ITER and JET AVDE disruptions

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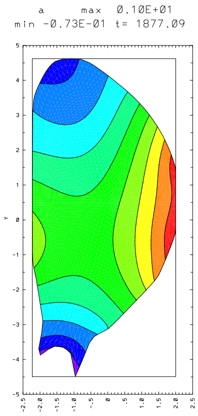
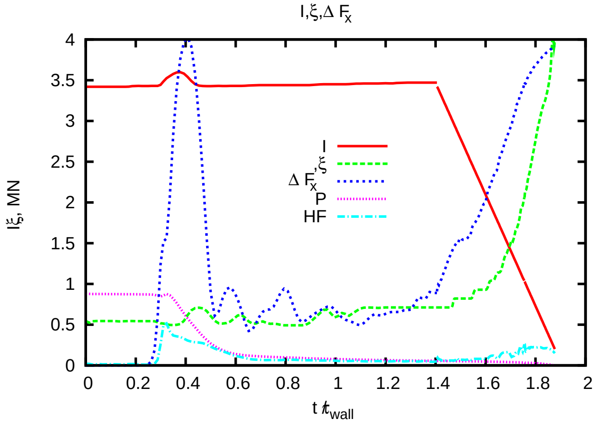
ITER AVDE simulations

AVDE disruptions depend on the ratio of current quench time τ_{CQ} to resistive wall penetration time τ_{wall}.

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 TQ. The plasma was also vertically unstable to a VDE.



(a)



(b)

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 driven using

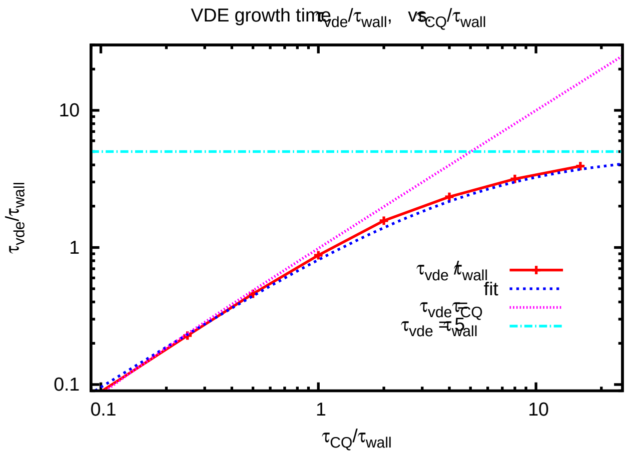
$$I(t) = I_0 \frac{\tau_{CQ} + t_1 - t}{\tau_{CQ}}$$

(a) Contour plot of poloidal magnetic flux ψ at time $t = 1.9\tau_{wall}$ in the (R, Z) plane with $\phi = 0$, $S_{wall} = \tau_{wall}/\tau_A = 1000$, with $\tau_{CQ}/\tau_{wall} = 1/2$

(b) Time history of I, ξ, ΔF_x,P, $10 \times HF$ in wall time units.

scaling of VDE growth time in ITER simulations

AVDE growth time depends on τ_{CQ}/τ_{wall}.



The growth time of the VDE is well fit by

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

where $\tau_{vde} = t(\xi = 4m) - t_1$.

There are two limits of the VDE.

Small τ_{CQ}/τ_{wall}, $\tau_{vde} = \tau_{CQ}$. VDE is driven by CQ. ITER is in this limit.

CMOD, NSTX, AUGC, AUGW, DIID have $\tau_{CQ} \leq 5ms$, $\tau_{wall} \approx 10ms$. [Myers, 2016]

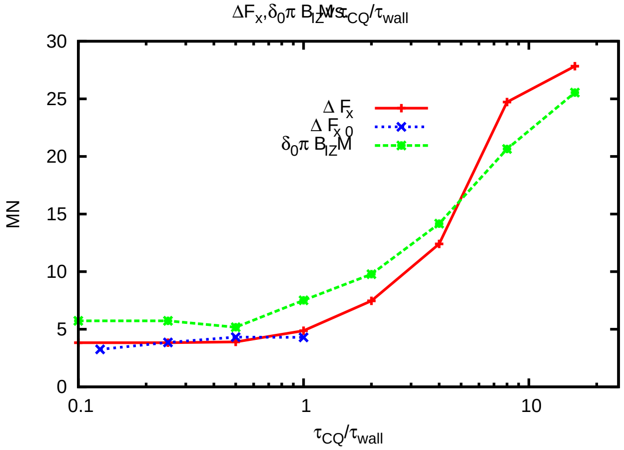
Large τ_{CQ}/τ_{wall}, $\tau_{vde} = 5\tau_{wall}$. VDE is an $n = 0$ RWM. This is the JET limit.

