Experiments in Disruption Avoidance for ITER Using Passive and Active Control

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Key plasma physics and real-time control elements needed for robustly stable operation of high fusion power discharges in ITER have been demonstrated in US fusion research. Optimization of the current density profile has enabled passively stable operation without $n = 1$ tearing modes in discharges simulating ITER's baseline scenario with zero external torque. Stable rampdown of the discharge has been achieved with ITER-like scaled current ramp rates, while maintaining an X-point configuration. Significant advances have been made toward real-time prediction of disruptions: machine learning techniques for prediction of disruptions have achieved 90% accuracy in offline analysis, and direct probing of ideal and resistive plasma stability using 3D magnetic perturbations has shown a rising plasma response before the onset of a tearing mode. Active stability control contributes to prevention of disruptions, including direct stabilization of resistive-wall kink modes in high-β discharges, forced rotation of magnetic islands to prevent wall locking, and localized heating/current drive to shrink the islands. These elements are being integrated into stable operating scenarios and a new event-handling system for off-normal events in order to develop the physics basis and techniques for robust control in ITER.

Work supported by the U.S. Department of Energy under DE-SC0008520, DE-FC02-04ER54698, DE-SC0016372, DE-FG02-04ER54761, DE-AC52-07NA27344, DE-SC0015878, DE-SC0014264, DE-FG02-99ER54524, DE-FOA-0001498, DE-AC02-09CH11466, DE-FC02-99ER54512, DE-SC0010720, DE-SC0010492, and the U.S. Department of Energy Computational Science Graduate Fellowship, and by the EUROfusion Consortium with funding through FuseNet from the Euratom research and training programme 2014–2018 under Grant Agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Published as a journal article in Nuclear Fusion
http://iopscience.iop.org/article/10.1088/1741-4326/ab15de

PROGRESS IN DISRUPTION PREVENTION FOR ITER

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Abstract

Key plasma physics and real-time control elements needed for robustly stable operation of high fusion power discharges in ITER have been demonstrated in recent research worldwide. Recent analysis has identified the current density profile as the main drive for disruptive instabilities in discharges simulating ITER's baseline scenario with high and low external torque. Ongoing development of model-based profile control and active control of MHD instabilities is improving the stability of multiple scenarios. Significant advances have been made toward real-time physics-based prediction of instabilities, including path-oriented analysis, active sensing, and machine learning techniques for prediction that are beginning to go beyond simple disruption mitigation trigger applications. Active intervention contributes to prevention of disruptions, including forced rotation of magnetic islands to prevent wall locking, and localized heating/current drive to shrink the islands. Stable discharge rampdowns have been achieved with the fastest ITER-like scaled current ramp rates, while maintaining an X-point configuration. These elements are being integrated into stable operating scenarios and a new event-handling system for off-normal events in order to develop the physics basis and techniques for robust control in ITER.

1. INTRODUCTION

The large thermal and magnetic energy contained in a full-performance discharge means that ITER must have an exceedingly low rate of disruptions by the time it reaches DT operation. A disruption budget [1] will be part of the ITER's operating plan [2], in order to track the cumulative effects of all disruptions. Although early operation at reduced parameters will allow more leeway for disruptions, unmitigated disruptions at currents above 8.4 MA may be severe enough (Category III) to be tolerable only once or twice in the machine's lifetime [3]. Thus, as experiments advance toward the planned current of 15 MA, the tolerance for unmitigated disruptions is expected to become of the order 1 in 10^4 discharges. Even with an actual disruption rate as low as 1%, this requires 99% accuracy of disruption mitigation. Achieving this value requires a very low disruption rate, probably less than 1%, as well as highly reliable mitigation of any disruptions that do occur [4]. Uncertainties in prediction [5] and mitigation [6] of runaway electrons in ITER disruptions may place an even higher premium on disruption-free operation.

Sustaining a low disruptivity tokamak plasma is fundamentally a plasma control problem. Beginning with a minimally disruptive target scenario, continuously-operating algorithms in the plasma control system must be able to actively regulate the plasma state to maintain passive stability to as many potentially disruptive modes as possible. Any remaining potentially disruptive modes must be actively and robustly stabilized. In addition to quantifiably robust continuous algorithms, the control system must be able to detect and respond asynchronously to hardware faults and off-normal plasma conditions ("exceptions" in ITER terminology) [7], [8] in such a way as to prevent the exception from leading to a disruption. However, the plant and the nominal scenario should be so reliable that exceptions are extremely rare. Disruption mitigation must also be integrated into the plasma control system [9], but is outside the scope of this paper. In ITER, disruption mitigation should be a rarely-used last resort.

This paper provides an overview of recent research toward the goal of disruption-free operation. Section 2 discusses progress in identifying stable operating scenarios and robust control to maintain the desired operating state. Section 3 describes real-time algorithms that detect off-normal conditions, or predict that an instability will occur later in the discharge. Section 4 describes active intervention by various means to enable recovery of stable operation in the same scenario or an alternate one (maximizing the physics productivity of the discharge), or allow a controlled termination of the discharge. These elements contribute to an integrated control solution, capable of robustly maintaining stable plasma conditions, or recognizing and responding to off-normal and fault events so as to reliably prevent disruptions (section 5).

