# Resistive Wall Tearing Mode Disruptions

**H. Strauss, HRS Fusion, hank@hrsfusion.com**

There is evidence from theory, simulation, and experimental data that disruptions are caused by resistive wall tearing modes (RWTM) in JET, ITER, DIII-D, and MST.

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

1. Madison Symmetric Torus (MST)

Simulations find MST is RWTM unstable, with a TQ time much longer than the experimental shot time.

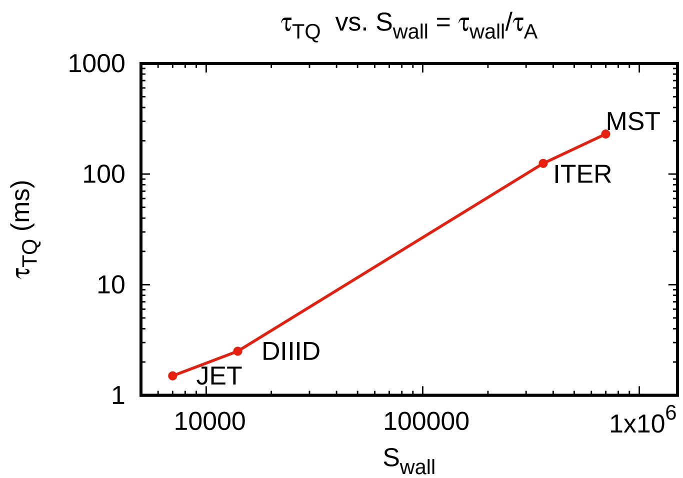
2. Locked Mode Model

How common are RWTM disruptions? Nearly all disruptions in JET are preceded by locked modes. Simulations and an analytic model shows that current contraction destabilizes RWTMs.

3. Feedback

Can feedback eliminate RWTMs and perhaps disruptions?

# RWTMs are highly mitigating for ITER



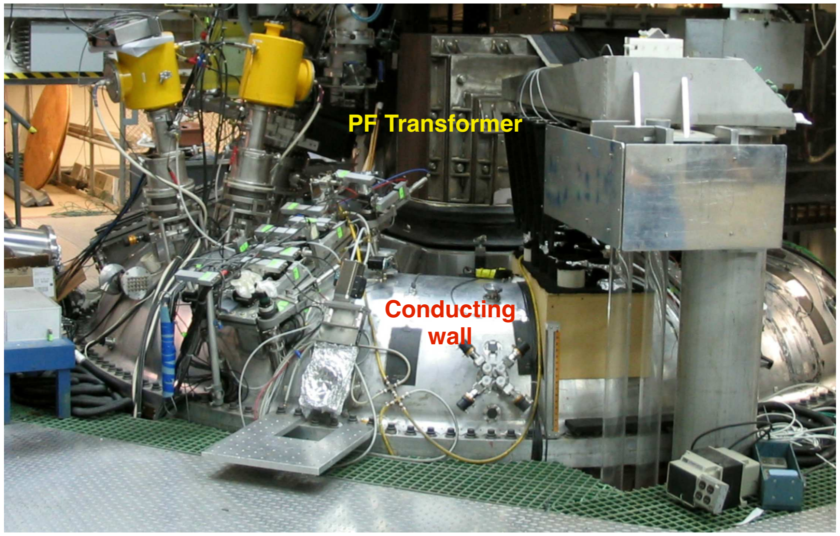

*TQ time - measured (JET, DIII-D) and simulated (ITER, MST)*

- 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, Lyons, Knolker, Phys. Plasmas **29** 112508 (2022)]
- MST - [Strauss, Chapman, Hurst, Plasma Phys. Control. Fusion 65 084002 (2023)]

$\tau_{wall} = 5ms$ (JET, DIII-D), $= 250ms$ (ITER), $= 800ms$ (MST).

$S_{wall} = \tau_{wall}/\tau_A$, $\tau_{wall} = r_w\delta_w/\eta_{wall}$, $\tau_A = R/v_A$.

