The Physics of Sawtooth Stabilisation in Tokamak Plasmas

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Abstract. Long period sawteeth have been observed to result in the low-β triggering of neo-classical tearing modes (NTMs), which can significantly degrade plasma confinement. In ITER, the stabilising effects of the fusion-born α particles are likely to exacerbate this. Consequently, it is important to develop a detailed physical understanding of sawtooth behaviour. Recent work on plasmas heated using neutral beam injection (NBI) in JET, MAST, ASDEX Upgrade and TEXTOR has provided significant insight into the physical processes that determine sawtooth behaviour. The asymmetric dependence of sawtooth period upon neutral beam power injected in either the co- or counter-current direction exhibited in both JET and TEXTOR can be explained by including the effects of the passing energetic ions, the toroidal flow and the flow shear. In JET, the counter-passing fast ions destabilise the $n = 1$ internal kink mode – thought to be associated with sawteeth – whilst the flow shear strongly influences the stabilisation from the trapped particles. The sawtooth behaviour in TEXTOR has been explained through a combination of both kinetic effects and stabilisation from toroidal rotation. In order to avoid triggering NTMs, many techniques have been proposed to control, and in particular, to destabilise the sawtooth oscillations. Here, sawtooth behaviour in off-axis NBI-heated plasmas in JET, MAST and ASDEX Upgrade is presented. It is found that the energetic particles born outside the $q = 1$ surface due to the off-axis NBI can destabilise the sawteeth, even in the presence of stabilising on-axis fast particles. We also consider sawtooth control using ion cyclotron resonance heating (ICRH). Previously it had been assumed that the change in sawtooth behaviour in ICRH heated plasmas arose due to the change in the magnetic shear at $q = 1$. The energetic passing ions are found to influence the internal kink mode when the distribution of ions is asymmetric in $v_{\|}$, a natural feature of co or counter propagating ICRH waves.

1. Introduction

Magnetohydrodynamic (MHD) stability of plasmas is a critical issue for baseline scenario operation of ITER. Based on experimental evidence, it is thought that the fusion-born α particles will lead to long sawtooth periods [1], which have been shown to result in the triggering of neoclassical tearing modes (NTMs) [2], which in turn can have deleterious ramifications for plasma confinement. Thus, recent experiments have identified various methods for the control of sawteeth in order to avoid seeding NTMs whilst retaining the benefits of small, frequent sawtooth crashes, such as the prevention of core impurity accumulation. Whilst ICRH and ECCD sawtooth control actuators are also envisaged for ITER, here we concentrate on results from plasmas heated using neutral beam injection, as these experiments have helped to exemplify the physical processes that determine sawtooth behaviour. For example, shorter sawtooth periods than those in Ohmically heated plasmas can be achieved in JET [3], MAST [4] and TEXTOR [5]. Each experiment exhibits an asymmetry of sawtooth period with respect to NBI direction. In order to understand sawtooth stabilisation, the interaction of MHD and fast particle effects must be considered. In section 2.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 [6] and the HAGIS drift-kinetic code [7].

Following the explanation of the observed sawtooth behaviour in on-axis NBI-heated plasmas in JET and TEXTOR, we investigate whether the passing fast ions could be used as a sawtooth control tool if the distribution function was peaked outside the $q = 1$ radius [8]. Experiments on JET have shown that sawteeth are considerably less stable when heated with off-axis co-NBI than with on-axis beams, and that off-axis NBI can *destabilise* sawteeth which had been previously strongly stabilised by a population of energetic ions in the core [9]. These results are explained in section 3. Recent work from ASDEX Upgrade and MAST to assess sawtooth behaviour in off-axis NBI-heated plasmas is also presented. Finally, these improvements in our understanding have also been used to assess the viability of employing off-axis N-NBI for sawtooth control in ITER in section 4.

2. Sawtooth Behaviour in NBI-Heated Plasmas

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 [4]. Whilst fast ions do have a stabilising influence, the high trapped fraction in spherical tokamaks is 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 observed to vary in the same way as in MAST, with lengthening period as the co-NBI power increases, and a minimum in sawtooth period in the counter-NBI regime[3].

