Disruption study advances in the JET metallic wall

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* See the Appendix of F. Romanelli et al., Proceedings of the 25nd IAEA Fusion Energy Conference 2014, Saint-Petersburg, Russia.
Disruption is the highest risk for ITER operation

- The domain where mitigation is not required is very small (I_p<5MA; W<25MJ).
- High current operation requires high mitigation success rate (EM loads).
- High efficiency >90% needed at high energies.

Lehnen et al., EX/P6-39
JET disruption rate has dramatically increased with the ITER-like wall

- Disruption rate with the JET-C: ~3.4%
- Operation with ILW showed a marked increase in disruption rate.

Massive gas injection mandatory in JET operation for:
- Ip > 2MA OR
- $W_{TH} + W_{MAG} > 5MJ$

JET has led a significant programme on disruption mitigation physics in the past 5 years.
Outline

- JET disruption mitigation system (DMS)
- Optimisation of disruption mitigation
- Disruptions radiation asymmetries
- Disruption prediction/avoidance
- Run-aways mitigation and outlook for 2018-2019
JET is equipped with a comprehensive disruption mitigation system (DMS)

<table>
<thead>
<tr>
<th>DMV1</th>
<th>Upper port</th>
<th>4.6m to LCFS</th>
<th>1.8ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMV2</td>
<td>Horiz. port</td>
<td>2.8m to LCFS</td>
<td>1.0ms</td>
</tr>
<tr>
<td>DMV3</td>
<td>Upper port</td>
<td>2.4m to LCFS</td>
<td>0.8ms</td>
</tr>
</tbody>
</table>

D2+ 10%Ar

The fast camera can be equipped with Argon filter

Error field correction coils

U. Kruezi, SOFT 2015
EM forces can be mitigated up to 30-40% for a given magnetic configuration.

- Vertical force measured by strain gauges on the vessel support.
- Independent from the DMV location.
- Note that $F_v$ is not purely the result of halo current but may also include forces induced by Eddy currents and poloidal coils.

For ohmic plasmas:

- DMV1: $1.710^{22}$ Ar
- DMV3: $3.510^{20}$ Ar
- DMV2: $5.910^{22}$ Ar

For ohmic plasmas:

- $F_v (MN)$
- $I_p^2 (MA^2)$

$3.5MA$

*S. Jachmich, PSI & EPS 2016*
Disruption efficiency does not depend on plasma current and $q$

- Below an Argon quantity less than $\sim 2.10^{20}$, the efficiency of the disruption mitigation decreases dramatically.
- Radiation fraction degradation at the current quench does not depend on plasma current nor safety factor.
- This is observed for both horizontal and vertical bolometers.

$\exists$ Impact of massive gas injection on operation (gas inventory, cryogenic, conditioning) can be minimised.

V. Riccardo, 2016
Radiative gas quantity is a key parameter for improving disruption mitigation efficiency

- Argon quantity is a key parameter for controlling the disruption time.
- DMV1 looks slightly less efficient than the new DMVs closer to the plasma.
- The current quench duration is decreasing with the quantity of injected Argon.
Radiative energy fraction at disruption degrades with the thermal energy fraction

- The mitigation efficiency degrades with the thermal energy.
- The drop is less severe at high Argon injection amount.
- DMV3 looks slightly more efficient than the other DMVs.
- This decay indicates that the mitigation is less efficient during TQ.

\[ f_{\text{RAD}} = \frac{W_{\text{RAD}}}{(W_{\text{MAG}} + W_{\text{TH}} - W_{\text{COUPLED TO COILS}})} \]

\[ f_{\text{TH}} = \frac{W_{\text{TH}}}{(W_{\text{MAG}} + W_{\text{TH}} - W_{\text{COUPLED TO COILS}})} \]

Integrated over the disruption sequence

\[ \Rightarrow \text{At the TQ a significant fraction of the thermal energy can be lost by conduction when the plasma becomes stochastic.} \]

