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Particle-in-cell simulations of two plasmon decay in a non-monotonic density profile

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Abstract. Strong scattering during electron cyclotron resonance heating (ECRH) experiments in several magnetically confined fusion devices has been attributed to parametric decay instabilities (PDIs). Analytical modeling has shown that a non-monotonic density profile and excitation of trapped waves through two plasmon decay (TPD) play an important role. Using a particle-in-cell (PIC) code, decay of an X-mode wave into waves trapped inside a non-monotonic density profile is observed. The time evolution and composition of the daughter waves are investigated for different density profiles. A build up of the TPD daughter waves is only observed when they are supported by the plasma.

1 Introduction

Observations of strong scattering at unexpected frequencies in electron cyclotron resonance heating (ECRH) experiments in TEXTOR suggests that part of the ECRH power does not heat the plasma as intended. The scattering is observed in spite of the injected gyrotron power levels of ECRH being far below traditional threshold estimates of nonlinear wave interactions. Characteristic for the scattering is that it is shifted in frequency relative to the injected waves by approximately a lower hybrid frequency which is an indicator that it is caused by parametric decay instabilities (PDIs).

PDIs are nonlinear wave interactions that facilitate a transfer of energy between the interacting waves. The waves may interact if certain selection rules ensuring conservation of energy and momentum are satisfied and may become unstable above a wave amplitude threshold. Two plasmon decay (TPD) is a particular type of parametric decay where a pump wave decays into two similar daughter waves.

The traditional PDI threshold estimate is based on an inhomogeneous monotonic density profile in which implicated waves only interact with the PDI decay region briefly. However, a number of effects have been observed to cause a non-monotonic density profile to occur. By taking into account that a non-monotonic density profile may allow for the injected waves to decay into trapped waves through TPD, the trapped waves may build up in intensity without leaving the decay region. With trapped waves building up, the gyrotron power threshold for PDIs to take place is effectively reduced. This potentially drains power from strong millimeter waves intended for heating and may produce strong scattering which microwave diagnostics might not be shielded against. Some estimate up to ~20% of ECRH power might be lost for TEXTOR parameters[1].

Trapping of TPD daughter waves is possible if the density profile is non-monotonic in a way such that an upper hybrid (UH) layer surrounds the TPD decay region. X-mode and EBWs excited through TPD will then largely be trapped as either converts into the other and changes its direction of propagation at the UH layer. The TPD conversion rate depends on the population of the pump and daughter waves so a mechanism that keeps the daughter waves in the vicinity of the decay region can cause a significant build up of the TPD daughter wave population locally. When that happens, other PDIs and nonlinear effects may become prevalent which may, in the end, account for the observed strong scattering at shifted frequencies.

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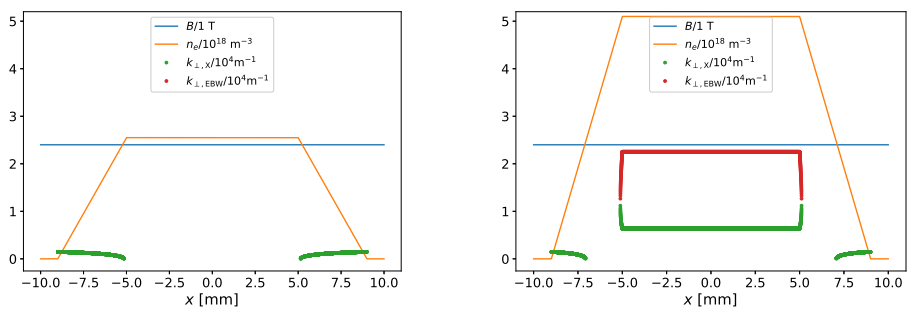
The aim of the herein presented investigation is to look into excitation of trapped waves using numerical simulations. The particle-in-cell (PIC) code EPOCH[2] is used to compare excitations of TPD daughter waves for an X-mode wave passing through two non-monotonic density profiles. One profile supports trapped TPD daughter waves whereas the other does not. The time evolution and composition of TPD daughter waves is compared for the two density profiles. Whilst the trapped waves are not the experimentally observed waves, they do play a fundamental role in the reduced threshold PDI models that explain the observed strong scattering.

