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Disruption studies in the JET metalic wall

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Disruption study advances in the JET metallic wall

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Abstract

Recently, the JET disruption mitigation system has been augmented with new disruption mitigation valve making the disruption mitigation system (DMS) of JET very close to the future ITER set-up. Experiments have focussed on optimizing the operating parameters of the DMV in JET plasmas and studying the disruption asymmetries. It is found that each DMV can mitigate the JET vessel vertical reaction force by ~40% on the machine with respect to vertical displacement (VDE) tests and an optimum impurity injection of 10^{22} atoms can be found. In addition, a minimum radiative gas quantity can be also determined experimentally independently from the plasma current for ensuring efficient mitigation. The use of two valves in opposite octant has successfully been used to reduce the radiation asymmetry. Progress has also been made on disruption prediction focussing on predictors that minimizes the required training or using physics based predictors for use in JET scenarios.

1- Introduction

Disruption remains the major risk for the operation of ITER and fusion reactors. Since 2011, JET operates with plasma facing components foreseen for the ITER wall (with tungsten components in the divertor and beryllium in the main chamber). The wall change from carbon to Tungsten/Beryllium, , led to a significant increase of the current quench time and hence larger electromagnetic forces (EM) and high heat loads on the plasma facing components due to lower radiation. Since 2015, JET is now equipped with three disruption mitigation valves (DMVs) located at different poloidal and toroidal locations mimicking the ITER set-up. Additional bolometers in 4 different toroidal locations have been refurbished and a fast visible camera is available for studying radiation asymmetries and disruption heat loads.

For routine JET operation, massive gas injection from one DMV is operated using a mix of 90% deuterium and 10% Argon. The use of this injection system is mandatory when a disruption event is detected for plasma current above 2MA or for total internal energy content (poloidal magnetic and kinetic) in excess of 5MJ. In the past two years JET has developed a comprehensive scientific programme in view of understanding and optimizing disruptions mitigation in the JET metallic first wall. In particular, important advances have been achieved in understanding the efficiency of massive gas injection, the impact of the electro-magnetic loads and radiation asymmetry and the operational consequences of the use of DMV. The disruption mitigation efficiency can be characterized by the radiative fraction, sufficient fast current quench and reduced vertical displacement.

Also, the need to mitigate disruptions up to high plasma current (4.5MA) has prompted pragmatic approaches to develop reliable disruption predictors. Modelling efforts have also been carried out for a better understanding of the electromagnetic loads and massive gas injection physics.

2- Recent JET disruption statistics with the ITER-like wall and ITER requirements

In the operation with the ITER-like wall and JET has experienced a significant change in disruption rate with respect to the operation with the carbon wall. JET has operated during the last years of the carbon wall era with a relatively low disruption rate of 3.4%. The start of operations with the ILW in 2011/2012 showed a marked rise in the average disruption rate [1], mostly because of core radiation peaking caused by high Z impurities. Since 2011 up to now, JET-ILW has produced 8176 plasma discharges with a current above 0.8MA (exceeding 2s duration) and 1112 unintended disruptions thus making a disruption rate of almost 13.6%. Among those, 612 have been mitigated by massive gas injection (mostly when Ip>2MA and the internal energy is in excess of 5MJ) triggered by locked mode signal threshold or vertical displacement measured by or vessel restraint ring flux loops. With JET expanding its operational range with the ILW for the baseline scenario [2] in preparation for the future D-T experiments (by increasing the auxiliary heating power >30 MW at higher plasma currents Ip > 3.5 MA), it has become clear that disruption prevention and mitigation efficiency optimisation is essential for operating JET safely at these levels of plasma current and input power. Note that in ITER, disruption mitigation is required above typically 5MA and 25MJ of thermal energy. In addition, high current (15MA) operation requires high mitigation success rate and at least 90% of the 800MJ of thermal and magnetic energy must be radiated [3].

