Confinement degradation and plasma loss induced by strong sawtooth crashes at W7-X

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Abstract
Sawtooth-like crashes were observed during electron cyclotron current drive experiments for strikeline controls at the optimised superconducting stellarator Wendelstein 7-X (W7-X). The majority of the crashes did not have a relevant impact on plasma performance. However, a limited number of events, characterised by a large plasma volume affected by the instability, have been related to a strong deterioration performance and even to the premature termination of the plasma. The hot plasma core expelled during these sawtooth crashes can reach the plasma edge, where plasma surface interaction can occur and impurities can be released. The x-ray tomography shows a strong radiation increase starting from the edge and moving towards the inner plasma regions. This results in the cooling down and shrinking of the plasma, which eventually leads to a poor coupling of the ECRH to the electrons, that can in turn result in a plasma loss. A relation between the size and amplitude of the sawtooth crashes and the impurity increase is reported.

Keywords: stellarator, sawtooth, ECCD, plasma termination event

(Some figures may appear in colour only in the online journal)

1. Introduction
Magnetohydrodynamic (MHD) instabilities play a crucial role in magnetic confined plasmas, since they can lower the plasma performance and even lead to the termination of the plasma discharge, thus limiting the maximum achievable plasma parameters [1]. Disruptions are amongst the most violent and dangerous plasma events that can be linked to MHD instabilities. In tokamaks, they can occur under different conditions, but they are generally related to the growth of an \( m = 2 \) tearing mode as the result of the evolution of an unstable current profile [1]. The mode grows until a sudden loss of confinement and release of thermal energy occur. The loss of thermal energy causes a drastic increase of the plasma resistance, thus letting the toroidal current decay on a time scale faster than the confinement time. Large forces on the vessel can also be generated, potentially damaging the device. For this reason, disruption avoidance is crucial for future fusion power plants. In this regard, stellarators offer a valuable alternative to...
tokamaks [2]. Since in stellarators the rotational transform is created, in total or in part, by external magnetic coils, the toroidal current is not required for confinement and is generally orders of magnitude lower with respect to tokamaks of comparable size. Termination events are not completely unknown in stellarators. However, they are not routinely observed as they are often triggered to investigate the operational limits of the devices. This is the case for experiments conducted at the Compact Toroidal Hybrid (CTH) device [3] and Wendelstein 7-AS [4], with large ohmic current drive. In Wendelstein 7-X (W7-X) the existence of density and impurity limits have already been investigated in previous works [5, 6], but no current limit experiments were conducted, since the toroidal current was expected to be negligible, in accordance with a key optimisation criterion of the device. Although small, a bootstrap current can still be present concerning in particular divertor operations.

Most W7-X magnetic configurations are designed to avoid rational values in the rotational transform profile. Rational values are instead located at the plasma edge, where large magnetic islands are formed and intersect the divertor. The intersection produces a scrape-off layer, representing the boundary between the confinement region and the target elements, where the power flowing out from the confinement region is deposited [7]. The island divertor concept is sensitive to toroidal currents which shift the position of the strikelines [8] and therefore a proper toroidal current control might be necessary for magnetic configurations yielding a relatively high bootstrap current. Due to the electromagnetic response of the plasma, the toroidal current $I_{\text{tor}}$ evolves on the timescale of $\tau = L/R$, where $L$ is the plasma inductance and $R$ the plasma resistance, as follows:

$$I_{\text{tot}}(t) = I_{\text{tot}}(t \to \infty)(1 - \exp(-t/\tau)).$$

$I_{\text{tot}}$ represents the sum of all toroidal current components flowing in the plasma, such as the bootstrap current $J_{\text{bs}}$, the current drive $J_{\text{dr}}$ and the induced counter current [9]. For typical W7-X plasma parameters, $\tau$ is generally between 10–30 s. The evolution of the toroidal current leads to a change of the edge rotational transform $\ell_{\text{LFS}}$, which in turn results in a change of the strikeline position. One of the concerns for safe divertor operation is that the strikelines may deposit power on components which are not suited for high heatfluxes. The strike-line position control is a requirement for W7-X operations and electron cyclotron current drive (ECCD) [10, 11] is foreseen to be one of the tools for toroidal current control, thus assuring safe divertor operation [12].

