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Sawtooth crash dynamics during ECCD operations at W7-X

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The plasma in the superconducting optimized stellarator Wendelstein 7-X 1 is mainly heated by an electron cyclotron resonance heating (ECRH) system, which allows up to 7.5 MW of injected power. The heating system can also be used to drive net toroidal current in the plasma (electron cyclotron current drive, ECCD) [2]. Toroidal current is not necessary for plasma confinement in stellarators, since the rotational transform, ι, is generated by means of external coils only. Since the W7-X divertor concept relies on the existence of magnetic island chains at the edge, current drive can be beneficial for strike line control. During ECCD experiments, fast and repetitive crashes of the central electron temperature have been detected (Figure 1). These crashes look very similar to the well-known sawtooth instability observed in tokamaks [3], generally associated with an unstable (m,n) = (1,1) reconnecting non-ideal mode. Due to magnetic reconnection process, the hot plasma is expelled, producing a region of flat pressure profile in the central part of the plasma. While small sawteeth can be beneficial, having a positive impact on core impurity accumulations [4], large crashes can be detrimental for plasma confinement. In W7-X, magnetic configurations avoid major resonances in the core rotational transform profile by design, but the localized current drive can also distort the rotational transform, making the plasma susceptible to MHD-like instabilities. While the understanding of the physical origin of sawteeth in W7-X is still an open question [5] [6], a crucial role seems to be played by local changes of the rotational transform. Current drive and power deposition are simulated with a ray-tracing code TRAVIS [7] and the evolution of the plasma current can be inferred with the use of a 1-D cylindrical diffusion equation. Local changes of toroidal current occur on a timescale faster than the skin time (around 1s for typical plasma parameters), thus locally changing the rotational transform and making it locally approach ι=1, where an instability can be triggered.

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Co- and counter-ECCD experiments were conducted using different magnetic configurations, in particular in the standard configuration (central ι0 ~ 0.85, edge ιa ~ 1) and high-iota configuration (central ι0 ~ 1.04, edge edge ιa ~ 5/4), to investigate the effects on resonance crossing with positive and negative shear. In order to increase current drive efficiency, comparatively low electron density values of ne = 2·10 19 m-3 and electron temperature around Te = 5-6 keV have been choosen in the experiments. The dynamics of the sawtooth instability was analyzed using electron cyclotron emission (ECE) and soft x-ray tomography data. For on-axis current drive experiments, no strong precursor activity is detected. The combination of the two diagnostics indicates that the temperature crash is preceded by a fast, displacement of the plasma core, characterized by a dominant structure which does not contradict the topology of a (m,n)=(1,1) perturbation. The displacement develops in a few hundreds of microseconds, leading to a fast expulsion of the plasma core, occurring in tens of μs, resulting in a flattening of the electron temperature profile. The central temperature peak is then restored again, till the next temperature crash occurs. In experimental configurations where the current drive deposition is located off-axis, a relatively strong oscillating precursor activity is detected in ECE measurements, but the amplitude of these oscillations is not strong enough to be clearly detected by tomographic reconstructions. Two main types of crash have been identified: one affecting up to 50% of the plasma volume, with a central electron temperature drop up to 50-60%, while the second is more localized in the centre, with a smaller amplitude (around 35% of Te).
The crash frequency and the spatial crash localization were found not to be constant: as the discharge evolves, the crash amplitude becomes stronger and stronger, the inversion radius moves outwards, while the temporal interval between two collapses increases. It is noticed that these parameters strongly depend on the total toroidal current. The position where ι = 1 is crossed was simulated with the 1-D current diffusion model and compared with the inversion radius position, showing good agreement.
In most cases the plasma performances were not strongly affected by sawtooth crashes. However, in some discharges with relatively high toroidal plasma current, the discharge was suddenly terminated. The entire phenomenon happened on ms time scale. Despite the little sample number of discharges, it is possible to identify common elements in these terminating discharges: in particular a relatively high toroidal current (> 10kA) was found. Plasma loss is generally preceded by a large sawtooth crash (central Te drop of 60 −65%), which is followed by a strong increase of density. When the density increase is too strong for the plasma to be sustained, the plasma starts to cool down from the edge and to shrink. The increase in radiated power de-

grades the confinement, until the plasma is not able anymore to absorb ECRH power, as indicated by a strong increase in the stray radiation signal. This leads the interlock to switch off the heating system. The global mechanism is not completely understood yet, but it might be related to the change of magnetic flux surfaces given by the toroidal current. Remarkably, in one of these discharges, the interlock was not triggered and the plasma was able to recover pre-crash parameters after 1 second.
The classification the effects of these instabilities on W7-X plasma is crucial for future operations in order to identify safe ECCD configurations which can be used for strike lines control without limiting discharge performances.

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