Disruption Simulations

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HRS Fusion

Disruption simulation is controversial

- It’s claimed that
  - The slow timescale of disruptions relative to the Alfven time requires a 3D equilibrium code
  - Present simulation codes (M3D, Nimrod) use incorrect velocity boundary conditions
  - Magnetic boundary conditions do not include ``wetting” of the wall by plasma so that ``Hiro current” can flow

Disruptions have many causes: need XMHD, not 3D equilibrium

- VDE and kink modes
  - VDE carries plasma to wall, where it is scraped off, and destabilizes kink / tearing mode
  - Probably causes the most sideways wall force
- Tearing mode / NTM
  - NTM can be excited by a sawtooth
  - Requires kinetic closure
- RWM
  - RWM extensively studied linearly, not nonlinearly
  - Kinetic closure needed for better model
  - wall force may be small because of small growth rate
- Pellet / piece of wall tile falling into plasma
  - Wall tile causes 1/3 of C – mod disruptions
  - Local cooling increases pressure gradient

Causes of disruptions 2

- Pressure driven modes
  - Important for thermal stress on wall
  - Could be caused by alpha heating in burning plasma
  - Mitigation - MGI
- In general need XMHD, kinetic effects
  - RWM
  - NTM
  - Can these modes saturate before disrupting?
  - Are they important for sideways wall force?
  - Runaway electrons
- Time – scale: will return to this later
- A 3D equilibrium is inadequate to deal with disruption physics

Boundary conditions

- M3D and NIMROD assume no flow through boundary condition
- A possible boundary condition was used in DEBS (Schnack et al, JCP 70, 333, 1987)

$$v = \frac{E \times B}{B^2} \qquad E = \eta_w J_w \qquad J_w = \frac{B_{vac} - B_{plasma}}{\delta}$$

$$v_n = \frac{\eta_w}{\delta} \frac{F_w}{B_w^2} \qquad v_n = \frac{\eta_w}{\delta} \frac{(B_{vac}^2 - B_{plasma}^2)}{B_w^2}$$

Boundary conditions 2

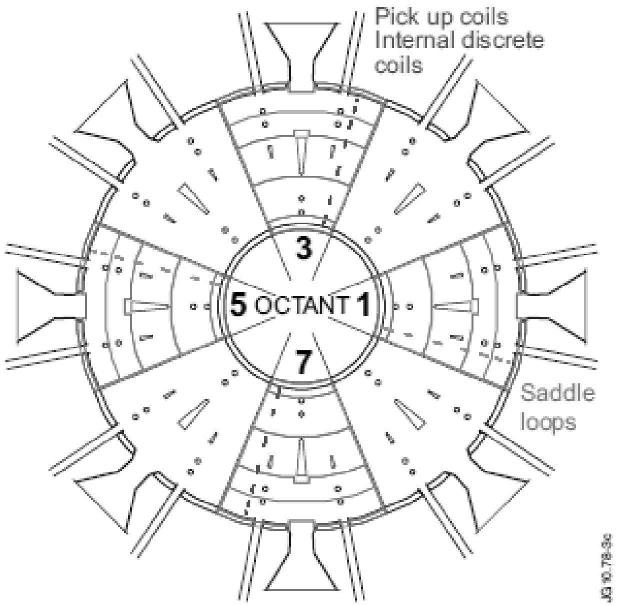
- DEBS boundary condition was tried in M3D
  - Made little difference
- Flow though boundary condition

