Sawtooth control with modulated ICRH in JET-ILW H-mode plasmas

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Abstract. Sawtooth pacing with modulated ion-cyclotron resonance heating (ICRH) has been demonstrated to be very efficient in JET-ILW L-mode plasmas [1,2], where the main heat source in the plasma centre is provided by the RF accelerated minority ions. In H-mode plasmas with substantial neutral beam injection (NBI) power, this technique is more challenging since the fast beam particles have a stabilizing effect on the sawteeth, making it more difficult to trigger a sawtooth crash by removing the additional fast particle sources induced by ICRH inside the q=1 surface. New results from JET-ILW experiments, showing that this technique can also be used in high power H-modes with considerable success will be presented, with focus on the sawtooth triggering efficiency at different pacing frequencies and plasma parameters, both during the flat-top phase of the discharges and during the H-mode exit and plasma termination.

1. Introduction

The sawtooth instability has been observed ever since the early days of tokamak operation [3]. This instability occurs when the central safety factor $q=d\Phi/d\Psi$ (where Φ and Ψ are respectively the toroidal and poloidal magnetic fluxes) drops below unity. It manifests itself through periodic magnetic reconnection events, where the plasma density and temperature profiles inside a certain plasma minor radius - the inversion radius - drop abruptly. The energy released from the central part of the plasma is expelled to the part of the plasma outside the inversion radius, resulting in an increase of plasma temperature and density in this region. Between reconnection events, often labeled as 'sawtooth crashes', the temperature and density increases on a slower timescale before 'crashing' again, with the resulting sawtooth-like time traces giving rise to the name.

Though the transient flattening of the central density and temperature is not, in itself, very damaging for the plasma performance, the sawtooth crash can induce other, more deleterious, instabilities, notably Neoclassical Tearing Modes (NTMs) [4,5]. These modes, associated with other rational q surfaces (q=3/2, q=2/1 etc.) strongly reduce the plasma confinement and, if large enough, potentially lead to the plasma being lost through a disruptive sequence of events. Even if the excited tearing modes are of moderate amplitude, recent experiments showed that they can significantly enhance the central peaking of high-Z impurities in full-metal machines [6]. Finally, it is known that the triggering of NTMs by sawtooth crashes becomes more likely when the sawtooth period increases [4]. It is therefore desirable to develop techniques that allow controlling the sawtooth periods to sufficiently small values to avoid the excitation of such deleterious modes.

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The mechanism responsible for the very fast reconnection event at the sawtooth crash has first been described by Kadomtsev [7] with the reconnection centered around the q=1 magnetic surface. In this description, the initiating event is the growth of a (*N=1, M=1*) internal kink instability. The mechanism described by Kadomtsev is for full reconnection, where the *q*-profile is modified by the crash so that q_0, the value of the safety factor at the plasma centre, becomes less than one. Other manifestations of the sawtooth crash, the so-called partial sawtooth crashes, results in smaller modification to the q-profile, with the q_0 remaining above unity. Between sawtooth crashes, the q-profile evolves resistively until the internal kink mode becomes sufficiently unstable to provoke the next sawtooth crash. The criteria for determining the onset of a sawtooth crash is complex, with competing stabilizing and destabilizing effects. According to Porcelli *et al.*, the main criteria for triggering a sawtooth crash can be cast in terms of the shear at the *q*=1 surface, $s_1 = \frac{r}{q}\frac{dq}{dr}$, with a sawtooth crash occurring when this shear exceeds a certain value that depends on various core plasma properties [8,9]. Fast ions in the central part of the plasma strongly affect the shear threshold at which a sawtooth crash occurs, with NBI ions and α-particles from fusion reactions expected to be strongly stabilizing, leading to long sawtooth periods and high risk of triggering NTMs. Fast ions generated by ICRH can be both stabilizing and destabilizing, depending on the details of their orbits [10] and the position of the ICRH absorption with respect to the *q*=1 magnetic surface.

Minority ion-cyclotron resonance heating (ICRH) relies on accelerating a minority species injected in the plasma (typically H or ^{3}He) to supra-thermal energies. These ions will slow-down by Coulomb collisions and transfer the absorbed wave power to the main plasma species. Depending on the energy they reach (which is a function of their mass, the RF power density, the minority concentration and the background plasma kinetic profiles), they will preferentially collide with electrons ($E>E_{crit}$) or bulk plasma ions ($E<E_{crit}$), where the critical energy is defined as $E_{crit}=14.8A_{fast}T_e\,(\Sigma X_jZ_j^2/A_j)^{2/3}$, with A_{fast} being the minority ion atomic mass, T_e the electron temperature and $X_j=n_j/n_e$, Z_j and A_j being respectively the bulk ion concentrations, charges and masses. The critical energy is typically around 80-120keV for JET-ILW deuterium H-mode discharges with H minority ICRH and about 3 times larger when ^{3}He minority heating is used, which explains the dominant bulk ion heating observed with the latter scheme even at modest minority concentrations in recent experiments [11].

In general, fast ions also create local shear and induce local currents near their cyclotron resonance layer in the plasma, not only in the perpendicular direction but also in the radial direction if their orbits become fat. On the other hand, the fast ions created by ICRH have a strongly anisotropic distribution function (ICRF heating mainly accelerating ions in the direction perpendicular to the equilibrium magnetic field), which can have a strong influence on the stabilization, destabilization and even excitation of MHD modes [12,13]. The influence of the fast ions on the stability of the internal (*N=1, M=1*) kink mode depends in a complex way on the details of fast ion orbits in relation to the location of the *q*=1 surface. The ions can give energy to the mode, in which case the fast ion effect is destabilizing or they can take energy away from the mode, having a stabilizing effect [10,14,15]. For fast ions born near the centre of the plasma (inside *q*=1), this effect is generally stabilizing, resulting in an increase in the shear at the *q*=1 surface required for the sawtooth crash to be triggered. This leads to a lengthening of the sawtooth period w.r.t the natural period that would be observed in the absence of the fast ion population [16,17].

Many plasma parameters can in fact influence the sawtooth dynamics [18]. In the conditions of the plasmas considered in this paper, the equations derived by Porcelli [9] ascertain that a sawtooth crash will occur when both of the following criteria are fulfilled:

$$s_1 = \left(\frac{r}{q}\frac{dq}{dr}\right)_{q=1} > s_{crit} \quad \text{and} \quad \delta\hat{W} < c_\rho\hat{\rho} \qquad (1)$$

Here s_1 is the shear at the q=1 surface and s_{crit} is the critical shear which depends on the layer physics in the vicinity of the q=1 surface. $\delta\hat{W}$ is the normalised potential energy functional associated with the M=1 mode, $\hat{\rho}$ is the ion Larmor radius normalised to the minor radius of the q=1 surface (r_1) and c_ρ is a constant of the order of unity. Following the arguments in [19], the normalised potential energy functional can be split in two components: $\delta\hat{W} = \delta\hat{W}_0 + \delta\hat{W}_{fast}$, where $\delta\hat{W}_{fast}$ is associated with the fast ion population inside q=1. According to [9], $\delta\hat{W}_{fast}$ is proportional to $\int x^{3/2}(dp_{fast}/dx)dx$, where $x = r/r_1$, r is the minor radius and $p_{fast}(x)$ is the fast ion pressure profile. It's worth noting that the details of the fast ion orbits near the q=1 surface [10] affects $\delta\hat{W}_{fast}$ in a more complicated way than can be captured purely by the fast ion pressure profile. In the case where the fast ions are mainly generated by centrally deposited ICRF power (inside q=1), as in the experiments discussed in this paper, the above expression captures the essential physics of the $\delta\hat{W}_{fast}$ modifications due to ICRH. Given that $\delta\hat{W} \propto \delta W / s_1$, the second criterion of eq.(1) can be written as $s_1 > \delta W / (c_\rho \hat{\rho})$ and one can summarize the crash criteria into a single expression:

$$s_1 > \max(s_{crit}, s_W) \qquad (2)$$

where $s_W = \delta W / (c_\rho \hat{\rho})$. A more detailed description of the various components making up s_W can be found in [20]. In the current experiments, when sufficient ICRH is injected, s_W is dominated by the fast ion contribution and is therefore a function of the fast particle distribution function, the fast ion energy density inside q=1 (W_{fast}) and the Larmor radius of the heated ions. The time evolution of this parameter can be affected by varying the applied ICRH power and this is the basis for the sawtooth pacing technique described in this paper.

The influence of ICRH on the dynamics of sawteeth has been first shown in TEXTOR [16,23,24] and was subsequently explored in other tokamak's in the 90's [21,22]. More recently, attempts to control the sawtooth period with ICRH in TEXTOR [25], JET-C [26,27] and in JET-ILW [10,14,15,28-31] has been mainly explored in two ways:

1) By applying continuous ICRH close to the q=1 surface it has been shown that the kink mode can be partially destabilized and the sawtooth period reduced. Best results were obtained by aligning the ICRF resonance to q=1 on the low-field-side of the plasma and by using a current-drive antenna excitation that induces an outward pinch of the fast ion orbits in the core [30,31]. The major advantage of this technique is that it acts directly and continuously on the sawtooth stabilization criteria while its main drawback is the fact that the RF frequency has to be adjusted in real-time to follow the q-profile evolution during the plasma discharge, a feature that is challenging in current day devices, where the frequency can only be fine-tuned by adjusting the variable elements in the high-power transmission lines.

2) When applying the ICRH power inside the q=1 surface it was shown that a sawtooth crash can be induced by switching-off the RF power (thus removing the stabilizing effect of the fast ions inside q=1) and that, by modulating the RF power at an appropriate frequency, it is possible to control the sawtooth frequency [1,2]. The advantage of this method is that the RF power can be applied at the very centre of the plasma (which has proven to be important for impurity control in full-metal machines such as in JET-ILW [32,33]), while its main drawback is the fact that the sawtooth de-stabilization is controlled indirectly, namely starting from a situation in which the sawtooth are stabilized by the RF-accelerated ions and inducing a crash by removing them. This, by definition, imposes a maximum sawtooth pacing frequency that can be achieved.

