JET disruption simulations

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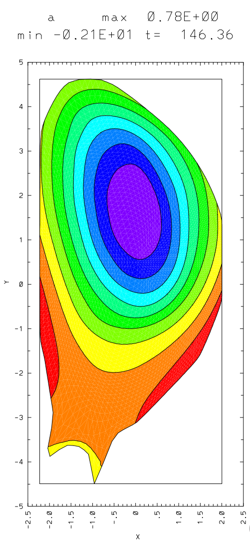
previous AVDE ITER disruptions

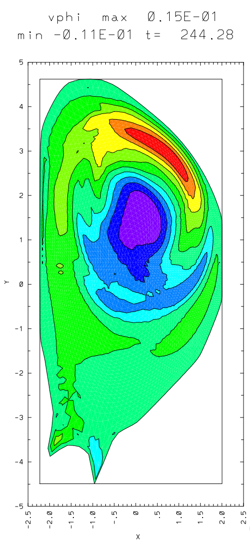
AVDE disruptions: magnetic flux is scraped off until $q_{LCFS} \geq 2$. [Strauss *et al.* 2010, 2014] dominated by $(2,1)$ mode.

AVDE with $(m,n) = (1,0)$ vertical displacement ξ along with $(2,1)$ mode δB.

Together they produce sideways or asymmetric force $F_x \propto \xi\delta B$. They also produce $n = 1$ variation of toroidal current. There is net toroidal rotation. The direction of the asymmetric force rotates.



(a)



(b)

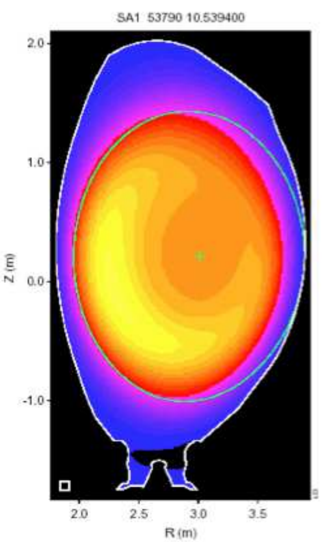
Rotation and force scalings with ξ, δB were obtained using an ITER model, and are consistent with JET data. [Strauss, Asymmetric Wall Force and Toroidal Rotation in Tokamak Disruptions, Phys. Plasmas **22**, 082509 (2015)]
Is the disruption model really consistent with JET? JET disruptions have $q_{LCFS} \approx 1$, "most" disruptions occur when $q_{LCFS} \approx 2$.

JET disruptions vs. AVDE ITER disruptions

JET disruptions appear to have $1 < q_{LCFS} < 2$.

TQ is followed by AVDE. During the AVDE, plasma seems nearly in equilibrium.

This is different from AVDE disruptions in which magnetic flux is scraped off until $q_{LCFS} \geq 2$. [Strauss *et al.* 2010, 2014] dominated by $(2,1)$ mode.



Radiation from a JET disruption, which looks like a $(1,1)$ island, suggesting $q \approx 1$, with large inversion radius. From Plyusnin *et al.* IAEA 2004.

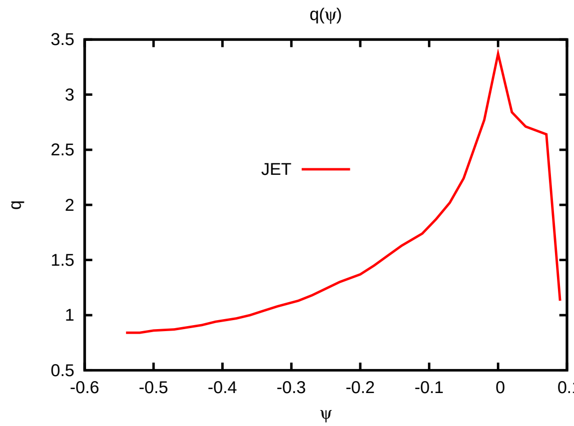
a state with $q_{LCFS} \approx 1$ can be produced by "giant saw-teeth," stabilized by hot ion kinetic effects [Porcelli *et al.* Plasma Phys. Cont. Fusion 38, 2163 (1996)]

JET has short wall time: $\tau_{w-JET} = 3ms, \tau_{w-ITER} = 300ms$.

