Calculation of Wall Force produced during an ITER Disruption

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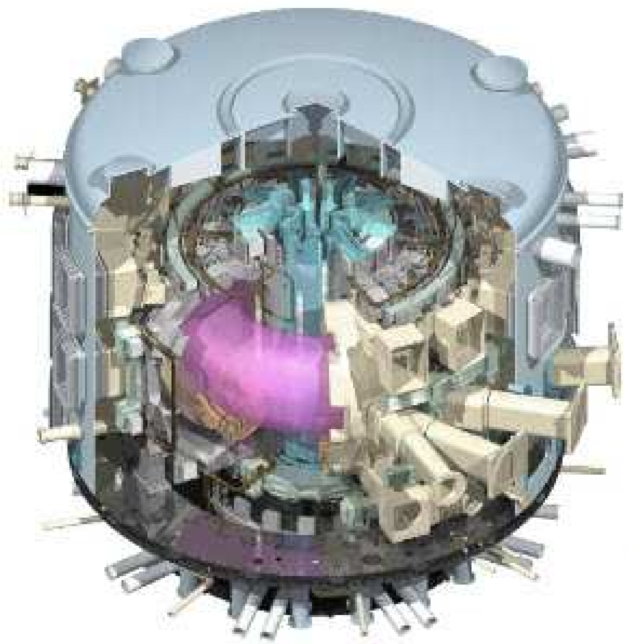
ITER



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.

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

Outline

- Is ideal MHD or XMHD a better model?
- What are correct boundary conditions?
- ITER resistive wall model
- Relation of toroidal current to halo current
- Simulation of kink mode and tearing / RWM
- dependence of wall force on wall penetration time τ_w.
- toroidal angular correlations of currents, forces, displacements
- plans and conclusions

Is ideal MHD or XMHD a better model?

• In ITER, $S = 10^{10}$. Boozer and Zakharov argue that a disruption is a saturated ideal MHD kink mode, which is brought into contact with the wall by a VDE. Resistive reconnection is slow, so there is no island overlap and magnetic stochasticity. This picture does not explain the rapid thermal quench which occurs in disruptions in all tokamaks up to now.

• Resistivity and two fluid effects permit fast reconnection, independent of S. Fast reconnection needs to be studied with multiple helicity overlapping islands, to see if there is fast development of stochasticity. After the thermal quench, S is low, so that further evolution is described by standard resistive MHD.

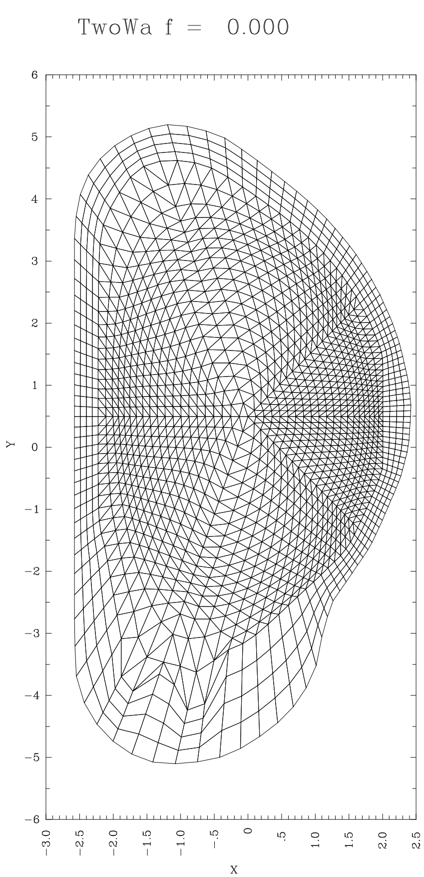
what are correct boundary conditions?

• Zakharov argued that plasma is absorbed by walls. Hence the normal component of velocity v_n should satisfy an absorbing boundary condition, $\partial v_n/\partial n = 0$.

