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# OFF-NORMAL EVENTS IN A FUSION DEVELOPMENT FACILITY

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GENERAL ATOMICS

# A0.3 / A.5: OFF-NORMAL EVENTS

## Issue: Damage Due to Off-Normal Events

Burning plasma devices including ITER, FDF, and DEMO cannot tolerate frequent off-normal events, i.e., unplanned events with the potential to generate large transient heat loads and electromagnetic loads that could damage plasma-facing components. Events in this class include disruptions, edge-localized modes (ELMs), and bursts of lost alpha particles.

**Disruptions.** An unmitigated disruption will contribute significantly to the erosion of plasma-facing surfaces. In addition, a disruption will lead to loss of operating time, in order to assess the cause and consequences of the disruption and then to regain satisfactory operating conditions. Rapid shutdowns generated by a disruption mitigation system must also be minimized, owing to their potential for wall erosion or melting and subsequent downtime.

Many of the attributes of disruptions in FDF are likely to be comparable to those in ITER [1,2], as shown by representative values in Table 1. Given rough estimates of thermal quench times, the thermal energy load per wall area in FDF is somewhat larger than in ITER, but both are below the limit of ~50 $MJ/m^2/s^{1/2}$ for tungsten melting or carbon sublimation. On the other hand, the thermal load per divertor area in both FDF and ITER is well above this limit, suggesting that a single disruption could cause significant erosion of divertor surfaces in either device. The electromagnetic wall pressure, overturning pressure, and vertical force in FDF are estimated to be comparable to or smaller than those in ITER (not shown). The current integrated runaway electron avalanche gain, $G_{RE}=e^{2.5\ Ip(MA)}$, is significantly smaller in FDF than in ITER, but could still lead to potentially damaging runaway currents given a large enough seed population. The mass of injected gas required for collisional suppression of runaways is an order of magnitude smaller than in ITER.

**Table 1**
**Disruption Attributes**

| Device | DIII-D | FDF | ITER |
|---|---|---|---|
| $W_{th}$ = thermal energy (MJ) | 1.5 | 70 | 350 |
| $t_Q$ = thermal quench time (ms) | 0.7 | 1.0 | 2.0 |
| $A_W$ = wall area (m2) | 70 | 100 | 840 |
| $W_{th}/A_W/t_Q^{1/2}$ ($MJ/m^2/s^{1/2}$) | 0.8 | 22 | 10 |
| $A_D$ = divertor area ($m^2$) | 1.5 | 11 | 17 |
| $W_{th}/A_D/t_Q^{1/2}$ ($MJ/m^2/s^{1/2}$) | 38 | 208 | 465 |
| $t_C$ = current quench time (ms) | 3.5 | 6 | 36 |
| $G_{RE}$ = runaway electron gain | $3x10^1$ | $2x10^7$ | $2x10^{16}$ |
| $m_D$ = deuterium mass to achieve Rosenbluth density (g) | 4 | 15 | 133 |

**ELMS.** In "high" confinement mode (H-mode) operation, repetitive ELM instabilities expel plasma thermal energy that impulsively heats divertor plasma facing component (PFC) surfaces. In reactors the ELM power pulses are predicted to melt or erode divertor surfaces and prohibitively limit their service life. A rough estimate summarized in Table 2, shows that the maximum ELM size $\Delta W_{ELM}/W_{ped}$ that can be tolerated without reaching the threshold energy density of 0.5 ($MJ/m^2$) for significant erosion [3] becomes very small in FDF (~5%) and ITER (~1%). For comparison, typical values of $\Delta W_{ELM}/W_{ped}$ ~10-20% are found in present tokamaks with low collisionality plasmas [4]. Consequently, ELMs must be mitigated or eliminated in future burning plasma devices.

**Table 2**
**Estimated ELM Characteristics**

| Device | DIII-D | FDF | ITER |
|---|---|---|---|
| $W_{ped}$ = pedestal energy (MJ) | 0.4 | 20 | 100 |
| Lp = heat flux scrape-off width (m) | 0.010 | 0.007 | 0.005 |
| M = area multiplier for flux expansion and target plate angle | 5 | 20 | 15 |
| $A_{target}$ = effective target area (m2) | 0.4 | 2 | 2.5 |
| $W_{ped}/A_{target}$ (MJ/m$^2$) | 1 | 10 | 40 |
| Maximum tolerable $\Delta W_{ELM}/W_{ped}$ | 50% | 5% | 1% |

**Alpha Particle Bursts**. Present tokamak experiments with Alfvénic instabilities show flattening of neutral beam fast ion profiles and loss of injected beam ions during periods of strong Alfvénic activity [5,6]. This type of redistribution or loss of fusion born alpha particles in a burning plasma experiment could reduce the performance of these devices and potentially damage the first wall. A reliable capability does not yet exist to predict MHD-driven alpha particle loss in burning plasmas. However, as an example, experimental observations and ORBIT code simulations suggest redistribution or loss of ~10-15% of the fast ions during millisecond-scale TAE avalanche events in NSTX [7]. If alpha particle energy represents about 0.1 of the total plasma energy, and if lost alphas were deposited in a 10 cm wide band on the outboard wall, this could yield energy densities approaching the erosion threshold of 0.5 MJ/m$^2$ in both FDF and ITER.

