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## INTRODUCTION

Sawtooth instabilities are periodic relaxations of the plasma core parameters in standard tokamak scenarios. They have beneficial effects such as the ejection of impurities, the removal of Helium ashes, or can have negative effects such as the trigger of pressure limiting neo-classical tearing modes [1] or of other coupled MHD (e.g. X-event leading to disruption). The prediction of the sawtooth period or the possibility of controlling their amplitude in ITER is therefore of importance.

Energetic particles resulting from either ion cyclotron resonance heating (ICRH) [2] or fusion reactions are known to have a strong stabilising influence on the behaviour of sawtooth oscillations in tokamaks. The role of the lower-energy fast particles in neutral beam injection (NBI) is less apparent, although stabilisation was observed directly [3]. It has also been observed indirectly in tritium experiments in the Joint European Torus (JET) with (NBI), where an increase of the sawtooth period with tritium concentration was explained as a stabilising effect of NBI [4]. In such an interpretation the NBI fast ion energy content is changing due to the mass dependence of the slowing-down time.

## 1. EVIDENCE OF FAST PARTICLE STABILISATION EFFECTS

Recent discharges in JET have shown that ions arising from only deuterium NBI, with the beam injection energy of 80 and 140keV, can have similar effects. In pulses with NBI as the sole source of auxiliary heating an inverse correlation has been found between the sawtooth period $\tau_{saw}$ and the electron density $n_e$, as shown in Fig.1, for different plasma shape conditions. This inverse density scaling [5] is unlike the usual ohmic scaling laws for the sawtooth period, which show an increase in sawtooth period with density. Since the beam ion pressure is proportional to the slowing-down time, which varies as $T_e^{1.5}/n_e$, the observed anti-correlation with density suggests that beam ions have a stabilising effect. The strong $T_e$ dependence suggested by collisionality arguments is confirmed by regression analysis over the sawtooth database, which yields $\tau_{saw} \sim T_e^{1.7}\, n_e^{0.23}$ [6].

The linear relation between $\tau_{saw}$ and the fast ion energy content $W_{i,fast}$ calculated from the PENCIL post-processing code is shown in Fig. 2. This is a further indication pointing to the role of the fast particles. Also, when the evolution of $\tau_{saw}$ is plotted against NBI power (PNBI), it exhibits hysteresis behaviour as PNBI rises and decays, which is slightly reduced when plotted against $W_{i,fast}$ (the NBI waveform is an approximation of a trapeze as in Fig. 3a). This suggests that the changes in $\tau_{saw}$ are better correlated to the changes of $W_{i,fast}$ than to the ones of PNBI. The hysteresis reduction is stronger when the time variation of the NBI power waveform is short and comparable to $\tau_{slow\text{-}down}$ (~50-100ms). In the experiments presented in this paper however, slow NBI ramp-up and ramp-down were made to improve on sawtooth statistics over a large power range (see Fig. 3a).

## 2. SAWTOOTH MODEL AND CRASH REGIMES IN JET

The sawtooth simulations presented in this paper are making use of a model introduced to predict the sawtooth period in ITER [7]. They include the stabilising effect of a beam ion contribution to the m=1 internal kink energy, the dimensionless energy functional $\delta\hat{W}_{fast}$, to $\delta\hat{W}core = \delta\hat{W}_{MHD} + \delta\hat{W}_{KO}$, with

$$\delta W_{fast} = -\frac{\beta_{0\,fast}}{\sqrt{2}\, s_1 \varepsilon^{1/2}} \int_0^{r_1} \left(\frac{r}{r_1}\right)^{3/2} \frac{dp_{fast}}{dr}\, dr$$

Note that the internal kink is unstable for $\delta\hat{W} = -\gamma\tau_A$. In the JET experimental cases analysed here, the ideal internal kink mode is always stable, since equations (1) and (2) are not fulfilled:

$$-\delta\hat{W}_{core} > c_h \omega_{Dfast} \tau_A \qquad (1) \qquad\qquad -(\delta\hat{W}_{core} + \delta\hat{W}_{fast}) > 0.5\omega_{*i}\tau_A \qquad (2)$$