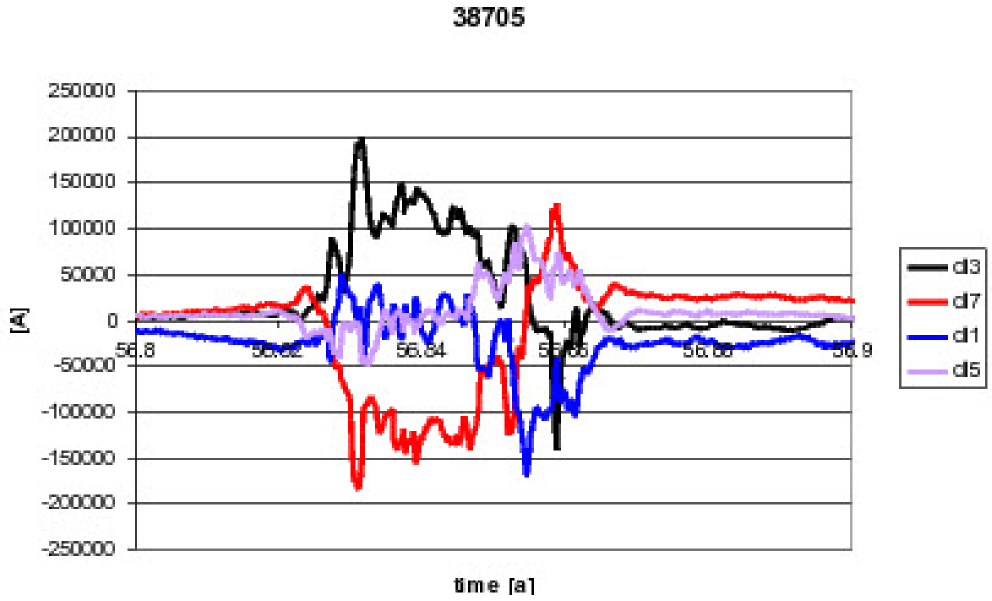
$$\frac{\partial v_n}{\partial n} = -\frac{v_n}{d} \qquad\qquad v_n = -d v_n{}' \cong 0$$

- If d << a, (d = a/4) verified that it makes little difference
- There is no theory of absorbing boundary condition for normal velocity, only parallel velocity
- sheath potential: if wall is an equipotential, $v = \frac{\partial \Phi}{\partial n} n \times B / B^2$

Hiro current

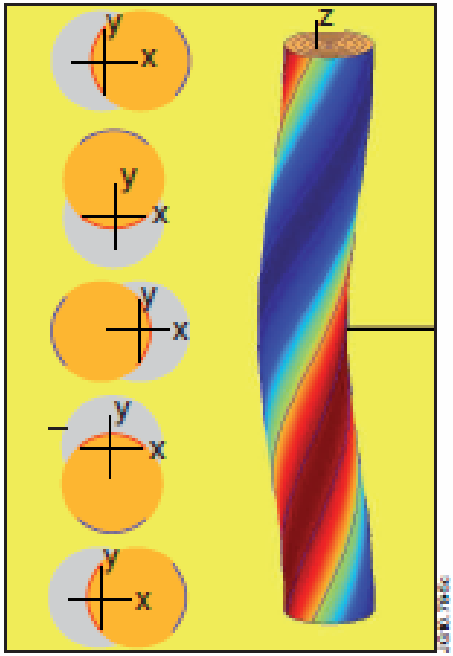
- In JET, the toroidal current varied as a function of toroidal angle
- This was correlated with toroidally varying vertical displacement
- From Gerasimov et al, JET 2009





Hiro current 2

- This was ”explained” using the Hiro current theory (Zakharov, Phys. Plasmas 15, 062507 2008)
  - Plasma is unstable to n = 1 kink
  - Where the kinked plasma ``wets” the wall, hiro current can flow into the wall
  - This causes remaining bulk plasma current to vary toroidally, in phase with the toroidally varying vertical plasma displacement
- The “hiro current” and “wetting” ideas caused a lot of confusion
  - Are codes like M3D and NIMROD able to produce hiro current effects?



Hiro current 3

- M3D and NIMROD allow halo current
- Hiro current is a component of halo current
  - It was confusing because in 2D studies of VDEs there is no hiro current
  - Hiro current is a 3D effect

Hiro current vanishes in 2D

- Hiro current is net normal current through the wall

$$J_n = \nabla I \times \nabla \varphi$$

$$I_{hiro} = \int J_n R dl$$

$$\nabla \bullet J = 0$$

implies

$$\frac{dI_\varphi}{d\varphi} = -I_{hiro}$$

$$I_\varphi = \int J_\varphi dRdZ$$

Toroidal variation of toroidal
Current ~ hiro current

halo current

- Halo current is poloidal current that flows into the wall in a VDE or disruption
  - Net total halo current is hiro current
  - Net conventional (2D) halo current vanishes
  - Conventional halo current can be measured by ½ absolute value

$$I_{halo} = \frac{1}{2} \int | J_n - J_{hiro} | R dl$$

$$J_{hiro} = \int J_n R dl / \int R dl$$

Where does Hiro current come from?

