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# DEVELOPMENT OF JET HYBRID PLASMAS IN DEUTERIUM AND DEUTERIUM-TRITIUM FOR IMPURITY SCREENING

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**Abstract**

The low density and high temperature at the pedestal in hybrid scenarios on JET provide a unique test of the neo-classical screening in the periphery of the plasma that has previously been observed on JET in such plasmas. Hybrid scenario plasmas have been further developed to aid in the study of temperature gradient screening of high-Z impurities from the core of the plasma via plasma current, toroidal field, gas fuelling, density and isotope variations. The steps required to adapt the pulses from deuterium to deuterium-tritium are discussed and provide some guidance for future experiments that may operate in deuterium-tritium. The optimisation of the scenario allowed for improved bolometry data compared to the Deuterium Tritium Experiment 2 (DTE2) campaign on JET, hence this work provides vital evidence of impurity screening in a high fusion power, deuterium-tritium plasma.

## 1. INTRODUCTION

On fusion devices with tungsten plasma facing components the radiation losses can cause significant plasma cooling if the tungsten reaches the core of the plasma, this can indeed be the limiting factor in achieving a burning plasma. There are a number of effects that may prevent or reduce the source or transport of this influx, one such effect is the screening of tungsten from the core due to neoclassical convection in the situation where the ion temperature gradient is sufficiently high compared to the electron density gradient. For ITER plasmas this "temperature gradient screening" is predicted [1] and is important for successful ITER plasma operations.

This impurity screening in the periphery of the plasma has been successfully demonstrated on the JET tokamak as part of the hybrid plasma scenario development [2]. The hybrid scenario on JET was developed in order to achieve high fusion power and was typically characterised by a broad q-profile with $q_{min}$ slightly above 1 and $\beta_N$>2 [3]. These plasmas provide good conditions for screening thanks to high input power, low collisionality and strong rotation [8]. These effects were also seen during the Deuterium Tritium Experiment 2 (DTE2) experiments on JET [4][5]. Further investigations into this effect were carried out and continued into the Deuterium Tritium Experiment 3 (DTE3) campaign [6][7].

To access the screening conditions on JET the hybrid scenario pulses have been optimised to achieve low pedestal density ($n_{e,\,ped}$), and high ion pedestal temperature ($T_{i,\,ped}$), and consequently a low collisionality and strong rotation which lead to neo-classical screening as discussed in [8]. To achieve this on JET an optimised gas fuelling timing is used, with a phase of no gas injection at the beginning of the high power phase to build up a strong temperature pedestal, followed by a timed gas puff to trigger the first edge localised modes (ELMs). This is to avoid having a very large first ELM that brings in large amounts of tungsten, degrading the pedestal temperature leading to reduced overall plasma fusion power and removing the conditions necessary for screening.

As part of the experiment variations, in plasma density were performed to attempt to quantify the impact on screening. This was achieved by varying plasma current, affecting particle confinement and/or gas fuelling. Further variations performed were in plasma isotope by performing experiments in deuterium-tritium (D-T) compared to pure deuterium (D). As part of the development of D-T plasmas the toroidal field was also increased to account for changes to H-mode entry associated with isotope dependence, rather than to determine an explicit dependence of the screening effect on toroidal field.

The presence of impurity screening in JET plasmas is assessed by detailed examination of bolometry data as in [2]. This analysis shows strong screening in many of the pulses performed, including those in DTE3. Due to the dependence of the study on bolometry, further development to ensure good quality data was required. Analysis of the plasma profiles with FACIT [8] can determine if a given time point in a plasma is in the conditions required for neoclassical screening or not. This analysis and the outcome of this are the subject of a separate publication [9]. Here the scenario development and experimental observations are presented.

## 2. SCENARIO DEVELOPMENT IN DEUTERIUM

The goal of the experiments was to develop hybrid plasmas that could explore the peripheral screening further to the work presented in [2] and to prepare for possible experiments in DT with improved diagnostic coverage compared to the previous results. The starting point was the best results from the previous data, in particular the pulse 97781 as analysed in [2]. Given the dependence of the results of neoclassical screening on density, ion temperature gradients and on rotation these were the parameters that were desirable to modify. However, on JET it is not straightforward to independently vary these parameters.