JET and ITER τ_A are comparable, $\tau_A \approx 1 - 3\mu s$.

JET simulations

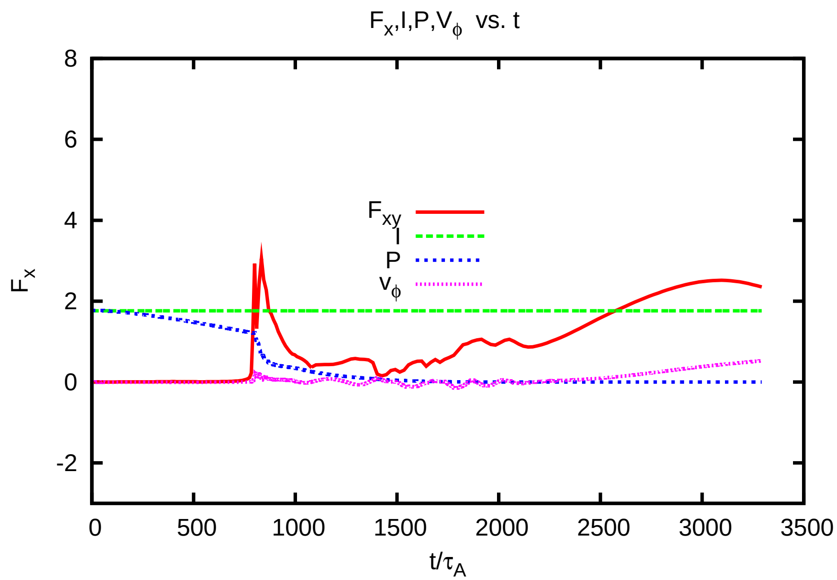
- JET simulations were done with M3D
- Initialized with JET eqdsk file
  - shot 72926 at 66998ms
  - Gerasimov *et al.* Nucl. Fusion **54**, 073009 (2014) rapidly rotating case
  - $q_0 = 0.8$, causing "giant sawtooth" $(1,1)$ mode
  - evolved in 3D from the initial eqdsk state



JET 72926 initial q profile

- Parameters: $S = 10^6$, $S_{wall} = \tau_{wall}/\tau_A = 10^2 - 10^4$.
- The initial state is MHD unstable and causes TQ. Unstable modes include $(1,1)$, $(3,2)$
- The initial state is also unstable to VDE, which develops at the same time
- During CQ, plasma drifts vertically. Large asymmetric force and toroidal rotation can occur.

JET time history

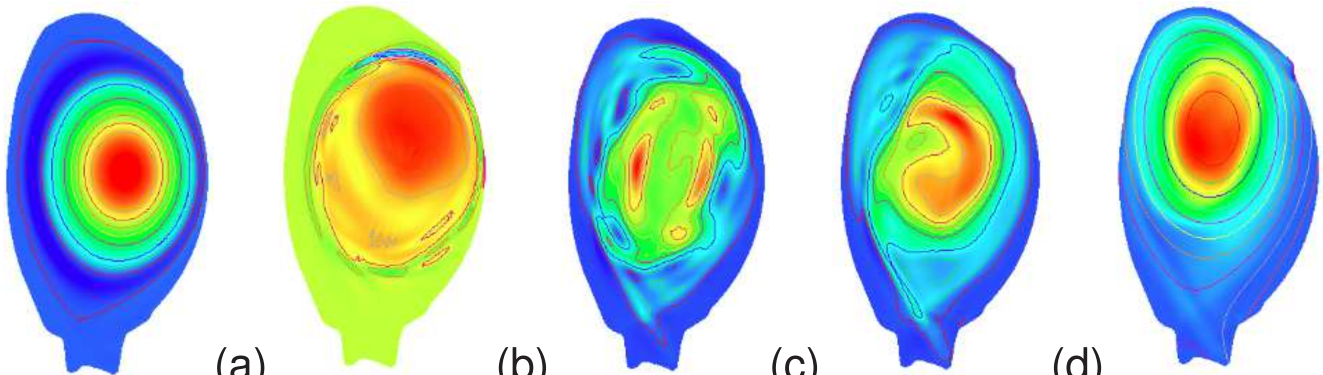


(a) Time history showing sideways force F_x, total current I, total pressure P, and total toroidal velocity V_ϕ, with constant current model and $S_{wall} = 10^3$.

