Slow thermal quench in ITER disruptions

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Disruptions are a serious problem in tokamaks, in which thermal and magnetic energy confinement is lost. It was not known what instability causes disruptions, and how to avoid them. Recent work identified the thermal quench (TQ) in JET locked mode disruptions with a resistive wall tearing mode (RWTM) [1, 2]. A similar instability is found in DIII-D locked mode shot 154576 [3, 4]. The RWTM instability is studied with simulations, theory, and comparison to experimental data. Linear theory and simulations show the mode is stable for an ideal wall, and unstable with a resistive wall. Nonlinear simulations show that the mode grows to large amplitude, causing a thermal quench. The RWTM occurs when the $q = 2$ surface is sufficiently close to the plasma edge. These results are important for ITER, greatly mitigating the effects of disruptions. The thermal quench time might be two orders of magnitude longer than in presnt experimrnts.

Fig. 1 shows data from DIII-D shot 154576 [4]. The upper panel shows the temperature T_e on a core flux surface, and the lower panel shows magnetic perturbations. The TQ time is $\tau_{TQ} = 2.5ms \approx .5\tau_{wall}$ where the resistive wall penetration time is $\tau_{wall} = 5ms$. The TQ time is approximately the growth time $1/\gamma$ of an $n = 1$ mode. Before the TQ occurs, there are low amplitude precursors, identified as tearing modes (TM) [4].

The linear dispersion relation [1, 3, 9] includes TMs and RWTMs. The dispersion relation is given by

$$\hat{\gamma}^{5/4} S^{3/4} = \Delta_i + \frac{\Delta_x}{\hat{\gamma} S_w + 1} \tag{1}$$

where $\hat{\gamma} = \gamma\tau_A$, S is the Lundquist number, $S_w = S_{wall}(1 - x_s^{2m})/(2m)$, $S_{wall} = \tau_{wall}/\tau_A$, internal drive $\Delta_i = r_s\Delta'_w/m$, external drive $\Delta_x = 2x_s^{2m}/(1 - x_s^{2m})$, $x_s = (r_s/r_w)$, poloidal mode number m, rational surface radius r_s, wall minor radius r_w. The external drive is the difference between the no wall and ideal wall stability parameter.

Ideal wall TMs have $\Delta_i > 0$, $\Delta_x = 0$. Resistive wall tearing modes have $\Delta_i \leq 0$. For $\Delta_i = 0$ and large S_{wall}, their growth rate scales asymptotically as $S_{wall}^{-4/9}$. For $\Delta_i < 0$ the growth rate scales asymptotically as S_{wall}^{-1}.

Linear stability of the equilibrium reconstruction of this shot was studied using the M3D-C1 [5] code, with a resistive wall [6]. The reconstruction had safety factor $q > 1$ to avoid the $(1, 1)$ mode from dominating the simulations. Fig. 2(a) shows the growth rate as a function of $S_{wall} = \tau_{wall}/\tau_A$, where τ_A is the Alfvén time. Two additional curves are shown from linear