- In 2D, toroidally averaged case, there is no Hiro current, only halo current
- M3D magnetic field and current

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

$$J = -\Delta^{*}\psi\nabla\hat{\varphi} + \nabla I \times \nabla\varphi + \frac{1}{R^2}\nabla_\perp \frac{\partial\psi}{\partial\varphi} + \ldots$$

Toroidal current

Halo term gives halo at wall

Hiro term

Hiro current calculation

- In Strauss et al, Phys. Plasma 17, 082506 (2010) it was shown in a model calculation and verified in simulations that, as in JET

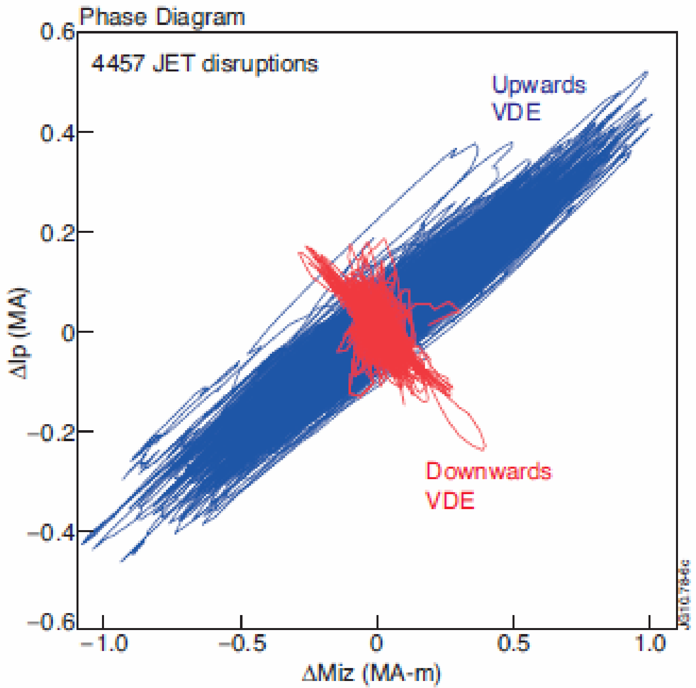
$$\frac{dI_\varphi}{d\varphi} = \frac{\xi_{VDE}}{a^2}\frac{dM_{IZ}}{d\varphi}$$

Hiro current is given by

$$I_{hiro} = -\frac{\xi_{VDE}}{a^2}\frac{dM_{IZ}}{d\varphi}$$

Where the vertical Current moment is

$$M_{IZ} = \int ZJ_\varphi dRdZ$$



From Gerasimov. EPS 2009

Hiro current can be calculated directly

TPF and halo current fraction

- Can relate TPFxHalo current fraction to toroidal current perturbation
- It appears that the varying part of halo current is mostly hiro current, while the average part is halo current, and they have comparable magnitude

