OVERVIEW OF DISRUPTIONS WITH JET-ILW

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Abstract

The paper presents an analysis of disruptions occurring during JET-ILW plasma operations covering the period from 24/08/2011 (#80128) up to 15/11/2016 (#92504). The total number of disruptions was 1951 including 466 with deliberately induced disruptions. The average disruption rate of unintended disruptions is 16.1 %, which is significantly above the ITER target at 15 MA. The pre-disruptive plasma parameters are plasma current $I_p = (0.82 - 3.38)$ MA, toroidal field $B_T = (0.98 - 3.4)$ T, safety factor $q_{95} = (1.52 - 9.05)$, plasma internal inductance $l_i = (0.58 - 1.86)$, Greenwald density limit fraction $FGWL = (0.04 - 1.61)$, 1032 X-point and 919 limiter configurations. Massive gas injection (MGI) has been routinely used in protection mode both to terminate pulses when the plasma is at risk of disruption and to mitigate against disruptions. The MGI was mainly triggered by $n = 1$ locked mode amplitude or by the disruption itself, either $dI_p/dt$ or toroidal loop voltage exceeding threshold values. For mitigation purpose, only the locked mode was treated as a precursor of disruptions. However, long lasting locked modes ($\geq 100$ ms) do exist prior to disruption in 75% of cases. Though, 10% of non-disruptive pulses have a locked mode which eventually vanished without disruption. The plasma current quench (CQ) may result in 3D equilibria, termed as asymmetrical disruptions, which are accompanied by sideways forces. Unmitigated VDEs generally have significant plasma current toroidal asymmetries. The unmitigated disruptions also have large plasma current asymmetries presumably because there is no plasma vertical position control during the CQ. However, MGI is a reliable tool to mitigate 3D effects and correspondingly sideways forces during the CQ. The vessel structure loads depend on the force impulse and force time behaviour or rotation. The toroidal rotation of 3D equilibria is of particular concern because of potential resonance with the natural frequencies of the vessel components in large tokamaks such as ITER. The amplitude-frequency interdependence is presented.

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1. INTRODUCTION

The first non-disruptive tokamak pulse, also known as magnetohydrodynamical (MHD) stable plasma, was obtained on the TM-3 tokamak in 1962 [1, 2]. The TM-3 experiments manifested the Shafranov’s predictions for MHD stable plasmas [3]. The MHD mode structure during the pulse and prior to disruption was carefully investigated on the T3-A tokamak in 1970 [4]. It revealed that low m mode \((m = 2)\) is as precursor to disruptions. During a major disruption a rapid change of the poloidal mode number from \(m = 2\) to \(m = 3\) was discovered on the T-6 tokamak in 1978 [5]. Later on disruption studies have been made in various tokamaks including JET [6]–[15]. Nevertheless, the occurrence and behavior of disruptions remain poorly understood and so further studies have been made. The paper presents an analysis of disruptions occurring during JET-ILW plasma operations covering the period from 24/08/2011 (#80128) up to 15/11/2016 (#92504).

In many tokamaks, massive gas injection (MGI) became a popular tool to prevent machine damage during disruptions, particularly to eliminate melting of the plasma facing component and to mitigate disruption electromagnetic loads [12], [16], [17]. A disruption mitigation system (MGI and shattered pellet injection, SPI) is intended to be used on ITER [18], [19]. On JET, MGI has been routinely used in protection mode both to terminate pulses when the plasma is at risk of disruption, and to mitigate against disruptions, where MGI mainly was triggered by thresholds in the \(n = 1\) locked mode amplitude and also by the disruption itself, specifically by plasma current derivative \((dI_p/dt)\) or by toroidal loop voltage. Hence, on JET only the locked mode was treated as a precursor of disruptions for the purposes of triggering the MGI.

The plasma current quench (CQ) may result in 3D equilibria, termed as asymmetrical disruptions, which are accompanied by sideways forces [14], [15]. The vessel structure loads depend on the force impulse and force time behaviour or rotation. The toroidal rotation of 3D equilibria is of particular concern because of potential resonance with the natural frequencies of the vessel components in large tokamaks such as ITER. The amplitude-frequency interdependence is important, since a simultaneous increase of amplitude and frequency would potentially create the most challenging load conditions. The relevant JET experimental results are presented.

