

Effects of Fast Ions Produced by Fast Wave Heating in Neutral Beam Injected Plasma on Sawteeth Activities in the DIII-D Tokamak

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I. Introduction

Theory predicts that high pressure from fast ions in the center of a plasma may act to provide a stabilizing kinetic effect on the ideal internal kink mode involved in sawteeth events. DIII-D experiments have demonstrated strong acceleration of deuterium (D) beam ions above the injected beam energy when 60 MHz fast wave (FW) was launched in a neutral beam (NB) heated plasma [1]. Measured neutron emissions were enhanced up to a factor of two during rf heating. Signals from the Doppler shifted D_α fast-ion diagnostic also showed a significant increase when the rf pulse turns on. Simulations predicted beam ion tails to reach a few hundred keV. In this paper, we evaluate the kinetic contribution of beam ion tails generated by fast wave (FW) heating to the ideal magnetohydrodynamic (MHD) potential energy in DIII-D experiments, using δW analysis with Porcelli's model, and numerical solutions from the Monte-Carlo Hamiltonian code ORBIT-RF [2].

II. Theoretical Models

A. Stochastic Resonant Interaction of Ion With FW

The relative phase between FW and ion, defined by $\Delta\phi = \int_t^{t'} [\omega - \omega_c(t) - k_{\parallel} v_{\parallel}(t)] dt$, where the integral follows the drift-orbit trajectory, may become highly stochastic in the resonance region due to decorrelation mechanisms in the plasma. In a collisionless, high temperature plasma, if the wave amplitude is large enough, typical of the power levels in the experiments in consideration, it can be rapidly randomized on a time scale much shorter than thermal ion slowing down time since rapid changes in the particle orbit due to an rf "kick" can lead to sampling of different local cyclotron frequencies (ω_c) and parallel wave number (k_{\parallel}) in $\Delta\phi$. Collisions and multiple waves may provide further decorrelation between successive cyclotron resonance encounters. Therefore, assuming that resonant ions lose their phase information with the FW through collisions and wave stochasticity before they re-enter the resonance region, we model a simplified rf-induced random walk to reproduce the quasi-linear ($Q-L$) diffusion in velocity space where the change of magnetic moment ($\Delta\mu_{rf}$) is expressed by the sum of the mean change ($\overline{\Delta\mu_{rf}}$) and a very rapidly fluctuating change ($\overline{\overline{\Delta\mu_{rf}}}$) [2]. The $Q-L$ diffusion operator appearing in the formulations for $\overline{\Delta\mu_{rf}}$ and $\overline{\overline{\Delta\mu_{rf}}}$ is expressed by

$$D_1(k_{\parallel}) \sim \sum_m \left[E_+^{m'} J_{l-1}(k_{\perp}^{m'} \rho_i) \right]^* \sum_m \left[E_+^m J_{l-1}(k_{\perp}^m \rho_i) \right] ,$$

where J_{l-1} is the $(l-1)$ th order Bessel function of the first kind and $\rho_i = v_{\perp}/\Omega_i = \sqrt{2\mu B/\Omega_i}$. E_+^m is the wave amplitude corresponding to the m th poloidal Fourier mode. The 2D full wave solver TORIC [3] calculates E_+^m (unit current wave field), k_{\perp}^m (perpendicular wave number) and k_{\parallel}^m for each poloidal Fourier mode in (R,Z) coordinate for a given single toroidal mode number. The unit current wave field is rescaled using the experimental input power.

