

## Disruption, Halo Current and Rapid Shutdown Database Activities for ITER

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**Abstract.** Disruption characterization and database development and analysis activities conducted for ITER under the aegis of the International Tokamak Physics Activity (ITPA) Topical Group on MHD Stability are described. An International Disruption Database (IDDB) Working Group and a MDSplus-based IDDB infrastructure for disruption-relevant tokamak data, first established in 2006, comprises one of the several ‘joint activities’ conducted by the MHD Stability Group. Analysis reported in 2006 of current quench data is updated to assess sensitivities to current decay metrics and continues to support the 2006 recommendation about the lower bound on the plasma current decay time expected in ITER. Expansion of the IDDB scope and content to encompass halo current data has been initiated, and new combined current decay and halo current data sets have so far been received from four tokamaks. Analysis reported herein in a preliminary fashion will provide an “integrated” current decay and halo current basis for recommendations to ITER for halo current magnitude and toroidal asymmetry and how these attributes correlate with the parent plasma aspect ratio, elongation and triangularity and current and toroidal field magnitude. The feasibility of interpreting database composite and device-specific data in terms of a ‘statistical’ load severity spectrum is being explored. Activity has also been initiated to add data categories for rapid plasma shutdowns effected by massive gas and pellet injection.

### 1. Introduction

This paper describes the status and results of on-going disruption characterization and database development and analysis activities conducted in support of ITER under the aegis of the International Tokamak Physics Activity (ITPA) Topical Group on MHD Stability. An ITPA International Disruption Database (IDDB) Working Group and a MDSplus-based IDDB infrastructure for collection and retrieval of disruption-relevant tokamak data, first established in 2006, comprises one of several disruption-related ‘joint activities’ conducted by the

MHD Stability Topical Group. Analysis reported in 2006 [1] of current quench data provided a new ‘multi-machine-based’ recommendation about the lower bound on plasma current decay time expected in ITER. Activities are now in progress to expand the IDDB to encompass halo current data, and new combined current decay and halo current data have been received from four tokamaks. This data is eventually expected to provide an ‘integrated’ basis for design recommendations to ITER with regard to the rate of plasma current decay and halo current magnitude and toroidal asymmetry. In addition, activities were initiated to add IDDB data categories for rapid plasma shutdowns effected by massive gas and pellet injection.

## 2. Motivation and ITER Design Issues

Data on the expected characteristics of disruptions and on the nature and magnitude of disruption and rapid plasma shutdown consequences are needed for the design and functional validation of ITER components, systems and operations planning. Key pending design issues related to the electromagnetic loadings on the torus vacuum vessel and the in-vessel blanket-shield modules include peak vertical forces on the vessel support system, forces and torques owed to halo and induced currents in the in-vessel shield modules and their attachments to the vessel, and load dynamics for in-vessel components such as radio-frequency launching systems and divertor and first-wall protective surfaces. Similar electromagnetic loading issues and also first-wall surface thermal loading issues arise from the effects of the rapid plasma shutdowns envisioned to be used for disruption mitigation. The focus of IDDB activities has been on developing plasma current decay and now halo current and rapid shutdown consequence data to provide guidance for ITER systems design and operational qualification. Data needs and examples of circa 1996 ITER Engineering Design Activity (EDA) disruption data are described in [2]. More recent application of this EDA-legacy data to the ITER design is described in [3] and [4].

Present IDDB activities are focused on compiling improved versions of the EDA-legacy databases. An ITPA-sanctioned IDDB, with structure and implementation and user and public access principles paralleling those of other existing ITPA databases was established in 2006. Key features included the use of scalable/expandable data storage means (MDSplus [5]) and configuration of the database structure to allow for full traceability of data origins. An IDDB Working Group, comprising representatives from contributing devices, plus additional members interested in using IDDB data, has been established. General Atomics hosts the IDDB and provides administrative and technical support. Content for the 2006 v.1 MDSplus data tree comprises data from some 3500 disruptions and rapid shutdowns, with ca 50 scalar variables that quantify the contributing device and device-specific configuration attributes, before-disruption plasma current, shape and other disruption-relevant magnetic and kinetic attributes, plus detailed data on the rate and waveform characteristics of the plasma current decay. Table I summarizes the v.1 content and parameters of the contributing devices.

