Preventing tokamak disruptions with feedback

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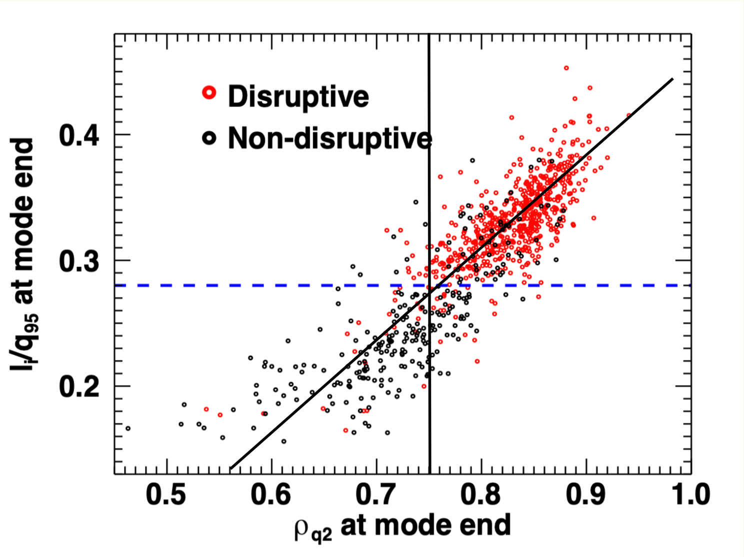
1. Introduction

Disruptions have been considered to be a major obstacle to tokamak fusion. Many disruptions are caused by resistive wall tearing modes (RWTM). They can be prevented with feedback.

- there are two main criteria for locked mode disruptions in DIII-D
  - $\rho_{q2} > 0.75$. This shows that the disruption is caused by a tearing mode close enough to the wall to interact with it. Here ρ_{q2} is $q = 2$ radius $R_{q2} - R_0$ normalized to wall radius.
  - $li/q_{95} > 0.28$. The current must be sufficiently peaked. This can be caused by edge cooling and other precursors.
- RWTMs can grow to much larger amplitude than ideal wall TM, and cause a complete thermal quench.
- Feedback can make effectively ideal wall, which can prevent major disruptions.
- RWTMs are also found at high β, in NSTX and KSTAR. They too can be feedback stabilized.

2. DIII-D database and ρ_{q2}, l_i/q_{95} disruption criteria



Disruptivity in a DIII-D locked mode disruption database. [Sweeney 2017]. One disruption criterion is $\rho_{q2} = .75$ or $q_{75} = 2$.

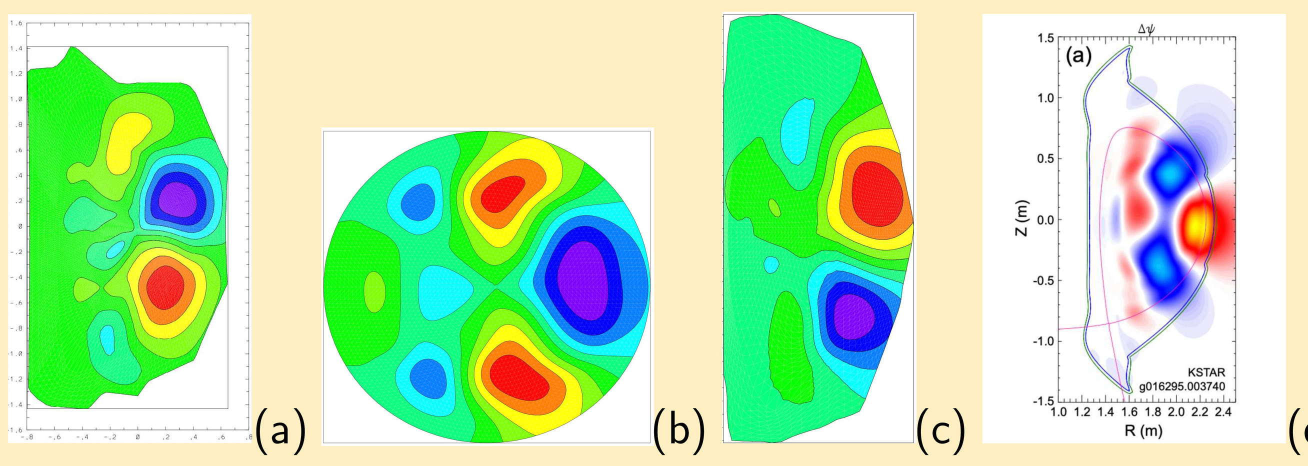
The sloping line is a fit to the data.

The condition $\rho_{q2} > 0.75$ is necessary but not sufficient: also a critical $l_i/q_{95} = 0.28$, contraction of the current profile.

