Thermal quench in JET and DIII-D disruptions

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Outline

1. Experimental data on locked mode disruptions in JET and DIII-D

2. Linear theory and M3D-C1 simulations of resistive wall tearing mode (external drive, wall time dependence)

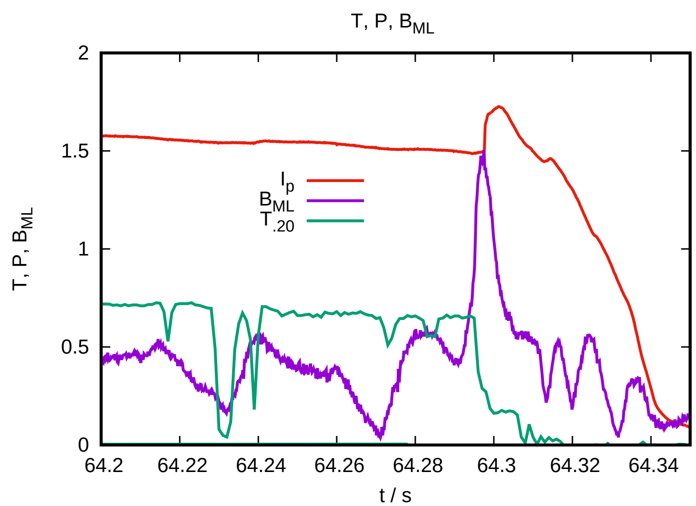
3. Nonlinear simulations of resistive wall tearing mode (large enough amplitude to cause thermal quench, external drive)

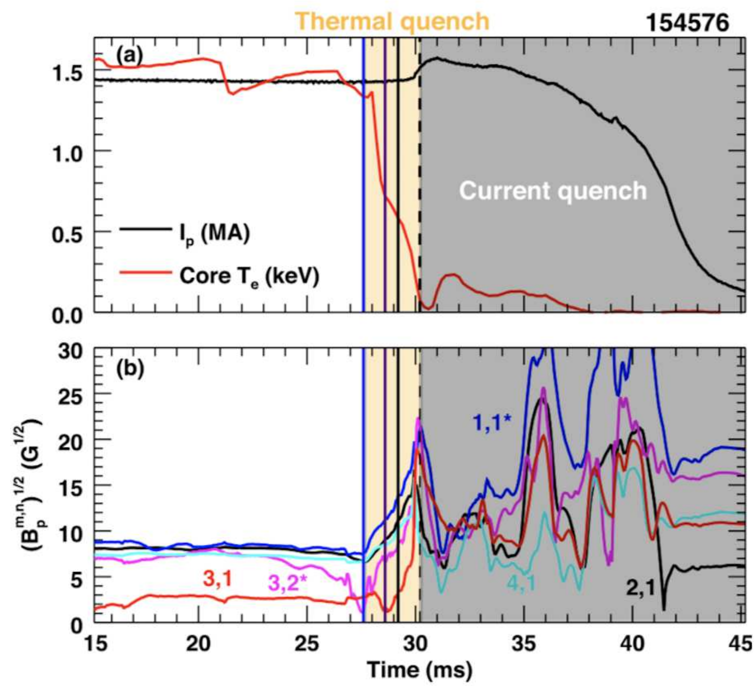
4. Explanations of thermal quench in locked mode disruptions

5. Summary and conclusions

JET and DIIID locked mode disruption

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





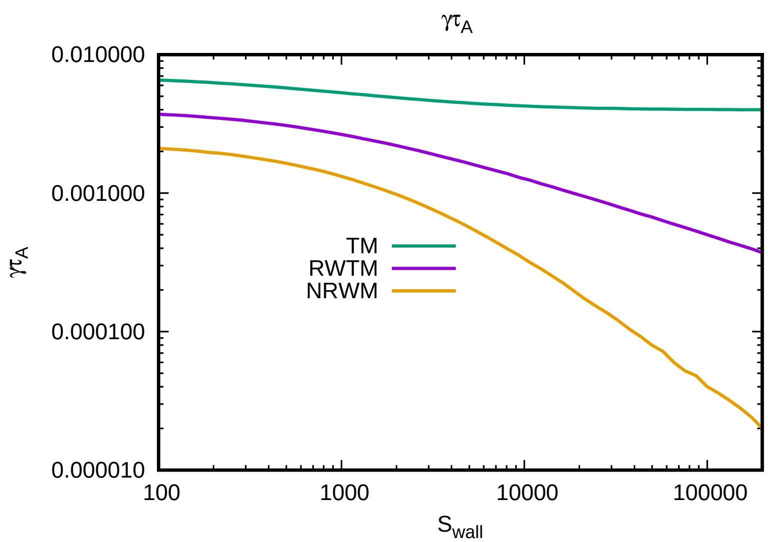
JET shot 81540, showing time histories of (a) plasma current $I_p(MA)$, $B_{ML}(mT)$, $T_e(KeV)$ at $r = 0.2a$. [Strauss,2021] TQ time $\tau_{TQ} = 1/\gamma$, where γ is mode growth rate. The TQ time $\tau_{TQ} \approx .3\tau_{wall}$, where $\tau_{wall} = 5ms$. Locked mode DIII-D disruption, shot 154576 [Sweeney *et al.*NF 2018]. $\tau_{TQ} \approx .5\tau_{wall}$, $\tau_{wall} = 5ms$. (Simulations with ideal wall did not find TQ.)

