ITER disruptions and wall force

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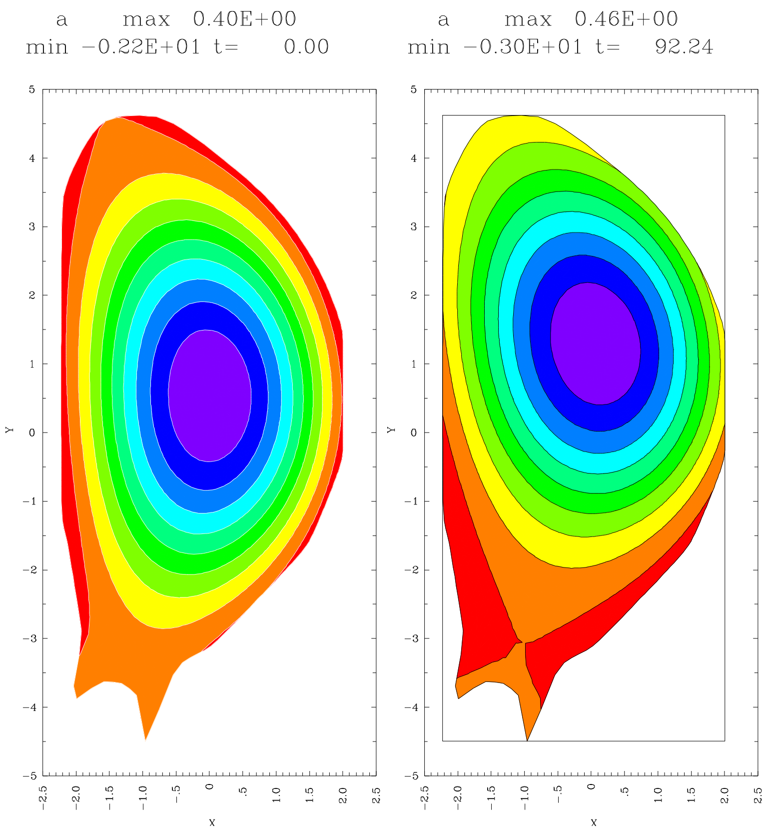
Outline

- VDE and disruption
  - Unmitigated disruptions, caused by VDE, (2,1) mode
  - Mitigated disruptions (or disruptions not caused by VDE)
- Theory of sideways force - (1,0), (1,1) and (2,1) modes
- 3D halo current
  - Toroidal variation of toroidal current
  - Simulations, data, theory
- Future plan: ITER vessel force
- Summary

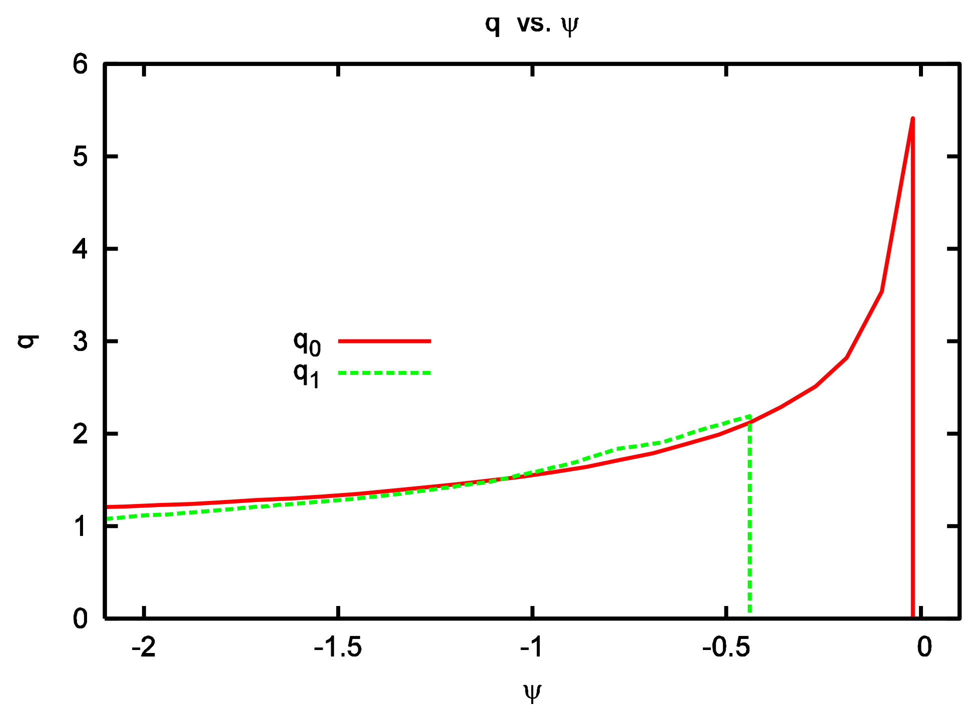
AVDE disruptions

- VDE
  - Timescale: τ_{wall}
  - As plasma approaches wall, flux scrapes off and (2,1) mode is destabilized
- TQ
  - Timescale: independent of S, Alfven (?)
  - fast reconnection, stochastic magnetic field
  - T drops to about 30 eV
- CQ
  - Timescale: $\tau_{resistive}$ (30eV)
  - Halo current as plasma hits wall
  - Large wall force including sideways force F_x

