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The merits of ion cyclotron heating schemes for sawtooth control in tokamak plasmas

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Abstract.

JET experiments have compared the efficacy of low- and high-field side ion cyclotron resonance heating (ICRH) as an actuator to deliberately minimise the sawtooth period. It is found that low-field side ICRH with low minority concentration is optimal for sawtooth control for two main reasons: Firstly, low-field side heating means that any toroidal phasing of the ICRH (-90°, +90° or dipole) has a destabilising effect on the sawteeth, meaning that dipole phasing can be employed since this is preferable due to less plasma wall interaction from RF sheaths. Secondly, the resonance position of the low-field side ICRH does not have to be very accurately placed to achieve sawtooth control, relaxing the requirement for realtime control of the RF frequency. These empirical observations have been confirmed by hybrid kinetic-MHD modelling, and suggest that the ICRH antenna design for ITER is well positioned to provide a control actuator capable of having a significant effect on the sawtooth behaviour.

1. Introduction

The baseline scenario in ITER for achieving fusion yield of Q=10 [1] – that is to say ten times more fusion power out than the power required to initiate plasma burn – is expected to have sawtooth osciallations in the plasma core. The sawtooth instability in the core of tokamak fusion plasmas [2] has been observed in every tokamak and is manifest as a redistribution of the core plasma during a magnetic field reconnection event [3, 4]. Both theory [5, 4] and experimental evidence [6, 7] suggest that this reconnection process occurs due to the growth of a plasma magnetohydrodynamic (MHD) kink instability with $m = n = 1$, where m and n are the poloidal and toroidal periodicities respectively. Whilst these quasi-periodic redistribution events are not anticipated to be detrimental to the performance of ITER plasmas as long as the period between reconnection events is longer than the slowing down time of the fusion-born alpha particles, the triggering of other MHD instabilities by the sawteeth can have implications for fusion yield. It has been observed that sawteeth trigger higher-m neoclassical tearing modes (NTMs) [8], and that this triggering is exacerbated at low plasma rotation, as expected in ITER. Furthermore, the presence of fusion-born alpha particles is expected to have a stabilising influence on the internal kink mode [9, 10], which leads to longer sawtooth periods, which have been empirically observed to increase the likelihood of triggering NTMs [11]. This observation has resulted in efforts to deliberately destabilise the sawtooth oscillations, to avoid the long sawtooth periods associated with triggering NTMs at lower core pressures. An ancillary purpose for sawtooth control (which is to say the deliberate timing of the sawtooth period and ensuing determination of the amplitude of the crash) is to affect the population of impurities in the plasma core. The advent of tokamaks with tungsten divertors as planned for ITER, such as JET [12] or ASDEX Upgrade [13], has highlighted the need to develop mechanisms to remove the high-Z impurities which occur due to erosion of the divertor plates, as well as removing the Helium ash from the plasma core which is known to adversely affect plasma confinement [14]. The two primary mechanisms for destabilising sawteeth are either by increasing the local magnetic shear near the rational surface where sawteeth are localised, the $q = m/n = 1$ surface, where q is the safety factor [15, 9]; or by tailoring the energetic ion population to reduce the potential energy required to drive the kink mode [16, 17].

The sawtooth control actuators envisaged for ITER [18] are electron cyclotron current drive (ECCD) to affect the local magnetic shear and ion cyclotron resonance heating (ICRH) to tailor the fast ion distribution and by so-doing counteract the stabilising effects of the alpha population. The presence of fusion-born alphas in a burning D-T plasma is expected to be so stabilising to the $n = m = 1$ kink mode that ICRH will be necessary to complement current drive schemes [18] which have been demonstrated to be particularly effective even at low power in present day machines [19, 20, 21, 22]. In this paper we concentrate on the effects of tailoring the distribution of energetic particles using ICRH to control sawteeth. In recent years, ICRH sawtooth control has been demonstrated on JET using radio frequency heating schemes with the resonance on either the low- or high-field side of the magnetic axis, as well as for various concentrations of the minority species resonant with the ion cyclotron waves from low ($n_{min}/n_{bulk} < 10\%$) to high ($n_{min}/n_{bulk} \sim 30\%$) concentrations. Furthermore, the toroidal direction of propoagating waves has also been changed in JET, with ensuing variations in both the radial and pitch-angle space distribution of the ICRH super-Alfvenic ions. This paper summarises the efficacy of the different ICRH schemes for sawtooth control in JET and so infers the likely optimal solution for ITER. In section 2 the mechanisms for sawtooth control are briefly recapitulated together with a brief review of the ICRH capability in ITER. The effect of the resonance position of the ICRH deposition on the effectiveness of sawtooth control in JET is compared to numerical modelling in section 3, before the effect of the minority concentration on ICRH sawtooth control is discussed in section 4. Finally, the merits of the different schemes are discussed for ITER application in section 5 before conclusions are drawn.