As the maximum available input power has previously been required for accessing screening conditions and a stable scenario [2][4], it is not a viable path to vary the input power to adjust the screening in a controlled fashion. Pulses within the development of the scenario that had lower power would typically fail due to strong impurity accumulation. If the input power is fixed, then a change in the density will also lead to a change in temperature and also to the resulting rotation in the plasma.

Additionally, there were some issues with available diagnostics necessary to the study of impurity screening and changes to the ELM behaviour. These issues were: uncertainty in the ion temperature profile, bolometer data being affected by main chamber gas puffing during DT experiments and the lack of diagnostics showing the source of impurities from the divertor. A further goal of the new experiments was to mitigate these issues by adapting the plasma scenario where possible.

### 2.1. Parameter variations in Plasma to Study Screening

The hybrid scenario on JET in preparation for DTE2 had primarily operated at 2.3MA/3.45T, this operating point was chosen following optimisation studies carried out in [4] to maximise fusion performance as defined by high neutron rates which requires high core plasma temperature and low core impurity radiation. The toroidal field was chosen based on the ICRH frequencies available, while the plasma current was chosen based on the q95 desired for a hybrid plasma with further refinement based on considerations such as the optimal density for fusion performance on JET and the avoidance of hotspots on the main chamber caused by ICRH accelerated fast particles.

A plasma similar to 97781 at 2.3MA/3.45T was established to achieve this. The gas waveform used was optimised to allow for the highest plasma temperature in the H-mode entry phase, during which the plasma performance peaks before reducing to a stationary state, while ensuring the first ELM is not so large as to degrade performance. The main phase gas is also optimised so that the ELM frequency is not so high that the analysis of the inter-ELM phase is impossible.

The first variation attempted as part of the study was a plasma current scan downwards to lower the plasma density. Plasmas were run at 2.2MA and 2.1MA. The 2.2MA pulse was unsuccessful but as the 2.1MA pulse (pulse 102825) provided a greater variation compared to 2.3MA (pulse 102813) and experimental time was limited the 2.2MA pulse was not repeated. The variation in plasma current changed the plasma density and temperature as shown in Fig. 1. The ion temperature shown here is a fixed position that is close to the plasma edge but inside of the pedestal. There is a difference in the gas waveform, this was found to be necessary to account for a small variation in first ELM timing when the plasma current was changed.

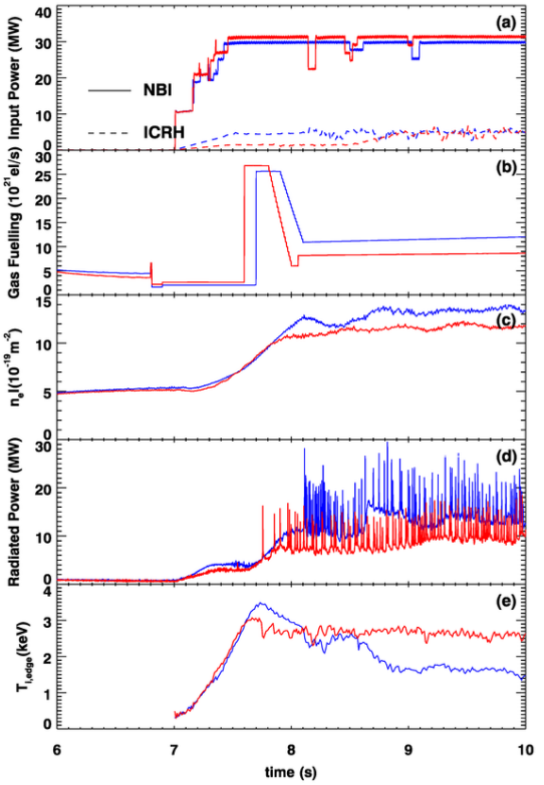


Figure 1: Comparison of 2.1MA (red, 102825) and 2.3MA (blue, 102813) plasmas. Input power, NBI solid and ICRH dashed (a), gas fuelling (b), line integrated density (c), Radiated power (d) and edge ion temperature ($\rho_{pol}$=0.85) (e).

The data and fitted profiles of these pulses are shown in Fig. 2 where it can be seen that the density pedestal in the 2.1MA plasma is lower than the 2.3MA case. Ion temperature data is measured by charge-exchange-recombination spectroscopy (CXRS) systems. The data is obtained from a core system [10] (labelled CXG6 in Figure 2 and an edge system [11] (labelled CX7C and CX7D in Fig. 2) then combined and fitted, details of the fitting and issues with the data are discussed in [9].