$$I_{hiro} \approx I_{halo}$$

$$TPF = \frac{I_{hiro-\max} - I_{hiro-\min}}{< I_{halo} >} \approx 2$$

< .. > is toroidal average

Halo current fraction is ratio of average halo current to toroidal current

$$H_f = \frac{< I_{halo} >}{< I_{\varphi} >}$$

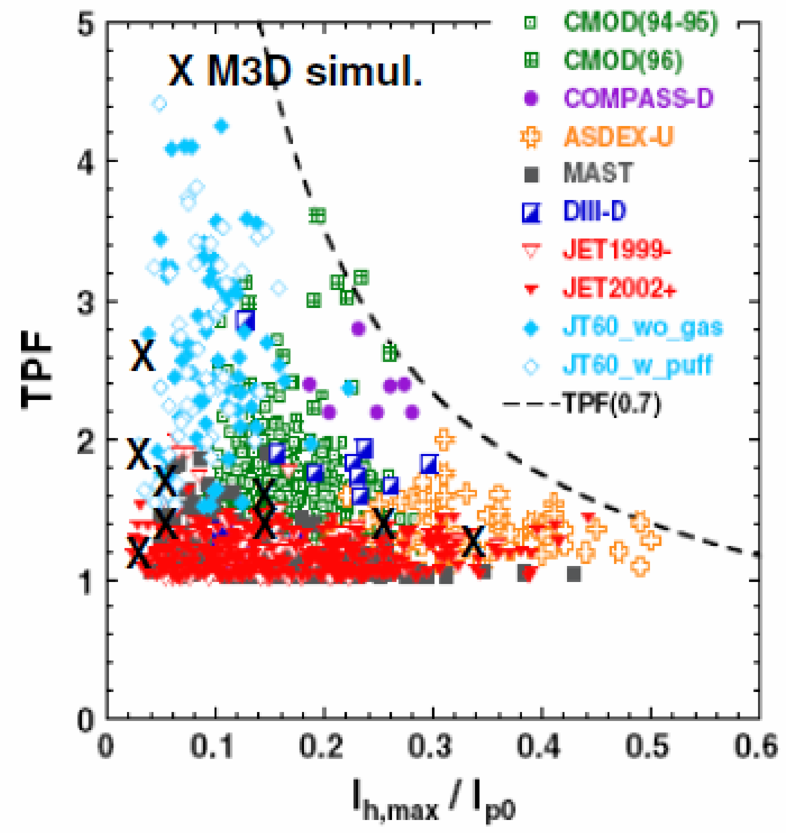
TPF and halo fraction 2

- Simulational results and ITER database

$$TPF \times H_f = 2\frac{I_{hiro}}{< I_\varphi >}$$

$$= \frac{2}{< I_\varphi >}\frac{dI_\varphi}{d\varphi} = 2\frac{\Delta I_\varphi}{I_\varphi} < 0.7$$

$$\frac{\Delta I_\varphi}{I_\varphi} < 0.35$$



M3D simulations have current perturbation ~ 0.2

“Wetting” and halo model

- If plasma is surrounded by a real vacuum, wetting is a problem
- In M3D and NIMROD the “vacuum” is represented by cold plasma
  - Current can flow from the plasma to the wall
  - No need for plasma to penetrate the wall
  - Halo plasma = SOL
- Halo width is time dependent, it gets bigger in a disruption
- Wall force is only weakly dependent on halo resistivity

Halo resistivity model

- Halo (SOL) resistivity model used in TSC (Sayer et al. Nucl. Fusion 33, 969, 1993) : 3 regions

