Sawtooth Stability in JET Deuterium-Tritium discharges

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1. INTRODUCTION

A recent series of JET experiments using deuterium and tritium [1], has made it possible to study sawtooth stability in plasmas approaching thermonuclear conditions. It was found that large sawtooth crashes in ELM-free H-mode plasmas may seriously limit the achievable fusion power. Record fusion yields were obtained in discharges where the sawtooth was delayed. In addition, in a sequence of discharges designed to study α-heating [2], an interesting new phenomenon was observed: the sawtooth period increases with tritium concentration. We have studied internal kink stability for both high performance and α-heating experiment plasmas, and considered possible reasons for a dependence of the sawtooth period on the mean ion mass.

2. SAWTOOTH OBSERVATIONS IN HIGH PERFORMANCE DISCHARGES

Record values of fusion power, P_{fus}, were obtained in hot-ion H-mode discharges, with plasma tritium concentration $\eta_T=n_T/(n_D+n_T)\approx 50\%$, heated by a combination of neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH) with input powers of the order of 25MW. Experimentally, sawtooth stability in these discharges was increased by careful adjustments of the gas fuelling rate (as shown in figure 1) and by ICRH heating. Comparison of similar discharges with and without ICRH, confirmed the well-known result that ion cyclotron resonance heating is stabilising. Calculations (discussed below) show that α-particles make a significant stabilising contribution to the potential energy δW of the m=1 internal kink.

Magnetic, SXR and ECE fluctuation data show that the sawtooth crash is preceded by long lived m=1, n=1 modes with a kink-like structure. The sawtooth triggers n=3 and n=4 modes outside the q=1 surface. Saturation of both the plasma stored energy and the neutron rate coincide with the duration of such post-cursor oscillations. In the high performance DT discharges, large sawteeth lead to a double core temperature crash. The first crash is due to the sudden growth of the precursor m=1, n=1 kink mode, while the second appears to be associated with the onset of an m=1,n=1 island.

Figure 1 shows that a large sawtooth crash during the high performance phase may irreversibly limit the plasma stored energy and the neutron yield. An increase in the initial gas fuelling rate led to an increase in the time between sawtooth crashes from 0.6s to >1.1s. P_{fus}, which saturated at 10MW in the discharge with

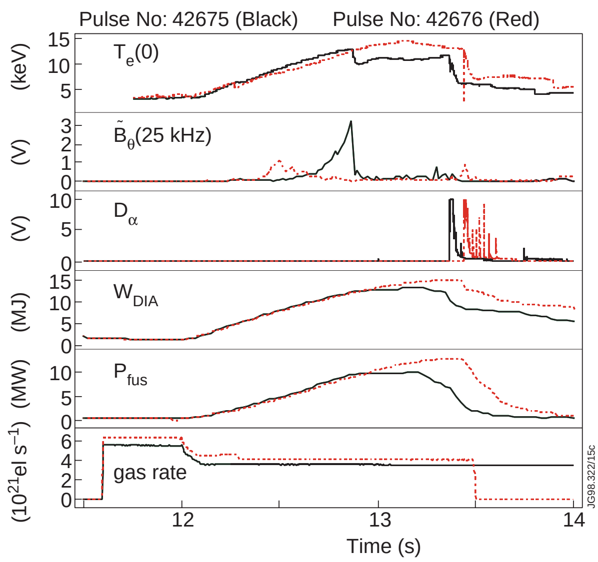

Figure 1: Temporal evolution of similar discharges, except for the gas fuelling rate (P_{NBI}=20 MW, P_{ICRH}=3MW, B_T=3.4T, I_P=3.8MA)

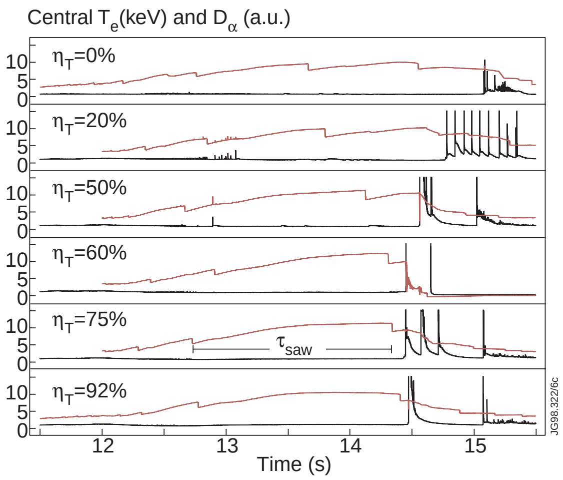

Figure 2: Sawtooth and ELM behaviour in discharges with D and T injected into a DT plasma.