There are two phases, the TQ and CQ. The TQ also has two phases, a slow phase related to a VDE and a fast phase produced by the $(1, 1)$ and other 3D MHD modes.

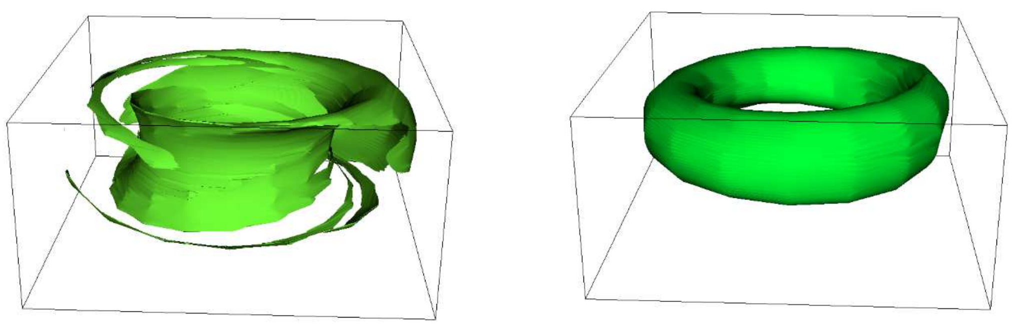
The CQ is accessed using a driving toroidal electric field, or constant current model, which prevent the current from decaying during the CQ.

Current with $\tau_{wall} = 10^3 \tau_A$



(a) (b) (c) (d) (e)

Time history with the same parameters as in the previous figure (b), with constant current and $\tau_{wall} = 10^3$, at times (a) $676\tau_A$, (b) $794\tau_A$, (c) $1531\tau_A$, (d) $1684\tau_A$, (e) $3286\tau_A$.

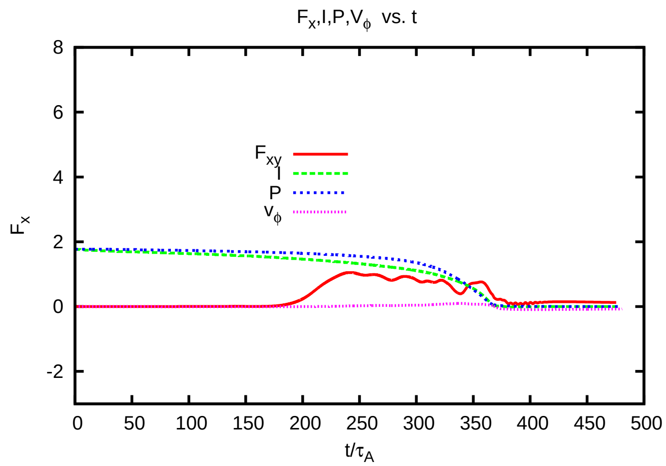


(a) (b)

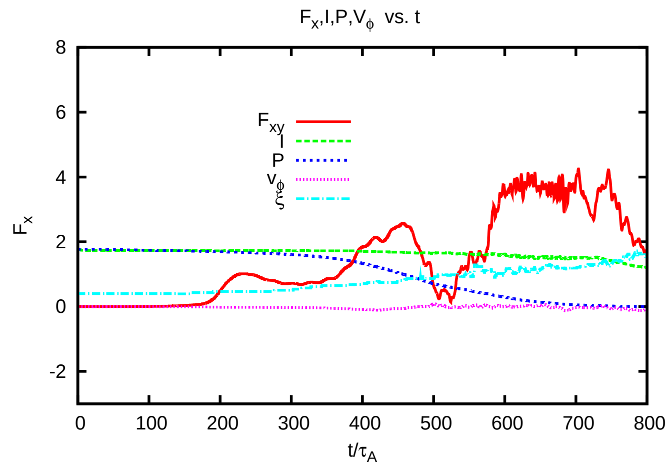
Isoplots with the same parameters as in the previous figure, at times (a) $794\tau_A$, (b) $3286\tau_A$.

