Thermal quench in ITER locked mode disruptions

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Theory and Simulation of Disruptions Workshop

Disruptions in ITER could be much milder in ITER than in JET and present experiments. Disturbances – disruption precursors rather than disruptions.

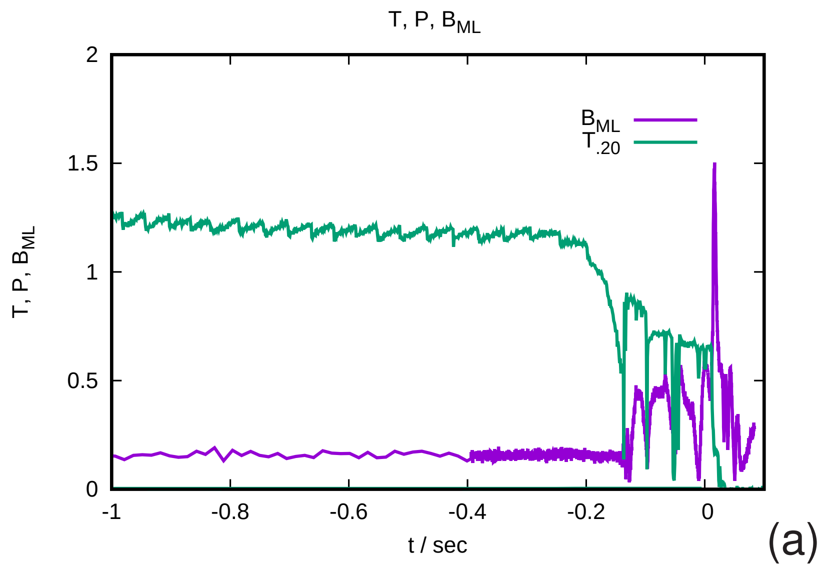
• JET Locked mode TQ is caused by resistive wall tearing mode (RWTM)

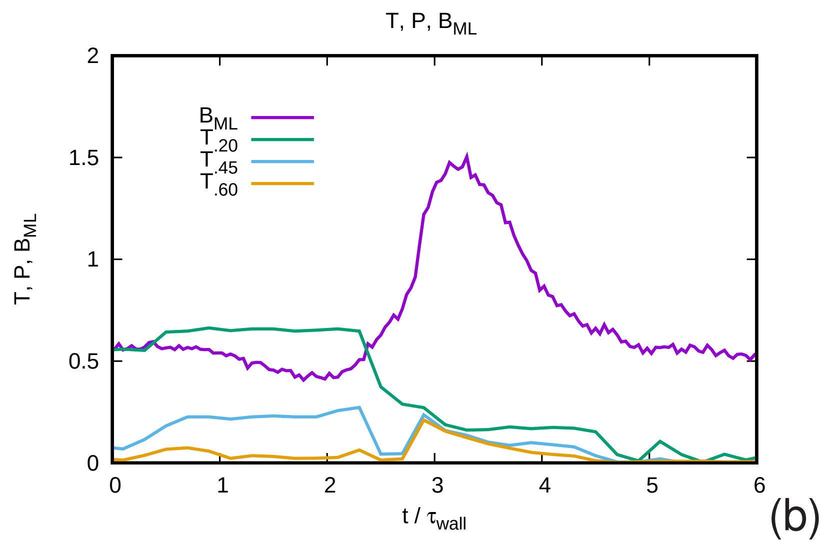
H. Strauss and JET Contributors, Effect of Resistive Wall on Thermal Quench in JET Disruptions, Phys. Plasmas **28**, 032501 (2021)

• ITER is designed to suppress RWM and RWTM, TQ time can be 10 - 100 times longer than in JET

H. Strauss, Thermal Quench in ITER Locked Mode Disruptions, Phys. Plasmas **28** 072507 (2021); https://doi.org/10.1063/5.0052795

Resolving the TQ in JET





Cause of TQ has not been established previously. Island overlap? Large (2,1) island? history of a JET locked mode disruption shot 81540 (a) precursor, time in s, (b) TQ, time in units of wall time $\tau_{wall} = 5ms$.

