Thermal quench and asymmetric wall force in ITER disruptions

H. Strauss, HRS Fusion

TSDW

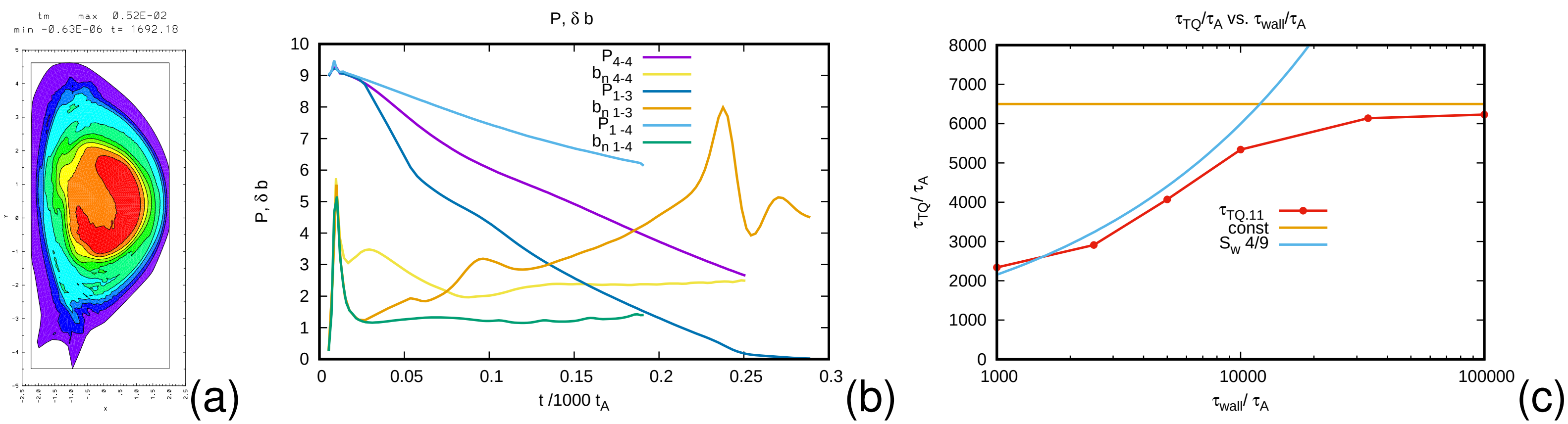
PPPL, August 7, 2019

Outline

The long ITER resitive wall penetration time τ_{wall} can have mitigating effects on TQ, REs, and asymmetric wall force

- Thermal quench
  - TQ time can depend on τ_{wall} because of resistive wall tearimg mode
- Asymmetric wall force depends on $S_{wall} = \tau_{wall}/\tau_A$
  - Cold disruptions : small force when CQ time $\tau_{CQ} \leq \tau_{wall}$
  - Hot disruptions : small force when $S_{wall} >> 100$.
- REs in cold disruptions
  - Runaway electrons can cause large wall force when RE current fraction ≈ 1.
  - Longer TQ time can reduce RE current fraction

Thermal Quench Simulations



Simulations with M3D initialized with ITER [Strauss, PoP 2018] inductive Scenario 2 15 MA with current profile modified to represent MGI mitigation. Current set to zero outside $q = 2$ magnetic surface [Izzo 2008], keeping total current unchanged. Temperature also lowered outside the q =2 surface, increasing the resistivity which varied as $T^{-3/2}$. This made plasma MHD unstable. Parallel thermal conduction assumed with $T_e = 100eV$ at the wall. In the simulations $S = 10^6$ initially on axis.

(a) T at $t = 2163\tau_A$, $S_{wall} = 10^3$.

