Control of Energy Deposition Profile for Electron Cyclotron Resonance Heating in Open Trap

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Abstract. A technique is proposed for the energy deposition profile adjustment at electron cyclotron resonance heating using relatively small perturbation of the external magnetic field in an axisymmetric magnetic trap. This method is based on high sensitivity of EC power deposition profile of quasi-longitudinal propagating right-polarized electromagnetic waves to radial inhomogenity of external magnetic field strength and direction. A possibility of an effective control of power deposition profile and heating efficiency is demonstrated both analytically and numerically for the longitudinal launch of microwave radiation into a magnetic mirror region.

INTRODUCTION

In recent years, electron cyclotron heating of the plasma, which is confined in open magnetic traps, by using millimeter waves allowed one to reach significant progress in solving the task of producing discharges with required parameters. This was done both in relatively small-size setups [1, 2], where the transition to higher frequencies of the heating radiation made it possible to increase sharply the efficiency of operation of the multicharged-ion sources based on open traps, and in large-scale setups operated within the framework of controlled fusion developments, in which the implementation of additional electron cyclotron heating ensured a significant increase in the time of confinement of hot "fusion" ions due to the increase in the electron temperature to the values which are record-breaking for this class of devices [3,4].

Unlike the toroidal systems, where the radial profile of energy deposition during electron cyclotron heating is easily controlled, in principle [5,6], no efficient control methods have been developed for open magnetic traps so far. Depending on the object of the experiment, it may be necessary to generate either a profile with a strong maximum or a more homogeneous radial profile. In this paper, we consider the possibility to control the radial profile of energy deposition, which is based on the properties of refraction of electromagnetic waves near the surface of the electron cyclotron resonance.

Due to the smallness of the wavelengths, propagation of waves with frequencies close to the electron cyclotron frequency in laboratory magnetic traps is described, as a rule, by the geometric-optical approximation with good accuracy. Studying the trajectories of geometric-optical beams allows one to evaluate the possibility of plasma heating, heating efficiency, and dimensions of the energy deposition region qualitatively and, frequently, even quantitatively. It was demonstrated in [8–11] that the qualitative pattern of ray trajectories is strongly dependent on the two-dimensional distribution of the magnetic field near the resonance point. In some cases, beam trajectories are "attracted" to the trap axis, while in other cases, even those corresponding to a close configuration of the magnetic field, they can be "repelled" away from it. In this paper, we analyze this possibility. The required level of magnetic-field perturbations is determined on an example of the simplest geometry of the magnetic field in the trap. We present evaluations of the possibilities to control the radial profile of the energy deposition for some modern experiments with electron cyclotron plasma heating in open magnetic traps.

CONTROL OF THE RESONANCE SURFACE CURVATURE

In the paraxial approximation by expanding the magnetic field near the trap axis for undercritical plasmas it was shown [9] that under the condition $(\xi-1/2)>0$ stationary point for geometrical optics rays on axe of trap is unstable (unattractive) and at $(\xi-1/2)<0$, it is stable (attractive). Where ξ is the dimensionless parameter, which characterizes the curvature of the resonance surface determined by the condition $\omega=\omega_B$ (where ω_B is electron cyclotron resonance frequency) and described by the condition $z=-\xi r^2/2L_B$, where L_B .is the characteristic scale of magnetic field inhomogeneity along axis z.

The theoretically predicted dependence of the pattern of ray trajectories (and, therefore, efficiency of radiation absorption) on the parameter ξ prompts the idea about the possibility of controlling the heating efficiency and the radiation absorption profile by means of minor perturbations of the magnetic field. Consider several simplest ways to control the resonance surface curvature on an example of the simplest mirror configuration of the magnetic field, which is produced by identical current coils located at a certain distance. Note that the distribution of the parameter ξ in this case depends only on the ratio between the coil radius r_0 and the trap length $2L$ or on the mirror ratio Q: for the case of $Q>>1$, the approximate equality $Q\approx L^3/2r_0^3$ takes place.

Idea is to add two coils symmetrically with respect to the resonance region and start countercurrents in them. Such a system does not shift the resonance, but changes the local curvature of the resonance surface noticeably. Calculations show that in this case, a change in the parameter ξ from 0.4 to 0.6 requires a variation in the current in additional coils being equal to about 3% of the current in the main coils: $I_{add}/I_{mirr}\in(-0.05, 0.10)$, see Fig. 1.

