Full-wave simulations of the O–X conversion in plasmas with fluctuations

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Introduction

Electron cyclotron resonance (ECR) heating is a useful and often indispensable method to heat a plasma. If, however, the plasma frequency ω_{pe} exceeds the ECR frequency ω_{ce}, the microwave is reflected and can no longer be absorbed at the ω_{ce}–layer. One possibility to overcome this problem is to use electron Bernstein waves (EBWs), which have no high-density cutoff and are very well absorbed at ω_{ce} and its harmonics. EBWs are electrostatic waves that need to be coupled to electromagnetic waves. The O–X–B mode conversion is such a coupling process, which was first described in 1973 by Preinhaelter *et al.* [1]: an O-mode needs to be injected at an optimum angle into the plasma and is converted into an X-mode around the ω_{pe}–layer. The X-mode is subsequently converted into an EBW in the vicinity of the upper-hybrid resonance (UHR) layer. The efficiency of this process depends strongly on the efficiency of the O–X conversion, which, in turn, is mainly a function of the injection angle of the microwave. The sensitivity on this angle is given by the normalized density gradient length $k_0L_n = k_0 \cdot n/|\nabla n|$ (with k_0 the vacuum wavenumber of the injected microwave and n the plasma density).

In a magnetic confinement experiment, the mode conversion layer is usually located near the plasma boundary, where large density fluctuations can occur. These fluctuations locally change the value of k_0L_n and, hence, the conditions for optimum conversion efficiency. Furthermore, the fluctuations can lead to a spread in the beam divergence [2], which would then result in a reduced O–X conversion efficiency. Here, we present first studies with the full-wave code IPF-FDMC on how the conversion efficiency is influenced by different levels of density fluctuations.

The full-wave code IPF-FDMC

The full-wave code IPF-FDMC is a time-dependent code which solves Maxwell's equations and the fluid equation of motion of the electrons on a 2D Cartesian grid by applying the finite-difference time-domain technique. Details about the code can be found in Ref. [3].

The background parameters plasma density and magnetic field can be both of arbitrary shape. This allows to investigate the influence of density fluctuations on the mode conversion efficiency. Here, we restrict ourself to the O–X conversion to isolate the influence of turbulence on this process. Furthermore, the inclusion of the X–B conversion would largely increase the computational time [4]. The turbulence is generated numerically by first generating random

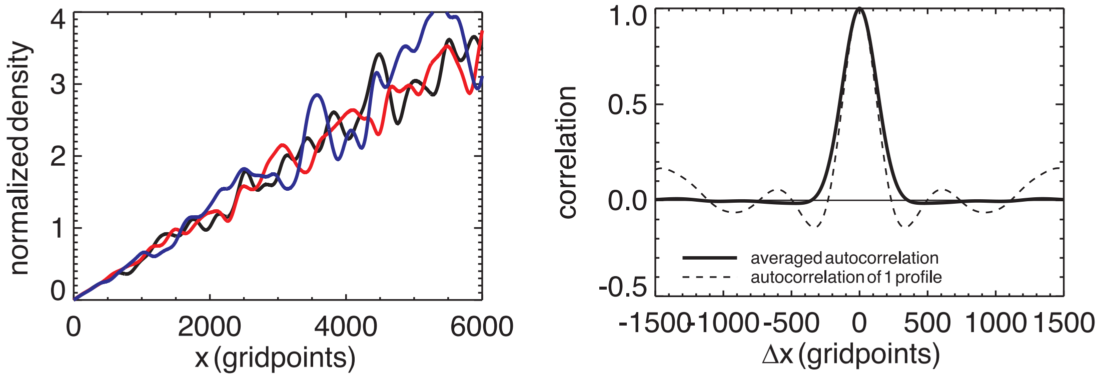

Figure 1: Left: Three density profiles with an averaged fluctuation amplitude of $\sigma_n \approx 10\%$ and an averaged correlation length of $c_L \approx \lambda_0/4$.. Right: Auto correlation function of a single density profile and the averaged auto correlation function of 100 density profiles with the same parameters as on the left side.