ECCD experiments were conducted to verify the feasibility of ECCD as an actuator for strikeline control [8]. It has been shown that it was possible to control the strikeline position either by driving counter current, in order to keep $I_{\text{tor}} \sim 0$ kA [13] or by accelerating the convergence of the bootstrap current itself by driving co-current for a limited amount of time. During these experiments, repetitive sawtooth-like crashes were observed [14–17].

Most crashes associated with ECCD do not have a significant impact on plasma performances. However, it was observed that very strong crashes, at relatively high toroidal currents, could lead to a fast decay of the stored magnetic energy (on a timescale faster than the confinement time) the dissipation of the toroidal current and even an abrupt termination of the plasma [18].

In this work we will analyse the main features of these events. We will show that a sawtooth crash is followed by a density and impurity increase, which in turn can result in a violation of the power balance. Although only few events have been detected, a relation between increasing density and the size of the sawtooth crashes was found. The study of these events is crucial for understanding whether a threshold for the toroidal currents in W7-X plasmas exists and how plasmas and the device can be affected by these termination events. Although toroidal currents, which are generally observed in W7-X, are small compared to tokamaks, fast current dissipation can induce electromagnetic forces in the vessel. Since this was not part of the original design of the device, understanding and possibly preventing such events or mechanically strengthening in- or near-vessel components is also important for avoiding damages.

The work is organised as follows. The experimental set-up is described in section 2. In section 3 we provide an overview of the experiments in which the plasma confinement was strongly reduced as a consequence of the sawtooth crashes. In section 4 we compare the crash parameters of different experiments, in order to identify common elements of the previously analysed crashes. In section 5 we present an overview of a remarkable experiment, where sawtooth crashes are associated with a stepwise density increase and no degradation of the plasma parameters are detected. The conclusions are discussed in section 6.

### 2. Experimental set-up

W7-X is a superconducting optimised low shear stellarator [19, 20], whose magnetic field is generated by 50 superconducting non-planar coils and 20 planar coils. It has a major radius $R = 5.5$ m, a minor radius $a \approx 0.5$ m and an axis magnetic field $B = 2.52$ T in the so-called bean-shaped plane. The W7-X ECRH system is composed of 10 gyrotrons, which can selectively operate in X- or O-mode at 140 GHz and can provide up to 7.5 MW of heating power [13, 21]. If the electromagnetic beams are obliquely injected, the ECCD is generated. During ECCD experiments, sawtooth crashes are detected [14]. A local net toroidal current modifies the rotational transform profile and low order rational values, such as $\ell = 1$ can be crossed [14, 22]. The plasma stability conditions are altered [17], thus making the plasma susceptible to the sawtooth instability.

The experiments analysed in the present work were conducted using the so-called standard configuration, characterised by a magnetic axis rotational transform $\ell_{\text{A}} \approx 0.85$ and a last closed flux surface (LCFS) rotational transform $\ell_{\text{LCFS}} \approx 0.97$. The main plasma parameters of the experiments analysed in this work are summarised in table 1.
In most experiments the core electron temperature $T_{e,0}$ is in the range of 5–6 keV and the electron density $n_e$ about $2.5 \times 10^{19} \text{ m}^{-3}$. The experiment 20171207.026 was conducted with no ECCD. All the other experiments were conducted using co-ECCD, i.e. the current was driven in such a way that the rotational transform was increased, in order to accelerate the convergence of the toroidal current (equation (1)).

The ECCD deposition is strongly localised, generally around at an effective radius $r_{\text{eff}}/a \approx 0.15$, where $r_{\text{eff}} = \sqrt{\langle A \rangle}/\pi$ and $A$ is the volume averaged area of a flux surface of radius $r_{\text{eff}}$ and $a$ the minor plasma radius. Direct measurements of the rotational transform profile are currently not possible at W7-X. The current and the rotational transform modelling for comparable experiments is discussed in other works [14, 22] and is beyond the scope of this manuscript. In figure 1, a simplified sketch showing the comparison between the vacuum rotational transform (black dotted lines) and the modification given by 5 kA and 15 kA (blue and red, respectively) is plotted.