Effect of current sustainment on time history

After TQ, plasma is very resistive (especially numerically) and it was necessary to sustain the current. Here $S_{wall} = 10^2$.



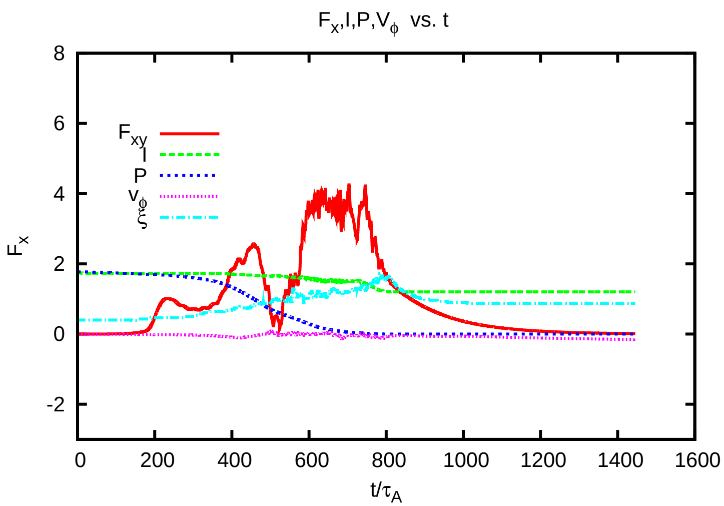
(a)



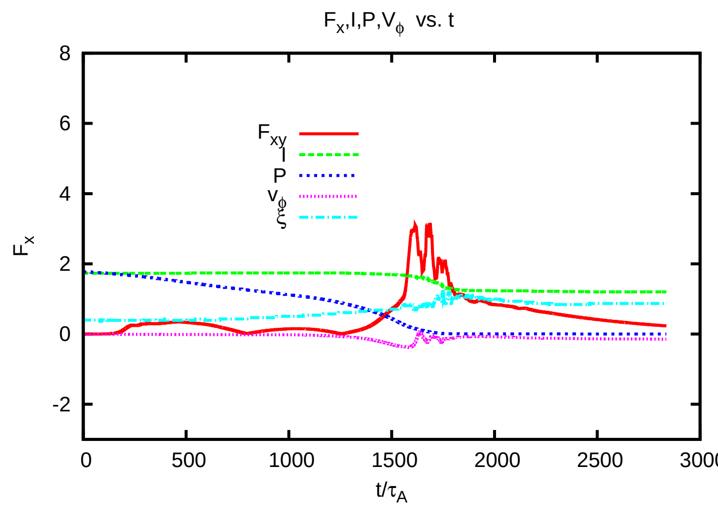
(b)

(a) Time history of F_x, I, P, and V_ϕ. There is no current sustainment, so TQ and CQ are simultaneous. (b) electric field sustainment with current controller.

Effect of wall penetration time on time history



(a)



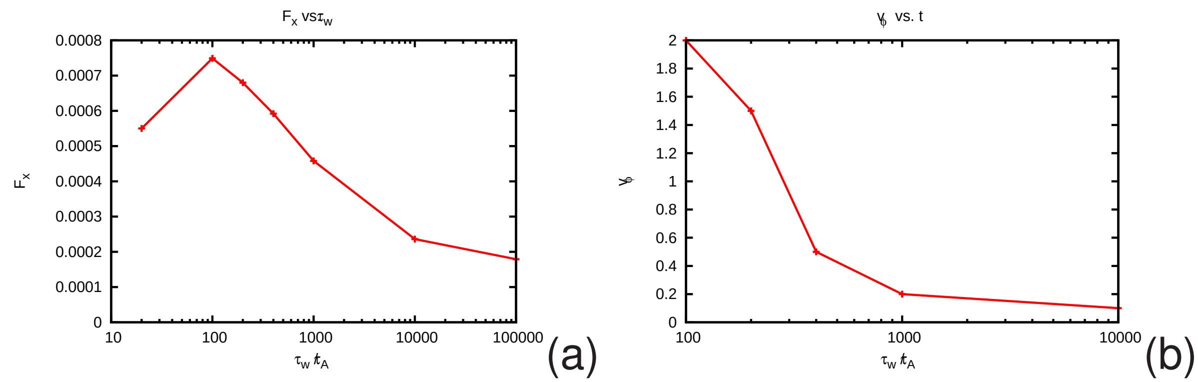
(b)

