RWTM disruptions

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1. Recent Results

There is evidence from theory, simulation, and experimental data that disruptions are caused by resistive wall tearing modes (RWTM).

2. DIII-D

A DIII-D locked mode equilibrium is stable with an ideal wall, unstable with a resistive wall. Nonlinearly the RWTM grows to large amplitude, causing a complete thermal quench (TM). The simulated TQ time, and the magnetic perturbation amplitude, agree with the experimental data.

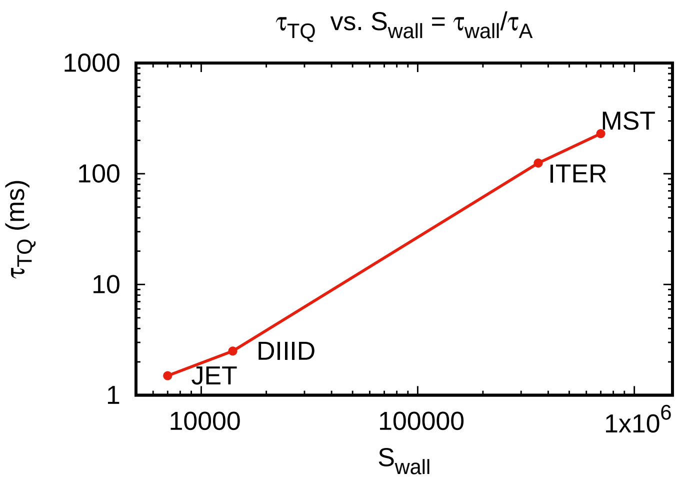
3. Madison Symmetric Torus (MST)

Disruptions are not observed in MST when operated as a standard tokamak. It has a nearly ideal wall on the timescale of the experiment. Simulations find that it is RWTM unstable, with a TQ time much longer than the experimental shot time.

4. Locked Mode Model

How common are RWTM disruptions? Nearly all disruptions in JET are preceded by locked modes. During the locked mode, the edge cools and the current contracts. A semi analytic model shows that current contraction destabilizes RWTMs.