Force asymmetry in ITER simulations with CQ

Asymmetric wall force ΔF_x depends on τ_{CQ}/τ_{wall}.

The asymmetric wall force in the wall is

$$\Delta F_x = \left[\left(\oint d\phi \mathbf{F} \cdot \hat{\mathbf{x}} \right)^2 + \left(\oint d\phi \mathbf{F} \cdot \hat{\mathbf{y}} \right)^2 \right]^{1/2}, \qquad \mathbf{F} = \delta_{wall} \oint dl R \mathbf{J}_{wall} \times \mathbf{B}_{wall}$$



Simulations with varied τ_{CQ}/τ_{wall}. The maximum in time of ΔF_x is plotted for simulations with different τ_{CQ}/τ_{wall}. ΔF_x has $S_{wall} = 10^3$, $\Delta F_{x0}, S_{wall} = 10^4$. Small τ_{CQ}/τ_{wall} ITER relevant regime has small ΔF_x. Large τ_{CQ}/τ_{wall} JET relevant regime has large wall force.

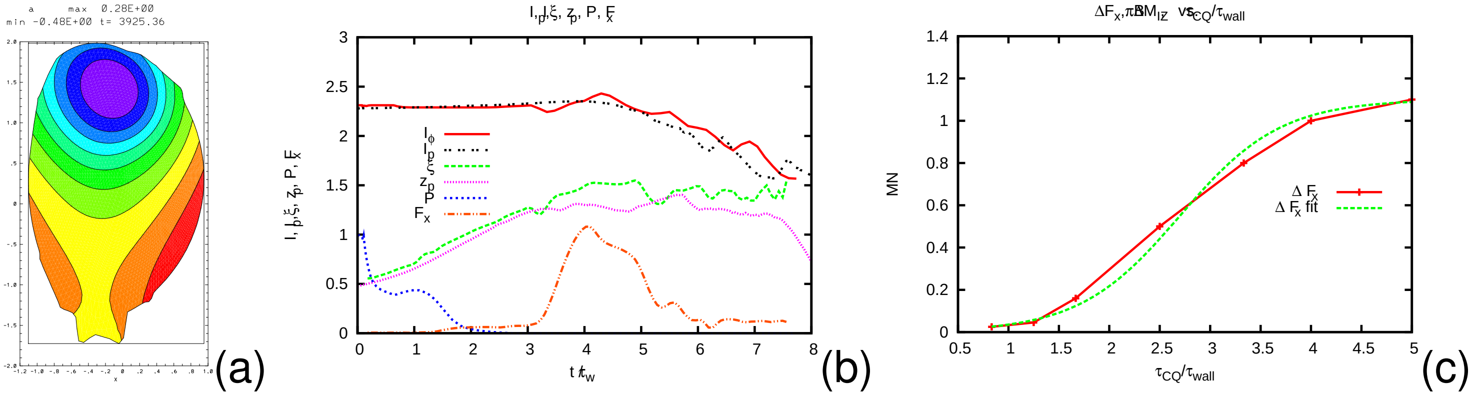
The asymmetric wall force ΔF_x is approximately proportional to the maximum in time of $M_{IZ} = \xi I$.

$$\Delta F_x \approx \delta_0 \pi B M_{IZ}, \qquad \delta_0 = 0.03$$

This reduces 3D to 1D, and explains why the force is less in the ITER regime: when ξ is large, I is small.

Time history of simulation of shot 71985 with VDE and CQ

Effect of τ_{CQ}/τ_{wall} was found in JET simulations [Strauss *et al.* Phys. Plasmas, 2017] M3D asymmetric vertical displacement event (AVDE) disruption simulations initialized with reconstruction of JET shot 71985 $B = 2T$



(a) Poloidal flux ψ at AVDE saturation (b) Time history in units of wall time τ_{wall}. The current was driven using experimental time history data for shot 71985, in wall time units.

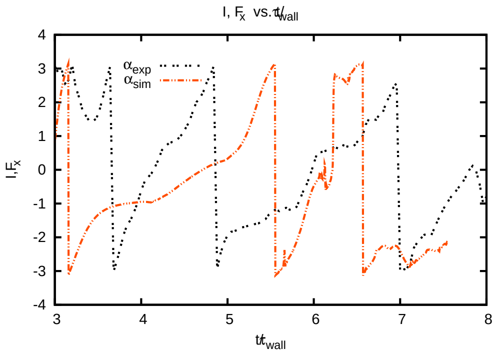
$$I_\phi(t/\tau_{wall}) \approx I_p(t/\tau_{wall}^{JET})$$

Shown are simulation total current I and vertical displacement ξ, and the measurements of I_p and z_p. Note that ξ agrees well with z_p during the growth and saturation phases. The normalized pressure P shows the TQ. Also shown is asymmetric wall force F_x, in MN. (c) Peak ΔF_x and fit as a function of τ_{CQ}/τ_{wall}, where τ_{wall} was artificially varied. ΔF_x varies by an order of magnitude.

