Thermal Quench in DIII-D locked mode disruptions

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Second Technical Meeting on Plasma Disruptions and their Mitigation

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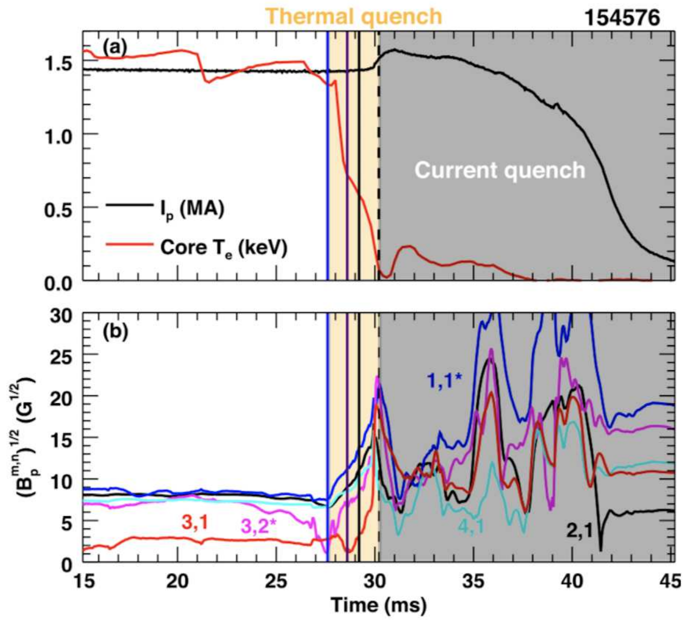
Introduction and Overview

- It is important to know what mode causes disruptions, to mitigate effectively. “Can’t cure illness without a diagnosis”
- Recently JET and ITER data, theory, linear and nonlinear simulations identified cause of locked mode disruption as resistive wall tearing mode (RWTM). [Strauss *et al.* Phys, Plas. 28, 032501 (2021)], [Strauss Phys. Plas. 28 072507 (2021)]
- DIII-D data, theory, linear and nonlinear simulations confirm locked mode disruption is RWTM [Strauss, Lyons, & Knolker arXiv (2022)]
- onset requires $q = 2$ surface sufficiently close to plasma edge.
- DIII-D RWTM has a more favorable scaling with resistive wall penetration time τ_{wall} than JET
- ITER TQ time could be $\approx 100ms$.

DIIID locked mode disruption

Locked mode: toroidal rotation slows, destabilizing TMs, the disruption precursor.



DIII-D shot 154576, [Strauss *et al.* 2022, Sweeney *et al.* 2018] TQ time $\tau_{TQ} = .5\tau_{wall} = 2.5ms = 1/\gamma$, where γ is mode growth rate. and $\tau_{wall} = 5ms$.

Suggests RWM or resistive wall tearing mode (RWTM) causes TQ.

Linear resistive wall tearing mode theory

The RWTM dispersion relation is [Finn 1995,Strauss 2021]

$$\hat{\gamma}^{5/4} S^{3/4} = \Delta_i + \frac{\Delta_x}{\hat{\gamma} S_w + 1} \tag{1}$$

where $\hat{\gamma} = \gamma\tau_A$, $S_w = S_{wall}/(2m)$, $S_{wall} = \tau_{wall}/\tau_A$, internal drive $\Delta_i = r_s\Delta'_w/m$, external drive $\Delta_x = 2x^{2m}/(1 - x^{2m})$, $x = (r_s/r_w)$, poloidal mode number m, rational surface radius r_s, wall minor radius r_w.

Eq. (1) includes ideal wall ($S_w = \infty$) and no wall tearing modes ($S_w = 0$)

$$\hat{\gamma} = (\Delta_i + \Delta_x)^{4/5} S^{-3/5} \tag{2}$$

The RWTM growth rate scalings can be approximated from (1). If $\Delta_i = 0$, then assuming $\hat{\gamma} S_w \gg 1$