2. Review of sawtooth control mechanisms and ITER capability

2.1. Sawtooth control mechanisms

A heuristic model for the triggering of a sawtooth crash was developed in reference [9]. Whilst this model does not capture all the known effects on the stability of the internal kink mode, it has had significant success in interpreting the behaviour of sawteeth in a number of tokamak plasmas [23, 24, 25, 26]. The model consists of three different criteria, the satisfaction of which is predicted to incur a sawtooth crash. In plasmas with a large fast ion population, the criterion which ultimately determines the crash is that

$$s_1 > \max\Big(s_{crit} = \frac{4\delta W}{\xi_0^2 \epsilon_1^2 R B^2 c_\rho \hat{\rho}}, s_{crit}(\omega_*)\Big) \tag{1}$$

where the ideal growth rate normalised to the Alfven frequency is $\gamma_I/\omega_A = -\pi\delta\hat{W}/s_1$, with the change in the normalised potential energy of the kink mode, $\delta\hat{W} =$

$\delta W/(2\pi^2\xi_r^2 R_0 B_0^2 \epsilon_1^2)$, the change in the potential energy of the kink mode given by $\delta W = \delta W_f + \delta W_{KO} + \delta W_h$ where $\delta W_{f,KO,h}$ are the potential energy change due to the fluid drive [29], the thermal ions [28] and the fast ions [27] respectively. The magnetic shear at the $q = 1$ surfaces is $s_1 = \mathrm{d}q/\mathrm{d}r$, R_0, B_0 are the major radius and magnetic field at the position of the magnetic axis respectively, $\epsilon_1 = r_1/R_0$ is the inverse aspect ratio, r_1 is the minor radius at the $q = 1$ position, $\xi_r(r)$ is the leading order rational eigenfunction of the $m = n = 1$ mode at the magnetic axis and finally the critical magnetic shear determined by the pressure gradient, $s_1 > s_{crit}(\omega_{*i})$ and ω_{*i} is the ion diamagnetic frequency. The inequality condition given in equation 1 indicates that a sawtooth crash can be instigated by either increasing the local magnetic shear, s_1, or by reducing the potential energy of the kink mode, primarily through the contribution from fast particles, δW_h. The ICRH can modify equation 1 via either or both of these quantities since the high energy ion populations born from radio frequency heating can also give rise to a fairly strong local current perturbation, which when appropriately positioned can affect s_1 [15]. Two ICCD schemes have been used, namely (i) minority ICCD where a minority ion species resonates with the fundamental cyclotron frequency of the ICRH wave, absorbing the RF power and carrying the fast ion current, and (ii) second harmonic ICCD, where an ion species (not necessarily a minority species) resonates at its second harmonic cyclotron frequency, $\omega = 2\omega_{ci}$ with the RF waves.

The current drive resulting from resonant minority wave-particle interactions at cyclotron frequencies, or majority ions at harmonics of the cyclotron frequency, relies on an asymmetry in the passing ion distribution induced by directed wave spectra (ie waves propagating preferentially in one direction) and on the velocity dependence of the collisional pitch angle scattering [30]. The resonance condition between a wave and the cyclotron motion of the resonant particles is given by $\omega - n\omega_{ci} - k_\parallel v_\parallel = 0$, meaning that preferentially propagating waves can resonate with either co-transiting or counter-transiting ions, depending on the direction of wave propagation and the location of the interaction with respect to the cyclotron resonance. The Fisch model [30] predicts that waves propagating in the co-current direction ($k_\parallel > 0$) result in driven current with a dipole structure characterised by a positive part with respect to the plasma current on the low-field side of the cyclotron resonance and a negative part on the high field side. For counter-propagating waves, the currents in the dipole structure change sign. This mechanism is reviewed in references [31] and [15].

As well as the potential to drive current and change the local shear, the ICRH also generates very energetic particles of course. These energetic ions directly contribute to δW since [32, 5, 33]:

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

where θ is the poloidal angle, $\boldsymbol{\kappa} = \mathbf{b}\cdot\nabla\mathbf{b}$ is the magnetic curvature vector, $\mathbf{b} = \mathbf{B}/B$, δf is the change in the energetic particle distribution function due to the $n = m = 1$ kink perturbation, Γ is phase space, M is the particle mass, $v_{||}$ is the parallel velocity of the particle, r is the radial position of the particle, and ϕ, θ are the toroidal and poloidal angles. For many years it has been known that trapped energetic particles result in strong stabilisation of sawteeth [5]. However, passing fast ions can also significantly influence sawtooth behaviour. For highly energetic ions, the radial drift motion becomes comparable to the radial extent of the kink mode. The strong contribution of the circulating particles comes from the ions close to the trapped-passing boundary where their orbit widths, Δ_b are large, $\delta W_h^p \sim \Delta_b$. Passing fast ions can destabilise the internal kink mode when they are co-passing and the fast ion distribution has a positive gradient across $q = 1$, or when they are counter-passing, but the deposition is peaked outside the $q = 1$ surface. This mechanism is described in detail in references [34] and [17] with an overview of fast ion effects in reference [42].