RWTMs are highly mitigating for ITER

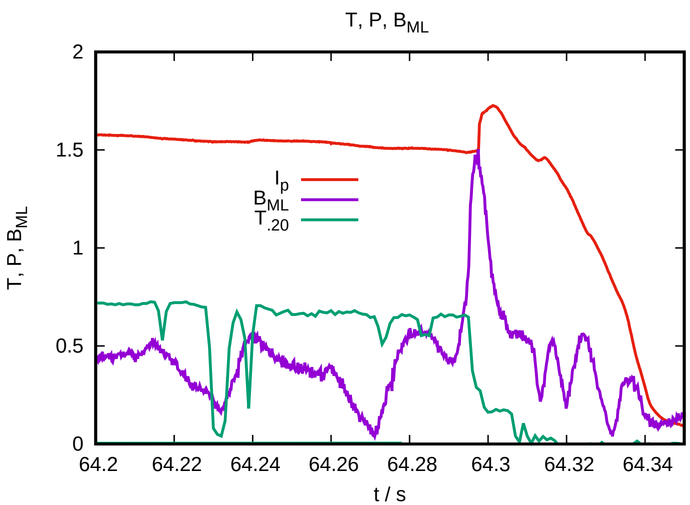


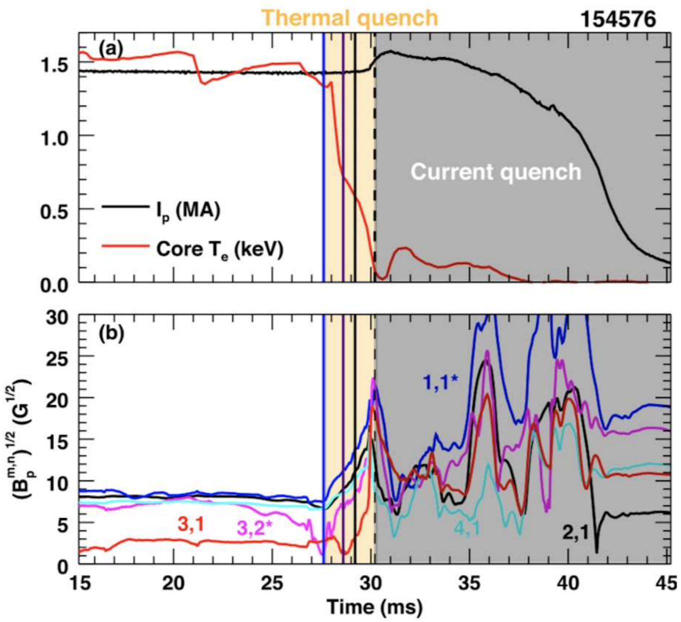
TQ time - measured (JET, DIII-D) and simulated (ITER, MST)

- JET - locked modes [Strauss *et al.* Phys. Plasmas **28**, 032501 (2021)]
- ITER - ITER inductive scenario 2 15MA [Strauss, Phys. Plasmas **28** 072507 (2021)]
- DIII-D - locked modes [Strauss *et al.* Phys. Plasmas **29** 112508 (2022)]
- MST - [Strauss, Chapman, Hurst, arXiv 2023]

JET and DIII-D locked mode disruption

Disruptions have two phases: precursor, followed by disruption. In JET and DIII-D precursor is locked mode.



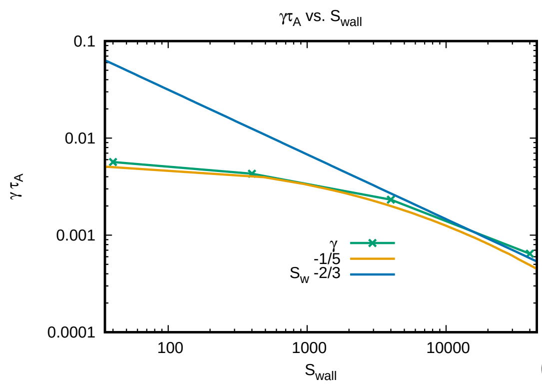


Locked mode disruptions in JET shot 81540 and DIII-D shot 154576. [Sweeney *et al.* NF 2018]. $\tau_{TQ} = .5\tau_{wall} = 2.5ms$ with $\tau_{wall} = 5ms$.

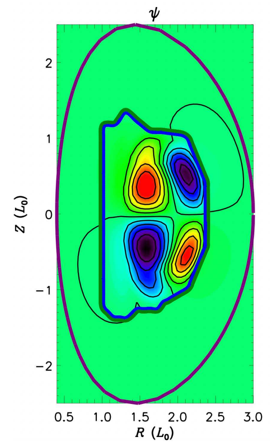
JET: [H. Strauss *et al.* Phys. Plasmas **28**, 032501 (2021)]

DIII-D: [Strauss *et al.* Phys. Plasmas 29, 112508 (2022)]

Linear M3D-C1 resistive wall simulations of DIIID 154576



(a)



(b)

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 linear simulations. The fit is to a RWTM with $S_{wall}^{-2/3}$ asymptotic scaling,

