Wall Force produced during a Disruption

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- Nonaxisymmetric wall forces in ITER
  - are produced on conducting structures during a disruption.
  - can be a significant fraction of total magnetic pressure

- Simulations with M3D
  - used thin resistive wall model
  - external magnetic perturbations calculated with GRIN code
  - Jump in magnetic field gives wall force
  - scaling with wall resistivity and wall thickness

Wall Force

The plasma is bounded by a thin wall of thickness δ and resistivity η_w. The current in the wall is given by

$$\mathbf{J}_w = \nabla \times \mathbf{B} \approx \frac{\hat{\mathbf{n}}}{\delta} \times (\mathbf{B}_v - \mathbf{B}_p)$$

where $\hat{\mathbf{n}}$ is the outward normal to the wall, $\mathbf{B}_v$ is the vacuum magnetic field just outside the wall, and $\mathbf{B}_p$ is the magnetic field in the plasma, just inside the wall.

The normal component of the force density is

$$F_{wn} = \hat{\mathbf{n}} \cdot \mathbf{J}_w \times \mathbf{B}_w = -\frac{1}{\delta}(\mathbf{B}_v - \mathbf{B}_p) \cdot \mathbf{B}_w$$

where the continuity of the normal component of the magnetic field, $\hat{\mathbf{n}} \cdot (\mathbf{B}_v - \mathbf{B}_p) = 0$ was used, which follows from $\nabla \cdot \mathbf{B} = 0$.

Inside the wall assume that

$$\mathbf{B}_w = \frac{1}{2}(\mathbf{B}_v + \mathbf{B}_p).$$

The normal wall force density can be expressed

$$F_{wn} = \frac{1}{2\delta}(|\mathbf{B}_p|^2 - |\mathbf{B}_v|^2).$$

It has a simple physical meaning. It is the difference in magnetic pressure across the wall, divided by the wall thickness.

Integrating over the wall thickness δ gives the magnetic pressure on the wall. The normalized wall pressure P_w is

$$P_w = \frac{(|\mathbf{B}_p|^2 - |\mathbf{B}_v|^2)}{2B_0^2}$$

where B_0 is the vacuum toroidal magnetic field on axis.