Note that geometric optical modeling leads to a conclusion that the transition from $\xi=0.4$ to $\xi=0.6$ corresponds to a total change in the pattern of beam trajectories [9,11].Therefore, in a sufficiently cold plasma this corresponds to the transition from the case where all injected radiation is absorbed near the trap axis to the case where the density of the radiation energy is localized at the plasma periphery. Most probably, a significantly smaller variation of the parameter ξ can be sufficient for a noticeable control of the energy deposition profile. Thus, in the context of control over the energy deposition profile, the most promising scheme is that with two magnetic coils of countercurrents. It should be noted as well that the perturbation produced by this additional system is local. It introduces small perturbations to the main field of the trap, which is usually optimized from the viewpoint of plasma confinement and in some cases, from the viewpoint of transportation of the radiation to the resonance region as well [12].

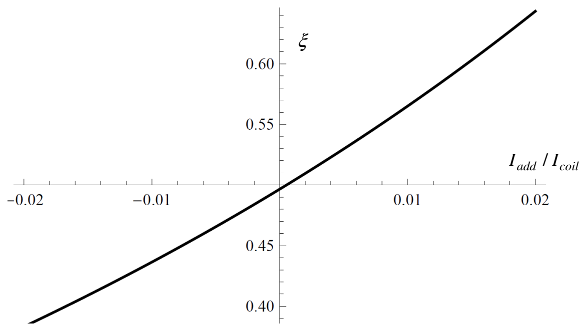

FIGURE 1. Variation of the ξ as a function of I_{add}/I_{mirr}.

RESULTS OF NUMERICAL SIMULATIONS FOR WARM INHOMOGENEUS PLASMA

In the above-presented theoretical considerations, we did not allow for the fact that the radiation was absorbed in a certain vicinity of the resonance surface, whose width is determined by the plasma temperature, rather than on the resonance surface itself. In this case, a significant width of the absorption region is typical of the heating of a dense plasma by the first harmonic of the extraordinary wave [13, 14].

In order to check the possibility of controlling the energy deposition profile by adding countercurrent coils, we simulated the absorption of the radiation power near the electron cyclotron resonance numerically for a sufficiently warm plasma (with $T_e \approx 150$ eV), which is confined in a small-size mirror machine being the source of multi-charge ions with a direct quasi-longitudinal radiation input [1, 2, 14].

To simulate the magnetic field in a small-size mirror machine, we used the magnetic field of two current coils with a radius of 8 cm placed apart at the distance $2L$ = 32 cm, which corresponds to the micrror ratio Q = 6. The current in the coils was chosen such that the electron cyclotron resonance condition for a radiation frequency of 37.5 GHz is fulfilled at the trap axis at a distance of 7 cm from the central cross section. Symmetrically to this point and a distance of 4 cm from it, we added coils with countercurrents amounting to 2% of the current in the main coils. Scheme of magnetic coils and magnetic field for different cases are shown on Fig 2.

The density (n_e = $0.5*10^{13}$ cm^{-3}) and temperature of the plasma were assumed constant in our model. The radiation was injected from the side of one of the mirrors in the form of a set of rays parallel to the trap axis. The Gaussian distribution of the intensity of the injected beam was simulated by weight coefficients of the radiation intensity corresponding to individual rays. In this work, a formula for the refractive index in the cold plasma limit was used as the Hamiltonian. In this case, the optical thickness, which characterized the decrease in the intensity of the injected power along the beam due to absorption, was calculated using the equation $d\tau / dl = 2\,\mathrm{Im}\,k \cos\beta$ where l is the coordinate along the beam, β is the angle between the wave vector and the group velocity, and the imaginary part of the wave vector was found from the dispersion relation, which allowed for the influence of the thermal electron motion on the dielectric response. In all calculations which we performed, the imaginary part of the wave vector always remained less than the real one by more than three times, up to the value $\tau = 5$. The used simulation method and the limitations imposed by the geometrical-optics approximation were considered in more detail in [16]. It should be noted that in the case of quasi-longitudinal propagation, near the cyclotron resonance the real part of the wave vector, which is determined by a more accurate dispersion relation, can differ from the analogous value determined by the "cold" dispersion relation. To control the accuracy, we simulated beam propagation using the real part of the "warm" dispersion relation [13]. This simulation did not demonstrate any significant difference in the profiles of energy deposition compared with the simulation based on the "cold" dispersion relation. In this case, to model power absorption, the use of a "warmer" dispersion relation, rather than just next-order corrections of the "cold" approximation is essential due to the peculiarities of polarization of the electromagnetic wave during quasi-longitudinal propagation near cyclotron resonance.