Recent experiments in JET have isolated the dominant mechanism for sawtooth control with ICRH as the effect from energetic ions [37, 49]. By using ^{3}He minority heating the ion cyclotron driven current is negligible due to the current dragged by the background plasma which tends to cancel the ^{3}He current [36], but yet the control of sawteeth is still highly efficient [37]. The dominance of the fast ion contribution was unequivocably demonstrated by variation of the minority concentration. At very low concentration the absorbed power is reduced, and consequently the effect on the sawteeth was mild; similarly at high concentration, the energy tail of the energetic ion population is lower, so the radial drift excursion of the ICRH fast ions which intersect the $q = 1$ surface is smaller, and so the ability to affect the sawteeth is again reduced. However, at minority concentrations intermediate between these extremes, the radial orbit drift of the energetic ion distribution tail and the absorbed power are both sufficient to have a strong effect on the sawteeth, even in H-mode in the presence of a population of stabilising core fast ions when there is negligible drive current. Furthermore, experiments with low-field side H minority ICRH showed that any phasing of the ICRH (-90°, +90° or dipole) has a destabilising effect on the sawteeth, ie reduces the sawtooth period, when the resonance position is just outside the $q = 1$ surface. Whilst the driven current is mild, in all cases the magnetic shear at $q = 1$ is actually *reduced* which should stabilise the sawteeth, whilst a marked destabilisation is observed, emphasising that the conventional 'change in magnetic shear' interpretation for the control of sawteeth cannot apply in these minority-H low-field side experiments, and furthermore that the fast ion effects on the kink mode could be inferred to be typically the dominant effect of ICRH.

2.2. ITER capabilities

ITER is expected to have 20MW of ICRH as part of the portfolio of 73MW of auxiliary heating and current drive tools. Ion cyclotron waves will be strongly damped in ITER, leading to various possible heating schemes: Second harmonic tritium or fundamental ^{3}He heating; Fundamental D heating (although a low deuterium concentration is required for efficient wave damping making this low relevance); Electron Landau Damping (ELD) / Transit Time Magnetic Pumping (TTMP), both of which are fast wave current drive scenarios leading to insignificant fast ion populations; or off-axis

^{3}He heating, which has moderate absorbed power density but can result in a significant population of ICRH energetic ions near the $q = 1$ surface. At full magnetic field in ITER ($B_0 = 5.3$T), the ICRH antenna design precludes high field side resonance positions. Variable frequency ICRH is currently planned for ITER. The ICRH frequency will be able to vary in real-time between 40-55MHz [38]. The ^{3}He resonance just outside $q = 1$ is likely to require a frequency of approximately 47MHz. It will be possible to rapidly change the RF frequency in a preset 2MHz band, which is equivalent to moving the resonance location by approximately 20cm, which should provide sufficient scope for real-time sawtooth control. In the ^{3}He minority heating scheme envisaged for ITER, the resultant current drive is negligible [17, 36].

3. The effect of the ICRH resonance position on sawtooth control in JET

The ICRH system in JET has a wide frequency variation meaning that resonance positions on either the low- or high-field side of the magnetic axis are possible. In this section we describe the merits of high-field side heating with either H or ^{3}He minority species compared to low-field side heating with H minority. Figure 1 shows the configuration of typical JET plasmas which have the ICRH resonance on the low-field side (37MHz with $B_t \in [2.7, 2.35]$T using fundamental H minority resonance) and on the high-field side (33MHz with $B_t \in [2.88, 2.96]$T using fundamental ^{3}He minority resonance) compared to the approximate position of the $q = 1$ surface found from the sawtooth inversion radius measured by soft X-ray emission in JET discharge 84500, which is typical of the plasmas used in this study. In both cases an optimal minority concentration is employed.

3.1. Sawtooth control with low concentration ^{3}He minority ICRH resonance on the high field side

Sawtooth control was demonstrated with ^{3}He minority heating on the high field side, whereby the current drive was minimised to verify that the passing fast ion effect dominated [37, 39]. In order to demonstrate the effect of the ICRH fast ions on the sawtooth behaviour, the ICRH resonance position has been moved with respect to the $q = 1$ surface by ramping the magnetic field to move the ICRH resonance and the current commensurately to keep the q-profile fixed. Typically the ICRH resonance is moved from outside the $q = 1$ surface, where the ICRH barely affects the sawtooth behaviour, to inside it, where it is known that the ICRH trapped energetic particles have a strongly stabilising effect, increasing the sawtooth period. Through sweeps like this, the change in the sawtooth period when the resonance position is just in/outside $q = 1$ can be studied, since it is at this point that the fast ion population with radial drift excursions cutting the rational surface is maximised, and it is this population deliberately placed near the $q = 1$ surface which affect kink stability [17]. Figure 2 shows the sawtooth behaviour as the ICRH resonance is swept from outside to inside the $q = 1$ surface

