Radial localization of electron temperature pedestal and ELM-like events using ECE measurements at Wendelstein 7-X

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Abstract. A magnetic configuration scan was performed at Wendelstein 7-X stellarator by varying the rotational transform to analyze the plasma confinement for magnetic configurations with different edge magnetic island locations and sizes. For the magnetic configurations, where the 5/5 island chain was moved inside the last closed flux surface, it was observed with electron cyclotron emission measurements that an electron temperature, T_e, pedestal develops in the plasma buildup phase and followed by the edge localized mode (ELM)-like crashes. From the mapping of the island to the plasma radius from HINT equilibrium, it was found that the T_e pedestal is formed at the island location on the high field side of the plasma. The ELM-like crashes occur at the location of the pedestal and the transport barrier is broken typically with an energy loss of 3-4% during a single ELM-like event. The frequency and the amplitude of the ELM-like crashes were observed to be changing with island size, plasma heating power and density. Additionally during the plasma decay, after the heating was switched-off, a transition to degraded plasma confinement state was observed with changed T_e profile gradients, faster decay rate of diamagnetic energy, and increased H-alpha levels.

1 Introduction

Wendelstein 7-X (W7-X) is a high iota and low shear optimized stellarator concerning magnetic field geometry with a scientific objective to attain 30 min of detached steady-state plasmas [1–3]. Due to the low magnetic shear, it is possible to shape the separatrix by large islands constituting an island divertor [4]. During the operational campaign OP 1.2 of W7-X, a magnetic configuration scan was performed by varying the rotational transform with magnetic configurations between iota = 5/4 and iota = 5/5 at the boundary [5, 6]. During the configuration scan the location of the 5/5 magnetic island chain was moved inside the last closed flux surface, and the island size was varied by changing the control coil current. For these magnetic configuration scan experiments, it has already been reported that the plasma energy increased for the configurations where the 5/5 island chain is close to the plasma boundary but still inside the last close flux surface [5]. However, the reason behind the improved confinement for certain configuration from the scan is not fully understood yet.

The electron cyclotron emission (ECE) at W7-X is measured by a heterodyne radiometer, in the spectral range of the second harmonic extraordinary mode (X2-mode) from 126 to 162 GHz with a collection optics located at the low field side (LFS) observing a bean shaped plasma cross section [7, 8]. The 32 channel radiometer has a temporal resolution of the order of µs which enables the measurement of the rapid fluctuations in T_e, for example, the ELM-like crashes possibly caused by the formation of the T_e pedestal, and moreover the diagnostic provides a measurement of the spatial location of the T_e fluctuations in the plasma. For the magnetic configuration scan experiments where the 5/5 island chain was moved inwards, it was observed with the ECE diagnostic that a T_e pedestal develops in the plasma indicating the formation of the transport barrier. Furthermore, it was observed that the transport barrier is broken by a fast (2-3 ms) crash which has characteristic like a tokamak ELM [9], and hence for this work these crashes are referred to as ELM-like crashes. Additionally, these crashes are also reported to be observed with multiple diagnostics at W7-X and are referred to as island localized mode (ILM)s [6, 10, 11].

The paper reports on the experimental observation of the T_e pedestal and the ELM-like crashes and provides the spatial location of the T_e pedestal and the ELM-like crashes with respect to the location of the magnetic island in the plasma. The ECE measurements were used to localize the T_e pedestal and ELM-like crashes in the plasma and an equilibrium calculation done with HINT code [12, 13] was used to determine the location of the magnetic island. Moreover, this work focuses on investigating the changes in the T_e profile gradients for different magnetic configurations to understand the effect of island location and size on the transport in the plasma and hence overall confinement.

