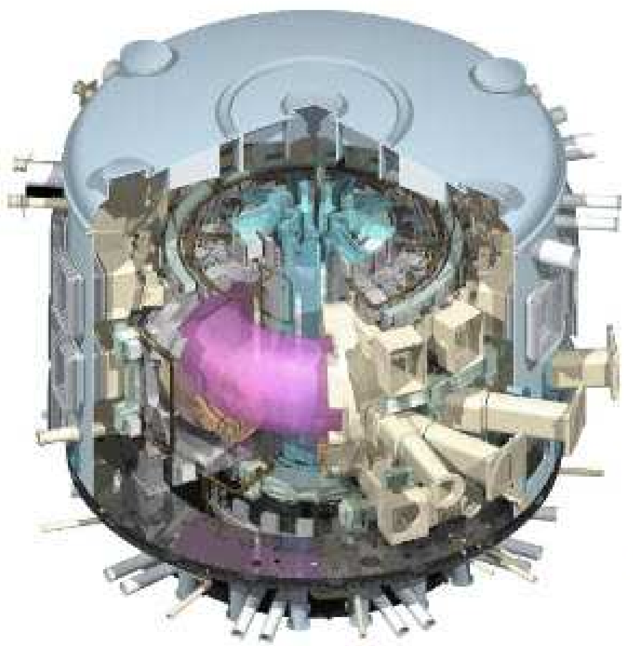
Wall Force produced during an ITER Disruption

H. Strauss, *HRS Fusion*

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

J. Breslau, *PPPL*

ITER



Disruptions have become an ITER issue. They can cause large electromechanical stress on conducting structures. ITER wall forces can be more than 10 times larger than in existing tokamaks. Need more info on worst case scenario, avoidance, mitigation. Main concern is “sideways force.”

Theory and simulation of tokamak disruptions

- all tokamaks experience disruptions (5% of JET shots). The discharge terminates, evidently caused by MHD instability. Several kinds of instability can initiate disruptions. Worst case is thought to be a VDE bringing the plasma close to the wall, where it becomes kink unstable,

- Three dimensional simulations in 1980's showed that overlapping magnetic resonant perturbations "islands" produced chaotic rupturing of the magnetic field and loss of equilibrium. This causes quenching of the plasma current and pressure.

- Not many disruption simulations since 1980's. It's numerically challenging.

Outline

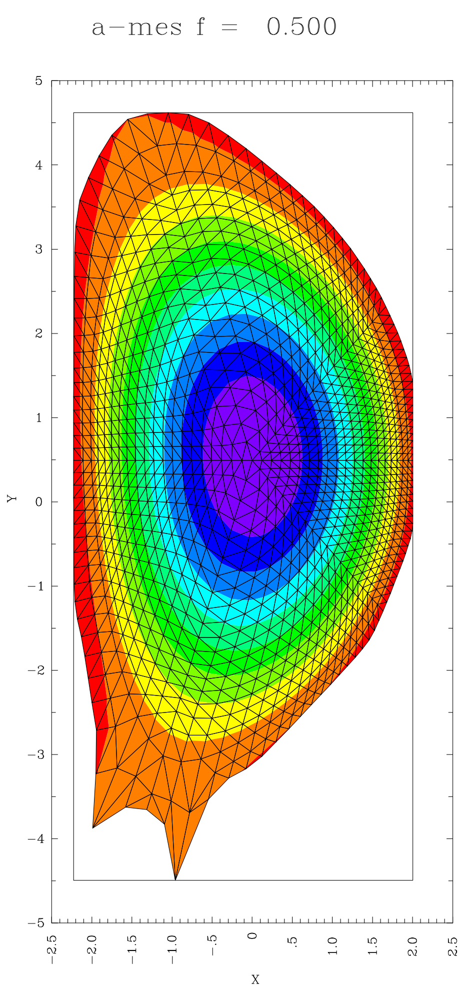
- MHD model of thin resistive shows force is produced by discontinuity of the magnetic field across the resistive wall.

- MHD simulations with M3D code with thin resistive wall, produced by kink instability. Quench of temperature, current, and wall force.

- ”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.

