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Influence of density perturbations on the O–X mode conversion

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Microwave heating is widely used to transfer energy to plasmas. If, however, the plasma density exceeds the corresponding cutoff density of the injected microwaves, the plasma becomes inaccessible and the waves are reflected. Electron Bernstein waves (EBWs) provide a method to overcome this limitation: they are electrostatic waves that have no high-density cutoff and are very well absorbed at the electron cyclotron resonance layer and its harmonics. Due to their electrostatic nature, EBWs cannot propagate in a vacuum but need to be coupled to injected electromagnetic (EM) waves. A possible coupling mechanism is the O–X–B mode conversion [1]: if an O-mode is injected at the optimum angle it is converted into an X-mode in the vicinity of the plasma frequency layer. This X-mode is then reflected and propagates outwards until it reaches the upper-hybrid resonance layer, where it is transformed into a backwards propagating EBW. The efficiency of the whole process strongly depends on the efficiency of the O–X conversion which itself is mainly dependent on the injection angle. The optimum injection angle is determined by the normalized density gradient $k_0 L_n = k_0 \cdot n / |\nabla n|$ (where k_0 is the vacuum wave number of the injected microwave and n the plasma density) at the O–X mode conversion layer, which is usually situated at the plasma boundary. This is a region with strong gradients leading to instabilities or perturbations of the density profile. These perturbations can influence the conversion process and the propagating microwave in general. We have studied theses effects using the full-wave code IPF-FDMC [2].

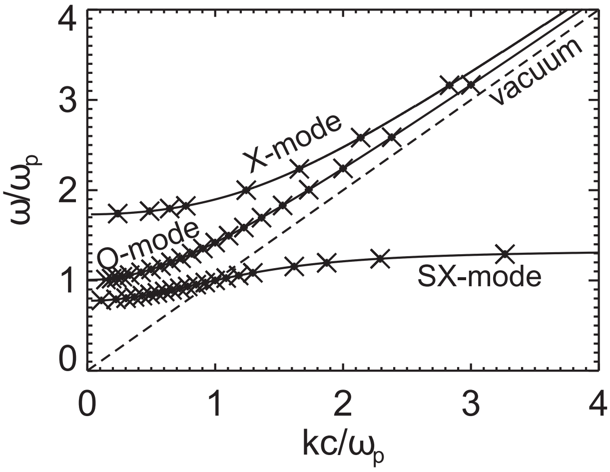

Figure 1: *Dispersion relation of the O- and X-mode as obtained from simulations (crosses) and cold plasma theory (solid lines).*

The full-wave code IPF-FDMC is a 2D finite-difference time-domain code which simulates wave propagation in a cold magnetized plasma. It has been used previously to study the feasibility of heating scenarios relying on the O–X–B mode conversion process [3]. To check the

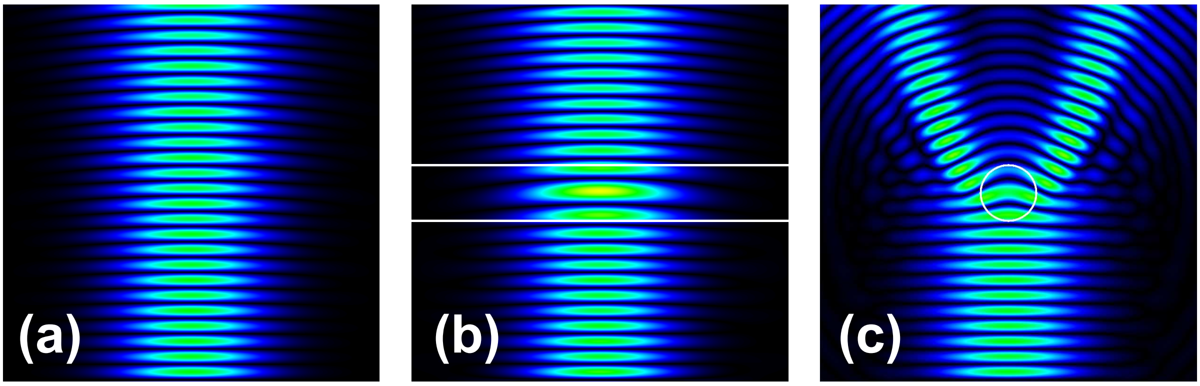

Figure 2: *Simulation of a microwave beam propagation in a plasma with a background density of* $n = 0.4n_{cutoff}$ *and without magnetic field for the case (a) without a density perturbation, (b) the Gaussian shaped perturbation being elongated inside the simulation plane and (c) the perturbation being elongated perpendicular to the simulation plane; shown is* $|E|$.

