JET AVDE disruption simulations

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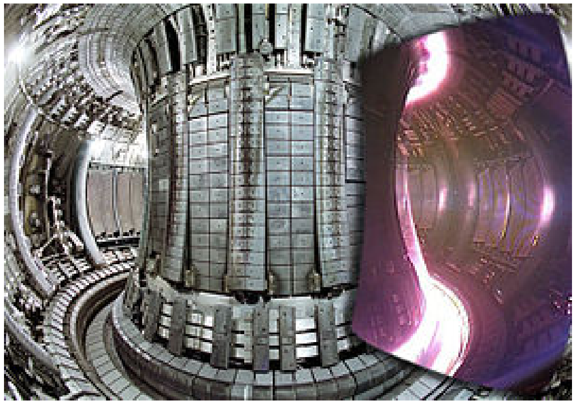
Introduction



The JET experiment is a main source of information about the possible effects of disruptions in ITER. JET measurements indicate large forces will be generated on conducting structures surrounding the plasma. It was also found in JET that the halo current, and hence the wall force, rotates during disruptions. This is potentially important if the force oscillations are resonant with the mechanical response of the external structure.

MHD disruption simulations using the M3D code were carried out, initialized with equilibrium reconstructions of JET disruption shots.

The simulations obtained asymmetric wall force, toroidal rotation, toroidal variation of toroidal current and toroidal magnetic flux, and halo current. The simulations include thermal quench (TQ), vertical displacement event (VDE), and current quench (CQ). The simulations were carried out for much longer times than previous M3D disruption simulations, to accommodate VDE and CQ times.

JET AVDE disruption simulations

• MHD asymmetric vertical displacement event (AVDE) disruption simulations using the M3D code were carried out, initialized with EFIT equilibrium reconstruction of JET disruption shots 72926 at $t = 66.9986s$ and 71985 at $t = 67.3128s$, $B = 2T$

Gerasimov *et al.* Nucl. Fusion **54**, 073009 (2014), Riccardo *et al.* Plasma Phys. Contr. Fusion, **52**, (2010)

• Simulation parameters: $S = \tau_R/\tau_A = 10^6$, $S_{wall} = \tau_{wall}/\tau_A = 250 - 1300$.

• Experimental parameters: $S = 10^9$ (pre TQ), $S \approx 10^5$ (post TQ), $S_{wall} = 7 \times 10^3$

• In shot 72926 simulations, current I_ϕ was held constant until plasma reached the wall. In more recent shot 71985 simulations, the CQ was included, using experimental data $I_\phi(t)$.

• $q_0 \approx 0.8$ in EFIT reconstruction, hightly unstable to $(1, 1)$ mode, initiating TQ.

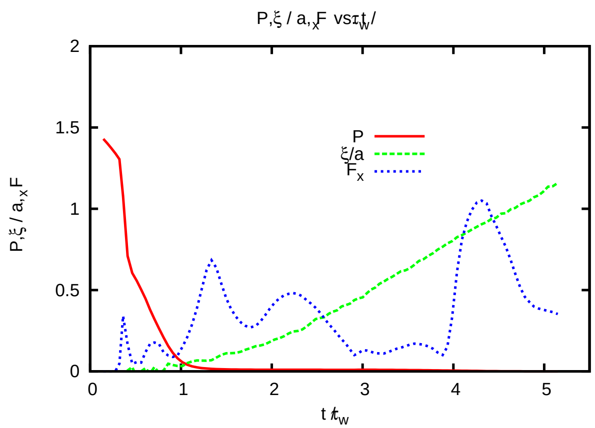
Time history of shot 72926 simulation and force rotation

Time history plots for case with $S_{wall} = 800$. Time in units of wall time τ_{wall}.

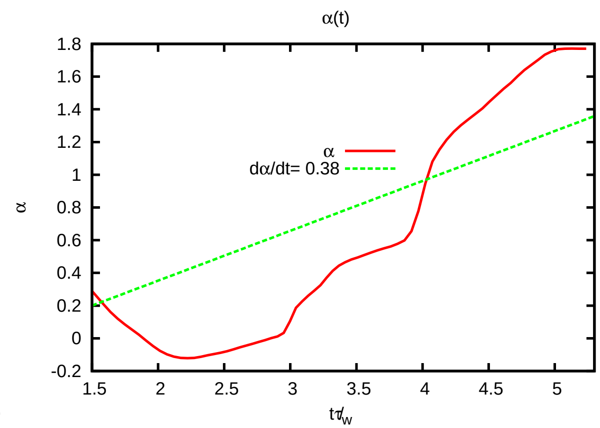
(a) Total normalized pressure P - TQ at time $0.5\tau_{wall}$, drops by $1/2$ in $100\tau_A$, then slower drop on τ_{wall} time scale

(a) Asymmetric or sideways normalized wall force F_x - a short burst at the TQ, followed by several longer impulses. Maximum $F_x \approx 1MN$.

