Aymmetric wall force in disruptions, and other matters

H. Strauss, HRS Fusion

CTTS meeting

Princeton, 14 April 2019

Outline

- Quench of asymmetric wall force in disruptions by current quench
  - Compare M3DC1 with M3D and JET data.
  - halo current effect on wall force
- fluid model for runaway electrons
- Modify tokamak MHD codes for stellarators

simulations JET shot 71985

Validation of M3D compared maximum values in time of several variables

[Strauss, *et al.* Phys. Plas. **24** (2017)]

variable	simulation	experiment
Z_p	1.5m	1.4m
HF	0.16	0.16
ΔF_x	1.1 MN	
$\pi B \Delta M_{IZ}$	1.2 MN	1.3 MN

Z_p - vertical displacement
HF - halo fraction
Δ - amplitude of toroidal variation
ΔF_x - asymmetric wall force
$M_{IZ} = Z_p I_p$ - vertical current moment

$$\mathbf{F}_x = \delta \oint \oint \mathbf{J}_{wall} \times \mathbf{B}_{wall} \cdot \hat{\mathbf{x}} R dl d\phi \qquad \Delta F_x = (\mathbf{F}_x^2 + \mathbf{F}_y^2)^{1/2}$$

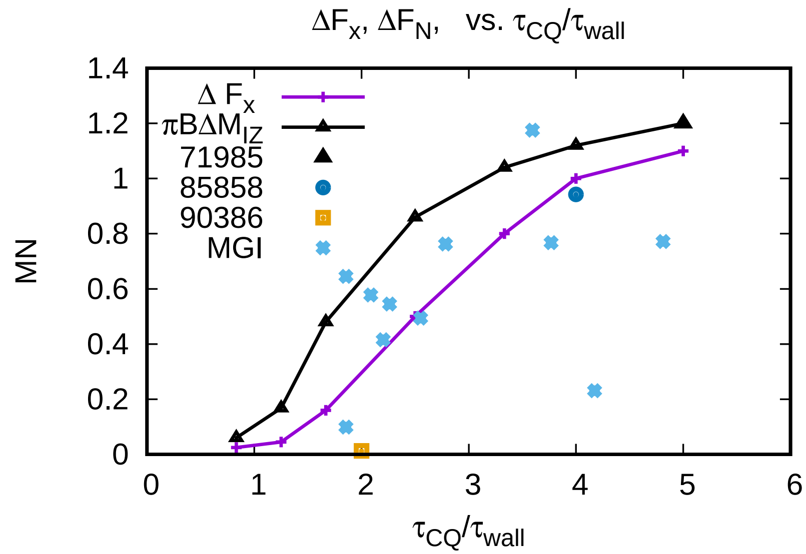
Asymmetric wall force is approximated by Noll force: $\mathbf{F}_x \approx \Delta F_N$,

$$\Delta F_N = \pi B \Delta M_{IZ}$$

The wall penetration time $\tau_{wall} = a_{wall}\delta_{wall}/\eta_{wall}$ was varied by changing η_{wall}, in order to find the effect of τ_{CQ}/τ_{wall}, where τ_{CQ} is current quench time.

Quench of asymmetric wall force

Asymmetric wall force depends on τ_{CQ}/τ_{wall}, where τ_{CQ} is the current quench time and τ_{wall} is the resistive wall penetration time.



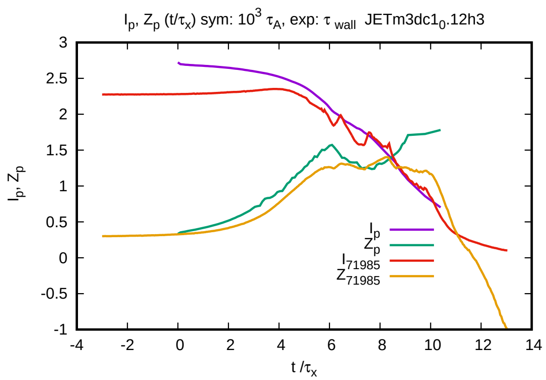
Solid curves: M3D simulations of shot 71985 where τ_{wall} was varied. Plots of asymmetric wall force ΔF_x and Noll force $\Delta F_N = \pi B \Delta M_{IZ}$. Highest end of the curves have experimental values τ_{CQ}/τ_{wall}.

