Requirements for triggering the ITER Disruption Mitigation System

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Disclaimer: This presentation includes new directions for management of disruptions that are not yet introduced into the ITER technical baseline. These results don’t commit the nuclear operator. The views and opinions expressed in this paper do not necessarily reflect those of the ITER Organization.
Introduction

A disruption of the tokamak discharge is an unfortunate phenomenon, in which the control and confinement of the plasma is lost within a very short duration.

The fast release of plasma energy could result in large thermal and electromagnetic loads that may affect the lifetime of its components.

Therefore, such events should be avoided and otherwise mitigated.
Disruption avoidance, prediction and mitigation

The following aspects are relevant to disruption avoidance

- **Detailed preparation and validation of tokamak operations**
  *before a discharge*

- **Continuous analysis to resolve problems and optimize further operations**
  *after a discharge*

- **Real-time event detection and control/avoidance/termination by PCS**
  *during a discharge*

Disruption prediction

- **However if a disruption is inevitable, the last line of defense at ITER is to trigger the disruption mitigation system (DMS).**
Scope of this presentation

The term ‘disruption prediction’ can have a too broad interpretation.

This presentation will discuss the requirements specifically to trigger the ITER disruption mitigation system (DMS)

To develop these requirements the following questions need to be answered:
- What is a disruption and how can they be detected?
- What mitigating techniques will be applied?
- What is their impact and what are the device design limits?
- How many disruptions are to be expected and can be tolerated?
- How will ITER be operated?

Information relevant to the requirements for the DMS trigger will be indicated in red on various slides.
What is a disruption?

A tokamak disruption is made up out of several different facets, and the order in which they appear may differ:

- Vertical displacement event (VDE) ➔ loss of VS
- Thermal quench (TQ) ➔ loss of confinement
- Current quench (CQ) ➔ too high a resistivity
- Runaway electrons (REs) ➔ too fast a CQ

The following variants can occur …
What is a disruption?

**Minor disruption** starts with TQ but is not followed by CQ.
What is a disruption?

Major disruption starts with a TQ followed by CQ (and possibly VDE, RE)
What is a disruption?

- **Hot VDE** starts with a VDE which triggers a TQ and CQ (and possibly RE)

Note that, besides these main three, further variants exist.
How can these events be detected?

For a predictor one may first think of disruption precursors, but for a trigger to the DMS, the most obvious might be the detection of the disruption itself:

- **VDE** → Detect maximum vertical excursion $\Delta z_{\text{MAX}}^{[1]}$
- **CQ** → Detect large $|dl_p/dt|^{[2]}$
- **TQ** → Too fast and prediction required.

Variants of the first two schemes are used on several devices and it has been shown that such triggers could be sufficient to still properly mitigate forces and some of the heat loads$^{[2]}$.

A disruption is either initiated by a TQ or a VDE, hence the detection/prediction of both a VDE and TQ are essential for the trigger.

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Detection/prediction of a VDE

DIII-D: increasing elongation in a single discharge to increase growth rate $\gamma_Z$ until VDE

Uncontrollable VDE occurs at$^1$:

$$\frac{\Delta Z_{\text{max}}}{<Z>_{\text{noise}}} \sim 2–3$$

Consistent with controllability threshold DIII-D:

- VS control lost at $\frac{\Delta Z_{\text{max}}}{a} \sim 2\%$ (red dashed line)
- Typical $<Z>_{\text{noise}}/a \sim 0.7\%$ \(\Rightarrow\) $\frac{\Delta Z_{\text{max}}}{<Z>_{\text{noise}}} \sim 3$

Projecting evolution of $\Delta Z_{\text{max}}$ via simulations can predict impending loss of controllability!

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Prediction of the TQ

Requires a highly reliable and timely prediction that a TQ is inevitable and no other control options, but DMS are possible.

There are a number known precursors to precede a TQ, such as the growth of large magnetic islands, ideal kink modes, etc.

Prediction of the TQ

Requires a highly reliable and timely prediction that a TQ is inevitable and no other control options, but DMS are possible.

Improving the physics basis for these individual TQ precursors allows transfer of thresholds to future devices, such as ITER.

How to mitigate their impact?

Traditionally the thermal and electromagnetic loads due to disruptions are mitigated by the massive injection of high Z impurities (Neon or Argon)

Done either in the form of gas mixtures (Massive Gas Injection, MGI\(^{[1,2,3]}\)) or by shattering pellets (Shattered Pellet Injection, SPI\(^{[4]}\)).

The high Z impurities will:
- increase radiation and reduce the energy that is convected to PFCs.
- affect the post TQ resistivity and thus affect the CQ duration.
- affect the generation of runaway electrons.

