REDUCTION OF ASYMMETRIC WALL FORCE
IN JET AND ITER
INCLUDING RUNAWAY ELECTRONS

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Abstract
It was shown that asymmetric vertical displacement event (AVDE) disruptions in JET and ITER do not produce a large asymmetric force on conducting structures surrounding the plasma, provided that the current quench (CQ) time is less than the resistive wall penetration time. This is verified with JET data. In ITER the CQ is expected to be comparable to the resistive wall penetration time, which gives a small wall force. It is shown that runaway electrons (REs) in JET do not produce a large wall force, and this is verified with JET data. This occurs if the RE current is about half of the initial plasma current. In ITER, the RE current might be comparable to the initial current, and REs might lengthen the CQ time sufficiently to produce a large wall force.

1. INTRODUCTION
It has been thought that asymmetric vertical displacement event (AVDE) disruptions in ITER might produce large electromechanical forces on the conducting structures surrounding the plasma. A straightforward projection from JET data predicts that ITER might experience a large asymmetric wall force. It was shown recently that ITER and JET are in different parameter regimes, and a fast current quench (CQ) in JET and ITER AVDE disruptions greatly reduces the asymmetric wall force. The key parameter is the ratio of current quench (CQ) time \( \tau_{CQ} \) to the resistive wall penetration time \( \tau_{wall} \). This is demonstrated in AVDE disruption simulations of JET and ITER with the M3D 3D MHD code. In this paper the JET simulations are confirmed by comparison to JET experiments in which the current was quenched with massive gas injection (MGI).

\[ \text{see author list of X. Litaudon et al 2017 Nucl. Fusion 57 102001} \]
A concern in ITER is that a fast current quench might cause production of runaway electrons (REs). If the current is carried by REs, which take a long time to decay resistively, then it is possible that \( \tau_{\text{CQ}} / \tau_{\text{wall}} \ll 1 \). In that case the asymmetric wall force will be large, comparable to previous predictions. Simulations of runaway electrons (REs) in JET are reported, which do not produce a large wall force. This is verified by comparison with JET data. The reason for this is that the ratio of RE current to initial current, \( I_{\text{RE}} / I_{p0} \), is less than unity. In JET disruptions, \( I_{\text{RE}} / I_{p0} \approx 1/2 \).

In ITER the RE current might be comparable to the initial current, \( I_{\text{RE}} / I_{p0} \approx 1 \). In ITER, the ratio \( \tau_{\text{CQ}} / \tau_{\text{wall}} \ll 1 \) is expected. The ITER resistive wall penetration time is estimated as \( \tau_{\text{wall}} = 250 \text{ ms} \).

JET and ITER simulations in which \( \tau_{\text{CQ}} / \tau_{\text{wall}} \) was varied artificially showed that the asymmetric wall force varied by more than an order of magnitude, and it was small when \( \tau_{\text{CQ}} / \tau_{\text{wall}} \leq 1 \).

JET is in a different parameter regime, with \( \tau_{\text{CQ}} / \tau_{\text{wall}} \gg 1 \). This because JET has a short resistive wall penetration time is \( \tau_{\text{wall}} = 5 \text{ ms} \), which is only 2% as long as the ITER wall time. It is noteworthy that most existing tokamaks have \( \tau_{\text{wall}} \) of the same order as JET. In this regime the asymmetric wall force is quite large, and if extrapolated to ITER, it predicts an unacceptably large force.

**FIG. 1:** (a) Poloidal flux \( \psi \) at AVDE saturation (b) Time history in units of wall time \( \tau_{\text{wall}} \). Shown are simulation and experimental total current \( I \) and vertical displacement \( Z_p \) of the current centroid. The normalized pressure \( P \) shows the TQ. Also shown is asymmetric wall force \( \Delta F_x \), in MN.