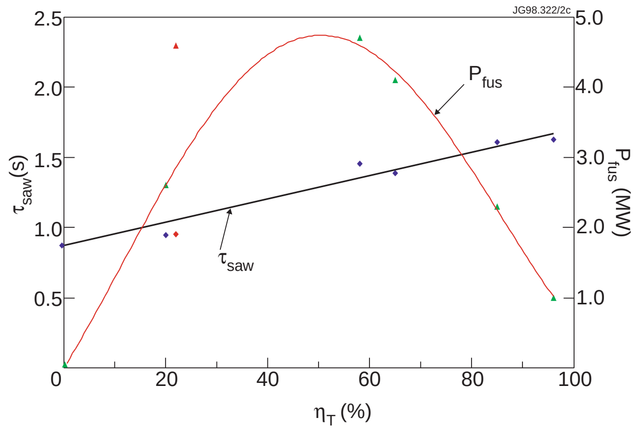

Figure 3: Sawtooth period and fusion power versus core Tritium concentration computed by TRANSP [3]. at r(q=1) The open symbols correspond to a discharge where 100%T was injected onto a D plasma.

τ_{saw}=0.6s, increased to 13MW in the discharge with improved core stability. Sawtooth stabilisation by gas puffing poses a challenging problem for theory: the analysis is still in progress.

3. OBSERVATIONS IN ALPHA-HEATING DISCHARGES

In a sequence of beam-heated discharges, intended to study α-particle heating, τ_{saw} increases with tritium concentration (figures 2 and 3). The experiment consisted of discharges with 10.5MW of D and T injected into a target plasma with the same DT mixture. The fusion power has a non-monotonic dependence on η_T, the maximum P_{fus} occurring when η_T~50% (see fig. 3). It has also been found that τ_{saw} strongly correlates with the perpendicular energy density of the fast ions,$u_\perp$, which is mostly due to beam ions.

4. INTERNAL KINK STABILITY

The strong correlation observed between the sawtooth period and tritium concentration can be understood qualitatively in terms of sawtooth stability criteria based on kinetic and diamagnetic modifications of the MHD energy principle. The onset of the m=1 internal kink mode, responsible for the sawtooth crash, involves a normalised potential energy functional, $\delta W = (\delta W_{MHD} + \delta W_{ki})_{core} + (\delta W_{k(NBI)} + \delta W_{k(ICRH)} + \delta W_{k\alpha})_{fast}$, where $\delta W < \delta W_{crit}$ may trigger a sawtooth crash. Mass effects, which could contribute to the observed dependence of τ_{saw} on η_T, are found: a) directly in the sawtooth crash threshold conditions through quantities such as: the Alfvén time $\tau_A \propto \overline{m}_i^{1/2}$ and the Larmor radius $\hat{\rho} \propto \overline{m}_i^{1/2}$, where $\overline{m}_i = \dfrac{m_T n_T + m_D n_D}{n_D + n_T}$ is the average ion mass; and b) indirectly in $\delta W_{k(NBI)}$ through the slowing down time $\tau_{s(NBI)} \propto \overline{m}_b$, where $\overline{m}_b$ is the beam ion mass. In the sequence of α-heating discharges $\overline{m}_b = \overline{m}_i$. Porcelli et al [4] suggest that sawtooth crashes occur when any of the following conditions are satisfied:

$$\delta W_{core} < -c_h s_1 \omega_{df} \tau_A \quad (1)$$

$$\delta W < -\frac{1}{2} s_1 \omega_{*i} \tau_A \quad (2)$$

$$s_1 c_\rho \hat{\rho} > \delta W > -\frac{1}{2} s_1 \omega_{*i} \tau_A \text{ and } s_1 > s_{1crit} \quad (3)$$

where quantities are evaluated at q=1 and all notation is defined in Ref.[4].

