Implications of Disruption Mitigation for the ITER Vacuum System

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ORNL, *FZK, # ITER IO
• ~1400 m³ vacuum vessel volume, neutral beam, cryostat and service vacuum system [1].


• Plasma contains ~2 bar-L equivalent gas

• Tritium compatibility of all systems from day one

• Operational 2016
ITER has up to 15 MA of Plasma Current
What is a Disruption?

- ITER is a tokamak with a plasma current of 15 MA.
- MHD instabilities can cause plasma to become unstable and collide against chamber. (This is called a disruption)
- Plasma current is dissipated in ~30 ms in a disruption causing thermal and structural design challenges [3].
  - Structural problems can be handled by careful design
  - Thermal excursion of first wall can lead to damage
- Runaway electrons can be generated by Coulomb-collisions during the current decay phase of the disruption
  - ITER could have up to 10 MA of RE current in MeV range of energies
  - Component melting and water leaks are possible [4]
Example of a 1 MA Disruption on Alcator C-Mod

- Unmitigated 1 MA disruption in C-Mod with 3ms current quench [5]

D. Whyte, EPS 2006
How is a Disruption Mitigated?

- Large increase of plasma density during disruption can lower the plasmas temperature and thus mitigate effects of thermal damage
- Particles must penetrate into the current channel during the current quench to prevent runaway electron formation
- Methods to increase the density are:
  - Gas injection: Large burst of gas from a fast valve
  - Pellet injection: Solid pellets accelerated by gas
  - Liquid jet: Cryogenic liquid forced through a nozzle
- The ITER current quench time scale is estimated to be 30-35 ms [1].
- See the example in the following slide showing faster current quench with gas jet mitigation in C-Mod [5].
Example of Disruption Mitigation on Alcator C-Mod

- Comparison of unmitigated disruption with Ar gas jet mitigation showing faster current quench. [5]
How is a Disruption Mitigated?

- High flow-rate fast valves with up to $10^6$ Pa·m$^3$/s (10$^4$ bar·L/s) flow rates for 2 ms produce gas jet into plasma [6].

- Impurity or large $D_2$ pellets (3cm) can also be used.

Jumbo Valve – $10^6$ Pa·m$^3$/s

Medusa Valve – $3\times10^5$ Pa·m$^3$/s
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How Many Particles are Needed in ITER?

- Table based on avalanche growth model by Rosenbluth-Putvinski [7] and a plasma current of 15 MA and 35 ms current decay time [8].

- Higher Z than Ar is not useful because of slower sound speed and is more likely to generate runaway electrons. (R. Granetz, C-Mod, APS2006 [9])

<table>
<thead>
<tr>
<th>Species</th>
<th>AMU</th>
<th>N</th>
<th>Pa-m3</th>
<th>Resulting Press (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D$_2$</td>
<td>4</td>
<td>1.7x10$^{25}$</td>
<td>6.5x10$^4$</td>
<td>65</td>
</tr>
<tr>
<td>He</td>
<td>4</td>
<td>1.7x10$^{25}$</td>
<td>6.5x10$^4$</td>
<td>65</td>
</tr>
<tr>
<td>Ne</td>
<td>20</td>
<td>3.5x10$^{24}$</td>
<td>1.3x10$^4$</td>
<td>13</td>
</tr>
<tr>
<td>Ar</td>
<td>40</td>
<td>1.9x10$^{24}$</td>
<td>7.2x10$^3$</td>
<td>7</td>
</tr>
</tbody>
</table>

- Assimilation of gas is at best 10% in present experiments, so as much as 10x more may be needed if the avalanche model is correct.

- Pellet sizes of 30 mm for D$_2$ and 2.5 mm for Ar would provide the needed number of electrons.
ITER Pellet Disruption Mitigation Scheme

- A large “golf ball size” pellet made with D₂ or some combination of D₂ and Ne or other impurity is a possible option to mitigate disruptions in ITER.
- A reliable single stage gas gun can accelerate the pellet to 1 km/s speed. (Alternatively a 460 cc driver with T. Woods)
A large “golf ball size” pellet made with D$_2$ or some combination of D$_2$ and Ne or other impurity is a possible option to mitigate disruptions in ITER.

A reliable single stage gas gun can accelerate the pellet to 1 km/s speed.

10 mm pellets have been produced easily and larger sizes are possible.

Pellets can be shattered to minimize risk of damage to inner wall.
ITER Fuel Cycle Block Diagram
ITER Fuel Cycle Block Diagram
ITER – Vacuum Issues for Disruption Mitigation

- Gas type must be compatible with pumping system and avoid activation from fusion neutrons
- Cryopumps for the torus and neutral beams may regenerate and allow pumped impurities back into torus
- Roughing Pumps must be able to handle the additional load in a timely fashion
- Neutral Beam Injectors (NBI) must be switched off when DMS is actuated and gate valves closed (several seconds).
- Tritium Plant must be able to process the extra DMS exhaust gas in a timely fashion
ITER Torus Pumping System

- Cartoon (not to scale) of the torus pumping system showing the cryopumps and divertor ring and foreline manifold connection to the roughing pumps.
ITER Roughing Pump System

- Roots blowers are used as the first two stages in all the pump train options that are under consideration.
- One attractive option uses a screw pump to back the roots pumps.
- Pumping speed of 5000 m$^3$/h is possible with this configuration.

From FzK presentation 2003
Pumpdown Time Scale After DM

- Crude VACSIM calculation shows time scale if 10x gas is introduced to be > 10 minutes. More detailed ITERVAC simulation is needed to for accurate pumpdown time.
Disruption mitigation is unlikely to cause torus cryopumps to regenerate spontaneously. Valves can be throttled and pumps regenerated naturally after pumpdown.

NBI cryopumps will likely regenerate since valves are totally open and take seconds to close. If normal cryogenic flow is available then pumps can resume operation in ~20 minutes.
Disruption mitigation is an important subsystem for ITER machine protection, but hopefully will be used infrequently
- High reliability and redundancy are needed

Technology to both detect disruptions and mitigate them in ITER are under development

DM will introduce large amount of particles (gas or pellet) into the torus from 2 upper ports during the current decay in a few ms.

Cryopumps for the neutral beams will likely regenerate, but probably not the torus cryopumps (4 that are pumping during disruption).

Roughing pumps can handle the gas in a timely fashion – probably less than 20 minutes to get back into operational state.

NBI systems can recover as soon as cryopumps are cooled down which takes ~20 minutes.

Tritium Plant must be able to process the gas in a timely fashion
- Capable only of 150 Pa-m3/s, so could be ~2 hours for 10X gas load
References

[1] ITER Design Description Document
[9] Granetz, R., Mitigation on C-Mod, APS 2006?