The final part of the experiment in deuterium plasmas was the variation of the density at constant plasma current by changes to the gas fuelling. This was performed in two separate ways, firstly by lowering the plasma density at the start of the beam injection and secondly by the delay in the gas puff to trigger the first ELM. The variation in gas puff and resulting changes to the plasma density, edge ion temperature and impurity radiation are shown in Fig.3. These scans were successful, partly due to consistent plasma conditions and input power over the scans.

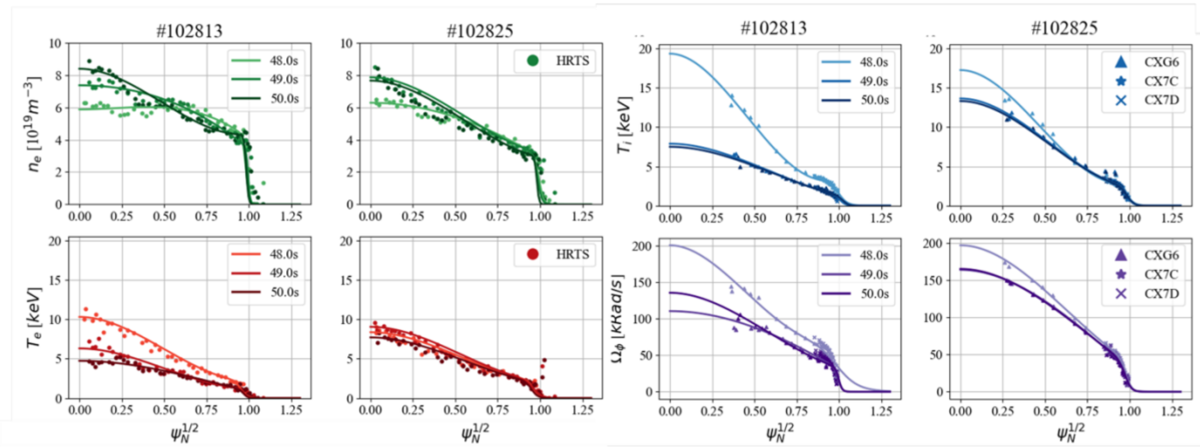


Figure 2: Density (top left), electron temperature (bottom left), ion temperature (top right) and rotation (bottom right) for the 2.1MA (102825) and 2.3MA (102813) plasmas at different times in the evolution of the pulse.

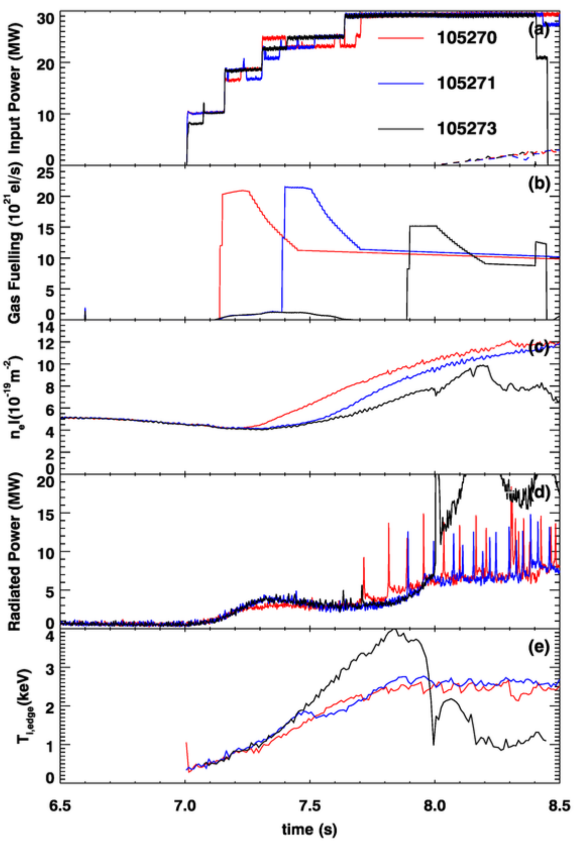


Figure 3: Plasma behaviour with varying gas puff timing. Shown in (a) is the heating power, NBI solid and ICRH dashed, (b) is the gas fuelling rate, (c) is the line integrated plasma density, (d) is the total radiation power and (e) is the edge ion temperature ($\rho_{pol}$=0.85)

In the variation of the gas puff timing, it was observed that with very early or very late gas puff the plasma performance was reduced. An early gas puff prevented the formation of a high ion temperature and had increased impurity radiation, while a late gas puff led to a very large first ELM and reduced performance. This reflected the earlier work on optimisation of the hybrid plasma gas fuelling, discussed in detail in [4] but here performed in more controlled conditions over a wider range of gas puff timing. The changes to pre-heat density had a similar effect.

