Progress in preparing real-time control schemes for Deuterium-Tritium operation in JET

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Operation of a magnetic fusion experiment, such as JET, relies on the availability of real-time (RT) control schemes, which supervise the plasma as it approaches the expected target performance while maintaining the integrity of the machine and its subsystems. At JET, there have been a series of recent efforts since (Lennholm M. et al 2017 Fusion Engineering and Design 123 535-540) to develop and test RT control schemes in preparation for the upcoming Deuterium-Tritium (DT) campaign. When operating JET in DT, each plasma discharge will in fact be a precious resource, being both T and neutron budget limited. Among the developed control schemes, this paper deals with the isotope ratio controller, which will maintain the required 50:50 DT ratio needed to favor nuclear fusion processes; the dud detector (L. Piron et al 2019 Fusion Engineering and Design 146 1364-1368), which will terminate a discharge moving toward under-performing states; and a series of improved RT controllers for detecting excessive radiation. Moreover, brand-new detectors, also based on machine learning approaches, have been implemented for detecting off-normal events or pre-disruptive states and have been included in the Plasma Event TRiggering and Alarms system (C.I. Stuart et al 2020 SOFT conference). Work is also ongoing to deploy into JET the RAPTOR suite, a RT observer for plasma state monitoring (C. Piron et al 2020 SOFT conference), and to identify control schemes within RAPTOR capabilities, which could contribute to support the development of high performance plasma scenarios.

Keywords: JET, Plasma, Real-time control, DT, Tritium Operation, Isotope control, Plasma termination.

1. Introduction

JET offers the unique opportunity to study the behavior of Deuterium (D) and Tritium (T) plasmas in conditions and dimensions approaching those required in ITER and fusion reactors in its future DT campaign, which is planned in 2021 (DTE2) [1]. With respect to the previous DT campaign which took place in 1997 (DTE1) [2], the Carbon wall has been changed to an ITER-like wall with a Tungsten divertor and a Beryllium first wall, the total auxiliary power has been increased to 40 MW, and a wide coverage of diagnostics has been installed.

DTE2 will provide physics, engineering and technology insights relevant to burning plasmas, such as alpha particle and isotopic effects, particle and heat transport, retention and wall cleaning.

When operating JET in DT, each plasma discharge will be a precious resource, being both T and neutron budget limited. To ensure robust and lasting DT scenarios, while gathering the maximum insight and experience from them, new plasma control schemes have been designed and sophisticated tools for monitoring plasma evolution have been developed.

In this work, Section 2 reports the main progress on real-time (RT) control in support to DT since [3]. Section 3 summarizes the ongoing work on using machine-learning tools and plasma monitor observers to optimize plasma scenarios. Section 4 gives the conclusions.

2. Novel controllers for DT

In this section, we provide an overview of brand-new controllers which have been designed, tested and optimized for DTE2 operation: isotope ratio controller; ELM frequency controller using D and T valves; decoupling scheme for isotope ratio and ELM frequency controllers; dud detector; temperature hollowness detector; and radiation peaking control. These controllers

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have been developed with the aim of increasing the robustness and duration of DT scenarios and of reducing T inventory and neutron budget consumption, by triggering an early plasma termination of underperforming discharges.

2.1 Isotope ratio controller

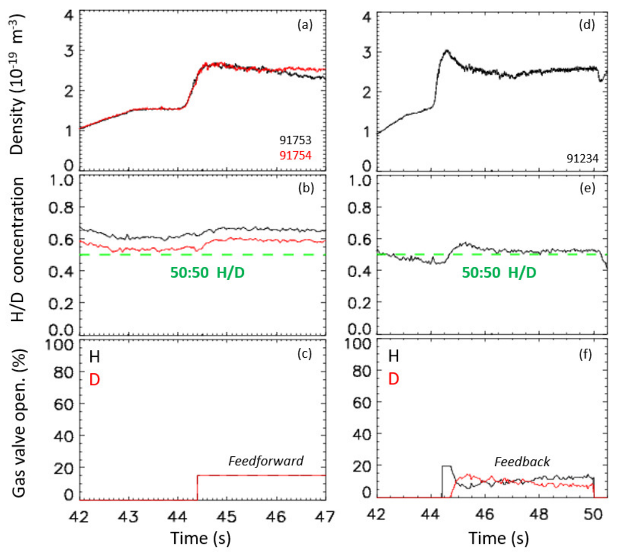

Fig. 1. Time behavior of (a, d) plasma density, (b, e) H/D concentration from visible spectroscopy and (c, f) H, D gas valve opening in a series of 1.4 MA, 1.7 T discharges with gas valve opening in feedforward, on the left, and in feedback, on the right.