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

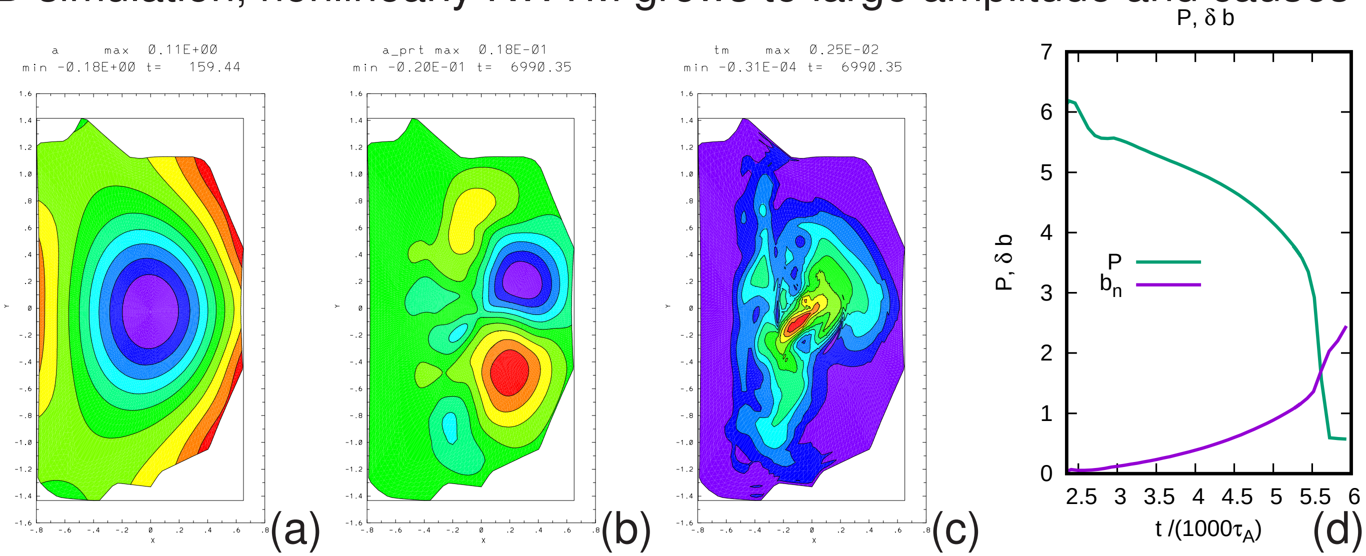
Linear RWTMs have scaling

$$\gamma \propto S_{wall}^{-\alpha} \qquad 0 \leq \alpha \leq 4/9 \qquad S_{wall} = \tau_{wall}/\tau_A.$$

RWTM has $\Delta_i \leq 0$, $\Delta_n \geq 0$, where $\Delta_i = \Delta'$ (ideal wall), $\Delta_n = \Delta'$ (no wall).

