3D Effects on Disruptions and their Mitigation

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Disruptions and their consequences are 3D

- Thermal quench and current quench
- Consequences heat + EM loads, VDE, halos (which can be non-axisymmetric, i.e. 3-D)

- Pre-disruption energy loss, 3-D precursors

1999 ITER Phys Basis, Nucl Fus
Disruptions get more severe in bigger tokamaks

In general local heat loads higher, due to conductive losses

<table>
<thead>
<tr>
<th>Plasma Energy W (MJ)</th>
<th>0.2</th>
<th>0.8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Area $A_{\text{plas}}$ (m$^2$)</td>
<td>7</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>$W/A_{\text{plas}}$ (MJ/m$^2$)</td>
<td>0.03</td>
<td>0.02</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Disruptions main driver of ITER engineering

Perfect disruption mitigation

C-Mod
DIII
ASDEX
JET
JT60-U

ITER
Disruption consequences

- Key issues to be resolved for disruptions:
  - Forces (VDE symmetric load ~10,000 Tonnes, asymmetric ~5,000 Tonnes in ITER)
  - Heat Loads
  - Runaways (~10MA at 10-20MeV in ITER)

Examples from JET

G Martin IAEA 2004
3-D mechanisms causing disruptions
Classical disruption picture

Limit approached

3D Instability → Energy Loss → Plasma moves and hits wall → Impurities enter plasma → Plasma cools and highly resistive → $I_p$ lost

Plasma current (MA)

Wesson et al. Nucl Fus 1989
Classical picture - energy loss is stochastic

Carreras et al, 1980
Phys of Fluids

MHD simulation
Bondeson et al, NF 1991
Explosive instability picture

Kleva et al, Phys Plas 2001

Ballooning mixing

J Paley, S Cowley et al  JET preprint EFDA–JET–CP(04)02/16
3-D consequences of disruptions:-

- Halo currents and EM forces
- Heat Loads
- Runaway electrons
Forces

- Forces from halo and eddy currents are the main design constraint on the vessel and in-vessel components in ITER
  - Symmetric loads on the vessel reach ~10,800 tonnes
  - Asymmetric sideways loads ~5,000 tonnes

Halo current flowing in vessel etc, (normally dominantly poloidal flow for symmetric currents)

Core plasma:- shrinking and $I_p$ decreasing

Halo region

Toroidal halo current flows in $I_p$ direction and poloidal current in direction to increase $B_t$

- For JET peak sideways force ~400Tonnes
Halo Currents can be toroidally asymmetric

- In JET 41% of disruptions have significant asymmetry

JT-60U NF 1999, Nevanti et al

C-MOD 1999 ITER Phys Basis

AUG NF 2011, Pautasso et al
Halo Current Asymmetries

- Empirically data bounded by $\text{TPF}*I_{\text{halo}}(\text{average})/I_p$

  - $\Rightarrow$ A limit on maximum halo current flowing to vessel?

- But in a given machine evidence is weaker

Maximum in space and time

$$TPF = \left| \frac{I_{\text{halo}}(\text{max})}{I_{\text{halo}}(\text{average})} \right|$$

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Maximum in space and time

$$TPF = \left| \frac{I_{\text{halo}}(\text{max})}{I_{\text{halo}}(\text{average})} \right|$$
At $q_a=2$, $m=2, n=1$ kink distortion:

- Ellipse just touches at $\phi=0$ and $180^\circ$.
- \( I_{\text{halo}}(\text{av}) = 0 \)

$\Delta a / a = 0.1$

- Similar result at $q=1$, with $m=n=1$ kink.

$\phi = 0$

$\rho = \rho_h$

$\rho = 1$

$Z = Z_{\text{wall}}$

$\Delta a$

$\Delta a / a$

$\text{d} \gg a$ all current in halo

NB Helically rotating elliptic distortion

Pomphrey et al, Nucl Fus 1998
Halo currents can rotate

n=1 structure rotating counter to I_p

- Poloidal halo currents phase leads ΔI_p by ~90°
• Vacuum vessel and coil systems have low frequency resonances
• Possibility of dynamic amplification

<table>
<thead>
<tr>
<th>Mode</th>
<th>F (Hz)</th>
<th>Mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>U – xy</td>
<td>2.77</td>
<td>0.95</td>
</tr>
<tr>
<td>U – z</td>
<td>8.61</td>
<td>0.77</td>
</tr>
<tr>
<td>Rot - xy</td>
<td>8.41</td>
<td>0.80</td>
</tr>
<tr>
<td>Rot - z</td>
<td>4.50</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Natural frequencies of the 360° VV

