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ABSTRACT.
The disruption rate, the frequency at which disruptions take place, in JET was found to drop steadily over the years. Recent campaigns (2005-2007) show a yearly averaged disruption rate of only 6% while from 1991 to 1995 this was often higher than 20%. Beside the disruption rate, the so-called disruptivity, defined as the likelihood of a disruption depending on the plasma parameters, has been determined. The disruptivity of plasmas was found to be significantly higher close to the three main operational boundaries for tokamaks; the low-q, high density and β-limit. The frequency at which JET operated close to the density-limit, increased 6 fold over the last decade, however, only a small reduction in disruptivity was found. Similarly the disruptivity close to the low-q and β-limit was found to be unchanged. The most significant reduction of disruptivity was found far from the operational boundaries, leading to the conclusion that the improved disruption rate is due to a better technical capability of operating JET, instead of safer operations near to the physics limits. The statistics showed that a simple protection system was able to mitigate the forces of a large fraction of disruptions, although it proved to be at present more difficult to ameliorate the heat flux.

1. INTRODUCTION

A disruption is a sudden loss of stability or confinement of a tokamak plasma. Because of the fast time scale in which the plasma thermal and electromagnetic energy are dissipated, these events lead to large thermal loads on in-vessel components and strong electromagnetic forces on surrounding conductors [1]. Especially in larger tokamaks, like JET, disruptions have been able to cause considerable damage. In order to preserve the integrity of the device it is therefore important to prevent or mitigate such events.

Hence, disruption physics has 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. Magneto-Hydrodynamic (MHD) instabilities are usually observed prior to a disruption. Often the events that lead to a disruption are a complex combination of several of these destabilising factors, making it difficult to determine a clear cause or to classify disruption types [2]. Although disruptions can be related to plasma stability physics it is not uncommon that technical problems are found to be the root cause. Because of the fast time scales and the complexity of the causes, disruptions are not easy to predict, making it difficult to take preventive or mitigating actions. So far it has proven impossible to eradicate disruption events from tokamak operations, although mitigating action can be taken to limit the impact.

A tokamak discharge disrupts with a sudden loss of confinement, yielding a quench of the plasma current, and/or a Vertical Displacement Event (VDE) due to the loss of vertical stability. While in smaller devices disruptions can be nuisance, prevention or mitigation of its effects is of the utmost importance in larger fusion devices. In JET a plasma current of several MA is typically expelled on a time scale of ~5-50ms. Halo and eddy currents can result in forces of several MN on the tokamak vessel [3]. Furthermore, heat loads up to $2MJ/m^2$ have been observed after major disruptions [4, 5].

In ITER the forces and heat loads are predicted to be two orders of magnitude larger than those in JET. In addition, burning plasma operation will require ITER to be operated close to major operation limits, combined with need for active stabilization techniques for several types of MHD instabilities and control of power exhaust. Hence, the development of ITER-applicable operation scenarios with low disruption rates is an issue.

Disruptions research is focused on the underlying physics causes of disruptions and operational limits, while technical issues are often put aside. The question arises what factors determine the disruption rate and disruptivity of tokamak plasmas. Here the disruption rate is defined as the percentage of discharges that disrupt, while the disruptivity is the likelihood of a tokamak discharge in a specific state to disrupt. General disruption rates are not often reported, but it has been shown that these can be as high as 30% to 50% in various devices [2]. More detailed studies have shown the link between the disruptivity of tokamak plasmas and the closeness to operational limits [6, 7, 8], while others have reported reliable operations close to the operational boundaries [8, 9]. More information on the disruptivity of tokamak plasmas would be useful for the planning of future experimental campaigns on large tokamaks such as ITER.

Previously statistical analyses have been carried out over earlier periods of JET operations [10, 11]. This paper will present a statistical analysis of disruptions and detail the disruption rate and disruptivity of JET plasmas. For JET operations, minimising the disruption forces and the number of disruptions itself is a key objective in order to prevent loss of experimental time and preserve the lifetime of components or the device itself. Hence, since the start of JET operations, 25 years ago, all disruption events have been recorded in a dedicated database. Firstly, the overall JET disruption rate is determined for the entire period of JET operations, with a more detailed analysis for the period from 2000 to 2007. These results are shown in section 2 of this paper and will give an idea of the general levels of the disruption rate and the trends thereof. In section 3 the disruptivity with respect to operational limits will be presented. The main question to be answered is whether JET disruptivity can be linked to operational limits. Many disruptions have precursors that may give an early warning. At JET a simple, straightforward protection system is in place that terminates the plasma discharge in case of control problems or when plasma instabilities are detected. In this way, some disruptions may be prevented or their effects can be mitigated. A basic analysis has been carried out on the precursors or triggers used by the JET protection system and the effectiveness of this system with respect to the mitigation of forces and heat loads, which will be presented in section 4. The conclusions are summarised and discussed in the final section of this paper. It is important to note that this paper will not deal with the detailed discussion on the causes of disruptions or the underlying physics of operational boundaries, but merely show the statistics where in the operational space disruptions take place.

2. GENERAL TRENDS OF DISRUPTION RATES

In order to get a general idea of the average frequency of disruptions over the entire period of JET operation, the disruption rate can be approximated as the number of disruptions as recorded in the database divided by the number of JET pulses carried out over a specific period. Figure 1 shows this number, i.e. the disruption rate per pulse number, using a sliding averaged over 2000 pulse numbers. It can be seen that JET operational life features periods of low and very high disruption rates. Figure 1 shows average disruption rates higher than 20%, however, choosing a shorter averaging interval often reveals periods with a disruption rate above 70%. A detailed analysis over the year 1991 shows that the disruption rate per day can vary significantly, between less than 10% to above 60% [11]. Table 1, summarises the disruption rates for the various operational stages of JET operations.

In figure 1, average disruption rate of 40% around #26800 (in 1991) suggests that about 800 of the 2000 pulses in this interval disrupted at that time. However, prior to #46000 (=1998) there are 3 periods with notably lower disruption rates; 1987-1988 (#12300-#18300), early 1994 (#27900-#30900) and in 1997 (around #42900). These periods can be identified as a long sustained campaign of limiter operations, an extended commissioning period after the installation of the Mark I divertor and the main Deuterium-Tritium (DT) campaign, respectively. All these periods are characterised by careful operations using well-tested or standard scenarios. These contrast with a phase of high disruption rate that start after approximately pulse number 20000. This coincides with the first X-point operations at JET. The early attempts were prone to VDEs resulting in a large number of disruptions. A similar period with a high number of disruptions is found in the times leading up to the DT campaign where many of the high power and high current scenarios for these experiments were being developed. Less well explained is the much lower disruption rates observed in the recent campaigns, where after 2001 (#54345) the disruption rate drops significantly below 10%.

The above method of determining the disruption rate only requires an accurate list of pulses that disrupt and can easily be determined over long periods of operation. However, because not every JET pulse will result in a plasma discharge the disruption rate per pulse number as shown in figure 1 is not entirely accurate. Sometimes, so-called dry-runs are carried out, or the break-down is not sustained and, although the pulse number is stepped up, no real plasma discharge is maintained. Hence it gives an under-estimation of the plasma disruption rate. The plasma disruption rate can be determined by taking the ratio of the number of disruptions to the number of actual plasma pulses, here defined as plasmas with a minimum current of 1MA. In Table 1, the plasma disruption rate is given for each of the main JET operation phases. As expected these numbers are considerable higher (by about 30%) than those found in figure 1, for the disruption rate per pulse number. The overall plasma disruption rate of JET was reported to be approximately 26% prior to 1993 while in 1994 this dropped to 17% [2]. Note that this last period was identified as the long commissioning phase after the installation of the first (Mark I) JET divertor. A decreasing trend for the plasma disruption rate is found, reaching low values of only 8.3% in recent campaigns.

Disruption research is part of the JET experiments and therefore, some are triggered on purpose. For example density limit disruption physics or new mitigation techniques are studied during experimental campaigns. Furthermore, during commissioning periods, the disruption forces of new plasma configurations are often studied by intentionally triggering VDEs. Since the start of operations with the MKII divertor these intentional disruptions have been flagged in the database. It is found that since that time about 15% of all disruptions were done intentionally. The rate of unwanted disruptions, as given in table 1, is therefore lower than the total plasma disruption rate. However, one may argue that these disruption tests may be an essential part of tokamak operations and cannot be avoided, although one will be able to better control the effects.

2.1. THE DISRUPTION RATE SINCE 2000

A more detailed breakdown of the disruption rates can be given for the period from 2000 to 2007. During this time, no major changes to the structure have been undertaken and the basic protection system remained untouched. Although, modifications were carried out to the divertor, it is not thought that these changes may have influenced the disruption rate. Over this period, a total of 1701 disruptions in plasmas with a current above 1MA were recorded and overall plasma disruption rate was 11.3%. But 406 of these, almost 24%, were done intentionally as part of experiments.

In figure 2 the plasma disruption rate for all disruptions and excluding intentional disruptions is shown averaged over the various commissioning and experimental campaigns that took place since 2000. So-called, restart campaigns precede actual experimental campaigns and are used to restart plasma operations, condition the machine, commission the various auxiliary heating systems and diagnostics and finally test newly installed equipment. A wide variation is observed, with campaigns with a disruption rate of more than 20%, while at other times this can be as low as 2%. So-called restart or commissioning campaigns show lower than average disruption rates (i.e. an averaged value of 8.6% is found) compared to experimental campaigns which have a higher than average rate of 12%.

Campaigns with a strong focus on stability and disruption studies show understandably larger disruption rates. For example campaigns C13 and C14 (2004) show high rates because several of disruption experiments were carried out during these campaigns, while the unintentional number of disruptions was actually quite low. Another marked phase with low rate and no intentional disruptions took place during the campaigns C11 restart, C11 and C11 Clean-up in 2003. Trace Tritium experiments were done at that time, requiring careful operations and a minimisation of disruptions. This resulted in a plasma disruption rate of less than 5%. As mentioned above, a similar, lower than average rate, was found during the JET DT campaign in 1997. During the campaigns C3 and C4 in 2001 experiments with Helium plasmas resulted in an increased disruption rate. Density control in Helium plasmas is generally worse because it is usually not affected by the JET pumped divertor. The high number of disruptions in campaign C16 can be explained by the presence of a small vacuum vessel leak, yielding higher impurity levels. Because of the variable length of each campaign, some of which carried out only a small number of plasma discharges, while others lasted for months, an overall drop in disruption rate over the period 2000-2007 is less clear from figure 2. At the start of this period however, the yearly rate of unintentional disruptions was 12.7% and 15.9%, in 2000 and 2001, while this was reduced to 6% and 6.2% over the years 2006 and 2007, respectively.

