T ratio and ELM frequency was demonstrated using a combination of pellet and gas fuelling [6].
Furthermore, the fact that developed controllers maintain enough machine agnosticism, implies the work methodology shown here will serve as a template for the development of controllers for future DT operating devices, like ITER and DEMO.

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