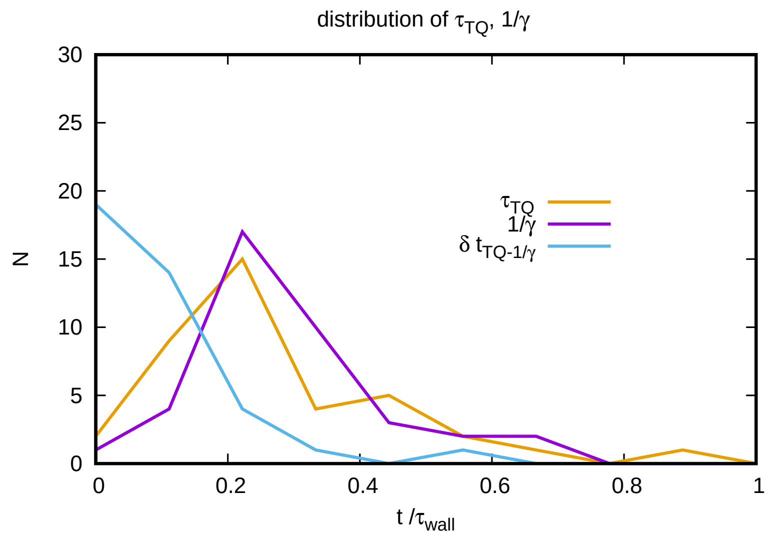
The TQ is caused by the growth of a single mode on a timescale $\tau_{TQ} \approx 1/\gamma \approx 0.3\tau_{wall} = 1.5ms$. Simulations and theory suggest it is a resistive wall tearing mode (RWTM).

RWTM growth rate is

$$\gamma\tau_A = c_0 S^{-1/3} S_{wall}^{-4/9} \tag{1}$$

where $S_{wall} = \tau_{wall}/\tau_A$.

JET Locked mode shot 81540 is representative

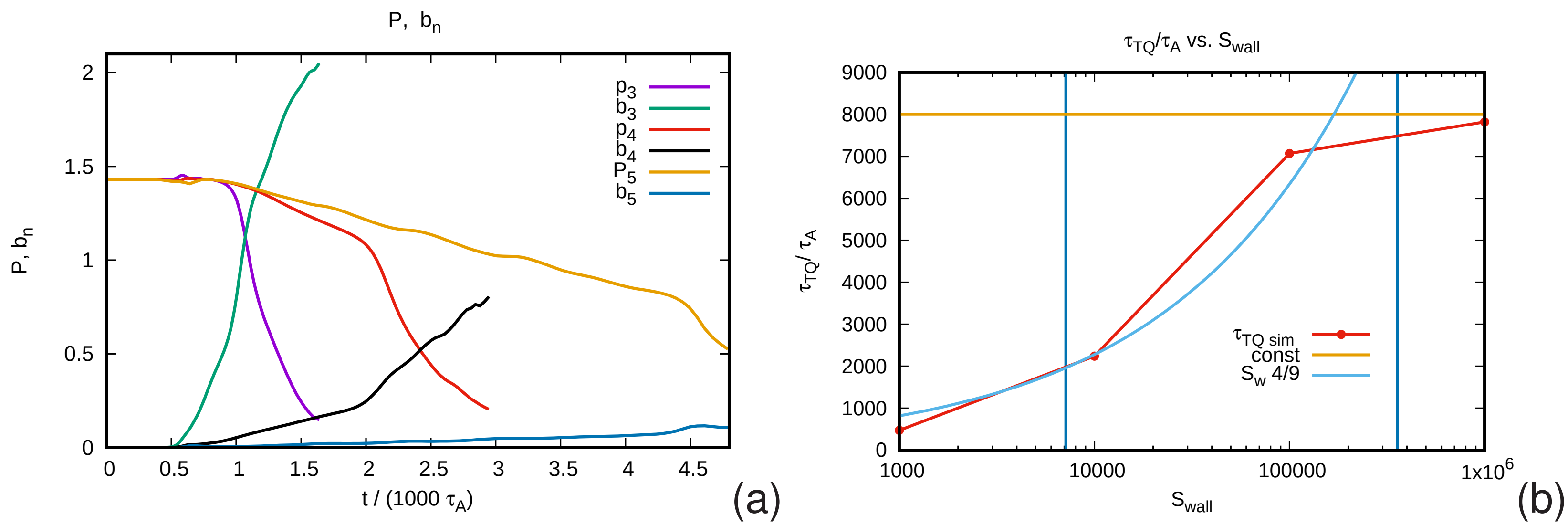


Most JET disruptions are locked mode, this shot is typical

Distribution of τ_{TQ} and $1/\gamma$ for shots in the JET ILW 2011-2016 database that were unintentional disruptions, where ECE temperature data was verified.