Determining the disruption rate of a specific operational scenario, such as H-mode operations, is more difficult and can be quite subjective. An attempt has been made by, taking a sample of 145 experimental sessions, manually classifying the operational scenario and counting disruptive and non-disruptive discharges between 2000 and 2007. The sample consisted of approximately 12% of the total operational period. This gave an average disruption rate for a typical ELMy H-mode scenario of 5.7%, while this was 3.9% and 8.3% for the Hybrid scenario and an Advanced Tokamak scenario with an internal transport barrier, respectively. All three scenarios show disruption rates that are lower than the averaged levels of unintentional disruptions. Especially running ELMy H-mode or Hybrid scenario seems to trigger significantly fewer disruptions than at other occasions during experimental campaigns. The scenario featuring internal transport barriers shows the highest rate, which may be due to its ongoing development.

3. DISRUPTIVITY AND OPERATIONAL LIMITS

The disruption rate indicates how often disruptions take place. The disruptivity, however, is a measure for the likelihood that a disruption takes place when the plasma is in a specific state and could be linked to, for example, the operational boundaries of tokamaks. Although often confused, disruptivity and the disruption rates are two different quantities and are definitely not directly related to each other. The disruptivity is defined as the number of disruptions that take place in a specific parameter space divided by the accumulated time that a discharge remains in this state. If no or little plasma operation is achieved in a certain parameter space this doesn't necessarily mean that the disruptivity is high. It could also suggest that the machine capabilities are insufficient to operate in that area, for example due to lack of auxiliary power. But it could suggest that an operational boundary prevents operation in this area. In order to come with a proper disruptivity one should be able to provide a good statistical overview of the plasma state and the number of disruptions therein. Studying disruptivities is complicated by the highly non-linear nature of plasma stability, such that the disruptivity may depend on a complex set of multiple parameters. It may therefore be difficult to link disruptivity to a plasma state described by only 1 or 2 plasma parameter(s). Nevertheless, the insight of where in the operational space disruptions take place may reveal indications of the main causes of JET disruptions.

Sufficient statistics are required in order to determine the disruptivity accurately; hence one has to average over a long period of operations. The following studies have been carried out over the recent operational period from 2000 to 2007. For each discharge the plasma state is sampled each 250ms (i.e. 4Hz) when the plasma current is above 1MA. This gives the total number of times (within a 250ms interval) that a plasma is in a specific state, i.e. has a specific plasma current or density. The frequency of 4Hz was chosen to be the same as the JET Thompson scattering diagnostic which provided part of the data. In total more than 15000 plasma discharges were sampled, resulting in 1.4 million sample points for each requested parameter. The disruptivity is defined as the number of disruptions when one plasma is in a specific state (i.e. occurs the same time frame in which the plasma can be described by one or more particular plasma parameter) divided by the total number of time frames in which the plasma has the same plasma parameters. The value of disruptivity is arbitrary and depends on the sampling rate that is chosen for the analysis. This makes it also difficult to project these values to for example ITER operations. Nevertheless, if a disruptivity of 1 is found, each time the plasma was found in this state it disrupted. In order to have sufficient statistics the analysis should be carried out over a long period of operations. The quality of the results depends, furthermore, on the accuracy with which the parameters that describe the plasma, (e.g. plasma current, density, safety factor etc.) can be determined and furthermore, the availability of these signals over a long period of time at each time in a discharge. The measurement(s) should be available over the whole operational period that is being studied, and not only at specific times in a discharge. For example at JET, ion temperatures and rotation velocities are only measured when neutral beam injection is present, which may bias the analysis.

3.1. DISRUPTIVITY VERSUS POWER AND CURRENT

Firstly, the disruptivity as a function of auxiliary power and plasma current will be presented. In figure 3a the number of disruptions is given as a function of auxiliary power and plasma current. Of all 1707 disruptions, with a plasma current of 1MA, or more, that took place during this period, almost 75% happened in plasmas with less than 5MW of auxiliary power. At JET, it requires usually more than 5MW to run a proper H-mode at average plasma current. More disruptions took place with little or no power; however, this doesn't mean that the disruptivity is higher at low power levels. Usually the plasma spends considerable time without additional power, for example during current-ramp-up and ramp-down phases. 19.7% of all disruptions happened in plasmas with no auxiliary power at all, while 38.9% occurred after the power was stepped down. The remaining 41.4% took place during the application of additional heating. If the disruptivity is plotted as function of power, shown in figure 3b, one finds significantly higher levels for larger powers. This suggest that plasmas with more auxiliary power are more prone to disrupt.

Figure 4a shows the fraction of disruptions as a function of plasma current. Of all disruptions, 81% occurred at a plasma current of less than 2MA, which is approximately the average plasma current over the period from 2000 to 2007. Disruptions are less frequent at higher currents. The larger fraction of disruptions at lower plasma current is partly due to the protection system that shuts down the plasma and ramps down the plasma current following control problems or when plasma instabilities are detected. Furthermore, experiments that are predicted to cause disruptions or those where they are triggered deliberately are mostly with at lower plasma current to limit the impact on operations. Hence, the disruptivity is expected to be higher for lower plasma currents as verified by figure 4b. The lowest values of disruptivity are found around the average plasma current of about 2MA while it is seen to rise towards higher currents again. The maximum plasma current over this period was 4.3MA, but no disruptions were recorded over this period with a plasma current of 3.56MA or higher. Hence, above this value the disruptivity is set to zero. The statistics at higher currents are however less accurate, due to the small number of disruptions (i.e. only 15 with a plasma current above 3MA). These trends are confirmed by enlarging the period, hence increasing the number of discharges and disruptions, which shows again a peak in disruptivity around 3MA, although even with improved statistics, it was not possible to obtain an accurate disruptivity for plasma currents above 4MA.

3.2. DISRUPTIVITY AND OPERATIONAL LIMITS

The question is of course if one can link disruptivity with arbitrary parameters, like the plasma current and auxiliary power. The higher disruptivities may for example be more directly linked to high density operations while using high levels of auxiliary power. It is therefore more interesting to look into the disruptivity with respect to the operational boundaries of tokamak operation. The most commonly used plot depicting the operational range of a tokamak is the so-called Hugill-diagram [12, 13]. Here the inverse edge safety factor, 1/q, is plotted against the Murakami parameter or normalised density, $n \cdot B_T/R$, where n is the line-averaged plasma density, B_T, the central toroidal field and R the major radius. This diagram gives the operational range with respect to two well-known stability limits, the low-q or $q = 2$ limit and the density limit. As discussed above the JET data over the period 2000 to 2007 can be sampled to produce a statistical overview of JET operations, as shown in figure 5a. Operation near or at the $q = 2$ limit is less frequent, and a clear density limit independent of the power is found being the well-known Greenwald limit. [14, 15]. This emperical density limit is directly proportional to the average current density and is indicated in the Hugill-diagram as a straight line. More detailed studies at JET and ASDEX-U suggest a slighltly more complex dependency while the underlying physics of this operational boundary is thought to be linked to the properties of the outer edge of the plasma [16, 17].

The disruptivity Hugill diagram is shown in figure 5a. Similar results have been obtained in TCV [7]. The quality of the statistical analysis depends mainly on the number of disruptions found in each selected block within the operational range. Increasing the block-size will improve the statistics but will deteriorate the resolution of the plot. The block-size chosen here is found to be an optimum between statistics and resolution. Another issue is the error, which should be smaller than the block-size. It can be seen in figure 5a, that sometimes operations has been achieved at $q_{95}<2$. In some cases this may be due to errors with the parameter signal or in this specific case the reconstruction of the plasma shape from magentic signals. Lowest disruptivities are found far from the limits, while the highest disruptivities are seen to be close to the $q = 2$ and Greenwald-limits, indicating that operation near these limits is more difficult and prone to instability. The data can also be represented by doing the statistics for the safety factor and Greenwald-fraction only. Here the Greenwald-fraction is the line-averaged density devided by the Greenwald-density. Figure 6a shows a clear increase in disruptivity for operations below $q_{95} = 2.5$. For values of $q_{95}>3.5$ the disruptivity is at a constant low level, while figure 6b shows the highest disruptivity at or above the Greenwald-limit. The highest fraction of disruptions is found, however, far from these limits, and the cause of these disruptions can be less well classified and not be connected to the operational limits shown in the Hugill-diagram. A detailed look into theses points show them to be from times in discharges without or with low auxiliary heating power, during the ramp-up or ramp-down phase, while the points on the far right-hand-side of the operational range can only be achieved with sufficient auxiliary power. It could be that the trends seen in figure 3b and the increased disruptivity near the Greenwald limit are related. Disruptions sometimes happen at lower densities due to excessive radiative power. Plasmas with a high radiative power fraction could be prone to a radiative collapse, sometimes seen as classical density limit disruption. However, the quality (e.g. statistical availability and accuracy) of this parameter was not good enough to study its effect on the disruptivity.

One may also argue that the rise in disruptivity with auxiliary power is in fact caused by the increased likelihood of a disruption when operating at higher pressures or β, which is the plasma pressure normalised to the magnetic pressure. The b-limit is another operational limit for tokamaks [18]. In figure 7a, the JET operational range is shown as a function of the toroidal β, β_T, and the parameter: $li \cdot I_p/aB_T$. Here I_p, a and B_T are the plasma current, minor radius and toroidal magentic field, respectively. The β-limit was found to scale with I_p/aB_T [18] while the dependency with the internal inductance, li, was introduced to factor in the effect of the current density profile [19]. Usually tokamaks struggle to operate above levels of $\beta_N = \beta_T \cdot aB_T/ I_p \sim 4 \cdot li$, where b_N is called the normalised b, which is shown in figure 7 as a dashed line. Nevertheless, the b-limit is quite complex and proper tuning of the scenario and the pressure profile and futhermore stabilisation by plasma rotation, and other features seem to allow operations at higher values. The limit doesn't appear very clear in the operational diagram. As shown in figure 7b, at lower values of I_p/aB_T the disruptivity is not increased near the limit, and these values are again often obtained either during the ramp-up or ramp-down of a discharge. Most high-power scenarios operate with $li \cdot I_p/aB_T \sim$ 0.8-0.9 for which indeed higher disruptivity is found at high b. A clear disruptive boundary can be seen on the right-hand-side of the operational range, but this is directly linked to the low-q limit, similar as found in figure 6a.