$$\eta = \eta(T) \qquad \psi < \psi_{core}$$

$$\eta = \eta_{halo} \qquad \psi_{core} < \psi < \psi_{vacuum}$$

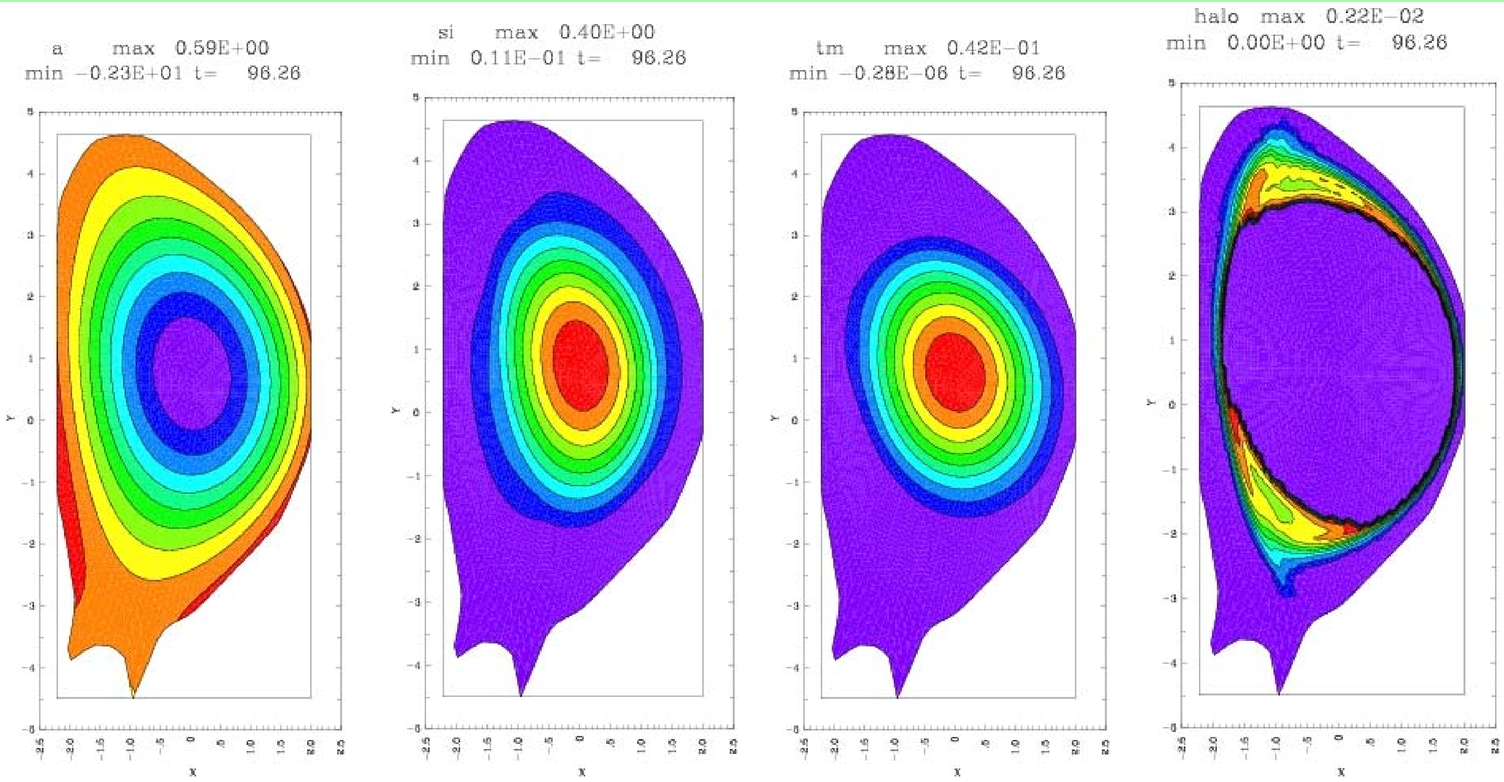
$$\eta = \eta_{vacuum} \qquad \psi_{vacuum} < \psi$$

- in 3D this does not work because flux surfaces might not exist

$$\text{replace} \quad \psi_{core}, \psi_{vacuum} \text{ with } T_{core}, T_{vacuum}$$