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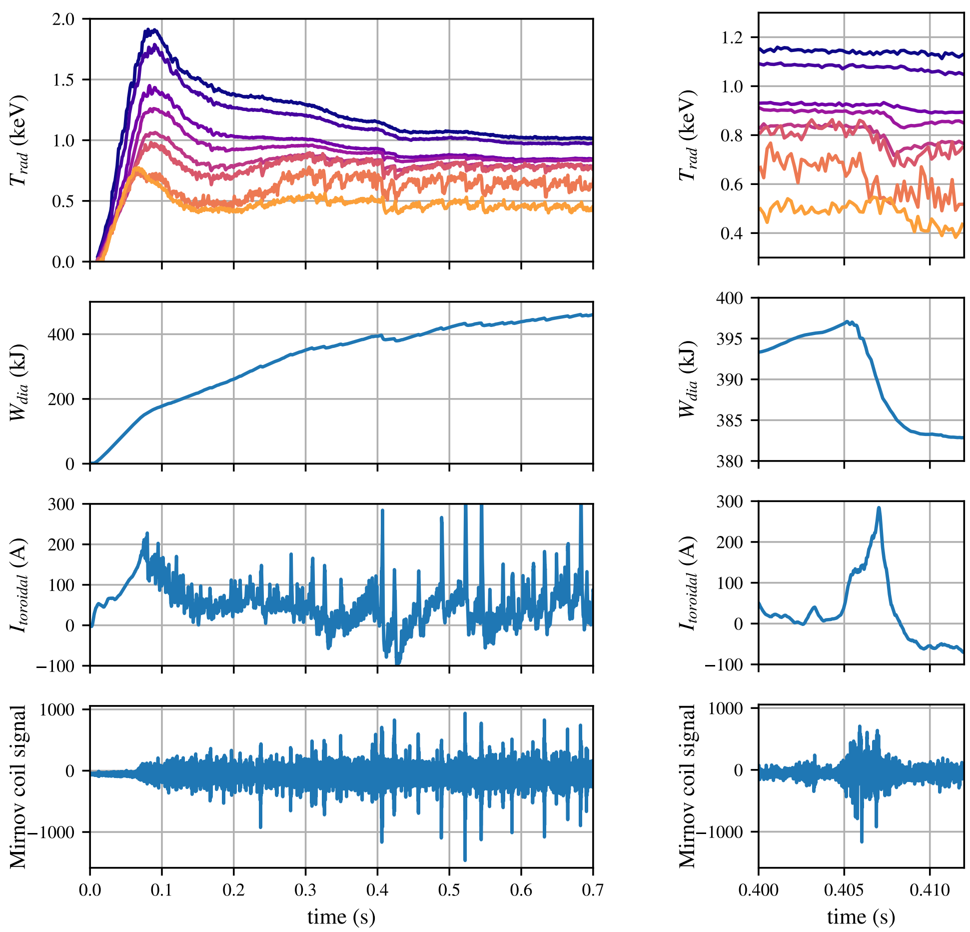

(a) Time traces showing ELM-like crashes

(b) Single ELM-like crash

Figure 1: (a) Time traces of the ECE radiation temperature, T_{rad}, at high field side (HFS) frequencies, the diamagnetic energy, W_{dia}, the toroidal current, $I_{toroidal}$, and the magnetic fluctuations measured by Mirnov coils are shown for the plasma discharge #20180927.026 where the 5/5 island chain was moved inside the last closed flux surface. (b) Zoomed in time traces of (a) at 0.4 s showing the temporal evolution of different parameter during a single ELM-like crash.

The experimental observations are discussed in details in the following sections.

2 ELM-like crash observation in multiple plasma diagnostics

The ELM-like crashes were observed in multiple plasma diagnostic measurements during the magnetic configuration scan experiments for the plasma discharges where the magnetic island chain was moved inside the last closed flux surface. Figure 1a shows the time trace of ECE radiation temperature, T_{rad}, at the HFS frequencies (144.86-153.56 GHz). The line of sight of the ECE diagnostics crosses the X-point of the magnetic island at HFS and the ELM-like crashes were observed in the T_{rad} for these HFS channels. However a more thorough mapping is presented in the next section. The ELM-like crashes were more pronounced in the high resolution temporal measurements of toroidal current, $I_{toroidal}$, and the magnetic fluctuations.