3.3. DISRUPTIVITY TRENDS

In the previous section it was shown that the disruption rate at JET has decreased over the years. In order to see if there is a link between the trend in the disruption rate and that of the disruptivity, this last parameter is calculated for a specific operational area and time period. In order to obtain sufficient statistics, the time pariod cannot be choosen too short and the operational area where the disruptivity is calculated should be large enough. The operational period from 1996 to 2007 has been divided into 5 equivalent parts of equal number of plasma pulses and three specific areas of the Hugill-diagram have been selected. The first area comprises all data where q_{95}<2.5, the second, all data with a Greenwald-fraction larger than 0.8, and the last area is made up of the central 'safe-zone' in the Hugill-diagram (i.e. $2.5<q_{95}<5$ and a Greenwald-fraction below 0.6). The frequency of operations close to the Greenwald-density (area 2) was found to increase with time. In 2006/2007 almost 7 times more often discharges at the Greenwald density were run, then in 1996/1997. The number of times that JET operated at low-q or operated in the central zone remained more or less constant over the same period. One may argue that the disruptivity close to the Greenwald limit has reduced sightly because the number of disruptions only increased by a factor of 4, although the statistics are rather thin. When the trends for the values are plotted as a function of time (figure 8a), no clear change is found for the disruptivity at the low-q and density-limit. A similar analysis has been carried out for the disruptivity near the β-limit. Here the averaged disruptivity for operations with $\beta_N>4 \cdot li-1$ is taken. Like with operations near the density-limit, the frequency of operations at high β ($\beta_N>3.5 \cdot li$) increased over the last 10 years. Especially in the last period, from October 2005 to April 2007 (#63418-#70750) when the frequency was more than 1000 times higher than in the previous 4 periods. Figure 8a shows a decrease in the disruptivity near this limit over time. From figure 8a one can also see that the averaged disruptivity is highest for the q = 2 limit, followed by the density limit, while the β-limit has the lowest levels for the three operational limits. When observing the trends of these disruptivities one should keep in mind that, because of the limited statistics, the error bars are considerable (>30%). The clearest trend is found for the disruptivity of the central zone, which follows the decrease of the disruption rate nicely as shown in figure 8b. This is consistent because the largest fraction of disruptions happen in this parameter space such that these are a dominant contributor to the disruption rate.

4. PRECURSORS AND MITIGATION.

At JET a straightforward protection system is in place that terminates the plasma discharge in case of control problems or when plasma instabilities are detected. Hence, some disruptions may be prevented or their effects can be mitigated. Thus the observed average disruption forces and heat loads may be lowered by the action of the protection system. The pulse termination network is activated by various triggers which can be divided into 3 groups. Firstly, those caused by technical control errors within the PPCC (Plasma Position & Current Control) and Shape Controller system or for example manual stops. Secondly, those triggered by detected two types of MHD instabilities, e.g. rotating modes and those that are locked. The trigger levels have been determined empirically for the last two cases. The detection of locked modes (magnetic perturbations that couple (e.g. lock) to external error fields) are especially important as these tend to persist in the plasma, causing a reduction in confinement and in many cases disruptions, while external correction of error fields have shown to lead to reduced disruptivity [20].

The mitigating action presently in place at JET, is to try to terminate the plasma discharge in a controlled manner. This is done by switching off the auxiliary heating and ramping down the plasma current and density. Furthermore, the plasma shaping is reduced, by a quick reduction of one of the shaping coils. This will mainly lower the triangularity of the plasma. In JET disruption forces, when using plasma configurations with high triangularity are generally larger hence this action has a mitigating effect. Sometimes the system is able to successfully terminate the discharge, while in other cases the plasma still ends with a disruption.

4.1. STATISTICS OF DISRUPTION PRECURSORS

In table 2, the statistics of the pulse termination triggers in disruptive pulses are given over the operation period from 2000 to 2007. In many cases several triggers happen consecutively. Here only the earliest observed precursor is considered. The precursor that is observed prior to most disruptions is a Locked Mode, while only a few show a too large rotating MHD mode as the first initial trigger. It is interesting to note that of the 40 discharges where this was the case, 35 were operating with a safety factor $q_{95}<3$. Quite a large fraction (~37%) is not detected. These can be associated with the fastest disruptions, often VDEs while some of these disruptions occurred in discharges with strong internal transport barriers. Many VDEs are triggered intentionally. Furthermore, for many intentional disruptions the protection system was overridden because it may otherwise complicate the experiment. If only unintentional disruptions are considered, the fraction that is not detected by this system is reduced to (~ 25%).

The above statistics is for precursors to disruptions, but not always a triggered stop leads to a disruption. It was found that 82.5% of discharges that were stopped because of a Locked Mode disrupted, while 17.5% landed safely. However, every discharge with a large rotating MHD mode trigger eventually disrupted. Table 2 shows that in 304 cases the plasma disrupted after an initial technical problem, however, in 1313 (80% of the total) of such cases the plasma terminated without any problems. This also means that a total of 1617 of these triggers occurred, while over this period 15798 discharges (with a current of more than 1MA) were carried out, which gives a percentage of just over 10% of all discharges.

The system will not always be fast enough to react, and the disruption may follow too soon afterwards. In figure 9 the accumulated fraction of disruptions preceded by a pulse termination trigger is shown, for all and only unintentional disruptions, respectively. The main mitigating actions by the system are the reduction of the plasma and shaping currents. These actions have a characteristic time at JET of approximately 200 and 30ms, respectively. The figure shows that 37.4% of all disruptions and 49% of all unintentional disruptions can be detected with a warning time of 200ms or more. For a warning time of 30ms or more, these fractions are approximately 50% and 66%, respectively. It should be noted that the above analysis deals only with the technical precursors used within the JET protection system. It has not been attempted to connect these precursors to more detailed causes or to classify the type of disruptions, such as done for ASDEX Upgrade in [21].

4.2. MITIGATION OF DISRUPTION FORCES

The database contains the forces induced by disruptions from 1994 onwards (i.e. from the start of MKI divertor operations). The average vertical force produced by disruptions in JET increases with square of the plasma current. However, individual disruptions show a large scatter and the disruption force normalised to the square of the plasma current) can vary significantly between 0.58MN/MA^2 and 0.03MN/MA^2. This scatter may be attributed to differences in the vertical growth rate caused variations in the plasma shape and furthermore to differences in the disruption dynamics. Especially high triangularity plasmas have shown to produce larger disruption forces in JET. The statistical distribution of disruption forces is shown in figure 10a. Over the entire database the maximum disruption force was 4.77MN while for the period 2000 to 2007 the maximum was 4.05MN. The normalised disruption force (i.e. per plasma current squared) seemed to be relatively constant over the operation period of JET.

The averaged disruption force for all disruptions with a particular warning time is plotted in figure 10b, which shows that the JET protection system is clearly able to mitigate these forces. Those disruptions with no and little warning time available caused average forces above 1MN, while clearly with a warning time larger than approximately 100-200ms a significantly lower force was experienced. Of course this result is based on statistics and the trend is based on averaged data. However, a similar trend is found if the maximum disruption force is considered. For disruptions with a warning time less than 30ms (including those without warning), the maximum force was 4.05MN while the maximum for those with a warning time of more than 100ms was only 2.1MN. This can be attributed to the lower plasma current at which these discharges disrupt. Similarly, a lower normalised disruption force is found when the warning time is 20ms or more, which may suggest that the fast reduction of the triangularity is effective. For the period 2000-2007 the averaged disruption forces was 0.71MN, while the average normalised force was 0.28MN/MA^2.

4.3. HEAT LOAD AND DISRUPTIONS

It is less straightforward to calculate the disruption heat load for all disruptions, because, beside the determination of the plasma energy, this also involves an accurate evaluation of the energy quench time. This has been done previously for a smaller number of disruptions [5]. Here only the plasma energy just prior to the disruption is considered. In figure 11a it can be seen that only 3.2% (i.e. in total 55) of all disruptions between 2000 and 2007, had an energy of more than 4.5MJ. These disruptions may be able to produce power fluxes exceeding 1.5MW/m^2 and have the potential to damage plasma facing components in JET [5]. However, 4.5% of the disruptions had an energy of more than 4.5MJ at the time of the warning trigger (i.e. in total 77) indicating a mitigation of the heat load. In figure 11b the plasma energy is plotted as a function of the warning time. The maximum energy prior to a disruption is found to be of the order 8MJ at JET. Both the average and maximum values drop when a longer warning time is available although less convincing than as shown with the disruption force. Although switching of the auxiliary power can be done quickly at JET, even within 10ms, the energy decay is predominantly determined by the plasma confinement. Typical energy confinement times can be of the order of 100-300ms in JET. This may partly be affected by the events that lead up to the disruption, such as high impurity and/or radiation levels or the presence of MHD instabilities, etc. However, in some cases the plasma was able to maintain its energy right up to the time of disruption, even when the auxiliary heating is turned down. Quite a number of such cases, many with plasma currents above I_p>2MA, are found in the warning time interval from 300ms to 1s leading to the peak around these times in figure 11b. It shows that ameliorating action to reduce the disruption heat loads at JET is less effective compared to that acting on the force.

CONCLUSIONS

In this paper a statistical analysis of JET disruptions has been.presented. Instead of studying the details of underlying physics causes of disruptions, these studies give a broad insight in the trends of disruption rates and levels of disruptivities over a long period of tokamak operations.

