Trapping of Electron Bernstein Waves in a magnetic mirror configuration

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Introduction

The Electron Bernstein wave is an electrostatic wave that propagates in a hot magnetized plasma. Absence of high density cutoff and damping at harmonics of the cyclotron resonance make them interesting for plasma heating as well as for diagnostics. Most of the previous studies concerning the wave were carried out for quiescent plasmas with weak gradients [1] and did not attempt detailed simulations of the field patterns and caustics [3]. Therefore, it is of a considerable interest to perform a new study to investigate both numerically and experimentally how the EBW propagates in an inhomogeneous plasma. As a model to work with we chose to simulate the EBW propagation for the magnetic mirror configuration. In this contribution, the results of the ray-tracing and wave kinetic equation methods are reported.

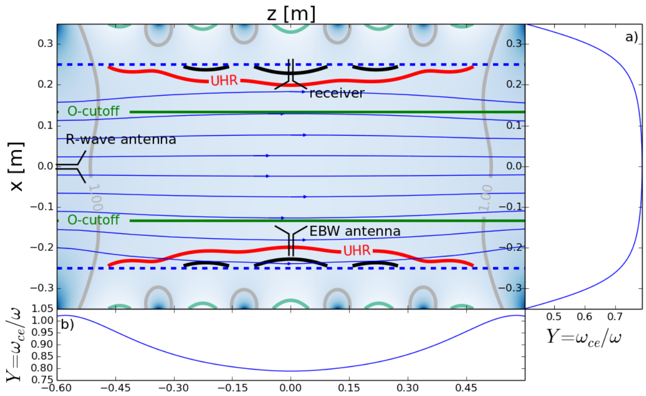

Figure 1: *Shallow axial magnetic field gradient. $I_{out} = 500$ A and $I_{inner} = 300$ A. Thick gray lines show the fundamental cyclotron resonance where the R-wave is absorbed. a), b) show the magnetic field strength along x at $z = 0$ and along z at $x = 0$, respectively.*

Experimental setup and magnetic field configurations

Experiments are carried out in the linear device FLiPS which has a radius of 0.5 m and 1.2 m long. Its 6 magnetic field coils are used to produce a magnetic field of up to 0.2 T. 3 power supplies are at our disposal which can be used to independently control the coils giving us access to a variety of magnetic field configurations. The plasma is produced by the axially propagating 2.45 GHz R-wave. The experiment is equipped with a Langmuir probe and an interferometer. The typical electron density is of the order of 10^{17}m^{-3} and the electron temperature is around 10 eV. The magnetic field configuration which the most relevant for this study is shown in fig. 1. It is characterised by a slowly changing magnetic field both in the axial and radial directions.

In this configuration the field line curvature is small. Therefore, the main effect on the wave propagation is the magnetic field inhomogeneity.

Ray-tracing

A ray-tracing code which uses the electrostatic approximation has been developed in order to simulate EBW propagation. Being short wavelength waves the WKB approximation is fulfilled very well. Hamilton's equations are solved with the Runge-Kutta 4th order method. To speed up the calculations only the first two terms of the plasma dispersion function asymptotic expansion are used [2]. The rays that have large $n_\parallel$ will be quickly damped due to Landau damping and can not propagate beyond the UHR. To estimate the range of $n_\parallel$ for the rays that propagate we use inequality [1]

$$\frac{1-nY}{n_\parallel} \gg \gamma \tag{1}$$

where n is a harmonics number, $Y = \frac{\omega_{ce}}{\omega}$, $\gamma = \sqrt{\frac{2T_e}{m_e}}$. For $T_e = 10$ eV and the configuration in fig. 1 the damping is significant only for $n_\parallel > 33$.

Fig. 2 shows that the rays follow sinusoidal paths. The calculations imply that the rays are confined within a wave channel which is formed by the inhomogeneous axial magnetic field. One sees that the rays form caustics where the eikonal approximation is not valid in x-space. Within the standard framework of ray-tracing calculations one constructs local wave equations in the regions of caustics to resolve them. Instead, being mostly interested in the amplitude distribution we have applied the wave kinetic equation formalism. The results of this approach are discussed in the next section.

