Reduction of Asymmetric wall force in JET and ITER including Runaway Electrons

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Outline

- Asymmetric wall force in ITER disruptions was thought a major problem
  - JET AVDE simulations with M3D and data are in good agreement
  - asymmetric wall force reduction in simulation and JET MGI experiments
  - wall force is smaller in JET with faster current quench
- ITER disruption simulations
  - predict asymmetric wall force comparable to JET
  - not 25 times larger as in previous predictions
  - ITER CQ is relatively fast except when runaway electrons carry current
- Runaway electron fluid MHD
  - small asymmetric wall force wall force in JET with REs
  - possible asymmetric wall force wall force in ITER

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Comparison of M3D simulation and 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
ΔF_x	1.1 MN	
$\pi B \Delta M_{IZ}$	1.2 MN	1.3 MN
$N_{rotation}$	2.8	2.8
$\Delta I/I$	0.045	0.055

Z_p - vertical displacement

Δ - amplitude of toroidal variation

ΔF_x - asymmetric wall force

$M_{IZ} = Z_p I_p$ - vertical current moment

$N_{rotation}$ - number of toroidal rotation periods

ΔI - amplitude of toroidally varying part of toroidal current

Asymmetric wall force is approximated by Noll force:

$$\Delta F_x \approx \pi B \Delta M_{IZ}$$

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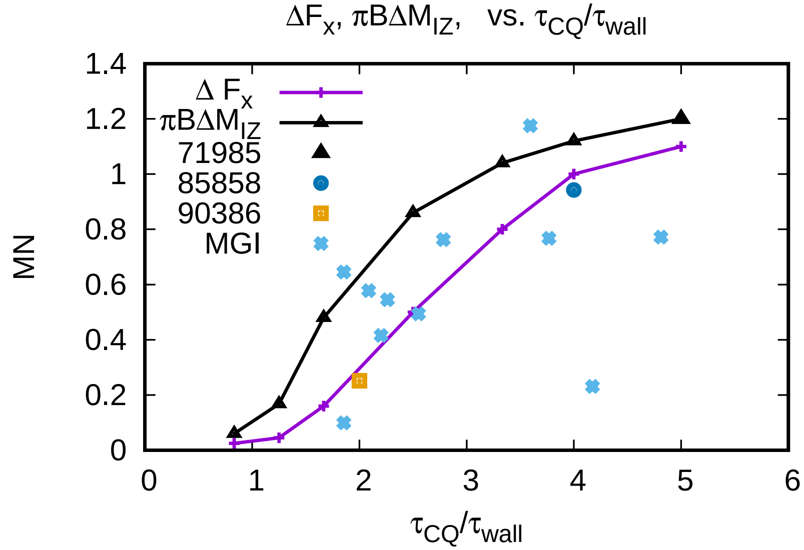
Reduction of asymmetric wall force

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_{CQ}/τ_{wall} was artificially varied. Plots of asymmetric wall force ΔF_x and Noll formula $\Delta F_x \approx \pi B \Delta M_{IZ}$. Highest end of the curves have experimental values τ_{CQ}/τ_{wall}.

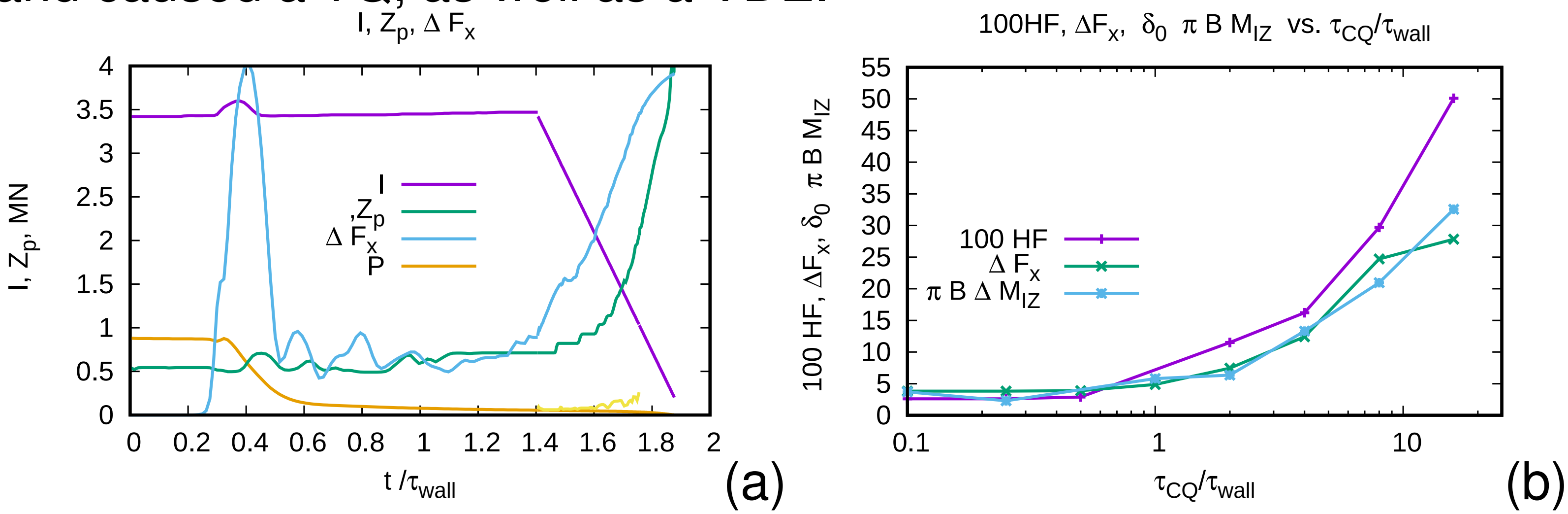
Comparison with data: dots: ΔM_{IZ} and τ_{CQ} calculated for shots 85858 and 90386 in [S. Jachmich, *et al.* , EPS (2016)]