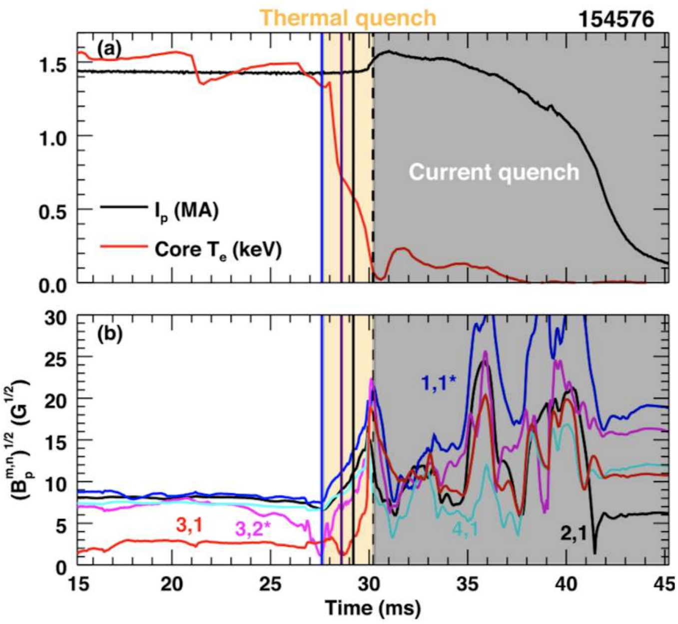

Figure 1: *DIII-D shot 154576 [4], where the upper panel shows the temperature T_e on a core magnetic surface, and the lower panel shows magnetic perturbations. The TQ time $\tau_{TQ} = .5\tau_{wall} = 2.5ms \approx 1/\gamma$, where γ is mode growth rate, and $\tau_{wall} = 5ms$. Figure reproduced from [4] with IAEA permission.*

theory (1), with $S_{wall}^{-4/9}$ and S_{wall}^{-1} asymptotic scaling.

Fig. 2(b) shows the perturbed magnetic flux ψ, showing a $(2,1)$ structure. Fig. 2(c) shows perturbed magnetic flux ψ, when the wall is ideally conducting. In this case the mode is stable. This shows that the mode is not an ideal wall TM. The curves in Fig. 2 have $\Delta_x = 1$ and are RWTMs with $\Delta_i = 0$, and $\Delta_i = -0.5$. If $\Delta_x + \Delta_i \leq 0$, there are no unstable solutions of (1).

Nonlinearly, the RWTM grows to large amplitude, sufficient to cause a thermal quench. Fig. 3 shows a simulation with M3D [7] with a resistive wall [8], of the same equilibrium reconstruction of DIII-D 154576. The simulation had $S_{wall} = 10^4$, and on axis $S = 10^6$. Experimentally, $S_{wall} = 1.2 \times 10^4$. The initial magnetic flux ψ is shown in Fig. 3(a), and the perturbed ψ is in Fig. 3(b), at a time late in the simulation, when the TQ is almost complete. The perturbed ψ still has the linear structure of Fig. 2(b). The pressure, shown at the same time in Fig. 3(c) has a large perturbation that causes the TQ. The pressure plot is shown when the total pressure P is about 20% of its initial value. The reason the mode grows to large amplitude may be the external drive. TMs have internal drive which depends on the current profile. Growth of an island flattens the current gradient and stabilizes the TM at a moderate amplitude. The external drive Δ_x depends only on r_s/r_w, independent of island size. It is not saturated by local flattening of

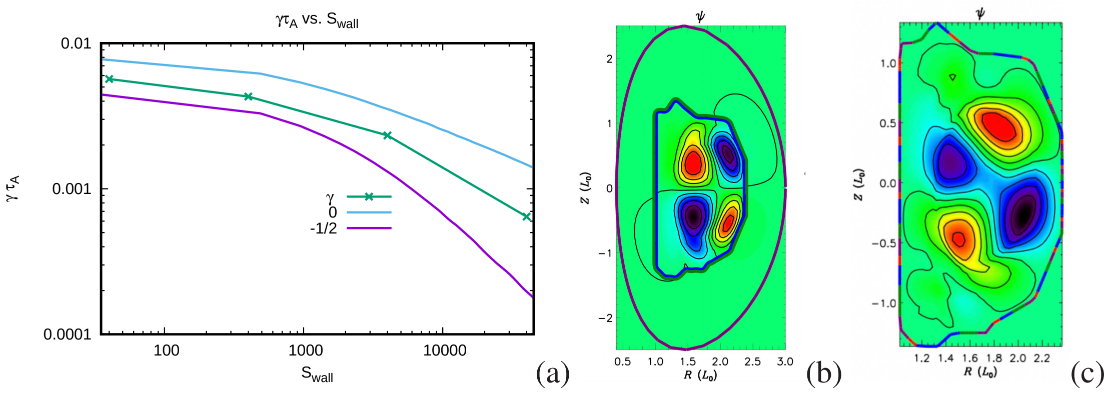

Figure 2: *(a) $\gamma\tau_A$ in DIIID shot 154576 as a function of S_{wall} from M3D-C1 linear simulations. The fits are to RWTMs with $S_{wall}^{-4/9}$ and S_{wall}^{-1} asymptotic scaling, from the linear dispersion relation. (b) perturbed ψ in (a). The mode is $(2,1)$. and penetrates the resistive wall. (c) ideal wall. The mode is stable.*

the current profile. It saturates by driving the $q = 2$ surface to the origin, $r_s = 0$. This is evident from the $m = 2$ structure in p near the axis in Fig. 3(c).