Sawtooth crashes are studied using different diagnostics. Electron cyclotron emission (ECE) allows to reconstruct a 1D profile of the electron temperature $T_e$ [23, 24]. Channels are mapped to a radial position $r_{\text{eff}} = \sqrt{\langle A \rangle}/\pi$. Channels detecting on the plasma low field side (LFS) are mapped to a negative value and high field side (HFS) channels are mapped to a positive value. ECE has a high sample rate (200 kHz–2 MHz) and a great sensitivity to relative signal changes due to a relatively small noise contribution (less than 6%). An example of the profile of relative electron temperature change as a consequence of a sawtooth crash is depicted in figure 2(b), where the relative temperature change is plotted and is calculated as $\Delta T_e/(T_e^{\text{after}} - T_e^{\text{before}})$, where $T_e^{\text{after}}$ and $T_e^{\text{before}}$ are respectively the electron temperature after and before the crash. The location of the plasma where no temperature changes occur is called inversion radius ($r_{\text{inv}}$). Additionally, the crash amplitude $\Delta T_{e,0}$ is defined as the relative central temperature change.

The soft x-ray tomography system (XMCTS) [25, 26], composed of 20 cameras each one with 18 lines of sight (LOS) (figure 3), was used to detect the soft x-ray emission in the energy range of approximately 1–12 keV. Tomographic inversion is performed to reconstruct the emissivity in the poloidal plane for selected time windows. It is obtained using the minimum Fisher regularized inversion [27] and does not use any information about either the plasma equilibrium or the magnetic field topology. Two selected LOS (depicted in red in figure 3) are used to show the x-ray intensity $I_{\text{SX}}$ at different plasma locations. Although $I_{\text{SX}}$ is a line-integrated measurement, it is possible to assign a radial location to each LOS by considering the flux surface the LOS is tangential to. In our case, the radial positions are $r_{\text{eff}} \approx 0a$ and $r_{\text{eff}} \approx 0.4a$, where $a \approx 0.52$ m is the plasma minor radius.

The line integrated electron density $\int n_e dl$ is measured by means of a single channel dispersion interferometer [28] with a sample rate up to 100 kHz. Abrupt increase in $n_e$ are often detected in correspondence of strong sawteeth. Although a single channel line integrated measurement is not suited to provide information about the position of such density increase, the interferometer data can be used to characterise the crashes that can have a global impact on the plasma parameters.

Four VUX/XUV spectrometers (HEXOS) [29, 30], detecting from 2.5 to 160 nm were used to study the emission of impurities, such as carbon, oxygen and nitrogen after the sawtooth crashes, which led to a deterioration of the stored plasma energy.

### Table 1. Overview of the main plasma parameters for different experiments. The values in this table refer to an average of the values over the experiment.

| Experiment | $P_{\text{ECHR}}$(MW) | $T_{e,0}$(keV) | $(n_e)_0$(m$^{-3}$) | $Z_{\text{eff}}$ | $W_{\text{nuc}}$(kJ) | $B_{\text{pol}}$(T) | ECCD |
|------------|------------------------|----------------|-------------------|----------------|-------------------|----------------|------|
| 20171206.025 | 1.2 | 4.7 | $2.1 \times 10^{19}$ | 2.8 | 180 | $-2.52$ | Co-ECCD |
| 20171206.028 | 1.9 | 5.5 | $2.6 \times 10^{19}$ | 2.3 | 250 | $-2.52$ | Co-ECCD |
| 20171206.030 | 1.9 | 5.7 | $2.3 \times 10^{19}$ | 2.8 | 240 | $-2.52$ | Co-ECCD |
| 20171207.008 | 1.9 | 5.9 | $1.9 \times 10^{19}$ | 3.7 | 220 | $-2.52$ | Co-ECCD |
| 20171207.026 | 3.0 | 4.6 | $2.6 \times 10^{19}$ | 5.4 | 220 | $-2.52$ | No ECCD |
| 20180816.022 | 3.4 | 6.2 | $2.2 \times 10^{19}$ | 2.6 | 310 | $+2.52$ | Co-ECCD |

### Figure 1. Sketch showing the modification of the toroidal current (a) to the rotational transform (b) in a simplified 1D geometry. The black dotted curve indicates the rotational transform generated by the magnetic coils. In blue and red the modification provided by toroidal currents of 5 and 15 kA, respectively.
Figure 2. (a) Example of a core ECE timetrace during a sawtooth crash. The crashes are automatically detected and the temperature before (blue) and after (red) the crash are used to calculate the relative temperature change. (b) Profile of the relative temperature change ($\Delta T_e$). The positions where $\Delta T_e = 0$ are called inversion radii ($r_{\text{inv}}$).

