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The Physics of Sawtooth Stabilisation

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ABSTRACT.

Long period sawteeth have been observed to result in low- triggering of neo-classical tearing modes, which can significantly degrade plasma confinement. Consequently, a detailed physical understanding of sawtooth behaviour is critical, especially for ITER where fusion-born particles are likely to lead to very long sawtooth periods. Many techniques have been developed to control, and in particular to destabilise the sawteeth. The application of counter-current Beutral Beam Injection

(NBI) in JET has resulted in shorter sawtooth periods than in Ohmic plasmas. This result has been explained because, firstly, the counter-passing fast ions give a destabilising contribution to the $n = 1$ internal kink mode – which is accepted to be related to sawtooth oscillations – and secondly, the flow shear strongly influences the stabilising trapped particles. A similar experimental result has been observed in counter-NBI heated plasmas in MAST. However, the strong toroidal flows in spherical tokamaks mean that the sawtooth behaviour is determined by the gyroscopic flow stabilisation of the kink mode rather than kinetic effects. In NBI heated plasmas in smaller conventional aspect-ratio tokamaks, like TEXTOR, the flow and kinetic effects compete to give different sawtooth behaviour. Other techniques applied to destabilise sawteeth are the application of Electron Cyclotron Current Drive (ECCD) or Ion Cyclotron Resonance Heating (ICRH). In JET, it has been observed that localised ICRH is able to destabilise sawteeth which were otherwise stabilised by a co-existing population of energetic trapped ions in the core. This is explained through the dual role of the ICRH in reducing the critical magnetic shear required to trigger a sawtooth crash, and the increase of the local magnetic shear which results from driving current near the $q = 1$ rational surface. Sawtooth control in ITER could be provided by a combination of ECCD and co-passing off-axis Negative NBI fast ions.

1. INTRODUCTION

The control of sawteeth is likely to be of critical importance for baseline scenario operation of burning plasmas as large amplitude sawteeth have been shown to result in the low-β triggering of Neo-classical Tearing Modes (NTMs) [1], which in turn can significantly degrade confinement. The stabilising effects of fusion-born α-particles are likely to exacerbate this [2, 3] so recent experiments have identified various methods to deliberately destabilise sawteeth in an attempt to avoid seeding NTMs whilst retaining the benefits of small, frequent sawteeth, such as the prevention of core impurity accumulation [4]. Experimental results concerning sawtooth control were summarised in Reference [5].

For example, Neutral Beam Injection (NBI) operation demonstrates that shorter sawtooth periods than those in Ohmically heated plasmas can be achieved in JET [6], MAST [7] and TEXTOR [8]. Each experiment exhibits an asymmetry of sawtooth period with respect to NBI direction. In order to understand sawtooth stabilisation, the interaction of MagnetoHydroDynamic (MHD) and fast particle effects must be considered. We present a coherent physics explanation of these results by studying MHD stability (allowing for the presence of toroidal flow and ion diamagnetic drifts), combined with the effects of anisotropic hot ion distributions. Appropriate tools for studying these effects are the Mishka-F linear, ideal MHD stability code [9] and the Hagis drift-kinetic code [10].

In JET, there are insubstantial toroidal flows, so sawtooth stability is governed by the energetic particle population. It is found that whilst the trapped particles are always stabilising [11], passing particles can be destabilising [12, 13]. The small flows do not affect the mode stability, but the flow shear does change the stabilising effect of the trapped particles [14, 15] and together with the passing particle destabilisation, explains the experimental asymmetry [16]. On MAST, the toroidal rotation profile is broad and relatively flat, and therefore the small flow shear at the q = 1 surface does not significantly affect the stabilisation by the predominantly trapped population. However, the high beam power per unit volume and low moment of inertia results in a plasma which rotates at velocities approaching the thermal deuterium sound speed. Such strong rotation can stabilise the kink mode [17,18] with the asymmetry being explained by the direction of the beam-induced flow relative to the ion diamagnetic drift [7, 19].

