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Fusion Burn Regulation via Deuterium Tritium Mixture Control in JET.

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***See the author list of 'Progress on an exhaust solution for a reactor using EUROfusion multi-machines capabilities' by E. Joffrin et al. To be published in Nuclear Fusion Special Issue: Overview and Summary Papers from 29th Fusion Energy Conference (London, UK, 16-21 Octorber2023)*

The first generation of nuclear fusion reactors is expected to operate using a mixture of deuterium(D) and tritium(T) fuel. Controlling the D:T ratio is a promising option to control the fusion burn rate. The Joint European Torus (JET), as the only operational tokamak which can use tritium, is uniquely placed to test the feasibility of such control. Experiments carried out in 2023, during the 3rd JET Deuterium-Tritium (DT) campaign, have demonstrated effective feedback control of the D:T ratio in H-mode conditions. The D:T ratio was measured using visible spectroscopy and the tritium was injected via gas valves, while the deuterium was injected either via gas valves or pellets. In these experiments the fusion power, measured via the neutron rate, responded promptly to variations in the measured D:T ratio. This demonstrates that, although the plasma is fuelled mainly at the edge, rapid mixing of the isotopes occurs throughout the plasma and that controlling the D:T ratio is an effective way of controlling the burn rate. In order to sustain a stable type-I ELMy H-mode plasma it is desirable to maintain a given 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 more frequent ELMs. For this reason, the D:T ratio controller was combined with an ELM frequency controller in a multi-input multi-output (MIMO) controller. Successful simultaneous, decoupled, control of D:T ratio and ELM frequency was demonstrated using a combination of pellet and gas fuelling. This is the first and, for the time being, only demonstration of such an advanced burn control scheme in a DT plasma.

Nuclear fusion has the potential to play a major role in assuring sufficient energy supply in the second half of this century. The most promising reaction to achieve this is the fusion of deuterium (D) and tritium (T) producing a large amount of energy in the form of a energetic neutrons (14MeV) and energetic alpha particles (3.5MeV). The plasma confined in the JET machine has recently produced a world record fusion energy of 69MJ (>10MW for the duration of the 6s fusion power phase) [1]. In a fusion reactor the fusion power is strongly dependent on the ratio of D concentration to T concentration, with the maximum fusion power occurring for a 1:1 D:T ratio. Controlling this ratio is therefore essential to maximise the fusion power and doing this in real time can be an important tool for dynamic control of the fusion power [2, 3, 4, 5, 6] This letter describes such real time control of the DT mixture in JET showing how the fusion power responds promptly to the DT mixture variation. The results presented are unique, representing the first, and only, demonstration of such control. As JET is the only magnetic confinement device capable of operating with DT fuel and as JET has finished operation and will be decommissioned, further exploration of such control will have to wait a number of years before experiments can be performed on new DT capable devices (ITER, SPARC, etc.) [7, 8].

The experiments presented here were carried out in the final JET DT campaign in high confinement (H-mode) plasmas, heated by deuterium neutral beam injection (NBI) with a tritium fraction ranging from 30% to 70%. The main plasma parameters for the discharges described below are shown in figure 1.

In these plasmas part of the fusion power is due to reactions between thermal D and thermal T. Another part is due to reactions between fast, neutral beam injected, D and thermal T. Note that, whereas experiments in the 2021 JET DT campaign [9, 10, 11, 12] used a mixture of D and T neutral beams, the 2023 experiments, reported in this letter, used only D neutral beams, with tritium being injected via gas valves [13]. The thermal DT reactions are maximised for a 1:1 D:T plasma ratio, whereas reactions due to fast D increases approximately linearly with the plasma T fraction. The optimum plasma T fraction thus depends on the proportion of the fusion power which is due to direct reactions of NBI injected D with thermal T as illustrated in figure 2a. Interpretative simulations using the TRANSP evolutive transport code [14, 15] have been used to predict the