The second method is the subject of this paper. As mentioned before, when high power ICRH is locally applied in the plasma centre (as in JET for heating and impurity control and in ITER for bulk ion heating), the sawteeth may become excessively long due to the RF-induced fast ions accelerated inside the q=1 surface and limit the amount of RF power that can be safely applied to the discharge without causing deleterious MHD. To avoid this limitation, the option of pacing the sawteeth period to a desired value by modulating the ICRH power instead of reducing the power altogether would be a convenient solution. Experimental investigation of this technique in high power H-modes is the focus of the current paper.

So far, sawtooth control with ICRH modulation has been demonstrated in L-mode and low power H-mode discharges in JET-ILW [1,2]. In these conditions, the main fast particle drive in the plasma core is due to ICRH and modulating or notching the RF power has a large probability to trigger a sawtooth crash [34]. Modulation frequencies between 2-6Hz have been applied with high triggering efficiency (>80%) in plasmas with otherwise long natural sawtooth periods (f<=1Hz with continuous ICRH). By controlling the sawtooth frequency with ICRH, N=2 MHD activity was fully suppressed while it was always present in the non-controlled cases, sometimes leading to a plasma stop or disruption in case of large N=2 amplitude modes.

The main challenge to apply this technique to high power H-mode discharges is the fact that the injected neutral beam ions (NBI) also have a stabilizing effect on the sawteeth. In this case the fast ions induced by ICRH only constitute a fraction of the fast ions existing inside q=1 and the RF switch-off effect is partially 'diluted' by the presence of the continuously injected beam particles. But, the fact that the ICRH power deposition is much more localized than the corresponding NBI one (higher power densities) and that the fast ions created by ICRH typically have higher energies and strongly anisotropic distribution functions, suggests that sawtooth control with ICRH can also work when high NBI power is applied. The second challenge in high power H-modes is that the slowing-down time of the fast ions is longer, due to the higher central electron temperatures obtained in these conditions (τ_{SD}≈100ms instead of τ_{SD}≈50ms in L-mode plasmas). To first order, this should not impact on the SWT triggering efficiency but will increase the response time of the induced sawtooth crash with respect to the RF power removal.

This paper describes recent JET-ILW experiments in which this technique was extended to high power H-modes. Baseline-like plasmas (q_0<1) with B_0=2.8T, I_P=2.2-2.5MA were used for the systematic studies but this method is now also used in other scenarios, in particular during the H-mode exit (see section 5). The NBI power was gradually increased (from 12-20MW) to allow the study of the sawtooth triggering efficiency as function of stabilizing background NBI ion populations. Central hydrogen minority ICRH with 5-6MW at 42.5MHz and dipole phasing was used in all discharges and the minority concentration was varied between $X[H]=n_H/n_e$=1.5-4.0%. The natural sawtooth period for these discharges with 20MW of NBI and no ICRH is about τ≈0.3s while the typical periods observed when 5-6MW of central ICRH is added can reach up to τ=1s. The value without ICRH power sets the minimum boundary for sawtooth control with on-axis ICRH modulation. Unlike for the L-mode experiments reported in [1], in which a pre-programmed RF modulated waveform was imposed in most cases, the RF power was controlled by a real-time control (RTC) network that (i) only switches-off the RF power once a certain (imposed) time has elapsed after the last sawtooth crash detection and (ii) re-applies the power immediately after a new sawtooth crash is detected. This has the advantage that the RF notches are not applied when a spontaneous sawtooth crash has occurred and it minimizes the notch time of the ICRH power. Furthermore, one can impose a maximum switch-off time to account for the longer slowing-down times expected in high power H-modes and to limit the minimum RF duty-cycle to a desired value.

Before presenting the actual sawtooth pacing results obtained, it is worthwhile describing in more detail some of the properties of the H minority ICRF heating scenario used in the experiments. Figure 1a and 1b show, respectively, the RF power absorption profiles and the average energy profile of the fast H^+ ions obtained with simulations using a 2D ICRF wave code [35] coupled to 1D ion Fokker-Planck code [36] for plasma parameters close to the experiments (for simplicity, the beam ions were excluded from this exercise). A hydrogen concentration of X[H]=4% was considered with 5.5MW of ICRH power. One immediately sees that the hydrogen absorption is dominant and that the power deposition is quite peaked near the plasma centre (within approximately 1/3 of the minor radius, a_p=0.9m). The averaged fast ion energy reaches about E_H=1MeV near the maximum absorption region, as a combination of the high RF power density (~1.2MW/m^3) and the relatively low core collisionality of these plasmas. The dashed vertical lines on Figs. 1a and 1b correspond to the location of the q=1 surface, inferred from the inversion radius of the sawtooth crashes measured by the fast ECE diagnostics. To have a first estimate of the fast ion orbits and to assess whether they remain inside the q=1 region, a simple orbit solver [37] that imposes two constants of motion (energy and magnetic moment) and draws the contour plots of the toroidal angular momentum (third constant of motion) was used. The results are shown in Fig.1c for two values of the fast ion energy, E=0.1MeV and E=1.0MeV, for ions accelerated tangentially to the ion-cyclotron resonance in a magnetic surface close to the maximum ICRF absorption. These results suggest that most of the fast H^+ ions do remain inside the q=1 region in these conditions and therefore primarily contribute to the stabilization of the kink mode. Because the absorption is quite central, the respective trapped orbits are relatively fat (so called 'potato' type orbits). These type of orbits also impact considerably the fast component of the potential energy ($\delta\hat{W}_{fast}$) [38, 39], remaining strongly stabilizing because, as shown above, the orbits are confined inside the q=1 region.

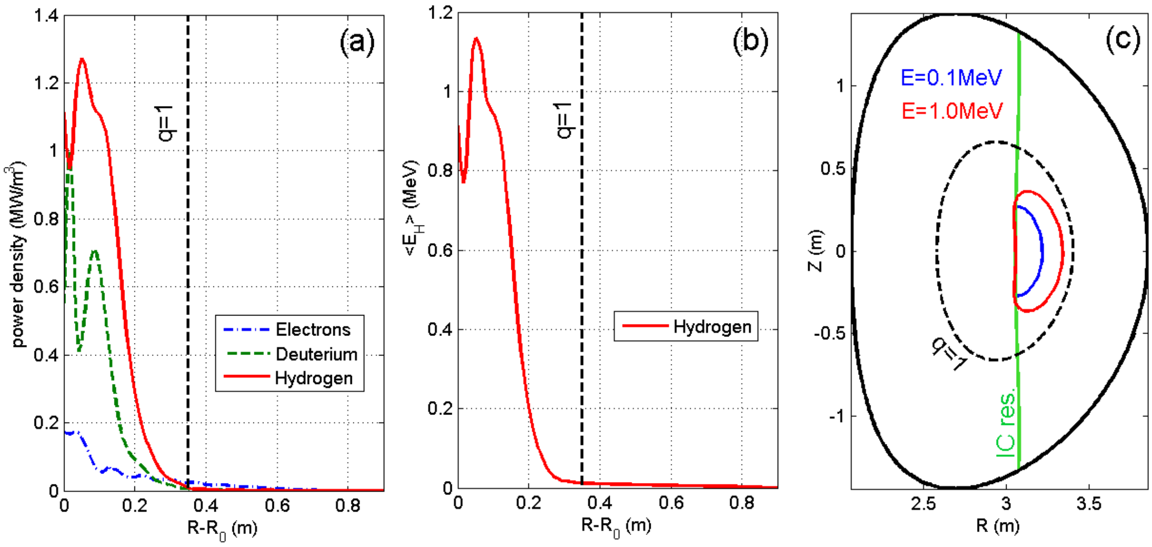

Figure 1: (a) Power absorption profiles, (b) average fast H^+ ion energy and (c) fast ion orbit topology for the H minority ICRH scheme used in the experiments for sawtooth pacing with ICRH modulation. The simulation parameters were chosen to match closely the actual experimental conditions (B_0=2.8T, I_P=2.2MA, f=42.5MHz, n_0=6x10^{19}/m^3, T_0=6.5keV, X[H]=4%).

The paper starts with a test of the RTC algorithm in low power H-modes (section 2). In section 3, sawtooth control at high NBI power (20MW) is presented, focusing on the impact of the minority concentration and the sawtooth pacing frequency on the sawtooth triggering efficiency. The consequences of unsuccessful sawtooth pacing on the plasma performance are briefly discussed. To help interpreting the experimental results, simplified modeling based on the sawtooth crash criterion shown in eq.2 is shown in section 4. In section 5, the application of sawtooth pacing during H-mode exit and during the subsequent plasma landing phase (L-mode) is presented. The paper ends with a brief summary and perspectives for further studies of sawtooth pacing with real-time controlled ICRH modulation.

2. Low power H-modes

The first step was to test the real-time sawtooth pacing algorithm in low power H-modes with P_{NBI}=12MW and P_{ICRH}=5.5MW. The results are shown in Fig.2, where two similar plasma discharges with constant (left) and RTC modulated (right) ICRH power are compared. The respective natural (left) and paced (right) sawtooth periods are shown in Fig.3, together with the RT control parameter τ_{ctrl}, which corresponds to the maximum time delay allowed between a sawtooth crash has been detected before the RF power is removed. The RF power is re-applied once a new crash is detected or when the maximum notch time is reached (τ_{notch}=0.2s). The hydrogen concentration was X[H]=4% in both discharges.