The onset condition for RWTMs is $\Delta_i < 0$. Using a step function current equilibrium model [9], this condition is $x > (2/q_0)^{1/2}(q_0 - 1)^{1/4}$, where q_0 is the value of q on axis. Taking $q_0 = 1.05$, the onset condition is $x > 0.625$. Physically, the disruption occurs when the $q = 2$ surface is sufficiently close to the plasma edge.

These results are very favorable for ITER disruptions. The ITER resistive wall time, $250ms$, is 50 times longer than in JET and DIII-D. The TQ time, instead of being $1.5 - 2.5ms$ in JET and DIII-D respectively, could be $75 - 125ms$, assuming the TQ is produced by a RWTM with S_{wall}^{-1} scaling. If the TQ is caused by a RWTM with $S_{wall}^{-4/9}$, and the edge temperature is $500eV$, then $\tau_{TQ} = 70ms$.

To summarize, theory and simulations were presented of resistive wall tearing modes, in an equilibrium reconstruction of DIII-D shot 154576. The simulations found that the equilibrium was stable with an ideally conducting wall, and unstable with a resistive wall. Solutions of the linear tearing mode dispersion relation with a resistive wall were presented. The RWTMs grow to large amplitude nonlinearly. The onset condition for disruptions is that the $q = 2$ surface is close enough to the plasma edge.

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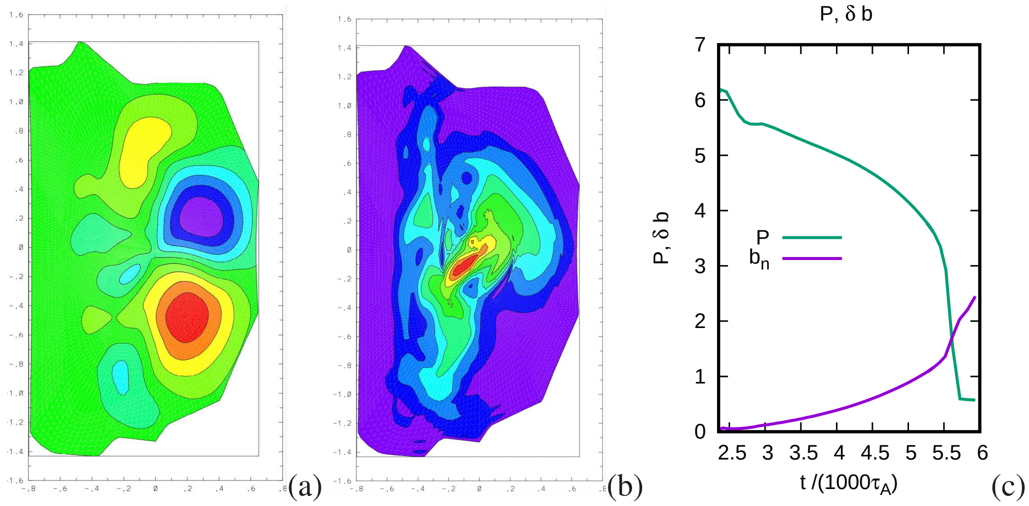

Figure 3: *(a) perturbed* ψ *at* $t = 5690\tau_A$, $S_{wall} = 10^4$. *(b)* p *at* $t = 5690\tau_A$. *when* P *is about 20% of its initial value. (c) time history of volume integrated pressure* P*, and perturbed radial magnetic field at the wall* b_n*, normalized to toroidal field.*

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