Parametric Decay Instabilities in Electron Cyclotron Wall Conditioning: Comparison Between Models and Experiments

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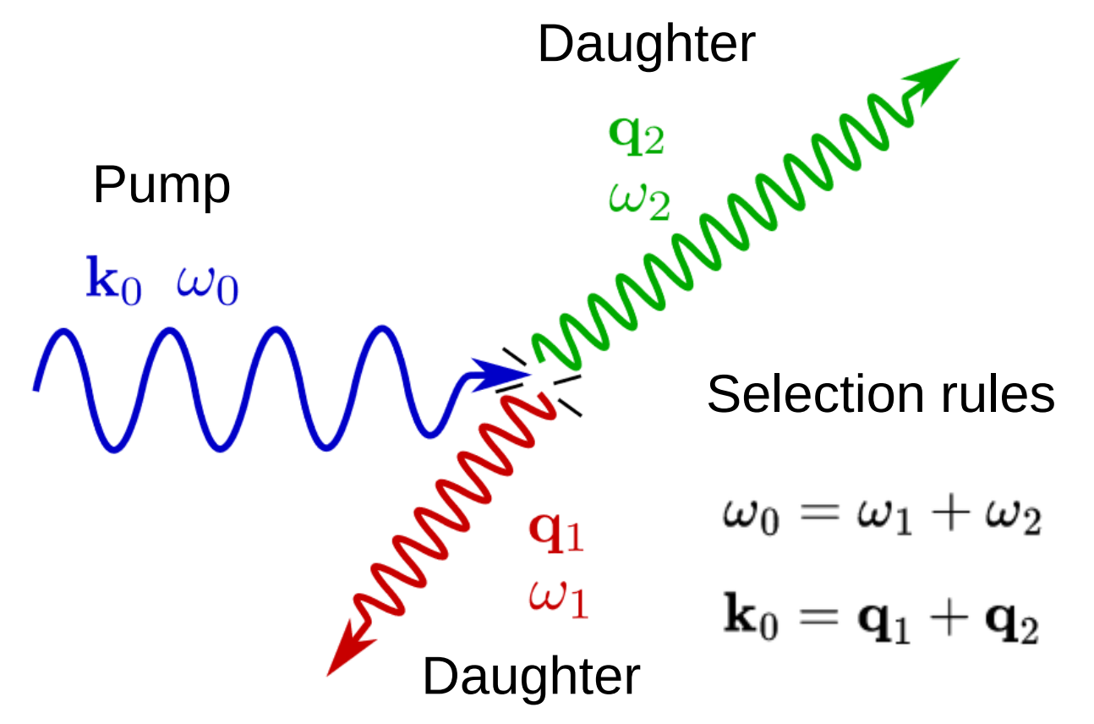
Introduction

Parametric decay instabilities might play a significant role in various plasma physics phenomena and have garnered considerable interest in recent years [1]. In this study, we compare a model of parametric decay instabilities against the data observed during experiments conducted in the AUG (ASDEX Upgrade) fusion device while performing Electron Cyclotron Wall Conditioning (ECWC)[2]. During these experiments, an unexpected observation was made—clear spectral signals appeared at approximately half the main gyrotron frequency. Here we present a model that describes the necessary conditions for a primary decay to occur in ECWC discharges and compare the prediction of the model against the features observed in the experiments.

Parametric Decay Instability

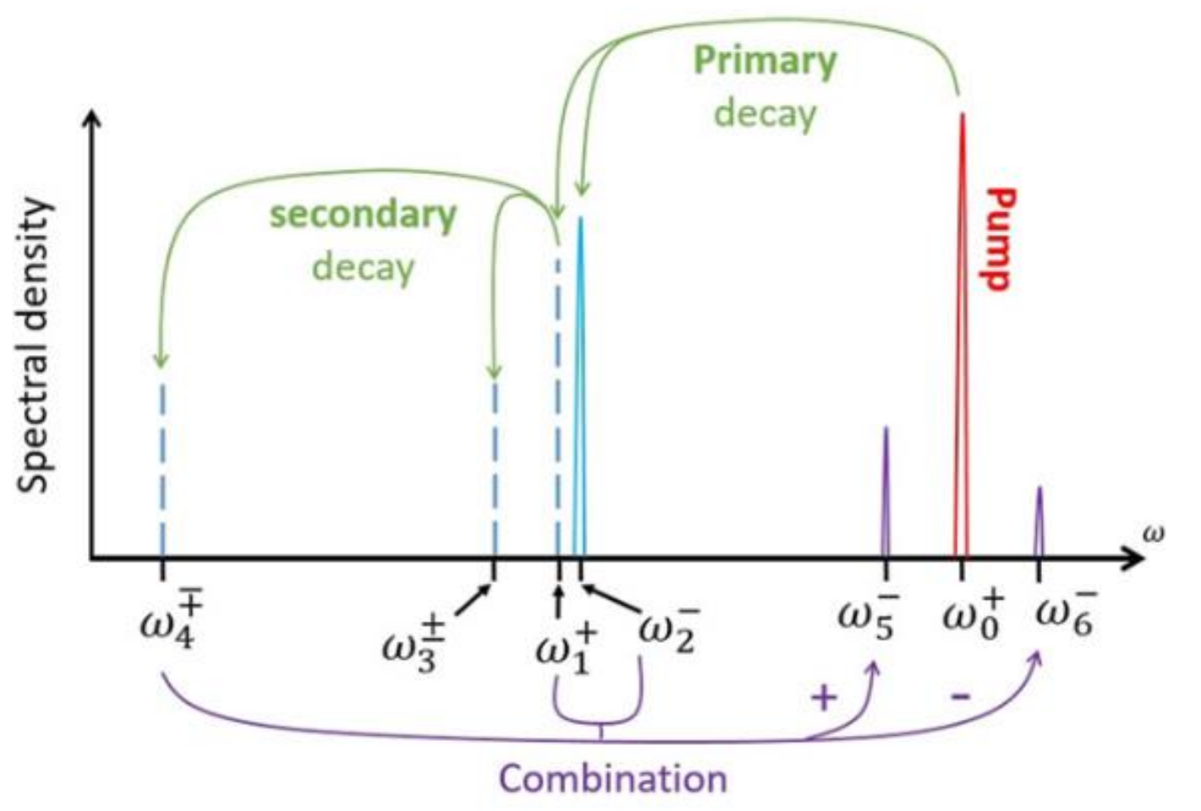
Parametric decay instability (PDI) is a non-linear process where a pump wave decays into two daughter waves. Subsequent decays are possible when the growth of the daughter waves is saturated by non-linear mechanisms. The daughter waves could recombine and scatter with the pump wave. A decay can be convective or absolute, where the last could be characterized by waves that are trapped in the interaction region, with intensities that can grow exponentially.



