Survey into the occurence of disruptions and their root causes at JET

P.C. de Vries 1), M.F. Johnson 2) , B. Alper 2), P. Buratti 3), T.C. Hender 2), R. Koslowski 4), V. Riccardo 2), and JET-EFDA Contributors*

JET-EFDA Culham Science Centre, Abingdon, OX14 3DB, UK.
1) FOM institute Rijnhuizen, Association EURATOM-FOM, 3430BE, Nieuwegein, Netherlands
2) CCFE/Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK.
3) Associazione EURATOM/ENEA sulla Fusione, Centro Ricerche Frascati, 00044 Frascati, Italy
4) Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, EURATOM Association, 52425 Jülich, Germany.
* See Appendix to F. Romanelli, Proc. 23nd IAEA Fusion Energy Conf., Deajeon, Korea, 2010.

E-mail: Peter.de.Vries@jet.efda.org

Abstract. A survey has been carried out into the causes of all 2309 disruptions over the last decade of JET operations. The aim of this survey was to obtain a complete picture of all possible disruption causes, in order to devise better strategies to prevent or mitigate their impact. The analysis allows the effort to avoid or prevent JET disruptions to be more efficient and effective. As expected, a highly complex pattern of chain-of-events that led to disruptions emerged. It was found that the majority of disruptions had a technical root-cause, for example due control errors, or operator mistakes. These bring a random, non-physics, factor into the occurrence of disruptions and the disruption rate or disruptivity of a scenario may depend more on technical performance than on physics stability issues. The main root cause of JET disruptions was nevertheless due to neo-classical tearing modes that locked, closely followed in second place by disruptions due to human error. The development of more robust operational scenarios has reduced the JET disruption rate over the last decade from about 15% to below 4%. A fraction of all disruptions was caused by very fast, precursor-less unpredictable events. The occurrence of these disruptions may set a lower limit of 0.4% to the disruption rate of JET. If one considers on top of that human error and all unforeseen failures of heating or control systems this lower limit may rise to 1% or 1.6%, respectively.

1. Introduction

Disruptions occur due to loss of stability and/or confinement of Tokamak plasmas [1, 2]. Because of the fast time scale in which the plasma thermal and electromagnetic energy are released, strong electromagnetic forces and large thermal loads on the surrounding components can be induced. In larger devices, like JET, it is not uncommon that disruptions cause considerable damage and prevention or mitigation is essential. It is therefore not surprising that disruptions of Tokamak plasmas have been the subject of intense investigations, analysing the causes and consequences of this phenomenon. A multitude of precursors, in many cases related to operation close to the plasma stability boundaries, have been identified. It is well-known that Magneto-Hydrodynamic (MHD) instabilities are thought to play an important role in the onset of disruptions. Although in many cases the plasma is driven to instability by other events such as radiation instabilities at the edge. Furthermore, many elongated plasmas can become vertically unstable, yielding so-called vertical displacement events or VDEs. Often the events that lead to a disruption are a complex combination of several of these destabilising factors, hence it is not always easy to classify disruptions[3].

A previous study into the occurrence of disruptions at JET showed that the fraction of discharges that disrupted at JET dropped remarkably until 2007 [4]. This decreasing trend continued since, as shown in figure 1, achieving unintentional disruptions rates as low as 3.4% in recent campaigns. The indications were that fewer disruptions occurred due to a better technical capability of operating JET, instead of saver operations near to the physics limits [4]. Indeed, although disruptions are often caused by the onset of physics instabilities, it is not uncommon that technical issues are found to be the root of the problem [5].

Higher disruption rates were found during exploratory campaigns while disruptions occurred much less frequently when disruption avoidance was essential, such as during D-T operations. This suggests that the occurrence of disruptions may partly be connected to less careful operations; moreover the downward trend could be interpreted as a learning curve of JET operations. For ITER an engineering limit for the number of disruptions that can be tolerated has been set to a fraction of 10% of the plasmas operated at high current, while only 1% may develop a VDE, usually the cause of the highest forces [6].