2 Numerical setup

Using the PIC code EPOCH, an X-mode high power millimeter beam passing through a hot magnetized 1D deuterium plasma bump is simulated. The pump wave frequency is $f_0 = 140$ GHz and it has an intensity of $I = 10^5$ W/cm^2. The plasma temperature is $T_\mathrm{e} = T_\mathrm{i} = T = 100$ eV and a background magnetic field of $B = 2.4$ T is applied. The setup is somewhat idealized to allow for later k-analysis; the magnetic field is homogeneous and pointing in the homogeneous y-direction. The density profile is given by

$$n_e = n_i = n = \begin{cases} n_\mathrm{max}, & |x| \leq \delta \\ n_\mathrm{max}\left(1 - \dfrac{|x| - \delta}{\ell}\right), & \delta < |x| \leq \delta + \ell \\ 0, & \delta + \ell < |x| \leq w \end{cases}, \tag{1}$$

where $2w = 2$ cm is the width of the numerical domain, $2\delta = 1$ cm is the width of an initially entirely homogeneous region, and $\ell = 0.4$ cm is the length of a gradient regions on both sides of the density bump which bridge the maximum density to vacuum at the boundaries. Two simulations are run with different maximum densities which are shown in figures 1 (a-b). Figure 1 (a) shows a profile where TPD daughter waves should not be supported whereas figure 1 (b) shows a profile where the TPD daughter waves are trapped inside the density bump.



(a) (b)

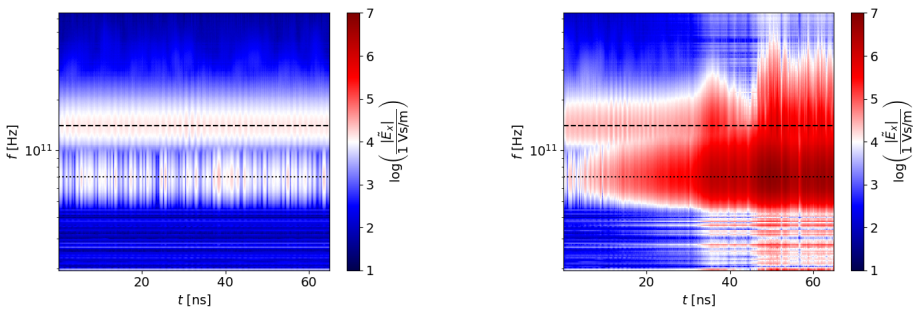
Figure 1: Plots showing the density profile (orange) given by equation (1) for two simulations. Furthermore, the magnetic field (blue) as well as the perpendicular wavenumber of the TPD X-mode (green) and EBW (red) daughters. Figure (a) is for $n_\mathrm{max} = 0.255 \times 10^{19}$ m^{-3} where TPD daughter waves are not support. Figure (b) is for $n_\mathrm{max} = 0.51 \times 10^{19}$ m^{-3} where trapping is possible.

3 Comparison between trapping and no trapping

For the analysis of the simulation data, just the longitudinal electric field component, E_x, is used as this is the component that carries most information about the electrostatic TPD daughter waves.

3.1 Build up of TPD daughter waves

If TPD occurs and the daughter waves are supported by the plasma, a build up of spectral power near $f_0/2$ should be observable. To investigate this, a CWT of E_x for both density profiles is calculated at the center position, $x = 0$, and is shown in figures 2 (a-b). In figure 2 (a) where TPD daughters are not supported, the spectral power at the pump frequency is stable at the initial level. At half the frequency, where TPD daughter wave live, the level is intermittent but no build up is observed. For the density profile that supports trapped TPD daughter waves, figure 2 (b) shows a level at the pump frequency that stays stable for the first ~ 30 ns while the level at the TPD daughter waves is seen to increase by several orders of magnitude until at ~ 30 ns when the level at both pump and TPD daughter frequencies start fluctuating in a coherent manner. The time scale of X-mode traversing the density bump is approximately 30 ns.



