Slow thermal quench in ITER disruptions

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Introduction

Disruptions are loss of plasma confinement in tokamaks, which could damage large tokamaks like ITER. The thermal flux in an ITER disruption would be intolerable if it occured on a *ms* timescale typical of present tokamaks. Until recently, the instability which caused locked mode disruptions was not known. Recent work identified the thermal quench in JET locked mode disruptions with a resistive wall tearing mode (RWTM) [1]. The RWTM was also predicted in ITER [2]. It produces a slow self mitigated thermal quench. New research finds a similar instability in a DIII-D locked mode shot. 154576 [3, 4]. The instability is studied with simulations, theory, and comparison to experimental data. Linear theory is extended to include resistive wall modes with a rational surface in the plasma. Linear simulations show the mode is stable for an ideal wall, and unstable with a resistive wall. Nonlinear simulations show that the mode grows to large amplitude, causing a thermal quench. The mode onset occurs when the radius of the $q = 2$ rational surface is sufficiently close to the plasma edge. These results are important for ITER, greatly mitigating the effects of disruptions. The thermal flux during an ITER disruption could reduced by two orders of magnitude, greatly limiting the requirements for mitigation.

Main results

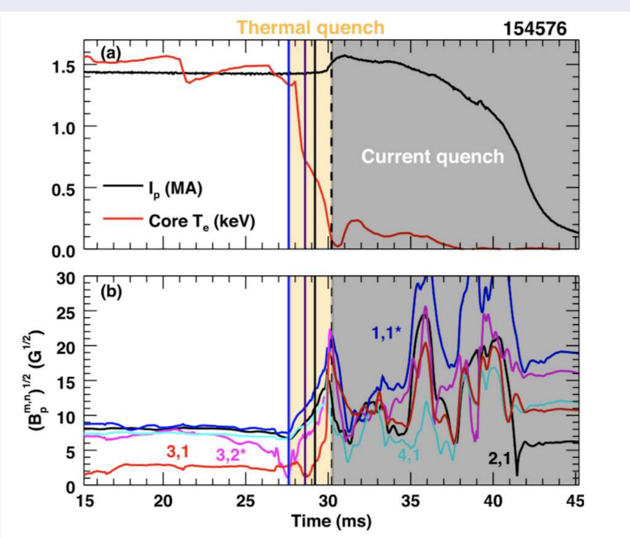
- DIII-D data, theory, linear and nonlinear simulations identify locked mode DIII-D disruption with resistive wall tearing mode.
- DIII-D shot 154576 has thermal quench time $2.5ms = 1/2\tau_{wall}$ TQ time and $n = 1$ magnetic signal time γ^{-1} are equal.
- RWTM occurs when ideal wall tearing mode is stable
- onset condition is that $q = 2$ surface is sufficiently close to plasma edge.
- RWTM in JET has $\gamma \propto \tau_{wall}^{-4/9}$.
- RWTM in DIII-D has $\gamma \propto \tau_{wall}^{-1}$
- RWTM grows to large amplitude nonlinearly
- ITER TQ time could be $\sim 100ms$.

Outline

1. Experimental data on locked mode disruptions in DIII-D
2. Linear theory and simulations of resistive wall tearing mode
3. Nonlinear simulations of resistive wall tearing mode
4. Onset condition for disruptions
5. Application to ITER

DIII-D locked mode disruption

Locked mode: toroidal rotation slows, destabilizing tearing modes (TMs), which are the disruption precursor.



DIII-D shot 154576 [3, **?**], with TQ time $\tau_{TQ} = .5\tau_{wall} = 2.5ms = 1/\gamma$, where γ is mode growth rate. and $\tau_{wall} = 5ms$, where τ_{wall} is the resistive wall penetration time. Suggests RWM or resistive wall tearing mode (RWTM) causes TQ. /it Figure reprinted from [4] with IAEA permission.

