

## Massive gas injection experiments at JET - performance and characterisation of the disruption mitigation valve

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Disruptions, the fast accidental losses of the plasma current and stored energy in tokamaks, are a critical issue for reactor-scale fusion facilities like ITER. They present a serious risk of damage to the plasma facing components. The avoidance of such damage is also essential for the upcoming ITER-like wall (ILW) experiments (Be and W used as plasma-facing material in the main chamber and divertor, respectively) at JET, the tokamak experiment closest to ITER in terms of operating parameters and size.

Massive gas injection (MGI) is considered one of the most viable methods for disruption mitigation. The injection of noble gases is preferred because of their high recycling and low sticking probabilities to the wall, which should enable a reliable plasma breakdown and normal plasma operation after injection. To allow scaling of the mitigation efficiency towards ITER and to study the possibility of a JET protection by MGI, a disruption mitigation valve (DMV) has recently been brought into operation at JET.

The JET set-up and the function principle is explained in this article. Furthermore, first results of its performance by means of time of flight (TOF) measurements during various gas injections are presented. Finally, the implications on the machine condition and the subsequent machine operation are discussed.

**The disruption mitigation valve at JET** – The recently installed DMV at JET is shown in figure 1 (b) in its technical detail. It is mounted on one of the probe drives on top of the JET octant 1 and is connected via a 4 m long tube (diameter 40 mm, distance to separatrix ca. 0.5 m) to the JET vacuum vessel (fig. 1a). This high pressure valve (injection pressure 0.2-3.6 MPa) consists exclusively of non-ferro-magnetic materials and therefore stays operational inside high magnetic fields as present in fusion devices [1]. The restoring force is generated by the variable gas pressure  $p_{CV}$  in the closure volume, a secondary separated volume (fig. 1d (i)), which is kept at a factor of 1.5 below the pressure  $p_{IV}$  in the injection volume [2]. The factor is based on the force balance (fig. 1c) given by the surfaces  $A_1, A_2$  and the present pressures in the two volumes  $p_{IV}, p_{CV}$  according  $A_1/A_2 = p_{IV}/p_{CV} = 1.5$ . This ensures that the valve piston is pressed tightly against the seal at the orifice (10 mm) of the injection volume ( $6.5 \times 10^{-4} \text{m}^3$ ) and optimises the restoring force to provide maximum throughput (fig. 1d (iii)). The piston is opened by eddy currents induced by an transient current in an actuating coil (fig. 1d (ii)).

The gases which can be used for MGI at JET are Ar, Ne, He,  $H_2/D_2$  and mixtures of these which can be created inside the injection volume with an accuracy of 1%. The amount of injected helium is restricted to  $0.3 \times 10^{-3} \text{MPa} \cdot \text{m}^3$  in JET due to the applied cryogenic divertor pump; the low pumping speed and high heat conductance can lead to a spontaneous regeneration of the cryogenic panels.

The injection system is integrated into the JET machine protection system to avoid damage which might occur due to overheating of the neutral beam injection (NBI) duct or arcing in the ion cyclotron resonance heating (ICRH) antennae during a gas injection. Therefore, both additional heating systems are switched off automatically before the massive gas injection occurs.

**Performance of the disruption mitigation valve** – The valve throughput depends on the injection pressure. The maximum injected amount of gas is achieved at the maximum allowed pressure of 3.6 MPa

\*See the Appendix of F. Romanelli et al., FEC 2008 (Proc. 22nd Int. Conf. Geneva, 2008) IAEA, (2008)