2. PLASMA CONFIGURATION CONTROL

Reliable operation of ITER (and burning plasmas beyond ITER) requires a robustly stable, stationary operating state. Active control measures, up to and including a rapid shutdown by massive impurity injection, must be available to recover from off-normal conditions and prevent a disruption, or mitigate the severity of a disruption. However, it is clear that high reliability is needed in the normal operating state, so that the use of these safeguards is very rare. This is achieved through the selection of a stable plasma configuration, controls to achieve and maintain that configuration, stable paths to access the configuration at the beginning of the discharge and to exit from it at the end, and (where needed) active stabilization to extend the stability limits.

Optimization of the equilibrium configuration has been shown to improve the stability of zero torque ITER-like discharges. Previously, many such discharges in DIII-D disrupted due to tearing modes, and in general neoclassical tearing mode (NTM) stability appeared to become poorer as neutral beam torque was reduced [10]. In JET, NTMs were the largest single cause of disruption with the carbon wall [35], and could enhance core accumulation of impurities in operation with the ITER-like wall [11]. Recent DIII-D results have shown that

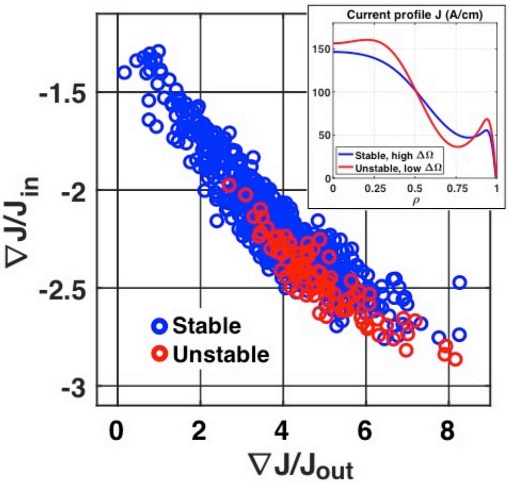

FIG. 1. Current density gradient inside and outside the minimum or "well" of current density near the q=2 surface (see inset) in DIII-D discharges simulating the ITER baseline scenario. Colours indicate discharges stable (blue) or unstable (red) to m/n=2/1 tearing modes. [Reprinted from F. Turco, et al., Nuclear Fusion 58 (2018) 106043]

tearing instabilities in ITER baseline scenario plasmas are related to the shape of the current density profile around the q=2 surface. A deeper current "well" between the ohmic current in the core and the bootstrap current at the edge is correlated with greater instability [12] (see Fig. 1).

In addition to the existence of a stable operating state, it is essential to have controls that will maintain the discharge in that state. Tokamak plasma control is complex, with nonlinear, coupled processes to be controlled, and possible bifurcations of the plasma state, putting a premium on integrated, model-based control [13]. The advent of transport simulations that can operate faster than real time [14] will be important for discharge monitoring and control. Simultaneous control of plasma pressure and safety factor using model-based control has been demonstrated in TCV [15]. In DIII-D, as shown in Fig. 2, a model-based feedforward+feedback algorithm [16] controls both neutral beams and gyrotrons to achieve simultaneous targets of plasma energy and a current density profile with high q_{min}, in development of discharges for non-inductive operation [17]. Model-based control may be applicable to other scenarios as well.

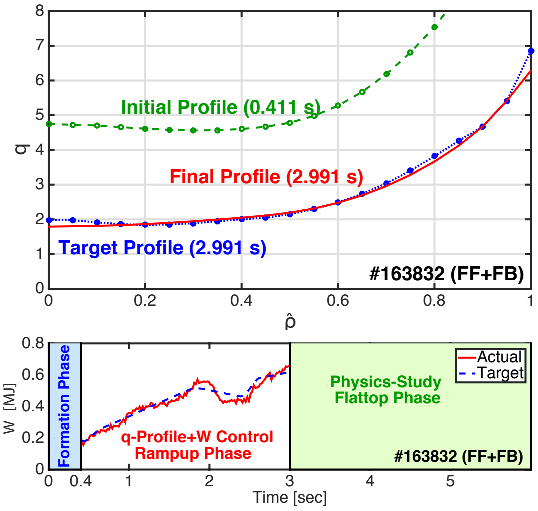

FIG. 2. Demonstration in DIII-D of a feedforward+feedback q-profile control scheme with model-based optimization, achieving a target profile with qmin = 1.9 while tracking a target value for plasma energy W. [Reprinted from W.P. Wehner, et al., paper EX/P6-39, Proc. 27th IAEA Fusion Energy Conference, IAEA, Vienna (2018).]

