Effect of Resistive Wall on Thermal Quench

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HRS Fusion

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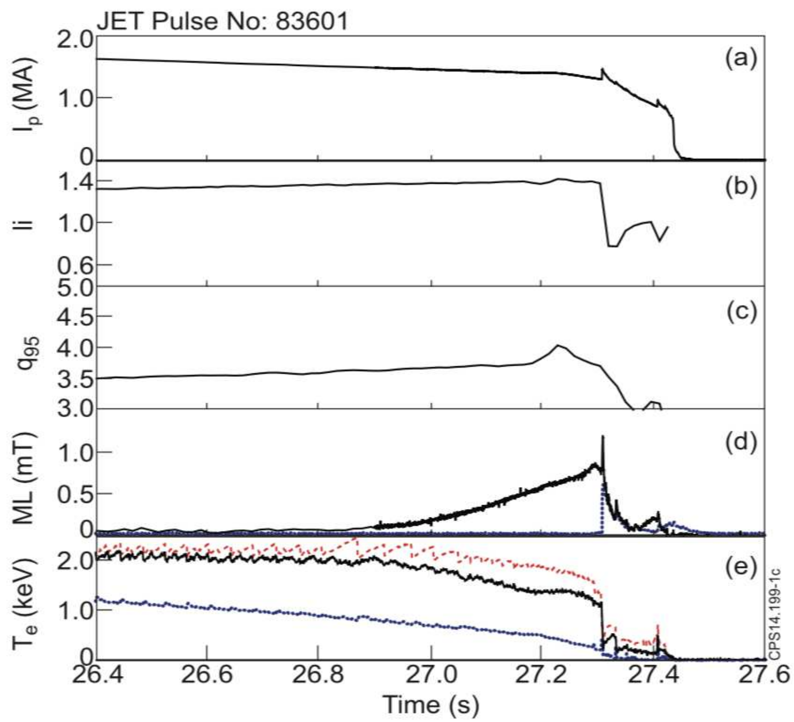
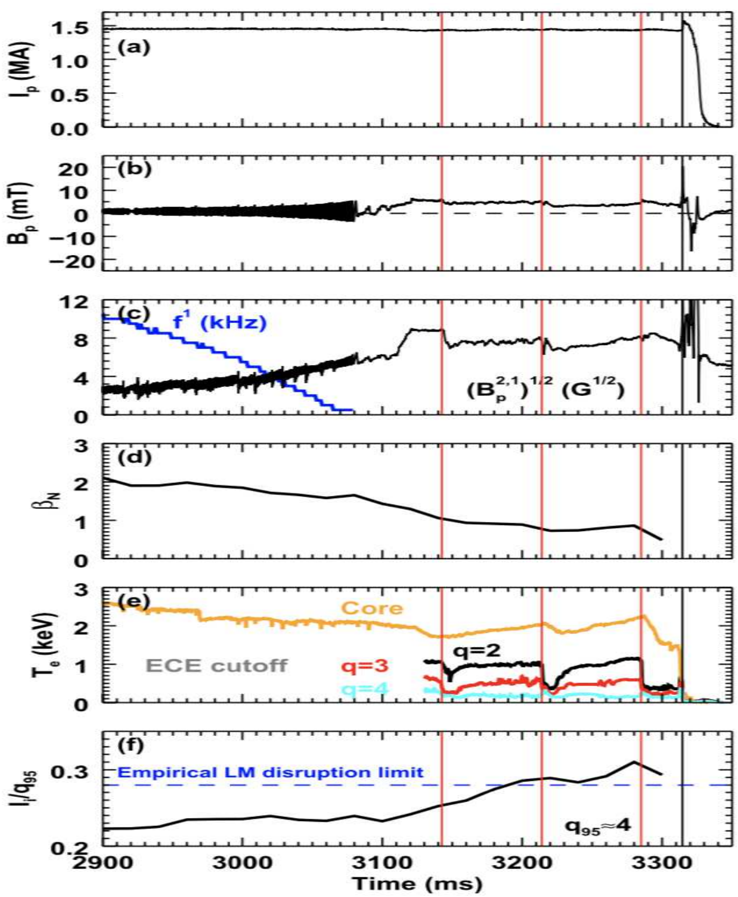
H. Strauss, Thermal Quench in ITER Disruptions, Phys. Plasmas *submitted (2021)*

TQ in locked mode disruptions is a fast event, $\tau_{TQ} \sim 1ms$. It is preceded by a slower "minor disruption" caused by tearing modes. What causes the fast termination TQ? What happens to the fast TQ in ITER?