Electron Cyclotron Current Drive (ECCD) has also been employed to destabilise sawteeth by driving current localised near the q = 1 surface in ASDEX Upgrade [20], TCV [21] and JT-60U [22]. Similarly, Ion Cyclotron Resonance Heating (ICRH) and Current Drive (ICCD) have been used to destabilise sawteeth [23]. Furthermore, in the JET experiments in Reference [23], the sawteeth were already stabilised by a co-existing population of trapped fast ions in the core before the ICRH was applied near the q = 1 surface. The effect of the ICRH is (i) to increase the magnetic shear localised at q = 1, and (ii) to reduce the critical magnetic shear [24], hence facilitating a sawtooth crash [2].

Modelling of the use of ICCD [25] and ECCD [26] has been used to predict the current drive planned for ITER. It is anticipated that changes to the magnetic shear at the q = 1 surface due to this current drive will be the primary actuator for sawtooth control in ITER. However, it has been proposed [12] that the off-axis Negative-NBI could also be employed for sawtooth control.

This paper reviews the experimental data and physical understanding of these sawtooth control methods. In section 2 the gyroscopic stabilisation of sawteeth by momentum input from NBI is reviewed. The effects of fast ions born due to NBI are presented in section 3. Sawtooth control by ICRH is reviewed in section 4 and implications for ITER are discussed in section 5.

2. EFFECTS OF TOROIDAL ROTATION ON SAWTEETH

The trigger condition for a sawtooth collapse is believed to be associated with the linear stability threshold for a reconnecting 1/1 mode. Although this differs from the threshold for ideal MHD instability, it nevertheless depends strongly on the magnitude of the ideal potential energy, $\delta W = \delta W_{\mathrm{thermal}} + \delta W_{\mathrm{hot}}$. It has been proposed [2] that – provided the magnetic shear at q = 1, S_1, exceeds a critical value – reconnection is triggered when $c_\rho S_1/r_1 > \delta W$, where c is a normalisation coefficient, r_1 is the radial position of the q = 1 surface and ρ is the ion Larmor radius. Assuming that the trigger criterion can be represented by a linear time dependence for $r_1(t) \approx \hat{r}_1 t/\tau_\eta$, with τ_η a measure of the resistive diffusion time and $S_1 \sim r_1$, and a quasi-stationary value of δW(t), then the sawtooth period, τ_s, can be represented in the form $\tau_s/\tau_\eta \sim (\delta W_{th} + \delta W_h)\, \hat{r}_1/c_\rho S_1$ with longer ramp times predicted when δW_h is larger. As such the sawtooth period can be considered as a measure of sawtooth stability.

In MAST, the sawtooth period is shown to increase as the co-NBI power, and thus the toroidal plasma rotation, is increased [7]. Conversely, as the counter-NBI power is increased, the sawtooth period decreases to a minimum that is shorter than in Ohmically heated plasmas, before lengthening at higher toroidal flows, as illustrated in figure 1. The sawtooth period is minimised when the sawtooth precursor mode changes direction of rotation, which occurs when the rotation induced by the counter-NBI balances the ion diamagnetic rotation of the plasma [27]. MHD stability analyses of the ideal n = 1 internal kink mode with respect to toroidal rotation at finite ion diamagnetic frequency show good agreement with the experimental results [7]. When MAST discharges are modelled at the experimental ion diamagnetic frequency, ω_{*i}, the ideal n = 1 internal kink mode is stabilised completely by co-rotation approaching the ion sound speed [17]. When the rotation is oriented in the counter$-\omega_{*i}$ direction, the mode is initially driven more unstable, before being stabilised by high toroidal flows [19]. Experimentally, the radial extent of the sawtooth crash, and hence the q = 1 surface, varies with respect to the sawtooth period. Stability analyses show that the marginally stable radial location of the q = 1 surface reaches a minimum at approximately the same counter-toroidal rotation as that which minimises the sawtooth period experimentally, as shown in figure TEXTOR also exhibits asymmetric stabilisation of sawteeth due to toroidal flows, but with a minimum in sawtooth period in the co-NBI direction [8]. This is because Ohmic plasmas in limited machines intrinsically rotate in the counter-I_p direction due to the radial electric field established by thermal ions lost due to the proximity of the limiter [28], so a small amount of NBI is required co-Ip to negate the gyroscopic stabilisation of the kink mode. When both the intrinsic rotation of the plasma and the toroidal rotation induced by momentum input from the neutral beams are included, the MHD stability of the 1/1 mode accurately models the minimum in sawtooth period in the co-NBI regime exhibited experimentally [8], as illustrated in figure 2.