The current was driven using experimental time history data for shot 71985, in wall time units.

\[
I_\phi(t/\tau_{\text{wall}}) \approx I_\phi(t/\tau_{\text{wall}}^{\text{JET}})
\]

JET simulations were validated by comparison to JET shot 71985 data and were in good agreement. Table 1 compares several quantities measured in both JET shot 71895 and the simulations. These include the maximum vertical displacement \( Z_p \) of the current centroid. It is noteworthy that in JET, a vertical displacement saturates, unlike in ITER and other experiments. Also compared was the toroidal variation of the toroidal current \( I \), where \( \Delta I \) is the amplitude of the \( n = 1 \) toroidal harmonic of \( I \). The toroidal rotation was also compared, and was about 3 periods. The wall force asymmetry, \( \Delta F_x \) was calculated in the simulations. This is not measured in the experiment, but instead it is possible to measure the Noll force

\[
\Delta F_x \approx \pi B \Delta M_{IZ}, \quad M_{IZ} = \int Z J_\phi \text{d}R\text{d}Z.
\]
TABLE I: Comparison of simulation and data of JET shot 71985.

<table>
<thead>
<tr>
<th>variable</th>
<th>simulation</th>
<th>experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z_p)</td>
<td>1.5m</td>
<td>1.4m</td>
</tr>
<tr>
<td>(\Delta F_x)</td>
<td>1.1 MN</td>
<td>1.4 MN</td>
</tr>
<tr>
<td>(\pi B \Delta M_{IZ})</td>
<td>1.2 MN</td>
<td>1.3 MN</td>
</tr>
<tr>
<td>(N_{rotation})</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>(\Delta I/I)</td>
<td>0.045</td>
<td>0.055</td>
</tr>
</tbody>
</table>

The simulations were repeated with the wall time \(\tau_{wall}\) artificially increased, keeping \(\tau_{CQ}\) fixed, and it was found that the wall force decreased. This is shown in Fig.2. The curve labeled \(\Delta F_x\) is obtained from simulations of JET shot 71985. \(\Delta F_x\). The upper curve shows the Noll relation \(\pi B \Delta M_{IZ}\), calculated for the same simulations. It is seen that \(\Delta F_x \leq \pi B \Delta M_{IZ}\), with the best agreement for the largest and smallest values of \(\tau_{CQ}/\tau_{wall}\).

2. COMPARISON OF SIMULATIONS WITH JET DATA

The reduction of the asymmetric wall force was also found in analysis of experimental data of JET MGI mitigated disruption shots. The data from shots 85858 and 90386 given in [4] was analyzed to calculate \(\tau_{CQ}\) and \(\pi B \Delta M_{IZ}\), shown in Fig.2. The data points agree well with the simulations.

![Fig. 2: simulated asymmetric wall force \(\Delta F_x\), and wall force estimated from JET MGI shots. Also shown are simulations and data with REs.](image)

The CQ time and Noll force were then calculated for all the shots in the JET database for disruptions with ILW, 2011-2016, labeled "VDE+MGI." There is some scatter, but the experimental Noll force is approximately bounded by the simulated values. It is clear that reducing the ratio \(\tau_{CQ}/\tau_{wall}\) also lowers the Noll force and by implication lowers directly calculated wall force \(\Delta F_x\). The other curves and data points in Fig.2 are relevant to REs and will be discussed below.

The reduction of the asymmetric wall force was confirmed in simulations of ITER [2]. It should be noted that in ITER, \(\tau_{wall} = 0.25s\), while most estimates of CQ time have \(\tau_{CQ} < \tau_{wall}\). In JET \(\tau_{wall} = 0.005s\). In the simulations, an ITER FEAT 15MA initial state was used, with the current profile modified to represent MGI mitigation. The current was set to zero outside the \(q = 2\) magnetic surface, keeping the total current unchanged. This made the plasma MHD unstable and caused a thermal quench. The plasma was also vertically unstable to a VDE. The plasma was evolved at constant current until \(t = t_1 = 1.4\tau_{wall}\), when the VDE reached a small amplitude. The current was then decreased linearly,

\[
\frac{I(t)}{I_{p0}} = 1 + \frac{t_1 - t}{\tau_{CQ}}
\]
until $t = t_1 + \tau_{CQ}$.