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 is calculated [10]

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

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 $\mathrm{d}\Gamma$ 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_{hk}, and an adiabatic (fluid) part, δf_{hf}. Analytic theory developed for large aspect ratio circular plasmas [11] gives the contributions to the perturbed distribution function as

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

and $\delta f_{hf} = -(Ze/m_h)\vec{\xi}\cdot\vec{\nabla}\psi_p \partial f_h/\partial \mathcal{P}_\zeta^0$ where $\omega_{*h} = (\partial f_h/\partial \mathcal{P}_\zeta^0)/(\partial f_h/\partial \mathcal{E}^0)$ is the hot ion diamagnetic frequency, $\Delta\Omega = \Omega_E(r) - \Omega_E(r_1)$ 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.

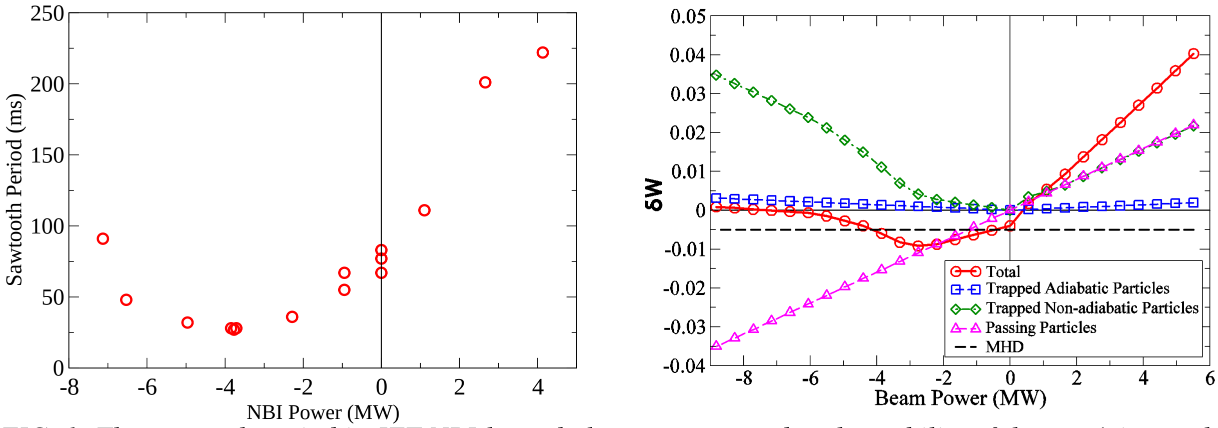

FIG. 1. The sawtooth period in JET NBI-heated plasmas compared to the stability of the $n = 1$ internal kink mode.

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 [12] and the rotation profile is taken from the charge exchange diagnostic and scaled linearly with injected power. The potential energy is normalised such that $\delta\hat{W}_h = \delta W_h \mu_0/(6\pi^2 R_0 \xi_0^2 \varepsilon_1^4 B_0^2)$ where $\varepsilon_1 = r_1/R_0$ and ξ_0 is the displacement at the magnetic axis. Figure 1 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 [8], 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 $\delta W_h^p \sim -\int_0^{r_1} (\vec{\xi}\cdot\nabla\langle P_h\rangle)(\vec{\xi}\cdot\vec{\kappa})\mathrm{d}\vec{r}$, 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 significantly. 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 is illustrated in Figure 9 of Reference [9]. This mechanism depends strongly on the local gradient $\partial f_h/\partial P_\zeta$ at the $q = 1$ surface and as such is sensitive to localised heating. The strongest contribution per ion 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 [10], only occurs [13] when $\langle\omega_d\rangle + \Delta\Omega - \tilde{\omega} \gg 0$, where $\langle\omega_d\rangle$ is the bounce-averaged hot particle toroidal drift precession frequency. Since this condition is more readily satisfied for co-rotation ($\Delta\Omega > 0$), co-rotating plasmas with velocity shear support more effective stabilisation of the kink mode, because particles with low energy are able to provide a positive contribution through equation 2. Conversely, the stabilising effect is diminished in counter-rotating plasmas ($\Delta\Omega < 0$) since Φ_{ad}-conservation is inhibited, and the stabilising contribution can only come from the less numerous higher energy ions. Figure 1 shows that the minimum in mode stability occurs at approximately 3MW of counter-NBI power, in excellent agreement with JET experimental results [3]. 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 [14]. It should be noted that only a qualitative comparison can be drawn between the modelling and the JET data since various assumptions are made about the scaling of rotation to injected power, the distribution function and the equilibrium, and further this modelling only considers the linear stability thresholds for the mode.

