

## Magnetic fluctuations during the thermal and current quench of mitigated disruptions and comparison with 3D non-linear MHD predictions

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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. In view of the JET DT campaign with the metallic wall, the need to mitigate disruptions thermal energy up to high plasma current (4.5MA) for high performance scenario has prompted detailed experimental studies to understand the mitigation effectiveness of massive gas injection (MGI) and its extrapolation to high plasma current and larger device like ITER. Therefore, JET has been equipped with three disruption mitigation valves (DMVs) located at different poloidal and toroidal location.

In this paper, the effectiveness of the three DMVs to mitigate disruption thermal loads is first characterized using a scan of the radiative gas quantity at different plasma currents and for all three DMVs. This first step is important to define what is a “bad” and a “good” mitigation. The differences of effectiveness between the three DMVs is characterised using radiation measurements from bolometry. In a second part, the magnetic fluctuations at the time of the thermal quench (TQ) and current quench (CQ) are analysed in details using the full sets of magnetic probe arrays available at JET (both low frequency and high frequency sensors) and the soft X-ray diagnostics. These results are compared qualitatively with the latest modelling results from the 3D non-linear MHD code JOREK for the same JET discharge, the main conclusion being that JOREK does predict the right MHD mode phenomenology observed in the experiment. The magnetic fluctuation analysis is then repeated for both “good” and “bad” mitigation cases and conclusions are drawn about the magnetic instabilities involved in the mitigated disruption process.

### 2- Experimental set-up and analysis method

The JET disruption mitigation system (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 apart toroidally) and DMV2 in the equatorial port of octant 3 thus offering a broad range of options for studying the physics of disruption mitigation and the resulting toroidal asymmetries [1]. They are featuring different delivery gas tube geometry and maximum pressure making their operating conditions also different for an efficient disruption mitigation. Each valve allows the supply of different mixes of gases (D with noble gases like Argon or Neon) with adjustable quantities and fractions.

On the diagnostic side, JET is also equipped with two bolometer cameras (vertical and horizontal) toroidally spaced by 145deg. The analysis of magnetic fluctuations during disruptions, makes use of the JET full poloidal (18 coils) and toroidal (8) arrays of pick-up coils sampled at 50kHz, and the 14 saddle loops for low frequency (<1kHz cut-off frequency at 3dB) modes. The discrete coils thus offer complete sets toroidal and poloidal arrays for identifying the mode numbers of plasma instabilities. The analysis has also made use of the JET soft X-ray vertical and horizontal arrays to confirm the internal structures of the modes in correlation with the magnetics. Also, five fast MHD coils have been used (frequency response up to 500 kHz) to check high frequency mode activities.

Fluctuations from the magnetic sensors have been analysed with a singular value decomposition (SVD) technique to identify the mode structure. Disruption is a fast transient event where rotation (and therefore the mode frequency) is changing in a rapid time scale of typically few milli-seconds. Classic Fourier cross-correlation analysis relying on large statistics cannot be used efficiently when the frequency of the mode changes so rapidly. SVD is a space time eigenvalue decomposition of the matrix built from experimental signals that can be run for short time windows. The eigenvalues determined by SVD (or modes) can be identified in space and time even with time varying frequencies and each signal component in space (“topo”) and time (“chrono”) determined. This analysis has been run for both toroidal and poloidal mode analysis. The poloidal analysis has in addition made use of the so-called “Merezhkin” correction [2] to take into account the plasma geometry (Shafranov shift and elongation) and the plasma fast vertical movement during the thermal and current quench which is particularly important during the transient phase of a disruption. This correction is supplied by data either from fast calculation of the current centroid of the plasma or from magnetics or high time resolution equilibrium reconstruction with EFIT.

Three disruptions have been analysed using this experimental setting and analysis procedure. The first discharge (86887) has been chosen for it has been already modelled by the JOREK code as described in reference [3]. This discharge used DMV2 with pure deuterium gas at 5 bar (no radiative gas added). The other two discharge are part of the study with the radiative gas (Ar) quantity scan but have not been modelled by JOREK yet because JOREK did not include atomic physics to describe the radiation until recently. As it can be seen from table I, 89795 has injected approximately 60 times more Ar atoms than in 89801 and this has resulted in a significant difference in radiative fraction and current a quench duration. The pulse without Argon (86997) has also produced a low radiation fraction despite the larger initial pressure in the DMV and a current quench duration close to the pulse with low amount of radiative gas (89801). The difference on the mitigation effectiveness with different gases had been reported previously in [4]. The analysis in the sections below will report on the detailed difference observed between these two discharges and the comparison with the JOREK results.