In the simulation process, we specified the initial coordinates and momenta for the ray trajectories in the dense plasma directly. In accordance with [11], we assumed that the pattern of ray trajectories, which is determined by the type of Hamiltonian singularities, depends only weakly on the initial conditions largely determined by the vacuum—plasma transition.

Figure 3(a,b) presents the beam trajectories for two ways of the current switch-on The closer-to-the-trap additional coil from whose side the radiation was injected, is switched in the same direction with the mirror coils, while the farther-from-the-trap one, in the opposite direction (a), and vice versa (b). The dashed line means the electron cyclotron resonance surface. The dots mark the regions where the optical thickness integrated along the beam reaches unity. . The energy deposition calculated by using the equation of transfer along the rays for two cases is shown in Fig. 3(c). One can see that it is possible to change the width of the energy deposition profile almost twice by varying the current in additional coils within 2% of the current in the main coil, thus achieving a sharper or smoother energy deposition profile, depending on the purpose of the experiment.

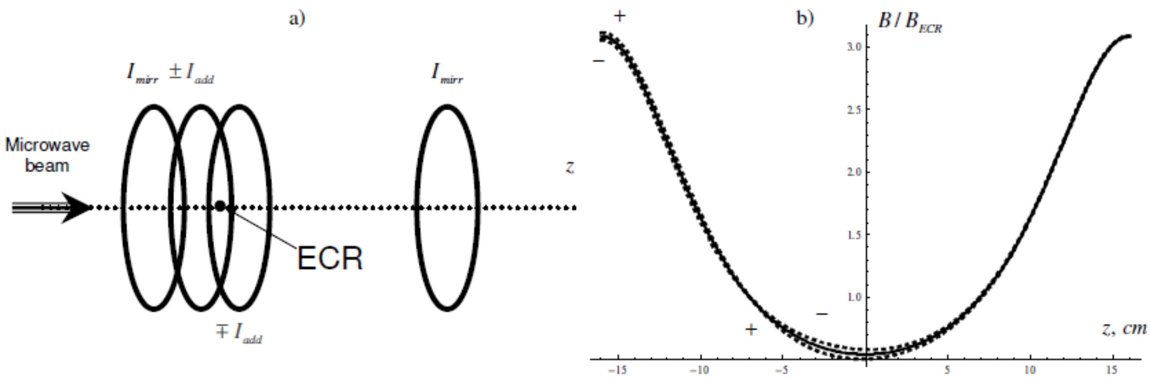

FIGURE 2. (a) Scheme of magnetic coils, (b) magnetic fields for only mirror coils – solid line, and two schemes of switchin on additional coils, sign + corresponds for upper sign in figure 2(a), sign - - for lower sign in figure 2(a)

