The ITPA disruption database

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Abstract

A multi-device database of disruption characteristics has been developed under the auspices of the International Tokamak Physics Activity magneto-hydrodynamics topical group. The purpose of this ITPA disruption database (IDDB) is to find the commonalities between the disruption and disruption mitigation characteristics in a wide variety of tokamaks in order to elucidate the physics underlying tokamak disruptions and to extrapolate toward much larger devices, such as ITER and future burning plasma devices. In contrast to previous smaller disruption data collation efforts, the IDDB aims to provide significant context for each shot provided, allowing exploration of a wide array of relationships between pre-disruption and disruption parameters. The IDDB presently includes contributions from nine tokamaks, including both conventional aspect ratio and spherical tokamaks. An initial parametric analysis of the available data is presented. This analysis includes current quench rates, halo current fraction and peaking, and the effectiveness of massive impurity injection. The IDDB is publicly available, with instruction for access provided herein.

Keywords: magnetic confinement, equilibrium, tokamaks

(Some figures may appear in colour only in the online journal)

1. Introduction

Large instabilities can cause a tokamak discharge to rapidly terminate, releasing the stored thermal and magnetic energy in a sequence called a disruption [1]. The high heat flux and mechanical loads transmitted to the vessel during a disruption have the potential to erode the first wall and stress critical mechanical components [2, 3]. In contemporary tokamaks the consequences of a disruption are typically relatively minor, and, when breakage does occur, repairs can be made in a timely manner. However, in ITER [4] and future burning plasma devices the electromagnetic pressure load on the vessel wall will increase by a factor \( \sim 3 \) over present devices, and the time-normalized surface energy loading to the divertor is expected to increase by almost an order of magnitude [5, 6]. These increased loads could result in prompt mechanical failure of the in-vessel components [7] and significantly limit the lifetime of plasma facing components (PFCs) [8]. Given the highly activated nuclear environment of ITER, as well as its sheer size, repair of in-vessel components will be very costly, both in terms of lost time and expense.

The rapid injection of massive quantities of radiating impurities into the plasma can be used to mitigate the most virulent consequences of disruptions. This process converts the thermal and magnetic stored energy of the plasma into electromagnetic radiation in order to distribute the energy as isotropically as possible across the PFCs, minimizing localized thermal and mechanical loads. The most commonly used method for impurity injection is massive gas injection (MGI) [9–13], although various forms of impurity pellets have also been studied [14–17].

Understanding both how the effects of disruptions and the effectiveness of their mitigation will scale from present devices to a burning plasma device (e.g. ITER) will be critical for the design of such a device. Unfortunately, the combination of rapid time scales, highly nonlinear processes,
intense wall interaction, and large-scale impurity transport make comprehensive quantitative numerical predictions of disruption phenomena difficult. While individual aspects of the disruption and mitigation processes have been modelled (references [18–22] for example), these models often require significant assumptions regarding the plasma state during the disruption, making accurate predictions difficult. For example, models of halo current evolution are highly dependent upon the core and halo plasma temperatures that in turn are largely dependent upon poorly understood plasma–wall interactions, thereby requiring critical assumptions about temperature in the model. An empirical database like the IDDB can provide limits on the halo effect to inform engineering limit when the comprehensive model is incomplete. Similarly, no reliable model exists for modelling the assimilation of MGI into a plasma, so questions of scaling to ITER must be answered empirically. An empirical database of disruption parameters is therefore desirable both to complement and enhance the existing modelling efforts, as well as to provide empirical scaling where no viable model exists.

A multi-device disruption database has been developed under the auspices of the International Tokamak Physics Activity (ITPA) [23] magneto-hydrodynamics (MHD) stability topical group. The ITPA Disruption Database (IDDB) aims to illustrate the commonalities in disruption characteristics and mitigation over a wide variety of tokamaks. Contributing devices include the conventional aspect ratio tokamaks (ST's) MAST [32] and NSTX [33]. The work described herein represents an expansion of the effort originally initiated in [34, 35].

In contrast to previous smaller disruption data collation efforts [5, 36], the IDDB aims to provide significant experimental context for each shot provided. This allows exploration of a wide array of parametric relationships between pre-disruption and disruption parameters rather than limiting the investigator to a small number of parameters chosen a priori. Sufficient provenance information is provided for identification and further detailed investigation of particularly interesting data points with the providing institutions.

The IDDB is made available for public access and research. This article presents an introduction to the IDDB and exposition of the available data, but it is not intended, nor able, to serve as an exhaustive reference for all the relationships that can be explored using the IDDB. Continued examination of IDDB data by interested parties is enabled and encouraged. Moreover, the IDDB is in a continuing state of development, and additional variables and data may be added as deemed necessary by the ITPA MHD topical group to better clarify physics. Devices wishing to join the IDDB effort or expand upon previous submissions may do so, as detailed in section 4.

The remainder of this article is structured as follows. The structure and content of the IDDB is discussed in section 2. An initial parametric analysis of the IDDB data is provided in section 3. Details for gaining access to and participating in the IDDB are given in section 4, followed by closing remarks in section 5. A table of acronyms and abbreviations is provided in appendix A for the reader’s convenience.

2. Database description

2.1. Structure of the database

Although it is formally structured as a single MDSPlus [37] database, the IDDB can be split into three conceptual tables: general plasma pre-disruptive and current quench (CQ) characteristics, halo current, and massive impurity injection. The names and descriptions of the fields contained within the tables are listed in tables B.1, B.2, and B.3 in appendix B, respectively. Each record within the database corresponds to a unique shot.

All submitted disruptions (natural or otherwise) must include data for table B.1. Shots with halo current information should include the data in table B.1 and table B.2 (and table B.3, if mitigated). Shots with massive impurity injection must include the data in tables B.1 and B.3. Due to the inevitable variation in diagnostic and analytic capability between devices, it is not possible for all devices to provide data for all fields within a given table. Therefore, only a subset of fields within each table, believed to be commonly available to most devices, are designated as critical and strongly requested in order to submit data to the table. Those fields are highlighted in the tables of appendix B.

The IDDB experimental data is composed almost exclusively of scalar variables, as the decision was made early in IDDB development that the complexity of time-series data across such a large dataset would confuse, rather than clarify, subsequent analysis. Additional explanatory data is included as text fields.

Table B.1 includes provenance information for each shot, equilibrium information describing the pre-disruptive plasma, and characterization of the CQ. The provenance information includes the submitting device’s name, shot number, and miscellaneous comments that allow the data record to be traced back to its source if more complete, time-dependent analysis is desired. The plasma geometric and kinetic data is reported at the time of the last acceptably converging equilibrium reconstruction (TIMEQD) before the onset of the disruption (TIMED). Those times, as well as key times during the CQ, are illustrated in figure 1. Table B.2 describes the halo current resulting from a disruption, including both descriptions of the halo current itself as well as plasma parameters at the time of maximum halo current. The halo current time fields are also illustrated in figure 1. Table B.3 describes massive impurity injection for disruption mitigation. One part of the table describes the inputs to the mitigation, including a specification of the hardware involved, the type and amount of impurity used, and the trigger timing. The second part of the table describes the outputs of the mitigation, including details of the radiated power and particle assimilation.