One readily sees that, for these conditions, the natural sawtooth periods with constant ICRH are large (τ_{SWT}=0.6-0.9s) and that RF-induced sawtooth pacing is very efficient both at 3Hz (τ_{ctrl}=0.25s) and at ~4.5Hz (τ_{ctrl}=0.15s). The triggering efficiency, defined as the number of successfully triggered sawtooth crashes divided by the number of RF notches attempting to drive a sawtooth crash, is η=100% in this case and the maximum hold-off time has never been reached, resulting in a high duty-cycle (~80%) of the RF power waveform. The time delay between the RF notches and the sawtooth crashes are correlated with the slowing-down time of the fast ions ($\tau_{SD}\approx$100ms), as described in [1]. From Fig.2, one also sees that when the sawteeth are shorter, the amplitude of the N=1 MHD activity is reduced, except for a few cases where the crashes are only partial (t=52-53s). This reduces the variations observed in the plasma stored energy due to MHD but the average value remains the same as in the non-paced case. Because of the low values of β_N=1.2, there is no N=2 MHD excitation in these pulses. It is interesting to note that when the sawteeth are paced too fast (e.g. with τ_{ctrl}=0.15s), the peak electron temperatures reached during the sawtooth cycles is reduced. The impact on the plasma energy is small, since this effect is well localized in the plasma core (small volume) but this suggests that an optimal sawtooth frequency exists for a given plasma scenario, both avoiding deleterious effects coming from long sawtooth crashes (e.g. MHD) while keeping the core electron temperature sufficiently high for e.g. high-Z impurity control. Pacing the sawteeth at lower frequencies - closer to their natural frequency - is easier, as demonstrated in other experiments performed in similar conditions (not shown).

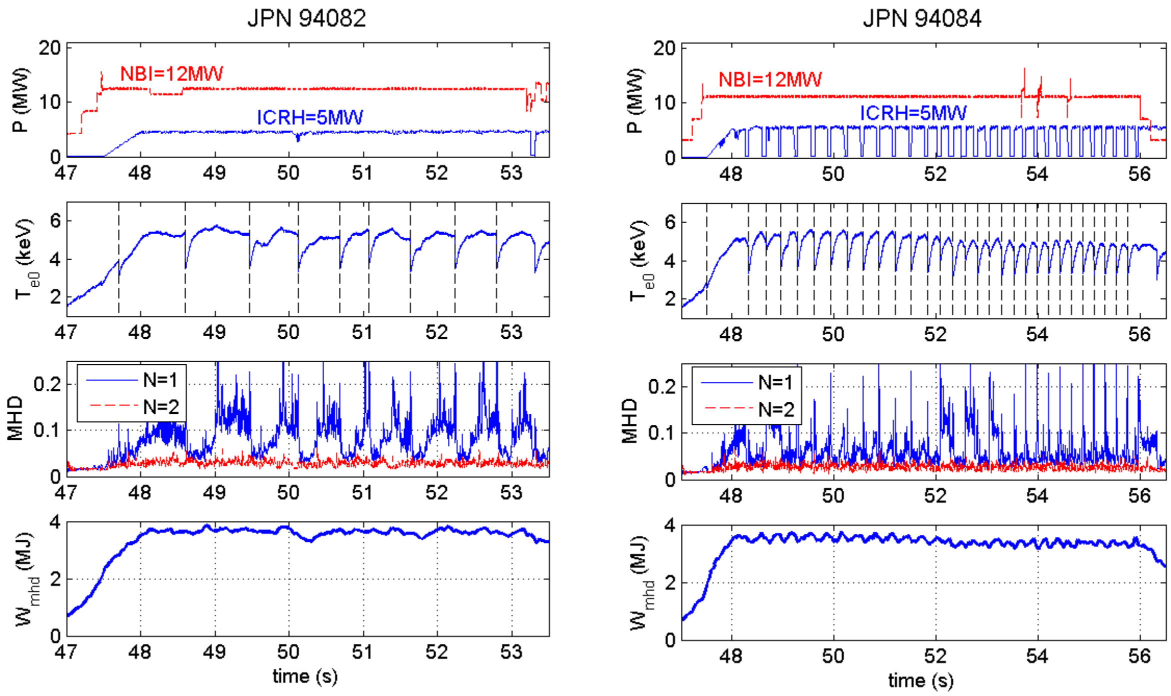

Figure 2: Time traces of ICRH and NBI power, central electron temperature (ECE), N=1 and N=2 MHD mode amplitudes and plasma stored energy for two similar discharges with constant (left) and RTC modulated ICRH power (right) with 12MW NBI and 5.5MW ICRH. X[H]=4% in both discharges.

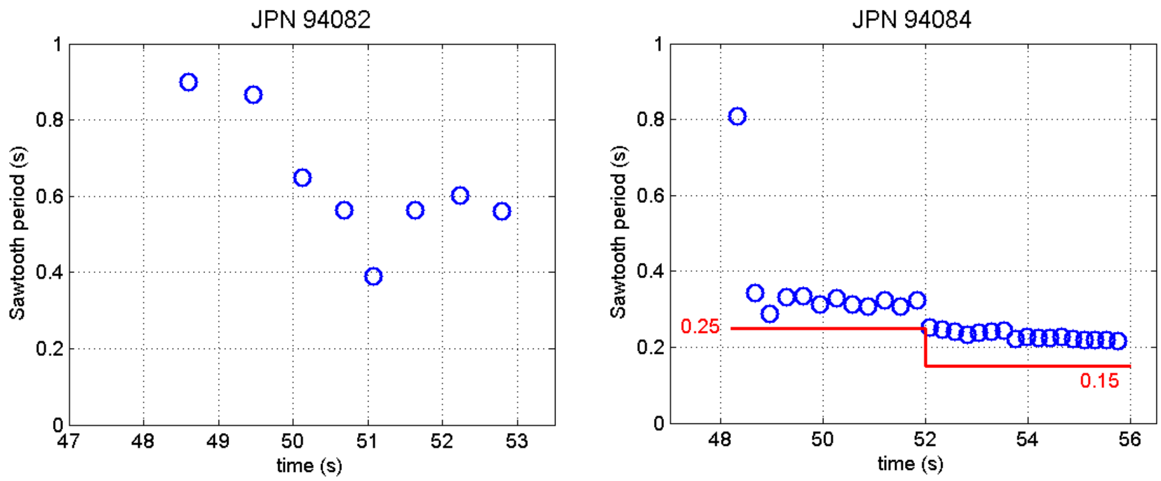

Figure 3: Sawtooth periods for similar plasmas with constant (left) and RTC modulated ICRH power (right). The left plot depicts the natural sawtooth periods while the right plot shows the paced sawtooth periods for two values of the imposed delay time, τ_{ctrl}=0.25s and τ_{ctrl}=0.15s.

3. High power H-modes

The next step was to test the RTC algorithm in high power H-modes and characterize the pacing efficiency as function of the Hydrogen minority concentration, the imposed sawtooth pacing period and the plasma current (q-profile). The results will be discussed next.

3.1 Impact of minority concentration

Figure 4 shows the comparison between two similar discharges with constant (left) and modulated (right) RF power with B_0=2.7T, I_P=2.2MA and P_{NBI}=20MW, X[H]=4%. The ICRF power was 5.5MW in both pulses. Figure 5 shows the respective sawtooth periods together with the RTC settings used. The natural sawtooth period is longer than in the P_{NBI}=12MW case ($\tau_{SWT}\approx$0.7s), showing the stabilizing nature of the NBI ions. Note that, although the N=2 MHD activity remains low in these cases (β_N=1.6), the N=1 MHD amplitude is larger than in the pulses discussed before and it is only reduced in the RF-modulated pulse when a complete - as opposed to partial - sawtooth crash is triggered. The plasma stored energy is similar in the two discharges.

From Fig.5 it is clear that, although sawtooth pacing is partially accomplished, in particular after t=50s, the triggering efficiency is lower than with P_{NBI}=12MW, η=80%, and some sawtooth crashes are only partial while others occur spontaneously, showing that the sawtooth cycle hasn't fully locked with the RF-modulation waveform. This suggests that for the given conditions, the imposed sawtooth period (τ_{ctrl}=0.25s) during the H-mode phase is borderline for full sawtooth control. Again, some crashes are only partial in which cases the N=1 MHD activity is not reduced w.r.t. the natural sawtooth case. Moreover, in the cases where the RF-notch is applied without triggering a sawtooth crash (t=49-50s), one sees that the central electron temperature drops considerably and that the N=1 MHD characteristics changes from a fishbone-like activity to a (1,1) continuous mode behavior. The latter has a stronger impact on the plasma stored energy as seen in Fig.4-right.

