The depolarizing effect of plasma density fluctuations on microwave beams

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Electromagnetic waves in the microwave range of frequencies play an indispensable role in plasma experiments as they are used for heating and diagnostic purposes. This is especially true for fusion experiments on the path towards a burning plasma in which only very little space is available for any type of internal hardware installations. Microwaves offer the advantage of requiring comparatively little space inside the machine [1]. On top of that, microwaves in the electron cyclotron frequency range provide efficient heating and current drive capabilities mandatory for the efficient and successful operation of current and future tokamaks [2].

Microwaves injected into the plasma or emitted by it have to propagate across the plasma edge where significant plasma density fluctuations with fluctuation levels of several 10 % are known to occur [3]. In previous investigations, we have studied their influence on a propagating beam: significant broadening of the beam was found when performing an average over an ensemble of plasma density profiles with fluctuations [4]. Here we are interested in a different, more subtle effect: if the density fluctuations are located at very low plasma density values where the two modes of the electromagnetic wave, the O- and X-mode, are not yet well separated, an energy transfer between them can occur. This unwanted mode coupling can be a problem for high-power microwave injection as the wrong mode would likely be not absorbed at the intended spatial location but might even constitute a threat for in-vessel components. Here we present full-wave simulations to illustrate and quantify this effect.

The cold plasma full-wave code IPF-FDMC has been used for the investigations discussed in this contribution. It is a finite-difference time-domain code which solves Maxwell's equations and the fluid equation of motion of the electrons on a 2D Cartesian grid:

$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E} \tag{1}$$

$$\partial_t \mathbf{E} = c^2 \nabla \times \mathbf{B} - \mathbf{J}/\varepsilon_0 \tag{2}$$

$$\partial_t \mathbf{J} = \varepsilon_0 \omega_{pe}^2 \mathbf{E} - \omega_{ce} \mathbf{J} \times \hat{\mathbf{B}}_0 - \nu_e \mathbf{J} \tag{3}$$

with c the speed of light, $\omega_{pe} = \sqrt{n_e e^2/(\varepsilon_0 m_e)}$ the electron plasma frequency, $\omega_{ce} = |e|B_0/m_e$ the electron cyclotron frequency, $\hat{\mathbf{B}}_0$ the unit vector into the direction of the background magnetic field, and an electron collision frequency ν_e as a dissipation mechanism. The code has been successfully benchmarked against cold plasma theory [5] and other full-wave codes [6, 7].

Turbulent plasma density fluctuations are frozen within the time frame of the microwave which makes it straight-forward to study their influence in the full-wave simulations: one simply needs to put a constant (in time) plasma density profile with fluctuations into the full-wave code and analyze the resulting steady state solution. To be statistically relevant, however, ensemble averaging over a number of profiles is required. The full plasma density profiles are generated as follows: first, an unperturbed background profile is created as described by Eq. (4).

$$n_{e,0}(x) = \begin{cases} n_{e,\max}, & \text{if } x < 2.30\,\mathrm{m} \\ \frac{n_{e,\max}}{x_{n1}-x_{n2}}\left(x_{n1}-x\right), & \text{if } 2.30\,\mathrm{m} \leq x \leq 2.45\,\mathrm{m} \\ 0, & \text{if } x > 2.45\,\mathrm{m}, \end{cases} \tag{4}$$

with $x_{n1} = 2.45\,\mathrm{m}$, $x_{n2} = 2.3\,\mathrm{m}$, and $n_{e,\max} = 2 \cdot 10^{19}\,\mathrm{m}^{-3}$. Then, fluctuations are generated by a truncated sum of Fourier-like mode with random phases such that their correlation length corresponds to the average perpendicular structure size $L_\perp$. The spatial profile of the fluctuations are convoluted with a function

$$F(x) = A_0 \cdot \exp\left\{-(x - x_{\mathrm{fluct}})^2 / w_{\mathrm{fluct}}^2\right\} \tag{5}$$

of Gaussian shape to allow for control over the spatial localization (via x_{fluct} and w_{fluct}) and over the average amplitude of the fluctuations (via A_0). Figure 1 shows the corresponding profiles of the background density and an example for the average fluctuation amplitude.

