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Use of the Disruption Mitigation Valve in Closed Loop for Routine Protection at JET

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ABSTRACT

Disruptions are a major concern for next-generation tokamaks, including ITER. Heat loads, electromagnetic forces and runaway electrons generated by disruptions have to be mitigated for a reliable operation of future machines. Massive gas injection is one of the methods proposed for disruption mitigation. This article reports the first use of Massive Gas Injection as an active disruption protection system at JET. During the 2011-2012 campaigns, 67 disruptions have been mitigated by the disruption mitigation valve following a detection by mode lock amplitude and loop voltage changes. Most of disruptions where the valve was intended to be used were successfully mitigated by the DMV, although at different stages of the typical slow disruptions of the ITER-like wall. The fraction of magnetic and thermal energy radiated during the disruption was found to be increased by the action of the DMV. Vertical forces dispersion was also reduced. No non-sustained breakdown was observed following pulses terminated by the Disruption Mitigation Valve.

1. INTRODUCTION

The consequences of disruptions are considered to be a major issue for the operation of next generation tokamaks, including ITER. Thermal loads, electromagnetic forces and runaway electrons have to be mitigated to allow for efficient operation of the machines. Massive gas injection is one of the methods proposed for disruption mitigation. It aims at injecting a large amount of gas (several times the plasma content) to provoke a disruption less dangerous than the one that would have happened naturally. Many massive gas injection experiments have been carried out on most of the large tokamaks in the world, including JET [1, 2, 3]. However, almost all these experiments were done on stable and healthy plasmas and not in a plasma which is going to disrupt. Only a few machines have tried to use massive gas injection systems on incoming disruptions, either real (Asdex-upgrade [2] or pre-programmed ones (JET, [1]). Moreover, the entire process of detecting the disruptive plasma conditions, activating the valve and allowing time for the gas to reach the plasma has to be considered to estimate the mitigation effectiveness. Due to the fragility of the all-metal ITER-like Wall recently installed on JET and some localized melting events observed during unmitigated disruptions [4, 5], mitigation using massive gas injection has been routinely used during the 2011-2012 campaigns. The following article is divided as follows. The first part deals with the integration of the disruption mitigation valve (DMV) in the JET real-time protection system. The second part is focused on the way the valve is triggered and the results of the disruption detection scheme used in the 2011-2012 experimental campaigns. The third part is devoted to the results obtained in terms of mitigation effectiveness.

2. SYSTEM SETUP

2.1. DISRUPTION MITIGATION VALVE SETUP

The disruption mitigation valve is located on the top of the torus [6]. The gas is guided to the plasma by a 4m tube whose end is 0.5m away from the separatrix. The valve injection volume is 0.65l and the usual pressure is 33 bar for routine disruption mitigation. Based on previous experiments [1,

4], a mixture of 90% Deuterium and 10% Argon was used. Pure D_2 was found to generate too long current quenches and low radiated energy with the ITER-like Wall whereas pure argon generated runaway electrons with the carbon wall. The time-of-flight with this mixture from the valve to the plasma is around 3.4ms [6]. The valve has to be refilled by an operator in the control room after every injection.

2.2. INTEGRATION IN THE REAL-TIME PROTECTION SYSTEMS

The triggering of the valve was integrated in the Real Time Protection Sequencer (RTPS) developed for the ITER-like Wall protection [7]. It allows the session leader to decide in which phases of the discharge (current ramp-up, X-point formation, heating, scenario termination, ...) the DMV is to be enabled. The triggering of the DMV can be attached to any of the stops sent to the Plasma Termination Network (PTN) either directly or through an RTPS response.