The question arises what factors determine the occurrence of disruptions and what sets the lower limit of the disruption rate. Hence, an extensive survey has been carried out at JET to shed more light into the complete picture of all the chain-of-events that led to disruptions. Usually disruption studies have focussed on a few well diagnosed and documented cases often caused by characteristic physics instabilities. The holistic approach presented here tried to determine the causes of all disruptions over a whole last decade of JET operations, not neglecting those that were poorly diagnosed.

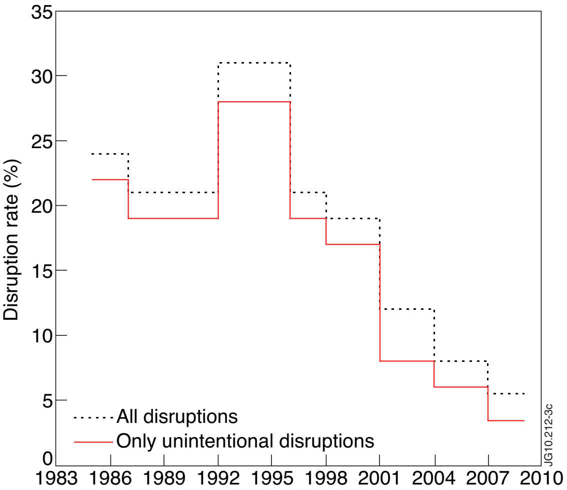

Figure 1: The fraction of JET discharges, with a plasma current large than 1MA, that disrupt for various operational periods, due to all disruptions (dashed) or only unintentional (solid red) disruptions. The increase around 1992 was identified as being due to the transition of pure limiter to diverted plasma operations at JET [4].

This study focuses on the root causes, or the problems that trigger the chain-of-events, as these initial problems may be most helpful in devising proper strategies to prevent disruptions. At JET this is especially relevant in view of the installation of the new, more fragile, full metal ITER-like plasma facing components that is presently being undertaken. But specific chain-of-events can also be used to classify disruptions, grouping those that follow specific paths. Characterisation of these disruption classes and their precursors could furthermore be used to improve the detection methods and techniques to mitigate each class.

This paper is organised as follows, in section 2 the analysis method is discussed followed by a detailed description of the various disruption causes and their statistics. Thereafter, in section 3 a brief summary is given on the characterisation of the various JET disruption classes that could be identified with this analysis. Here also methods to avoid or better detect these disruptions will be discussed. The last section summarises the main lessons learned from this analysis.

2. Statistics of disruption causes

The study was preformed from an operational point of view and the analysis should try to find what could have been done to avoid the problem. Hence, the answer that the disruption was caused by physics instabilities, for example a locked mode, is not sufficient, and the reason why this mode developed in the first place should be discovered. Hence, to find the root-cause that sets into motion a chain-of-events that eventually leads to the disruption

The survey has been done for the complete set of disruptions that occurred during JET operations between 2000 and 2010. During this period, 22243 plasma discharges with a plasma current of I_p>1MA where generated at JET. A total of 2309 of these discharges disrupted. Here, the few disruptions of plasmas with a current of less than I_p<1MA were not taken into account, as the effects are often benign at JET. This gives a total disruption rate of 10.4%. However, about 28% (i.e. 655 cases) were done intentionally; hence the unintentional disruption rate over the entire decade was 7.5%. Because of the continuing drop in the disruption rate, as shown in figure 1, this average rate is lower than that found for the period between the year 2000 and 2007 [4].

For each of these disruptions, the sequence of destabilizing problems was determined, using the labels given in table 1 and 2, forming a database of event chains. A detailed description would go too

Type of physics problem	Label
General (rotating) n=1 or 2 MHD	MHD
Mode Lock	ML
Low q or q95~2	LOQ
Edge q close to rational (>2)	QED
Large sawtooth crash	SAW
Neo-classical tearing mode	NTM
Internal kink mode	KNK
Reconnection	REC
Radiative collapse ($P_{rad}>P_{in}$)	RC
MARFE	MAR
Greenwald limit (n_{GW})	GWL
High density operation (near n_{GW})	HD
Too low density (and low q)	LON
H to L back-transition	HL
Strong density peaking	NPK
Too strong internal transport barrier	ITB
Strong pressure profile peaking	PRP
Negative central magnetic shear	MSH
Large edge localised mode (ELM)	ELM
Vertical displacement event	VDE

