

Plasma heating by microwaves in high- β devices

E.D. Gospodchikov, A.G. Shalashov, A.G. Kutlin

Institute of Applied Physics RAS, Nizhniy Novgorod, Russia, egos@appl.sci-nnov.ru
Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia

Microwave heating of electrons under the electron cyclotron resonance conditions is one of the most efficient ways to increase the electron temperature of magnetically confined plasmas. Recent progress in plasma confinement in axially symmetric magnetic traps led to the achievement of high- β regimes, in which β -ratio between the plasma kinetic pressure and the magnetic field pressure is of the order of unity. Under these circumstances the Langmuir plasma frequency is much greater than the electron cyclotron frequency, $\omega_{pe} \gg \omega_{ce}$. Therefore, the use of common schemes of electron cyclotron heating based on direct launch of electromagnetic waves from a vacuum window meets obvious difficulties because the resonance region is screened by dense plasma for all electromagnetic modes except waves propagating strictly along the external magnetic field. However, in many cases strictly longitudinal propagation is not technically possible.

One way to overcome this problem is to use the linear transformation of electromagnetic waves in quasi-electrostatic plasma oscillations in the vicinity of the plasma upper hybrid (UH) resonance

$$\omega_{UH}^2 = \omega_{pe}^2 + \omega_{ce}^2 \approx \omega_{pe}^2.$$

Once excited, the quasi-electrostatic oscillations can be effectively damped by electrons, in particular, in overdense plasmas. Such microwave heating schemes at low cyclotron harmonics have been implemented in magnetic traps with low kinetic pressure: stellarators, classical and spherical tokamaks. The heating frequency for this systems is of the order of the electron cyclotron frequency, $\omega \sim \omega_{ce} < \omega_{pe}$. On the other hand, the opposite ordering $\omega_{ce} \ll \omega_{pe} \sim \omega$ is more natural for high- β devices, otherwise the linear coupling and plasma heating are localized at the very periphery of the plasma column. As the quasi-electrostatic waves are well absorbed even at high cyclotron harmonics, the key factor controlling the efficiency of the heating is the excitation efficiency of quasi-electrostatic waves by electromagnetic waves launched from vacuum.

In magnetized plasma excitation of the quasi-electrostatic oscillations is possible as a straight-forward XB tunneling of the fast extraordinary wave (X) into the electron Bernstein wave (B) in the vicinity of the UH resonance, and as so called OXB process, a consequent linear transformations of the ordinary wave (O) into the slow extraordinary wave, and then to the then Bernstein wave.

The efficiency of the XB and OX coupling (the later in major extend defines the efficiency on the entire OXB process) is traditionally evaluated with Budden–Ginzburg approach as an integral of the purely imaginary wave vector over the evanescent coupling region in the vicinity

of the UH resonance [1, 2]. This approach is based entirely on the dispersion relation of waves in locally homogeneous plasma and do not take into account the peculiarities of the vector nature of Maxwell's equations in weakly inhomogeneous gyrotropic media. The resulting formulas work fairly well in case of strong magnetic field $\omega_{ce} \sim \omega$, however do not allow correct transition to the isotropic plasma, in which the efficiency of the linear coupling of electromagnetic waves to Langmuir oscillations is also known [3]. In recent papers it was shown that the existing theory does not work in the domain of finite but low magnetic fields, $\omega_{ce} \ll \omega$, that is of interest for high- β plasmas [4, 5].

In this work we discuss results of calculation of XB and OXB conversion efficiency for smoothly inhomogeneous weakly anisotropic magnetized plasma.

We use the following simplifications. First, we consider one-dimensional geometry in which the external magnetic field is uniform and directed along the z axis, and the plasma density changes by parabolic law along the x axis, $n_e = n_0(1 - x^2 / L^2)$. Second, we consider cold but weakly collisional plasma, thus neglecting effects of spatial dispersion due to thermal motion but introducing the effective collision rate $\nu_{eff} \ll \omega$. Here we rely on well-known conclusion of the equality of the weak electromagnetic energy losses due the collisional and resonant collisionless wave absorption in the vicinity of the UH resonance. In this frame, the efficiency of coupling to the quasi-electrostatic mode is calculated simply as the absorption coefficient of the electromagnetic wave. Third, we consider a plane electromagnetic wave $\propto \exp(i\omega t - i\mathbf{k}\mathbf{r})$ launched from the vacuum at certain direction.

In case of smoothly inhomogeneous plasma $k_0 L \gg 1$ transformation efficiency depends only on three combinations of physical parameters [4,5]:

$$\tilde{g} = \xi^{2/3} \omega_{ce} / \omega, \quad \tilde{N}_{y,z} = \xi^{1/3} k_{y,z} / k_0,$$

where $\xi = k_0 L n_c / 2\sqrt{n_0(n_0 - n_c)}$ is the large parameter of geometrical optic, n_c is the critical plasma density. These parameters characterize magnetic field strength and direction of a wave launch correspondently.

As a reference point, the case of non-magnetized plasma $\tilde{g} = 0$ is shown in figure 1 (left panel). Here we reproduce well the analytical formula [3] for the absorption of the oblique TM wave due to coupling to the Langmuir oscillations. Non-magnetized plasma is characterized by the axially symmetric extremum $C_{TM} \approx 0.5$ reaching at $\tilde{N}_\perp \approx 0.66$. Absorption for the orthogonal TE wave here is negligibly small.