How to mitigate their impact?

The ITER Disruption Mitigation System (DMS) is currently being designed (CDR completed in 2012) will have multiple (individual) injectors (a MGI and SPI hybrid) grouped together on different ports\[1\].

When triggered, the DMS should be told how to fire, i.e. which individual injector, for example, to avoid radiation asymmetries.

How to mitigate their impact?

The ITER Disruption Mitigation System (DMS) is currently being designed (CDR completed in 2012) will have multiple (individual) injectors (a MGI and SPI hybrid) grouped together at different ports[1].

Typical reaction times[2]:
- Delivery time by SPI:
  \[ \Delta t_{\text{actuator}} = 25-30\text{ms (UPP)}, \Delta t_{\text{actuator}} = 15-20\text{ms (EPP)} \]
- Delivery/pre-TQ time by MGI:
  \[ \Delta t_{\text{actuator}} = 10-15\text{ms (UPP)} \text{ or } 2-3\text{ms (from inside PP)} \]

Hence, a working assumption for the minimum trigger time is approximately \( \Delta t > 30\text{ms}. \)

What impact is to be expected at ITER?

A disruption has different facets and therefore also can impact the device in multiple ways and there are different tolerances for each of them:

- Heat loads due to the fast release of the thermal energy (TQ)
- Heat loads due to the release of part of the magnetic energy (CQ)
- Heat loads due to the impact of runaway electrons (REs)
- Forces due to too fast a CQ and eddy current forces
- Forces due to too slow a CQ with respect to the VDE
What impact is to be expected on ITER?

**Thermal loads**
Caused by the loss of magnetic energy (CQ), the fast loss of thermal energy (TQ), and impact due to possible runaway electrons (REs).

- Even for low current ($I_p=5-6\text{MA}$) a CQ can lead to local melting\(^1\).

- From $I_p=5-6\text{MA}$ heat loads need to be mitigated.

- At TQ a $W_{th}=25\text{MJ}$ can lead to shallow melting of the inner divertor\(^1\).

  Timely prediction of a TQ is needed for $W_{th}>25\text{MJ}$.

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\[1\] M. Lehnen, et al., Proc. PSI conference (2014, Japan)
What impact is to be expected at ITER?

Electromagnetic forces

- Fast current quenches (CQ) lead to large eddy current forces
- Too slow a CQ with respect to the VDE leads too large halo current forces
Balancing halo and eddy current forces

During the start-up of ITER operations, the disruption load models need to be confirmed experimentally.

DMS should be given information how to fire, such as to optimize the CQ rate and hence, balance the halo and eddy current forces.
How many can be tolerated over ITER life-time?

Above about $I_p = 8.4$ MA, it is possible for unmitigated disruptions to enter the Cat. III range\[1\].

\[1\] M. Lehnen, et al., Proc. PSI conference (2014, Japan)
Disruption accounting and prediction performance

\[ N_{\text{non-disruptive}} + N_{\text{false}} + N_{\text{correct}} + N_{\text{late}} + N_{\text{intent.}} = N_{\text{pulses}} \]

- \( N_{\text{mitigated disr.}} \)
- \( N_{\text{natural disr.}} \)
- \( N_{\text{unintentional disr.}} \)
- \( N_{\text{disruptions}} \)

* The number of false alarms can only be assessed with non-active predictor
Disruption accounting and prediction performance

The prediction performance can be defined by:

- $R_{\text{prediction}} \Rightarrow \frac{N_{\text{correct}}}{N_{\text{unintentional disr.}}}$
- $R_{\text{late}} \Rightarrow \frac{N_{\text{late}}}{N_{\text{unintentional disr.}}}$
- $R_{\text{false}} \Rightarrow \frac{N_{\text{false-alarm}}}{(N_{\text{pulses}} - N_{\text{intent.}})}$
- $R_{\text{unintentional disr.}} \Rightarrow \frac{N_{\text{unintentional disr.}}}{(N_{\text{pulses}} - N_{\text{intent.}})}$

$$N_{\text{non-disruptive}} = N_{\text{false}} + N_{\text{correct}} + N_{\text{late}} + N_{\text{intent.}} = N_{\text{pulses}}$$

* This assumed that a correct trigger to DMS ensures a proper mitigation
Disruption accounting and prediction performance

The prediction performance can be defined by:

- $R_{\text{prediction}} \Rightarrow \frac{N_{\text{correct}}}{N_{\text{unintentional disr.}}}$
- $R_{\text{late}} \Rightarrow \frac{N_{\text{late}}}{N_{\text{unintentional disr.}}}$
- $R_{\text{false}} \Rightarrow \frac{N_{\text{false-alarm}}}{(N_{\text{pulses}} - N_{\text{intent.}})}$

