Sawtooth Activity during Impurity Accumulation in ASDEX

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Introduction

Previous investigations in ASDEX have revealed that sawteeth instabilities not only result in a flattening of density and temperature in the plasma center but lead also to a reduction of impurity concentration in this region /1/. This counteracting mechanism is most important in regimes with peaked density profiles (e.g. pellet injection, IOC, Counter-NBI), because here the dominating neoclasssical effects induce a strong inward drift of impurities. In ASDEX-discharges with peaked density profiles we generally observe an increase of the sawtooth repetition time ending with complete suppression of sawteeth. The subsequent accumulation of impurities then leads to a central radiation collapse.

Invoking the Kadomtsev model of the sawtooth relaxation /2/ this behaviour may be explained by the influence of impurities on the evolution of the conductivity profile during the sawtooth rise. If a rapid influx of impurities keeps the conductivity profile flat after the sawtooth crash, the current profile will not be able to peak again to bring q below the critical threshold $q_{crit} < 1$ for sawtooth initiation. In this picture the sawtooth repetition time should be related to the resistive time scale $\tau_j = \mu_0 r_1^2 \sigma / 15$, where σ and $r_1 \simeq a/3$ denote the conductivity and radius of the sawtoothing region respectively.

In a similar way, it has recently been demonstrated that peaking of the Z_{eff}-profile can explain the suppression of sawteeth during pellet refuelled discharges in ALCATOR C /3/.

In this paper we present a detailed study on the behaviour of sawteeth during Counter-NBI discharges with additional ICRH, which showed density peaking and a remarkable content of light impurities after the onset of ICRH. By investigating the temporal change of $Z_{eff,0}$ and $T_{e,0}$ it is possible to get information about the influence of the central concentration of impurities on the quenching of sawteeth activity.

1. Sawteeth activity in discharges with Counter-NBI and ICRH

In ASDEX density peaking was observed for Counter-NBI discharges (P_{NBI} = 1.05MW) with additional ICRH at plasma currents of 380kA /4/ (q_a = 3.0, no peaking found for slightly higher currents). Although the discharges were different in ICRH-power (P_{ICRH} = 0.65 − 1.95MW), peaking factor, impuritiy concentration (Z_{eff} = 3.5 − 4.0), total radiated power P_{rad} and SX-radiation, they all showed great temporal coherence in the evolution of the sawtooth oscillations. This is depicted in Fig. 1, where SX-traces of discharges with different ICRH-powers are reproduced. Before t = 1.25s there is only very little phase difference between the sawteeth of different discharges. After this time the discharges evolve differently, ultimately showing sawtooth quenching succeded by a disruption within less than 0.2s.

The discharges with $P_{ICRH} \leq 1.0$MW behave almost like discharges without ICRH. The sawtooth repetition time τ_R increases from about 8ms to roughly 15ms before the sawteeth are suppressed completely. At higher ICRH-powers strong modification of the sawtooth are to be seen. Actually a rapid rise phase at the beginning can be distinguished from a slow slope phase extending until sawtooth crash.

2. The influence of impurities on sawteeth suppression

The following discussion is based on the assumption that after the sawtooth crash flat q- and T_e-profiles are established within a core region $r < r_1 \simeq a/3$. The related profiles of current density j and conductivity σ are also essentially flat at this time, but central heating tends to restore a peaked T_e-profile on a short time scale $\tau_{T_e} \sim r_1^2/5\chi$ with a thermal conductivity of orders of $1\text{m}^2/\text{s}$. The j-profile develops towards the peaked conductivity profile $\sigma \sim T_e^{1.5}/Z_{eff}$ but is largely delayed because of the very long diffusive time scale $\tau_j \sim r_1^2 \mu_0 \sigma/15$ $((\mu_0\sigma)^{-1} \simeq 0.015\text{m}^2/\text{s})$. After the repetition time τ_R a sufficient large increase of Δj_0 on axis (i.e. a decrease of Δq_0) is reached by which the next sawtooth is triggered. Impurities can change the outlined procedure by changing the conductivity via radiation losses ($\dot{T}_e < 0$) as well as by central accumulation ($\dot{Z}_{eff} > 0$). The total change of the conductivity on axis,

$$\langle \frac{\dot{\sigma}_0}{\sigma_0} \rangle = \frac{3}{2} \langle \frac{\dot{T}_{e,0}}{T_{e,0}} \rangle - \langle \frac{\dot{Z}_{eff,0}}{Z_{eff,0}} \rangle$$

averaged over a sawtooth period is therefore an important quantity. As soon as $\langle \dot{\sigma}_0/\sigma_0 \rangle$ is approaching negative values sawtooth quenching is expected because no peaked j-profile will be restored under this conditions.

In fig. 2 the central values of the two contributions $3/2\langle \dot{T}_e/T_e \rangle$ and $\langle \dot{Z}_{eff}/Z_{eff} \rangle$ are compared for the discharge with $P_{ICRH} = 0.65$MW and the upper of the two discharges in fig. 1 with 1.70MW. The temperature change was taken from the ECE-diagnostic. Z_{eff} was derived from data of the visible Bremsstrahlung diagnostic /5/. To provide sufficient time resolution the density from the HCN interferometer was taken to correct $Z_{eff} \sim P_{Brems}\sqrt{T_e}/n_e^2$ which normally is evaluated with Thomson scattering data (sampled every 15ms).