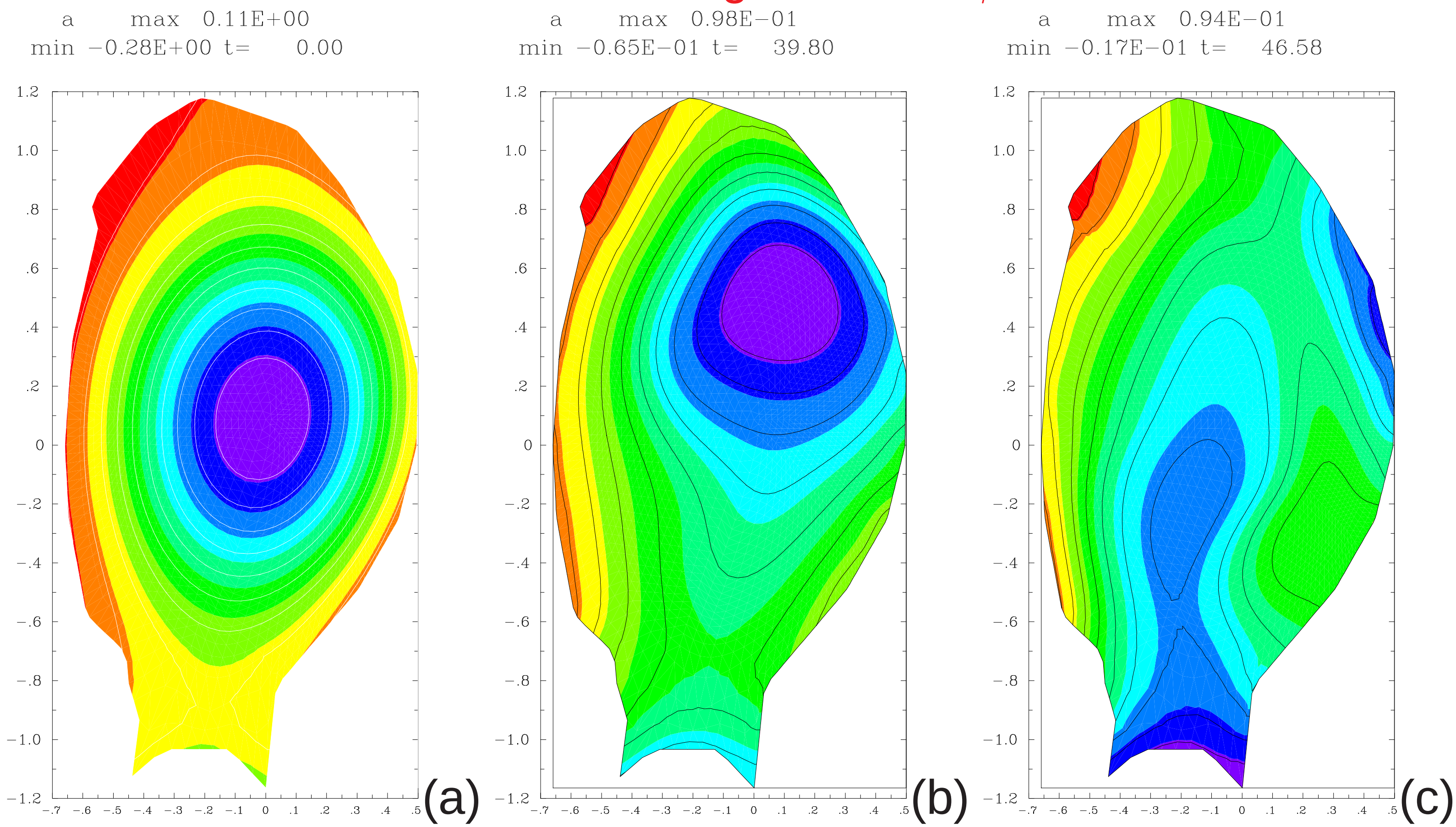
Disruption Simulation

In the following M3D is used to calculate a disruption. The initial state is an ASDEX equilibrium, AUG 12/09/2004 #014271, calculated by CHEASE, and written to a file in EQDSK format. This was read into M3D and used to generate a mesh and initialize a nonlinear simulation. The initial equilibrium had $q = 1.1$ on axis. Multiplying the magnetic flux ψ, and the toroidal current by a scale factor, the pressure by the square of the scale factor, an approximate near equilibrium initial state was obtained with $q = 0.52$ on axis. This state models what might have occurred if outer layers of plasma were scraped off during a VDE. The resulting state is highly unstable to an external kink. A small $m = n = 1$ perturbation was added to the plasma and it was allowed to evolve nonlinearly.

In the simulation the Lundquist number was chosen to be $S = 10^4$ on axis and $S = 10$ at the wall. The resistivity is calculated self consistently as $T^{-3/2}$, where T is the temperature. When the temperature decays during the simulation, the value of S drops, although its value is held fixed at the wall. The large value of resistivity was chosen to improve numerical stability. The wall constant, the wall resistivity η_w divided by wall thickness, η_w/δ, was varied from 10^{-4} to 10^{-1}.