Condition (2) is found to be the most relevant for JET hot-ion H-mode data, which implies $\delta W_{crit} \propto -\overline{m}_i^{1/2}$. The only energetic ions in these discharges are α-particles and beam ions. For each species of fast ions the internal kink potential energy is given by: $\delta W_{kfast} = c_f \in_1^{3/2} \beta_{pfast}$, with $\beta_{pfast} = -\frac{2\mu_0}{B_p^2(r_1)} \int_0^1 dx \cdot x^{3/2} dp/dx$, where the fast ion pressure $p \approx u_\perp$. The potential energies δW_{crit}, $\delta W_{k\alpha}$ and $\delta W_{k(NBI)}$, shown in fig. 5, were calculated to zeroth order in 1-q and shear s using the following input parameters: r(q=1)=0.37m, s_1=0.4, $T_i(0)$=14keV, $T_e(0)$=10keV, $n_i(0)=3\times10^{19}m^{-3}$, exponential α-particle and beam ion pressure profiles with e-folding widths 0.4m and 0.46m respectively, beam ion energy E_{inj}=140keV. Both δW_{crit}, and $\delta W_{k(NBI)}$ have a positive correlation with τ_{saw}, with $\delta W_{k(NBI)}$ being the dominant term.

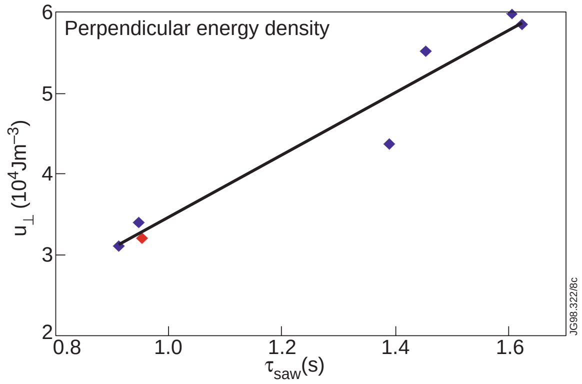

Figure 4: Central $u_\perp$ calculated with TRANSP at t=13.5s versus τ_{saw}. (The open symbol corresponds to a discharge where 100%T was injected into a D plasma.)

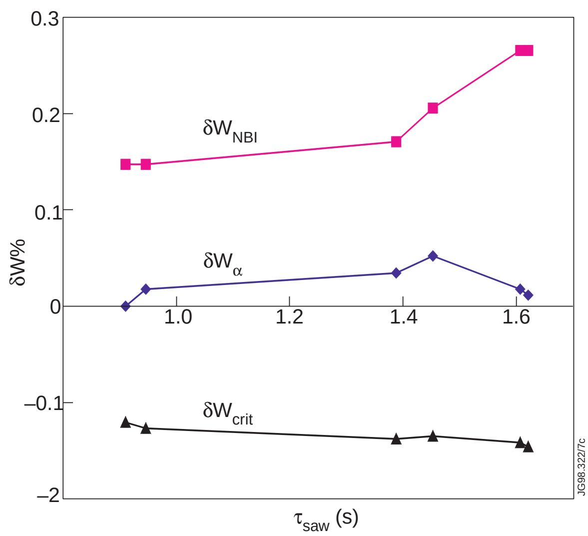

Figure 5: Calculated δW_{crit}, $\delta W_{k\alpha}$ and $\delta W_{k(NBI)}$ versus the sawtooth period

5. INTERNAL KINK STABILITY FOR HIGH PERFORMANCE DISCHARGES

Internal kink stability was studied for record fusion discharge 42976 at the time of maximum P_{fus}=16MW. Calculations were performed with the codes PEST and NOVA-K [5] using TRANSP [3] data. There are 3 types of fast ions: beam (η_T=50%), ICRH (η_H=1%) and α-particles, all with similar values. The following growth rates γ/ω_A ($\propto \delta W$) were obtained:

	$\beta(0)$%	γ/ω_A %
MHD	5.81	-1.49
ICRH	0.65	+0.89
NBI (D)	0.25	-0.00
NBI (T)	0.44	+0.08
α-particles	0.6	+0.51

It is found that the internal kink in this discharge is marginally unstable. The α-particle stabilising contribution to δW_{fast} is of the same order as that arising from the ICRH minority H ions.

6. CONCLUSIONS:

Calculations show that in the high performance discharges, α-particles make a significant stabilising contribution to the potential energy δW of the m=1 internal kink perturbations.

In the α-heating series of discharges we found a strongly positive correlation between the kinetic energetic ion component of the m=1 internal kink energy and the sawtooth period. This is mostly due to beam ions rather than α-particles. The sawtooth period increases with tritium concentration through an increase in the slowing down time of the beam ions.

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