B. δW Analysis Using Porcelli's Model

The ideal MHD potential energy, δW_{MHD} , associated with internal kink displacements plays an important role in determining sawtooth activities. This mode with $\delta W_{\text{MHD}} < 0$ can be stabilized by kinetic effects from fast ($\delta W_{\text{fast}} > 0$) and thermal trapped ions ($\delta W_{\text{KO}} > 0$). Depending on the collisionality regime and the closeness of the plasma to marginal ideal MHD stability boundary, different sawteeth models have been used to model the sawtooth activity in tokamaks. In this paper, we use Porcelli's model [4], which is the most relevant model proposed for ITER. The normalized total potential energy functional can be approximated as $\delta \hat{W} = \delta \hat{W}_{\text{MHD}} + \delta \hat{W}_{\text{fast}} + \delta \hat{W}_{\text{KO}}$. For more accurate evaluation of $\delta \hat{W}$, each term should be calculated by numerical stability and orbit analysis. However, in this paper, we evaluate $\delta \hat{W}_{\text{MHD}}$ and $\delta \hat{W}_{\text{KO}}$ using analytical approximations by Bussac and Porcelli [4], while $\delta \hat{W}_{\text{fast}}$ is calculated numerically using ORBIT-RF. The ideal MHD Bussac term is calculated as $\delta \hat{W}_{\text{Bussac}} = -c_{\text{MHD}} \epsilon_1^2 (\beta_{\text{pl}}^2 - \beta_{\text{pc}}^2)$ and, the shaping contribution from the elongated plasma as $\delta \hat{W}_{\text{el}} = -c_{\text{el}} [(\kappa_1 - 1)/2]^2$ where $c_{\text{MHD}} = 9\pi(l_{11} - 0.5)/s_1$ and $c_{\text{el}} = 18\pi(l_{11} - 0.5)^3/s_1$. The Kruskal-Overman term, $\delta \hat{W}_{\text{KO}}$, is evaluated as $\delta \hat{W}_{\text{KO}} = 0.6c_p \epsilon^{1/2} \beta_{\text{io}}/s_1$. The contribution from this effect only remains valid when the characteristic mode frequency exceeds the thermal ion diamagnetic frequency ($\delta \hat{W}_{\text{KO}} > \omega_{*i} \tau_A$) [4]. The ORBIT-RF code computes $\delta \hat{W}_{\text{fast}} = c_f \epsilon_1^{3/2} \beta_{\text{ph}}/s_1$ where $c_f \sim 1$, p_h is the trapped hot ion pressure and its poloidal beta inside $q=1$ surface is defined by

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

Sawtooth crashes are triggered when one of the following conditions is met [4]: (1) $-\delta \hat{W}_{\text{core}} = -(\delta \hat{W}_{\text{MHD}} + \delta \hat{W}_{\text{KO}}) > c_h \omega_{\text{Dh}} \tau_A$ or (2) $-\delta \hat{W} > 0.5 \omega_{*i} \tau_A$, or (3) $-c_p \hat{\rho} < -\delta \hat{W} < 0.5 \omega_{*i} \tau_A$ and $s_1 > s_{\text{crit}}$ where ω_{Dh} is the average toroidal precession drift frequency of fast ions, computed explicitly from ORBIT-RF, τ_A the Alfvén time, ω_{*i} the thermal ion diamagnetic frequency and $c_h \approx 0.4$.

III. Simulation Results

We select two L-mode DIII-D discharges (122080 and 96043), showing different sawteeth activities during rf heating. Electron cyclotron emission (ECE) diagnostic for $T_e(0)$ indicates for 96043 that the sawtooth amplitude and period become larger and longer as soon as the FW heating turns on. However, for 122080, rf heating does not change significantly the sawtooth behavior. We apply Porcelli's model to the reconstructed discharge equilibria to understand whether the kinetic contribution from energetic beam ions can play a role in stabilizing sawtooth activity. Table I summarizes the heating and relevant sawtooth parameters. In both discharges, the q profile increases monotonically with $q(0) < 1$.

Table I. Heating and Sawtooth Relevant Parameters for 122080 and 96043

Shot No.	P_{NB} (MW)	P_{RF} (MW)	$n_e(0)$ (cm^{-3})	$T_e(0)$ (keV)	$T_i(0)$ (keV)	B(0) (T)	ω_{*i} (rad/s)	ω_{*e} (rad/s)	τ_A (μs)
122080	5.0	1.7	6.8×10^{13}	1.5	1.9	1.8	9.3×10^3	-6.8×10^4	5.4
96043	2.7	1.0	4.7×10^{13}	3.4	2.9	1.9	9.7×10^3	-1.9×10^3	4.4

Deuterium beam ions injected at 80 keV are accelerated to a few hundred keV due to the interaction with the 60 MHz FW at the 4th (96043) and 8th (122080) harmonic resonances located near the magnetic axis. Before rf, the neutral beam injection gives $\beta_{ph} \sim 2.0 \times 10^{-2}$ and $\omega_{Dh} \sim 4.7 \times 10^3$ rad/s for 122080 and $\sim 6.5 \times 10^{-2}$ and $\omega_{Dh} = 3.6 \times 10^4$ rad/s for 96043. With rf, these values are changed to $\beta_{ph} \sim 1.99 \times 10^{-2}$ and $\omega_{Dh} \sim 5.0 \times 10^3$ rad/s for 122080 and $\beta_{ph} \sim 8.0 \times 10^{-2}$ and $\omega_{Dh} \sim 4.0 \times 10^4$ rad/s for 96043. Here, these quantities are time averaged approximately during one slowing down time. For 96043, ω_{Dh} and β_{ph} are increased (10%–20%) after rf heating, while little changes are calculated for 122080. Table II summarizes the three criteria associated with the sawtooth trigger and the values of each term in the $\delta \hat{W}$ analysis in Porcelli's model. For 96043, since the Kruskal-Oberman term $\delta \hat{W}_{KO} < \omega_{*i} \tau_A$, we do not include $\delta \hat{W}_{KO}$ in $\delta \hat{W}$. We find in 96043 that sawtooth instability can be triggered by the third criterion. Result with $\delta \hat{W} > 0$ would suggest that 96043 is stable to the internal kink and that the fast ion contribution is sufficient to stabilize the kink against the ideal MHD term, which is consistent with experimental result.