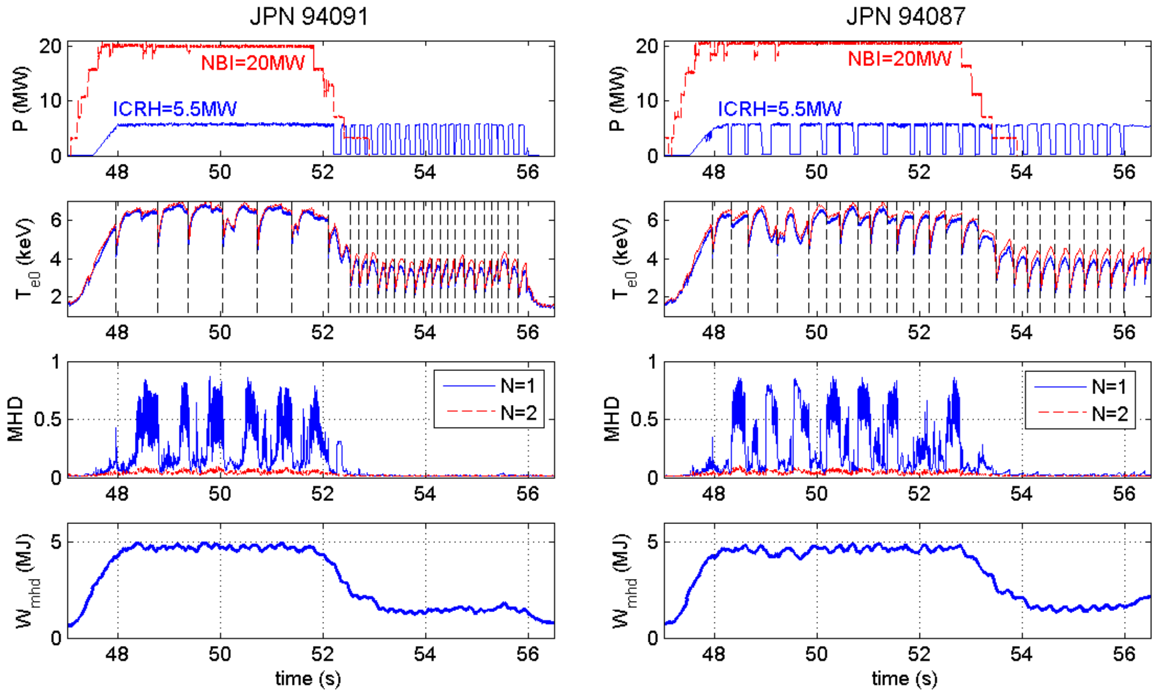

Figure 4: Time traces of ICRH and NBI power, central electron temperature (ECE), N=1 and N=2 MHD mode amplitudes and plasma stored energy for two similar discharges with constant (left) and RTC modulated ICRH power (right) with 20MW NBI and 5.5MW ICRH. X[H]=4% in both pulses.

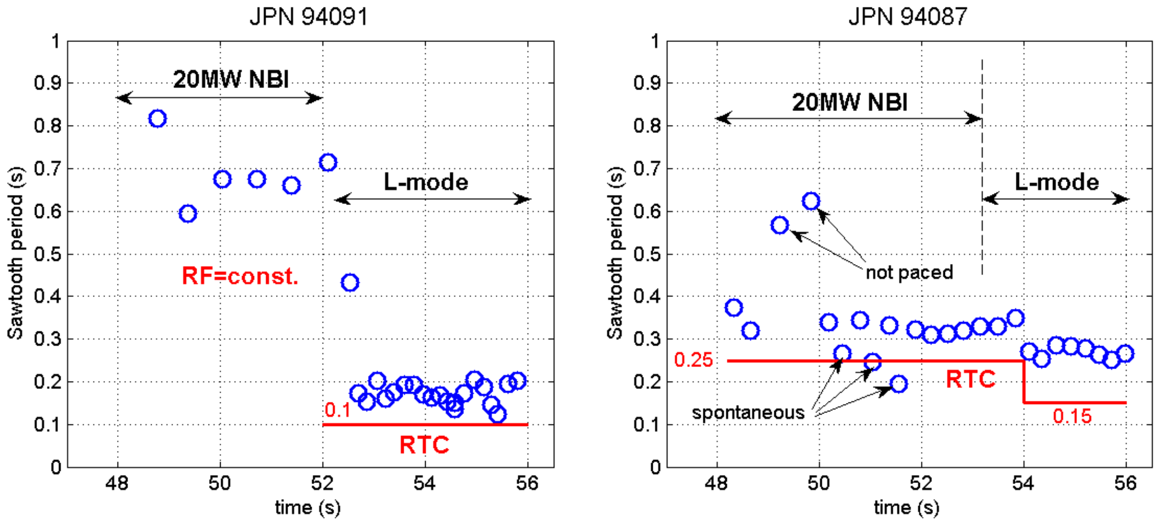

Figure 5: Sawtooth periods for similar plasmas with constant (left) and RTC modulated ICRH power (right). The 20MW NBI power H-mode phase is between t=48-52s. The left plot depicts the natural sawtooth periods during the H-mode phase and the paced ones after t=52s with τ_{ctrl}=0.10s (L-mode). In the right plot the sawtooth are paced with τ_{ctrl}=0.25s during H-mode and with τ_{ctrl}=0.15s during L-mode.

To study the impact of the minority concentration on the sawtooth pacing efficiency, a similar pair of pulses was repeated at reduced concentration, X[H]=1.5%, as shown in Fig.6. The respective sawtooth periods are shown in Fig.7 (the same RTC settings were used as in the previous example). From Fig.7-left one sees that the natural sawtooth periods (with constant ICRH) has slightly increased w.r.t to the X[H]=4% case ($\tau_{SWT}\approx$0.8s), reflecting the higher energy ion tails that are being pulled in the plasma core, as expected by theory when the minority concentration is lower [12]. Figures 6 and 7 (right) show that sawtooth control is poor in these conditions, η<50%, and that the maximum hold-off time (0.2s) was reached several times, which reduces the effective RF power duty-cycle. The fact that the triggering efficiency is lower when the H concentration is reduced in otherwise similar conditions can be related to various effects (larger fast ion energies, stronger distribution anisotropy, wider orbits, etc…) but simplified modeling suggests that a too strong 'RF kick' in the fast particle shear threshold s_W may not be optimal for efficient sawtooth triggering (see section 4).

Once more, for the cases of unsuccessfully triggered sawteeth one observes a strong electron temperature drop together with the excitation of a large amplitude (1,1) continuous mode. Both the lower averaged ICRH power due to the low RF duty-cycle and the presence of the continuous (1,1) mode have an impact on the plasma performance, as seen from the lower plasma stored energy observed in JPN 94088 (Fig.6-right). The effect of the RF-notch on the plasma performance for the non-triggered sawteeth will be discussed later in more detail (section 4) but it is already clear from the results shown in Figs. 6 and 7 that these conditions should be avoided. It is interesting to note that although the sawtooth pacing is generally not accomplished, the sawteeth are slightly faster than the natural ones with constant RF power since they lock at twice the RF triggering frequency, a feature that was observed before in the L-mode pacing experiments [1].

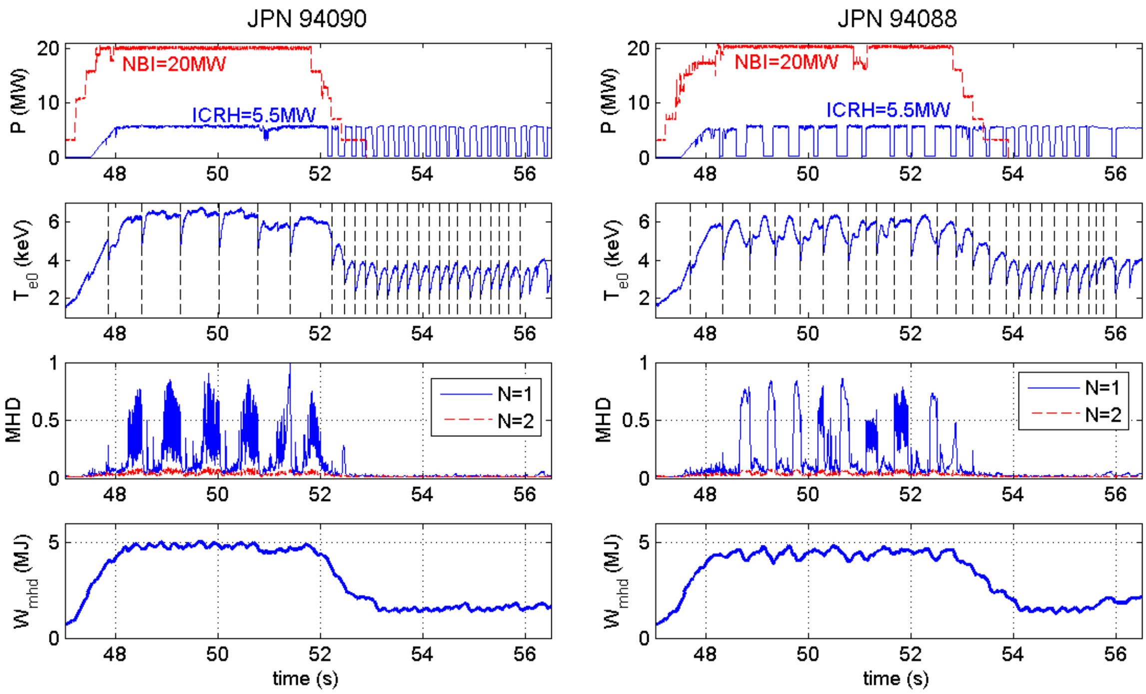

Figure 6: Time traces of ICRH and NBI power, central electron temperature (ECE), N=1 and N=2 MHD mode amplitudes and plasma stored energy for two similar discharges with constant (left) and RTC modulated ICRH power (right) with 20MW NBI and 5.5MW ICRH. X[H]=1.6% in both pulses.