To achieve the optimal 50:50 DT fuel concentration, which maximizes nuclear fusion processes, an isotope ratio controller has been developed. This controller relies on visible spectroscopy from an outer divertor line of sight for inferring the isotopic ratio, and it acts in real time, using a proportional–integral–derivative (PID) feedback law, on the gas valve opening. Compared with gas opening in feedforward, where the user prescribes the gas valve openings, it has the advantage of achieving the desired DT concentration without being influenced by wall conditions and by what happens in the previous shots.

To deliver a reliable tool for DT operation, the isotope ratio controller has been tested in Hydrogen (H) and D plasmas. Fig.1(a-c) and Fig1.(d-f) compare the performance of the isotope ratio controller when operating in feedforward and in feedback, respectively. These tests, performed in 1.4 MA, 1.7 T plasmas, show that several pulses are required, varying the feedforward gas valve openings to reach the desired H/D concentration. On the other hand, by using gas opening in feedback, a stable H/D concentration at the selected value is straightforwardly achieved and the shot budget is preserved. It is worth mentioning that the performance of the isotope control when requiring 50:50 HD fuel concentration has been presented here, as an example. The controller can ensure any desired isotope fuel mix.

2.2 ELM frequency controller using D and T valves

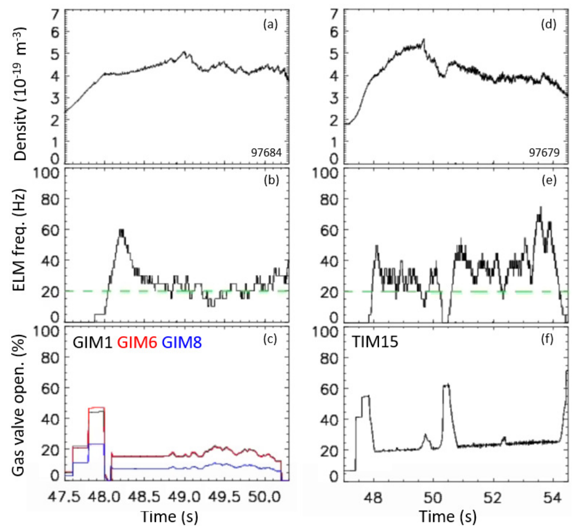

Fig. 2. Time behavior of (a, d) plasma density, (b, e) the ELM frequency and (c, f) GIMs and TIM gas valve opening. Data refers to 2.4 MA, 3.4 T D plasmas.

The presence of core impurity accumulation, associated with the presence of high-Z_{eff} particles in the machine, has been a matter of concern for JET ITER-like wall operation since this is likely to lead to plasma disruptions. To limit impurity accumulation events, the ELM frequency controller, is routinely used [4]. Such a controller helps in flushing Tungsten from the plasma edge, beside reducing the energy release per ELM to the plasma facing components.

The ELM frequency controller relies on the fact that the ELM frequency increases with gas injection rate and acts when the ELM frequency drops below a threshold. In particular, the controller compares the desired ELM frequency with the measured ELM frequency to generate an error signal. The error is sent to a PID controller, which generates a valve opening to the Gas Introduction Module (GIM) that is currently used in the discharge. The request takes into account the drop in the reservoir pressure that is associated with the valve opening into the vacuum chamber.

In preparation to DT operation, multiple gas valves, including the new five Tritium gas Introduction Modules (TIMs), are envisaged as actuators for the ELM frequency controller. Therefore an algorithm, which takes into account both the pressure and temperature dependence of the gas reservoir and the hysteresis of the piezoelectric valve crystals, has been developed. More details on operation with TIMs are reported in [5]. Fig. 2

shows the performance of this controller in 2.4 MA, 3.4 T deuterium plasmas when multiple GIMs valves, on the left, and a TIM valve, on the right, are used to counteract an ELM frequency decrease below the 20 Hz threshold (green dashed line).

