EFDA–JET–CP(12)06/05

I.T. Chapman, R. Buttery, T. Goodman, J. Graves, V. Igochine, R. La Haye,
O. Sauter, O. Asunta, S. Coda, T. Johnson, M. Lennholm, the ASDEX Upgrade
DIII-D and TCV Teams, the ITPA MHD Topical Group
and JET EFDA contributors

Assessing the Power Requirements for Sawtooth Control in ITER through Modelling and Joint Experiments

Assessing the Power Requirements for Sawtooth Control in ITER through Modelling and Joint Experiments

I.T. Chapman[1], R. Buttery[2], T. Goodman[3], J. Graves[3], V. Igochine[4], R. La Haye[5],
O. Sauter[3], O. Asunta[5], S. Coda[3], T. Johnson[6], M. Lennholm[7],
the ASDEX Upgrade, DIII-D and TCV Teams, the ITPA MHD Topical Group
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1] EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[2] General Atomics, PO Box 85608, San Diego, CA 92186, USA
[3] Association EURATOM-Confederation Suisse, CRPP, EFPL, Lausanne, Switzerland
[4] MPI für Plasmaphysik, EURATOM-Association D-85748 Garching, Germany
[5] Association Euratom/Tekes, Aalto University, PO Box 14100, FI-00076, Aalto, Finland
[6] EURATOM/VR Association, EES, KTH, Stockholm, Sweden
[7] JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK
** See annex of F. Romanelli et al, “Overview of JET Results”,*
(24th IAEA Fusion Energy Conference, San Diego, USA (2012)).

Preprint of Paper to be submitted for publication in Proceedings of the
24th IAEA Fusion Energy Conference (FEC2012), San Diego, USA
8th October 2012 - 13th October 2012

ABSTRACT.

13MW of electron cyclotron current drive (ECCD) power deposited inside the q = 1 surface is likely to reduce the sawtooth period in ITER baseline scenario below the level empirically predicted to trigger neo-classical tearing modes (NTMs). However, since the ECCD control scheme is solely predicated upon changing the local magnetic shear, it is prudent to plan to use a complementary scheme which directly decreases the potential energy of the kink mode in order to reduce the sawtooth period. In the event that the natural sawtooth period is longer than expected, due to enhanced a particle stabilisation for instance, this ancillary sawtooth control can be provided from > 10MW of ion cyclotron resonance heating (ICRH) power with a resonance just outside the q = 1 surface. Both ECCD and ICRH controlschemes would benefit greatly from active feedback of the deposition with respect to the rational surface.

1. INTRODUCTION

Sawtooth control remains an important unresolved issue for baseline scenario operation of ITER. Since the monotonic q-profile of baseline ELMy H-mode plasmas has a large q = 1 radius, r_1, with low magnetic shear at the q = 1 surface, $s_1 = r_1 dq/dr$, these plasmas are expected to be unstable to the internal kink mode. Furthermore, the energetic trapped fusion-born α-particles are predicted to lead to significant stabilisation of the internal kink mode [1], resulting in very long sawtooth periods. However, such long sawtooth periods have been observed to result in triggering NTMs at lower plasma β [2], which in turn can degrade confinement. Consequently, there is an urgent need to assess whether sawtooth control will be achievable in ITER and how much power is required from the actuators at our disposal.

Sawtooth control can be achieved by tailoring the distribution of energetic ions; by changing the radial profiles of the plasma current density and pressure, notably their local gradients near the q = 1 surface; by rotating the plasma, or changing the rotation shear local to the q = 1 surface; by shaping the plasma; or by heating the electrons inside the q = 1 surface. The primary actuators to achieve these perturbations are electron cyclotron current drive (ECCD), ion cyclotron resonance heating (ICRH) and neutral beam injection (NBI). The highly localised perturbations to the current density profile achievable with ECCD have been employed to significantly alter sawtooth behaviour on a number of devices. ECCD is foreseen as the primary sawtooth control actuator in the ITER design [3] due to both the highly localised current density that can be achieved when compared to ICRH for instance, and because of the ability to provide real time control of the current drive location by changing the launcher angle of the steerable mir rors. However, complementary control schemes which work via kinetic effects, such as ICRH or NBI, are also useful for sawtooth control in the presence of a population of core energetic particles.