The data implies the disruptions are caused by RWTMs. The modes are tearing, because $\rho_{q2} < 1$, and resistive wall modes, because $\rho_{q2} > 0.75$, allowing wall interaction and making feedback possible.

RWTMs grow to large amplitude, sufficient for a complete thermal quench. If the wall is ideal, the modes only cause minor disruptions. Feedback can emulate an ideal wall and prevent major disruptions.

3. ρ_{q2} criterion



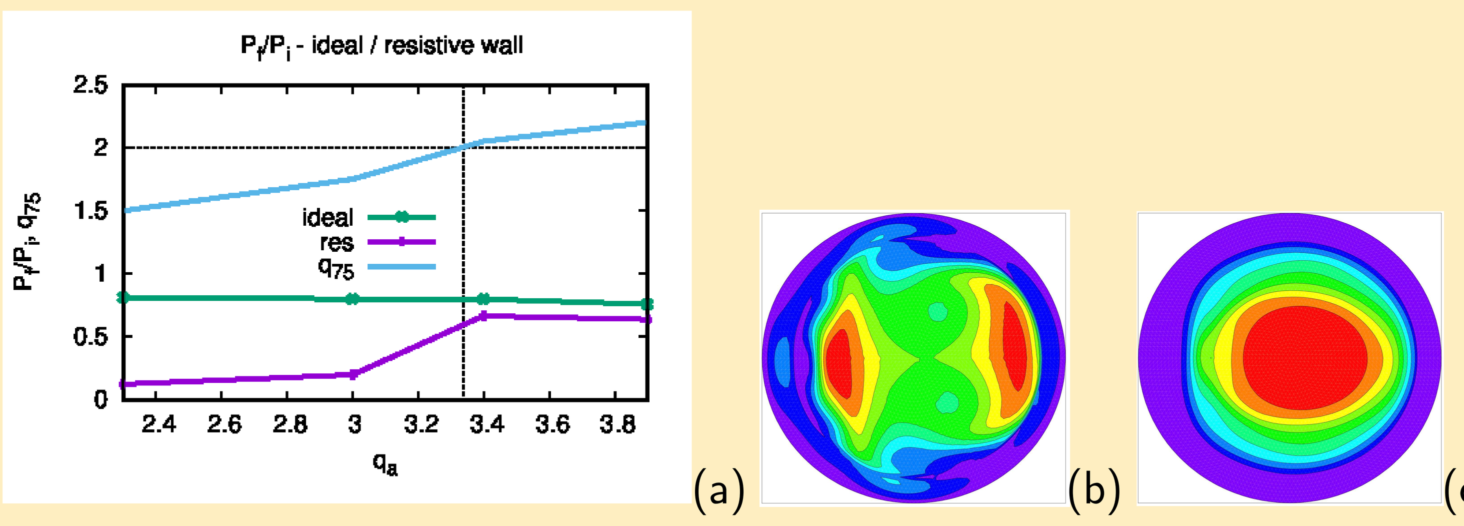
(a) Perturbed ψ in DIII-D simulations [Strauss 2023], (b) MST - based sequence in Section 4, (c) NSTX in section 8, (d) KSTAR [Y.S. Park 2020].

Criterion is condition for lobe of mode to reach the wall, so the mode "knows" the wall boundary condition,

$$\rho_w \approx \rho_{q2} + 1/(k_\perp a) \quad k_\perp a = m/\rho_{q2} \quad \rho_{q2} \approx \frac{\rho_w}{1 + 1/2} \approx 0.8 \tag{1}$$

where $\rho_w \approx 1.2$ in examples (a) - (d). More accurately, $\rho_{q2} \geq 0.75$ for $\rho_w = 1.2$, $\rho_{q2} = 0.625\rho_w$
Also get maximum wall distance, for $\rho_{q2} < 1$, $\rho_w < 1.5$. Otherwise have a no wall tearing mode. [Strauss 2025].

4. MST equilibria and nonlinear simulations



MST doesn't have disruptions because the wall is ideal on a shot timescale. In M3D simulations of a sequence of equilibria with $2.3 \leq q_a \leq 3.9$, the wall time was artificially short. The wall distance was increases to $\rho_w = 1.2$, like DIII-D. For an ideal wall, only minor disruptions occur. (a) Total pressure drop $P_{final}/P_{initial}$ for ideal and resistive wall, and q_{75} as functions of q_a. Major disruptions for $q_{75} \leq 2.0$, $\rho_{q2} \geq 0.75$. (b) Pressure p contours in nonlinear simulation of the $q_a = 3$ case for resistive wall, (c) Pressure p contours in nonlinear simulation of the $q_a = 3$ case for ideal wall.