(a) Vertical displacement ξ/a, where a is the minor radius. The VDE reaches $\xi = a$ in time $5\tau_{wall}$.



(a)

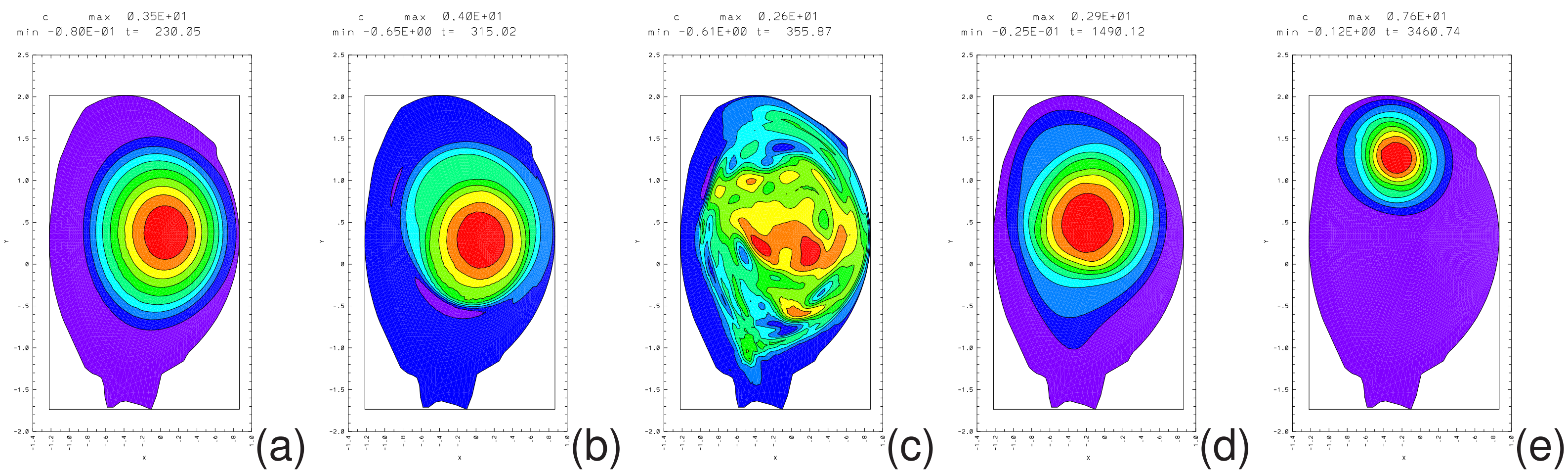


(b)

(b) Force rotation angle $\alpha = (2\pi)^{-1} \tan^{-1} F_{xy}/F_{xx}$, where F_{xx}, F_{xy} are the $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ components of the toroidally varying wall force in the midplane, with $d\alpha/dt \approx 3.8 \times 10^{-4}\tau_A^{-1} \approx 540Hz$. In JET shot 72926 the frequency was $f = 280Hz$.

Current density evolution in shot 72926

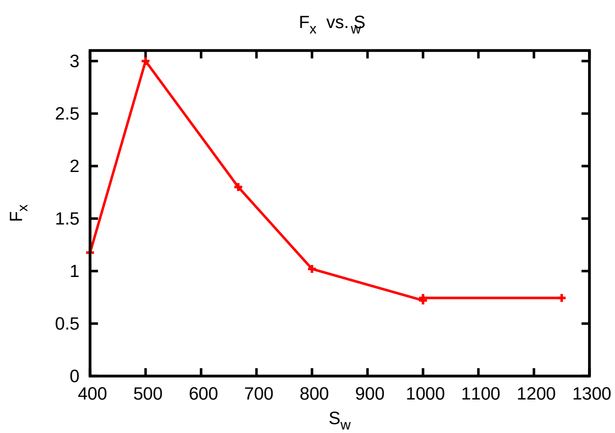
- The JET initial state is unstable to $(1,1)$ and $(1,0)$ modes
- The $(1,1)$ mode causes TQ.
- This is followed by vertical instability (VDE)
- After this a $(2,1)$ kink mode occurs



