Perturbations of microwaves due to plasma density fluctuations

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Electromagnetic waves in the microwave regime play an important role in present plasma experiments as they are used for heating [1] and diagnostics purposes [2]. In both cases, the microwaves have to traverse the plasma boundary. In fusion related plasma, substantial density fluctuation levels are known to occur there [3] which can significantly distort the traversing microwave beam and thus lead to reduced coupling efficiencies to the plasma or to ambiguous diagnostics results. This work aims to investigate the average perturbation of a fluctuating plasma on a microwave beam by means of full-wave simulations. The advantage of a full-wave treatment is that no a-priori assumptions about the strength or size of the plasma density perturbations need to be made. The 2D full-wave code IPF-FDMC [4] is used to study the effect of a fluctuating plasma density on a propagating microwave beam. It is a finite-difference time-domain code based on a cold plasma description.

Ensemble averaging over a number of density profiles is required in order to be statistically relevant. The density fluctuations appear to be frozen in the frame of the microwave since they vary on the kHz scale [3], whereas the microwave oscillates on the GHz scale. The fluctuations itself are created by a Hasegawa-Wakatani drift-wave turbulence model within the BOUT++ framework [5]. A slice of fluctuating plasma density is then superimposed onto a homogeneous background density n_0 with a value of $n_0 = 0.5\,n_{\text{e,cut-off}}$, where $n_{\text{e,cut-off}}$ is the corresponding cut-off density of the injected microwave.

The numerical grid has a size of $10\,\lambda_0$ in the x-direction, where λ_0 is the vacuum wavelength of the injected microwave, and $5\,\lambda_0$ into the y-direction. It is surrounded by absorbing (non-radiating) boundaries. The fluctuating density slice extents along the whole x-direction but only from $y = 1\ldots4\,\lambda_0$. The microwave beam is injected along $y = 0$ and along $y = 5\,\lambda_0$, a receiving antenna is placed. The injected beam has a Gaussian shape with the beam waist located in the antenna plane having a radius of $w_0 = 2\,\lambda_0$. The polarization is such that an O-mode is injected and the background magnetic field points into the direction perpendicular to the 2D numerical grid with a constant strength of $Y = \omega_{ce}/\omega_0 = 0.5$, where ω_{ce} is the electron cyclotron frequency.

Figure 1 shows two snapshots of the absolute value of the wave electric field taken after the