Type of technical problem	Label
Impurity control problem	IMC
Influx of impurities	IMP
Density control problem	NC
Too much gas from gas injection	GIM
No (effective) pumped Divertor	DIV
Shape control problem	SC
Plasma too close to the wall	WAL
High recycling	RCY
Other real-time control problem	RTC
Emergency shut-down	STOP
Manual emergency stop by operator	SL
Wrong validated density for feedback	PDV
Magnetic signal(s) error	MAG
Reciprocating probe	PRO
Na influx by Lithium beam diagnostic	LIB
Other diagnostic problem	DIA
Too little auxiliary power	AUX
Too little torque / rotation	ROT
Problem with Neutral Beam Injection	NBI
Impurity release due to LHCD	LHC
Impurities from ICRH antennae	ICH
Problem with vertical stability control	VS
(Intentional) vertical kink	VSK
Temperature too high in VS amplifier	VST
Over-current in VS amplifier	VSI
Other failure of VS amplifier	VSA
Human error	HUM
Too fast a current ramp-up	IP
Other power supply problem	PS
Unidentified impurity influx	UFO
Problems due to pellet injection	PEL
Impurity influx by laser ablation	ABL
No clear cause	NON

Table 1 (top) and **2** (right): List of physics and technical issues related to JET disruptions found during period of 2000 to 2007, respectively. The second column gives the label assigned to this event in the database.

far for the scope of this paper, but most of them are well-known and reviewed in many earlier publications [7, 8]. Only precursor events up to the start of the energy and current quench have been considered. Hence, a VDE was only recorded when it developed prior to the thermal quench. In some cases a straightforward chain could be determined, such as too low a density yielding an error field locked mode. For other disruptions a highly complex pattern was found, with sometimes multiple destabilizing factors acting at the same time, or those that starts as a simple NTM but eventually yielded shape and density control errors and a radiative collapse.

Each disruption was analysed manually, not only by doing a full signal analysis (studying for plasma radiation, various MHD instabilities, etc.) but also checking various real-time control systems, and even by reading the experimental reports by the Tokamak operators or minutes of subsequent meetings that discussed problematic issues with sub-systems. An automated analysis would be able to point out a physics trigger for the disruption, but would be unable to find for example control or sub-system failures. Some problems with impurity contaminated gas release valves were solved days or weeks after they first caused disruptions. Hence a manual diagnoses, although time consuming and not entirely unambiguous, turned out to be the better method.

The holistic approach required the study of all disruptions, even those that were less well diagnosed. This may have led to a further ambiguity in the analysis. Nevertheless, in most cases a satisfactory analysis was achieved and, although the complexity of disruptions, absence of diagnostics, may have resulted in some errors, the survey is thought to give a statistically realistic picture of the main chain-of-events that led to disruptions at JET. In figure 2 a schematic overview of the chain-of-events that led the unintentional disruptions are shown. Although the picture is rather complex, distinct paths can be recognised that could be seen as specific types or classes of disruptions.

Firstly, one could look into the statistics what process eventually causes the disruption, i.e. the last steps in the chain-of-events. As expected all disruptions at JET were eventually pushed close an operational limit resulting in the on-set of physics instabilities. For unintentional disruptions these were: edge radiation instabilities (51.8%), mode locking (20.1%), growth of internal kink modes (4.4%), vertical position instability (3.9%) and too low a safety factor (or q~2) (2.5%). Those cases