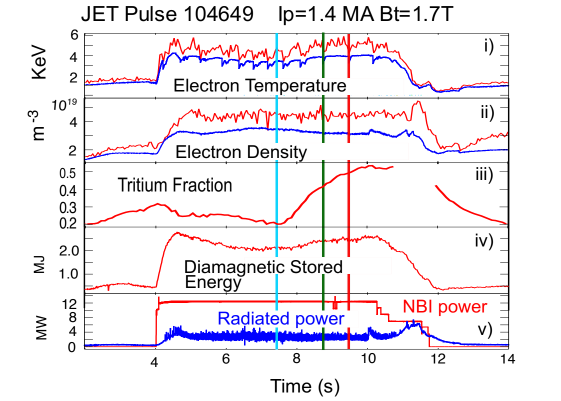

Figure 1: Typical plasma parameters for discharges presented. i) Central (red) and slightly off axis (blue) Electron temperatures from Thompson Scattering and Electron Cyclotron Emission respectively. ii) Central (red) and line averaged (blue) electron densities from Thomson Scattering and Interferometry respectively. iii) Tritium fraction. iv) Stored energy. v) Neutral beam power (red) and total radiated power (blue).

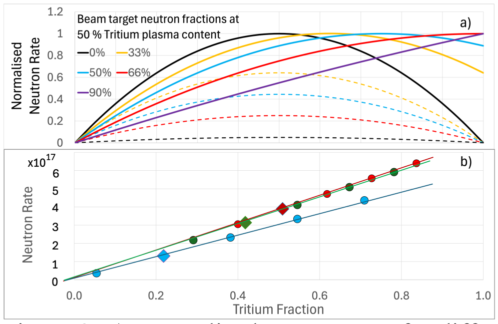

Figure 2: a) Normalised neutron rate for different proportion of beam-plasma reactions. Full lines: total neutron rate, dashed lines: thermal reactions only. b) Neutron rates predicted by TRANSP based on data from JET pulse 104649 at three time points. The diamonds are computed using the measured Tritium fraction. The circles are computed scaling the Tritium fraction while keeping other parameters as measured.

dependence of the 14MeV neutron rate on T fraction for plasma conditions as achieved in the discharge shown in figure 1. The dependence expected for the plasma conditions associated with three different time points in this discharge is shown in figure 2b. Note that, in the plasmas considered, the DD reaction rate is ignored as it constitutes ~1% of the total rate.

Figure 2b shows that the dependence is expected to be linear, indicating that, for these experiments, the fusion power is completely dominated by reactions between fast, NBI injected, D and thermal T. Controlling the T fraction is therefore an efficient way to control the fusion power in these experiments. For conditions with a higher proportion of thermal reactions, controlling the Tritium fraction will also be required, for example to assure operation near the optimum seen in figure 2a. Many other parameters, such as plasma density, heating power, confinement time, impurity content etc. influence the fusion power strongly and a combination of these dependencies will be exploited when controlling the power produced in a fusion power plant.

In the experiments discussed below, the JET real time system took control of the tritium gas fuelling rate and the deuterium pellet or gas fuelling rate with the injection locations shown in figure 3 [16, 17, 18, 19, 20, 21]. The gas fuelling rates were controlled by varying gas valve openings, while pellet fuelling rates were controlled by varying the pellet injection frequency. NBI also contributes to the deuterium fuelling, with this fuelling being deposited more centrally, but as this constitutes <10% of the total fuelling it is treated as a disturbance by the controller. One concern that could be raised when using gas valves to control the DT mixture, is whether the injected gas mixes quickly with particles already in the plasma. In other words, would an increase in T injection and a reduction in D injection result in a timely change in T concentration throughout the plasma and would this result in the desired change in the fusion power [22]. Efficient mixing has been demonstrated in JET Protium(H)-Deuterium(D) plasmas [13,23] and this has been exploited to achieve the highest steady fusion power via maximisation of beam-target reactivity at high T fraction [13]. The effect of fast ion mixing has been evaluated theoretically in [23], and the existence of conditions where the mixing of isotopes would be suppressed has been predicted with the transition between mixing and non-mixing being demonstrated experimentally in [24]. The experiments described in this work rely on plasma conditions with sufficiently strong D-T ion mixing.