Figure 1b shows the zoomed in time traces during a single ELM-like crash lasting typically 2-3 ms. From the ECE time traces, it can be observed that the crash occurs at $T_{rad} \approx 0.6$ keV. The occurrence of crash in temperature lead to propagation of a heat wave and the amplitude of this heat wave decrease in the direction away from the location of crash. The W_{dia} measurements show that a single ELM-like crash was accompanied by an energy loss of on average 3.5%. In addition, $I_{toroidal}$ also increased during the ELM-like crash with simultaneously increase in magnetic fluctuations activity observed with Mirnov coils [14].

3 Electron temperature pedestal

At the start of the magnetic configuration scan experiments specially for the configurations where the magnetic island chain was moved inside the plasma [5], it was observed from the ECE diagnostic that an electron pedestal develops during the plasma buildup phase. Figure 2 shows the ECE time traces for the plasma startup phase, and around 0.27 s

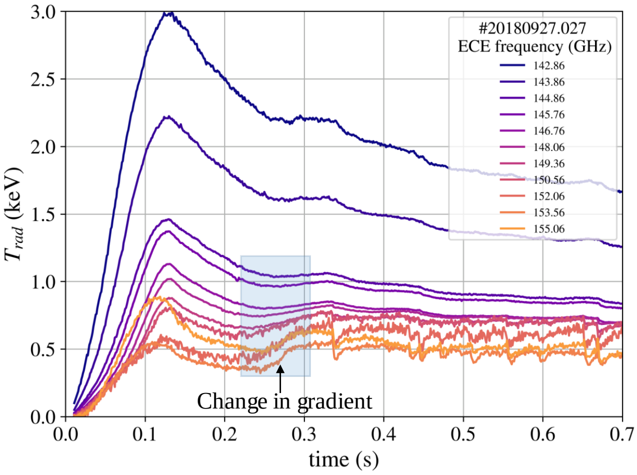
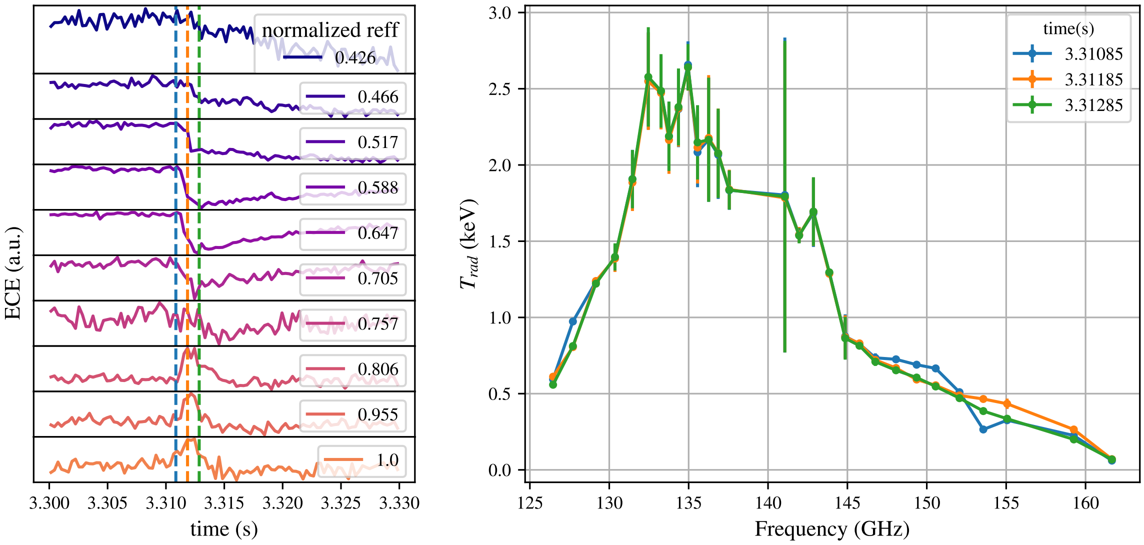