Comparison with data: dots: ΔF_N and τ_{CQ} calculated for shots 85858 and 90386 in [S. Jachmich, *et al.* , EPS (2016)]

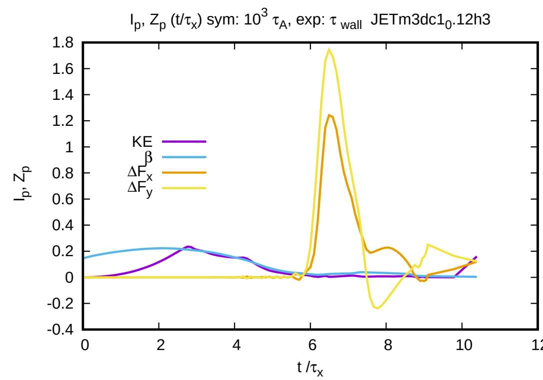
Points "MGI" are all JET shots "VDE+MGI" with ILW, 2011-2016. τ_{CQ} and ΔF_N were calculated from the data.

Comparison of M3DC1 and JET time history data

M3DC1 time history of JET shot 71985 was compared with JET data, normalizing the simulation RW time to the experimental wall time. The total current in simulation I_p, total current in experiment I_{71985}, vertical displacement in simulation Z_p, vertical displacement in experiment Z_{71985}, were in reasonable agreement.



(a)



(b)

(a) total current in simulation I_p, total current in experiment I_{71985}, vertical displacement in simulation Z_p, vertical displacement in experiment Z_{71985},

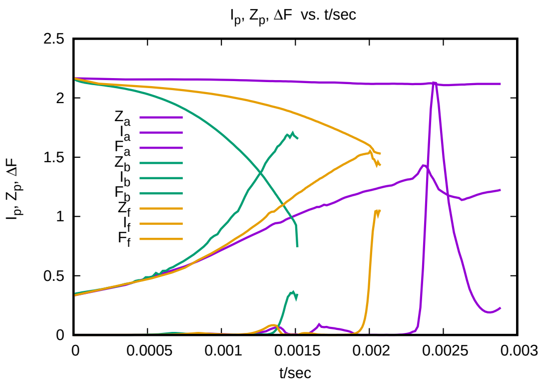
(b) KE, 100β, components of sideways F_x, F_y in MN.

Driving electric field to control current quench rate added by S. Jardin,

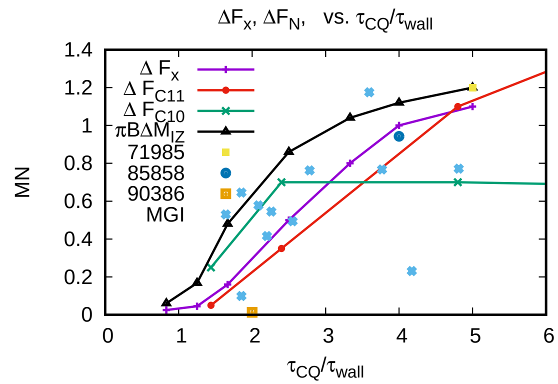
$$I = \frac{I_0 + I_f}{2} + \frac{(I_0 - I_f)}{2} \tanh\left(\frac{t_0 - t}{t_1}\right) \quad (1)$$

Verification of wall force quench in AVDE disruptions

The dependence of wall force on τ_{CQ}/τ_{wall} is being verified with M3DC1 simulations. Preliminary results have been obtained, initialized with a reconstruction of JET shot 71985. Both $n = 1$ sideways force and $n = 0$ vertical force are quenched by CQ.



