# Resistive Wall Tearing Mode Major Disruptions with Feedback

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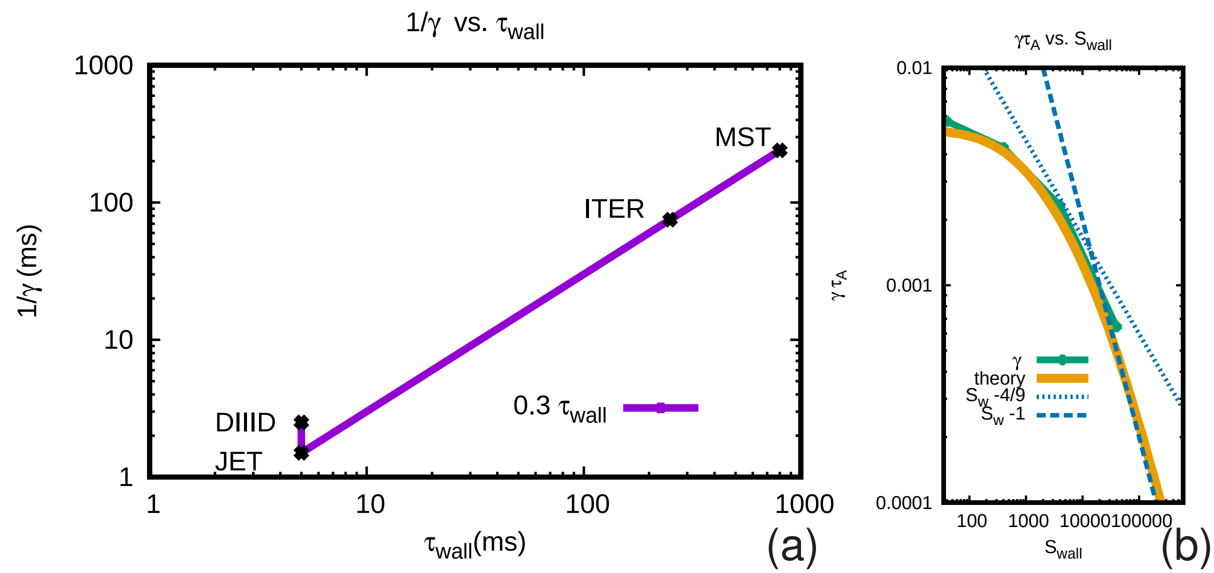
- Resistve wall tearing modes (RWTM) and resistive wall modes (RWM) can cause major disruptions. They have much longer growth time in ITER $\sim 100ms$, than in JET, DIII-D, long enough for detection and mitigation if needed.

- The disruption TQ has both a slow MHD phase, RWM / RWTM, and a fast phase, stochastic parallel transport. The fast phase does not occur until the MHD modes reach a large enough amplitude, which occurs on the slow timescale.

- At low $\beta$, RWTM can cause major disruption for $q_a \lesssim 3.4$. Feedback acts like an ideal wall, allowing only minor disruptions.

- At high $\beta$, both RWM and RWTM can occur, and can be feedbck stabilized above the no wall limit.

# RWTM, RWM growth time

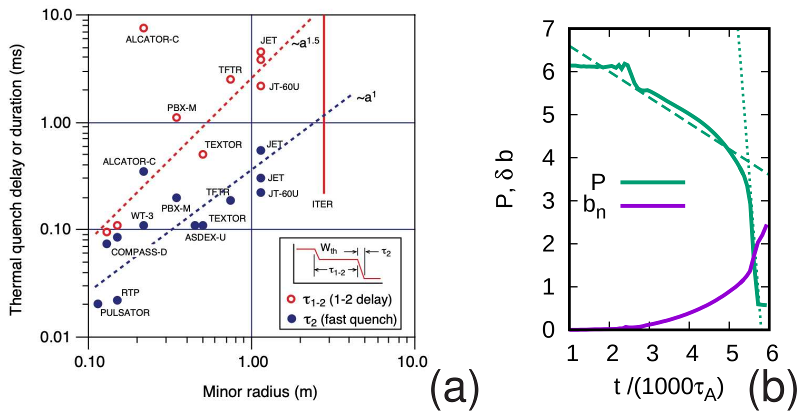



(a) RWTM growth time - measured (JET, DIII-D) and simulated (ITER, MST) $\tau_{wall} = 5ms$ (JET, DIII-D), $= 250ms$ (ITER), $= 800ms$ (MST). Fit by $\tau \approx \tau_{wall}/3$.

