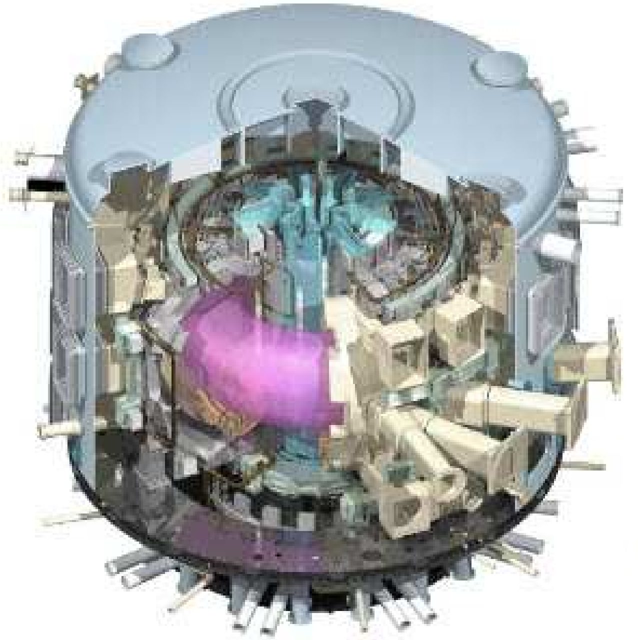
Calculation of Wall Force produced during an ITER Disruption

H. Strauss, *HRS Fusion*

R. Paccagnella, *Instituto Gas Ionizzati del C.N.R.*

J. Breslau, *PPPL*

ITER



Disruptions in ITER can cause large electromechanical stress on conducting structures. In particular, toroidally asymmetric magnetic perturbations can produce a sideways force. This research is concerned with the sideways force produced by a vertical displacement event (VDE) and a tearing mode or kink mode.

Theory and simulation of tokamak disruptions

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

- The worst case for asymmetric wall force may be caused by a vertical displacement event (VDE) along with an unstable tearing or kink mode.

- The force depends strongly on the product of the mode growth rate γ with the wall resistive penetration time τ_{wall}. The force is maximum when $\gamma\tau_{wall} \approx 1$. In this regime the force is produced by halo current.

- The force also is proportional to γI^2 where I is the total current.

- sideways horizontal force is consistent in magnitude with JET data and ITER projected force.

- Simulations and simple analytic calculations produce several correlations that can be compared to experiment and other theory and simulations.

Modeling and Simulation Issues

I. Modeling Issues

a. is ideal MHD or XMHD a better model?

b. what are correct boundary conditions?

c. resistive wall model: 2 walls, 3D blanket

II. Simulation issues

a. plasma is supposed to scraped off by VDE, lowering edge q, destabilizing MHD mode. instead initial state is VDE and $n = 1$ unstable.

b. should have higher S.

ideal MHD vs. XMHD

ideal MHD

• $S = 10^{10}$, $\tau_R \approx hour$

– no time for reconnection and magnetic island growth

• current sheets, no magnetic stochasticity

– VDE causes thermal quench

– different physics than expected in ITER

• absorbing velocity boundary condition needed, $\partial v_n/\partial n = 0$, for wetting of wall

• difficult for VDE to scrape off edge plasma to destabilize kink

XMHD

• $S^{1/3} = 2.15 \times 10^3$, $\tau_R \approx ms$

– fast reconnection (Aydemir, Drake, Breslau ...), single helicity

• island overlap, magnetic stochasticity, expected for

– thermal quench

– RMP

– prompt loss of runaways

• standard boundary condition $v_n = 0$, is OK, because wall is wet by halo plasma.

• easier for VDE to scrape off edge plasma

velocity boundary condition

• M3D uses standard rigid wall boundary condition $v_n = 0$.

Zakharov has claimed $\partial v_n/\partial n = 0$, because the plasma penetrates the wall.

A more general boundary condition would be $v_n/d + \partial v_n/\partial n = 0$, where d is the plasma penetration depth into the wall. But d must be less than the wall thickness, which is in turn much less than the width k_n^{-1} of MHD kink modes, where $|\partial v_n/\partial n| = k_n|v_n|$. Because $k_n d \ll 1$, it is a good approximation to take $v_n = 0$.

– does it matter if the plasma penetrates microns into the wall?

• If plasma penetrates the wall, need equations of motion inside the wall.

• Need a physics based analysis.

M3D and Resistive Wall

• The plasma is bounded by a thin resistive wall of thickness δ, resistivity η_w. Outside the wall is vacuum. Normal component of magnetic field is continuous at the wall,

$$B_n^v = B_n^p,$$

where B_n^v, B_n^p are the normal component of magnetic field in the vacuum, and the plasma, adjacent to the wall. ITER wall is more complex, with 3D structures, will have to be modeled.