M3D MHD Code



Simulations are done with the M3D code used at PPPL, a 3D initial value resistive MHD code. Unstructured mesh (Strauss and Longcope, 1988) shown at low resolution, in poloidal (R,Z) plane and pseudospectral (Fourier) representation in toroidal ϕ direction. Upwinding and dealiasing provided adequate numerical stabilization to permit the simulation of complete disruption events. The open field line ”vacuum” region surrounding the plasma is modeled with high resistivity.

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.

• Green's identity yields other other components of $\mathbf{B}^v$, 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

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

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

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

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). Initial equilibrium had $q = 1.1$ on axis and current I_0. The equilibrium was rescaled to generate equilibria with $q < 1$ on axis. The equilibrium was both kink and VDE unstable. This models what might have occurred if outer layers of plasma were scraped off during a VDE. The kink couples strongly to sideways force.

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

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

Wall Boundary Conditions

• v_n boundary condition

$$\frac{\partial v_n}{\partial n} \sim \frac{v_n}{L}$$

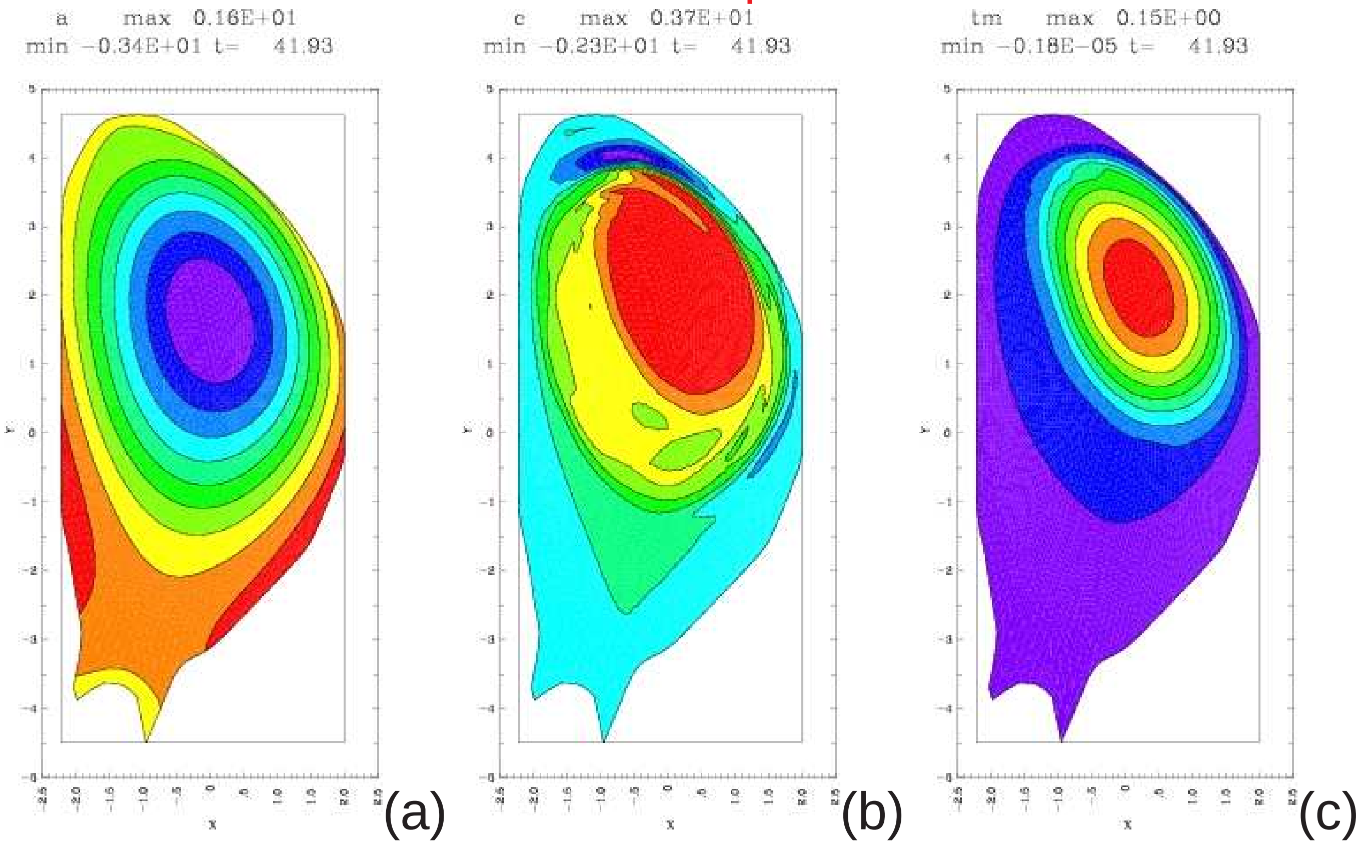
where $L \ll \delta \ll a$. Hence

$v_n \approx 0.$

• Plasma is in electical contact with the wall. Region inside wall boundary is filled with plasma.

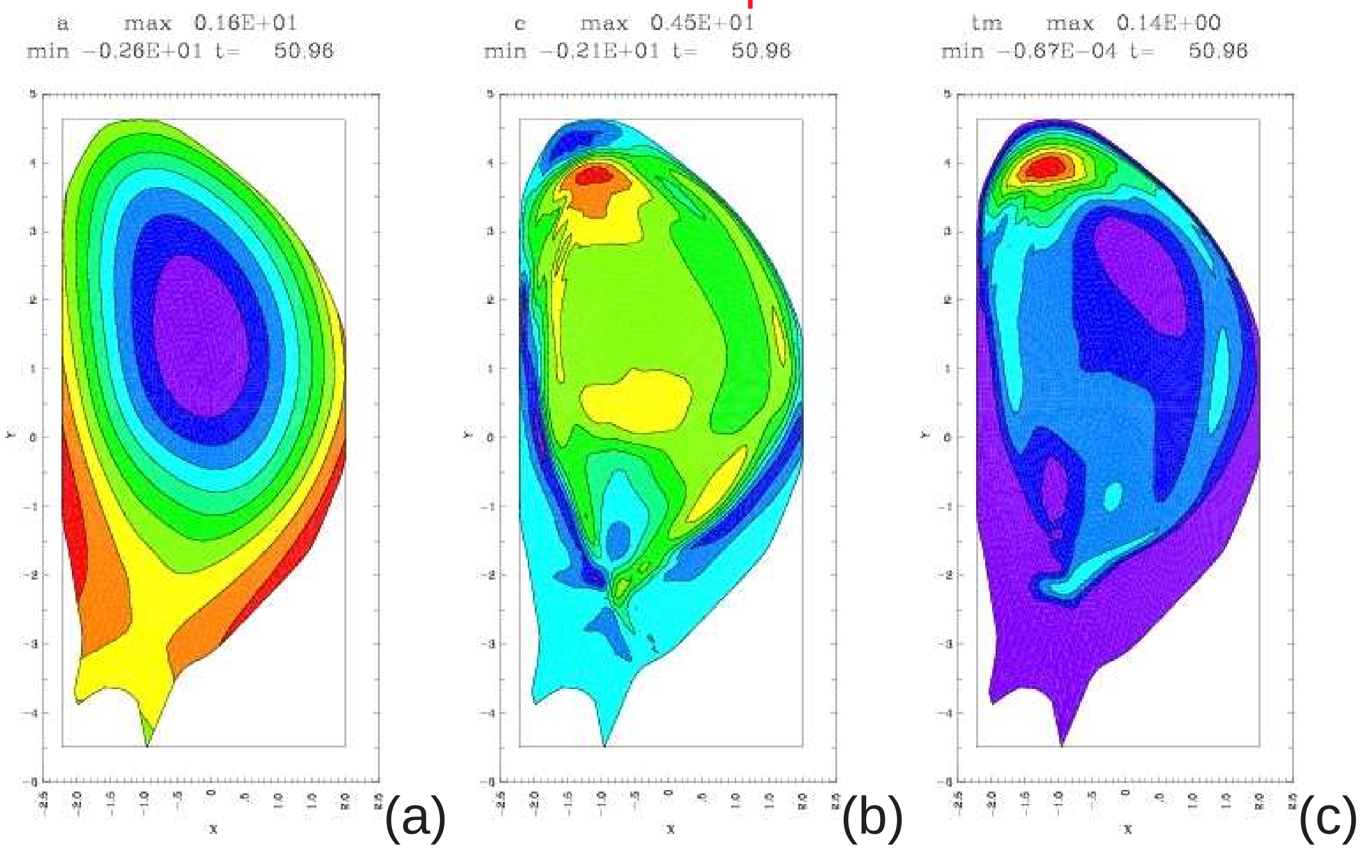
• plasma wall contact depends on sheath, plasma facing wall material, not included in simulations.