3- The JET Disruption Mitigation System (DMS)

The JET DMS has been developed over the last years and, since 2015, is composed of three massive gas injection valves (DMV1, 2 and 3) installed in three different octants. DMV1 and DMV3 are installed in the upper vertical port of octant 1 and 5 respectively (at therefore 180deg toroidally) and DMV2 in the horizontal port of Octant 3 thus mimicking the future ITER set-up. They are featuring different delivery gas tube geometry and maximum pressure as summarized in table 1 making their operating conditions also different for efficient disruption mitigation. Each valve is attached to a complete gas handling system that allows the supply of different mix of gases (D with noble gases) with adjustable quantities and fractions. The three DMVs are integrated into the JET control system and can be triggered with various plasma signals characteristic of an on-coming disruptions such as locked mode signals (from magnetic saddle loops), vertical flux variations (from full flux loops) or specific built-in real time

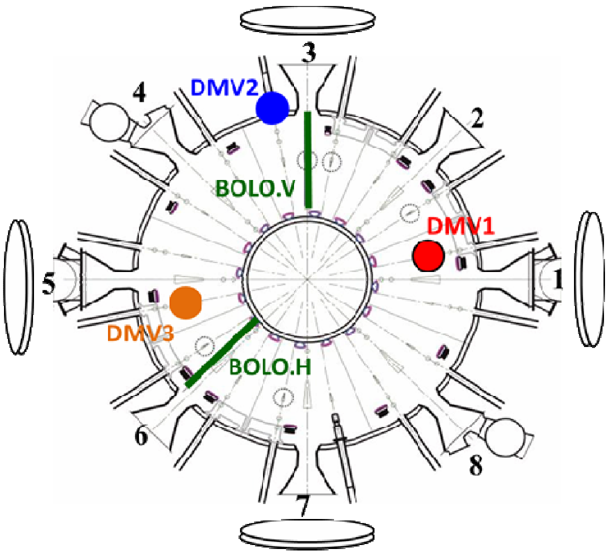

Fig 1: Layout of the disruption mitigation valves in JET. The locations of the bolometers (vertical and horizontal) and the error field correction coils are also indicated.

predictors (see below section 7). As soon as the trigger is received, the control system shutdowns the main machine heating systems (Neutral beam heating and Ion cyclotron heating) within a few milliseconds before the DMV is fired.

In order to synchronize the DMV gas flow for specific experiment such as the disruption asymmetry studies (see below), specific modelling has been undertaken using 3D gas flow simulation solving the Euler conservation laws for stiffened gas (i.e. including molecules) and the full geometry of each injector [4]. The fluid equations are solved by finite volume method and using 10bar in each DMV1 and DMV3 and a sound speed in vacuum of 4m/s for stiffened gas. These results are providing the first idea of the timing delay between the DMV and can be used as input to codes (such as JOREK) for the calculation of the gas penetration into the plasma.

Table 1	DMV1	DMV2	DMV3
Location	Oct1 / midplane	Oct3 / midplane	Oct5/upper port
Distance to separatrix	4.6m	2.8m	2.4m
Time of flight (D2)	1.6ms	1.1ms	0.8ms
Max pressure	1.0kPa.m^3	4.9kPa.m^3	1.7kPa.m^3

4- Mitigation of electro-magnetic loads in JET.

At the disruption current quench phase, electro-magnetic loads originate from halo currents induced in the vessel structures during vertical displacement and from eddy currents in the first wall components from the fast decay of the plasma current. They also induce electro-magnetic-loads and displacements of these structures.

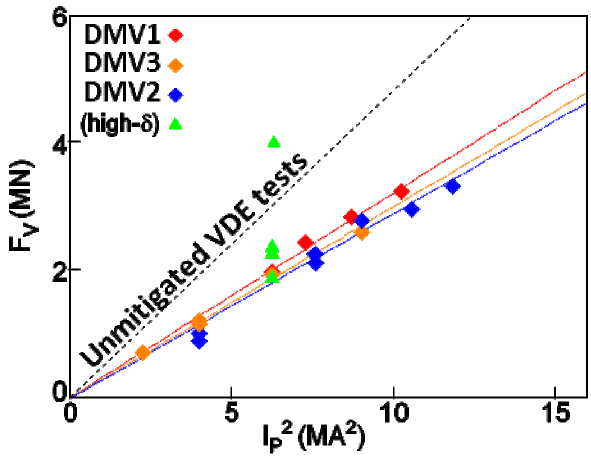

Fig 2: Vertical vessel force Fv versus plasma current squared; in black: Fv without MGI for pure vertical displacement event; dashed lines are the scaling derived from the data set for each injector;

The vessel reaction vertical force following a MGI has been measured by strain gauges on the vessel support over a plasma range up to 3.5MA at fixed magnetic configuration for all three injection locations separately using constant amount of injected radiative gas (Argon). Note that the vessel reaction force measurement is not purely the result of the halo currents but may also include forces from the eddy currents and from the poloidal coils. These results are compared with intentional vertical displacement tests (VDE) which are expected to provide the worst case vertical displacement and the largest induced halo current [5]. With respect to VDE test carried out for the same plasma shape, it can be seen that the EM vertical forces can be reduced by 33% to 40% depending on the DMV used. There is a small dependence upon the choice of the injection location (or type of DMV) used within this range [6]. Note also that this trend is also true when the magnetic configuration is changed to higher triangularity (green triangles).