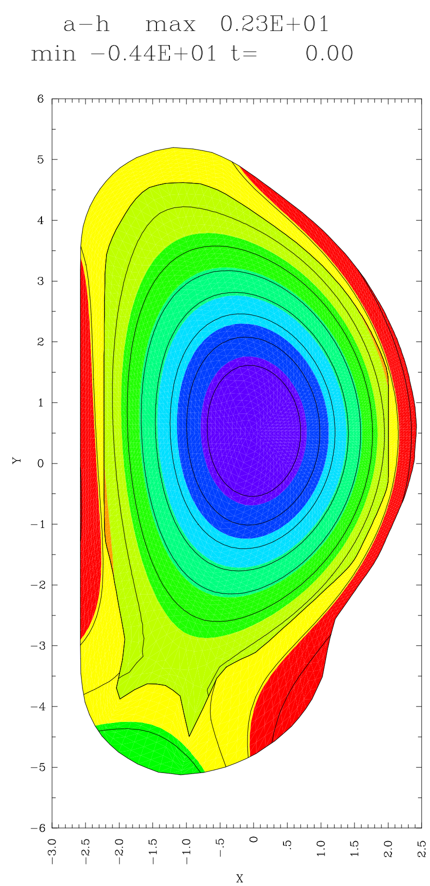
• M3D assumed $v_n = 0$. The PPPL theory review study group report "Plasma-wall boundary conditions for MHD simulations of disruption events", by A. Boozer, J. Breslau, E. Fredrickson, and D. Stotler, March 21, 2011, states that "The assumption in existing simulations that the plasma can not flow into the wall, $v_n = 0$, is unphysical. Since existing codes assume, rather than calculate, the properties of the halo, the impact of this boundary condition on current simulations is limited to essentially the inertia of the halo plasma, which is negligible in the overall simulation." (?)

ITER two wall model

The PPPL study group also states “the complicated geometry of actual walls affects both the plasma and the magnetic boundary conditions and should be represented to obtain an accurate simulation.”



(a)



(b)

ITER has two walls: inner first wall, and outer vacuum wall. In between is the blanket with various conducting structures. Presently developing a computational model. The inner and outer walls are thin resistive shells. The blanket is a resistive “plasma” with no flow, and variable 3 D resistivity to model blanket structures.

M3D and Resistive Walls

• The plasma and blanket are bounded by thin resistive walls of thickness δ_w, resistivity η_w (different for each wall, and η_w can be spatially varying.)

• Normal component of magnetic field B_n is continuous at walls.

• In blanket the magnetic field is advanced resistively, given B_n on the inner and outer walls.

• Outside the outer wall the magnetic field is solved with Green's functions.

• The normal magnetic field on the walls is time advanced with

$$\frac{\partial B_n}{\partial t} = -\hat{\mathbf{n}} \cdot \nabla \times (\eta_w \mathbf{J}_w)$$

Wall Force

The current in the walls is given by the jump in the components of B tangential to the wall,

$$\mathbf{J}_w = \nabla \times \mathbf{B} \approx \frac{\hat{\mathbf{n}}}{\delta} \times \left[\mathbf{B}^{(+)} - \mathbf{B}^{(-)} \right].$$

where $^{(+)}$ is the outside and $^{(-)}$ is the inside of each wall.

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

$$\mathbf{F} = \delta \int d\phi \int dl R (\mathbf{J}_w \times \mathbf{B}_w). \tag{1}$$

Of particular importance is the horizontal force, $F_x = \hat{\mathbf{x}} \cdot \hat{\mathbf{F}}$ where $\hat{\mathbf{x}} = \hat{\mathbf{R}} \cos\phi - \hat{\phi} \sin\phi$. To get a nonzero F_x, there must be an $n = 1$ or $\exp(i\phi)$ perturbation of the wall current.

Halo Current

- Halo current is the normal component of current J_n flowing into the wall:

$$I_{halo}(\phi) = \frac{1}{2}\int |J_n| R dl,$$

where dl is the length element tangent to the wall.

The toroidal peaking factor is defined as the maximum of

$$\text{TPF} = \frac{2\pi I_{halo(max)}}{\int I_{halo} d\phi}. \quad (2)$$

In the simulations, TPF ≈ 2.

