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Modelling of Sawtooth Stabilisation by Beam–Injected Energetic Particles in JET

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1. Introduction

Stabilisation of sawteeth due to α–particles or ion cyclotron resonance heating (ICRH) is well–established experimentally and understood theoretically [1]: it arises from third adiabatic invariant conservation for trapped fast ions precessing around the torus in a time shorter than the $m = 1$ internal kink mode period. This mode has frequency $\omega \sim \omega_{*i}$, the bulk ion diamagnetic frequency, and so stabilisation requires $\omega_{Dh} \gtrsim \omega_{*i}$, where ω_{Dh} is the fast ion precession frequency. In JET this condition is easily satisfied by ICRH ions with energies $\mathcal{E} \sim$ MeV; for NBI ions with $\mathcal{E} \lesssim 100$ keV it is generally only marginally satisfied. Clear evidence for NBI stabilisation of sawteeth has nevertheless been found, for example in TEXTOR [2]. In recent JET discharges, with beam injection energies of up to 140 keV, sawtooth periods $\tau_{\rm saw} \sim 500$ ms have been observed. To investigate the processes determining $\tau_{\rm saw}$ in these discharges we have used a transport code (PRETOR) to implement a model that was developed to predict the sawtooth period in ITER [3] and has been applied successfully to TCV [4]. The value of $\tau_{\rm saw}$ in any Next Step device is likely to have a strong bearing on plasma performance: for example, crashes following long sawtooth periods can give rise to seed magnetic islands that trigger neoclassical tearing modes [5].

2. JET experiments

In the JET shots considered here the beam power $P_{\rm NBI}$ was gradually ramped up [6]. In shot 53593, for example, with plasma current $I_p = 2$ MA and toroidal field $B_0 = 2.48$ T, there was a linear rise and decay in $P_{\rm NBI}$ (Fig. 1). The use of relatively low $P_{\rm NBI} < 5$ MW and high B_0 kept the plasma in L–mode throughout the heating phase, with the line–average electron density n_e evolving symmetrically in time. The time trace of electron temperature T_e in Fig. 1 corresponds to a position inside the sawtooth inversion radius. There is a rise in $\tau_{\rm saw}$ from 50–80 ms in the ohmic phase to 500 ms at the time of peak $P_{\rm NBI}$. Discharges with both symmetric and asymmetric $P_{\rm NBI}(t)$ waveforms have been analysed: in all cases $\tau_{\rm saw}$ is correlated with the fast ion energy content $W_{\rm fast}$, evaluated using a steady–state Fokker–Planck code (PENCIL).

[†] See annex of J Paméla et al., "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001)

3. Sawtooth period model

The dimensionless internal kink energy functional $\delta\hat{W}$ is defined such that

$$\delta\hat{W} = -\gamma\tau_A\,, \quad \tau_A = \sqrt{3}R_0/c_A,$$

in the ideal limit, where γ is the growth rate, R_0 is major radius and c_A is the Alfvén speed. A sawtooth crash is assumed to occur when any one of three conditions is satisfied [3,7]:

$$-\delta\hat{W}_{\rm core} > c_h\omega_{Dh}\tau_A, \tag{1}$$

$$-\delta\hat{W} > \frac{1}{2}\omega_{*i}\tau_A, \tag{2}$$

$$-c_\rho\hat{\rho} < -\delta\hat{W} < \frac{1}{2}\omega_{*i}\tau_A, \tag{3a}$$

$$\text{and} \quad \max(\gamma_\rho, \gamma_\eta) > c_r\left(\omega_{*i}\omega_{*e}\right)^{1/2}. \tag{3b}$$