5. Feedback stabilization of RWTM

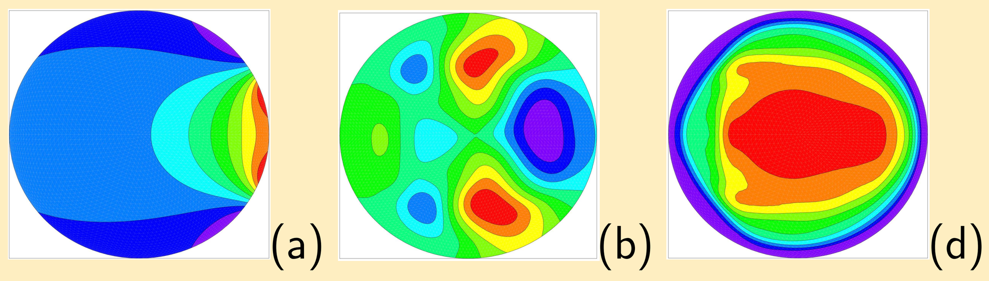
Feedback experiments on DIII-D and RFX [Hanson 2014,Piovesan 2014] showed stabilization of with RWM with $q_a = 2$. Feedback was used to stabilize high β RWM in NSTX [Sabbagh 2010], and KSTAR [Y. S. Park 2020]. Complex feedback in DIII-D [Okabayashi 2009] prevented mode locking.

In simulations, feedback is added to the thin wall boundary condition,

$$\frac{\partial \psi_w}{\partial t} = \frac{r_w}{\tau_{wall}}(\psi'_{vac} - \psi'_p) - \gamma_w \psi_{sensor} \Psi_{coil} \tag{2}$$

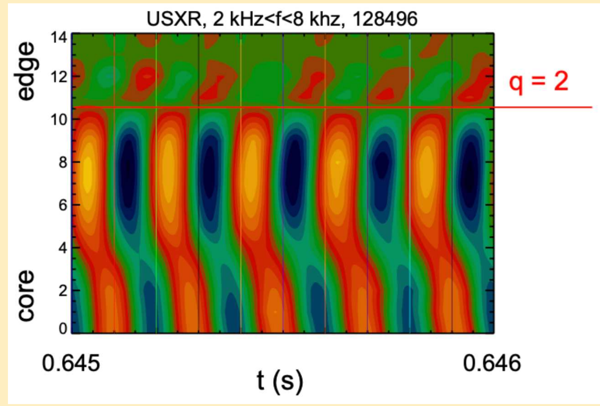
where ψ'_{vac} is the vacuum magnetic flux normal derivative at the wall excluding the contribution of the feedback coils, ψ'_p is the magnetic flux normal derivative from the plasma at the wall, γ_s is gain and ψ_{sensor} is ψ at sensors, Ψ_{coil} is normalized ψ of the coils on the wall. A simplified feedback model was used in [Strauss, 2025].

6. MST feedback simulations



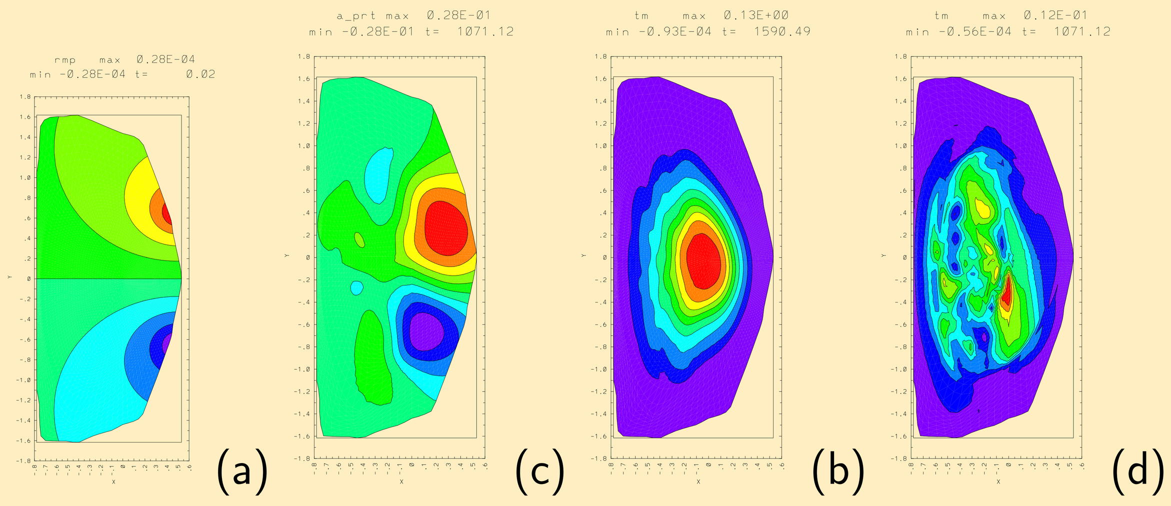
(a) perturbed magnetic flux ψ from coils (b) perturbed ψ with resistive wall, $q_a = 3$. (c) pressure contours with feedback stabilization using the coils.
Note overlap of (a),(b). The magnetic flux ψ of the coils approximately matches ψ of the perurbation.