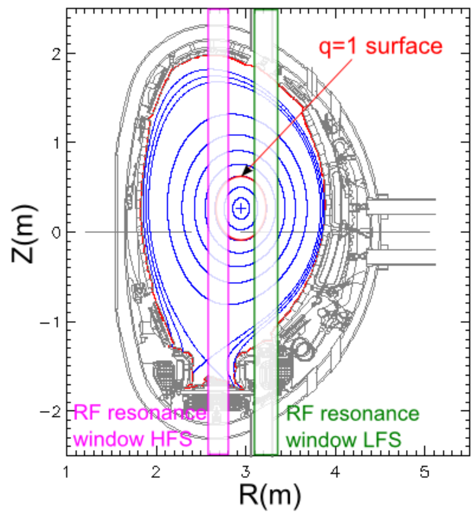

Figure 1. The plasma configuration used in JET discharge 84500 at 15s, which is representative of the plasmas studied in this paper, showing the $q = 1$ surface and the ICRH resonances for ^{3}He on the high-field side and H on the low-field side

when the resonance is on the high-field side of the magnetic axis. It is evident that the sawtooth period is minimised as the RF resonance is positioned just inside the $q = 1$ surface. Note, this occurs for $r_{res} < r_{inv}$ even though $R_{res} > R_{inv}$ when the resonance is on the high-field side. For effective sawtooth destabilisation, ie a minimisation of the sawtooth period, the location of the RF resonance must be highly accurately placed with respect to the rational surface, with a localisation closer than $\sim$ 2cm. Given significant uncertainty in the radial localisation of the $q = 1$ surface in ITER, and the ray-tracing to predict the resonance position being subject to uncertainties in the plasma density profile as well as approximations in the ray propogation models, this narrow window for effective sawtooth control implies that a real-time feedback scheme is needed for robust high-field side ICRH sawtooth control [40].

It is found that the toroidal phasing of the ICRH antenna configuration has a marked affect on the sawtooth control for high-field side resonance [39]. When the ICRH has $-90°$ phasing, the ICRH resonance just inside the $q = 1$ surface gives rise to destabilisation of the kink mode, and so shortening of the sawtooth period, whilst $+90°$ phasing has the opposite effect, stabilising the sawteeth. This is illustrated in figure 3, which shows the sawtooth period as a function of the resonance position with respect to the $q = 1$ surface for both $\pm 90°$ phasings when the ICRH resonance is on the high-field side. It is clear that when the resonance is just inside $q = 1$ the counter-propagating waves give rise to a minimum in the achievable sawtooth period, significantly lower than

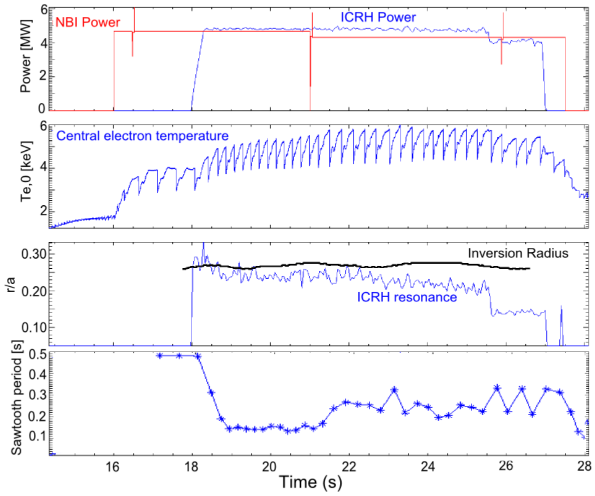

Figure 2. Timetraces for JET pulse 78764 showing (a) the auxiliary NBI and ICRH heating power, (b) the central electron temperature measured by the electron cyclotron emission diagnostic demonstrating the sawtooth activity, (c) the resonance position of the high-field side ICRH compared to the radial position of the sawtooth inversion radius and (d) the sawtooth period. The ICRH had $-90°$ phasing. The toroidal magnetic field was ramped linearly from 2.85T to 2.95T and proportionately the plasma current was ramped from 1.95MA to 2.05MA.

the reference case without ICRH, whilst the co-propagating waves result in a significant increase in the sawtooth period. In this case, the lengthening of the sawtooth period to $\sim$ 1s actually results in the triggering of an NTM, even in L-mode at $\beta_N = 0.8$ (well below the target level of the $Q = 10$ scenario for ITER, where $\beta_N = 1.8$). At this point it is worth pointing out that phased ICRH waves are considered sub-optimal compared to dipole phasing due to the slightly lower absorbed power, and importantly, the enhanced plasma-wall interaction due to radio frequency sheath redistribution effects [41], which is a considerable limitation in devices with metal walls due to sputtering of tungsten.