(a) Time history with the same parameters as in the previous figures, with electric field controller and $S_{wall} = 10^2$. Also shown is the VDE vertical displacement ξ.

(b) The same, with $S_{wall} = 2.5 \times 10^3$.

The TQ has two phases: a slow phase whose duration increases with S_{wall}, and a fast phase independent of S_{wall}. The force F_x decreases with S_{wall}.

Peak force and peak toroidal velocity vs. S_{wall}



The peak force F_x as a function of wall penetration time S_{wall}. As in previous papers, with a different equilibrium model, F_x has a maximum for $S_{wall} \sim 100$ and decreases for larger S_{wall}. (b) Peak velocity v_ϕ as a function of S_{wall}. The velocity also decreases with S_{wall}, although the decrease is faster and it asymptotes at smaller S_{wall}.

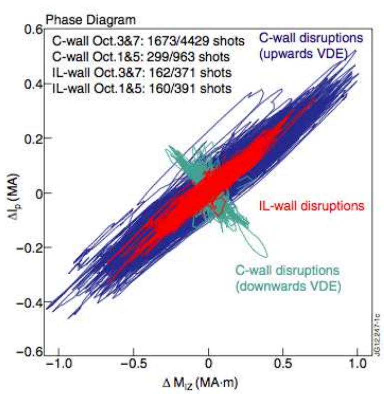
H. R. Strauss, R. Paccagnella, J. Breslau, Wall forces produced during ITER disruptions, Phys. Plasmas **17**, 082505 (2010)

H. R. Strauss, R. Paccagnella, J. Breslau, L. Sugiyama, S. Jardin, Sideways wall force produced during tokamak disruptions, Nucl. Fusion **53**, 073018 (2013).

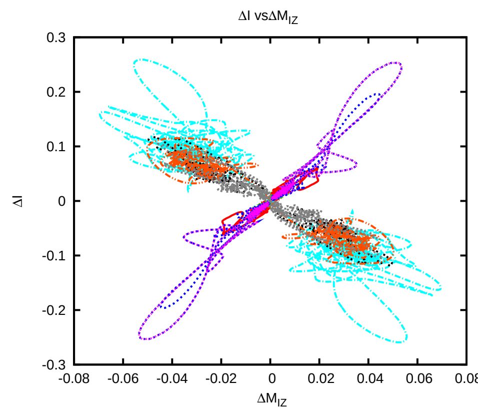
V.D. Pustovitov, General approach to the problem of disruption forces in tokamaks, Nucl. Fusion **55** 113032 (2015)

δI and δM_{IZ} in JET and ITER

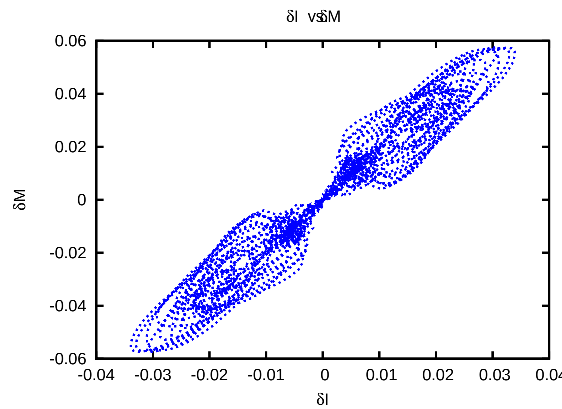
JET experimental features can be obtained with both JET and ITER modeling This shows the observed relation of 3D current perturbations δI to vertical current moment δM_{IZ}



(a)