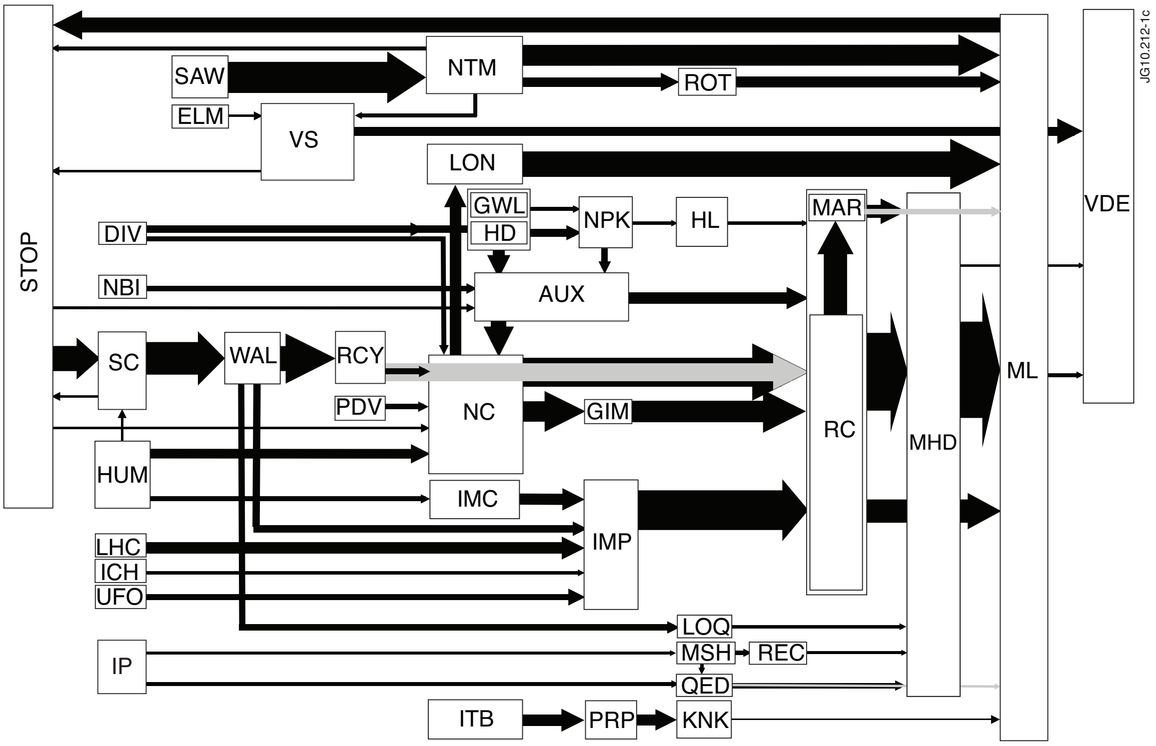

Figure 2: A schematic overview, showing the statistics of the sequence-of-events for only the 1654 unintentional disruptions at JET during the period 2000 to 2010. The width of the connecting arrows indicates the frequency of occurrence that each sequence took place (only those paths with an occurrence of >0.2% are shown). Note that the disruption process could start at any node (event) in the overview, which generally, but necessarily, flows flow from left to right. The labels correspond to those listed in table 1 and 2.

that disrupted a locked mode could be divided into: low density error field modes (10.3%), neo-classical tearing modes that locked (6.7%) and those locked modes created by edge kink instabilities during too fast a current ramp-up (3.1%). Note, that even those discharges that disrupt due to for example a radiative collapse often show a detectable locked mode. In 48% of the cases a mode lock was detected by the JET safety system (with a warning time of 30ms or more) [4]. It is notable that not many disruptions seem to occur because the plasma is either at the Greenwald density limit or at too low a safety factor. Also few unintentional disruptions at JET develop a VDE.

Secondly, various characteristic paths can be recognised in figure 4 that could be used to classify typical JET disruptions. From the bottom, two clear paths due to too strong an internal transport barrier and too fast a current rise can be identified, while the top two paths are related to NTMs and low density error field lock modes. Furthermore, a small set of disruptions flow via the vertical stability control error node. The centre part of the diagram is rather complex and hence more difficult to classify. Various possible routes can be seen flowing towards a radiative collapse. These are often set in motion by density or impurity control problems or are initiated by shape control problems and plasma wall interaction. The latter could also result in a low-q disruption when the plasma is pushed against the wall. A for JET characteristic loop is found, via a detected locked mode, which starts an emergency shut-down, yielding shape and density control errors and hence a radiative collapse. Although, the JET emergency shut-down has been shown to be effective in mitigating the effects of the disruptions [4], an improved and better controlled shut-down scenario could possibly avoid a number of these events. Only small number of disruptions was found during operations at the Greenwald limit, characterised by an H to L back transition prior to MARFE development or a radiative collapse. A much larger group disrupted, due to density or radiation control issues during the shut-down of auxiliary heating at high density (i.e. near the Greenwald limit) H-mode operations.

