Reduction of Asymmetric wall force in JET and ITER including Runaway Electrons

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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. It was shown recently that asymmetric vertical displacement event (AVDE) disruptions in ITER should produce a relatively small force on the wall surrounding the plasma, in contrast to previous predictions based on JET data. This is shown in simulations [1, 2] with the M3D 3D MHD code [3] and confirmed in JET experiments [4] in which the current was quenched with massive gas injection (MGI). A concern in ITER is that a fast current quench (CQ) might cause production of runaway electrons (REs). Here simulations and data are presented that show the REs will not produce significant wall force, regardless of what other damage they may cause.

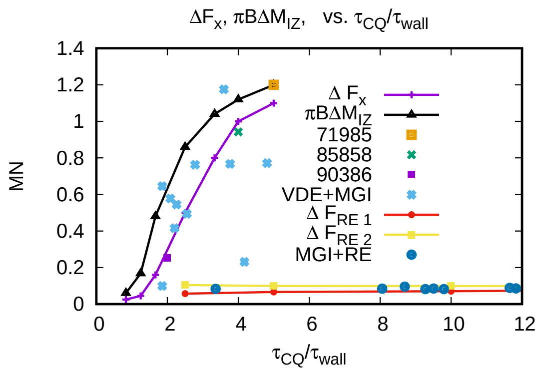

Figure 1: *simulated asymmetric wall force ΔF_x, and wall force estimated from JET MGI shots. Also shown are simulations and data with RRs.*

In ITER the CQ time τ_{CQ} is less than or equal to the resistive wall penetration time τ_{wall}. This causes reduction of the wall force. JET is in a different parameter regime, with $\tau_{CQ}/\tau_{wall} > 1$. JET simulations were validated by comparison [1] to JET shot 71985 data and were in good agreement. These include the maximum vertical displacement Z_p of the current centroid. It is noteworthy that in JET, a vertical

*see author list of X. Litaudon et al 2017 Nucl. Fusion 57 102001 displacement saturates, unlike in ITER and other experiments. Next, the wall force asymmetry, ΔF_x. This is not measured in the experiment, but instead it is possible to measure the Noll force [5],

$$\Delta F_x \approx \pi B \Delta M_{IZ}, \qquad M_{IZ} = \int Z J_\phi dRdZ. \qquad (1)$$

Here Δ is the amplitude of the toroidal variation.

The simulations were repeated the wall time τ_{wall} artificially increased, keeping τ_{CQ} fixed, and it was found that the wall force decreased. This is shown in Fig.1. The curve labeled ΔF_x is obtained from simulations of JET shot 71985. ΔF_x. The next 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 τ_{CQ}/τ_{wall}.

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 τ_{CQ} and $\pi B \Delta M_{IZ}$, shown in Fig.1. The data points agree well with the simulations.

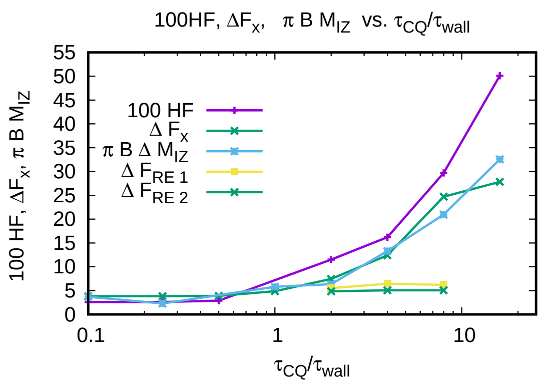

Figure 2: ΔF_x *is plotted for simulations with different* τ_{CQ}/τ_{wall}*, similar to JET.*

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 τ_{CQ}/τ_{wall} also lowers the Noll force and by implication lowers directly calculated wall force ΔF_x. The other curves and data points in Fig.1 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 $1.4\tau_{wall}$, when the VDE reached a small amplitude. The current was then decreased linearly. The asymmetric wall force, vertical current moment, and halo fraction vary an order of magnitude with τ_{CQ}/τ_{wall}, the ratio of current quench time to resistive wall time. Fig.2 shows results of 3D MHD ITER disruption simulations with the M3D code, asymmetric wall force ΔF_x. and Noll force in MN, These quantities are approximately $100 \times HF$, the halo current fraction, which is the ratio of the halo current to toroidal current.