Table I. International Disruption Database devices and data attributes

Device	N	R (m)	A	$\kappa$	$I_p$ (MA)	Contribution Basis <sup>(a)</sup>
ASDEX-U	51	1.50–1.69	3.02–4.09	1.53–1.96	0.72–1.15	Fastest
C-Mod	2167	0.54–0.70	2.90–3.29	0.94–2.01	0.22–2.02	Survey
DIII-D	1153	1.28–2.00	2.52–6.62	1.01–2.43	0.18–2.39	Survey
JET	200	2.75–3.05	2.76–3.72	1.25–1.92	1.45–3.42	Fastest + Survey
JT-60U	20	3.08–3.19	3.51–3.98	1.82–1.92	2.39–2.90	Fastest
MAST	55	0.72–0.91	1.37–1.88	1.53–1.99	0.62–1.06	Survey
NSTX	200	0.73–0.98	1.27–1.84	1.52–2.52	0.36–1.20	Survey
TCV	29	0.86–0.89	3.51–3.98	1.16–2.35	0.08–0.61	Fastest

<sup>(a)</sup>Survey of all current decays or selection for fastest current decays.

Working Group findings from the v.1 data are described in [1] and [6]. Key results include verification of the self-inductance scaling of minimum area normalized current quench times with toroidal aspect ratio ( $A = R/a$ ), and a finding, for plasmas with  $2.5 \leq A \leq 3.5$ , that the time for current decay,  $t_{CQ}$ , is bounded by  $t_{CQ}/S \geq 1.7 \text{ ms/m}^2$ . Here  $S$  is the before-disruption poloidal cross-section area. Figure 1 shows key findings from analysis of the v.1 data: normalization of the  $t_{CQ}$  data by the product of the pre-disruption plasma poloidal cross-section area  $S$  and the dimensionless self-inductance,  $L^* \approx \ln(8R/a) - 1.75$ , results in a unification of the current quench data from low-aspect-ratio and conventional-aspect-ratio devices.

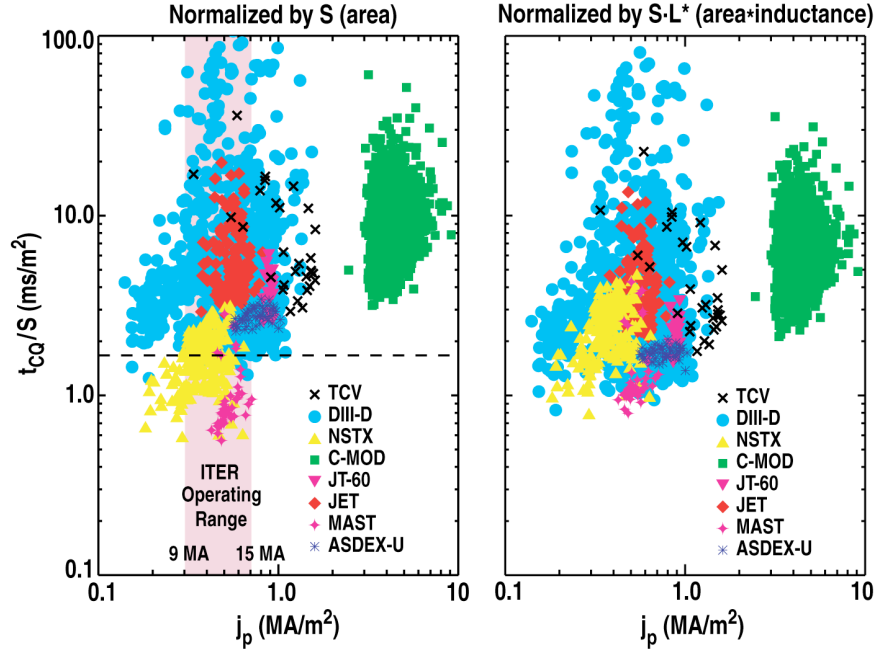


FIG. 1. Current quench data (2006 v.1 database). Low- $A$  devices exhibit shorter area-normalized quench times, but further renormalization by  $L^*$  brings the low- $A$  and conventional- $A$  data into better agreement, especially with regard to their respective lower bounds