The inversion radius $r_{\text{inv}}$ and the crash amplitude $\Delta T_e$ of experiment 20171206.028 are plotted in the second and third panels of figure 4, respectively. For this work it is important to note that the crash size ($r_{\text{inv}}$ and $\Delta T_e$) gets larger as the $I_{\text{tor}}$ increases (panel (g)).

The crash depicted in red in figure 4 is found to be related to a fast dissipation of stored energy, toroidal current and eventually to the premature termination of the experiment. Plasma parameters during the plasma termination process are displayed in figure 5 and we can divide it into 4 phases. The first phase is represented by a strong crash ($r_{\text{inv}} \approx 0.5 a$, where $a \approx 0.52$ m is the minor radius), occurring at $t = 13.525$ s and a density increase, detected by the dispersion interferometer (panel (g)) at about $t = 13.525$ s. The density increase was not caused by the gas inlet system. A zoom of the ECE timetraces is depicted in the top plot of figure 6(a). The coloured dotted lines indicate the time at which the $T_e$ profiles in figure 6(b) are measured. The black solid line represents the $T_e$ before the crash, whereas the red dashed line depicts $T_e$ after the crash, with a strong central temperature decrease ($\Delta T_e \approx 65\%$). A temporary $T_e$ increase, caused by the expulsion of the plasma core, can be seen at the HFS edge. The blue dotted line represents $T_e$ after the density increase. The $T_e$ profile has peaked again, however the pre-crash $T_e$ could not be recovered and a plasma cooling down is observed. The additional drop in ECE signals (figure 6(a), top plot) at $t = 13.526$ s does not seem to be a real temperature drop; instead, since it is detected by all ECE channels except the very edge HFS channels, it seems to be caused by a temporary cut-off of the X-2 emission detected by the ECE radiometer.

In figure 5 (panel (d)) the timetraces of a core and mid-plasma x-ray LOS are plotted for the whole process and a zoom is depicted in figure 6(a), bottom plot. The x-ray camera detects an increase in signal for both LOS and a strong peak can be seen in the mid-plasma one at $t = 13.526$ s.

The x-ray radiation is produced by bremsstrahlung and by line-radiation. The tomographic reconstruction (figure 7(b)) shows the regions of stronger signal increase right after the crash in the triangular plane within the LCFS (from

The effective charge $Z_{\text{eff}}$ indicates the impurity content of the plasma. At W7-X it is measured from the intensity of the bremsstrahlung emission using a compact spectrometer with a time resolution of 100 ms, detecting in the spectral region between 627 and 641 nm [31].

Finally, the plasma energy $W_{\text{diss}}$ is measured by means of diamagnetic loops and the toroidal current $I_{\text{tor}}$ is measured by a continuous Rogoswki coil [32].

3. Experimental overview

In this section we analyse two remarkable experiments in which a strong degradation of the plasma energy was detected after a sawtooth crash. We will start with experiment 20171206.028, in order to describe the dynamics of this event and then we will analyse the experiment 20171206.030, in which a more detailed impurity analysis was possible.
Figure 4. Crash and plasma parameters for the experiment 20171206.028. The inversion radius $r_{\text{inv}}/a$ and the crash amplitude are plotted in panels (b) and (c), respectively. The crash highlighted in red is shown in details in figure 5. The core temperature $T_e$ detected by an ECE channel, the line integrated density $\int n_\text{el} \, dl$, the effective charge $Z_{\text{eff}}$ and the toroidal current $I_{\text{tor}}$ are plotted in panels (d)–(g), respectively. The current has a negative sign due to the reversed magnetic field configuration.