2.3 Decoupling scheme for isotope ratio and ELM frequency controllers

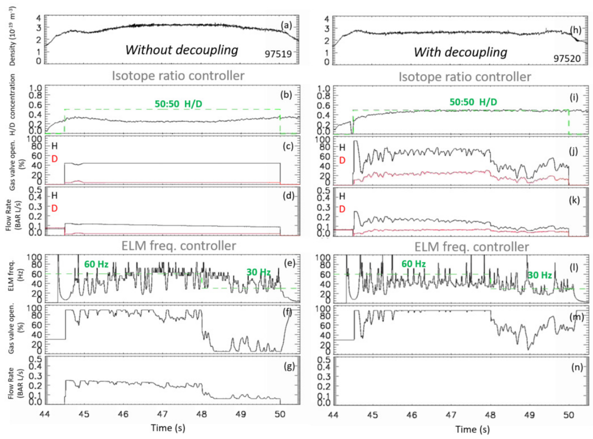

Fig. 3. Time behavior of (a, h) plasma density (b, i) H/D concentration and (c, j) H, D gas valve opening from the isotope ratio controller, (d, k) H, D flow rates, (e, l) ELM frequency, (f) gas valve opening from ELM frequency controller, (g) D flow rate from ELM controller, (m) total gas opening requested by the ELM controller, (n) total flow rate from the ELM frequency controller. This quantity is zero being the ELM control done via the isotope ratio controller. The traces refer to 1.4 MA, 1.8 T discharges without, on the left, and with decoupling, on the right.

To achieve high plasma performance regimes during DT operation, multiple single input single output controllers will act simultaneously and it is important that they can operate together. Dedicated RT tests have been performed to quantify their coupling.

Such tests have highlighted that the isotope ratio controller interferes with the ELM frequency controller, since both act on the gas valve opening.

The effect of the coupling on a 1.4 MA, 1.8 T deuterium-hydrogen plasma using GIM valves is shown in Fig. 3 (a-g). In this test, a square waveform with two steps of 60 Hz and 30 Hz has been programmed for the ELM frequency controller, as reported in Fig. 3 (e), while a constant 50:50 H/D isotope ratio is requested from the isotope controller.

From the very beginning of the pulse, the ELM frequency controller requests an opening of the GIM valve such that the isotope ratio controller reaches the saturation level and cannot provide the required 50:50 H/D concentration, as shown in Fig.3 (b).

To eliminate the coupling among the controllers, a decoupling algorithm has been developed.

The decoupling algorithm combines the outputs of the Isotope controller, i.e. A: H-GIM flow, B: D-GIM flow, which satisfy the relation A+B = K, where K is the total gas flow request from the isotope controller. C is the total flow request from the ELM frequency controller. In the absence of decoupling A, B and C are translated into GIM opening requests, by applying factors to compensate the opening to flow translation given the GIM pressures and the number of GIMs used. The corresponding flow rate traces are reported in Fig. 3(d, g), respectively.

When the decoupling scheme is applied, the H-flow request, A_x, and the D-flow request, B_x, are determined as follows:

$$A_x = A\,C / K,$$
$$B_x = B\,C / K.$$

In this way, the total flow request is:

$$A_x + B_x = C\,(A+B) / K = C,$$

as required by the ELM frequency controller.

While the H and D flow fractions are:

$$A_x / (A_x+B_x) = A / (A+B),$$
$$B_x / (A_x+B_x) = B / (A+B),$$

as required by the isotope ratio controller. Once A_x and B_x are determined, that translation to GIM opening requests is applied exactly like in the non-decoupled case. Note that with the decoupler, the flow rate from the ELM frequency controller is zero, as shown in Fig. 3(n), being such flow control request done via the isotope ratio controller.

In this new algorithm, in other words, the requested valve opening from the ELM frequency controller, instead of being sent to the corresponding gas valve, it is sent to the isotope ratio controller and multiplies each of the outputs to the D and H gas valve opening. In this way, the decoupling scheme controls the total gas injected by the isotope controller from the ELM frequency network.

Such a decoupling scheme has been successfully tested in the discharge reported in Fig.3(f,j). In this case, a stationary 50:50 H/D concentration has been maintained. Note that despite the reduction on gas opening to control the ELM frequency from 60 Hz to 30 Hz, the H/D concentration is kept constant. This demonstrates that the developed algorithm has good decoupling characteristics and presents satisfactory responses in terms of ELM frequency variation request.