Not included: VDEs, MGI, pellets, Also shown is the difference $|\tau_{TQ} - 1/\gamma|$ for each each shot.

Simulations show the TQ depends on τ_{wall} in JET.



(a) time history of total P and wall magnetic perturbations b_n for M3D simulations with $S_{wall} = 10^3, 10^4, 10^5$.

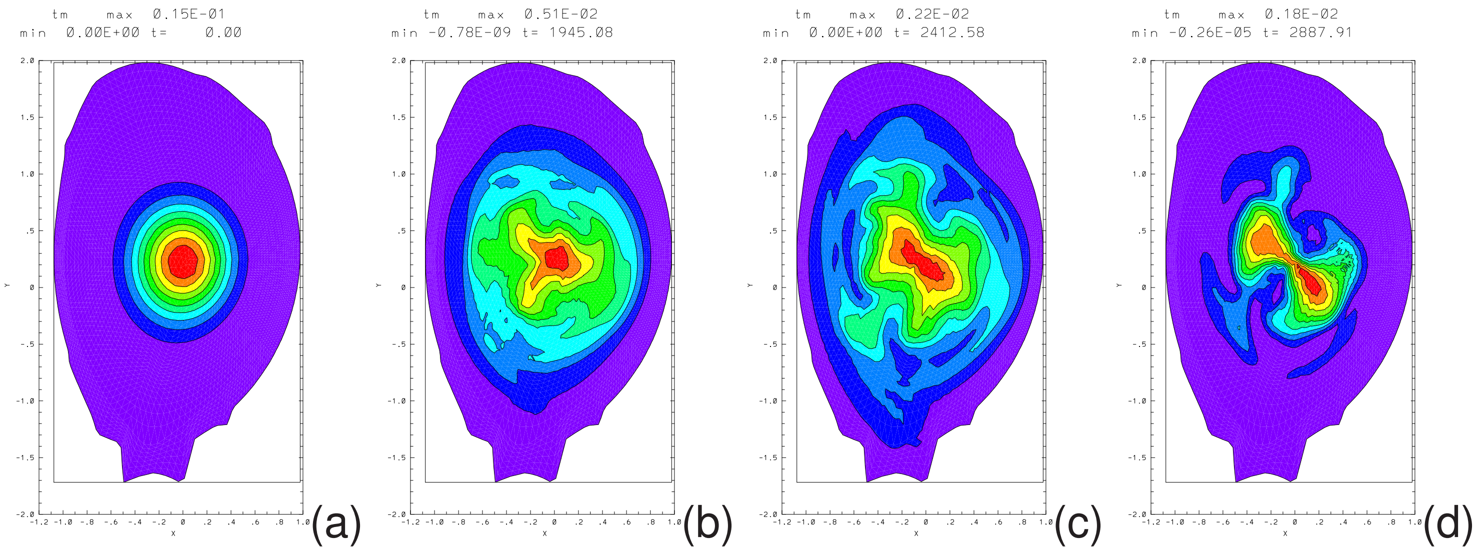
(b) τ_{TQ} in Alfvén time units as a function of S_{wall}. The curve is fitted to a RWTM growth time. For large S_{wall} the RWTM not important and τ_{TQ} is independent of S_{wall}. Left vertical line is JET value, right is ITER.