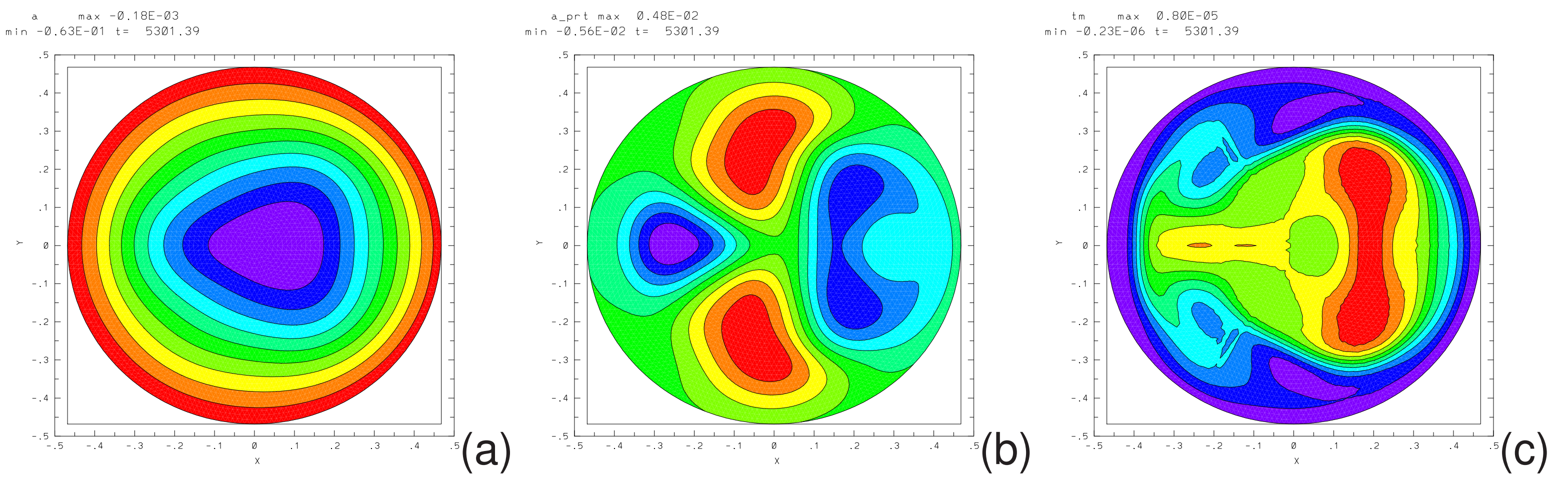
## MST experiment




- RFP operated as tokamak. Pulse time is $50ms$, wall time $\tau_{wall} = 800ms$.
- Can operate with $q_a \leq 2$. [Hurst *et al.* Phys. Plasmas 29, 080704 (2022)]
- No disruptions seen when operated as a standard tokamak.
- No disruptions at high density $10\times$ Greenwald limit

# 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 $\chi_{\|} = 10R^2/\tau_A$. (experimental value $4R^2/\tau_A$.)




(a) contour plot of $\psi$ 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 $(2, 1)$ and $(3, 2)$.

## $S_{wall}$ scaling of linear growth rate

The RWTM linear dispersion relation is [Finn (1995), Bondeson (1988)]

$$c_1^{-1} S^{3/4} S_{wall}^{-5/4} (\hat{\gamma}^{9/4} + g_s \hat{\gamma}^{5/4}) = \Delta_i \hat{\gamma} + g_s \Delta_n \qquad (1)$$

where $\hat{\gamma} = \gamma \tau_{wall}$, $S$ is the Lundquist number, $c_1 \approx 1.7$, $g_s = 2m/[1-(r_s/r_w)^{2m}]$, Resistive wall tearing modes have $\Delta_i \leq 0$, and require finite $S_{wall}$.

The RWTM growth rate scalings vary as $\gamma \propto S_{wall}^{-\alpha}$, with $4/9 \leq \alpha \leq 1$. In a JET example $\alpha = 4/9$, ($\Delta_i = 0$) while in a DIII-D example $\alpha = 2/3$. In MST ($\sigma << 1$) $\alpha = 1$.