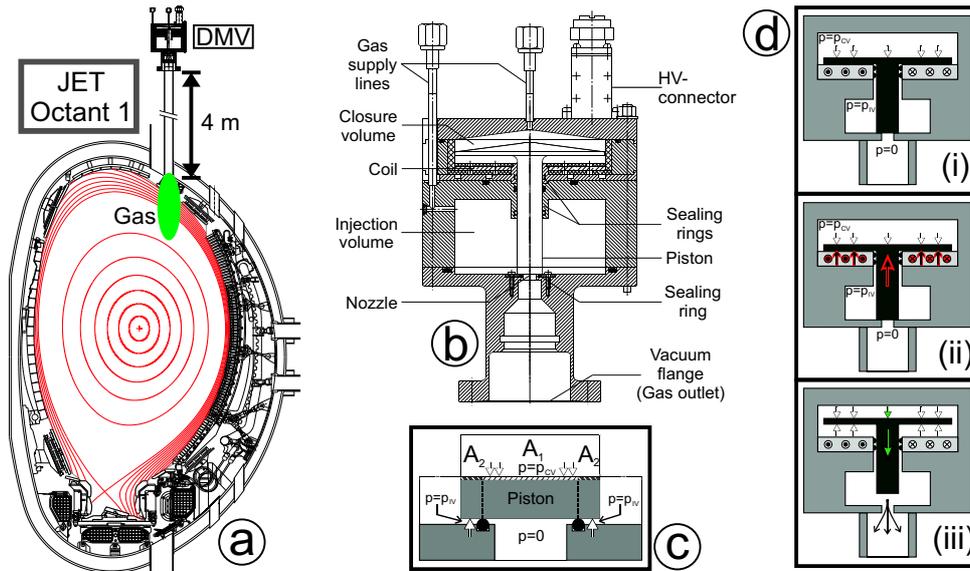


Figure 1: (a) Poloidal cut of JET. The DMV position on top is indicated. Magnetic configuration is representative for the plasma experiments discussed below. (b) Technical drawing of the DMV. (c) Illustration of the variable force on the piston. (d) Valve operation principle. (i) Initial position sealed tightly by  $p_{CV}$ . (ii) Transient current induces eddy currents to lift the piston. (iii) Gas flows through the nozzle. The pressure  $p_{CV}$  forces the piston to close (green arrow).

and is equal to  $0.85 - 1.0 \times 10^{-3} \text{MPa} \cdot \text{m}^3$  ( $1.9 - 2.3 \times 10^{23}$  particles) depending on the gas type, with the amount being higher for lighter gases. The throughput efficiency varies between 40% and 100% depending on the injection pressure and the gas species. The efficiency is higher for lighter gases (with higher velocities) and for lower pressures. The latter can be understood by the operation principle (fig. 1d). The force (given by  $p_{CV}$ ) which closes the valve (green arrow) depends on the absolute value of the pressure inside the closure volume. Hence, if the pressure is lower, the time taken for the piston to reach its initial sealing position will be longer so more gas can flow through the nozzle.

In figure 2, a typical sequence of a MGI experiment in JET is shown. After the pre-programmed requests for the DMV activation, a dead time of 23-50 ms (mean:47 ms) caused by the machine protection system passes before the high voltage power supply is triggered. In figure 2 the DMV request has been sent at 60.0 s and the DMV activation, indicated by a voltage drop, can be seen 46 ms later. Once the valve has opened, the pressure decreases in the injection volume (Note: The pressure gauges which are providing the pressure signals in fig. 2 have a low time resolution therefore do not present e.g. the pressure drop correctly.). After a time delay caused by the time of flight through the tube and the plasma edge cooling, the disruption takes place. This is indicated as shown by the rapid plasma current decrease (see [3] for more detailed description). In the case shown, the noticeable change of the plasma current, as a first measure for the TOF of the injected gas, gives a gas travel time of 6.1 ms which corresponds to 738 m/s (2.3 times the sound speed for Ar). This is consistent with the theoretical expectation which allows velocities for a component of the gas of up to 3 times the sound speed (454 m/s for Ar) [4]. Another method to determine the TOF is provided by the electron cyclotron emission (ECE) analysis of the plasma edge temperature shown in fig. 2 (right). This method is preferred because it is spatially resolved in the edge where the gas is penetrating the plasma, whereas the plasma current represents an integral value. The moment  $t_{ECE}$  the injected gas starts to cool the plasma edge is determined by a standard extrapolation of the ECE time signal, as illustrated. This is done for each ECE spatial position. The gas starts to cool down the plasma edge at 5.19 ms and evolves towards the plasma centre until the thermal quench occurs - here at about 10 ms. Note that the TOF for the different species in the table show a difference between the JET measurements and the laboratory. The reason might be the higher