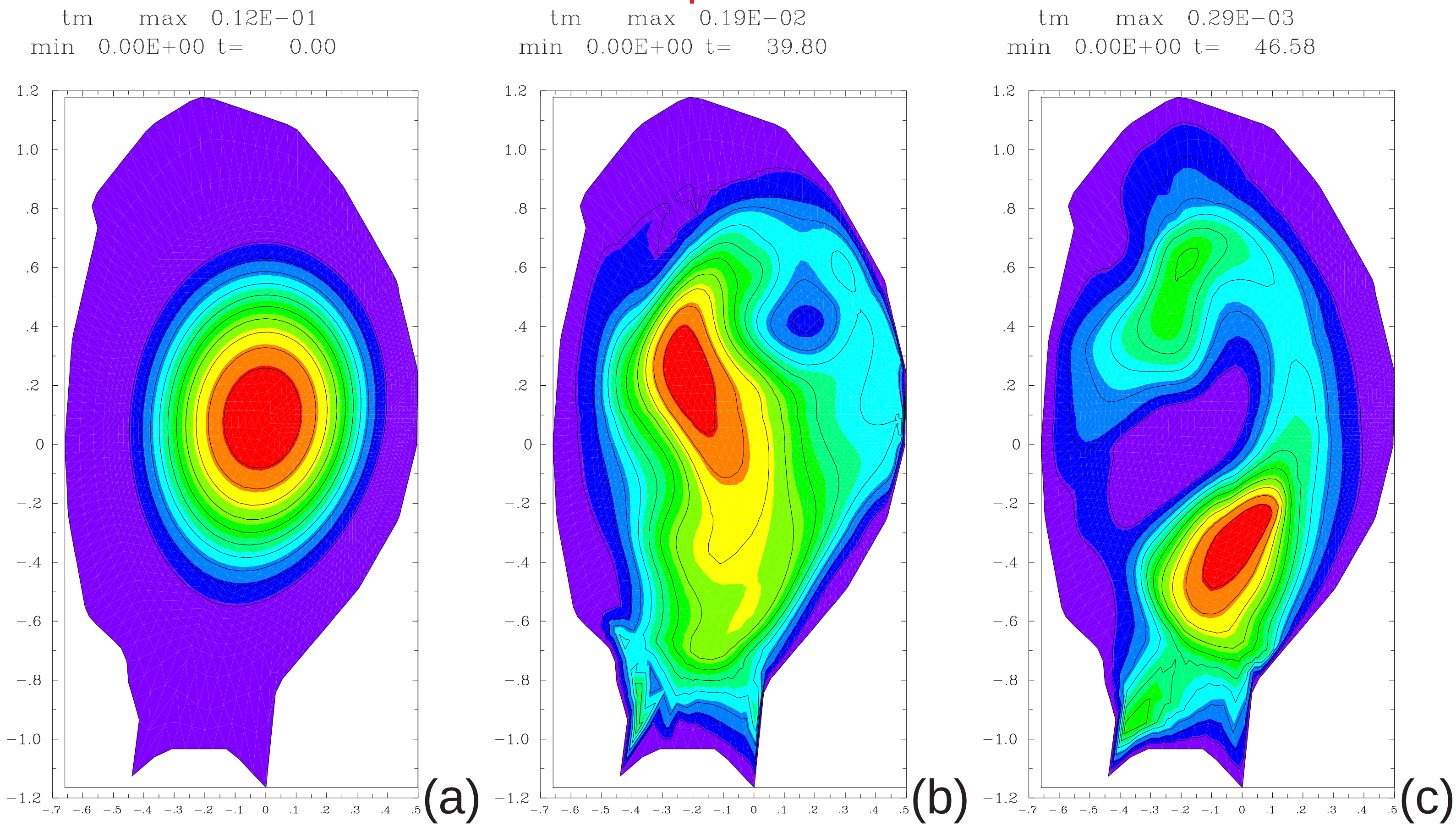
In the simulation shown in the following pictures, $\eta_w/\delta = 10^{-2}$.