The halo current fraction H_f is

$$H_f = \frac{\int I_{halo} d\phi}{I_\phi(0)}, \quad (3)$$

where I_ϕ is the toroidal current.

Relation of Toroidal and Halo Currents

The total toroidal plasma current I_ϕ is measured to vary with ϕ in JET disruptions. By $\nabla \cdot J = 0$, this is related to the net halo current:

$$\frac{dI_\phi}{d\phi} = -\oint J_n R dl \tag{4}$$

where the r.h.s. is the net halo current.

In M3D the magnetic field is represented

$$\mathbf{B} = \nabla\psi \times \nabla\phi + \frac{1}{R}\nabla_\perp F + I\nabla\phi$$

Relation of Halo Current to Toroidal Current

The current in M3D is

$$\mathbf{J} = -(\Delta^*\psi + \frac{1}{R}\frac{\partial F}{\partial Z})\nabla\phi + \frac{1}{R^2}\nabla_\perp\frac{\partial \psi}{\partial \phi} + (\nabla I - \frac{1}{R}\nabla\frac{\partial F}{\partial \phi}) \times \nabla\phi$$

where

$$\Delta^*\psi = R^2\nabla\cdot(\frac{1}{R^2}\nabla_\perp\psi)$$

and

$$\nabla_\perp\psi = \frac{\partial\psi}{\partial R}\hat{\mathbf{R}} + \frac{\partial\psi}{\partial Z}\hat{\mathbf{Z}}.$$

The ψ contribution to J_n can produce a non vanishing net halo current. The I part of J_n gives a vanishing contribution to the net halo current. (The F terms give a small contribution to both net and varying halo current.)