(b) scaling of $\gamma$ with $S_{wall} = \tau_{wall}/\tau_A$. For low (JET) $S_{wall} = \tau_{wall}/\tau_A$, $\gamma\tau_A \approx S^{-1/3}S_{wall}^{-4/9}$. For high $S_{wall}$, as in ITER, $\gamma \sim S_{wall}^{-1}$.

# Two stage disruption thermal quench

Many disruptions have two stage TQ: a slow phase followed by a fast phase.




(a) ITER phys. basis [1999], showing fast and slow TQ phases MHD and stochastic thermal transport. (b) DIII-D simulation [Strauss 2022] showing total pressure and normal edge magnetic perturbation as a functions of time. There are two TQ rates: slow, then fast.

The slow phase could be the growth time of a RWTM:

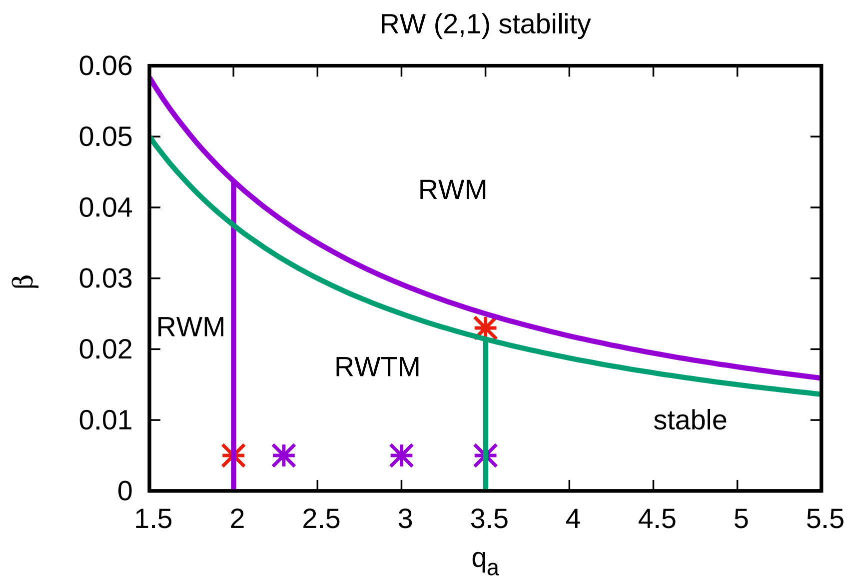
$$\tau_{MHD} = \tau_A S^{1/3} S_{wall}^{4/9} \propto a^{4/3} \tag{1}$$

In large $S_{wall}$ devices, $\tau_{MHD} \sim \tau_{wall} \propto a$. The scaling does not fit ITER. The fast phase is parallel thermal transport,

$$\tau_{\|} = a^2/(\pi R v_{Te} b_n^2) \propto a \tag{2}$$

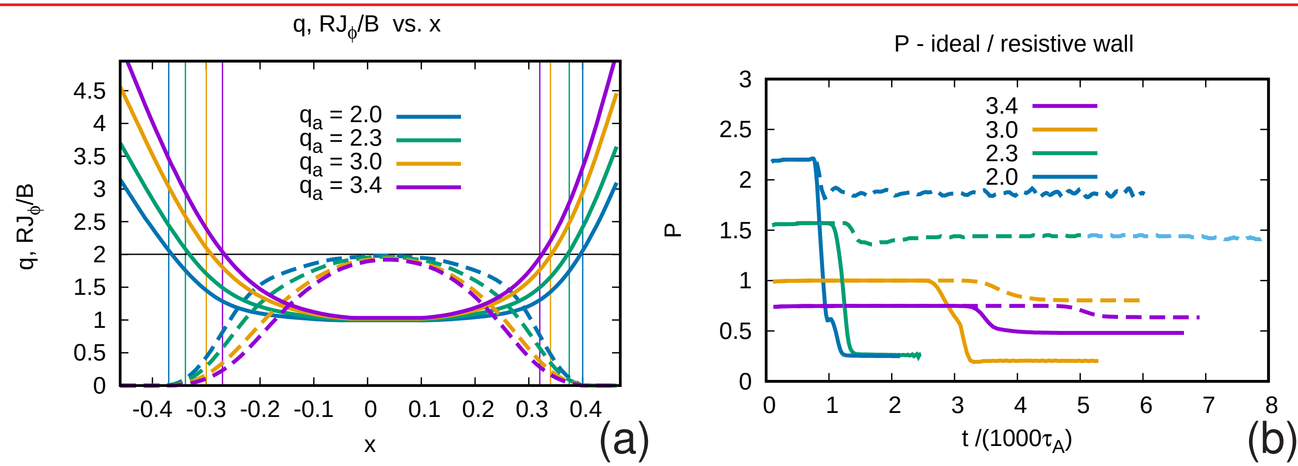
where $b_n = B_n/B \approx 10^{-2}$ [Devries 2016] , $a = 1m$, $T_e = 1KeV$, giving $\tau_{\|} \approx 0.1ms$.