(b)



(c)

(a) JET measurements [Gerasimov 2014] of ΔI_ϕ vs. ΔM_{IZ} (b) ITER simulations [Strauss 2014] (c) JET simulations

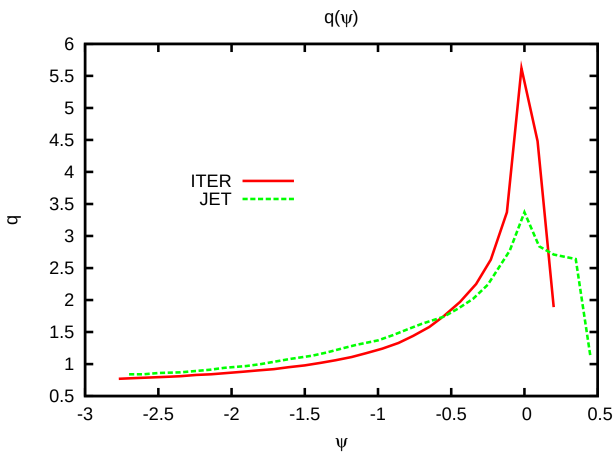
$$\tilde{M}_{IZ} = \int Z \tilde{J}_\phi dRdZ, \quad \tilde{I}_\phi = \int \tilde{J}_\phi dRdZ \tag{1}$$

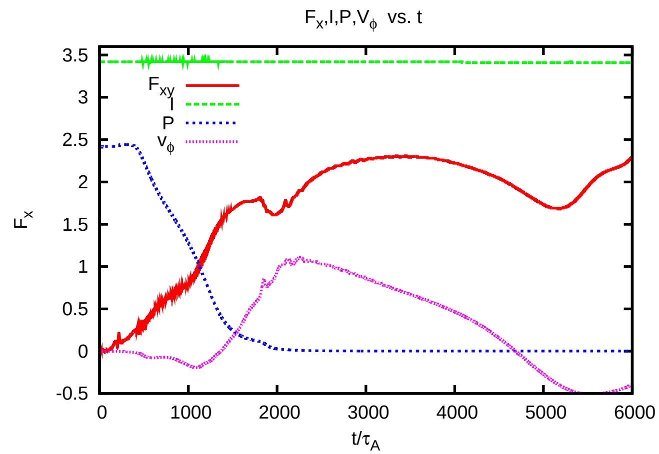
where $\tilde{J}_\phi = J_\phi - \oint J_\phi d\phi/(2\pi)$.

$$\Delta I \propto \xi \Delta M_{IZ}$$

ITER low q disruptions

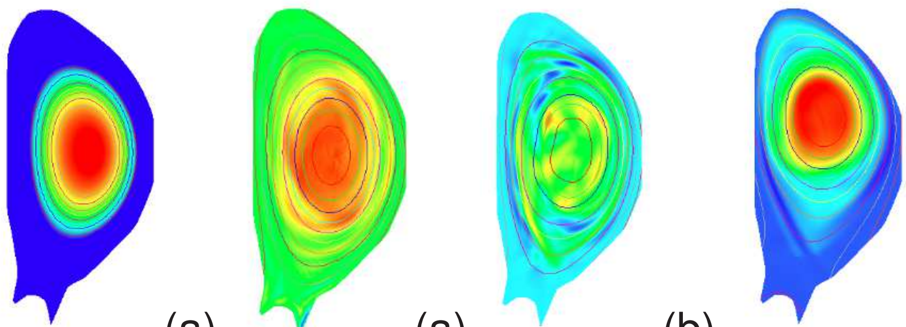
Giant sawteeth may occur in ITER as well as JET.