2.2. Overview of contributing devices

The numerous devices contributing to the IDDB provide a wide variety of operating parameters. Table 1 displays the ranges of select plasma parameters submitted by each device to the IDDB to illustrate this variety.

With the exception of Aditya, which is purely a circular limited configuration, all of the devices can operate in a diverted configuration, although some of the submitted data
Figure 1. Illustration of key times within description of pre-disruptive plasma, CQ, and halo current evolution.

Table 1. Parameter range of IDDB data, sorted by device.

| Device         | R (m)        | Aκ | I_p (MA) |
|----------------|--------------|-----|----------|
| Aditya         | 0.72–0.84    | 3.1–5.0 Circular | 0.05–0.09 |
| Alcator        | 0.54–0.70    | 2.9–5.5 | 1.0–2.0 | 0.22–2.02 |
| C-Mod          | 1.50–1.69    | 3.1–4.2 | 1.2–2.0 | 0.60–1.16 |
| DIII-D         | 1.28–3.09    | 2.6–5.7 | 0.8–2.3 | 0.13–2.39 |
| JET            | 2.86–3.14    | 2.9–4.1 | 1.1–2.2 | 1.00–4.06 |
| JT-60U         | 3.08–3.33    | 3.5–3.9 | 1.4–1.9 | 0.67–1.41 |
| MAST           | 0.70–0.91    | 1.5–2.0 | 1.4–2.0 | 0.41–1.06 |
| NSTX           | 0.38–0.99    | 3.6–4.1 | 1.2–2.4 | 0.86–0.89 |
| TCV            | 0.86–0.89    | 3.6–4.1 | 1.2–2.4 | 0.08-0.61 |

*Headings in brackets represent IDDB variable names corresponding to the given column.

may be from limited plasmas. Excepting Aditya, all devices utilize a Grad–Shafranov equilibrium reconstruction code (e.g. EFIT) [38] to provide the IDDB plasma equilibrium parameters.

A majority of the contributing devices have provided halo current data to the IDDB. Comparing each halo current monitoring system is beyond the scope of this paper. However, salient references describing the halo current monitoring systems and providing in-depth device-specific analysis of the halo current data are listed in table 2. Similarly, the injectors used for disruption mitigation by massive impurity injection and the diagnostics and methods used to analyse the results differ from device to device. A listing of references for device-specific massive impurity injection data is also provided in table 2.

Table 2. References for device-specific halo current and massive impurity injection data.

| Device               | Halo reference | Massive impurity reference |
|----------------------|----------------|---------------------------|
| Alcator C-Mod        | [39]           | [9, 40–42]                |
| ASDEX-Upgrade        | [43, 44]       | [12, 43, 45]              |
| DIII-D               | [15, 46]       | [9, 16, 17, 47, 48]       |
| JET                  | [3, 49, 50]    | [51, 52]                  |
| JT-60U               | [53]           | [54]                      |
| MAST                 | [55]           | [13, 56]                  |
| NSTX                 | [57–59]        |                           |

It should be noted that responsibility for ensuring the veracity of the contributed IDDB data lies with each of the contributing devices. The maintainers of the IDDB do not have the capability to validate the contributed data themselves, given the large variety of devices, discharges, and diagnostic configurations involved. However, the maintainers do make an effort to screen for clear outliers and inconsistent physics data and to resolve those issues on a case-by-case basis with the contributing party.

2.3. Distribution of contributed data

The IDDB data population is not evenly distributed across topical categories or devices. Not all devices are capable of contributing to all sections of the IDDB due to diagnostic constraints. In addition, when data is available, the criteria utilized by each device to determine the number of shots that it provides to the IDDB varies greatly. This disparity in populations is illustrated figure 2.
As can be seen in figure 2(a) displaying the categorical distribution, the number of shots including halo current data (table B.2) is over five times the number including massive impurity injection data (table B.3), but both of those are only a minority of the total number of shots (including at least the basic data of table B.1). This categorical disparity is a result of several factors. First, not all devices have the diagnostic capability or impurity injectors to provide halo current and/or impurity injection data. Second, while the basic disruption characterization and halo current measurements can largely be accomplished in the background, thereby providing data from almost every discharge, massive impurity injection is typically only utilized on dedicated run days, and as such represents a very small minority of a device’s total discharges. Finally, the population disparity reflects the varying level of analysis required for each category. Collecting the basic plasma equilibrium and CQ data for table B.1 is fairly straightforward and amenable to automation given that the necessary diagnostics and methods are critical to basic device operation and thus are almost always available and archived. Likewise, the halo current data, if available, is readily extracted via simple automated processes. In contrast, the massive impurity injection data (particularly regarding radiated power and time-dependent particle injection) require more intense analysis for each shot, resulting in a much lower rate of submission to the IDDB.

Figure 2(b) displays the relative contribution of each device to the total number of shots within each category. It is clear from this plot that the IDDB data is skewed towards a minority of devices. Alcator C-Mod, DIII-D, and JET dominate the total shot population (i.e. those discharges including data for at least table B.1). The halo current distribution is more evenly distributed, although JET is the dominant contributor by almost a factor of two. The impurity injection data is largely dominated by Alcator C-Mod and DIII-D contributions. However, as the Alcator C-Mod data does not include radiated power or time-dependent particle injection components, the DIII-D contribution is by far the largest in the analysis presented in section 3.3. Whenever possible in the analysis of section 3, the data is separated by device in order to provide a visual indication of any disparities in population density that may be present.

The overlap of the IDDB data with ITER’s nominal operating points also varies significantly. This is illustrated in figure 3, which displays the relative distribution of (a) aspect ratio, (b) $\beta_N$, and (c) $l_i$ in the IDDB versus the nominal ITER operating ranges given in [4]. The illustrated ITER operating ranges include the expected values during flattop operation in the ITER inductive, hybrid, and steady-state scenarios [4]. These ranges would expand if the dynamic ramp-up and ramp-down phases of each scenario were included. As seen in figure 3(a), the IDDB aspect ratio distribution peaks almost exactly at the ITER value of $A = 5.1$. In contrast, it is evident from the $\beta_N$ distribution in figure 3(b) that the IDDB contains dominantly low $\beta_N$ plasmas compared to the ITER operating range ($\beta_N \approx 1.8-2.7$), peaking at less than a third of the ITER range. The distribution of $l_i$ shown in figure 3(c) represents a middle ground, showing significant overlap with the ITER operating range but skewed towards more peaked current profiles than expected for ITER. These examples illustrate that...
the strength of the IDDB data is not in matching the ITER parameters, but rather for elucidating the physical models that will allow extrapolation to the ITER operating range.