# RWTM occurs at low and high $\beta$




Schematic RWM and RWTM parameter space $(q_a, \beta)$ of RWM and RWTMs. The RWM is limited by $q_a = 2$, and approximately by the Troyon limit $\beta_N$. The RWTM is limited by $2 < q_a < 3.5$ at low $\beta$, with stable region is $q_a > 3.5$ and at high $\beta \le \beta_{RWM}$. The labeled points correspond to the low $\beta$ examples on the next slides, followed by a high $\beta$ case. Both low and high $\beta$ RWTM and RWM can be stabilized by feedback.

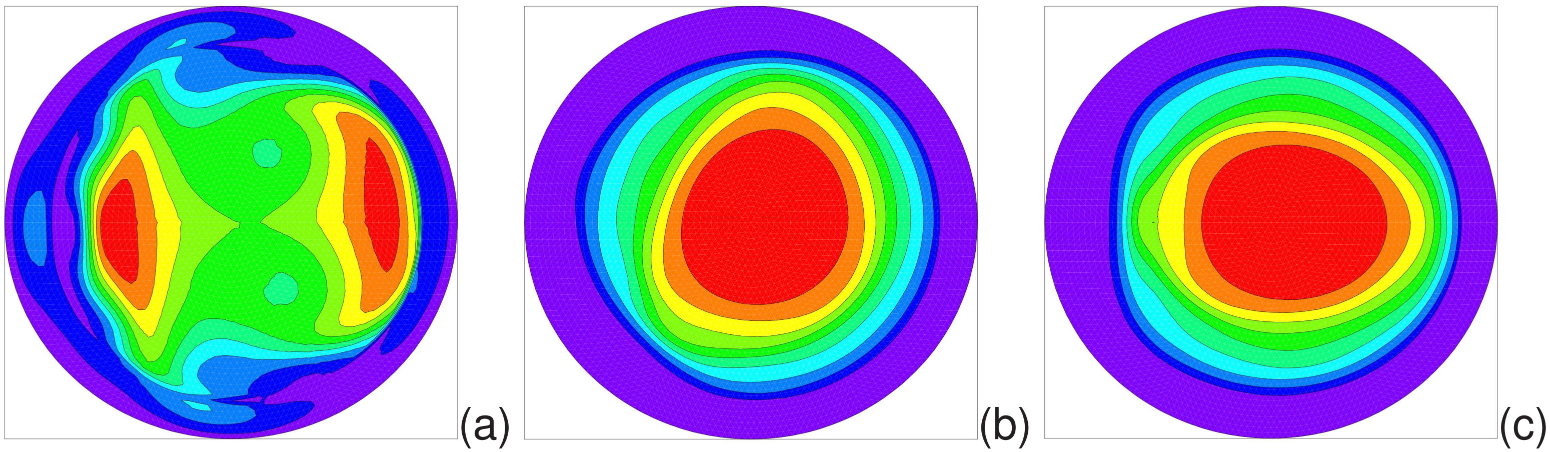
# Low $\beta$ equilibrium sequence has major disruptions only for resistive wall




A sequence of low $\beta$ equilibria [Strauss 2023b] prepared from MST reconstructions, with $r_w/r_a = 1.2$ like DIII-D, ITER. (a) $q$ and current profiles, $2 \leq q_a \leq 3.4$. corresponding to the previous schematic. (b) Time history of total pressure $P$ in nonlinear M3D simulations with different $q_a$. Solid lines have a resistive wall, while dashed curves have an ideal wall. There are no major disruptions with an ideal wall, indicating that major disruptions are RWTMs. For $q_a = 3.4$, there are no major disruptions even for a resistive wall.