VDE disruption



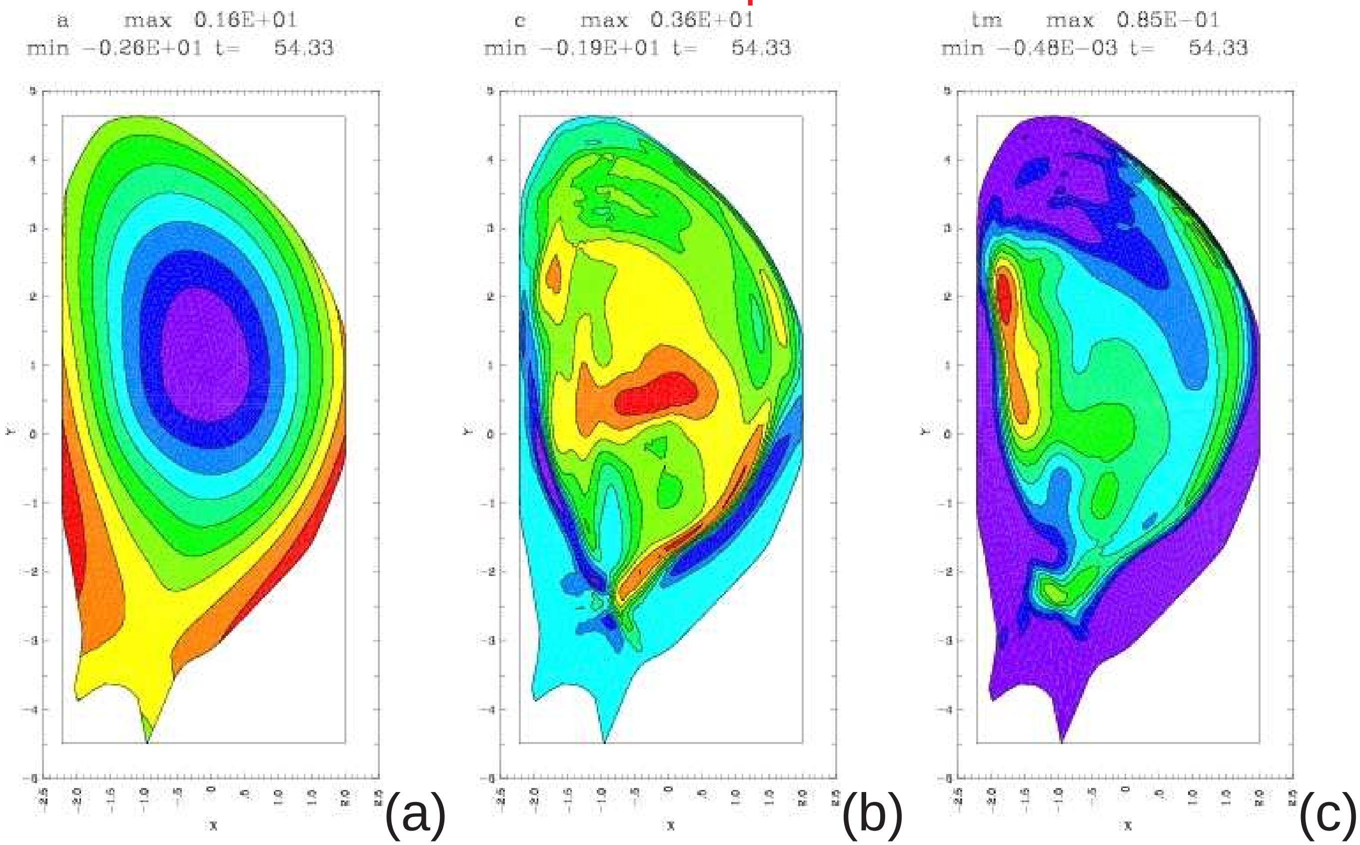
(a) poloidal flux ψ, (b) toroidal current $-RJ_\phi$, (c) temperature T, at $t = 40.9\tau_A$, with toroidal angle $\phi = \pi$. This example has $I/I_0 = 2$, and $\gamma\tau_w \approx 15$. A VDE brings the plasma to the upper wall, where an $(m, n) = (1, 1)$ kink mode grows.