3. EFFECTS OF ENERGETIC IONS FROM NBI ON SAWTEETH

In MAST, the asymmetric stabilisation of sawteeth by NBI heating has been explained in terms of the direction of the strong toroidal flows induced by the NBI, relative to the ion diamagnetic drift. Whilst fast ions do have a stabilising influence, the high trapped fraction in spherical tokamaks is equally stabilising in either co- or counter- NBI regimes, meaning that kinetic effects cannot explain the experimentally observed minimum in sawtooth period. However, in JET, the toroidal rotation is significantly smaller, and the sawtooth behaviour can only be explained by the effects of the fast ions. The sawtooth period is seen to vary in the same way as in MAST, with lengthening period as the co-NBI increases, and a minimum in sawtooth period with counter-NBI [6].

In order to model the effects of the anisotropic fast ions born due to NBI, the change in the potential energy of the n = 1 internal kink mode caused by the fast particles has been calculated as [2, 29]

$$\delta W_h = \frac{1}{2} \int \mathrm{d}\Gamma (m v_{||}^2 + \mu B)\, \delta f \sum_m \vec{\kappa} \,\text{¥}\, \vec{\xi}^{(m)*} (r, t) \mathrm{e}^{-i(n\zeta - m\theta)} \qquad (1)$$

where θ is the poloidal angle, $\vec{\kappa} = \vec{b} \cdot \nabla\vec{b}$ is the magnetic curvature vector, $\vec{b} = \vec{B}/B$ and $d\Gamma$ is an infinitessimal volume element of phase-space. The perturbed fast ion distribution function, δf, can be separated into a non-adiabatic (kinetic) part, δf_{hf}, and an adiabatic (fluid) part, δf_{hf}. Analytic theory developed for large aspect ratio circular plasmas [15] yields that these contributions to the perturbed distribution function can be expressed as

$$\delta f_{hk} = \sum_{l=-\infty}^{\infty} \frac{\tilde{\omega} - \Delta\text{‰} - n\omega_{*h}}{\tilde{\omega} - \Delta\text{‰} - n\langle\dot{\zeta}\rangle + l\omega_b} \frac{\delta f_h}{\delta\varepsilon^0} \left\langle \left(v_{\|} + \frac{v_{\perp}^2}{2} \right) \vec{\kappa} \cdot \vec{\xi}_{\perp} e^{-i(\omega + l\omega_b + n\langle\dot{\zeta}\rangle)t} \right\rangle \tag{2}$$

and $\delta f_{hf} \sim \vec{\xi} \cdot \vec{\nabla}\phi_p \partial f_h / \partial P_\zeta$ where $\omega_{*h} = (\partial f_h / \partial P_\zeta^0)/(\partial f_h / \partial \mathcal{E}_\zeta^0)$ is the hot ion diamagnetic frequency, $\Delta\Omega = \Omega_E(r) - E(r_1)$ is the sheared toroidal flow, $\tilde{\omega}$ is the Doppler shifted mode frequency, ζ is the toroidal angle, $\omega_b = 2\pi/\tau_b$ and τ_b is the poloidal orbit transit time.