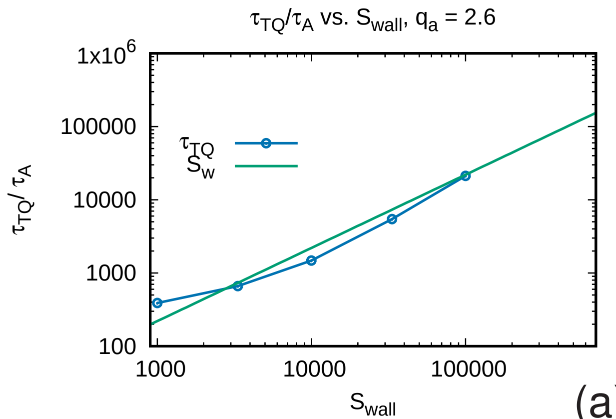
The left side of (1) $\propto \sigma = S^{3/4} S_{wall}^{-5/4}$. For small $\sigma$, $\alpha \approx 1$.

| | $S$ | $S_{wall}$ | $\sigma$ |
|---|---|---|---|
| MST: | 1.e5 | 7.e5 | 2.8e-4 |

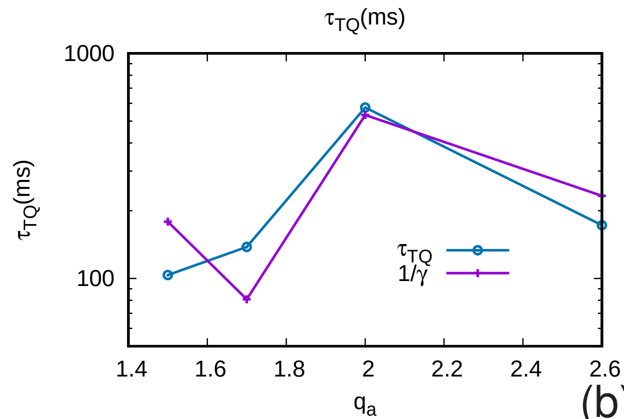
| | $S$ | $S_{wall}$ | $\sigma$ |
|---|---|---|---|
| ITER: | 1.e6 | 3.5e5 | 3.7e-3 |
| | 1.e7 | 3.5e5 | 0.027 |
| | 1.e8 | 3.5e5 | 0.16 |

| | $S$ | $S_{wall}$ | $\sigma$ |
|---|---|---|---|
| JET: | 1.e6 | 7.e3 | 0.49 |
| DIII-D: | 1.e6 | 1.4e4 | 0.21 |

# Nonlinear simulated TQ scaling with $S_{wall}$




(a)




(b)

(a) TQ time $\tau_{TQ}$ measured from time histories. for $q_a = 2.6$. Note $\tau_{TQ} \propto \tau_{wall}$, like RWM. The projected TQ time at the experimental $S_{wall} = 7 \times 10^5$ is $\tau_{TQ} \approx 2 \times 10^5 \tau_A = 230ms$.

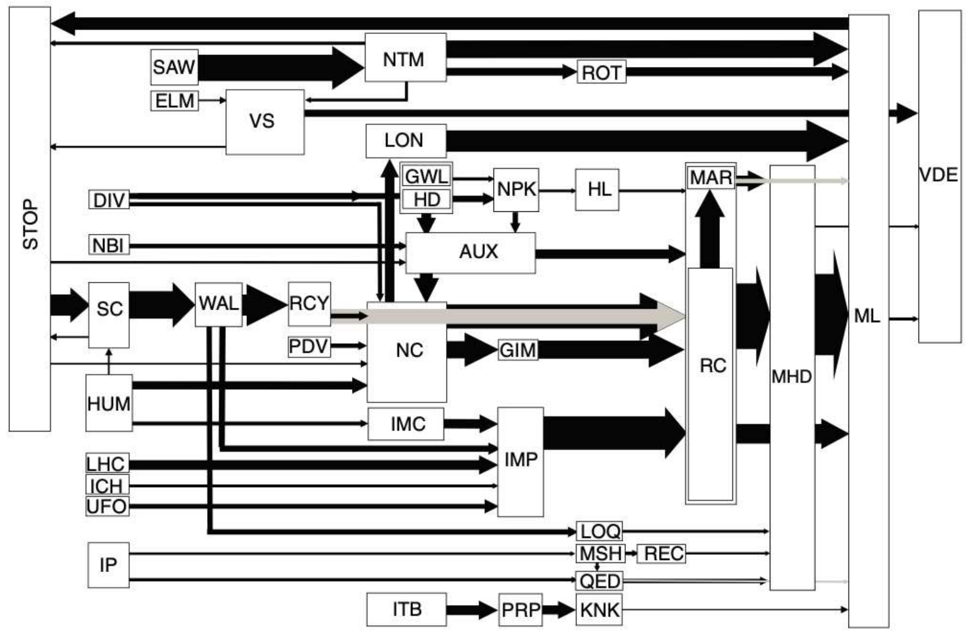
(b) $\tau_{TQ}$ as a function of $q_a$, from the simulations, and $1/\gamma$ from model [Finn, 1995] RWM / RWTM dispersion relation,

