Visualization of the O-X-B mode conversion process with a full-wave code

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***Abstract* – The O-X-B mode conversion is a process to couple electromagnetic waves into an over-dense plasma. At the vicinity of the cutoff, the wave converts into a Bernstein wave, which is very well absorbed in the plasma without further density cutoff. Therefore these waves are a promising tool to heat high density plasmas. The conversion process has been investigated in great detail using a full-wave code and for the first time the time-dependent formation of the Bernstein waves has been visualized using the data obtained with this simulation.**

Heating plasmas by means of microwaves is a widespread tool nowadays. This applies for industrial plasmas as well as for fusion plasmas. In industrial plasmas the energy transfer from the microwave to the plasma usually happens via non-resonant collisional damping. Another possibility of energy transfer, which applies for most fusion plasmas, is the well-known concept of electron cyclotron resonance heating (e.g. [1]): A background magnetic field $\mathbf{B}_0$ is necessary, which lets the electrons (mass m_e, elementary charge e) gyrate around the magnetic field lines with the frequency $\omega_{ce}=eB_0/m_e$. If this frequency or a harmonic of it coincides with the microwave frequency, energy can be transferred to the electrons by accelerating them.

For perpendicular injection, one has to distinguish between the O- and the X-mode: for the O-mode, the electric field oscillates parallel to $\mathbf{B}_0$, for the X-mode it oscillates perpendicular to it. The absorption of the O- and X-mode at ω_{ce} and its harmonics has been calculated for example in ref. [2]. The absorption decreases with the number of harmonics and increases with electron temperature T_e. Furthermore, absorption is limited by the density of the plasma: if it exceeds the cutoff density for the corresponding mode of the incident microwave this mode is reflected. To obtain access to higher densities, the O-X-B mode conversion process was proposed [3]: An O-mode (elliptically polarized) is launched at an optimum angle with respect to $\mathbf{B}_0$. When the wave reaches its cutoff it will be transformed into an X-mode which is then reflected and propagates in direction out of the plasma and reaches the upper hybrid resonance (UHR), which is usually located near the plasma edge. At the UHR the X-mode is transformed into a backward propagating Bernstein-mode (B-mode), which has no density cutoff. It is shown here, that the X-B transformation happens slowly on the wave time scale. The B-mode is absorbed very well even at high harmonics of ω_{ce}. In ref. [4] a recent review has been given about this way of plasma heating. The O-X-B scheme has been investigated in a number of ray tracing codes [5] and particle simulations [6]. Here, we present the O-X-B conversion obtained with a full-wave code that solves Maxwell's equations with the FDTD method. The plasma current is obtained by solving the equation of motion for the electrons [7]. To include hot plasma effects, which are necessary for the X-B conversion, the warm dielectric tensor is included according to [8].

The result of the simulation can be seen in Fig. 1: Three different moments are shown, where the time is indicated in terms of wave periods, given in the upper left corner of each plot. $\mathbf{B}_0$ is parallel to the x-axis and the constant density gradient is parallel to the y-axis. Arbitrary orientation and shear of $\mathbf{B}_0$ can be included. The positions of the UHR and the O-mode cutoffs are indicated by dashed lines. The positive values of the wave electric field are plotted, negative values are suppressed. On the upper left plot one can see the O-mode, which is incident from the lower left side at the optimum angle. A Gaussian antenna beam is used, although the code can handle arbitrary beams. At the upper right plot the O-X conversion has already occurred. One sees that the conversion and reflection of the X-mode happens over a finite region around the O-mode cutoff. The X-mode then reaches the UHR and its wavelength becomes shorter. In the lower left plot, the X-B conversion has been started and the extremely short wavelength of the B-mode can be seen. This is emphasized by the lower right plot, which is a zoom into the X-B conversion region of the lower left plot. The duration is indicated in terms of wave periods in the plots and one sees that it takes 195 wave periods before the B-mode has developed significantly. This is due to its short wavelength on the order of the gyration radius of the electrons, resulting in a low phase velocity.