## 3. PREPARATION FOR DEUTERIUM-TRITIUM

The injection of tritium into JET plasmas is done via the Tritium Introduction Modules (TIMs) [19]. These TIMs have different gas flow characteristics to the standard Gas Injection Modules (GIMs) due to the longer pipework required and are also in fewer locations around the vessel. There are 3 TIMs in the divertor and 2 in the main chamber. Those in the divertor are slower to start delivering gas and reach the maximum gas flow rate in the torus than those in the main chamber. As the gas fuelling optimisation for these plasmas requires a fast response from the gas injection the use of the TIMs causes issues due to the long pipe length. This is further complicated by the impact the faster, main chamber TIMs have on the bolometry data due to the proximity to the bolometer cameras [4]. As the bolometry data is essential for the analysis, those TIMs should be avoided as much as possible. Also, the ICRH coupled power to the plasma is increased by the use of main chamber gas, whether D or T.

The previous hybrid development in DTE2 had used one of the faster, main chamber TIMs (TIM 15) to inject tritium and the standard main chamber GIMs to inject deuterium. The NBI system was also used in a mixture of D and T providing approximately balanced fuelling. Due to this use of TIM15, the quality of DTE2 bolometry data was reduced. In DTE2 plasmas TIM15 fulfilled two roles, (1) to provide balanced DT, plasma density control in the pre-heat phase and (2) to provide T dosing during the main H-mode phase.

The strategy devised for DTE3 was to retain the use of TIM15 for the density control during the pre-heat phase and then to use a different TIM during the main phase. The fast injection of gas to trigger the first ELM would all be deuterium provided by 2 main chamber GIMs (numbered 1 and 6) as in the deuterium plasmas already described, because the divertor TIMs could not respond quickly enough. A further change for DTE3 compared to DTE2 was that all of the beams were in D in DTE3 while in DTE2 it was a roughly equal mixture of D and T. As this large injection of D combined with the all D fuelling from the beams would change the isotope ratio it was decided to begin the pulse with all T gas fuelling to attempt to compensate for this. While this variation in DT ratio is not desirable it was considered a worthwhile compromise to obtain good quality data for the purpose of this experiment. A schematic of this approach is shown in Fig. 4. The "gap" in fuelling was as previously discussed to allow a high temperature pedestal but also to account for the slower turn-off characteristic of the TIM, particularly when using T2 rather than D2 which has a slower response due to pipework and also due to the isotope with a scaling of $\sqrt{(M3/M2)}$.

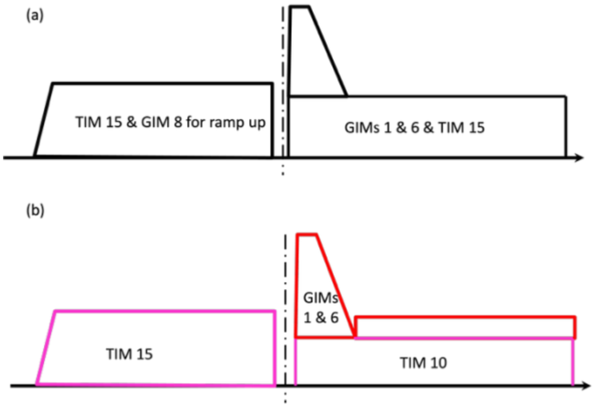


Figure 4: Strategy for gas usage in the DT plasmas, (a) shows the strategy used in DTE2 with all gas shown together, (b) shows the strategy used in DTE3 with tritium injection shown in magenta and deuterium injection shown in red, the dashed line represents the heating start time in both plots.

To test this change to the gas strategy before going to DT operations plasmas in D with a similar combination of injection points were attempted. Firstly, the gas dosing in the main phase was moved to the divertor (GIM10) and later to the equivalent TIM (TIM10) still fed with deuterium gas. A similar performance has been achieved in the main phase with controlled radiation and an ELM frequency of ~40Hz as desired.