In order to understand the effect of these different fast ion distributions on the stability of the internal kink mode, coupled hybrid kinetic-MHD numerical modelling has been employed. The ICRH fast ion population is modelled with either the SELFO [43] or SCENIC [44] ICRH wave codes, whilst the NBI distribution is modelled with the NUBEAM model within the TRANSP code [45]. Meanwhile, the plasma equilibrium is constrained by the sawtooth inversion radius and reconstructed using the HELENA [46] Grad-Shafranov solver. The linear MHD stability of this equilibrium is then studied using the MISHKA code [47] to find an unstable $n = m = 1$ eigenfunction. The interaction between this unstable kink mode and the fast ions is then studied with the drift-kinetic HAGIS code [48] which calucates δW_h. Figure 4 shows the change in the potential energy of the kink mode as a function of radial position of the peak of the ICRH distribution with respect to the q=1 surface position. It is evident that the $-90°$ phasing reduces δW_h, consistent with the reduction in the sawtooth period

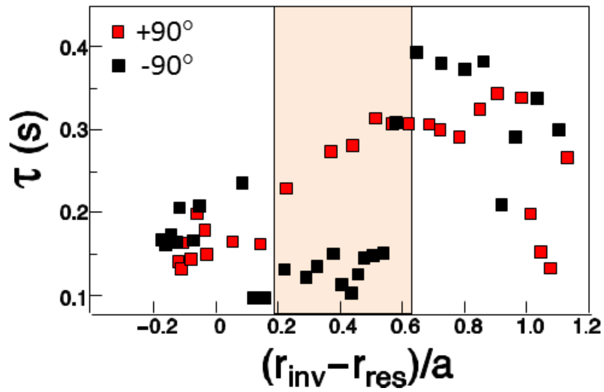

Figure 3. The sawtooth period as a function of the resonance position with respect to the inversion radius for different ICRH phasings in JET for ICRH with low $\sim 0.5\%^3$He minority concentration located on the high-field side. The shaded area represents the region with an ICRH resonance just outside the $q = 1$ surface, where the fast ions have the strongest effect on the sawtooth behaviour.

observed in JET, whilst the $+90°$ phasing increases δW_h, once again consistent with the experimental sawtooth behaviour. The effect on kink stability is governed by the asymmetry in the parallel velocity of the ICRH distribution function, and specifically in the radial variation of this asymmetry. When the population of fast ions is such that the number of co- and counter-passing ICRH ions whose radial drift is large enough that it cuts across the $q = 1$ surface is unequal, they result in a change in the kink mode potential [17, 42].

3.2. Sawtooth control with low concentration H minority ICRH resonance on the low field side

Similar sweeps of the ICRH resonance position across the $q = 1$ surface have been performed with the resonance located on the low-field side of the magnetic axis in JET, as expected for ITER at full magnetic field. In JET this means using H minority ICRH heating, which does drive a small ion cyclotron current, but as demonstrated in reference [49], the effect on the sawteeth is dominated by the fast ion mechanisms over the shear mechanism. Figure 5 shows the sawtooth behaviour as the ICRH resonance is swept from outside to inside the $q = 1$ surface when the resonance is on the low-field side of the magnetic axis. It is evident that the sawtooth period is minimised as the RF resonance is positioned close to the $q = 1$ surface. However, in contrast to the result with high-field side resonance, the window for effective sawtooth destabilisation, ie a reduction of the sawtooth period, is signficantly wider. In the case of low-field side resonance, the resonance position must only be in a window of $\sim$ 15cm around the $q = 1$ surface to achieve sawtooth destabilisation, which is much broader than for high-field side ICRH. If this can be replicated in plasma with a dominant core fast ion population this would negate the requirement for realtime control of the RF frequency, greatly simplifying the

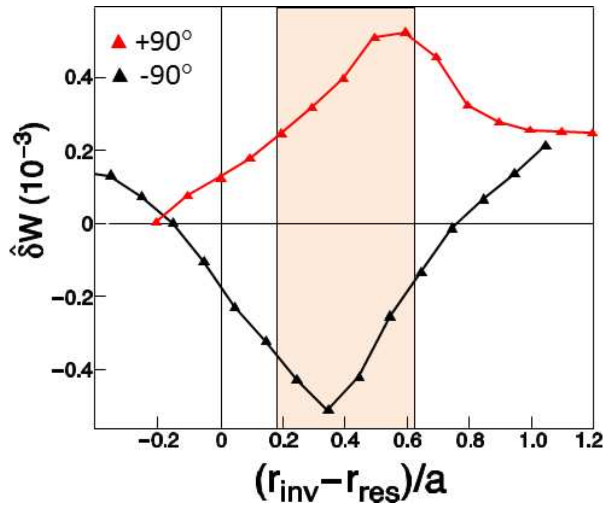

Figure 4. The $\delta\hat{W}_h$ calculated by HAGIS for different ICRH phasings with the ICRH resonance on the high-field side and the ICRH distribution taken from SELFO modelling. The shaded band is the same as in figure 3 demonstrating that for $-90°$ phasing the $\delta\hat{W}_h$ is negative, ie destabilising in this region, in line with the shorter sawtooth period seen in figure 3. Conversely, the $+90°$ phasing in the same region give positive $\delta\hat{W}_h$, ie sawtooth stabilisation, commensurate with the longer sawtooth period observed experimentally.

coupling of the RF waves to the plasma.