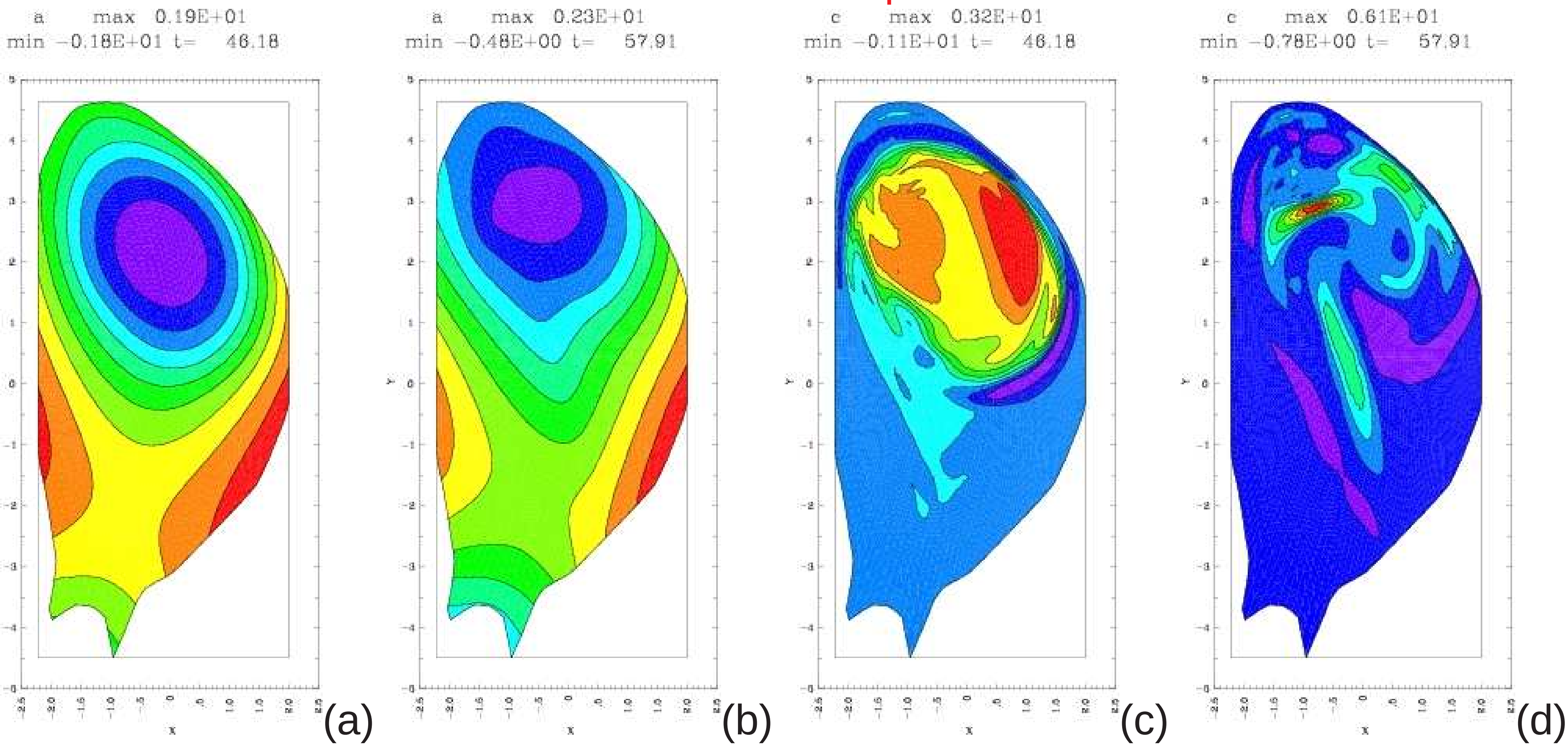
Disruption Simulations

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 $q = 0.82$ 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: $\eta R/(v_A a^2) = 10^{-5}$, $\eta_w R/(v_A a \delta) = 5 \times 10^{-2}$.

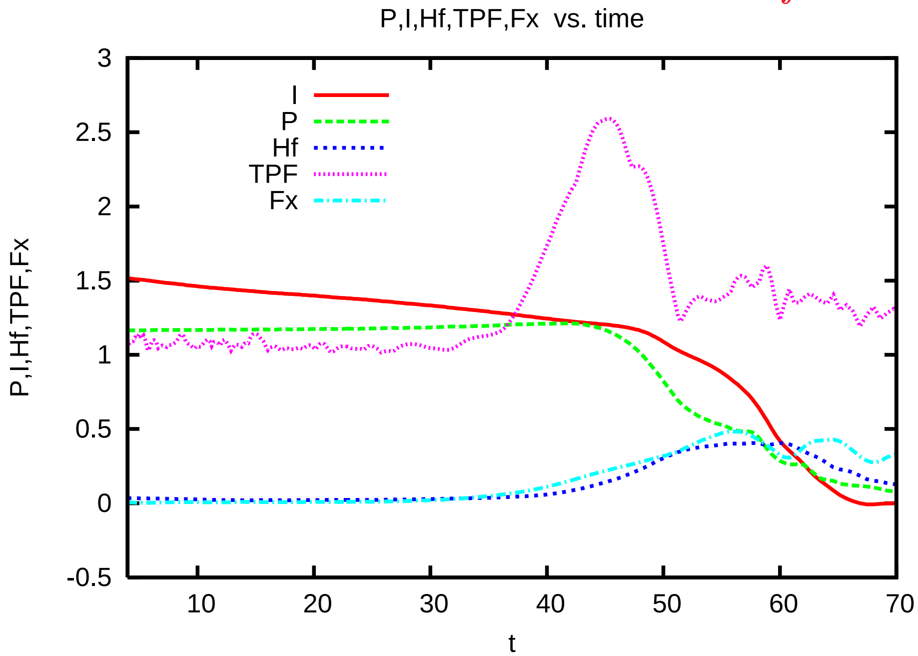
VDE - kink disruption



A nonlinear kink mode at time $t = 46.18\tau_A$,, showing (a) poloidal flux ψ, at time $t = 46.18\tau_A$, (b) ψ at time $t = 57.91\tau_A$, (c) toroidal current $-RJ_\phi$, at time $t = 46.18\tau_A$, (d) toroidal current at time $t = 57.91\tau_A$,