Maintaining a stable operating state may include extending the bounds of stable operation through direct control of instabilities. Real time active tracking and control of NTMs is well established, but recent analysis [18] indicates that the presence of ITER's blanket modules can cause m/n=2/1 tearing modes to lock in a time significantly shorter than previous estimates that considered only the vacuum vessel wall. If active NTM stabilization is required, this result reduces the time available for re-aiming gyrotrons to suppress the mode after detection, and increases the attractiveness of continuous ECCD applied at the rational surface to maintain NTM stability. The estimated power requirement of about 5 MW for pre-emptive stabilization of the 2/1 mode is consistent with ITER's electron cyclotron system, and would still allow demonstration of a fusion gain of Q=10 [19]. Small-amplitude sweeping of the deposition location across the rational surface can reduce the requirements for accuracy of aiming, as first tested on TCV [20] and later on AUG [21]. Alternatively, a recently demonstrated fast EC diplexer [22] could allow some gyrotrons to switch as needed between central heating/current drive and NTM control, without delay.

A need for control of the sawtooth instability is also anticipated in ITER, in order to avoid long period sawteeth with large amplitude crashes that could trigger an NTM instability [23], and several schemes using ECCD or ICRF heating have been proposed [24]. Recent JET experiments have shown that the sawtooth period can be controlled with low field side ICRF heating (as will be available in ITER) near the q=1 surface [25], and that sawtooth pacing can be achieved with modulated central ion cyclotron heating [26], a method that is less sensitive to the deposition location. Further work is needed to validate ICRF sawtooth control in ITER-relevant H-mode discharges.

Equilibrium control for stable operation includes non-axisymmetric aspects of the equilibrium. A large body of literature exists on the topic of n=1 error fields, and ITER will include external non-axisymmetric coils for n=1 error field compensation. However, recent data from DIII-D and EAST show that the threshold for n=2 error field penetration and driven reconnection may be similar to that of n=1 error fields [27]. This result suggests that the use of the in-vessel coils for n=2 error field correction should be kept as an option for ITER, since the external correction will be hard-wired for n=1. High beta, high q_{min} discharges in ITER's steady state scenario are expected to exceed the no-wall ideal MHD kink stability limit. Despite the predicted stabilizing effects of particle-orbit resonances, active feedback control of the resistive wall mode or dynamic error field correction with non-axisymmetric coils may be needed in this regime. As seen in Fig. 3, experiments on NSTX [28] and DIII-D [29] have shown that feedback stabilization can indeed extend the stable operating range toward the ideal-wall limit (the theoretical maximum). Advanced state space control algorithms can achieve stabilization with external coil arrays [28], [30].

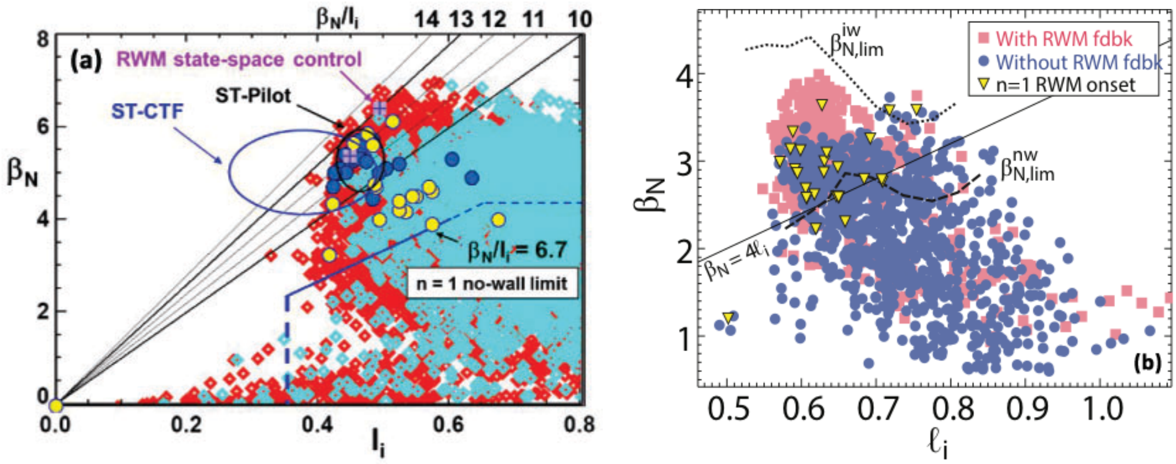

FIG. 3. Normalized beta vs. internal inductance, showing the effects of active feedback stabilization of the resistive wall mode (RWM) in high β_N discharges in (a) NSTX and (b) DIII-D. [Reprinted from (a) J.W. Berkery, et al., Proc. 24th IAEA Fusion Energy Conference, IAEA, Vienna (2012), paper EX-P8-07, and (b) J.M. Hanson, et al., Nucl. Fusion 57 (2017) 056009.]