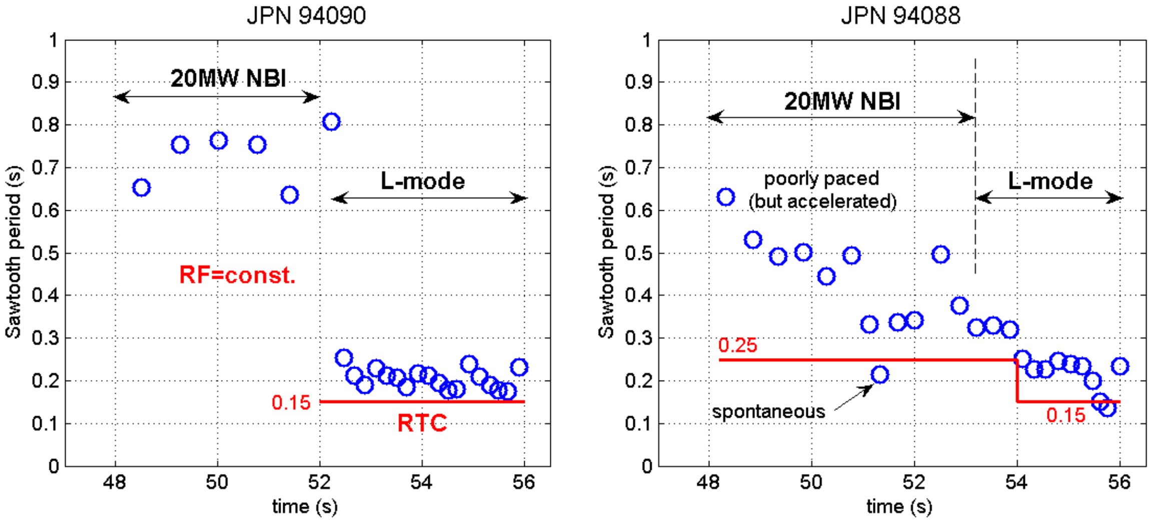

Figure 7: Sawtooth periods for similar plasmas with constant (left) and RTC modulated ICRH power (right). The left plot depicts the natural sawtooth periods during the H-mode phase (t=48-52s) and the paced ones with τ_{ctrl}=0.15s in L-mode. In the right plot the sawtooth are paced with τ_{ctrl}=0.25s until t=54s (one second after the end of the H-mode phase) and with τ_{ctrl}=0.15s thereafter.

3.2 Impact of the sawtooth pacing frequency

It was seen in the previous section that, for the given plasma conditions, efficient sawtooth pacing at 3Hz (τ_{ctrl}=0.25s) is borderline with X[H]=4% and is too fast for lower H minority concentrations, since this pacing frequency is too close to the natural sawtooth frequency obtained without ICRH (f_{SWT}≈0.33Hz). Figure 8 shows that in the same conditions, by slightly increasing the RF modulation period to τ_{ctrl}=0.35s while keeping the H concentration low (X[H]=1.6%), η=100% efficient sawtooth pacing at ~2.5Hz can be achieved. This is because by waiting longer for trying to trigger a sawtooth crash, the local shear parameter s_1 had more time to approach the s_W shear curve and a smaller perturbation on the latter (provoked by the RF-switch-off) allows reaching the stability condition for a sawtooth crash $s_W < s_1$ (see section 5). Because of the high triggering efficiency and the fact that the s_W shear is close to s_1 when the RF power is removed, the RF-off time intervals are short (Δt<70ms) and the RF power duty cycle is maximized (~90%). The central electron temperature practically does not have the time to decrease before the sawtooth crash is induced and the *N*=1 MHD activity is strongly suppressed as compared to the constant ICRH power case (pulse #94090, Figs. 6 and 7 - left). Also, the peak electron temperature and the averaged stored energy are very similar to the non-paced case, which suggests that the pacing frequency is quite appropriate to not impact the plasma performance. Based on the results of the previous section, it is expected that increasing the H concentration would retain the triggering efficiency at η=100% at this pacing frequency.

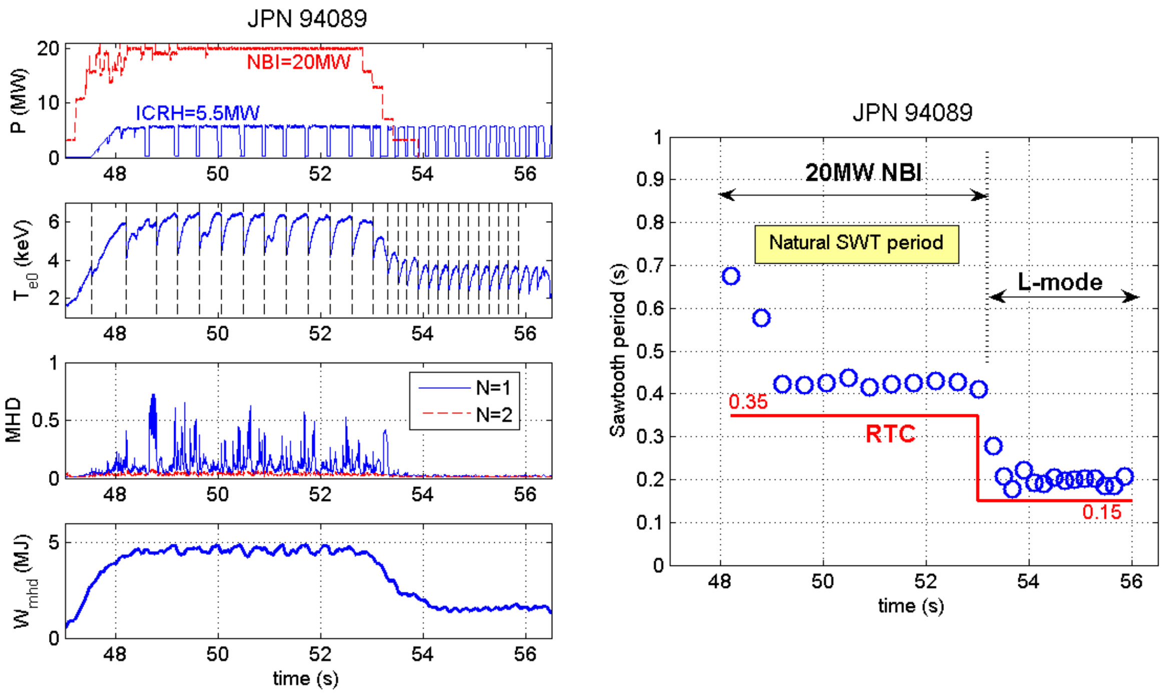

Figure 8: (left) Time traces of ICRH and NBI power, central electron temperature (ECE), N=1 and N=2 MHD mode amplitudes and plasma stored energy in a plasma discharges with RTC modulated ICRH power with 20MW NBI and 5.5MW ICRH. (right) Sawtooth periods during the H-mode phase (with τ_{ctrl}=0.35s) and during the L-mode phase (τ_{ctrl}=0.15s). X[H]=1.6%.

As mentioned before, it is expected that at higher NBI power levels, sawtooth pacing with modulated ICRH becomes more challenging and that the minimum period that the sawteeth can be paced at increases in these conditions. Figure 9 shows the minimum sawtooth periods obtained with efficient RF-modulated pacing (η>80%) as function of the NBI power applied for P_{ICRH}=5.5MW. The natural sawtooth periods (with constant ICRF power) are also shown for comparison. The L-mode results correspond to the P_{NBI}=0 values. The solid bars represent pulses with low H minority concentrations (X[H]<2%) while the dashed ones, only shown for P_{NBI} =0 and P_{NBI} =20MW, correspond to pulses with X[H]=4%.

First note that in L-mode, the natural sawtooth periods are large (even larger than in H-mode at low H concentrations) but efficient sawtooth control is rather straightforward since the RF accelerated fast ions are the only source perturbing the fast particle shear parameter s_W, so that the natural sawtooth periods can be reduced by a large factor (almost 5x for low

X[H]). Also note that the natural sawtooth period is considerably affected by the H concentration but the minimum paced periods are not, indicating that there is a limit for efficient sawtooth triggering even in L-mode (τ_{SWT}≈0.15s). For the H-mode pulses, one sees indeed that the minimum sawtooth periods achieved with efficient pacing increase with NBI power and that for P_{NBI}=20MW, the natural sawtooth periods can only be reduced by a factor of ~2x in the given conditions, even at higher H concentrations. This confirms that it is indeed more difficult to trigger high frequency sawteeth when more NBI power is present (or when P_{ICRH} / P_{NBI} is reduced), reflecting their stabilizing nature and the 'dilution' of the ICRH impact on the fast particle shear parameter s_W.

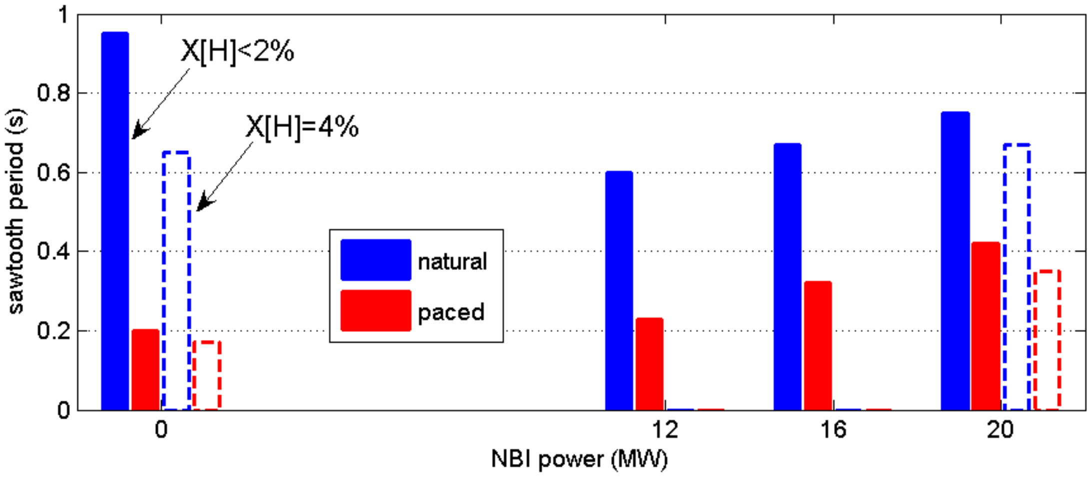

Figure 9: Natural sawtooth periods and minimum sawtooth periods achieved with efficient sawtooth control (η>80%) as function of the NBI power with P_{ICRH}=5.5MW. The solid bars represent discharges with X[H]<2% while the dashed bars correspond to pulses with X[H]=4%.