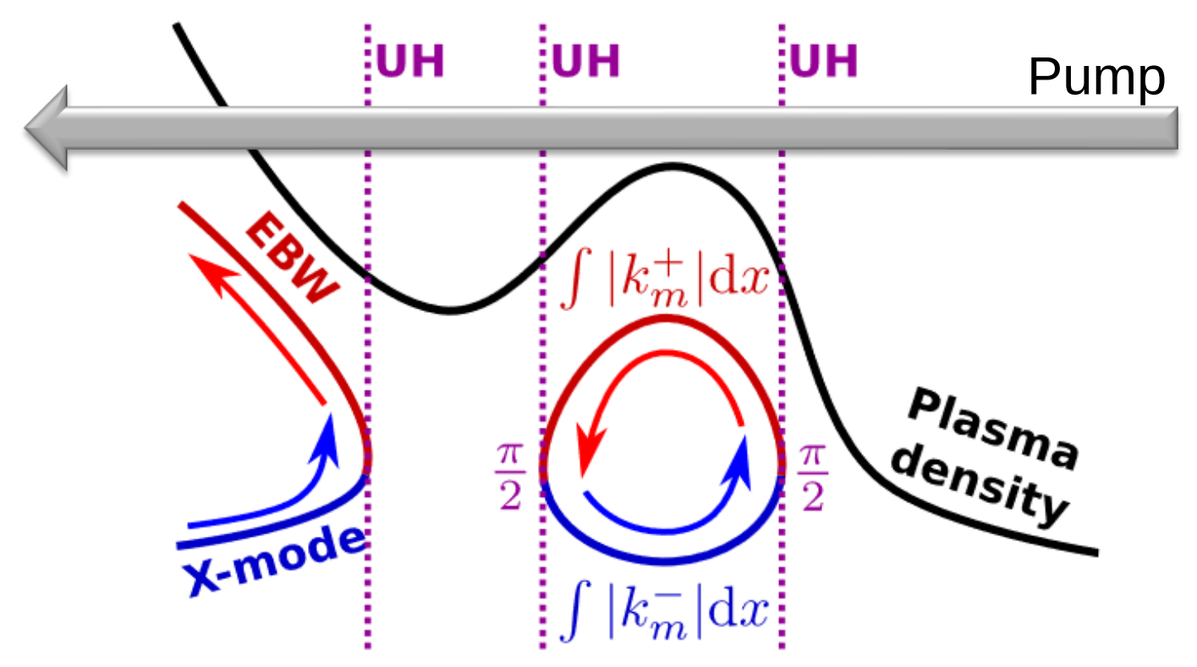
Selection rules

$$\omega_0 = \omega_1 + \omega_2$$

$$\mathbf{k}_0 = \mathbf{q}_1 + \mathbf{q}_2$$



In a region between two Upper Hybrid resonance (UHR) layers, two waves can be trapped as they bounce on the UH layer converting from the electron Bernstein wave (EBW) branch to a slow-X-mode branch (and vice-versa), giving rise to an absolute decay.