2.4 Dud detector

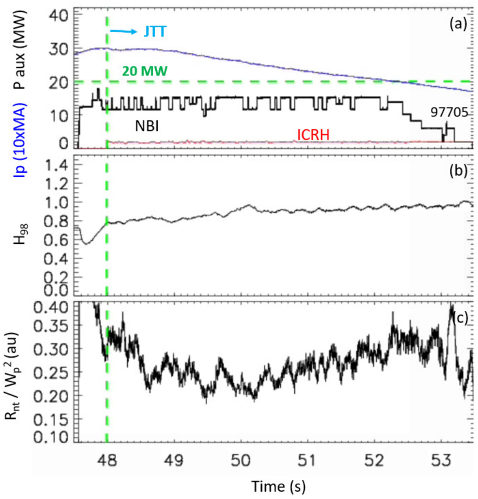

Fig. 4. Time behavior of (a) plasma current and auxiliary heating power, (b) H_{98} and (c) R_{nt}/W_p^2. In this test, the dud detector used as metric for alarm triggering the delivered NBI power only.

During DT operations, care has to be taken to reduce the T inventory as much as possible, to minimize any potential escape of T, while restricting the total number of DT neutrons, which are generated in order to limit the activation of the machine.

To this aim, a RT algorithm, named dud detector, has been developed. The dud detector calculates and monitors the time evolution of various plasma performance indicators, which can be used to trigger an alarm and a proper plasma termination if the plasma is not behaving as expected. The development and the implementation of the dud detector have been described in [6].

Recently this detector has been implemented in a sophisticated Plasma Event TRiggering and Alarms (PETRA) system [6]. The metrics that have been included are the delivered NBI power, $H_{IPB98(Y:2)}$ and the neutron rate normalized to the square of the plasma stored energy, R_{nt}/W_p^2.

The capability of dud detector to raise an alarm within the PETRA system and the performance of the associated plasma termination strategy have been tested in the 3MA, 2.8 T discharge reported in Fig.4. In this preliminary test the dud detector was switched on from t = 47.5 s with only the delivered NBI power in the alarm triggering metrics.

As shown in Fig.4(a), the alarm is correctly raised at around t=48 s for insufficient NBI power and an ad-hoc plasma termination scheme, named jump to termination (JTT), is initiated. Within JTT, various control schemes such as beta and gas injection controllers are used to soft land unhealthy plasmas.

It is worth mentioning that the PETRA system includes not only the dud detector, but also new event detectors for disruption avoidance and mitigation, which are described in Section 3.

2.5 Temperature hollowness detector

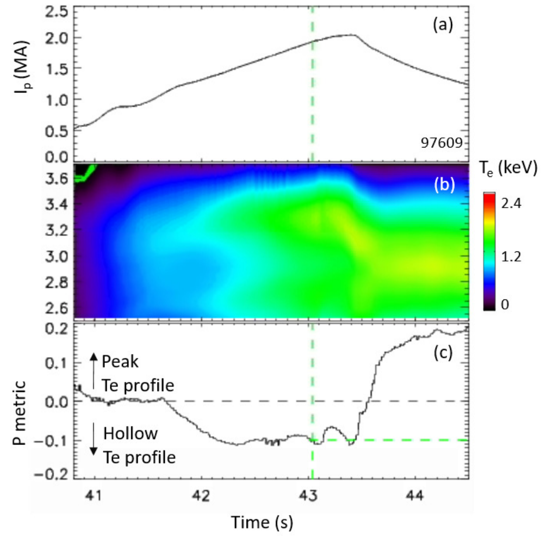

Fig. 5. Time behavior of (a) plasma current (b) Te contour from ECE diagnostic and (c) P metric. The Te hollowness detector was activated from t=43 s. The horizontal green dotted line corresponds to the P-threshold for alarm triggering while the vertical green dotted line indicates the actual triggering time.

Impurity accumulation is one of the mechanisms responsible for plasma disruptions in JET with the ILW, not only during the main heating phase of H-mode plasmas, but also during the plasma current ramp-down, in L-mode ones.

When a high-Z_{eff} impurity accumulates in the core, a hollow plasma temperature profile develops, which in turn affects the plasma current density, and thus the q-profile. Statistically, it has been shown that after this chain of events, an MHD instability with 2/1 poloidal/toroidal mode number develops [8]. The mode amplitude increases in time until the JET protection system fires the disruption mitigation valve.

An algorithm based on temperature profiles from electron cyclotron emission (ECE) diagnostic has been developed and allows for detecting hollow temperature profile [9]. In particular, when the metric $P = \frac{T_{core}-T_{edge}}{T_{core}}$, being T_{core} and T_{edge} the volume averaged temperature in the core and at the edge, respectively, is below -0.1 for more than 0.02 s, an alarm is raised.

The performance of this detector during the plasma current-ramp phase of a targeting 2 MA, 3.4 T plasma is reported in Figure 5. The detector, which is activated from t = 43 s, promptly triggers an alarm after few milliseconds. A safe plasma termination scheme is then requested, because the plasma condition before the impurity accumulation could not be restored.