The contribution to the stability of the n = 1 internal kink mode in JET discharges has been calculated for each class of particles when there is sheared flow present. The fast particle distribution function was obtained from Transp [30] and the rotation profile is taken from the charge exchange diagnostic and scaled linearly with respect to injected power. The potential energy is normalised such that $\delta W_h = \delta W_h \mu_0 /(6\pi^2 R_0 \xi^2{}_0 \in_1{}^4 B^2{}_0)$ where $\in_1 = r_1/R_0$ and ξ_0 is the displacement at the magnetic axis. Figure 3 shows that for the realistic beam distribution used in these simulations, the passing ions – which are often ignored in studies concerning energetic particles – are as important as the trapped ions. In accordance with analytic theory [12], the co-passing ions are strongly stabilising, whereas the counter-passing ions are strongly destabilising. The stabilisation of the passing fast ions is determined by a contribution to δW_h of the form $\delta W_h{}^p \sim \int_0^{r_1} (\xi \cdot \nabla\langle P_h\rangle)(\vec{\xi} \cdot \vec{\kappa}) d\vec{r}$, where P_h is the hot particle pressure. First let us consider the case of on-axis co-NBI. When a co-passing beam ion is born inside the q = 1 surface it experiences a inward ∇B drift, which means that it stays within the q = 1 surface and never crosses it. The distribution function has a negative hot particle pressure gradient, $\nabla\langle P_h\rangle < 0$, so this particle will give a stabilising contribution when in the region of good curvature, but will be destabilising when in the region of adverse curvature on the outboard side. These two contributions tend to cancel, and the beam ions inside q = 1 (which make up the majority of on-axis NBI ions) do not affect the mode stability. However, the few ions which are born outside q = 1 will only pass through the q = 1 surface in the region of good curvature due to the inward ∇B drift. As such, these will give a stabilising contribution to the kink mode (since for q > 1 $\xi = 0$). Intuitively the opposite is true for counter-passing ions which have an opposite ∇B drift upward from their flux surface; those born inside q = 1 will only contribute in the region of adverse curvature. Since they have a negative hot particle pressure gradient, the contribution from counter-passing ions is destabilising. Consequently, the n/m = 1/1 internal kink mode is stabilised by co-passing on-axis NBI ions or by counter-passing off-axis NBI ions, but is destabilised by counter-passing on-axis NBI ions or co-passing off-axis NBI ions. This mechanism depends strongly on the local gradient $\delta f_h / \partial P_\zeta$ at the q = 1 surface and as such is sensitive to localised heating. The strongest contribution from the passing ions comes from the ions close to the trapped-passing boundary, where their orbit widths, Δ_b, are large, $\delta W_h \sim \Delta_b$.

The strong flow shear significantly influences the stabilisation arising from the presence of low-energy trapped ions. Conservation of the third adiabatic invariant, Φ, which gives rise to strong stabilisation from the trapped particles [2], only occurs [15] when $\langle\omega_d\rangle + \Delta\Omega - \tilde{\omega} >> 0$, where $\langle\omega_d\rangle$ is the bounce-averaged hot particle toroidal drift precession frequency. Figure 3 shows that the minimum in mode stability occurs at approximately 3MW of counter-NBI power, in excellent agreement with JET experimental results [6]. This minimum occurs because (i) the counter-passing ions give a strongly destabilising contribution and (ii) the flow shear in JET reduces the stabilising effect of the trapped ions injected counter-I_p.

Similarly, the destabilising effect of the counter-passing ions can be seen in TEXTOR discharges, as shown in figure 2 and Reference [8]. The sawtooth period reaches a maximum in the counter-NBI regime in TEXTOR due to a competition between the gyroscopic stabilisation of the kink mode and the destabilisation arising in the presence of counter-passing fast ions. At low counter-NBI power, the gyroscopic stabilising effect is stronger than the counter-passing fast ion destabilising effect since the fast ion effect scales linearly with respect to beam power, whereas the rotation increases more rapidly. However, there comes a point when the rotation tends to an upper limit and any increase in the injected beam power does not result in a significant increase in plasma rotation. At this point, the destabilising influence of the passing ions begins to dominate and the kink mode becomes more unstable again.