The use of a pure tritium plasma during the ramp of the pulse required a further adaptation to the pulse setup. The density during the gas ramp is tuned to avoid hollow temperature profiles [12] leading to early disruptions. The density in this phase also affects the q-profile that has been highly tuned for hybrid plasmas. Data from DTE2 was available to aid this preparation.

## 4. OPTIMISATION IN DT

The first part of the DT experiments involved ohmic plasma tests to ensure that the ramp designed above for optimal q-profile was achieved. There are two criteria used in this part of the development, the avoidance of hollow temperature profiles and the arrival time of the first sawtooth when no heating is applied [12]. By comparing the ohmic pulse in DT with those in D it was possible to demonstrate whether this had been achieved. The use of an ohmic pulse is necessary to observe the first sawtooth with minimal use of tritium or production of 14MeV neutrons, both of which are subject to strict operational budgets [7].

In DT conditions it was expected that some minor tuning to the gas rates would be required but that the preparations in D would minimise these. The first pulse exhibited similar initial ion temperature in the pedestal compared to the reference pulses however the density in the ramp of the input power rose slightly more quickly than in D. This is due to the lower power required to enter H-mode in tritium plasmas [13]. This pulse appeared to have a larger amount of radiated power, which is consistent with the increased density in DT caused by increased particle confinement [14][15], reducing the screening of impurities although a detailed analysis of this failure has not yet been carried out and other causes for the failure of the pulse are possible.

To compensate for this effect the power in the ramp was adjusted such that H-mode entry was matched more closely to that of the plasmas in deuterium. A comparison of the pulse in D (103793), the full ramp in DT (104215) and the adjusted ramp in DT (104216) is shown in Fig. 5. Note that the full power ramp pulse 104215 is terminated and power ramped down due to the high radiated power. The isotope ratio as measured in the sub-divertor is shown also to demonstrate how this ratio is varying during the pulse.

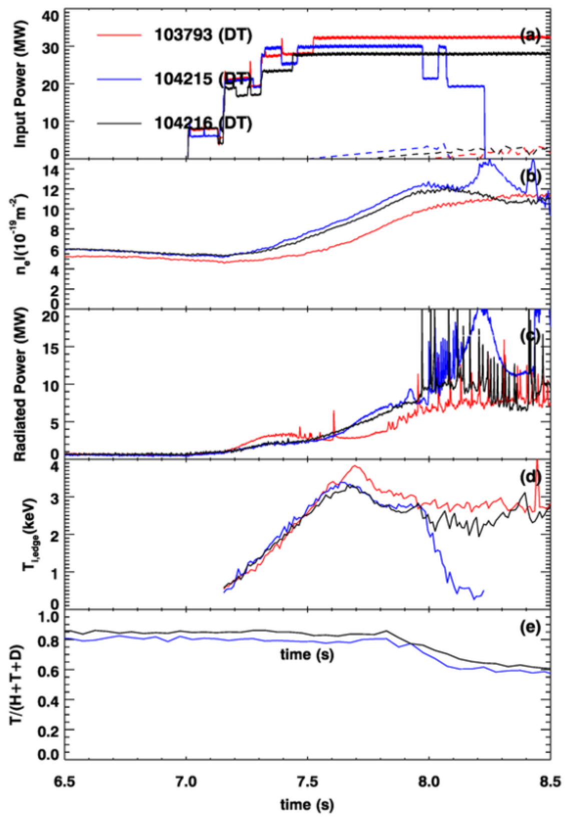


Figure 5: H-mode entry in D (red, 103793) and DT with faster power ramp (blue, 104215) and DT with slower power ramp (black, 104216). Input power, NBI solid and ICRH dashed (a), line integrated density (b), radiated power (c), edge ion temperature ($\rho_{pol}$=0.85) (d) and tritium concentration (e)

A number of the pulses demonstrated strong MHD activity, in particular 3/2 modes, which reduce the plasma performance and were not seen in D due to lower $\beta_N$. While this was undesirable it was not a barrier to the analysis of the screening behaviour in this case, particularly during the initial phase as there was typically a smaller effect on the plasma periphery and there was long enough before the mode to complete the analysis. Hence no action was taken to compensate for the modes given the short experimental time available.