RWTMs cause major disruptions in this model for $q_a < 3.4$.

# Mode amplitude much larger with resistive instead of ideal wall

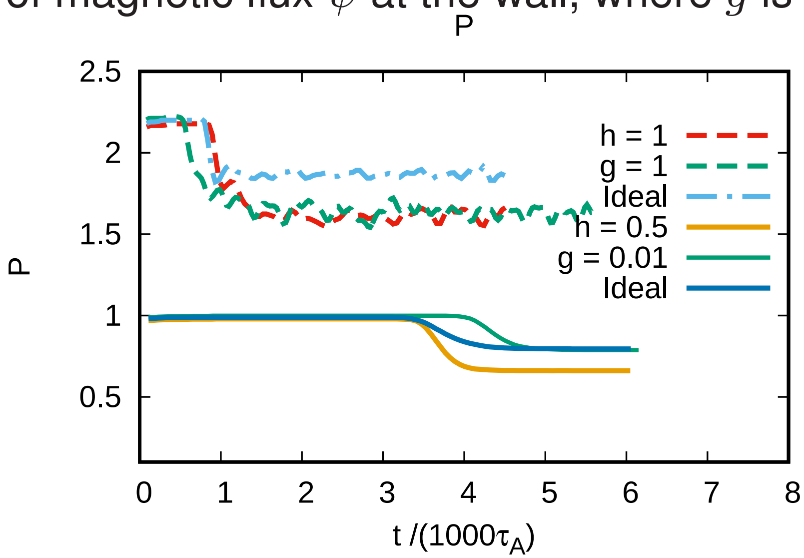



Simulations of disruptions with $q_a = 3$ from previous equilibria: (a) resistive wall showing pressure $p$ contours with large $(2, 1)$ island structure, (b) ideal wall $p$ contours with small $(2, 1), (3, 2)$ amplitude. (c) $p$ contours for the same case, using feedback stabilization.

Ideal wall limits growth of tearing mode. Resistive wall allows TM to reach much larger amplitude. Ideal wall: minor disruption; resistive wall: major disruption [Strauss, 2023b]. Feedback is similar to ideal wall [Strauss, Chapman, Lyons, NF (2024)].

# Feedback stabilization of low $\beta$ RWTM

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 magnetic flux $\psi$ at the wall, where $g$ is the normal gain, $h$ is the transverse gain.



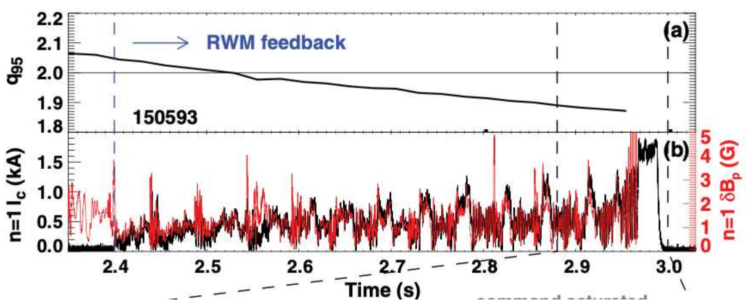

Nonlinear simulations with $q_a = 2$ (dashed curves) and $q_a = 3$ (solid curves) from previous equilibrium sequence. Curves are plotted with feedback $h = 1, 0.5$ with $g = 0$; and $g/S_{wall} = 1, 0.01$, with $h = 0$. These values prevent major disruptions but not minor disruptions. In the simulations less gain is needed for $q_a = 3$ than for $q_a = 2$.

Feedback makes the wall effectively ideal, preventing major disruptions.

An example with $q_a = 3, g = .01$ shown on previous slide.