4. EFFECTS OF ION CYCLOTRON RESONANCE HEATING ON SAWTEETH

A model predicting when a sawtooth crash will occur was presented in Reference [2]. It was proposed that in heated plasmas, a sawtooth crash would occur when

$$-\frac{c_\rho \hat{\rho}}{\tau_A} < -\frac{\delta \hat{W}}{S_1 \tau_A} < \frac{\omega_{*i}}{2} \tag{3}$$

and concurrently

$$\gamma_\eta = > c_r \sqrt{\omega_{*i}\,\omega_{*e}} \tag{4}$$

where c_ρ and c_r are constants of order unity, $\tau_A = \sqrt{3}R_0/v_A$ and v_A is the Alfvén speed, γ_η is the resistive growth rate of the n/m = 1/1 mode and w_{*e} is the electron diamagnetic drift frequency. Equations 3 and 4 can be recast as a criterion in the magnetic shear at $q = 1$:

$$S_1 > \max\left(S_{\mathrm{crit}} = \frac{\pi \delta W}{\hat{\rho}},\ S_{\mathrm{crit}}(\omega_*)\right) \tag{5}$$

Consequently, raising the magnetic shear at $q = 1$ leads to earlier sawtooth crashes in both crash criteria (equations 3 and 4). This has been done by driving current due to resonant wave-particle interactions at cyclotron frequencies [31] using both ICCD [32] and ECCD [20, 21].

When ICRH is applied there are two sawtooth control mechanisms, namely the current perturbation which changes the local magnetic shear and the effect of the hot trapped ions on the potential energy of the kink mode. Experiments in JET [23] have shown that applying off-axis -90^o counter-current propagating ICRH waves can destabilise the sawteeth despite the stabilising drive from a co-existing $+90^o$ copropagating fast ion population in the plasma core. This destabilisation arises because the localised current drive raises the magnetic shear at $q = 1$ and the off-axis trapped hot ions reduce the critical shear from the large critical shear normally associated with the presence of on-axis fast particles. The experiments are very sensitive to the location of the cyclotron resonance with respect to the $q = 1$ surface, and it is found that the heating must be directed near or just outside the inversion radius to destabilise the sawteeth.

In order to model the effect of the fast ions caused by ICRH, the distribution function obtained by the SELFO code [33] is parameterised as a bi-Maxwellian [34]. The resonance location of the off-axis fast ion distribution function is then varied with respect to the $q = 1$ surface. Figure 4 indicates that when the cyclotron resonance is inside the $q = 1$ surface, there is a strong stabilisation of the n = 1 internal kink mode from the energetic ions, and the mode is more stable than when heated with on-axis +90% waves only. This mirrors the increase in sawtooth period exhibited experimentally. As the cyclotron resonance is moved towards the $q = 1$ surface, the internal kink mode becomes more unstable since the trapped off-axis ions give a destabilising contribution. The stabilisation from the trapped fast ions is determined by a contribution to δW_h of the form $\delta W^t_h \sim -\int_0^{r_1} \xi_1 \left(\frac{r}{r_1}\right)^{3/2} \left(\frac{P_{h\perp}}{P_{h\|1}}\right) dr$, where æ1 is the perturbation at the $q = 1$ surface. Consequently, when the fast ions are born inside the $q = 1$ radius, the hot particle pressure gradient is negative, and so the fast ions stabilise the kink mode. Conversely, a fast ion population born outside the inversion radius has a positive pressure gradient and results in a destabilisation of the kink mode. As such, when the -90^o counterpropagating waves have a cyclotron resonance just outside the $q = 1$ radius, they give a destabilising contribution to the kink mode. The sawteeth in the JET experiments are thus destabilised since the off-axis fast ions reduce the critical shear in equation 5 and the driven current causes S1 to increase [32]. As the resonance location is moved further outside the inversion radius the kink mode is stabilised once more as the role played by the off-axis ions becomes smaller than the stabilising ions in the core and the current dipole perturbation is outside the $q = 1$ surface. Destabilisation of sawteeth cannot be obtained by employing $+90^o$ co-propagating waves off-axis [32]. This is because the $+90^o$ ions are pinched inwards towards the magnetic axis [35], thereby peaking the pressure profile and giving rise to large negative fast ion pressure gradients within the $q = 1$ surface. The driven current also has the effect of moving the $q = 1$ radius outwards, exacerbating the stabilisation effect of the trapped energetic ions.