G. Sannazzaro and T Schioler
ITER Organisation
No obvious pattern for why some shots have substantial halo rotation.

71790, 71791

I_p (Oct5-Oct1)

I_p (Oct7-Oct3)

I_p [A]

Z_centroid [m]

70238, 70237

Neighbouring similar shots have very different halo rotation.
- But long tails to multi-turns and ~400Hz

\[ A = \frac{1}{I_{p,\text{pre}}} \int I_{p,\text{asym}} \, dt \]

\[ A > 0.5\text{ms} \]

\[ A_{p,\text{asym}} > 0.5\% \]
Halo Asymmetry is $m=1$ dominantly

Consistent with $m=n=1$

kink mode (Zakharov et al)
Asymmetric force normal to wall

Strauss and Paccagnella, PoP 2010
Runaway electrons are generated, which
- are accelerated to ~ MeV range.
- carry much of the original current.
- usually hit the wall => hard X-rays.
- can cause serious damage.
- occasionally remain in the cool plasma (~ 10 eV) for several s.
No REs left

Note the tokamak continued to operate normally after this event
Runaway Electron Heat Loads

\[ I_{RE,lb} = \max_t \{ I_{meas} - I_{fit} \} \]

\[ \Delta T_{dum} \]

\[ I_{fit} \]

\[ I_{meas} \]

\[ \tau_{RE} \approx 2 \text{ms} \]
Runaway Electron energy is localised

- The poloidal extent less than two tiles (area <1.3 m²) of which only a fraction is wetted (installation inaccuracy)
- 0.5 MJ in 2 ms give ΔT~ 800°C → wetted area is ~0.3-0.5 m²
Disruption Control and Mitigation
Known for a long time that applying static helical field can control rotating instabilities (e.g. 1980’s on DITE and 1990’s COMPASS-C)

\[ \frac{d}{dt} \left( \frac{W}{a} \right) \propto \Delta'_0(W)a - 1210.4 \frac{I}{(n_s)^2(W/r_s)^2} \left( \frac{\Delta f \tau_H}{\tau} \right)^2 \]
Can extend disruption boundaries

• Also experiments using rotating helical fields as means of direct disruption control (e.g. on DITE)

COMPASS-C Hender NF 1992
Disruption Avoidance & Mitigation

- Most popular mitigation method is massive gas injection (using noble gas)

  - Very effective at reducing disruption forces and heat loads but not proven on REs

  - ASDEX Upgrade, Germany

  - Valve screened by a protecting tile

  - D Whyte et al Jrnl Nuc Mat 2003
Massive Gas Injection is localised \( \rightarrow 3D \)

DIII-D

gas jet port

Ar-I plume

\( \rho = 1.0 \)

\( \rho = 0.7 \)

\( \rho = 0.4 \)

E Hollmann, Nucl Fus 2008

JET M Lehnen

\[ \text{visible emission [counts]} \]

\[ \text{toroidal angle [deg]} \]

\( t - t_0 = 3.9 \text{ ms} \)

\( 4.3 \text{ ms} \)

\( 4.9 \text{ ms} \)

\( 5.6 \text{ ms} \)

\( 6.9 \text{ ms} \)

\( 8.3 \text{ ms} \)
G Pautasso Nucl Fus 2011, $\phi = 0^\circ$ is MGI neon injection location
1 gas jet results:

- Pre-TQ
- TQ
- CQ

M Reinke, NF 2008

2 gas jet results:

- With 2 gas jets asymmetry can be controlled pre-thermal quench
- But MHD still affects asymmetry during thermal quench
- ITER plan with 3 equally spaced upper port toroidal locations and 1 equatorial port for MGI
Summary

- Disruptions are caused by helical instabilities and are intrinsically 3D.
- More importantly, consequences are 3D:
  - Halo currents non-symmetric toroidal (leads to sideways forces on vacuum vessel, more difficult to handle)
  - Non-symmetric halo currents can rotate → can cause mechanical resonances
  - Runaway electron power loads can be non-symmetric due to asymmetries in surrounding structures
- Disruption control by applied helical fields demonstrated but not considered viable in general (risk of locked modes)
- Disruption mitigation by massive gas injection – local radiation loads a issue → multiple injection locations on ITER (needs careful timing)