For 122080, the plasma seems already in the stable regime to ideal kink since $\delta \hat{W}_{MHD} > 0$. Nevertheless, experimental result for 122080 clearly showed that the sawtooth activity does not change even due to the addition of rf power. This discrepancy between experiment and theory may be understood as follows. The model for $\delta \hat{W}$ is based on the assumption that the internal kink mode is in the Bussac regime in which the displacement ξ is a "top-hat" [5]. Figure 1 shows displacements calculated from GATO as a function of the normalized poloidal flux (ψ) for 122080 [Fig. 1(a)] and 96043 [Fig. 1(b)]. Especially for 122080, there is a considerable

departure from this displacement. Note that this appears to be fairly typical of numerically generated equilibria though marginal points are generally well described by the Bussac model. This may reflect the fact that the Bussac analytic model may not be appropriate for the 122080 equilibrium. Analysis with the NOVA-K [6] code may help to resolve this discrepancy.

Table II. Stability Results Using Porcelli's Model for 96043 and 122080

	96043	122080
	$\delta\hat{W}_{\text{KO}} < \omega_{*i}\tau_A$	$\delta\hat{W}_{\text{KO}} > \omega_{*i}\tau_A$
$-\delta\hat{W}_{\text{core}} > c_h\omega_{\text{Dh}}\tau_A$	No	No
$-\delta\hat{W} > 0.5\omega_{*i}\tau_A$	No	No
$-c_{\rho}\hat{\rho} < -\delta\hat{W} < 0.5\omega_{*i}\tau_A, s_l > s_{\text{crit}}$	Yes (trigger on)	No
$\delta\hat{W}_{\text{Bussac}}$ (analytical)	-2.4×10^{-3}	4.2×10^{-3}
$\delta\hat{W}_{\text{el}}$ (analytical)	-1.4×10^{-3}	-1.1×10^{-3}
$\delta\hat{W}_{\text{MHD}}$ (analytical)	-3.8×10^{-3}	2.9×10^{-3}
$\delta\hat{W}_{\text{KO}}$ (analytical)	Not valid	1.5×10^{-2}
$\delta\hat{W}_{\text{fast}}$ (ORBIT-RF)	1.0×10^{-2}	6.6×10^{-3}
$\delta\hat{W} = \delta\hat{W}_{\text{MHD}} + \delta\hat{W}_{\text{fast}} + \delta\hat{W}_{\text{KO}}$	6.2×10^{-3}	2.5×10^{-2}

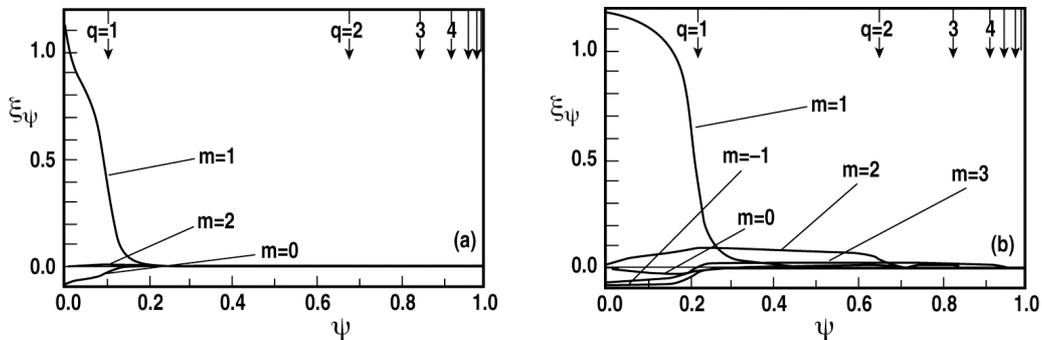


Fig. 1. Displacements calculated from GATO as a function of ψ for (a) 122080 and (b) 96043.

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