5. MODELLING THE STABILITY OF THE N = 1 INTERNAL KINK MODE IN ITER

The large trapped α population in the plasma core in ITER is likely to significantly stabilise the sawteeth [2, 3], so clearly it will be necessary to employ techniques to modify S_1 and tailor δW_h such that sawtooth crashes are triggered more readily. It has been proposed that sawtooth control in ITER will be achieved by ICCD [23] and ECCD [20]. Ancillary sawtooth control using the Negative-ion Neutral Beam Injection (NNBI) system has also been proposed [12].

By using the off-axis co-passing NNBI ions, the $n = 1$ internal kink mode may be sufficiently destabilised so that the sawtooth crash can be triggered using the current drive from resonance heating. The tangential 1MeV NNBI provides a predominantly passing population of ions. When the fast ions are born off-axis, the hot particle pressure gradient is positive, so the co-passing ions can give a destabilising contribution to δW_h [5]. Figure 5 shows the total δW_h – comprising the contribution from the α particles in the plasma core and the off-axis NNBI fast ions – with respect to the injected beam power. Here, an ITER equilibrium is derived from transport simulations of the inductive 15MA baseline scenario for ITER using the ASTRA code [36] with on-axis beams, such that $r_1 \sim 0.2a$, $q_0 = 0.95$, $\beta_N = 1.9$ and $s_1 \sim 0.2$ [37]. The NNBI fast particle population born when the neutral beam injector is directed off-axis is calculated using Transp [38]. It can be seen that at the maximum beam power planned for ITER [39], the kink mode is significantly destabilised by the passing ions. Further modelling of the current drive will be able to determine whether this destabilisation is sufficient to allow the ECCD to increase the local magnetic shear in order to trigger frequent small sawtooth crashes.

CONCLUSIONS

There have been significant recent advances in the understanding of sawtooth control mechanisms. Experimental results showing sawtooth destabilisation using both neutral beam heating and ICRH have been discussed and the physical explanation of these important results has been elucidated. In JET, the sawteeth are destabilised by counter-NBI since the counter-passing ions give a strongly destabilising contribution to the internal kink mode potential energy, and the strong flow shear at the $q = 1$ surface inhibits the stabilisation from the trapped ions. In contrast, in MAST, the kinetic effects are always stabilising to the internal kink mode, but the gyroscopic stabilisation of the mode is minimised when the intrinsic plasma rotation caused by ion diamagnetic drifts is balanced by the flow induced by counter-NBI, at which point sawtooth destabilisation also occurs. The combined effects of the energetic beam ions and plasma rotation compete in TEXTOR to give different sawtooth behaviour, but allow a mild sawtooth destabilisation in the co-NBI regime. Important results in JET have shown that sawteeth, which are initially stabilised by an energetic trapped ion population in the core, can be destabilised by off-axis counter-propagating ICRH waves. This is due to the combined effect of driving current at the $q = 1$ surface to raise the localised magnetic shear, and also by reducing the critical magnetic shear required to facilitate a sawtooth crash by peaking the hot ion population outside the inversion radius. Such understanding of the mechanisms which determine sawtooth control is essential for ITER given the expectation that the fusion-born α particles will lead to long sawtooth periods, which are likely to trigger neo-classical tearing modes if not inhibited by one of these sawtooth control mechanisms.