It has been shown that for JET the disruption rate has dropped significantly from average levels around 25% since the start of X-point operations more than 20 years ago to recent low levels of the order of only 6%. One could see this as a learning curve of tokamak operation, where over the years many elements of plasma scenarios, such as for example the X-point formation, and control systems, like that for the density or vertical stability, have been optimised or improved. Furthermore, protection systems were empirically calibrated to provide optimum cover. The downward trend could also be due to a better physics understanding of the operational boundaries of JET. Studies showed however that the levels of disruptivities near these boundaries did not change significantly over the period from 1996 to 2007. But plasmas were more frequently run close to the b-limit and Greenwald-limit in recent campaigns. The reduction in disruption rate correlated best with the drop in disruptivity in the area of operation far from the operational boundaries. Many of these disruptions are thought to be caused by technical problems, tail disruptions, bad machine conditions and erratic impurity influxes, etc. Because these comprise the largest fraction of disruptions, a reduction in their disruptivity will have a dominant effect on the disruption rate. Therefore, the lower disruption rates are thought to be primarily due to an improvement in the technical ability to operate JET which in part can be attributed to faster software, simpler machine interfaces. But human error, i.e. pulse programming, setting up reference waveforms, etc., also affect the disruptivity in the area.

The analysis showed furthermore that in case it was important to prevent disruptions, lower disruption rates were obtained: for example during campaigns where Tritium was used. This suggests that during other period of operation, a fraction of disruptions is due to less careful operations. Although many of these 'don't-care' disruptions are at low current and energy and thus have effects that are less severe, one may question what the impact of a large number of such disruptions could have on the device or the experimental programme. Running well-known scenarios, such as commissioning pulses, cause fewer problems, than newly developed ones. Proper scenario development will reduce the disruption rate.

High-power operation increased the likelihood of disruptions. Clearly higher disruptivities were found when operating with low edge safety factors, i.e. q_{95}<2.5 and/or in proximity to the Greenwald density. Similarly, higher disruptivities were found close to the b-limit, at low q, high li. It should be said that the results presented here are based on statistics, and certainly do not suggest that it is impossible to operate close to or above an operation boundary when done so in a carefully planned scenario.

It may, however, not always be correct to link disruptions to a single operational boundary or plot disruptivity as a function of only a few parameters. As said in the introduction, the causes that lead up to a disruption can be due to a complex mixture of events but it may be very difficult to determine the disruptivity as function of such a multiple dimensional operation space. The results showed that operating JET close to the three main operational boundaries clearly increased the likelihood of disruptions. Whether the same is true for the disruption rate is not clear. Although at first one may think that there is a direct link between disruptivity and disruption rate, this is not the case. The first can be related to a physics boundary of operation while the latter cannot. The disruption rate may be dominated by inconsequential disruptions, while changes in the disruptivities near the operational limits, at high current and power, have only a limited impact on its value.

At JET, between 15% and 25% are actually done intentionally as part of the experimental campaign or to carry out an assessment of the disruptions forces for a particular scenario. Disruptions provide not only detailed information on the physics behind disruptions and their consequences, but allow further optimisation of operational scenarios. It is however questionable if these levels of intentional disruptions can be tolerated in ITER.

Intentional disruptions also provide input to tune the settings for protection systems. The basics system that is in place at JET was shown to be able to detect 50% of all disruptions with sufficient warning time (>200ms) to mitigate the disruption forces. The protection system is predominantly triggered by the detection of a locked mode. It was found that it is more difficult to reduce the plasma energy after a warning. The auxiliary heating systems in JET can be switched off quite fast, but the energy decay is mainly determined by the energy confinement time which can be of the order of several 100ms in JET. Hence, better and faster methods to reduce the resulting heat loads should be found. The precursor analysis presented here is rather basic and future work plans to look into more detail to the technical and physics causes of disruptions in JET.

Disruptions may never be completely avoidable in tokamak. Even in times when the utmost effort was taken to prevent disruptions, for example during D-T campaigns in JET, the disruption rate was still about 5%. ITER aims to operate with a disruption rate of 1% or less, for operations in the high current base-line scenario. Because this number does not include all operations, it is not easy to be compared with the disruption rates obtained at JET. A more relevant number to be determined would be the ITER disruptivity in high current base-line scenario. One should be aware, however, that phases of significantly higher disruption rate, i.e. scenario development at lower plasma current, may be required to precede high current operations, in order to learn to operate without disruptions. Nevertheless, longer times scales in ITER, better detection systems and faster mitigation techniques may enable a better amelioration.

ACKNOWLEDGEMENTS

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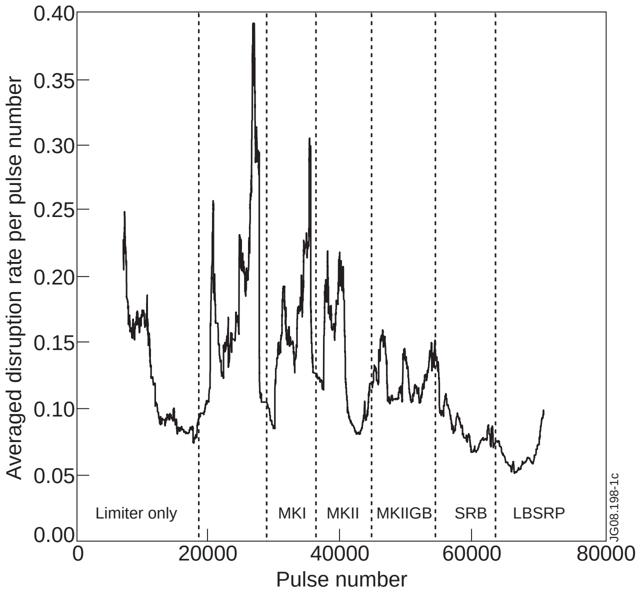
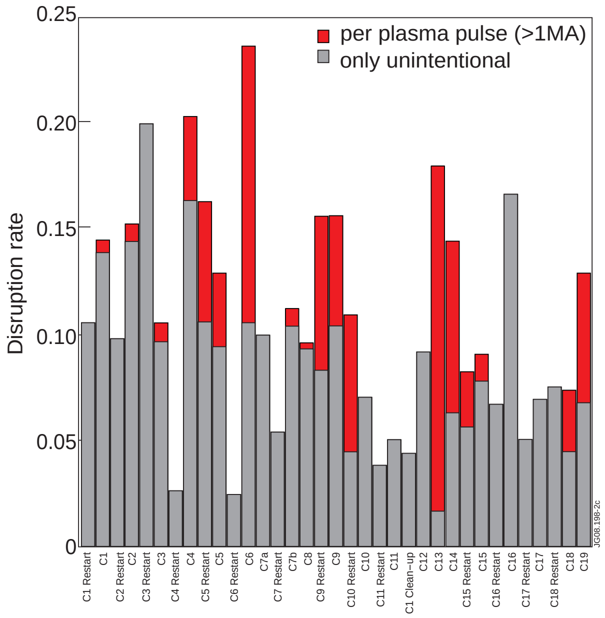
Operational phase	**Period**	**Plasmas**	**Disrupt.**	**Intent.**	**%¹**	**%²**	**%³**
Limiter only	*Mar 84* - Aug 87	*4017*	*960*	–	*16.7*	*23.9*	–
Limiter + X-Point	Aug 87 - Feb 92	11080	2335	–	14.8	21.1	–
MKI	Mar 94 - Jun 95	4367	1344	–	19.2	30.8	–
MKII	May 96 - Feb 98	6059	1253	121	15.3	20.7	18.6
MKII GB	Jul 98 - Mar 01	7327	1348	60	13.9	18.4	17.6
MKII GB SRP	Jul 01 - Mar 04	6562	788	242	8.7	12.0	8.3
MKII GB LBSRP	Aug 05 - Apr 07	5093	432	104	6.0	8.3	6.3

Table 1: The disruption rates for various stages of JET operations. The later phases are characterised by different divertor types: Mark I, II, Gas Box, Septum Replacement and Load Bearing Septum Replacement Plate, respectively. The middle 3 columns give the number of plasma pulses with more than 1MA, total number of disruptions and number of intentional disruptions. The last 3 columns give the disruption rate per pulse number (%¹), disruption rate per plasma (%²) and the unintentional plasma disruption rate (%³). JET started operations in June 1983 but for this analysis only data after March 1984 was available. Intentional disruptions were no recorded in the first 3 periods.

Total	All disruptions (I_p>1MA)		Unintentional disruptions	
	1707		1301	
Type of shutdown				
Mode Lock	736	43.1%	630	48.4%
Technical (PPCC, SC, etc.)	304	17.8%	304	23.4%
MHD mode	40	2.3%	40	3.1%
None	627	36.7%	327	25.1%

Table 2: The number of shutdown triggers observed prior to disruptions over the operational period from 2000-2007. The first two columns give the numbers for all the disruptions, while in the last two columns intentional disruptions are excluded. The technical shutdowns combine all possible stops triggered by PPCC, Shape Controller (SC), power supply protection systems and even manual stop buttons.





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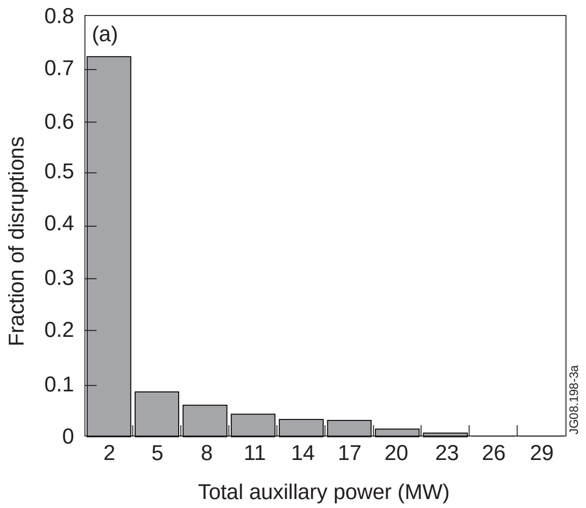


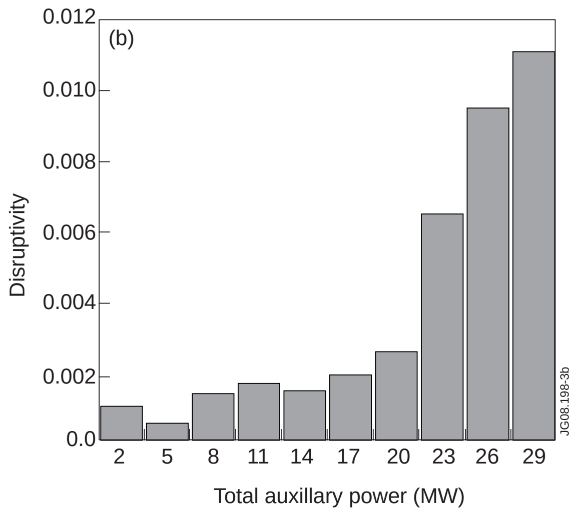


Figure 3: a) Histogram showing the fraction of disruptions as a function of power. b) Same for the disruptivity as a function of power. The values on the x-axis represent the centre of the sample area.

