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ABSTRACT.
Important advances have been made recently in the invention and application of experimental methods to control the sawtooth instability in tokamak plasmas. The primary means of control involves the application of either ion cyclotron resonance heating, or electron cyclotron heating, with resonance very close to the q = 1 radius in the plasma core. Reported here are experiments which have successfully applied these methods in order to either shorten or lengthen the sawteeth deliberately, in a variety of plasma conditions, in three tokamaks: JET, TCV and TORE-SUPRA. It is shown that despite the sensitivity of the sawtooth period to the resonance position, sawteeth can be controlled using either real-time control of the electron cyclotron deposition, or in the case of ion cyclotron heating, very careful adjustment of the magnetic field strength and minority ion concentration. The latter technique has been guided by theoretical advances which have enabled the control of sawteeth in JET with ITER relevant ICRH scenarios.

1. INTRODUCTION

The need for effective control of sawteeth has been well documented over the last few years. Due to the stabilising role of trapped alpha particles, sawteeth are expected to be strongly stabilised in ITER [1] leading to long cyclic intercrash times (sawtooth period). Of particular concern is that interaction between large sawteeth and Neoclassical Tearing Modes (NTM's) has been observed [2,3] in the Joint European Torus (JET) [4], while discharges with smaller regular sawteeth are typically found to have increased core confinement, and are less likely to be coupled to confinement degrading NTM's. Hence greater understanding and eventual control over the mechanisms that determine sawtooth stability is required.

This contribution aims to review the primary recent advances in the application of sawtooth control methods in tokamaks. Over recent years there has been renewed interest in the theoretical understanding of sawteeth, and the experimental implementation of control techniques. In these studies, control refers to objective of deliberately manipulating the period of sawteeth, and usually the objective is to shorten it. An important advance has been to show that energetic ions have a significant, and moreover, a controllable effect on the stability of the internal kink mode, thought to underlie the sawtooth phenomenon. As well as the established stabilising effect of trapped fast particles (e.g. [2,5,6]), it has recently been shown [7,8] that passing fast ions with a large orbit widths also strongly influence sawtooth stability, due to the radial drift excursion of the energetic ions which are distributed asymmetrically in the velocity parallel to the magnetic field. Such distributions occur naturally when unbalanced neutral beams are applied, or ICRH is employed with asymmetric antenna phasing. Analytical techniques [7,8] and numerical modelling [8,9] have enabled not simply interpretation of observations, but the prescription of conditions required for the desired sawtooth period.

There have been notable advances in sophisticated experimental control techniques. Recent results exhibiting control of sawteeth by steerable Electron Cyclotron Resonance Heating (ECRH) in TCV

[10] and TORE-SUPRA [11] have included real-time feedback schemes and robust control of the magnetic shear via Electron Cyclotron Current Drive (ECCD) and localised heating. Moreover, dramatic changes in sawtooth stability have also be achieved in JET [12] by the application of off-axis ICRH with toroidally asymmetric antenna phasing. Consistent with theory [8], ICRH has been shown to control sawteeth due to kinetic effects even under conditions where the modification to the magnetic shear is minimised [12]. It is concluded that various robust control schemes have been established, and ever more sophisticated analytic and numerical modelling are helping define the requirements of sawtooth control actuators in ITER. Other notable advances not discussed in this paper include sawtooth control using lower hybrid [13] and mode conversion techniques [14]. A summary of these contributions and some of those discussed in this document will reviewed in due course [15].

This paper starts in section II with a brief overview of the internal kink stability criteria of the internal kink which is widely used to interpret and design experiments. In section III we report real-time techniques in TCV which aimed to manipulate the sawtooth period via ECCD. In section IV similar techniques employed in TORE-SUPRA are shown, but with the primary difference being that the control techniques functioned despite a fast ion population in the core which originally lengthened the period. In section V, simulations are shown predicting the contribution of driven current from the planned upper EC launcher of ITER on the q prole and shear. In section VI we report experiments in JET which have exploited neutral beam ion (NBI) deposition in order to control sawteeth in JET, while section VII reports recent experiments employing ICRH with ITER-relevant minority 3He in order to control sawteeth. Summarising remarks are to be found in section VIII.

2. THE THEORY OF THE SAWTOOTH TRIGGER

The sawtooth trigger problem is addressed by seeking to correlate equilibrium properties at the onset of the m = n = 1 instability with the crossing of a theoretical stability boundary for the internal kink mode. The theoretical boundary differs as additional physical effects are added into the linearised `MHD' equations. It is generally found that the sawtooth period further increases with increasing heating power. Such a dependence on heating is consistent with the sawtooth trigger being described by resistive MHD with two fluid effects [16]. Although the m = n = 1 instability is always unstable in one-fluid resistive MHD, accounting for two fluid effects in the layer reveals stable regions of parameter space which might account for quiescence during sawteeth [17]. The instability criterion can be written in the form $s_1 > s_c(\beta)$. In Ref. [18] it is pointed out that the effects in the layer, which are described by the latter critical shear criterion, are only important when the macroscopic drive $\delta\hat{W}$ of the internal kink mode is not strongly stabilising, i.e. there is not a very large energy sink. The criterion for instability is thus given by [18]:

$$\pi = \frac{\delta\hat{W}}{s_1} < c\hat{\rho} \tag{1}$$

and

$$s_1 > s_c\ (\beta) \qquad (2)$$

where $\hat{\rho}$ is the ion Larmor radius normalised to the q = 1 radius, c a numerical constant of order unity, and s_c is a critical shear governed essentially by the pressure prole [18,17,19]. The ideal growth rate $\gamma\tau_A = \in_1\pi\delta\hat{W}/s_1$ so that $\delta\hat{W} = \delta W/(2\pi^2\xi_0^2\in_1^2 R_0B_0/m_0)$. The definition of s_c depends on the regime of interest. In large tokamaks with significant heating, sc is governed by instability in the ion kinetic regime, while in smaller machines it is governed by resistive instability. Nevertheless, s_c increases monotonically with plasma beta, and it is typically found that $s_c \approx 0.2$ close to the sawtooth crash threshold. In section III and IV the sawtooth trigger condition will be understood in terms of the impact of a manipulation in the shear, via electron cyclotron current drive, on the thresholds of Eqs. (1) and (2). Furthermore, in the TORE-SUPRA pulse described section IV, ICRH ions initially stabilise the sawteeth via the stabilising trapped ICRH ion contribution to W^ in Eq. (1), but as shown in Ref. [11], ECCD can nevertheless sufficiently modify the shear in order to trigger sawteeth. For the simulations of the expected current drive in ITER, illustrated in section V, it is found that ECCD should be capable of enhancing the magnetic shear at q = 1 to around 0.4. It is hoped that this enhancement in the shear is sufficient to trigger sawteeth in the presence of a large alpha particle population, which is expected to create a very large stabilising $\delta\hat{W}$ in e.g. Eq. (1).

To leading order in accuracy, kinetic contributions to $\delta\hat{W}$ contribute to stability in an additive fashion, and thus do not affect the essential form of the MHD contribution to stability δW_{MHD} nor the overall structure of the stability criterion of Eq. (1). Important kinetic effect arise from asymmetrically distributed passing particles with finite orbit widths. Both unbalanced NBI [7,9], and toroidally propagating ICRH [8,12] yield such populations, and their distributions can be manipulated in such a way so as to deliberately affect stability. In ITER, $\delta\hat{W}$ is expected to be very large and positive due to the stabilising effect of trapped fusion alpha particles, whilst $\hat{\rho}$ will be much smaller than in most present day experiments. Consequently, in ITER, an actuator will have to generate a large change in s_1 in order to satisfy Eq. (1). By contrast, the fast ion mechanism proposed in Refs [7,8] generates a decrease in the macroscopic energy of the internal kink mode due to either 'NBI' or 'RF' ions, and as a result, it is envisaged that the criterion for instability (e.g. (1)) can be met even when there is a significant stabilising trapped ion population in the core, and especially in conjunction with enhanced s_1, via e.g. an additional ECCD actuator. JET evidence of direct control of sawteeth with fast ion kinetic effects is shown in section VI and VII. In section VI the control is via neutral beam injection, while in VII the control is via ICRH. The mechanism can be understood with the aid of Fig. 1, which is reproduced from Ref. [20]. Passing ion orbits with wide orbit widths are illustrated. Due to the top-hat structure of the internal kink mode, particles only contribute to mode stability when their orbits are within the q = 1 radius. Consequently, for particles that happen to intersect q = 1, only the portion of the orbit that is inside q = 1 will contribute to stability. Whether such a particle is stabilising depends on whether such a particle is inside q = 1 on the region of good curvature or poor curvature. It turns out that this depends on the sign of the parallel velocity of the single passing particle. A net effect requires an asymmetry in the parallel velocity of the distribution function F. Moreover, stability also depends on the radial gradient of the distribution function. In general, destabilisation occurs if when $\partial F(v_{||} > 0)/\partial r > \partial F(v_{||} < 0) = \partial r$. Destabilisation will therefore occur for off-axis NBI ($\partial F = \partial r > 0$) with injection orientated along the plasma current ($F(v_{||} > 0) > F(v_{||} < 0)$), or with on-axis beams ($\partial F = \partial r < 0$) with injection orientated counter to the plasma current ($F(v_{||} > 0) < F(v_{||} < 0)$). Both of these combinations of unbalanced NBI are demonstrated to destabilise sawteeth in section VI. This mechanism also explains the control of sawteeth using toroidally propagating ICRH, with resonance close to the q = 1 radius. Nevertheless, for a given antenna phasing, the ratio of the number co and counter passing ions depends sensitively on radial position relative to the resonance radius. Thus a given antenna phasing can be stabilising or destabilising to sawteeth, depending sensitively on the resonance position relative to the q = 1 surface. In section VII recent JET experiments are described briefly which aim to verify the control mechanism, and minimise the effect of ICRH on the current prole. Without such experiments, it could be argued that sawtooth control occurred because of a magnetic shear change, as in the ECCD experiments of TCV [10] and TORE-SUPRA [11].