VMEC equilibrium). The first tomogram represents the 2D emissivity distribution $E_{\text{SX}}$ before the temperature crash, while the others display the $E_{\text{SX}}$ at different instants afterwards. Strong deformations of the pre-crash $E_{\text{SX}}$ are visible, especially in (VI–IX) tomograms. In these tomograms a signal as strong as the one of the core is detected in the outboard side of the plasma. To highlight the interaction region, the relative change of the emissivity was taken into account and plotted in figure 7(c). A normalised relative 2D emissivity distribution $\Delta T_e$ is estimated as follows:

$$\Delta E_{\text{SX}}(t) = \frac{E_{\text{SX}}(t) - \langle E_{\text{SX}} \rangle}{\langle E_{\text{SX}} \rangle},$$

where $E_{\text{SX}}(t)$ represents the emissivity at a certain time and $\langle E_{\text{SX}} \rangle$ represents the time averaged emissivity before the sawtooth crash.

Figure 7(c) confirms a strong signal increase of radiation at the edge of the confined region. The tomogram III is related to the sawtooth crash and shows a weak increase of signal at the edge as the result of the core expulsion. A stronger emissivity increase, initially located in the outboard plasma region, is detected in tomogram IV, spreads to the whole plasma edge and eventually increases in the centre (tomograms V–IX). Both the ECE and the tomography suggest that, during the plasma cooling down phase, the plasma centre does not move.
Figure 5. Plasma parameters for 20171206.028, between $t = 13.52$ s and $t = 13.57$ s. The dashed lines indicate the different phases described in the text.

Figure 6. (Top plot (a)) Timetraces of a core (red) and a mid-plasma (dark red) ECE channels. The $T_e$ crash happens at $t = 13.5252$ s. The decay at $t = 13.526$ s might be an artefact (Bottom plot (b)). Core (light purple) and mid-plasma (dark purple) x-ray diodes. (b) $T_e$ profiles measured by ECE at different timesteps, represented by the vertical dotted line in (a). In black before the crash, in red right after the crash and in blue during the energy dissipation phase.
During the second phase, the plasma energy drops from 250 kJ to about 50 kJ within 25 ms.

The third phase (t = 13.552 s) is characterised by the dissipation of \( I_{\text{tor}} \), which can be explained by the fact that the plasma resistance \( R \) increases due to the \( T_e \) drop.

Finally, the last phase is characterised by an increase in the stray radiation (figure 5), representing the unabsorbed ECRH power, caused by a poor coupling of the ECRH to the electrons due to the extremely low \( T_e \). Triggered by the increase in stray radiation, the interlock system stops the ECRH (t = 13.56 s).

The strong increase in the x-ray signal may indicate that the energy decay happens due to enhanced radiation losses. The energy decay phase occurs too fast for an impurity radiation analysis to be carried out. We therefore present another remarkable experiment (20171206.030) (figure 8), in which a similar chain of events is detected. The failure of one gyrotron occurs at \( t \approx 17.65 \) s, decreasing the heating power down to 1200 kW. A strong sawtooth is detected after about 100 ms, at \( t \approx 17.75 \) s, followed by an increase in density. For this time window, no x-ray data are available. Since the ECRH
was not stopped by the interlock system, the plasma was able to recover, after the energy collapse, from \( t = 18 \) s, as it can be seen in the \( T_e \) and \( W_{\text{dia}} \) time traces (figures 8(c) and (e)). The recovery is slower than a normal plasma discharge start up (tens of milliseconds), however after about 2 s the stored energy and \( T_e \) display similar values to those before the crash.

The \( T_e \) decay in 20171206.030 is slow enough for the dynamics of the impurity emission lines to be studied by means of the high efficiency XUV overview spectrometer (HEXOS). A clear conclusion regarding the impurity dynamics and effects was not possible since several parameters such as \( n_e \), \( T_e \), \( r_{\text{eff}} \) are changing at the same time. We therefore qualitatively compared the results with another experiment (20171207.026) in which a sudden drop of temperature but no density increase are detected. The temperature drop in the latest experiment is not related to ECCD experiments. Selected plasma parameters can be found in figure 9 and table 1, whereas the comparison of the impurity emission can be seen in figure 10. The x-axis represents \( t - t_{\text{ref}} \), where \( t_{\text{ref}} \) is a reference timestep shortly before the \( T_e \) decrease. The y-axis represents the signal renormalised to its average value within the first 50 ms. The direct comparison between the signal increases for the two experiments shows that H- and He-like carbon emission is similar in the two experiments. The other emission lines show differences, since the relative emission increase detected in 20171206.030 is orders of magnitude stronger than the emission increase in 20171207.026.