Unmitigated disruption: VDE scrapes off magnetic flux, lowers q at last closed flux surface



ψ initially $\quad\quad$ ψ during VDE

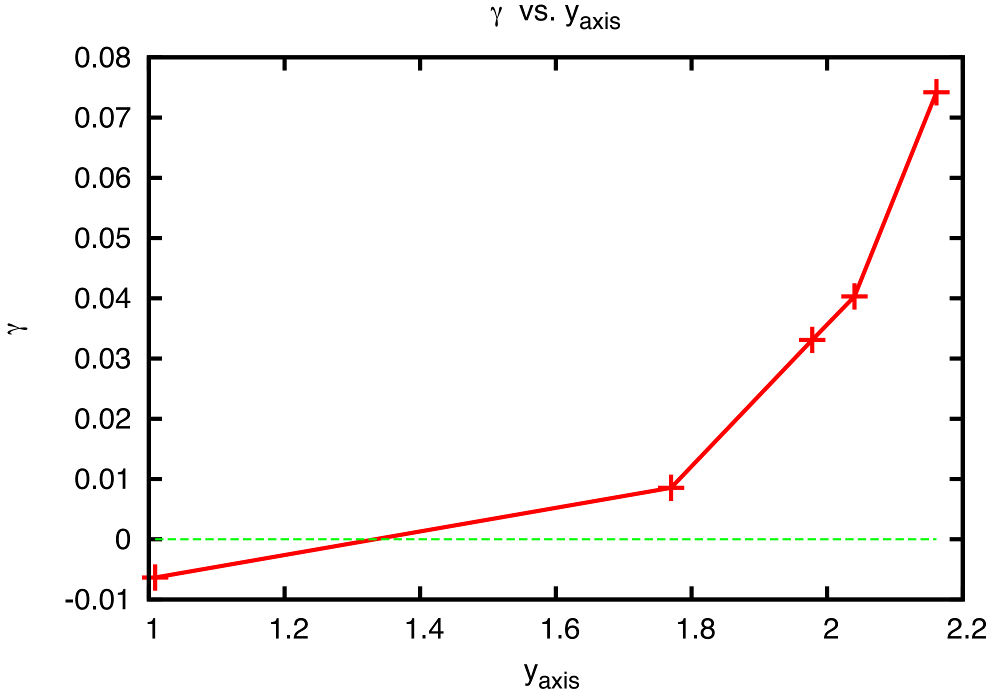


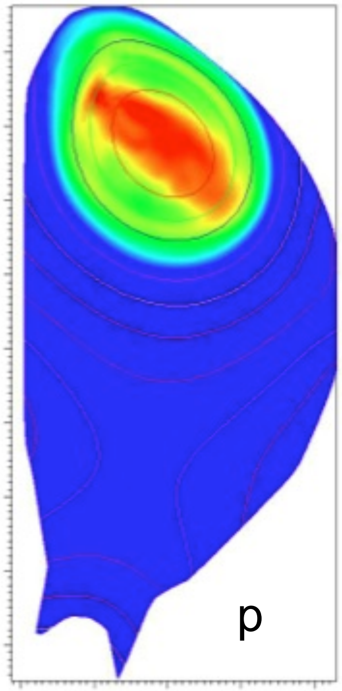
When separatrix flux surface penetrates wall, last closed flux surface has q=2. This destabilizes external kink or RWM