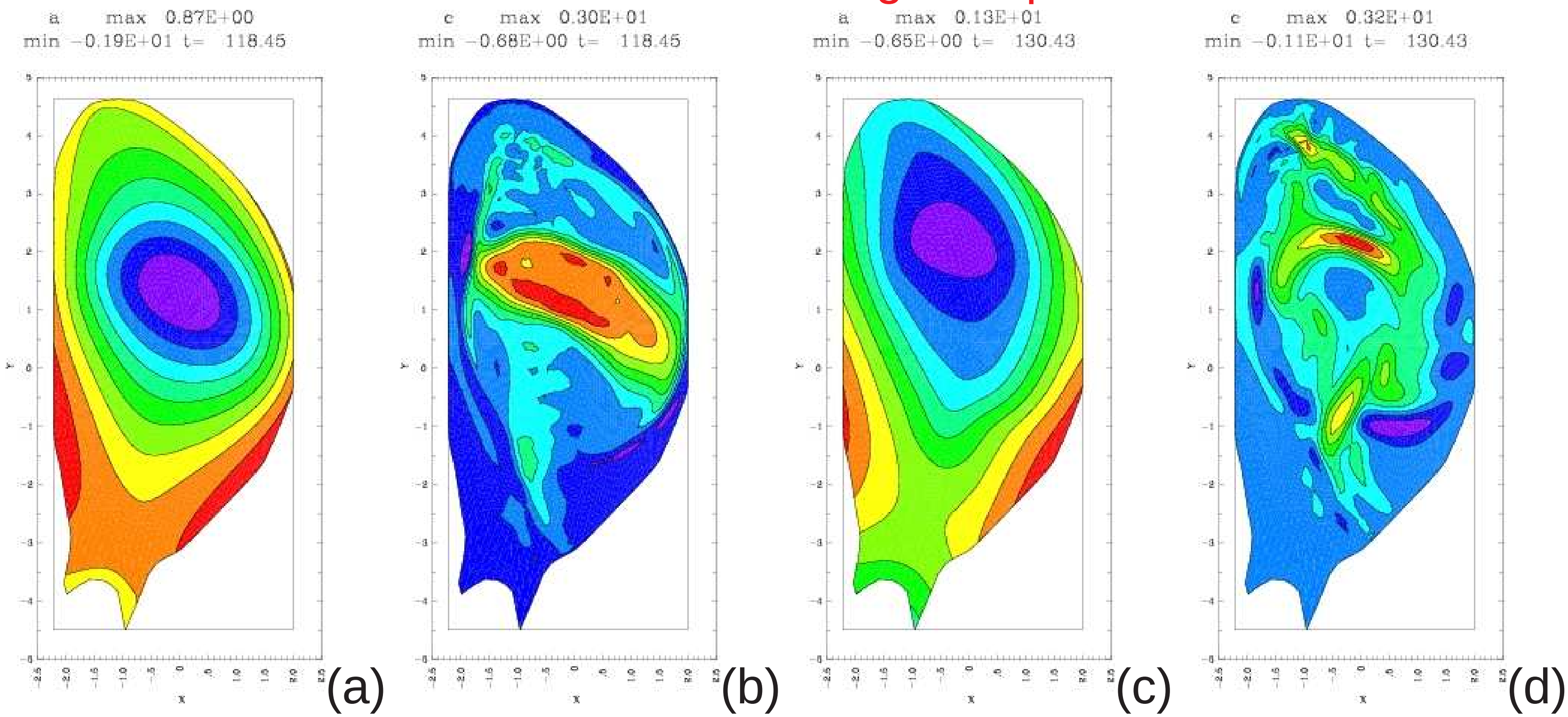
The magnetic field becomes stochastic, limiting the wall force.