In a different set of experiments, the gas amount in the mid-plane injector (DMV3) has been varied for both 1.5MA and 2.0MA to determine the optimum impurity injection that minimises the vertical force. For both currents a minimum vertical force can be found for typically an amount of injected impurity of 1x10^{22} particles. Changing the amount of impurity in the DMV has an effect on the current quench time which has been shown [3] to act on the balance between halo and eddy currents and therefore on the EM forces on the vessel. This amount of gas could be considered as the optimum gas injection where the impact of the forces on the structure and vacuum vessel components is minimal.

In previous studies [7] it has been demonstrated that the sideway force acting on the vessel during VDEs is mainly due to the asymmetric currents flowing in the walls and imposed by the asymmetry of the plasma current. Current and toroidal flux asymmetries [8] have been observed and studied in JET during and after the current quench. The resulting forces and their oscillations could cause severe loads for the ITER vacuum vessel (by mechanical resonance). Massive gas injection does significantly reduce the Ip asymmetries during the plasma current quench, thus participating in reducing the EM forces in JET, therefore the modelling of the current asymmetry and their mitigation remains a key objective. VDE modelling has been carried out using the M3D code [9]. M3D simulates 3D plasma evolution with axisymmetric wall covering the thermal quench (TQ), vertical displacement event (VDE), and current quench (CQ). The disruption simulation is initialized with an equilibrium reconstruction using EFIT. A vertical perturbation is added to this equilibrium and the calculation shows a vertical mode (1, 0) instability and a (1, 1) mode as well. The vertical growth rate is well reproduced by the code and an n=1 structure of the normal component of the wall force is predicted. To obtain realistic distribution of vessel asymmetric currents the next step is to use the source terms from M3D into the complete three-dimensional (3D) description of the conducting structures surrounding the plasma already modelled with the CARIDDI code. Recently, modelling of asymmetric currents is also invoking the possible role of asymmetric conductive paths which arise in the structures when the plasma column asymmetrically touches the wall [9].

5- Optimisation of the DMV operation in JET

Given the large amount of gas that can be delivered by the JET DMVs (up to 4.6kPam3), establishing the optimal mitigation parameters of the valves is also an important objective for the operation of the tokamak (thus minimizing the impact on cryogenic systems or wall conditioning).

In recent JET experiments the amount of radiative gas has been varied for both DMV2 and DMV3 for different plasma current and edge q to determine the optimal mitigation parameters for mitigating JET disruptions. The following results have been achieved:

- With reduced injected radiative gas amount (Ar), the radiation fraction degradation at the current quench does not depend on plasma current nor safety factor (fig 3). This observation is made for both vertical and horizontal bolometer. Note that below an Argon quantity less than $1\text{-}2.10^{20}$, the efficiency of the disruption mitigation decreases dramatically.
- The current quench duration as a function of the amount of injected Ar also does not depend on plasma current or safety factor.
- Normalised force as a function of Ar injected does not depend on plasma current, but it depends on the safety factor as the toroidal field is varied.

As a result, it is possible to determine the minimum quantity of matter that should be injected to ensure good mitigation which is typically 5 bar, 10% Ar for DMV 3, located at the top of the machine. The other DMV located in the mid-plane of the machine, DMV2, has been compared with these results and looks less efficient than DMV3. The disruption amelioration is equivalent with slightly more Ar (factor of ~1.6 typically). At this stage it is not clear whether this difference comes from the different poloidal location of the valve or the different characteristics (see table 1). These results mean that the DMV gas inventory can be significantly reduced and therefore the side effects (on wall conditioning) and cryogenic regenerations and inventory can be minimised.