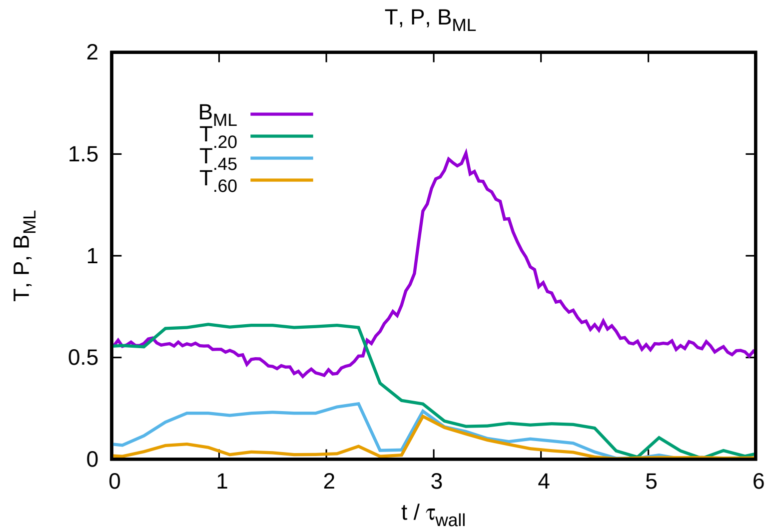


[Devries 2016, JET]



[Sweeney, 2018, DIIID]

Resolving the TQ in JET



history of a JET locked mode disruption with time in units of wall time $\tau_{wall} = 5ms$. (The same as in DIIID).

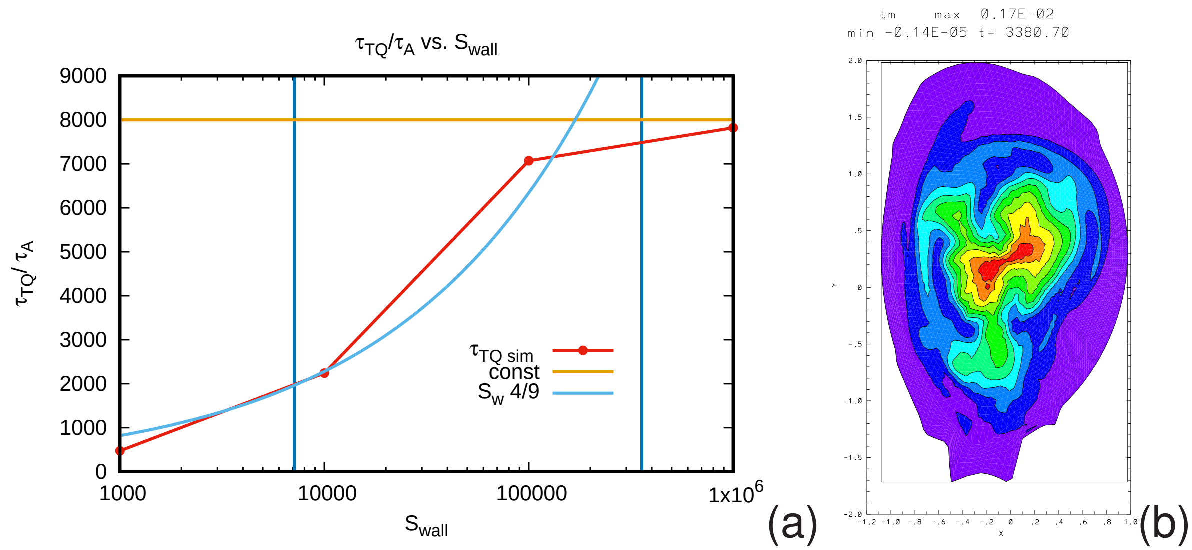
The TQ is caused by the growth of a single mode on a timescale $\tau_{TQ} \approx 1/\gamma \approx 0.3\tau_{wall} = 1.5ms$. Simulations and theory suggest it is a resistive wall tearing mode (RWTM).

RWTM growth rate is

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

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

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



(a) 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 (and DIIID) value, right is ITER. (b) T.