VDE does not have to move plasma very far

Manickam et al. 2011

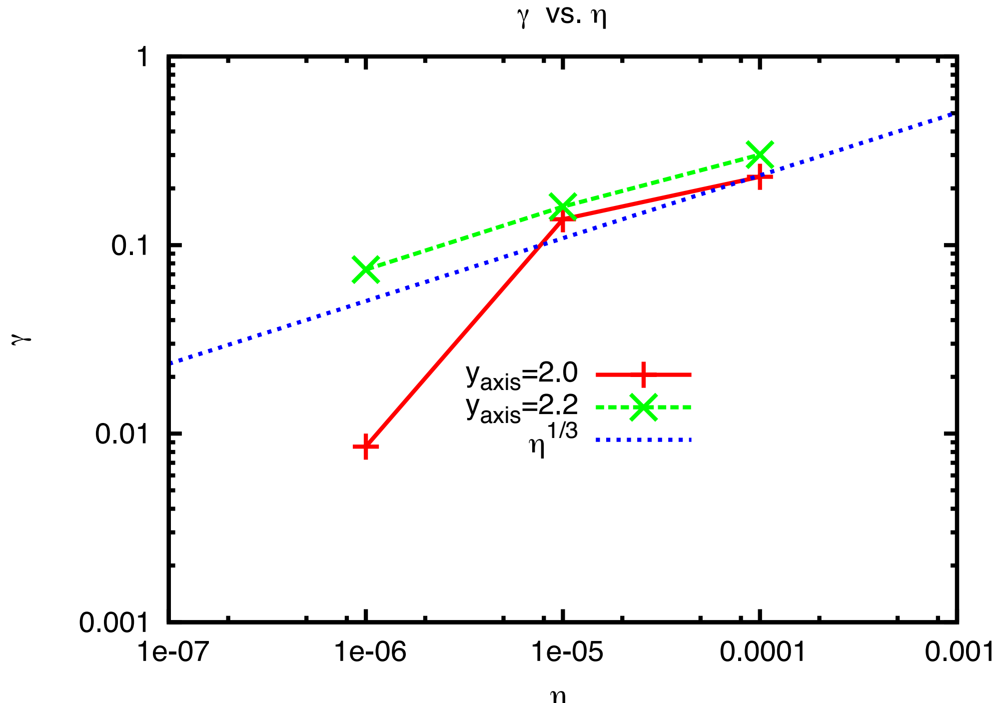
Scrape off destabilizes (2,1) mode





- Growth rate increases with y_{axis} , the vertical displacement of the magnetic axis, which lowers edge q
- Mode structure is (m,n) = (2,1)
- Mode is resistively unstable, approaches ideal marginal stability

(2,1) growth rate scales as $S^{-1/3}$



- As y_{axis} increases, growth rate tends to $S^{-1/3}$ scaling
- Approaches marginal ideal instability
- The S value near q=2 is what matters
- In graph S on axis is plotted

Sideways wall force

- Wall force is calculated from the jump in magnetic field across thin resistive shell

$$\text{current in wall is given by } J_{wall} = \frac{\hat{n}}{\delta} \times \left(B_{vac} - B_{plas}\right)$$

$$\delta \text{ is wall thickness}$$

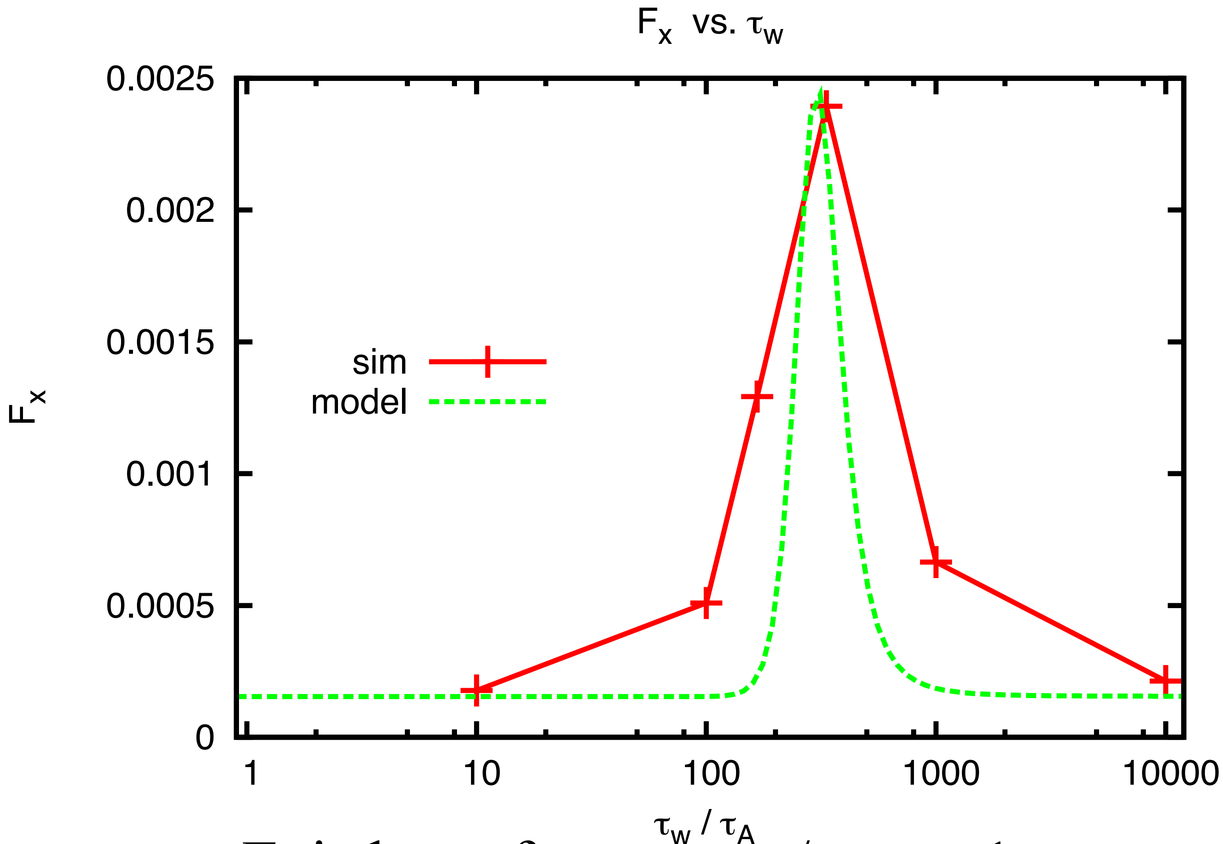
$$\text{sideways wall force is } F_x = \delta \int d\varphi \int dlR\left(J_{wall} \times B_{wal}\right) \bullet \hat{x}$$

$$\text{where } \hat{x} = \hat{R}\cos\varphi \approx \hat{n}\cos\theta\cos\phi$$

- **Indicates that (1,1) perturbations required for sideways force**
- **also (2,1) beating against (1,0) VDE**

$$\text{resistive wall penetration time } \tau_{wall} : \frac{\delta}{\eta_{wall}}$$

