Parametric decay of microwave beams in the edge island of Wendelstein 7-X: Theoretical modelling and correlation with edge fluctuations

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Introduction – An electromagnetic "pump" wave injected into a plasma can decay into a pair of daughter waves with similar frequency, if the pump power exceeds a given threshold, P_{thr}^{PDI}. In Wendelstein 7-X (W7-X) stellarator, parametric decay instability (PDI) can take place when an electron cyclotron resonance heating (ECRH) beam crosses a density bump in an edge magnetic island [1] and this may reduce the efficiency of the ECRH system, degrade microwave-based diagnostics [2], and damage plasma facing probes. In campaign OP1.2(b), PDI-related side-bands were observed around the gyrotron frequency [1], 140 GHz, with the collective Thomson scattering (CTS) [3] radiometer. Trapping of upper hybrid waves (UHWs) within the density bump in the island (measured with high spatial resolution by the alkali beam emission spectroscopy (ABES) [4]) is essential for strengthening the non-linear coupling between UHWs and the pump wave and reducing P_{thr}^{PDI} [5]. Here we present experimental evidence of the trapping mechanism in the island, predicted in [1].

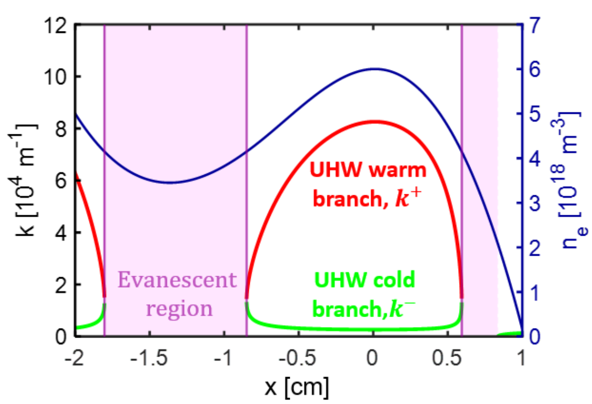

Figure 1. Sketch of the density bump with cold and warm dispersion curves for UHWs, $k^{\pm}$, at $f = 65$ GHz

Trapping mechanism and edge fluctuations – Fig.1 shows a sketch of an edge density bump, n_e, along the x direction, perpendicular to a background magnetic field, $B = 2.23$ T, in a plasma with electron temperature, $T_e = 40$ eV (typical values in the edge island of

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W7-X). The closed loop formed by the cold (green) and warm (red) branches of the UHW dispersion relation below the local density maximum shows trapping between evanescent regions (pink-shaded), where n_e is too low for propagation. If the local density minimum grows producing a flat profile, trapping and build-up of UHWs are prevented, and P_{thr}^{PDI} may exceed the maximum gyrotron power. Flattening of the ABES density profile was observed in connection with island localized modes (ILMs) [6], in magnetic configurations (MCs) with an island chain at 70-90% of the minor radius. ILMs are strong sawtooth-like crashes observed in the plasma edge [7] by several diagnostics, which evolve, in MCs with islands cut by the divertor plates (see fig.2a), into quasi-continuous oscillations [7].