The results shown in Fig.9 were obtained from a collection of 12 discharges with B_0=2.7T and I_P=2.2MA, in which the RTC pacing control parameters where varied at different NBI power levels. They do not necessarily represent the absolute minimum pacing periods that could have been achieved if more time for fine-tuning the ICRH and RTC parameters would have been available. For the case with P_{NBI}=20MW and X[H]=4%, the successfully paced sawtooth periods are indeed very close to the minimum value possible with ICRF modulation, namely τ_{SWT}≈0.3s, as observed with pure NBI heating (P_{ICRH}=0).

3.3 Note on unsuccessful sawtooth triggering

As discussed in section 3.2, there is a minimum τ_{ctrl} limit for successful sawtooth pacing with modulated ICRH, depending on the ICRH/NBI power fraction and the natural sawtooth frequency in the absence of ICRF heating. When the requested sawtooth period is too short, removing the ICRH power does not lead to a sawtooth crash but to a gradual decrease in the core plasma temperature, as depicted in Fig.10-left. As will be discussed in the next section, this is because the local shear s_1 is still too low as compared to the fast particle shear threshold s_W when the ICRH power is removed and the crash criterion (eq.2) is not achieved in a short enough time interval (note that the maximum RF hold-off time of 200ms has been reached in this case and the ICRH power is re-applied before a sawtooth crash occurs). As a matter of fact, the drop in the core plasma temperature is followed by a strong increase in the N=1 MHD activity (with a continuous rather than fishbone-like nature in this case), which impacts considerably the plasma stored energy and the neutron rate. So even if every other sawtooth is triggered by ICRH in these conditions leading to a sawtooth period that is shorter than the natural one (see Fig.7-right), this scenario should be avoided since it degrades the plasma performance and unnecessarily offers a window of reduced temperature peaking, which may lead to core impurity accumulation. When the pacing period is increased (Fig.10-right), a sawtooth crash is triggered in a relatively short time interval (Δt~70ms) and the central electron temperature does not have time to drop significantly during the RF-notch. The burst in MHD activity is not observed in this case. It is interesting to note that although the temperature takes some time to respond to the RF switch-off (30-40ms), the plasma stored energy and the neutron rate respond almost promptly to the RF power removal. This is partly explained by the fact that these quantities also reflect the ICRF heating of the bulk D ions, for which a subpopulation is accelerated to slightly supra-thermal energies ($E<<E_{crit}$) and thus exhibit a shorter slowing-down time as compared to the high energy minority H ions. Therefore, keeping a minimum RF notch time interval is important to keep the averaged plasma performance as high as possible.

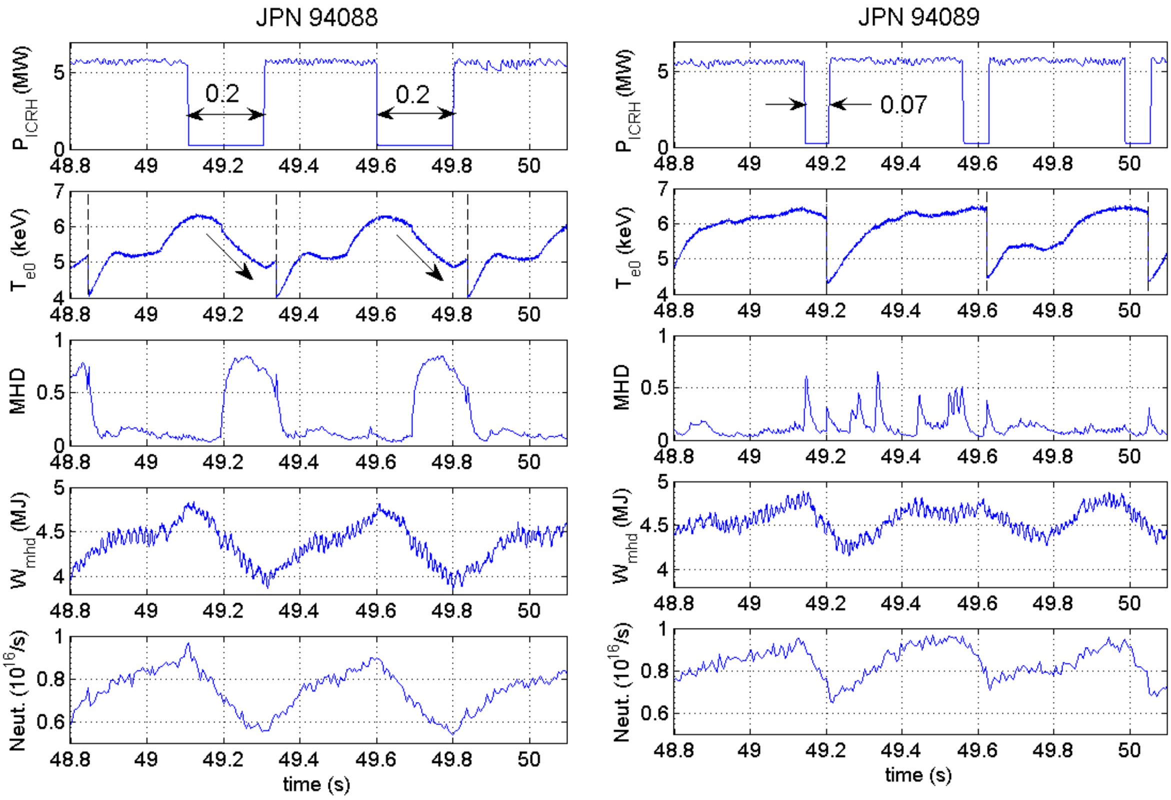

Figure 10: Comparison of unsuccessful (left, τ_{ctrl}=0.25s) and successful (right, τ_{ctrl}=0.35s) sawtooth pacing in two similar plasma discharges with X[H]=1.5%: Time traces of ICRH power, central electron temperature (ECE), N=1 MHD amplitude, plasma stored energy and total neutron rate.

4. Simple (qualitative) pacing modeling

The detailed physics describing the change in the fast ion distributions when ICRH is switched-off and its impact on the sawtooth stability is very complex to model. It requires not only a proper description of the fast ion dynamics (a 3D time-dependent Fokker-Planck solver) and of the q-profile evolution during the sawtooth cycle but, in particular, a good model describing the impact of the fast ion distribution functions on the (N=1, M=1) MHD mode stability [40]. Nonetheless, simple simulations based on the sawtooth stability criterion proposed by Lennholm [20] and using only a qualitative representation of the impact of RF-induced fast particles on the s_W parameter ('RF kick'), already allows to interpret the experimental results shown earlier. For these simplified simulations, both the central electron temperature T_e and the fast particle shear s_W are assumed to respond to the RF power (more strictly speaking to the central RF power density p_{RF}) as:

$$T_e(t) = T_0 + C_T . p_{RF}(t).(1 - e^{-t/\tau_E}) \quad \text{and} \quad s_W(t) = s_0 + C_W . p_{RF}(t).(1 - e^{-t/\tau_E}) \qquad (3)$$

where τ_E=120ms represents a typical energy confinement time (representative of the JET H-mode discharges discussed here), T_0 and s_0 are the initial values of the temperature and fast particle shear right after a sawtooth crash, respectively, and the time variable t represents the time elapsed since the sawtooth crash. The parameter C_T is chosen to approximately reproduce the central temperature evolution observed in pulse #94090 with constant ICRH power and low H concentration (Fig.6-left) while the C_W parameter was adjusted to reproduce the natural sawtooth period, τ_{SWT}=0.75s, in the same shot (Fig.7-left). The parameter C_W, which maps the total RF power to the local RF power density inside the q=1 region, can also be used, in a qualitative way, to assess the impact of changing the hydrogen concentration in the plasma. For simplicity, the local magnetic shear s_1 is assumed to be independent of the RF power and of the electron temperature values, and is described as growing almost linearly between sawtooth crashes, $s_1(t) = C_1.(1 - e^{-t/\tau_{s1}})$, with a large time constant τ_{s1}=1.4s. The RF waveform was controlled with an algorithm identical to the one used for the RTC control in the experiments, enabled after t=3.9s.

In Figures 11 and 12, the simulation results for a case with τ_{ctrl}=0.35s and for a case with τ_{ctrl}=0.25s are compared, mimicking the experimental observations of pulse #94089 and #94088, respectively (see Figs. 6-8). In Figure 13, the sawtooth control period is kept at τ_{ctrl}=0.25s but the RF power normalization parameter C_w is reduced by 20%, qualitatively describing the less energetic fast ion distributions expected when the minority H concentration is increased to X[H]=4% (as in pulse #94087, Figs. 4 and 5 - right).

From Fig.11 one sees that once the RF power is increased to 5MW, long sawteeth are induced because the s_W parameter receives a strong 'RF kick' and takes longer to intersect the s_1 shear curve. Once the RF power is modulated, the s_W parameter is forced to decrease fast during the RF switch-off period and successful sawtooth pacing at the desired frequency is achieved, in good agreement with the experimental results of pulse #94089 (Fig.8). Also note that the time delay between the RF switch-off instant and the actual sawtooth crash is of the same order as seen in the experiments. Once the τ_{ctrl} parameter is reduced to τ_{ctrl}=0.25s (Fig.12), the s_W parameter does not drop fast enough to meet the crash criterion in the first RF notch attempt with the given hold-off time interval (0.1s) and the sawtooth pacing cannot be achieved. Interestingly, the second RF-notch does trigger a sawtooth crash because the s_W and the s_1 curves are closer to each other so that the effective sawtooth period is slightly reduced w.r.t. the natural sawtooth frequency (RF=constant). This is in line with the poor pacing efficiency observed in pulse #94088 (Fig.7-right). Increasing the hold-off time interval would, eventually, allow a sawtooth to be induced at every RF notch but the decrease in the plasma temperature would be significant, as observed experimentally.