2. AN ACCEPTABLE SAWTOOTH PERIOD TO AVOID TRIGGERING NTMS

An open question which predicates the assessment of required actuator power level is what an acceptable sawtooth period will be in ITER. The issue of whether a sawtooth period in the range of 20-50s in ITER, as predicted by transport simulations [4, 5] will avoid triggering NTMs is currently poorly understood, and so a multi-machine empirical scaling has been developed in order to provide some basis for extrapolation and specification of sawtooth control actuators in ITER [2]. This dataset contains details for over 200 shots from nine tokamaks; namely ASDEX Upgrade, DIII-D, HL-2A, JET, JT-60U, MAST, NSTX, TCV and Tore Supra. A subset of the data has been considered which retains only discharges with ITER like shape ($\delta \in [0.3,0.4]$ and $\kappa \in [1.65,1.85]$), a broad flat q-profile with a wide q = 1 surface (r_1/a 2 [0.33,0.45]) and with auxilliary heating power just above the L-H threshold ($P_{aux}/P_{LH} \in [1.3,1.7]$) [3].

It is clear from figure 1 that this subset retains the general trend revealed by the full database, namely that NTMs are triggered at lower β_N for longer sawtooth periods with respect to the resistive diffusion time.

Figure 1 shows the critical β_N for triggering NTMs for the ITER-like subset, compared to the predictions of an empirical scaling law developed from the entire database [2], showing good agreement between the two. Also overlaid is the critical achievable pressure predicted for a range of sawtooth periods in ITER. At the target operating pressure for ITER ELMy H-mode scenario – $\beta_N = 1.8$ – this scaling law suggests that a sawtooth period of around 70s will be permissible. This scaling law is, of course, only an empirical fitting and not based on any physics model, so its application to future devices is certainly not quantitative. For instance, the experimental database is primarily for unidirectional NBI-heated plasmas, so supplementing this database with plasmas run at more ITER-relevant low torques would help to clarify whether the rotation plays an important role in mediating the coupling between the sawtooth crash and the NTM onset.

3. EXPERIMENTAL DEMONSTRATION OF SAWTOOTH CONTROL IN ITER CONDITIONS

Whilst ECCD has been shown to control sawteeth effectively for decades, only recently have such demonstrations been replicated in the presence of core energetic particles. Destabilisation of long period sawteeth – which in turn were induced by ICRH generated core fast ions with energies¸ ≥0.5MeV – was achieved in Tore Supra, even with modest levels of ECCD power [6]. Similarly, ECCD destabilisation has also been achieved in the presence of ICRH accelerated NBI ions in ASDEX Upgrade [7]. More recently sawtooth control using ECCD has even been demonstrated in ITER-like plasmas with a large fast ion fraction, wide q = 1 radius and long uncontrolled sawtooth periods in DIII-D [8]. As expected from simulation, the sawtooth period is minimised when the ECCD resonance is just inside the q = 1 surface. Sawtooth control using driven current inside q = 1 allows operation at $\beta_N = 3$ without 3/2 or 2/1 NTMs in ITER demonstration plasmas in DIII-D when sawtooth control is applied using only modest ECCD power [8]. Such avoidance of NTMs permitting operation at higher pressure than otherwise achievable by application of core ECCD sawtooth control has also been demonstrated in ASDEX Upgrade [9]. Examples from DIII-D and

ASDEX Upgrade are shown in figure 2,whereby the core ECCD leads to a shorter sawtooth period, avoiding the triggering of NTMs which otherwise happens, and permitting stable operation at considerably higher normalised pressure.

A major advantage of ECCD is that it provides a simple external actuator in a feedback-control loop through the angle of inclination of the launcher mirrors. Consequently, there has been considerable effort to develop real-time control of the deposition location in order to obtain requested sawtooth periods. Recently, fine control over the sawtooth period has been demonstrated on TCV using ‘sawtooth pacing’ via modulated ECCD with real-time crash detection [10], or ‘sawtooth locking’, where the sawtooth period is controlled even in the absence of crash detection [11]. Meanwhile, Tore Supra has implemented a ‘search and maintain’ control algorithm to vary the ECCD absorption location to find the minimum sawtooth period then keep the distance between the ECCD deposition location and the inversion radius constant despite perturbations to the plasma [6].

Control of sawteeth by ICRH in the presence of core energetic particles has been widely exploited on JET [12]. Furthermore, ICRH control has also been demonstrated in plasmas with significant on-axis NBI and high β_P, well above the critical threshold for triggering 3/2 NTMs in the absence of sawtooth control [13]. The sawtooth control mechanism from localised off-axis toroidally propagating waves is due to the radial drift excursion of the energetic ions distributed asymmetrically in the velocity parallel to the magnetic field [14]. This kinetic mechanism results in a deep and narrow minimum in the change of the potential energy when the peak of the passing fast ion distribution is just outside the $q = 1$ surface, helping to explain the extreme sensitivity of the sawtooth behaviour to the deposition location of the ICRH waves.