2. DISRUPTION DATABASE AND STATISTICS

2.1. Disruption database

In presented off-line analysis, a shot is treated as a relevant plasma shot if the plasma current \(|I_p| \geq 0.8\ \text{MA}\) for at least 0.25 s. The number of plasma pulses during #80128 - #92504 JET-ILW operation was 9686, this corresponds to 77 % of the total number of shots. The magnetic diagnostic quantities, which are recorded at a 5 kHz sampling rate, have been used to identify the disruption shots and define the time of disruption \((T_{\text{dis}})\). The quantities are plasma current \((I_p)\), plasma current vertical centroid position \((Z_p)\) and their derivatives, and toroidal loop voltages, which are measured in two poloidal locations on the inner wall of JET vessel [15]. In this paper the left-hand coordinate was chosen for disruption analyses, hence the \(I_p\) is positive. The loss of the poloidal magnetic flux, due to the large MHD events, causes the electromagnetic circuit of the plasma to respond with a positive spike in the plasma current. The induced negative current which flows along the vessel manifests itself as a large negative impulse in the toroidal full flux loops. The following disruption criteria have been used to build disruption shot list:

i. Fast drop of the plasma current, \(-dI_p/dt > 20\ \text{MA/s}\) for at least 0.25 ms,
ii. Normalised average toroidal voltage \(V_{\text{AN}} < -13\ \text{V/MA}\), FIG. 1,
iii. \(|Z_p| > 0.225\ \text{m} - (a/4)\), VDE criteria, where \(Z_p\) is displacement respect of the study-state prior to CQ, \(a\) is minor plasma radius.

![FIG. 1. Major disruption must satisfy at least one criterion, \(-dI_p/dt > 20\ \text{MA/s}\) or \(V_{\text{AN}} < -13\ \text{V/MA}\): (a) plasma current, (b) plasma current derivative (c) normalised toroidal voltage.]

![FIG. 2. Disruption rate during whole JET-ILW campaign.]

JET Pulse No: 85185
The somewhat arbitrary choice of the criteria has been justified by manual analyses of the numerous disrupted pulses. Thus during #80128 - #92504 JET-ILW it was counted 1951 disruption shots, including 466 MGI (massive gas injection), VDE (vertical displacement event) and EFCC (error field correction coil) experiments, which led to intentional disruptions. Hence the average disruption rate of unintended disruption is 16.1% for overall JET-ILW pulses, FIG. 2. The drop on the FIG. 2 in the #83168 - #83795 range belongs to special (named EX-1.2.5) experiment, when 153 H -mode identical reliable pulses were executed [20]. However, 5 shots (3.3%) disrupted, hence this quantity reflects the lowest disruption rate during JET-ILW exploitation. It is thought that the plasma pollution by copper from NBI caused a disruption, FIG. 3 and FIG. 4. The disruption rate significantly increases in the last group of pulses from #91960 to #92442, FIG. 2. It can be attributed to exploration of operational space for high performance plasmas and optimisation in preparation for the upcoming JET DT campaigns.

![FIG. 3. The waveforms of the EX-1.2.5 pulses: (a) plasma current, (b) NBI power, (c) maximum electron temperature, (d) average electron liner density, (e) total bolometer power, (f) Cu19 line (273.36 Å) emission intensity.](image1)

**2.2. Disruption time**

Disruption criteria (i) – (iii) used to create disruption shot list. Plasma pulses with multiple subsequent disruptions are very common. A special criterion is used to determine the disruption in these cases:

(iv) if $|\frac{dI_p}{dt}| > 1$ MA/s between two sequential voltage spikes with $V_{rrAN} < -13$ V/MA, then the disruption is defined to start at the first voltage spike. Should $|\frac{dI_p}{dt}| > 1$ MA/s not occur between two sequential voltage spikes, then the disruption is defined to start at the second voltage spike. If $|\frac{dI_p}{dt}| > 1$ MA/s not occur between any of the voltage spikes, then the last voltage spike with $I_p > 0.8$ MA defines the disruption; an example is shown in FIG. 5.