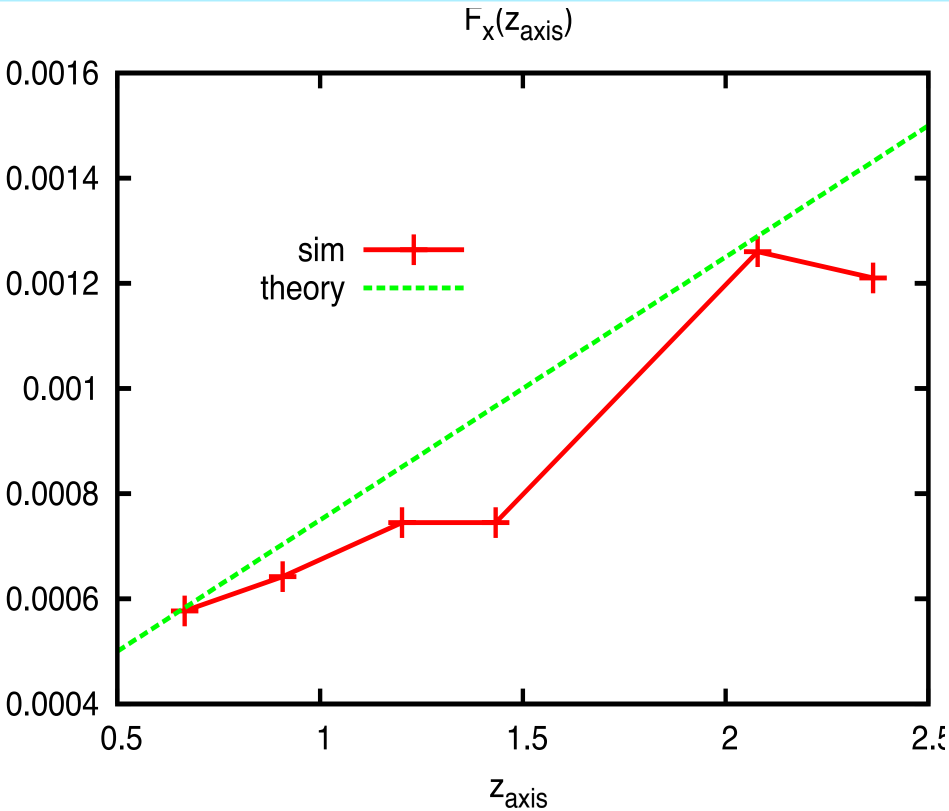
Wall force depends on $\gamma\tau_{wall}$



$$F_x \text{ is large for } \gamma\tau_w \approx \gamma / \gamma_{VDE} \approx 1.$$

The value of $\gamma\tau_w$ for which F_x peaks depends on initial conditions, as will be shown analytically

Mitigated disruptions



- MGI (Izzo et al. 2008)
- Radiation cools plasma for q > 2
- Profiles become unstable to (2,1) and (1,1) modes
- In simulations, profiles were modified to set current = 0 for q > 2
- Current was increased for q<2 to keep total current constant

- VDE was evolved to different displacements of the magnetic axis in 2D before allowing 3D mode evolution
- Sideways force F_x increased linearly with magnetic axis displacement
- $\gamma\tau > 10$

Theory of wall force produced by (2,1) modes

- Previous theory explained sideways force F_x produced by (1,1) mode (Zakharov 2008, Strauss et al. 2010)
- MGI disruption simulations show that F_x is linear in VDE displacement ξ_{VDE}
- F_x is linear in (1,1) amplitude and bilinear in the (2,1) and (1,0) (VDE) amplitude. Explains MGI F_x dependence on VDE amplitude, as well as peaking of F_x when $\gamma\tau$~1
- Based on Strauss et al. PoP 2010 model: circular cross section, constant current density. Plasma radius a, wall radius b

$$\text{sideways force is } F_x = \frac{1}{(2\pi)^2}\oint d\phi\, d\theta\, f_r \cos\theta \cos\phi$$