Recent JET experiments using ^{3}He minority heating on the high-field side just outside the $q = 1$ surface lead to a strong destabilisation for counterpropagating waves (-90^o) and a strong stabilisation for co-propagating waves ($+90^o$) [15]. Figure 3 shows the sawtooth period for a pair of otherwise-identical JET plasmas with different ICRH phasing. The deliberate sawtooth control leading to short sawteeth avoids triggering NTMs whereas in its absence, a 3/2 NTM is triggered when $\tau_{ST} = 1$s, even at $\beta_N < 1$. This sawtooth control scheme via affecting the kink mode potential energy has subsequently been demonstrated in H-mode plasmas with significant core heating too [16], adding credence to its applicability in ITER where using ^{3}He minority ICRF heating means the driven current will be negligible [17]. Finally, real-time control through variation of the ICRH frequency has been attempted with some success on JET [18], though the frequency variation is much slower than anticipated in ITER.

4. ECCD POWER REQUIREMENTS FOR SAWTOOTH CONTROL

The effect of local EC heating on the q-profile in ITER has been modelled with the ASTRA transport code [19], which solves a reduced set of 1-D equations for the evolution of the electron and ion temperatures, the helium density and the poloidal magnetic flux. The NBI components are self-consistently evaluated with a Fokker-Planck subroutine which calculates the separate

NB contributions to the electrons and ions. The EC power density and current drive profiles are evaluated by the beam tracing GRAY code [20]. The change in the magnetic shear generated by the application of ECRH has been tested for a range of different launcher configurations [21, 22]. When the deposition location is far outside the q = 1 surface, there is no significant effect on the shear at the q = 1 location; the s1 value stays approximately constant around 0.15. With the deposition just outside q = 1, the s1 value drops close to zero, and as the resonance moves inward, the shear rapidly increases and stays constant at approximately $s_1 = 0.4$, even for very on-axis heating. It should be noted that the q = 1 radius changes rapidly as the ECCD deposition moves across its initial position, meaning that the deposition needs to be adjusted in real time in order to follow the q = 1 radius and allow optimum sawtooth destabilization. That said, the significant increase in s1 achievable with core ECCD means that good shear control can be achieved irrespective of the exact resonance provided the EC deposition is inside q = 1. Figure 4(a) shows the difference of s1 from the original value without ECCD as a function of the difference between the deposition position, rdep, and the radial position of the q = 1 radius, r_1 for the case without ECCD [22]. The significant increase in s_1 over a broad range of central EC resonance positions inside q = 1, relaxing requirements on the real-time control system.

In order to model the nonlinear sawtooth period, the ASTRA transport code includes a heuristic model for when a sawtooth crash will occur, as described in reference [23]. The sawtooth period in ITER is predicted to be considerable, due to the influence of α-particle stabilization [1]. Since the sawtooth period is related to the free parameter of the model, c_r, this has been chosen to provide $\tau_{ST} =$ 40s for the reference case without any additional EC power, which is a lower bound of the sawtooth period for triggering NTMs predicted from empirical evidence in section 2.. The corresponding value for c_r is 4.3. If the free parameter in the Porcelli model is taken to be $c_r = 1$ (as originally in the model [24]), the sawtooth period approaches 200s and the safety factor on axis drops very low, making these predictions unreliable. Figure 4(b) shows the sawtooth period as a function of the radial deposition location, ρ_{dep}, of the injected co-ECCD for different mixtures of EC power from the equatorial launcher or the upper launcher [22]. The most efficient design uses 20MW of EC power from the equatorial launcher. In this case, the sawtooth period can be reduced from the reference case of 40s to 23-24s with $\rho_{dep} = 0.3$ meaning that the ECCD also leads to efficient heating of the core and minimal impact on the fusion gain, $Q = P_{fusion}/P_{aux}$. A combination of co-ECCD driven by 2 rows of the equatorial launcher (13.3MW) and the remaining power driven by the upper launcher, at a fixed location, can also decrease the sawtooth period down to less than 30s. 13.3MW was assumed for control in order to leave more than 5MW available for NTM control if required (reference [25] suggests that relatively low ECCD power could be sufficient for NTM suppression in ITER). The degraded control in both destabilizing and stabilizing the sawteeth by using only the upper launcher can be ameliorated with a real-time control (RTC) algorithm, through which the deposition location is recalculated every time step by the simple formula: $\rho_{dep} = r_1 + \eta w_{CD}$, where h is a real-time control parameter that was scanned between -2 and +2, and wCD is the full width at half-maximum of the Gaussian ECCD profile. With real-time feedback controlling the rdep, the sawtooth period can be increased up to 70s, i.e. over 50% more than the fixed deposition case.