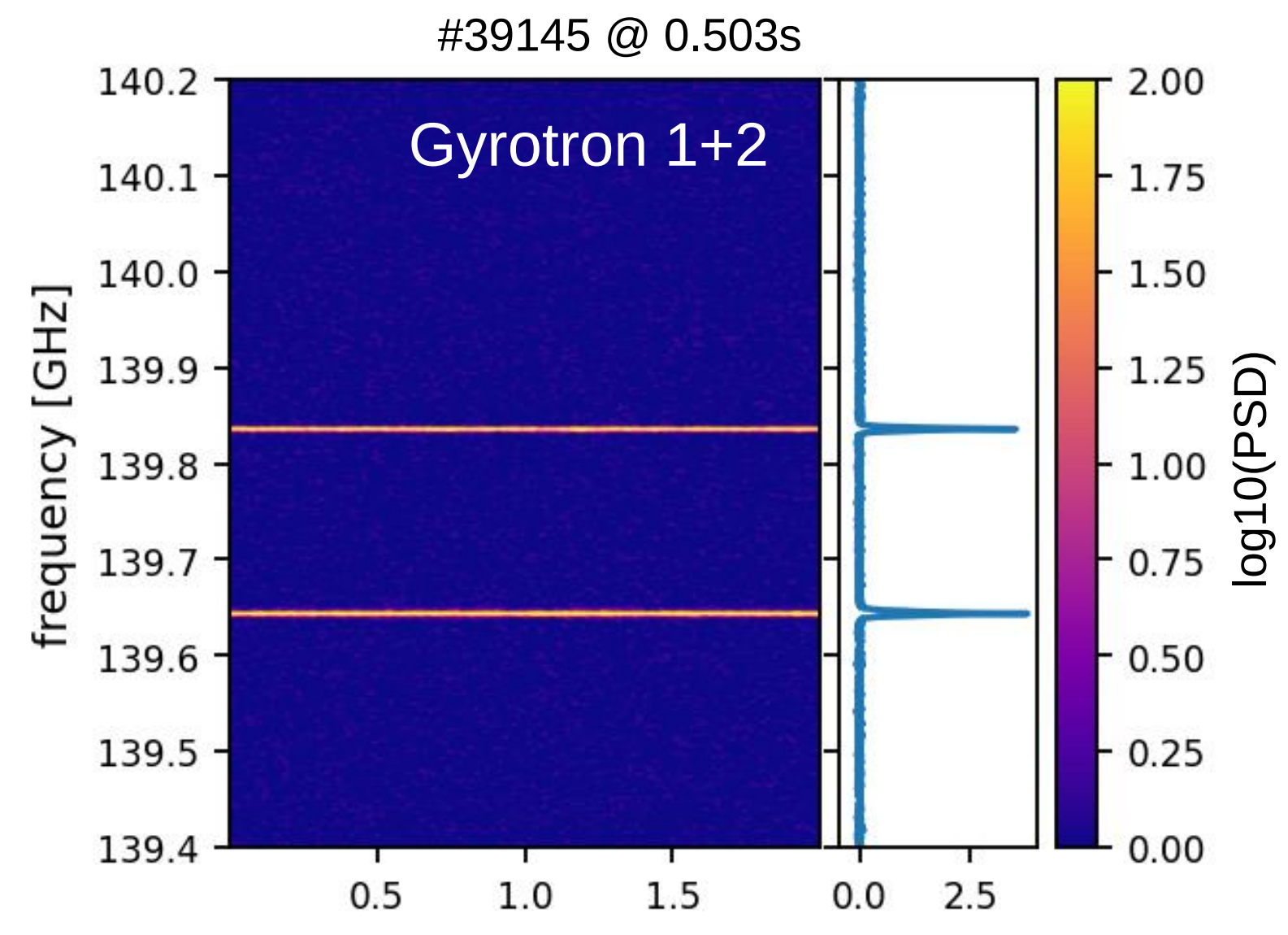
Bohr-Sommerfeld quantization rule:

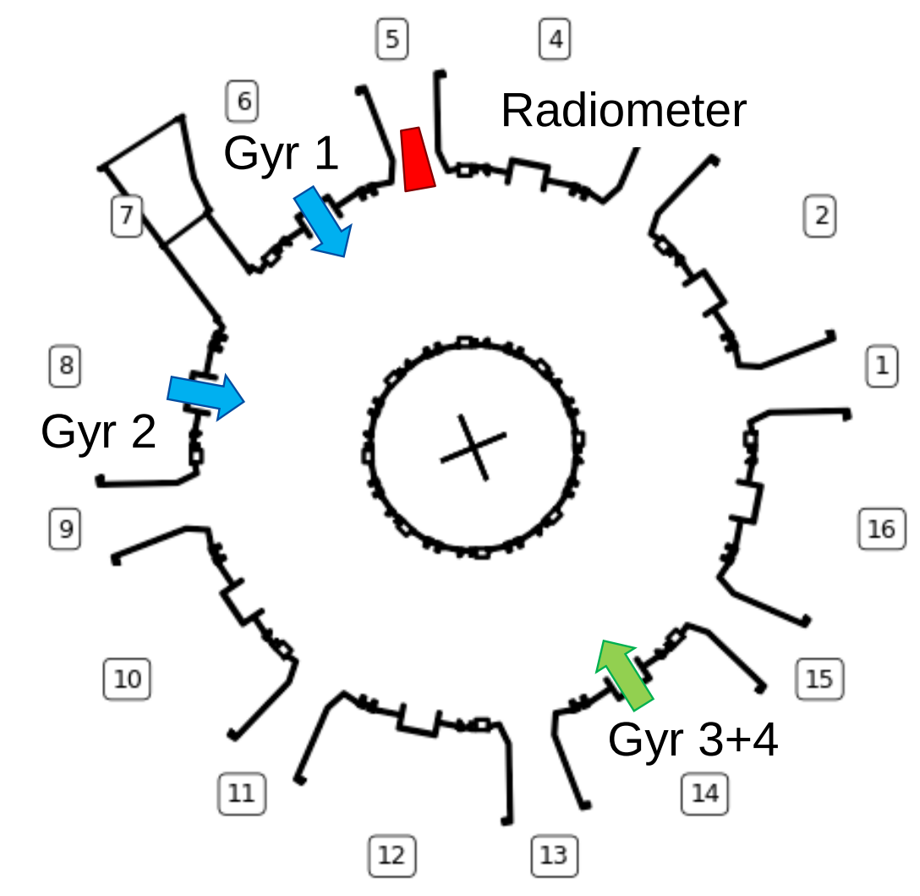
$$\int_{x_r}^{x_l} |k_x^+| + |k_x^-| \mathrm{dx} = (2m+1)\pi, \quad m \in \mathbb{Z}$$