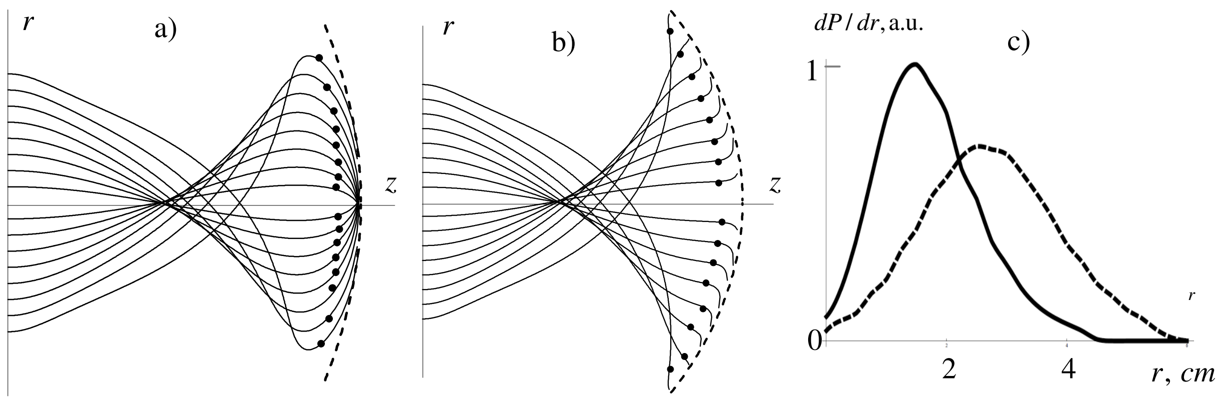

FIGURE 3. (a,b) Ray trajectories near the electron cyclotron resonance surface tor two ways of using additional coils. a) upper sign in Fig 2(a), b) – lower sign on Fig 2(a) The dashed line means the electron cyclotron resonance surface. The dots mark the regions where the optical thickness integrated along the beam reaches unity. (c) Distribution of the linear density dP/dr of the energy deposition, where P is the radiation power, as a function of the transverse coordinate. The solid and dashed lines correspond to the switch-on methods shown in Fig. 3*a* and Fig. 3b, respectively).

In this paper, we have demonstrated the possibility to control the energy deposition profile in a sufficiently warm plasma confined in an open magnetic trap by introducing a local magnetic-field perturbation produced by additional magnetic coils with countercurrents.

In a small-size mirror machine with an end radiation input and the resonance in the central part of the trap, this possibility is connected with controlling the curvature of the resonance surface. By making this curvature higher and lower than the critical value, one can readjust the energy deposition profile in a wide range, thus achieving a smoother or sharper profile depending on the purpose of the experiment.

For a large-scale gas-dynamic trap with a resonance near the mirror unit, such a possibility can be connected with suppression of a parasitic resonance in the rarefied plasma in the radiation input region [15]. Additionally, the method proposed herein does not require such a strong “additional” current. Therefore, its implementation would make it possible to operate with a closer to optimal configuration of the magnetic field in the trap.

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REFERENCES

[1] V.Vodopyanov, S.V.Golubev, V.G. Zorin, et al., Tech. Phys. Lett., 25, No. 7, 588 (1999).
[2] S.V.Golubev, S.V. Razin, V. E. Semenov, et al. Rev. Scientific Instrum., 71, No. 2, 669 (2000).
[3] P. A. Bagryansky, S.P. Demin, E.D.Gospodchikov, et al., Fusion Sci. Technol., 63, No. 1T, 40 (2013).
[4] P.A.Bagryansky, A.G. Shalashov, E.D.Gospodchikov, et al., Phys. Rev. Lett., 114, 205001 (2015).
[5] E.Westerhof, Nuclear Fusion, 27, No. 11, 1929 (1987).
[6] K. Hamamatsu and A.Fukuyama, Plasma Phys. Contr. Fusion, 42, 1309 (2000).
[7] M. A. Balakina, O.B. Smolyakova, and M.D.Tokman, Plasma Phys. Rep., 29, 53 (2003).
[8] E. D. Gospodchikov, O.B. Smolyakova, and E.V. Suvorov, Probl. Atomic Sci. Technol., 6, 76 (2010).
[9] E. D. Gospodchikov and O.B. Smolyakova, Plasma Phys. Rep., 37, No. 9, 768 (2011).
[10] D. S. Bagulov and I. A.Kotelnikov, Phys. Plasmas, 19, 082502 (2012).
[11] E. D. Gospodchikov and O.B. Smolyakova, Radiophys. Quantum Electron., 57, No. 12, 857 (2014).
[12] A.G. Shalashov, E.D.Gospodchikov, O.B. Smolyakova, et al., Phys. Plasmas, 19, 052503 (2012).
[13] E. D. Gospodchikov and E.V. Suvorov, Radiophys. Quantum Electron., 48, No. 8, 569 (2005).
[14] E. D. Gospodchikov, O.B. Smolyakova, and E.V. Suvorov, Plasma Phys. Rep., 33, No. 5, 427 (2007).
[15] E. D. Gospodchikov and O.B. Smolyakova, Radiophys. Quantum Electron., 58, No. 11, 825 (2016).