$$\hat{\gamma} = \Delta_x^{4/9} S^{-1/3} S_w^{-4/9} \tag{3}$$

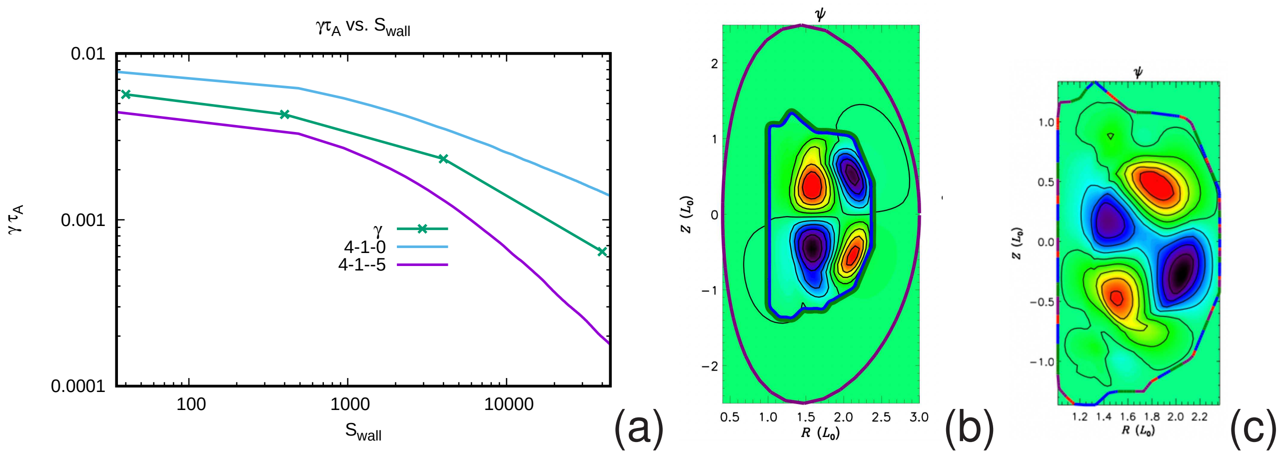
If $\Delta_i < 0$ and $\Delta_i + \Delta_x > 0$, then neglecting the left side of (1) gives a kind of RWM with rational surface in the plasma,

$$\hat{\gamma} = -(1 + \Delta_x/\Delta_i) S_w^{-1}. \tag{4}$$

Crossover from (3) to (4) is for $\Delta_i < -\Delta_x/(1 + S^{-1/3} S_{wall}^{5/9}) \approx -(1/4)\Delta_x$.

If $\Delta_i + \Delta_x < 0$ there are no unstable solutions of (1).

Linear M3D-C1 resistive wall simulations of DIIID 154576



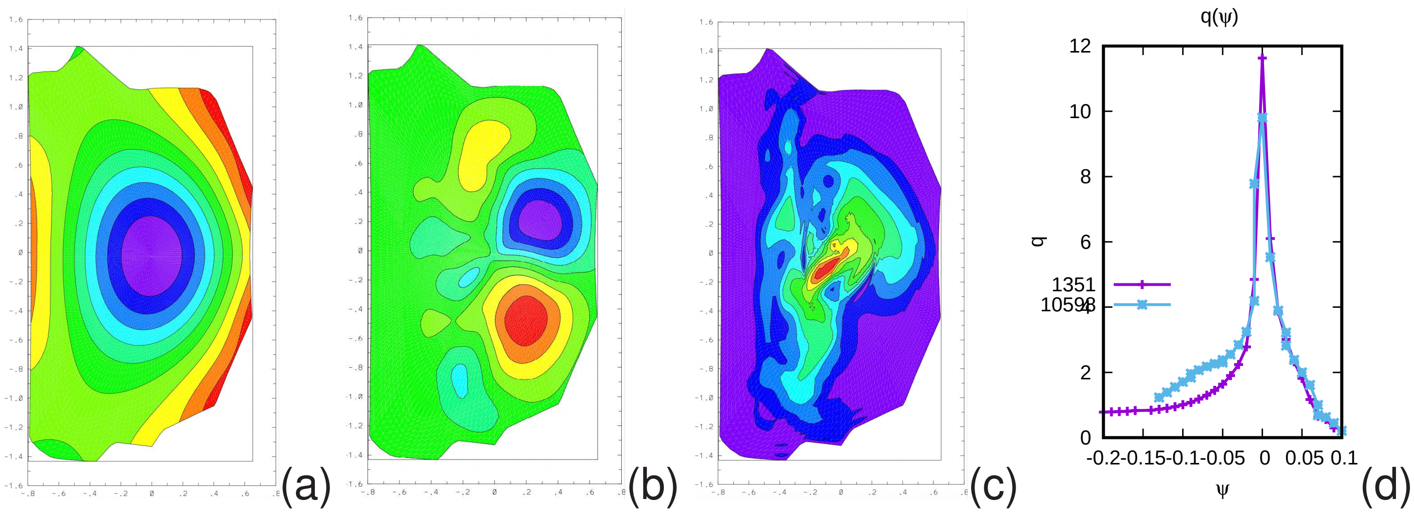
EFIT reconstruction (a) $\gamma\tau_A$ in DIIID shot 154576 as a function of S_{wall} from M3D-C1 linear simulations. The fits are to RWTMs with $\Delta_x = 1, \Delta_i = 0$, and $\Delta_x = 1, \Delta_i = -0.5$. The $S_{wall} = 0$ limits are no wall tearing modes which are stable with an ideal wall.