7. NSTX RWTM



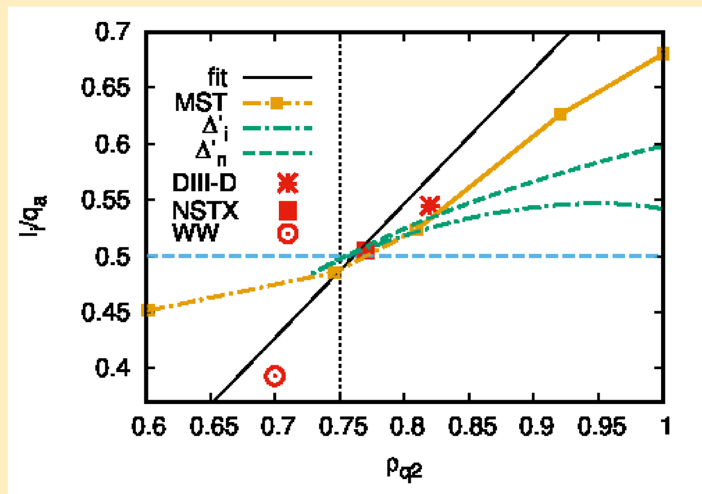
NSTX example with $\beta_N > 4$, above the no wall limit. showing soft X ray emission as a function of radius and time. Radial mode structure of feedback stabilized (2, 1) mode. It can be identified as a RWTM by its phase inversion at $\rho_{q2} = 0.75$. [Sabbagh 2010].

8. NSTX feedback ksimulation



Simulations with modified equilibrium reconstruction of NSTX example [Strauss 2025], with $\beta_N = 3$. Contours of pressure for NSTX with $\beta_n = 3$ and (a) ψ produced by feedback coils; (b) pressure contours with feedback; (c) perturbed ψ without feedback; (d) pressure contours without feedback. Note approximate alignment of (a),(c).

9. Current contraction criterion



fit of DIII-D database ; "DIII-D" is shot 154576 [Strauss 2023]; "MST" are high q_a MST, "NSTX" is previous example, dashed lines Δ'_i, Δ'_n are marginally stable TMs with ideal and no wall [Strauss 2024], "WW" are TM disruption simulations with highly unstable initialization [White 1977, Waddell 1979], ideal wall. Qualitatively OK, but doesn't fit data. DIII-D and NSTX are rescaled to account for geometry dependence,

$$\frac{l_i}{q_{95}} \gtrsim \frac{1}{2\kappa} \tag{3}$$

10. Locked mode disruption precursors

During locked mode disruption precursors the plasma can develop low temperature in the edge. This causes the current to contract. This is called a "deficient edge" [Schuller 1995] or "minor disruption" [Wesson 1989]. $T_{e,q2}$ minor disruptions [Sweeney 2018] Resistive ballooning turbulence causes edge cooling, might cause Greenwald density limit [Giacomin 2022], or MARFE formation [Lipschultz 1984].The current contraction causes increase of internal inductance l_i. Disruptions can be caused in simulations if the plasma is initialized in a highly unstable initial state [Waddell 1979, White 1980]. Massive gas (MGI) or shattered pellet injection force the plasma into a highly unstable state [Izzo 2008, Nardon 2017].

Disruptions are probably not caused by neoclassical tearing modes (NTM). Edge cooling suppresses edge current, including bootstrap current which drives NTMs. In simulations [LaHaye 2022] they do not grow large enough for a major disruption. Typically they cause minor disruptions and degrade confinement.

11. Summary

- there are two main criteria for locked mode disruptions
  - $\rho_{q2} > 0.75$, a condition for RWTM, which makes feedback possible.
  - $li/q_{95} > 0.28$, a condition for sufficient current peaking.
- RWTMs can grow to much larger amplitude than ideal wall TM, and cause a complete thermal quench, but can be feedback stabilized.
- RWTMs are found at high β in NSTX. Feedback stabilization of RWMs also stabilizes RWTMs.
- Feedback could allow tokamaks to be free of major disruptions.

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