Their requirements depend on:

- How many unmitigated disruptions can be tolerated? $R_{\text{tol}} = \frac{N_{\text{tol}}}{N_{\text{pulses}}}$
- How many and what kind of pulses will be scheduled? $N_{\text{pulses}}$
- How many disrupt? disruption rate $R_{\text{natural}}$ or $R_{\text{unintentional disr}}$

The false alarm rate should not dominate the disruption rate: $R_{\text{false}} < 0.5 R_{\text{natural}}$
Disruption accounting and prediction performance

The disruption rate is determined by the success of the avoidance methods and therefore the prediction requirements are too.

For low tolerances (i.e. 1-2 events in 10000 pulses), even for very low $R_{\text{diss}}$, the prediction performance should be $R_{\text{prediction}} > 98-99\%$.
How many disruptions are to be expected?

This requires information on how ITER is going to be operated ➔ define the operational/research plan.

Below, a rough outline of ITERs progressive start-up, a possible path from low current non-active operation to full performance active operation[^1].

[^1]: D. Campbell, The ITER Research Plan
How many disruptions are to be expected?

The disruption rate is determined by the success of the avoidance methods.

One can set reasonable targets for ITER operation\([1,2]\), based on experience from present day devices, such as JET.

![Graph showing the relationship between plasma current (MA) and the number of pulses](image)

\[1\] M. Sugihara, et al., 24th IAEA FEC (2012, San Diego)
\[2\] P.C. de Vries, Nucl. Fusion 51 (2011) 053018
Required performance

Although the design limits are well known, the tolerances to lower disruption impact, such as shallow melting due to a TQ, are not easy to assess.

The detection and prediction performance and false alarm rate have been calculated based on a simple estimate of tolerable number of disruptions$^{[1]}$.

Prediction requirements differ for each operational phase.

$^{[1]}$ M. Sugihara, et al., 24th IAEA FEC (2012, San Diego)
Disruption prediction development

- First operations: medium requirements \( R_{\text{predict}} < 80\% \) and \( R_{\text{false}} \approx 10\% \)
  Can be achieved by simple, physics based disruption thresholds
  \( \Rightarrow \) 1st level of prediction

- For \( I_p=15\text{MA} \) operations \( \Rightarrow \) high requirements \( R_{\text{pred.}} > 98\% \), \( R_{\text{false}} \approx 2.5\% \).
  Currently are only achieved by advanced predictors\(^1\).
  \( \Rightarrow \) 2nd level of prediction

\[ \text{At ITER may have time to develop/assess disruption prediction} \]

\(^1\) J Vega, et al., Fus. Eng Des. 88 (2013) 1228
## Prediction and detection of disruptions

**Different levels of the DMS trigger**

<table>
<thead>
<tr>
<th>Detection of the disruption itself (VDE, CQ)</th>
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<tbody>
<tr>
<td><em>fall back option</em></td>
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<th>Simple prediction of TQ or VDE</th>
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<tr>
<td><em>first level of prediction</em></td>
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<th>Balancing input from advanced predictors and forecasting methods by PCS</th>
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<tr>
<td><em>second level of prediction</em></td>
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</table>
Requirements list

Heat loads due to the CQ need to be mitigated from $I_p=5$-6MA.

Timely prediction of VDEs and TQ (for $W_{th}>25$MJ) is needed.

A working assumption for the minimum trigger time is $\Delta t >30$ms.

DMS should be given information how to fire.

False alarms should not dominate the disruption rate: $R_{\text{false}} < 0.5 \ R_{\text{natural}}$

For early operations, lenient performance req. $R_{\text{predict}} < 80\%$, $R_{\text{false}} < 15\%$

But for higher currents ($I_p>8.4$MA): $R_{\text{predict}} > 98\%$ and $R_{\text{false}} < 2.5\%$

ITERs progressive start-up may allow time to develop disruption prediction.
Summary

A disruption is made up of different facets (VDE, TQ, CQ, REs) that each develop on different time-scales and create different impacts, to which the device will have different tolerances. Therefore the prediction/trigger requirements may have to be determined per impact type.

Often the scope of ‘disruption prediction’ is too broadly defined. The requirements for event detection/prediction can only be determined clearly, if the event and its related actions are well defined.

This presentation aimed to give basic requirements of the trigger to the ITER DMS. Further details will depend on,

- final design of the DMS,
- development of mitigation physics,
- improved tolerance assessment
- detailing of the operation schedule/research plan.