To enable closed loop feedback control, the tritium fraction in the plasma was computed in real time from the intensities of specific deuterium and tritium lines in the measured visible spectroscopy spectrum [10, 25]. Figure 3 illustrates the spectroscopy lines of sight. The line emission is primarily due to excitation and recombination, which predominantly occurs in the cold divertor. Hence, the fuel ratio measurements, which mainly give information about the DT mixture in the divertor region, may not be representative of the mixture in the plasma core. This could deceive the controller if the fuelling was not effective in reaching the plasma core as it would almost certainly show up in the divertor.

One of the principal aims of these experiments were to demonstrate that the core plasma DT mixture can be controlled in real time, using peripheral actuators and sensors. The neutron rate measured by the JET neutron detectors [16] can give a good indication of the extent to which this is achieved as discuss in the following.

Figure 4 shows the scheme used for controlling the T fraction. This control scheme was developed in

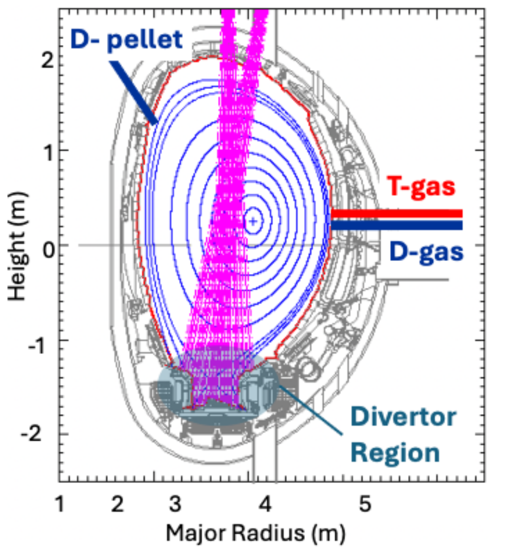

Figure 3: Cross-section of a JET plasma showing the visual spectroscopy lines of sight and the pellet and gas injection locations.

preparation for these experiments and tested in HD plasmas as described in [26]. In this scheme, the measured T fraction is subtracted from the reference and the resulting error is sent to a Proportional, Integral, Derivative (PID) controller. The PID output is deducted from the D feedforward flow request and added to the T feedforward request. In this way the total flow stays constant while the injected T and D fractions vary. Not shown in the figure is the factor translating requested flow to valve openings. This factor is continuously updated to correct for measured variations in gas reservoir pressures. In pulses using D pellet injection rather than D gas injection a similar factor is used to translate requested D flow to required pellet frequency. Note that no real-time measurement of actual flow rates was available to the controller. Figure 5 shows an example demonstrating the successful use of the controller. 12MW of D NBI power is switched on at 4s, resulting in an increase in plasma density, temperature and neutron rate. The T fraction is feedback controlled from 4.5s to 10s, with the reference stepping from 0.3 to 0.6 at 7.5s. The controller initially regulates the measured T fraction to 0.3 and then responds to the step, bringing the fraction to the requested value of 0.6 in ~2.5s. The response time is due to i) delays and time constants associated with the transport of gas from gas valves through gas pipes to the vacuum vessel, ii) the vacuum pumping efficiency and iii) the time constants associated with particle transport within the plasma. The response associated with the combination of i) and ii) has been measured in conditions without a plasma in the vessel and it can be approximately described by a delay of ~400 ms and a time constant of ~200ms. If the majority of the injected gas flowed directly between the injection location and the measurement location in the divertor, the spectroscopic measurements would be expected to respond on the time scale associated