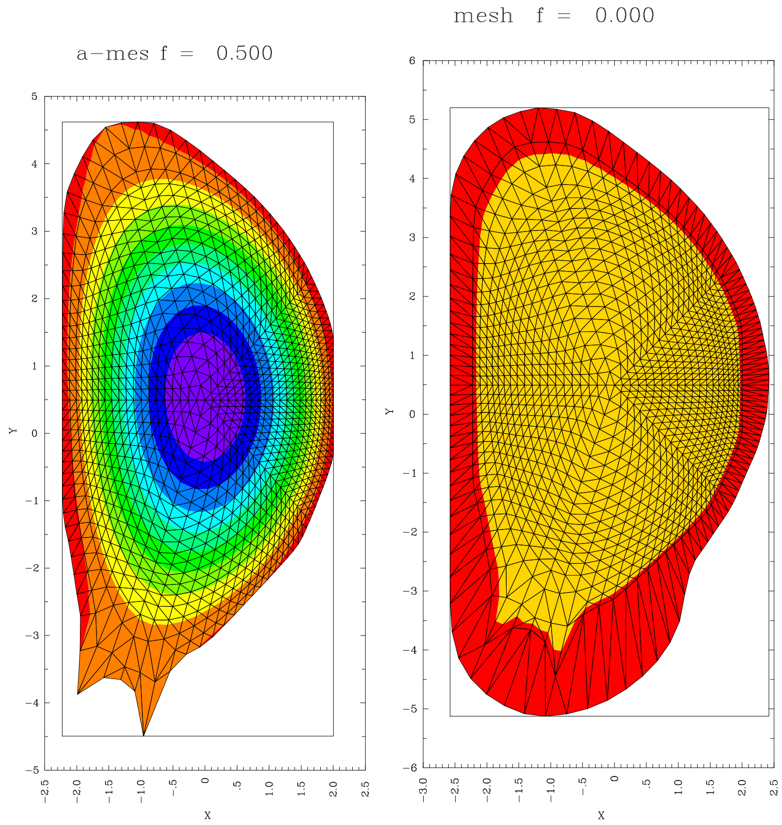
• other components of $\mathbf{B}^v$ solved with Green's functions, given B_n^v. The current in the wall is given by

$$\mathbf{J}_w = \nabla \times \mathbf{B} \approx \frac{\hat{\mathbf{n}}}{\delta} \times (\mathbf{B}^v - \mathbf{B}^p).$$

This allows time advance of

$$\frac{\partial B_n}{\partial t} = -\hat{\mathbf{n}} \cdot \nabla \times \eta_w \mathbf{J} = -\frac{\eta_w}{\delta} \nabla \cdot [\hat{\mathbf{n}} \times (\mathbf{B}^v - \mathbf{B}^p)] \times \hat{\mathbf{n}}]$$

ITER two wall model



ITER has two walls. $\tau_w^{outer} >> \tau_w^{inner}$. M3D modeling assumes $\tau_w^{inner} = 0$. The magnetic field is continuous at inner wall, no force on inner wall. In between is a 3D blanket structure with intermediate penetration time,

$$\tau_w^{outer} >> \tau_{blanket} >> \tau_w^{inner},$$

which will need to be modeled.

Wall Pressure

The normal component of the force density is

$$f_{wn} = \hat{\mathbf{n}} \cdot \mathbf{J}_w \times \mathbf{B}_w = -\frac{1}{\delta}(\mathbf{B}^v - \mathbf{B}^p) \cdot \mathbf{B}_w.$$

Inside the wall assume that $\mathbf{B}_w = \frac{1}{2}(\mathbf{B}^v + \mathbf{B}^p)$. The normal wall force density is the magnetic pressure jump across the wall:

$$f_{wn} = \frac{1}{2\delta}(|\mathbf{B}^p|^2 - |\mathbf{B}^v|^2). \quad (1)$$

The tangential components of the wall force multiplied by the wall thickness are

$$f_{wl} = J_\phi B_n = \frac{B_n}{\delta}(B_l^v - B_l^n), \quad (2)$$

$$f_{w\phi} = -J_l B_n = \frac{B_n}{\delta}(B_\phi^v - B_\phi^n), \quad (3)$$

where the tangent to the wall is $\hat{\mathbf{l}} = -\hat{\mathbf{n}} \times \hat{\phi}$. Force is produced by magnetic field jump across the wall.

Wall Force

The total wall force, normalized to be dimensionless, is given by

$$\mathbf{F} = \frac{\delta}{2\pi R_0 L_w B_0^2} \int d\phi \int dl R(f_{wn}\widehat{\mathbf{n}} + f_{wl}\widehat{\mathbf{l}} + f_{w\phi}\widehat{\phi}). \tag{4}$$

where B_0 is the magnetic field on axis, and $L_w = \int dl$ is the wall circumference. Of particular importance is the net horizontal force, F_x.

• Halo current is the normal component of current J_n^p flowing into the wall: It contributes to the wall force through $B_\phi^v - B_\phi^p$ where $RB_\phi^p \approx \int^l dl' R J_n + \text{constant}$.

