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ABSTRACT

We evaluate the accuracy of the Porcelli sawtooth model using more realistic numerical models from the ORBIT-RF and GATO codes in DIII-D fast wave heating experiments. Simulation results confirm that the fast wave-induced energetic trapped particles may stabilize the sawtooth instability. The crucial kinetic stabilizing contribution strongly depends on both the experimentally reconstructed magnetic shear at the $q = 1$ surface and the calculated poloidal beta of energetic trapped particles inside the $q = 1$ surface.

In tokamak discharges, the central plasma becomes unstable to the ideal internal kink mode (toroidal $n = 1$ and dominant poloidal $m = 1$ mode) when q_0 (central safety factor) drops below 1. The resulting sawtooth instability may significantly degrade the central plasma heating and confinement. In addition, sawtooth (ST) crashes after a giant ST period may easily trigger other magnetohydrodynamic (MHD) modes such as tearing modes, as observed in the Joint European Torus (JET) [1] and DIII-D tokamaks [2]. Therefore, suppression or delay of the ST has been a critical issue for present tokamak plasmas as well as for burning plasma experiments such as ITER.

In the Porcelli ST model [3], the total perturbed potential energy in the presence of a trapped ion population is expressed as $\delta\hat{W} = \delta\hat{W}_{MHD} + \delta\hat{W}_{fast} + \delta\hat{W}_{KO}$. The ideal perturbed MHD potential energy, associated with the internal kink displacement, $\delta\hat{W}_{MHD} < 0$, can be stabilized by non-ideal kinetic contributions from trapped fast ions ($\delta\hat{W}_{fast} > 0$) and trapped thermal ions ($\delta\hat{W}_{KO} > 0$). The Porcelli ST model using simplified expressions for the three contributions in $\delta\hat{W}$ has been extensively tested against a variety of sawtoothing tokamak discharges and found to predict average ST periods reasonably well. But, its accuracy has not been well tested quantitatively as a predictor of the actual crash time in a specific ST cycle in a specific discharge. The present work is intended to evaluate the accuracy of the Porcelli ST model using more realistic numerical models for $\delta\hat{W}_{MHD}$ and $\delta\hat{W}_{fast}$, and address the ST stabilization effect of trapped fast ion population in DIII-D FW heating experiments. We evaluate $\delta\hat{W}_{MHD}$ numerically from the ideal stability code GATO using EFIT reconstructed DIII-D equilibria. For the comparison of our numerical models with previous ST modeling we also evaluate $\delta\hat{W}_{MHD}$ using the formula obtained from fitting to numerical calculations by Martynov [4]. This is expressed as $\delta\hat{W}_M = 0.45\ \varepsilon_1\kappa_1/1{+}7\varepsilon_1 s_1\ (\beta_{p1} - \beta^*_{pc})$ with $\beta^*_{pc} = 0.7–0.5\ \kappa_1$. In particular, the linear dependence on $(\beta_{p1} - \beta^*_{pc})$ and the weak dependence on the shear at the $q = 1$ surface $s_1 = r\ (dq/dr)$ with no pole at $s_1 = 0$ are notable; the formula used in the original 1996 Porcelli model based on the Bussac ideal kink used $\delta\hat{W}_B \sim \kappa_1/\varepsilon_1 s_1\ (\beta^2_{p1} - \beta^{*2}_{pc})$. In the present work, $\delta\hat{W}_{fast}$ is evaluated using the Hamiltonian Monte-Carlo guiding center drift code ORBIT-RF [5] coupled with wave solutions computed from the 2D full wave code TORIC [6], which is expressed by $\delta\hat{W}_{fast} = c_f\,\varepsilon_1^{3/2}\beta_{ph}/s_1$ with $c_f \sim 1$. ORBIT-RF/TORIC computes the poloidal beta of trapped ions inside the $q = 1$ surface (β_{ph}),

$$\beta_{ph} = -\frac{2\mu_0}{B_p^2}\int_0^1 x^{3/2}\frac{dp_h}{dx}\,dx = \frac{2\mu_0}{B_p^2}\left[\int_0^{\psi_{p1}}\psi_p^{-1/4}\,p_h\,d\psi_p \Big/ \int_0^{\psi_{p1}}\psi_p^{-1/4}\,d\psi_p - p\left(\psi_{p1}\right)\right] ,$$

where p_h is the pressure of trapped ions, and ψ_{p1} the poloidal flux at $q = 1$ surface. Finally, $\delta\hat{W}_{KO}$ is evaluated using the Kruskal-Oberman formula that appears in

Porcelli's previous work [3]. This is given by $\delta\hat{W}_{KO} = 0.6 C_p \varepsilon_1^{1/2} \beta_{i0} / s_1$ with $C_p \equiv (5/2)\int_0^1 x^{3/2} p_i(x)/p_{i0}\, dx$ and $x = r/r_1$.