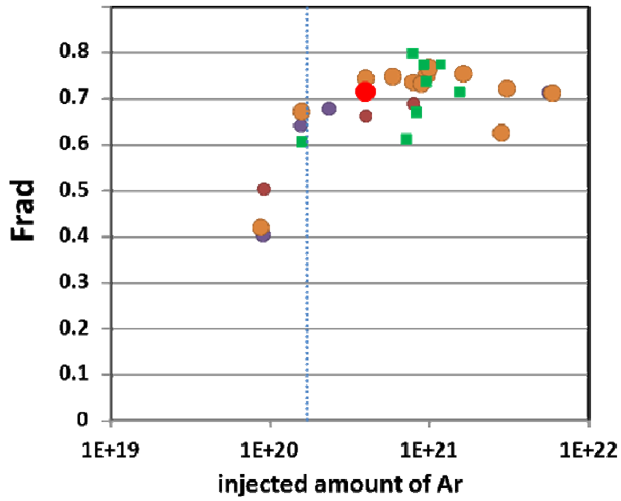

Fig 3: Radiated fraction at the current quench as function of the Ar quantity injected for various plasma current (3.0MA=red; 2.5MA=orange, 2.0MA=violet, 1.5MA=brown). Green squares are 2MA plasma at higher q95=4 instead of 3.

The magnetic activity measured at the edge by pick-up coils and bolometry reconstruction are showing that where the Argon quantity is not sufficient, the magnetic activity increases in amplitude and the level of radiation in the core is less than in the case with larger amount of injected Argon. As a result, the plasma core temperature does not decay immediately and there is evidence for a succession of several small thermal quenches lasting for 20 to 30ms before the final thermal quench occurs.

The above data are providing the basis for the benchmarking of the codes simulating the gas penetration. First simulations of a Deuterium MGI-triggered disruption in an Ohmic JET plasma have been performed with the first principle JOREK 3-D non-linear MHD code [11]. The gas penetration into the plasma has been modelled with the JOREK code. At this stage the gas source is adjusted so as to best match interferometry data. In the future the gas flow calculation described above could be used as an input to the code. JOREK simulations can qualitatively reproduce the JET disruption although the magnitude of the simulated radiation and MHD total signal amplitude is still weaker than in the experiment possibly because only deuterium gas was so far considered. Simulations show that the MGI causes the formation of a 2/1 island and the consecutive growth of several magnetic island chains that leads to a formation of a partial stochastization of the plasma and fast loss of the plasma thermal energy by parallel conduction. The work with JOREK shall in the future be pursued, aiming for quantitative validation using radiative impurities as well as toroidal rotation and diamagnetic effects.

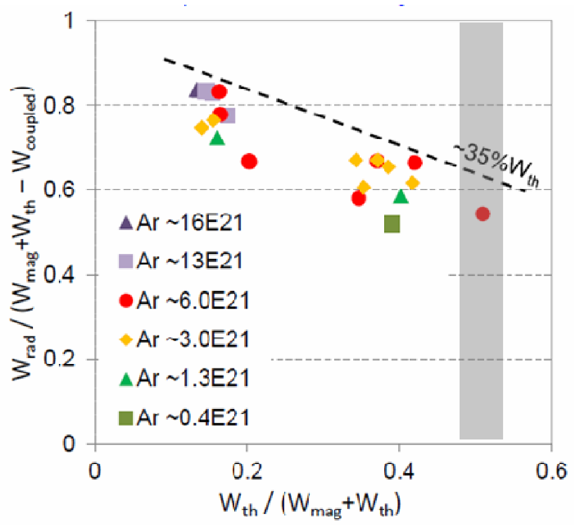

Fig 4: Degradation of the radiation energy as function of the thermal energy. Note that at high thermal energy only 60 to 70% is radiated. The shaded area indicates the ITER domain.

The ITER DMS also aims at establishing radiation fractions at high thermal energy (W_{th}) of W_{rad}/W_{th} ultimately greater than 90%. Initial experiments at JET carried out with DMV1 injector have observed a saturation of the radiated energy fraction with increasing radiative impurity injection. Similar saturation levels have been observed when using DMV2 or the new DMV3, although, both are significantly closer to the plasma and capable of injecting a higher amount of impurities. Since the required minimum injection could depend on plasma thermal energy, recent experiments have extended the operational domain to different fraction of W_{th}/W_{tot} up to relevant ITER fraction (0.5) using different input power and plasma current. Here the total stored energy in the plasma is defined as: $W_{tot}=W_{th} + W_{mag} = W_{rad} + W_{coupled}$, where W_{mag} is the magnetic energy of the plasma, and $W_{coupled}$ the energy dissipated into the vessel and poloidal field coils as calculated in [10]. As seen on figure 4, there is a steady degradation of the radiation fraction with the plasma energy fraction measured at the disruption including CQ and TQ independently from the gas injected Argon amount. The decay in W_{rad}/W_{tot} with increasing fraction of thermal energy indicates that mitigation is less efficient during the TQ [5]. As shown by JOREK, the thermal energy during the TQ is lost mostly by conduction and convection. The radiation peaks later during the CQ and participates mostly to the dissipation of the magnetic energy W_{mag}.