Nonlinear simulation of DIII-D 154576

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

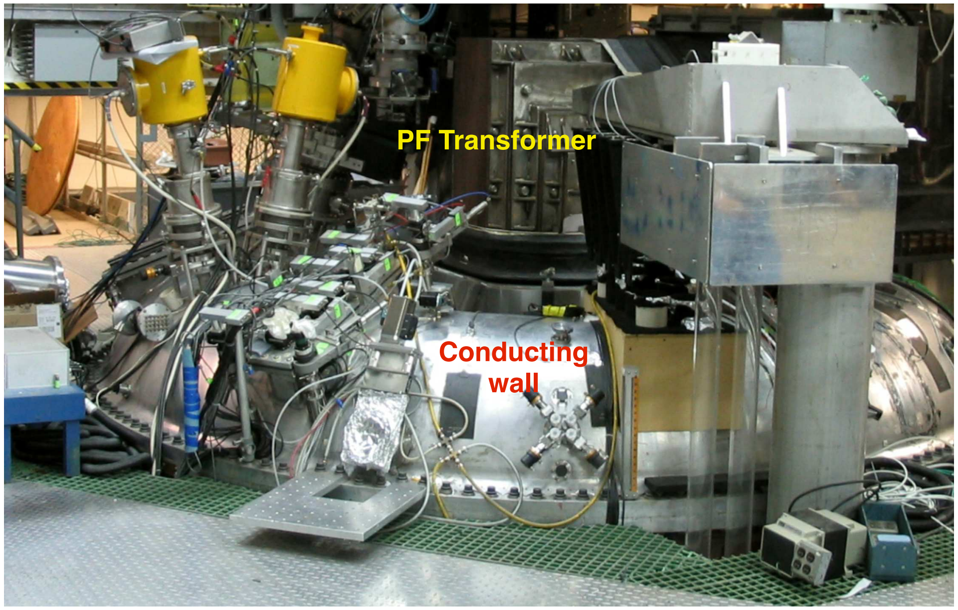


(a) initial ψ of DIII-D 154576 (b) perturbed ψ at $t = 5690\tau_A$, $S_{wall} = 10^4$. (c) p at $t = 5690\tau_A$. when P is about 20% of its initial value. (d) Time history of total pressure P and normal magnetic perturbation at the wall b_n.

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

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

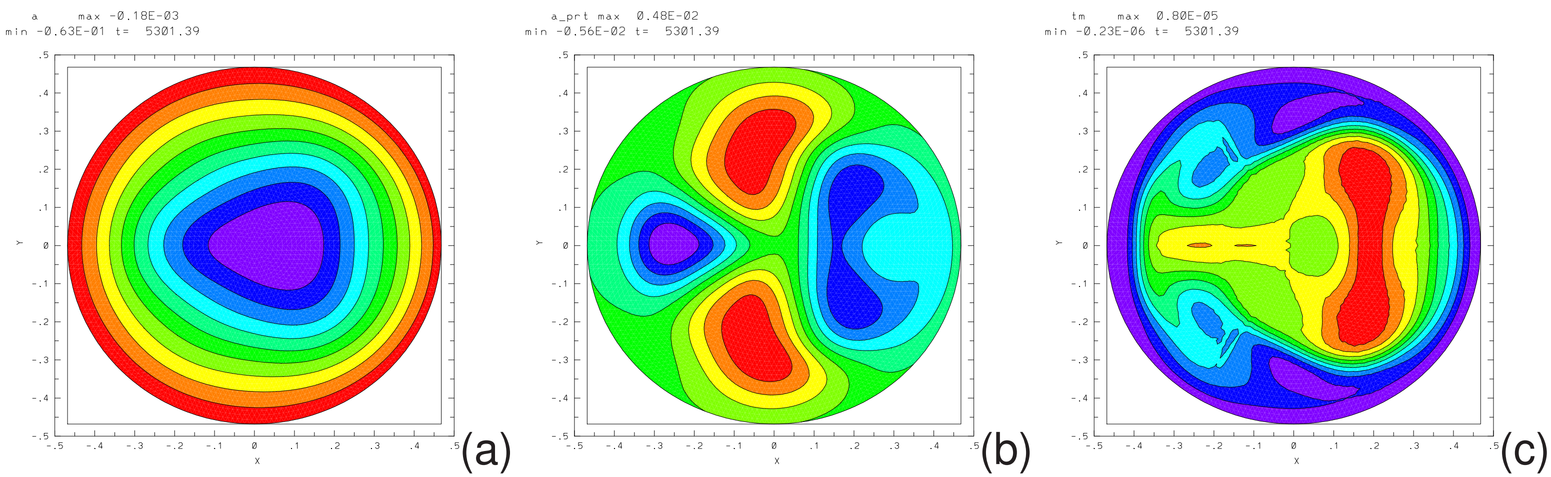
MST experiment



- RFP operated as tokamak. Pulse time is $50ms$, so wall is effectively ideal.
- Can operate with $q_a \leq 2$. [Hurst *et al.* Phys. Plasmas 29, 080704 (2022)]
- No disruptions seen when operated as a standard tokamak.