On the next stage the two specific subroutines analyse $I_p$, $V_{rrAN}$ (for non-VDE) and $\Delta Z_p$ (for VDE) waveforms and extracted a disruption time, $T_{dis}$. The $T_{dis}$ calculated float value trims to 1 ms digit and recorded in database. FIG. 6 illustrates $T_{dis}$ calculation for sharp plasma current spike and large loop voltage drop ($|\frac{dI_p}{dt}| > 20$ MA/s and $V_{rrAN} < -13$ V/MA) disruption. In case of VDEs, another subroutine examines $\Delta Z_p$ and it derivative to calculate $T_{dis}$, namely the conditions for $T_{dis}$ are when $|\Delta Z_p| > 0.225$ m and $|\frac{d\Delta Z_p}{dt}| > 0.02$ m/ms, FIG. 7.

![FIG. 5. Illustration of criterion (iii) usage: (a) plasma current, (b) plasma current derivative (c) normalised toroidal voltage.](image2)

![FIG. 6. Illustration of $T_{dis}$ calculation: (a) plasma currents, (b) plasma current derivatives, (c) normalised toroidal voltage.](image3)
2.3. Disruption classification

The pre-disruptive plasma parameters are: plasma current \( I_p = (0.82-3.38) \) MA, toroidal field \( B_T = (0.98-3.4) \) T, safety factor \( q_{95} = (1.52-9.05) \), plasma internal inductance \( l_i = (0.58-1.86) \), Greenwald density limit fraction FGWL = (0.04-1.61), 1032 X-point and 919 limiter configurations, with in the majority of pulses x-point loss before the disruption. Dimensionless internal inductance \( l = l_i(3) \) and safety factor \( q_{95} \) were taken from 5 kHz EFIT data. Presented pre-disruptive plasma parameters calculated as an average in the \( [T_{dis} - 5 \text{ ms} : T_{dis} - 1 \text{ ms}] \) time window. FGWL is the line-averaged density divided by the Greenwald-density, \( n_G = I_p/ (\pi a^2) \) in (MA, m, \( 10^{20} \text{ m}^3 \)) [21]. Line-average density measured by Thomson scattering diagnostics (HRTS and LIDAR) and mapped to a horizontal principal chord, the final available measurement prior to disruption presented in FIG. 8.

Using three quantities, \( dI_p/dt, V_{roh} \) and \( \Delta Z_p \), the disruptions were sorted in four categories, specifically

i. Fast \( dI_p \) drop (> 20 MA/s) and large negative voltage spike (< -13 V/MA), 76.5 % of disruptions, FIG. 9;

ii. Slow \( dI_p \) drop and large negative toroidal voltage spike, 11.7 % of disruptions, FIG. 10;

iii. Fast \( dI_p \) drop and small negative toroidal voltage spike, 5.8 % of disruptions, FIG. 11;

iv. VDE, 5.9 % of disruptions.

Dimensionless internal inductance \( l \) and safety factor \( q_{95} \) presented in FIG. 12. The category (i) disruption has an extended cloud of points, while category (iii) disruptions are characterised by flat current profile and moderate safety factor.

\[ l \equiv l_i - 1 \]

\[ q_{95} \]

\[ l - q_{95} \] stability diagram.
3. MGI USAGE

3.1. MGI triggering statistic

MGI has been routinely used in protection mode both to terminate pulses when the plasma is at risk of disruption, and to mitigate against disruptions [12], [22]. During JET-ILW plasma operations (from #80128 up to #92504), in total 896 shots were ended by MGI, typically 3.0 bar∙l of a mixture of (90% D2 + 10% Ar). In the majority of the mitigated disruptions, the MGI was triggered by a $n = 1$ locked mode threshold (523 shots) or by the disruption itself, specifically by $\frac{dI}{dt}$ (207 shots) or by toroidal loop voltage (145 shots). There are 21 exceptional cases when MGI triggered by other causes including pick up of an $n = 2$ mode oscillation by plasma vertical control system (14 shots), various tests and faults. Moreover 249 disruption shots were dedicated for MGI experiments.