Assuming that the natural sawtooth period is approximately 50s as predicted by transport simulations [4, 5], then a reduction of ~30% to 35s is likely to avoid triggering NTMs according to the empirical scaling (section 2).. However, the largest uncertainty is what the natural sawtooth period will be. The reference of 40s can be justified by scaling by resistive diffusion time from 1s monster sawtooth crashes in JET, and lengthening to account for the stabilising effect of the alphas by scaling the period in proportion to δW_α in ITER with respect to that in JET. Furthermore, the value of cr results in a crash when $s_1 \in [0.5,0.6]$, which is in line with typical empirical evidence on a number of devices when active control is applied in plasmas with a large fast ion fraction.

5. ICRH POWER REQUIREMENTS FOR SAWTOOTH CONTROL

In order to assess the effect of ICRH fast particles on the stability of the internal kink, the distribution of fast ions simulated by SELFO [26] and SCENIC [27] have been fed as Monte Carlo markers into the HAGIS code [28]. This is then compared to the potential energy contributions from the NNBI simulated by TRANSP [29], the alphas simulated by ASCOT [30] and the thermal ions and fluid drive to assess the linear stability of the kink mode. Whilst such a linear assessment cannot be used to infer the sawtooth period, it qualitatively provides insight into the applicability of ICRH as a control tool, and the ratio of these contributions can be considered as a guide to its efficacy.

Figure 5(a) shows the change in the potential energy of the mode arising due to the ICRH energetic ions as a function of the difference between the resonance position and ρ_1. There is a clear narrow well in the potential energy when the RF resonance is just outside the rational surface, that is to say when the gradient of the distribution of energetic passing ions is strong and positive. This narrow region (~2cm) in which the sawteeth will be sensitive to the destabilising influence of the ICRH energetic ions implies that real-time control will be required, though this is expected to be available between 40-55MHz in ITER with requisite latency. Also shown is good agreement for δW_{ICRH} when the distribution of markers is taken either from SELFO or SCENIC for the case with 0.5% ^{3}He, –90^o antenna phasing and 20MW injected power with the resonance at R = 7.284m (f = 48.58MHz in SELFO and f = 48.9MHz in SCENIC). Despite the fact that the power absorbed by the minority species increases with the concentration [1], the strongest effect on mode stability is for a 3He concentration of only 1%. When there is too much 3He, the energy of the particles in the tail of the distribution becomes too low to have a strong effect on the kink mode whereas too little 3He means that the absorbed power is low and the broader distribution function leads to increased fast ion losses.

The influence of the ICRH fast ions compared to the stabilising effect of the alpha particles and NNBI distributions is shown in figure 5(b) for the case when the ICRH resonance is at r = 0.43m (f_{ICRH} = 50MHz). In these simulations the q = 1 surface is moved by changing the equilibrium rather than re-simulating the fast ion distribution for different resonance locations. It is evident that the mid-radius ICRH fast ions, despite the poor power absorption and low energy tails, retain a strongly destabilising influence, comparable to the magnitude of stabilisation afforded by the alphas or the NBI heating. Whilst the power absorption is better when the resonance layer is nearer to the axis, resulting in improved core heating, the passing fast ions are only destabilising when the peak of the distribution is outside the $q = 1$ surface. These simulations are for 1% 3He concentration and +90± phasing of the antenna, though the −90± phasing gives similar results, with a slightly diminished destabilisation. The fact that the ICRH is able to completely negate the stabilising term from the presence of the a population is significant and important, and makes the ICRH an essential part of the portfolio of control tools in ITER.

Figure 5(b) also shows that if the $q = 1$ surface could be maintained closer to the magnetic axis, sawtooth control would be significantly easier to achieve, since the alphas would be less stabilising, the NNBI would be less stabilising, and could even be used as a destabilising control tool in the most off-axis orientation, and the control and flexibility afforded by the ICRH would be increased. Furthermore, the ECCD used to control the sawteeth would be closer to the plasma core, and so have the dual benefit of heating the plasma, hence affording a potential reduction in other auxiliary heating power and subsequent increase in Q. This may be possible with early heating to delay the current penetration into the core, as regularly employed on JET, and then deliberate sawtooth destabilisation to mediate the q-profile once the $q = 1$ surface enters.