The experimental conditions are such that the relevant crash physics always involves magnetic reconnection, and since $\rho_i > \delta_\eta > c/\omega_{pe}$, the relevant regime is the ion kinetic regime or semi-collisional regime. Equations (3(a)) represent the fast particle trigger and (3(b)) the critical shear

$$-c_\rho \rho < -(\delta\hat{W}_{core} + \delta\hat{W}_{fast}) < 0.5\omega_{*i}\tau_A \qquad (3(a)) \qquad\qquad c_* \max(\gamma_\eta, \gamma_\rho) > \sqrt{\omega_{*i}\omega_{*e}} \qquad (3(b))$$

trigger $s_1 > s_{1,crit}$, which need both to be fulfilled simultaneously to get a crash, where the second to be fulfilled actually triggers the crash. Note inclusion of frequency $\omega_{*e}$ in addition to $\omega_{*i}$ in (3(b)) to be able to describe both high $T_i$ or $T_e$ regimes, relevant to α- or ECW-heating [8,9]. The above crash criteria are implemented in the PRETOR transport code [9,10].

## 3. COMPARISON OF EXPERIMENTAL RESULTS WITH MODELLING

A detailed analysis of a few discharges specially designed for this purpose has been performed. The approach is done in two steps. The first step is to assess the relevant instability thresholds using above crash criteria. This makes use of the experimental pressure profiles, of the fast particle energy from PENCIL code, the q profile from PRETOR equilibrium reconstructions constrained by the inversion radius and assuming $q_0 \sim 0.9$. This q profile compares well with the MSE profiles and is an average profile over the sawtooth ramp.

Figure 3(d) shows that at low NBI power, below typically 1-2MW, we have the ion kinetic (reconnecting character) kink unstable with $-\delta\hat{W} > -\delta\hat{\rho}$, but the crash time is determined by the critical shear criterion (3(b)), the second to be fulfilled. At higher NBI power, we have stabilisation with $-\delta\hat{W} < -\hat{\rho}$ over most of the sawtooth period, except at the crash which is determined by this fast particle criterion (3(a)), the second to be fulfilled. The measured sawtooth period, Fig. 3(b)), effectively starts to increase or decrease essentially from the time $-\delta\hat{W}$ crosses $-\hat{\rho}$, at the switching between the two crash criteria.

In a second step, the time evolution of the terms involved in the stability threshold is calculated with PRETOR, which yields a calculation of the sawtooth period. The latter agrees with measured values within 20%.

PRETOR uses the presented analytical expression for the fast particle energy functional $\delta\hat{W}_{fast}$

fast, valid for isotropic distributions. Realistic distributions, as computed by TRANSP, are anisotropic. The effect of anisotropy on $\delta\hat{W}_{fast}$ has been computed with the NOVA-K MHD code [11], which takes as input the TRANSP distribution functions and properly describes the fast particle toroidal precession, considering the realistic geometry. The NOVA-K calculations of $\delta\hat{W}_{fast}$ have been found in very good agreement (errors within 15%) with the evaluations provided by the analytical formula used in PRETOR, whereas the same formula is found to generally under-estimate the fast particle contribution compared to numerical results obtained with isotropic distributions in NOVA-K. This validates the use of the analytical formula in PRETOR simulations of the present JET discharges. The beam ion contribution is found to be strongly stabilising, causing $\tau_{saw}$ to be much longer than it would otherwise be. When this contribution is not taken into account, the model predicts a sawtooth period, which, at full NBI power, is about two times lower than the experimentally observed period.