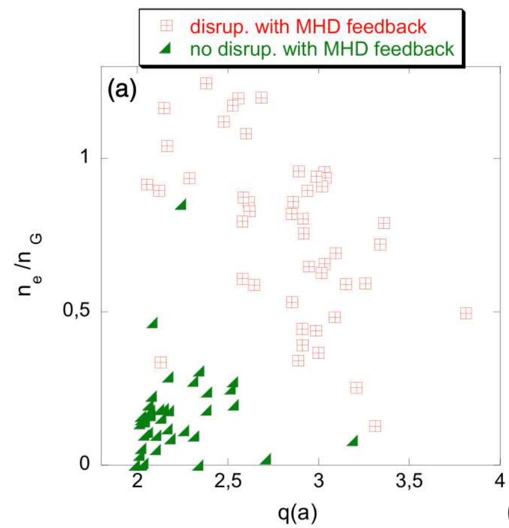
# RWM and RWTM feedback experiments

Feedback experiments on DIII-D and RFX [Hanson 2014,Piovesan 2014] showed stabilization of with RWM with $q_a = 2$. [Zanca 2015] studied RWTM with $q_a > 2$.




(a)

(a) DIII-D feedback stabilization [Piovesan, 2014] with $q_{95} < 2$. feedback coil saturated and major disruption occurred. It was also stabilized for $q_{95} > 2$.

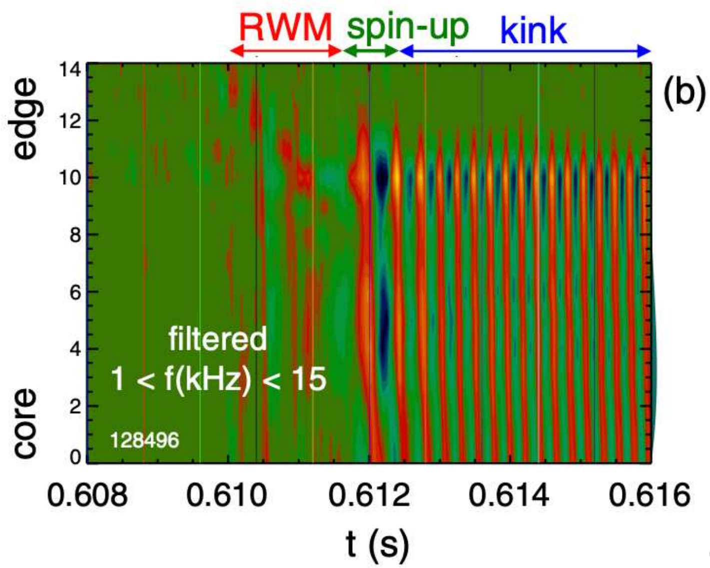



(b)

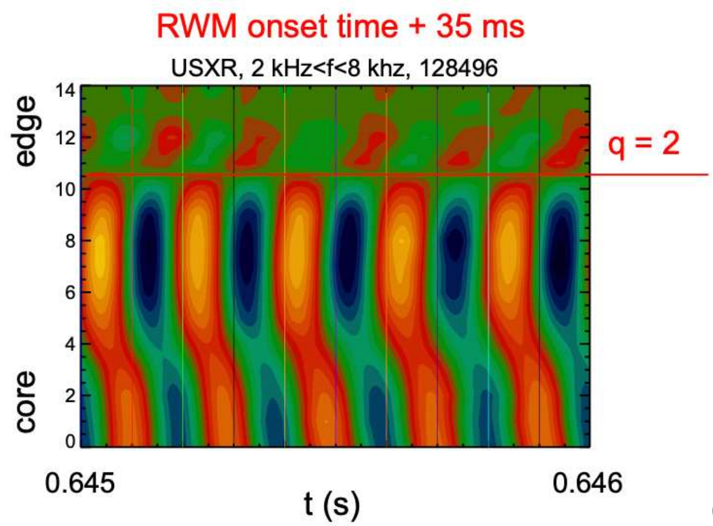
RFX - mod - feedback experiments [Zanca 2015] In RFX - mod, could get feedback stabilization for $q_a \leq 3.2$, but only at low $n/n_G$.
In contrast, MST operated at $10 n_G$.

# High $\beta$ NSTX RWM - RWTM

RWM and RWTM can be found together at high $\beta$. Both can be feedback stabilized.