6- Radiation asymmetry mitigation

Radiation asymmetries (poloidal and toroidal) at the thermal quench during MGI disruptions can result in substantial first wall heat loads in ITER and have to be minimised. The toroidal asymmetries of radiation could also be at the origin of the observed degradation of the mitigation efficiency with increasing thermal plasma energy.

In JET, a toroidal radiation peaking factor of 1.5 to 2.1 has been estimated for a range of plasma thermal energy [13]. High toroidal peaking factor in radiation might lead to local heat load beyond melt limit [3]. Also, there are evidence that there exists a relation between the 1/1 mode and the observed radiation asymmetry [14, 15].

First of all, there is evidence that the phase of the n=1 activity can be influenced by the DMV injection itself. By varying the gas pressure up to 3.6MPa in a series of DMV injections for different radiative gases in ohmic plasmas with Ip=2MA, there is evidence that the O point of the n=1 mode is "attracted" to the toroidal location of the DMV. This is supported by JOREK simulations which shows that just prior to the thermal quench the gas injection from the DMV induces a 2/1 mode with its O-point at the DMV toroidal location. The cold front produced by the DMV could generate a local (i.e. non-axisymmetric) drop of the resistivity, leading to a contraction of the current profile and provide the drive the island creation with its O-point close to the injection location similar to the one observed in pellet injections [16]. Note that when this experiment is done with beam heated plasma (and therefore with significant injected torque), this correlation does not exist indicating that the plasma rotation is also an important parameter to consider in the observed radiation asymmetry.

To demonstrate the role of the n=1 mode, JET has conducted a series of DMV injection triggered disruption using different phases of the error fields generated by error field coils (EFCCs, see figure 1). The DMV injection was triggered for a fixed level of the locked mode signal (i.e. for a fixed level of error field for given plasma). These experiments have demonstrated that when the gas injected from DMV2 (octant 3) together with an n=1 error field induced by the coils in octant 3 and 7, then the radiation asymmetry measured by the bolometry is large (~0.55). Here the radiation asymmetry is defined at the CQ as the difference of peak radiation divided by the sum of the peak radiation for the 2 bolometers in octant 6 and 3 (see figure 1). On the contrary, if the phase of the induced error field is changed by 90deg (i.e. using the coils in octant 1 and 5) then the radiation asymmetry is strongly reduced down to 0.13. Depending of the phase of the n=1 mode, a single massive gas injection can lead to large localised radiation and hence to significant local thermal loads to the first wall. It is

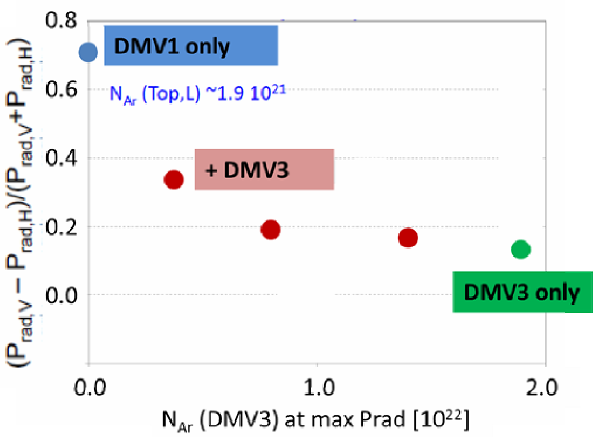

Fig 5: Radiation asymmetry factor for dual injections as a function of the Argon amount from DMV3 while the Ar injected from DMV1 was kept constant.

interesting to note though, that the radiation asymmetry factor is smaller when Neon is used instead of Argon as a radiative gas possibly because of a different distribution and/or penetration for these two gases.