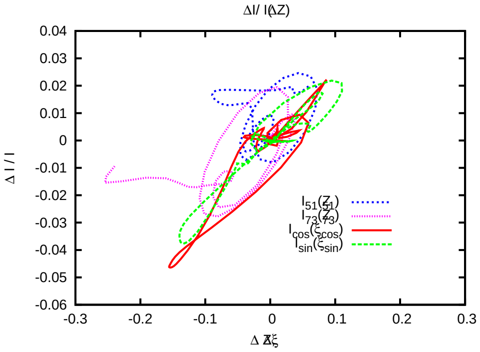
Comparison of simulation and JET shot 71985 data

Validation of M3D compared maximum values in time history of several variables.

variable	simulation	experiment
ξ_{max}	1.5m	1.4m
HF ΔHF	0.16 0.07	0.16 0.05
$\pi B \Delta M_{IZ}$ ΔF_x	1.2 MN 1.1 MN	1.3 MN
$N_{rotation}(a)$	2.8	2.8
$\Delta I/I$	0.045	0.055
$\Delta I a/(I \Delta \xi)(b),(c)$	0.27	0.27



(a)



(b)

Runaway Electrons - Fluid model

MHD simulations were extended by added RE fluid [Helander 2007],[Cai and Fu 2015].

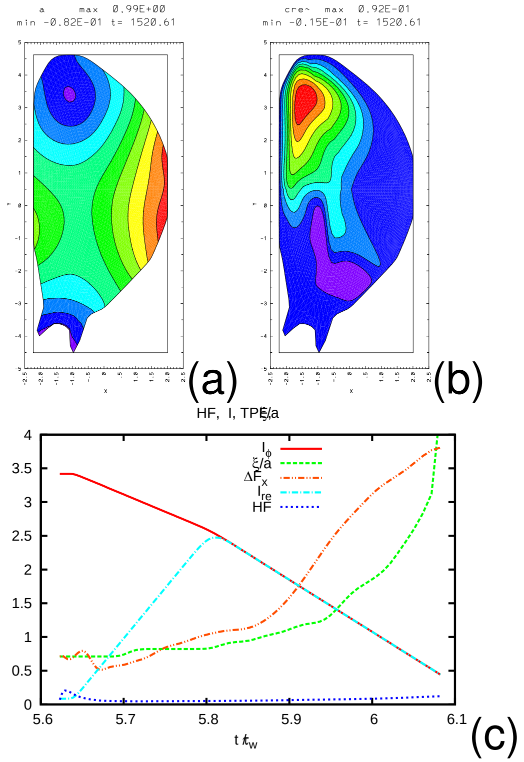
$$\frac{1}{c}\frac{\partial \psi}{\partial t} = \nabla_{\|}\Phi - \eta(J_{\|} - J_{\| RE}) = -E$$

where $J_{\| RE}$ is the RE current density.

$$\frac{\partial J_{\| RE}}{\partial t} \approx -c\mathbf{B}\cdot\nabla\left(\frac{J_{\| RE}}{B}\right) + S_0(E - E_0)J_{\| RE}$$

where S_0 is source strength, E_0 is threshhold. Source has avalanche [Rosenbluth and Putvinski (1997)] form.

REs quench slowly, might change the regime to $\tau_{CQ}/\tau_{wall} > 1$ According to [Konovalov *et al.* IAEA FEC 2016 TH/P3-31] it is possible to have $\tau_{CQ} \le 0.3s \lesssim \tau_{wall}$, even with REs.



(a) ψ with REs included, $\tau_{CQ} = 0.5\tau_{wall}$ (b) $J_{\| RE}$ (c) $I, I_{RE}, \xi, \Delta F_x, HF$ as functions of t. Maximum $\Delta F_x = 3.8MN$, about the same with no REs.

Summary and Conclusions

- AVDE depends on τ_{CQ}/τ_{wall}
  - small τ_{CQ}/τ_{wall} regime
    - ITER, NSTX, CMOD, DIII-D, AUG
    - ΔF_x is relatively small
    - $\tau_{vde} = \tau_{CQ}$
  - large τ_{CQ}/τ_{wall} regime
    - JET
    - ΔF_x is relatively large
    - $\tau_{vde} = \tau_{wall}$
- AVDE depends can depend on REs
  - Fluid nonlinear RE model