TQ time is

$$\tau_{TQ} \approx \left(\frac{1}{\gamma}, \frac{a^2}{\chi_{\|} b_n^2} \right)_{min} \tag{2}$$

Simulations and theory: $c_0 \sim 1$, $b_n \sim 10^{-3}$

RWTM causes large scale advection



Simulation of JET shot 81540, with $S_{wall} = 10^4$. (a) initial temperature T. (b) temperature T at $t = 1945\tau_A$, showing $(2,1)$ and $(3,2)$ magnetic perturbations. At this time $P \approx 70\%$ of its initial value. (c) T at $t = 2428\tau_A$. At this time $P \approx 30\%$ of its initial value. (d) T at $t = 2888\tau_A$, at the end of the simulation. Advection explains why mode growth time is TQ time.

RWTM Theory

RWTM branches from a marginally stable tearing mode. The linear growth rate of the tearing mode is

$$\gamma \tau_A = 0.55 \left(\frac{mq' r_s}{q^2} \right)^{2/5} (\Delta' r_s)^{4/5} S^{-3/5} \tag{3}$$

where r_s is the rational surface and m is the poloidal mode number. with no toroidal current for $r > r_s$. Let $\Delta' = \Delta'_0$ if the wall is an ideal conductor. Including resistive wall at $r = r_w$,

$$\Delta' r_s = \Delta'_0 r_s + \frac{4m^2 f}{\gamma \tau_{wall}}. \tag{4}$$

where

$$f = \frac{(r_s/r_w)^{2m}}{[1 - (r_s/r_w)^{2m}]^2} \tag{5}$$

$$\gamma \tau_A = c_0 S^{-1/3} S_{wall}^{-4/9}, \qquad c_0 = 2.46 \left(\frac{mq' r_s}{q^2} \right)^{2/9} f^{4/9} \tag{6}$$

TQ Theory

Thermal transport in stochastic magnetic field is modeled as

$$\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r(\chi_{\parallel} b_r^2)\frac{\partial T}{\partial r} \tag{7}$$

where b_r is the normalized asymmetric radial magnetic field, assuming circular flux surfaces for simplicity. Integrating in r, the total temperature is

$$\frac{\partial < T >}{\partial t} = a\chi_{\parallel} b_n^2 T' \tag{8}$$

where $< T >= \int T r dr$, and assume that $T'/ < T >= -a^{-3}$. The normal magnetic field at the wall is $b_n = b_{n0} \exp(\gamma t)$ where b_{n0} is the initial amplitude, and γ is the RWTM growth rate.

Integrating in time, from $t = 0$ to τ_{TQ},

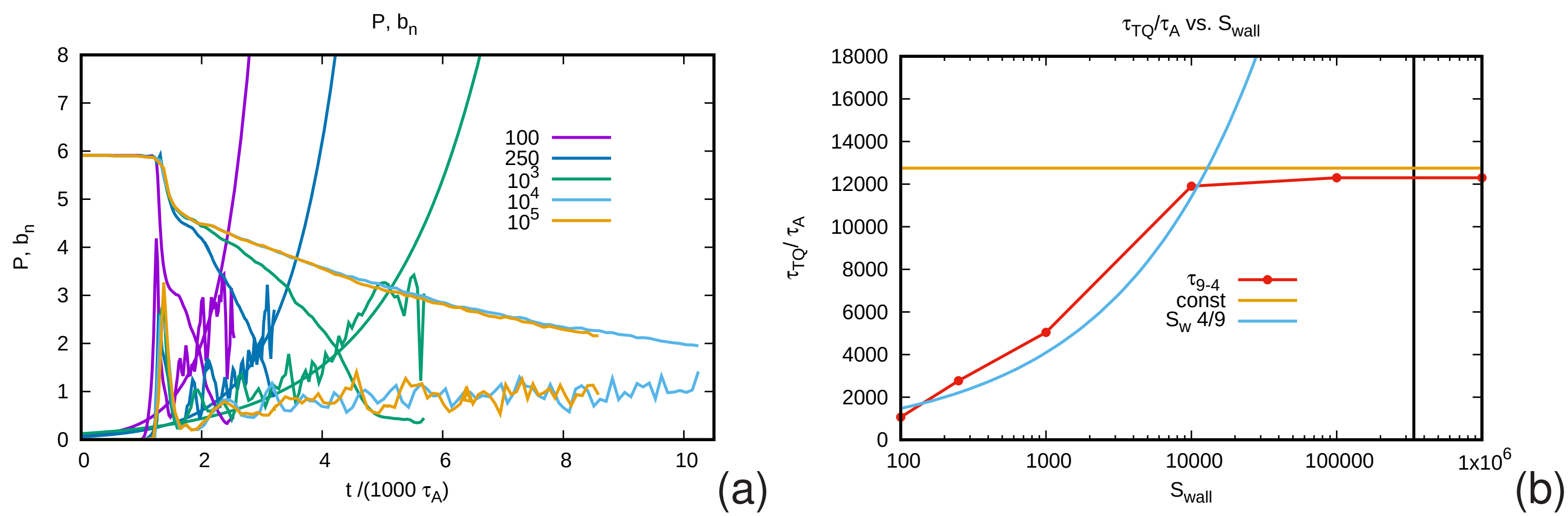
$$1 = \frac{\chi_{\parallel} b_n^2}{2\gamma a^2}[\exp(2\gamma\tau_{TQ}) - 1] \tag{9}$$