### 3. Refinements in Current Decay Analysis

Close inspection of the conventional- $A$   $t_{CQ}/S$  data in Fig. 1 (left panel) shows that the lower bound for the DIII-D data ( $\sim 1.7 \text{ ms/m}^2$ ) is appreciably below the  $\sim 2$ – $2.5 \text{ ms/m}^2$  lower bounds for ASDEX-U, JET, JT60-U and TCX, and further below the  $\sim 3 \text{ ms/m}^2$  lower-bound for Alcator C-Mod. A further dimensionless-inductance renormalization that takes the lower external self-inductance (owed to the presence of close-coupled poloidal field shaping coils) of DIII-D into account brings the resulting rescaled lower-bound data into better agreement (Fig. 2). The rationale for this renormalization basis follows from the elementary model, detailed in [1], that the current decay time constant is  $L_{\text{eff}}/\mathcal{R}$ , where  $\mathcal{R}$  is the toroidal plasma resistance and  $L_{\text{eff}}$  is the effective inductance, comprising the sum of the internal inductance,  $L_{\text{int}} = \mu_0 I_p R/2$ , and the effective external inductance,  $L_{\text{ext}} = \Phi_{\text{ext}}/I_p$ , with  $\Phi_{\text{ext}}$  being the flux between the plasma surface and the applicable flux-conserving boundary. For tokamaks with remote or open poloidal field coil systems or non-

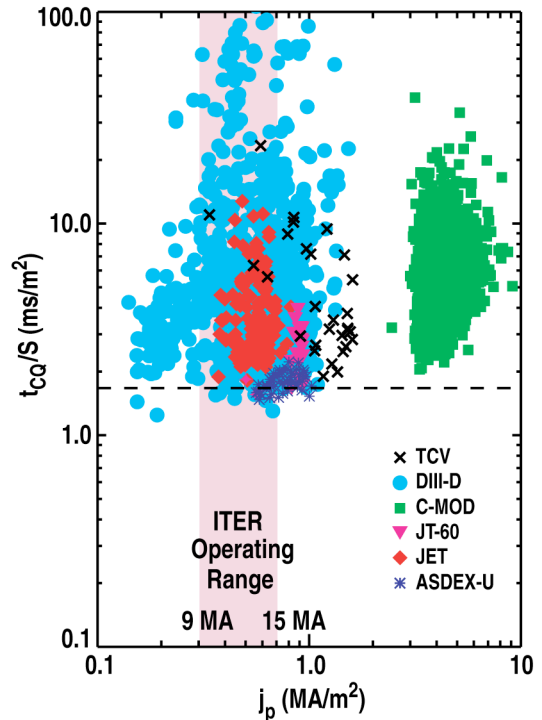


FIG. 2. Conventional- $A$  data in v.1 IDDB, rescaled by effective dimensionless inductance ratio  $L_{\text{eff}}(\text{DIII-D})/L_{\text{eff}}$

conducting torus vessels, the effective external inductance is essentially equal to the free-space external inductance. For DIII-D and also for ITER, the effective external inductance is approximately half of the free-space inductance. Hence the effective dimensionless inductance,  $L_{\text{eff}}^*$ , for DIII-D or ITER, is approximately two-thirds that for the balance of the conventional-A tokamaks in IDDB v.1. This difference is responsible for the lower-bound differences seen in Fig. 1.

Figure 2 demonstrates that scaling the  $t_{\text{CQ}}/S$  data by a factor of  $L_{\text{eff}}^*(\text{DIII-D})/L_{\text{eff}}^*$  brings the various conventional-A lower bounds into more uniform agreement. In this regard, we note that  $L_{\text{eff}}^*$  for DIII-D and ITER turn out to be nearly equal (for fast  $I_p$  decays, the ‘close-fitting’ ITER vacuum vessel provides a similar inductance-limiting effect as the DIII-D shaping coils, see Fig. 3). Hence the 1.7 ms/m<sup>2</sup> lower bound on the decay time observed in DIII-D and also recommended from the IDDB will apply directly to ITER.