The toroidal phasing of low-field side RF schemes has also been varied in order to compare to the result from high-field side heating, where the sawtooth control was strongly dependent upon the ICRH phasing. Figure 6, which shows the sawtooth period as a function of the resonance position with respect to the $q = 1$ surface for $-90°$, $+90°$ and dipole phasings when the ICRH resonance is on the low-field side. In contrast to high-field side ICRH sawtooth control, all phasings have a destabilising effect on the sawteeth when the resonance is on the low field side. Again, this is positive for ITER if it can be sustained in plasmas with a high fast ion fraction, since using dipole phasing does not have the by-product of enhanced plasma wall interaction.

Finally, the change in the kink mode stability resultant from the low-field side ICRH fast ion populations has also been modelled using the hybrid MHD-kinetic code package as before. Figure 7 shows the change in the potential energy of the kink mode as a function of radial position of the peak of the ICRH distribution with respect to the q=1 surface position. Whilst the $+90°$ ICRH population has the most destabilising effect on the kink mode, as expected from reference [17], all of the phasings do reduce δW_h. Qualitatively these simulations verify the empirical observations, namely that with the ICRH resonance on the low-field side the $+90°$ phasing is most destabilising, but that all phasings do reduce kink stability provided the resonance is centred just outside $q = 1$. Furthermore, the window in $r_{res} - r_1$ for which δW_h is reduced is much broader for low-field side heating than when the resonance is on the high-field side.

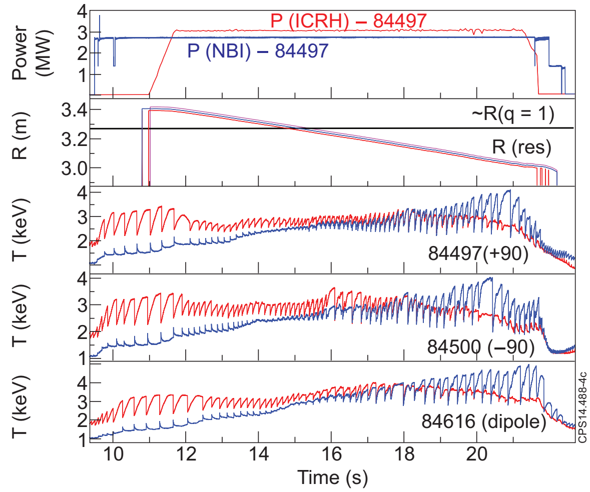

Figure 5. Timetraces for three similar JET pulses with different ICRH phasings showing (a) the auxiliary NBI and ICRH heating power, (b) the resonance position of the low-field side ICRH compared to the radial position of the sawtooth inversion radius and (c)-(e) the central electron temperature measured by the electron cyclotron emission diagnostic demonstrating the sawtooth activity for $+90°$, $-90°$ and dipole ICRH phasing respectively. The toroidal magnetic field was ramped linearly from 2.7T to 2.35T and proportionately the plasma current was ramped from 2.4MA to 2.05MA.

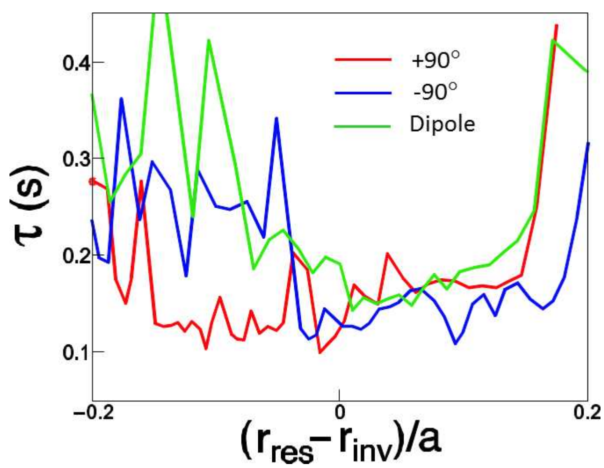

Figure 6. The sawtooth period as a function of the resonance position with respect to the inversion radius for different ICRH phasings in JET for ICRH with $\sim 4\%H$ minority concentration located on the low-field side.

4. The effect of the minority concentration on sawtooth control

It was shown in reference [37] that sawtooth destabilisation from high-field side ICRH was extremely sensitive to the minority species concentration. This is essentially due to the fast ion (de)stabilisation mechanism dependence on the need to develop an asymmetry in the parallel velocity of the passing fast ions which cross the $q = 1$ surface.

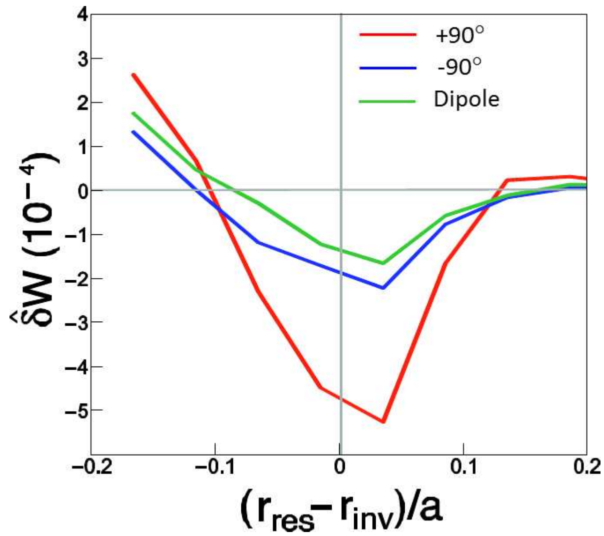

Figure 7. The $\delta \hat{W}_h$ calculated by HAGIS for different ICRH phasings with the ICRH resonance on the low-field side and the ICRH distribution taken from SCENIC modelling.