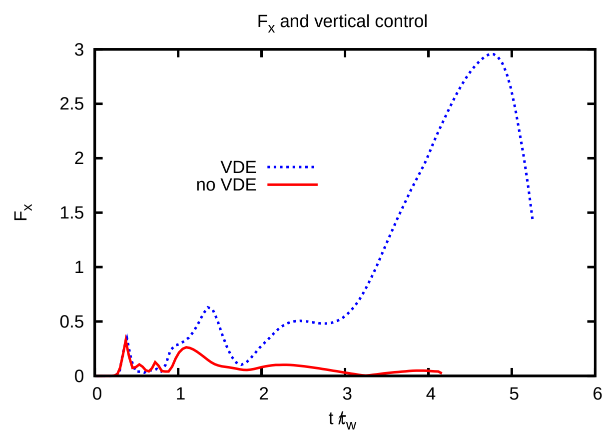
Contour plots of toroidal current with $S_{wall} = 800$, at times (a) initial state, (b) internal $(1,1)$ kink instability at time $t = .47\tau_{wall}$, (c) turbulent state at time of TQ, $t = .53\tau_{wall}$,(d) VDE with $(2,1)$ mode, at $t = 1.9\tau_{wall}$, (e) scrape off of flux and $(2,1)$ mode at $t = 4.2\tau_{wall}$.

Force Mitigation in shot 72926

The wall force is reduced by (a) increasing S_{wall} and (b) suppressing the VDE.



(a)

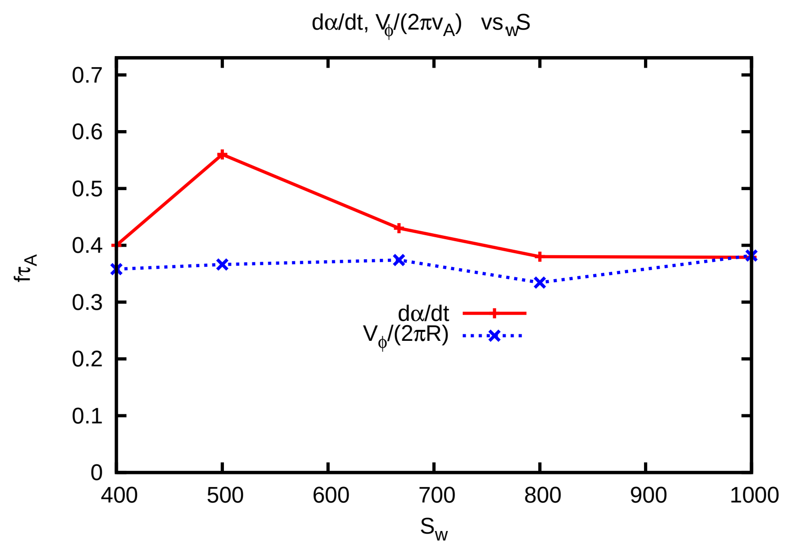


(b)

(a) Maximum value of F_x as a function of S_{wall}. Similar to [Strauss *et al.* , Nucl. Fus. (2013)], peak is caused by interaction of $(2,1)$ and $(1,0)$ (VDE) modes. Maximum for $\gamma\tau_{wall} \sim 1$, where γ is mode growth rate. Asymptotes to a constant, lower value, caused by $(1,1)$ mode, which is the regime of the experiment.