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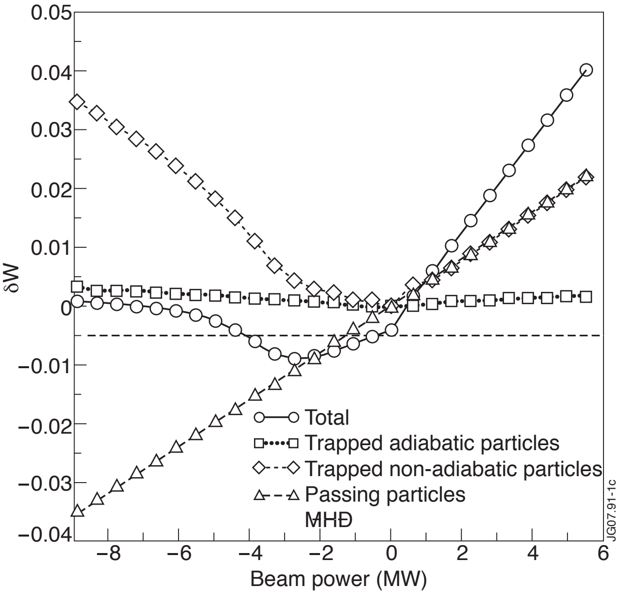


Figure 1. The radial location of the marginally stable q = 1 surface in MAST discharge 13541 with respect to the toroidal rotation at the resonant surface as modelled using the Mishka-F stability code (squares) compared to the sawtooth period of similar MAST shots (circles).

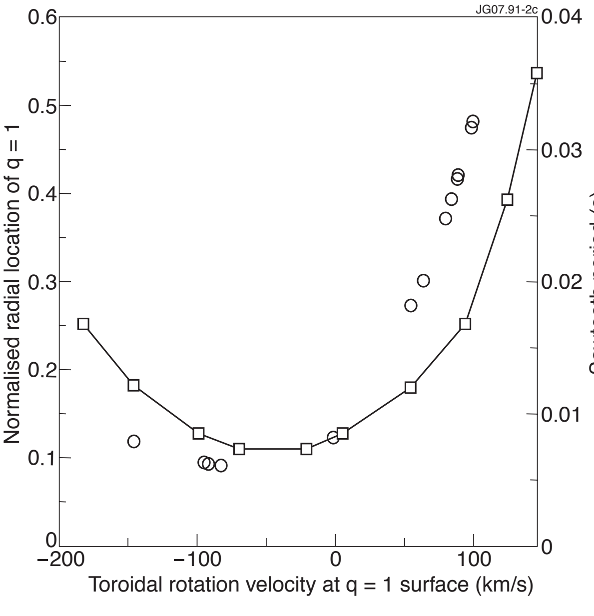
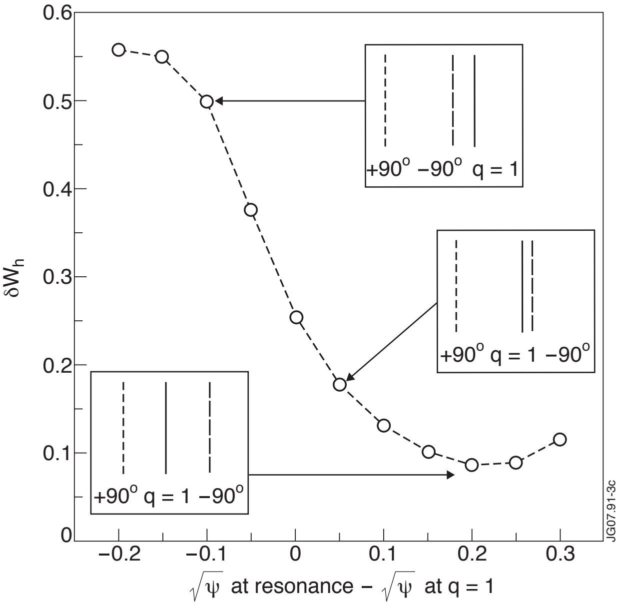