The High Voltage (HV) JET system, which includes the auxiliary heating (NBI, ICRH, LH) and some diagnostics (Li-beam, NPA, VUV spectroscopy etc.) have to be in a safe state when large gas quantities arrive in the vessel, hence the HV systems impose a delay before the MGI is fired. The initial MGI usage set up conservative HV delay up to 60 ms, however later the requested HV delay was reduced to as low as ~10 ms, FIG. 13.

3.2. Effect MGI on CQ duration

The MGI has a profound effect on CQ duration, which help to reduce thermal loads on plasma facing surfaces (PFS), [16]. The CQ duration describes by $\tau_{80/20}$ which is the time linearly extrapolated from the time taken to quench from 80% to 20% of $I_{dis}$. The distribution of the fraction of occurrences is shifted to low CQ time and is much narrower for MGI mitigated shots in comparison with non-mitigated disruptions, FIG. 14; this is consistent with modelling where MGI boost MHD instabilities, which enhance the penetration of the MGI into the plasma, [23], [24]. On JET, when MGI fired in “healthy”, pre-disruptive and post-disruptive plasma, there are small differences in the CQ duration; it is surprising that the fraction of occurrence distribution even slightly shifted to low CQ time for MGI experiments, when gas fired mainly into healthy plasmas, FIG. 15.

FIG. 13. High voltage systems requested MGI delay, which was significantly reduced in the course of JET-ILW operation.

FIG. 14. Fraction of distribution occurrences: with and without MGI applied.

FIG. 15. Fraction of distribution occurrences: MGI experiments and when MGI triggered prior or after TQ.
3.3. Impact MGI on vessel vertical force

The electro-magnetic (EM) loads arise during the CQ when the currents occur in machine conductive structures [13]–[15]. Due to the EM loads, the JET vessel experiences oscillatory deformations, while vessel reaction forces \( F_v \) are measured. In general, for MGI mitigated disruption, vertical forces are below non-mitigated disruptions, particularly non-mitigated VDEs, FIG. 16.

4. ASYMMETRIC VDE

The plasma CQ may result in 3D equilibria, termed as asymmetrical disruptions, which are accompanied by sideways forces [14], [15]. Unmitigated VDEs generally have significant plasma current toroidal asymmetries

\[
A = \int A_p^{\text{asym}} \, dt, \quad A_p^{\text{asym}} = I_p^{\text{asym}} / I_p^{\text{av}}, \quad I_p^{\text{asym}} = \sqrt{(I_{p7} - I_{p3})^2 + (I_{p5} - I_{p1})^2} \text{ with } I_{o1} = \text{octant 1 plasma current measurement etc.}
\]

The unmitigated disruptions also have large plasma current asymmetries presumably because there is no plasma vertical position control during CQ. However, MGI is a reliable tool to mitigate 3D effects and correspondingly sideways forces during the CQ, FIG. 17.

The vessel structure loads depend on the force impulse and force time behaviour or rotation. The toroidal rotation of 3D equilibria is of particular concern because of potential resonance with the natural frequencies of the vessel components in large tokamaks such as ITER. The amplitude-frequency interdependence is important, since a simultaneous increase of amplitude and frequency would potentially create the most challenging load conditions.

The amplitude envelope of the plasma current asymmetries decreases with increasing frequency, FIG. 18

FIG. 17. Normalised time integral of plasma current asymmetries vs. CQ time.

FIG. 18. Rotation frequencies vs. \( I_p \) asymmetry magnitude.