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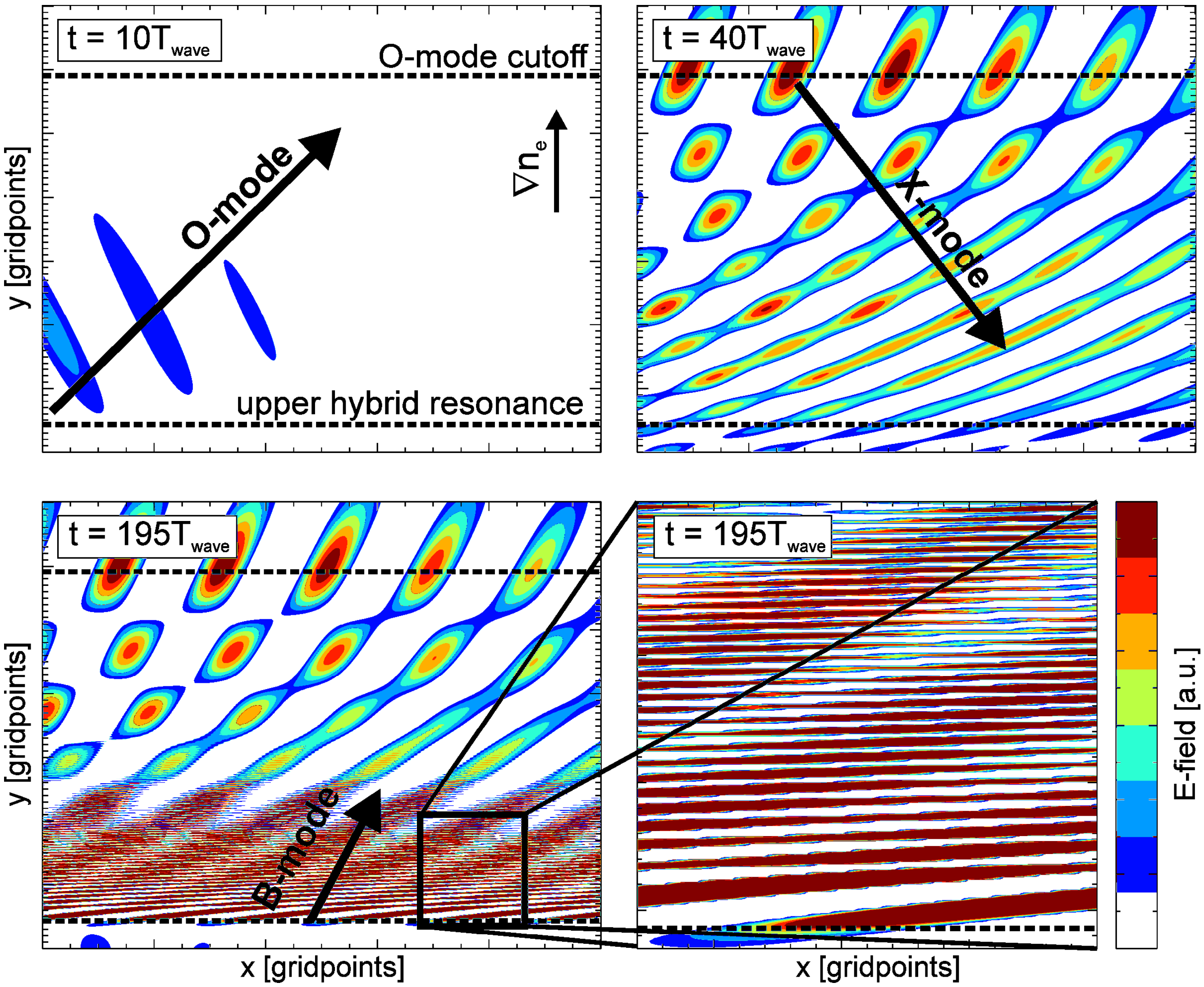

Fig. 1. O-X-B mode conversion. Plotted are the positive values of the wave electric field. $\mathbf{B}_0$ is parallel to the x-axis, ∇n_e is parallel to the y-axis. The wave is incident from the lower left side. Coloured plot in online version.

In conclusion, the O-X-B mode conversion process has been shown in detail. The B-mode can be identified clearly by its short wavelength. It has been shown that this full-wave code offers the possibility to study wave plasma interaction in great detail.

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