If it proves that a combination of >10MW of ICRH power on top of the primary actuator of 13.3MW of ECCD from the equatorial launcher is insufficient for successful sawtooth control, then it is important that an alternative solution is provided within the specification of the heating and current drive actuators. Consequently, a sawtooth stabilisation scenario has been envisioned, whereby the natural sawtooth period is deliberately lengthened, and the (very probable) NTM that ensues at the crash is pre-emptively stabilised before it reaches its saturated width. Provided the seed island is sufficiently small (~7cm), all models for ECCD island suppression indicate that 13.3MW from the upper launchers can fully suppress the mode within 6s [25]. The sawtooth period could be lengthened by either counter-ECCD in the core, off-axis co-ECCD or on-axis ICRH followed by provocation of a crash by dropping auxilliary heating coupled with simultaneous pre-emptive application of ECCD near the $q = 2$ surface to suppress the subsequent NTM growth. This has been demonstrated in TCV where sawtooth pacing using modulated core ECCD coupled with pre-emptive NTM avoidance by ECCD at $q = 3/2$ has avoided the triggering of NTMs [31]. It should be noted that deliberate stabilisation of the sawteeth using either ICRH or core counter-ECCD/off-axis co-ECCD will require real-time control and core ECH to reverse the on-axis accumulation of higher-Z impurities that would otherwise cause degradation of energy confinement due to impurity radiation [32].

CONCLUSIONS

An empirical scaling of the sawtooth period that will trigger an NTM in ITER suggests that the "natural" sawtooth period predicted by transport modelling is approximately at the threshold for

NTM seeding. Whilst this means that active sawtooth control is essential, it suggests that sufficient control can be achieved through a relatively small reduction in the sawtooth period. ,Transport modelling coupled to ray-tracing predictions and using the linear stability thresholds for sawtooth onset suggests that 13MW of ECCD from the equatorial launcher could be sufficient to reduce the sawtooth period by ~30%, and this being the case, dropping it below the NTM triggering threshold. This modelling is predicated upon choosing a natural sawtooth period of 40s; should the stabilising contribution from the alpha particles and on-axis NBI injection prove to give rise to a significantly longer natural sawtooth period, the ability of the ECCD to control sawteeth will be diminished. There are naturally large uncertainties associated with this modelling, and it is prudent to plan to use more than one control actuator in order to reduce this risk. Consequently, it is recommended that > 10MW of ICRH at ~50MHz (with real-time feedback) is also reserved for sawtooth control. The largest uncertainty in the modelling is the position of the $q = 1$ surface; if the $q = 1$ surface could be maintained closer to the magnetic axis, sawtooth control would be significantly easier to achieve, since both the alphas and the beam-induced fast ions would be less stabilising. Furthermore, the ICRH and ECCD for sawtooth control would be further towards the axis, thus heating in the good confinement region and so affording a potential reduction in other auxiliary heating power and subsequent increase in Q. Finally, should active sawtooth destabilisation prove to be unattainable then there is a viable alternative strategy of sawtooth stabilisation coupled with pre-emptive NTM suppression, which would provide long periods of good performance. The power requirements for the necessary degree of sawtooth control using either destabilisation and stabilisation schemes are expected to be within the specification of anticipated ICRH and ECRH heating in ITER, provided the requisite power is dedicated to sawtooth control.

ACKNOWLEDGEMENTS

This work was conducted under the auspices of the ITPA MHD Topical Group. This work was partly funded by the RCUK Energy Programme under grant EP/I501045 and the European Communities under the contract of Association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]. Chapman I.T. et al, Plasma Physics and Controlled Fusion **53** (2011) 124003
[2]. Chapman I.T. et al, Nuclear Fusion **50** (2010) 102001
[3]. ITER Physics Basis, Nuclear Fusion **47** (2007) S1
[4]. Onjun T. and Pianroj Y, Nuclear Fusion **49** (2009) 075003
[5]. Budny R.V. et al, Nuclear Fusion **48** (2008) 075005
[6]. Lennholm M. et al, Physical Review Letters **102** (2009) 115004
[7]. IGochine V. et al, Plasma Physics and Controlled Fusion **53** (2011) 022002
[8]. Chapman I.T. et al, Nuclear Fusion **52** (2012) 063006

