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Sawtooth Tailoring Experiments with ECRH in ASDEX Upgrade

A.Mück[1], T.P.Goodman[2], H.R.Koslowski[3], F.Ryter[1], E.Westerhof[4], H.Zohm[1], ASDEX Upgrade Team[1]

[1] *Max-Planck-Institut für Plasmaphysik, EURATOM Assoziation, D-85748 Garching*
[2] *CRPP EPFL, Association Euratom, CH-1015 Lausanne*
[3] *Forschungszentrum Jülich, Institut für Plasmaphysik, D-52425 Jülich*
[4] *FOM-Rijnhuizen, EURATOM-FOM, TEC, PO Box 1207, 3430 BE Nieuwegein, NL*

1. Introduction:

A tokamak plasma is unstable against the sawtooth instability when the safety factor q drops below unity. In a sawtooth, a slow rise in plasma temperature is followed by a rapid crash, triggered by a (1,1) kink mode. In the crash phase, the hot plasma center is thrown out into colder outer plasma regions. This process can be used to remove helium ash or impurities from the plasma center.

The control of the sawtooth instability is of great relevance for future reactor-grade devices such as ITER. It is expected that the α-particles created in D-T fusion processes lead to sawtooth stabilization. Long sawtooth free periods might lead to so-called monster sawteeth which could trigger a Neoclassical Tearing Mode (NTM) [1].

The goal of this work is to investigate how to control the sawtooth instability.

2. Experiments:

In ASDEX Upgrade, to influence sawteeth in neutral beam injection (NBI) heated plasmas, local electron cyclotron current drive (ECCD) or electron cyclotron resonance heating (ECRH) is used. The sawtooth period and amplitude can be changed by relatively small amounts of ECRH/ECCD. The ECRH deposition was swept by magnetic field ramps. All following discharges except the one in figure 1 are H-mode plasmas with 0.8 MA plasma current, 5 MW NBI power, densities about $6 \cdot 10^{19}$ m^{-3}, and about 0.9 MW of ECRH power, provided by two gyrotrons. The cold resonance for 2nd harmonic X-mode lies at $B = 2.5$ T in the plasma center. By magnetic field variations from about -2.05 T to -2.65 T, the ECRH deposition was moved from $\rho_{pol} \approx 0.6$ on the high field side out to $\rho_{pol} \approx 0.3$ on the low field side.

The influence of different NBI sources on the sawtooth behaviour seems to be dependent on the NBI beam trace geometry. In the discharge in figure 1, the different beam sources were used separately for about 1 s each. There was a plasma current of 0.8 MA, 2.5 MW NBI power, densities about $3 \cdot 10^{19}$ m^{-3} and a -2.0 T magnetic field. The beams NBI 6 and 7 are the most tangential beams with more deposition outside of the plasma center than the other beams. There the highest stabilization was seen (no Soft X-Ray (SXR) signal available). NBI 2 and 3 deposit closer and more perpendicular to the center and seem to show less stabilization. The beams 5,8 and 1,4 are the least tangential ones and have even more central deposition. There the sawteeth seem to be least stabilized. In future, this will be further investigated.