Similarly, the destabilising effect of the counter-passing ions can be seen in TEXTOR discharges, as shown in Figures 2 and 12 of Reference [5]. 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.

3. Sawtooth Control Using Off-axis NBI

Since the passing fast ions have a strong influence upon the sawtooth behaviour, it was suggested that energetic ions born outside the $q = 1$ surface due to off-axis NBI could be used as a sawtooth control actuator [8]. In order to demonstrate the suitability of off-axis co-NBI for this purpose, it is necessary to show whether its application is able to result in *destabilisation* of otherwise strongly stabilised sawteeth. Such sawtooth control has been demonstrated in JET using off-axis ICRH to shorten the sawtooth period when a co-existing fast ion population exists in the core due to concurrent ICRH heating with a different phasing [15]. However, this actuator is very strongly dependent upon the precise location of the deposition of fast ions, making it difficult to control. By applying on-axis NBI throughout the discharge in order to stabilise the sawteeth, the sawtooth behaviour under simultaneous application of off-axis NBI is an appropriate test of the use of off-axis beams as a sawtooth control mechanism [9]. Figure 2 shows the beam time traces and soft X-ray emission from JET discharge 58855. The sawtooth period is substantially lengthened during the on-axis only phase ($\sim$ 315ms) before decreasing to approximately the period of Ohmic sawteeth when the off-axis power is applied ($\sim$ 120ms) but the total applied power is held constant. This clear destabilisation of the sawteeth when off-axis NBI is

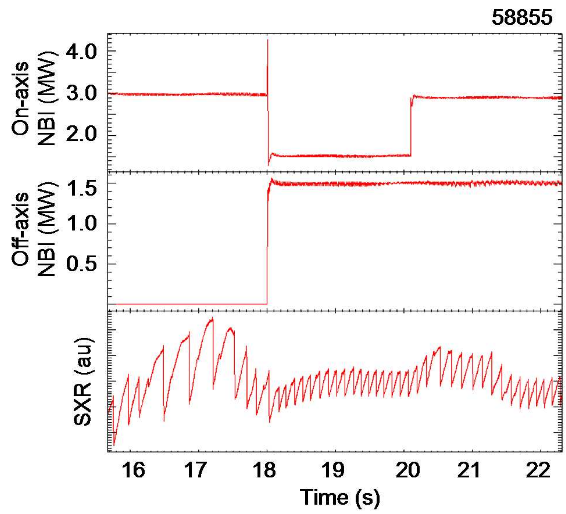

FIG. 2. Sawtooth destabilisation from the application of off-axis NBI in JET shot 58855.

applied is also demonstrated in other JET discharges. Furthermore, if the sawtooth behaviour is compared between 16-18s and 20-22s when there is constant on-axis power, then it is evident that the off-axis NBI can be used to destabilise long sawteeth. The sawtooth period decreases by a factor of two when the off-axis NBI is applied, even though β increases. Whilst using the exact distribution function gives the most accurate calculation of the stability of the kink mode in these NBI heated plasmas, it is possible to gain improved qualitative understanding by using a model distribution function. By doing this, the deposition location of the fast ions can be altered whilst keeping the equilibrium unchanged. This allows an intuitive insight into how the rôle of the fast ions changes when they are born either inside or outside of r_1. The trapped fast ion distribution function is assumed to be symmetric throughout. When the co-NBI is injected on-axis, the passing ion population is peaked inside $q = 1$ and so gives a strongly stabilising contribution. Thus, the Porcelli criteria outlined in Reference [1] is not met, and as a result, long sawtooth periods are likely. However, as the peak of the fast ion distribution is moved further outwards, the passing ions become less stabilising, and when the energetic ions are deposited slightly outside $q = 1$, the sawtooth crash criterion is met. For such NBI heated plasmas in JET, the passing ions primarily determine the stability of the mode, and consequently when the sawtooth crash will occur. When the distribution function is centred at r_1 the passing ions are weakly stabilising due to higher order terms, despite having an equal number of fast ions inside and outside $q = 1$ [9].