Poloidal Magnetic Flux ψ



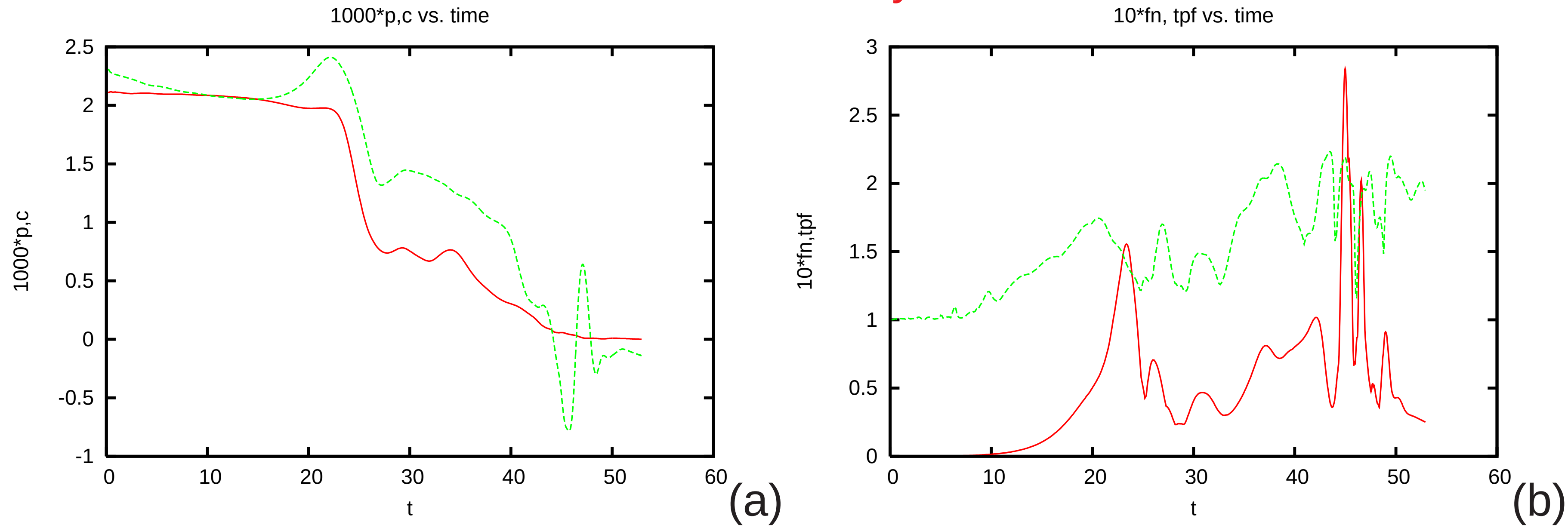
(a) initial magnetic flux contours of rescaled ASDEX equilibrium reconstruction. (b) magnetic flux contours in the poloidal plane with toroidal angle $\phi = 0$, at time $t = 39.8\tau_A$. The flux resembles a typical VDE. (c) magnetic flux contours in the poloidal plane with toroidal angle $\phi \neq 0$, at time $t = 46.6\tau_A$. There are no closed poloidal flux contours.

Temperature



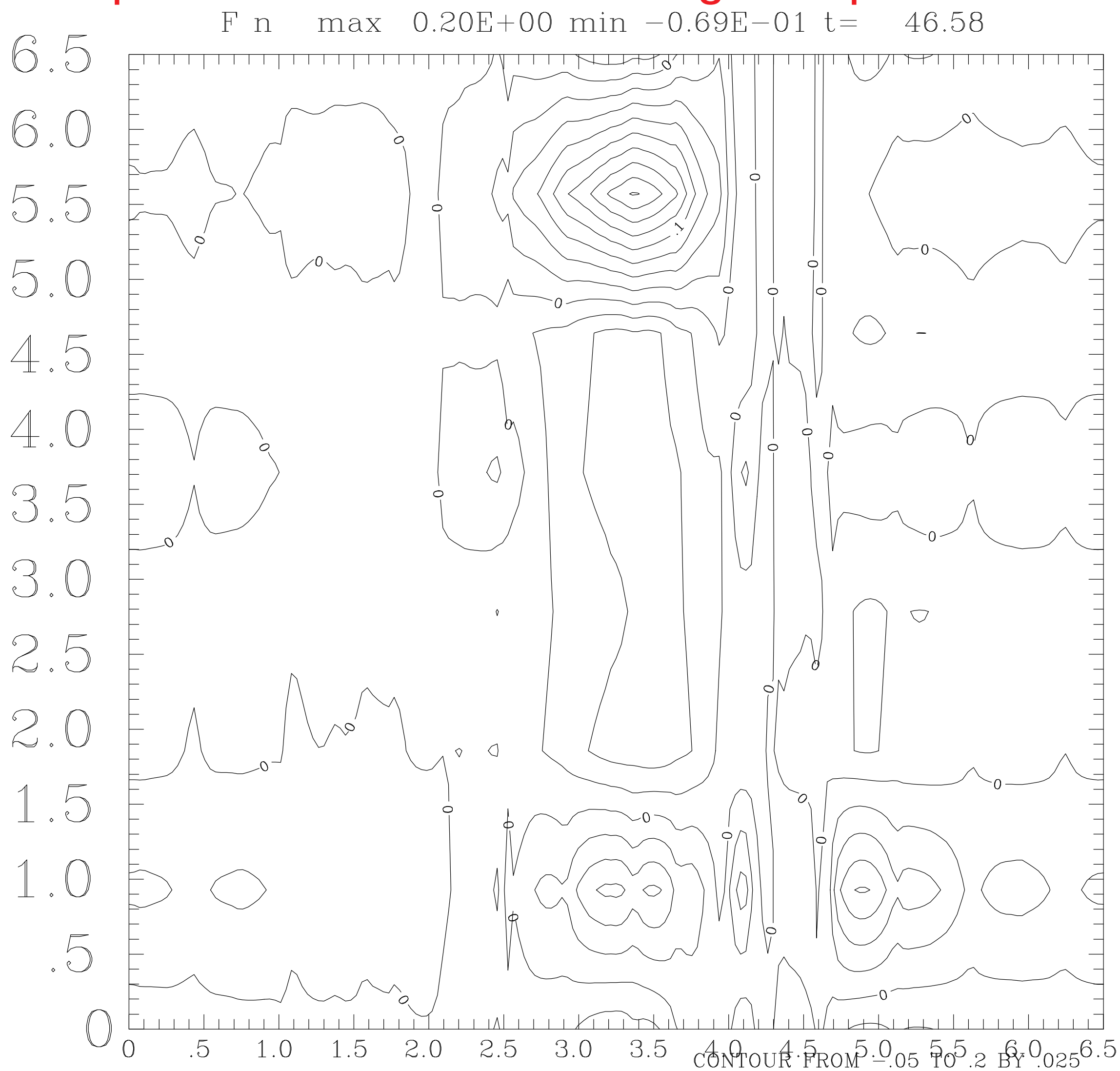
(a) initial temperature contours in the poloidal plane with toroidal angle $\phi = 0$. (b) temperature contours at $t = 39.8\tau_A$. The temperature has dropped a factor of 6 from its initial peak. (c) temperature contours at time $t = 46.6\tau_A$, where the temperature has dropped by a factor of 40 from the initial peak.