(a)



(b)

(a) Time history of current I,vertical displacement Z, and asymmetric wall force F_{wall}. (b) ΔF_x , ΔF_N and F_v as a function of τ_{CQ}/τ_{wall}, the ratio of the TQ time to the RW time. (τ_{wall} was calculated from thin wall model, will calculated it directly.))

Halo current effects

In 2D, wall force is not affected by halo current [Wesson], [Clauser, this meeting]

In 3D, Noll force depends on 3D halo current.

$\nabla \cdot J = 0$ implies

$$\frac{\partial J_\phi}{\partial \phi} = -\oint R J_n dl \tag{2}$$

or

$$\frac{\partial I_\phi}{\partial \phi} = -I_{halo3D} \tag{3}$$

$$\Delta I_\phi = \Delta I_{halo} \tag{4}$$

where Δ is the rms amplitude of $n = 1$ perturbation. The Noll force is approximately

$$\Delta F_n = \pi B Z \Delta I_\phi = \pi B Z \Delta I_{halo} \tag{5}$$

(assuming here that $\Delta Z \approx 0$.)

Runaway Electrons - Fluid model

If REs carry the current, it is possible that $\tau_{CQ} >> \tau_{wall}$. MHD simulations were extended by adding RE fluid model. Runaway fluid equations are

[Helander 2007],[Cai and Fu 2015][Strauss *et al.* FEC 2018]

$$\frac{1}{c}\frac{\partial \psi}{\partial t} = \nabla_{\|}\Phi - \eta(J_{\|} - J_{\| RE}) \tag{6}$$

and $J_{\| RE}$ is the RE current density.The RE continuity equation can be expressed,

assuming the REs have speed c

$$\frac{\partial J_{\| RE}}{\partial t} \approx -c\mathbf{B} \cdot \nabla \left(\frac{J_{\| RE}}{B} \right) + S_{RE} \tag{7}$$

where S_{RE} in the following is a model source term.

$$S_{RE} = \alpha(t)(J_{\|} - J_{\| RE})J_{\| RE} > 0 \tag{8}$$

Approximately

$$\mathbf{B} \cdot \nabla \left(\frac{J_{\| RE}}{B} \right) = \mathcal{O}(v_A/c) \approx 0 \tag{9}$$

which is solved similarly to electron temperature, like a bounce average method.

RE advection

It is numerically difficult to solve advection dominated transport, where $c >> v_A$.

$$\frac{\partial J_{RE}}{\partial t} = -c\nabla_{\|} J_{RE} \tag{10}$$

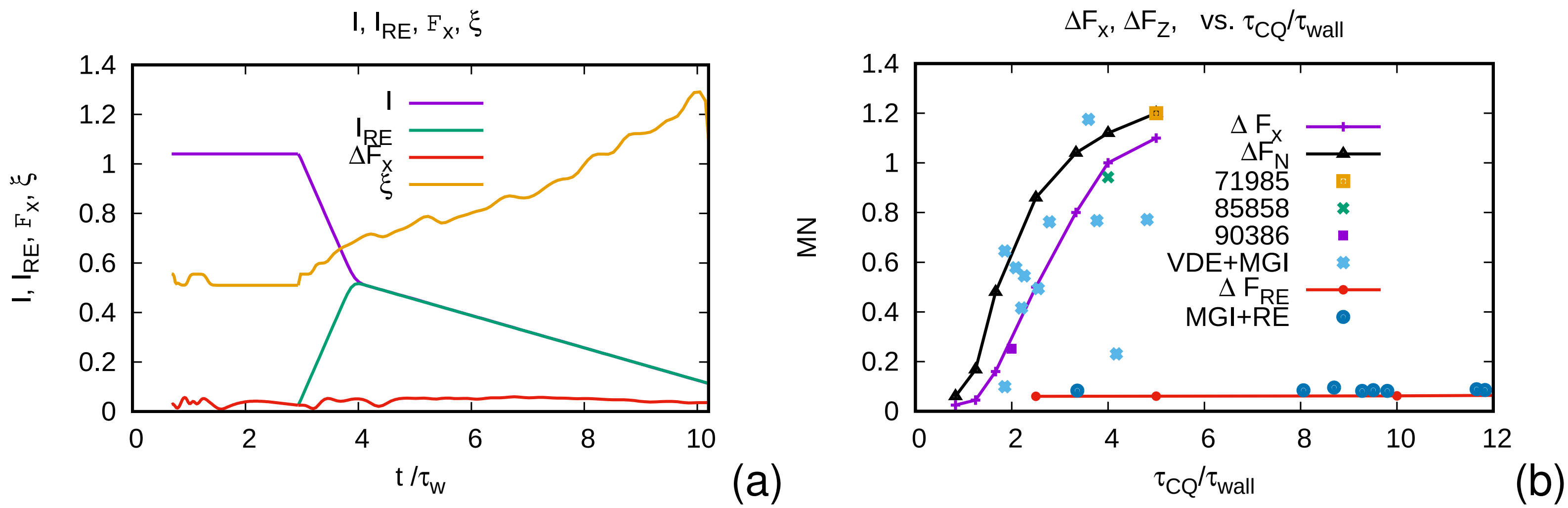
Physically, J_{RE} is constant on magnetic field lines. A robust, simple method