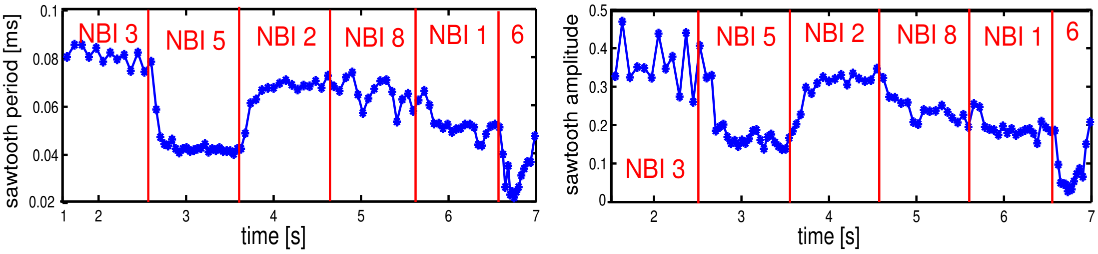

Figure 1: Influence of different NBI sources on sawtooth behaviour

To obtain an ECRH deposition profile in the *heating case* comparable to the following co-/ctr-ECCD experiments, one gyrotron was driving co-ECCD, the second one ctr-ECCD with a toroidal angle of ± 15 degrees. The net current is expected to add up to zero. In all figures, the jump at $\rho_{pol} \approx -0.25$ is due to different NBI sources. In the sawtooth period graphs, negative values for ρ_{pol} are chosen to distinguish between high field side (HFS) and low field side (LFS), $\rho_{pol} > 0$. By using the ray tracing code TORBEAM, the ρ_{pol} values for the varied B field were simulated. The amplitude is still drawn over B field. The small dots in all figures are reference points without ECRH.

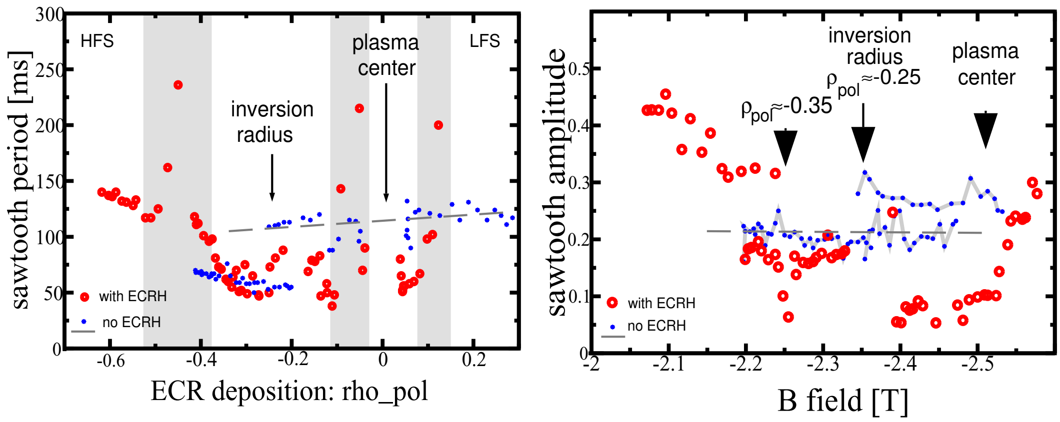

Figure 2: Sawtooth period variation by magnetic field scan with ECRH

In Porcelli's model [2], the kink mode is destabilized if its growth rate $\gamma > c_r \omega_{*i}$ with c_r a constant of order unity and ω_{*i} the diamagnetic frequency. This equation can be rewritten as a triggering condition for sawteeth: $s_1 > s_{1,crit}$. s_1 is the shear at the $q = 1$ surface and $s_{1,crit}$ the critical shear, calculated from different plasma parameters.

Generally by using ECRH in addition to the NBI heating, higher values of power density are created which lead to larger pressure gradients. Larger pressure gradients cause an increase in the critical shear [2]. This increase in the critical shear leads to stabilization of sawteeth (increase in sawtooth period) with NBI. In NBI heated plasmas, as well, fast particle effects have to be taken into account. In figure 2 at $\rho_{pol} \approx -0.45$, a strong increase in the sawtooth period is observed in the shaded area. Slightly inside this peak at $\rho_{pol} \approx -0.35$ a very narrow minimum in sawtooth amplitude appears. In the center, there is a broad minimum in sawtooth amplitude. Close to $\rho_{pol} \approx \pm 0.1$, a second, very narrow peak in sawtooth period is observed. To make sure that this peak is not a side effect of the overlay of co- and counter-ECCD, a narrow region was scanned with pure heating. The raw (SXR) data is shown in figure 3.