Time history



(a) time history of the total plasma pressure (red) and total toroidal current (green). (The current rings a bit near zero.) The temperature and current collapse coincide, about $t = 20 - 40\tau_A$. (b) time history of the peak normal wall force (red) multiplied by a factor of 10, and the TPF (toroidal peaking factor, green). The maximum normal wall pressure is about 25% of the vacuum magnetic pressure! However it is large for a very short time. A more average value is 5%.

Spatial structure of wall magnetic pressure



magnetic pressure on the wall as a function of poloidal angle (horizontal) and toroidal angle (vertical) at time $t = 46.6\tau_A$.

Numerical Difficulties

The wall magnetic pressure is very localized in space and time. This may well be due to numerical effects. Disruption simulations tend not to converge.

- Current generated (kink) disruptions cause magnetic island overlap, stochastic magnetic field. Arbitrarily short spatial scales are generated.

- Pressure driven (ballooning modes) are unstable for all wavelength in ideal MHD.

- Dissipation is required to limit the spatial scales. A large resistivity η varied from 10^{-4} on axis to 10^{-1} at the wall. A spatial constant perpendicular viscosity was used, $\mu = 10^{-3}$.

Dissipative Numerical Methods

Two additional methods were used to improve numerical stability:

- Upwinding to maintain positivity of density and temperature
- Nonlinear diffusion:

$$D_{nonlinear} \sim dt(\tilde{\mathbf{v}}^2)$$

- To get reliable results, calculations have to be repeated with higher resolution and less dissipation.

Scaling of Force with Wall Resistivity

The normal component of the magnetic field is continuous at the wall: it satisfies

$$\frac{\partial B_n}{\partial t} = -\frac{\eta_w}{\delta}\nabla \cdot (\mathbf{I} - \mathbf{nn}) \cdot (\mathbf{B}^v - \mathbf{B}^p)$$

The tangential, ℓ component of the wall force is

$$F_{w\ell} = \frac{1}{\delta} B_n (\mathbf{B}_\ell^v - \mathbf{B}_\ell^p).$$

Approximately

$$F_{w\ell} = \frac{\delta}{\eta_w k_\perp} B_n \frac{\partial B_n}{\partial t}$$

where $k_\perp$ is the poloidal wavenumber of the mode driving the disruption.