Points "MGI" are all JET shots "VDE+MGI" with ILW, 2011-2016.

τ_{CQ} and ΔM_{IZ} were calculated from the data.

ITER disruption simulations

[Strauss, Phys. Plasmas **25** 020702 (2018)] An ITER inductive scenario 2 15MA initial state was used, with current profile modified to represent MGI mitigation. The current was set to zero outside the $q = 2$ magnetic surface. This made the plasma MHD unstable and caused a TQ, as well as a VDE.



The plasma was evolved at constant current and then decreased linearly.

(a) Time history of I, Z_p, ΔF_x, P in wall time units. Simulation with $\tau_{CQ}/\tau_{wall} = 1/2$

(b) ΔF_x, Noll relation $\pi B \Delta M_{IZ}$, in MN, and halo current fraction $100 \times HF$ as functions of τ_{CQ}/τ_{wall}. **ITER might be in the regime $\tau_{CQ} \sim \tau_{wall}$, so the asymmetric wall force could be small.** **ITER:** $\tau_{wall} = 250ms$, **JET:** $\tau_{wall} = 5ms$.

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Runaway Electrons - Fluid model

MHD simulations were extended by adding RE fluid model. Runaway fluid equations are [Helander 2007],[Cai and Fu 2015]

$$\frac{1}{c}\frac{\partial \psi}{\partial t} = \nabla_{\parallel}\Phi - \eta(J_{\parallel} - J_{\parallel RE}) \quad (1)$$

and $J_{\parallel RE}$ is the RE current density.The RE continuity equation can be expressed, assuming the REs have speed c

$$\frac{\partial J_{\parallel RE}}{\partial t} \approx -c\mathbf{B}\cdot\nabla\left(\frac{J_{\parallel RE}}{B}\right) + S_{RE} \quad (2)$$

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

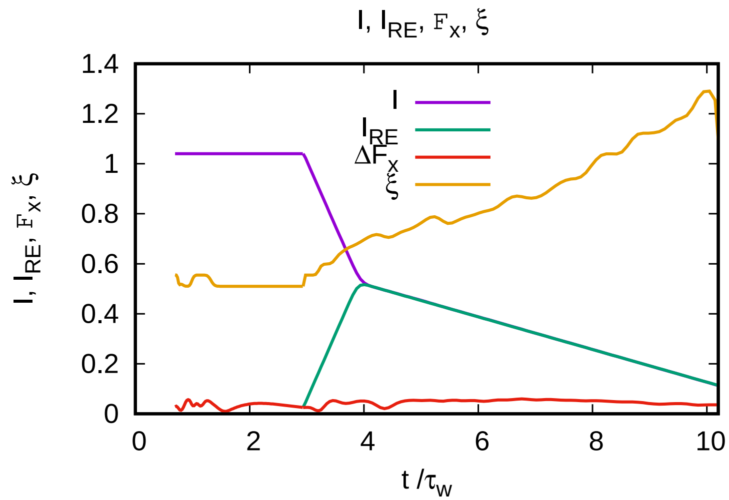
$$S_{RE} = \alpha(t)(J_{\parallel} - J_{\parallel RE})J_{\parallel RE} > 0 \quad (3)$$