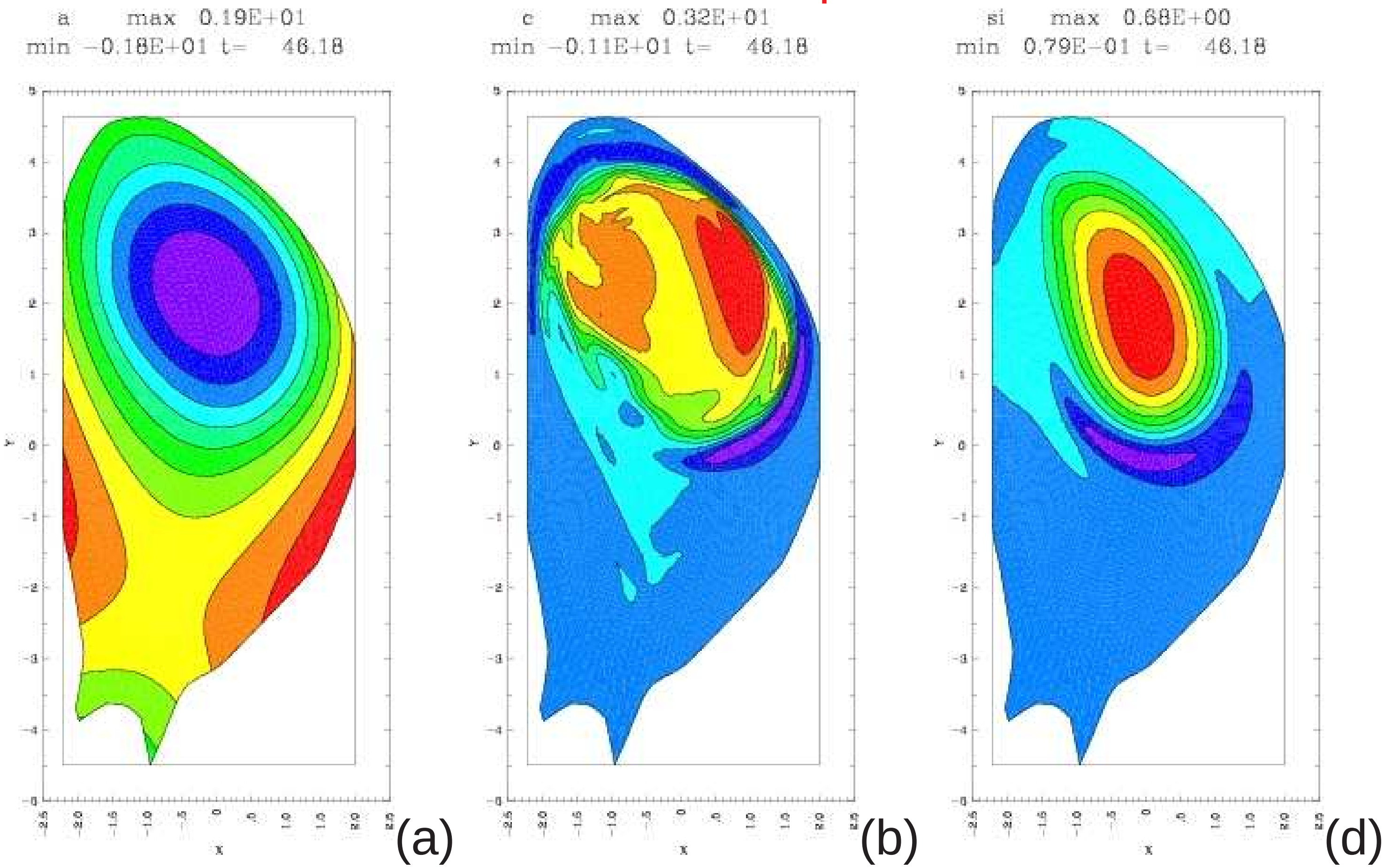
Disruption Simulations

The M3D code was used to calculate disruptions. The initial state is an ITER reference case equilibrium (FEAT15MA) with $q = 1.2$ on axis, which is VDE unstable. The equilibrium was rescaled to generate a RWM / tearing unstable equilibrium with $q = 1.1$ on axis, and kink unstable equilibria with $q = 0.82$ and $q = 0.6$ on axis. The latter model what might occur if outer layers of plasma were scraped off during a VDE.

Boundary conditions: $\partial B_n/\partial t \neq 0$, $v_n = 0$.