It is important to note that the characteristics of each disruption class can vary widely. Detectable precursors may be different or their impact. An important feature may be the typical speed with

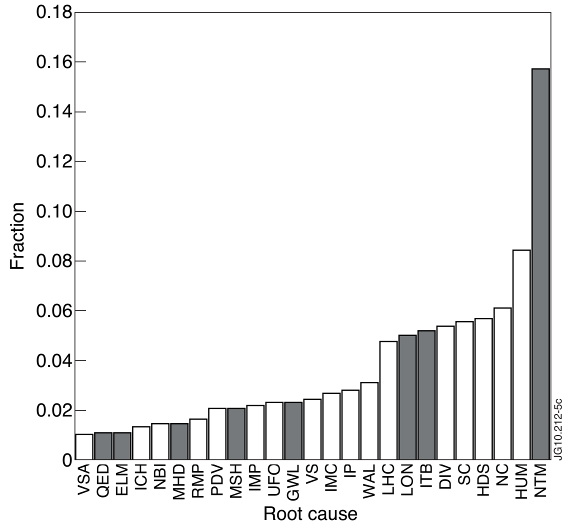

Figure 3: Ranking of root-causes of all 1654 unintentional JET disruptions over the period 2000 to 2010. Only those that cause 1% or more of all disruptions are shown. But this set is responsible for 93% of cases. Additionally, 18 minor root-causes were found for the remaining 7%. Physics and technical root-causes are shown by grey and white coloured boxes, respectively.

which the sequence-of-events for a specific a disruption class unfolds (i.e. how long does it take from the root-cause trigger until the disruption). Even among disruptions of the same class large variations may; however, for some a reasonable typical average duration can be given. Some chains can last from up to several seconds down to only a few 10ms or ms. In the first case it would provide ample time for detection, though one has to remember that not all events presented in figure 2 can be detected in real-time at JET.

The impact of each disruption class also differed. Disruptions due to vertical stability issues and VDEs were responsible for 42% of all cases with vessel normalised forces (F/I_p^2) higher than 0.5 MN/MA^2. It seems that for many disruptions (especially those that develop as a radiative collapse) the induced vessel force is somehow mitigated Similarly VDEs were also responsible for those disruptions with the fastest current quench rate (48% of all cases with the fastest current quench rate $\Delta t/S$ between 1 and 2 ms/m^2). Here the normalised current quench time ($\Delta t/S$) is defined as in ref. [9]. Disruptions of plasmas with W>4MJ are capable of damaging the Carbon plasma facing components of JET [10], moreover, after the installation of the full metal wall, this will be significantly lower ~1-2MJ [11]. The largest fraction of disruptions with W>4MJ is due to ITBs (42%) while VDEs caused 12% of these cases.

Finally, one could look at the root-causes that initiate the chain-of-events. Obviously, knowledge of root-causes is most useful if one wants to prevent or detect precursors to disruptions. The spectrum of main root-causes is shown in figure 3. Clearly, the most common disruption cause at JET is due to a neo-classical tearing mode. This is quickly followed by human error, i.e. due to mistakes by the operators. The wide range of possible root-causes can be grouped together and the 42.3% have a pure physics root. This nevertheless means that more than half of all unintentional disruptions are due to other reasons than pure physics instabilities. 22% of them were caused by a failure of one of the sub-systems, such as auxiliary heating, 15.8% were the direct result of control errors, 8.3% due to human error, while 7.8% was due to plasma-wall interaction, such as high recycling or UFOs entering the plasma. Note that, disruptions caused by human error, failure of sub-systems or wall conditioning issues bring a ‘random’ factor, i.e. not determined by physics, into the occurrence of disruptions. For 2.6% of all disruptions no clear root-cause could be determined. These cases may well be related to fast, unpredictable, badly diagnosed, plasma-wall events. Together with the fraction of disruptions due to identified UFOs (2.3%), they could set the lower limit of the unintentional disruption rate to approximately 0.4%

3. Prevention and mitigation

The statistics on disruption causes and characterization of the various disruption classes, presented above, tell us a few basic things on how to handle the prevention and mitigation of disruptions, specifically at JET.