3. REAL-TIME PREDICTION

Achieving a low rate of disruptions requires the ability to recognize or anticipate exceptions (i.e., conditions and events that are likely to lead to a disruption) in real time, and to take action that enables a return to normal operation or a controlled shutdown. It is important to distinguish such warnings from those that trigger a rapid shutdown by the disruption mitigation system; the latter require only a short warning time, perhaps as little as 30 ms before the thermal quench [4], and a binary output. In contrast, in order to allow the discharge to continue, notification of an exception must include information about the nature of the exception, enabling a control decision on a course of action using available actuators, and must occur early enough that the control system has time to change the evolution of the discharge. Potential solutions to this problem include "physics-driven" methods based on a qualitative or quantitative model of the physical processes that would ultimately lead to an instability, and "data-driven" or machine learning methods, where statistical analysis of a large database of discharges yields empirical correlations between measured data and instabilities. This is an area of rapid development in physics and mathematics.

To date, most real-time systems have used one or more single-parameter physics-based detectors (e.g., MHD mode amplitude, radiated power fraction, global energy confinement level, …) to trigger a disruption mitigation system when a specified threshold is passed, or (with a lower threshold) to initiate more benign preventive actions. Analysis of a multi-machine database [31] has provided a basis for normalizing the critical locked mode amplitude for disruption, independent of machine size, while analysis of a DIII-D database [32] shows that the proximity of the outer edge of the island to the plasma surface is a key factor in whether a locked mode leads to a disruption. Machine-learning approaches (discussed below) should be applicable to data analysis for optimization of these individual physics-based tests [33] and the control responses. Although each such test is specialized to certain classes of disruptions, multiple threshold tests can be combined with suitable weighting to make a more general warning system with a high success rate [34].

Path-oriented analysis seeks to identify specific chains of events that can lead to a disruption [35]. Detection of an event or condition early in the chain could enable a warning signal in time for modification of the discharge before it becomes unstable. The Disruption Event Characterization and Forecasting (DECAF) code [36], now being used to analyze data from several devices, identifies events that may precede a disruption, such as a tearing instability, loss of density control, plasma-wall contact, etc. DECAF includes a successful reduced model for resistive wall mode stability with kinetic effects [37] (Fig. 4), and aims to predict other instabilities using validated physics models such as tearing mode torque balance bifurcation to a locked state [38]. Multiple variable tests in DECAF have produced early warnings on transport timescales, potentially allowing time for actions to prevent a disruption. A path-oriented approach is also described in [39], including a discussion of the sensor and actuator requirements. Fig. 5 shows an example in ASDEX Upgrade of recovery after crossing the H-mode density limit boundary.

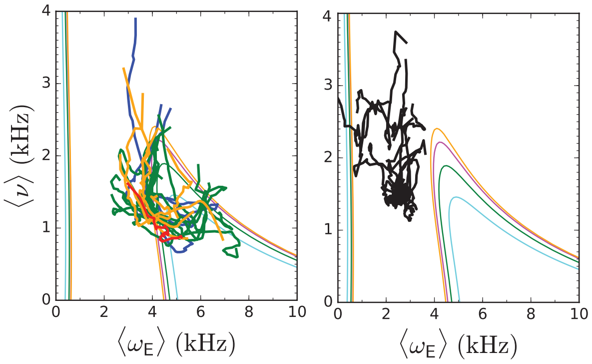

FIG. 4. Stability diagram, in ExB rotation frequency ω_E and collisionality ν, of unstable (left) and stable (right) NSTX discharges in comparison with resistive wall mode stability boundaries predicted by a reduced kinetic model. [Reprinted from J.W. Berkery, et al., Phys. Plasmas 24 (2017) 056103.]

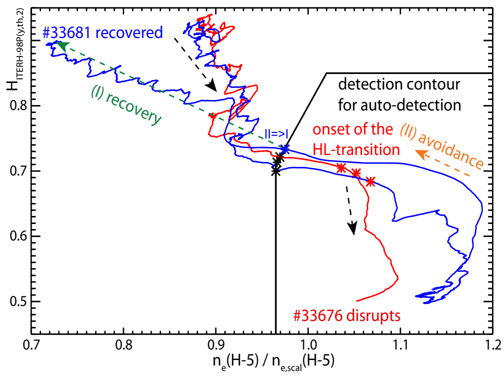

FIG. 5. Operation diagram of H-mode density limit discharges in ASDEX-Upgrade, in terms of scaled energy confinement time vs. scaled density. One discharges disrupts after crossing the density limit detection contour; the other is recovered by turning off gas fueling and applying ECCD. In all cases the proposed trigger threshold would have been early enough to safely avoid the approaching disruption. [Reprinted from M. Maraschek, et al., Plasma Phys. Control. Fusion 60 (2018) 014047.]

