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Observation and Modelling of the Onset of Parametric Decay Instabilities during Gyrotron Operation at ASDEX Upgrade

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Abstract. We investigate parametric decay instabilities (PDIs) occurring for gyrotron radiation near the upper hybrid resonance at the ASDEX Upgrade tokamak. The PDIs are observed through anomalous millimeter-wave scattering which is recorded using the high resolution, fast acquisition collective Thomson scattering system installed at ASDEX Upgrade, and an experiment in which such observations are made during a scan of the toroidal magnetic field is performed. A previously published theoretical model is used to calculate the gyrotron power necessary to excite PDIs in the experiment; the theoretical model is capable of predicting whether or not PDIs will be observed at a given toroidal magnetic field with a high degree of accuracy.

1 Introduction

When high power gyrotron beams are injected into magnetically confined fusion plasmas, the wave amplitude may in some cases become so large that the linear approximation breaks down and a parametric decay instability (PDI), which couples the incoming electromagnetic wave to two (electrostatic) plasma waves, is excited. Energy and momentum conservation in the three-wave process require the selection rules,

$$\omega_0 = \omega_1 + \omega_2, \quad \mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2, \tag{1}$$

to be satisfied; here, ω is the angular frequency, $\mathbf{k}$ is the wave vector, subscript 0 refers to the gyrotron wave, and subscripts 1,2 refer to the plasma waves excited by the PDI. In the cases of interest to us, the wave referred to by subscript 1 is a low-frequency wave whose frequency lies near the lower hybrid (LH) frequency, ω_{LH}, while the wave referred to by subscript 2 is a high-frequency wave whose frequency is close to that of the gyrotron. Because of the frequency selection rule, the high-frequency wave will be down-shifted by approximately ω_{LH} ($\sim 2\pi \times 1\,\mathrm{GHz}$ in the main plasma of ASDEX Upgrade) from the gyrotron radiation, generally placing it outside the notch filters protecting the detectors used for millimeter-wave diagnostics such as ECE and collective Thomson scattering (CTS), causing it to hamper or

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potentially even damage said diagnostics. It is thus critical to understand PDIs in order to mitigate their potentially deleterious effects and, ideally, exploit the diagnostic tools that may be provided by them.

In this paper, we investigate PDIs occurring for X-mode radiation near the upper hybrid resonance (UHR), where $\omega_0 = \omega_{UH}$, with ω_{UH} being the UH frequency. PDIs are likely to occur for X-mode radiation near the UHR due to field enhancement effects, as noted by [1], who particularly considered the case of decay of the X-mode wave to a warm LH wave and an electron Bernstein wave, in connection with X1 ECRH of an optically thin resonance. The occurrence PDIs in connection with X1 ECRH was observed in a number of small toroial devices with optically thin resonances, e.g. Versator II [2], FT-1 [3], W VII-A [4], and TCA [5]. Such PDIs were also observed in connection with O1 ECRH at TCA, which was attributed to conversion of a significant amount of power to X-mode upon reflection from the vessel walls [5]; these observations indicate that the PDIs may also be of relevance during the start-up phase in ITER. The latter mechanism has also been used to explain PDIs observed during CTS experiments at ASDEX Upgrade [6–8], where the ECR is optically thin due to its location far on the high-field side in order to minimize the ECE background, and may also explain similar observations from LHD [9]. Beside the above cases, PDIs near the UHR have been shown to occur in connection with O-X-B heating of overdense plasma, e.g. at W-7AS [10, 11], MAST [12], and TJ-K [13]; such PDIs may also be expected in connection with O-X-B heating at W-7X. In the present work, we seek to validate the theoretical model from [8], which gives the gyrotron power threshold, P_0^{th}, that must be exceeded in order to excite PDIs in the CTS experiments at ASDEX Upgrade, by calculating the fraction of power converted to X-mode upon the reflection from the wall, the optical thickness of the ECR, the field enhancement near the UHR, and assuming decay of the X-mode wave to a warm LH wave and an electron Bernstein wave. To do this, millimeter-wave pulses in which the power, P_0, is swept from 0 to 300 kW are injected in O-mode by a gyrotron with $\omega_0 = 2\pi \times 105$ GHz from the system described in [14], and the electromagnetic emission/scattering in O-mode at frequencies close to ω_0 is measured during the pulses using the fast acquisition CTS system presented in [15]. From the above observations, the presence or lack of presence of PDI features in a given pulse can be established and compared with whether $\max(P_0)$ exceeds P_0^{th} from [8] in said pulse, thus allowing the predictive value of the theoretical model to be assessed.