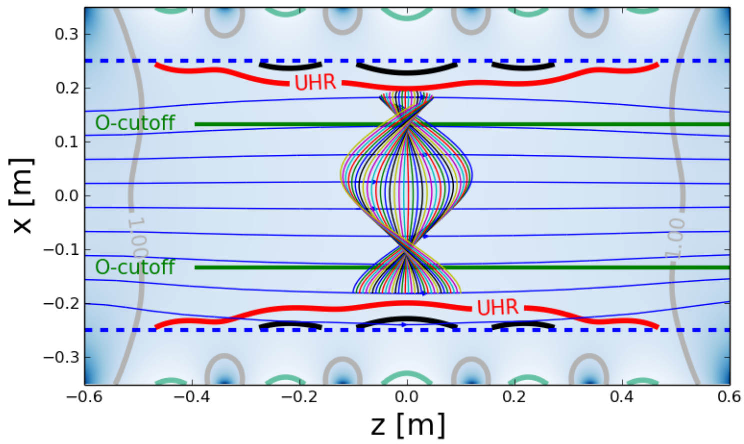

Figure 2: *The same configuration as in fig. 1. The rays are launched just above the UHR and propagate upwards.*

Steady state wave kinetic equation

Caustics can be effectively avoided in the Weyl-phase representation which is decribed in ref. [4]. Assuming a local plasma response, the usual EBW dispersion is applied to trace the rays using the program described in the previous section. In the absence of damping the value of the Wigner function $\omega(\mathbf{x},\mathbf{N})$ stays constant along the rays. It allows reconstruction of the field intensity as follows

$$|\psi(\mathbf{x})|^2 \propto \int \mathrm{d}^3 N \omega(\mathbf{x}, \mathbf{N}) \tag{2}$$

Boundary conditions similar to ref. [5] are used. At the antenna plane a gaussian beam of the form

$$\psi(x_A, z) = e^{-(z/\sigma)^2} e^{ixk_{x,0}}, \tag{3}$$

is assumed, where $k_{x,0}$ is the central wave vector which is found from $\varepsilon_{EBW}(\mathbf{x}_A, k_{x,0}, k_{z,0}, \omega) = 0$. The Wigner function corresponding to eq. 3 can be analytically calculated

$$\omega(x_A, z) \propto e^{-(z/\sigma)^2} \cdot e^{-(k_z \sigma)^2} \cdot \delta(k_{x,0} - k_x) \tag{4}$$

To reconstruct the field of the EBW 10^4 rays were traced. Along each ray the Wigner function was calculated according to the initial conditions given by eq. 4. Then the rays were "lifted" into $(\mathbf{x}, k_z)$ space where interpolation was performed. It allows us to reconstruct $\omega(\mathbf{x}, k_z)$. Then integration along k_z was performed. The result is shown in fig. 3. The most important feature of the field is the formation of two regions of high intensity caused by beam focusing. This strongly resembles the results to wave propagation in a lens-like medium [5].

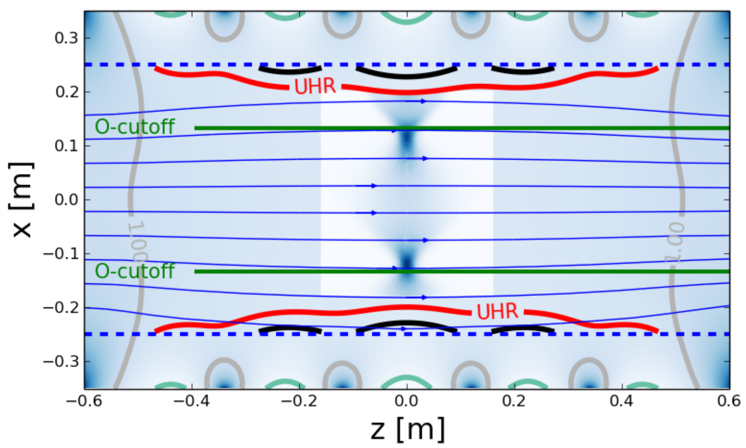

Figure 3: *field intensity* $|\psi(\boldsymbol{x})|^2$

Conclusion

Propagation of the EBW has been studied numerically. The ray-tracing calculations show that the plasma in the inhomogeneous magnetic field can form a wave channel along which the EBW propagate. However, this method was not pursued further to solve the question about caustics. As an alternative, we have successfully applied the method of the wave kinetic equation. As a result, EBW field intensity has been calculated. Periodic refocusing of gaussian beam has been found. This theoretical prediction will be investigated experimentally in the linear device FLiPS.

References

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