3. REAL TIME CONTROL OF SAWTEETH USING ELECTRON CYCLOTRON CURRENT DRIVE IN TCV

The 2nd harmonic X-mode (82.7GHz-X2) EC heating system at TCV (major radius 0.88m, max toroidal field = 1.5 T, max current = 1 MA) consists of 6×0.5MW gyrotrons with individual launchers. Each launcher is rotated about its longitudinal axis (inter-shot) to change the parallel wave number (i.e. changing between ECRH and ECCD). The final launcher mirror rotates to control the location of the poloidal deposition; however, in general this motion also affects the current drive. It is this final mirror that controls the poloidal angle which is controllable in real time. In order to build a real time control system, it is desirable to have a model of the sawtooth response to movements in the EC launcher injection angle which can be used to develop and test the control algorithm. Figure III shows a plot of the sawtooth period in response to feed forward sweeps of EC deposition across the q = 1 surface [10]. One EC beam was used to modify the shear. As well as modifying the local current prole, movement of the EC beam causes a redistribution of the global plasma current on a slower timescale, which manifests itself as hysteresis in the peak of the sawtooth period when the EC beam is swept across the q = 1 surface in the subsequent reverse direction. Off-axis deposition broadens the global current prole, shrinking the q = 1 surface, whereas core deposition peaks the current prole, moving the q = 1 surface to a larger radius. The result of the feed forward sweep was used to generate a lookup table of the launcher angle versus sawtooth period. In Fig. III is shown the sawtooth period as a function of varying launcher angle, using co-current ECCD/ECRH.

The algorithms developed in Ref. [10] rely exclusively upon the detected response of the sawtooth period to movements of the launcher and required the deposition to be targeted off-axis, outside the q = 1 surface (or more accurately outside the peak in the sawtooth period). In this case the controller moves the launcher to a larger angle in order to increase the sawtooth period and to a smaller angle for a shorter period, although alternatively, the deposition could be targeted for the plasma core, in which case the controller gains would be reversed. The central philosophy is to generate sawteeth of a pre-determined, where the target reference period typically varying in time.

An example [10] of the closed loop realtime control of sawteeth in TCV is shown in Fig. III. The initial target sawtooth period of 3ms is obtained within 0.15ms of the activation of the controller. Next, a step change in the target is demanded, and it is seen that the new reference of 8.5ms is obtained within around 0.4s, and the target is maintained for the duration of the activation phase of the pulse.

4. REAL TIME CONTROL OF FAST ION LENGTHENED SAWTEETH USING ELECTRON CYCLOTRON CURRENT DRIVE IN TORE-SUPRA

The experiments reported in this section were carried out on the Tore Supra tokamak (major radius: 2.4m, minor radius: 0.8 m) using a toroidal field of 3:8T, and a plasma current of 1MA. Similarly to previous JET experiments of Refs. [21,22], central ICRH (57MHz) was used to create a significant central pressure of fast ions with energies in the MeV range. The effect of co- and counter-ECCD on the sawtooth period has been explored in discharges where the Tore Supra ECCD system was capable of varying toroidal and poloidal injection angles over a wide range in order to sweep the ECCD deposition from outside the q = 1 surface, to inside, and towards the plasma center.

To explore the robustness of these results, the experiments reported in Ref. [11] were repeated at different values of ICRH power and plasma density. Sawtooth destabilization was achieved for the full range of available ICRH powers (0 to 4MW) and over a wide range of densities. In all cases, an abrupt change in sawtooth period was observed. Real time sawtooth period control was implemented varying the poloidal ECCD injection angle in real time to modify the ECCD absorption location. To overcome the problem of oscillations between two values (common problem of feedback systems), a search and maintain [11] control algorithm has been implemented. This algorithm initially varies the ECCD absorption location, in search of a location where the sawteeth are sufficiently short; once this has been achieved, the controller maintains the distance between the ECCD location and the measured sawtooth inversion radius, thereby maintaining short sawteeth throughout the ECCD pulse as seen in Fig.IV. At the beginning of the pulse 4MW of central ICRH was applied, and it is seen that the sawteeth become much longer than during the Ohmic phase. After the controller becomes active, the controller moves the mirror until the measure sawtooth period is less than the target period (during the green shaded duration in Fig.IV). After this, when the blue shaded region is started in Fig.IV the distance between the resonance location and the inversion radius is noted, and following this, feedback control ensures that the distance between the measure inversion radius and the ECH deposition is kept within 2cm. During the operation of the controller, the sawtooth period is kept relatively low despite the presence of fast ions in the core.

5. CALCULATIONS OF MAGNETIC SHEAR CONTROL VIA THE ECH UPPER LAUNCHER IN ITER.

The original design of the ITER upper launcher [1] was intended uniquely for Neoclassical Tearing Mode (NTM) stabilization (and heating), by off-axis co-ECCD. As we have seen already, sawtooth period control can be achieved with the help of non-inductive current drive, via a change magnetic shear prole. Since the stabilizing effect of the fast particles scales inversely with the values of s_1, it is hoped that a similar control can be obtained in ITER. Indeed, the TORE-SUPRA results [11] shown in section IV demonstrate that sawtooth control, via control of the magnetic shear, can be effective when fast particles initially stabilise the sawteeth. An optimized and enhanced upper launcher design [23] can drive co-ECCD at different radial locations inside the plasma and is therefore suitable for the purpose of sawtooth control. Thus, it is important for ITER to identify the effects of localized heating and current drive by EC waves on the total current density, and to infer an effect on the sawteeth.