(b) P history for cases, $S_{wall} = 10^3, 2.5 \times 10^3, 10^4$, showing normal asymmetric magnetic field at the wall b_n as a function of time. As b_n increases in time, P falls more rapidly. (c) normalized TQ time τ_{TQ}/τ_A vs. S_{wall} Fit to $\tau_{TQ} \propto S_{wall}^{4/9}$, suggests a RWTM [Finn, 1995].

Thermal Quench with RWTM

$$\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r(\kappa_{\|} b_r^2 + \kappa_{\perp})\frac{\partial T}{\partial r} \tag{1}$$

where b_r is the normalized asymmetric normal magnetic field, assuming circular flux surfaces for simplicity. Integrating, the total temperature is given by

$$\frac{\partial < T >}{\partial t} = a(\kappa_{\|} b_r^2 + \kappa_{\perp})T' \tag{2}$$

where $< T >= \int Trdr$, $T' = \partial T/\partial r(a)$, $c_1 =< T > /(a^3 T')$.

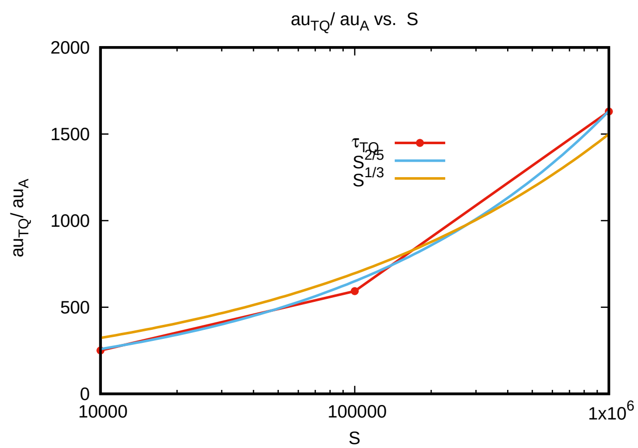
$$\frac{c_1 a^2}{\tau_{TQ}} = \kappa_{\|}[b_0^2 + b_2^2 \exp(\gamma_{RW} t)] + \kappa_{\perp} + \frac{\gamma_{RW}}{k_{\perp}^2} \tag{3}$$

where the last term is quasilinear diffusion, and $\gamma_{RW}\tau_A \propto S^{-1/3} S_{wall}^{-4/9}$. Then obtain the *ad hoc* formula

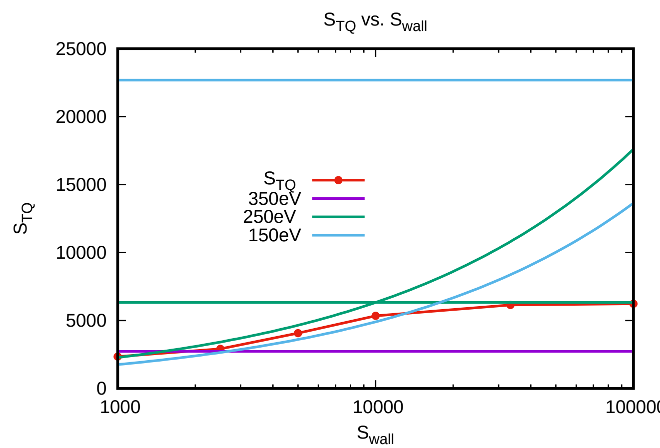
$$\tau_{TQ} \approx \frac{c_1 \tau_A}{c_0 S^{-1/3} S_{wall}^{-4/9} + \widehat{\kappa}_{\perp} + \widehat{\kappa}_{\|} b_0^2} \tag{4}$$

where $\widehat{\kappa}_{\|} = \kappa_{\|}/(a^2\tau_A)$, $\widehat{\kappa}_{\perp} = \kappa_{\perp}/(a^2\tau_A)$, with $c_0 = \mathcal{O}(1)$.