We have also examined whether our 2006 conclusions about minimum  $t_{\text{CQ}}/S$  were biased by the use of the Working-Group-recommended ‘80%–20%’ linear-decay metric [1]. This is the metric we routinely employ to obtain  $t_{\text{CQ}}$  from the current decay waveforms of the various devices. Figure 4 shows the effect of applying various linear- and exponential-fit metrics, 70%–10%, 90–30%, 75–25%, etc., to the DIII-D, JET and C-Mod data. While there is some relative ‘motion’ of the centroids and lower bounds of the respective data among the three devices as the metric basis is varied, we conclude from these sensitivity studies that our 2006 recommendations about absolute and device-relative lower bounds on  $t_{\text{CQ}}/S$  are not strongly sensitive to the choice of the current decay evaluation metric.

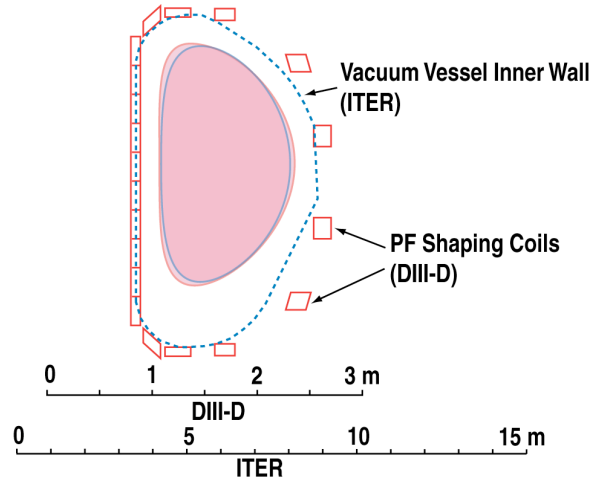


FIG. 3. DIII-D and ITER poloidal cross-sections superposed (normalized to same-size generic plasmas). The location and contour of the ITER inner vacuum vessel wall matches the location and configuration of the DIII-D PF shaping coil set.

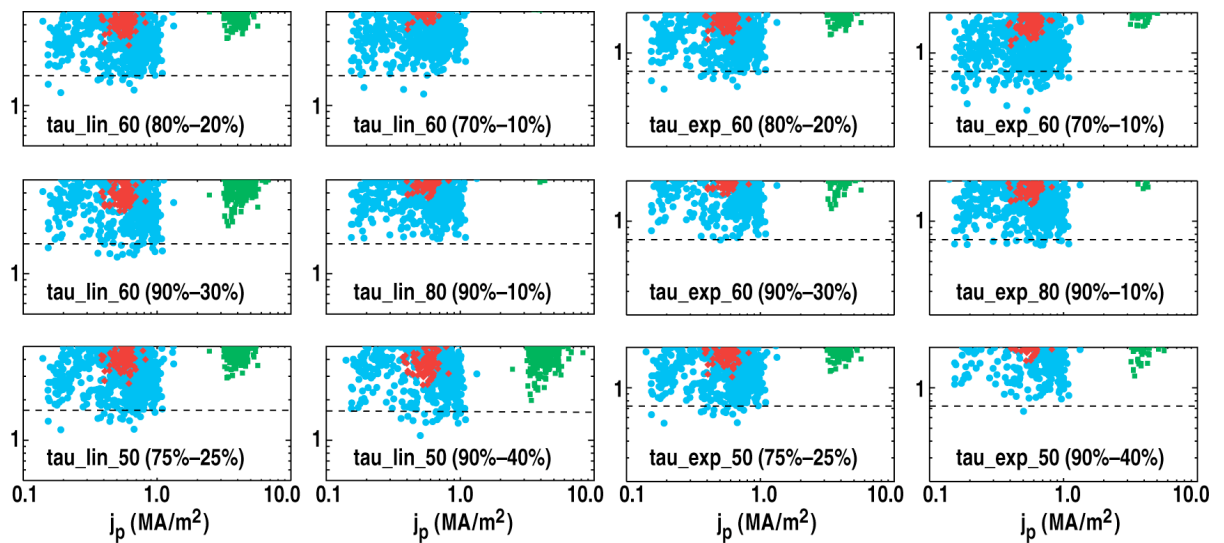


FIG. 4. Metric sensitivity studies of  $t_{\text{CQ}}/S$  for v.1 data. DIII-D data in cyan, JET data in red, C-Mod data in green. Linear-fit metrics (‘lin’) on the left, exponential-fit metrics (‘exp’) on the right