Figure IV (a) shows the total current density, including ECCD proles corresponding to various ECH resonance locations [24]. Figure IV (b) and(c) also show the corresponding q and s proles respectively. The original prole without ECCD is plotted in dashed-black and the circles indicate the position of the q = 1 surface. Without ECCD, the value of the magnetic shear at q = 1 is 0:15, which turns out to be a typical value expected at a sawtooth crash in present experiments in the absence of fast particle stabilisation. Gaussian proles of co-ECCD driven by the revised upper launcher provided a total ECCD current of about 100-130kA. In Fig. IV(c) it is seen that by depositing co-ECCD inside or outside the q = 1 radius, the shear at q = 1 spans a rather large range, from 0 to 0:4. The increase in s1 from the nominal value of 0.15 is about a factor of 2. It is envisaged that this modification should allow stabilization of sawteeth with $0 < s_1 < 0.2$, or at least a significant increase of the period with consequent delay of the first sawtooth crash. In contrast, the increase in s1 with the addition of co-ECCD inside the deposition radius should enable destabilisation of sawteeth. Note that if the deposition location is far outside the q = 1 surface, there is no significant effect on the shear at the q = 1 location, and the s1 value stays approximately constant around 0.15 (red-blue-black lines from right in the shear plot). By moving the deposition inwards, the s1 value drops rapidly to about 0 (yellow line in shear plot), and if the deposition is moved still further inward, the shear then rapidly starts increasing (cyan line in the shear plot) and finally stays constant at around 0.4 even if we keep on moving towards the magnetic axis (magenta-green-red-blue lines on the shear plot). This sensitive variation of the shear with resonance position is clearly similar to that observed in TCV [10] and TORE-SUPRA [11], and therefore it is hoped that realtime control of the ECH deposition in ITER to control the period will be equally successful.

6. SAWTOOTH CONTROL WITH UNBALANCED NEUTRAL BEAM INJECTION

The possibility of using off-axis NBI as a sawtooth control actuator has been investigated experimentally and through stability analysis. The JET Pulse No: 58855 reproduced in Fig.6 from

Ref. [25] shows that sawtooth oscillations are considerably more unstable when the plasma is heated with co-directed off-axis NBI than with on-axis NBI. Such a configuration corresponds to the conditions ($\partial F = \partial r > 0$) and $F(v_{||} > 0) > F(v_{||} < 0)$ as described in the introduction. Furthermore, the application of NBI heating deposited off-axis can destabilize sawteeth which had previously been strongly stabilized by concurrent on-axis NBI heating. Clearly, this is explained qualitatively through the role of the passing ions in determining the stability of the n/m = 1/1 internal kink mode [7]. In JET the sawtooth behaviour is dominated by fast ion effects as the off-axis neutral beam current drive is weak and broadly deposited.

In the experiments reported in [9], the total beam power is kept constant when the off-axis power is applied in order to keep the fast ion content the same, and to minimise the effect the ideal mode stability. However, in order to demonstrate the suitability of off-axis co-NBI as a control tool, it is shown that ancillary application of off-axis beams is able to result in destabilization of otherwise strongly stabilized sawteeth. By applying on-axis NBI throughout the discharge in order to stabilize 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]. The sawtooth period in Fig. 6 is substantially lengthened during the on-axis only phase (.315 ms) before decreasing to approximately the period of Ohmic sawteeth when the off-axis power is applied (.120 ms), but with the total applied power is held constant. This clear destabilization of the sawteeth when off-axis NBI is applied is also demonstrated in other JET discharges [9]. Furthermore, if the sawtooth behaviour is compared between 16s and 20s when there is constant on-axis power, then it is evident that the additional application of off-axis NBI can be used to destabilize long sawteeth. The sawtooth period decreases by a factor of 2 when the off-axis NBI is applied, even though the total NBI power and fast ion pressure increases after 20s.

It is also possible to deliberately destabilise sawteeth with on-axis NBI, but with the orientation of the beams counter to the plasma current [26,27]. Such a configuration corresponds to the conditions ($\partial F = \partial r < 0$) and $F(v_{||} >0) < Fv_{||} < 0)$ as described in the introduction. In JET, these conditions were achieved during a reverse field campaign, where it was shown [26,27] that sawteeth could be destabilised, even relative to Ohmic sawteeth by the application of moderate power of the order of 4MW. The pulses shown in Fig.7 summarise the variation of the sawtooth period with respect to the orientation and power of on-axis NBI in JET. Similar trends to that shown in Fig.7 have been observed in MAST [28] and TEXTOR [29]. In these JET pulses, it was apparently necessary to have at least 7MW of cntr-NBI power before sawteeth are as long as there of Ohmic sawteeth. But even 8MW of counter on-axis NBI yields sawteeth that are much shorter than with 4MW of co on-axis NBI. These are much smaller than sawteeth obtained for the same power of on-axis co-beams. It should be mentioned that there are other effects that could play a role in the sawtooth period in addition to the finite orbit width effects discussed in the introduction. While it is argued that the current drive effects are probably negligible, the effect of plasma rotation on the kinetic response of trapped thermal and NBI ions could be important. Such effects have been derived and given due attention in various publications, e.g. [30,31,25].