Heating systems cannot be operating when the DMV is activated (limitation beam duct pressure and antennae lines). Consequently, they have to be switched off via interlocks before the triggering of the valve. This causes an additional delay in the opening, but ensures the safety of the heating systems. It takes only 2ms to switch off the NBI power supplies, but approximately 38ms to switch off RF. Due to the fact that no feedback signal is sent by RF plant to confirm that power supplies have been switched off, additional margin was taken leading to an overall delay of 50ms between the request and the actual injection. Pressure-sensitive diagnostics like spectrometers also need time to be switched off to avoid breakdowns. The Li-beam is the longest one and takes 30ms to be turned off, in parallel to heating systems.

3. TRIGGERING OF THE VALVE

Two types of triggers have been used throughout the recent campaigns: i) detection of dangerous MHD activity (locked modes) and ii) detection of plasma current excursion or loop voltage. All of them are based on available real-time signals with simple thresholds and assertion times. More elaborate triggering systems are being developed at JET [8] but have not been used yet.

1. Mode-lock detection. The mode lock signal computes the norm of cosine and sine amplitude of the mode lock signal as seen by saddle loops and normalizes it to the plasma current. It is already used at JET to soft-stop the pulse, albeit with a lower value than the one used to trigger the DMV. A non-normalized version is also used for the DMV.
2. Detection of plasma current excursion. The aim of this trigger is to detect the current spike occurring at the beginning of major disruptions or during minor disruptions. This trigger is usually reached in cases where the mode lock signal is not high enough to exceed its threshold. The current spike detection is made using either the plasma current derivative measurement or flux loops located near the restraint rings on the high field side of the torus. These loops detect large variations of the loop voltage at the current spike. As for the locked mode detection, the flux loops signals can be normalized to the plasma or not.

A summary of the range of thresholds used for detection and the number of DMV activations each of those has triggered is given in table 1. The most common trigger is the mode lock signal normalized to the plasma current. Some of the disruptions missed by the mode-lock signal are caught by the flux loop a bit later. Please note that in some cases, more than one trigger was raised at the same time. This simple triggering scheme tends to open the DMV quite late in the disruption process, sometimes missing the first thermal quench-like events (Fig.1). However, typical disruptions mitigated by the DMV in these campaigns are due to impurity accumulation followed by a radiative collapse. These disruptions are slow to develop, and do not generate a single thermal quench (current spike) followed by a fast current quench. Most of them have several thermal events indicated by successive current spikes and the plasma temperature does not immediately drops to current quench-like values. Consequently, even if the first thermal quench is missed by the DMV, a significant part of the thermal energy and of the plasma current may still be present in the plasma. This will be further discussed in the next section.

The DMV was used systematically for scenarios above 2.5MA, and for some other risky scenarios between 2.0MA and 2.5MA. In addition, it is usually left active down to 1.75MA. The use of the DMV is enabled only for a pre-programmed time window during the pulse, generally between the X-point formation and the end of the post- heating phase. 67 unintentional disruptions were mitigated by the DMV in the 2011-2012 campaigns. 5 disruptions were missed due to inhibits in the real-time protection systems that prevented the valve from ring. This was part of the commissioning of the DMV operation in closed loop, and was rapidly solved. 4 disruptions were missed due to an incorrect setting of the time window when the DMV was enabled. Finally, 7 disruptions were detected at a plasma current lower than the minimum current needed for the DMV to be red. In these cases, the first thermal quench event happened at higher current, but was not detected by any of the signals previously mentioned.

4. IMPACT ON DISRUPTIONS

Assessing the impact of the DMV in routine operation is quite difficult due to the absence of a controlled non-mitigated disruption for every plasma condition encountered in closed-loop mitigations. However, some general trends can be drawn from the statistics of all the recent disruptions. Runaway electrons are not discussed in this paper because none of the ITER-like wall disruptions produced high energy runaways. Besides, no non-sustained breakdowns following DMV injections were observed.