S. Jachmich, PSI & EPS 2016
Mitigation produces a chain of magnetic islands leading to ergodisation at TQ

Ad-hoc gas source adjusted to match interferometry data

3D gas flow simulation

3D non-linear MHD Neutral included \( \eta = 2-20 \times \text{Spitzer} \)

JOREK simulation at the thermal quench with D2 only

OR

E. Nardon, PPCF 2016

2/1 island \( \Rightarrow \) chain of island \( \Rightarrow \) stochatization \( \Rightarrow \) loss of thermal energy at TQ
DMV can create radiation asymmetry: island O-point is “attracted” at DMV location

Cold front produced by DMV $\Rightarrow$ Local resistivity increase $\Rightarrow$ Local suppression of current profile $\Rightarrow$ Drives the island with O-point close to injection location

Note: this effect is not observed in NBI-heated plasma (i.e. with rotation)
The n=1 mode creates toroidal radiation asymmetries

- The phase of the n=1 mode on radiation asymmetry can be imposed at JET using the EFCC polarity to seed the mode.
- Radiation asymmetries are observed when the toroidal location of seeded n=1 mode is changed.
- The radiation asymmetry is larger for injection into the O-point of the island.
Radiation peaking determined by 1/1 phase and massive gas injection

\[ n_i \text{ from DMV} \times \frac{\text{Pradmax}}{\langle \text{Prad} \rangle} \]

Lehnen Nuc Fus, 2015
Dual DMV injection could lead to the reduction of radiation asymmetries

Gas amount varied by timing DMV3

- Dual injection with opposite DMVs:
  - The reduction of radiation asymmetry is very sensitive to the relative DMV timing (<0.5ms)
  - There is a reproducible sweet spot for which radiation asymmetry is close to 0.
  - Still unexplained presently by the analysis (additional data collected last week).

Drewelow, 2016
Disruption predictor not requiring advanced training is installed in JET.

Cumulative fraction of detected disruptions

- Tested on 1738 JET-ILW pulses and 566 unintentional disruptions with the JET-ILW.

In JET-ILW H-mode scenario development, more than 50% of the disruption cause is core radiation.

=> Earlier alarm required for disruption avoidance in the JET-ILW should include signals representative of the disruption root causes radiation peaking, MHD precursors...

Lock-mode amplitude threshold detector

- Former predictor relying on training of several signals including locked-mode (FEC 2014)

New predictor (WITHOUT TRAINING) based on anomalies in the locked mode signal data flow.
Magnetic perturbations are inefficient in mitigating run-aways in JET.

- EFCC and TF–ripple do not lead to a reduction of RE population in JET
- Relativistic (5-20MeV) electron particle motion modelling predicts no stochastization of trajectories at maximum EFCC coil currents.
In JET Massive gas injection is also inefficient in mitigating run-aways

- Massive gas injection inefficient at JET for mitigating RE for different gas (Ar, Kr, Xe,...) and pressures.
- Run-away beam can be mitigated by MGI in DIII-D, Tore Supra and ASDEX Upgrade.
- Hypotheses: the machine size or the surrounding plasma has a screening effect.

- JET experiments this month to test this hypothesis

- Shattered pellet injector installation in JET for the 2018-19 campaigns

C. Reux, Nuc. Fus 2015

SPI in lieu of DMV1
Conclusions / outlook

- JET-ILW has a DMS for studying disruption in support of ITER.
- Massive gas injection can reduce the vertical force by up to 30-40%.
- The disruption efficiency does not depend on plasma current.
- Radiation fraction decreases with increasing thermal energy.
- Disruption radiation asymmetries is created by a combination of the n=1 mode and massive gas injection location.
- Dual injection appears necessary for reducing radiation asymmetry. (Note: most of these studies are made for “healthy plasmas”.)
- Disruption predictors without advanced training are installed on JET.

Installation of the SPI in JET in 2018 under international framework:
  - Disruption mitigation with more efficient gas penetration
  - Run-away beam mitigation in conditions closer to ITER.

See next talk
Current asymmetry observed and modelled with M3D for pure vertical disruption event (VDE)

Gerasimov, Nuc. Fus. 2015