7. ICRH EXPERIMENTS IN JET USING MINORITY ^{3}HE

In this section it is shown that it is possible to control sawteeth with localised ICRH. In order to clearly show that the fast ion mechanism is responsible for sawtooth control it is desirable to attempt to reduce the effect that fast ions have on the magnetic shear. By doing this it was possible to verify the fast ion control mechanism outlined in Ref. [8], and to remove the possibility that the sawteeth were controlled by a change in the magnetic shear (as in the ECCD experiments described in section III and IV). We summarise here dedicated experiments [12] employing minority ^{3}He, with resonance placed on the high field side close to r_1. These experiments are also important because minority 3He is expected to be used routinely in ITER.

The gross fast ion current density $j_h = en_hZ_hv_h$, where v_h is the $v_{||}$ moment of the distribution function. However, the plasma is dragged along with the fast ions, such that the total current is proportional to a drag coefficient jd, so that $j_{tot} = j_h \times j_d$. The fast ion current is subject to momentum conservation, quasi-neutrality and the balance of collision rates of electrons on all ion species [32], giving

$$j_d = 1 - \left[\frac{Z_h}{Z_{eff}} + \frac{m_h \sum_i Z_i n_i (1-(Z_i/Z_{eff})}{Z_h \sum_i n_i m_i} - G \left(\frac{Z_h}{Z_{eff}} - \frac{m_h \sum_i n_i Z_i^2}{Z_h Z_{eff} \sum_i n_i m_i} \right) \right]$$

where $G = 1.46A(Z_{eff}) \in^{1/2}$, A is a weak function of Z_{eff} and i denotes ion species other that hot (h). Due to the minority ion mass number $m_h = 3$ and charge $Z_h = 2$ and moderate $Z_{eff} \approx 1.8$ giving A $\approx$ 1.4, the effect of the plasma drag on ^{3}He minority is to reverse the sign of the net current density inside q = 1, and to neutralise the current density and the change in the shear at q = 1. Thus, it is seen that the driven current for ^{3}He minority ICRH is very small, or even in reverse. For this reason, it was suggested by Bhatnagar et al [33] that sawtooth control using localised ICRH with minority ^{3}He would not work. However, as discussed in some detail in Ref. [12], the fast ion mechanism devised in Ref. [8] is independent of the driven current.

A particular configuration was chosen which permitted the ^{3}He resonance to access a q=1 radius which was not compromised in size [12]. The two pulses summarized in Fig. 8 had the slowest field and current ramp, and the clearest sawtooth control signatures. The field was varied from 2.9T to 2.96T. The pulses were identical, except crucially, Pulse No: 78737 employed 4.5MW of counter-propagating waves (−90), while 78739 employed 4.5MW of co-propagating waves (+90). Also shown in Fig. 8 is the NBI power, the core central electron temperature, the sawtooth period and the n = 1 magnetics amplitude for both pulses. All of these signals show the contrasting effects of the antenna phasing on the sawteeth (and internal kink instability in the case of the magnetics signal).

The minority ion concentration was less than 1 percent, giving large fast ion tail temperatures . Sawteeth were strongly affected when the resonance was close to the inversion radius (r_{inv}). Pulse No: 78737 (−90) demonstrates sawtooth destabilisation (small period) as the resonance position is varied over a width of a few percent of the plasma minor radius. For Pulse No: 78739 (+90), when the resonance position was sufficiently close the q = 1 radius, the sawteeth became so long that a neoclassical tearing mode was triggered. This occurred despite being in L-mode, with normalised beta of around 0.8. The two pulses in Fig. 8, reproduced from [12], clearly demonstrate the importance and feasibility of sawtooth control. It is pointed out here that it was possible to reproduce the signatures of the sawteeth (with respect to magnetic field variation) on demand.

CONCLUSIONS

This paper attempts to bring together some of the primary sawtooth control experiments conducted over recent years. The work presented here is of relevance to experiments in burning plasmas where it is expected that long sawteeth may trigger confinement degrading NTMs, which in some cases may lead to disruption. It has been shown that realtime control of the deposition of the ECH resonance can be exploited in order to achieve realtime control of the sawtooth in both TCV and TORE-SUPRA. That sawteeth can be controlled in TORE-SUPRA even when there is a substantial fast ion content is particularly encouraging for ITER where it is expected that alpha particles will otherwise lengthen sawteeth. For this reason, the present contribution also attempts to calculate the expected contribution of the ECH launchers to the magnetic shear at $q = 1$. In the ITER simulations, it is shown that the shear can be significantly modfiied by ECCD. However, it is as yet unclear whether this effect will be sufficient to overcome the alpha particle stabilisation.

A contrasting means of controlling sawteeth is through the direct non-MHD effects brought about by collisionless fast ions, either NBI ions or RF ions. A selection of JET experiments demonstrate that by deliberate manipulation of the fast ion distribution function, it is possible to control sawteeth without the requirement of magnetic shear modification. It is hoped that with these techniques it might be possible to counter the stabilising effect of alpha particles in a more direct way. Before ITER operations commence, it should be possible to conduct more experiments, and perform more analysis and simulations to test whether this is feasible. Indeed, ITER will have real time capability over both ECH and ICRH actuators. Such studies are ongoing.