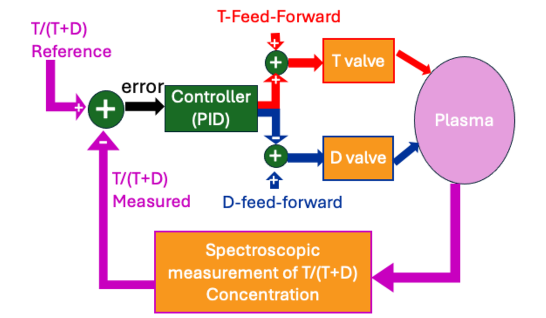

Figure 4: Tritium fraction controller

with i) and ii). The observed response is significantly slower displaying a delay of ~400ms and a time constant of ~1s, indicating that plasma particle transport dynamics is the dominant factor determining the spectroscopic measurement response to variations in gas injection. This indicates that gas injection is effective in changing the plasma composition. It is, however, still not guaranteed that the measured T fraction is representative of the concentration throughout the plasma volume. JET has no direct measurement of the T concentration as a function of plasma minor radius. However, the neutron rate seen in Figure 5 responds with the same time signature as the measured divertor T concentration indicating that this measurement is representative of the core T concentration and that peripheral gas fuelling is effective in varying the core composition.

To go one step further in assessing whether the T fraction is changed globally, the TRANSP transport code [14] has been run in interpretative mode for the discharge from figure 1 as seen in figure 6. To achieve these interpretative results, the measured profiles of the main plasma parameters (density, temperature, etc.) were used. The T concentration was assumed to be as the measured value throughout the plasma with no radial variation. The agreement between the neutron rate predicted by TRANSP and the measured value is remarkably good. Such agreement would be unlikely if the measured T fraction was not representative of the T fraction throughout the entire plasma.

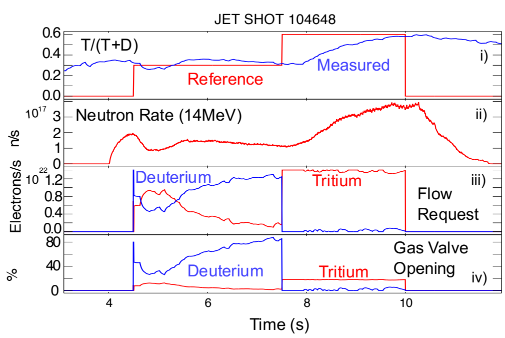

Figure 5: Closed loop control of tritium fraction. All signals are real-time signals except the neutron rate which is a post pulse calibrated signal. Main plasma parameters like in discharge 104649 shown in figure 1.

The important take-aways from these investigations are:

i) The injected gas mixes effectively in the entire plasma volume.

ii) The T concentration measured through spectroscopy is representative of the T concentration throughout the plasma.

iii) The T concentration can be effectively controlled in real time.

The above experiments were repeated replacing the D gas injection by D pellet injection. The pellets used were small 'ELM pacing' pellets injected from the vertical high field side as illustrated in figure 3 [19]. To achieve this, the required D fuelling rate was translated into a requested pellet frequency. Figure 7 shows two examples of such discharges. In the discharge shown on the left, the behaviour is very similar to the behaviour with D gas injection, though the density in the phase dominated by D pellet injection is slightly higher than in the T gas dominated phase. This illustrates that the fuelling efficiency from small pacing pellets injected from the vertical high field side is slightly larger than the fuelling efficiency achieved with low field side T gas injection. The discharge on the right in figure 7b shows an example where the pellets did not start as desired, resulting in the total gas flow being too low in the initial phase. This reduction in gas flow resulted in a substantial drop in ELM frequency [27]. As described in [27], having a sufficiently high ELM frequency is a requirement to avoid tungsten influx and accumulation in JET discharges with the 'all metal' wall. Hence the drop in ELM frequency resulted in tungsten accumulation in the plasma core and a significant drop in plasma temperature, ultimately resulting in a reduced fusion power/neutron rate. It is interesting to note that the isotope control still works perfectly under these conditions, with the response being, if anything, more rapid, probably due to the

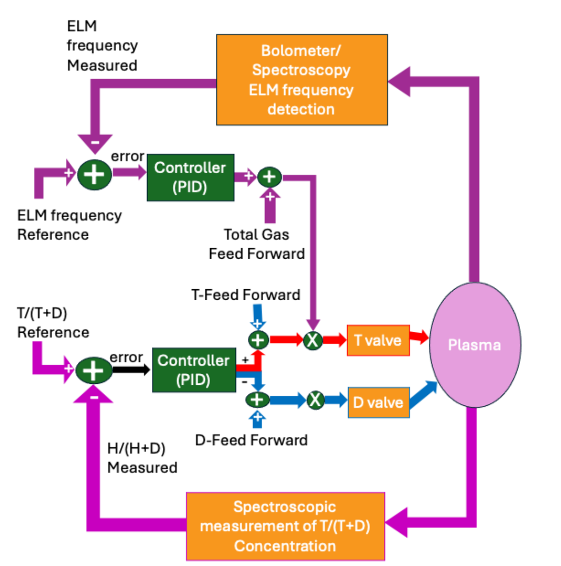

Figure 8: Combined ELM frequency and tritium fraction controller.