The DIII-D experiments using neutral beam injection (NBI) and FW have demonstrated beam ions accelerated by FW can significantly modify ST activity. Figure 1 shows the experimental results from DIII-D discharge 96043. The 80 keV deuterium (D) beam ions are injected with P_{NBI} = 2.7 MW. At 1.8 s, the 60 MHz FW is launched with P_{RF} = 1.0 MW. The fourth harmonic resonance of D beam ions is located near the magnetic axis. Measured D-D reaction rates are significantly increased after the FW is turned on, indicating strong acceleration of beam ions above their birth energy due to resonant interactions of beam ions with the FW at 4 Ω_D. The central electron temperature $T_e(0)$ measured from ECE strongly suggests that the FW accounts for the change in ST behavior. Experimentally reconstructed axis safety factor q_0 using the EFIT code with MSE data shows that during the FW heating period, q_0 drops significantly below 1 and returns back to near 1 right before each ST crash. In the present work, we focus our stability evaluation on the first giant ST cycle from 1800 to 2040 ms. During this period, the magnetic shear at the $q = 1$ surface (s_1) increases continuously until the ST crash occurs at about t = 2030 ms. EFIT reconstructed equilibrium analysis finds no $q = 1$ surface at 1800 and 2040 ms. For the stability analysis, we select six equilibria at 1820 ms, 1860 ms, 1900 ms, 1940 ms, 1980 ms and 2020 ms, and evaluate $\delta\hat{W}$ with the calculated ideal ($\delta\hat{W}_{MHD}$) and kinetic contributions ($\delta\hat{W}_{fast}$, $\delta\hat{W}_{KO}$) separately at each equilibrium.

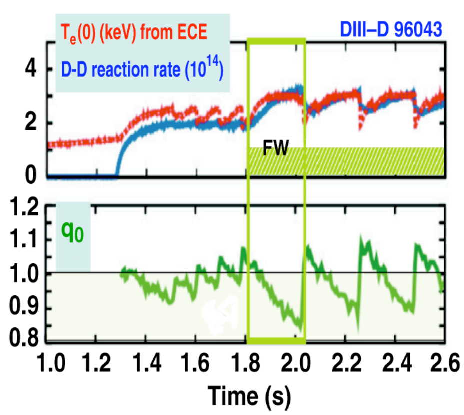

Fig. 1. Time evolutions of $T_e(0)$ from ECE, D-D reaction rates and q_0 in DIII-D discharge 96043.

Figures 2 and 3 summarize the stability results evaluated at the selected equilibria using two different models for $\delta\hat{W}_{MHD}$: GATO (Fig. 2) and the numerically fitted formula by Martynov (Fig. 3). Both models for $\delta\hat{W}_{MHD}$ predict an ideally unstable plasma with $\delta\hat{W}_{MHD} < 0$. However, GATO predicts the equilibria are more unstable than the fitted formula. The results for $\delta\hat{W}_{KO}$ indicate the kinetic effect of thermal trapped ions may be significant in the initial FW heating phase when the fast ion population inside

$q = 1$ is small. But its effect becomes small as the fast ion population increases due to continuous FW heating. For the calculation of β_{ph}, we use 30,000 test particles in the ORBIT-RF code. The calculated β_{ph} shows an uncertainty due to the Monte-Carlo noise associated with the relatively small number of test particles. Therefore, we average β_{ph} over simulation time. This is justified by benchmarking against a simulation with 200,000 particles. In addition, the uncertainty in the experimentally reconstructed s_1 is an important factor in determining the accuracy of $\delta\hat{W}_{fast}$. The error bar marked on $\delta\hat{W}_{fast}$ at 2020 ms in Figs. 2 and 3 represents the uncertainty in $\delta\hat{W}_{fast}$ that is expected from roughly ±30% uncertainties in s_1 and β_{ph}. The calculated β_{ph} increases rapidly in the initial FW heating phase and then saturates once the fast ion population builds up enough in the center of the plasma. During this period, the experimentally reconstructed s_1 increases continuously until the crash time. Therefore, the dependence of $\delta\hat{W}_{fast}$ on β_{ph}/s_1 resuls in a decreasing contribution of $\delta\hat{W}_{fast}$; consequently, $\delta\hat{W}$ decreases. To predict the ST crash at 2030 ms as observed in the experiments, $\delta\hat{W}$ evaluated at 2020 ms (right before crash) should be close to zero. Compared to the ST model using the fitted formula (Fig. 3), the ST model using GATO (Fig. 2) indicates that fast ions play a significant role in stabilizing the plasma against the unstable ideal kink mode during most of the simulated ST cycle and eventually yields $\delta\hat{W}$ much closer to zero at 2020 ms.