(b) perturbed ψ in (a). The mode is $(2, 1)$ and penetrates the resistive wall.

(c) ideal wall. The mode is stable. It is not an ideal wall tearing mode.

Nonlinear simulation of DIII-D 154576

In M3D simulation, nonlinearly RWTM grows to large amplitude and causes TQ.



(a) initial ψ of DIII-D 154576 (b) perturbed ψ at $t = 5690\tau_A$, $S_{wall} = 10^4$. (c) p at $t = 5690\tau_A$. when P is about 20% of its initial value. (d) q profiles, initially and at time after (c).

The reason mode grows to large amplitude may be external drive. Internal drive depends on current profile. Growth of an island flattens the current and stabilizes the mode at a moderate island width.

External drive Δ_x depends only on r_s/r_w, independent of island size. The $q = 2$ surface is driven to the origin.

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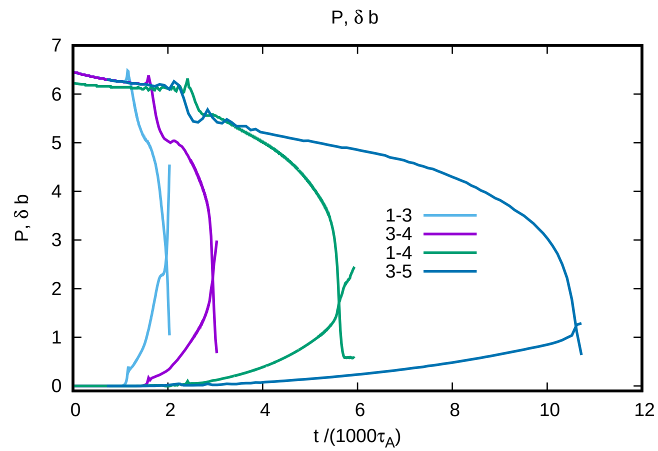
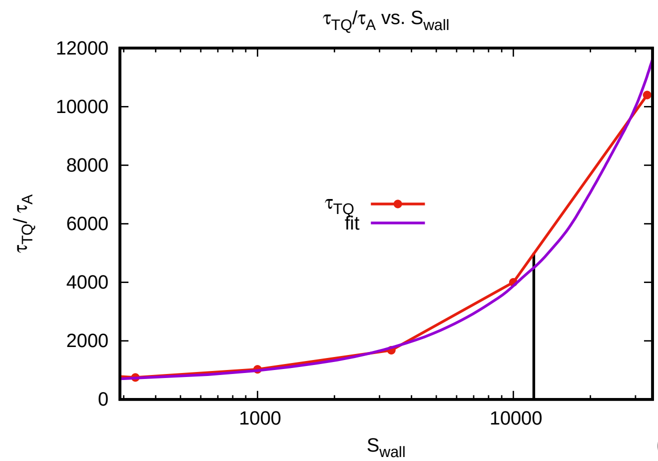


(a)



(b)

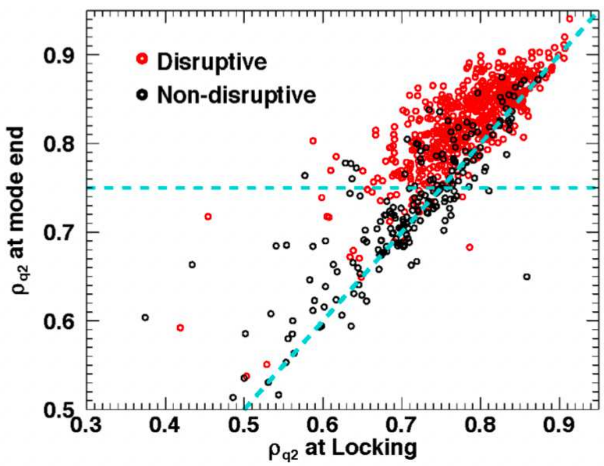
(a) time histories of P and b_n in M3D simulations of DIII-D 154576, where P is total pressure, b_n is perturbed normal $\delta B/B$ at the wall. The labels indicate the value of S_{wall} where $1-3$, $3-4$ $\ldots$ denote $S_{wall}^{-1} = 10^3, 3\times 10^4, 10^4, 3\times 10^5$. (b) TQ time τ_{TQ} measured from the time histories. The fit is to an RWTM with $\Delta_x = 1$, $\Delta_i = -.5$. The vertical line is the experimental value of S_{wall}. At the vertical line $\tau_{TQ} \approx 0.5 S_{wall}\tau_A = .5\tau_{wall}$, as in the experimental data.