Considering 20171206.030, a massive increase in radiation is detected at \( t - t_{\text{ref}} \approx 0.3 \) s. The increase is up to 30 times for selected, non saturating oxygen lines (third column). A massive increase in nitrogen (70 times) and carbon (8 times for selected lines) is detected as well. Moreover, chlorine and
Figure 10. Impurity emission detected by HEXOS, 20171206.030 in red and a reference experiment 20171207.026 in black. The x-axis represents the time from which the temperature drop is detected ($t_{ref}$).

Fluorine emission lines, not detectable before the crash, are measured, although their origin is not understood. Although it is not possible to reconstruct the dynamics of the process, one can draw the following conclusions. First of all, the temperature decrease alone, as detected in 20171207.026, cannot explain the 20171206.030 data. The strong increase in signal for the three elements is then probably caused by an influx of impurities. Moreover, comparing the inner lines (He- and H-like) of carbon and oxygen, we can observe it increases up to 2–4 times for the first element and 5–15 times for the second. This could represent an additional indication for oxygen influx into the plasma.

We would like to point out that the energy drop does not seem to be related to the gyrotron failure. In fact, if the ECRH power drop alone had led to a negative power balance, it would not be possible to explain the fact that the plasma recovers the pre-crash plasma parameters ($t \approx 19$ s). Instead, the increase in density is more likely related to the sawtooth crash.

Figure 11. In black: parameters of crashes not related to a density increase. In red: parameters of crashes where a density increase was detected by the interferometer.
4. Crash size and density increase

The number of experiments in which a strong degradation or even a premature plasma termination was observed is very limited, therefore we lack of a proper statistics.

It was empirically noticed that these few events occurred at relatively high toroidal current (|I_{tor}| > 10 kA). As shown in figure 4, I_{tor} influences the size of the crashes, since a higher I_{tor} shifts outwards the position where \( r = 1 \) is crossed. We considered four different experiments with comparable plasma parameters and heating schemes and verify whether a significant increase in density is detected after the crashes. The results are displayed in figure 11, where \( r_{inv} \) of each crash is plotted against \( \Delta T_e \). If no density increase is detected, the points are depicted in black and in red if a density increase is detected. Three crashes, depicted in red, are related to a density increase. All of them are characterised by large \( \Delta T_e \) and especially by an average \( r_{inv} \approx 0.5a \).

A possible explanation consists in assuming that the expelled core interacts with the neutrals/impurity located at the plasma edge as indicated by the soft x-ray increase (figure 7) or by the impurity emission (figure 10). The indication for a threshold \( r_{inv} \) value may indicate that a certain amount of energy is necessary to trigger the ionisation of the edge particle. Additionally, a large \( r_{inv} \) is not only related to a large expelled energy but it also decreases the plasma distance to reach the edge.

It should be noted that an increase in density does not necessarily trigger a plasma termination event, as it will be shown in the next section.

5. Stepwise density increase

The previous examples show that the plasma can be lost by a fast increase in \( n_e \) and/or impurities, following a sawtooth crash. However, in this section we show an overview of one experiment, where the sawtooth activity induced a density increase in the plasma, without leading to a premature termination of the experiment (figure 12). The experiment is characterised, with respect to the other experiments presented before, by a higher heating power and wall boronisation. Additionally, no reversed magnetic field configuration was used, therefore \( I_{tor} \) has a positive value. At the beginning of the experiment no strong differences with respect to the crashes presented in figure 4 are observed. In the second part of the experiment, depicted in figure 13, stepwise density increases are detected by the interferometer and the x-ray camera with every sawtooth crash. The crash parameters around \( t = 8 s \ (\Delta T_e \approx 65\% \) and \( r_{inv} \approx 0.5a \) ) are comparable with those of the sawtooth crashes plotted in red (i.e. sawtooth crash followed by a density increase) in figure 11.