validity of the code, the dispersion relations for O- and X-mode have been deduced from it and compared with the analytic solutions from cold plasma theory. As can be seen from Fig. 1, excellent agreement is found.

To investigate the role of density perturbations one could in principle generate an ensemble of density profiles with randomly generated fluctuations and average over this ensemble to see how the conversion process is, on the average, influenced. This can be easily realized for 1D simulations [4] but is significantly more demanding in terms of computational resources for a 2D geometry due to the large ensemble necessary to get a reliable average. Furthermore, the insight gained into the underlying process altering the conversion is limited by just looking at the average effect.

We have therefore chosen to reduce the problem to the case of the interaction between an electromagnetic wave and a single density perturbation of Gaussian shape which is added at a specific position to the background density profile. The perturbation is characterized by its width $w_{\tilde{n}}$, its peak density $\tilde{n}_{\text{peak}}$ and its position on the simulation grid: $\tilde{n}(r) = \tilde{n}_{\text{peak}} \exp(-r^2/w_{\tilde{n}}^2)$. These perturbations resemble so-called blobs or filaments, perturbations of the plasma density that are elongated along the magnetic field lines and appear at the plasma boundary where they are responsible for a significant fraction of particle and heat losses. Therefore, the treatment of such isolated perturbations is not just a simplification but the inclusion of an important physical problem.

In fusion plasmas, injected microwave beams have to traverse the plasma boundary where blobs usually occur. Therefore, it is of interest to investigate the general interaction process of electromagnetic waves with blobs. Such a process is illustrated in Fig. 2(b) and Fig. 2(c),

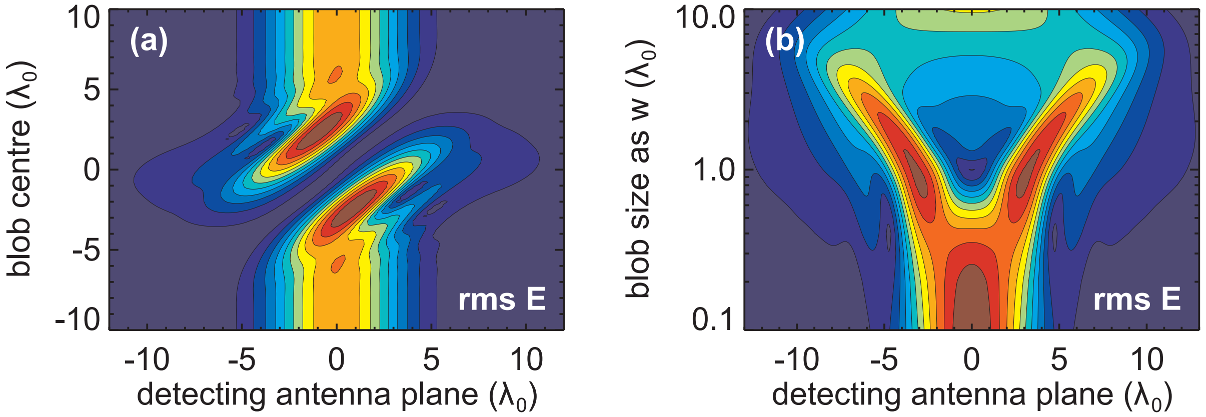

Figure 3: *Contour plots of the spatial distribution of E_{rms} in the receiving antenna plane located at the top of the simulation grid (see Fig. 2) (a) as function of the horizontal position of the blob-like structure and (b) as function of the width of the blob-like structure.*