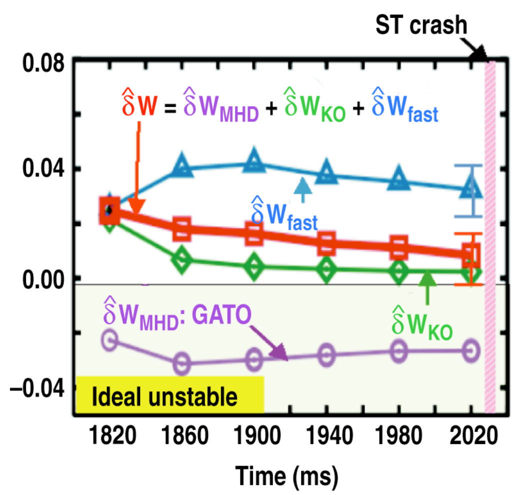

Fig. 2. Simulation result on $\delta\hat{W}$ using GATO for $\delta\hat{W}_{MHD}$ in DIII-D discharge 96043.

To understand the ST instability triggering mechanisms, we applied the ST triggering criteria at six selected times. The ST crashes are triggered when one of the following conditions is met [4]: (1) $-\delta\hat{W}_{core} = -(\delta\hat{W}_{MHD} + \delta\hat{W}_{KO}) > c_h\,\omega_{Dh}\,\tau_A$ or (2) $-\delta\hat{W} = -(\delta\hat{W}_{MHD} + \delta\hat{W}_{KO} + \delta\hat{W}_{fast}) > 0.5\omega_{*i}\,\tau_A$ or (3) $-c_\rho\,\hat{\rho} < -\delta\hat{W} < 0.5\omega_{*i}\,\tau_A$ and $s_1 > s_{crit}$. Here, ω_{Dh} is the average toroidal precession drift frequency of fast ions, computed explicitly from the ORBIT-RF, τ_A is the Alfvén time, ω_{*i} is the thermal ion diamagnetic frequency and $c_h \approx 0.4$. The results demonstrate the first two ST criteria (1) and (2) are not satisfied over the simulated ST cycle in either model for the ideal contribution using the GATO or Martynov result. This implies that the ST crash can only be triggered by the resistive kink instability since the fast ions and thermal ion diamagnetic frequency effects stabilize the ideal kink mode. Figure 4 shows the result of the resistive criteria (3) from the ST model using GATO. This indicates that the resistive criterion is likely satisfied at 2020 ms, consistent with the observed ST crash at 2030 ms. In contrast, in the model using the Martynov formula, even criterion (3) is not satisfied at 2020 ms. It should be noted that the Martynov formula is a parameterization of many simulated cases and is subject to some statistical uncertainty. Nevertheless, this still yields a result within the ballpark of the experimentally deduced marginal stability at the time of the crash.

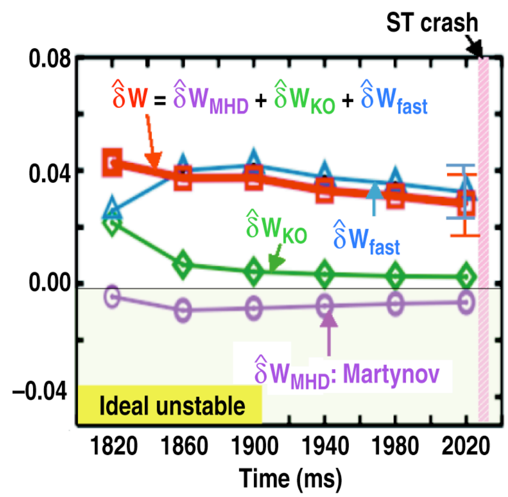

Fig. 3. Simulation results on $\delta\hat{W}$ analysis using Martynov in discharge 96043.

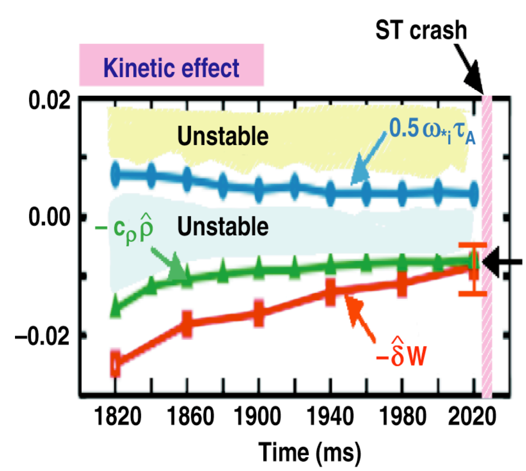

Fig. 4. Results on ST resistive criteria using GATO in discharge 96043.

In summary, the Porcelli ST model using realistic models from the ORBIT-RF and GATO codes, predicts a crash time consistent with the experimental ST crash in DIII-D FW heating experiments. However, the crucial kinetic stabilizing contribution strongly depends on the combined uncertainties in s_1 and $\beta_{ph.}$ To confirm the accuracy of the present ST model using ORBIT and GATO, we plan to investigate more discharges in future work

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