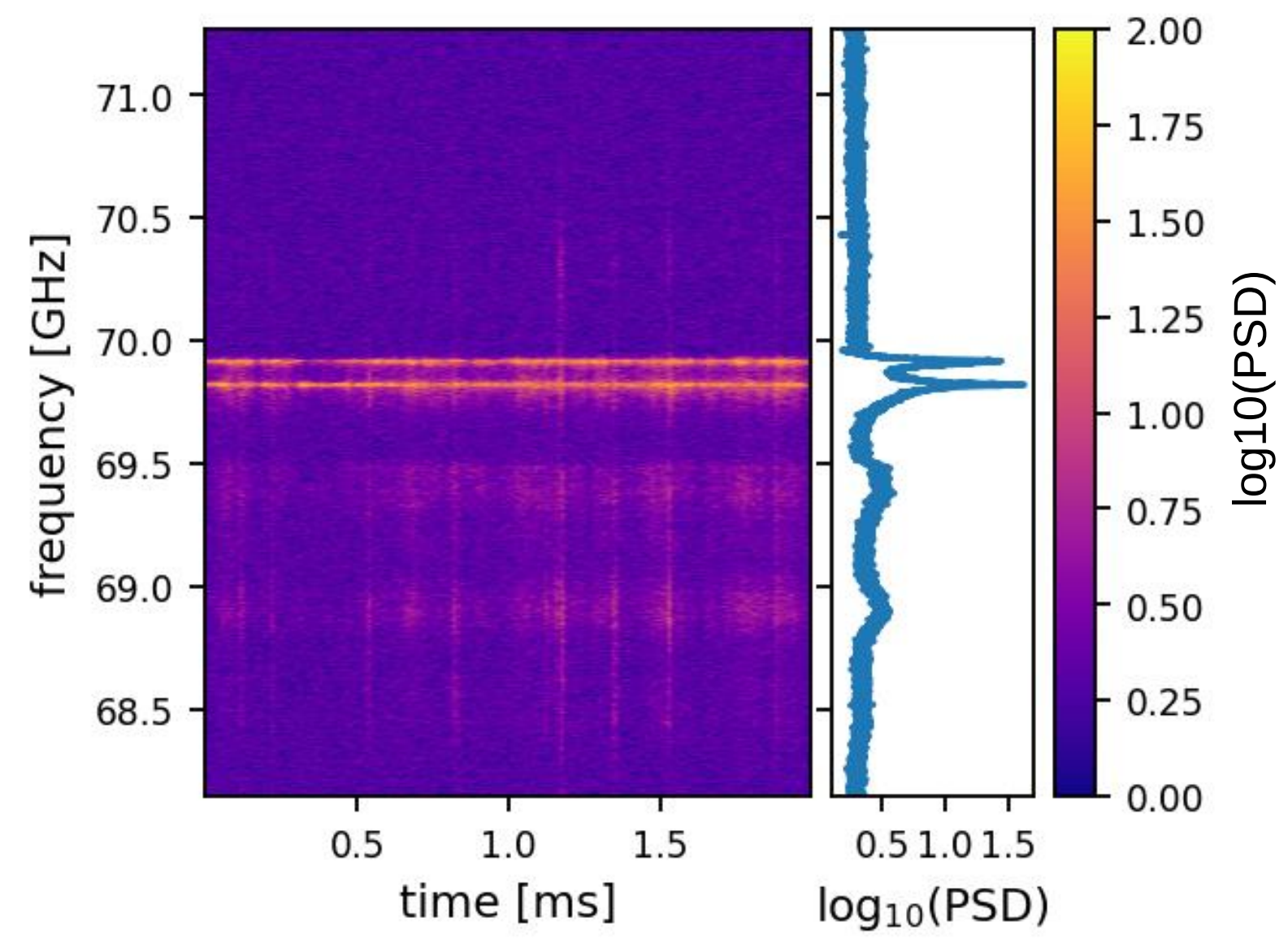
where x is the direction of the inhomogeneity and k_x^+, k_x^- are the hot and cold wave numbers of an eigenmode of the cavity.