The paper is arranged as follows: in Section 2 the experimental setup and observations at ASDEX Upgrade are described; in Section 3 the results of the theoretical modelling are presented and compared with the observations; finally, in Section 4 we draw our conclusions.

2 Observations

The observations presented in this paper stem from ASDEX Upgrade discharge #34575, which is an H-mode deuterium discharge, during which the toroidal magnetic field, B_t, was scanned from −2.66 T to −2.43 T; the most important effect of the B_t-scan for our purposes is the displacement of the ECR from inside the main plasma to the high-field side scrape-off layer which increases its transmission by an order of magnitude, as will be shown in Section 3. The basic setup in ASDEX Upgrade discharge #34575 is seen in Figure 1, and the procedures used for obtaining the experimental results follow what was outlined in Section 1: during the B_t-scan 200 pulses (each of 2 ms duration, which is very short compared with the 3.5 s duration of the scan) in which P_0 is varied from 0 to 300 kW are injected in O-mode from the low-field side, using a gyrotron with $\omega_0 = 2\pi \times 105$ GHz and fixed launcher settings. In each pulse the electromagnetic scattering/emission signal in O-mode at frequencies close ω_0 is recorded using the fast acquisition CTS system, which also has a fixed receiver located

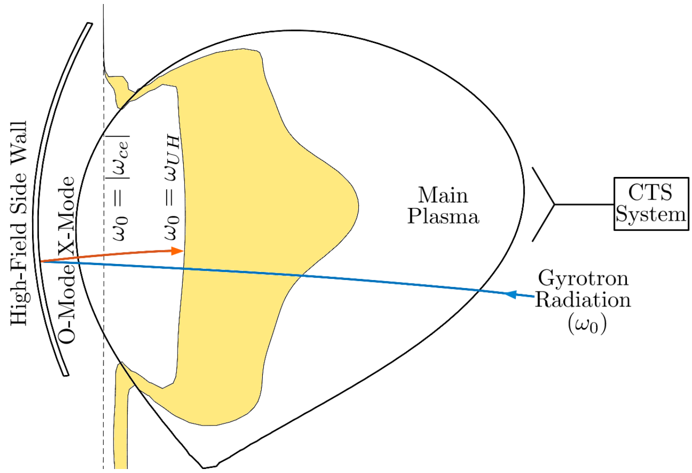

Figure 1. Experimental setup in ASDEX Upgrade discharge #34575. Gyrotron radiation, with $\omega_0 = 2\pi \times 105\,\text{GHz}$, is injected in O-mode from low-field side, partially transmitted by the (optically thin) ECR ($\omega_0 = |\omega_{ce}|$) and reflected by the high-field side wall. After the reflection, part of the radiation re-enters the plasma in X-mode; if the ECR is not optically thick for the X-mode radiation, a significant amount of power may reach the UHR ($\omega_0 = \omega_{UH}$) where PDIs can be triggered due to field enhancement effects. The electromagnetic emission/scattering in O-mode at frequencies close to ω_0 is measured using the fast acquisition CTS system. No propagating X-mode radiation exists in the shaded region.