Methods for direct assessment of the plasma's stability are conceptually elegant, but are still in their infancy. Recent advances in numerical methods and computing power have enabled first-principles calculation of ideal MHD stability in real time [40] and resistive stability in near real time [41]. Low-frequency active MHD spectroscopy offers the possibility of a direct real-time measurement of plasma stability. Originally developed for measuring the damping rates of ideal MHD modes [42], the technique has also shown a rising response correlated with the onset of tearing modes in ITER baseline scenario discharges [43]. As shown in Fig. 6, the dependence of the inferred damping rate on plasma parameters is in qualitative agreement with ideal MHD modeling [44], and this stability-related measurement has been used for closed-loop control of the heating power in an ITER baseline scenario discharge.

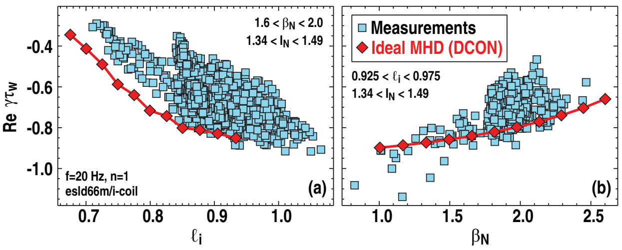

FIG. 6. Stable ITER baseline scenario discharges in DIII-D: (a) ℓ_i and (b) β_N dependences of the normalized RWM growth rate Re(γτw), comparing the values inferred from plasma response measurements (blue squares) with predictions of the linearized, ideal MHD, resistive wall dispersion relation (red diamonds). [Reprinted from J.M. Hanson, et al., Proc. 45th EPS Conf. on Plasma Physics, Europhysics Conf. Abstracts, Vol. 42A (2018) paper P2.1110.]

Data driven approaches such as the APODIS system [45] at JET have, so far, been used mainly for binary warnings where the actuator is a disruption mitigation system. Adaptive methods to train an algorithm "from scratch" have achieved satisfactory performance after only a few tens of disruptive shots [46], [47]. Probabilistic predictors express output in terms of a likelihood of disruption rather than a binary classification [47], [48], and the probabilistic approach has also been applied to forecasting the onset of a tearing mode [49]. Deep-learning algorithms have begun to incorporate time-sequential data and higher-dimension data via advanced neural net methods with promising results, including accurate cross-machine predictions [50].

A key challenge for machine learning algorithms is to deliver detailed information about the exception that has been detected, so that the control system can generate an appropriate response to prevent the disruption. Work toward this goal is in progress. As seen in Fig. 7, Random Forest algorithms can reveal the relative contributions of the various input data signals to the final disruption probability [51], [52]. Generative Topographic Mapping (GTM) reduces a complex multi-dimensional space of input data to a 2-D or 3-D space of safe and unstable regions, simplifying the tasks of classification, prediction, and control of instabilities [53], [54] (see Fig. 8). A proposed general approach [55] is to estimate the future trajectory of a discharge in the multidimensional space of input data – or perhaps in a reduced space such as that of Fig. 8 – in order to project its future proximity to disruption boundaries and the time to collision with a boundary; any necessary actions would be based on the gradient of the decision function (e.g. disruption probability) and its dependence on the input data and available actuators. Translating these principles to a practical control scheme is a challenge for future work.

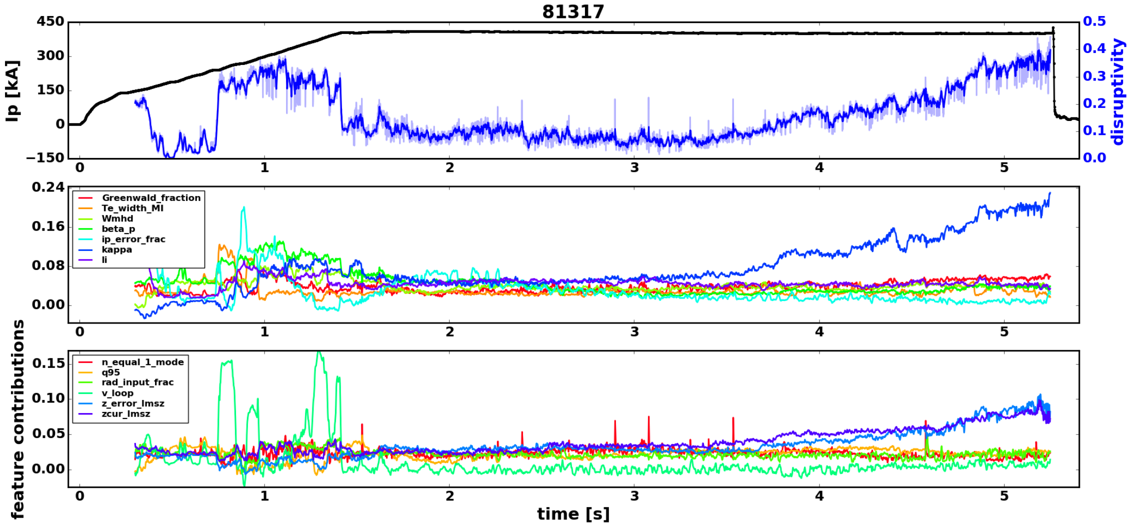

FIG. 7. (a) Disruptivity signal (blue curve) from a Random Forest machine-learning algorithm rises as an EAST discharge approaches a Vertical Displacement Event (VDE) instability. (b) and (c) show the relative importance of the 13 input signals. Rising blue traces indicate high importance for discharge elongation, vertical position, and vertical control error. [Reprinted from R.S. Granetz, et al., Proc. 27th IAEA Fusion Energy Conference, IAEA, Vienna (2018), paper EX/P6-20.]