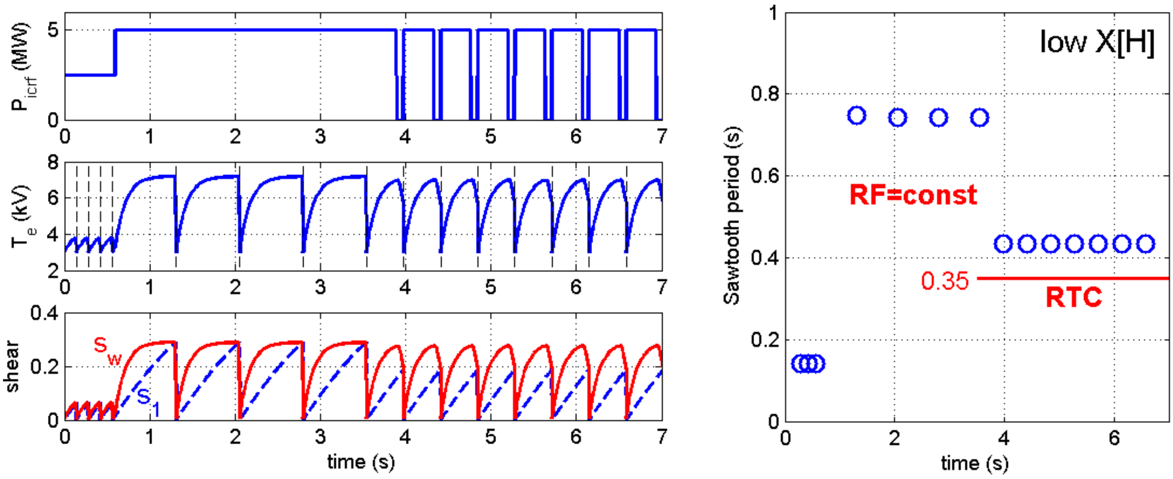

Figure 11: Simulation of the sawtooth dynamics for constant and RT controlled ICRH with τ_{ctrl}=0.35s (as in JPN 94089, Fig.8), showing the efficient sawtooth pacing as observed in the experiments.

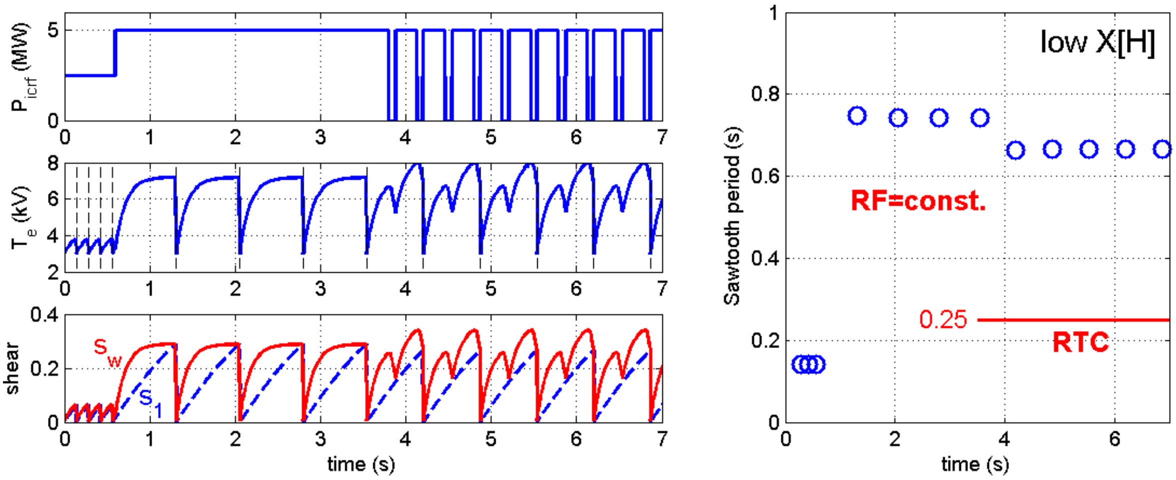

Figure 12: Same as in Fig.10 but using τ_{ctrl}=0.25s (as in JPN 94088, Figs. 6 and 7 - right), showing the non-efficient pacing at similar plasma conditions when the imposed sawtooth period is too low.

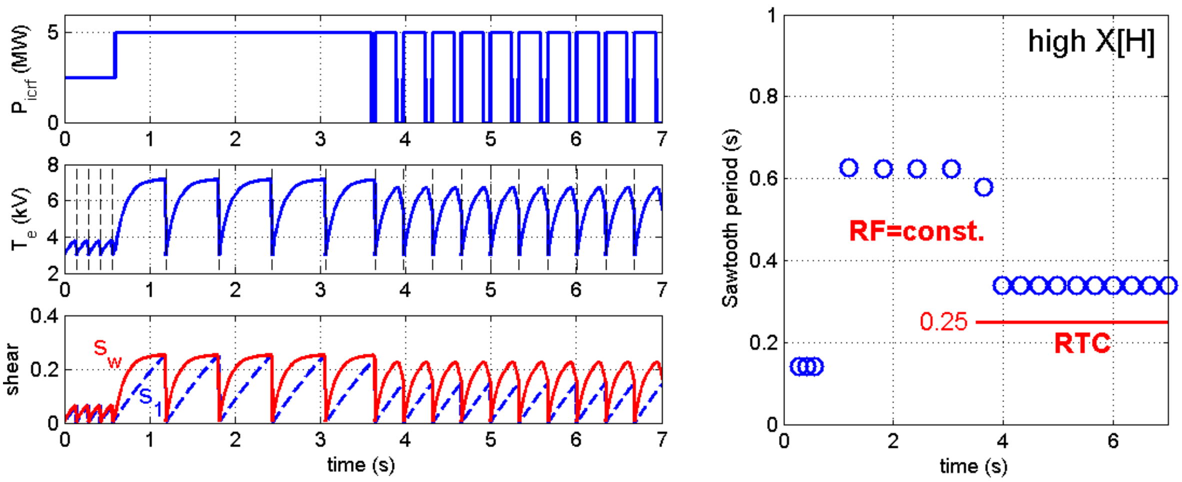

Figure 13: Same as in Fig. 12 (τ_{ctrl}=0.25s) but with a 20% reduced value of the RF power density coefficient C_w, representing a case with higher hydrogen concentration / lower fast ion energy (in agreement with JPN 94087, Figs. 4 and 5 - right).

Figure 13 illustrates how increasing the H concentration (thus reducing the RF-driven fast ion energies in the core) allows to recover the ability to pace the sawteeth at higher frequencies, since the 'RF kick' on the s_W parameter is smaller and the s_W curve evolves closer to s_1, so that the RF power removal leads quicker to a sawtooth crash. This is again in qualitative agreement with the results obtained in pulse #94087 (Figs. 4, 5 – right), which showed more efficient pacing with τ_{ctrl}=0.25s when the H concentration is larger. Also note that the natural frequency with constant ICRH power is somewhat reduced in these conditions, as also seen experimentally (pulses #94090 and #94091).

The simplified modeling presented can qualitatively grasp the main aspects of the sawtooth pacing technique described here but does not have the scope of making a quantitative description nor can be used to predict the pacing performance in different plasma scenarios. Aside from the rather complicated RF physics underneath, in a real plasma discharge, other phenomena such as MHD redistribution of the fast ions in the plasma core as well as radiation / impurity effects that affect the electron temperature evolution also play a role. For example, the T_e decrease observed experimentally during an unsuccessful sawtooth pacing attempt is stronger than predicted by the simple model, probably due to the presence of the continuous (1,1) mode that is excited in these cases and not included in the modeling.

5. H-mode exit

Once the NBI power is switched-off, the plasma undergoes an H-L transition, in which the plasma temperature starts to decrease followed by a large drop in the plasma density (from typically n_0=7-8x10^{19}/m^3 in H-mode to about half this value in L-mode). During the H-mode exit, the RF power is usually kept constant to maintain a heat source in the plasma centre, thus avoiding impurity migration to the core and the formation of hollow T_e profiles, which can lead to premature plasma termination or, in the worst cases, to a disruption. During the NBI switch-off phase and in the following L-mode phase, it is often observed that long sawteeth can be induced, as long as there is enough central electron heating applied to avoid strong impurity peaking and hollow temperature profiles, which typically suppresses the sawteeth altogether. This is partly related to the change in the kinetic profiles during the H-L transition but also due to the fact that, in the absence of NBI and at reduced temperature, the H minority ions absorb most of the ICRH power (aside from a small fraction directly absorbed by the electrons by Landau damping / transit-time magnetic pumping) and the energetic hydrogen tails become stronger, which enhances the sawtooth stabilization. In many cases, strong N=2 MHD modes are excited by the sawtooth crash following a long sawtooth during both the H-mode exit and the L-mode plasma landing phase. If these modes achieve too high amplitude or if they lock (either internally amongst different rational surfaces or ultimately to the wall), the plasma is likely to be stopped by the protection system. If a stop is issued in the wrong conditions (e.g. when the plasma radiation is still too high or if the central electron temperature is too low), the plasma often goes into a radiation collapse and disrupts [41]. To avoid this undesired outcome, sawtooth pacing with modulated ICRH was tested in various scenarios during the H-mode exit and in the L-mode landing phases. It was confirmed that efficient pacing can be obtained at various frequencies and that complete suppression of the N=2 modes is achieved without compromising the central ICRF heating needed to keep the electron temperature peaked. An example is shown in Fig.14, where two discharges with constant (left) and RTC modulated (right) ICRH power waveforms applied during the H-mode exit are compared. In the constant ICRH case, a long sawtooth develops during the NBI drop-off phase and immediately after its crash, a moderate amplitude N=2 MHD mode is excited (in this case not high enough to stop the plasma).