3. Database analysis

The following section presents select analyses of data available within the IDDB. It is not intended to represent an exhaustive discussion of IDDB data, but rather to illustrate the utility of the IDDB by presenting parametric relationships that have been of historic interest for characterizing tokamak disruptions and those relevant to the design of the ITER disruption mitigation system. Parameter names listed in CAPITAL letters refer to IDDB fields, which can be referenced in the tables of appendix B.

3.1. Toroidal CQ rate

The rapid loss of toroidal current during the CQ can induce significant eddy currents that can threaten the mechanical integrity of in-vessel components. It is necessary to place a lower bound on the expected CQ time ($\Delta t_{cq}$) in ITER to robustly design in-vessel components. The CQ rate is typically normalized by the plasma cross-sectional area ($S$, or AREAD in the IDDB) in order to better compare the CQ rates of disparate devices ($\Delta t_{cqS}$), as detailed in [36]. In [5], a database of non-circular conventional aspect ratio tokamaks estimated a lower bound for the linear area-normalized CQ time of 1.8 ms m$^{-2}$. However, the portion of the CQ in [5] used to derive the linear CQ rate differed from device to device. This limit was further refined and reduced in [34, 35] to 1.67 ms m$^{-2}$, using a consistent linear CQ extrapolated time $\Delta t_{80−20} = t_{20} − t_{80}/0.6$, where $t_{80}$ and $t_{20}$ (TIME8 and TIME2) are the times where the toroidal current reaches 80% and 20% of its pre-disruptive value (IPD), respectively (figure 1). This limit corresponds to a $\Delta t_{80−20} = 36$ ms in ITER. ITER simulations with a prescribed linear CQ of that duration, as well as an equivalent exponential CQ ($t_{cq} = 16$ ms), are the design basis for the ITER blanket module and vacuum vessel against the induced electromagnetic forces [7]. $\Delta t_{cq} = 1.67$ ms m$^{-2}$ will be referred to as the ‘ITER minimum’ in the discussion below.

The present IDDB CQ data, shown in figure 4, largely confirms the analysis of [34, 35], and as such does not introduce new limitations into the ITER design. The linear CQ time is calculated uniformly for all devices as $\Delta t_{cqS} = \Delta t_{80−20}/S$, as in [34, 35]. Plotted versus toroidal current density ($j_p$) in figure 4(a), the minimum $\Delta t_{cqS}$ fall under 0.6 ms m$^{-2}$, far below the ITER minimum (indicated by the horizontal dashed line). However, the low-A devices (MAST and NSTX) exhibit a distinctly shorter $\Delta t_{cqS}$ distribution than the conventional A devices, which is made clearer by plotting $\Delta t_{cqS}$ versus aspect ratio, as in figure 4(b). It was noted in [35, 36] that the low-A and conventional distributions can be better equalized by an additional normalization of the area-normalized CQ time by the plasma self-inductance, $L^* = \ln (8R/a) − 1.75$, yielding the normalized time $\Delta t_{cqSL} = \Delta t_{80−20}/(SL^*)$. As shown in figure 4(c), this additional normalization significantly increases the overlap of the two populations, resulting in an almost identical lower bound to $\Delta t_{cqSL}$ formed by the low-A and conventional-A devices. However, that lower bound falls below the specified ITER minimum $\Delta t_{cqSL}$.

Figure 4. (a) Area normalized CQ duration versus toroidal current density ($j_p$), separated by device. (b) Area normalized CQ duration versus aspect ratio. Red arrow and dotted lines indicates difference between low-A and conventional-A distributions. (c) Additional normalization by the dimensionless self-inductance $L^*$ versus aspect ratio. (d) Magnification of area below ITER limit for area and $L^*$ normalized CQ duration versus $j_p$. The ITER flattop range of $j_p$ is indicated by the vertical red lines. The black dashed line indicates the ITER minimum. The dotted blue line is an extrapolation to the ITER limit at the maximum ITER $j_p$.
Using this metric, the fraction of discharges with indicated by the vertical dashed line. The minimum allowable value for ITER is IDDB for ITER remains 1.67 ms/m² using either the early to between 1–2% when the linear CQ time is calculated /Δt. By this analysis, the lowest expected 'unsafe' zone, but that data is not used to set limits for the conventional-A ITER.

As noted in [61] ΔtCQ can change significantly depending upon which portion of the CQ is used as the reference. Figure 5 displays the cumulative fraction of shots with ΔtCQ below a given value. The fraction of CQs falling below the minimum allowable duration increases to between 1–2% when the linear CQ time is calculated using either the early [ΔtCQ = (t80−50)/0.3] or late [ΔtCQ = (t80−20)/0.3] portion of the CQ. This indicates that a portion of the CQs exhibit a strong exponential behaviour (fast early decay) or a slow early decay followed by a faster late decay. In [52], Δt100−70 is utilized to minimize any effect from runaway electron formation during the CQ. The IDDB does not include t100, but a close approximation of it, ΔtCQ = (t80−t60)/0.2, is also shown in figure 5. Using this metric, the fraction of discharges with ΔtCQ shorter than the ITER minimum rises to nearly 5%. Given the analysis of [7], wherein the linear and exponential waveforms produced similar electromechanical results in the ITER vessel and blanket modules, it is not expected that these short timescale differences will matter significantly for the large ITER components with long time constants. However, as noted in [7], the design of smaller in-vessel components (e.g. antennas) with shorter time constants may be affected.

Figure 5 also reveals slightly skewed distributions for vertical displacement event (VDE) and massive impurity injection discharges. When only discharges positively identified as VDEs are considered within the conventional aspect ratio subset, the fractional occurrence of Δt80−20/S shorter than the ITER minimum increases by a factor of ~3, to slightly below 1%. However, this is likely reflecting the smaller population of identified VDE discharges in the IDDB versus the general population rather than true physical causes. The disruptions resulting from massive impurity injection (typically MGI) within the database do not represent the fastest CQs. The distribution of ΔtCQ for MGI discharges exhibits a more compact distribution than the non-MGI cases, with the longest Δt80−20/S < 10ms/m² and the shortest still exceeding the ITER minimum. That the ‘natural’ disruptions exhibit a lower minimum in ΔtCQ compared to the MGI cases is likely due to the fact that the fastest IDDB CQs occur in DIII-D, which has entirely carbon PFCs that are known to emit significant amounts of carbon impurity into the plasma during the thermal quench (TQ) [47]. The distribution for natural disruptions skews significantly towards longer ΔtCQ for beryllium first wall and tungsten divertor devices, as has recently been reported for the ITER-like wall in JET [51] (data not presently available in IDDB), and is expected to do so in ITER as well.