Approximately

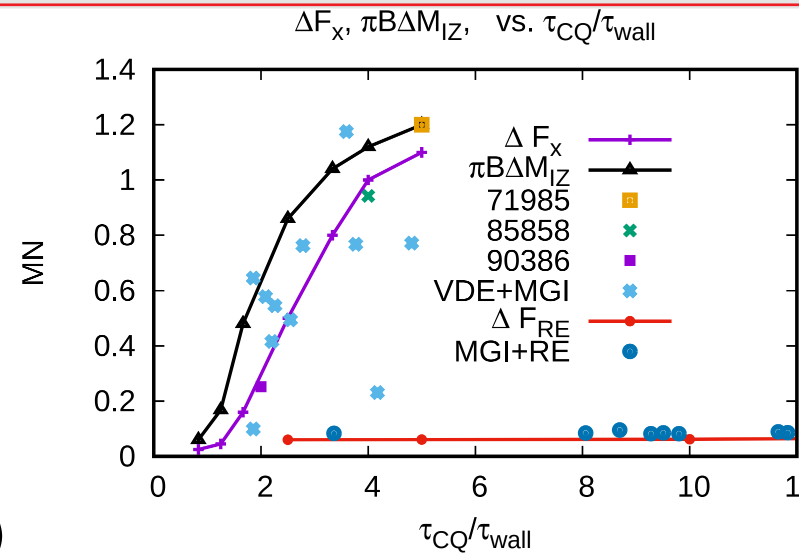
$$\mathbf{B}\cdot\nabla\left(\frac{J_{\parallel RE}}{B}\right) = \mathcal{O}(v_A/c) \approx 0 \quad (4)$$

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

JET RE asymmetric wall force



(a)



(b)

(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 artificially 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) $I_{REmax} = I_{p0}/2$.

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.

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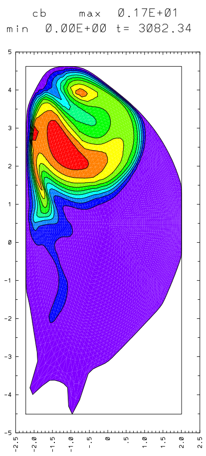
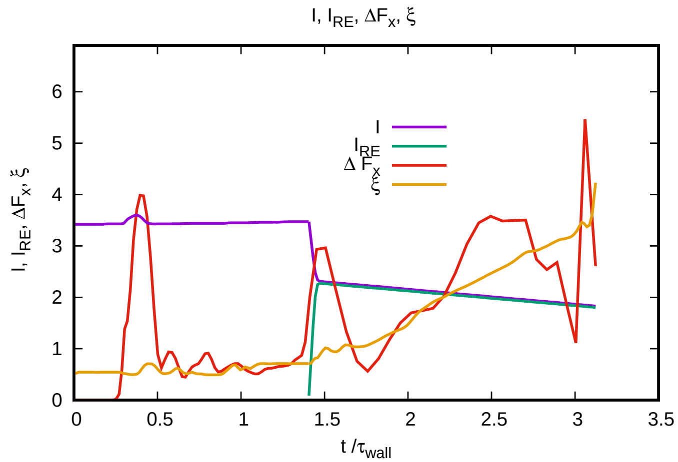
ITER REs

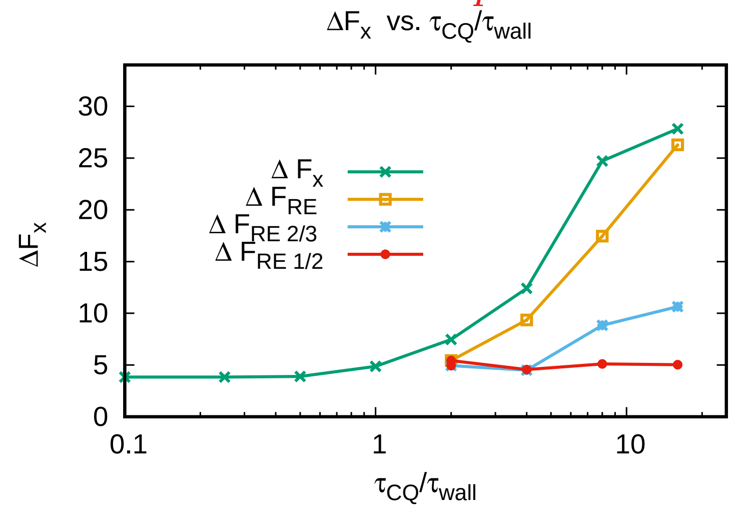
With REs, 2 quantities determine wall force, τ_{CQ}/τ_{wall} and I_{REmax}/I_{p0}.



