Off-Normal Event Control

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Background:

There is a category of infrequent phenomena collectively known as *off-normal events* or *faults* (ONF) that must be detected and responded to appropriately rather than controlled in the sense of feedback. The most serious are those faults that can cause loss of control of the plasma, which, in certain cases, can have serious consequences for the device itself. We will use the term *plasma terminating event* (PTE) to mean any fault that leads to the loss of the plasma. Not all ONF are a danger to the device; some simply lead to a loss in performance or to a different plasma regime, which may be more or less close to instability than the previous regime. Such faults must also be detected and steps taken to re-establish optimal plasma performance, since performance is a key factor in the economic viability of power-producing reactors, and/or to improve control safety margins.

The ONF can be grouped into three categories:
(1) sensor failure,
(2) actuator failure, or
(3) unexpected loss of stability.

A significant amount of research exists on sensor validation and sensor fault detection, some of it specific to tokamaks. A sensor failure can have serious consequences if no redundancy in sensors is provided. However, the cost to provide this redundancy is likely to be manageable in ITER and in future power-producing reactors, although appropriate methods for intelligently using redundant sensors still need development. Providing redundant actuators, on the other hand, can have a significant impact on the overall device cost. Prevention of all plasma instabilities may not be possible. Methods to detect faults or, preferably, to foresee impending faults and then respond appropriately must be provided to ensure safe operation.

The most serious faults are unexpected loss of control due to actuator or sensor failure or plasma instabilities. In fact, much of the attention paid to ONF at experimental devices has focused on disruptions, but there have been efforts to expand ONF detection and response (ONFD/R) systems to a wider set of faults, particularly the PTE. The most systematic work on a comprehensive ONF system has been been done at ASDEX Upgrade, where efforts have been made to incorporate real-time ONFD/R for several types of faults into routine operation of the device [1]. A source of confusion in this area of research, however, is the fairly widespread tendency to apply the term "disruption" to any PTE. We will use PTE in this document, since the methods required to deal with different PTE (e.g. major disruption versus VDE) or different causes of similar PTE (e.g. plasma instability versus hardware fault) are potentially very different.

A few studies have indicated that the causes of PTE are understandable and can be planned for. Some sources of PTE, such as plasma stability limits and control limits, appear to be predictable and therefore avoidable, although the research is not complete enough to guarantee that this can be done with one hundred percent reliability. Some sources of PTE, such as a power supply fault, an unanticipated shutdown of a control system, or foreign material falling into the plasma, cannot be predicted and therefore must be detected in real time and an appropriate control response applied. Some research has been done in developing methods for detecting PTE, either as it is happening or by its precursors, but this work is far from complete. Methods for avoiding or responding to PTE have also been under development, but are also far from complete solutions.

The Needs of ITER and DEMO:

ITER is an experimental device, which means that new plasma regimes will be explored; with this exploration comes the risk of PTE. It is desirable to have PTE-free operation for ITER, but it is not presently assumed. However, ITER does require that effective PTE avoidance and mitigation techniques be available to protect the device, so that the total number of unmitigated PTE is close to zero. It is reasonable to expect that, over the lifetime of the ITER device, significant knowledge will be accumulated that allows a transition to more PTE avoidance and less PTE mitigation.

While a very small number of unmitigated PTE and an unknown number of unplanned plasma shutdowns due to mitigation may be acceptable for ITER, both are unacceptable for a power-producing reactor. PTE-free operation must be developed before DEMO. A power plant requires steady operation with high reliability. Unplanned interruptions are unacceptable. Risk of damage or erosion of plasma-facing components must be minimized. For example, the ARIES-AT design calls for <1 disruption per year. On the other hand, steady-state operation with high beta for large bootstrap fraction requires operation near stability limits. Thus the capability to avoid PTE must be in hand before a decision to build DEMO. It must be a robust, licensable supervisor system with a quantified performance versus risk. It's not clear that zero shutdowns can be achieved, but the system *must* guarantee personnel and device safety. DEMO must also have methods to restore nominal operation that would be useful for ITER but are not necessarily required.