Figure 2: Time traces of ECE channels measuring plasma core to edge (142.86-155.06 GHz) region are shown for #20180927.027. At the start of the plasma discharge around 0.27 s, the temperature gradient changes (the increasing T_{rad} at HFS channels) leading to development of an edge pedestal which is broken by an ELM-like crash at approximately 0.34 s.


(a) ECE time trace

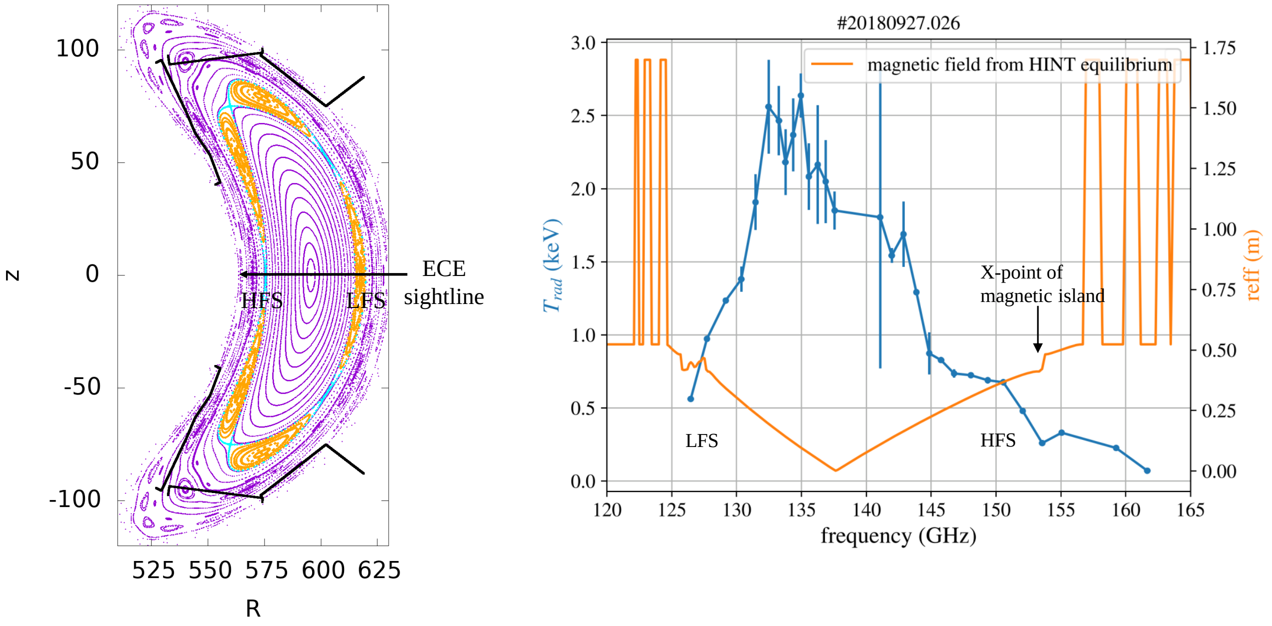
(b) ECE spectra

Figure 3: (a) A single crash in T_e shown using ECE data for #20180927.026. Three time points from this crash have been chosen to see the ECE spectra during the crash. The channel around which the neighbouring channels are out of phase is the location of the crash and correspond to inversion radius ($r_{eff} = 0.757$) of the crash in the plasma. (b) The corresponding ECE spectra before (blue curve) and during (orange and green curve) the crash are shown. It can be clearly observed that the location of crash coincides with the location of the pedestal.

in the discharge (marked in figure), it can be seen that the edge channels (lower than 1 keV) start to show change in electron temperature gradient and a transport barrier develops leading to the delayed increase in the core temperature. The pedestal develops at the start of the plasma by flattening of the radiation temperature near the plasma edge and this is followed by an ELM-like crash in the electron temperature at the location of the pedestal. The frequency and amplitude of ELM-like crashes vary depending on the plasma pressure.