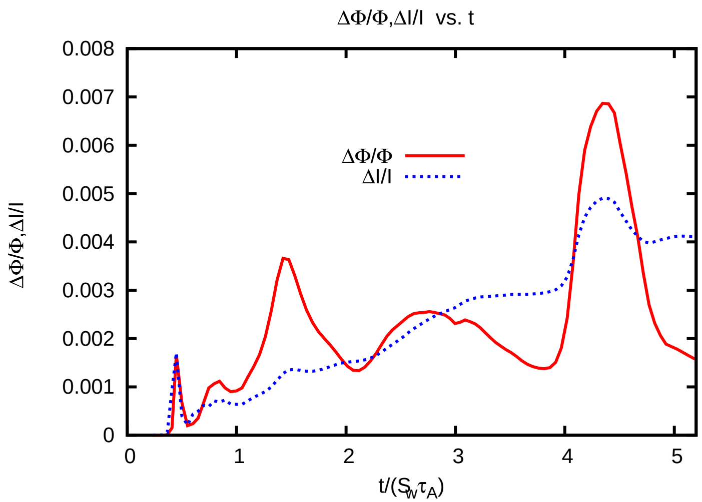
(b) VDE suppression: the wall force as a function of time in two cases with $S_{wall} = 500$. The vertical displacement is suppressed by setting the time evolution of the toroidally averaged normal magnetic field at the wall to zero. This suppresses the VDE and the wall force.

Effect of S_{wall} on force rotation and toroidal velocity



This shows force angle rotation frequency $f = d\alpha/dt$ for several values of S_{wall}. Also shown is the rotation rate calculated from the peak volume averaged rotation velocity [Strauss *et al.* Nucl. Fus. 2013] $f = V_\phi/2\pi R$. The frequencies are in units of $10^{-3}/\tau_A$. The two frequencies are comparable, and not sensitive to S_{wall}.

Toroidal current and toroidal flux in shot 72926



Toroidal $n = 1$ variation of toroidal current and toroidal flux was observed in JET [Gerasimov, 2015]. Time history plot shows magnitude of toroidal current variation and toroidal flux variation.
Here $\tilde{\Phi} = \int \tilde{B}_\phi d^2x$, where $\tilde{f} = f - \oint f d\phi/2\pi$, and

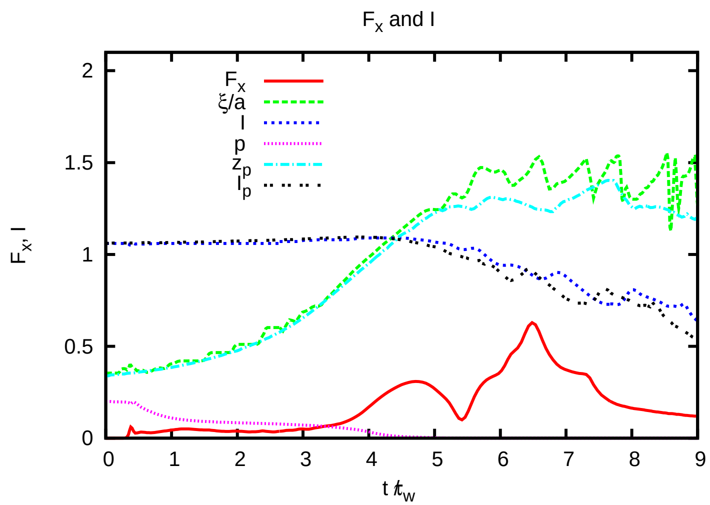
$$\frac{\Delta\Phi}{\Phi} = \frac{1}{\sqrt{2\pi}\Phi}\left[\oint \tilde{\Phi}^2 d\phi\right]^{1/2}, \qquad \frac{\Delta I}{I} = \frac{1}{\sqrt{2\pi}I}\left[\oint \tilde{I}^2 d\phi\right]^{1/2}$$

The toroidal variation of toroidal current and toroidal flux follows from $\nabla \cdot \mathbf{B} = 0$, and $\nabla \cdot \mathbf{J} = 0$, which have the integral form $\partial\Phi/\partial\phi = -\oint B_n R dl, \quad \partial I/\partial\phi = -\oint J_n R dl$. Suppose $J_\phi = \lambda B_\phi$, then $\partial I/\partial\phi = \lambda\partial\Phi/\partial\phi$. Taking $\lambda = I/\Phi$, then

$$\frac{\Delta\Phi}{\Phi} = \frac{\Delta I}{I}.$$

Time history of simulation of shot 71985 with TQ, VDE, and CQ

This example includes the TQ, VDE, and CQ.