To avoid the early H-mode entry related to the isotope and thereby be able to maintain full power in the ramp it was decided to increase the toroidal field as the LH threshold power typically increases with toroidal field [13][16]. Hybrid like plasmas in tritium rich conditions had already been performed in DTE2 at 3.85T as part of the fusion power optimised scenario [17] and this provided data the q=1 arrival time required to prepare the ohmic ramp up.

Three pulses were performed at 2.1MA/3.85T with some variation in the gas fuelling used, 104406-104408. While some good data was provided by these pulses there were issues with either the gas flow or the input power of each pulse. Further to this, analysis of the bolometry data from the pulses with the use of divertor T fuelling was carried out in parallel with ongoing experiments. It was shown that even with this pulse setup the bolometer still suffered from some interference from this TIM gas. To further reduce this interference, it was decided to remove the use of TIM15 from the density ramp as well as the main phase and instead use the same divertor TIM as used in the main phase.

On the final day of the DTE3 campaign pulse 104681 without any fuelling from TIM15 was successful on the first attempt with a suitable density ramp to avoid temperature hollowness - data from the pulse is shown in Fig. 6 along with deuterium reference pulses carried out following the DT campaign. The pedestal performance of this pulse appeared to exceed that of the earlier pulses with the peripheral ion temperature ($\rho_{tor}$~ 0.85) here exceeding 4keV in the overshoot phase and continuing at approximately 3keV for the main, ELMy phase of the pulse. This was in excess of any previous edge ion temperature observed on JET during the metallic wall period. Through the modification to the gas waveform for this pulse it appeared that the behaviour of the MHD was improved in this pulse, the $\beta_N$ was slightly lower than a previous DT plasma (104408) and hence did not trigger a mode and allowing for more consistent performance. It should be noted that the gas fuelling plot does not consider the difference in the response time and fuelling efficiency of the different locations, the large initial level in the divertor fuelled pulse is used to increase the response time of that GIM and does not mean that a much larger actual gas flow was present at that time.

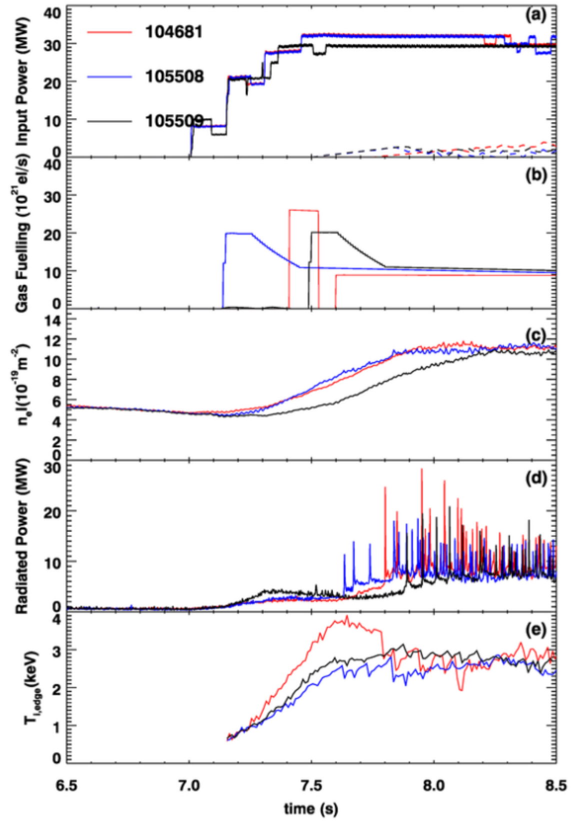


Figure 6: Comparison of 3.85T D with DT plasmas. Shown in (a) is the heating power, NBI solid and ICRH dashed, (b) is the programmed gas fuelling rate, (c) is the line integrated plasma density, (d) is the total radiated power and (e) is the edge ion temperature ($\rho_{pol}$=0.85)

## 5. IMPURITY SCREENING RESULTS

To determine if the plasmas are in the screening regime a time-dependent analysis of the bolometer data is performed as in [2]. This analysis shows if the transport of the tungsten is inwards or outwards at a given time, and in particular the difference between the ELM and inter-ELM transport. It is performed by examining the bolometer reconstruction and following the spatial and time dependence to determine if at a given location there is transport of the impurity inwards or outwards. There are assumptions made within this analysis, in particular that the total radiated power is dominated by tungsten and that the cooling factor of tungsten is approximately constant of the spatial range considered. These assumptions and the analysis method are more thoroughly described in [2].