3.1 Pedestal breakage and heat wave propagation

Figure 3a shows from ECE measurements, a single ELM-like crash with inversion radius at normalized effective plasma radius, $r_{eff} = 0.757$ (from cold resonance mapping with HINT). The corresponding heat wave propaga-



(a) Magnetic flux surfaces along ECE sight line

(b) Location of temperature pedestal versus magnetic isalnd

Figure 4: (a) Poincaré plot showing the magnetic flux surface for finite pressure with magnetic island chain (orange color) moved inside the last-closed-flux-surface. The sight line of ECE diagnostic crosses the island O-point on LFS passing the plasma center, and X-point on the HFS. (b) An ECE spectrum is shown where the pedestal can be seen around the channels from 150 to 155 GHz and the magnetic field calculated from the HINT equilibrium is shown as a function of effective plasma radius. The location of the magnetic island is marked in the figure.

tion through ECE channels can be observed with inverted phase of signals at neighbouring channels to the location of crash and the heat wave moves outwards with decaying amplitude in both directions. Three time points are selected (marked in blue, orange and green) before and during the crash to show the temporal evolution of ECE spectra. In figure 3b, a pedestal in ECE spectrum is observed before the crash (blue color) around the channels 150-155 GHz, and the pedestal breaks during ELM-like crash (orange and green color). The typical duration of the crash is $2-3$ ms with longer recovery time and the frequency of the crash changes with different plasma parameters.

3.2 Pedestal location with respect to magnetic island

Figure 4a shows the Poincaré plot of the magnetic flux surfaces with the magnetic island chain shifted in the edge confinement region. The ECE diagnostic measures perpendicular to the magnetic field direction and the radiation collection optics is located at the LFS. And hence crosses the O-point of island from LFS channels and X-point of island from HFS channels. Figure 4b shows the measured ECE spectrum and calculated magnetic field along the ECE line of sight with HINT code which is a magnetic equilibrium code that also includes magnetic islands in the calculation. The magnetic island location is marked in the figure and represents the discontinuity in the magnetic field values. It can be seen that the pedestal develops approximately at the location of the magnetic island in the plasma. This suggests that presence of island impacts the plasma confinement via development of a transport barrier, however the exact mechanism is yet to be understood.

4 H to L-mode back transition

Figure 5 shows a possible back transition from a high confinement state to a lower one from different diagnostic measurements. The top plot shows the ECE time traces during the plasma decay phase after the heating was stopped at 4.5 s. At around 4.8 s, a change in the slope of T_{rad} decay rate can be observed in different HFS channels resulting in changed electron temperature gradients accompanied by an ELM-like crash. Simultaneously, an increase in the W_{dia} decay rate was observed alongside increased H-alpha levels and magnetic fluctuations. Hence, the change in temperature gradient and W_{dia} decay rate suggest that the plasma confinement has changed to a degraded state, and this could be a possible fingerprint of a H to L-mode transition. However, a clear forward transition from L to H-mode is so far not observed as the temperature pedestal develops already within the plasma buildup phase.

