ON THE POSSIBILITY OF ECR-DISCHARGE WITH OVERCRITICAL PLASMA DENSITY IN AXISYMMETRICAL MAGNETIC TRAP

E.D.Gospodchikov, S.V.Golubev, O.B.Smolyakova, E.V.Suvorov, A.V.Vodopyanov
Institute of Applied Physics RAS , 46 Ul'yanov Street , 603950, Nizhny Novgorod , Russia
eggos@mail.ru

New approach to realizing high plasma parameters in electron cyclotron resonance discharge supported by microwave radiation in axisymmetric magnetic trap has been proposed. This approach is based on using the inverted radial distribution of plasma density (with minimum at the trap axis). Such plasma density distributions allow efficient cyclotron heating and sustaining the steady-state discharge with high plasma density including densities above the critical value (corresponding to the density for which plasma frequency equals to the frequency of heating radiation). Simulations of power deposition for EC heating of plasma with overcritical density in axisymmetric mirror magnetic trap are presented, in which the effect of increasing the heating efficiency for inverted radial plasma density profiles has been demonstrated.

I. INTRODUCTION

ECR discharge in open magnetic systems has been used as source of multi-charge ions for particle accelerators for a long time. For further progress of accelerators the ion beams with high ion current and charge numbers are needed. It is clear that ion current from ECR ion sources grows as plasma density in discharge. This fact determines interest for increasing the plasma density. Experiments demonstrate that plasma density in ECR discharge is limited by critical value when plasma frequency and heating frequency are equal to each other [2]. Further increase of plasma density and efficiency of ion sources may be obtained in two way. In the first one the increase in plasma density is reached by using of higher heating frequencies. At present time ion sources with heating frequency near 30 GHz and correspondently plasma densities near $10^{13}\,cm^{-3}$ has been developed [3]. Next step is source with heating frequency 75 GHz and plasma densities up to $10^{14}\,cm^{-3}$. Of course, the increase in heating frequency requires corresponding increase of the magnetic field in the trap, which considerably increases the cost of the whole installation. Second way is injection of the dense low temperature plasma into the trap from high-voltage discharge and subsequent heating of this plasma by right-hand polarized waves, which can propagate and be absorbed near electron cyclotron resonance region [4]. But in overdense plasma the efficiency of such heating scheme is significantly suppressed by refraction of ECR waves [4]. In present paper the new approach to realizing high plasma parameters in electron cyclotron resonance discharge supported by microwave radiation in axisymmetric magnetic trap has been proposed. This approach is based on using the inverted radial distribution of plasma density (with minimum at the trap axis). Such plasma density distributions allow efficient cyclotron heating and sustaining the steady-state discharge with high plasma density including densities above the critical value (corresponding to the density for which plasma frequency equals to the frequency of heating radiation). Simulations of power deposition for EC heating of plasma with overcritical density in axisymmetric mirror magnetic trap are presented, in which the effect of increasing the heating efficiency for inverted radial plasma density profiles has been demonstrated.

II. REFRACTION OF ECR WAVES IN AXISYMMETRICAL MAGNETIC TRAP

It can be shown that for quasi-longitudinal propagation of ECR waves in axisymmetrical magnetic trap ray trajectories $r_\perp(z)$ are defined by the following equation:

$$\frac{d^2 r_\perp}{dz^2} = \frac{\varepsilon_\parallel + \varepsilon_-}{4\varepsilon_-\varepsilon_\parallel}\frac{\partial \varepsilon_-}{\partial r_\perp}, \qquad (1)$$

where $\varepsilon_\parallel = 1-\omega_P^2/\omega^2$, $\varepsilon_- = 1-\omega_P^2/\omega(\omega-\omega_B)$, $\omega_P^2 = 4\pi N_e e^2/m$.

For region where $\frac{\varepsilon_- + \varepsilon_\parallel}{\varepsilon_-\varepsilon_\parallel}\frac{\partial \varepsilon_-}{\partial r_\perp} > 0$ rays tend away from trap in radial direction, and for region where $\frac{\varepsilon_- + \varepsilon_\parallel}{\varepsilon_-\varepsilon_\parallel}\frac{\partial \varepsilon_-}{\partial r_\perp} < 0$ and rays are “attracting” to the axis of a system. So, from what was said above, it follows that ray distributions are qualitatively different for cases of udercritical ($\varepsilon_\parallel > 0$) and overcritical ($\varepsilon_\parallel < 0$) plasma.