(d)



(a)



(b)

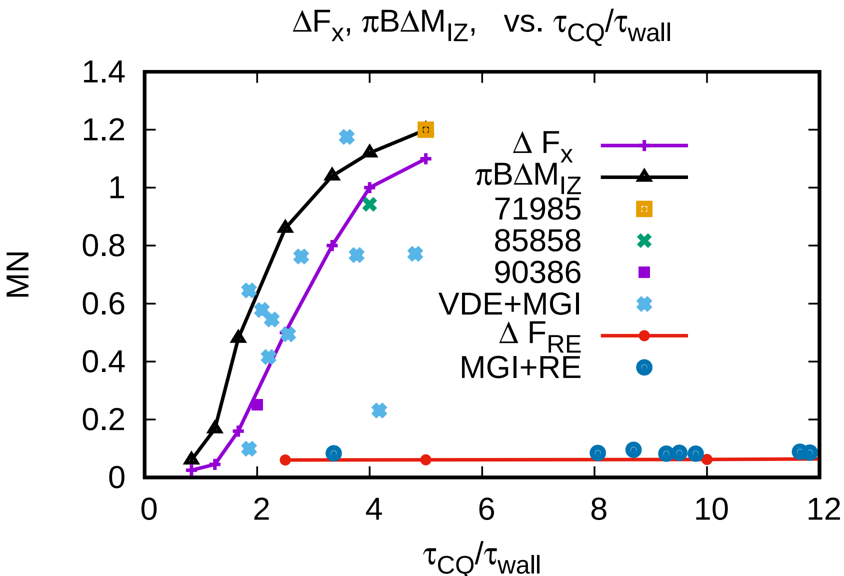
(a) Time history plot of toroidal current I, RE current I_{RE}, ΔF_x, and $\xi = Z_p$. The ratio $I_{REmax}/I_{p0} = 2/3$, and $\tau_{CQ}/\tau_{wall} = 16$.

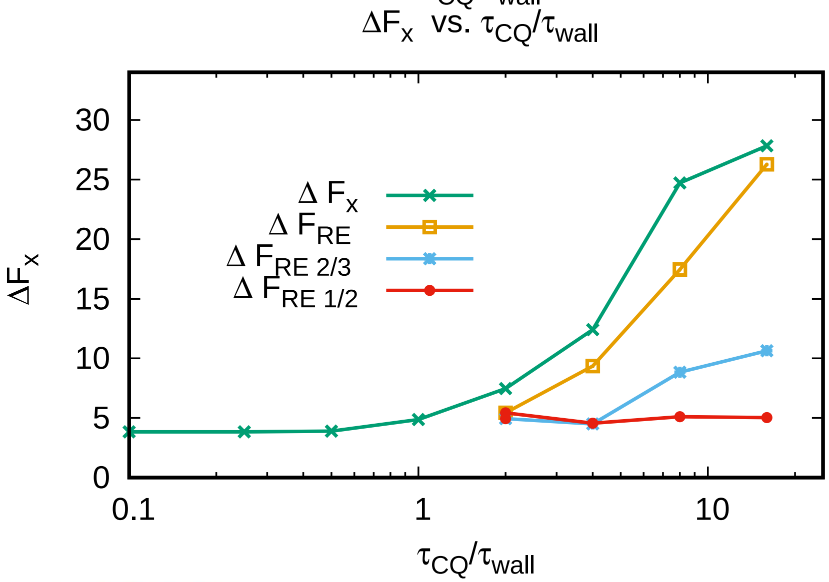
(b) ΔF_x, ΔF_{RE} for $I_{REmax}/I_{p0} = 1, 2/3, 1/2$, as a function of τ_{CQ}/τ_{wall}.

When $I_{REmax}/I_{p0} = 1/2$, the force is small, as in JET with REs.

When $I_{REmax}/I_{p0} = 1$, the force is large when $\tau_{CQ}/\tau_{wall} >> 1$.

Summary





- Simulations of asymmetric wall force with M3D 3D MHD code are consistent with JET data.
- JET asymmetric wall force decreases with ratio of CQ time to resistive wall time, τ_{CQ}/τ_{wall}.
- ITER might be in $\tau_{CQ} \sim \tau_{wall}$ regime, where asymmetric wall force and halo current could be small.
- Runaway electrons (REs) in JET produce small asymmetric wall force even with $\tau_{CQ} >> \tau_{wall}$.
- In ITER, the wall force depends on the ratio of the maximum RE current to initial current. If $I_{RE}/I_{p0} \approx 1$, the force can be large.

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