**Table I: Overview of the discharge studied in this analysis**

Discharge	86887	89795	89801
Ip (MA) / BT (T)	2/2	2.5/2.5	2.5/2.5
Wrad/Wtot at TQ	0.31	0.71	0.42
DMV No	DMV2	DMV3	DMV3
DMV time (s)	21.013s	12.0113	12.013
DMV gas and pressure	D2 at 5bar	D2+10% Ar at 2.4bar	D2+1%Ar at 5bar
Amount of Ar injected	0	5.9e21 atoms	8.8e19 atoms
TQ time	21.0265s	12.0169s	12.0495s
CQ start time (Ip peak time)	21.028s	12.018s	12.055s
CQ duration = t(20%)-t(80%) * 1.3	61.2ms	19.2ms	76.6ms
q95	2.9	3.1	3.1

### 3- Effectiveness of the massive gas mitigation for disruption mitigation in JET

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 radiative fraction is determined here by the ratio of the radiation energy by the total energy measured during the current quench. The following results have been achieved:

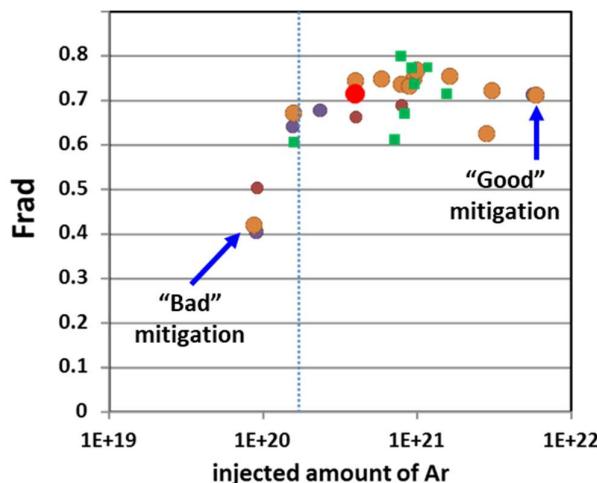


Fig 1: Radiated fraction at the current quench as function of the Ar quantity injected for various plasma current (3.0MA=red; 2.5MA=orange, 2.0MA=violet, 1.5MA=brown). Green squares are 2MA plasma at higher  $q_{95}=4$  instead of 3. The arrow are showing the two pulses studied in this paper.

mitigation which is typically 5 bar, 10% Ar for DMV 3 (i.e.  $2.10^{20}$  Argon atoms), located at the top of the machine. Pulses 89795 (“good” mitigation) and 89801 (“bad” mitigation) chosen for the analysis (Table1) are indicated on figure 1.

### 4- Magnetic fluctuations during the thermal and current quench of mitigated disruptions

The SVD analysis of magnetic fluctuation during the disruptive events has been carried out during 3 different following phases:

1. Pre Thermal Quench window: from the time when the DMV is fired to the start of the thermal quench TQ as characterized by the peak on the central soft X-ray channel.
2. Thermal Quench window between the start of the TQ until the plasma current peak (TQend). In practice this window is the shortest and last 2ms or 3ms typically.
3. Current Quench window from the end of the TQ and during the CQ until the end of the current.