## 4. FURTHER EXPERIMENTAL OBSERVATIONS

The possible role of other experimental variables in determining $\tau_{saw}$, such as plasma rotation [11], requires further evaluation. The repetitive feature observed on the sawtooth period occurring at switch-on/-off, see Fig. 5, may give some clues. The $\tau_{saw}$ increases 0.2-0.3s after switch-on, then decreases. The rotation first gradually increases, as measured by magnetic coils, followed by a strong acceleration at 0.8s. One possible interpretation of the first peak in $\tau_{saw}$ is sawtooth stabilisation by the freshly injected non-thermalised fast particles which, when thermalisation occurs modifies both diamagnetic rotation and momentum transfer rotation, playing a role in the later transients. Note that at low power, rotation is a dominant ingredient of the crash trigger (equation 3(b)).

## CONCLUSIONS.

Several experimental observations point to the role of NBI fast particles in stabilising sawteeth in JET: the density behaviour of $\tau_{saw}$, the hysteresis reduction, the linear relation of $\tau_{saw}$ versus $W_{i,fast}$. In the framework of a model introduced to predict the sawtooth period in ITER [7], we have included the stabilising effect of a beam ion contribution to the m=1 internal kink energy. This has been implemented in the PRETOR transport code [9], and a detailed analysis of a dedicated JET discharges has been performed. The beam ion contribution is found to be strongly stabilising, causing $\tau_{saw}$ to be much longer than it would otherwise be. The sawtooth trigger condition occurring in JET, namely excitation of the ion kinetic (also called semi-collisional, with reconnecting character) internal kink mode, was found to be the one most likely to be relevant to ITER, with the role of beam ions in JET played by $\alpha$-particles in ITER [7]. The NBI discharges in JET thus allow us to study fast particle effects likely to play an important role in determining the performance of Next Step Devices.

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## REFERENCES

[1]. O. Sauter et al., this Conference, Oral OT.08.

[2]. D.J. Campbell et al. Phys. Rev. Lett. **60** (1988) 2148; F. Porcelli, Plasma Phys. and Contr. Fusion **33** (1991) 1601; J.P. Graves et al., PRL **84**, (2000) 1204.

[3]. J. Ongena et al., Proc. of 17th EPS Conf. on Contr. Fus. and Plasma Heating, Amsterdam, Vol. 3 (1990) 155; P.-A. Duperrex et al., Nuclear Fusion 32 (1992) 1161.

[4]. M.F. Nave, K.G. McClements et al., 25th EPS Contr Fus & PP, ECA Vol **22C** (1998) 365.

[5]. R. Buttery, T. Hender, D. Howell et al., priv. com. 2000 (Sawtooth database 1999).

[6]. P. de Vries et al., this Conf., Poster P5.001.

[7]. F. Porcelli et al., Plasma Phys. Control. Fusion **38**, (1996) 2163.

[8]. O. Sauter et al, Th. Fus Plasmas, Varenna 98, ISSP-18, Ed. Compos., Bologna(1999) 403

[9]. C. Angioni et al., Th. Fus Plasmas, Varenna 00, ISSP-19, Ed. Comp., Bologna (2000) 73.

[10]. D. Boucher, P.-H. Rebut, JET Pre-print JET-P (92) 51, p3 (1992).

[11]. N. Gorelenkov, M.F. Nave et al., 27th EPS Contr. Fus. & Plasma Phys., P4 079 (2000). 7

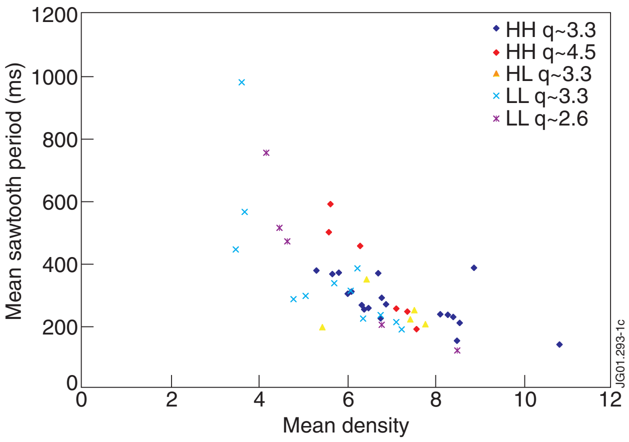


*Figure 1: Sawtooth period in NBI discharges decrease with density (different symbols indicated different plasma shapes).*