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



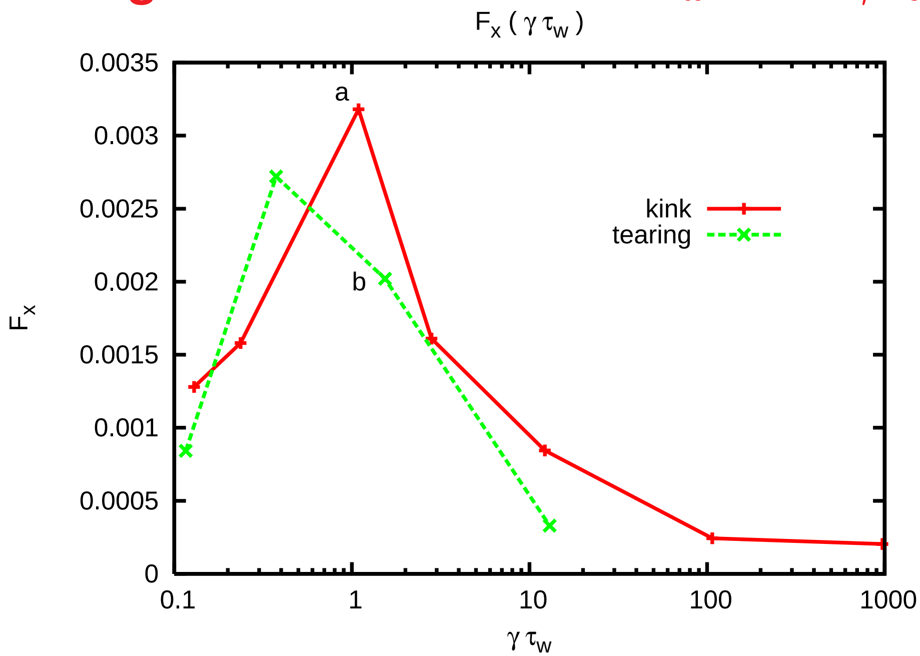
toroidal current I, pressure P, TPF, halo current fraction H_f and horizontal force F_x as a function of time. The quantities I, P, and F_x are in arbitrary units. The VDE causes thermal and current quench of P and I. The close time correlation of halo current fraction H_f and horizontal force F_x indicates that F_x is produced by halo current. The entire time history can be simulated.

VDE - RWM / tearing disruption



A nonlinear RWM / tearing mode at time $t = 118.45\tau_A$,, showing (a) poloidal flux ψ, at time $t = 118.45\tau_A$, (b) ψ at time $t = 130.43\tau_A$, (c) toroidal current $-RJ_\phi$, at time $t = 118.45\tau_A$, (d) toroidal current at time $t = 130.43\tau_A$, The mode has predominantly $m, n = 2, 1$ structure. The magnetic field again becomes stochastic.

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



The force tends to a limit for an ideal conducting wall $\gamma\tau_w \rightarrow \infty$, and is zero for $\tau_w = 0$. Note that F_x can vary an order of magnitude. The force has a maximum for $\gamma\tau_w \approx 1$. The curves correspond to the previous cases.

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, with growth rate γ, and VDE with growth rate τ_w^{-1}, to reach the wall.

- force appears $\propto \gamma I^2 f(\gamma\tau_w)$, has numerical and analytic support. The factor γ indicates that slow modes like RWM will not give a large wall force. Needs more study.

- 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. Need mesh refinement where VDE localizes the plasma

- halo model - resistivity and width of halo region outside the separatrix might have an effect on wall force. The halo region becomes stochastic, so its detailed properties may not matter.

Current vs. Displacement Calculation

It is found experimentally in JET that

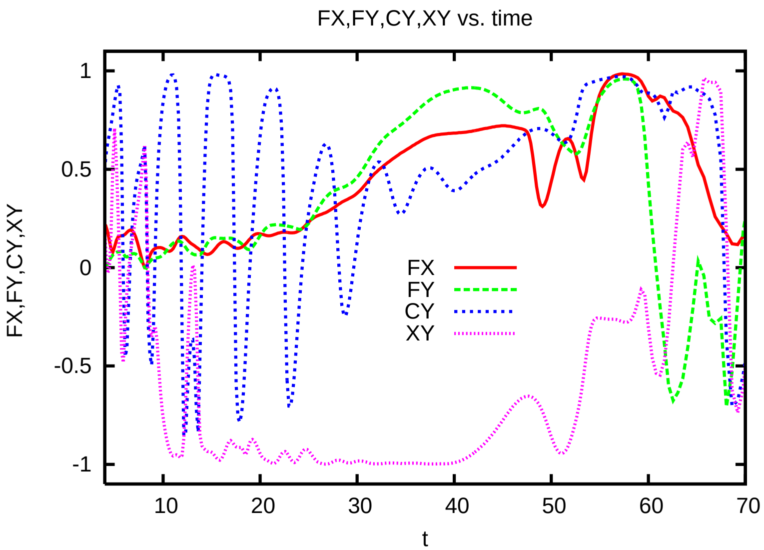
$$\frac{dI_\phi}{d\phi} \propto \frac{dM_{IZ}}{d\phi}$$