[9]. Chapman I.T. et al, in prep Plasma Phys. Control. Fusion (2012) “Destabilisation of sawteeth in the presence of core energetic particles in ASDEX Upgrade”
[10]. Goodman T.P. et al, Physical Review Letters **106** (2011) 245002
[11]. Lauret M et al Nuclear Fusion **52** (2012) 062002
[12]. Eriksson L-G et al, Nuclear Fusion **46** (2006) S951
[13]. Coda S. et al, in Proceedings of the 34th EPS Conference on Controlled Fusion and Plasma Physics, Warsaw (2007) P5.130
[14]. Graves J.P. et al, Physics of Plasmas **17** (2009) 056118
[15]. Graves J.P. et al, Nuclear Fusion **50** (2010) 052002
[16]. Graves J.P. et al, Nature Communications **3** (2012) 624
[17]. Laxaback M and Hellsten T, Nuclear Fusion **45** (2005) 1510
[18]. Lennholm M. et al, Nuclear Fusion **51** (2011) 073032
[19]. Pereverzev G.V, Max Planck - IPP Report 5/42 (1991)
[20]. Farina D. et al, Fusion Science and Technology **52** (2007) 154
[21]. Graves J.P. et al, Fusion Science and Technology. **59** (2011) 539
[22]. Zucca C et al, Theory of Fusion Plasmas, Joint Varenna-Lausanne Theory Conference 1069 (2008) 361
[23]. Sauter O et al, Theory of Fusion Plasmas, Proc Joint Varenna-Lausanne International Workshop, Varenna (AIP) p403 (1998)
[24]. Porcelli F, Boucher D and Rosenbluth M, Plasma Physics and Controlled Fusion **38** (1996) 2163
[25]. Sauter O. et al, Plasma Physics and Controlled Fusion **52** (2010) 025002
[26]. Hedin J. et al, Nuclear Fusion **42** (2002) 527
[27]. Jucker M. et al Computer Physics Communications **182** (2011) 912
[28]. Pinches S.D. et al, Computer Physics Communications **111** (1998) 133
[29]. Budny R.V. Nuclear Fusion **32** (1992) 429
[30]. Heikkinen J.A. and Sipila S.K. Physics of Plasmas, **2** (1995) 3724
[31]. Goodman T.P. et al, European Physical Society Conf on Plasma Phys, Stockholm, Sweden (2012) P2.029
[32]. Dux R. et al, Journal of Nuclear Materials **313** (2003) 1150

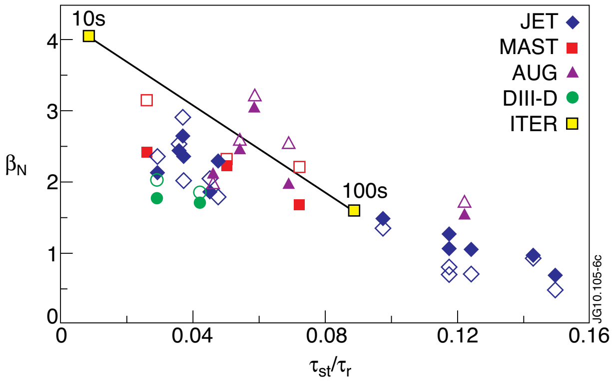

Figure 1: The β_N at which an NTM is triggered with respect to the sawtooth period normalised to the resistive diffusion time (filled symbols) for ITER-like shape, q = 1 radius and injected power normalised in a range just above the PLH threshold, compared to the critical β_N predicted by the scaling law from reference [2] (open symbols). For comparison, ITER baseline scenario is indicated with sawtooth period ranging from 10s to 100s.