3.2. Halo current

Similar to the eddy currents induced during the CQ, the induction of open field line poloidal ‘halo’ currents during a VDE can expose in-vessel components to potentially damaging J × B forces [46]. The ratio of the maximum axisymmetric halo current (Ih, max, HMAX in the IDDB) to the pre-disruption plasma current (Ip0) is termed the halo fraction, \( F = \frac{I_{h, \text{max}}}{I_{p0}} \). The halo current also often exhibits a non-axisymmetric structure, which is captured in the toroidal peaking factor (TPF) [39]. The TPF is recorded at the time of maximum halo current in the IDDB (TPFATMAX), as illustrated in figure 1. The product \( F \times \text{TPF} \) gives a measure of the maximum local poloidal halo current density within the vessel as a function of the pre-disruptive Ip0.

The measurements of Ih and TPF are dependent upon both the toroidal resolution of the halo current sensors in a given device and the structure of the halo current asymmetry. For a system of N toroidally distributed poloidal halo current monitors each measuring a poloidal halo current density \( j_{\text{h},n} \) (A/(rad)), the IDDB standard definitions of the axisymmetric halo current Ih and TPF are

\[
I_h = 2\pi \sum_{n=1}^{N} j_{\text{h},n},
\]

and

\[
\text{TPF} = \max \left( \frac{j_{\text{h},n}}{I_h/2\pi} \right),
\]

where the maximum function represents the largest poloidal halo current density measured at a discrete toroidal location. The accuracy of these definitions depends upon toroidal mode structure of the halo current asymmetry and the ability of the halo current sensors to resolve it. Equation (1) is accurate as long as the spatial resolution of the halo current sensors is sufficient to avoid aliasing the actual halo current mode structure (i.e. an \( n = 1 \) mode structure requires two sensors separated by 180° toroidally). If, as observed in [59], the asymmetry resembles a toroidally localized ‘lobe’ rather than an \( n = 1 \) mode, a high toroidal resolution is required to avoid aliasing. The measurement of the TPF (equation (2)) depends upon both the same aliasing constraint as Ih as well as the phase of the halo asymmetry. For example, even if two sensors
This IDDB distribution is almost certainly an overestimate only ∼ the cumulative fraction of events exceeding I (dashed circle) occurred late in a T p and B T rampdown, inflating the halo fraction calculation and for that reason were not included in establishing the F · TPF limit. In addition, there are two JET discharges at f > 0.58 (solid circle in figure 6), exceeding the previous limit of f < 0.52 in [5, 6, 36]. This new bound may have important engineering implications for ITER, as the maximum F is a critical design point in determining operational limits. Upon closer examination, both of these points were found to be measured by only a single toroidally localized halo current sensor. As noted above, a single sensor would alias any toroidal asymmetry, convoluting F and TPF. Thus, it is possible that the extreme halo fraction presented by the two points is the result of such aliasing and does not represent a new halo fraction limit for ITER. Further analysis of the discharges in question is required to make that determination.

The population of discharges reaching a given F · TPF value in the IDDB falls off rapidly as F · TPF increases. Figure 7 displays the cumulative fraction of discharges within the database exceeding a given value of F · TPF. Globally, the cumulative fraction of events exceeding F · TPF = 0.6 is only ~1%, and exceeding F · TPF = 0.7 is less than 0.2%. This IDDB distribution is almost certainly an overestimate of the actual unfiltered distribution (i.e. skewed toward higher F · TPF), as typically IDDB participants established a minimum threshold for halo current when choosing halo current measurements to submit, significantly skewing the database towards higher halo current fractions. For ITER, the actual probability of extreme events will likely be much lower.

It should be noted that the IDDB low-A F · TPF distribution does not include many of the extreme points reported for MAST in [55]. This is due to a change in the MAST halo current analysis to avoid unwarranted distortions in F · TPF. The MAST halo current monitor system includes detectors at various poloidal locations. In [55], the largest single halo fraction measured at any of those poloidal locations was multiplied by the TPF at all the locations, even though the locations with largest F may have recorded low TPF. This led to a skewing of the data towards large F · TPF. In the present MAST IDDB data, F · TPF is derived only from the measurement with the largest halo fraction, avoiding such distortion.

It was noted in [49] that the maximum F · TPF in JET decreases with an increasing value of the pre-disruptive edge safety factor, q95. A cross-device comparison shown in figure 8 indicates that this is a global trend, with all devices exhibiting a downward trend in the maximum observed F · TPF as the pre-disruptive q95 increases. This is consistent with the axisymmetric halo current model presented in [18], which states that the poloidal halo current is strongly dependent upon the edge safety factor, with lower safety factors producing a larger fraction of poloidal halo current. This is a positive result for ITER, as it indicates that the maximum expected halo current in the lower I p ITER operating scenarios (hybrid, steady-state), as well as during the ramp-up and ramp-down periods of every shot, will not simply be reduced linearly in I p, relative to the 15 MA ITER baseline flattop (i.e. F · I p falls linearly with I p, for constant F), but also benefit from a reduction in F itself due to increased q95.

In contrast, the observation in [49] that JET F · TPF decreases with increasing current decay rate does not appear
Figure 8. $F \cdot \text{TPF}$ versus $q_{95}$, separated by device.

Figure 9. $F \cdot \text{TPF}$ versus current decay rate, separated by device. The current decay rate is given by $1/\Delta t_{fo-20}$. The two distinct groups of MAST data correspond to lower single-null (faster decay group) and double null and upper single-null (slower decay group) plasma shapes.

Figure 10. Comparison of $F$ versus $W_{th}/W_{th,max}$, organized by device. $W_{th,max}$ is the maximum $W_{th}$ reported by each device for the halo current data plotted.

To be well supported within the IDDB. As shown in figure 9, JET $F \cdot \text{TPF}$ maximum exhibits a non-monotonic behaviour, peaking around 50 s$^{-1}$ and falling off to either side. The differing interpretation of the JET data in [49] and the IDDB JET data is likely due to the fact that the IDDB possesses many more data points than [49]. The higher data resolution in the IDDB makes it clear that the inverse relationship interpreted from the data in [53] was a figment of the relatively small number of samples available. NSTX exhibits a monotonic increase in the maximum $F \cdot \text{TPF}$ as the current decay rate increases. MAST maintains fairly consistent values over a wide range of decay rate, and the other devices fail to exhibit any identifiable structure. A significant hidden variable may be the variation in the vertical displacement growth rate of the plasmas, which is not recorded in the IDDB, as $F$ is strongly determined by the ratio of the current decay rate to the vertical displacement growth rate [18].

A reduction in halo fraction as the thermal energy ($W_{th}$) of the pre-disruptive plasma increases, observed in NSTX [57] and JT-60U [53], is not globally supported by IDDB data. This effect is attributed to an increase in impurity density due to increased conducted heat flux to the divertor, which in turn cools the halo region, makes it more resistive, and reduces the total halo current [49, 53]. However, as shown in figure 10, this is not a consistent trend across devices. Although NSTX does exhibit a reduction in the maximum $F$ as $W_{th}$ increases (JT-60U $W_{th}$ is not available for the halo current measurements presently available in the IDDB), the trend is not consistent in other devices.