The simulation domain is meant to represent a poloidal cut at the edge of a typical fusion plasma. The grid has an extension in radial and vertical direction of respectively $\Delta x \approx 20\,\mathrm{cm}$ and $\Delta z \approx 47\,\mathrm{cm}$. It is surrounded by absorbing (i.e. non-radiating) boundaries. The background magnetic field is homogeneous over the simulation domain and points with equal magnitude of $0.5\,\mathrm{T}$ into vertical and toroidal direction, where the latter corresponds to the direction perpendicular to the domain. A Gaussian antenna beam is injected into the grid

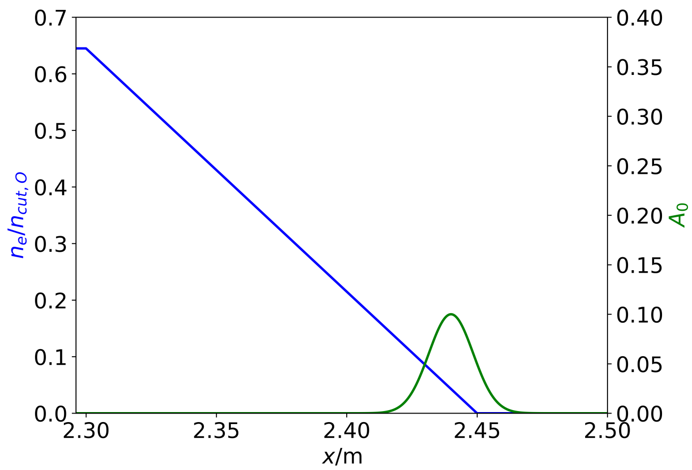

Figure 1: *Radial profile of the background electron plasma density (blue, left axis) and of the average fluctuation amplitude profile (green, right axis).*

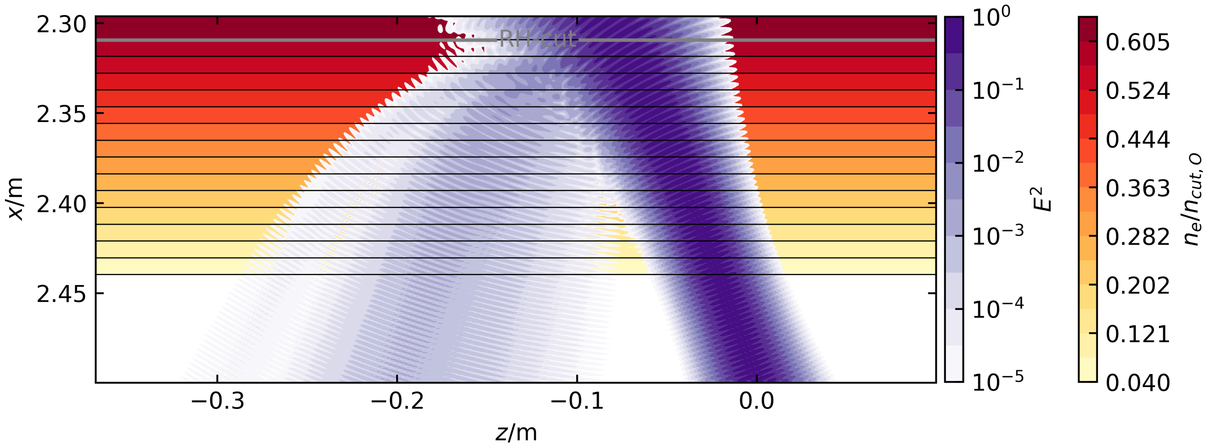

Figure 2: *Snapshot of the squared absolute value of the wave electric field after the steady state solution is achieved together with the electron plasma density (note the logarithmic color-scale of the wave fields). Full video is available online [8].*

along z at $x_{\text{ant}} = 2.50\,\text{m}$ with its center at $z_{\text{ant}} = 0$. The radius at the waist is $w_0 = 1.5\,\text{cm}$ and the focal point is located approximately at the position of the fluctuation layer corresponding to an axial distance along the beam to the emitting antenna of 58.2 mm. A microwave frequency of $f_0 = 50\,\text{GHz}$ corresponding to a vacuum wavelength of $\lambda_0 \approx 6\,\text{mm}$ in O-mode polarization is chosen and the beam is injected at an angle of $20°$.