Observations

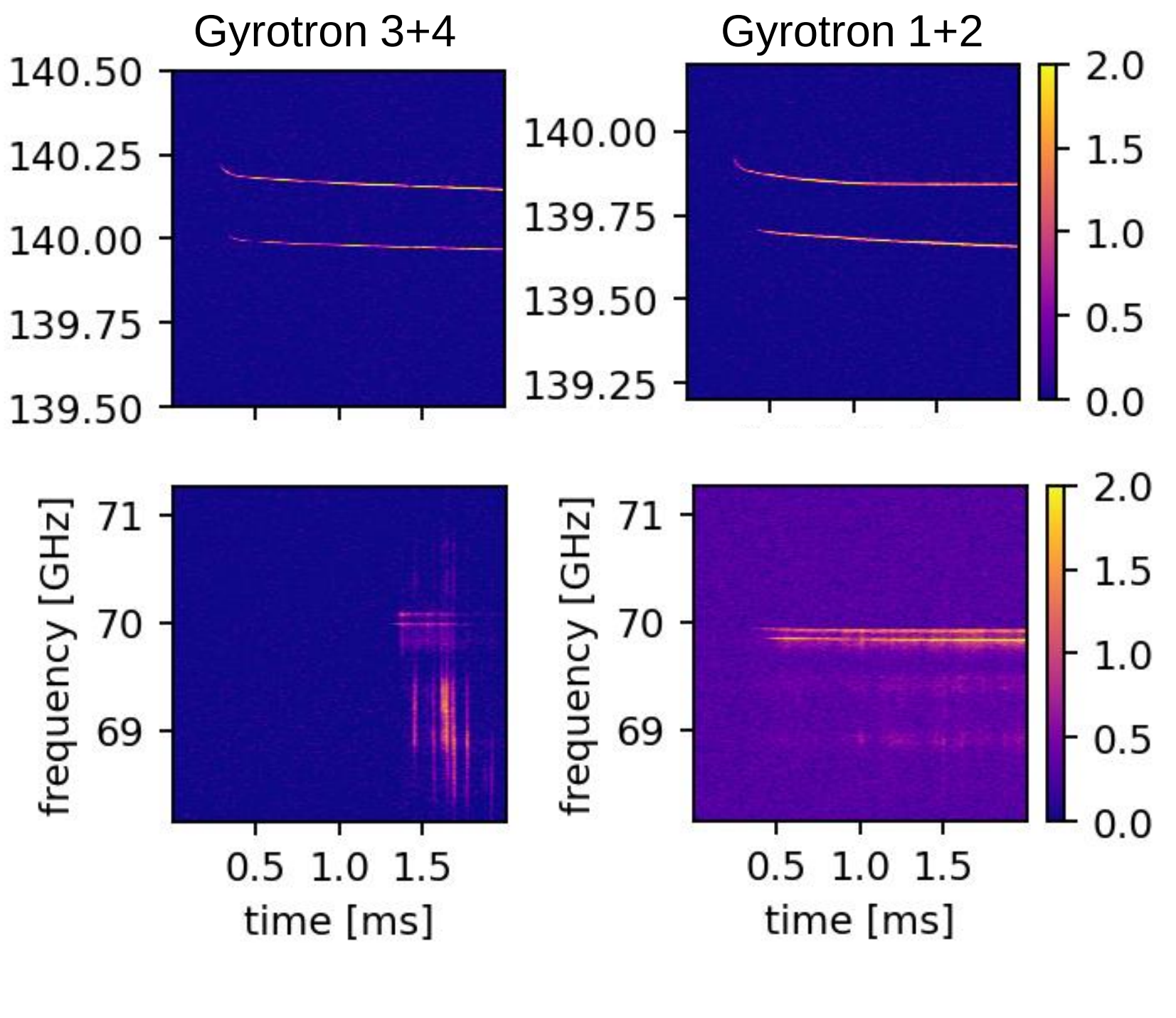
During ECWC experiments at AUG [2], a radiometer covering the 140 GHz band and the 70 GHz band was used to monitor the discharges. Two couples of gyrotrons were used: (3+4) and (1+2). Visible cameras were used to monitor the emitted light. In particular, we observed microwave emission at half the pump frequency, and light emission from a location (ring) in agreement with the location of the UHR.