TQ Timescales



(a)



(b)

(a) τ_{TQ} for cases with $S = 10^4, 10^5, 10^6$, with $S_{wall} = 10^4, \hat{\kappa}_{\|} = 10, \hat{\kappa}_{\perp} = 10^{-4}$. The scaling is $S_{TQ} \approx S^{1/3}$. This gives $S_{TQ} = \tau_{TQ}/\tau_A = 0.7 S_w^{4/9} S^{1/3}$.

(b) effect of varying T_e on $\kappa_{\|}$ and S_{TQ}.

$t_{TQ} \approx 1/(\hat{\kappa}_{\|} b_0^2) \approx 10^4 \tau_A = 10ms$, $b_0 \approx 3 \times 10^{-3}$, $T_e \approx 100eV$.

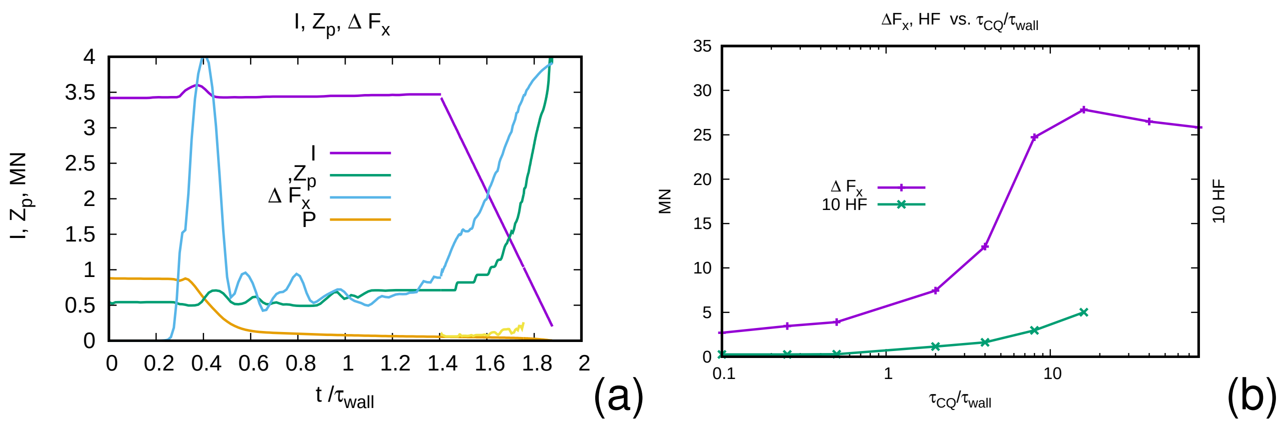
If $c_0 \approx 1/3, S = S_{wall} = 10^4$, then $t_{TQ} \approx S^{1/3} S_{wall}^{4/9} \approx 2ms$.

If TQ time is due to RWTMs, then $\tau_{TQ} \propto S_{wall}^{4/9}$ is about 6 times longer in ITER than in JET.

This could reduce thermal loading and RE generation.

ITER cold disruptions - asymmetric wall force

- cold disruptions - TQ precedes VDE and CQ. ΔF_x depends on τ_{CQ}/τ_{wall}. For expected ITER $\tau_{CQ}/\tau_{wall} < 1$ $\Delta F_x \approx 5MN$.