Linear resistive wall tearing mode theory

The RWTM dispersion relation is [Finn95,Strauss2021]

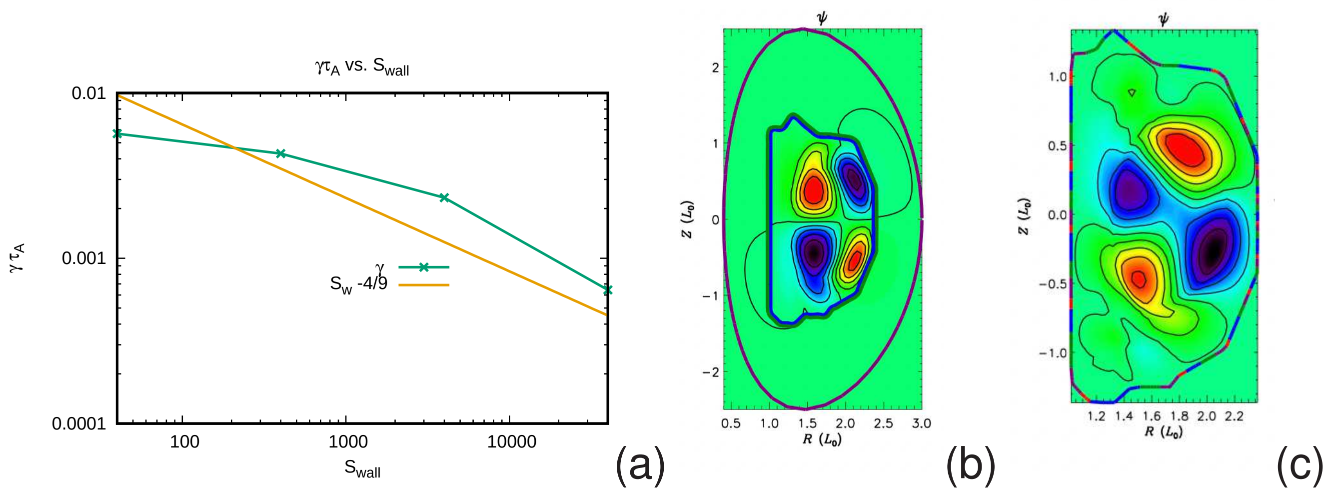
$$\hat{\gamma}^{5/4} S^{3/4} = \Delta_1 + \frac{\Delta_0}{\hat{\gamma} S_w + 1} \tag{1}$$

where $\hat{\gamma} = \gamma \tau_A$, $S_w = \tau_{wall}/\tau_A$, internal drive $\Delta_1 = r_s \Delta'_w/m$, external drive $\Delta_0 = 2x/(1-x)$, $x = (r_s/r_w)^{2m}$, poloidal mode number m, rational surface radius r_s, wall minor radius r_w,



Solutions of (1) with $\Delta_0 = 1$,
TM : $\Delta_1 > 0$.
RWTM: $\Delta_1 = 0$, $\gamma \propto S_{wall}^{-4/9}$
NRWM: $0 > \Delta_1 > -\Delta_0 > 0$. $\gamma \propto S_{wall}^{-1}$
(neo RWM) If $\Delta_0 + \Delta_1 \leq 0$, there are no unstable solutions of (1).