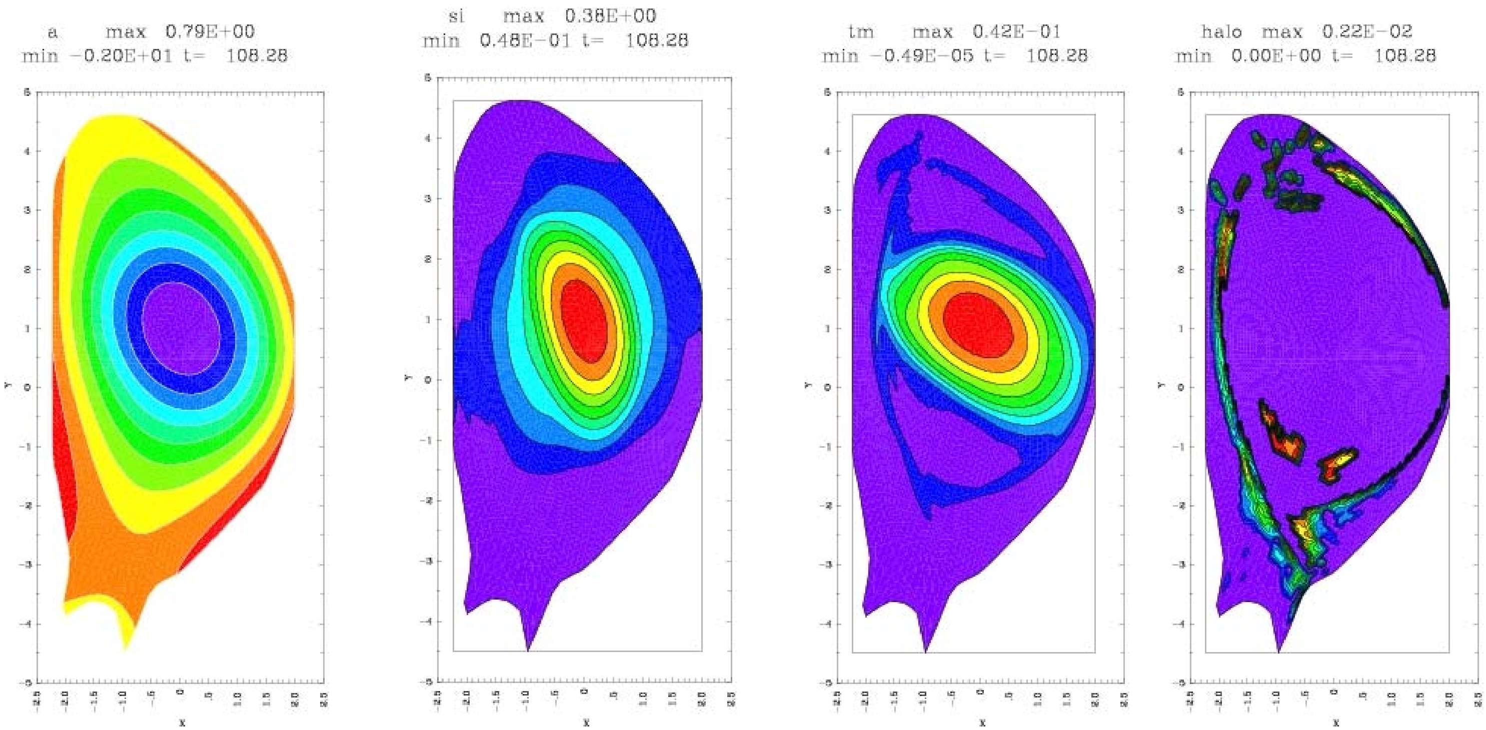
- want to determine effect of these parameters on wall force, etc.
- halo width increases during disruption