What Needs to be Done:

A substantial research program involving theory and modeling, development of detection algorithms and response scenarios, and software infrastructure is required to support this development. This research program must have support from multiple existing devices in terms of dedicated experimental time for scenario development and validation, as well as for development, installation, and use of new or redundant actuators and sensors to support the ONFD/R system development and validation. This development will also need experimental time on ITER to demonstrate the solutions developed on other devices in preparation for DEMO.

Detailed Research Needs:

It's useful to think of requirements for ITER as a milestone along the path to providing for the needs of DEMO. In both cases, an integrated system is required for detecting ONF and responding appropriately based on the determined status of the plasma.

- If the plasma is stable and within nominal operating parameter space, no action is required.
- If the plasma is approaching an operational limit or has moved outside of nominal operating conditions, then some action is required to recover nominal, stable operation.
- If the plasma exhibits some form of instability that could lead to a PTE, then active stabilization controls need to be applied.
- If it is determined that available stabilization methods cannot restore stability, then a "soft shutdown" of the plasma should be initiated.
- If it is determined that a soft shutdown cannot adequately protect the device or if there is some failure of device systems that makes a soft shutdown infeasible, then a fast shutdown with mitigation must be performed.

Although there is fairly general agreement on this overall approach for dealing with ONF, present capabilities for ONFD/R are still rather far from what is needed for ITER, much less for DEMO. Aside from the work done at ASDEX [1], there hasn't been a concerted effort to construct the integrated systems for ONFD/R at operating tokamaks. In fact, most of the individual components needed for such a system have not been fully developed. Necessary components of such a system include *realtime*:

- Predictors of plasma stability boundaries.
- Detectors of approach to or violation of stability boundaries.
- Detectors of loss of control from any source.
- Detectors of off-normal conditions such as a parameter outside nominal operating range.
- Methods to detect and deal with degradation or loss of diagnostic information.
- Methods to detect failure or impending failure of actuator and adapt to that failure.
- Methods to detect failure or impending failure of sensor and adapt to that failure.
- Methods for restoring nominal operation.
- Control scenarios for controlled ("soft") shutdowns.
- Solutions for preventing or mitigating device damage, including development of needed actuators.
- Architecture that integrates the multi-layered response described above for the dozens, perhaps hundreds, of possible ONF and the most appropriate response for each layer.

Because of the large number of possible ONF and the variability of required responses due to differing plasma and machine conditions at the time of the fault, the sheer number of detection algorithms and response scenarios required, even for ITER, is huge. The issue of ONF system architecture is also not a trivial one, partly because of the number of potential faults and responses, but also because of the condition-dependent nature of those responses. For example, proximity to a stability boundary may trigger a switch to an avoidance response by the ONF system. If successful, the ONF system would need to then switch to a recovery scenario to return to nominal operation. If not, the system might need to trigger a soft shutdown response, then perhaps a fast shutdown response, every one of these changes of response requiring some customization based on an evaluation of the present state of the system to select the most appropriate response for that state.

Key characteristics of the ONF systems needed for ITER and DEMO are that they must be *complete*, i.e. able to respond to all possible faults that can lead to device damage (and performance loss in DEMO), and they must be *extrapolable* to ITER and DEMO from work done on previously existing devices in such a way as to provide *guaranteed* safety and performance margins. The need for guarantees is driven by licensing requirements for both ITER and DEMO and to demonstrate the economic viability of fusion power in DEMO. Licensing will likely require demonstration that the probability of a device-damaging fault is below some (very low) specified threshold. Economic considerations will likely require that some measure of performance has an average value above one threshold and variance below another. Development of the methods needed to demonstrate these requirements will be a challenge in itself.