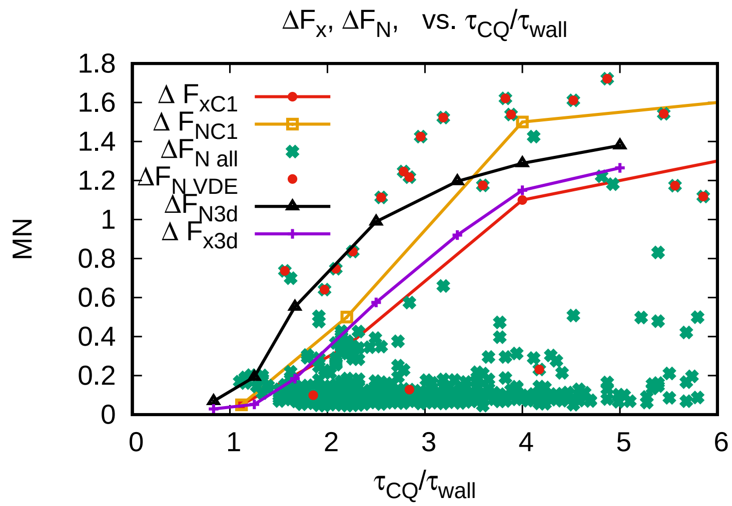


(a) Time history of I, Z_p, $\Delta F_x, P$ in wall time units [Strauss, 2018]. Simulation with $\tau_{CQ}/\tau_{wall} = 1/2$

(b) ΔF_x vs. τ_{CQ}/τ_{wall} with $\Delta F_x < 30MN$. Also shown is halo fraction HF.

Sideways wall force in JET disruptions

Simulations were done with M3D and recently with M3DC1 codes. The runs were initialized with a reconstruction of JET shot 71985. The current quench time τ_{CQ} was controlled by an applied electric field. The wall force is quenched for $\tau_{CQ} \leq \tau_{wall}$.

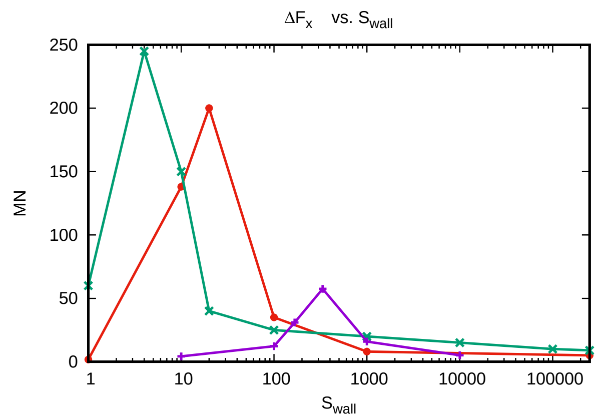


Solid curves: M3D and M3DC1 simulations where τ_{CQ}/τ_{wall} was varied. Plots of asymmetric wall force ΔF_x and Noll force $\Delta F_N = \pi B \Delta M_{IZ}$. ΔF_{xC1}, M3DC1 wall force, ΔF_{NC1}, M3DC1 Noll force, ΔF_{xm3}, M3D wall force, ΔF_{Nm3}, M3D Noll force.

Comparison with data: dots: ΔF_N and τ_{CQ} calculated for all JET shots in ILW disruption database, 2011 - 2016, labeled ΔF_{NJET}. Points "VDE" are VDE shots, and all shots. (JET Data discussed with E. Joffrin and S. Gerasimov and presented at ITPA meeting, Daejeong, Korea, April 2019)

ITER hot disruptions

- hot disruptions - VDE precedes TQ and CQ ΔF_x is maximum for $\gamma\tau_{wall} \sim 1$. In ITER $\gamma\tau_{wall} >> 1$ and ΔF_x is small.



asymmetric force in hot disruption simulations [Strauss *et al.* NF 2013] with $\Delta F_x < 60MN$. VDE caused plasma and flux to scrape off at the wall, until the edge $q \approx 2$. Also shown are "extra - hot" disruption with $\Delta F_x < 200, 250MN$. ΔF_x vs. S_{wall}. They were produced with 2D VDE of model MGI equilibria, then evolving in 3D.