$$\frac{\partial J_{RE}}{\partial t} = \chi_{\|}\nabla_{\|}^2 J_{RE} \tag{11}$$

where $K >> 1$. It loses the direction of advection, which might matter for wall damage calculations. The methods can be compared with known solutions, [Helander],[Cai and Fu, 2015]..

The following example is done with M3D , using the parallel diffusion method.

JET RE asymmetric wall force



(a) Simulation initialized with JET shot 71985, with REs added, showing time history of current I, RE current I_{RE}, vertical displacement Z_p, and ΔF_x.

(b) Solid curves: ΔF_x in M3D simulations of shot 71985 where τ_{CQ}/τ_{wall} was varied, without REs, same as in Slide 4. Data points and simulations with REs in lower right. ΔF_{RE} as a function of τ_{CQ}/τ_{wall}. As in (a) $I_{RE} = I_{p0}/2$.

dots: RE shots "VDE+MGI" and "MGI+Runaway" from ILW, 2011-2016 database.

JET data and simulations agree well. REs produce small asymmetric wall force. The reason: the current is reduced by half, typical of JET. Force is produced by $(1, 1)$ or by $(2, 1)$ and $(1, 0)$ modes. q is too high.

Modifying tokamak MHD code for Stellarators

For stellarator computations [Strauss *et al.* 2004] , introduce VMEC coordinates (s, θ, ζ). The vertices of the element triangles have (s, θ) coordinates independent of ζ.

In a tokamak, s might be a flux coordinate. The cartesian coordinates are

$$\begin{aligned} R &= R(s, \theta) \\ Z &= Z(s, \theta) \\ \phi &= \zeta \end{aligned} \tag{12}$$

In each triangle (s, θ) can be expressed in local coordinates, (ξ, η),

$$\begin{aligned} R &= R(\xi, \eta) \\ Z &= Z(\xi, \eta) \\ \phi &= \zeta \end{aligned} \tag{13}$$

In local coordinates it is possible to compute the derivatives of the basis functions, needed for the finite element discretization of the equations.

Stellarator Coordinates

In stellarators,the “only” difference is that the cartesian coordinates are VMEC coordinates,

$$\begin{aligned} R &= R(s,\theta,\zeta) \\ Z &= Z(s,\theta,\zeta) \\ \phi &= \zeta \end{aligned} \tag{14}$$

In each poloidal plane $\zeta =$ constant, the calculation of derivatives of basis functions is the same as if the mesh were 2D. The mesh topology in (s,θ) is independent of ζ. The $\nabla\zeta$ direction is not parallel to $\nabla\phi$. The ζ derivative of a function $f(R,Z,\phi)$ at constant s,θ is