Linear theory of RWTM

The RWTM dispersion relation is [1, 9]

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

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 $\Delta_x = 2x/(1-x)$, $x = (r_s/r_w)^{2m}$, poloidal mode number m, rational surface radius r_s, wall minor radius r_w. Includes ideal and no wall tearing modes ($S_w = 0$)

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

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

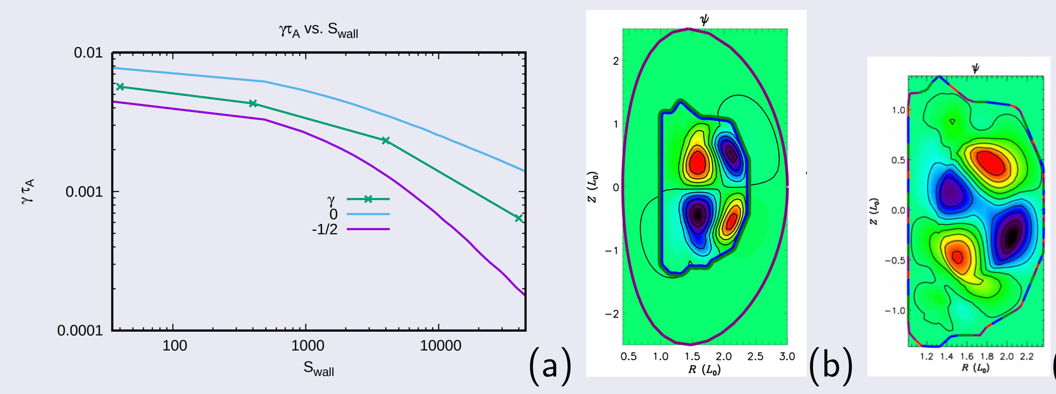
$$\hat{\gamma} = \Delta_x^{4/9} S^{-1/3} S_w^{-4/9} \quad (3)$$

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,

$$\hat{\gamma} = -\left(1 + \frac{\Delta_x}{\Delta_i}\right) S_w^{-1}. \quad (4)$$

If $\Delta_i + \Delta_x < 0$ there are no unstable solutions of (1). Intermediate asymptotic scalings of $\hat{\gamma}$ are possible depending on the ratio Δ_i/Δ_x.

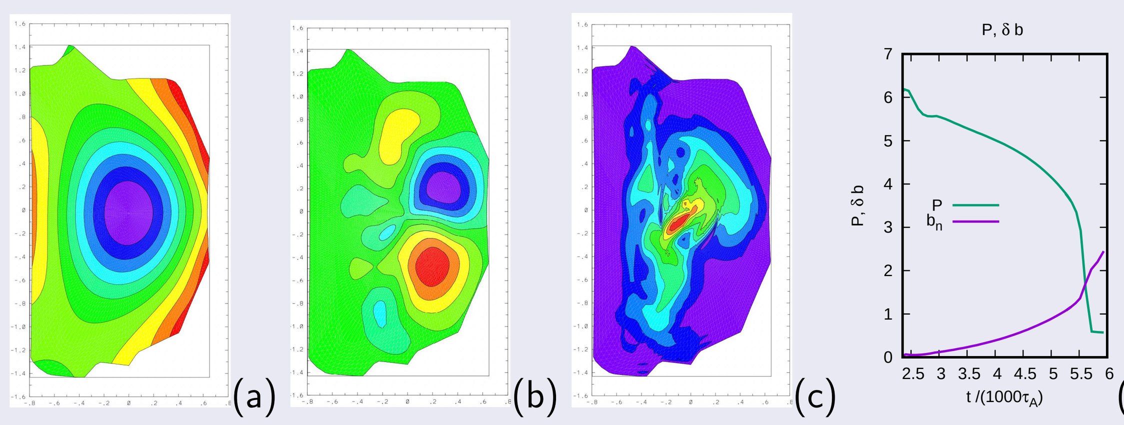
Linear simulations of DIII-D



EFIT reconstruction with $q > 1$ to avoid $(1, 1)$ mode. (a) $\gamma\tau_A$ in DIIID shot 154576 as a function of S_{wall} from M3D-C1 [5] with resistive wall [6] linear simulations. The fits are to RWTMs with $S_{wall}^{-4/9}$ asymptotic scaling, and S_{wall}^{-} asymptotic scaling. 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 DIII-D simulations

In M3D [7] with resistive wall [8] simulations, nonlinearly RWTM grows to large amplitude and causes TQ.