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 Theory

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. Zero pressure circular large aspect ratio geometry is assumed, with no toroidal current for $r > r_s$. Assume that $\Delta' = 0$ if the wall is an ideal conductor, Then

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

where

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

Substituting in the tearing dispersion relation (3) gives (1), with $m = q = 2$, where

$$c_0 = 2.46\left(\frac{q'r_s}{q}\right)^{2/9} f^{4/9} \tag{6}$$

TQ Theory

During the TQ, heat travels along stochastic magnetic field as

$$\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r(\chi_{\|} b_r^2 + \kappa_{\perp})\frac{\partial T}{\partial r} \tag{7}$$

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

$$\frac{\partial < T >}{\partial t} = a(\chi_{\|} b_n^2 + \kappa_{\perp})T' \tag{8}$$

where $< T > = \int Trdr$, $T' = \partial T/\partial r$ at $r = a$, and $b_n = b_r$ at the wall. 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.

Substituting for b_n in (8) and integrating in time, from $t = 0$ to τ_{TQ},

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

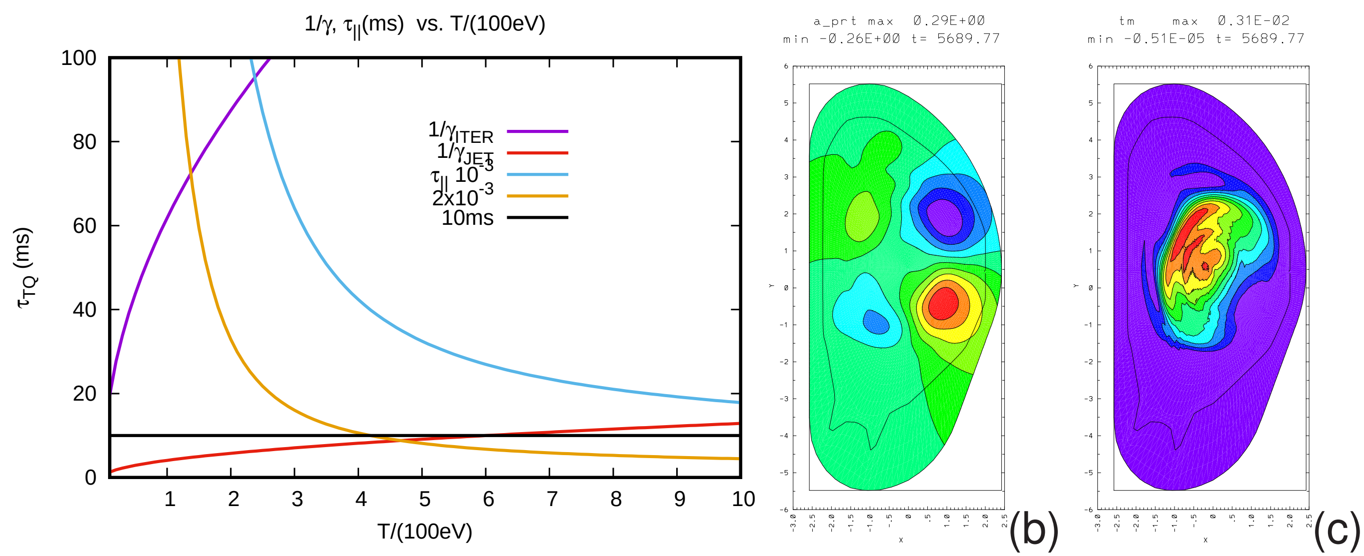
An *ad hoc* fit to (9) and simulations is given by (2).

ITER

In ITER, RWTM is much more stable. $\tau_{wall}^{ITER} = 50\tau_{wall}^{JET}$.

Parallel thermal conduction with collisional and collisonless [Rechester,Rosenluth,1978] limits

$$\chi_{\parallel} = \frac{\pi R v_e}{1 + \pi R/(2.1 v_e \tau_e)} \tag{10}$$



τ_{TQ} with ITER parameters. $1/\gamma$ for ITER and JET, (2) with model (10), $b_n = 10^{-3}, 2\times 10^{-3}$. (b) $\tilde{\psi}$, (c) T.

Collisional regime, TQ limited by RWTM, self mitigating.

Collisionless regime, RWTM unimportant - standard model disruption.

ITER Implications

- Locked mode disruptions will be different in ITER than in JET, DIIID
- Collisional regime, TQ time controlled by RWTM, self mitigating
- Collisionless regime, TQ time controlled by internal modes, standard model

Future Work

- simulate DIIID locked mode disruptions
  - Sweeney NF 58, 056022 (2018), shot 154576
  - minor or precursor part of disruption simulated with NIMROD, ideal wall
  - major disruption not simulated, need resistive wall time $\approx 5ms$, like JET
- ITER disruptions with MGI-type edge cooling in progress
- non locked mode disruptions: high β, other scenarios?