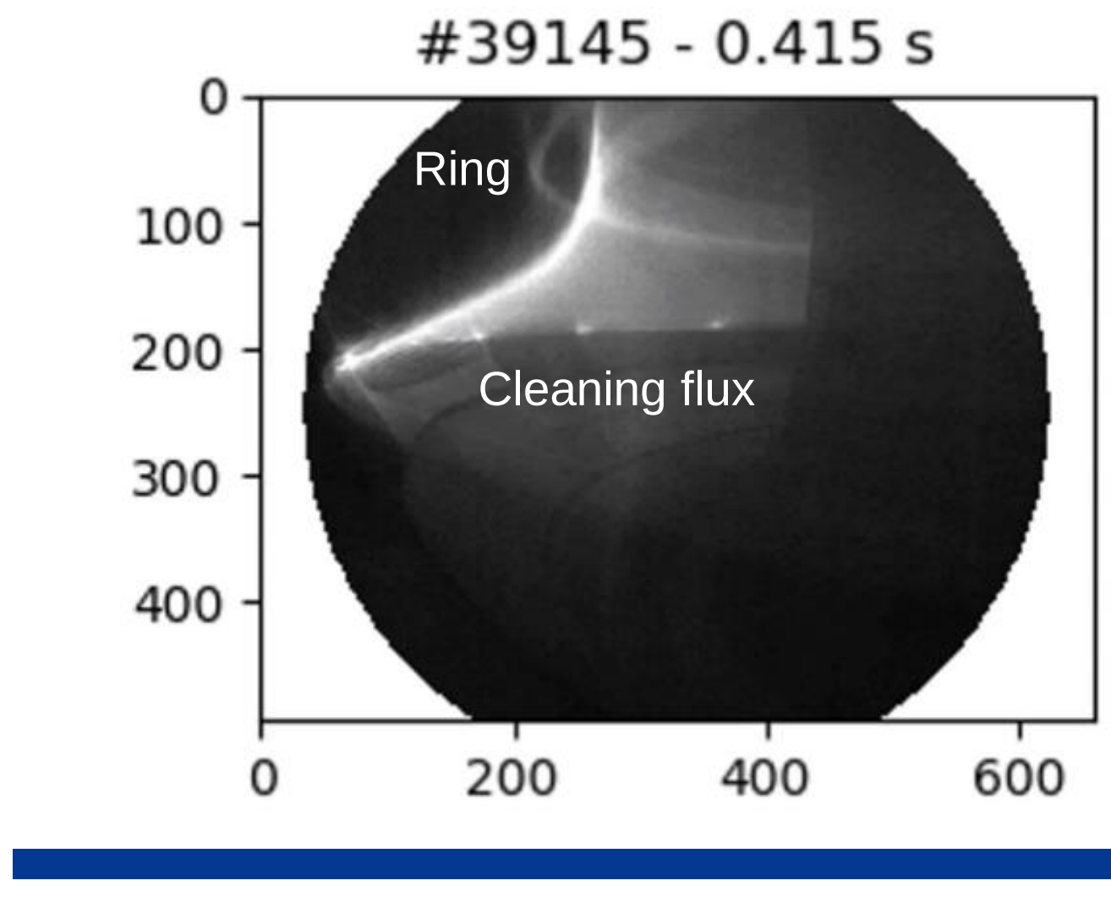






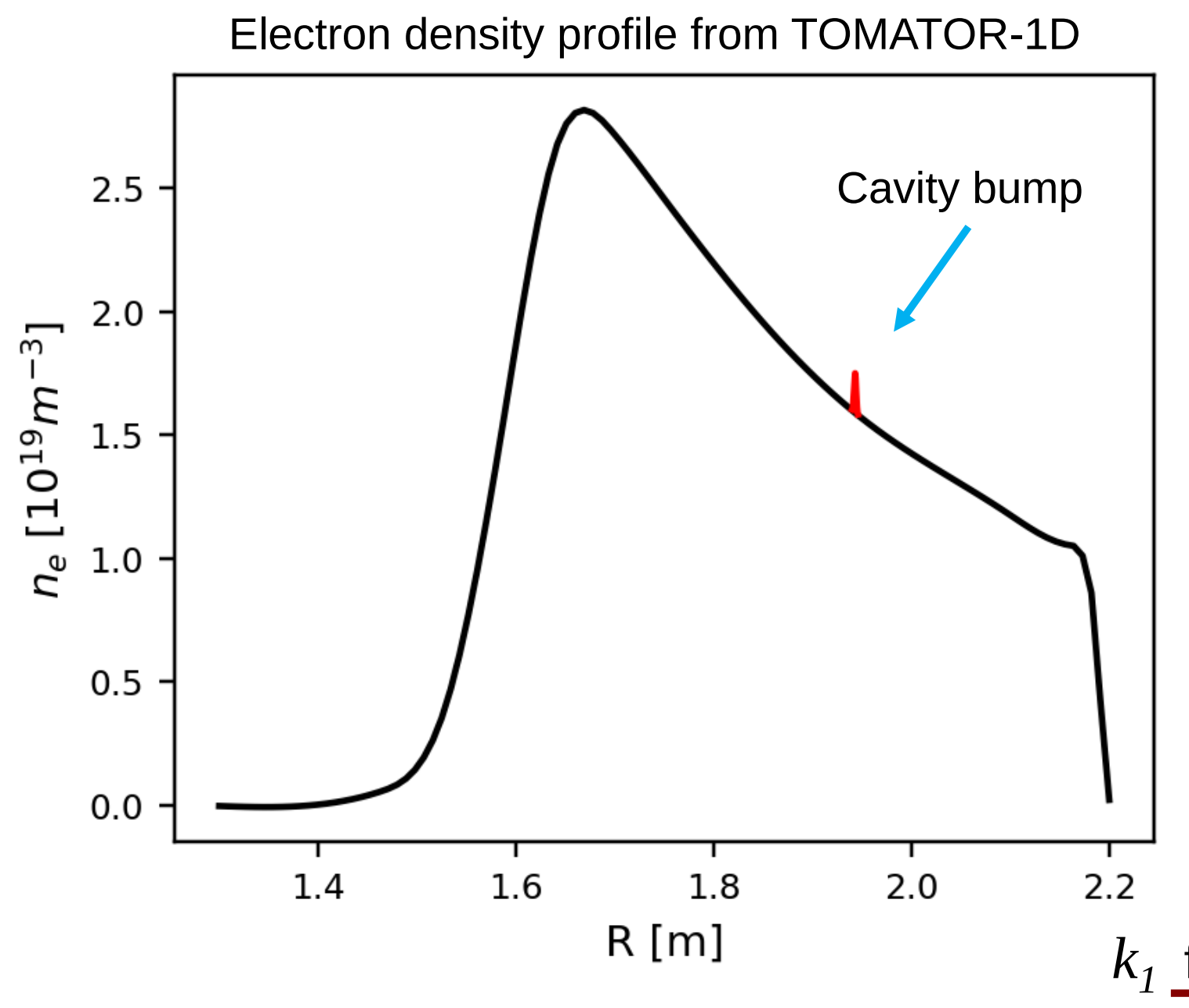
We observed also that in the first phase of the power injection, the PDI signal is delayed ~1ms while in the second phase the delay is considerably shorter.