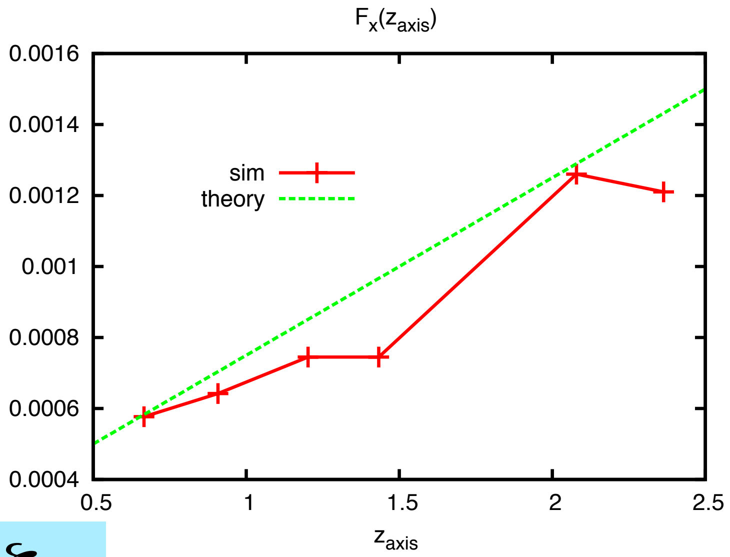
$$\text{where } f_r \propto \frac{b^m}{r^m}\xi_{m1}\sin(m\theta - \phi)$$

Theory of (2,1) wall force

The VDE displaces the force; expand in a Taylor series

$$f_r(r-\xi_{VDE}\sin\theta) = f_r(r) - \frac{\partial f_r}{\partial r}\xi_{VDE}\sin\theta$$

The force depends on (1,1) and (2,1) times (1,0) amplitude



$$F_x = c_1\frac{\xi_{11}}{a} + c_2\frac{\xi_{VDE}}{b}\frac{\xi_{21}}{a}$$

$$\text{where } c_m = \frac{mB_\theta^2}{B_\phi^2}\frac{\gamma_{m1}\tau(m-q)}{m(b/a)^m + \left[(b/a)^m - (a/b)^m\right]\gamma_{m1}\tau}$$

F_x is normalized as in Strauss 2010

Peaking of $F_x(\gamma\tau)$

The peaking of the force as a function of γτ can be explained as a competition between the (2,1) mode and VDE (1,0) mode to reach maximum amplitude. Let the amplitudes of the 2,1 and 1,0 modes have the form

$$\xi_{21} / a = \operatorname{sech}(\gamma t - \alpha_{21}) \qquad \xi_{10} / b = \operatorname{sech}(t / \tau - \alpha_{10})$$

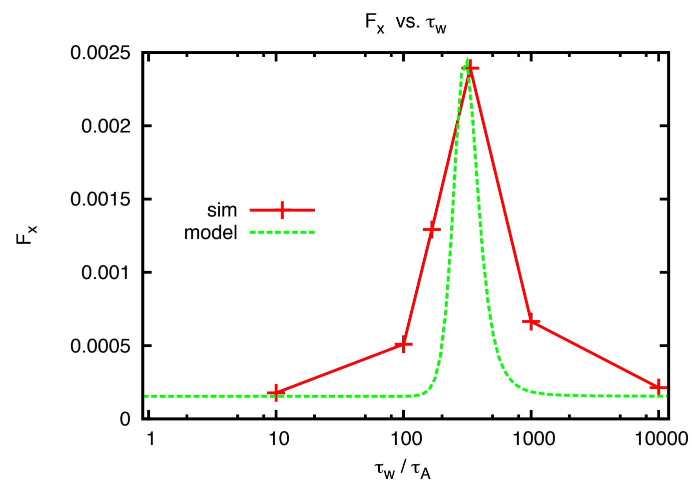
The model assumes the modes grow exponentially and then decay. The decay of the VDE models moving into the wall. The α terms are the initial amplitudes at t=0. The force is maximum when the time derivative of $\xi_{21}\xi_{10}$ is zero.

$$F_x \propto \operatorname{sech}^2\left(\frac{\gamma\tau\alpha_{10} - \alpha_{21}}{\gamma\tau + 1}\right)$$

peak of $F_x(\gamma\tau)$ occurs when $\gamma\tau = \dfrac{\alpha_{21}}{\alpha_{10}} \geq 1$

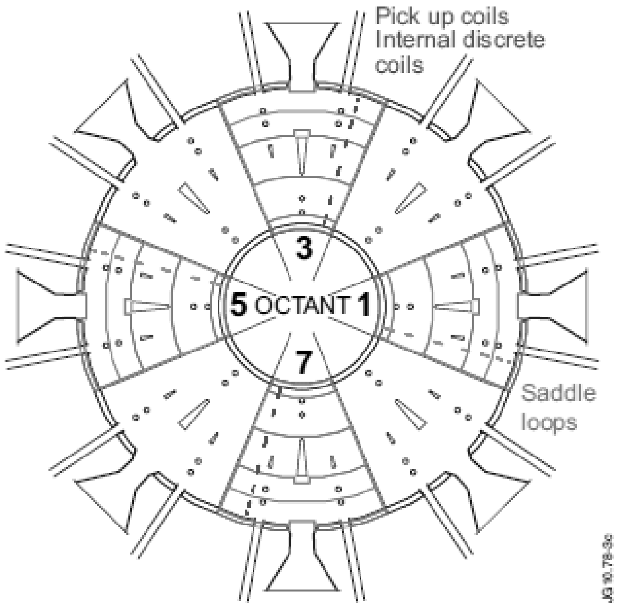
in scrape off case, $\alpha_{10} \leq 1,\ \alpha_{21} >> 1$