Here $M_{IZ} = \int ZJ_\phi dRdZ$, the vertical moment of the current. This relation was seen in JET (Zakharov 2008, Gerasimov 2010) and claimed to validate "Hiro" current model, although it is more general. The simulations show this correlation. They also show that the wall force has the same sign as the plasma displacement (opposite of the Hiro model), and the relation of toroidal current variation to halo current.

It can be deduced that

$$\frac{dM_{IZ}}{d\phi} \propto -\oint J_n R dl.$$

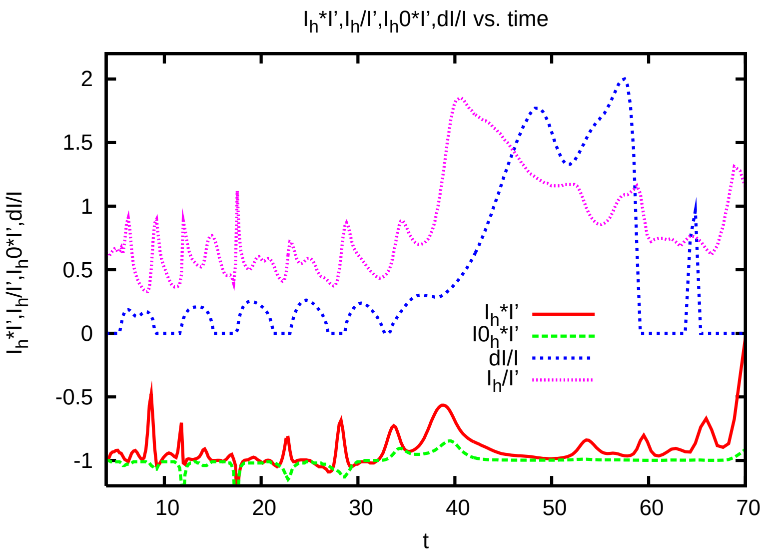
Correlation of force and displacement in simulations



Correlations as a function of time: $CY = C(I_\phi, M_{IZ})$ Here FX is the correlation of F_R, M_{IR}, FY is the correlation of F_Z, M_{IZ}, CY is the correlation of $\tilde{I}_\phi, M_{IZ}$, and $XY = C(M_{IR}, dM_{IZ}/d\phi)$.

where $C(a,b) = < ab >< a^2 >^{-1/2} < b^2 >^{-1/2}$ and $< a > = \int d\phi a$. $M_{IR} = \int (R - R_0) J_\phi dR dZ$, the horizontal moment of the current. 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.) FX,FY show that the force has the same sign as the plasma displacement, $\mathbf{F} \propto \xi$.

Correlation of force and displacement in simulations



correlation of I_ϕ to total halo current $I_h * I' = C(I_{halo}, I'_\phi)$, and to the net halo current: $I_h^0 * I' = C(I_{halo}^{net}, I'_\phi)$, relative magnitude of total halo current to I_ϕ: $I_h/I' = |I_{halo}|/|I'_\phi|$, and the amplitude of I_ϕ variation: $dI/I = |\tilde{I}_\phi|_{max}/I_\phi$.

The toroidally varying part of I_ϕ is $\pi/2$ radians out of phase with the halo current. The net halo current is very well correlated with the ϕ derivative I_ϕ. The varying and net halo current have about the same magnitude. The toroidally varying part of I_ϕ is about $10 - 20\%$ of the total toroidal current.

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.

• include ITER blanket and 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.

• Halo model: effect of varying S and width of halo region.