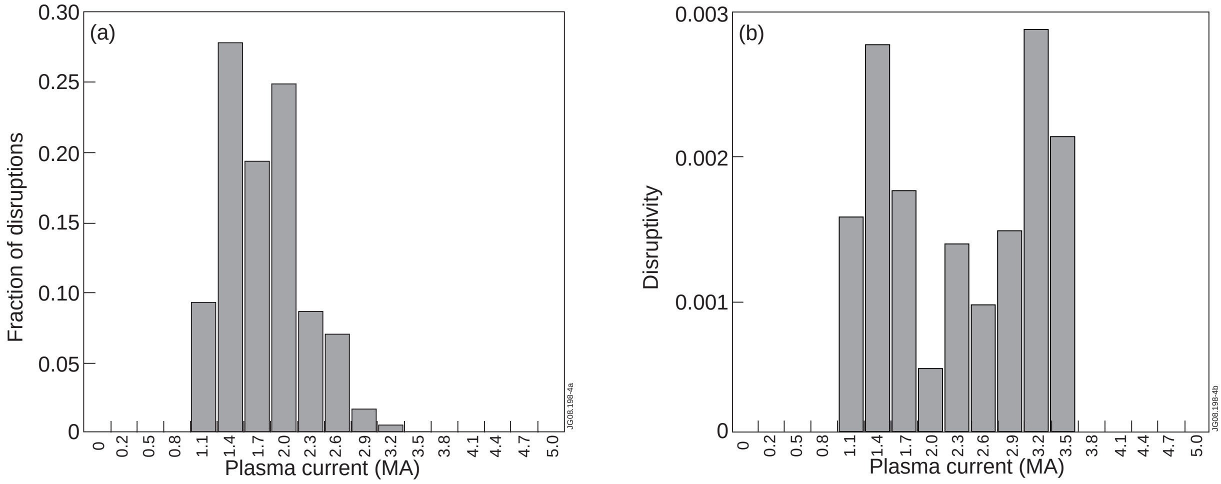


Figure 4: a) Histogram showing the fraction of disruptions as a function of plasma current. No disruptions below 1MA are recorded. b) Same for the disruptivity versus plasma current. The maximum plasma current achieved over the period of interest was 4.3MA but no disruptions above 3.56MA took place, hence the disruptivity is zero for the highest current values. The values on the x-axis represent the centre of the sample area.

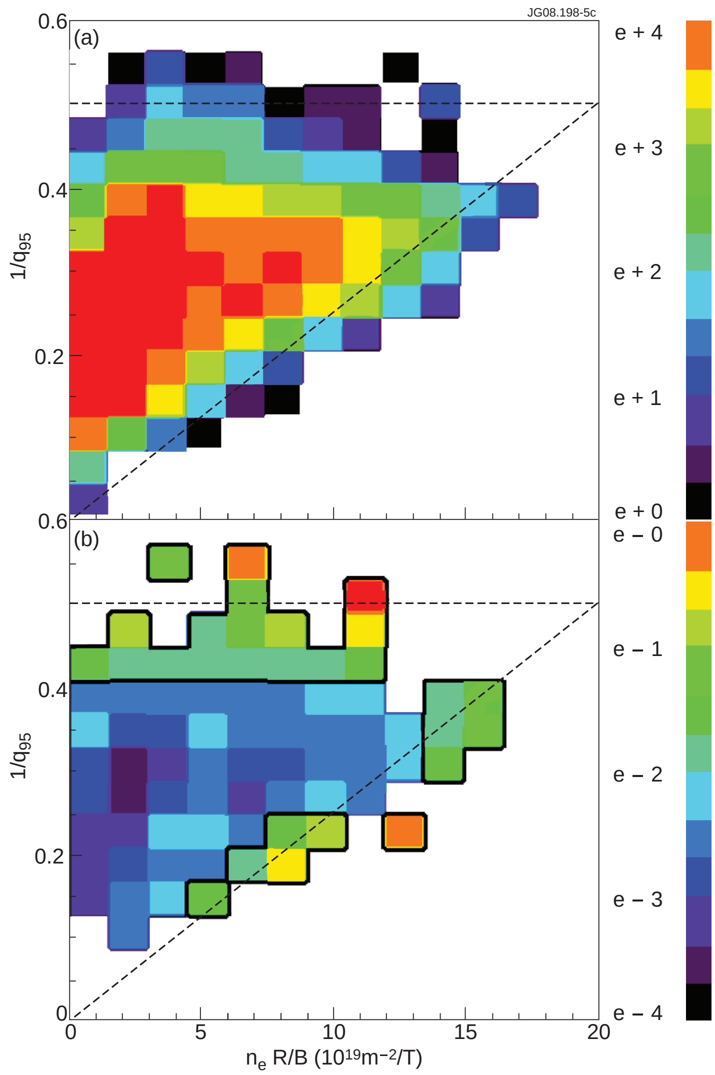
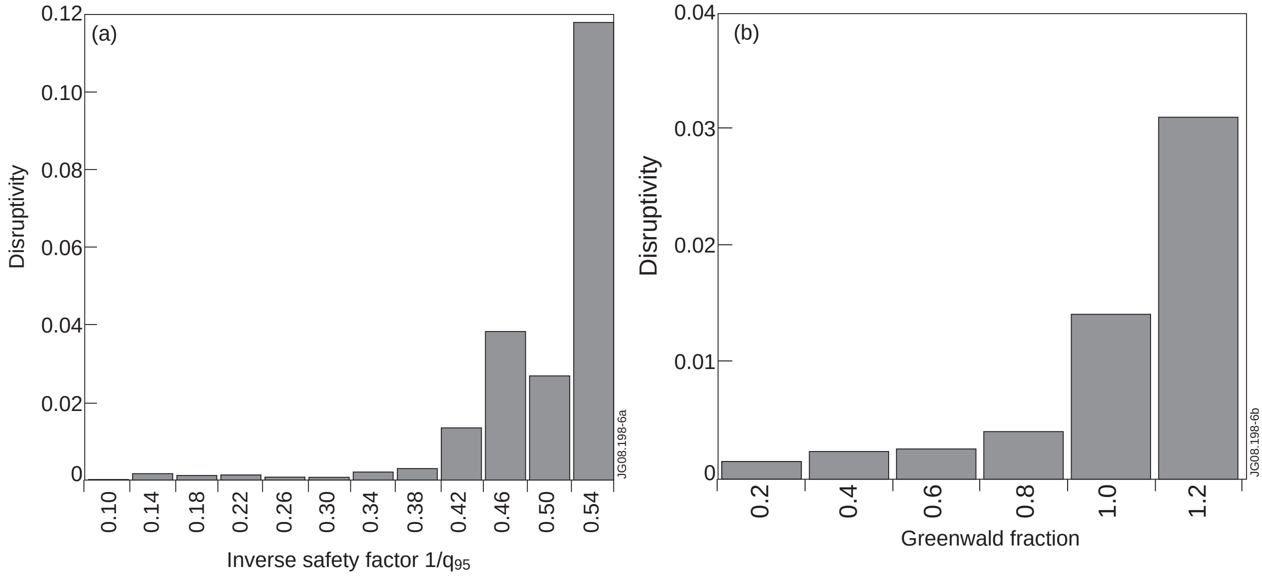


Figure 5: a) A so-called Hugill-diagram for the operations of JET between 2000 and 2007. The statistics for all operations is given with respect to two parameters, a normalised density. $n\sum B_T/R$. and the inverse safety factor, 1/q. The data comprises all discharges, sampled at 4Hz, when the plasma current exceeds 1MA. b) The disruptivity versus the same parameters. Note that, the contour levels are spaced logarithmically in both graphs. The area where the disruptivity exceeds an arbitrary level of 0.01 is given by the black thick line. The dashed lines in both graphs show the so-called Greenwald-limit and the q=2 limit, respectively.



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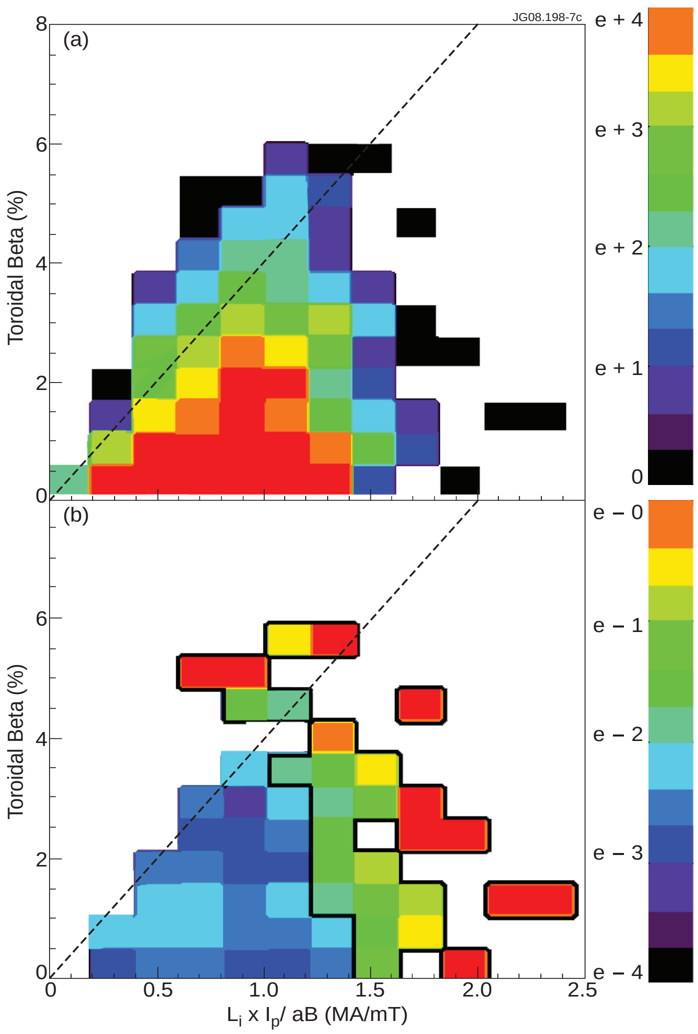