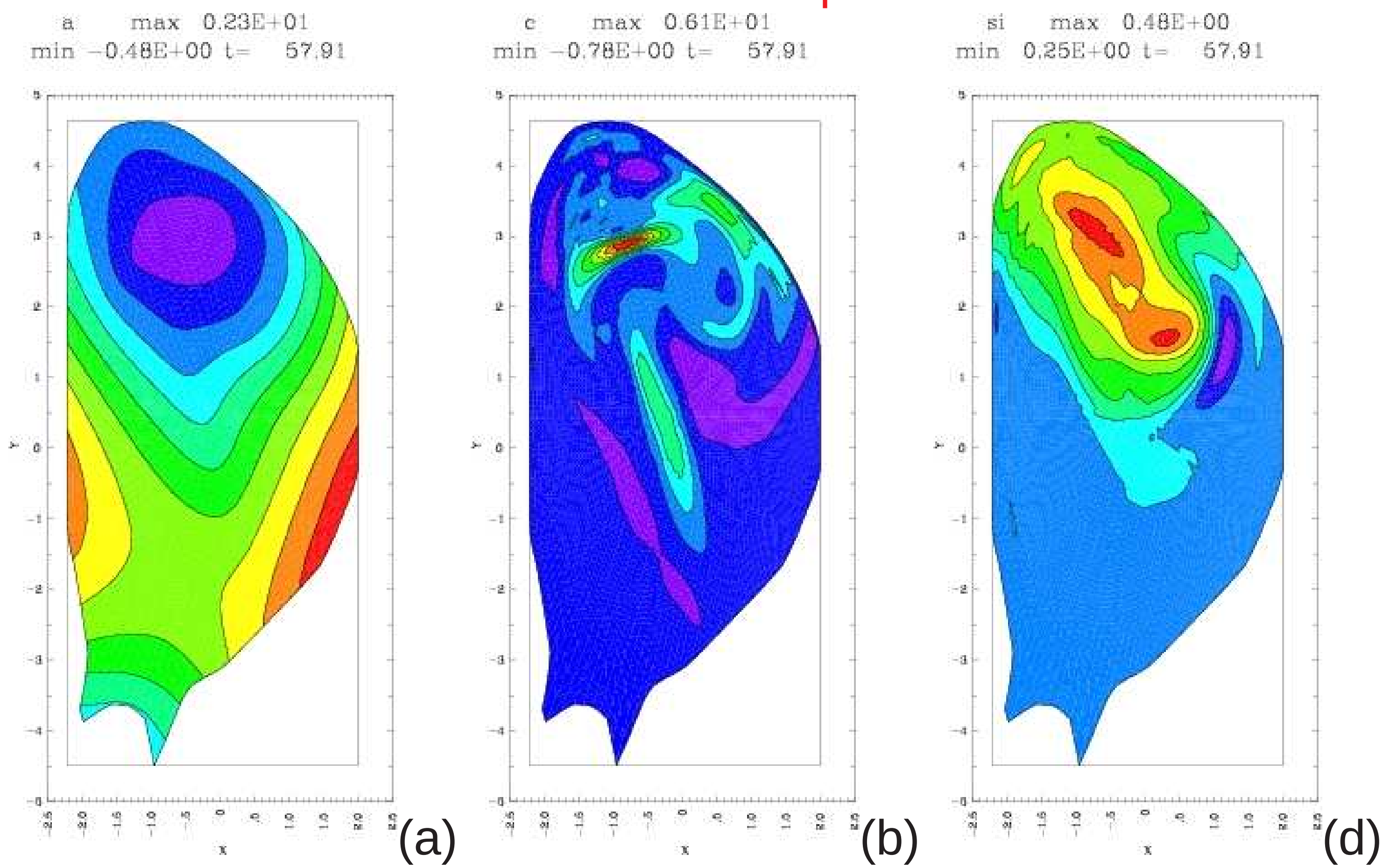
Parameters: $\eta R/(v_A a^2) = 10^{-5}$, $\eta_w R/(v_A a\delta) = 10^{-1}$.

VDE - kink disruption



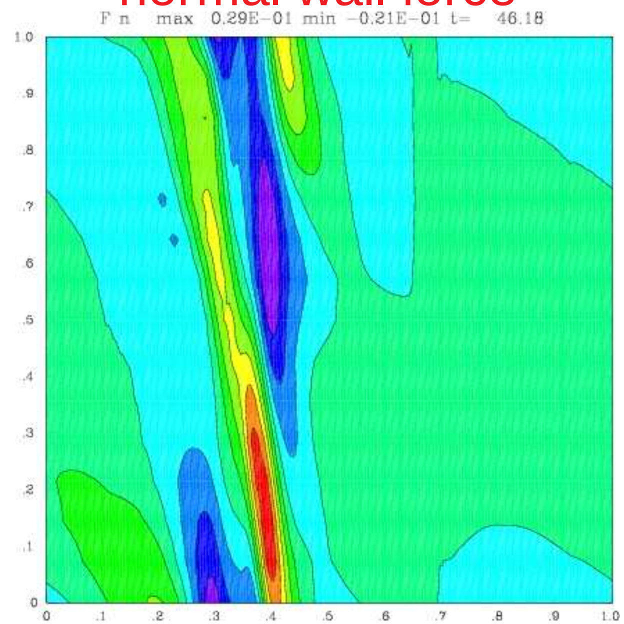
A nonlinear kink mode at time $t = 46.18\tau_A$,, showing (a) poloidal flux ψ, (b) toroidal current $-RJ_\phi$, (c) toroidal field RB_ϕ , at toroidal angle $\phi = \pi$.