There are several factors that may be contributing to this discrepancy. The first is the material of the PFC, in particular the divertor. For example, DIII-D and NSTX are both all-carbon devices and exhibit a general, if weak (in the case of DIII-D), reduction in $F$ as $W_{th}$ increases. In contrast, Alcator C-Mod (molybdenum) and ASDEX-Upgrade (tungsten) exhibit no noticeable trend. This may indicate a much higher heat flux threshold for the high-Z metal wall material to pollute and cool the halo region as compared to carbon, making $W_{th}$ unimportant for determining the halo fraction until that threshold might be reached. However, the carbon-wall data from MAST and JET (all JET data presently in IDDB pre-dates the JET ITER-like wall upgrade) [62] also fail to follow the NSTX trend, indicating that other factors in addition to wall material also play a role. The second factor that should play a role is the distribution of the heat flux during a VDE, which is a function of the plasma and device...
geometry. This may explain the different trends between the two STs, as NSTX has a simple open divertor [57], whereas MAST possesses a more intricate internal structure that provides multiple points of contact (of varying material) for the plasma boundary during a VDE [55]. With its beryllium wall and tungsten divertor, ITER is likely to behave more akin to the present metal wall devices (little relationship between $F$ and $W_{th}$) than NSTX, and should not expect the benefit of decreasing $F$ as $W_{th}$ increases.

### 3.3. Massive impurity injection

#### 3.3.1. Cooling time

The cooling time, $\Delta t_{cool}$, between the arrival of injected impurities at the plasma edge and the onset of the CQ has implications for both the response time of the ITER disruption mitigation system (DMS) as well as the assimilation fraction of the injected impurities [52]. For the present discussion, $\Delta t_{cool} = \text{TIMESPK-TIMPARRIV}$, using the current spike as a functional indicator of the end of the TQ phase. The arrival time of the impurities at the plasma boundary, TIMPARRIV, is measured slightly differently in each device, but is typically derived from the rapid rise in appropriately placed filterscopes or fast bolometer channels.

The relationship between $\Delta t_{cool}$ and the number of atoms injected prior to the current spike ($N_{inj-spk}$, which is NPARTSPK multiplied by the number of atoms per molecule) is subject to significant uncertainty, but that can be reduced at ITER-relevant quantities by focusing upon neon injection. Numerous devices have observed that the TQ is initiated by the arrival of the impurity cooling front reaching the $q = 2$ surface [45, 48, 56, 63]. In addition, it was shown in [36] that the TQ duration scales linearly with the plasma minor radius ($a$). Both of these findings suggest that the plasma minor radius should be used to normalize an inter-device comparison of $\Delta t_{cool}$. In addition, it was shown in [64] that $\Delta t_{cool}$ increases steadily with increasing $q_{95}$, which was attributed to the increasing distance of the $q = 2$ surface from the plasma edge as $q_{95}$ increased. Thus normalization by $q_{95}$ is also warranted. In figure 11, $\Delta t_{cool}$, normalized by both the plasma minor radius ($a$MIND) and $q_{95}$ (Q95D), $\Delta t_{cool}$, is plotted versus $N_{inj-spk}$, separated by device (figure 11(a)) and impurity species (figure 11(b)). $N_{inj-spk}$ is normalized to the vessel volume ($V_{vessel}$) to provide comparison between disparate devices. The maximum possible ITER normalized injection quantity, corresponding to 8 kPa m$^{-3}$ impurity gas all injected prior to the current spike, is indicated by the vertical dashed line.

Figure 11 displays a consistent weak decrease in the minimum $\Delta t_{cool}$ over a wide range of $N_{inj-spk}$ (as reported in [52]). However, the scatter in $\Delta t_{cool}$ is roughly an order of magnitude at any given injection value, including the ITER maximum. The floor of the distribution is dominated by the pure high-Z impurities (Ar, Ne) as well as He mixed with high-Z impurities. He mixtures, typically a large majority He with a minority of high-Z atoms (ratio specified by SPECIESRAT), are utilized to entrain the slow sound-speed high-Z impurities within the much faster flow of the He atoms, enabling significantly faster delivery of the high-Z radiators [42]. In figure 11(b), it is evident that these mixtures, even with a minority of high-Z radiators as low as 10%, can result in $\Delta t_{cool}$ matching even the pure high-Z radiators.

![Figure 11](image-url)

**Figure 11.** Normalized cooling time versus impurity atoms injected before the current spike, separated by device ($a$) and impurity species ($b$). Vertical dashed black line indicates maximum ITER injection capability, assuming all particles enter plasma before the current spike. The red dotted line indicates the empirical upper limit for neon injection.

The spread in $\Delta t_{cool}$ is significantly reduced if the analysis is restricted to only neon, a likely candidate for the ITER radiating species. As indicated by the red dotted line in figure 11(b), a reasonable ceiling on $\Delta t_{cool}$ can be established, indicating $\Delta t_{cool} < 1.22 \text{ ms m}^{-1}$ at the maximum ITER injection capability and increasing steadily below that level of impurity injection. Taking the ITER inductive baseline scenario $q_{95} = 3.1$ and $a = 2.2 \text{ m}$, this corresponds to a maximum $\Delta t_{cool} < 8.3$ for the maximum possible ITER neon injection.

A lower bound for the expected ITER $\Delta t_{cool}$ can be established by comparing $\Delta t_{cool}$ to $W_{th}$. It is reasonable to expect that, all else being constant, increasing $W_{th}$ would require increasing $\Delta t_{cool}$ to cool the plasma enough to induce the violent resistive MHD that brings on the TQ. However, [52] indicates that this trend is saturated for large injection.
quantities. A comparison of $\Delta \text{cool}_W$ to $W_{th}/N_{inj-spk}$ (a measure of the plasma thermal energy available to each impurity atom) across devices provides a broader view (figure 12). The minimum ITER $W_{th}/N_{inj-spk}$ corresponding to nominal baseline scenario flattop operation ($W_{th} = 350 MJ$, 8 kPa m$^3$ injected prior to current spike) is indicated by the dashed vertical line. While there is significant scatter in $\Delta \text{cool}_W$, a clear lower bound appears at a given $W_{th}/N_{inj-spk}$, indicated by the dotted red line in figure 12(b). That lower bound increases monotonically with $W_{th}$ (or decreasing $N_{inj-spk}$). It is set by the pure high-Z radiators (Ne and Ar) and high-Z mixtures (figure 12(b)), as is expected. This lower bound appears to asymptote at very low values of $W_{th}/N_{inj-spk}$ (<0.1 keV per atom), but those are over an order of magnitude below the ITER minimum. At the ITER minimum, the bound is $\Delta \text{cool}_W > 1 \text{ ms m}^{-1}$, and the bound increases slowly as $N_{inj-spk}$ decreases. Assuming the same ITER equilibrium values as above, this corresponds to a minimum $\Delta \text{cool}_W > 6.8 \text{ ms}$ at the maximum possible ITER neon injection capability.