An *ad hoc* fit to (9) and simulations is given by (2).

$$\tau_{TQ} \approx \left(\frac{1}{\gamma}, \frac{a^2}{\chi_{\parallel} b_{n0}^2}\right)_{min}$$

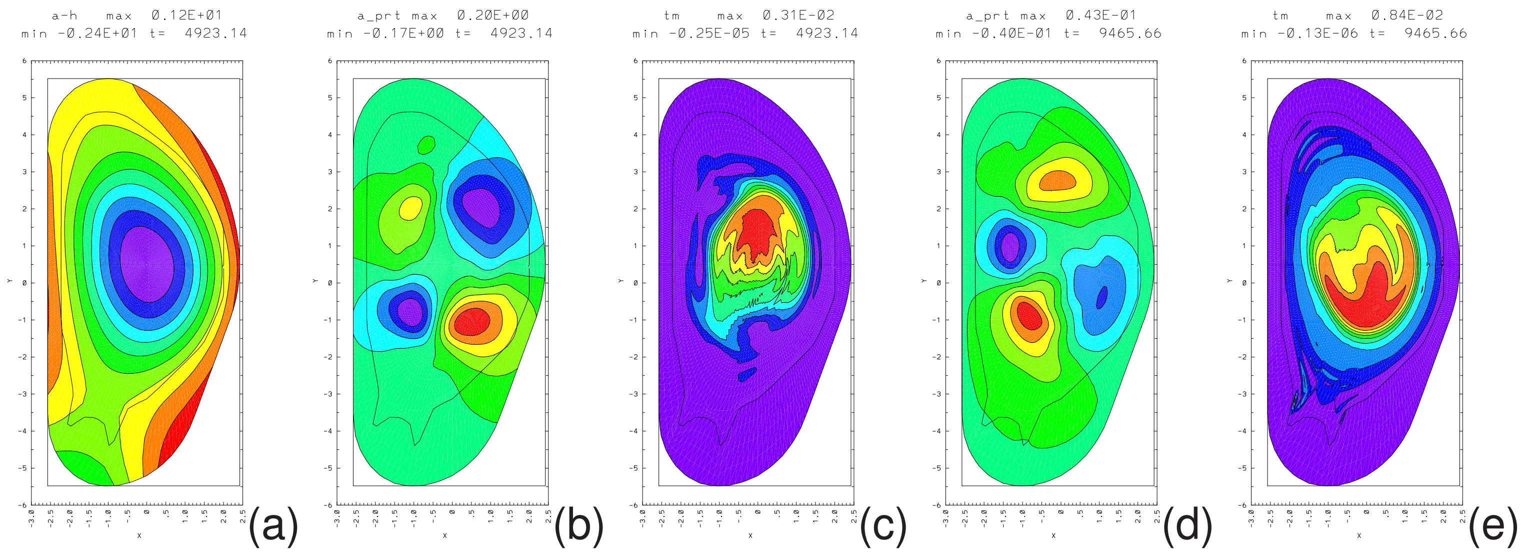
RWTM in ITER simulations

ITER was designed to be stable to RWM – and RWTM. $\tau_{wall}^{ITER} = 50\tau_{wall}^{JET}$.