## Research Requirements: Avoidance and Mitigation of Off-Normal Events

Burning plasma devices such as ITER, FDF, and DEMO will require systems to avoid off-normal events, and backup systems to mitigate their effects if they are not avoided. As discussed below, both types of protection systems must function with high reliability.

**Disruption Avoidance**. Several layers of plasma control are required for disruption avoidance (also see the discussion of Control in section A0.2 / A.2). The plasma shape, pressure profile, and current density profile will be controlled to avoid stability limits; for greatest accuracy the stability limits should be calculated in real time with measured plasma parameters. Some instabilities (e.g. neoclassical tearing modes) are amenable to active suppression. Conditions potentially leading to a disruption may still result from unanticipated events such as a sudden influx of impurities or failure of a control actuator. If a disruption threatens, the control system will attempt a controlled shutdown, or “soft landing”. As a last resort, when a disruption is inevitable, the mitigation system will create a rapid shutdown by gas injection or other means.

Requirements for the reliability of disruption avoidance become stringent in steady-state devices such as FDF and DEMO, as shown in Table 3. Here the desired pulse duration and number of pulses were chosen for 1-year campaigns in ITER (Q=10 inductive operation), FDF (2-week pulses) and DEMO (continuous burn). Suggested requirements are shown for the number of fast shutdowns and number of unmitigated disruptions per year. That the number of fast shutdowns exceeds the number of pulses for FDF and DEMO means that it is acceptable for a long burn to be interrupted by an occasional fast shutdown, provided that the recovery time is short compared to the desired pulse duration.

A **major remaining challenge** is the development of control algorithms that achieve the very low rates of fast shutdowns in Table 3 – with fast, accurate assessment of the plasma stability, followed by appropriate decisions that maintain or recover stable operation. Identification of situations requiring the mitigation system must also be accurate, avoiding false positives that will themselves lead to divertor erosion and downtime. A few rudiments exist in present facilities, such as feedback control of plasma pressure and soft shutdown in the event of a growing tearing mode. However, a focused, long-term research program is needed in order to develop a comprehensive, integrated, accurate, and reliable system that can ultimately achieve the very long times between fast shutdowns indicated in Table 3. Present short-pulse tokamaks can contribute much of the development of disruption avoidance algorithms. It will remain for the newer generation of tokamaks, EAST, KSTAR, SST-1, and JT-60SA, to demonstrate very low disruption rates in an ITER-like environment of long-pulse operation and superconducting coils.

**Table 3**
**Requirements for Disruption Avoidance (Per Year)**

| Device | ITER | FDF | DEMO |
|---|---|---|---|
| Pulse length (s) | 400 | $1 x 10^6$ | $3 x 10^7$ |
| Number of pulses per year | 1000 | 10 | 1 |
| Fast shutdowns per year | 100 | 20 | 5 |
| Required time between fast shutdowns (s) | $4 x 10^3$ | $5 x 10^4$ | $6 x 10^6$ |
| Unmitigated disruptions per year | 5 | 1 | 0.3 |

**ELM Avoidance.** Some method or combination of methods must be developed and ready to use for DEMO, to limit ELM thermal pulses to levels compatible with divertor PFCs. In general, the method(s) *must* be very highly reliable, and they must be effective over the *full* *range* of H-mode operating conditions during which ELMs might occur. The method(s) must not unacceptably degrade plasma confinement and stability. Suggested solutions include:

1. Develop a high-confinement, ELM-free operating mode, such as QH-mode, to a fusion relevant level.
2. Reduce ELM sizes, typically by triggering frequent small ELMs by means such as pellet injection or time-varying magnetic fields.
3. Reduce the plasma pressure and electric current free energy sources that drive Type I ELMs, notably by non-axisymmetric resonant magnetic perturbations (RMPs) to increase edge transport in a controlled way.
4. Use liquid plasma facing divertor surfaces.
5. Operate in ELM-free "low" confinement L-mode.

The last choice results in larger, more expensive fusion reactors. Here, we focus on ELM control by RMP coils.

For ELM suppression by RMP coils, many of the physics questions about how the method works and how to exploit it effectively should be answered by further experiments on existing conventional tokamaks (DIII–D, JET, AUG); STs (MAST, NSTX); and new superconducting magnet tokamaks (EAST, KSTAR, JT60-SA). However, further development may be required in ITER, presumably using low energy content plasmas in order to limit ELM damage to PFCs. The ITER experience will be passed on to FDF and DEMO.