4.1. FORCES

Vertical forces on the JET vacuum vessel are generated by halo and eddy currents and their interaction with the magnetic field. They are an indicator of the disruption severity and scale with the square of the plasma current at the time of the disruption. This scaling factor depends on the plasma configuration. The growth rate of q Vertical Displacement Event (VDE) is usually larger with high triangularity configurations, leading to a higher fraction of the plasma current being converted to

halo currents. Consequently, low and high triangularity disruptions have to be analyzed separately. Figures 2 and 3 are histograms of the normalized vertical forces for low average triangularity ($\delta_{av} < 0.32$) and high average triangularity ($\delta_{av} > 0.32$) disruptions (intentional DMV experiments excluded). As shown on the low triangularity histogram 2, mitigation by the DMV reduces the dispersion of forces. Instead of a flat distribution between 0.08 and 0.5MN/MA² (average 0.27MN/MA², standard deviation 0.15MN/MA²), the distribution is gaussian-like, centered on 0.28 MN/MA² with a standard deviation of 0.07MN/MA². The average value of forces is not reduced by the DMV, but the dangerous high disruption forces are avoided, which is the main objective of the mitigation. There is indeed not much difference in terms of leak danger between 0.1 and 0.3MN/MA², but this risk increases exponentially with higher forces.

This impact on the forces dispersion can be explained by the peculiar nature of the disruptions in the ITER-like Wall. Conversely to the carbon-wall, very slow disruptions are more frequent, with current quenches lasting more than 500-800ms. These slow disruptions are well controlled by the vertical stabilization system and do not end up in a high-force Vertical Displacement Event. They account for the low disruption forces on figure 2 around 0.05-0.15MN/MA². The rest of the disruptions at higher forces corresponds to cases where the plasma cannot be kept vertically stable and ends up in a VDE. On the contrary, a DMV-mitigated disruption always ends up in a VDE (Fig.1), but this quick VDE is much less severe than a natural one. This explains the fact that almost no DMV disruptions have forces lower than 0.15MN/MA².

The statistics of high triangularity disruptions are more difficult to analyze due to the fact that very few disruptions happened at high triangularity in the last campaigns. In most cases, a bad situation (mode-lock) has already been detected and soft-stop strategies have been initiated. They aim at reducing the disruption forces by transiting to a low-triangularity configuration, and are usually successful. This explains the lower number of disruptions at high . The mean value of normalized forces in unmitigated cases is 0.43MN/MA² and 0.3 MN/MA² (see figure 3) for mitigated ones (only 4 cases though).

4.2. THERMAL EFFECTS: RADIATED ENERGY FRACTION

The thermal loads on the plasma facing components cannot be directly analyzed in routine mitigations because it requires dedicated settings for the infrared cameras. However the fraction of the total energy (magnetic+thermal) not coupled back to the poloidal circuits which is radiated can still be computed. The method used in this calculation is described in [5, 4]. Figure 4 shows that DMV-mitigated pulses have a high fraction of radiated energy (between 80% and 100%) even at high initial energy content. Note that this is an underestimation because of saturation of bolometers in DMV disruptions. Non-mitigated disruption have a much lower radiated fraction, between 15% and 50% with the ITER-like wall (no bolometer saturation in these cases).

The radiated fraction can also be plotted in function of the delay between the thermal quench event (current spike) and the actual triggering of the valve. Figure 5 shows that no decrease of the efficiency can be observed, even for late injections (after several thermal quench events). However,

one has to bear in mind that in most of the mitigated disruptions reported in this article, the thermal energy before the first thermal quench is already low: heating systems have already been switched off in almost all cases, and the plasma is already radiating a lot before the disruption happens. Consequently, the magnetic energy dominates the total energy content. It is therefore difficult to estimate the fraction of thermal energy that has been conductively lost to the plasma facing components because of a late injection. No melting event has been observed following DMV-mitigated disruptions, conversely to unmitigated ones.