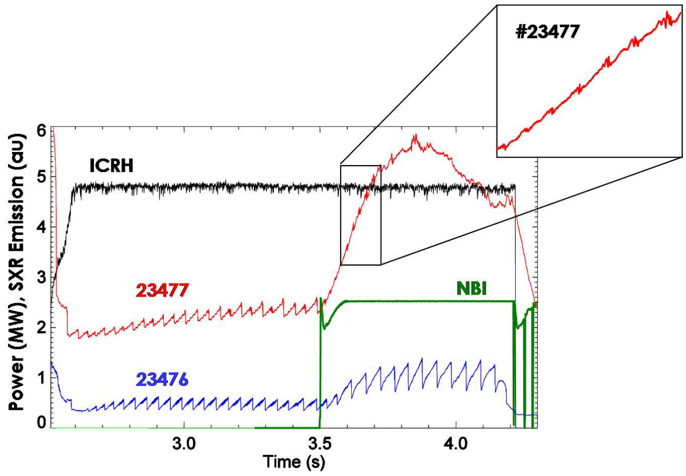

FIG. 3. ASDEX Upgrade shots 23476 and 23477 show a change in sawtooth behaviour when the NBI is injected near or well outside the $q = 1$ surface respectively.

Off-axis NBI has also been applied in ASDEX Upgrade discharges which have ICRH fast ion stabilised sawteeth. In discharges 23476 and 23477, the plasma is first heated with 4.5MW of ICRH power, leading to sawteeth in the presence of core fast ions. Then the most tangential off-axis PINI source is applied at the same time as the ICRH in an attempt to destabilise the sawteeth. Figure 3 shows the sawtooth behaviour in discharge 23476, a plasma with plasma current $I_p = 1$MA, toroidal magnetic field $B_T = 2.5$T, density $n_e \approx 9 \times 10^{19}\text{m}^{-2}$. The sawtooth period increases from approximately 45ms in the ICRH only phase, to $\tau_s \sim 55$ms when the ancillary off-axis NBI is applied. The current density profile has been calculated using the TRANSP code [12]. Although the neutral beam current drive does result in a small perturbation to the current density profile, the q-profile does not change significantly. Indeed, the inversion radius found from the soft X-ray emission does not change when the off-axis NBI is applied, indicating that the q-profile has not significantly altered. Conversely, figure 3 also shows the sawtooth behaviour in discharge 23477 where the toroidal field is raised to $B_T = 2.7$T in order to move the $q = 1$ surface radially inwards. Whilst the difference in the magnetic field means that the radial location of the ICRH resonance shifts towards the low-field side, the sawtooth period in the ICRH-only phase does not change significantly between shot 23476 and 23477. This occurs since the modest change in δW_h^t is offset by an increase in the magnetic shear at $q = 1$, so leaving the quotient $\delta W/s_1$ in the Porcelli trigger condition [1] approximately constant. When the off-axis NBI is applied in shot 23477, the sawteeth seem to become very small and their frequency doubles. However, it is not clear whether the sawtooth oscillations become imperceptibly small or disappear entirely. TRANSP calculations indicate that the neutral beam current drive is small and very broad and it is not anticipated to significantly alter the q-profile. The rise in the SXR emission in discharge 23477 cannot be explained by an increase in temperature alone; it is likely that such small or absent sawteeth cannot redistribute the core plasma sufficiently to avoid impurity accumulation. Modelling of neutral beam current drive and passing energetic ions will be reported elsewhere.