**FIG. 3:** (a) Contour plot of poloidal magnetic flux $\psi$ at time $t = 1.9\tau_{wall}$ in the $(R, Z)$ plane with $\phi = 0$, with $\tau_{CQ}/\tau_{wall} = 1/2$ (b) Time history of $I, Z_p, \Delta F_x, P$ in wall time units.

ITER is in the regime $\tau_{CQ}/\tau_{wall} \leq 1$, so the asymmetric wall force is small. The plasma was evolved at constant current until $t = t_1 = 1.4\tau_{wall}$, when the VDE reached a small amplitude. The current was then decreased linearly.

The asymmetric wall force and vertical current moment vary an order of magnitude with $\tau_{CQ}/\tau_{wall}$, the ratio of current quench time to resistive wall time. Fig. 5 shows results of 3D MHD ITER disruption simulations with the M3D code, asymmetric wall force $\Delta F_x$, and Noll force in MN. The reason for the force reduction was explained [2]. The faster current quench means that the maximum vertical current moment $M_{IZ}$ decreases. The relative amplitude of the 3D MHD perturbations $\Delta I/I$ tends to decrease with the decrease of current. Hence $\Delta F_x \propto \Delta M_{IZ}$ decreases with $\tau_{CQ}/\tau_{wall}$. It is clear that in the regime $\tau_{CQ} \leq \tau_{wall}$ expected in ITER, the asymmetric wall force is small, comparable to its value in JET. The other curves will be discussed below.

3. RUNAWAY ELECTRON EFFECTS

A serious problem in ITER is the possibility of RE generation because of relatively fast CQ. Runaway electron current tends to be damped slowly, and this could change the conclusion about ITER wall force. Preliminary simulations were carried out using a fluid model of REs [7].

The REs are coupled to the bulk plasma current by the resistive term in Ohm’s Law,

$$\frac{1}{c} \frac{\partial \psi}{\partial t} = \nabla_{||} \Phi - \eta (J_{||} - J_{||RE})$$

where $\psi$ is the poloidal magnetic flux, $\Phi$ is the electrostatic potential, $J_{||}$ is the parallel current density, and $J_{||RE}$ is the RE current density.

The RE continuity equation can be expressed in terms of the RE current assuming the REs have speed $c$

$$\frac{\partial J_{||RE}}{\partial t} \approx -c \mathbf{B} \cdot \nabla \left( \frac{J_{||RE}}{B} \right) + S_{RE}$$

where $S_{RE}$ is a model source term,

$$S_{RE} = \alpha(t)(J_{||} - J_{||RE})J_{||RE} > 0$$

where $S_{RE}$ is avalanche-like. To account for the large difference between the advection of the runaway beam at speed $c$ and the plasma motion at speeds less than the Alfvén velocity, [8] was averaged along the magnetic field, giving

$$\mathbf{B} \cdot \nabla \left( \frac{J_{||RE}}{B} \right) \approx 0,$$
which was approximately solved similar to parallel thermal conduction. This approach resembles bounce averaging.

The $\alpha$ term in (6) was used to model the time dependence of the RE source. As in (5) the current $I$ is decreased linearly in time $\tau_I$, $I = I_{\rho 0}(1 - (t - t_1)/\tau_I)$ and the RE current $I_{RE}$ is increased in time $\tau_{RE}$, $I_{RE} = I_{\rho 0}(t - t_1)/\tau_{RE}$. When $I = I_{RE}$, then $t = t_2 = t_1 + 1/(1/\tau_I + 1/\tau_{RE})$ and

$$\frac{I_{RE}}{I_{\rho 0}} = \frac{1}{1 + \tau_I/\tau_{RE}}$$

Then $I, I_{RE}$ are decreased together linearly in time $\tau_{CQ}$, $I_{RE} = I = I_{\rho 0}(t_2 - t)/\tau_{CQ}$. The asymmetric force depends on the ratio $I_{RE}/I_p$ as well as $\tau_{CQ}/\tau_{wall}$. Results in JET are shown in Fig.2(a). The initial equilibrium was the same as without the REs, shot 71985. In Fig.2(a), $\tau_{RE} = \tau_I = \tau_{wall}$. As shown in (5), $I_{RE} = I = I_{\rho 0}/2$. The currents $I, I_{RE}$ are then decreased in time $\tau_{CQ} = 4\tau_{wall}$. The ratio $I_{RE}/I_{\rho 0} = 1/2$ is typical of JET RE shots [3]. Fig.2 shows that $\Delta F_x$ is independent of $\tau_{CQ}$. Also shown is JET experimental data of shots labeled "MGI+RE" in the ILW database, 2011-16. The simulations and experimental data agree well. The asymmetric force is quite small.