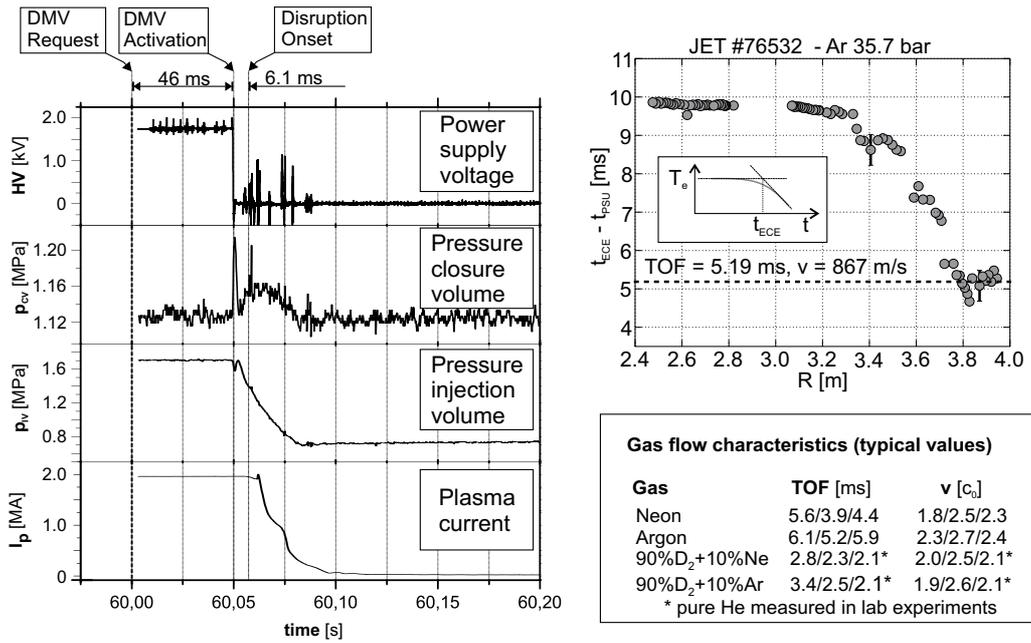


Figure 2: (left) Typical DMV sequence (JET #76541,  $B_t=3$  T,  $I_P=2$  MA, ohmic, DMV request time at 60.0 s, total injected gas  $0.5 \times 10^{-3}$  MPa · m<sup>3</sup> of argon). (right) ECE showing the influence of the temporal electron temperature change and typical TOF and velocities according to their first appearance in the signals of: (plasma current/ECE/laboratory [5]).

temperature (473 K) of the delivery tube at JET which could increase the velocity of the gas up to 25% compared to the laboratory measurements at about 298 K.

The TOF and the exact flow behaviour of the gas through the tube into the vessel is essential to determine the overall reaction time of the system. Taking these times for the various injected gases and comparing them with the typical time scales of disruptions at JET [6] shows that the DMV in its recent setup is capable of injecting gas into about 75% (25% are on much faster timescales and cannot be detected) of all intrinsically disrupting plasmas. However, the reaction time of the protection system decreases this fraction to 62-64%. A significant influence on a disruption depends on the gas species and amount of gas which can be delivered into the plasma before the thermal quench. This is described by the term *mixing efficiency* which depends on various conditions e.g. the flow pattern in the delivery tube as the gas front is flattened inside the tube (compare [7]) and, as a consequence, the efficiency decreases. The flattening effect can be observed in laboratory experiments [5] and is more pronounced for longer tubes.