In MAST, the effect of off-axis NBI has been assessed by varying the vertical height of the plasma, and thus scanning the deposition location of the peak of the NBI fast ion population with respect to the $q = 1$ surface. MAST is uniquely placed to be able to vary the beam deposition location since the large gap between the vessel and the plasma means that the magnetic axis can be moved by over 25cm from the midplane. It is found that the sawtooth period varies significantly as the plasma position changes. A minimum in sawtooth period exists when the $q = 1$ surface is outside the deposition location, consistent with destabilisation from the passing fast ions. However, as the plasma is shifted further from the NBI path, the sawtooth period increases. This could be because the fast ions are now sufficiently off-axis that they no longer pass inside the $q = 1$ surface, or it could be due to the degraded fast ion confinement in such extremely single null discharges. Further, the roles of toroidal flow, plasma shaping and neutral beam current drive have yet to be assessed in these MAST plasmas.

4. Sawtooth Control in ITER

We now consider whether the Negative ion based Neutral Beam Injection (N-NBI) planned for ITER could be used as a sawtooth control actuator if the beam is aimed outside the $q = 1$ surface. In order to penetrate the hot, dense plasmas in ITER, neutral deuterium beam energies of the order of 0.5-1.0MeV are necessary. The beam can be aimed at two extreme (on-axis and off-axis) positions by tilting the beam source around a horizontal axis on its support flange, resulting in N-NBI injection in the range of Z = -0.25 to -0.95 m [16]. TRANSP simulations have been carried out to predict the fast ion distribution function due to the N-NBI when it is aimed both on- and off-axis, as well as the corresponding pressure and current density profiles [17]. The beam-driven current profile is broad with a total driven current of 1.2 MA [17]. This equilibrium, which has a monotonic q-profile with $q_0 = 0.92$, is found to be unstable to an $n/m = 1/1$ internal kink mode. The most extremely off-axis fast ion population is peaked at approximately $r/a = 0.22$. The current driven by the neutral beams results in the $q = 1$ surface being slightly closer to the magnetic axis than when on-axis NBI is applied.

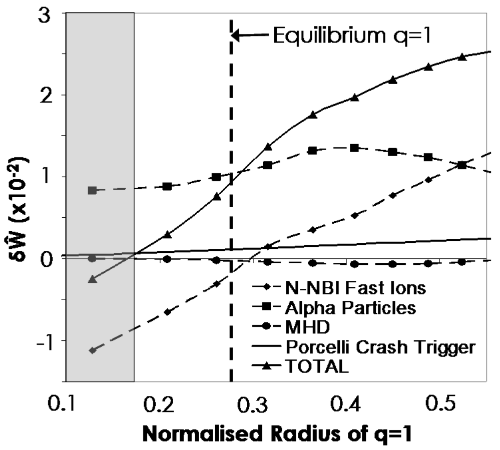

FIG. 4. δW due to energetic ions in ITER off-axis N-NBI heated plasmas as a function of r_1. When r_1 is sufficiently core localised the off-axis N-NBI can destabilise the kink mode.

In order to model the kink mode stability in baseline ITER plasmas, the safety factor at the magnetic axis has been scaled, and accordingly the radius of $q = 1$ has been moved with respect to the deposition location of the off-axis fast ion population. Figure 4 shows the change in the potential energy of the mode including the effects of both the passing beam ions and the fusion-born α particles in the case when the beam is oriented off-axis. When the beams are not applied the α particles are found to strongly stabilise the mode, and as such are likely to result in long period sawteeth. Additionally, if the peak of the fast ion population is inside the $q = 1$ surface, then the kink mode is even more stable. However, if the fast ions are deposited outside $q = 1$ then the passing ions have a strongly destabilising effect on the internal kink. As shown in figure 4, the off-axis N-NBI can destabilise the kink mode sufficiently to cause a sawtooth crash according to the Porcelli model [1] when 33MW of beam power is applied and the $q = 1$ surface is within $r/a \approx 0.2$. However, it should be noted that TRANSP predicts that the $q = 1$ surface in typical ITER baseline scenario plasmas will be outside $r/a \approx 0.2$, as indicated in figure 4. This implies that without ancillary current drive to move the $q = 1$ surface towards the axis, the N-NBI ions can also provide a stabilising effect on the $n = 1$ internal kink mode. Whilst N-NBI may not be a viable sawtooth control actuator in baseline scenarios in ITER, it is important to consider the NBI fast ions since these will be strongly stabilising when injected on axis.