on the low-field side, and power spectra are calculated by performing fast Fourier transforms on 655 ns windows of the recorded signal, giving a frequency resolution of 1.53 MHz. The mean power spectrum obtained during a pulse at $B_t = -2.531\,\text{T}$, i.e. near the middle of the B_t-scan, is seen Figure 2. In the figure, we clearly identify the gyrotron peak located inside a notch filter slightly below 105 GHz ($\omega_0 = 2\pi \times 104.93\,\text{GHz}$), as well as the down-shifted high-frequency peaks excited by the PDIs around 104 GHz. In addition to the down-shifted peaks, peaks up-shifted by a similar amount are seen; these peaks originate from scattering of the gyrotron wave by the low-frequency plasma waves excited by the PDIs, and satisfy the selection rules

$$\omega_3 = \omega_0 + \omega_1, \quad \mathbf{k}_3 = \mathbf{k}_0 + \mathbf{k}_1. \tag{2}$$

Apart from the peaks, we note the slanted ECE background which indicates the expected decrease of optical thickness with increasing frequency (decreasing major radii of the ECR location). For reference, we plot $(\omega_0 \pm \omega_1)/(2\pi)$ and $(\omega_0 \pm \omega_{LH})/(2\pi)$ at the point where the PDI model of [8] leads to the maximal amplification. Evidently, [8] overestimates the frequency shift of the PDI peaks relative to the gyrotron somewhat, while the simple estimate of the LH frequency underestimates it somewhat; both these findings are robust throughout the B_t-scan and also in agreement with those of [8], where they were attributed to use of the dipole approximation, $\mathbf{k}_0 \approx 0$, and finite temperature effects, respectively. The mean spectrum in Figure 2 is representative of those close to the onset of the PDIs; for pulses later in the B_t-scan more peaks occur, but in this paper we shall only be concerned with whether or not PDI peaks occur at all. Drawing only this distinction, the B_t-scan separates into three regions in terms of the types of spectra observed: for $B_t < -2.557\,\text{T}$ no spectra with PDI peaks are observed, for $B_t \in [-2.557\,\text{T}, -2.535\,\text{T}]$ spectra with and without PDI peaks are observed intermittently, and for $B_t > -2.535\,\text{T}$ all observed spectra contain PDI peaks; these observation are used for the comparison with the theory of [8] in Section 3.

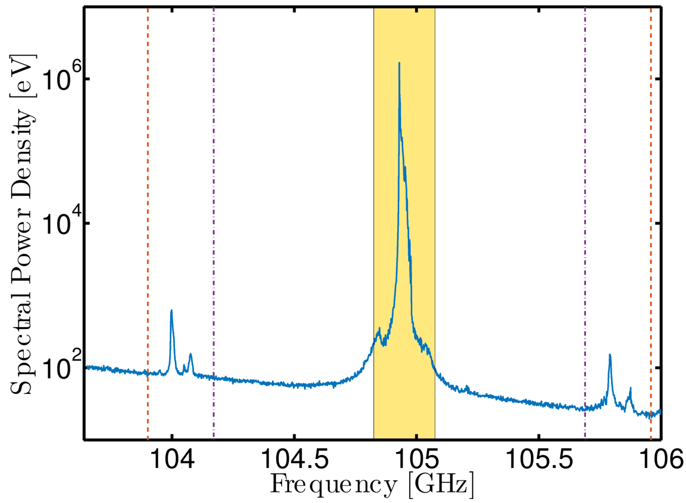

Figure 2. Semi-logarithmic plot showing the mean spectrum recorded using the fast acquisition CTS system during a pulse at $B_t = -2.531\,\mathrm{T}$ in ASDEX Upgrade discharge #34575. The gyrotron peak is clearly visible slightly below 105 GHz ($\omega_0/(2\pi) = 104.93\,\mathrm{GHz}$), and is located inside a notch filter, marked by the shaded area, where the calibration giving the spectral power density in eV is rather uncertain. The peaks due to the PDI generated plasma waves are shifted by 800 MHz to 900 MHz, roughly $\omega_{LH}/(2\pi)$, relative to the gyrotron peak; both down-shifted and up-shifted peaks are visible in the spectrum. For reference, $(\omega_0 \pm \omega_1)/(2\pi)$ and $(\omega_0 \pm \omega_{LH})/(2\pi)$ from the theory of [8] are plotted as dashed and dashed-dotted lines, respectively; the peaks are located between the lines as expected [8].