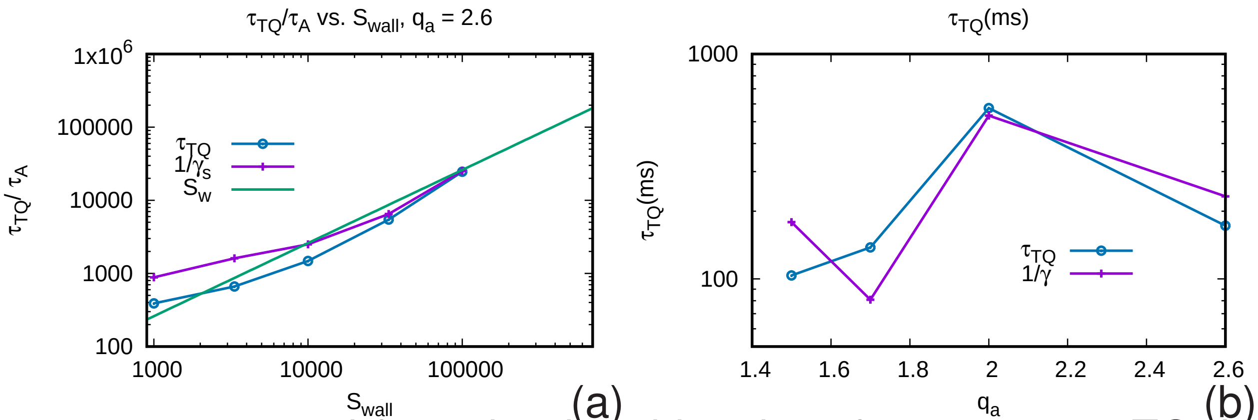
Simulations of case with $q_a = 2.6$

Simulations were done to see the effect of wall resistivity (or long run time). Initialized with MSTfit equilibria having $q_0 = 1$, $q_a = 2.6$. Plasma extended to the wall. Nonlinear 3D MHD simulations performed with the M3D code with resistive wall. Parameters: $S = 10^5$ (experimental value), and $\chi_{\parallel} = 10R^2/\tau_A$. (experimental value $4R^2/\tau_A$.)



(a) contour plot of ψ at time $t = 5300\tau_A$ for case with $q_a = 2.6$, $S_{wall} = 3.3 \times 10^4$. (b) perturbed $\tilde{\psi}$ at the same time. (c) temperature T at the same time. Perturbations are predominantly $(2, 1)$, with some $(3, 2)$.

Scaling with S_{wall}, q_a



(a) TQ time τ_{TQ} measured from the time histories. for $q_a = 2.6$. TQ time is proportional to the growth time, $\tau_{TQ} = 3/\gamma_s \propto S_{wall}$. The projected TQ time at the experimental $S_{wall} = 7 \times 10^5$ is $\tau_{TQ} \approx 2 \times 10^5 \tau_A = 230 ms$.

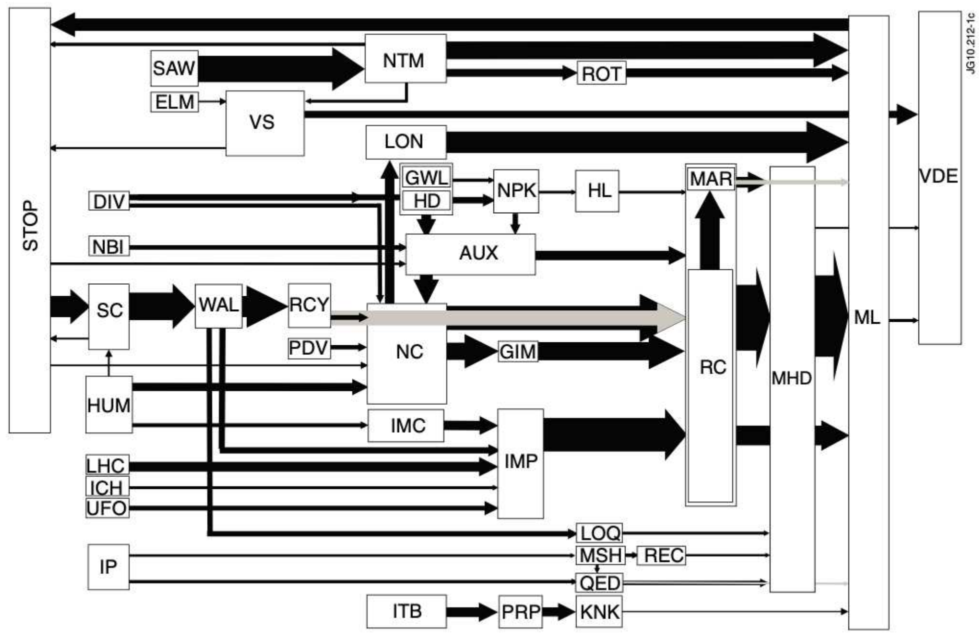
(b) τ_{TQ} as a function of q_a, from the simulations, and $1/\gamma$ from a model RWM / RWTM dispersion relation,