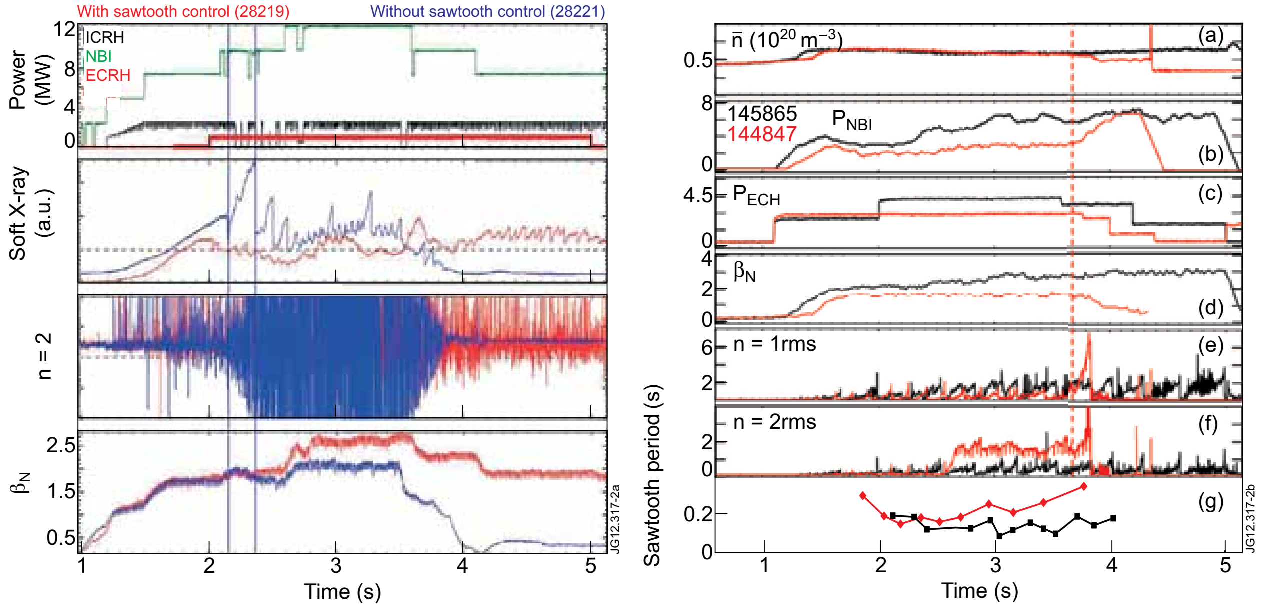

Figure 2: (left) (1) Auxiliary power, (2) Soft X-ray emission, (3) n=2 magnetics and (4) β_N for two ASDEX Upgrade shots with and without core ECCD inside q=1 for sawtooth control. With ECCD the sawtooth period is short, the 3/2 NTM is avoided and the maximum pressure is ~25% higher (right) (a) Density, (b) NBI power, (c) ECH power, (d) β_N, (e) n=1 magnetics, (f) n=2 magnetics and (g) sawtooth period for two DIII-D shots with and without ECCD sawtooth control. The core ECCD leads to 50% lower sawtooth period with no triggered NTMs in an ITER-like scenario with β_N = 3.

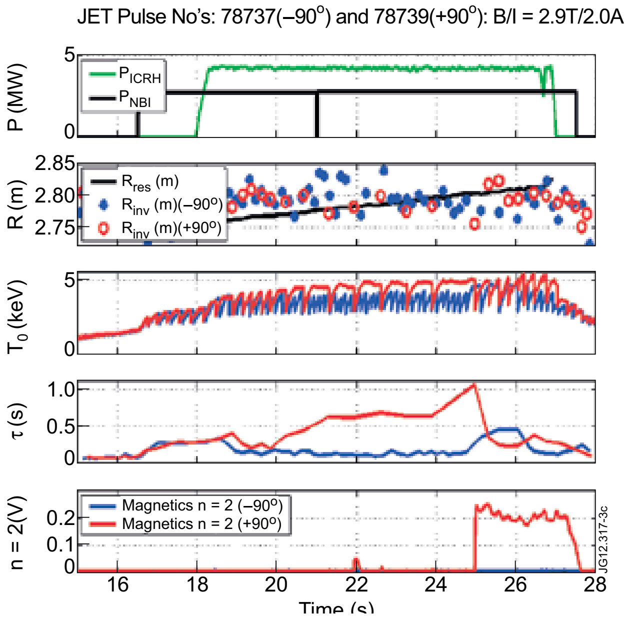

Figure 3: (1) Auxiliary heating power, (2) ICRH resonance position with respect to the inversion radius, (3) Central temperature, (4) Sawtooth period and (5) n=2 magnetic signal for two JET discharges, one with –90° ICRH for sawtooth control and one with +90° ICRH for core heating. The sawtooth control keeps small sawteeth which avoid the 3/2 NTM triggered in its absence