CONCLUSION

The disruption mitigation valve was successfully used for the first time on JET as a real routine disruption mitigation system. It was integrated in the real protection systems designed for the ITER-like wall and mitigated 67 disruptions in the 2011-2012 campaigns. The disruption detection was performed by simple threshold signals such as mode lock amplitude or current spike detection. None of the disruptions where the valve was intended to be used was missed by those triggers, although the valve was opened sometimes after one or several thermal quench events. The dispersion of disruption forces was reduced thus avoiding the dangerous high forces disruptions. The fraction of the plasma energy radiated by the injection ranges between 80% and 100% contributing to a likely reduction of the conducted heat loads. This efficiency remains even with late mitigation, most probably because of the low thermal energy content of the plasma at the time of the disruption due to soft-stop strategies. No melting event was observed after mitigated disruptions.

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Signal	Threshold	Assert	No. of trig.
M.lock	0.002 T	0 ms	15
M.lock/Ip	400-520 pT/A	0-20 ms	35
Fx.Loop	500 V	0 ms	10
Fx.Loop/Ip	$5 \cdot 10^{-11}$ V/A	0 ms	13
$\Delta(I_p)$	100 kA	14 ms	3

Table 1: Thresholds used for disruption detection.

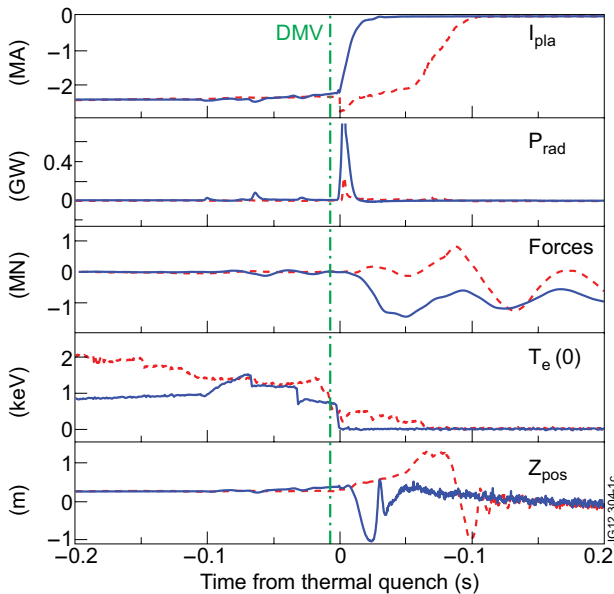


Figure 1: overview of two disruptions in ILW. Red line is unmitigated. Blue line is DMV-mitigated.