VDE disruption



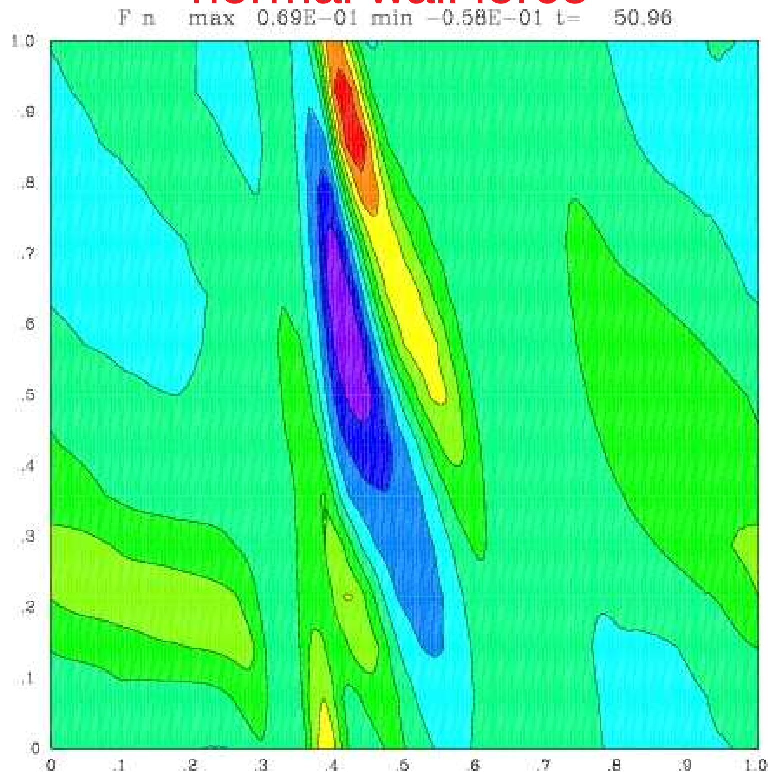
(a) poloidal flux ψ, (b) toroidal current $-RJ_\phi$, (c) temperature T, at $t = 51\tau_A$, with toroidal angle $\phi = \pi$.

VDE disruption



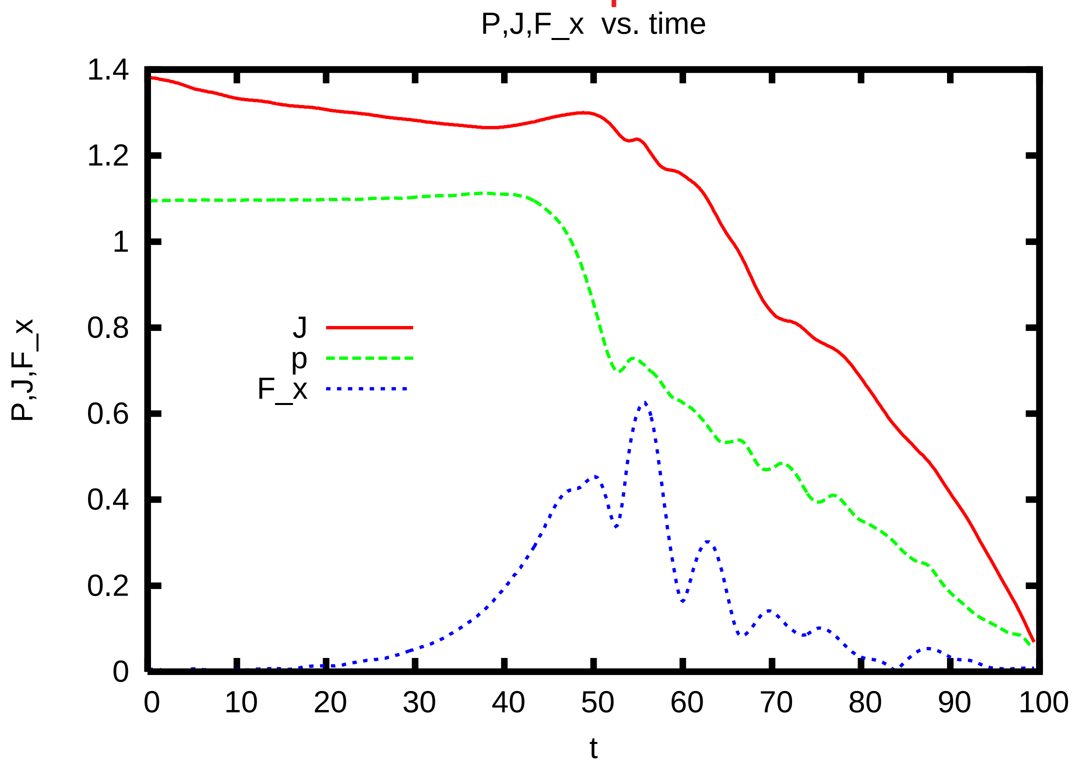
(a) poloidal flux ψ, (b) toroidal current $-RJ_\phi$, (c) temperature T, at $t = 54.3\tau_A$, with toroidal angle $\phi = \pi$. Current sheet, current and temperature maxima penetrate the wall.