$$\gamma \tau_{wall} = -2m \frac{nq_0 - (m-1)}{nq_0 - (m-1) - (r_0/r_w)^{2m}}.$$

with $q_0 = 1.08$. The model equilibrium has constant current $r \leq r_0$. The wall is at $r = r_w \approx r_a$. $q_a \approx q_0(r_w/r_0)^2$. For $S_{wall} >> S^{3/5}$, RWTM and RWM have the same dispersion relation. This is MST regime.

Locked Mode Precursors in JET

Type of physics problem	Labe
General (rotating) $n = 1$ or 2 MHD	MHI
Mode lock	ML
Low q or $q_{95} \sim 2$	LOQ
Edge q close to rational (>2)	QED
Large sawtooth crash	SAW
Neo-classical tearing mode	NTM
Internal kink mode	KNK
Reconnection	REC
Radiative collapse ($P_{\rm rad} > P_{\rm in}$)	RC
MARFE	MAF
Greenwald limit ($n_{\rm GW}$)	GWI
High density operation (near $n_{\rm GW}$)	HD
Too low density (and low q)	LON
H-to-L back-transition	HL
Strong density peaking	NPK
Too strong internal transport barrier (ITB)	ITB
Strong pressure profile peaking	PRP
Negative central magnetic shear	MSF
Large edge localized mode (ELM)	ELM
Vertical displacement event	VDE



How common are RWTMs? Almost all JET disruption precursors become a locked mode. [deVries *et al.* 2011]

“Disruptions have many causes” means “disruption precursors have many causes.”

A locked mode is not a disruption, but indicates an “unhealthy” plasma. [Gerasimov, 2022]

What happens during precursors and locked modes?

During locked mode disruption precursors the plasma can develop low temperature in the edge. This causes the current to contract.

“Deficient edge” [Schuller 1995]

“minor disruption” [Wesson 1989]

$T_{e,q2}$ disruption [Sweeney 2017]

The current contraction causes increase of internal inductance li.

It is also required to have the $q = 2$ surface sufficiently close to the plasma edge.

VDEs not considered here, or high β RWMs.

What happens after a locked mode?

Model of profile effect

To model the effects of current contraction and $q = 2$ rational surface r_s, introduce a set of model equilibria based on [Furth, Rutherford, Selberg 1973] but with a current cutoff radius r_c. [Strauss, arXiv 2023] In FRS, a peaked profile has $n = 1$, rounded, $n = 2$, and flattened, $n = 4$.

The FRS current, subtracting a constant c_r,

$$j(r) = \begin{cases} (2c_0/q_0)[(1 + r^{2n})^{-(1+1/n)} - c_r] & r < r_c \\ 0 & r \geq r_c. \end{cases}$$

where $c_r = (1+r_c^{2n})^{-(1+1/n)}$. The factor $c_0 = 1/(1-c_r)$ keeps $j(0)$ independent of r_c. The linear magnetic perturbation satisfies [Furth 1963]

$$\frac{1}{r}\frac{d}{dr}r\frac{d\psi}{dr} - \frac{m^2}{r^2}\psi = \frac{qm}{r}\frac{dj}{dr}\frac{\psi}{(m-nq)} \qquad (1)$$

The singularity is treated by regularizing [Cheng 1987]. A shooting code is used, integrating outward from $r = 0$, and inward from the wall radius $r = r_w$.