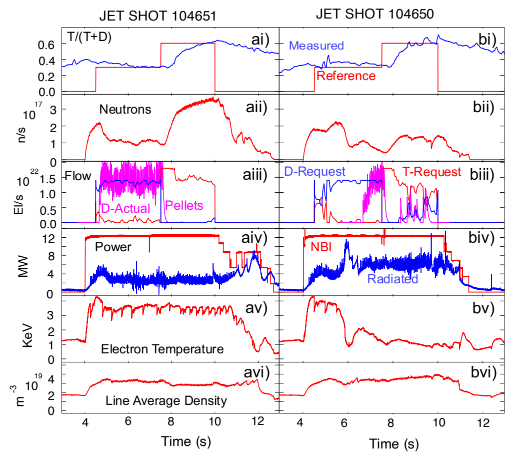

Figure 7: Two discharges with Tritium fraction control using pellets for deuterium and gas for tritium injection. the blue traces in box 3 show the required D flow while the magenta traces show the estimated actual flow due to the pellets being injected with varying frequency.

reduced particle confinement in this 'degraded' plasma.

In the experiments described above the total fuelling rate was kept constant. This total fuelling rate will, in general, have to be varied to control other parameters than the fuel mixture. In a reactor, variation of the fuelling rate is likely to be another important actuator for controlling the burning plasma and a combined controller will be required, controlling DT mixture and total fuelling independently. In JET H-modes the total fuelling rate is more commonly used to control the ELM frequency [27], which decreases with increasing T fraction. To maintain the desired ELM behaviour while varying the D:T ratio, a decoupled control scheme was developed to assure

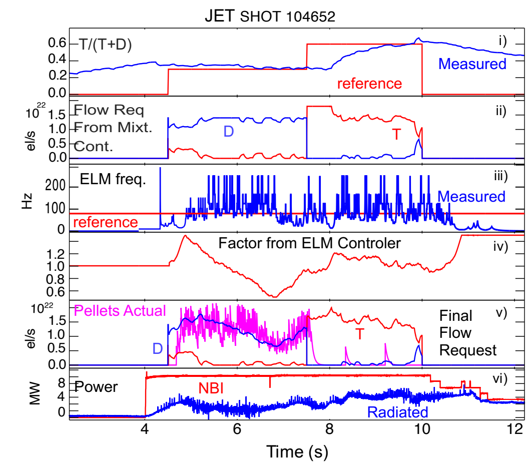

Figure 9: Combined ELM frequency and tritium fraction control using pellets for deuterium and gas for tritium injection. The Tritium and Deuterium flow requests from the isotope controller (ii) are multiplied by the factor produced by the ELM frequency controller (iv) to generate the flow requests (v)

simultaneous real-time control of T fraction and ELM frequency [28]. To achieve this, the output from the ELM frequency controller was scaled in the interval [0 1] and the two gas flow request from the isotope controller were multiplied by this scaling factor to derive the final D and T flow requests as illustrated in figure 8. Figure 9 shows effective combined control of ELM frequency and D:T ratio by simultaneous variation of total fuelling rate and fuel injection ratio. In this case the D was injected as pellets.

The experiments shown in this letter constitute the only demonstration of control of T fraction in plasma with reactor DT fuel mixtures. Such control will be essential in future fusion reactors. The mixture control was combined successfully with ELM frequency control and it was shown that gas fuelling can be replaced seamlessly with pellet fuelling. Following the termination of JET exploitation, further burn control experiments with the real DT fusion fuel will have to wait for future Tritium capable devices to come into operation.

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