#### 4. Halo Current Expansion

Seven halo-current and vessel-force data types have been added and solicitations have been sent to potential contributors for revisited or new ‘integrated’ data examples (shot records) with combined plasma current decay, halo current and [optional] vessel vertical force or impulse (force x time) data. Contributions from four tokamaks have been received to date. Table II summarizes the new data variable additions. Figures 5 and 6 show the specifications for data evaluation. The specifications are focused on yielding two key parameters, maximum halo current,  $I_{h,max}$  and toroidal peaking factor, TPF, evaluated at the time of  $I_{h,max}$ . These data, plus the usual IDDB specification for predischruption plasma current,  $I_{p0}$ , allow the familiar TPF versus  $I_{h,max}/I_{p0}$  ‘design basis’ plot, first developed in [2], to be generated. Figure 7 shows this plot for the 2010 data.

Table II. Halo currents and VDE characteristics [blue cells = required (minimum) data]

TAG NAME	Units or Data	
	Type	Definition and/or Options for Alpha Data
IHMAX	A	Maximum total in-vessel halo current (poloidal/vertical)
TIMEIHM	s	Time of IHMAX
TPFATMAX	float	Maximum localized halo current (A/rad)/toroidally averaged halo current
IPATMAX	A	Total plasma current (core + halo) at time of IHMAX
RATMAX	m	Major radius at time of IHMAX
ZATMAX	m	Height (Z-Z0) at time of IHMAX
KATMAX	float	Vertical elongation (b/a) at time of IHMAX
FZVVMAX	N	Peak vertical force on VV
TIMEFZM	s	Time of peak FZVV
IZVV	N*s	Total VV Z impulse (integral Fz dt)

The new IDDB data generally fall within domain bounding the 1998–2006 EDA-legacy data. A very small fraction of the new data exceeds the  $I_{h,max}/I_{p0} * TPF = 0.75$  bounding basis presently assumed as a guideline for ITER design. The significance of these ‘outlier’ data is still under consideration. Open issues include accuracies of the TPF data and how to interpret or whether to include data where the peak  $I_{h,max}/I_{p0} * TPF$  product reaches some maximum level for only a brief period of time. Resolution of these and other data-quality issues awaits submissions from more tokamaks, examination of whether to also include the less-well-documented EDA-legacy data, and results of an evaluation of all contributions using the same assessment basis.

Plans for completing and evaluating the 2010 expansion encompass revisiting the EDA-era basis for the bound on the product of normalized peak halo current ( $I_{h,max}/I_{p0}$ ) and toroidal peaking factor (TPF) and searching for correlations of these and other related halo-current attributes with the parent plasma aspect ratio and elongation, safety factor and rate of initial current decay. In addition, the feasibility of interpreting database composite and device-specific data in terms of a ‘statistical’ load severity spectrum will be explored.