3 Modelling

As mentioned in Section 2, the most important effect of the B_t-scan for PDI purposes is to displace the ECR from inside the main plasma to the high-field side scrape-off layer, which should lead to a significant reduction of its optical thickness. This is indeed confirmed by calculations of the fraction of reflected power coupled to the plasma in X-mode, the fraction of power transmitted by the ECR from the gyrotron to the UHR, and the total fraction of gyrotron power reaching the UHR based on the theory of [8] (except that all quantities related to the X-mode fraction are now calculated at the last closed flux surface) shown in Figure 3: the X-mode fraction remains constant close to 0.1 until the end of the B_t-scan where it drops somewhat, while the fraction of power transmitted by the ECR increases from 0.1 at the beginning of the scan to 1 towards the end of the scan; the total fraction of gyrotron power reaching the UHR essentially follows the development of the transmitted fraction. We note a rather large uncertainty in the transmitted fraction due to uncertainties in the reconstructed magnetic equilibria from CLISTE [16], which determine the location of the last closed flux surface, as well as the electron temperature and density profiles from IDA [17], which vary rather quickly near the last closed flux surface and the values of which are primarily determined from measurements on the low-field side. We also note that Figure 3 only includes data points for pulses in which central ray of the reflected X-mode beam reaches the UHR, which is necessary in order to apply the theory of [8].

To test the theory of [8] we compute P_0^{th} using said theory and plot the values obtained in Figure 4. P_0^{th} shows a development which is approximately the inverse of that of the total fraction from Figure 3 during the B_t-scan; this is as expected, since the conditions at the UHR are roughly similar throughout the B_t-scan (it remains well inside the main plasma)

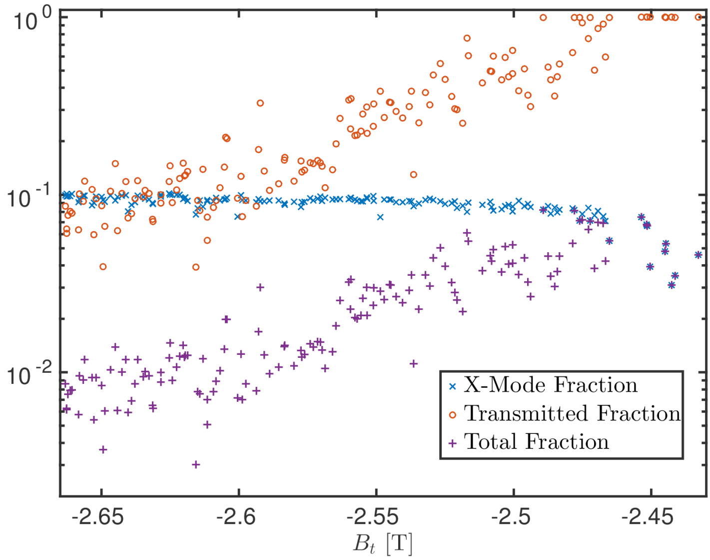

Figure 3. Semi-logarithmic plot showing the development of the fraction of reflected power coupled to the plasma in X-mode (×), the fraction of power transmitted by the ECR from the gyrotron to the UHR (○), and the total fraction of gyrotron power reaching the UHR (+) during the B_t-scan in ASDEX Upgrade discharge #34575, modelled using the theory of [8]. The X-mode fraction remains relatively constant with values around 0.1 throughout most of scan. The transmitted fraction fraction increases from approximately 0.1 to 1 during the B_t-scan; the development of the total fraction is similar to that of the transmitted fraction.

and the main variation is the amount of power transmitted from the gyrotron to the UHR. In Figure 4 the pulses for which PDI peaks (and no PDI peaks) are observed are marked, along with the maximum of P_0 ($\max(P_0) = 308\,\mathrm{kW}$). From [8] we expect that PDI peaks will be observed for $\max(P_0) > P_0^{\mathrm{th}}$, and this condition is indeed seen to provide a good indicator for whether PDI peaks will be observed or not in Figure 4: for the 88 pulses with $\max(P_0) < P_0^{\mathrm{th}}$, PDI peaks are only observed in 3 cases, while for the 61 cases with $\max(P_0) > P_0^{\mathrm{th}}$, PDI peaks are only not observed in 5 cases. The theory of [8] thus seems to provide a quite reliable indication of whether or not PDI peaks will be observed for given gyrotron settings and plasma conditions, in spite of the large uncertainty on the fraction of power transmitted by the ECR.