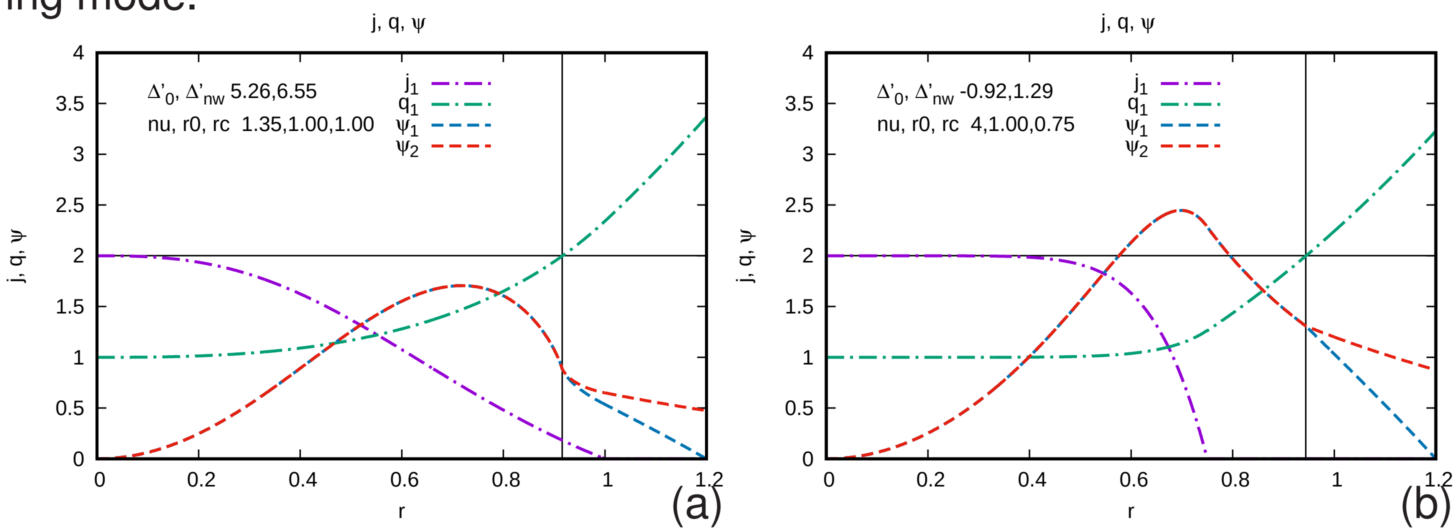
Boundary conditions: Origin, $\psi(0) = 0, d\psi/dr(0) = 0$ ($\psi \propto r^2$)

Ideal wall at $r = r_w$: $\psi(r_w) = 0$, $d\psi/dr(r_w) = 1$.

No wall: $\psi(r_w) = 1$, $d\psi/dr(r_w) = -(m/r_w)\psi(r_w)$.

solving for Δ'

Contraction of the current stabilizes tearing mode and destabilizes resistive wall tearing mode.