numbers, whose amplitudes are normally distributed. These numbers are then convoluted with a Gaussian to perform spatial low-pass filtering. The width of the Gaussian defines the average spatial size of the structures. The generated turbulence is then added to the density profile without turbulence. The turbulence is characterized by its normalized fluctuation amplitude σ_n calculated as the standard deviation and the correlation length c_L corresponding to a correlation of $C = 0.6$. As an example, Fig. 1 shows on the left side three turbulent density profiles. Each of them is based on the same linear profile with $k_0 L_n = 10$. The three different profiles are generated using different realizations of random numbers. They all have an averaged fluctuation amplitude of $\sigma_n \approx 10\%$ and an averaged correlation length of $c_L \approx \lambda_0/4$. (with the λ_0 the vacuum wavelength of the microwave). The corresponding auto correlation function for a single profile and the averaged over 100 profiles are shown on the right side of Fig. 1.

Influence of turbulence in a 1D geometry

First, we study the influence of density turbulence on the O–X conversion in a 1D geometry, where the turbulent density profiles are all based on a linear profile with $k_0 L_n = 10$. An ensemble of 100 profiles is used to obtain an average value of the conversion efficiency.

In Fig. 2, the conversion efficiency is shown as function of the injection angle for four different combinations of σ_n and c_L. For comparison, the conversion efficiency obtained for the non-turbulence profile is also shown. The deviations from the non-turbulence case are rather large, shifted towards lower efficiencies for the small-scale turbulence with $c_L = \lambda_0/10$. This is due to the requirement of a finite spatial width for the O–X conversion to take place [3], which is not fulfilled for the small-size turbulence. Hence, the conversion efficiency deteriorates.