Assume that B_n is independent of η_w - it depends on the amplitude of the unstable displacement - and

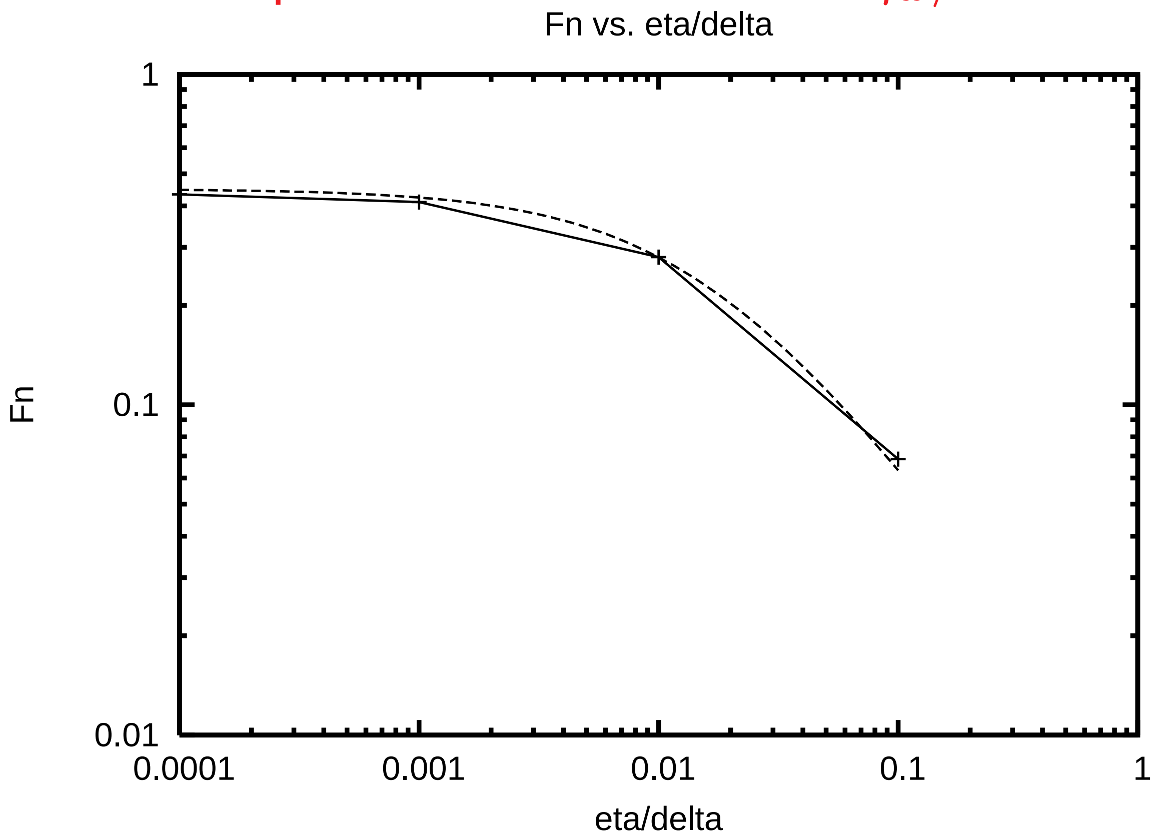
$$F_{w\ell} \approx \frac{\delta}{\eta_w k_\perp} \gamma \tilde{B}^2$$

This is infinite for an ideal wall! Let's assume that $F_{wn} \sim F_{w\ell}$ and the ideal and resistive wall limits can be combined, to give a normal wall force varying as

$$F_{wn} \propto \frac{\tilde{B}^2}{1 + \frac{\eta_w k_\perp}{\gamma \delta}}$$

For an ideal mode, $\gamma \sim v_A/R$. A highly resistive, thin wall will lower the wall force. This is verified by the simulations.

Wall pressure as a function of η_w/δ.



Variation of peak wall pressure $P_w = F_{wn}\delta/B_0^2$ as a function of wall resistivity divided by wall thickness, η_w/δ. The data is well fit by the formula, $P_w \propto 1/(1 + \alpha\eta_w/\delta)$ where $\alpha = 0.0125$.

Future Work

- use higher resolution will be used to improve results.
- try initial states corresponding to different disruption scenarios
- do simulations with ITER double wall