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Parametric Decay Instabilities during Electron Cyclotron Resonance Heating at ASDEX Upgrade

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In parametric decay instabilities (PDIs) a strong pump wave decays to two lower-frequency daughter waves when its amplitude exceeds a nonlinear threshold. PDIs are found in all media with quadratic nonlinearities, e.g. plasmas, and provide a limit of validity of linear wave theories. Scenarios in which PDIs play a role within plasma physics include ionospheric modification experiments and wave heating of laboratory plasmas. Unexpected PDIs can damage wave-based plasma diagnostics and may even lead to significantly different heating and current drive characteristics if a significant amount of power is coupled to the daughter waves [1].

Here, we investigate PDIs during X-mode electron cyclotron resonance heating (ECRH) of the fusion-relevant plasmas at the ASDEX Upgrade tokamak. In these scenarios, PDIs are usually strongly suppressed by convective losses of the daughter waves which yield pump power thresholds ~ 10 MW [3], one order of magnitude above the power available from the gyrotron ECRH sources at ASDEX Upgrade [2]. However, in the presence of non-monotonic electron density (n_e) profiles, the daughter waves may be trapped, drastically reducing the convective losses and permitting the occurrence of absolute PDIs with pump power thresholds $\sim 1-30$ kW [3], well below the typical power of an ECRH beam.

Specifically, we consider the PDI in which a 140 GHz X-mode pump wave from an ECRH gyrotron decays to two upper hybrid (UH) waves with frequencies near 70 GHz (the sum of the daughter wave frequencies must equal the pump wave frequency due to conservation of energy in the three-wave process). The UH plasmons may be trapped if the UH frequency has a maximum slightly above 70 GHz, as they only propagate when their frequencies are below the UH frequency for conventional tokamak conditions. When they are trapped, the aforementioned low PDI thresholds are obtained [3]. The above condition can particularly be fulfilled if the 70 GHz UH resonance (UHR) occurs near a maximum of n_e, e.g. near the centre of an edge localized mode (ELM) filament [5]. PDIs during ELMs require the 70 GHz UHR to be located near the plasma edge which is essentially always the case for H-mode plasmas at the standard toroidal magnetic field (-2.5 T) of ASDEX Upgrade; plasma scenarios from the two discharges considered in this work are seen in Fig. 1 (R, z are cylindrical coordinates).
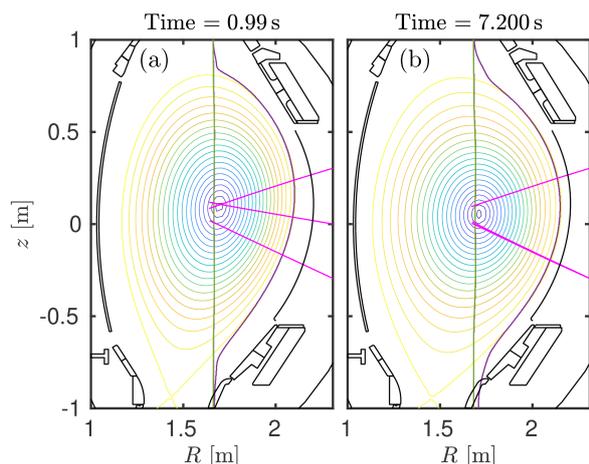
Figure 1: Plasma scenarios with PDIs during ELMs in ASDEX Upgrade: (a) #35676, (b) #33616. Green lines are the 2nd harmonic 140 GHz ECR, magenta lines are the ECRH beams, and purple lines are the 70 GHz UHR.
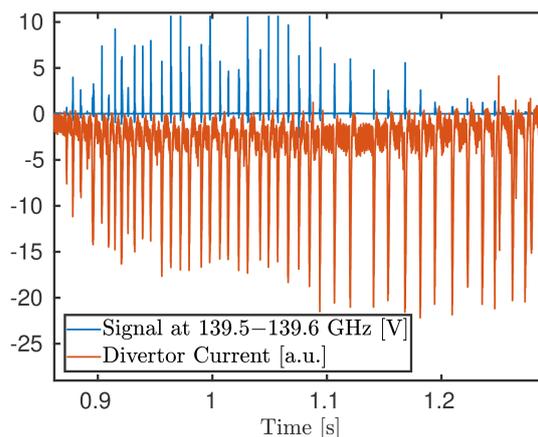
Figure 2: Signal from the slow CTS system at $139.5 - 139.6$ GHz and divertor current versus time in AS-DEX Upgrade #35676. A strong correlation between microwave bursts and ELMs is visible.

