Off-normal Events in a Fusion Development Facility

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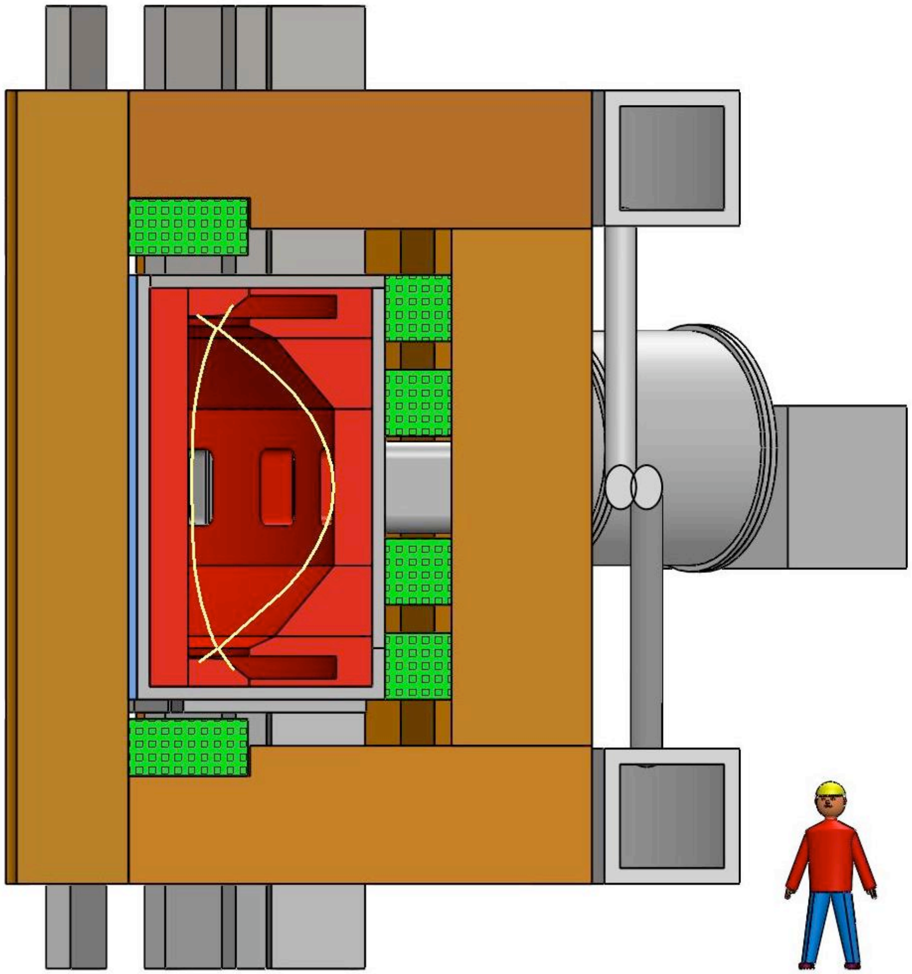
General Atomics



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A burning plasma must avoid off-normal events with high reliability

- **Off-normal events including**
  - Disruptions
  - Runaway electrons
  - Edge-Localized Modes
  - Bursts of α-particle loss

  can have severe consequences including
  - Large electromagnetic loads
  - Erosion of plasma-facing surfaces
  - Intense localized heating of plasma-facing components
  - Loss of operating time

- **These events must be reliably avoided in a burning plasma**

- **Effective and reliable mitigation systems must be in place for the rare occurrences where avoidance is not possible**

A disruption will lead to erosion of plasma-facing surfaces

Device	DIII-D	ITER	FDF
W_{th} = thermal energy (MJ)	1.5	350	70
t_Q = thermal quench time (ms)	0.7	2.0	1.0
$W_{th}/A_W/t_Q^{1/2}$ ($MJ/m^2/s^{1/2}$) – main chamber	0.8	10	22
$W_{th}/A_D/t_Q^{1/2}$ ($MJ/m^2/s^{1/2}$) – divertor	38	465	208
t_C = current quench time (ms)	3.5	36	6
$G_{RE} = e^{2.5\ Ip(MA)}$ = runaway electron gain	3×10^{1}	2×10^{16}	2×10^{7}
m_D = D_2 mass to achieve Rosenbluth density (g)	4	133	15