normal wall force



normal force density at $t = 51\tau_A$, $f_n(\theta, \phi)$, where θ, the poloidal angle from the origin, is the horizontal axis.

VDE disruption



total toroidal current I_ϕ, total pressure P, TPF, and horizontal force F_x as a function of time, in arbitrary units.

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 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 as large as 2.75MN. This value is consistent with JET experiments.

Transfer of current to the wall

- induction plasma current need not touch wall. Wall current flows to screen out changes in plasma current from the vacuum region. Perturbed wall current is opposite in sign to perturbed plasma current. Force is produced by magnetic field compression inside the wall.

- conduction normal component of current J_n (halo) flows directly into the wall.

- Hiro current Zakharov, Phys. Pl. (2008). Perturbed plasma current contacts the wall, so perturbed wall current has same sign as perturbed plasma current. Sign of current, force should be opposite to induced case.

Model Analytic Force Calculation

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

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

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

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

where a is plasma radius, b is wall radius, ξ_R is plasma displacement in the major radius $\hat{\mathbf{R}}$ direction. This gives an approximately $\gamma I^2/I_0^2$ 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

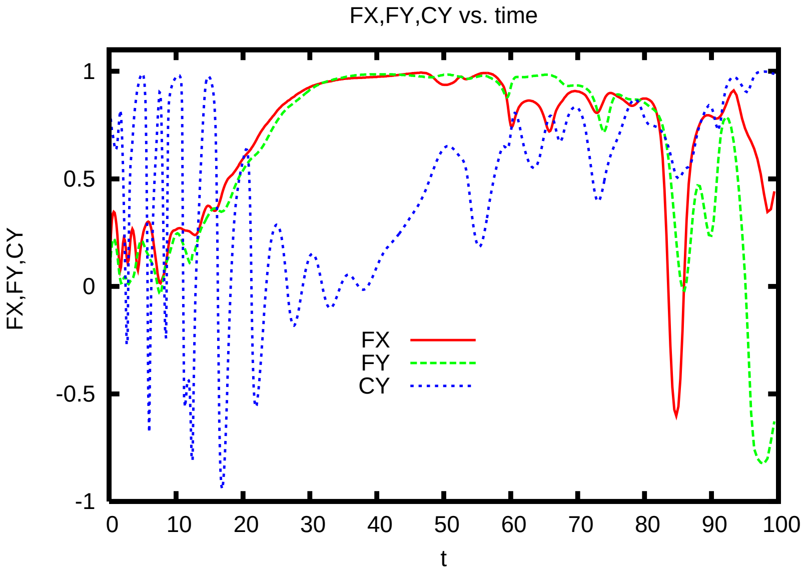
$$I_\phi = -\int dr r d\theta \frac{dJ_{\phi 1}}{dr} r_1 \sin\theta \cos(\theta + \phi) = -\pi \int dr J_{\phi 1} r_1 \sin\phi.$$

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

$$\frac{dI_\phi}{d\phi} = \frac{r_1}{a^2} I_\phi \frac{d\xi_Z}{d\phi}$$

correlates with JET experiment (Zakharov 2008).