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

with $q_0 = 1.08, \sigma = 0$. 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 $\sigma \ll 1$, RWTM and RWM have the same dispersion relation.

# Locked Mode Model: 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 ($P_{\mathrm{rad}} > P_{\mathrm{in}}$) | RC |
| MARFE | MAI |
| Greenwald limit ($n_{\mathrm{GW}}$) | GWI |
| High density operation (near $n_{\mathrm{GW}}$) | 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 | MSH |
| Large edge localized mode (ELM) | ELM |
| Vertical displacement event | VDE |



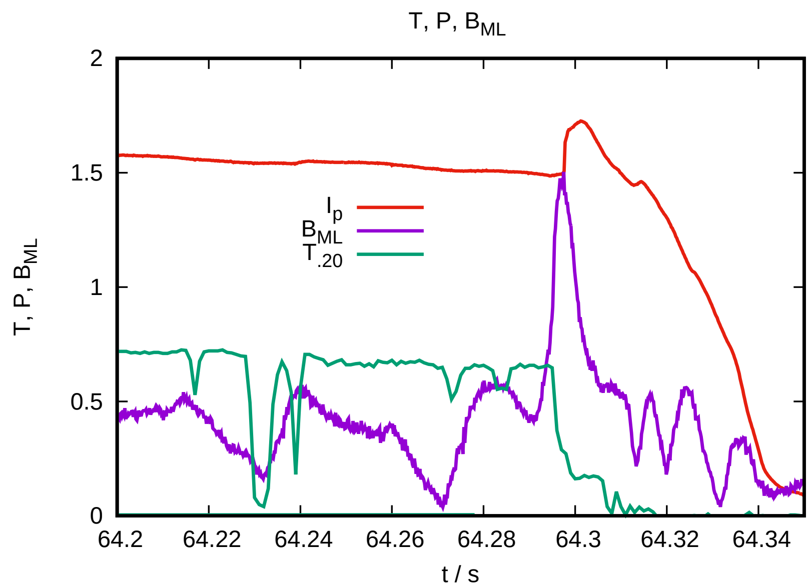

How common are RWTMs? Almost all JET disruption precursors become a locked mode. [deVries *et al.* 2011]

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

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

# JET locked mode disruption

In JET precursor is locked mode. What instability causes the TQ?




Locked mode disruptions in JET shot 81540. $\tau_{TQ} = .25\tau_{wall} = 1.25ms$ with $\tau_{wall} = 5ms$.

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

## 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]

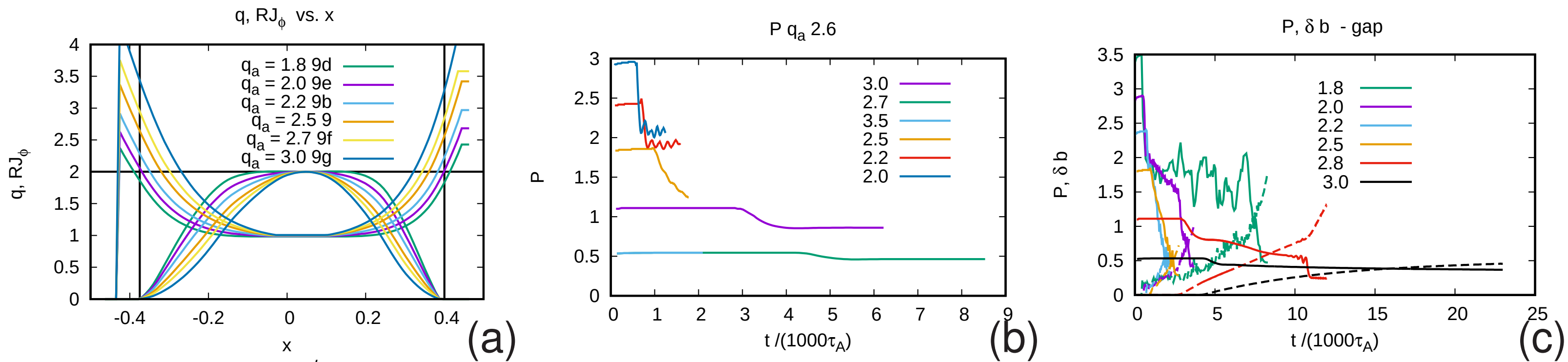
$T_{e,q2}$ disruption [Sweeney 2017]