**Consequences of massive gas injection experiments on machine condition** – Standard disruption mitigation by MGI must not only ensure a reduction in loads, but also machine conditions needed for reliable operation. It should be noted that during the open loop MGI experiments, an incomparably higher amount of gas is injected in total (over many discharges) to provoke disruptions. These amounts would be smaller if the DMV would be used as a closed loop machine protection system. Nevertheless, these extreme conditions can prove the applicability of the DMV as a standard protection system. In figure 3 the MGI effects on the following discharges of an experimental JET session (shotnumber #77803-77823,  $B_t=1.0$ -3.0 T,  $I_P=1.25$ -2.5 MA, ohmic and NBI heated, MGI with Ar and D<sub>2</sub>/Ar) are presented for the limiter and divertor phase. MGIs with Ne have shown a negligible effect on the machine condition and will not be discussed here. The Argon level measured spectroscopically rises after an injection of Ar or D<sub>2</sub>/Ar (#77812) with every additional MGI. The additional heating (#77817) increases the Ar level significantly as would be expected. This is not the case for previous discharges; this may be explained by the fact that most of the gas, which was implanted or absorbed by the wall during a disruption, is usually released during the limiter phase of the following discharge. NBI heating takes place during

the divertor phase of each discharge and releases more Ar in the divertor than in the limiter phase for discharge #77817 and #77820-77823. This indicates that there may be a dependence on the absolute amount of injected Ar because this effect can only be seen after a couple of pure Ar injections with the maximum amount. The difference of the released Ar level during the limiter and divertor phase decreases with subsequent discharges. In general, cleaning discharges (discharges without MGI and in particular plasma sweeps on the limiter and divertor) lead to a strong decrease of the absolute amount of Ar. In fact the Ar level is strongly reduced with the help of 2-3 cleaning discharges (#77819 (automatically terminated), #77822, #77822). However, a non sustained

breakdown (NSB) does not have a strong influence on the Ar level release as can be seen in discharge #77818. The concentration level is still high in the following discharge.  $Z_{eff}$  shows a pronounced effect during the injections, which in principle restores the conditions after the cleaning discharges or reaches a insignificantly higher level to those that existed prior to the injection.

In general the injection of pure Ar does not show a critical effect on the succeeding discharge. However, the injection of large amount of gas mixtures with  $D_2$  majority leads to a high wall load and as a consequence to a consecutive NSB each time followed by a "normal" discharge. Hence, the NSB has a cleaning effect which reduces the  $D_2$  wall load. Further analysis of this important MGI topic is ongoing.

**Conclusion** – The DMV has been successfully installed and reliable operation has been proven. It has been demonstrated that the recent JET DMV setup is fast enough to influence about 75% of all occurring disruptions. In practice however, the closed loop response time is limited by the cycle time of the current NBI and ICRH protection systems. A modification of the safety system is foreseen for the ILW project. The overall response time amounts to about 50-53 ms, which reduces the fraction of potentially mitigated disruptions down to 62-64%. An improved machine protection loop, with a response time of 10-20 ms which is restricted by the minimum ICRH power decay time, combined with a shorter delivery tube might enhance the disruption mitigation significantly.

An activation of the DMV, as part of the machine protection system for disruption mitigation, is unlikely to lead to an influence on the following discharges (for the discharge type used) and could be fully recovered after 2-3 cleaning discharges. However, pure gas injections have the disadvantage of runaway electron generation [3]. Gas mixtures with  $D_2$  suppress this generation but cause NSBs. With the variation of MGI mixtures, which can be provided by the DMV at JET, an optimum may be found for both runaway electron suppression and sustained breakdowns.

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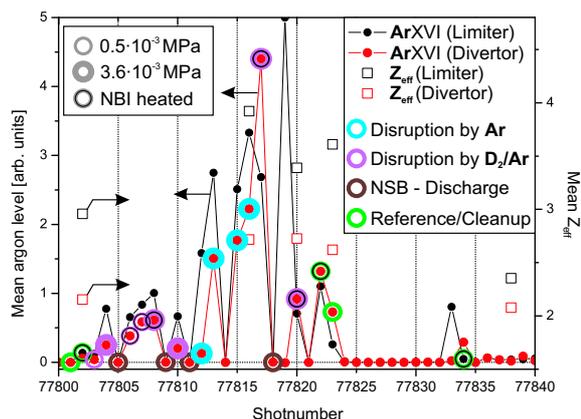


Figure 3: Mean argon level (ArXVI) and mean  $Z_{eff}$  level during limiter and divertor phase. (No data available for signals=0)