Related to this is the need to specify the required performance for both ITER and DEMO. No method for PTE prediction or detection will be perfect. The tradeoff usually considered is in the relative balance between probability of correct detection (P_D) and probability of false alarm (P_{FA}), i.e. incorrectly declaring a (impending or already occurring) PTE. Simultaneous probabilities P_D=1 and P_{FA}=0 are simply not possible. The balance between these two probabilities often comes down to a decision threshold, a change in whose value will cause these two probabilities to move up or down together. The setting of this decision threshold must be driven by the relative cost or risk of incorrect decisions. The cost of a soft shutdown due to a false alarm is likely to be dominated by lost experimental time recovering from the shutdown, while the cost of a missed PTE detection is possible device damage, which may in some cases be catastrophic. Analysis of the relative costs and risks of missed detections versus unnecessary shutdowns must be done to provide a basis for performance metrics.

Significant resources will be needed to develop the required ONF systems for ITER and DEMO. Theory, modeling, and analysis will be required to develop and validate reliable fault predictors and/or detectors. This work can and must be performed on existing devices in such a way as to enable extrapolation to guaranteed performance. The ability to extrapolate solutions to ITER and DEMO from existing devices implies that either theory-based methods (e.g. real-time stability calculations) are required or that some way to extrapolate from data-based methods be developed (e.g. training on simulated data). In either case, substantial effort must be made in improving physics-based models to be truly predictive of the plasma behavior near stability boundaries and during ONF such as disruptions. Validation of the developed methods' performance for ITER will require demonstration of PTE-free operation on long-pulse superconducting devices such as EAST, KSTAR, SST-1, and JT60-SA. Validation of performance for DEMO will need to be shown on ITER or perhaps on an intermediate device between ITER and DEMO. Demonstration on a device such as ITER is critical for DEMO, since there are likely to be issues unique to burning plasmas that cannot be demonstrated on the devices of today.

Significant modeling and experimental work will be needed for development of PTE avoidance, detection, and response scenarios. Dedicated experimental time will be required across a range of operating conditions in multiple facilities. For some response scenarios, new actuators will need to be developed on existing devices and experimentally demonstrated to provide the capability required by the scenario. Scenarios will need to be developed both for ensuring device safety (preventing or mitigating PTE) and for returning to nominal performance from off-normal conditions for the DEMO device.

Work will be also needed to develop the software tools to support the avoidance, detection, and response scenario development and evaluation. This software will need to include logic for transitioning between multiple response scenarios as plasma and device conditions change as well as methods for real-time estimation of the probabilities of impending faults that would be used as the basis for decisions to transition from one scenario to another. Some software work will also be needed to define the most appropriate architecture to implement the working ONF systems on ITER and DEMO. This architecture may or may not be similar to the one used for scenario development.

Work will be needed to develop methods to prevent loss of plasma or plasma performance due to a failure of individual sensors. It is expected that this work would focus on methods exploiting redundancy in diagnostics. However, most existing devices have little redundancy in diagnostics. Therefore, investment in additional diagnostics on existing devices for purposes of redundancy may be required.

Similarly, work will be needed to develop methods to prevent loss of plasma or plasma performance due to a failure of individual actuators. Because actuators are so expensive, a portion of this work must be on the evaluation of the tradeoff between the cost of providing redundancy and the consequences of lost performance or risk to the device if it is not provided. It is expected that the device protection cost/risk tradeoff will drive this evaluation.

There will be some work needed to define real-time computational requirements for an ONFD/R system. For example, it is not clear what calculations are sufficient for real-time instability boundary calculation, but many of the existing calculations of instability boundaries are computationally intensive. More generally, the better the ability to look ahead, the easier it will be to respond effectively to an anticipated ONF. At one extreme, one might imagine running a full predictive simulation in real-time, which would require a huge improvement in real-time computing capability over present technology.

[1] G. Raupp, W. Treutterer, V. Mertens, G. Neu, A. Sips, D. Zasche, Th. Zehetbauer and ASDEX Upgrade Team, Control processes and machine protection on ASDEX Upgrade, Fusion Engineering and Design, Volume 82, Issues 5-14, October 2007, Pages 1102-1110