In Eq. (1) $c_h \simeq 0.4$ and $\delta\hat{W}_{\rm core} = \delta\hat{W}_{\rm MHD} + \delta\hat{W}_{\rm KO}$ where $\delta\hat{W}_{\rm MHD}$ is the ideal MHD contribution and $\delta\hat{W}_{\rm KO}$ arises from collisionless trapped bulk ions. A fast particle term $\delta\hat{W}_{\rm fast}$ is also included in $\delta\hat{W}$. In Eq. (3) $c_\rho \sim c_r \sim 1$, $\hat{\rho} = (\rho_i^2 + \rho_s^2)^{1/2}/r_1$, where ρ_i is ion Larmor radius, ρ_s is the same quantity evaluated using T_e rather than ion temperature and r_1 is the minor radius at which the safety factor $q = 1$, γ_η and γ_ρ are growth rates applicable in the resistive and ion kinetic régimes respectively [3], and ω_{*e} is electron diamagnetic frequency. When Eq. (1) or Eq. (2) is satisfied the internal kink has an ideal mode structure. Equation (3) applies when the mode is non–ideal. If the resistive scale length $\delta_\eta > \rho_i$, resistive MHD is applicable; if $\rho_i > \delta_\eta$, ion kinetic effects cannot be neglected. In our case $\rho_i(\sim 0.4\text{cm}) > \delta_\eta(\sim 0.2\text{cm})$, and so the ion–kinetic régime applies. Reconnecting modes are unstable when the drive overcomes diamagnetic stabilisation [Eq. (3b)]. Both γ_η and γ_ρ involve s_1, the magnetic shear at $q = 1$, and so the trigger is equivalent to $s_1 > s_{1\,\rm crit}$, where $s_{1\,\rm crit}$ depends on whether the resistive or ion kinetic régime applies. When a trigger condition is satisfied, profiles are relaxed in PRETOR according to the Kadomtsev complete reconnection model.

4. Numerical computation of $\delta\hat{W}_{\rm fast}$

We have computed $\delta\hat{W}_{\rm fast}$ perturbatively for specified times using the NOVA–K code [8], which includes finite orbit width and finite Larmor radius (FLR) effects, realistic flux surface geometry and plasma rotation. The beam distribution $f_{\rm b}$ was computed using the TRANSP code [9] and fitted using $f_{\rm b} = f_v f_{P_\varphi} f_\chi$, where v is speed, P_φ is canonical toroidal momentum, and $\chi = (v_\perp^2/v^2)(B_0/B)$, $v_\perp$ being velocity perpendicular to the magnetic field. The factor f_{P_φ}, taken from TRANSP, represents essentially the radial variation of $f_{\rm b}$, while f_v is assumed to be a slowing–down distribution. The pitch angle factor f_χ is assumed to be of the form $f_\chi = \exp[-(\chi - \chi_0)^2/\Delta_\chi^2]$. TRANSP gives $\chi_0 \simeq 0.5$, while Δ_χ is determined by the slowing–down characteristic $v^3 = (v_{\rm cr}^3 + v_{\rm b0}^3)\exp(-3t/\tau_{\rm se}) - v_{\rm cr}^3$, where $v_{\rm b0}$ is beam injection speed, $v_{\rm cr}$ is the critical speed, and $\tau_{\rm se}$ is the slowing–down time. The pitch–angle diffusion coefficient is $D_{\chi\chi} = v_{\rm cr}^3/(\tau_{\rm se}v^3)$, and we can write

$$\Delta_\chi^2 = \Delta_0^2 + \int_0^t D_{\chi\chi}dt' = \Delta_0^2 + \frac{1}{3}\,\ln\left[\frac{v^3\,(1 + v_{\rm cr}^3/v_{\rm b0}^3)}{v^3 + v_{\rm cr}^3}\right]. \tag{4}$$

In general, $\delta\hat{W}_{\rm fast}$ is sensitive to Δ_χ when $\Delta_\chi < 1$ (Fig. 2). NOVA–K computations of $\delta\hat{W}_{\rm fast}$ can be compared with those obtained using an expression applicable to isotropic ions in the limit of zero orbit widths and $1 - q \to 0$, $dq/dr \to 0$ inside $q = 1$ [10]:

$$\delta\hat{W}_{\rm fast} = -\frac{\beta_{0\,\rm fast}}{\sqrt{2}s_1\epsilon_1^{1/2}}\int_0^{r_1}\left(\frac{r}{r_1}\right)^{3/2}\frac{d\hat{p}_{\rm fast}}{dr}dr, \tag{5}$$

where $\epsilon_1 = r_1/R_0$, $\beta_{0\,\rm fast}$ is the fast ion beta at $r = 0$, and $\hat{p}_{\rm fast}$ is the fast ion pressure profile. When the fast particles are isotropic Eq. (5) underestimates $\delta\hat{W}_{\rm fast}$ by a factor ~ 2, but when anisotropy and FLR effects are taken into account the discrepancy is always less than 15%. We can thus use Eq. (5) in PRETOR modelling of the sawtooth cycle, with $\hat{p}_{\rm fast}$ and $\beta_{0\,\rm fast}$ given by the PENCIL code.