(a) (b)

Figure 2: CWTs of the time evolution of the longitudinal component of the electric field. The pump frequency, $f_0 = 140$ GHz, is marked by the dashed black line, and the dotted black line marks the approximate TPD daughter frequency, $f_0/2 = 70$ GHz. Figures (a-b) use the density profiles shown in figures 1 (a-b) respectively.

3.2 Trapped modes in frequency- and k-space

Transforming the homogeneous region into frequency and k-space using an FFT, the spectra shown in figures 3 (a-b) are obtained. In both cases, thermally excited X-mode and EBW dispersion lines are clearly visible and agree well with the dispersion relations found in equation (8) of [1]. The thermally excited lines are placed in different positions in the two figures due to the difference in density. In figure 3 (a), a small peak is shown around the expected TPD frequency of 70 GHz, however, it does not lie along any dispersion line and can therefore be expected to dampen quickly. This would explain why no build up is seen in figure 2 (a). When the plasma does support TPD daughter waves, on the other hand, 4 peaks are observed along the X-mode and EBW lines as seen in figure 3 (b). In agreement with the model presented in [1], the frequencies are seen to vary slightly, suggesting that the TPD daughter waves are not exactly identical. All of these four waves would move towards a UH layer whenever they leave the homogeneous region and would thus be converted and back scattered, trapping them inside the density bump. It is noted that the four waves are not thermally excited as they would otherwise be visible in figure 3 (a) as well and cannot enter from outside the density bump because of the UH layers which also keeps them inside.

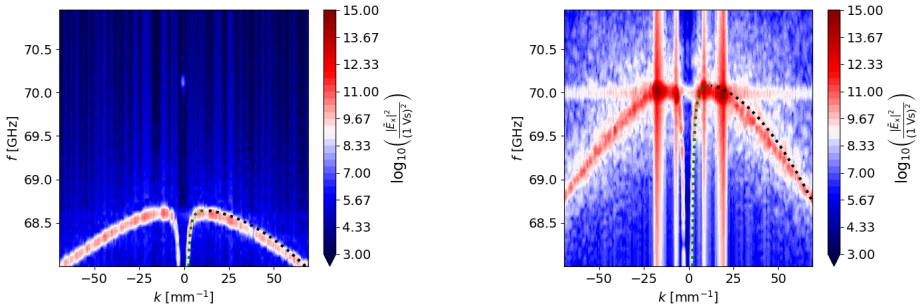


Figure 3: FFT of the E_x for -5 mm < x < 5 mm and 10 ns < t < 30 ns. The dotted green line in each plot are the X-mode dispersion lines and the dotted black lines are EBW dispersion lines. The frequencies of the TPD daughter waves are all approximately 70 GHz. Figures (a-b) use the density profiles shown in figures 1 (a-b) respectively.

4 Discussion and future work

TPD of an X-mode pump into X-mode and EBWs was successfully observed in PIC simulations. By comparing two simulations with different density profiles, it was concluded that although TPD will happen, an actual build up is unlikely unless the plasma supports the TPD daughter waves. While a build up was observed, the time scale was on the order of the X-mode traverse time and not of the full X-B-X roundtrip which makes it unlikely that cavity effects are causing the build up shown in figure 2 (b). It is possible that the level of the TPD daughters changes dramatically after a number of full roundtrips but those simulations would be much longer due to the slow group speed of EBWs. Whilst it might be possible to make a cavity in 1D, it is more likely to be successful at higher dimensions due to the infinitely many closed trajectories that exist. Lastly, TPD into trapped waves does not by itself explain the experimentally observed scattering but it is a crucial initial step of the analytical model. Escaping electromagnetic waves shifted in frequency from the pump is going to be the subject of future investigations.

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