The condition for ray attraction to the axis of a system is:

$$\frac{\varepsilon_- + \varepsilon_\parallel}{\varepsilon_- \varepsilon_\parallel}\frac{\partial \varepsilon_-}{\partial r_\perp} < 0 \,. \qquad (2)$$

For analyzing the condition (2) we use the explicit form for the derivative $\partial\varepsilon_- / \partial r_\perp > 0$:

$$\frac{\partial \varepsilon_-}{\partial r} = \frac{\omega_P^2}{(\omega_B - \omega)\omega}\left(\frac{1}{N_e}\frac{\partial N_e}{\partial r} - \frac{\omega_B}{\omega_B - \omega}\frac{1}{B}\frac{\partial B}{\partial r}\right) . \qquad (3)$$

Far from electron cyclotron resonance region second term in right-hand part of (3) can be neglected. For ray behavior near ECR region see other presentation to this Conference [5].

For high field side launch of radiation ($\omega_B > \omega$, $\varepsilon_- > 0$), rays tend to axis of system for conventional distribution of plasma density (with maximum at the axis) if the density is lower than the critical one ($\varepsilon_\parallel > 0$). For overcritical density ($\varepsilon_\parallel < 0$), ray trajectory behavior is determined by sign of expression $\varepsilon_\parallel + \varepsilon_-$. For $\varepsilon_\parallel + \varepsilon_- < 0$ situation looks like for udercritical plasma density. For $\varepsilon_+ + \varepsilon_- > 0$ anomalous refraction take place. In this case ray trajectories tend to axis of system for distribution of plasma density with minimum at the axis. It is necessary to underline that for region between ECR surface $\omega = \omega_B$ and "subharmonic" resonance surface $2\omega = \omega_B$, for all plasma densities higher then critical one "anomalous" refraction is realized. For case of high mirror ratio in the region between the mirror and surface $2\omega = \omega_B$ anomalous refraction takes place only for limited value of plasma density $N_e < N^*$, where N^* is determined from expression

$$\omega_P^* = \omega\sqrt{\frac{2(\omega_B - \omega)}{\omega_B - 2\omega}} \,. \qquad (4)$$

If $N_e = N^*$, a specific "resonance" takes place. For this plasma density value $\varepsilon_\parallel + \varepsilon_- = 0$, the ray Hamiltonian for quasi-longitudinal propagation of ECR waves does not depend on $N_\perp$ and group velocity is parallel to magnetic field direction for all $N_\perp$. As result rays "ignore" plasma density inhomogenity and propagate along magnetic field lines.

From the above short analysis the recommendations how to decrease negative influence of refraction may be formulated as following:

1) Near magnetic mirror it is useful to have densities higher than one following from expression (4), because in region where $\omega_P > \omega_P^*$, group velocity is nearly parallel to magnetic field direction;
2) In region where $\omega < \omega_P < \omega_P^*$ necessary to have density distribution with maximum at the axis.

If these conditions are satisfied, it is possible to transport EC radiation to the ECR region in wider range of magnetic surfaces which are fully situated in plasma. Note, that density distribution with the minimum at the axis results in additional MHD stability.

III. NUMERICAL SIMULATION

For illustration, the results of numerical simulation for conditions of SMIS-37 magnetic trap [3] are given. In Figs. 1-4 ray trajectories for different density distributions are presented. Ray trajectories are presented by black solid lines, resonance surfaces are denoted by gray solid lines, magnetic field lines and non-resonance surfaces of constant magnetic field are presented by dashed lines. Efficiency of electron cyclotron absorption of wave beam was estimated as number of ray, which approaches ECR region, such estimate is correct for ECR absorption of longitudinally propagated waves.

In Fig. 1 plasma density is constant. $N_e = 1.5N_C$, most of the rays are "thrown out" of the system.

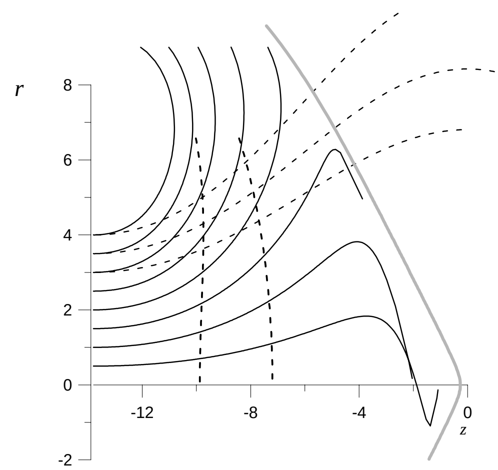

Fig. 1 Ray trajectories for $N_e = 1.5N_C$.