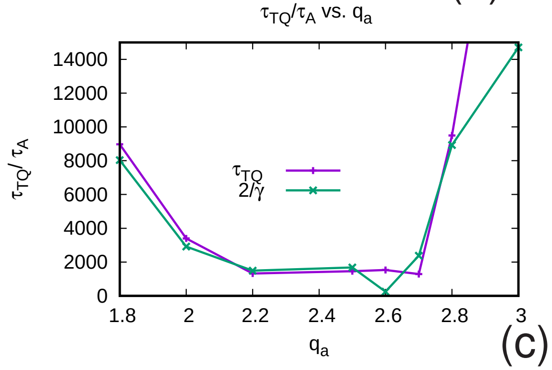
It is also required to have the $q = 2$ surface sufficiently close to the plasma edge.

VDEs not considered here, or high $\beta$ RWMs.

MHD instability occurs after locked mode.

# Onset condition for RWTM

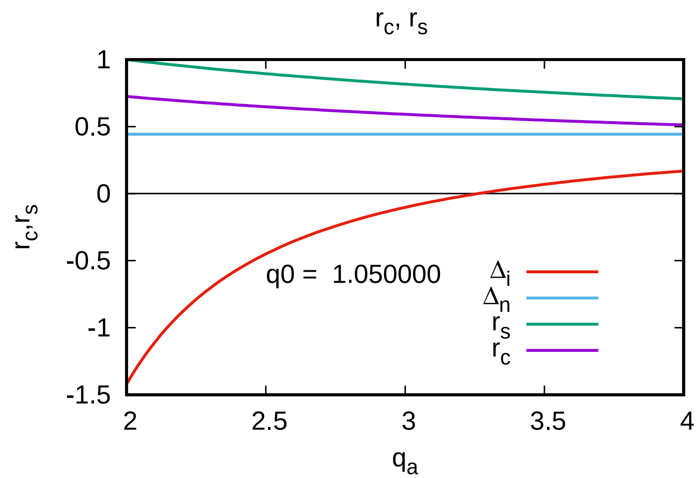



(a) $q$ and $RJ_\phi$ profiles with $q_a = 1.8, 2.01, 2.2, 2.5, 2.7, 3.0$ (b) total pressure $P(t)$ for ideal wall, with $q_a = 1.8, 2.01, 2.2$. (c) time histories of $P$ and $b_n$ in M3D simulations of MST with modified profiles, and $S_{wall} = 10^5$.

(d) TQ time $\tau_{TQ}$ from the time histories, as a function of $q_a$. Also $2/\gamma_s$. The TQ varies with $q_a$. For $q_a = 1.8$, the mode is a RWM and is much slower than the RWTMs with $2.0 < q_q < 2.8$. For $q_a = 3.0$ the mode is tearing; it does not cause a TQ. This gives sharp TM $\rightarrow$ RWTM onset of TQ.

# Model of mode onset




In the step current model [Furth 1973, Finn1995] with a constant current density and $q = q_0$ contained within radius $r_c$, zero current density for $r > r_c$, $q = q_0(r/r_c)^2$. Then $r_s/r_c = \sqrt{2/q_0}$. where $q_0 = 1.05$ is the value on axis, The internal stability parameter is for $(m,n) = (2,1)$, $r_w = 1.2r_a$.

$$\Delta_i = -2\frac{q_0 - 1 - (q_0/2)^2(r_s/r_w)^4}{[q_0 - 1 - (q_0/2)^2][1 - (r_s/r_w)^4]}. \tag{2}$$

Contraction: $r_c < r_s$. Onset and RWTM unstable: $\Delta_i \leq 0, \Delta_n > 0$. No wall $\Delta_n$: set $r_w \to \infty$ in (2).