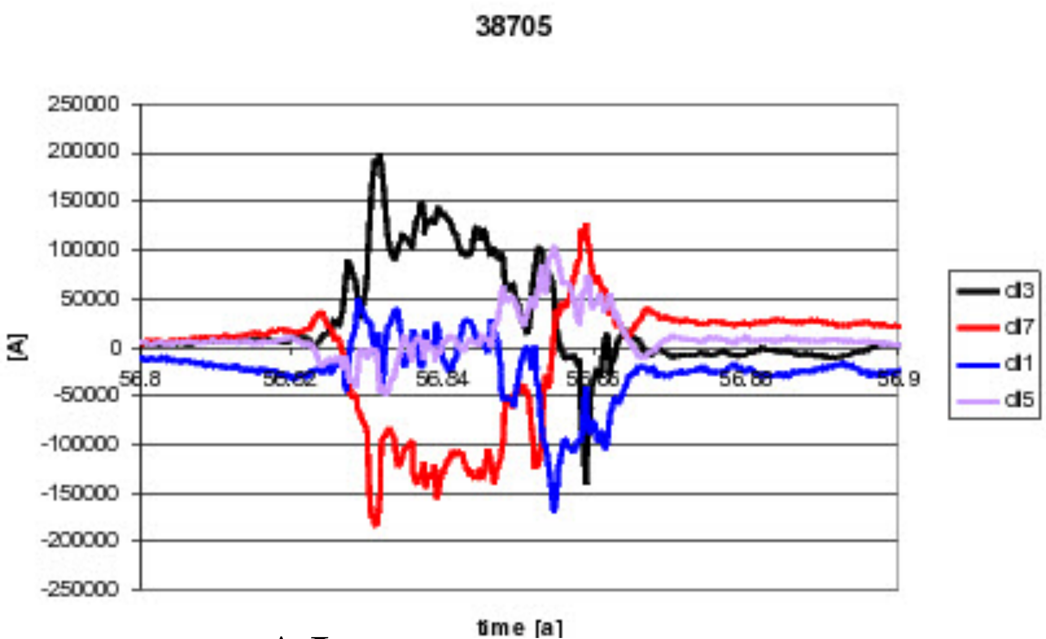
baseline is from ξ_{11}. Max/min $\propto \xi_{21} / \xi_{11}$



3D halo current

- In JET, the toroidal current varied as a function of toroidal angle during disruptions
- Zakharov PoP 2008, Gerasimov et al, JET 2009





Zakharov: caused by Hiro current

$$\frac{\Delta I_\varphi}{I_{\varphi 0}} \approx 0.08$$

2D and 3D halo current

- Halo current is poloidal current that flows into the wall in a VDE or disruption
  - Net conventional (2D) normal current density vanishes when integrated poloidally

2D halo current density

$$i_{halo} = \frac{1}{2}\int |J_n| R dl$$

- 3D halo current density:

$$i_{halo3D} = \oint J_n R dl$$

$$\nabla \bullet J = 0 \quad \Rightarrow \quad \boxed{\frac{dI_\phi^{plasma}}{d\varphi} = -i_{halo-3D}}$$

"Hiro current"

$$\frac{d}{d\phi}\left(I_\phi^{plasma} + I_\phi^{wall}\right) = 0$$

Halo currents and TPFs

Define Toroidal Peaking Factors (TPF) for halo current and 3D halo current

$$TPF = \frac{i_{halo-\max}}{< i_{halo} >}, \quad TPF_{3D} = \frac{i_{halo3D-\max}}{< i_{halo} >}$$

$$\text{where } < i_{halo} >= \frac{1}{2\pi}\int d\varphi i_{halo}$$

Halo fraction: $$HF = \frac{2\pi < i_{halo} >}{I_\phi}$$

$$\frac{\Delta I_\varphi}{I_{\varphi 0}} = TPF_{3D} \times \frac{HF}{2\pi}$$

In simulation, $\Delta I_\varphi / I_{\varphi 0} \approx 0.02$ $\quad TPF_{3D} / TPF \approx 0.5$

Theory of toroidal current variation

Same model as before from Strauss et al 2010
VDE displacement of (1,1) mode gives toroidal current variation

$$\frac{\Delta I_\phi}{I_\phi} = \frac{(\gamma\tau + 2)(1 - q_0)}{[1-(a/b)^2]\gamma\tau + 2}\left(\frac{a}{b}\right)^3 \frac{\xi_{11}}{a}\frac{\xi_{VDE}}{b}$$

example: $\gamma\tau >> 1,\ b/a = 2,\ \mathrm{q}_0 = 0.8,\ \xi_{11} = a,\ \xi_{VDE} = b$ $\qquad \frac{\Delta I_\phi}{I_\phi} = 0.03$