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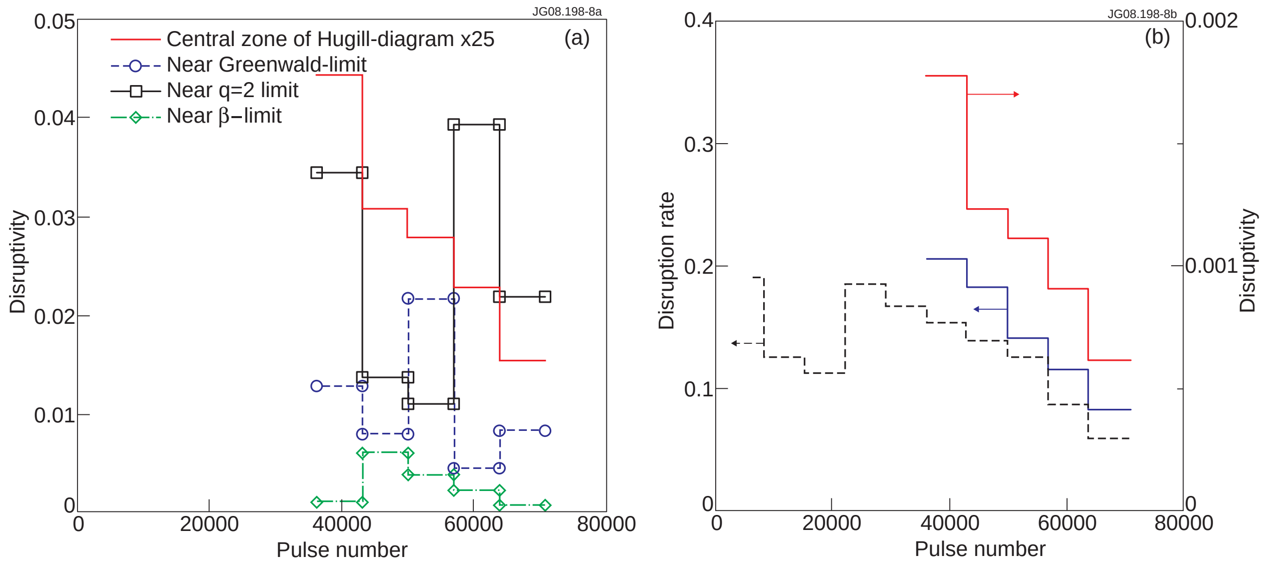

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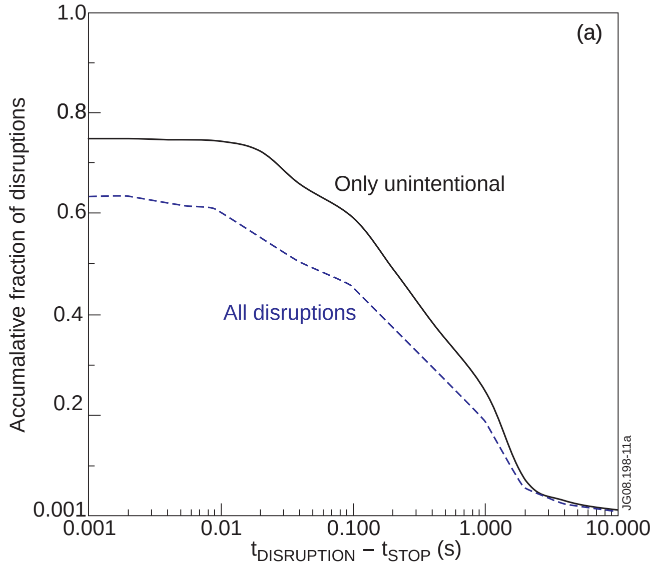

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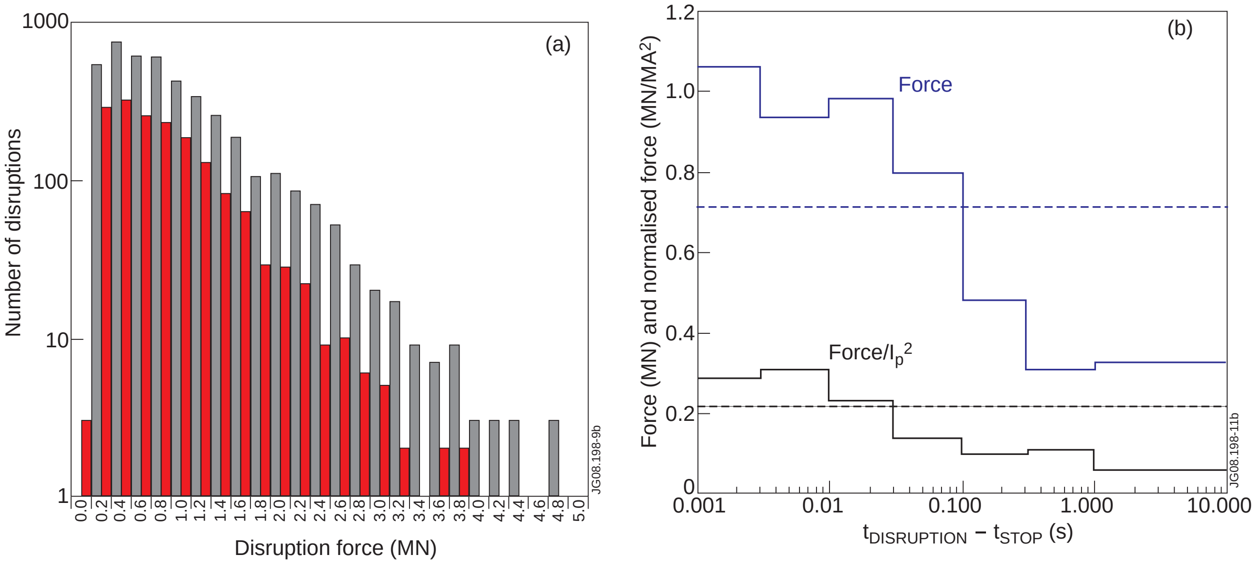

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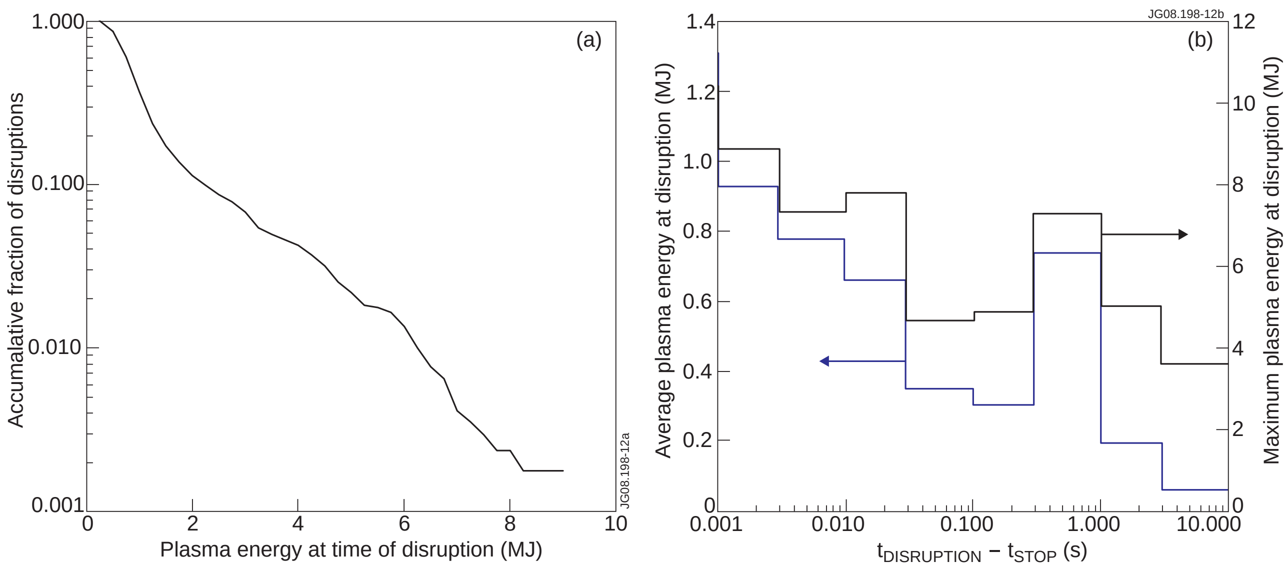

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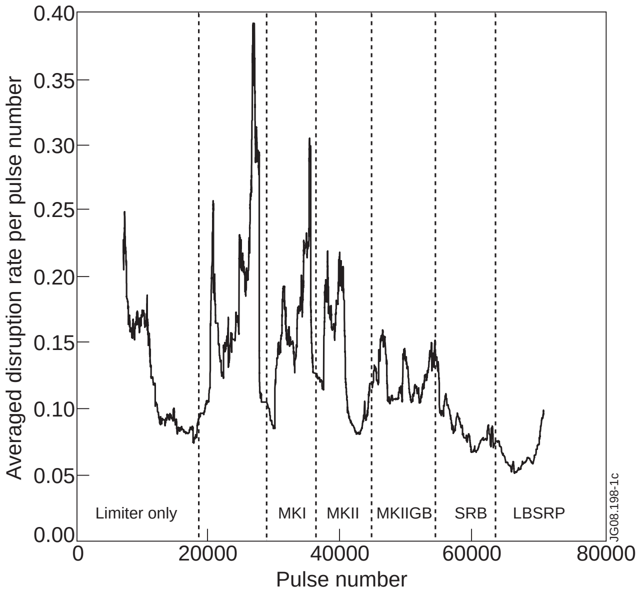