Firstly, in order to prevent disruptions, one ought to eliminate the root-cause. Most efficiently, one should focus on those root-causes that statically occur most often or those that are easy to eliminate. Moreover, to be effective, one has to reduce those disruption classes that are the most damaging. The presented statistical analysis of JET disruption causes provides a solid basis for this task. For JET disruptions, figure 3 shows that the focus should be on NTMs, human error, too strong ITBs, auxiliary power shut-down at high density and, furthermore, the improvement of control of vertical stability, plasma shape, density and impurities. For example simple measures could be taken to eliminate the most basic human errors.

Secondly, one has to focus on scenario development, i.e. the tuning of various operation scenarios of a Tokamak, in order to prevent instabilities or control errors. A large group of disruptions are due to the loss of control, often during the transient phases of the discharge scenario, such as when the auxiliary power is stepped down often at the end of a high-density H-mode. Fast changes in plasma pressure may complicate the plasma shape control and the proximity to the wall or changes in the divertor strike points may compromise the density control. Proper development of this important H-mode exit phase will prevent disruptions just as the start of the H-mode could be tuned to reduce the occurrence of NTMs. Similarly an improved design of the current and density ramp-down scenario may prevent many tail disruptions due to low-density error field modes. However, one should not forget that these thought-through scenarios could still be jeopardised by unexpected failure of sub-systems. A controlled step-down of the auxiliary power is not possible in case the auxiliary heating systems itself fails. Hence, the design of emergency exit strategies is important too. It has been shown that with proper scenario development it is well possible to operate close to the operational limits, at low q or more difficult with high radiation fractions, without risking high disruption rates. [12]. Although one may argue that such operations may have to follow a test and tuning phase (at lower current and plasma energy) where disruptions will be and can be more common.

Thirdly, one should improve detection methods in order to obtain advance warning of disruptions obviously in combination with developing a proper response. The basic protection system at JET is able to start an emergency shut-down predominantly triggered by presence of a large locked mode, although it also handles information on the status of sub-systems such shape and vertical stability control [4]. A longer warning-time will make it easier for an emergency shut-down to be effective or will even allow the mode to be controlled and thus prevent a disruption altogether. Because a large fraction of disruptions eventually developed into a radiative collapse, an improved, faster, detection could be achieved if these parameters were also monitored by the JET protection system. Tests of new JET disruption warning systems that include radiative power fraction therefore usually perform better, i.e. earlier detection [13]. Also the monitoring of specific plasma facing components may help avoid strong wall interaction events, such as hot spots that develop into UFOs or cause impurity influxes from RF antennae. A more detailed look into disruptions at the Greenwald limit (GWL) revealed that these could be detected earlier if the protection system would be able to detect the characteristic precursor signs as density profile peaking and H-to-L back-transition (see figure 4). Furthermore, an improvement on the detection of NTMs could be achieved, if the system would not wait until this mode has locked, but already detect the growing mode when it is still rotating. The speed with which some disruptions develop (vertical instabilities (VDEs) or those due to too strong ITBs) does not make it easy to obtain a clear and early warning and faster mitigation actions such as massive gas injection may become essential.

Far too often the development of a disruption warning system is decoupled from the response or action undertaken to mitigate the effects of the disruption. Various situations or disruption classes may require a different response while the consequences of mitigating actions (such as massive gas injections) should always be balanced against the impact of unmitigated disruption. As seen in figure 3, quite often the JET emergency shut-down leads to loss of control and further a destabilisation of the plasma. Hence, a disruption prevention and mitigation system should not only detect the precursor signs of a disruption but also be able to recognise the particular situation and chose the appropriate response. For many cases, such as with NTMs or low density error field modes, a simple controlled shut-down is perfectly effective. While for those with more damaging consequences, such as to VDEs or high β ITBs type disruptions, more stringent and faster measures such as a fast massive gas injection may be necessary. The issues with the emergency shut-down scenario as found in figure 2 also suggest that disruptions could be prevented by a further development of emergency exit scenarios.