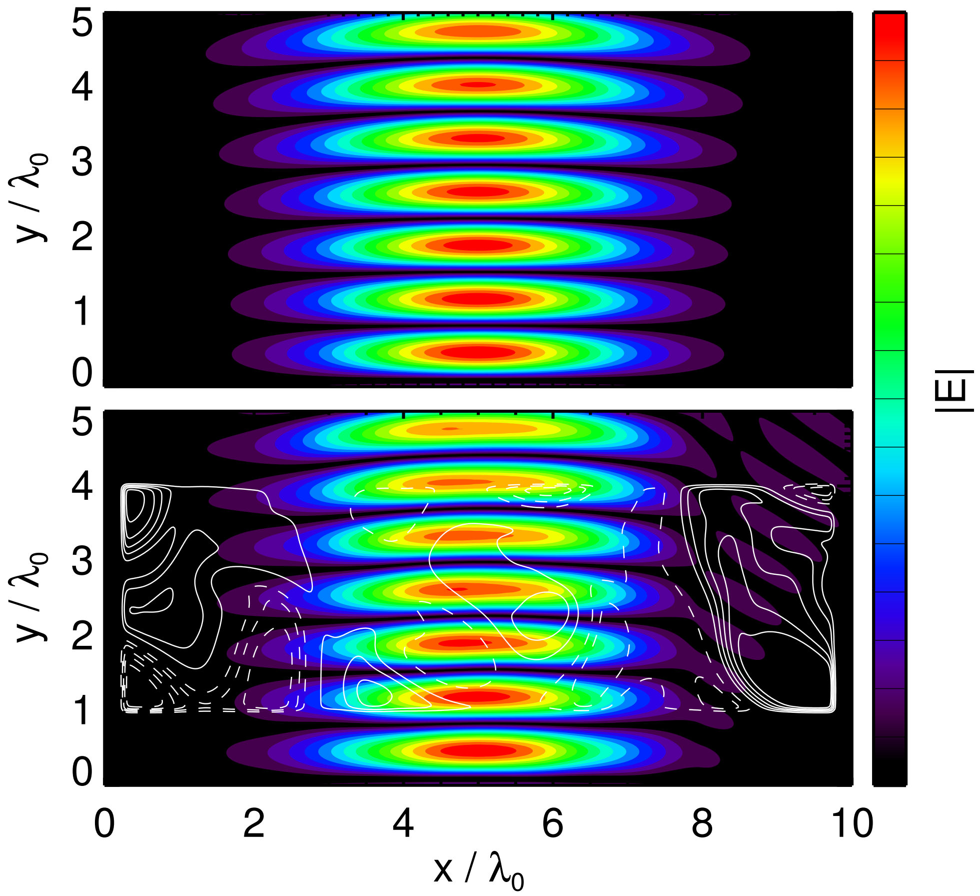

Figure 1: *Snapshots of the absolute value of the wave electric field after the steady state solution is achieved. Top: for the case of a homogeneous plasma with* $n_0 = 0.5\, n_{e,cut\text{-}off}$ *everywhere; bottom: for the case of a turbulence slice with an average structure size of* $c_L \approx 0.5\,\lambda_0$ *(white solid and dashed lines correspond to positive and negative density perturbations, respectively).*

steady state solution is achieved. The top snapshot shows the case for a homogeneous plasma with a density of $n_0 = 0.5\, n_{\mathrm{e,cut\text{-}off}}$ and the bottom snapshot for a fluctuating plasma with an average size of the density structures of $c_L \approx 0.5\,\lambda_0$ and an average fluctuation level of $\sigma \approx 4\,\%$. The average size c_L is taken as the distance where the spatial auto-correlation drops to a value of 0.5 and the fluctuation level is taken as the standard deviation of the mean-free density fluctuations. Comparing the two snapshots, it can be seen how the microwave beam is perturbed by the plasma density fluctuations. In this case, the position of the maximum signal is slightly shifted to the left and a sidelobe at the very right hand side occurs.

To quantitatively investigate the effect of the fluctuations on the microwave beam, the rms-value of the wave electric field $\tilde{\mathbf{E}}$ is continuously recorded at the detector antenna as a function of the coordinate x: $\tilde{E}_{\mathrm{rms}} = \sum_t \left(|\tilde{\mathbf{E}}|/\sqrt{T}\right)$, where t is the time coordinate and T the wave period.

This signal is then compared with the signal of the homogeneous case, E_{rms}. Figure 2 shows this comparison for the case of the average structure size which yielded the largest perturbation. The effect of the density fluctuations is obvious. Note, that for this plot only a few of the realizations from the ensemble of density profiles are shown. A scattering parameter α is defined as the sum of the squared deviations of the rms-signals, allowing to quantify the result of one full-wave run with a single value:

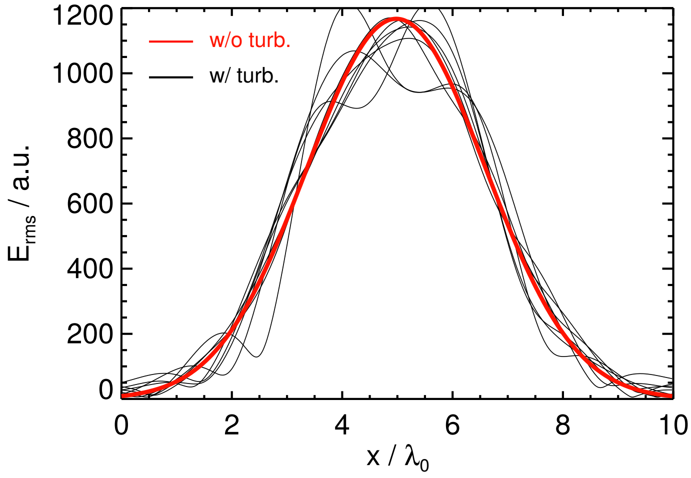

Figure 2: *Detector antenna signal for the homogeneous case (red) and for a few turbulence slices with an average structure size of* $c_L \approx 0.5\,\lambda_0$.

$$\alpha = \frac{\sum_x \left(\tilde{E}_{rms} - E_{rms}\right)^2}{\sum_x E_{rms}^2}. \tag{1}$$

Looking at Fig. 2, the necessity of sufficient ensemble averaging is apparent. To check the quality of the averaging process, the average position of the maximum signal in the detector antenna plane, $\tilde{x}_{max}$, is compared with the position for the homogeneous case, x_{max}. The difference of these two values should vanish, $\Delta = \tilde{x}_{max} - x_{max} \stackrel{!}{=} 0$. Only then, the results will be statistically relevant. The average value of Δ is plotted in Fig. 3 as a function of the number of ensembles N. It can bee seen that N is sufficiently large, since an asymptotic value of $\Delta = 0$ is reached (within the errorbars).