M3D simulations of TQ, initialized with ITER inductive Scenario 2 15 MA, with $S_{wall} = 10^2 - 10^6$. (a) total pressure P and magnetic perturbations b_n vs. time, with fits to $b_n \propto \exp(c_1 S_{wall}^{-4/9} t)$. Find $c_0 = 0.6$ (b) τ_{TQ}/τ_A vs. S_{wall}. The fits are $\propto S_{wall}^{4/9}$ and constant. The vertical line is the ITER S_{wall}.

ITER simulations - RWTM or precursor

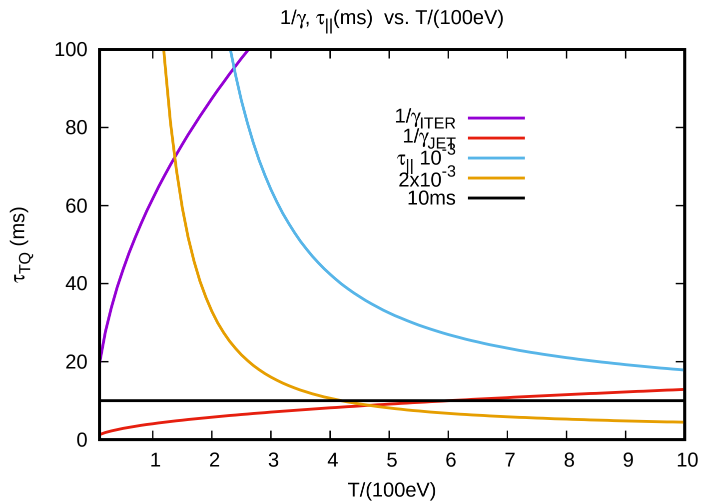


(a) ITER simulation, ψ at time $t = 4923\tau_A$, $S = 10^6$, $S_{wall} = 10^3$. (b) perturbed $\tilde{\psi}$, (c) T at $t = 4923\tau_A$. The $\tilde{\psi}$ contours penetrate the outer wall. (d) $S_{wall} = 10^4$, $\tilde{\psi}$, and (e) T at $t = 9465\tau_A$. The $\tilde{\psi}$ contours penetrate the outer wall only slightly. ITER is in precursor regime. RWTM is too slow.

ITER - TQ prediction

Analytic formulas can be used with realistic parameters to predict ITER TQ time. Parallel thermal conduction depends strongly on edge temperature, which is not known yet. Parallel thermal conduction with collisional and collisionless [Rechester,Rosenluth,1978] limits (mean free path $>$ connection length)

$$\frac{1}{\gamma\tau_A} = \frac{1}{c_0} S^{1/3} S_{wall}^{4/9}, \qquad \tau_\parallel = \frac{a^2}{\chi_\parallel b_n^2}, \qquad \chi_\parallel = \frac{\pi R v_e}{1 + \pi R/(2.1 v_e \tau_e)} \tag{10}$$



τ_{TQ} with ITER parameters. $1/\gamma$ for ITER and JET, $\tau_\parallel$ with model (10), $b_n = 10^{-3}$ from simulations and [Devries, 2016], and $b_n = 2 \times 10^{-3}$ island width $w = 0.3a$ model.

If the edge is collisional there are no disruptions, only disturbances! JET locked modes are caused by edge cooling, which removes current from $q > 2$ edge region.

If edge is collisionless, TQ caused by precursor, but still can be slow. Can cool the edge to produce collisional disruption

ITER Implications

- Locked mode disruptions depend on edge temperature
- Collisional regime, TQ time controlled by RWTM, self mitigating, probably no runaway electrons, no need for pellet injection, . . . ! Edge cooling by radiation, density limit
- Collisionless regime, TQ time controlled by internal modes, classical disruption, but can have TQ time $> 20ms$. edge heating might stabilize precursors

Future Work

- simulate DIIID locked mode disruptions
- other disruptions
  - other experiments
  - ITER advanced scenarios
  - high β_N, expect RWM $\tau_{TQ} = 1/\gamma = \tau_{wall}$.

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