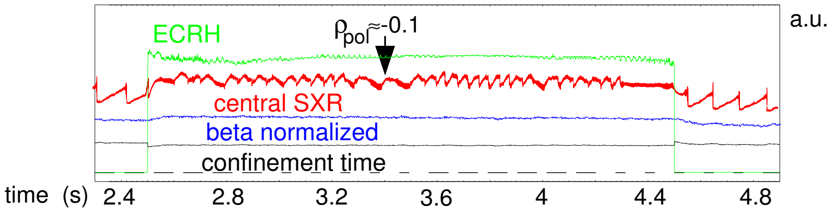

Figure 3: SXR time trace of B field scan with pure ECRH around $\rho_{pol} \approx -0.1$, NBI beams 3,7

Even in the pure heating case, a change in the sawtooth behaviour is observed at $\rho_{pol} \approx -0.1$. Possibly the ECRH was deposited in a magnetic island, but further investigation is needed.

In the *co-ECCD case*, two gyrotrons were used with a toroidal angle of -15 degrees. Close to $\rho_{pol} \approx -0.4$ in the shaded area in figure 4, an even bigger maximum in sawtooth period than for heating is observed. Complete stabilization was achieved at fixed magnetic field with ECRH deposition at $\rho_{pol} = -0.42$ and a total driven current of $I_{ECCD} = 23.9$ kA. A strong (1,1) mode was observed. Probably, the (1,1) mode was strongly destabilized that sawtooth activity was prevented by the mode itself.

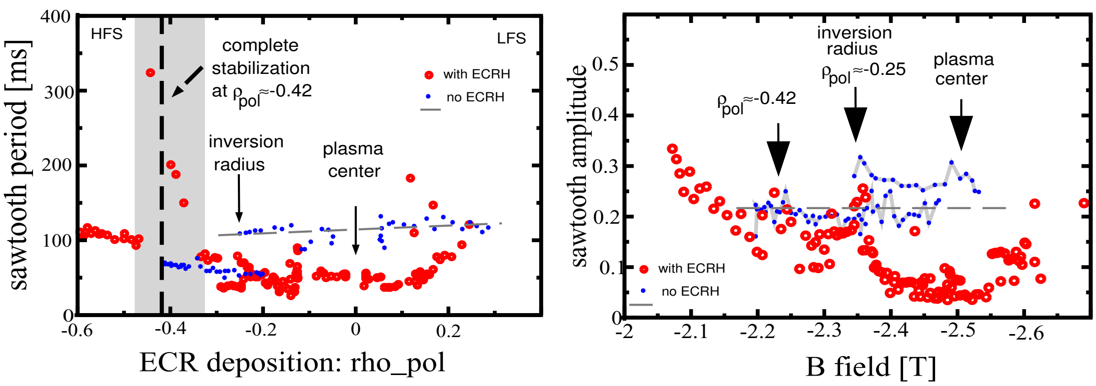

Figure 4: Sawtooth period variation by magnetic field scan with co-ECCD

Inside the sawtooth inversion radius, the sawteeth were destabilized. In this area, the amplitude is much less than in the reference case without ECRH. In a scan around $\rho_{pol} \approx -0.1$ like in the heating case, no change in the sawtooth period was observed. The amplitude remained low.

For *counter-ECCD*, two gyrotrons were used with a toridal angle of +15 degrees.