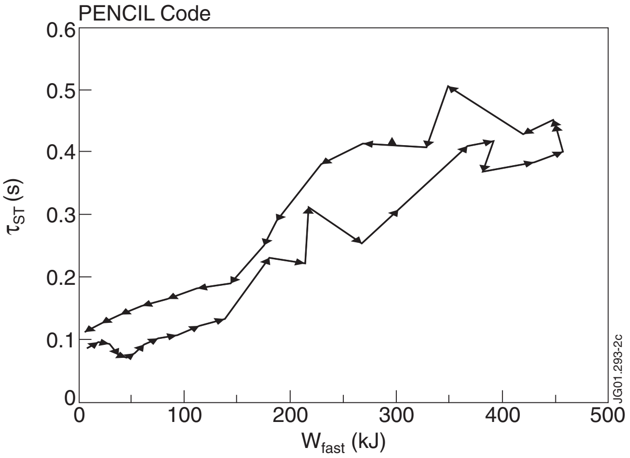


*Figure 2: The surface of the hysteresis $\tau_{saw}$ ($P_{NBI}$) is somewhat reduced when $\tau_{saw}$ ($W_{i\,fast}$) is plotted, as shown here. Note the linear behaviour of $\tau_{saw}$ ($W_{i\,fast}$).*

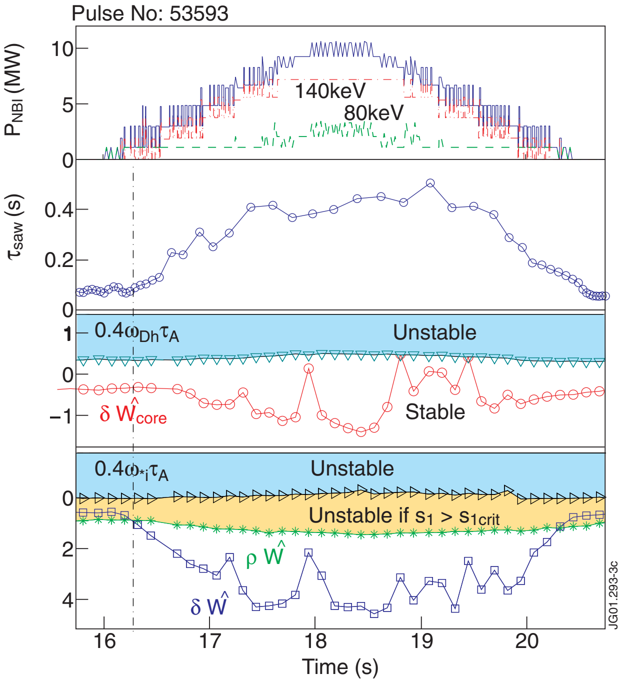
*Figure 3: Assessment of the relevant crash criteria ($\tau_{saw}$ averaged)*

*a) slow ramp trapeze-shaped NBI injection (8MW max)*

*b) obs. $\tau_{saw}$ increases once crit. (3a) no more fulfilled (Fig. 3d).*

*c) criterion (1) necessary for ideal internal kink stability,*

*d) criterion (2) necessary for ideal internal kink stability; once criterion (3a) is no more fulfilled, $\tau_{saw}$ increases, see in b).*