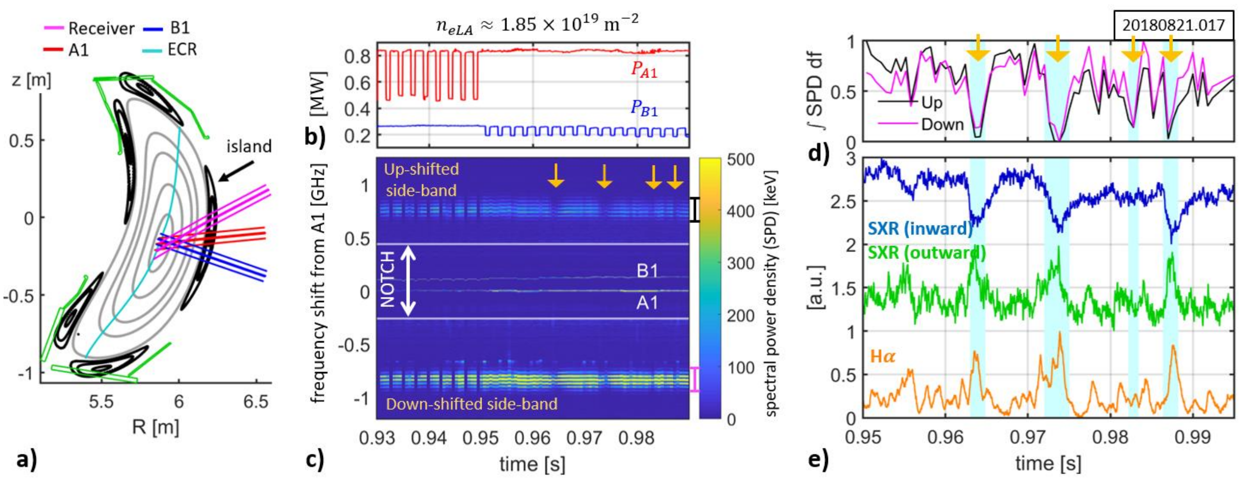

Figure 2. a) Poincare plot of the standard MC with ECRH beams, CTS receiver sight-line (magenta), and divertor plates (green). b) Time-traces of ECRH power and corresponding value of n_{eLA}. c) CTS mean spectrogram from t = 0.93-0.99 s. d) Time-traces of integrated and normalized SPD in PDI side-bands, and e) signals from SXR edge chords (inward and outward chords looking slightly inside and outside the last closed flux surface respectively) and Hα light.

Crashes in PDI-related side-bands: standard MC – Experimental setup and results for investigations of PDI in standard MC are shown in fig.2. A Poincare plot of the standard MC is provided in fig.2a, where ECRH beams (A1, B1) cross the equatorial plane magnetic island (black) and overlap with the receiver sight-line in proximity of the ECR. Time-traces of the injected microwave power are plotted in fig.2b where a modulation of P_{A1}~550-800 kW is followed from $t = 0.95$ s by a modulation of P_{B1}~180-250 kW, at constant line integrated density, $n_{e,LA}$. Fig.2c shows the resulting CTS mean spectrogram where the up-shifted and down-shifted side-bands around the notch filter region are the PDI-related signals. At $t = 0.93 - 0.95$ s, damping of the PDI side-bands is correlated with the modulation of P_{A1}, whereas the instability seems to be unaffected by P_{B1}. However, crashes in the PDI signals from $t = 0.95 - 1$ s are marked by yellow arrows in fig.2c and 2d. Correlation of crashes in the SPD of the PDI side-bands (see cyan-shaded areas in fig.2d) with the activity measured by soft X-rays (SXR) edge chords [8] and Hα light [9] (see fig.2e) suggests excitation of the instability in the plasma edge. Furthermore, comparable discharges with additional ABES measurements at high acquisition rate show a flattening of the island density profile during quasi-continuous fluctuations in the edge. The time-trace of the ABES density at the local density minimum ($R_{min} \approx 2.233$ m) reveals bursts corresponding to peaks in the edge SXR chords (cyan-shaded areas in fig.3, similar to fig.2e). The evolution of the ABES density profile for the event at $t \approx 0.891$ s is shown in the top panels in fig.3, where black curves and grey shades are the average and the standard deviation from 50 density profiles, computed over $\tau = 1$ ms. The hollow region of the density bump before the event rises producing a plateau during the burst, and is subsequently restored a few ms later. Such a flattening of the edge density profile could briefly suppress the trapping mechanism in the island (see fig.1), and substantially increase P_{thr}^{PDI}. Crashes in PDI-related signals (see fig.2c,d) during edge fluctuations could, then, provide a direct experimental validation of PDI in the ECRH beams in the island density bump, proposed in [1].