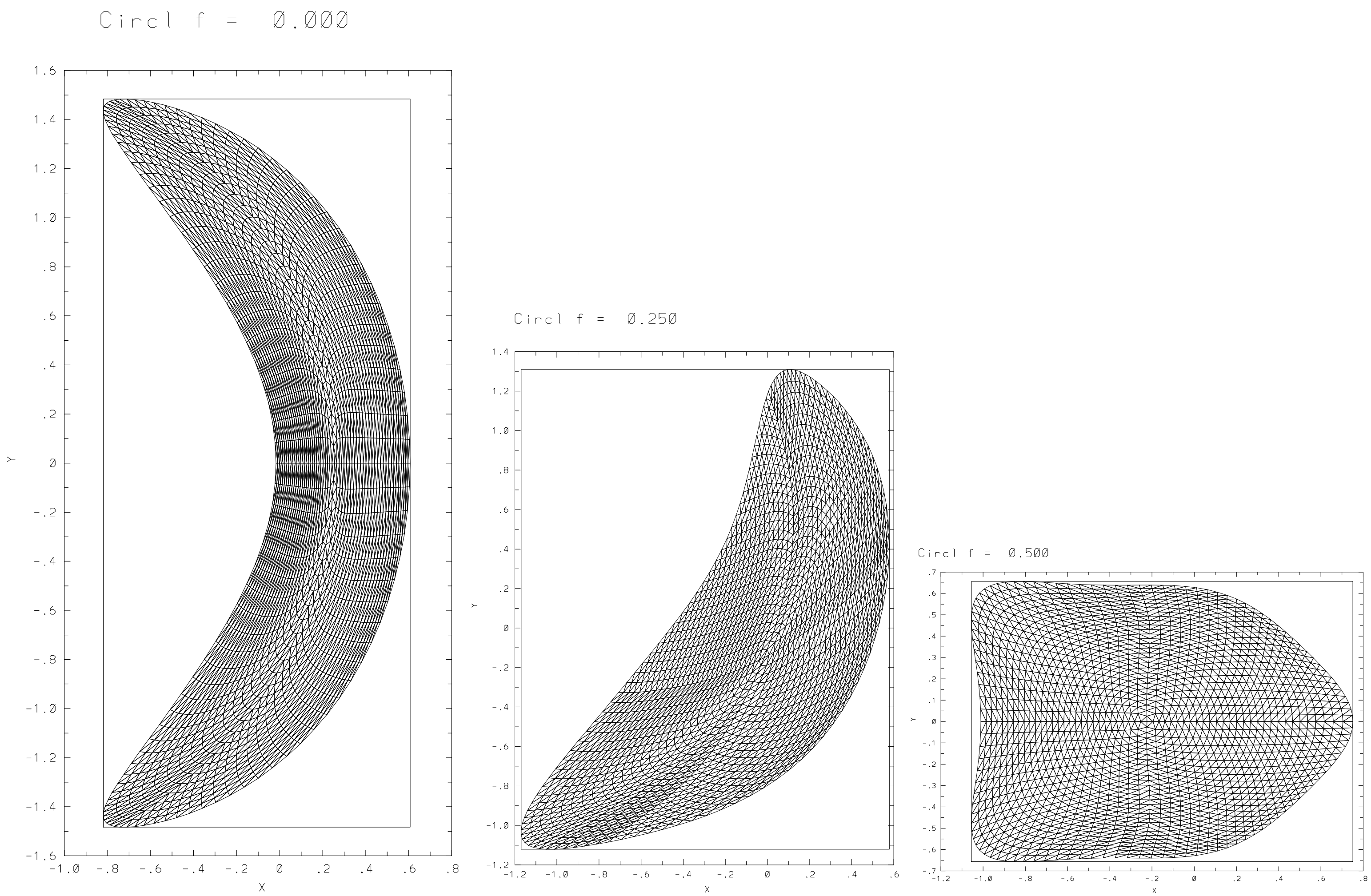
$$\frac{\partial f}{\partial \zeta}|_{s,\theta} = \frac{\partial f}{\partial R}\frac{\partial R}{\partial \zeta}|_{s,\theta} + \frac{\partial f}{\partial Z}\frac{\partial Z}{\partial \zeta}|_{s,\theta} + \frac{\partial f}{\partial \phi}|_{R,Z} \tag{15}$$

Reversing this expression gives

$$\frac{\partial f}{\partial \phi}|_{R,Z} = -\frac{\partial R}{\partial \zeta}\frac{\partial f}{\partial R} - \frac{\partial Z}{\partial \zeta}\frac{\partial f}{\partial Z} + \frac{\partial f}{\partial \zeta}|_{s,\theta} \tag{16}$$

where $\partial R/\partial\zeta$ and $\partial Z/\partial\zeta$ are known from the VMEC coordinates.