The screening vs flushing analysis for a series of pulses is shown in the following figures. Within these figures multiple time points within the main heating phase of the pulse are shown with the transport of impurities during an ELM shown on the y-axix and inter-ELM transport shown on the x-axis, negative transport referring to outward, removal of impurities. Points within the upper left quadrant show inter-ELM screening while points in the lower right quadrant demonstrate LM flushing. Fig. 7a shows how the variation in plasma current as in pulses 102813 (2.3MA) and 102825 (2.3MA) can affect the screening. While both pulses demonstrate screening the pulse at lower plasma current appears to have more timepoints in the upper left and deeper into that quadrant although this difference is marginal. The comparison of the D and D-T plasmas are shown in Fig. 7b both pulses demonstrate many time points in the screening regime with no major difference seen in this figure even though the D plasma has lower impurity radiation in total compared to the D-T plasma. These pulses show screening more clearly than the previous example, 97781 and the DTE2 results. Finally, the comparison of the pulses with different gas puff timing is shown in Fig 7c, both have many time points in the screening regime again while the earlier gas puff appears to have marginally more time points in the flushing regime than the later gas puff. Further analysis of these data including interpretation with respect to neo-classical expectations are published separately in [9]

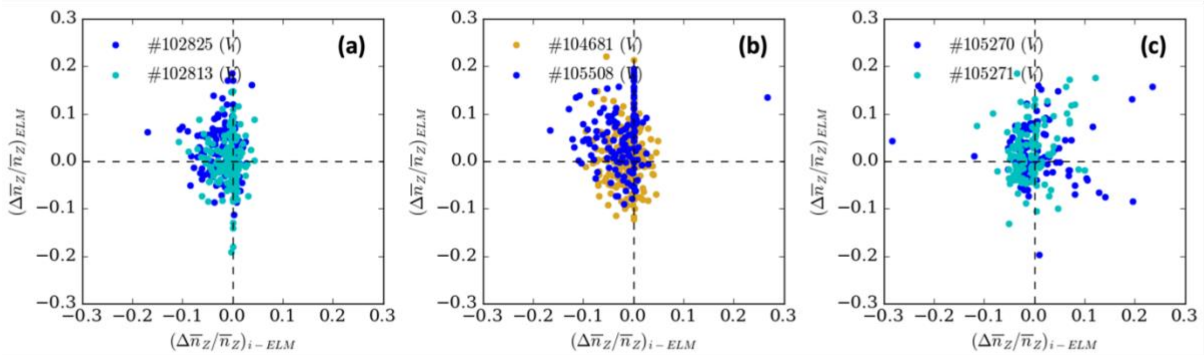


Figure 7: A comparison of the relative changes in the W content of the plasma due to ELM flushing (△¯nW /¯nW )ELM vs the change due to the inter-ELM influx (△¯nW /¯nW )i−ELM. The Ip variation is shown in panel (a), the D vs D-T variation is shown in panel (b) and the gas puff timing variation is shown in panel (c).

CONCLUSIONS

A series of hybrid plasmas have been developed to further test the peripheral impurity screening previously demonstrated on JET. Successful, inter-ELM screening of the impurities has been observed through analysis of the bolometer data in a range of plasma conditions. In particular, a range of pedestal densities and temperatures have been explored. The development of DT plasmas with gas fuelling optimised for diagnostic coverage has allowed the confirmation of screening results in DT operation on JET. The operational and scenario development steps required to obtain the results have been discussed, with a focus on how precise timing and setup of gas fuelling is essential to an optimised scenario. The methods discussed provide information on some of the tools required for the development of a plasma scenario from deuterium to deuterium-tritium operation. While this experience requires adjustment to specific operating conditions and plasma scenario it will still provide guidance for the efficient operation of upcoming fusion experiments and is discussed in more detail in [18].

The analysis of the data combined with the calculations of possible neo-classical screening are the subject of a further work [9]. The isotope dependence of the screening effect is a complex combination of different effects but the increased ion temperature of the DT plasmas is promising for the consideration of ITER and other reactor concepts beyond this.

## ACKNOWLEDGEMENTS

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