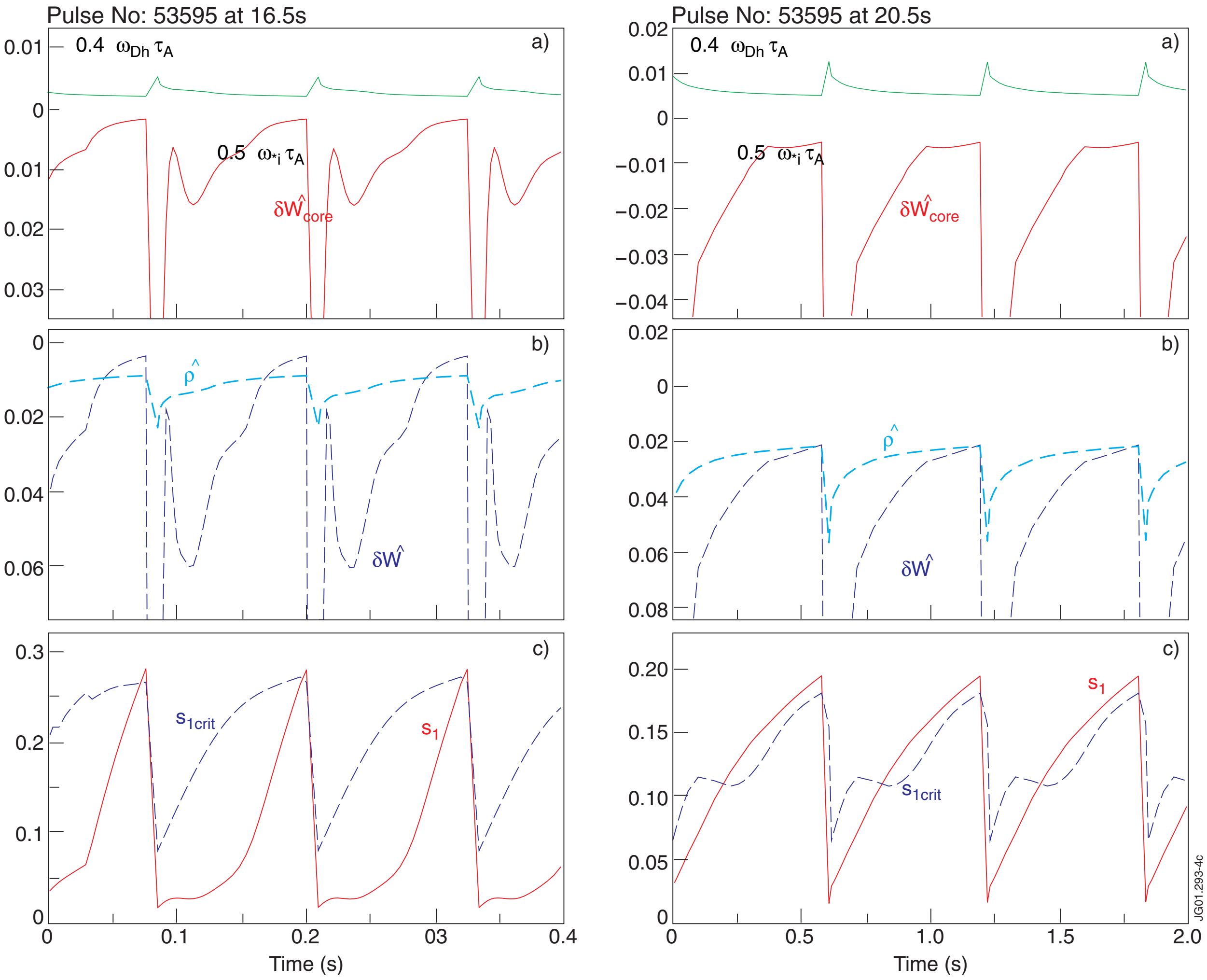


*Figure 4a,b): PRETOR evolution of crash criteria:*
*a) at low power: shear determines crash time, b) at high power: fast particles determine the crash time.*