VDE - kink disruption



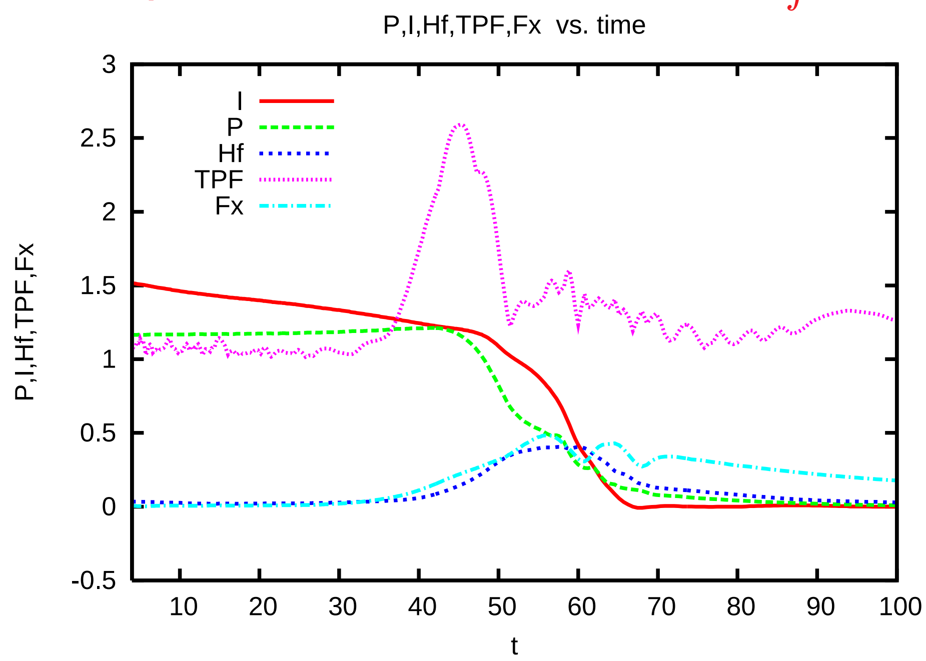
The nonlinear kink mode at time $t = 57.91\tau_A$,, showing (a) poloidal flux ψ, (b) toroidal current $-RJ_\phi$, (c) toroidal field RB_ϕ , at toroidal angle $\phi = \pi$. The current is concentrated at the o and x points of ψ.

normal wall force



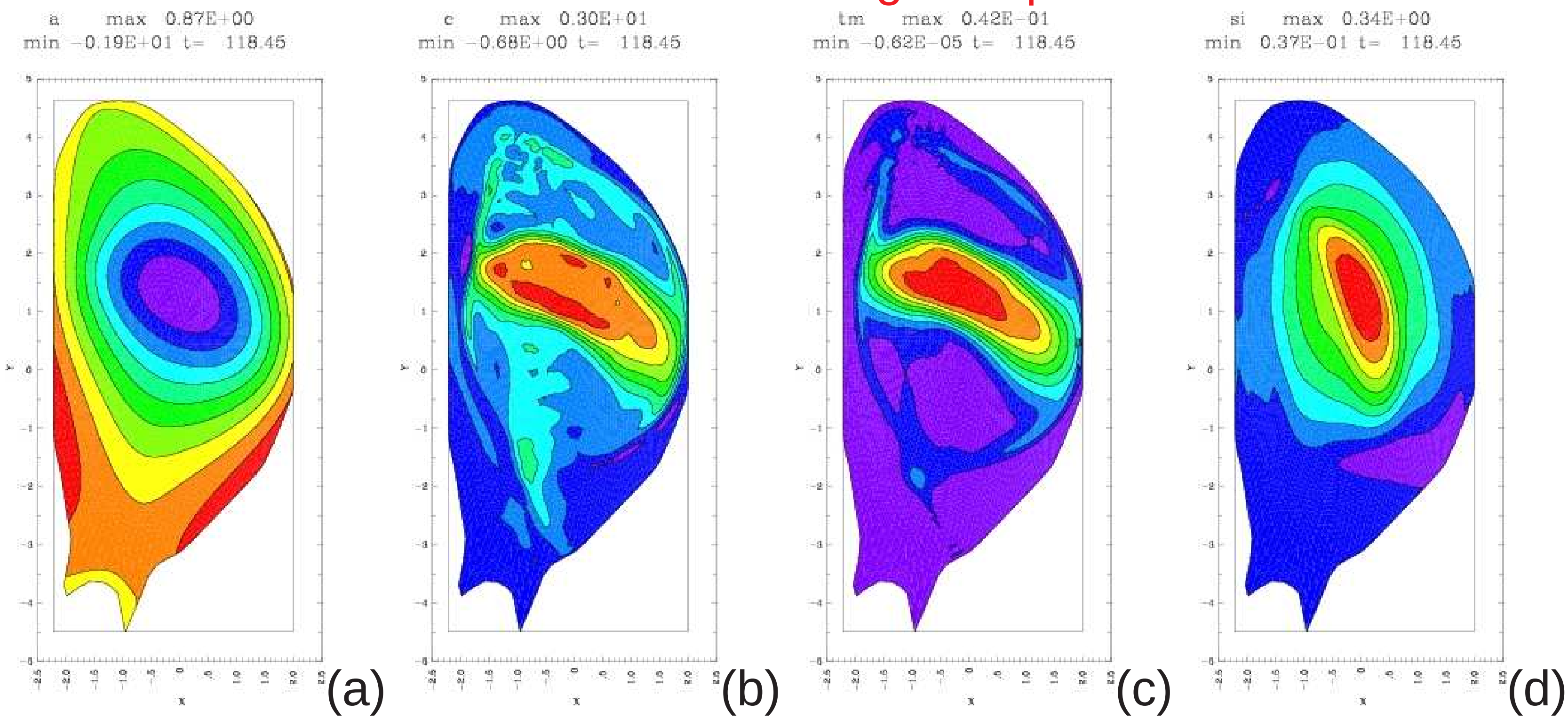
Normal force density at $t = 46.18\tau_A$, when it is maximum, $f_n(\theta/2\pi, \phi/2\pi)$, where θ is the poloidal angle from the origin, and ϕ is the toroidal angle. The horizontal axis is $\theta/2\pi$, and the horizontal axis is $\phi/2\pi$. The force is concentrated near the top of the wall, on the inboard side.