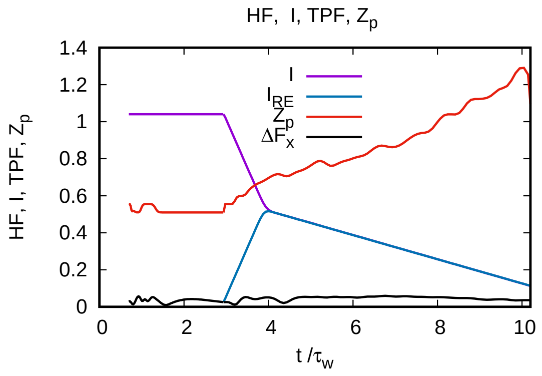

Figure 3: *Simulation intialized with JET shot 71985, with REs added, showing current I, RE current I_{RE}, vertical displacement Z_p, and ΔF_x.*

Large asymmetric force requires contact of plasma with the wall, as shown by halo current, and persistence of 3D perturbations, measured by ΔM_{IZ}. 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.

A remaining problem in ITER is the possibility of runaway electron (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 [6].

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

$$\frac{1}{c}\frac{\partial \psi}{\partial t} = \nabla_{\|}\Phi - \eta(J_{\|} - J_{\|RE}) \tag{2}$$

where ψ is the poloidal magnetic flux, Φ 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

$$\frac{\partial J_{\|RE}}{\partial t} \approx -c\mathbf{B}\cdot\nabla\left(\frac{J_{\|RE}}{B}\right) + S_{RE} \tag{3}$$

where S_{RE} is a model source term,

$$S_{RE} = \alpha(t) f_k(\mathbf{r}) J_{\|RE} > 0, \qquad f_1 = 1, \qquad f_2 = J_{\|} - J_{\|RE} \tag{4}$$

where $f_k = f_1$ is Dreicer - like and $f_k = f_2$ 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 velcity, (3) was averaged along the magnetic field, giving

$$\mathbf{B}\cdot\nabla\left(\frac{J_{\|RE}}{B}\right) \approx 0, \tag{5}$$

which was approximately solved similar to parallel thermal conduction. This approach resembles bounce averaging. Results in JET are shown in Fig.1. The initial equilibrium was the same as without the REs, shot 71985. The current was lowered to half its initial value in time τ_{wall}, and the RE current was increased to the same value, as shown in Fig.3. The current and RE current were then decreased linearly together in time τ_{CQ}. Fig.1 shows that ΔF_x is independent of τ_{CQ}. The subscripts refer to the two source models in (4). Also shown is JET experimental data of shots labeled "MGI+RE" in the ILW database, 2011-16. The simulations and experimental data agree well.

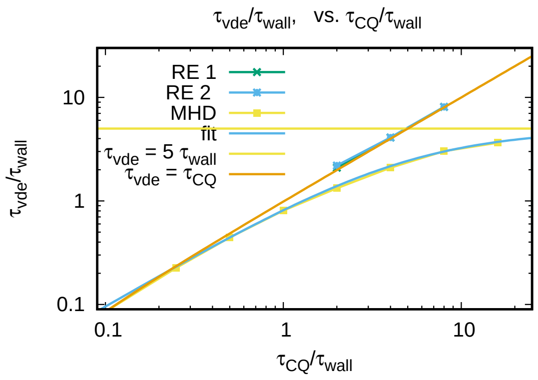

Figure 4: *Vertical displacement time τ_{vde} vs. τ_{wall} for MHD and RE simulations.*

ITER RE simulations are given Fig.2. 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 $0.25\tau_{wall}$, before the current decreased very much. A fast runaway generation is expected in ITER [7] . Fig.2 shows again that ΔF_x is independent of τ_{CQ}. The source models are the same as before.

In the MHD model, the growth time of the VDE τ_{vde} is well fit by [2]

$$\tau_{vde} = \frac{\tau_{CQ}}{1+\tau_{CQ}/(5\tau_{wall})}. \qquad (6)$$

In the RE model, as seen in Fig.4, there does not seem to be a saturation to $\tau_{vde} \propto \tau_{wall}$. The REs can persist for many wall times. They will not produce significant wall force.

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