- **Average wall heat load approaches the ~50 MJ m^{-2} $s^{-1/2}$ limit for tungsten melting or carbon sublimation**
- **Runaway electron gain in FDF < in ITER, but still large**
- **Electromagnetic loads in FDF expected ~ITER (not shown here)**

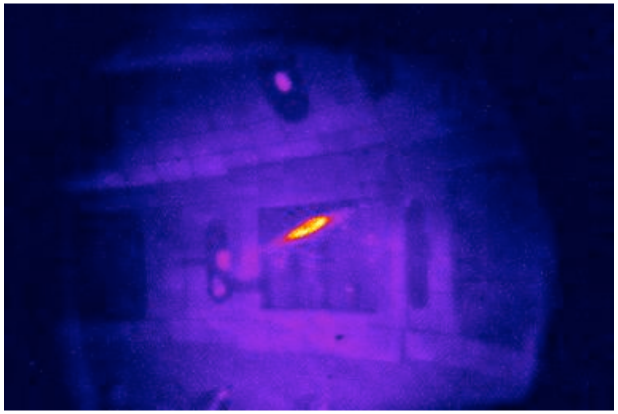
Disruption avoidance requires multiple levels of protection

Plasma configuration →	Multivariable shape control	Current, pressure profile control	Rotation profile control
Detect stability limits →	Real-time beta measurements	Real-time MHD damping rate	Real-time stability code
Actively suppress instabilities →	NTM stabilization (ECCD)	Rotation, error field control	RWM feedback (int./ext. coils)
Growing instability: soft shutdown →	Action depends on plasma state	Change heating, fueling	Radiated power (small pellets)
Onset of disruption: fast shutdown →	High-pressure gas jet, liquid jet	Large pellets: High-Z, Low-Z	Magnetic perturbations

These features must become integrated and routine!

Rapid-shutdown system will avoid damage to plasma-facing components

- **Further development needed in present and future facilities**
- **Candidate actuators include**
  - Gas injection
  - Cryogenic pellets
  - Solid pellets
  - Liquid jets
  - Magnetic perturbations



- **Gas injection in present devices has reduced thermal and electromagnetic loads**
  - Runaway electron suppression is the remaining challenge: requires an order of magnitude greater quantity of gas
- **Fast shutdown for ITER or DEMO requires ~99% reliability**
  - Hardware reliability achievable with sufficient redundancy (e.g. 5 systems of 95% reliability, of which any 3 are sufficient)

Conditions leading to disruptions must be avoided with high reliability

Typical requirements for disruption avoidance

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

- **Accurate, reliable control algorithms are a critical element**
- **High availability ➔ the fast shutdown rate must be kept low**
  - A few fast shutdowns during an extended burn may be acceptable if recovery time is << burn duration
- **Fast shutdown system must act with ~99% reliability for a low rate of unmitigated disruptions**
  - Hardware reliability achievable with sufficient redundancy

Multiple ELMs will lead to rapid erosion of divertor targets

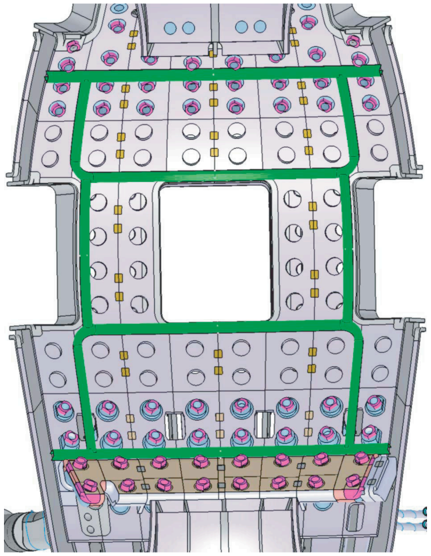
Estimated ELM characteristics

Device	DIII-D	ITER	FDF
W_{ped} = pedestal energy (MJ)	0.4	100	20
Lp = heat flux scrape-off width (m)	.010	.005	.007
M = multiplier for flux expansion, target angle	5	15	20
A_{target} = effective target area (m^2)	0.4	2.5	2
W_{ped}/A_{target} (MJ/m^2)	1	40	10
Maximum tolerable ELM size $\Delta W_{ELM}/W_{ped}$	50%	1%	5%