5 Discussion

For the magnetic configurations where the magnetic island chain was moved inside the edge confinement region, a

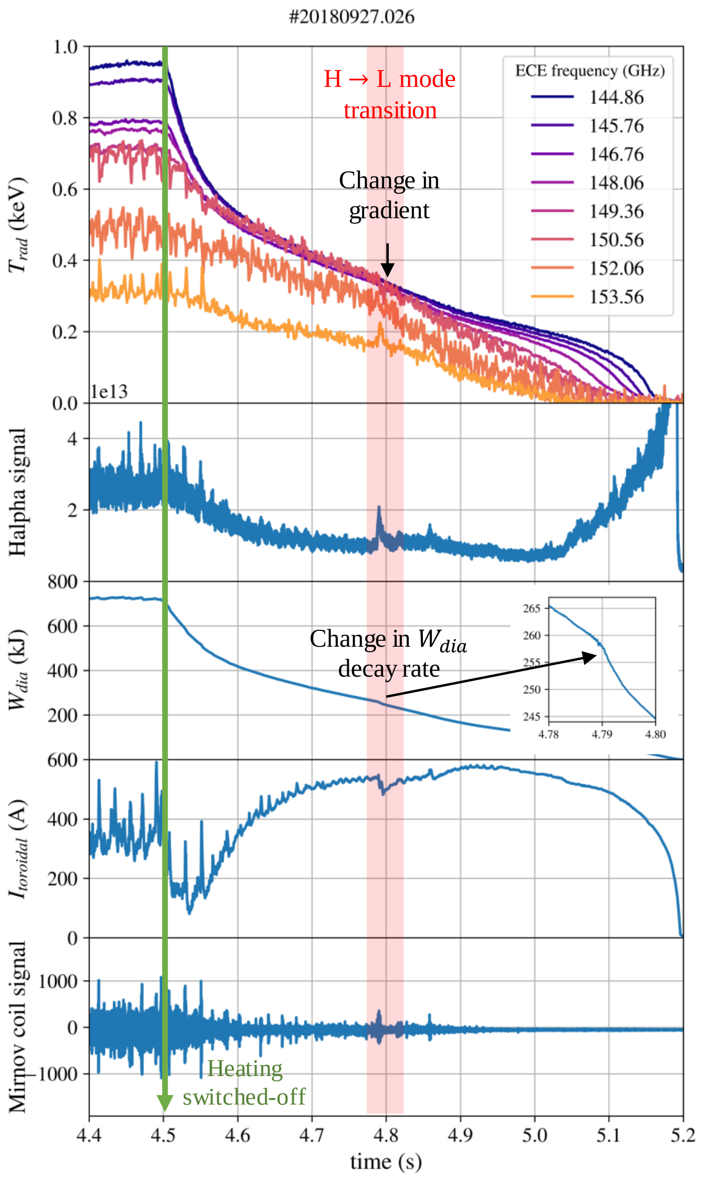


Figure 5: Time traces of ECE, H-alpha, W_{dia}, I_{tor}, and magnetic fluctuations are shown for the plasma discharge #20180927.026 where the magnetic island chain was moved inside the edge confinement region. Plasma heating was switched-off at 4.5 s, and at approximately 4.8 s, transition to a degraded confinement state can be observed through increased W_{dia} decay rate and changed temperature gradient with occurrence of an ELM-like crash (top plot).

temperature pedestal, as a consequence of a transport barrier, develops at the rational island location suggesting that islands affect the transport in that regime. The transport barrier is broken by ELM-like crash with an inversion radius $r_{eff} = 0.757$ at the location of pedestal. The ELM-like crash characteristics change with varying iota profile through changed island location and size, plasma density, heating, and hence vary with changes in the plasma pressure profile, and a typical ELM-like crash results in an energy loss of 3-5%. The pedestal builds up already during the plasma startup phase in W7-X stellarator, and hence no clear forward L to H-mode transition is seen for all the available configurations during iota scan experiments from OP1.2 of W7-X. However, a possible backward H to L-mode transition is observed during the plasma decay phase, after the heating is switched off, from different diagnostic measurements and the plasma parameters threshold values for back transition vary with different magnetic configurations. A detailed analysis of magnetic island impacting the transport and leading to the temperature pedestal developmental and an improved confinement state, alongside quantitative analysis for the H to L-mode back transition threshold values for different plasma parameter and magnetic configurations is yet to be followed.

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