4 Conclusions

We have investigated PDIs occurring for X-mode radiation near the UHR at ASDEX Upgrade. The PDIs were excited by injection of pulses of 105 GHz gyrotron radiation in O-mode from the low-field side, which was transmitted by the optically thin ECR, reflected by the high-field side vessel wall and partially converted to X-mode. Part of the reflected X-mode power was transmitted by the ECR, whose optical thickness could be varied from a significant value to essentially zero by scanning B_t, and reached the UHR where it could excite PDIs due to field enhancement effects. The excitation of PDIs was observed through the occurrence of peaks shifted by roughly the LH frequency relative to the gyrotron peak in the electromagnetic emission/scattering spectra recorded using the fast acquisition CTS system. The occurrence of the PDI peaks was shown to be predicted quite accurately by the theory

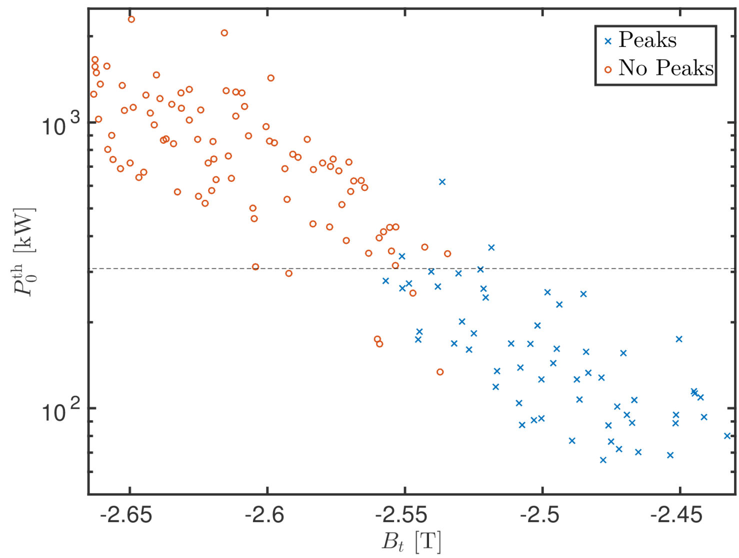

Figure 4. Semi-logarithmic plot showing the development of P_0^{th} during the B_t-scan in ASDEX Upgrade discharge #34575, calculated using the theory of [8]. The pulses for which peaks are observed in the PDI frequency range (cf. Figure 2) are marked by ×, while the pulses for which no such peaks are observed are marked by ∘; $\max(P_0) = 308$ kW is marked by the dashed line. Evidently, the occurrence of PDI peaks is closely correlated with the fulfilment of the condition $P_0^{\mathrm{th}} < \max(P_0)$ provided by the theory of [8].

of [8], which accounts for the fraction of power converted to X-mode at the wall reflection, the optical thickness of the ECR, field enhancement near the UHR, and models the PDI as decay of the X-mode waves into warm LH waves and electron Bernstein waves. Our findings indicate that the theory of [8] is capable of the describing the onset of PDIs near the UHR in a magnetically confined fusion plasma, although it is only capable of providing limits of the regions in which the PDI peaks occur due to the limits of the dipole approximation on which it is based. It would thus seem reasonable to apply the theory of [8] to start-up scenarios for ITER in order to assess whether PDIs near UHR are expected there; for the overdense plasmas expected in connection with O-X-B heating, the theory of [18] is presumably more appropriate.

Acknowledgements

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