4. RESPONSE TO OFF-NORMAL CONDITIONS

A warning of an off-normal condition that is about to occur, or that is already in progress, is likely to require a response by the control system in order to prevent a disruption, with the response being determined by the nature of the off-normal condition. If feasible, continuing the discharge is preferable to ending it prematurely, and a controlled shutdown is preferable to a rapid termination. For example, the onset of a locked tearing mode is often a precursor to a disruption, but may allow time for other actions aimed at removing the instability and recovering normal operation, or limiting its growth during a controlled shutdown.

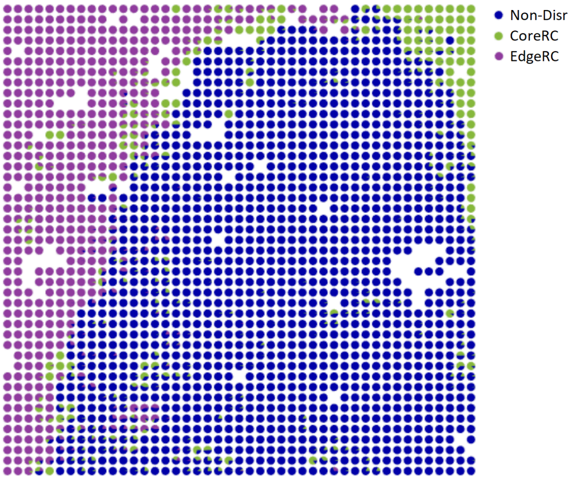

Fig. 8. Generative Topographic Mapping of 5-D JET data (peaking factors of electron temperature, electron density, and radiated power; internal inductance ℓ_i; andq_{95}/q_0 ratio) to a 2-D "latent space". Colours on the map distinguish stability regimes: core radiative collapse disruptions (CoreRC, green), edge radiative collapse (EdgeRC, magenta), andnon-disrupting cases (blue). [Reprinted from A. Pau, et al., IEEE Trans. Plasma Science 46 (2018) 2691.]

Forced rotation of magnetic islands by applied electromagnetic torque prevents locking to the wall, and reduces the island size. Several experiments [56], [57], [58], have demonstrated entrainment of a locked island by a rotating resonant magnetic perturbation (RMP) at frequencies in the 5-50 Hz range, limited in frequency by close coupling of the coils to the conducting vacuum vessel wall (Fig. 9). In the absence of strong wall currents, entrainment at several kHz has been achieved [59]. A modulated, non-rotating RMP is also proposed as a means of driving mode rotation [60]. During entrainment, the island maintains a saturated size, and in some cases the H-mode edge pedestal is recovered [61]. Two-fluid modeling shows that island stabilization can occur with sufficient rotation of the RMP relative to the electron fluid [62]. A reduced MHD simulation of island dynamics shows good qualitative agreement with experiment [63]. A simple 0-D model indicates that in ITER, the internal non-axisymmetric coils could entrain a locked island of 6-8 cm width at sub-10 Hz frequencies [58].

Pioneered in FTU, ASDEX Upgrade, and DIII-D, localized injection of electron cyclotron (EC) power at the q=2 surface has been developed as a means of preventing or postponing a disruption after a large amplitude locked mode is present – unlike the pre-emptive or small-amplitude NTM control by ECCD mentioned above in Section 2. Joint experiments in FTU and ASDEX Upgrade show similar behavior in low-beta density limit disruptions and high-beta NTM-driven disruptions [64]. Rutherford equation analysis indicates that while the island is large, electron cyclotron heating plays a larger role in stabilization than does current drive, and is less sensitive to the location of deposition. Real-time mirror steering has been included in the technique [65].