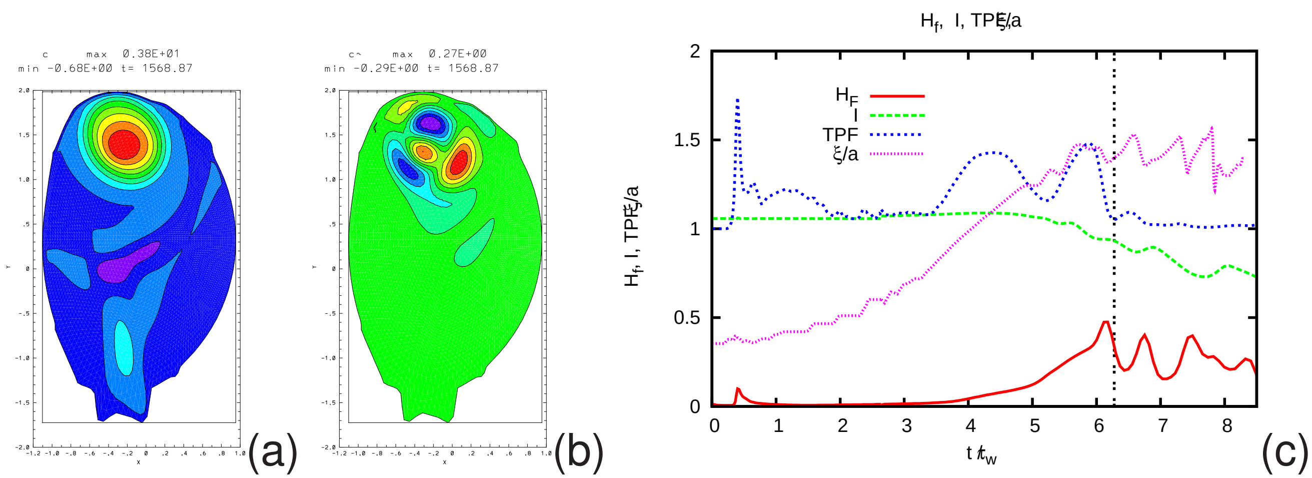
Time history plots for case with $S_{wall} = 250$. Time in units of wall time τ_{wall}. The current is ramped down using rescaled experimental time history data, where time in seconds is divided by $t_w = 0.005s$ to give wall time units. The simulation current is driven by normalized experimental current in wall time units.

Shown are simulation total current I, total pressure p, vertical displacement ξ/a, and wall force F_x. Also shown are the rescaled experimental measurements of I_p and $z_p = \xi$. It is noteworthy that ξ agrees well with z_p. The TQ is slow, because the initial temperature is highly peaked, and the central part of the plasma is not rapidly quenched. The wall force F_x is largest during the saturation of ξ and the CQ.

The computation time is proportional to S_{wall}. Simulations in progress will have larger S_{wall}. Perhaps inertia is not important during VDE and CQ, then only S_{wall}/S is significant.

Toroidal current and halo current evolution in shot 71985 during CQ

During the CQ, the VDE saturates. Some current flows along the separatrix.



Contour plots of toroidal current with $S_{wall} = 250$, (a) $t = 6.2\tau_{wall}$, and (b) perturbed current at same time, with $(1,1)$ and $(2,1)$ modes

It can be assumed that the current (a) is nearly parallel to B, so current outside closed contours is proportional to poloidal halo current.

(c) halo current fraction H_f as a function of time in units of τ_{wall}. Time t marked with vertical line. Also shown are vertical displacement ξ/a, total current I, and TPF.

JET AVDE Summary

- Simulations have three phases: TQ, VDE, CQ
- JET AVDE disruption involves three MHD instabilities
  - $(1,1)$ internal kink causes TQ, $(1,0)$ VDE, $(2,1)$
  - TQ predictor – EFIT equilibrium reconstruction has $q_0 \approx 0.8$
- asymmetric wall force
  - Asymmetric force $0.75MN \leq F_x \leq 3MN$
  - Maximum for $\gamma\tau_{wall} \sim 1$, asymptotes for $S_{wall} > 10^3$.
  - wall force mitigation – vertical control VDE suppression
- rotation
  - wall force rotation frequency $\approx 5 \times 10^4 \tau_A^{-1}$.
  - rotation is not sensitive to S_{wall}.
- toroidal variation of toroidal current and magnetic flux.

Future work and work in progress

- include CQ data in shot 72926
- simulate other JET shots
- perform simulations with larger S_{wall} and S
- couple M3D to CARIDDI model of JET external wall structure (R. Paccagnella, F. Villone)
- include fluid model of runaway electrons [Cai and Fu, 2015]

*See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

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