The large degree of scatter in figures 11 and 12 likely comes from two sources. First, it is indicative of numerous hidden variables that obscure the simple two-parameter relationship. A primary purpose of the IDDB is to clearly identify these points of ambiguity (which may not be obvious from controlled, single machine experiments) and provide the necessary context to gradually extract more complete and general multi-variable relationships. This strongly motivates further multi-variable regression analysis of the IDDB data to reveal further significant variables. A second source of the scatter may be the calculation of $N_{inj-spk}$ itself. $N_{inj-spk}$ is subject to significant uncertainty, as no device has a direct measurement of this quantity. Each device utilizes its own methods for estimating the time-dependent flow rate of its MGI valves (annotated in MNPARTSPK). Typically, analytic models of varying complexity are utilized, such as described in [65] for DII-D valves, [66] for the MAST and JET valve design, and [12] for AUG. JT-6U uses a fast vessel pressure measurement. The combination of the indirect nature of the methods to obtain $N_{inj-spk}$, as well as the variety of methods used between devices, may contribute to the observed data spread in figures 11 and 12 and any other parametric comparison involving $N_{inj-spk}$.

3.3.2. Fuelling efficiency. The effectiveness of an impurity injector is largely a function of its ability to get impurity particles across the plasma boundary, both to act as radiators of the plasma thermal and magnetic energy and to provide high electron density for runaway electron suppression. The ability to transport impurity ions into the core is measured by the fuelling efficiency, here defined as $f_{inj} = N_e/N_{inj}$ = (DENSSPKS5-DENS) VOLD/Ninj, where $N_e$ is the total number of free electrons in the CQ plasma averaged between the current spike and the 50% current level. This definition of $f_{inj}$ measures the efficiency creating free electrons during a disruption, and is equivalent to $F_{el}$ from [45], also used in [13], which is readily measured by multiple devices. This is in contrast to the fuelling efficiency $Y_{mix}$ defined in [47], which utilizes estimates of the average impurity charge state during the CQ to calculate the impurity ion population in the plasma, and therefore directly measures the ion assimilation. However, this second technique requires complex spectroscopic techniques to resolve the ion charge state, and hence is not included within the IDDB at this time. Figure 13 displays $f_{inj}$ as a function of $W_{th}$ per the total number of injected impurity atoms ($N_{inj}$). Consistent with the results in [47], the overall trend shows increasing maximum $f_{inj}$ as $W_{th}/N_{inj}$ increases, which appears consistent across impurity species (although there are a small number of outlier points using He, which possesses the fastest sound speed of all the impurities). This is likely due to a convolution of the increased ionization capacity of the plasma (more energy per atom available to convert neutrals into ions) and the trend of increasing $\Delta \text{cool}_W$ with increasing $W_{th}$ per atom shown in figure 12, which allows more time for impurity atoms to enter the plasma boundary before the TQ cools the plasma and limits further ionization. At the ITER minimum $W_{th}/N_{inj}$ (indicated by the vertical dashed line in figure 13), the expected maximum

![Figure 12. Normalized cooling time versus $W_{th}$ per impurity atom injected before the current spike, separated by device (a), and impurity species (b). The vertical dashed black line indicates minimum value for ITER flattop operation. The red dotted line indicates empirical lower limit for neon injection.](image-url)
3.3.3. Radiated energy fraction  One of the primary purposes of disruption mitigation by massive impurity injection is to isotropically radiate the stored thermal energy of a disrupting plasma before the TQ occurs and conducts the thermal energy to highly localized portions of the vessel wall. The effectiveness of this radiation process can be measured by the thermal energy radiation fraction, \( f_{th} = \frac{W_{rad - spk}}{W_{th}} \), where \( W_{rad - spk} \) (WRAD_SPK) is the energy radiated between the time of impurity arrival at the plasma edge (TIMPARRIV) and the time of the current spike (TIMESPK), and \( W_{th} \) is the plasma stored thermal energy (WTOTD). This definition assumes that minimal plasma magnetic energy is dissipated by the rapid radiation process before the CQ. Figure 14 shows that \( f_{th} = 1 \) is attainable at all thermal energy densities presented, although the wide distribution of \( f_{th} \) indicates that such high radiation fraction is by no means guaranteed. The only noticeable trend in figure 14 is an increasing population of \( f_{th} \) much greater than unity at low thermal energy densities. This due to the fact that at low \( W_{th} \) the assumptions in the definition of \( f_{th} \) break down, and the magnetic energy radiated prior to the CQ becomes a significant contributor to \( W_{rad - spk} \), as noted in [52]. The consistent existence of \( f_{th} = 1 \) cases over the full range of thermal energy density in figure 14 indicates that \( f_{th} = 1 \) may be accessible to ITER for high-Z (Ne or Ar) injection. This assumes that the trends in figure 14 remain flat when extrapolating from the thermal energy densities of the available dataset (<80 kJ m\(^{-3}\)) to the ITER baseline flattop value (~420 kJ m\(^{-3}\)).

4. Access to IDDB

Public access and up-to-date information on the IDDB is available through the IDDB web site [67]. The working database is contained in a restricted access MDSPlus database maintained by General Atomics. Parties wishing to contribute additional data to the IDDB should [67] for data submission.
instructions. The version of the database that is described in this paper is publicly available subject to ITPA database access guidelines. Instructions for obtaining access to the public version of the IDDB can be found at [67]. Any usage of the data contained within the public database should provide this article as reference, per ITPA database guidelines.

5. Conclusions

The ITPA MHD topical group has developed a multi-device disruption database characterizing tokamak disruptions and their mitigation. The IDDB provides a large number of parameters describing the pre-disruptive plasma, CQ, halo current, and mitigation by massive impurity injection. This context allows a wide variety of parametric relationships to be tested across the highly varied selection of participating devices, including both conventional and low aspect ratio tokamaks. The IDDB can be used to assess the generality of single-device results, re-assess previous multi-device parametric studies, and look for new relationships to provide scalings extrapolating to ITER and other large tokamaks.

Initial analysis of the present IDDB CQ data indicates that the previously accepted lower limit for area-normalized linear CQ in conventional aspect ratio devices of 1.67 ms m⁻² is still valid. The IDDB halo current data suggests an increase of the upper limit for halo current \( F \cdot TPF \) from 0.7 to 0.75. In addition, the upper boundary in halo fraction has increased from \( \sim 0.52 \) to 0.58, but further analysis is required to determine whether a change in the ITER boundary is warranted given the ambiguities associated with the new measurements. Measurements of the cooling time during massive impurity injection provide rough bounds to the minimum and maximum expected cooling times in ITER, providing a window of \( \sim 6-9 \) ms assuming 100% assimilation of injected neon particles prior to the CQ. Fuelling efficiency data indicates that the actual ITER assimilation will be \( < 50\% \), which would slide the cooling time window towards longer durations. Large scatter in the data motivates further multi-variable analysis to refine the results.