Fig. 2 demonstrates ray distribution for constant plasma density $N_e = 4N_c$. In region near magnetic mirror this value of plasma density is higher than one determined by expression (4). Boundary of region where our theory predict strictly longitudinal ray propagation is the surface $\omega_B = 3\omega$. One can see that rays propagate along magnetic field lines up to surface $\omega_B = 3\omega$, and are pushed out of the trap between this surface and resonant surface.

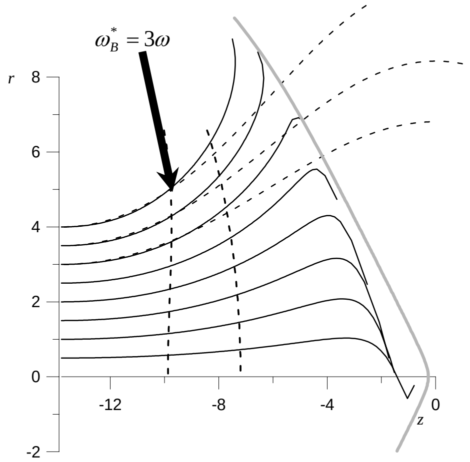

Fig. 2 Ray trajectories for $N_e = 4N_C$

In Fig. 3-4 the results of calculation are presented for density distributions with minimum at the axis: $N_e = N_0\left(1+\frac{r^2}{a^2}\right)$, where $a = 5cm$, $N_0 = 1.2N_c$ in Fig.3, and $N_0 = 3N_c$ in Fig 4. Such values chosen for comparison with Fig.1 and Fig. 2 correspondingly. In Fig.4 surface where $\omega_P = \omega_P^*$ is shown by fat dashed line.

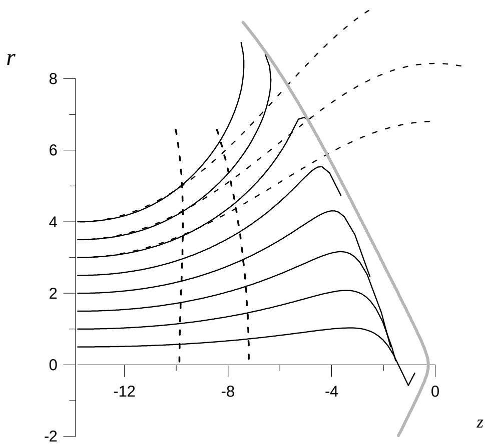

Fig. 3 Ray trajectories for $N_e = 1.2N_C\left(1+\frac{r^2}{a^2}\right)$

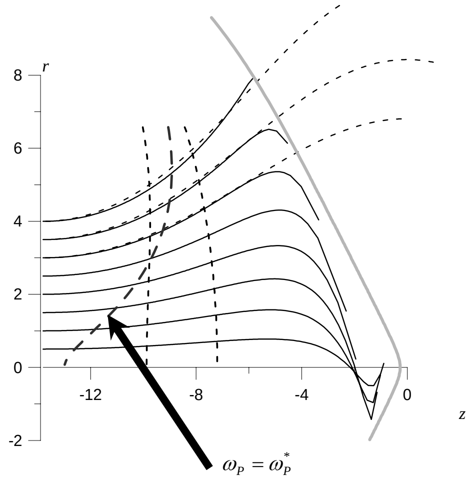

Fig 4. Ray trajectories for $N_e = 3N_C\left(1+\frac{r^2}{a^2}\right)$

IV. CONCLUSIONS

Analytical investigation and numerical simulation show that the effective ECR heating of overdense plasma in an axisymmetric mirror trap is possible for plasma densities higher than determinate from expression (4) one, and density distribution with minimum at the axis.

ACKNOWLEDGMENTS

The work has been supported by RFBR (projects 09-02-97041) and Presidential Council for Young Russian Scientist Support (project MK-2277.2009.2).

REFERENCES

1. S.V. GOLUBEV et al, *Transactions of Fusion Science and Technology*, **47**(1T) 345-347, (2005)
2. S.V. GOLUBEV et al. *Review of Scientific Instruments*, v**. 71**(2) 669-671 (2000)
3. A.V. VODOPYANOV, S.V. GOLUBEV, S.V. RAZIN, V.G. ZORIN, *Transactions of Fusion Technology*, **35** 288-291 (1999)
4. E. D. GOSPODCHIKOV, O. B. SMOLYAKOVA, E. V. SUVOROV *Transactions of Fusion Science and Technology*. **45**(1T) 252-255 (2005)
5. E.D.GOSPODCHIKOV, O.B.SMOLYAKOVA, E.V. SUVOROV "Influence of magnetic field directions inhomogeneity on longitudinal propagation of wave beams" *8th International Conference on Open Magnetic Systems for Plasma Confinement Conference proceeding* (2010)