Model

Tomator-1D simulations are used to estimate the electron density and temperature profile. The code [3] demonstrated good agreement with measurements obtained from AUG diagnostics. The temperature is here fixed at 2 eV. A density bump is created on top of the simulated density profile. The magnetic field is considered constant across the region of the perturbation.



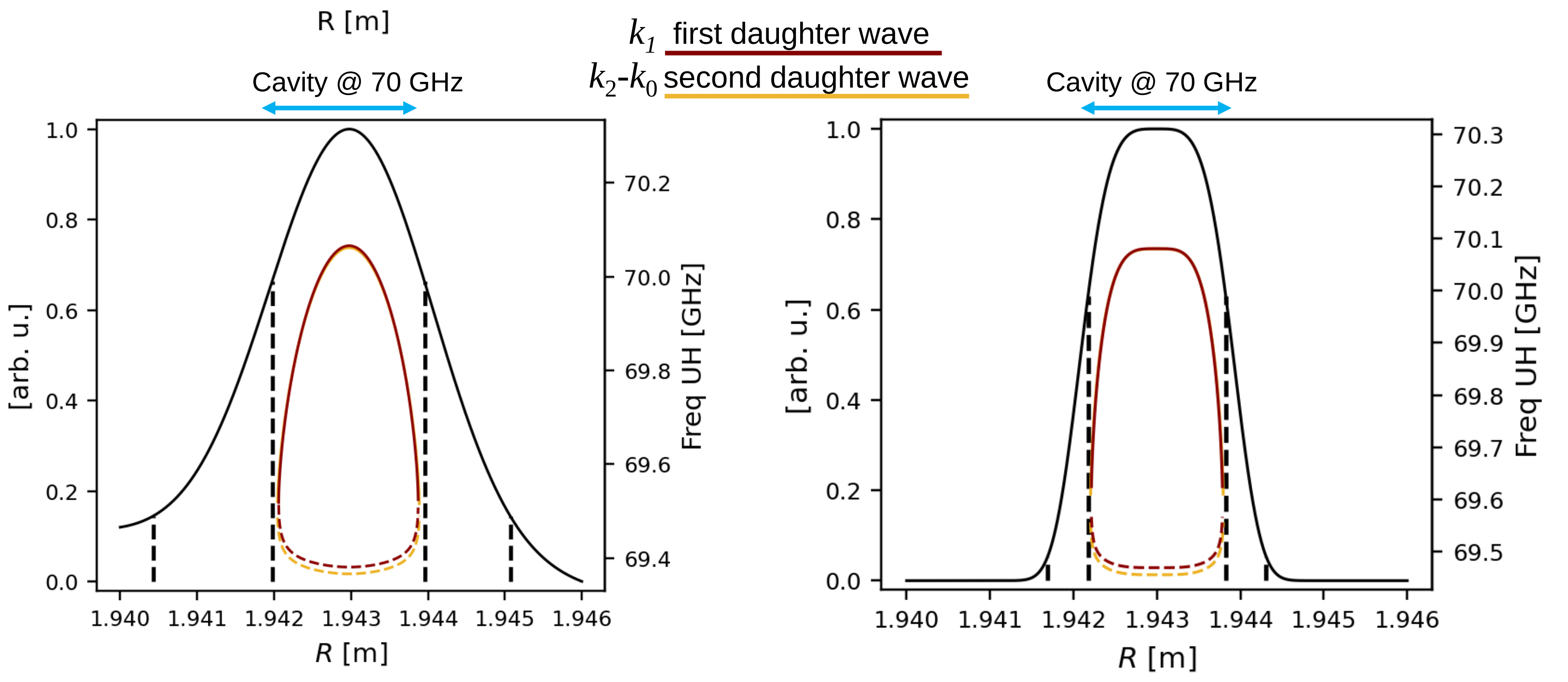
The dispersion relation is used to compute the trapped daughter waves [1] (the '*eggs*').

$$(k_\perp^{\pm})^2 = -\frac{S}{2l_{T_e}^2}\left(1 \pm \sqrt{1 - \frac{4Pk_\parallel^2 l_{T_e}^2}{S^2} + \frac{4\omega^2}{c^2}\frac{S^2 - D^2}{S^2} l_{T_e}^2}\right)$$