5. Comparison between theory and experiment

For five JET pulses we have computed the time evolution of all the quantities in Eqs. (1–3), taking data directly from the available diagnostics. Figure 3 shows results obtained for shots 50725 and 53593. In both shots $-\delta\hat{W}_{\rm core} < 0.4\omega_{Dh}\tau_A$ and $-\delta\hat{W} < 0.5\omega_{*i}\tau_A$ at all times, indicating stabilisation of the ideal kink mode. In every discharge $\tau_{\rm saw}$ starts to increase because fast ions cause $-\delta\hat{W}$ to be smaller than $-\hat{\rho}$, thereby stabilising the resistive internal kink mode. Before the NBI power ramps, $\tau_{\rm saw}$ is almost constant ($\lesssim 100\,$ms), and Eq. (3a) is satisfied during the sawtooth ramp: a crash occurs when s_1 exceeds the critical value, and $\delta\hat{W}_{\rm fast}$ plays no role in determining $\tau_{\rm saw}$. During the NBI power ramp $-\delta\hat{W}$ drops below $-\hat{\rho}$ due to rising fast ion pressure. The dominant term in $\delta\hat{W}$ is then $\delta\hat{W}_{\rm fast}$, and its time evolution determines $\tau_{\rm saw}$: this accounts for the correlation observed between $\tau_{\rm saw}$ and $W_{\rm fast}$.

To test this hypothesis we have carried out sawtooth period simulations using PRETOR, with $j(r)$ and $q(r)$ computed on the assumption of neoclassical resistivity. Results for shot 50725 are shown in Fig. 4. At $t = 67.0\,$s, when $P_{\rm NBI}$ is low, the condition $-\delta\hat{W} > -\hat{\rho}$ is reached during the sawtooth ramp, before s_1 crosses $s_{1\,\rm crit}$. At higher values of $P_{\rm NBI}$ ($t = 68.6\,$s and $70.5\,$s), the condition $s_1 > s_{1\,\rm crit}$ is satisfied before $-\delta\hat{W} > -\hat{\rho}$: the latter condition triggers a crash. Two other discharges have been analysed in a similar way: the simulated $\tau_{\rm saw}$ is found in every case to be within 20% of the measured period.

6. Conclusions

Recent JET experiments clearly show a stabilising effect of NBI ions on sawteeth. A sawtooth period model that includes two–fluid and finite Larmor radius effects, resistivity and fast particle stabilisation has yielded results in good agreement with the data. Sawteeth are found to be triggered in these experiments by excitation of the resistive internal kink mode in the ion kinetic régime: the same trigger mechanism is likely to operate in ITER. Further details of this work can be found in [11].

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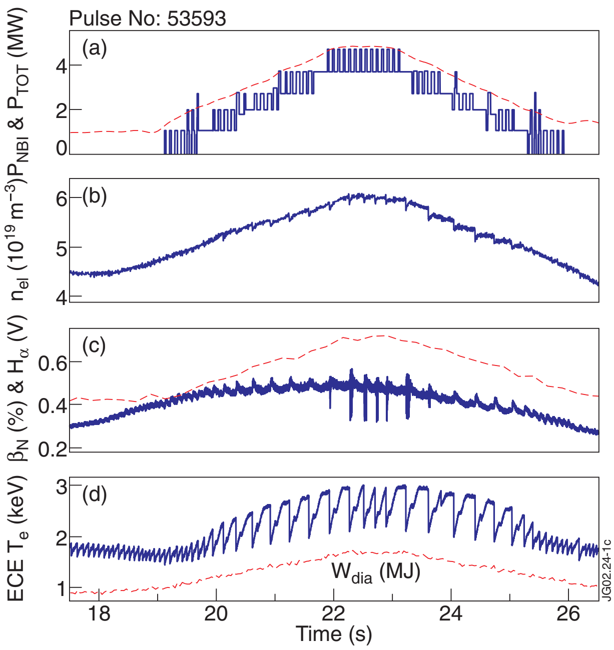

Fig.1: Time traces from JET shot 53593.
(a) P_{NBI} and smoothed total input power (dashed);
(b) line-average density;
(c) H_α emission and β_N (dashed); (d) T_e and diamagnetic energy (dashed).