We notice that in both cases a crossing occurs at times $t^* = 1.2$s and $t^* = 1.4$s after which $\langle \dot{\sigma}_0/\sigma_0 \rangle < 0$. This behaviour reflects qualitatively the observation presented in fig. 1. In reality, however, the true quenching time is delayed about 60ms and 200ms respectively. As to be seen in fig. 2 the transition to $\langle \dot{\sigma}_0/\sigma_0 \rangle < 0$ is caused by both, a decrease of the central T_e-variation and an increase of the Z_{eff}-variation. In contrast to the large decrease of the central T_e-variation the corresponding variation at larger radii stays about constant. This observation may be explained by assuming a non-central triggering event during the late sawtooth phase $t > t^*$.

3. The dependence of the repetition time τ_R on σ

From our picture a scaling of the sawtooth repetition time τ_R with τ_j is to be expected. To check such a dependence we plot in fig. 4 τ_R as a function of the conductivity σ_0 on axis for the lower of the two discharges in fig. 1 $P_{ICRH} = 1.7$MW. 1. The approximate scaling of τ_R with σ for most of the sawteeth is obvious. Deviating points are those of the last two sawteeth before suppression. This finding is contrary to the results reported in /6/ where a scaling of τ_R with the timescale of heat transport $\tau_{T_e} = r_1^2/5\chi$ is predicted.

4. Analysis of the current profile during sawteeth

To get more insight into the sawtooth mechanism we have started to analyze the sawtooth behaviour using measured n_e-, T_e-, P_{rad}-profiles, the sawtooth event times and a current profile mixing as in the Kadomtsev model using the TRANSP-code. Fig. 4 shows the resulting time behaviour of $q(0)$ with and without full current mixing for a Counter-NBI discharge with $q(a) = 2.5$. The measured sawtooth inversion radius can only be recovered with a weaker current mixing than predicted by the Kadomtsev model. This is in line with the results of section 2 suggesting a non-central mechanism for the sawtooth trigger. During the last large sawteeth in the beam-heated phase the influence of the j-mixing model on $r_{q=1}$ is reduced. T_e- and n_e-data show in all cases a much broader region of inverted sawteeth than can be generated by the Kadomtsev formulation. After the last sawtooth the decreasing T_e and increasing Z_{eff} (due to impurity accumulation) result in an increasing $q(0)$ i.e. decreasing $j(0)$ and the critical q-profile for the triggering of a sawtooth may not be reached again.

Summary

We find strong indications that quenching of sawteeth, which is preferentially observed in discharges showing peaked density profiles, can be explained by impurity accumulation. The reason is due to enhanced central radiation on account of metallic impurities (Fe, Cu) that lower $\dot{T}_e$ and in addition to the influence of low-Z impurities (C, O) increasing $\dot{Z}_{eff}$ after each sawtooth crash. Both effects finally prevent a peaking of the conductivity profile. A further support for this interpretation and the underlying physical picture is obtained from the sawtooth repetition time which scales approximately proportional to the central conductivity.

References

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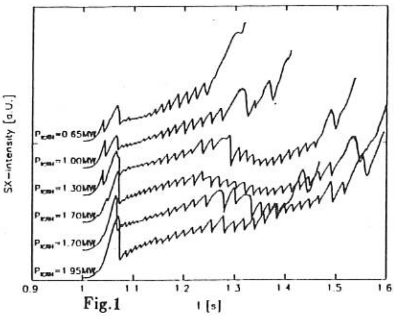

Fig.1

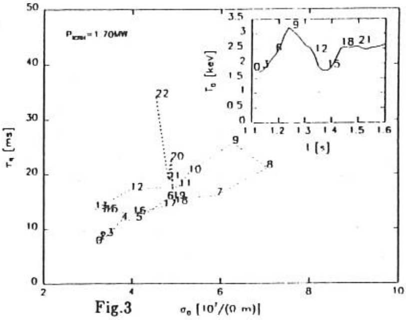

Fig.3

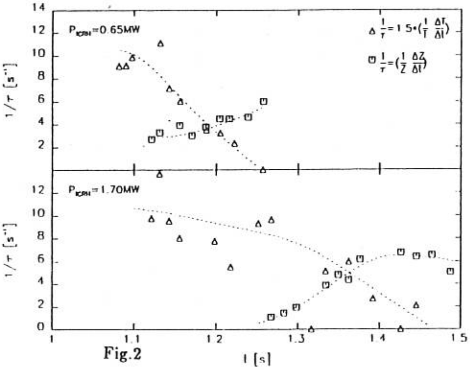

Fig.2

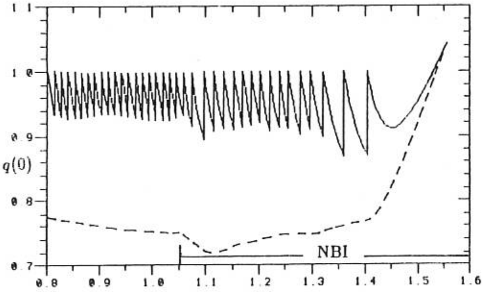

Fig.4

Fig.1: SX-Intensity showing the coherent sawtooth behaviour for discharges with CTR-NBI (1.05MW) and ICRH. NBI from 1.05s, ICRH from 1.10s until disruption. The traces are shifted equally against each other.

Fig.2: Contribution of the variation of $T_{e,0}$ (triangles) and $Z_{eff,0}$ (squares) to the variation of conductivity σ_0 on axis during sawtooth rise (see text).

Fig.3: Scaling of the sawtooth repetition time τ_R with conductivity σ_0. The numbers on the $T_{e,0}$-trace indicate the position of the sawtooth events (see text).

Fig.4: Time evolution of $q(0)$ with (solid line) and without (dashed line) full current mixing for a Counter-NBI discharge calculated using the TRANSP-code.