Temperature factor

k^+ is the EBW
k^- is the slow X-mode

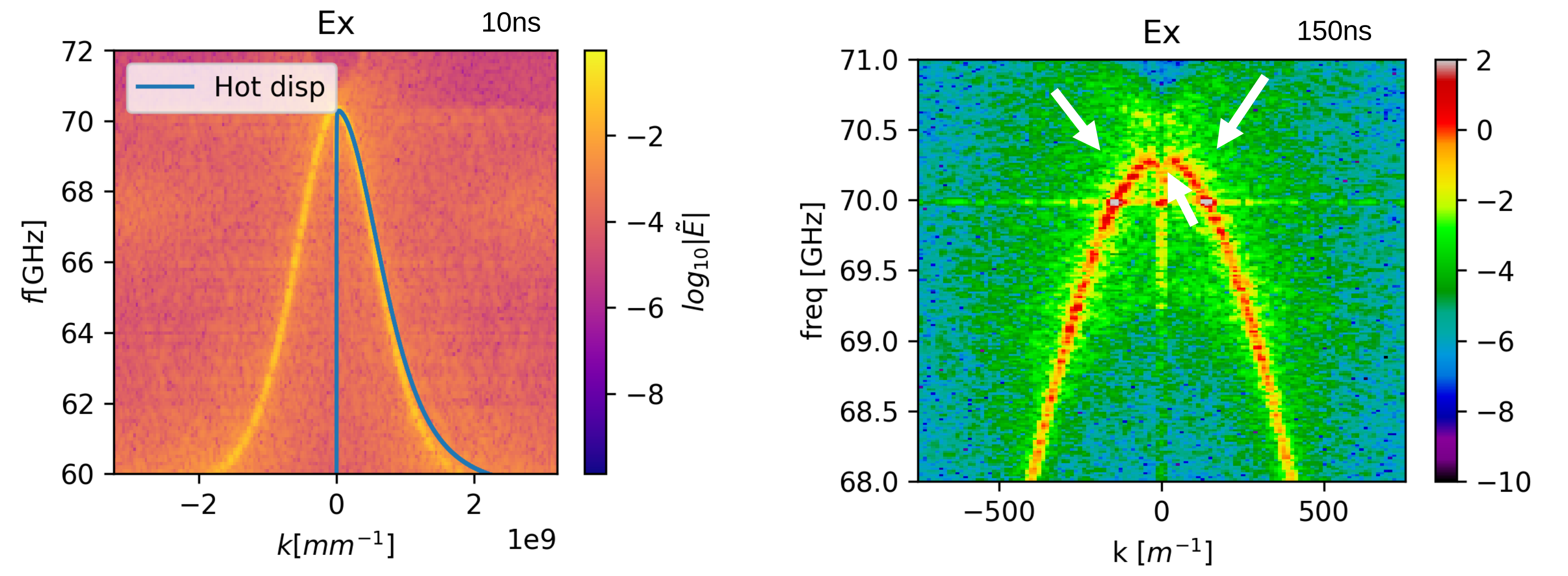
S,D,P: Stix parameters



Density profiles of the bump that could trap daughter waves. Two cases are considered: a gaussian profile and a super-gaussian. The second one is convenient from a simulation point-of-view, as it allows calculating the ω-k spectrum in the quasi-homogeneous region, i.e. the center. The trapped waves have similar characteristics in both cavities. The perturbation peaks at ca.1.5x10^{18} m^{-3}.

Particle-In-Cell simulation (1D-3v)

The SMILEI [6] code is used to verify the prediction of the model. An ω-k spectrum shows good agreement between the hot-kinetic dispersion relation and the dispersion relation computed from the electrostatic component of the electric field in SMILEI. The grid resolution is 4096 points, with 1000 particles per grid-point, a magnetic field of 2.12T, and a pump wave intensity of 5x10^5 W/cm^2. The injected polarization is X-mode. After 150ns the daughter waves appear at 70 GHz.



Discussion

During ECWC experiments, a signal at half of the gyrotron frequency was measured in correlation with a radiometer monitoring synchronously the 140 GHz and the 70 GHz bands. PDI is invoked as mechanism responsible for the creation of daughter waves trapped in a non-monotonic density profile. The delay observed in the appearance at the initial phase of power injection (gyr 3+4) is attributed to the time needed to breakdown the plasma and to increase the density above a threshold forming the trapping cavity. In the second phase (gyr 1+2), a target plasma is already present, and the daughter waves appears more rapidly. Moreover, the signal from gyr 1 and 2 is stronger than for gyr 3 and 4, due to the relative distance between the beams and the radiometer.
A model is used to investigate a possible density bump able to trap the daughter waves, leading to an absolute decay. A simulation of an ad-hoc density profile is carried out with the particle-in-cell code SMILEI. The results in the form of ω-k spectrum are compared against a hot-kinetic dispersion. Two daughter waves at approximately half the pump frequency are retrieved from the electrostatic component of the simulated fields. Both analytical model and numerical simulation are in agreement with the experimentally observed features. The location of the density bump, thus of the UHRs, appears in agreement with the location of the additional ring of emitted light [2]. The dynamics of the creation of the density bump is still unclear, and further experiments could provide insight on the mechanism of power absorption.

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