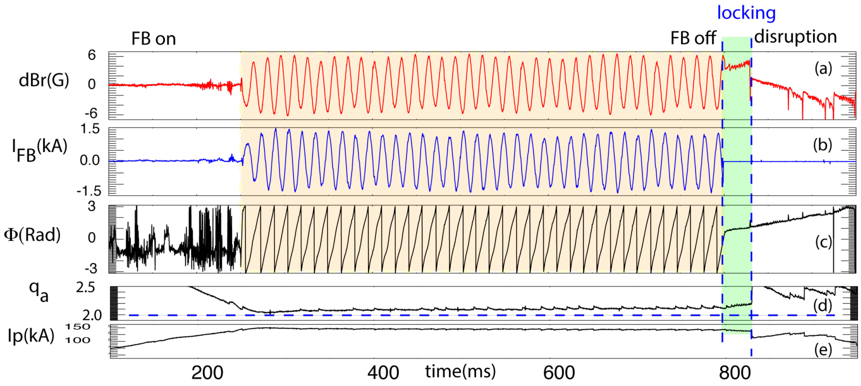

FIG. 9. Long duration of post-unlocked sustainment of m/n = 2/1 mode in RFX-mod (#33748): (a) 2/1 δBr signal, (b) feedback coil current, (c) phase time evolution of the observed 2/1 mode component, (d) safety factor qa and (e) the plasma current. Feedback-controlled magnetic perturbation drives the mode rotation during the orange-shaded interval. After feedback was turned off, the mode survived as a locked mode for a short interval (green) before disruption. [Reprinted from M.Okabayashi, et al., Nucl. Fusion 57 (2017) 016035.]

Forced island rotation has been combined with injection of EC power into the island for disruption prevention and discharge recovery [66]. A slow, controlled rotation of the island driven by the RMP, with modulated ECCD that is synchronized for deposition in the island O-point, avoids locking while maximizing the efficiency of stabilization by EC power. With this method, suppression of the island and recovery of H-mode operation has been demonstrated.

Stable discharge termination, whether planned or unplanned, is a critical element of disruption-free operation. An extensive study [67] of discharge terminations in existing tokamaks, in comparison with modeling for ITER, shows that ITER's expected trajectory may lie near the edge of the parameter space defined by present experiments (see Fig. 10). ITER's path is dictated by a rapid reduction of elongation while restricting the increase in internal inductance ℓ_i, in order to maintain vertical stability. Recent experiments in EAST and DIII-D (Fig. 11) have demonstrated stable rampdowns with equivalent scaled dI/dt up to the maximum expected for an unplanned "soft landing" shutdown in ITER, including ITER-like X-point shape with reduced elongation, and low ℓ_i for vertical stability [68]. KSTAR has also demonstrated a safe rampdown scenario in response to off-normal events, using simplified shape and position controls for robustness [69]. In these scenarios as well as in rampdowns of JET plasmas [70], an important feature is the use of modest auxiliary heating to maintain core power balance during the rampdown. JET also utilizes ELM control (vertical kicks and pellet pacing) to minimize impurity accumulation [71].

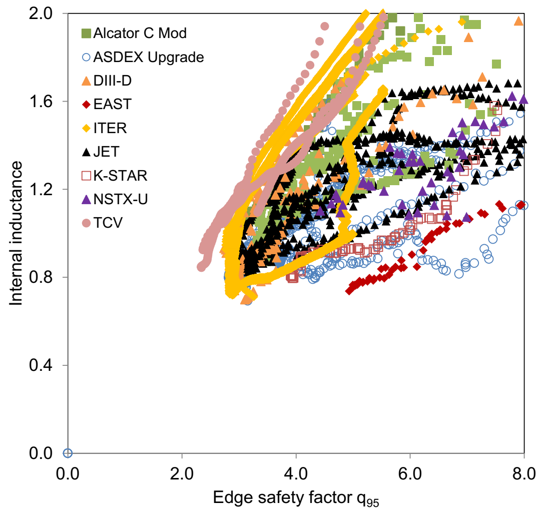

FIG. 10. Multi-machine discharge termination trajectories in q_{95}-ℓ_i space, including modeled ITER rampdown. [Reprinted from P.C. de Vries, et al., Nucl. Fusion 58 (2018) 026019.]

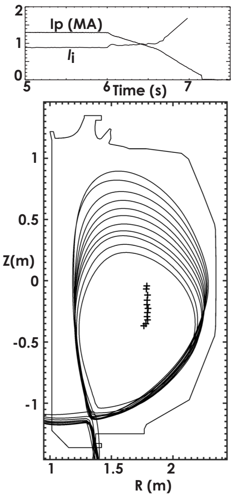

FIG. 11. Stable ITER-like rampdown with X-point configuration, in DIII-D. [Reprinted from J.L. Barr, et al., Proc. 27th IAEA Fusion Energy Conference, IAEA, Vienna (2018), paper EX/P6-21.]

5. INTEGRATED CONTROL

The elements needed to minimize the occurrence of disruptions must be integrated, routine, and highly reliable in ITER. These include robustly stable operation, real-time identification of conditions likely to lead to a disruption, and the means to recover, switch to an alternative operating scenario, or terminate the discharge safely after an off-normal event. –As discussed above, some building blocks are in hand in present experiments, while others are still under development. Conceptual design of exception handling for ITER and its integration into the plasma control system is in progress [7].