If the minority concentration is too high, there are insufficient number of fast ions which have sufficient energy to have a broad radial drift excursion and so cut across $q = 1$. Equally, if the minority concentration is too low, whilst there is a long-tail in the energy distribution with a large fraction of very energetic particles with large effective orbit width, the total absorbed power is too low to compete with the stabilising NBI fast ions. This dependence on the minority concentration is demonstrated in figure 8 where the δW_h modelled by HAGIS is shown for ICRH with a resonance position located on the high-field side with $-90°$ antenna phasing as the resonance is swept from outside to inside the $q = 1$ surface. Strong destabilisation is only observed for intermediate minority concentration ($n_{He3}/n_{bulk} \sim 1\%$), whilst a weak effect on the sawteeth is seen for both low ($n_{He3}/n_{bulk} \sim 0.15\%$) and high ($n_{He3}/n_{bulk} \sim 3\%$) concentrations.

5. Discussion of the merits of ICRH control schemes in ITER and conclusions

In section 3 it is shown that low-field side resonance heating has a significantly broader window in the resonance position to destabilise the sawteeth. With high-field side ICRH, the resonance must be placed with $\sim$ 2cm of the $q = 1$ surface in JET in order to reduce the sawtooth period. Conversely, with low-field side, this window is increased to $\sim$ 15cm, greatly reducing the likely need for real-time control of the resonance position through changing the RF frequency [50]. Furthermore, heating with a resonance on the low-field side is effective no matter which phasing of the ICRH antenna is employed. Even ICRH waves injected perpendicular to the magnetic field can destabilise the sawteeth, whereas dipole phasing is always observed to be stabilising on the high-field side. In section 4

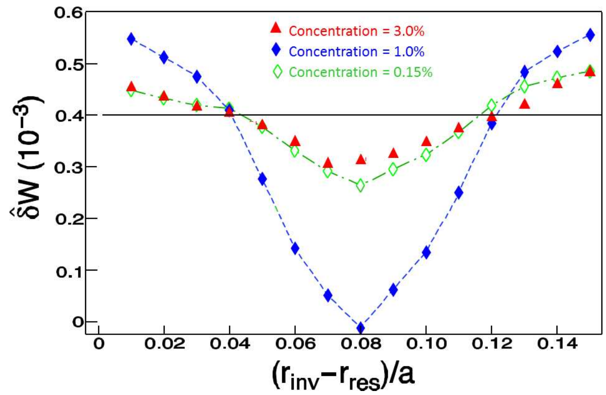

Figure 8. The $\delta\hat{W}_h$ calculated by HAGIS as a function of the resonance position with respect to the sawtooth inversion radius in JET plasmas when the ICRH resonance is on the high-field side for different ^{3}He minority concentrations.

it is demonstrated that by simultaneously optimising the coupled RF power **and** the energy of the ICRH distribution tail such that the radial width of the orbit excursion of particles crossing the $q = 1$ surface, the effect on the sawteeth is optimised. This occurs for intermediate minority concentrations ($n_{min}/n_{bulk} \sim 3 - 6\%$) in JET for H minority, but lower concentration ($n_{min}/n_{bulk} \sim 0.5 - 1\%$) for ^{3}He minority.

The anticipated ICRH heating scheme in ITER uses 51MHz RF heating of a low-concentration ^{3}He minority species on the low-field side of the plasma. The results from JET coupled with the numerical modelling in sections 3 and 4 suggest that this is the optimal ICRH antenna design for sawtooth control for two reasons: (i) low-field side heating means that any toroidal phasing of the ICRH (90°, +90° or dipole) has a destabilising effect on the sawteeth, ie reduces the sawtooth period, meaning that dipole phasing can be employed since this is preferable due to less plasma wall interaction from RF sheaths [41] with a metal wall; and (ii) the resonance position of the low-field side ICRH does not have to be very accurately placed to achieve sawtooth control. This relaxes the necessity for realtime control of the RF frequency. Calculations of the change of the kink mode potential energy due to ICRH fast ions using the SCENIC and HAGIS codes, as described in section 3, have been carried out for low-field side ICRH heating in ITER using ^{3}He minority with different antenna phasings and for different minority concentrations [42]. It is found that the most destabilising effect on the internal kink mode is achieved for $n_{He3}/n_{bulk} \sim 1\%$ and, whilst +90° phasing is optimal, a strong effect is attained even with dipole phasing. Together with the empirical observations from JET, this numerical modelling suggests that the ICRH antenna design for ITER is well positioned to provide a control actuator capable of having a significant effect on the sawtooth behaviour, and coupled with the electron cycltron current drive, aim to keep the sawtooth period below that expected to trigger NTMs [42].