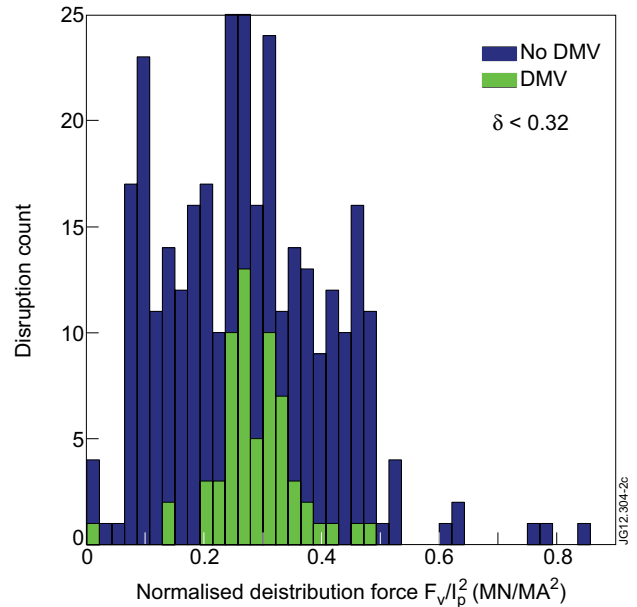


Figure 2: Normalized forces distribution - low triangularity

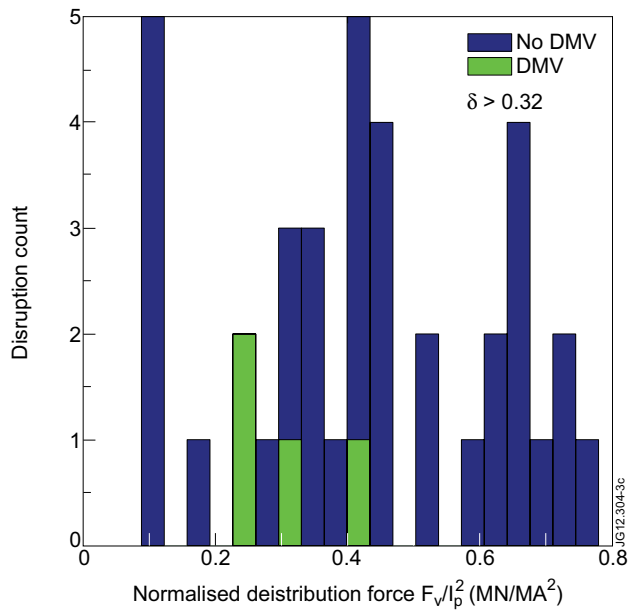


Figure 3: Normalized forces distribution - high triangularity

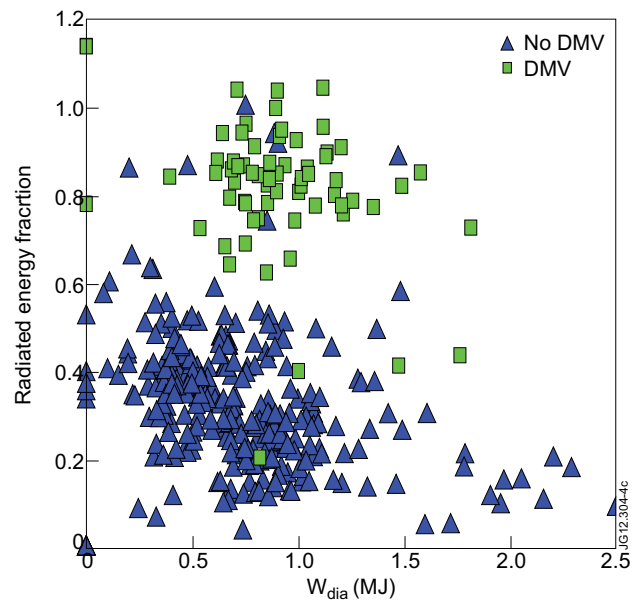


Figure 4: Radiated energy fraction versus thermal energy before the disruption.

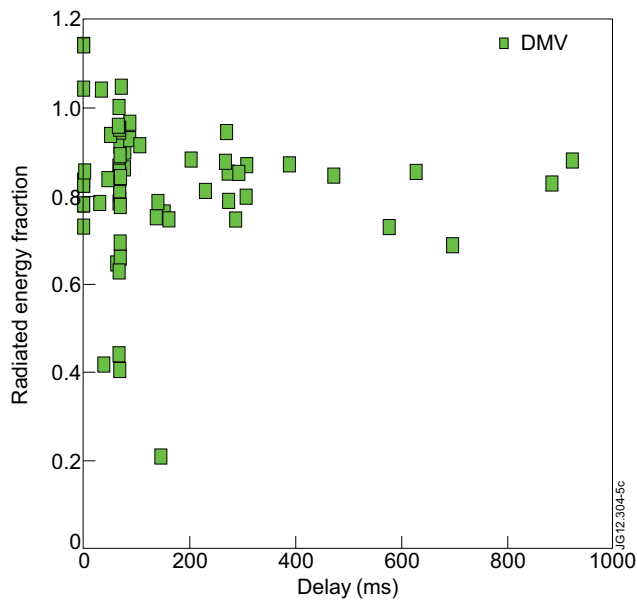


Figure 5: Radiated energy fraction versus the delay between the first thermal quench event and the DMV injection.