The IDDB is in a continuing state of development. A public ‘frozen’ version of the IDDB is made available, allowing for continued analysis of the available data beyond that presented in section 3. Future planned additions to the database that would significantly expand the analysis of existing data include measurements of the growth rate of the vertical displacement during VDEs and measurements of the TQ onset time. Additional expansion of the IDDB scope to include measurements of uncertainty in the submitted quantities (allowing for more robust extrapolation of results), as well as to include runaway electron dissipation, would also prove valuable. Moreover, the definition of the disruption time (TIMED) must be expanded to account for the ambiguous, extended disruption events that are sometimes observed on the all-metal JET ITER-like wall and recent AUG data, which are not included in the present version of the IDDB. Devices wishing to contribute additional data to the IDDB should refer to [67].

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Appendix A. Acronyms and abbreviations

| Description | \( A \) | \( CQ \) | \( F \) | \( f_{\text{inj}} \) | \( f_{\text{th}} \) | \( \text{IDDB} \) | \( h \) | \( h_{\text{max}} \) | \( i_{\text{pre}} \) | \( I_{\text{TPA}} \) | \( j_{\text{halo}} \) | \( j_{\text{p}} \) | \( L_{\text{s}} \) | \( \text{MGI} \) | \( \text{MHD} \) | \( N_{\text{inj-pak}} \) | \( \text{PFCs} \) | \( S \) | \( \text{ST} \) | \( \text{TPF} \) | \( \text{TQ} \) | \( \text{VDE} \) | \( V_{\text{vessel}} \) | \( W_{\text{rad-pak}} \) | \( W_{\text{th}} \) | \( \Delta t_{\text{cool}} \) | \( \Delta t_{\text{cool+t}} \) | \( \Delta t_{\text{cq}} \) | \( \Delta t_{\text{cq}}^{*} \) | \( \Delta t_{\text{cq}} \| \) | \( \Delta t_{\text{X} - \text{Y}} \) | \( \tau_{\text{cq}} \) |
|-------------|--------|--------|------|--------------|---------|-------------|-------|---------|--------|-------------|---------|----------|--------|----------|--------|----------|--------|-------------|---------|----------|--------|----------|--------|----------|--------|----------|
| Aspect ratio | Current quench | Halo fraction | Impurity fuelling efficiency | Thermal energy radiation fraction | ITPA Disruption Database | Halo current | Maximum halo current | Pre-disruptive plasma current | International Tokamak Physics Activity | Poloidal halo current density | Toroidal current density | Plasma self inductance | Massive gas injection | Magneto-hydrodynamic | Number of atoms injected prior to CQ | Plasma facing components | Plasma cross-sectional area | Spherical tokamak | Toroidal peaking factor | Thermal quench | Vertical displacement event | Vacuum vessel volume | Energy radiated prior to current spike | Plasma thermal energy | Cooling time | Cooling time normalized by plasma minor radius & \( q_{\text{ps}} \) | CQ duration | CQ duration normalized by \( S \) | CQ duration, normalized by \( S \) & \( L_{\text{s}} \) | \( X-Y \% \) linear CQ duration extrapolation | Exponential CQ duration |
## Appendix B. Tables of IDDB variables

**Table B.1.** Base IDDB variables (* = Required).

| Name       | Unit | Data type  | Description                                                                 |
|------------|------|------------|-----------------------------------------------------------------------------|
| *AMIND     | m    | Float      | Minor radius                                                                |
| *AREAD     | m²   | Float      | Poloidal cross-sectional area                                               |
| BEMPMD,D   |      | Float      | Poloidal $\beta$ at TIMED                                                   |
| BETAND     | %-m-T/MA | Float     | Normalized toroidal $\beta$ at TIMED                                        |
| BETANMAX   | %-m-T/MA | Float     | Maximum $\beta_N$ measured at TIME                                          |
| BETMHD,D   | %    | Float      | Toroidal $\beta$ at TIMED                                                   |
| BOUNDRD    | m    | Float      | Radial dimensions of plasma boundary at TIMED                               |
| BOUNDZD    | m    | Float      | Vertical dimensions of plasma boundary at TIMED                              |
| BFOLD      | T    | Float      | Average poloidal field around plasma cross-sectional surface at TIMED       |
| BTD        | T    | Float      | Vacuum toroidal field at RGEOD at TIMED                                      |
| CAUSED     |      | String     | Proximate cause of disruption (Internal, External)                          |
| CHISQD     |      | Float      | $\chi^2$ equilibrium fitting parameter                                       |
| CONFIGD    |      | String     | Plasma shape configuration: LIM, LSN, USN, DN, etc                           |
| DATE       |      | Integer    | Data of discharge. Format = yyyyymmdd                                        |
| DATAPROBLEM|      | Integer    | Flag indicating problems with part of data. Data should only be used with caution. 0 or empty = OK; >0=Problem, details noted in COMMENT |
| DATAIGNORE |      | Integer    | Flag indicating if data record is erroneous and should be ignored. 0 or empty = OK; >0= Ignore data, details noted in COMMENT |
| DELTALD    |      | Float      | Lower triangularity at TIMED                                                |
| DELTAUD    |      | Float      | Upper triangularity at TIMED                                                |
| DIDTMAX    | A s⁻¹| Float      | Smoothed $dl/dr$ measured at TIMEDDIDTMAX                                    |
| DIVNAME    |      | String     | Machine-specific divertor configuration: ADP, RDP, etc                       |
| DRSEPD     | m    | Float      | Outer midplane radial distance between surfaces defined by upper and lower $x$-points at TIMED |
| ELM,E      |      | String     | ELMing at TIMEQD: Y or N                                                   |
| EVIDRAE,E  |      | String     | Evidence of runaways seen? Y or N                                           |
| INDENTD    |      | Float      | Beamlike indentation at TIMED                                               |
| *INTLID    |      | Float      | Internal inductance (l1) at TIMED                                           |
| *IPD       | A    | Float      | Plasma current at TIMED                                                     |
| *IPEQD     | A    | Float      | Plasma current at TIMEQD                                                    |
| IPPHASED   |      | String     | Plasma current mode at TIMEQD                                               |
| IPSPK      | A    | Float      | Max current spike measured at TIMESPK                                       |
| IPSPK,E    |      | String     | Discernable current spike? Y or N                                           |
| IFT        | A, s | Signal     | Plasma current through disruption (time series)                             |
| *KAPPAD    |      | Float      | Elongation at TIMEQD (closest equation to TIMED)                            |
| NINDXD     |      | Float      | Vertical stability critical index                                           |
| PHASED     |      | String     | Performance mode at TIMEQD: O(hmic), H, L, Hyb, etc                        |
| *Q95D      |      | Float      | Safety factor at 95% flux at TIMED                                          |
| QMIND      |      | Float      | Minimum safety factor in plasma at TIMED                                    |
| RGEOD      | m    | Float      | Plasma geometric centre major radius at TIMED                               |
| *RMAGD     | m    | Float      | Plasma magnetic centre major radius at TIMED                                |
| *SHOT      |      | Integer    | Shot number                                                                 |
| SQUOD      |      | Float      | Plasma upper, outer squareness at TIMED                                     |
| SQUID      |      | Float      | Plasma upper, inner squareness at TIMED                                     |
| SQLOD      |      | Float      | Plasma lower, outer squareness at TIMED                                     |
| SQLID      |      | Float      | Plasma lower, inner squareness at TIMED                                     |
| TIME       | s    | Float      | Time of maximum performance in shot                                         |
| TIME1      | s    | Float      | Time $I_p$ falls to 10% of IPD                                              |
| *TIME2     | s    | Float      | Time $I_p$ falls to 20% of IPD                                              |
| TIME5      | s    | Float      | Time $I_p$ falls to 50% of IPD                                              |
| TIME6      | s    | Float      | Time $I_p$ falls to 60% of IPD                                              |
| TIME7      | s    | Float      | Time $I_p$ falls to 70% of IPD                                              |
Table B.1. (Continued.).