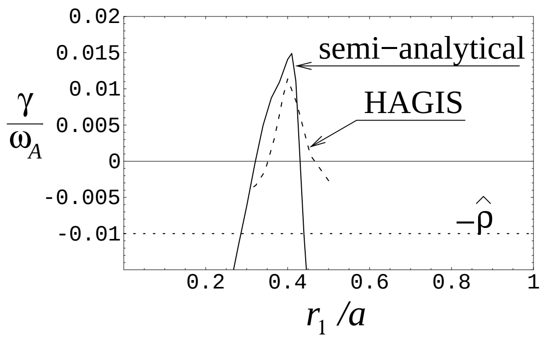

FIG. 5. The fast ion growth rate as a function of r_1. *Analytic calculations have been compared with drift-kinetic* HAGIS *calculations.*

The modelling of plasmas heated with neutral beams presented here has subsequently been applied to model the physics of sawtooth control using ICRH. Counter propagating waves could be more effective than off-axis N-NBI since they are highly energetic and have strong radial shears in the parallel asymmetries of the distribution function, accentuating the destabilisation term arising from the presence of energetic passing ions. Previously it had been assumed that the change in sawtooth behaviour in ICRH heated plasmas arose due to the change in the magnetic shear at $q = 1$ [15]. A new mechanism has been proposed that can explain the highly effective nature of sawtooth control using off-axis ion cyclotron resonance heating [18]. Energetic passing ions influence the internal kink mode when the distribution of ions is asymmetric in $v_{\parallel}$, a natural feature of co or counter propagating ICRH waves. JET discharge 58934 has been used to quantify the control mechanism, and demonstrate its viability, as illustrated in figure 5. In other recent discharges [19] it has been shown that a change in the magnetic field of only about two percent can be sufficient to enable or disable sawtooth control. The corresponding change in the magnetic shear has been calculated, and was shown to be extremely modest, thus questioning the viability of the classical sawtooth control mechanism relating to the change in the magnetic shear due to ICCD [15]. Nevertheless, it is shown here that when a counter propagating wave is deposited sufficiently accurately on the high field side, a newly discovered fast ion effect is so strong that the internal kink mode is driven not only resistive unstable, but ideally unstable, and this in turn is consistent with measured sawteeth that are much shorter in period than those obtained in Ohmic plasmas. Furthermore, unlike the classical sawtooth control mechanism, the fast ion mechanism is independent of the electron drag, which is expected [20] to limit the ICCD current drive efficiency of the proposed ICRF system for ITER.

5. Discussion and Conclusions

For the first time, comprehensive numerical modelling can now quantify the relative roles of fast anisotropic ions (including the hitherto neglected stabilisation from energetic passing ions), the toroidal rotation and changes to the magnetic shear profile in determining sawtooth behaviour. The control of sawteeth is important for baseline scenario operation of burning plasmas, since plasmas with long sawtooth periods are more susceptible to neo-classical tearing modes, resulting in substantial confinement degradation. The stabilising effects of alpha particles are likely to exacerbate this, so recent experiments have identified various methods for amelioration. Shorter sawtooth periods than in Ohmically heated plasmas have been achieved in JET, MAST and TEXTOR. Each experiment exhibits an asymmetry of sawtooth period with respect to NBI direction. In JET, the asymmetry is explained by combining the destabilisation arising from counter-passing ions with the effect of flow shear on the stabilising trapped ions. The sawtooth behaviour in TEXTOR is explained through a subtle combination of both gyroscopic effects and kinetic effects. The application of off-axis NBI can destabilise sawteeth which had previously been strongly stabilised by simultaneous on-axis heating. This is explained qualitatively through the role of passing energetic ions with a positive pressure gradient at the q=1 surface. Modelling of the effects of toroidal rotation and anisotropic fast particle distributions in the presence of sheared flows has significantly advanced the understanding of the physical mechanisms that determine sawtooth stability. Finally, the sensitive control of sawtooth oscillations with ICRH has also been explained through the (de)stabilisation arising from passing energetic ions. These fast passing ions can strongly influence the internal kink mode when their distribution is asymmetric in $v_{||}$, a natural feature of ICRH propagating waves.

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