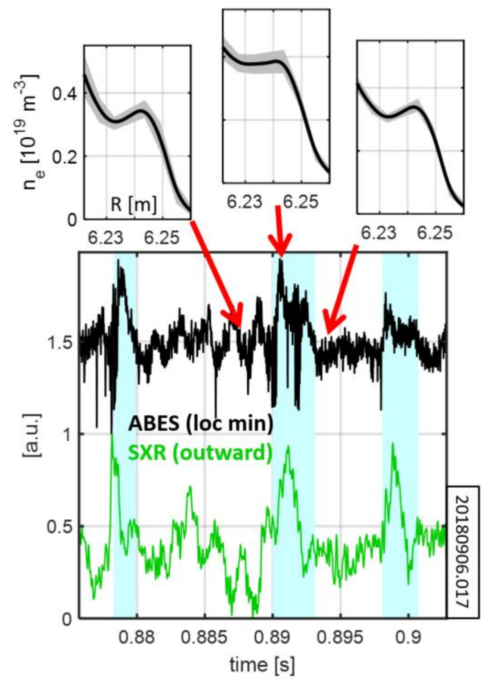

Figure 3 Time-traces of ABES profiles at R_{min} (black) and signal from an edge SXR chord (green). Top panels show the evolution of the density bump during one of the shown density bursts.

Crashes in PDI-related side-bands: high iota MC – The beam geometry and the power time-traces for experiments in high iota MC are analogous to those shown in fig.2a,b (with $n_{e,LA} \approx 3.32 \times 10^{19}$ m^{-2}) where, however, the ECRH beams cross a thinner magnetic island in the edge. Even though no density bump is generally measured in this MC, the absence of ABES data for the relevant discharge (20180822.013) prevents firm conclusions. In high iota MC, an additional down-shifted component is excited, termed down-weak, for its lower intensity compared to the symmetric side-bands. In fig.4a,b, time-traces of the normalized SPDs of both down-shifted PDI components are compared with time-traces of the edge SXR chords (Hα here unavailable). Here cyan-shaded regions highlight a strong correlation between crashes in the down-weak signal and SXR from the edge chords, suggesting excitation of this component in the plasma edge. However, since the SPD of the down-strong band does not display the oscillations of interest, this component may be generated in an inner region. A potential explanation involves PDI in the inner 10/9 island chain, crossed by the gyrotron beams in proximity of the overlap with the receiver line-of-sight, thus also providing a consistent explanation for the different intensity between the two components.

Summary – Crashes in the PDI-related side-bands correlated with quasi-continuous fluctuations in the plasma edge can shed light on the location of excitation of PDI in W7-X. In standard MC, the flattening of the density profile in the island during edge density fluctuations suggests suppression of the trapping mechanism, predicted in [1], and could explain the observed crashes in the PDI-related side-bands. In high iota MC, correlation of the down-weak component with edge SXR signals suggests PDI in the plasma edge whereas the stronger components could come from the inner 10/9 island chain, in proximity of the overlap between the gyrotron beams and the receiver sight-line.

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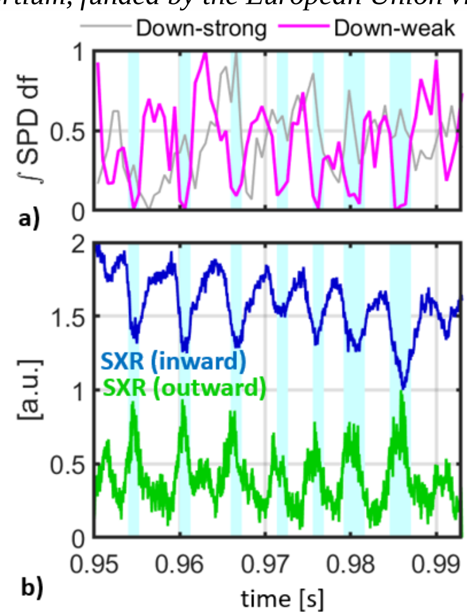

Figure 4. a) Time-traces of normalized SPDs for PDI down-shifted components in high iota MC, and b) corresponding signals from edge SXR chords.

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