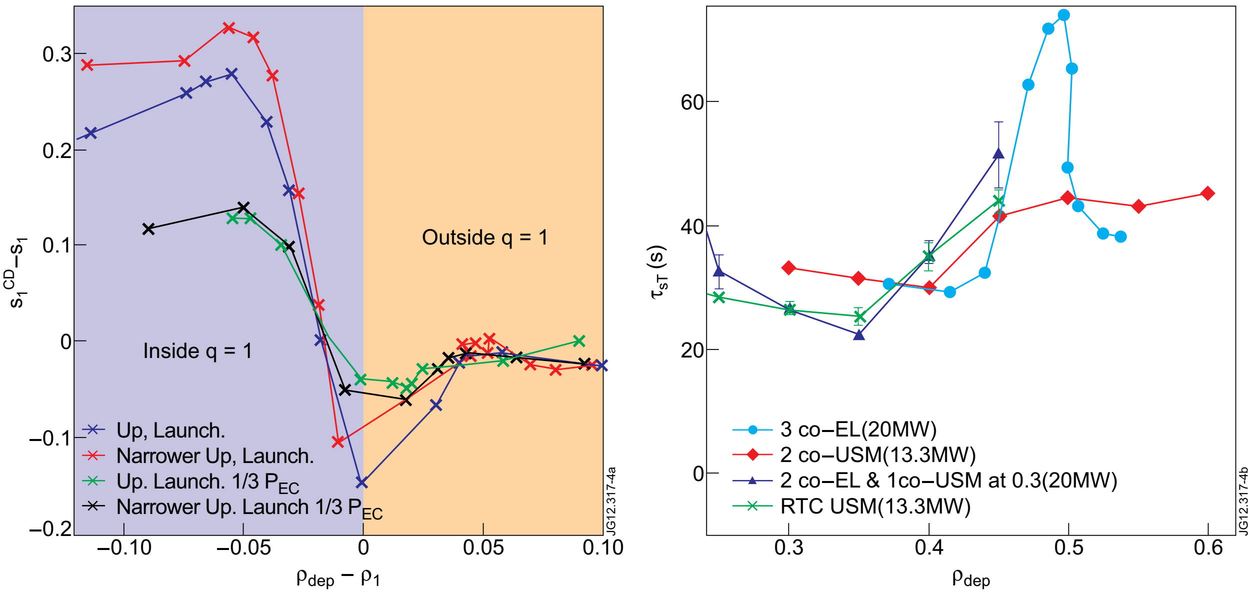

Figure 4: (a) The change in the magnetic shear at $q = 1$ with respect to the value without ECCD as a function of the deposition position with respect to the radial position of the $q = 1$ surface and (b) the predicted sawtooth period when the deposition is at different radii as predicted by ASTRA for a range of EC launcher configurations in ITER.

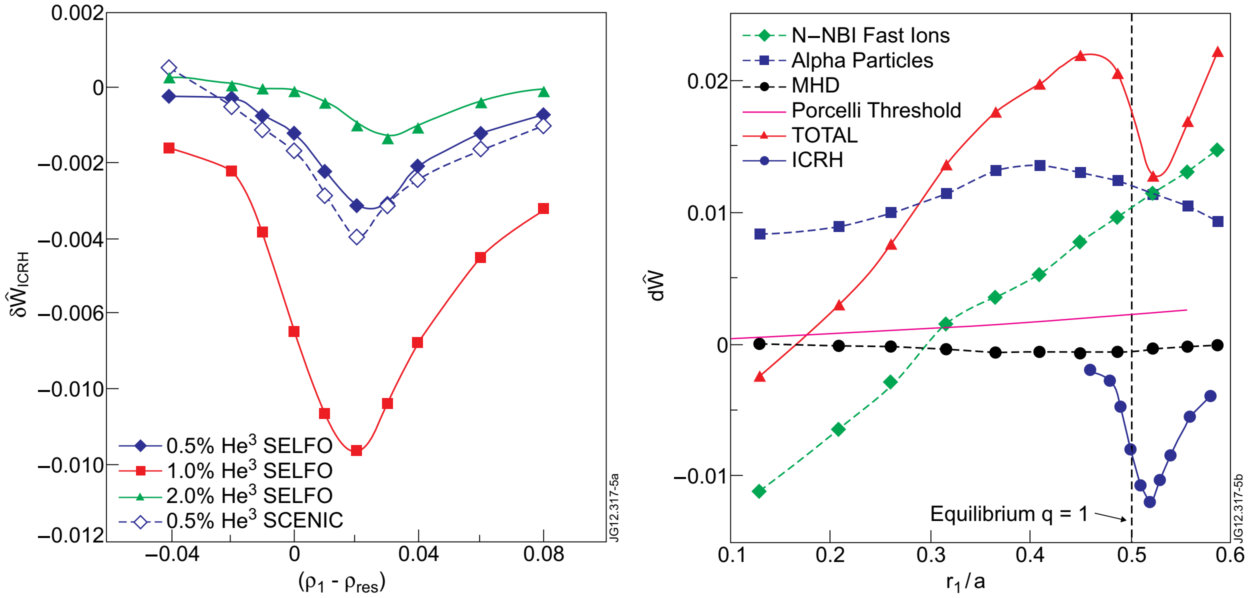

Figure 5: (a) The change in the kink mode potential energy as a function of the difference between the ICRH resonance and r_1 *for different* ^{3}*He minority concentration predicted by SELFO or SCENIC. (b) Various contributions to the change in the kink mode potential energy as a function of radial position of* $q = 1$ *for 33MW of* N_{NBI} *off-axis and 20MW of ICRH near mid-radius with* $f_{ICRH} = 50MHz$.