The first indication for the different behaviour of the impurities with respect to experiments 20171206.028 and 20171206.030 is given by the \( Z_{eff} \) trend, depicted in panel (d). Around \( t = 3 s \) a strong increase in \( Z_{eff} \), caused by a probe
Figure 13. Zoom of the main plasma parameters of 20180816.022 between 8 s and 12 s. Almost every sawtooth is associated with a density increase.

entering the plasma, is visible. The $Z_{eff}$ value remains constant until about $t = 8.8$ s, when the density starts to increase. During this phase of the experiment $Z_{eff}$ drops from about 2.5 to 1.6. This observation indicates that the new particles, which are now fuelling the plasma, are mainly hydrogen. If this were not the case, the $Z_{eff}$ decrease, along with a $n_e$ increase, could not be explained. A more detailed analysis regarding impurity line radiation was attempted with the HEXOS diagnostic. We do not have a proper analysis regarding the impurity dynamics, since it was not possible to disentangle the $T_e$ and $n_e$ contributions to the line emissions. Nevertheless, no strong increase in the impurity emission was detected, contrary to what we observed in experiment 20171206.030 (figure 10).

Thermographic measurement and heat flux calculation [33] at one of the divertor plate is performed in figure 14. The selected poloidal profile is along the most loaded divertor finger and the strike line movement [8] is found to be correlated with the toroidal current. Heat spikes are observed in correspondence with the $T_e$ drop, which indicates that the expelled energy reaches the divertor plate. The spikes are visible also for $t < 8.8$ s, i.e. before the stepwise density increase is detected. The origin and the cause of such density increases are not understood.

We can only speculate about the factors which lead to the differences between 20180816.022 and the experiments analysed in section 3 (20171206.028 and 20171206.030). An important difference consists in the higher heating power used in 20180816.022 (about 3400 kW against 2000 kW), which determines the maximum achievable density [5]. Additionally, the boronisation of the wall reduces the concentration of impurities in the plasma and therefore reduces radiation losses, thus contributing to keeping a positive power balance.

6. Conclusions

ECCD experiments show that a low shear stellarator, like W7-X, is very sensitive to localised toroidal currents and sawtooth crashes are observed during ECCD experiments.
A crucial question to be answered is whether the aforementioned crashes can affect plasma performance. In this work we report on a series of experiments where strong density increases were detected after sawtooth crashes. The analysis of different experiments with comparable plasma parameters suggests that the density increase is related to very large sawteeth with an inversion radius \( r_{\text{inv}} \approx 0.5a \), although the full mechanism is not understood.

In one case, after a large sawtooth has taken place, strong x-ray radiation is detected in the region where the hot core is expelled. It is assumed that the signal is caused by the ionisation of neutrals, which are present at the plasma edge or by an impurity content increase. Analysis of the impurity emission of a similar experiment confirms a strong increase in the N and O emission lines. The increased radiation losses, initially localised in the proximity of the LCFS, cool down the plasma. The total plasma current remains nearly constant until the plasma temperature is well below 1 keV and is eventually dissipated on a timescale some orders of magnitude faster than a normal experiment ending. The plasma energy is lost mainly through radiation and the plasma core maintains its position throughout the process. We also detected one case, in which the ECRH heating is not turned off and the plasma recovered after a few seconds. This event demonstrates the robustness of W7-X plasmas against terminating events.

Additionally, we report on an experiment in which a stepwise increase in the density is detected after almost every sawtooth crash, while the underlying mechanism is not understood.

In summary, we propose the following mechanism. Large crashes are found to trigger a density increase. If the energy balance is negative, i.e. the ECRH power is not sufficient to sustain the radiation losses, the cooling down of the plasma occurs and make it shrinks. Energy is mainly lost through radiation. Additionally, as indicated in another similar experiment, a higher heating power or an adequate wall conditioning can help avoid such events.

Several issues, such as the impurity origin and the density increase mechanism, could not be assessed because of the small number of experiments and the limited diagnostic availability during the first experimental campaigns. Although a more complete analysis is currently not possible, the fact that these events occurred only in few experiments indicates that they might be easily avoided.

Since ECCD and the related sawtooth crashes could still be important for W7-X, as for instance the the aforementioned strike-line control operation or the avoidance of core impurity accumulation [34], a safe operational range for ECCD experiments must be determined.

Additionally, the possibility of a sudden energy degradation and fast decay of the toroidal current should be taken into account in the design phase of future low shear stellarators.

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