Onset condition for RWTM

The onset condition is that the $q = 2$ surface is close enough to the plasma edge. In flat current model [Furth, Rutherford, Selberg (1973), Finn (1995)] with $(2, 1)$ For $\Delta_i < 0$ requires

$$x = r_s/r_w > [(4/q_0^2)(q_0 - 1)]^{1/4} \tag{5}$$

For example, if $q_0 = 1.04$ then $x > 0.62$.



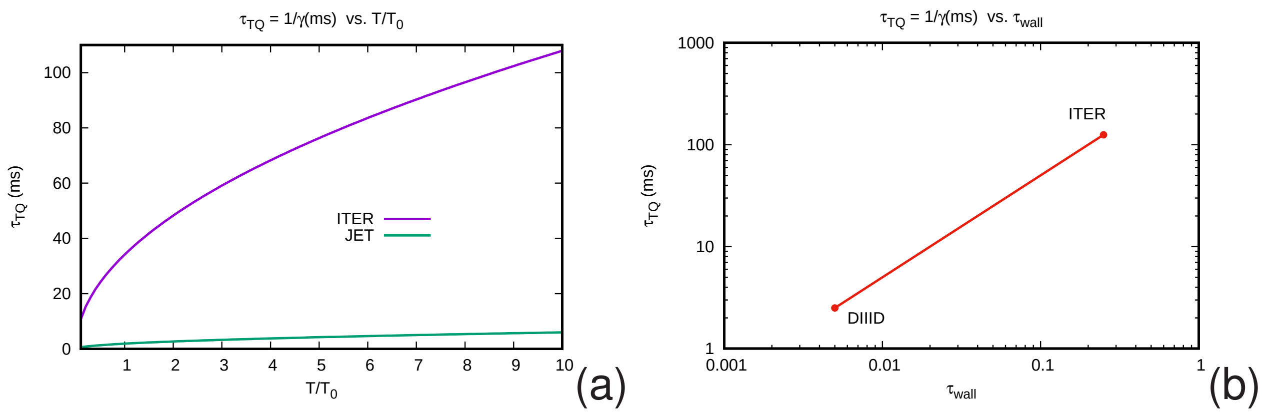
Disruption occurrence depends on ρ_{q2} in DIII-D for initially rotating locked modes [Sweeney *et al.* (2017)], where $x = \rho_{q2}(r_{sep}/r_w) \approx \rho_{q2}/1.2$. The stability boundary is $x \approx 0.75/1.2 = 0.625$. The equilibrium reconstruction of DIII-D 154576 has $x = 0.67$.

The value of x increases as disruption is approached.

How did DIII-D get past the $\Delta_i = 0$ onset condition? Perhaps residual rotation.

Application to ITER

τ_{wall} : ITER $250ms$, JET, DIII-D $5ms$.



(a) $\tau_{TQ} = 1/\gamma$ for JET, ITER as function of T/(100eV), $\tau_{TQ} \propto T^{1/2}$ assuming RWTM $\sim \tau_{wall}^{-4/9}$. (b) $\tau_{TQ} = \tau_{wall}/2$ for ITER, DIII-D as function of τ_{wall} for RWTM with DIII-D RWM scaling.

If ITER TQ is RWM with $\gamma = 2/\tau_{wall}$, or with $\gamma \propto S_{wall}^{-4/9}$ and $T_{edge} \approx 1KeV$, then $\tau_{TQ} \approx 100ms$.

ITER might not need any extra mitigation. No runaway electrons. Acceptable heat flux.

Summary

- DIII-D data, theory, linear and nonlinear simulations find locked mode disruption is caused by RWTM
- onset requires $q = 2$ surface sufficiently close to plasma edge.
- DIII-D has a more favorable scaling than JET, because RWTM is somewhat above the onset condition.
- ITER TQ time could be $100ms$. Might not need any mitigation.
- Future work - MST - an RFP operated as a tokamak which has no disruptions, even with $q_a < 2$, $\tau_{wall} = 800ms$. [Hurst, Chapman, *et al.* Phys. Plas. *submitted* (2022)] Suggests ideal wall prevents disruptions.