Time dependence of I, P, TPF, H_f and F_x



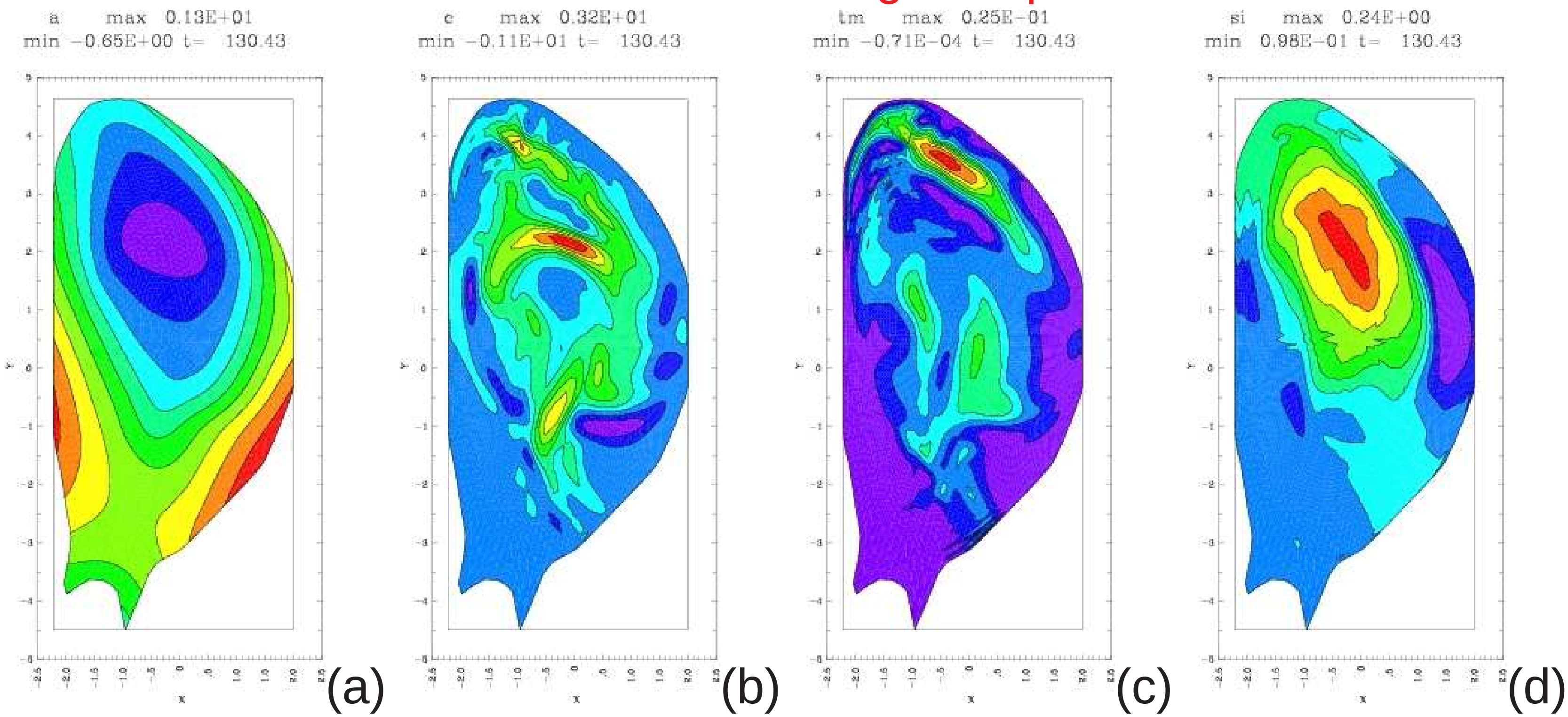
toroidal current I, pressure P, TPF, halo current fraction H_f and horizontal force F_x as a function of time. The quantities I, P, and F_x are in arbitrary units. There is a close time correlation of halo current fraction H_f and horizontal force F_x.