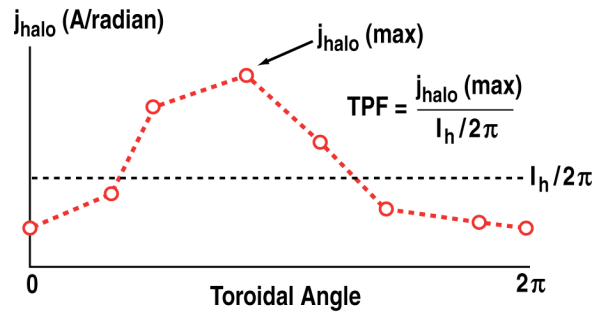


FIG. 5. Basis for toroidal peaking factor (TPF) evaluation

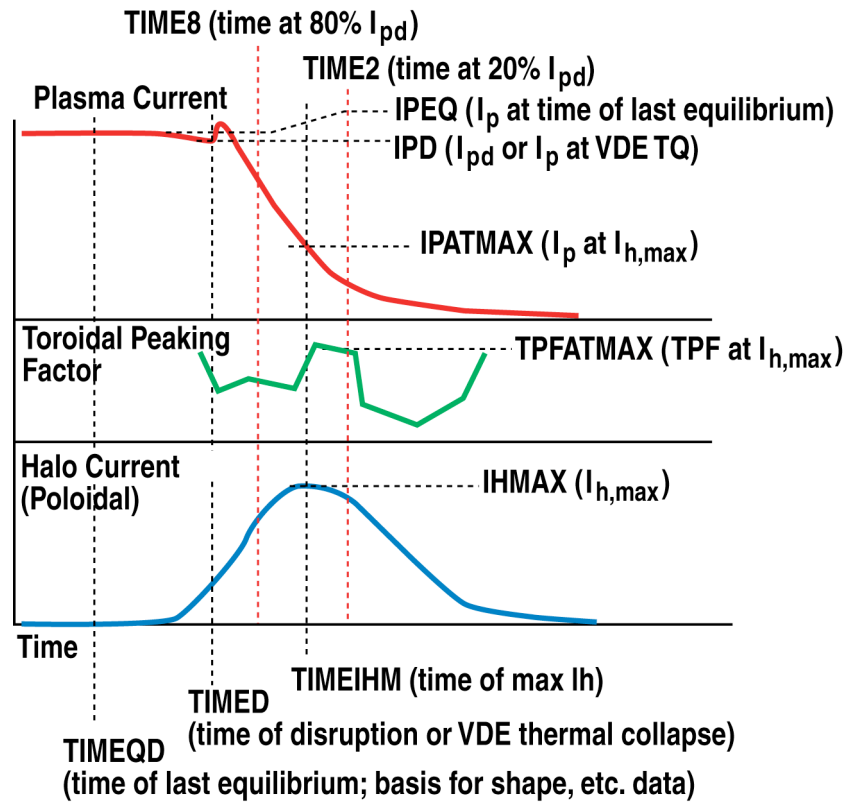


FIG. 6. Basis for maximum halo current ( $I_{HMAX}$ ) and TPF at time of  $I_{HMAX}$  evaluations.

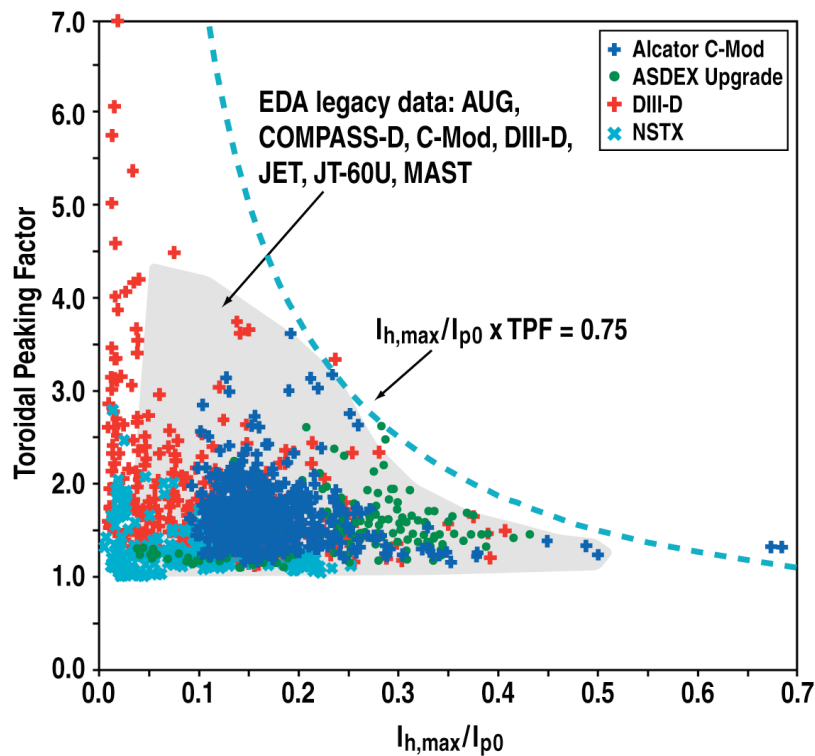


FIG. 7. Present (September 2010) IDDB halo current database. The gray-shaded area shows the bounding domain for the EDA legacy data. The 'ITER design basis' bound of  $I_{h,max}/I_{p0} \times TPF = 0.75$  is also indicated.