A significant decrease in the occurrence of a number of disruption classes has been observed over the last decade. It concerns in particularly disruptions due to NTMs, auxiliary power shut-down at high density and human error as can be seen in figure 4a. With respect to NTMs, the reduction cannot be attributed to a better detection, as over the last 10 years no large effort was invested to improve the current warning system at JET. It is thought that the reduction in occurrence of the first two classes is due to a steady improvement of the JET operation scenarios. Continuous scenario optimisation may have led to a lower disruptivity. Human errors were avoided by adding extra safety checks or by improving the operator interfaces. It is the reduction of these dominant three root-causes that is responsible for the drop in the JET disruption rate over the last 10 years.

In some cases large variations in the occurrence of disruption root-causes have been found as can be seen in figure 4b. Technical problems, such as an interaction between the JET vertical stability control and rotating n=2 MHD instabilities which led to an overheating and shut-down of the fast radial field amplifiers and hence loss of vertical stability control, have been solved [14]. In contrary small modifications to the diagnostic that measures the line-integrated density led to many more cases of disruptions due to an incorrect density control signal. Because these root-causes happen less often the variations have little impact on the overall disruption rate. More important, however, it shows that a Tokamak is a complex device with intricate control systems. Some problems that are discovered, are solved over time and eliminated as disruption causes, but small modifications can also give rise to a sudden appearance of new problems. Figure 4b furthermore shows that changes in plasma-wall interaction and high power operation could suddenly enhance a problem and for some reason the last year of JET operation is plagued by UFOs. These variations make complete disruption prevention difficult and show that it may be a continuous task to track and solve problems.

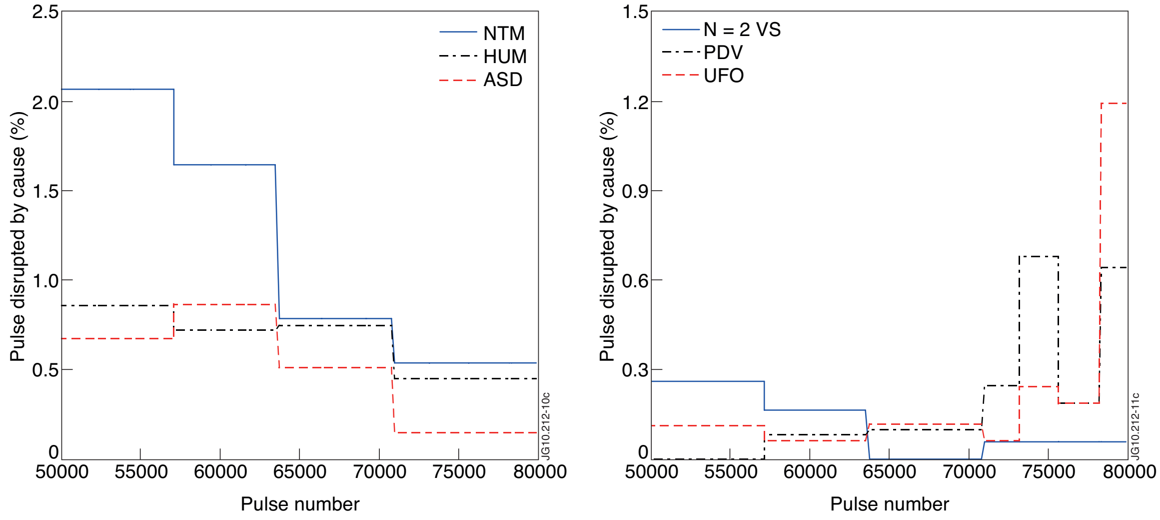

Figure 4: a) The fraction of plasma pulses (with a plasma current of >1MA) that disrupt due to an NTM, Auxiliary heating shut-down at high density (ASD) or human error (HUM) **b)** The fraction of plasma pulses that disrupt due to problems with the VS problems related due to the interaction with rotating n=2 NTMs, the density control signal (PDV) and UFOs.