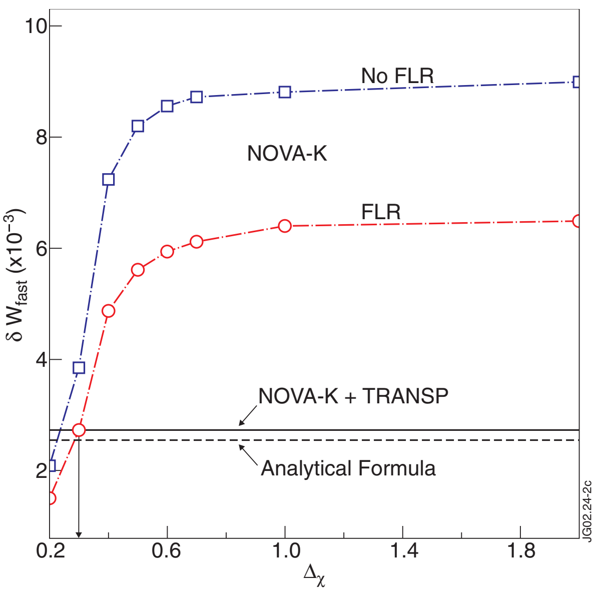

Fig.2: δW_{fast} verses Δ_x.

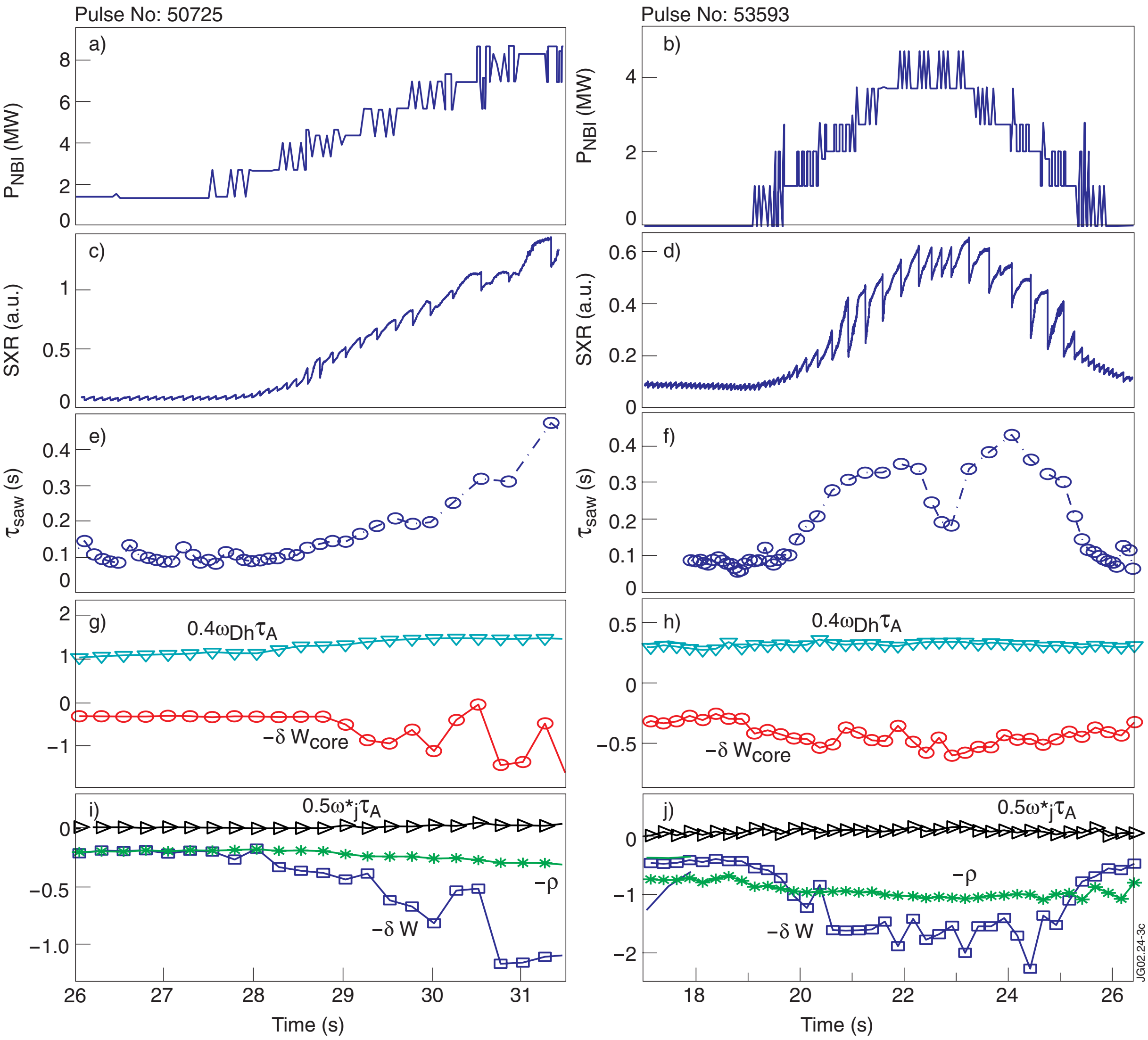

Fig.3: P_{NBI}, soft X-ray emission, measured τ_{saw} and computed stability threshold parameters in shots 50725 and 53593.

