Analysis of shaping effects on sawteeth in JET

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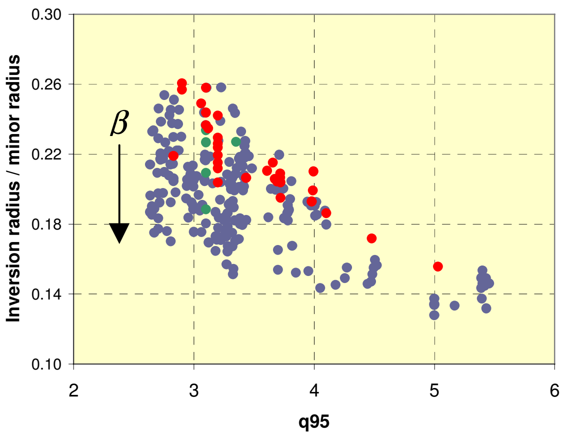
1. Introduction

Sawtooth oscillations are a common phenomenon in standard tokamak discharges. Although favourable in a reactor for Helium ash removal, large sawtooth crashes are known to provide seed islands for neo-classical tearing modes. For JET, a database has been set up to analyse a general scaling of sawtooth properties in order to predict sawtooth behaviour in ITER. The effect of plasma shaping on the sawtooth stability is analysed in more detail. Elongation and triangularity are predicted to affect the internal kink stability [1,2] and recent results showed that plasma shaping altered the sawtooth behaviour in the TCV tokamak [2,3]. Dedicated experiments have been carried out in JET to study these effects.

2. Sawtooth scaling in JET

The database contains over 300 discharges, mainly in ELMy H-mode, with Ohmic, Neutral Beam Injection (NBI) (largest subset) and ICRH auxiliary heating. The sawteeth are characterised by the period, amplitude and inversion radius. The amplitude is determined from the percentage drop in the central line-integrated soft X-ray emission. This is corrected for the dependencies of the line-integrated soft X-ray signal on density, temperature and profile factors to obtain a percentage pressure drop. Only discharges with a sufficient long quasi-stationary phase are included ($\Delta t >> \tau_{st}$, $\Delta t >> \tau_E$). The sawtooth and plasma parameters are averaged over this phase.

A regression analysis has been performed to determine the scaling of the inversion radius, sawtooth period and amplitude with global plasma parameters as central density (n_{eo}), temperature (T_{eo}), Z_{eff}, current profile peaking (l_i) , β_p, β_t, and the edge safety factor (q_{95}).



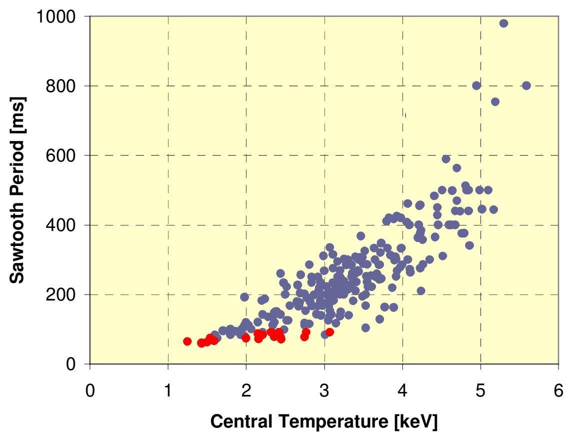


Fig. 1a: The inversion radius (r_{inv}/a) scales inverse with the edge safety factor. The scatter in the points is mainly caused by differences in poloidal β (β_p). A higher β_p results in a smaller inversion radius. Ohmic and NBI discharges are represented by the red and blue dots, respectively

Fig. 1b: The sawtooth period in JET scales strongly with the central electron temperature

The inversion radius at JET scales as:

$$\rho_{inv} = \frac{r_{inv}}{a} = 0.4 \times q_{95}^{-0.61\pm0.04} \beta_p^{-0.14\pm0.01} \delta^{0.07\pm0.02} \qquad (1)$$

The inverse scaling with the edge safety factor is clear. At higher β_p a broadening of the current profiles yields a higher q_o, and a smaller inversion radius (see Fig. 1a). From Fig. 1b it can be seen that the sawtooth period scales strongly with the central plasma temperature. Regression analysis showed that the sawtooth period in NBI heated JET discharges scales as:

$$\tau_{st}^{NBI} \propto T_{eo}^{1.7\pm0.07} n_{eo}^{0.23\pm0.03} \qquad (2)$$

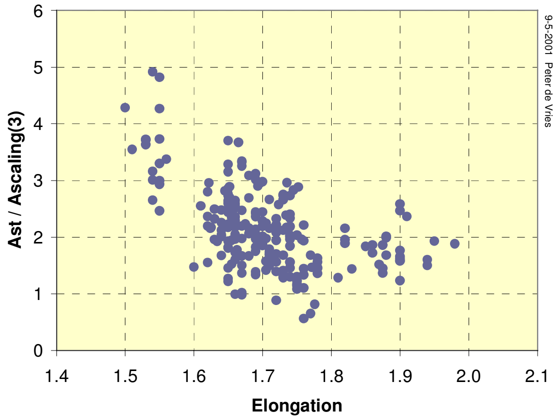
The correlation coefficient between scaling law and data points was as high as *R=0.9*. Other minor effects on the period might be hidden behind the strong temperature scaling and are undetected by the regression analysis.

3. Effect of plasma shaping on sawtooth stability

The sawtooth amplitude, defined as the percentage pressure drop, showed a more complex scaling. Without including the shaping parameters it was found to scale as:

$$A_{st}^{NBI} \propto n_{eo}^{-0.62\pm0.08} q_{95}^{-1.22\pm0.08} p_p^{0.32\pm0.1} \qquad (3)$$

where p_p is the pressure profile peaking factor (Thomson Scattering data). By normalising the amplitude by the above expression the influence of elongation on the sawtooth amplitude is clearly shown (see Fig.2a). The amplitude is strongly reduced at higher elongation.