6. Conclusions

An extensive survey of the cause of all disruptions over the last decade of JET operations has been conducted from which a number of conclusions can be drawn regarding the prevention and mitigation of these events. The statistics allow a focussed approach for JET to deal with those disruption causes that happen most often and/or could result larger damage. One has to be careful however to extrapolate the findings to other devises, such as ITER. Foremost, ITER will not operate in the same operational range as JET; hence the statistics of physics causes is likely to be different. Technical differences between devices, such as the reliability of sub-systems and capabilities of for example vertical stability control, will also result in a different character of the root-causes.

Nevertheless, one decade of JET operation could be seen as fairly representative for the general operations of a large Tokamak. And the basic conclusion that a large fraction of disruptions is caused by technical problems, should be taken into account when considering the disruption rate. Some of the disruption causes discussed in this paper, such as the interaction of rotating n=2 NTMs with vertical stability control, are typical for JET, nevertheless, they high-light the point that the complexity of a Tokamak may bring forward intricate interactions between several systems that could become a cause for disruptions. The elimination of such problems may be a continuous task, as long as scenarios are being developed.

The development of more robust operational scenarios has reduced the JET disruption rate over the last decade from about 15-10% to below 4%. This is in line with the observation that the disruption rate during the Deuterium-Tritium campaigns was considerably lower as only well tested scenarios were run [4]. It also shows that considerable periods of scenario development, preferably at lower current and energy to lower the risk of damage, need to be scheduled, to reduce the scenario disruptivity and disruption rate. Note that the disruptivity of an operational scenario is not only determined by its proximity to physics stability limits but even more so by technical complexity to control the scenario and the reaction to unexpected trips of heating or control systems. For each scenario proper exist strategies should be planned in case control or heating systems fail either to obtain a controlled landing of the discharge or, mitigate the disruption impact.

Operator (or human) mistakes were found to be a common source of disruptions at JET. Technical and human error will add a random, or non-physics, factor to the occurrence of disruptions. Even extensive development of scenarios will not be able to prevent unexpected fast events like those caused by tiny pieces of impurities coming off the plasma facing components. The question thus arises if one would really be able to operate a Tokamak disruption free. In JET these fast events have caused approximately 5% of all disruptions and setting a lower limit to the disruption rate of 0.4%. If one considers on top of that human error and all unforeseen failures of heating or control systems this lower limit may rise to 1% or 1.6%, respectively. Operating a Tokamak with the lowest disruption rate, is not only a question understanding the physics stability limits of a plasma, as well as prevention of operator errors, reducing the failure rate of control and heating systems and proper scenario development.

Acknowledgements

This research was funded partly by the European Communities under the contract of Association between EURATOM, FOM and CCFE. This work was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] WESSON, J.A., et al. Nucl. Fusion **29** (1989) 641
[2] HENDER, T.C., et al., Nucl. Fusion **47** (2007) S128
[3] SCHÜLLER, F.C., Plasma Phys. Control. Fusion **37** (1995) A135
[4] DE VRIES, P.C., et al., Nucl. Fusion **49** (2009) 055011
[5] PAUTASSO, G., et al., Proc. 25th EPS Conference on Controlled Fusion and Plasma Physics, Prague (1998). Vol 22C, Part III, p520
[6] ITER load specification (ITER_D_2MX47L) https://user.iter.org/?uid=2MX47L
[7] WESSON, J.A., Tokamaks (3rd Edition, Clarendon Press, Oxford, 2004)
[8] KOSLOWSKI, H.R., Trans. Fusion Sci. Techn. **53** (2008) 14
[9] WESLEY, J., et al., Fusion Energy Conference 2008 (Geneve) (IAEA Vienna) IT/P1-21
[10] RICCARDO, V., et al., Plasma Phys. Control. Fusion **44** (2002) 905
[11] RICCARDO, V., et al., Phys. Scr. **2009** (2009) 014033
[12] RAPP., J, Nucl. Fusion **49** (2009) 095012
[13] RATTA, G. et al., Nucl. Fusion **50** (2010) 025005
[14] SARTORI, F., et al., Fusion Eng. Des. **66–68** (2003) 727