For ITER relevant S_{wall} the force is small, unless there are REs with $\tau_{CQ} >> \tau_{wall}$

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]

$$\frac{1}{c}\frac{\partial \psi}{\partial t} = \nabla_{\parallel}\Phi - \eta(J_{\parallel} - J_{\parallel RE}) \tag{5}$$

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

assuming the REs have speed c

$$\frac{\partial J_{\parallel RE}}{\partial t} \approx -c\mathbf{B} \cdot \nabla \left(\frac{J_{\parallel RE}}{B}\right) + S_{RE} \tag{6}$$

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

$$S_{RE} = \alpha(t)(J_{\parallel} - J_{\parallel RE})J_{\parallel RE} > 0 \tag{7}$$

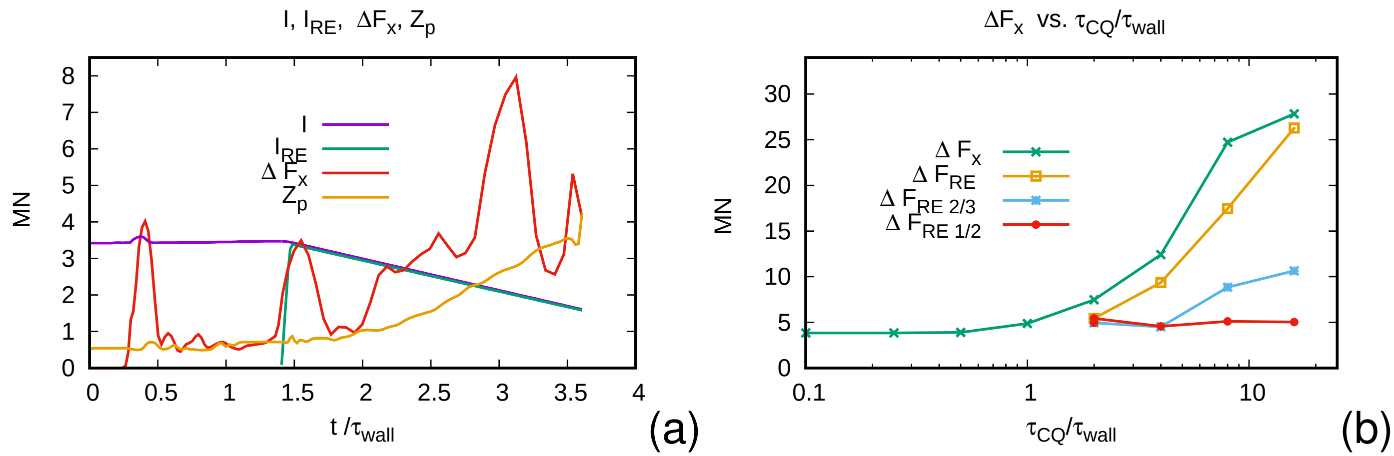
Approximately

$$\mathbf{B} \cdot \nabla \left(\frac{J_{\parallel RE}}{B}\right) = \mathcal{O}(v_A/c) \approx 0 \tag{8}$$

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

ITER REs

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



(a) ΔF_x, I, I_{RE}, and Z_p as functions of time t/τ_{wall}, for $I_{RE} = I_0$. (b) ΔF_x as a function of τ_{CQ}/τ_{wall}. Also shown are ΔF_{REa}, where $a = 1, 2/3, 1/2$. The wall force depends on the ratio of RE current to initial current.

If $I_{RE}/I_0 \leq 1/2$, the force is small.

If $I_{RE}/I_0 = 1$, the force is the same as having a long CQ time.

Summary

- **Long ITER τ_{wall} has a mitigating effect on disruptions**
- TQ time can depend on RWTM. In ITER, TQ time might be 10ms.
  - reduce thermal load rate
  - reduce RE generation rate
- ITER asymmetric wall force is small in cold and hot disruptions
  - cold disruptions - TQ precedes VDE. Force is small for $\tau_{CQ} \leq \tau_{wall}$.
  - hot disruptions - VDE precedes TQ, CQ. Force is small for $\gamma\tau_{wall} >> 1$
- REs
  - can affect cold disruptions, probably not relevant in hot disruptions
  - If ratio of RE current to initial current, $I_{RE}/I_{p0} \approx 1$, the force can be large.