Consistent with JET, simulations, and ITER database

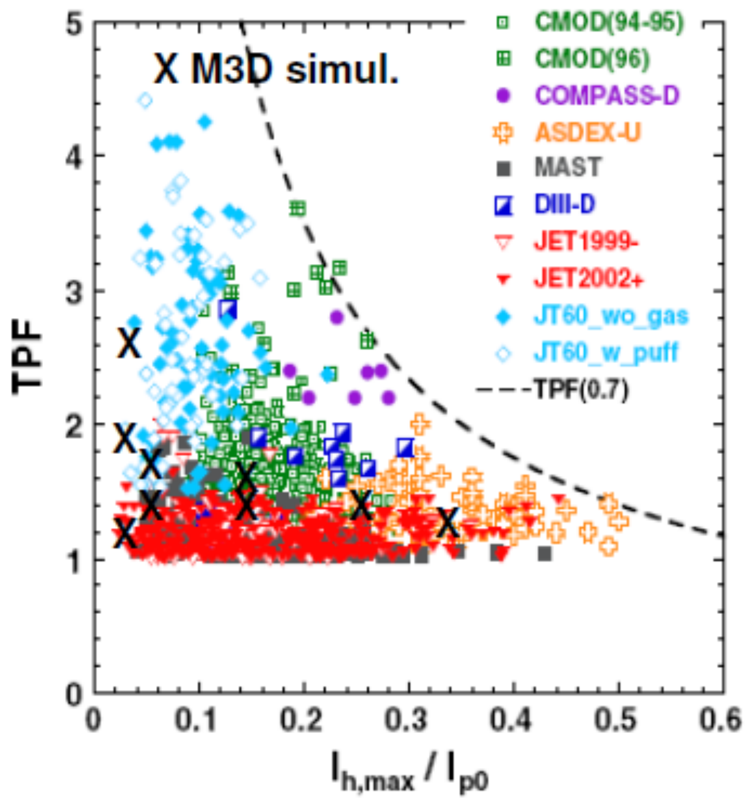
Toroidal Current variation – ITER database

$$\frac{\Delta I_\varphi}{I_{\varphi 0}} = TPF_{3D} \times \frac{HF}{2\pi}$$

$$TPF \times HF < 0.75$$

$$\frac{\Delta I_\varphi}{I_{\varphi 0}} < 0.12 \frac{TPF_{3D}}{TPF}$$

ITER database: X's are M3D results



ITER vessel forces

- Use GRIN to calculate Green's functions for vacuum B fields
- Resistive walls with different wall times
  - First wall
  - Blanket modules
  - Vacuum vessel
- Calculate wall forces
- Benchmark with DINA, TSC

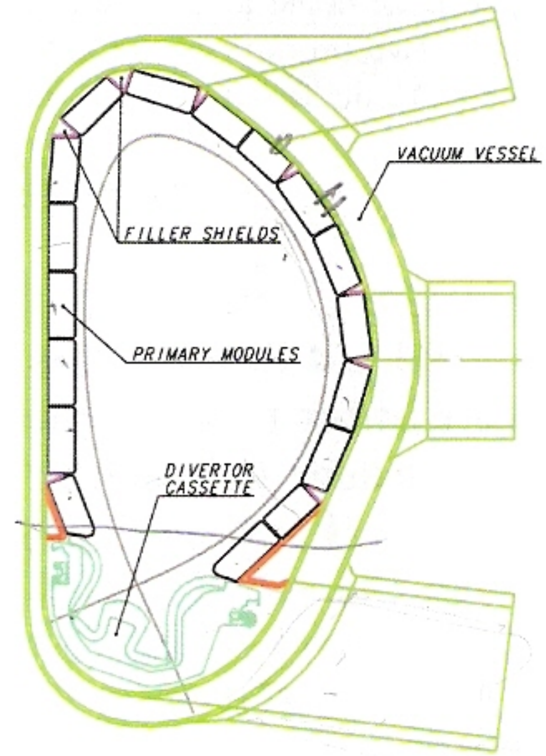
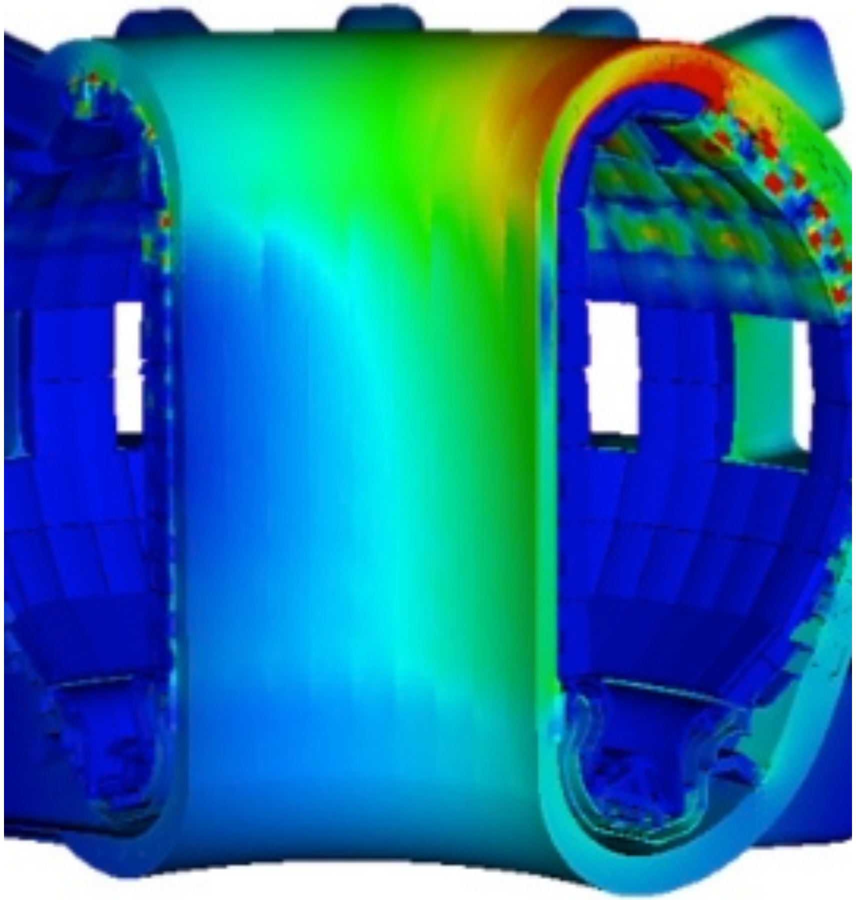