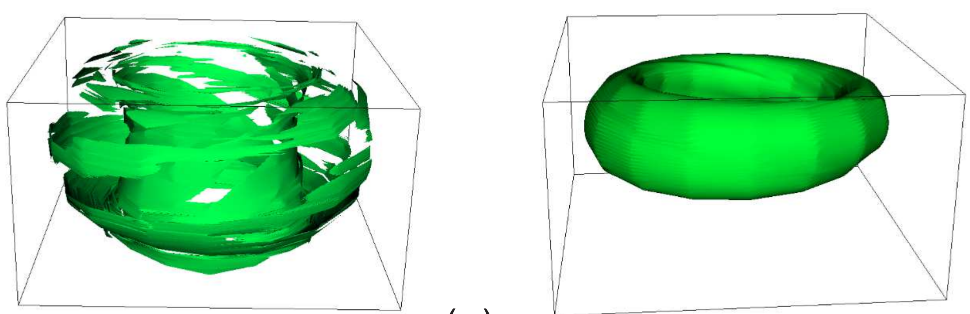
(a) q profile of ITER FEAT15MA equilibrium modified to have $q = 0.8$ on axis. The JET q used previously is also shown. JET has a lower edge q. A broader ITER current profile would give a better match. (b) Time history of ITER low q disruption, $S = 10^6, S_{wall} = 10^2$. This is similar to the JET giant sawtooth disruptions. The TQ seems to involve a combination of $(1,1), (3,2)$ and $(2,1)$ modes. This is followed by drifting steady state seems to be a $(1,1)$ mode.

Current contours in ITER low q disruption



(a) (a) (b) (d)

(a) toroidal current at $t = 697\tau_A$, at the start of the TQ. (b) $t = 1832\tau_A$, at the end of the TQ. (c) $t = 2201\tau_A$, when the current is nearly in a 3D equilibrium. (d) $t = 5991\tau_A$, when 3D equilibrium drifts upward in a VDE.



(a) (b)

(a) toroidal current at $t = 1832\tau_A$,. (b) toroidal current at $t = 5991\tau_A$.

Are JET disruptions predictive for ITER?

There are several differences between JET and ITER which indicate a need to be careful in extrapolating from JET to ITER.

• JET has a short wall time: $\tau_{w-JET} = 3ms$, $\tau_{w-ITER} = 300ms$.

JET and ITER τ_A are comparable, $\tau_A \approx 2\mu s$, so S_{wall} is 100 times longer in ITER than in JET. Hence for MHD instabilities, the scaled sideways force is larger in JET.

• JET disruptions have $q_0 \approx 0.8$, and are more dominated by $(1,1)$ mode.

• previously studied ITER disruptions have $q_0 \approx 1$, and $q_{LCFS} \approx 2$, dominated by $(2,1)$ mode and $(1,0)$ VDE.

Are "giant sawteeth" expected in ITER? what hot ion β_{hot} is expected? what will be the effect of fusion on the hot particle effects?

Extended MHD Modeling: simulate giant sawtooth, includig hot particles, two fluid effects. (Schnack)

Simulate runaway electrons generated during CQ (Cai-Fu)

Comparison of JET and previous ITER modeling

- Toroidal rotation
  - rotation is largest in beginning of CQ
  - asymptotic value $V_\phi \tau_A/(2\pi R) = 3 \times 10^{-4} \approx 300 Hz$
  - good agreement with Gerasimov (2014), $f = 278 Hz$.
  - also good agreement with ITER simulations in [Strauss, Wall Force and Toroidal Rotation in Tokamak Disruptions, Phys. Plasmas **22**, 082509 (2015)]
- Sideways force
  - peak normalized force $F_x = 8 \times 10^{-4}$, asymptotic $F_x = 3 \times 10^{-4}$. In dimensional units, the peak sideways force $F_x = 1.2$ MN, while the asymptotic value is 0.45 MN, consistent with JET data in Gerasimov (2014)
  - In [Strauss 2015], peak normalized force is $F_x = 4 \times 10^{-4}$
  - F_x decreases with with S_{wall}.

Conclusions

- JET disruptions can be initiated by giant sawtooth
  - simulate giant sawtooth in ITER
  - hybrid simulation, two fluid model
  - what happens to hot particles in a disruption?
- JET and ITER modeling are in reasonable agreement
  - scaled force and rotation frequency are comparable in JET and ITER
  - comparable for giant sawtooth and AVDE disruptions
- future plan: runaway electron modeling
  - introduce REs during CQ
  - H. Cai and G. Fu, N. F. **55**, 022001 (2015)