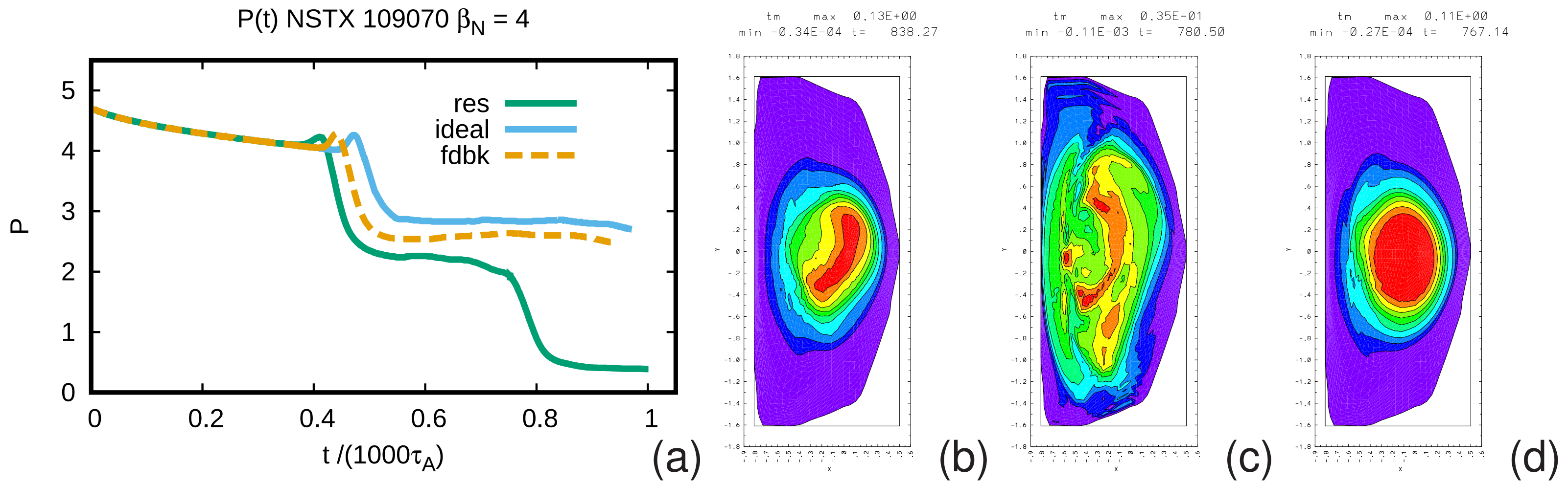
(a)



(b)

In this NSTX example, with $\beta_N > 4$, above the no wall limit, time dependent SXR shows radial mode structure. (a) locked RWM is stabilized by feedback. It then spins up and converts to a stabilized external kink, then finally becomes (b) a feedback stabilized $(2, 1)$ RWTM. The RWTM can be identified by its phase inversion at the $q = 2$ rational surface [Sabbagh *et al.* , NF (2010)].

# High $\beta$ NSTX simulations




In this example, based on NSTX 109070, $\beta_N = 4$, near no wall limit. (a) Time histories of total pressure $P$ with ideal wall; resistive wall; and feedback (in progress). Internal disruption is caused by $(3, 2)$ and $(2, 1)$ modes. With resistive wall, there is a major TQ caused by predominately $(2, 1)$ RWTM. Contours of pressure are shown for $\beta_N = 4$ for (b) ideal wall; (c) resistive wall; (d) feedback.

# Summary

- The wall determines whether a disruption is minor or major. Theory, simulation, and experimental data suggest that major disruptions are caused by resistive wall tearing modes (RWTM), RWMs with rational surface in the plasma, and RWMs.

- RWTM slows the TQ in ITER to $\sim 100ms$, long enough for detection and less mitigation, less REs.

- Two phase disruptions could be slow RWTM followed by fast parallel transport. Flux surfaces do not break until the RWTM grows to sufficiently large amplitude.

- RWTM can cause major disruption for $q_a \lesssim 3.4$.

- RWM and RWTM are observed at high $\beta$, as well as low $\beta$.

- RWM and RWTM can be stabilized by feedback, enough to change a major to a minor disruption, similar to the effect of a conducting wall.