Before studying the effects of fluctuations, we look at the case of a quiescent plasma (without fluctuations). Figure 2 shows a snapshot of the squared absolute value of the wave electric field taken after $T = 200$ oscillation periods (when the steady state solution has been achieved). The background plasma density with the right-hand cut-off labeled is also included in the plot. The cut-off acts as an analyzer for the unwanted mode content: it reflects the X-mode back into the antenna plane whereas the O-mode can pass. Although a pure O-mode is injected, one can clearly see part of the wave being reflected at the X-mode cut-off. Note the logarithmic scale of the wave-field indicating the small

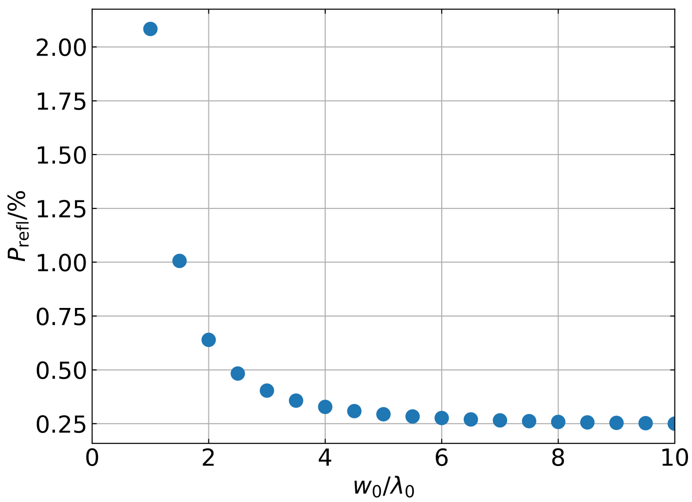

Figure 3: *Percentage of coupling into unwanted mode detected via the reflected power as a function of the beam size.*

amount of approximately 0.5 % of coupling to the X-mode. This coupling is due to the finite size of the Gaussian beam where the components in the angular spectrum further to the tails do not have the optimum polarization. This implies that the mode coupling should be reduced when using larger beams which is indeed the case as shown in Fig. 3.

To study the additional effect of turbulent plasma density fluctuations on mode coupling, referred to as *mode scattering* or *cross-polarization scattering*, we have introduced a layer of fluctuations as described above. The fluctuation amplitude has been varied by scanning the A_0 in Eq. (5). Figure 4 clearly shows that fluctuations with increasing amplitude leads to an increased amount of unwanted mode content.

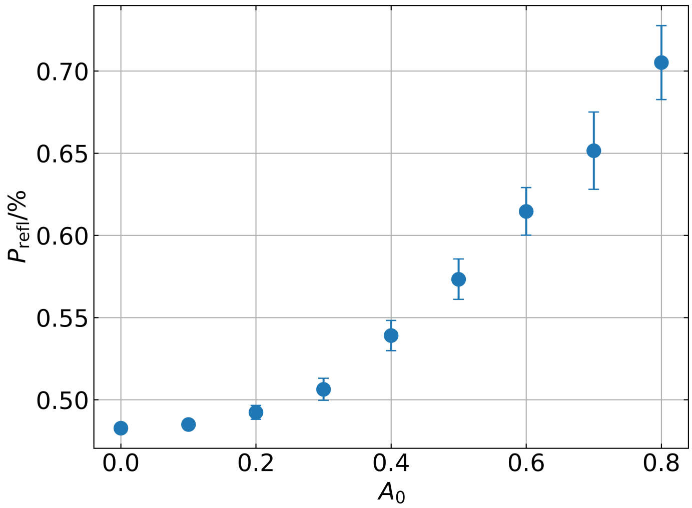

Figure 4: *Coupling to the wrong mode as a function of the fluctuation amplitude.*

Summarizing, we have successfully demonstrated the effect of mode scattering due to turbulent plasma density fluctuations. Our results are similar (but slightly smaller) to those found in previous studies using a numerical tool being valid in the limits of the Born approximation [9]. Additional simulations are performed at the moment in order to further elaborate the role of the underlying turbulence properties.

References

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