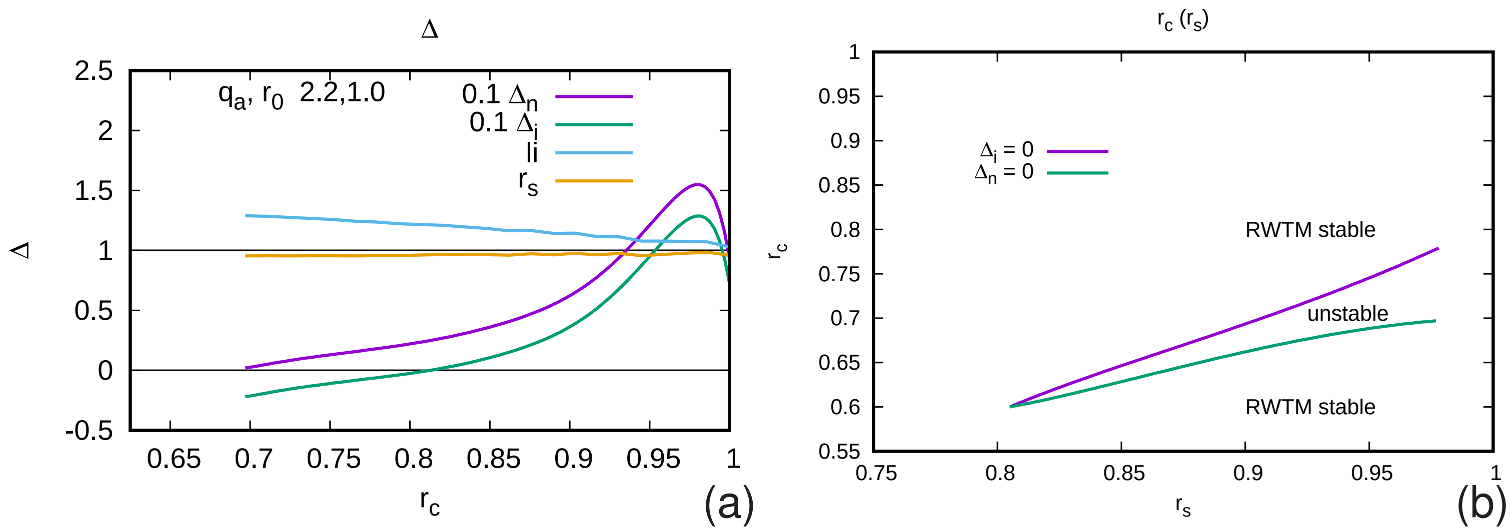


ψ, j, and q, with ψ for ideal (ψ_1) and no wall (ψ_2). Plasma radius $r_a = 1$, wall radius $r_w = 1.2$.

(a) tearing mode unstable. The current is nonzero for $r < 1$.

(b) RWTM unstable. The current is non zero for $r < r_c = .75$. The current profile is flattened so the total current is almost the same as in (a). In both cases $q_0 = 1$.

how Δ' depends on r_c, r_s.



(a) $0.1\Delta_n, 0.1\Delta_i$, li, *and* r_s *as a function of* r_c, *for* $r_s = 0.95$. li *increases as* r_c *decreases.* $\Delta_i < 0$ *for* $r_c < 0.8$, *and* $\Delta_n < 0$ *for* $r_c < 0.7$. *(*$q_a = 2r_a^2/r_s^2 = 2.2$.*)*

(b) r_c *as a function of* r_s, *for which* $\Delta_i \leq 0, \Delta_n > 0$ *(solid curves, RWTM unstable) and for which* $\Delta_i \leq 0, \Delta_n \leq 0$ *(dashed curves, RWTM stable).* $r_w = 1.5r_a$.

If $r_s \lesssim 0.75$, then no RWTMs are possible. This agrees with DIII-D database, that disruptions require $r_s \geq 0.75$, assuming RWTMs cause disruptions. [Strauss *et al.* 2022].

Summary

There is evidence from theory, simulation, and experimental data that disruptions are caused by resistive wall tearing modes (RWTM).

This is highly mitigating for ITER, which has a much more conducting wall than JET and DIII-D.

MST and ITER have highly conducting walls, so RWTM disruptions are slow.

JET and DIII-D locked mode disruptions can be caused by RWTMs.

Locked modes cause current contraction. This is shown to destabilize RWTMs. Too much contraction stabilizes RWTMs.