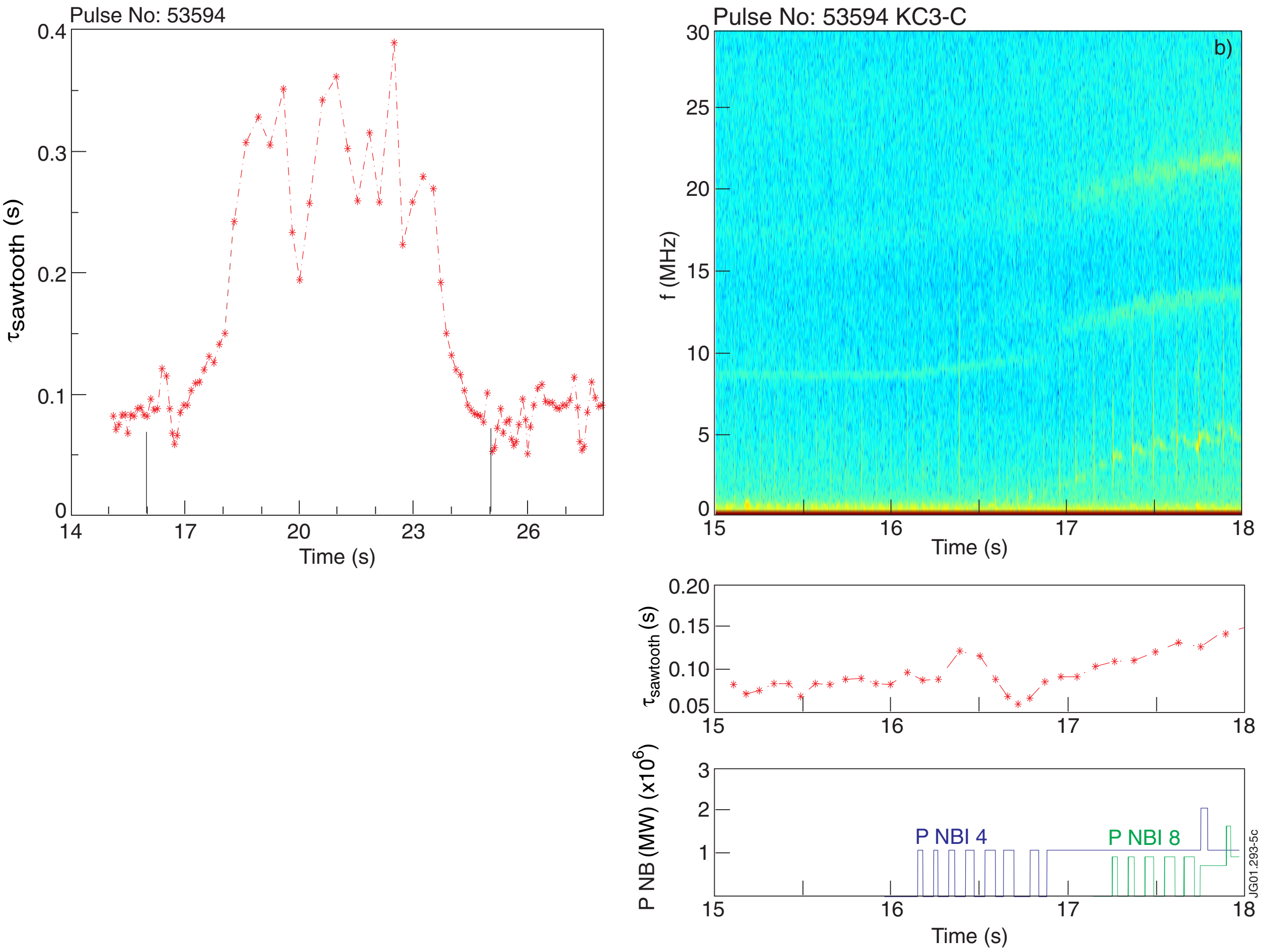


*Figure 5: a) (top left) Sawtooth period transient at NBI power switch-on/-off (indicated by vertical lines)*
*b) (bottom right) Expansion of sawtooth period transient at NBI power switch-on, details of the NBI waveform*
*c) (top right) Spectrogram of magnetic coil indicating rotation changes (same time scale as in Fig. 5b)*