Finally, the experimental results presented here are a subset of successful experimental techniques. Sawteeth are generally extremely sensitive to the paramterisation of their actuators. Nevertheless, via improving theoretical understanding, and advanced real-time techniques, it is now becoming possible to routinely control sawteeth. The challenge now is to repeat these techniques with large stabilising trapped ion populations in the core, and in H-mode. Such experiments have been conducted in JET and will be published in due course, but more experiments, theory and simulations are required in order to judge the capability of sawtooth control techniques in future burning tokamaks.

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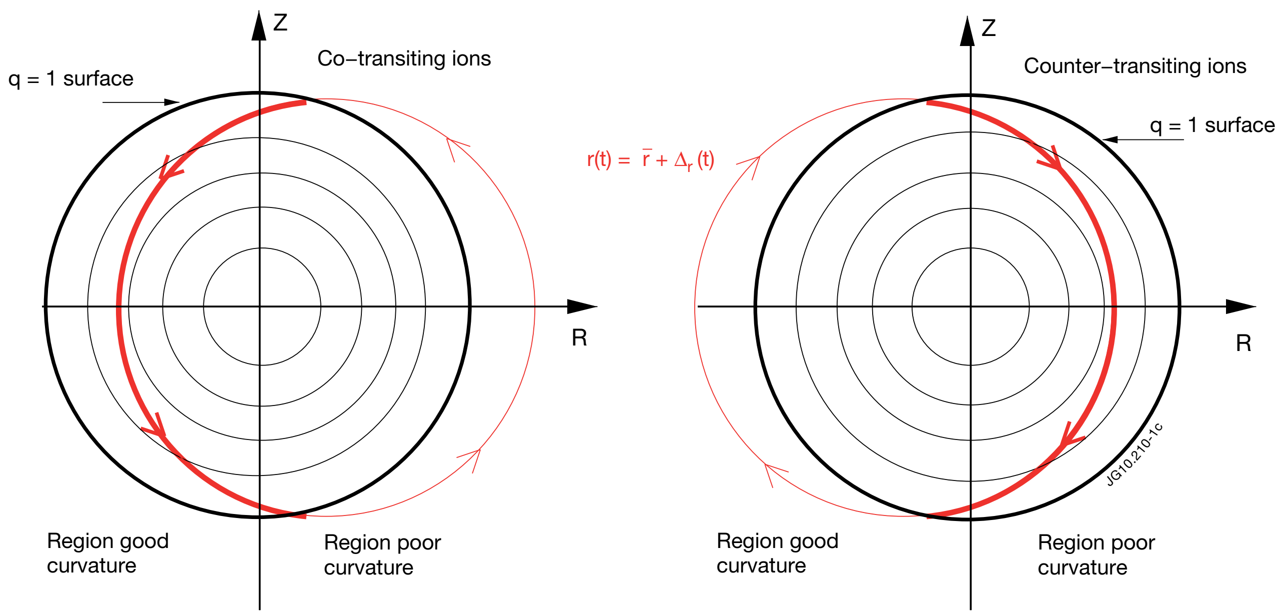
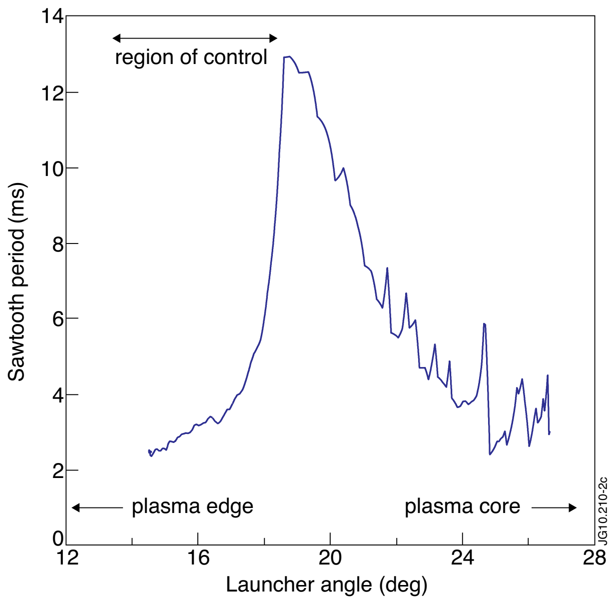


Figure 1: Plotting co-passing and counter passing ions intersecting the q = 1 surface.



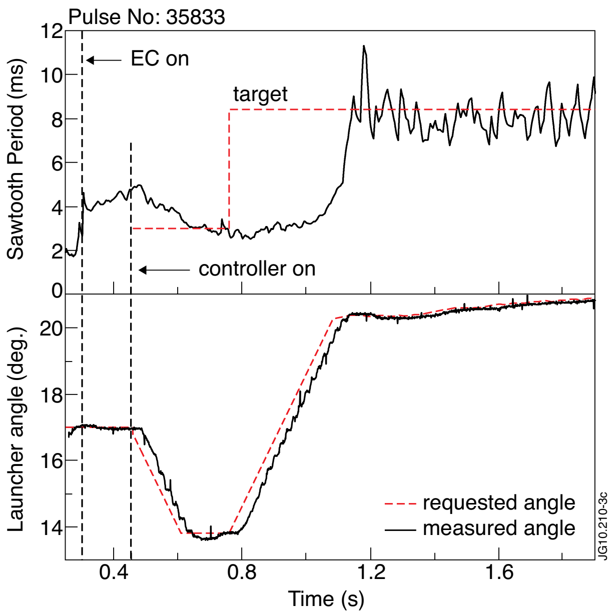


Figure 2: Showing the variation of the sawtooth period in TCV Pulse No: 35807 as the poloidal angle of the EC launcher moves the resonance position.