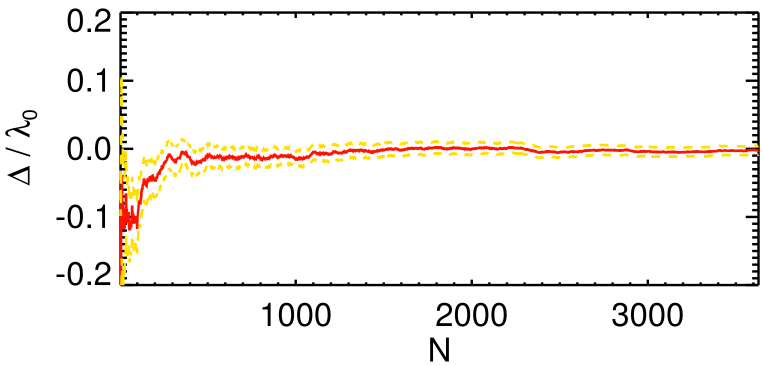

Figure 3: *Average value of the spatial difference of the maximum signal at the detector antenna (compared to the position of the maximum signal for the homogeneous case) as a function of the number of ensembles for an average structure size of* $c_L \approx 0.5\,\lambda_0$ *(the red curve corresponds to the average and the dashed orange curves to the error).*

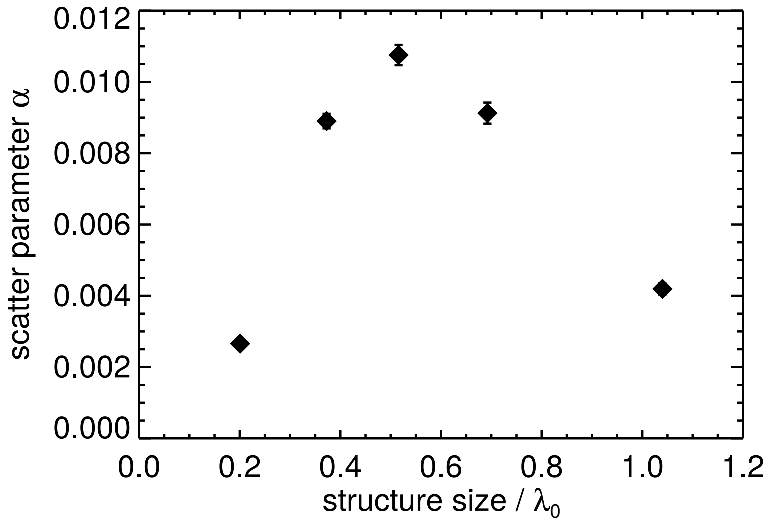

Figure 4: *Scattering parameter α (defined by Eq. (1)) as a function of the average size of the density structures for an average fluctuation level of $\sigma \approx 4\,\%$.*

The average size of the density structure is varied from $c_L \approx 0.2\,\lambda_0 \ldots 1\,\lambda_0$. With increasing structure size c_L, the number of ensembles N is also increased as a smaller number of density structures fit into one turbulence slice. Figure 4 shows the scattering as a function of the average structure size. A maximum scattering at a size of $c_L \approx 0.5\,\lambda_0$ can be clearly seen. For decreasing and increasing sizes, the average scattering is decreasing.

Note that in a previous study, the influence of a single blob-like structure on a traversing microwave beam was studied [6], and the deterioration was found to peak at a larger structure size. This is, however, not in contradiction to the result presented here, as we are interested in the *average* perturbation whereas in the previous study we were interested in the *maximum* perturbation.

Further investigations are performed at the moment in order to elaborate the role of the strength of the fluctuations and of the size of the turbulence region.

References

[1] V. Erckmann and U. Gasparino *Plasma Phys. Control. Fusion* **36** 1869 (1994)

[2] H.-J. Hartfuss and T. Geist *Fusion Plasma Diagnostics with mm-Waves* (Wiley-VCH, Weinheim, 2014)

[3] S. J. Zweben *et al.*, *Plasma Phys. Control. Fusion* **49** S1 (2007)

[4] A. Köhn *et al.*, *Plasma Phys. Control. Fusion* **50** 085018 (2008)

[5] B Dudson *et al.*, *Comp. Phys. Comm.* **180** 1467 (2009)

[6] T. Williams *et al.*, *Plasma Phys. Control. Fusion* **56** 075010 (2014)

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