FIG. 1 Vacuum vessel and blanket module poloidal segmentation

Coupling to 3D EM code

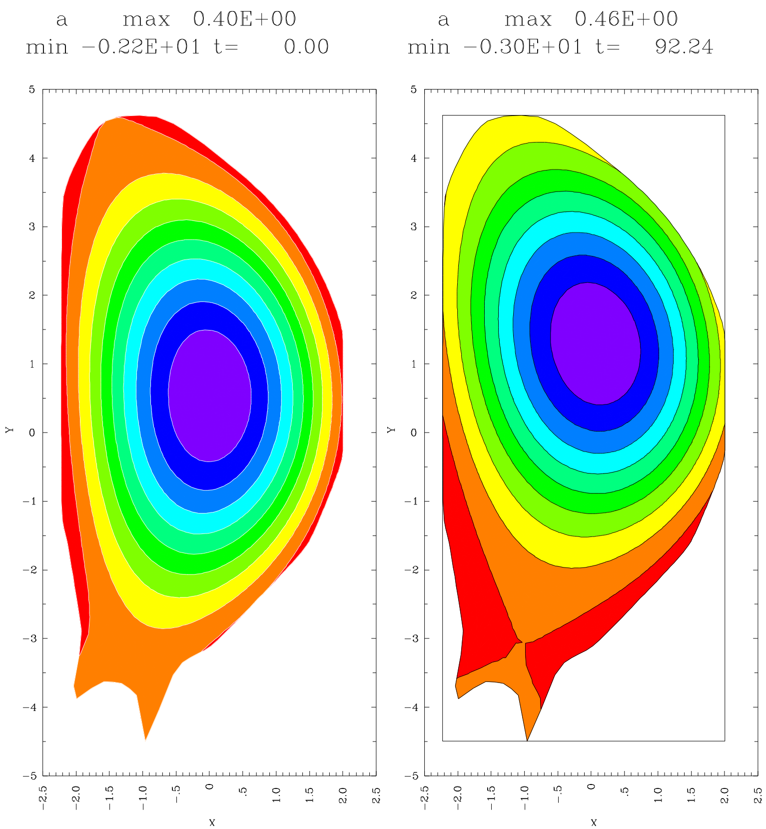
- Normal current given to CAFÉ 3D EM code
- Calculate vessel force
- Loose coupling – no feedback as with GRIN
- Should also provide toroidal current to calculate eddy current in vessel



Summary

- Calculated sideways force F_x in ITER disruptions
  - Disruption caused by VDE
    - scrapes off and cools plasma for q > 2
    - (2,1) mode more important than (1,1)
  - MGI induced disruption
    - F_x is offset linear in the VDE amplitude
- Theoretical model
  - can explain peaking of F_x
  - offset linear scaling with VDE amplitude
- 3D halo current gives toroidal variation of toroidal current
  - Consistent with data and simulations
- Future plans: calculate F_x on blanket modules, coils

Toroidal eddy current in wall



- Poloidal flux dissipation in resistive wall gives toroidal wall current
- Recently measured (LZ)
- Wall current opposite sign as plasma current

$$\frac{\partial \psi}{\partial t} = -\eta_{wall} J_{\phi}^{wall}$$

$$\psi = \psi(r - \xi_{VDE} \sin\theta)$$

$$\frac{J_{\phi}^{wall}}{I_{\phi}^{plasma}} = -\frac{\xi_{VDE} \sin\theta}{2\pi\delta b^{3}}$$

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NP8, Poster Session V
31 October 2012

Previous Simulations

Strauss, Paccagnella, Breslau, PoP 17, 082505 (2010)
Paccagnella, Strauss, Breslau, NF 49, 035003 (2009)

- Simulations with M3D MHD code with resistive wall boundary conditions
- Sideways wall force varied strongly with resistive wall penetration time, largest for mode growth time ~ wall penetration time
- S was relatively low (S = resistive time/Alfven time=10^5)
  - Now S=10^6
- T_{wall} was short
  - Now T_{wall} ~ 10^3 - 10^4