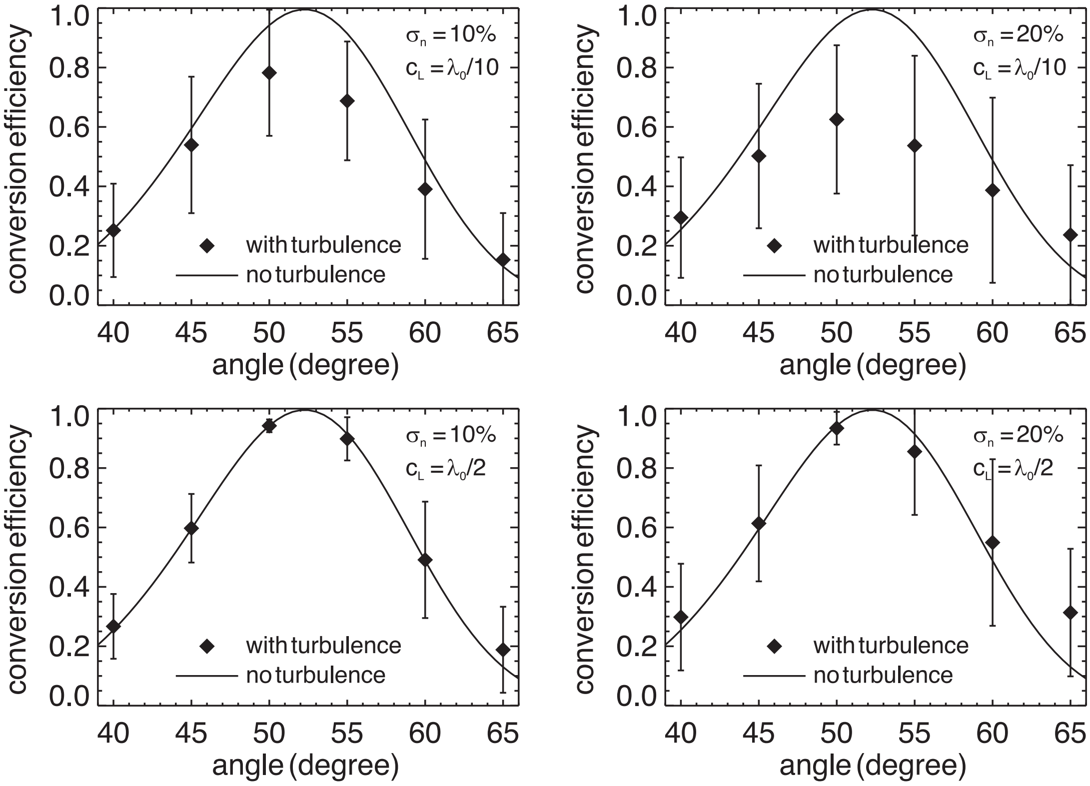

Figure 2: Average conversion efficiency as function of the injection angle for density profiles with different combinations of σ_n and c_L as given in each plot.

If the average correlation length is increased to $c_L = \lambda_0/2$, the behavior of the averaged conversion efficiency as function of the injection angle is similar to the non-turbulence case, as can be seen from Fig. 2. The average size of the structures is now large enough to allow the conversion to fully take place locally. With increasing fluctuation level, the average deviations of the efficiency increase as well, since the variation of the local value of k_0L_n at the conversion zone is also increasing.

Influence of turbulence in a 2D geometry

Some effects that are expected to deteriorate the conversion efficiency can only be seen in a 2D geometry. This includes, for example, the spreading of the beam divergence by small density structures. To investigate these effects, first simulations have been carried out. The geometry of the TJ-II stellarator has been chosen, which has been extensively studied previously [4]. If a microwave beam with a beam size of $w_0 = 4\lambda_0$ is injected at the optimum angle in this geometry, an efficiency of $\eta = 0.86$ is found.

The parameters of the turbulence considered for this case are $\sigma_n \approx 10\%$ and $c_L \approx \lambda_0/5$. Figure 3 shows the radial wave electric field (for clarity, only positive values are shown). In this geometry, the density is on the average increasing along the x-direction and the magnetic

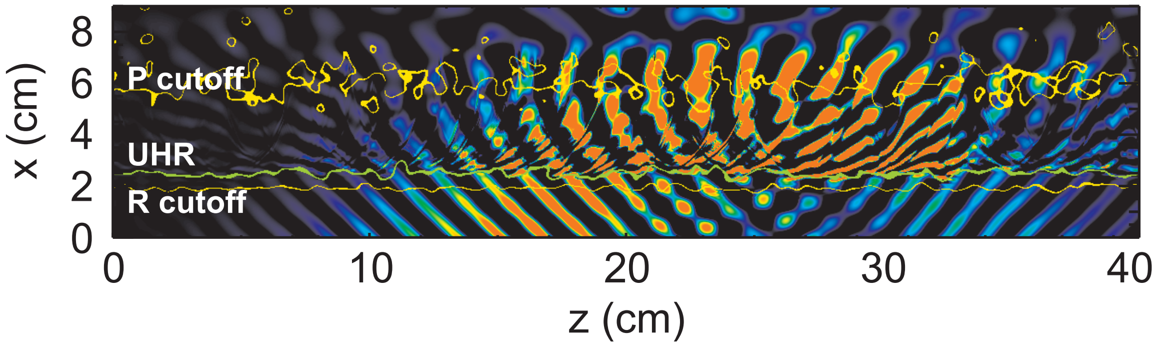

Figure 3: Radial wave electric field distribution (E_x) for a density profile with $\sigma_n \approx 10\%$ and $c_L \approx \lambda_0/5$. For clarity, only $E_x > 0$ is shown.

field points along the z-direction. The non-monotonous behavior of the cutoffs and resonances, labeled in the plot, is a result of the turbulence. The scattering of the wave electric field can be clearly seen, leading to a reduced conversion efficiency of $\eta \approx 0.6$ for this case.

As in the 1D case, an average over multiple realizations of turbulent profiles is necessary to obtain reliable results for the conversion efficiency. These time-demanding simulations are in progress. Additionally, the influence of fluctuations on the X–B conversion will be studied in order to be able to estimate the degradation of density fluctuations on the full O–X–B mode conversion process. These estimations are expected to provide valuable information for future experiments.

References

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