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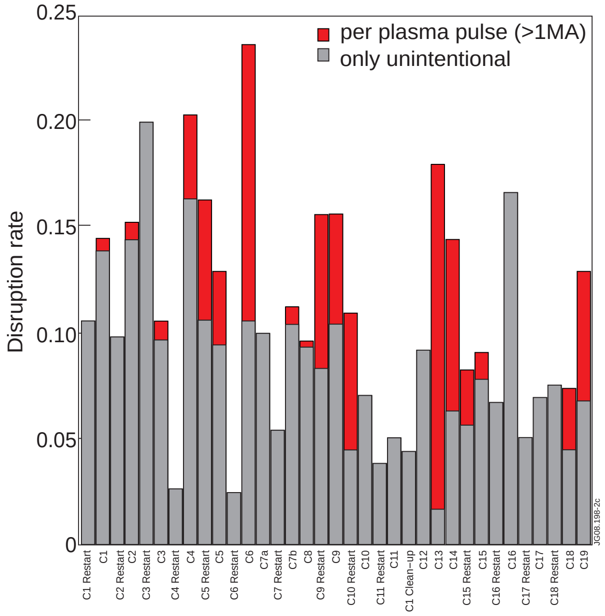

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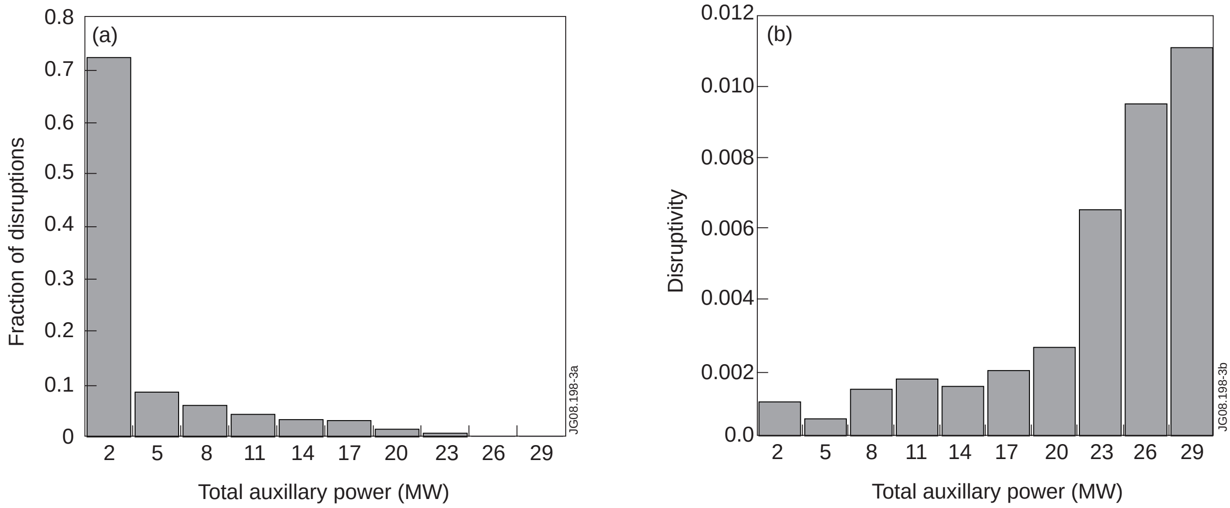

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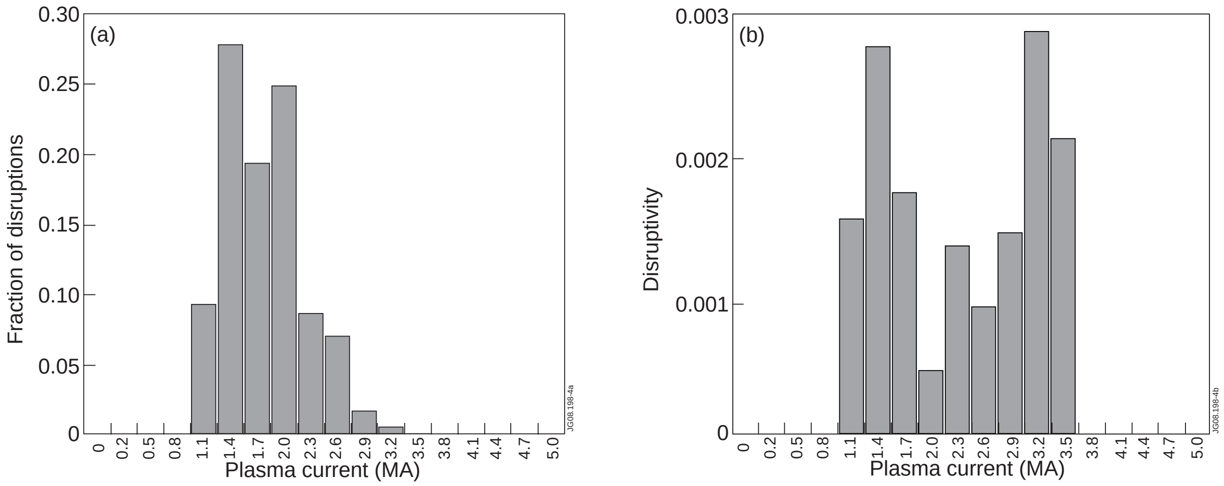

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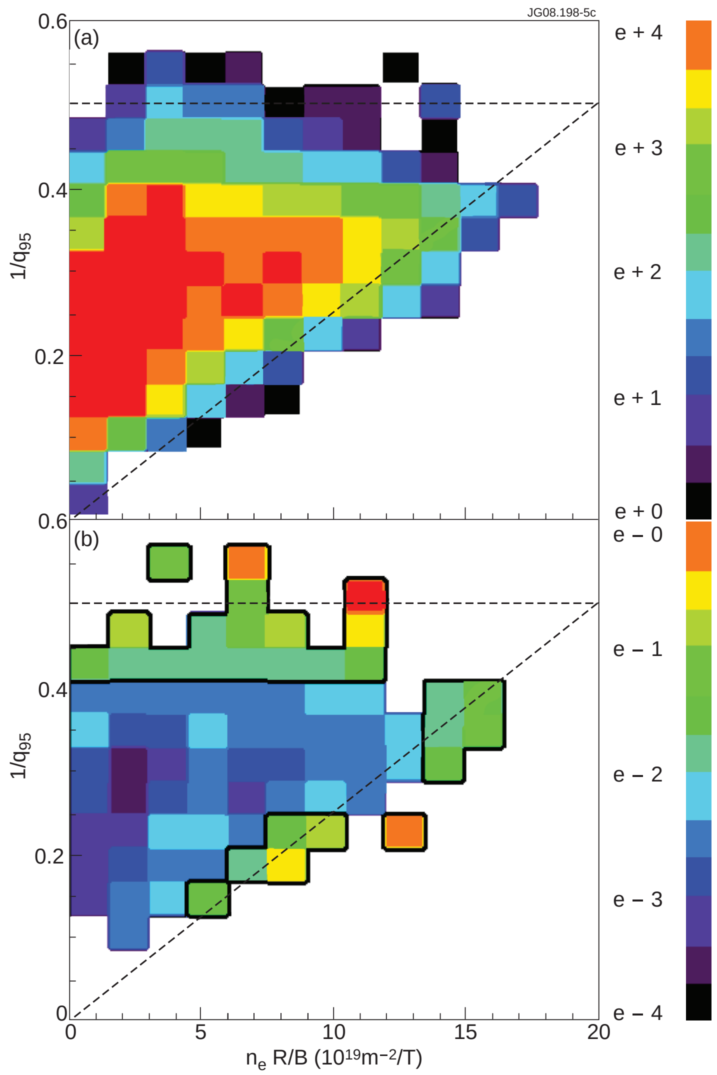

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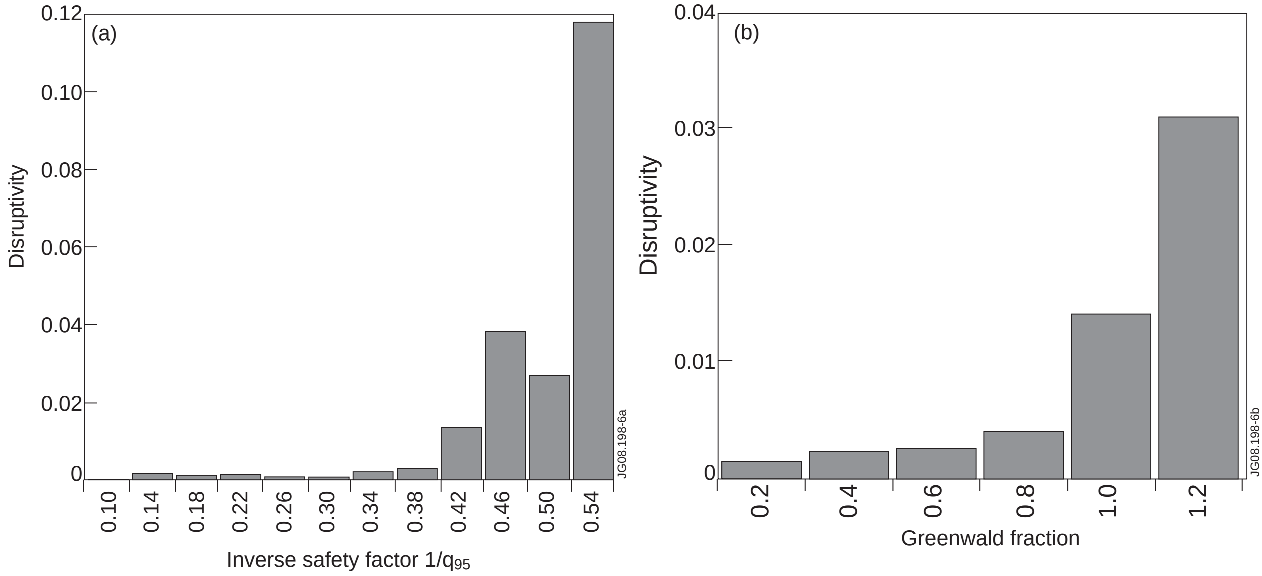