where a Gaussian beam with a beam waist of $w_{\text{beam}} = 3 \cdot \lambda_0$ is injected from the bottom into a homogeneous plasma with a density of $n = 0.4 \cdot n_{\text{cutoff}}$ with (b) a blob-like structure elongated inside the simulation plane and (c) elongated perpendicular to it. The perturbation is the same in both cases with a width of $w_{\tilde{n}} = 1 \cdot \lambda_0$ and a peak density of $\tilde{n}_{\text{peak}} = 0.8 \cdot n_{\text{cutoff}}$. For comparison, the unperturbed case is shown in Fig. 2(a). It is obvious that the modification of the beam is considerably stronger for the blob elongated perpendicular to the simulation grid. The following studies will therefore emphasize this case. To systematically investigate the deterioration of the injected beam, a receiving antenna is added to the simulation at the top of the grid. To get information about the spatial distribution of the wave field, the antenna is expanded over the whole width of the computational grid.

Figure 3(a) shows the signal of the aforementioned receiving antenna as function of the horizontal position of the blob-like structure, which has the same size and structure as before. The microwave is significantly distorted if the blob approaches a position within the (Gaussian) beam width of the microwave beam whose value is in the relatively small grid considered here still very close to the beam waist. The influence of the width of the blob-like structure can be deduced from Fig. 3(b): Only weak distortion is found if the width of the Gaussian-shaped perturbation is $w_{\tilde{n}} < \lambda_0/2$ or $w_{\tilde{n}} > 10\lambda_0$. Strong impact is found for values in between, most pronounced if the size of the density perturbation is on the order of the vacuum wavelength of the injected microwave. Having such strong influence on the wave electric field, these perturbations are expected to significantly alter the process of mode conversion which is sensitive to the spectral distribution of the microwave at the conversion layer.

The efficiency of the O–X conversion depends on the injection angle of the microwave beam, as mentioned in the beginning. For a linear density profile with $k_0 L_n = 30$ and a constant background magnetic field of $Y = \omega_{ce}/\omega_0 = 0.8$, the angular dependence is shown in Fig. 4. A pronounced maximum at an injection angle of $\theta \approx 42^\circ$ with an efficiency of $\eta \approx 0.8$ is found. Figure 4 also shows the case for the same density perturbations as considered in the simulations discussed above. The center of the perturbation is located at a background density value of $n = 0.4 \cdot n_{\mathrm{cutoff}}$ and for the perpendicular case, it is located approximately at the center of the microwave beam when injected at the optimal angle.

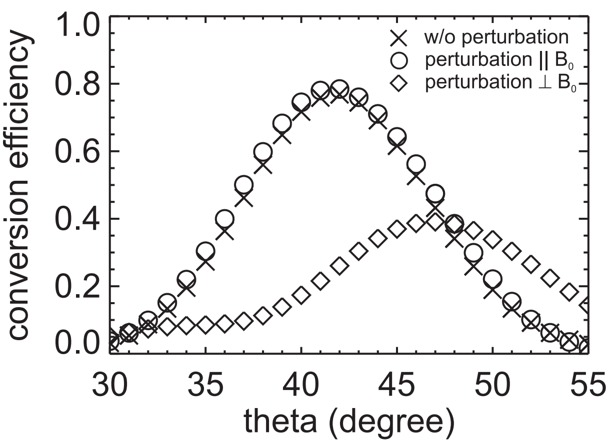

Figure 4: *O–X conversion efficiency as function of injection angle for the case with and without density perturbation as depicted in the plot.*

A strong reduction of the conversion efficiency is found for the perpendicular case and only a negligible influence when considering a perturbation along the background magnetic field, as expected from the simulations discussed above. For the perpendicular case, the maximum conversion efficiency is not only reduced by a factor of 2, but the injection angle for optimum conversion is also shifted by approximately 6° here.

To summarize, the influence of an isolated density perturbation on microwave propagation and on the O–X conversion has been simulated with a full-wave code. The influence of the size and position of the perturbation and its impact on the wave electric field has been systematically investigated. Strong modification was shown to occur depending on the size and position of the perturbation. The O–X conversion is sensitive to the orientation of the phase fronts of the microwave at the conversion layer and, hence, strong reduction was demonstrated to occur for case considered here. As a next step, a similar scan as the one performed for the impact on the wave electric field will be performed for the impact on the conversion efficiency.

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