| Name       | Unit | Data type | Description                                                                 |
|------------|------|-----------|-----------------------------------------------------------------------------|
| *TIME8     | s    | Float     | Time $I_p$ falls to 80% of IPD                                              |
| TIME9      | s    | Float     | Time $I_p$ falls to 90% of IPD                                              |
| TIME95MAX  | s    | Float     | Time $\beta_n$ reaches 95% of BETANMAX                                      |
| *TIMED     | s    | Float     | Time of initial thermal collapse. If current spike is evident, base of current spike may be used. If current spike is not visible, the end of core SXR collapse may be used. |
| TIMEDDIDTMAX | s  | Float     | Time of max increasing $dI/dt$                                              |
| TIMEQD     | s    | Float     | Time of acceptable $\chi^2$ EFIT closest to TIMED                           |
| TIMERMAX   | s    | Float     | Time of maximum radiated power                                              |
| TIMESPK    | s    | Float     | Time of current max after TIMEDDIDTMAX                                      |
| *TOK       | string | String   | Tokamak name, e.g. 'D3D', 'JET', etc                                       |
| *VDE       | string | String   | Significant vertical motion before or during disruption? Y or N              |
| VOLD       | m³   | Float     | Plasma volume at TIMED                                                      |
| WDIAD      | J    | Float     | Diamagnetic derived energy at TIMED                                          |
| WTOTD      | J    | Float     | Total kinetic energy at TIMED                                               |
| *ZMAGD     | m    | Float     | Plasma magnetic centre height above midplane at TIMED                        |

Table B.2. Halo Current Variables (* = Required).

| Tag name   | Unit | Data type | Description                                                                 |
|------------|------|-----------|-----------------------------------------------------------------------------|
| *IHMAX     | A    | Float     | Maximum total in-vessel halo current (poloidal/vertical)                    |
| *TIMEIHM   | s    | Float     | Time of IHMAX                                                               |
| *TPFATMAX  | A    | Float     | Maximum localized halo current (A/rad)/toroidally averaged halo current     |
| *IPATMAX   | A    | Float     | Total plasma current (core + halo) at time of IHMAX                          |
| RATMAX     | m    | Float     | Major radius at time of IHMAX                                               |
| ZATMAX     | m    | Float     | Height (Z-Z0) at time of IHMAX                                               |
| KATMAX     | float | Float     | Vertical elongation ($b/a$) at time of IHMAX                                 |
| TIME       | N    | Float     | Peak vertical force on VV                                                   |
| TIMEFZM    | s    | Float     | Time of peak FZVV                                                           |
| IZZV       | N*s  | Float     | Total VV Z impulse (integral Fz dt)                                         |

Table B.3. Impurity injection variables (* = Required).

| Tag name    | Unit  | Data type | Description                                                                 |
|-------------|-------|-----------|-----------------------------------------------------------------------------|
| VVESSEL     | m³    | Float     | Volume of the vacuum vessel                                                 |
| AVESSEL     | m²    | Float     | Surface area of first wall (Including port holes)                           |
| INJTYPE [1, 2] | string | Type of injector (VALVE: electromagnetic, piezo, guiding tube, etc) or (PELLET: solid, shell, SPI, etc) |
| INJDIST [1, 2] | m³ | Float     | Distance valve to separatrix                                                |
| INJANGPOL [1, 2] | deg | Float     | Poloidal angle of injector location (counter-clockwise from outer midplane) |
| INJANGTOR [1, 2] | deg | Float     | Toroidal angle of injector location                                         |
| NPARTMAX [1, 2] | l   | Float     | Maximum possible number of particles that can be injected with this valve   |
| PRESSMAX [1, 2] | Pa  | Float     | Maximum possible pressure [N/A for pellets]                                 |
| PRESS [1, 2] | Pa    | Float     | Pressure in valve [N/A for pellets]                                        |
| NPART [1, 2] | l     | Float     | Total number of injected particles (molecules, not atoms)                   |
| SPECIESMAJ [1, 2] | string | Injected gas species (majority)                                             |
| SPECIESMIN [1, 2] | string | Injected gas species (minority)                                             |
| SPECIESRAT [1, 2] | Float | Ratio majority/minority (particles)                                        |
| NPARTSPK [1, 2] | l    | Float     | Number of particles injected at time TIMESPK (molecules, not atoms)         |
| MNPARTSPK [1, 2] | string | Method to determine NPARTICLE_SPK (gas flow modelling, lab calibration, etc) |
| TINJTRIG [1, 2] | s   | Float     | Time of valve trigger                                                      |
TIMPARRIV  s  Float  Time of impurity arrival at plasma edge (from visible, bolometry, edge temperature, other)
MIMPARRIV  String  Method to determine TIMPARRIV
DIDTMIN  A s⁻¹  Float  Minimum negative dI/dt during CQ (max current drop)
TDIDTMIN  s  Float  Time of minimum negative dI/dt
IPDIDTMIN  A  Float  Plasma current at TIMEDIDTMIN
PRAD_MAX  W  Float  Maximum radiated power at time TIMERMAX
WRAD  J  Float  Total radiated energy during disruption (from TIMPARRIV to \(\text{TIME1}\))
WRAD_SPK  J  Float  Radiated energy until TIMESPK
PRADASYM  Float  Radiation asymmetry (max/min) at time TIMERMAX
PRADASYMANG  Deg  Float  Toroidal angle of radiated power measurement
DENSSPK5  m³  Float  Time-averaged line-averaged density from TIMESPK to TIME5
DENSMAXCQ  m³  Float  Maximum central line-averaged density during CQ
TE  eV  Float  Maximum electron temperature at TIMPARRIV
TI  eV  Float  Maximum ion temperature at TIMPARRIV
TEPED  eV  Float  Pedestal or LCFS electron temperature at TIMPARRIV
WDIAPED  J  Float  Pedestal energy at TIMPARRIV
WTH_Q2  J  Float  Thermal energy inside \(q = 2\) at time TIMPARRIV
CONTROLSHOT  Float  Control shot # without mitigation for comparison

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