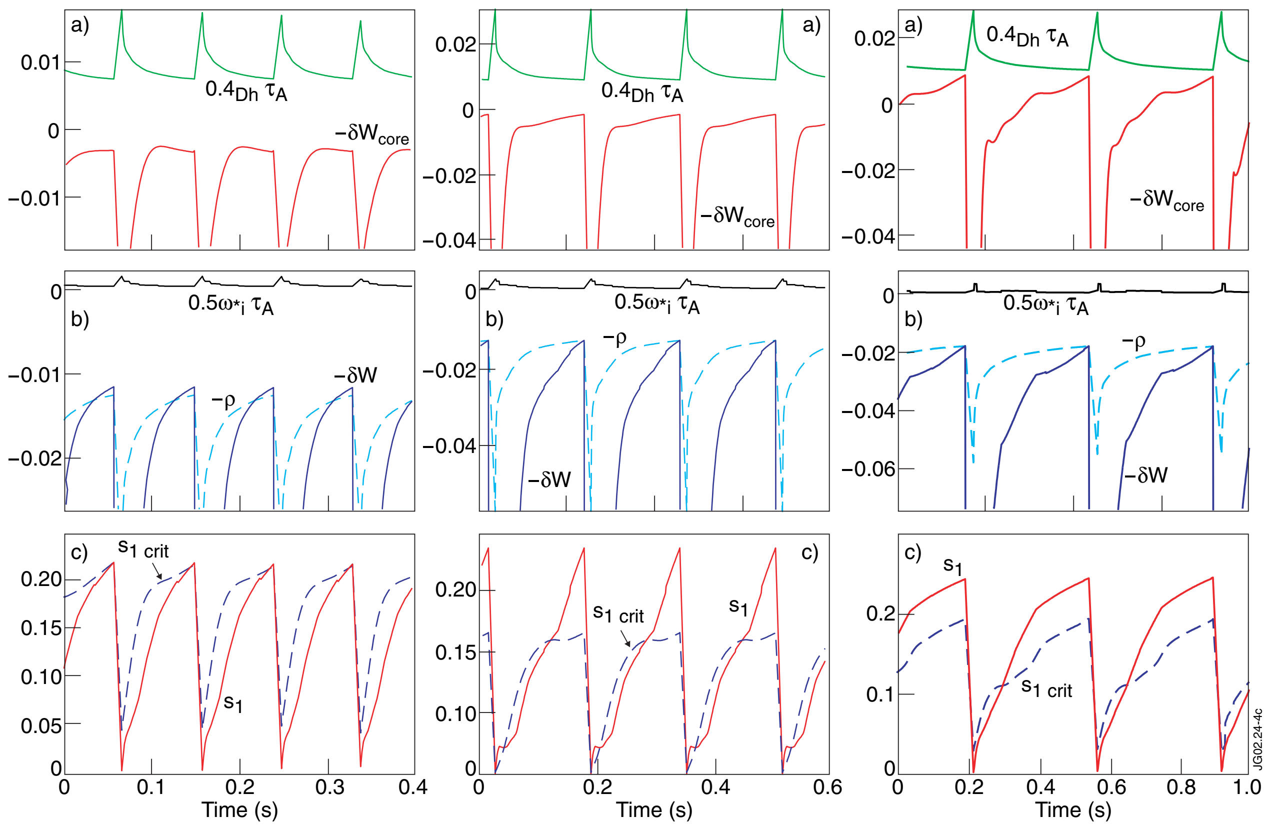

Fig.4: Computed evolution of terms in sawtooth period model for t=67.0s (left), t=68.6s (middle) and t=70.5s (right) in shot number 50725.