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. $M_{IZ} = \int Z J_\phi dR dZ$. The toroidal variation of the current $dI_\phi/d\phi$ is reasonably correlated with $dM_{IZ}/d\phi$. FX,FY: the force $\mathbf{F} \propto \xi$.

The correlations change sign after the force quench.

Summary

- MHD model of thin resistive shows force is produced by discontinuity of the magnetic field across the resistive wall.

- MHD simulations were done using M3D code with thin resistive wall. Disruption produced by VDE and kink instability, causing quench of temperature, current, and wall force.

- ”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.

Proposed Work

- Boundary condition on v_n.

– analyze plasma wall interaction to derive normal velocity boundary condition. Might be done in a slab model. Include plasma facing material properties, sheath effects.

– perform thick wall simulations to validate analysis.

- 3D wall effects important for ITER force calculation

– forces on blanket modules

– JET 3D limiter effects on boundary condition

Proposed Work

- Study types of disruptions

– VDE and kink, need to model the scrape off and edge cooling that destabilizes kink mode. Need to include radiation.

– RWM and pressure limit

– density limit, need radiation model.

– $q = 2$ disruptions

- Validate with comparison to experiments

– JET, NSTX, DIIID

Proposed Work

- Quench of plasma

– thermal quench: energy deposition

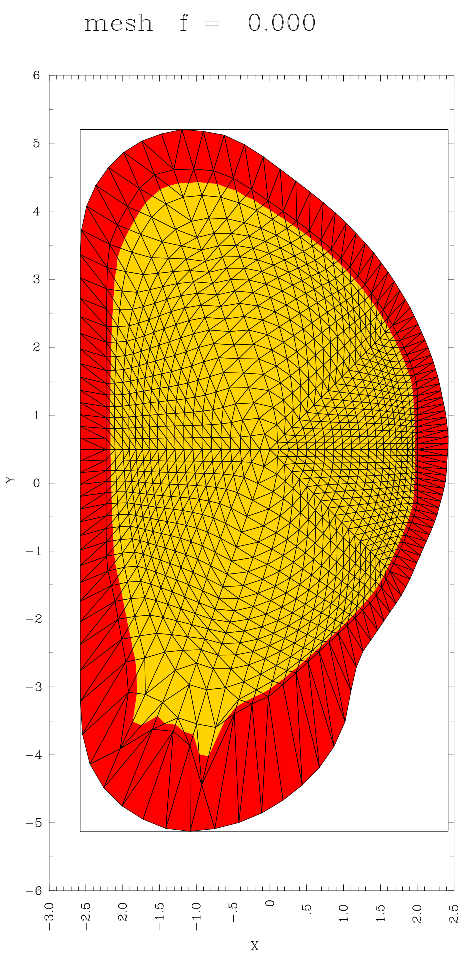
– current quench: relative importance of high resistivity and flow of current to the wall along the magnetic field.

- coupling to mitigation studies

– can anything be done once a disruption starts?