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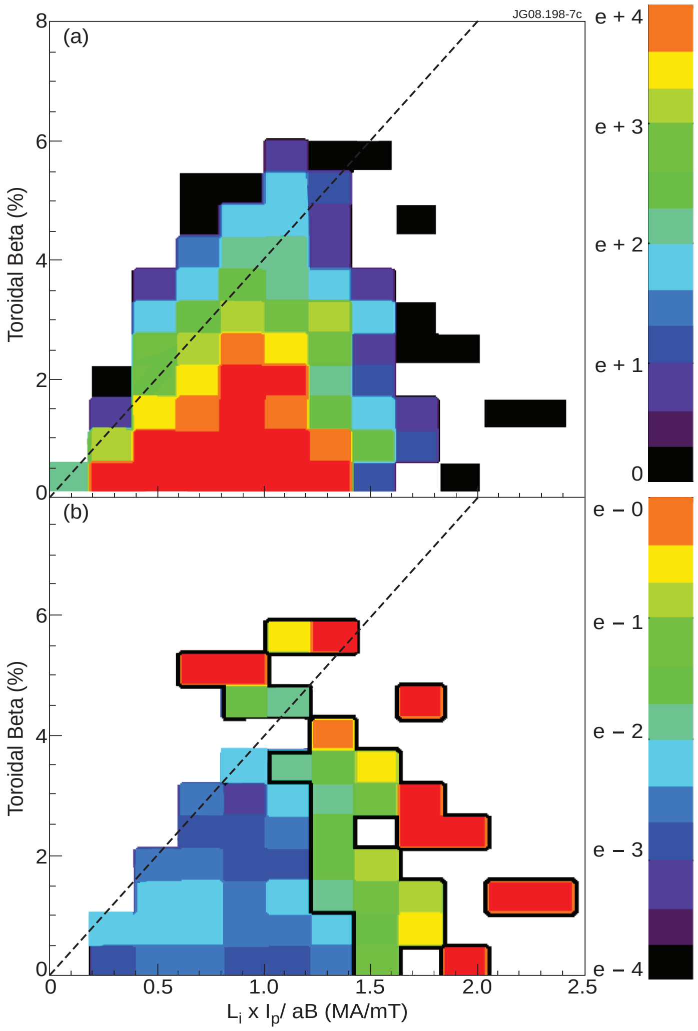

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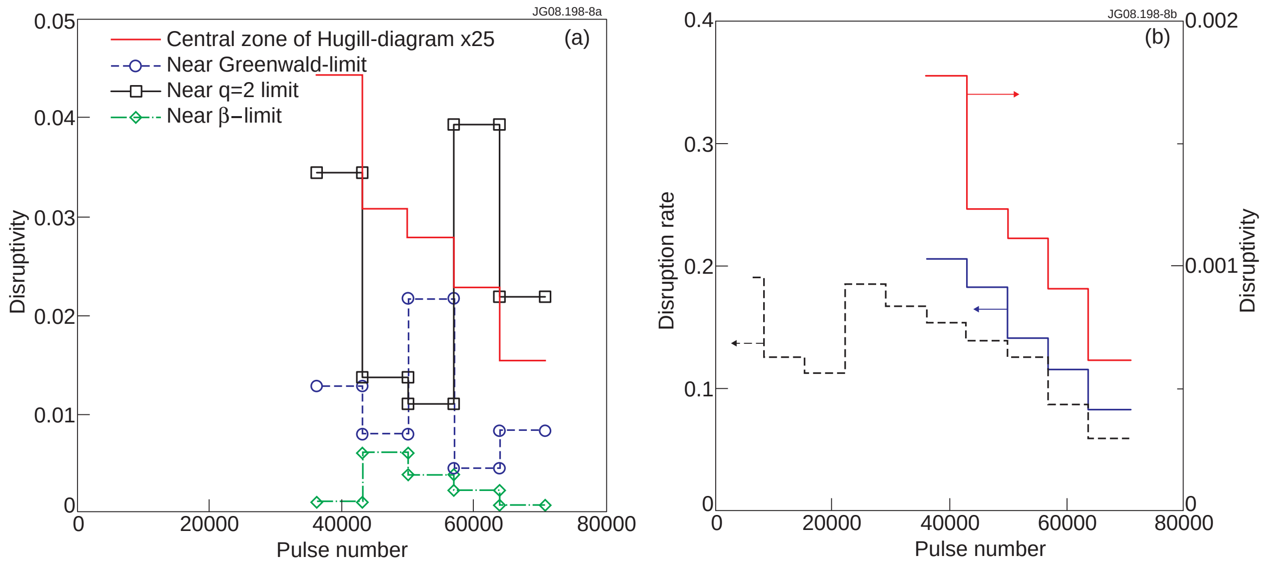

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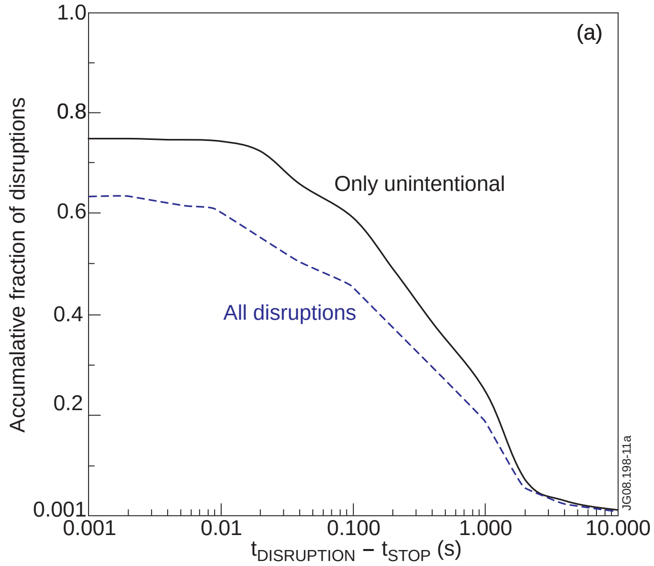

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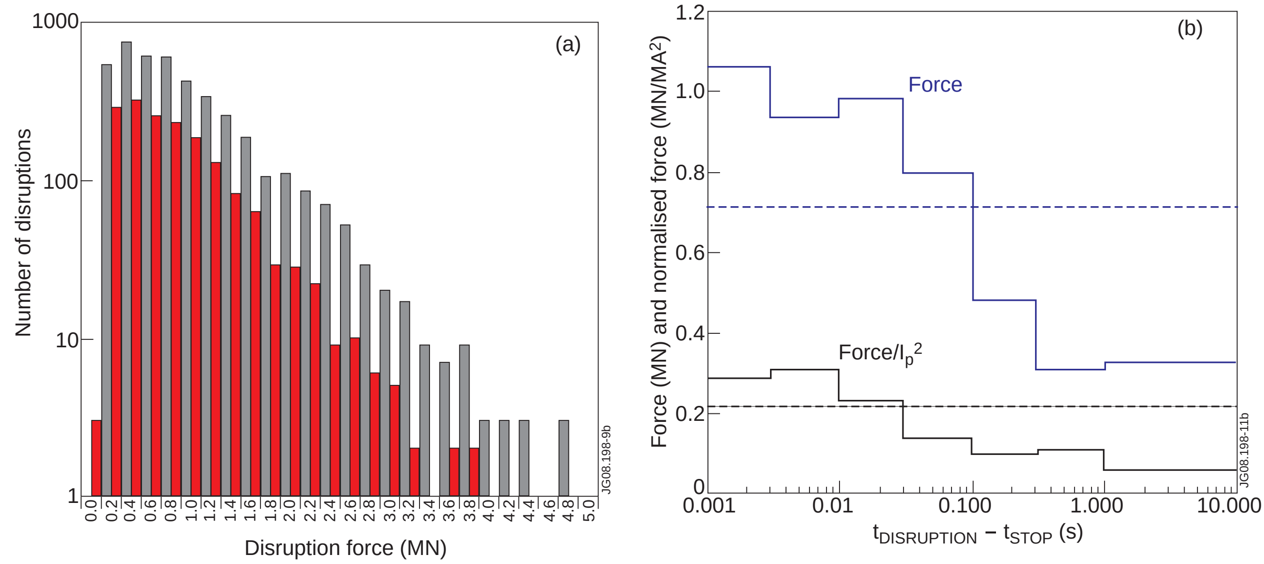

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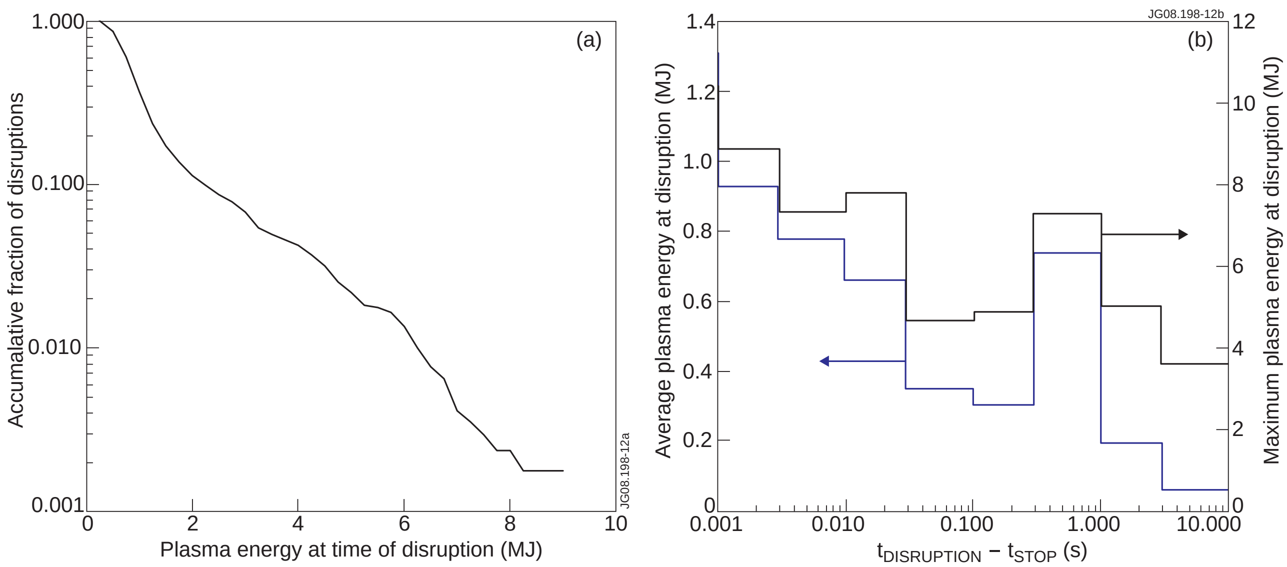

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