The temperature hollowness detector will be of crucial importance especially during DT operation, because it will preserve the neutron budget and the Tritium inventory, stopping the discharges that are predicted to have sub-par performance.

2.6 Radiation peaking control

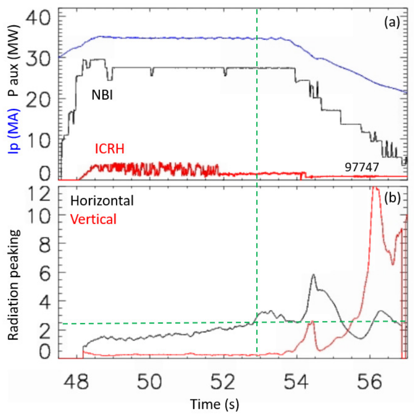

Fig. 6. Time behavior of (a) I_p and auxiliary heating power, (b) horizontal and vertical radiation peaking from bolometric data in a 3.5 MA, 3.35 T plasma.

In H-mode, in combination with ELM frequency controller, RT indicators based on bolometric signals have been exploited to detect impurity accumulation events. Such indicators are the horizontal and vertical radiation peaking; defined as the ratio between horizontal central and off axis bolometer signals and the ratio between vertical central and off axis bolometer signals, respectively.

These metrics allow to monitor the development of radiation peaking in different regions of the plasma, i.e. in the core and at the edge, respectively, and are thus used in conjunction.

Fig.6 shows an example of the radiation peaking detector performance in a 3.5 MA, 3.35 T discharge. As soon as the horizontal radiation peaking reaches the user defined threshold of 2.5 at t=52.85 s, the JTT sequence is triggered.

As will be described in the following section, a sophisticated tomography algorithm based on machine-learning [10] has also been developed to obtain a more accurate reconstruction of the radiation profile.

Noteworthy, the RT networks presented in this section will be tested during the planned TT campaign on JET, which will precede the DT one.

3. Advanced algorithms for disruption avoidance/mitigation

At JET, in recent years, there has been an increasing interest in using machine learning for disruption prediction, avoidance and mitigation.

In this context, a RT bolometry tomography algorithm [10] and a generative topographic mapping (GTM) algorithm [11] have been developed and included in the PETRA system. The former can estimate the amount of radiated power from different plasma regions, namely core, outboard and divertor, using existing bolometric profile reconstructions as training data. The latter computes the probability of disruptive evolution for core and edge radiative collapse combining information from a large set of diagnostics data.

At present, such algorithms can be exploited to develop brand-new detectors for off-normal events or pre-disruptive states and to monitor the plasma performance. In the future, once their robustness and reliability is established, they can be used to steer experiments away from the operating conditions that inevitably lead to plasma disruptions.

Moreover, efforts have been dedicated to develop the RAPTOR suite for JET [12]. The RAPTOR suite is made up of:

- the EQUINOX code [13], which allows for equilibrium reconstructions using magnetic, interferometric and polarimetric measurements, as constrains;
- the FLUXMAP code, which maps the diagnostic kinetic profiles from the geometrical to both poloidal and toroidal normalized magnetic flux coordinates, on the basis of the EQUINOX equilibrium reconstructions;
- the RABBIT code [14], which evaluates the neutral beam heating, current drive, fast ion distribution and the neutron emission;
- the RAPTOR state observer code [15], which integrates the outputs of the aforementioned codes with a 1D control-oriented transport model and the available diagnostic data, by means of an extended Kalman-filter algorithm.

RAPTOR can be used thus offline for a fast reconstructions of the plasma dynamics, supporting the plasma scenario development, and, once it is embedded in JET RT data network, for detecting and handling diagnostic faults, by providing model-based estimation of plasma variables, and for identifying the actual trajectories to steer the plasma towards high-performance.

4. Conclusions

The forthcoming DT operation on JET will provide a unique opportunity to investigate several physics, engineering and technology open issues towards ITER operation.

A number of novel RT controllers have been developed, each contributing to support a safe, reliable and high performing DT campaign. Such controllers have been tested in HD plasmas and are ready for exploitation.

Furthermore, advanced tools for detecting pre-disrupting states have been developed, using machine-learning techniques, such as GTM and radiation tomography. A real-time model-based reconstruction of the plasma state using the RAPTOR suite has also been made available. These tools will allow the identification of optimal actuator trajectories to improve the plasma performance, supporting the plasma scenario development.

Acknowledgments

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