# Feedback stabilization of RWTM

Feedback experiments on DIII-D and RFX [Hanson (2014),Piovesan (2014] showed stabilization of what was thought to be RWMs( but might have been RWTMs).

Saddle coils which sense normal magnetic perturbations $b_n \propto \partial\psi/\partial l$, and probes which sense tangential $b_l \propto \partial\psi/\partial n$ are used, which is fed back into the evolution of $\psi$ at the wall.

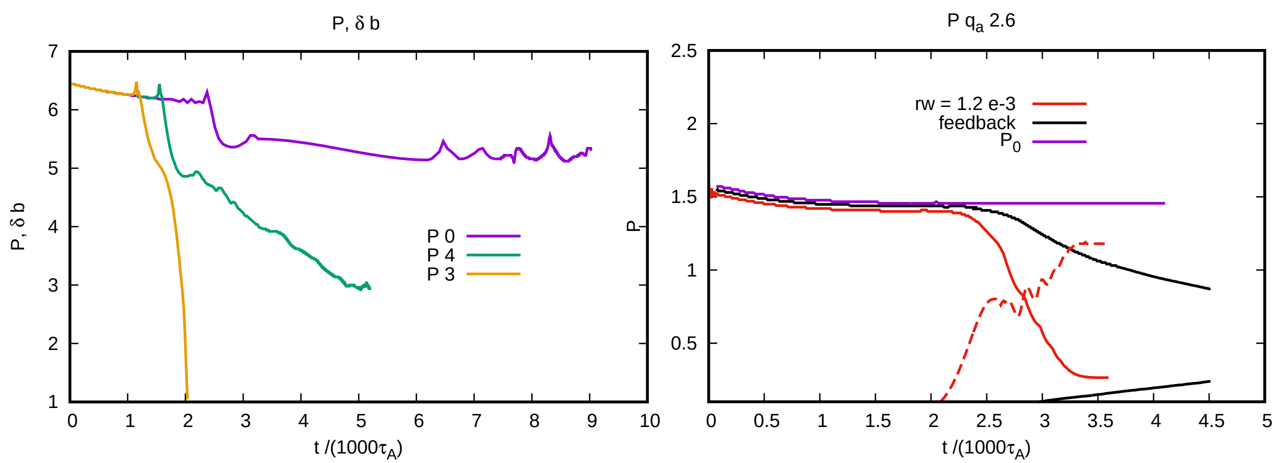
Simulations are being carried out to examine feedback stabilization. The simulations add $g, h$ and rotation $\Omega_w$ to the thin wall boundary condition,

$$\frac{\partial\psi}{\partial t} = \frac{r_w}{\tau_{wall}}[\psi'_{vac} - (1-h)\psi' - g\psi/r_w] - \Omega_w\frac{\partial\psi}{\partial\phi} \tag{3}$$

The terms with $g, h$ are included only for toroidal mode numbers $k$.

# Feedback examples

Shown are the total pressure $P$ as a function of time for several cases.




(a) $P$ in DIIID shot 154576 with $S_{wall} = 10^3$. The cases are labeled $0$ : ideal wall; label $4$ : feedback with $h = 1$, $k = 1$, and label $3$ : resistive wall with $S_{wall} = 10^3$. The cases all have $g = 0, \Omega_w = 0$. (b) MST / HBT examples with $S_w = 10^3$, without feedback and with $h = 1$ feedback stabilization of $k = 1, 2$. The results so far do not give complete stabilization of RWTM disruptions. Perhaps an order of magnititude improvement in TQ time.

# 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.

Locked modes cause current contraction which destabilizes RWTMs.

RWTMs are “soft disruptions,” can be passively or actively slowed.

“Hard disruptions” (ideal wall) caused by making highly unstable equilibrium, using MGI, SPI or initial conditions in simulations.

Feedback simulations are in progress.