Figure 2. The change in the potential energy of the n = 1 internal kink mode in TEXTOR shot 103110 as a function of applied beam power for the different particle species. When the contribution from the hot particles is combined with the MHD stability including toroidal flows, the kink mode stability strongly replicates the sawtooth behaviour exhibited in the experiments.



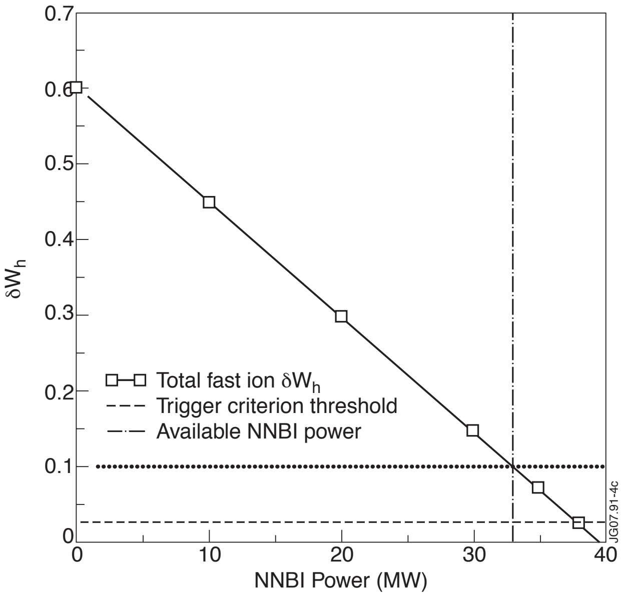


Figure 3. The contribution to the change in the potential energy of the n = 1 internal kink mode from each energetic particle species with respect to the injected beam power for JET Pulse No: 60998 when flow shear effects are included.

Figure 4. The change in the potential energy of the n = 1 internal kink mode as a function of the distance of the ICRH resonance location from the q = 1 surface in JET Pulse No: 58934.

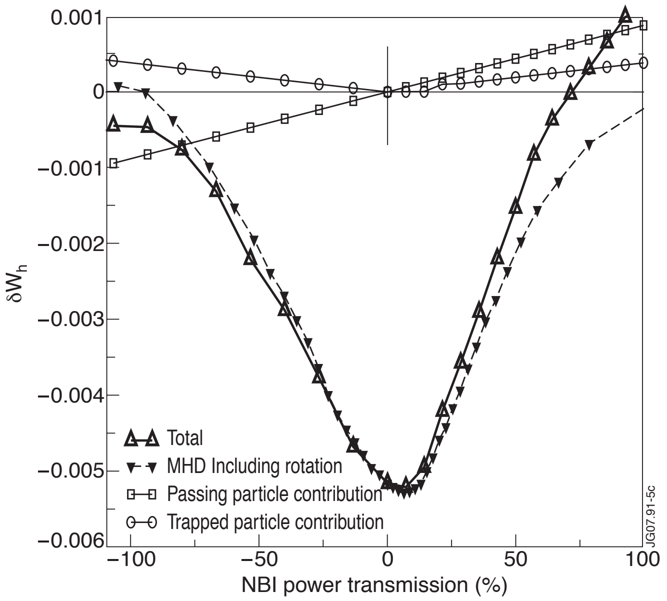


Figure 5. The total δW_h from the α-particles and the NNBI fast ions combined as a function of injected beam power. At the power planned for ITER, the kink mode is significantly destabilised by the off-axis co-passing fast ions and the sawteeth may be triggered by electron cyclotron current drive.