- **ELM size to avoid threshold ~0.5 MJ/m^2 for erosion becomes very small in ITER and FDF**
  - $\Delta W_{ELM}/W_{ped}$ up to 10-20% observed in present tokamaks

Reliable ELM control must be available over the full range of expected H-mode operation

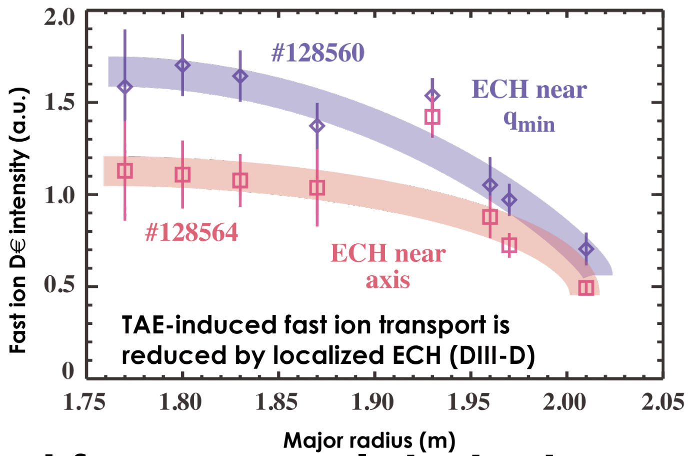
- **Candidate methods for ELM control include**
  - ELM-free, high-confinement operating mode (e.g.QH-mode)
  - ELM pacing with pellets or magnetic perturbations ➔ small ELMs
  - Resonant magnetic perturbation (RMP) to increase edge transport
  - Liquid divertor targets
  - ELM-free "low" confinement L-mode



- **Engineering challenges for RMP coils include**
  - Reliability in high neutron fluence environment
  - Redundancy against failure of a few coils
  - Remote maintainability
- **Rapid shutdown may be required in the event of a failure of ELM suppression**

Bursts of lost alpha particles may cause localized heating and erosion of PFCs

- **Alfvenic instabilities cause msec time-scale redistribution or loss of up to 10% of fast ions in existing experiments**
  - Localized deposition of lost α's could cause erosion
- **A reliable capability does not yet exist to predict MHD-driven alpha particle loss in burning plasmas**
- **Control is likely to occur through pressure, current density profiles**
  - TAE suppression by localized current drive has been observed



- **Burning plasma experiments are needed for a complete test of models for fast ion instabilities and transport**
  - Beam-injected or RF-heated fast ions cannot fully reproduce the characteristics of a fusion α-particle population

Research needs for avoidance of off-normal events

- **Techniques for avoidance and mitigation of off-normal events must be available for high-power operation of ITER**
  - Real-time stability assessment and control
  - Physics of ELM suppression
  - Procedures for soft shutdown
  - Actuators for rapid shutdown
- **Much of the development will be done in existing facilities and during low-power operation of ITER**
- **One major remaining challenge is development of control algorithms that achieve very low rates of rapid shutdowns**
  - Fast, accurate assessment of plasma stability
  - Procedures to maintain or recover stable operation
  - Accurate identification of conditions requiring rapid shutdown

A Fusion Development Facility fulfils a unique role in demonstration of sustained fusion power

- **DEMO represents a large leap from ITER in pulse length, neutron fluence, and (probably) tolerance of disruptions**
- **FDF can fill this gap, providing an opportunity for**
  - Disruption-free operation in a true steady-state burning plasma
  - Design and operation of RMP coils in a high neutron fluence
  - Study of alpha-driven instabilities and transport in steady-state, advanced-scenario burning plasmas
  - Flexibility of maintenance and modification in response to off-normal events and needs for their control