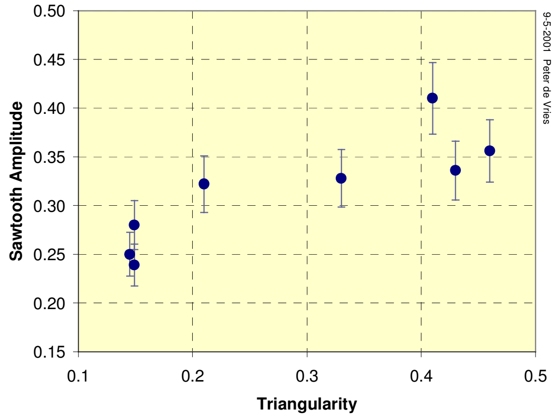


Fig. 2a: The sawtooth amplitude, normalised by the scaling law given in eq. 3, as a function of the elongation.
Fig. 2b: Scaling of the sawtooth amplitude versus the triangularity (obtained from a triangularity scan).

The correlation coefficient of the above scaling (3) was *R=0.71*. This significantly improves if shaping parameters are included in the regression analysis. One finds:

$$A_{st}^{NBI} \propto n_{eo}^{-0.53\pm0.07} q_{95}^{-0.98\pm0.08} p_p^{0.23\pm0.08} \delta^{0.15\pm0.07} (\kappa - 1)^{-1.8\pm0.2} \quad (4)$$

for which the correlation coefficient was *R=0.79*. It shows an inverse scaling with the elongation (κ), as expected from Fig. 2a. Furthermore, a small positive scaling with triangularity (δ) is found.

A shaping scan has been carried out at JET, scanning the triangularity, but keeping other plasma parameters, like the elongation, density and the edge safety factor, constant. As can be seen from Fig. 2b, an increase in sawtooth amplitude with triangularity is observed. In Fig. 3, two similar discharges, with a low ($\delta=0.15$) and a very high triangularity ($\delta=0.42$) are compared. Although the latter had a slighlty larger elongation, the sawtooth amplitude and period are increased.

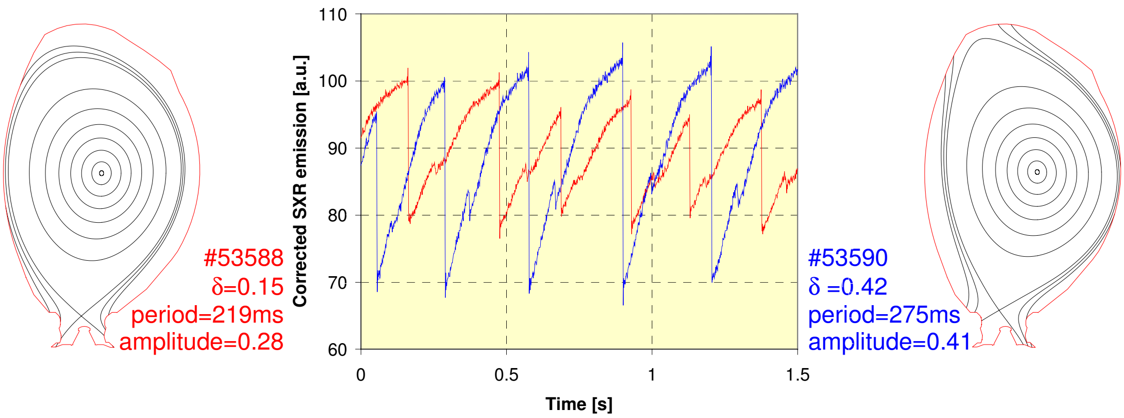


Fig. 3: two discharges with a low (#53588, red) and very high triangularity (#53590, blue). The high triangularity discharge exhibits sawteeth with a larger amplitude and period (P_{NBI}=2 MW, n_e = 5.5 10^{19} m^{-2}).

4. **Conclusions**

Sawtooth stability depends on local plasma parameters, for example the shear at $q=1$, or the pressure of fast particles inside the $q=1$ surface. However, these data are not always experimentally available with sufficient accuracy. Scaling sawtooth properties with basic plasma parameters may yield a larger data scatter. Nevertheless, it was possible to identify those parameters important for sawtooth stability.

Regression analysis shows that the sawtooth period for ohmically and NBI heated discharges is predominantly determined by the central temperature. The sawtooth period of NBI discharges shows a strong inverse density scaling, which might be an indication of fast particle stabilisation [4,5]. The scaling laws show that small amplitude sawteeth with a very long period occur in discharges with a high plasma pressure (i.e high T and n). Furthermore, the amplitude reduces with increasing edge safety factor and smaller pressure profile peaking, as expected.

Shaping was found to have a profound effect on the sawteeth. A larger elongation results in a smaller amplitude, i.e. elongation has a destabilising effect. While triangularity stabilises slightly, yielding larger sawteeth. This is similar to previous experiments performed in TCV [2,3]. Theory predicts elongation to destabilise sawteeth and a stabilising effect by triangularity [1,2,4]. Shaping affects the internal kink stability (the ideal MHD term of the sawtooth stability). These JET results show shaping effects in a regime with a strong fast-particle stabilisation term [5].

Plasmas with a high elongation exhibit smaller sawteeth. These discharges might benefit from a higher β threshold for the NTM onset, because of the smaller seed-islands created by the sawteeth [6].

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* This work has been conducted under the European Fusion Development Agreement