From this first results and starting from the strongest radiation asymmetry using DMV1 in octant 1, the impact of dual injection on the radiation asymmetry has been studied using DMV1 together with DMV3 (located in octant 5 opposite to DMV1) in an attempt to reduce the observed radiation asymmetry. Since these two injectors are different in terms of time of flight and distance to the separatrix (see table 1) synchronization of both DMVs has been achieved by tuning i) the time delay with respect to the current quench for each DMV and ii) modifying the gas pressure in the DMV for equal amount of impurity gas. Figure 5 shows the resulting reduction of the asymmetry as the amount of injected argon impurities is varied for fixed amount in DMV1 (1.910^{21}). With this dual injection from the opposite side the asymmetry can be reduced down to 10%. This experiment shows that the radiation asymmetry is very sensitive to the relative timing of the DMVs and confirms that using 2 DMVs the asymmetry can be reduced down to acceptable level. These results provides support to the choice of injection locations for the ITER-disruption mitigation system

7- Disruption prediction and avoidance

Detecting an on-coming disruption well in advance will be essential in ITER for either applying a strategy avoiding the disruption (if the alarm is early enough) or shutting down the plasma discharge by measures like those described above (MGI or exception handling).

In JET, a new type of disruption predictor [17] based on the temporal evolution of the locked mode signal has been established. This detector does not use a pre-set amplitude threshold but recognizes anomalies in relation to past samples of the locked-mode during a discharge. Its training is therefore much reduced with respect to other type of predictors. It has been tested off-line over more than 1700 JET discharges (including 566 disruptions) and has been recently implemented in the JET control system. This new predictor can produce 9% of false alarms and valid alarms in 83% of the cases 10ms prior to a disruption. This response time is sufficient for mitigating the disruption with MGI, but not yet for avoiding disruption using plasma recovery strategies. The detection rate is presently being improved by including other type of disruption relevant signals such as radiation or other MHD signals. This tool is now installed on JET and will be used on-line in the 2016 deuterium campaign.

In addition, physics-based detectors are also explored with the help of modelling aimed at understanding the amplitude of the locked mode signal [18] or analysing the amplitude of rotating MHD precursors to disruptions. Recently, this MHD activity has been characterized by the application of Singular Value Decomposition to the signals of a set of 16 fast poloidal pick-up coils. The entropy of the singular values (H), its time variation (DH) and the spatial rearrangement of the modes distribution (DR) allows the definition a disruptive region in the parameter space ($H<0.5$, $DH>0.018$, $DR>6$), wider than the regular termination region. This technique has been first applied to baseline H-mode scenario and shows encouraging results for last campaign: right alarms of 81% with a warning time of 1 to 2 seconds. There is not yet a clear separation between the disruptive domain and the non-disruptive domain and therefore the level of false alarms remains significant (16%). However this analysis was performed over a set of 74 discharges (42 disruptions) only and a larger statistics is needed to strengthen this predictor.

8- Conclusions and prospect for disruption and run-away mitigation in JET

The combination of experimental data and modelling activities does improve our understanding of disruptions mitigation in JET and provides the foundations for the extrapolation of the disruption mitigation to ITER.

In addition, it should be noted that the JET data shows absence of RE generation up to 3.5 MA when typical mixture of D2 80-90% or Ar 10-20% is used for thermal load mitigation.

In 2009, JET had tested the behaviour of run-away beam with applied static magnetic perturbation using the JET EFCC and ripple. Experimentally, little impact on the run-away beam has been observed with respect to cases without magnetic perturbation [19]. More recently, the modelling [20] of run-away trajectories under the influence of EFCCs has shown that there is insufficient stochastization even at the highest EFCC current to disperse the run-away beam as intended, thus supporting the experimental results.

More recently, JET has run dedicated experiments with run-away to test the mitigation efficiency of the DMV [21]. In these experiments the run-away beams are created using DMV1 using high level of Ar concentration (typically above 30%) to trigger the disruption and the run-away beam. A second DMV is then used to test the mitigation efficiency using different radiative gas (Kr, Ar, Xe) and pressure level. So far, the massive gas injection has proven inefficient in JET to mitigate the run-away beam after it has been accelerated. This may suggest that the gas penetration is poor possibly because of the JET size. Modelling [12, 22] as well as experiments with minimised gas injection and lower plasma current is in progress at JET to test this hypothesis.

The unsuccessful attempt at JET to mitigate a full blown away run-away beam has prompted the installation on JET of a shattered pellet injector (SPI, [23]) for the next experimental campaigns in 2018. With this new tool, JET will be able to assess for ITER the efficacy of SPI on runaway energy dissipation in disruption scenarios and its efficiency in preventing heat loads and in controlling the current quench rate.

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