Figure 3: The real time control of the launcher angle is activated at t=0.45s in TCV Pulse No: 35833. A target period of 3ms is obtained within 400ms of the controller being activated. The target period of 8.5ms is later achieved and tracked.

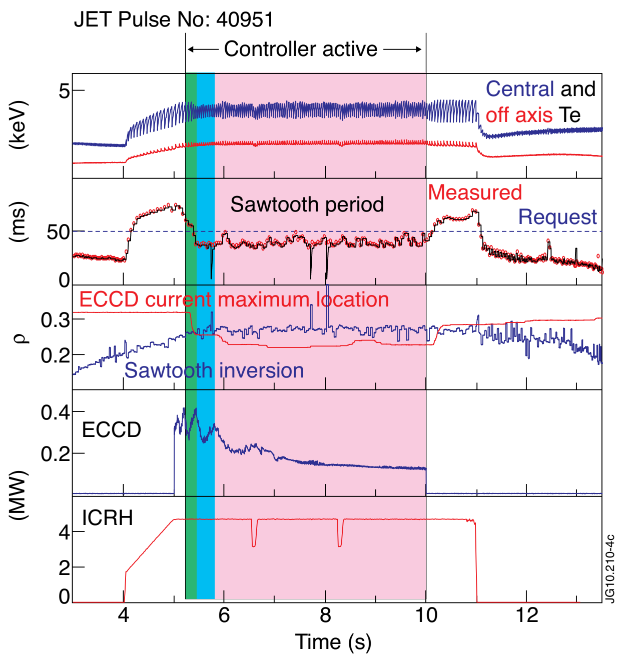
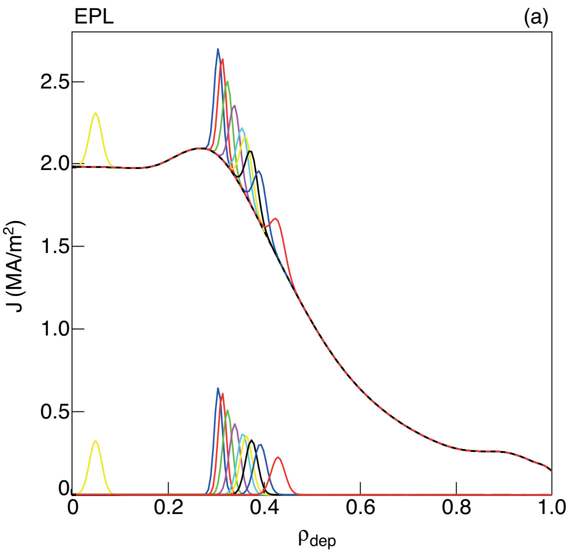


Figure 4: Showing the successful implementation in TORE-SUPRA of active real-time feedback control on sawtooth period, via control of the EC launcher angle. Prior to the ECH phase the ICRH ions lengthen the sawtooth period.



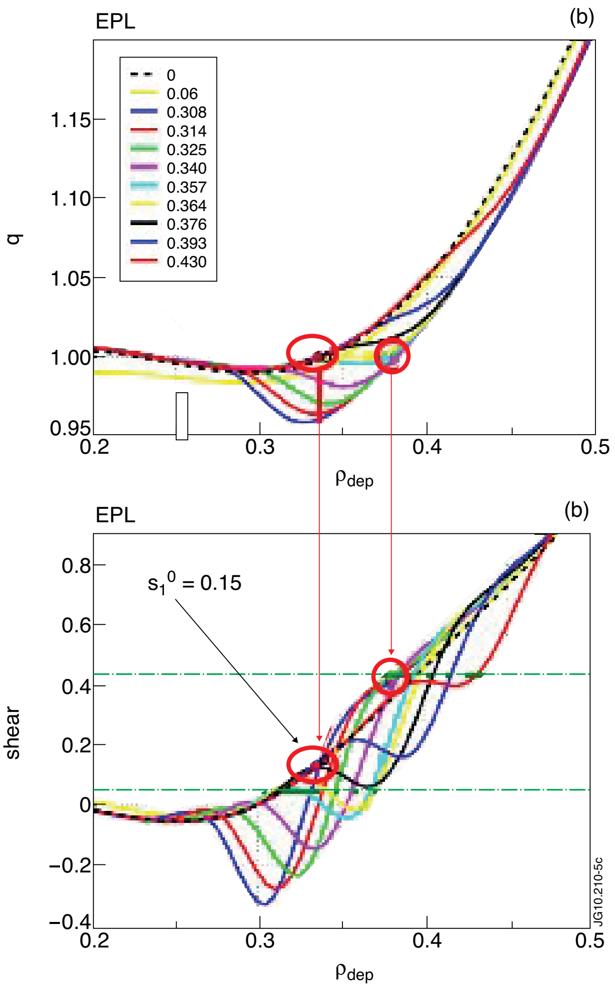


Figure 5: Showing (a) the equilibrium current density prole for an ITER standard scenario, together with realistic current perturbations corresponding to various local depositions of the current drive from the enhanced electron cyclotron upper launcher design. Showing in (b) and (c) respectively, the change to the q-prole and the magnetic shear proles corresponding to the current densities shown in (a).