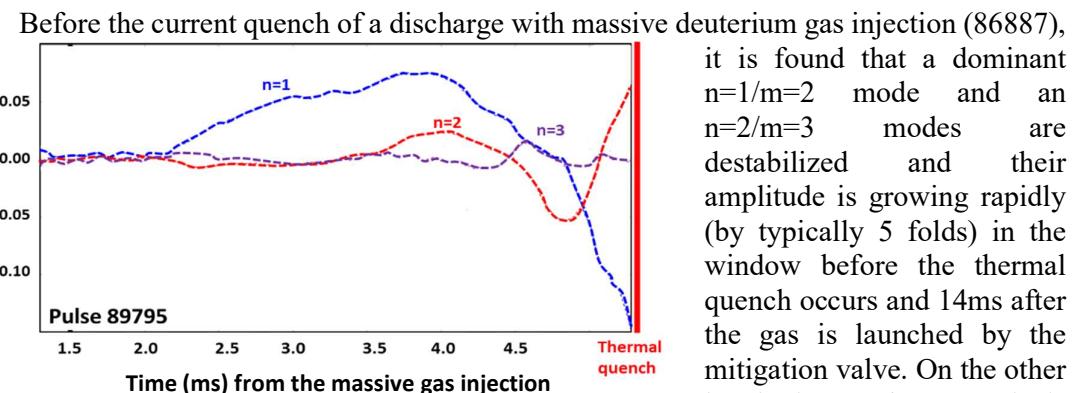


Fig 2: Sequence of  $n$  number modes observed in the “good” mitigation case from  $n=1$ ,  $n=2$  and then  $n=3$ . The poloidal analysis shows respectively  $m=2$ ,  $m=3$  and  $m=4$  dominantly.

Before the current quench of a discharge with massive deuterium gas injection (86887), it is found that a dominant  $n=1/m=2$  mode and an  $n=2/m=3$  modes are destabilized and their amplitude is growing rapidly (by typically 5 folds) in the window before the thermal quench occurs and 14ms after the gas is launched by the mitigation valve. On the other hand, the  $n=3/m=4$  mode is not detected in the analysis but was predicted by JOREK.

The analysis has been repeated for both discharges with massive deuterium + 10%Ar gas injection (89795 and 89801) and consistent results have been found regarding the 2/1 and 3/2 modes. In addition, the presence of an  $n=3/m=4$  structure growing in the last 2ms before the thermal quench occurs has been detected in the “good” mitigation case suggesting that more modes are destabilized in this case. These analyses also support the picture predicted by the JOREK code [1], that the MGI gas destabilizes the  $n=1/m=2$  tearing mode modifies the current profile, destabilizing a  $n=2/m=3$  mode, which in turn destabilizes higher  $n$  modes such as the  $n=3/m=4$ . This mode activity is observed to peak at the thermal quench with frequency of a few kHz and then is replaced in about 1 to 2ms by a low frequency activity (300 to 500 Hz) when the  $n=1/m=2$  mode locks at the time of the thermal quench and the plasma stops rotating.

Just after the thermal quench, the chain of mode activity disappears but there is a persistent 6kHz mode identified as a core  $n=1$  mode using the fast magnetic pick-up coils and the soft X-ray. Comparing two different massive gas injections with different pressures in the valve (90%D+10%Ar), it appears that this  $n=1$  structure (fig 3 and 4) is observed in the low valve pressure case, i.e. when the disruption is imperfectly mitigated. In this case, this indicates that the plasma inside  $q=1$  still exists and survives the massive gas injection for 40ms. In the high valve pressure case, this core  $n=1$  mode is not observed to persist, indicating that the core has collapsed. However, in both cases, there is still a detectable  $n=1/m=1$  bursting activity observed on magnetic probes (fig 3), indicating that the massive gas injection does not actually completely extinguish the plasma core and the  $q=1$  flux surface still subsist.

JOKEK simulations [3] also predict an  $n=1/m=1$  kink mode in the core at the time of the thermal quench and this behaviour is also found in NIMROD simulations for other tokamaks [5]. These results suggest that the resilience of the  $q=1$  surface is an important factor in preventing the gas penetration until a sawtooth occurs in the mitigation process and provide an explanation why massive gas injection has not been found efficient enough for radiating the plasma energy.

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*Fig 3 (top right): Current quench for the “good” mitigation (89795) in blue and “bad” mitigation (89801) in red. The bursts (circles) are internal 1/1 activity (analysed at the time of the yellow band) indicating that the  $q=1$  surface is still active late during the current quench.*

*Fig 4 (right): Soft X-ray reconstruction for 89801 “bad” mitigation case at 12.03s showing the emissivity in the plasma core close to the  $q=1$  surface.*