ITER RE simulations are given Fig.3(b). The initial state was the same as the MHD case. After time $1.4\tau_{wall}$, the current was decreased linearly as before, but the RE current was increased in time $0.125\tau_{wall}$, before the current decreased very much. A fast runaway generation is expected in ITER [8]. This suggests that the RE current will grow to the amplitude of the initial current, before it can decay very much. In this case the RE current is almost the same as the initial current. This makes a significant difference in the results, compared to the JET cases. The source models are the same as before.

In the JET RE examples, $\Delta F_x$ is small and independent of $\tau_{CQ}/\tau_{wall}$. The reason is that in the JET cases, the current decreased to half its initial value. This excluded unstable modes with poloidal and toroidal numbers $(1, 1)$ and $(2, 1)$ which are required to produce asymmetric wall force [10]. This is basically an MHD effect. The role of the REs is simply to change the total current.

Next, ITER examples are given in which REs change the current level. Theory predicts that the RE growth rate is large [3]. Examples are given in which the ratio of the RE current to the initial current is varied: $I_{RE}/I_{\rho 0} = 1, 2/3, 1/2$. This is demonstrated by reproducing the time dependence of the ITER simulations in Fig.3 but causing the current to decrease rapidly when the RE current increases. When $I_{RE}/I_{\rho 0} = 1$, the result is similar whether or not there are REs. The force increases to about $30MA$ when $\tau_{CQ} \approx 15\tau_{wall}$, as shown by the curves in Fig.3 labelled $\Delta F_x$, with no REs, and $\Delta F_{RE}$, the force with REs present. When $I_{RE}/I_{\rho 0} = 1/2$, the force remains small, as in JET, as shown by the curve $\Delta F_{RE1/2}$. The intermediate case $I_{RE}/I_{\rho 0} = 2/3$, is labelled $\Delta F_{RE2/3}$. The main feature of the RE model
FIG. 5: $\Delta F_x$, $\Delta F_{RE}$ $HF$, $HF_{RE}$, as a function of $\tau_{CQ}/\tau_{wall}$.

FIG. 6: (a) contours of magnetic flux $\psi$, for case with $I_{RE}/I_{p0} = 2/3$, at time $t = 3.1\tau_{wall}$, shown in Fig.1(b), $\tau_{RE} = 16\tau_{wall}$. (b) contours of toroidal current density $j_\psi$, same case, same time. (c) contours of toroidal RE current density $J_{RE}$, same case, same time.

is that the current can change from its initial value, and then decay slowly. The change of the current time evolution can change the asymmetric wall force.

An example of an ITER simulation is given in Fig.4. The time history is given in Fig.4(b). The contours show (a) poloidal flux $\psi$, (b) toroidal current density $j_\psi$, and (c) toroidal RE current density. The latter are very similar. They show evidence of poloidal asymmetry suggesting an $(m, n) = (1, 1)$ mode, which produces a large asymmetric force.

4. CONCLUSION

Simulations have shown that AVDEs produce a small asymmetric wall force with the CQ time is less than the resistive wall penetration time, $\tau_{CQ} < \tau_{wall}$. This is verified by comparison with JET data, in which the current was quenched rapidly with MGI. This is also expected in ITER. If the current is carried by REs, the ratio of runaway current to the initial current, $I_{RE}/I_{p0}$, is important. In JET, the ratio is about 1/2, which causes a small force, as shown in simulations, and confirmed in JET data. In ITER, if the ratio is nearly unity, and the current decay time is long, the wall force will be large.

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