The PDIs during ELMs are investigated using the collective Thomson scattering (CTS) system at ASDEX Upgrade. The CTS system consists of two heterodyne radiometers measuring the microwave signal close to 140 GHz: a "slow" filter bank-based system with a sampling rate of 100 kHz and a "fast" system sampling the full down-converted signal at a rate of 6.25 GHz (spectrograms are constructed by fast Fourier transforms of 164 ns time slices of the recorded signal) [5, 6]. Both systems are connected to a single receiver line viewing an ECRH beam near the plasma edge.

While fast electrons also lead to microwave bursts during ELMs [7], there are spectral structures just below the ECRH frequency (seen in Fig. 3) which cannot be explained by such a mechanism, as these frequencies correspond to cyclotron emission from electrons near the plasma centre which are virtually unaffected by ELMs. The PDIs discussed above do, however, provide an explanation of these structures through microwaves generated by the combination of two PDI-generated UH waves [4]. Their PDI-origin is further substantiated by the observations that the structures only occur during ECRH operation and have a significantly larger amplitude for receiver views overlapping with an ECRH beam near the plasma edge.

Fig. 2 shows the signal from a channel of the slow CTS system just below the ECRH frequency along with the divertor current, in which spikes indicate the occurrence of ELMs. The correlation of the microwave bursts with the ELMs is very clear. The strongest signals occur at low n_e. Fig. 3 shows the signal from the fast CTS system during an ELM at low n_e. The ELM crash is associated with the spikes extending from the low-frequency edge of the notch filter to
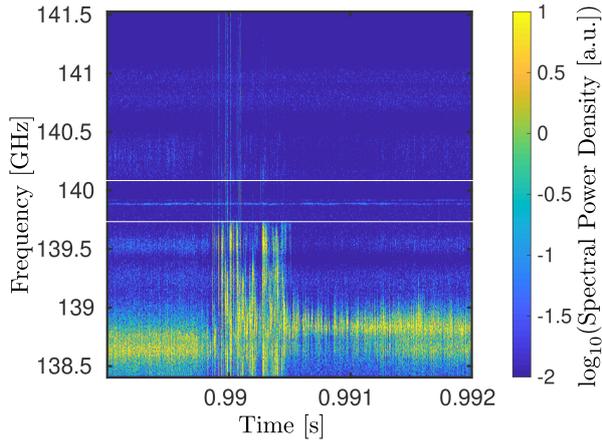
Figure 3: Spectrogram of the signal from the fast CTS system during an ELM at low n_e in ASDEX Upgrade #35676. The white lines mark the edges of the notch filter around the gyrotron lines.
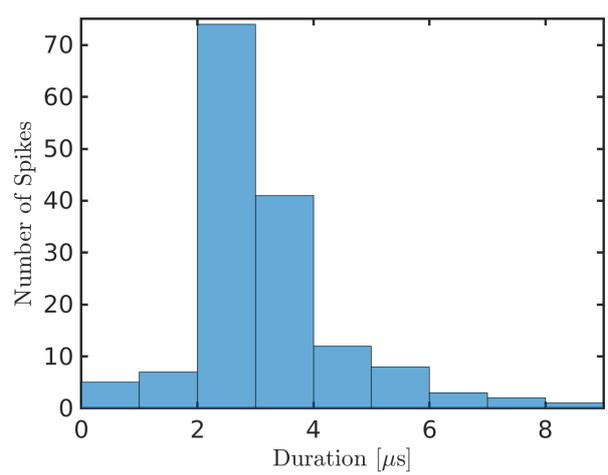
Figure 4: Histogram of the duration of spikes from $139.25-139.65$ GHz during ELMs in ASDEX Upgrade #35676.

the lowest frequency covered by the radiometer. The quasi-continuous lines from $138.5-139$ GHz before and after the ELM crash (also observed in [5]) are likely related to PDIs in the non-monotonic n_e-profiles set up by inter-ELM modes, which is consistent with them having different characteristics, e.g. frequency shifts, before and after the ELM crash. At higher n_e the spikes during the ELMs remain, although their amplitude is reduced significantly, while the quasi-continuous lines disappear, except for a small amount of activity just before an ELM crash. In order to characterize the spikes during ELMs, a histogram of their duration based on the observations from the fast CTS system is shown in Fig. 4. The majority of spikes last $2-4\,\mu$s and no spike lasts more than $8.62\pm0.05\,\mu$s; the average duration is $3.1\pm0.1\,\mu$s and the standard deviation of the duration is $1.3\,\mu$s.