VDE - RWM / tearing disruption



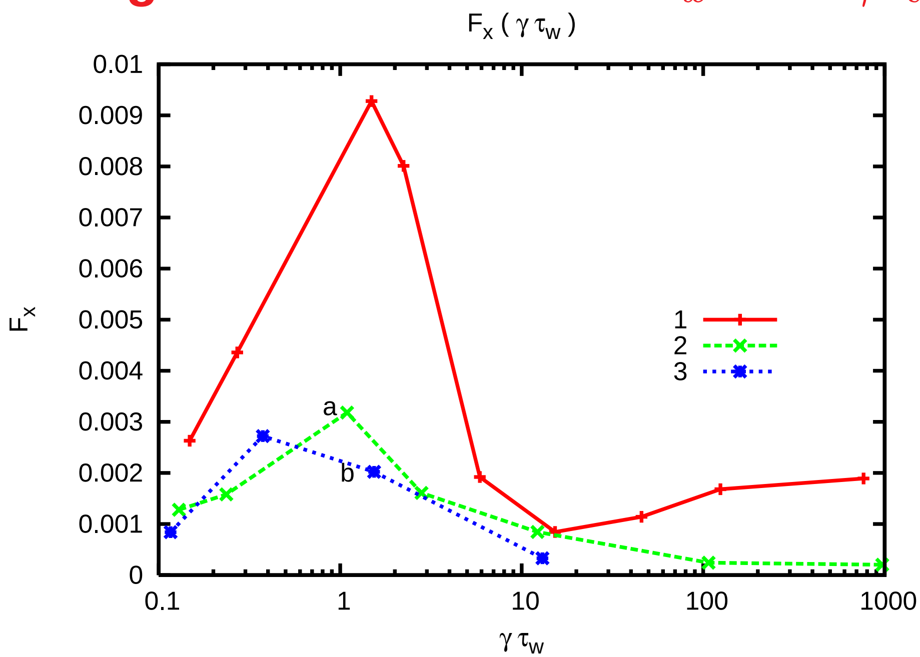
A nonlinear RWM / tearing mode at time $t = 118.45\tau_A$,, showing (a) poloidal flux ψ, (b) toroidal current $-RJ_\phi$, (c) temperature T, (d) toroidal field RB_ϕ , at toroidal angle $\phi = \pi$. The mode has predominantly $m, n = 2, 1$ structure.

VDE - RWM / tearing disruption



The nonlinear RWM / tearing mode at time $t = 130.43\tau_A$,, showing (a) poloidal flux ψ, (b) toroidal current $-RJ_\phi$, (c) temperature T, (d) toroidal field RB_ϕ , at toroidal angle $\phi = \pi$. The plasma current and temperature are more broken up, indicating magnetic stochasticity characteristic of "classical" disruptions.

Scaling of horizontal force F_x with $\gamma\tau_w$.



The force tends to a limit for an ideal conducting wall $\gamma\tau_w \to \infty$, and is zero for $\tau_w = 0$. The force has a maximum for $\gamma\tau_w \approx 1$. The curves correspond to different initial rescaling of the equilibrium: "1" – $q_0 = .6$, "2" – $q_0 = .8$, "3" – $q_0 = 1.1$ The difference between force "1" and "2" is $\propto \gamma$.

Scaling to ITER and JET

Outward wall force in ITER is $F_{ITER} = 9.03 \times 10^9 N$. The dimensional horizontal wall force is $F_{xITER} = F_x \times F_{ITER}$. The ITER horizontal force corresponding to point "a" of the previous graph is $65MN$. The factor F_{ITER} scales as I_p^2, where $I_p \propto (aB)$ is the plasma current, assuming fixed aspect ratio and q. In JET, the current is about 20% of the ITER current, so that the JET horizontal force could be 2.75 MN. This value is consistent with JET experiments.

More on simulation model

• $\gamma\tau_w = 1$ effect is because of competition between $n = 1$ mode and VDE to reach the wall.

• force appears $\propto \gamma I^2 f(\gamma\tau_w)$, has some numerical and analytic support

– ideal MHD RWM has $\gamma\tau_w \approx 1$, but for large τ_w, the force is small.