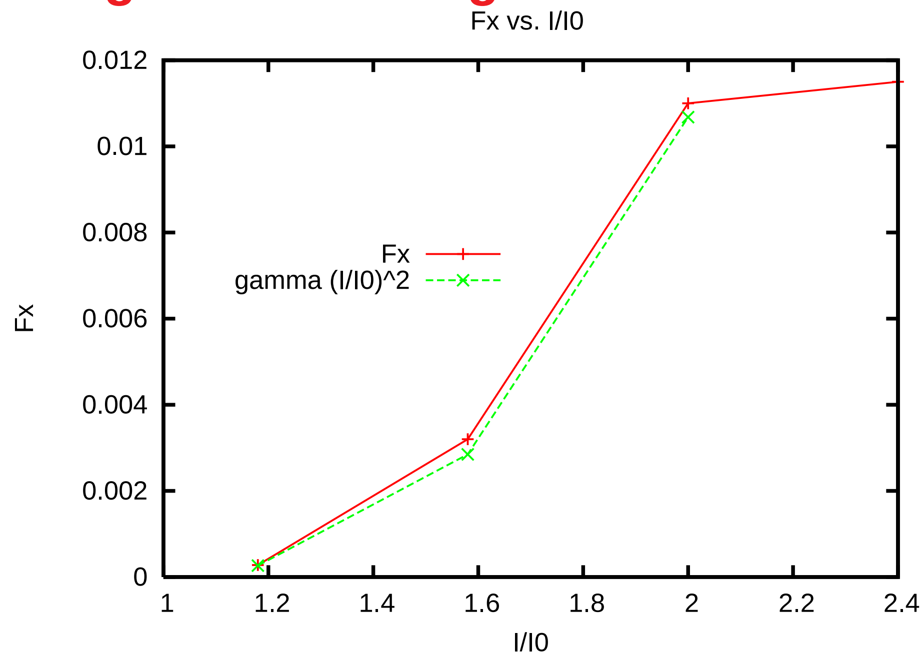
- higher resolution to improve results. Massively parallel simulations with 100's of processors.

ITER two wall model



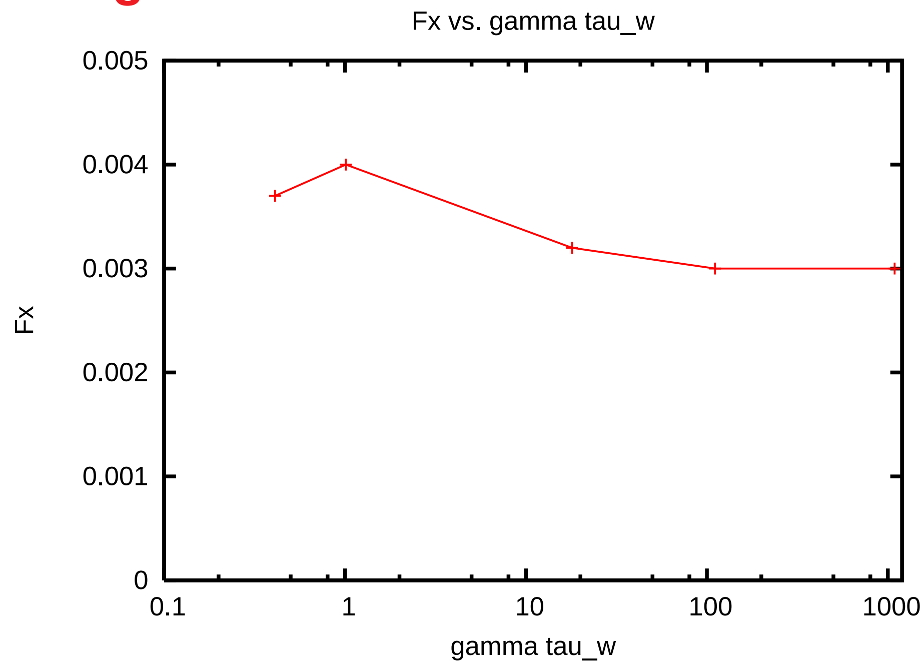
ITER has two walls. $\tau_w^{outer} >> \tau_w^{inner}$. M3D modeling assumes $\tau_w^{inner} = 0$. The magnetic field is continuous at inner wall, no force on inner wall. Forces on outer wall are about 25 % of forces in one wall model. Simulation results of 2 wall and 1 models are qualitatively similar.

Scaling of wall averaged horizontal force



Scaling of wall averaged non axisymmetric horizontal force density with total current I/I_0. Fit is $\propto \gamma(I/I_0)^2$. This scaling fits for $I/I_0 \leq 2$, and saturates for larger I/I_0. The horizontal force is as large as 1.2 % of the total magnetic pressure.

Scaling of wall force with wall resistivity



Scaling of horizontal F_x, with $\gamma\tau_w$. The cases shown have $I/I_0 = 1.6$. The force tends to a limit for an ideal conducting wall $\gamma\tau_w = \infty$. Flux penetration is important for $\gamma\tau_w = 1$.