Many facilities are now starting to work toward more integrated control as will be needed in ITER. Key actuators are likely to be oversubscribed, and integrated control with actuator sharing has been demonstrated on ASDEX Upgrade [72], [73], and TCV [74], [75] in the use of gyrotrons for simultaneous control of NTMs, beta, and (in TCV) q-profile. As the largest tokamak now in operation, JET faces many of the same issues as ITER. In preparation for the coming D-T campaign, JET has added controls to maintain the required operating point (including isotope ratio), carry out a controlled shutdown if the discharge is not evolving as planned, and trigger the disruption mitigation valve if a disruption is judged inevitable [76]. Work is in progress to ensure integration of these controllers with the rest of the control system [77].

As a demonstration of the path-oriented approach to disruption prevention, TCV has isolated a specific path to disruption – impurity influx leading to an NTM that later locks – and developed controls to address each step of this path [78]. Gyrotrons provided ECCD at the location of the q=2 surface, based on real-time equilibrium reconstructions and ray tracing to provide launcher angles. With detectors for the impurity radiation and the locked mode, the control system avoided NTM locking (if triggered promptly) or suppressed locking and returned to a state with a smaller, rotating island (if triggered after locking). In either case, with a rotating NTM controlled by ECCD, the plasma current, elongation, and EC power were then ramped down to the low plasma current limit of the control system.

DIII-D has implemented an Off-Normal/Fault Response (ONFR) system to handle off-normal plasma events, and hardware faults [79]. Based on finite-state machine logic, the ONFR consists of multiple discrete operating states with rules for the transitions between states; the rules may vary with the state. It provides the supervisory logic for recognition of off-normal conditions and appropriate actions to recover the discharge, change to an alternate mode of operation, or shut down the discharge. The sequence in Fig. 12 shows a discharge with higher β_N and q_{95}, in which the ONFR system employs ECCD (continuous and pulsed) and forced island rotation by an applied n=1 field to limit the growth of an n=1 tearing mode, enabling a stable rampdown without disruption.

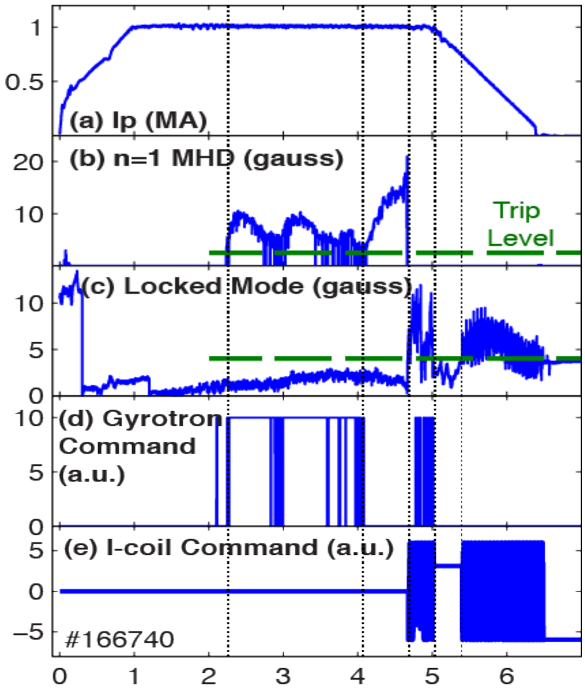

FIG. 12. DIII-D Off-Normal/Fault Response system uses ECCD and I-coils ($n = 1\ \delta B$) to control a tearing mode during rotation, locking, and discharge rampdown. [Adapted from N.W. Eidietis, et al. Nuclear Fusion 58 (2018) 056023.]

6. DISCUSSION

Many of the key elements of disruption-free tokamak operation have been demonstrated in present devices. The challenge for present large and medium-size tokamaks is now to develop these individual elements to become integrated parts of the facility's normal operation, in order to demonstrate robustly stable operation. Development for routine, integrated use over a range of plasma conditions will enhance the reliability and consistency of operation of today's devices, and in addition will drive the physics understanding and control engineering development that is necessary for extension to ITER and other future devices. This work is vital in preparation for disruption-free operation of ITER.

Theory and simulations will continue to be crucial in the development of disruption-free operation. Ideal MHD models have been successful in predicting stability limits and the response to external magnetic perturbations, and kinetic models have extended these capabilities to accurately predict the stability of resistive wall modes. In future work, nonlinear, nonideal models should be further extended, in order to predict the onset, growth, and saturation of metastable or linearly unstable tearing modes, for example, and to guide methods of maintaining or restoring stability through EC power [80], [81] or applied magnetic perturbations [62], [63]. In addition to physics understanding, a key goal of this research should be to validate "reduced" models capable of predicting instabilities in real time.

Work supported by US DOE under DE-FC02-04ER54698, DE-SC0008520, DE-SC0016372, DE-FG02-04ER54761, DE-AC52-07NA27344, DE-SC0015878, DE-SC0014264, DE-FG02-99ER54524, DE-FOA-0001498, DE-AC02-09CH11466, DE-FC02-99ER54512, DE-SC0010720, DE-SC0010492. DIII-D data shown in this paper can be obtained in digital format by following the links at https://fusion.gat.com/global/D3D_DMP.
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