The spike duration distribution found in Fig. 4 is consistent with the passage time of non-monotonic n_e-profiles allowing trapping of 70 GHz UH waves during an ELM crash through an ECRH beam. This is demonstrated in Fig. 5 which shows the evolution of n_e and the 70 GHz UHR according to a JOREK [8] simulation of an ELM in ASDEX Upgrade [9]. We note that the simulated discharge and the early phase of the experiment (seen in Fig. 2) have similar plasma and heating parameters, facilitating the comparison. In the snapshots, the simulation time (t) runs from $52.1-60.5\,\mu$s. During this time interval ($8.4\,\mu$s), a region allowing trapping of 70 GHz UH waves passes through the lower set of beams; $8.4\,\mu$s thus represents an upper bound of the burst duration which is close to the experimental value of $8.62\pm0.05\,\mu$s. We can further use the theory of [3] to estimate the ECRH power threshold which must be exceeded to excite PDIs when the trapping region crosses the central beam rays (at $t=55.4\,\mu$s); threshold values
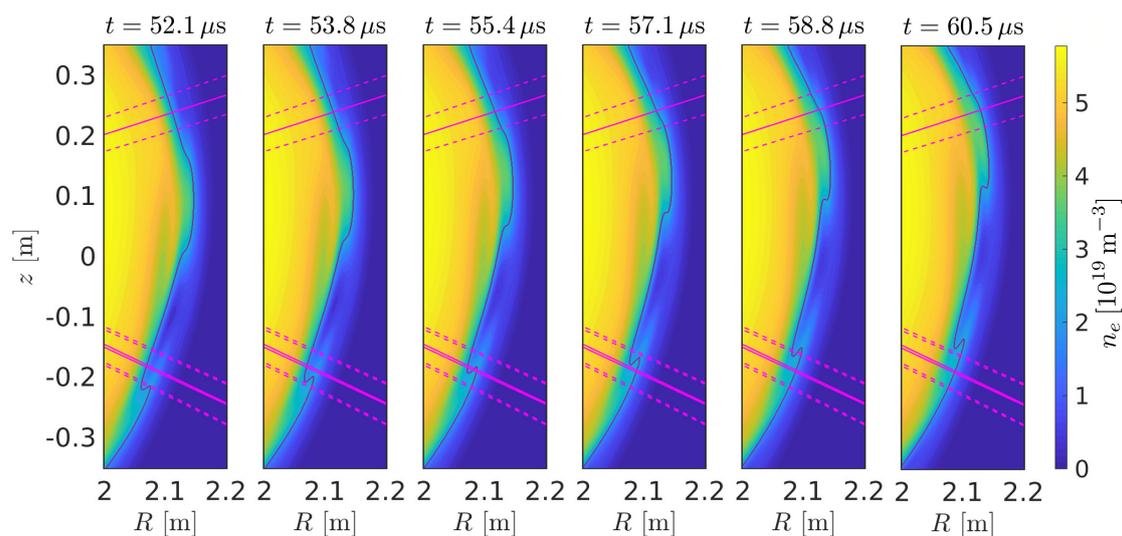
Figure 5: Evolution of n_e and the 70 GHz UHR (purple lines) in the JOREK simulation of an ELM in ASDEX Upgrade #33616. The solid magenta lines mark the gyrotron central beam rays; the dashed lines mark the beam widths.

of 891 W and 938 W are found for the two beams. Both these values are 3 orders of magnitudes lower than the power of the ECRH beams at ASDEX Upgrade, demonstrating that the PDI considered here can explain the generation of the microwave bursts observed during ELMs.

Acknowledgements

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