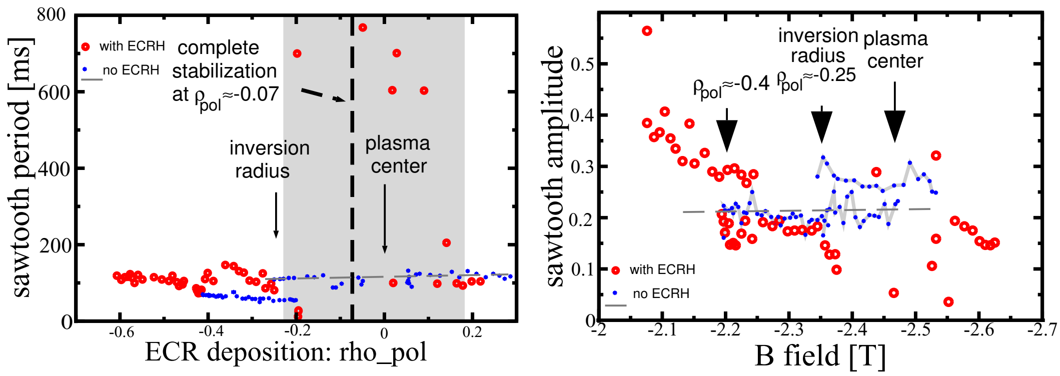

Figure 5: Sawtooth period variation by magnetic field scan with ctr-ECCD

At $\rho_{pol} \approx -0.4$ in figure 5, the maximum observed in the heating case completely vanished. For counter-ECCD with deposition slightly outside the $q = 1$ surface, the current gradient and with it q' likely increases. This has a destabilizing effect on the sawteeth. For deposition inside the sawtooth inversion radius, a broad maximum in sawtooth periode and minimum in amplitude was found in the shaded area. For deposition slightly inside the $q = 1$ surface, the current gradient and with it q' might decrease. This has a stabilizing effect on the sawteeth. With constant magnetic field, complete stabilization was achieved at $\rho_{pol} \approx -0.01$ and with a total driven current of $I_{ECCD} = -22.4$ kA and a strong (1,1) mode. To investigate the behaviour of the sawtooth period, amplitude and how much power is needed for stabilization, in figure 6 an ECRH power ramp was performed.

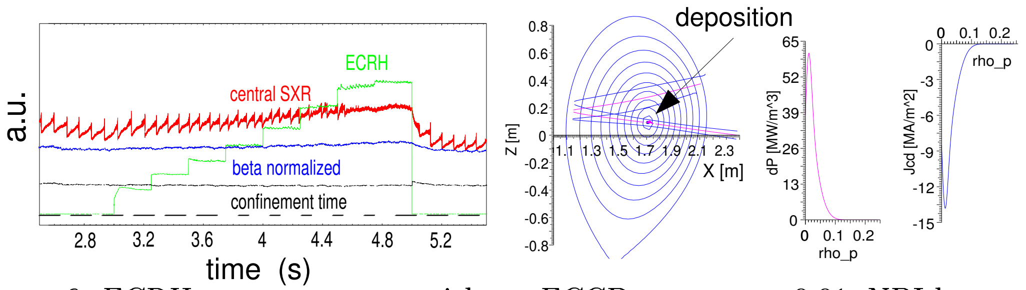

Figure 6: ECRH power ramp up with ctr-ECCD at $\rho_{pol} \approx +0.01$, NBI beams 3,7

With 0.7 MW heating power (same ctr-ECCD scenario than before), the sawteeth could be completely stabilized. The sawtooth period remained about constant, but the amplitude constantly decreased.

Summary:

Magnetic field scans were performed with additional ECRH or co-/ctr-ECCD. In the heating case, sawtooth stabilization was observed at about $\rho_{pol} \approx -0.4$ on the HFS. At $\rho_{pol} \approx -0.1$, a second peak in sawtooth period was found. With co-ECCD, the peak in the sawtooth period increased. Inside the sawtooth inversion radius, the sawteeth were destabilized. As expected, the co-ECCD behaviour inverted for the ctr-ECCD case pointing towards significant current drive. The peak at $\rho_{pol} \approx -0.4$ diminished, even disappeared. Inside the sawtooth inversion radius, a broad maxiumum in sawtooth period was observed. For central deposition, an ECRH power ramp up showed that with increasing power the sawtooth amplitude decreased to zero with constant period.

Generally, around the plasma center, a broad minimum in sawtooth amplitude is observed for heating, co- and counter-ECCD.

In the future, experiments will be performed using more NBI power to investigate the onset of NTMs by varying sawtooth behaviour. Additionally, a look at the influence of different NBI sources on the sawtooth behaviour and theoretical modelling of the sawtooth instability is planned.

References

[1] E. Westerhof et al., Nuclear Fusion, Vol. 41, No. 13

[2] Porcelli et al., Plasma Phys. Control. Fusion **38** (1996) 2163-2186