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[1] ITER Physics Basis 2007 *Nucl. Fusion* **47** S1
[2] Levinton FM, Batha SH, Yamada M and Zarnstorff MC, 1993 *Phys. Fluids B* **5** 2554
[3] Kadomtsev BB 1976 *Sov. J. Plasma Phys.* **1** 389
[4] Hastie RJ and Hender TC 1988 *Nucl. Fusion* **28** 585
[5] Porcelli F 1991 *Plasma Phys. Control. Fusion* **33** 1601
[6] IT Chapman et al, *Phys Rev Lett* **105** 255002 (2010)
[7] Park HK *et al* 2006 *Phys. Rev. Lett.* **96** 195003
[8] Sauter O *et al* 2002 *Phys. Rev. Lett.* **88** 105001
[9] Porcelli F, Boucher D and Rosenbluth M 1996 *Plasma Phys. Control. Fusion* **38** 2163
[10] Hu B, Betti R and Manickam J 2006 *Phys. Plasmas* **13** 112505
[11] IT Chapman et al, *Nucl Fusion* **50** 102001 (2010)
[12] F Romanelli et al, *sub Nucl Fusion* (2014)
[13] H Zohm et al, *sub Nucl Fusion* (2014)
[14] I Nunes et al, *sub Nucl Fusion* (2014)
[15] Eriksson L-G *et al* 2006 *Nucl. Fusion* **46** S951
[16] Graves JP 2005 *Phys. Plasmas* **12** 090908
[17] Graves JP, Chapman IT, Coda S, Eriksson LG and Johnson T 2009 *Phys. Rev. Lett.* **102** 065005
[18] IT Chapman et al *Nuclear Fusion* **53** 066001 (2013)
[19] IT Chapman et al, *Nuclear Fusion* **52** 063006 (2012)
[20] IT Chapman et al, *Plasma Physics and Controlled Fusion* **55** 065009 (2013)
[21] VG Igochine et al *Plasma Physics and Controlled Fusion* **53** 022002 (2011)
[22] TP Goodman *et al* 2011 *Phys Rev Lett* **106** 245002
[23] Angioni C *et al* 2002 *Plasma Phys. Control. Fusion* **44** 205
[24] Angioni C, Goodman T, Henderson M and Sauter O 2003 *Nucl. Fusion* **43** 455
[25] Zucca C *et al* 2008 *Theory of Fusion Plasmas, Joint Varenna-Lausanne Theory Conference* **1069** 361
[26] D Kim, TP Goodman and O Sauter, *Phys. Plasmas* **21** 061503 (2014)
[27] JP Graves *et al* 2011 *Fus. Sci. Tech.* **59** 539
[28] Kruskal M and Oberman C 1958 *Phys. Fluids* **1** 275
[29] Bussac MN *et al* 1975 *Phys. Rev. Lett.* **35** 1638
[30] Fisch NJ 1987 *Rev. Mod. Phys.* **59** 175
[31] Bhatnagar VP *et al* 1994 *Nucl. Fusion* **34** 1579
[32] Briezman B, Candy J, Porcelli F and Berk H 1998 *Phys. Plasmas* **5** 2326
[33] Porcelli F, Stankiewicz R, Kerner W and Berk H 1994 *Phys. Plasmas* **1** 470
[34] Graves JP 2004 *Phys. Rev. Letters* **92** 185003
[35] IT Chapman et al *Plasma Physics and Controlled Fusion* **53** 013001 (2011)
[36] Laxåback M and Hellsten T 2005 *Nucl. Fusion* **45** 1510
[37] JP Graves et al, *Nature Comms* **3** 624 (2012)
[38] P Lamalle et al *Fusion Engineering and Design* **88** 517 (2013)
[39] JP Graves et al, *Nucl Fusion* **50** 052002 (2010)
[40] M Lennholm et al *Nucl Fusion* **51** 073032 (2011)
[41] A Czarnecka et al *Plasma Phys Control Fusion* **53** 035009 (2011)
[42] IT Chapman et al *Plasma Phys Control Fusion* **53** 124003 (2011)
[43] J Hedin et al, *Nucl Fusion* **42** 527 (2002)

[44] M Jucker et al *Plasma Phys Control Fusion* **53** 054010 (2011)
[45] RV Budny et al *Nucl Fusion* **32** 429 (1992)
[46] Huysmans GTA *et al*, 1991 *Proc CP90 Conf on Comp Phys, Amsterdam* p.371
[47] IT Chapman et al *Phys Plasmas* **13** 062511 (2006)
[48] SD Pinches et al, *Comput Phys Commun* **111** 133 (1998)
[49] JP Graves et al, *Plasma Phys Control Fusion* **57** 014033 (2015)
[50] M Lennholm et al *accepted Plasma Phys Control Fusion* (2015)