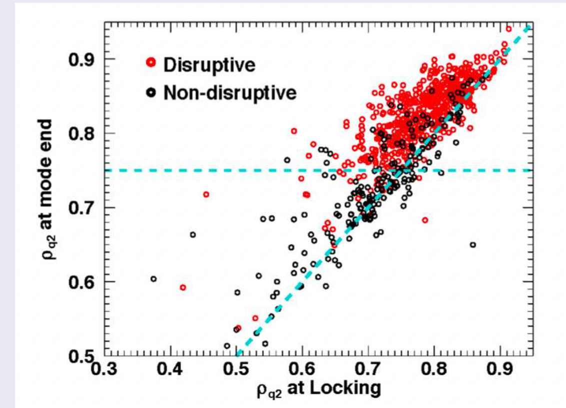
(a) initial ψ of DIII-D 154576. (b) perturbed ψ at $t = 5690\tau_A$, $S_{wall} = 10^4$. (c) pressure p at $t = 5690\tau_A$, when volume integrated pressure P is about 20% of its initial value. (d) Time history of P and normal magnetic perturbation at the wall b_n.
The reason mode grows to large amplitude 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.

Onset condition of RWTM

The onset condition is that the $q = 2$ surface is close enough to the plasma edge. In flat current equilibrium model [9] with $(2, 1)$, $\Delta_i < 0$ requires

$$x^4 > (4/q_0^2)(q_0 - 1). \quad (5)$$

For example, if $q_0 = 1.008$ then $x \geq 0.625$ for $\Delta_i \leq 0$.

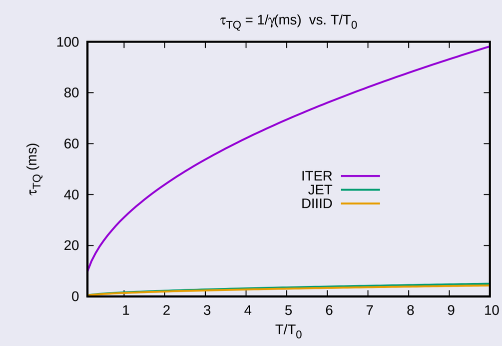


Disruption occurrence depends on $q = 2$ radius normalized to plasma radius ρ_{q2} in DIII-D for initially rotating locked modes [10], where $x = \rho_{q2}(r_{sep}/r_w) \approx \rho_{q2}/1.2$. The stability boundary is $x \approx 0.75/1.2 = 0.625$. This is the onset condition for RWTM. The equilibrium reconstruction of DIII-D 154576 has $\rho_{q2} = 0.8$.

The value of ρ_{q2} increases to a crtical value as disruption is approached. /it Figure reproduced from [10] with IAEA permission.

Implications for ITER

ITER $\tau_{wall} = 250ms$



$1/\gamma$ for ITER, JET, DIII-D as function of $T/(100eV)$, $\tau_{TQ} \propto T^{1/2}$ If $\tau_{TQ} = 1/\gamma$,
in ITER with $T \approx 500eV$, $\tau_{TQ} = 70ms$.
in JET with $T \approx 100eV$, $\tau_{TQ} = 1.5ms$.
in D3D with $T \approx 300eV$, $\tau_{TQ} = 2.5ms$.

If ITER TQ is RWTM with with $\gamma = 2/\tau_{wall}$, then $\tau_{TQ} = 125ms$.

Summary

- DIII-D data, theory, linear and nonlinear simulations identify locked mode disruption with resistive wall tearing mode.
- onset condition is that $q = 2$ surface is sufficiently close to plasma edge.
- ITER TQ time could be $100ms$, 50 times longer than in JET and DIII-D.

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