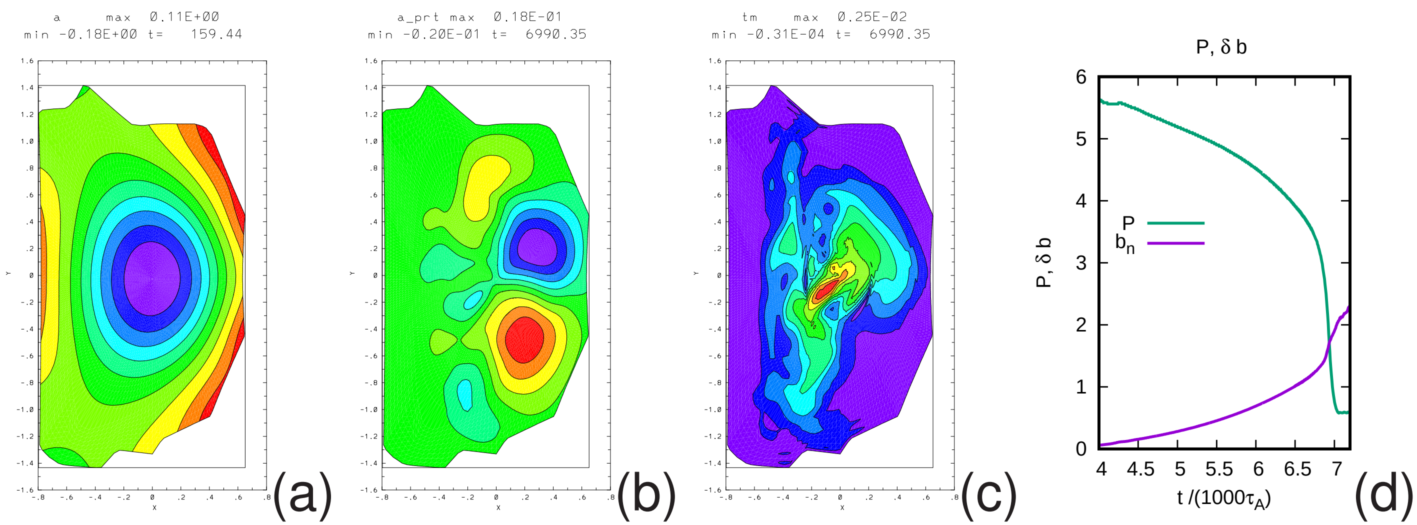
Linear M3D-C1 resistive wall simulations of DIIID 154576



EFIT reconstruction (M. Knolker) with $q > 1$ to avoid $(1, 1)$ mode. (Nonlinearly not a problem, will saturate.) (a) $\gamma\tau_A$ in DIIID shot 154576 as a function of S_{wall} from M3D-C1 linear simulations. $\tau_{wall} = d_{wall} r_{wall}/\eta_{wall}$. (b) perturbed ψ in (a). The mode is $(2, 1)$ and penetrates the resistive wall. (c) ideal wall. The mode is stable.

Nonlinear simulations of DIII-D 154576

Simulations with M3D-C1 in progress. In M3D simulation, nonlinearly RWTM grows to large amplitude and causes TQ.



(a) initial ψ of DIII-D 154576 (b) perturbed ψ at $t = 6990\tau_A$, $S_{wall} = 10^4$. (c) p at $t = 6990\tau_A$. (d) total pressure P and magnetic perturbation b_n.

The reason mode grows to large amplitude may be external drive. Internal drive depends on current profile. Locally $\Delta' \propto J'_\phi$. Growth of an island stabilizes the mode at a moderate island width.

External drive Δ_0 depends only on r_s/r_w, independent of island size.

Possible causes of disruption

• RWTM

Other mechanisms –

• Stochasticity: the precursor causes stochastic edge region [Ward & Wesson 1992], [Sweeney 2018] Precursor time $>> 10ms$. To get TQ time $\sim 1.0ms$, need a larger $\delta B/B$. (like RWTM)

• NTM? low β, low bootstrap current, timescale wrong. Tearing like modes in DIII-D ITER like discharges [Turco 2010] not correlated with β_N or bootstrap current.

• Edge impurities? slow influx destabilizes TMs [Pucella 2001], precursor

Fast influx (like MGI) causes MHD instability [Izzo, 2006] with $\gamma \sim \tau_A^{-1}$.

[Ward & Wesson 1992] rapid MHD event causes high heat flux to the edge, releasing impurities from the wall. (RWTM?)

Summary and Conclusions

- Locked mode disruptions have a precursor, followed by growth of a mode to large amplitude.

- TQ time is mode growth time, $\tau_{TQ} \approx \gamma^{-1}$.

- Resistive wall tearing mode (RWTM) is a good candidate for spontaneous disruption. Other explanations require large amplitude mode first, or lack needed features

- RWTM can grow to large amplitude. M3D-C1 simulations of DIII-D in progress.

- RWTM is stable for ideal wall. Its growth rate decreases with τ_{wall} as $\gamma \propto \tau_{wall}^{-4/9}$. The NRWM has $\gamma \propto \tau_{wall}^{-1}$.

- Bonus: τ_{wall} in ITER is $50\times$ longer than in JET and DIII-D, so TQ time is much longer [Strauss 2021]

- Onset condition for the RWTM needs to be clarified, perhaps residual sheared rotation with $\omega \sim \tau_{wall}^{-1}$. (M3D-C1 linear simulations)

- Identify disruption cause to find cure