Halo in (2,1) tearing disruption



ψ **I** **T** **halo**

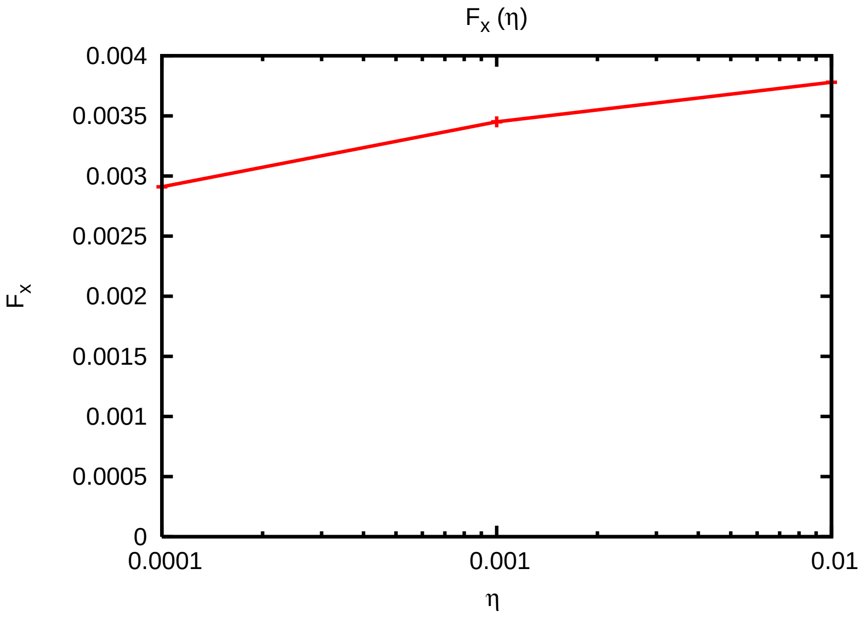
Halo in (2,1) tearing disruption



ψ **I** **T** **halo**

Halo resistivity and wall force

- The wall force is insensitive to the halo resistivity

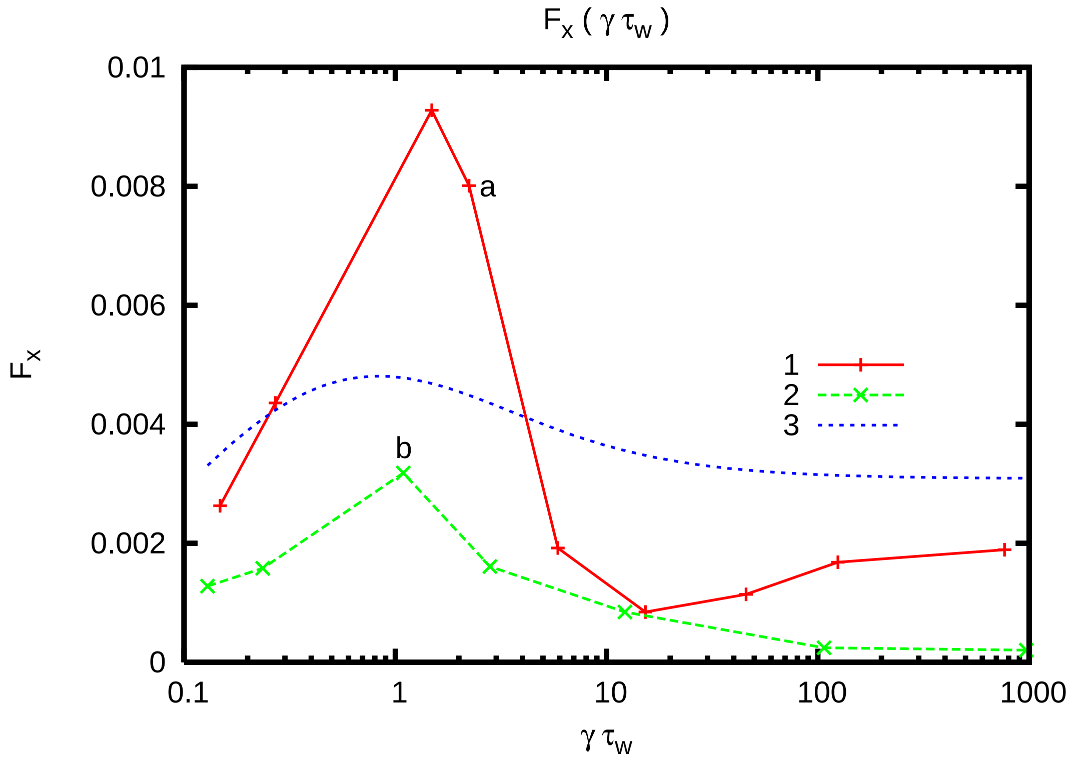


summary

- Many kinds of disruptions
  - Need X MHD physics
  - Even VDE/kink disruption involves scrape off at wall
  - 3D equilibrium code inadequate
- Velocity boundary condition
  - So far has not made much difference
- Hiro current
  - M3D contains “wetting”
  - Hiro current is the net halo current
    - Causes toroidal variation of toroidal current
- Halo modeling in progress
  - Region between plasma and “vacuum”
  - Halo resistivity had moderate effect on wall force

Time scale

- M3D simulations were criticized because the wall time in the simulations was short
  - In fact wall time was 10 – 10,000 Alfven times
  - It was found that the largest wall force occurred when the mode nonlinear evolution time was comparable to the resistive wall penetration time
  - The modes studied so far had fast growth rates so wall time was chosen to be short for maximum effect



Time scale 2

- resistive wall mode (RWM) grows at wall penetration rate
  - Does wall force scale with growth rate as well as depending on “resonance” with wall time? If so, wall force will be small.

$$F_{wall} \propto \gamma I^2 f(\gamma \tau_{wall})$$

- **Plan RWM simulations in future**
- **Other “slow” modes - NTM**

Future plans

- Improve modeling of “vacuum” and halo region
- Scrape off of plasma by VDE
- Improve wall model
  - Two ITER walls with blanket structure in between
  - Two thin walls
  - Blanket will be modeled by spatially varying resistivity, v = 0
- Higher S, higher resolution
  - Study of RWM disruptions
  - Dependence of wall force on growth rate