5. LOCKED MODE AND DISRUPTION

5.1. Locked mode diagnostics

On JET each vessel octant was originally equipped with 18 pick-up coils and 14 saddle loops, where coils measured tangential to vessel poloidal magnetic field \( B_p \) and saddles normal to vessel field \( B_n \), FIG. 19. In 1994, 9 upper coils were physically removed from octant 8. A few coils and saddles from octant 4 have failed so far. Full set of coils and saddles from four toroidally orthogonal locations (octant 1, 3, 5 and 7) has been routinely recorded (integrated signals) at 5 kHz from 2005 onwards. In addition, middle plane saddles (with 1 and 14 index) recorded at 5 kHz from 2012 onwards. The \( n = 1 \) locked mode amplitude and phase obtained from

\[
\begin{align*}
A_{\sin} &= \frac{(SAD_{\text{oct}3} - SAD_{\text{oct}7})/\text{Area}}{\sqrt{A_{\sin}^2 + A_{\cos}^2}}, \\
A_{\cos} &= \frac{(SAD_{\text{oct}1} - SAD_{\text{oct}5})/\text{Area}},
\end{align*}
\]

with \( SAD_{\text{oct}} \) = octant 1, sum of saddle 1 and 14 etc., Area is the geometrical area of two saddles 1 and 14, FIG. 19b. Hence locked mode amplitude \( Loca = \sqrt{A_{\sin}^2 + A_{\cos}^2} \), normalized locked mode amplitude \( LocaN = Loca / I_p \) and mode phase \( Phase = atan(A_{\sin}/A_{\cos}) \). The \( A_{\sin} \) and \( A_{\cos} \) offset must be subtracted prior to amplitude and phase calculations. Moreover, \( n = 2 \) mode mathematically could be calculated from 8 octant measurements. However, \( n = 2 \) mode computation appears to be a challenging task. An \( n = 1 \) locked mode calculated from 4 octant saddles loop data presented below.
5.2. Locked mode: causation or correlation?

In general, disruptions at JET have a locked or slowly rotating mode precursor [10]. The subset of 913 natural disruptions, which were not affected by special dedicated experiments or MGI protection, was used for analysis of pre-disruptive plasma behaviour. For mitigation purpose, only the locked mode was treated as either a precursor or the cause of disruptions, specifically MGI triggered by a locked mode threshold, either Loca or LocaN.

The locked mode exists in 95% cases prior to natural disruption, FIG. 20. Only 41 disruptions out of 913, disrupted without locked mode precursor. The threshold in locked mode amplitude of 0.2 mT/MA was taken on as an indicator of locked mode. Thus, considering reverse time, $\Delta T_{02b}$ was defined as the time between the disruption occurring and this threshold being exceeded, FIG. 20. The $\Delta T_{02b}$ quantity, presented in FIG. 21, shows that long lasting locked modes ($\geq$ 100 ms) do exist prior to disruption in 56% of disruptions with locked mode precursor. Locked modes with $\Delta T_{02b} \geq$ 10 ms occur prior to disruption in majority (94%) of the disruptions. Though, 10% of non-disruptive pulses have a locked mode which eventually vanished without disruption.

6. SUMMARY

JET–ILW data are presented for machine operation from 2011 (#80128) until 2016 (#92504). During this period, 1951 disruption shots were counted, including 466 deliberate disruption experiments. Thus, the average disruption rate of unintended disruptions is 16.1 %, which is significantly above the ITER target for full plasma current operation.

Three quantities, $dl/dt$, $V_{iAN}$ and $\Delta Z_p$, have been used to sort disruptions into four categories. Three separate categories (apart from VDEs) can be seen on the $l_s$-$q_{95}$ stability diagram, FIG. 12.

MGI has been routinely used in protection mode both to terminate pulses when the plasma is at risk of disruption, and to mitigate against disruptions, mainly to reduce CQ time and to eliminate plasma current asymmetries (~sideways forces).

The toroidal rotation of 3D equilibria is of particular concern because of potential resonance with the natural frequencies of the vessel components in large tokamaks such as ITER. In JET the amplitude of the plasma current asymmetries decreases as the magnitude of the observed rotation frequency increases.

The locked mode occurred prior to majority of natural disruption. However, the locked mode usually exists for long time before the disruption occurs, which could suggest it is not a primary causation of disruptions but is a good indicator of unhealthy plasma condition.
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