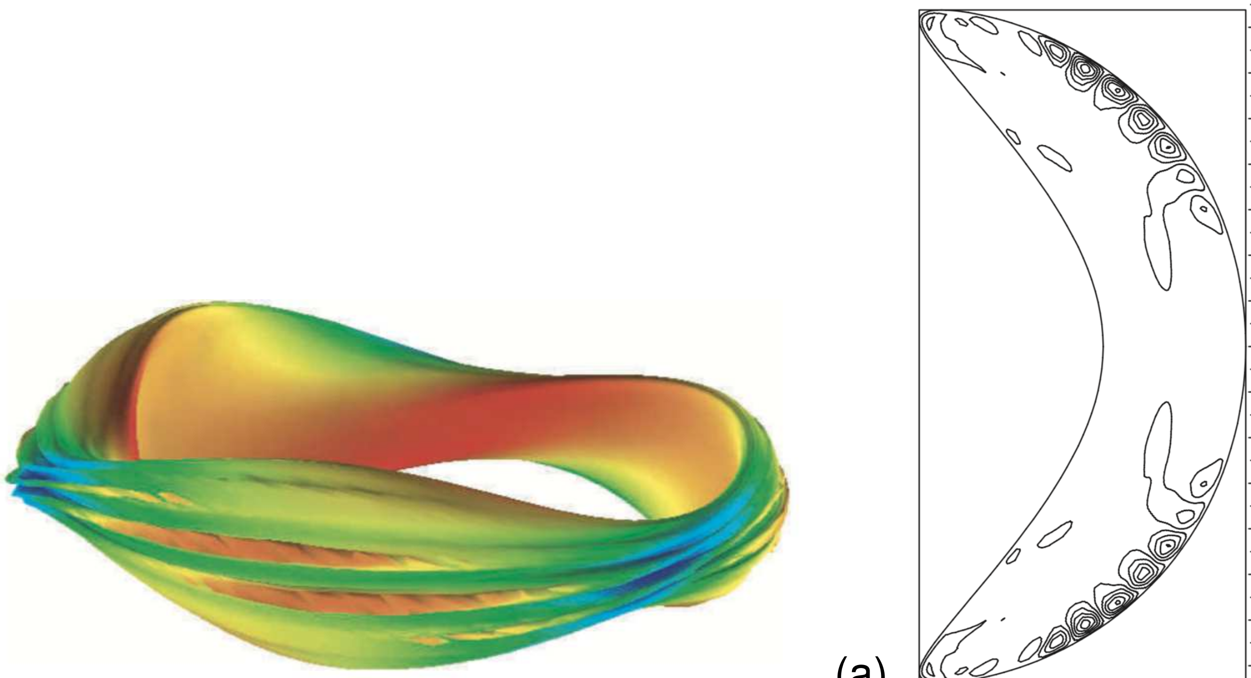
NCSX mesh



The mesh was used for NCSX simulations [Strauss *et al.* 2004].

simulations

H.R. Strauss, L.E. Sugiyama, G.Y. Fu, W. Park and J. Breslau, Simulation of two fluid and energetic particle effects in stellarators, Nucl. Fusion 44 (2004) 1008



(a) (b)

(a) CEMM logo, NCSX

(b) NCSX ballooning modes

Summary

- Simulations of wall force with M3DC1 consistent M3D and JET data.
- halo effect is different in 2D and 3D
- Runaway electrons simulations with fluid model.
- Modify tokamak MHD codes for stellarator simulations