When the RF power is modulated, the sawteeth are kept short and the excitation of the *N*=2 mode is avoided.

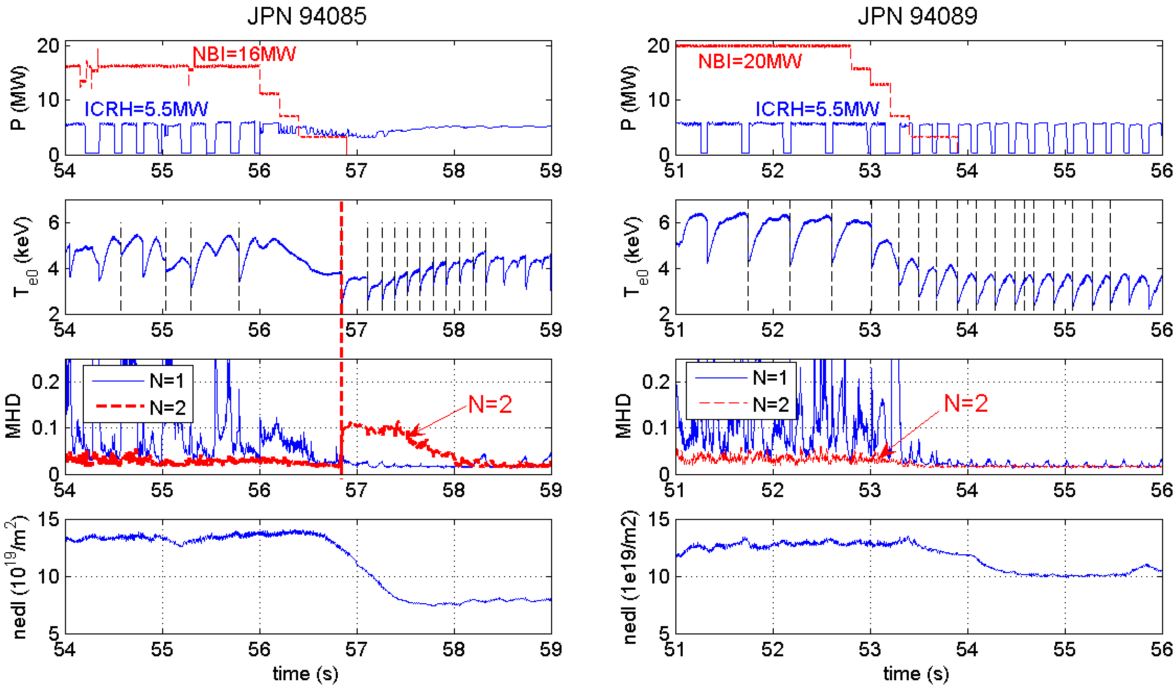

Figure 14: Comparison of two discharges with constant (left) and RF-modulated (right) power applied during the H-mode exit phase. Time traces of ICRH and NBI power, central electron temperature (ECE), N=1 and N=2 MHD mode amplitude and central line averaged electron density.

Although the here described experiments focused on sawtooth control during the high power H-mode flat-top, ICRH modulated sawtooth pacing was also applied during the H-mode exit and L-mode phases of many discharges. The results are summarized in Fig.15, which shows that in the absence of NBI, the RF modulated sawtooth pacing is extremely efficient up to f_{SWT}=6Hz (τ_{ctrl}=0.1s), in agreement with the L-mode pacing presented in [1]. Note that, despite higher pacing frequencies being possible in L-mode as compared to H-mode due to the absence of the stabilizing NBI ions, the time delays between the RF switch-off and the actual sawtooth crashes is comparable (70-100ms), once more illustrating the fact that sawtooth control by tailoring the fast particle shear parameter s_W is constrained by the slowing-down time of the RF accelerated ions in the core. Given these encouraging results, some high performance scenarios in JET-ILW (such as the hybrid scenario) have now routinely adopted this technique to ensure safe and reproducible H-mode exit and plasma termination.

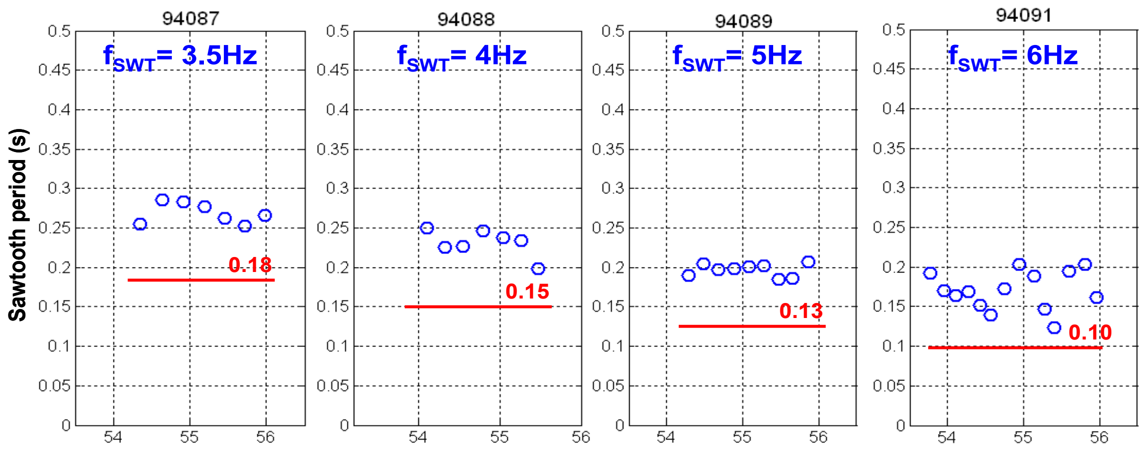

Figure 15: Examples of successful sawtooth pacing with real-time controlled ICRH modulation during the H-mode exit and following L-mode termination phases at various pacing frequencies (τ_{ctrl}=0.10-0.18s).

Conclusion

Sawtooth control with modulated ICRF heating was shown to also work in baseline type H-mode discharges (q_0<1), but the competing stabilizing nature of the fast NBI ions restricts the application range of this technique to lower pacing frequencies as compared to the L-mode pacing results reported earlier [1]. Real-time control of the ICRF modulation [2] proved to be essential in these conditions. Efficient sawtooth pacing was achieved in H-mode plasmas with 20MW of NBI and 5.5MW of ICRH. At low minority concentrations, X[H]<2%, where the natural sawtooth period with constant ICRH is about τ_{SWT}=0.7-0.8s (f_{SWT}≈1.3Hz), sawtooth pacing with full triggering efficiency (η=100%) could be achieved up to f_{SWT}=2.5Hz (τ_{ctrl}=0.35s), roughly twice the natural frequency. Faster pacing was rather unsuccessful: For τ_{ctrl}=0.25s (expected f_{SWT}≈3Hz) the triggering efficiency was poor (η≤50%) and, in the cases where the ICRF power was switched-off but a sawtooth was not triggered, a significant drop in the electron temperature was observed, accompanied by the excitation of a strong continuous (1,1) MHD mode with a clear degradation of the plasma performance (stored energy and neutrons). When the hydrogen concentration was increased to X[H]=4%, pacing at f_{SWT}≈3Hz (τ_{SWT}=0.33-0.35s) became possible (η=80%), showing that a fine tuning of the RF scenario is needed in H-mode to properly apply this pacing technique. This value is very close to the expected minimum period that can be obtained with ICRH modulation, namely the value of the natural sawtooth period in the absence of ICRH (τ_{SWT}≈0.3s). By using a qualitative description of the RF-induced fast particle populations and their influence on the sawtooth stability conditions, simplified modelling corroborates the experimental findings pretty well, in particular as far as the operational limits for successful sawtooth control are concerned. Sawtooth pacing with modulated ICRH has shown to be particularly useful during the H-mode exit and the L-mode plasma landing phases, where high levels of constant ICRH usually drive very long sawteeth (τ_{SWT}≈1s) which potentially excite strong N=2 MHD modes. Because the NBI stabilization effect quickly fades away and because the H minority ions become the main fast particle source in the plasma in these conditions, the sawtooth pacing efficiency is virtually 100% for pacing periods as short as τ_{SWT}=0.15-0.20s (f_{SWT}=6Hz), in agreement with previous results [1]. Using sawtooth control in the H-mode exit and landing phases completely suppresses the excitation of N=2 MHD instabilities, which often lead to premature plasma termination followed by a disruption. Because the triggering efficiency is high, the RF power is re-applied in a very short time interval and the RF power duty cycle is large (>80%), which guarantees efficient core electron heating for avoiding impurity accumulation and hollow temperature profiles in these phases. This became a standard procedure in various plasma scenarios in JET-ILW.

As far as future experimental studies are concerned, one could envisage testing different RF excitation phases (which impact the fast particle distributions and the local RF currents created with ICRH in the plasma core) and using other minority species such as He^3, which is particularly relevant for D-T operations. Another aspect concerns fine-tuning of the RTC parameters for specific plasma conditions, as e.g. re-applying the ICRH power even before the actual sawtooth is triggered (if the triggering efficiency is high enough) to further maximize the ICRF power duty cycle. From the modelling point of view, it would be extremely interesting to develop models that can quantitatively predict the impact of ICRF heating on the sawtooth stability in the presence of other stabilizing mechanisms such as α-particle heating, a topic that is fully relevant for evaluating the potential of this sawtooth pacing technique in D-T plasma in future fusion devices such as ITER. If this method would only be used to assist the H-L transition phase and the plasma termination, or in the non-active phase of ITER, these effects would obviously be of less concern.

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