• Worst case may be VDE carrying MHD stable plasma to wall

– plasma edge is scraped off, q drops, plasma becomes MHD unstable, but so far has been difficult to simulate

– may need mesh refinement where VDE localizes the plasma

Model Analytic Force Calculation

Inductive wall force can be calculated using a simple model. The magnetic field is approximately,

$$\mathbf{B} = \nabla\psi \times \widehat{\phi} + B\widehat{\phi},$$

assuming circular flux surfaces, $\psi = \psi_0(r) + \psi_{mn}\,\mathrm{exp}(im\theta + in\phi)$, with constant toroidal current $\nabla^2\psi_0 = 2B/(q_0 R_0)$ inside the plasma boundary at $r = a$.

$$F_R = \frac{B_0^2}{q_0^2 R_0^2}\frac{(1 - q_0)(a/b)}{1 - (a/b)^2 + 2\frac{\eta w}{\gamma \delta a}}\xi_R. \quad (5)$$

where a is plasma radius, b is wall radius, ξ_R is plasma displacement in the major radius $\widehat{\mathbf{R}}$ direction. This gives an approximately γI^2 scaling, for small growth rate, $\gamma \propto (1 - q_0)$. Testable: $F_R \propto \xi_R$, $F_Z \propto \xi_Z$.

Current vs. Displacement Calculation

A vertical (VDE) displacement interacts with the helical kink.

$$J_\phi = J_{\phi 0}(r - r_1 \sin\theta) + J_{\phi 1}(r - r_1 \sin\theta)\cos(\theta + \phi)$$

where $r_1 > 0$ for an upward displacement. The total toroidally varying plasma current is

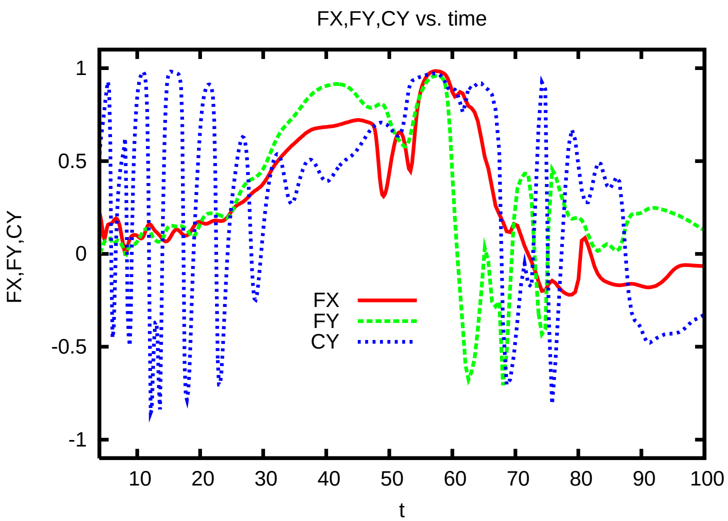
$$I_\phi = -\int dr r d\theta \frac{dJ_{\phi 1}}{dr} r_1 \sin\theta \cos(\theta + \phi) = -\pi \int dr J_{\phi 1} r_1 \sin\phi.$$

where $J_{\phi 1}$ was first Taylor expanded and then integrated by parts. Using analytic model gives

$$\frac{dI_\phi}{d\phi} = \frac{r_1}{a^2}\frac{dM_{IZ}}{d\phi}$$

Here $M_{IZ} = \int Z J_\phi dR dZ$, the vertical moment of the current. This relation was seen in JET (Zakharov 2008, Gerasimov 2010) and claimed to validate “Hiro” current model.

Correlation of force and displacement in simulations



Correlations as a function of time: $FX = C(F_R, \xi_R)$, $FY = C(F_Z, \xi_Z)$, $CY = C(I_\phi, M_{IZ})$

where $C(a,b) =< ab >< a^2 >^{-1/2}< b^2 >^{-1/2}$ and $< a >= \int d\phi a$. (ξ_R, ξ_y) is the (horizontal, vertical) displacement of the current centroid as a function of toroidal angle ϕ. The toroidal variation of the current $dI_\phi/d\phi$ is positively correlated with $dM_{IZ}/d\phi$ for an upward VDE. (verified negative correlation for downward VDE.) The positive correlations FX,FY show that the force has the same sign as the plasma displacement, $\mathbf{F} \propto \xi$.

Summary

• MHD simulations were done using M3D code with thin resistive wall. Disruptions were produced by VDE and either tearing or kink instability, causing quench of temperature, current, and wall force.

• The force depends strongly on the product of the mode growth rate γ with the wall resistive penetration time τ_{wall}. The force is maximum when $\gamma\tau_{wall} \approx 1$. In this regime the force is produced by halo current.

• The wall force could be mitigated by making the wall more conducting.

• sideways horizontal force is consistent in magnitude with JET data and with ITER projected values.

• Simulations and simple analytic calculations produce several correlations that can be compared to experiment and other theory and simulations.

Future Work

- carry out JET and NSTX simulations and compare with data.

- wall shape effects: ITER second vacuum wall, 3D wall: ports, external magnetic perturbations

- investigate the possible effects of boundary conditions.

- perform higher resolution simulations with more realistic S and other parameters, and study effect of very high S on development of magnetic stochasticity.

- study duration of wall force (impulse)