One can see that the dependence of the coupling efficiency over the incident direction \tilde{N}_y becomes asymmetric for the TM waves. This asymmetry is already visible at extremely low magnetic fields $\tilde{g} = 0.01$ see figure 1(right panel), where the coupling efficiency increases at $\tilde{N}_y > 0$ and decreases at $\tilde{N}_y < 0$ compared with the isotropic case.

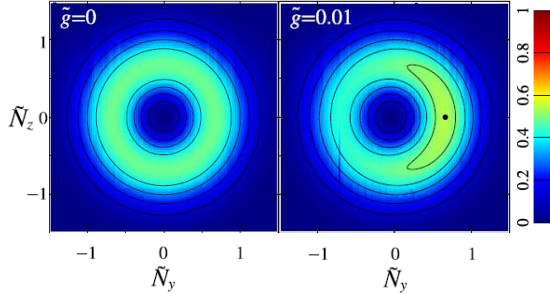


Fig. 1. Conversion efficiency for TM wave for isotropic (left panel), and weakly anisotropic (right panel) plasma

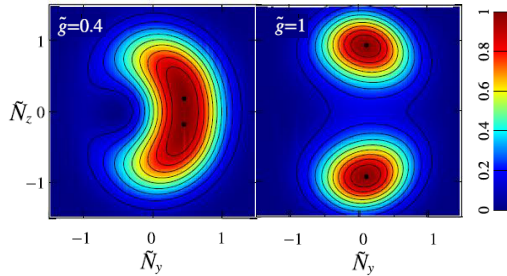


Fig. 2. Absorption coefficient for optimal polarization $C_{\max} = C_{TE} + C_{TM}$ for $\tilde{g} = 0.4$ (left) and $\tilde{g} = 1$ (right)

The asymmetry becomes more pronounced with increase of the magnetic field. Efficient absorption is localized near the propagation direction perpendicular to the magnetic field, $\tilde{N}_z = 0$, but with a particular angle with respect to the density gradient, $\tilde{N}_y \approx 0.5$. At $\tilde{g} > 0.4$ the maximum saturates close to the maximum possible value $C_{TM} \approx C_{\max} \approx 1$ (see figure 2). Moreover, the maximum splits into two maxima symmetric in \tilde{N}_z ; with that bifurcation efficient absorption becomes possible in a wide range of angles to the magnetic field. At the same time, the whole region $\tilde{N}_y < 0$ corresponds to practically zero absorption. As confirmed by numerical modeling, in high magnetic fields, $\tilde{g} > 1$, the optimal polarization corresponds to the wave polarized circularly in the direction of rotation of the ion. This is exactly the O mode of a weakly magnetized plasma (see figure 3).

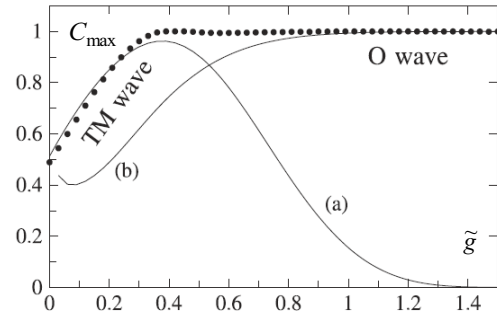


Fig. 3. Dependence of calculated absorption coefficient for optimal polarization on magnetic field strength (dotted line) versus analytical formulas for TM wave (a), and O wave (b) [5]

A straightforward approach based on the full Maxwell equations for interacting waves not only corrects the traditional theoretical views on wave coupling but shows new options for the efficient transformation of electromagnetic waves into quasi-electrostatic oscillations in weakly magnetized high- β plasmas. In our opinion, the most important, practical conclusion is demonstration of the possibility of almost total absorption for the optimally polarized plane wave by an inhomogeneous plasma slab at all magnetic fields satisfying $\omega_{ce} / \omega > 0.3\xi^{-2/3}$. At low fields, this occurs for the linearly polarized TM wave with $N_y \approx 0.5\xi^{-1/3}$ and $N_z \ll N_y$. With increasing magnetic field, the optimal wave becomes close to the plasma O mode propagating at $N_y \ll N_z$ and $N_z \approx \sqrt{\omega_{ce} / \omega}$. Another new feature outlined in this paper is pronounced asymmetry of the absorption process with respect to the plane defined by the gradient of the plasma density and the external magnetic field.

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References

1. Budden K.G. Radio Waves in the Ionosphere. 1966. Cambridge: Cambridge University Press
2. Ginzburg V.L. The Propagation of Electromagnetic Waves in Plasmas 2nd edn 1970. Oxford: Pergamon
3. Denisov N.G. On a Singularity of the Field of an Electromagnetic Wave Propagated in an Inhomogeneous Plasma // Sov.—JETP. 1957. V. 4. P. 544.
4. Gospodchikov E.D., Kutlin A.G., Shalashov A.G. Coupling electromagnetic and quasi-electrostatic waves in electron cyclotron frequency range in high- β devices // AIP Conf. Proc. 2016. V. 1771. P. 030016.
5. Gospodchikov E.D., Kutlin A.G., Shalashov A.G. Plasma heating and coupling of electromagnetic waves near the upper-hybrid resonance in high- β devices // Plasma Phys. Control. Fusion. 2017. V. 59. P. 065003.