Engineering challenges for an RMP-based ELM suppression system include

- Reliability, including survival of insulators in a high neutron fluence environment
- Redundancy that continues to provide ELM suppression if a few coils fail
- Remote maintainability

Provision must be made for a prompt shutdown of the discharge in the event of a failure of ELM suppression.

**Alpha Burst Avoidance.** Strategies for avoidance of potentially damaging bursts of alpha particle loss are likely to depend on control of pressure and current density profiles, in order to avoid (if possible) the multiple-resonance condition that can lead to avalanche events. A recent result [8], not yet fully understood, shows suppression of Alfvénic activity by localized electron cyclotron heating near the minimum of the q-profile, in plasmas with reversed magnetic shear as would be found in FDF or advanced scenarios in ITER.

A reliable predictive capability does not yet exist for alpha-driven instabilities and their effect on alpha particle transport. The ratio of the fast ion velocity to the Alfvén velocity, the ratio of Larmor radius to plasma minor radius, and the degree of anisotropy of the fast ion velocity distribution are key dimensionless parameters that differentiate ITER, FDF, and burning plasmas in general from present day and near future tokamak devices. (Also see the discussion of Alpha Particle Physics in section A0.4.) Therefore, only partial tests of fast ion instability and transport models are possible in present day experiments, and thorough tests will rely on burning plasma experiments like ITER and FDF.

**Mitigation of Off-Normal Events.** A backup system will avoid damage to plasma-facing components in the event that the avoidance strategies fail. Because a single disruption can have significant consequences, a rapid shutdown must be provided before the disruption. A disruption mitigation system that operates with 95% to 99% reliability will result in only a handful of unmitigated disruption per year in ITER, and even fewer for FDF and DEMO. The hardware elements of the mitigation system should readily achieve this level of reliability, if sufficient redundancy is built in. As indicated above, a critical element is the development of integrated, accurate, and reliable control systems that will avoid frequent need for rapid shutdowns.

Development is still needed to find the best set of actuators for disruption mitigation [9]; present and proposed candidates include

- Gas injection
- Cryogenic pellets
- Solid pellets
- Liquid jets
- Plasma jets
- Magnetic perturbations (in conjunction with mass injection)

Actuators for disruption mitigation and the control algorithm to decide when to trigger them are problems that must be solved before ITER begins high power operation. Present facilities can and should contribute most of this research. Work is in progress, primarily in DIII-D, Alcator C-Mod, ASDEX-Upgrade, JET, and TEXTOR, to assess the candidates for disruption mitigation actuators. The strongly exponential nature of the runaway avalanche process implies that it will be important to validate disruption and runaway electron mitigation at the highest available plasma currents (e.g. JET and JT-60SA) and with plasma energy densities approaching those of ITER and FDF.

If avoidance of ELMs or intense alpha bursts is not successful, remedial action must be taken promptly. A small number of such events may be tolerable, allowing the discharge to be brought to a "soft landing". The rapid shutdown system described above for disruption mitigation would serve as a last resort. Again, control algorithms must be developed in present facilities.

## Research Thrust: FDF

Because a single disruption can have significant consequences, much of the necessary development for disruption avoidance and mitigation must be done before ITER and FDF begin high power operation. However, as indicated in Table 3, the requirements for disruption avoidance in FDF are intermediate between those of ITER and DEMO. Therefore, FDF provides a unique opportunity to demonstrate **disruption-free operation in a true steady-state burning plasma**, before proceeding to DEMO.

The physics of RMP ELM control should also be largely resolved by the time FDF operates. However, FDF can make an important contribution to ELM control in DEMO through experience in the **design and operation of coils with a lifetime neutron fluence 10 times greater than ITER** (but ~0.1 times the DEMO fluence). The neutral beams envisioned for FDF also make it better suited than ITER for study and development of QH-mode operation in a burning plasma.

FDF has an important role to play in avoidance and mitigation of alpha particle bursts. The instabilities that drive such bursts are sensitive to the q-profile. FDF is expected to operate primarily in the regime of high beta and weak or reversed magnetic shear that is envisioned for an ARIES-AT class of DEMO facility. Therefore, FDF will provide a better opportunity than ITER to study **alpha-driven instabilities and transport in advanced-scenario burning plasmas**.

Finally, a key feature of FDF is the demountable TF coil that allows the blanket and other internal elements to be changed by remote handling. Such changes may be required, for example, to maintain or upgrade ELM control coils and other systems intended to withstand, avoid, or mitigate off-normal events. This **flexibility of response to off-normal events** is essential as part of the learning process before DEMO is built and operated.

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