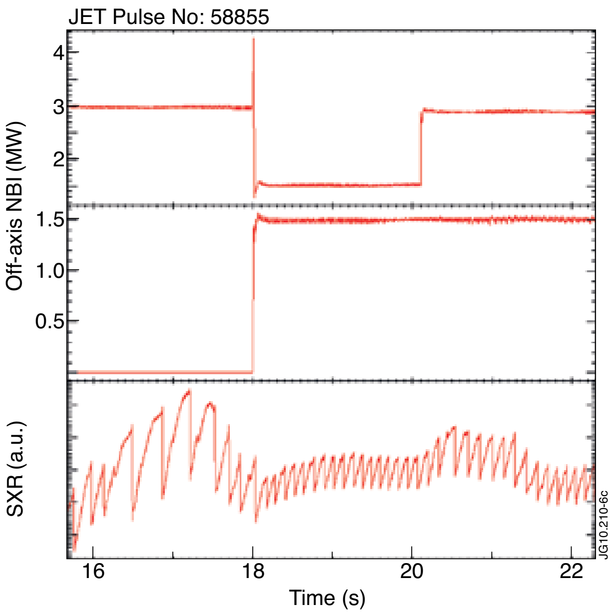


Figure 6: The soft-x ray and NBI power for JET Pulse No: 58855. The sawtooth period is shorter when o-axis NBI is used in place of on-axis heating. Moreover, using off-axis heating can reduce the sawtooth period relative to a purely-on axis phase with smaller total auxiliary heating, and thus high hot ion (and plasma) beta.

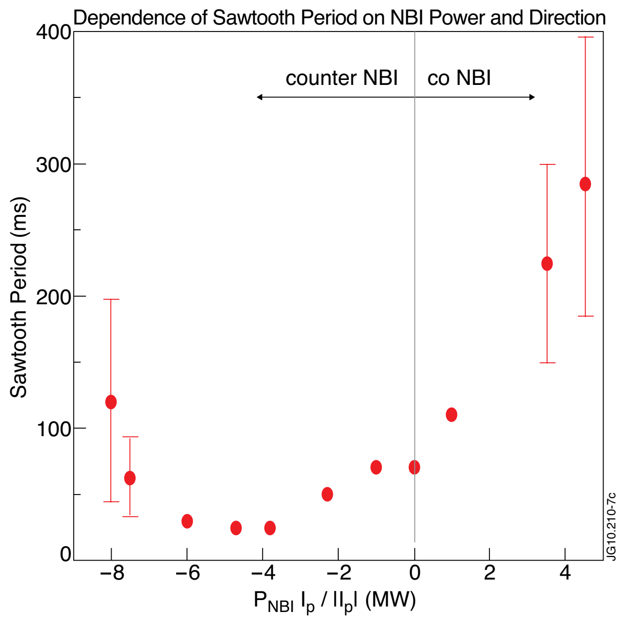


Figure 7: Showing the dependence of the sawtooth period on NBI heating power and direction relative to the plasma current in a series of dedicated JET discharges. Error bars indicate variation of sawtooth period over the measured two second interval during which measurements we taken.

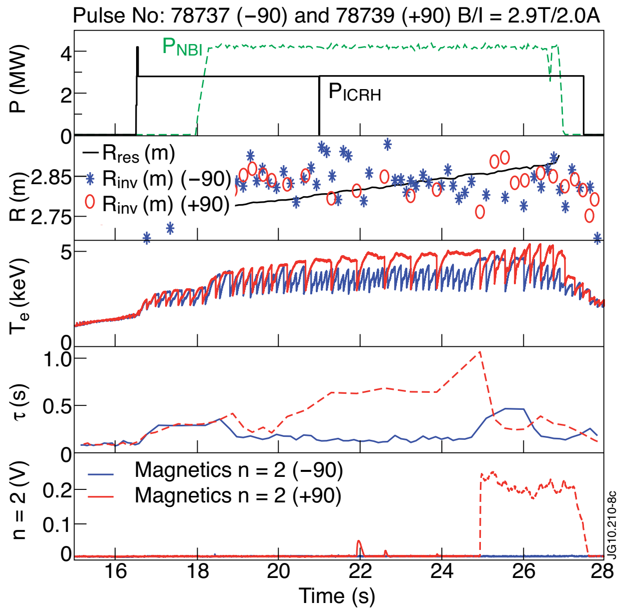


Figure 8: Time traces of NBI and ICRH power, ^{3}He resonance position and inversion radius, central electron temperature, sawtooth period and n = 2 magnetics amplitude for Pulse No's: 78737 (blue, −90 phasing) and 78739 (red, +90 phasing).