## 5. Rapid Shutdown Expansion

The similarity of many of the electromagnetic loading consequences of massive gas and/or pellet injection produced ‘rapid shutdowns’ to those obtained owing to ‘natural’ disruption or vertical displacement event onset make inclusion of rapid shutdown data in the IDDB a logical next step. Candidate RS-related variables have been identified. Some, like the plasma current decay rate, are already included in the present IDDB data, and other aspects of RS efficacy such as mitigation of halo currents and/or vessel vertical force reduction are potentially included within the scope of the new halo-current data requests. Other aspects of rapid shutdown implementation or efficacy, such the effect of rapid shutdowns on plasma thermal energy mitigation (e.g., reduction of deposition of pre-disruption plasma thermal energy on divertor surfaces) and the gas utilization efficacy (fraction of injected gas assimilated by the plasma) are more complex to quantify in a uniform manner suitable for a multi-machine database comparison. Discussion of how to proceed with these aspects of the IDDB expansion is on-going. Meanwhile, Fig. 8 illustrates how the current quench attributes (for massive gas injection in DIII-D) are already included in the v.1 database. Figure 9 shows recent massive gas injection data from JET [7] showing the dependence of  $t_{\text{CQ}}$  (100% to 70%  $I_{\text{p0}}$  evaluation basis) on target plasma  $q_{95}$  and injected gas species and quantity. This data is presented here for illustrative purposes only. We note that examples of ‘very-fast’ current decays (at or slightly below the 1.7 ms/m<sup>2</sup> ITER design recommendation) produced by massive gas injection in JET and by massive gas and massive pellet injection in DIII-D have recently been reported during Stability Group meetings, albeit (at this point) interpreted using different current decay metrics. Future work via the IDDB or otherwise is required to understand the implications of these observations. Our ultimate intent with regard to the IDDB will be to assemble a common-basis disruption/halo current/rapid shutdown database that will allow data similarities and differences and parametric correlations to be assessed on a common multi-machine basis for ITER and beyond.

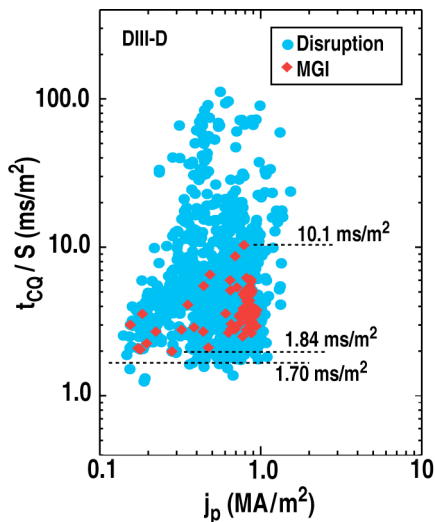


FIG. 8. Disruption and massive gas injection (neon and argon) rapid shutdown data from DIII-D (circa 2006), included in the v.1 database.

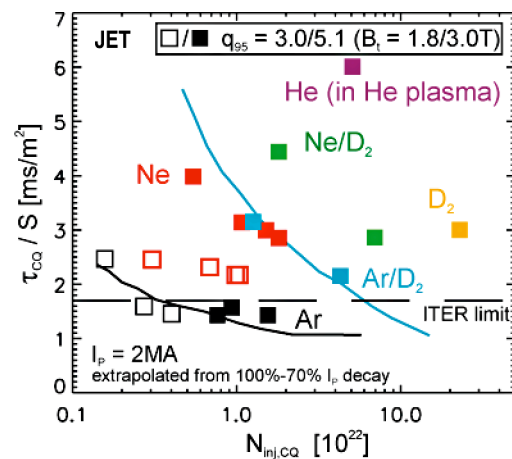


FIG. 9. Recent JET massive gas injection data [7] (not yet in the IDDB), included here for illustration only, with permission of M. Lehnen.



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