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CONFINEMENT THEOREM FOR HIGH-CURRENT PLASMA LENS

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The theorem about a fraction of magnetized electrons, which could reach the cylindrical wall, is generalized for the case of collisionless plasma lens for focusing of ion beams. Long electron column is considered. The electrons are partly noncompensated by ions. It is shown from the conservation of angular momentum that if the radius of electron column is small in comparison with the distance from the column to the wall then the only small fraction of electrons from the column could reach the wall.

Introduction

In [1] the theorem about a fraction of electrons, which could reach the cylindrical wall in collisionless case , is presented for the case of purely electron magnetized plasma. In high-current plasma lens for focusing of ion beams [2] the dynamics of electrons is similar to their dynamics in purely electron plasma. The latter is determined by the fact that the electrons in high-current plasma lens are partly noncompensated by ions. But the ions strongly influence on electron behavior in plasma lens. Therefore we generalize this theorem on the case of high-current plasma lens. Electron cloud or long electron column is considered here. It is trapped by longitudinal magnetic field, B_o, in the system of finite radial dimension, R. Conservation of angular momentum leads to estimation for fraction of electrons which could reach the cylindrical wall in radial direction. It is shown that if the radius of electron column r_o is small in comparison with the distance from the column to the wall R then the only small fraction of electrons $\Delta N_R = n_e(R)2\pi R\Delta R$ from the column could reach the wall. Here ΔR is the thickness of the hollow cylinder of electrons which reached the wall. Also it is shown that the fraction of electrons from the column which could reach the wall in collisionless case is depended on the difference of electron and ion densities n_e-n_i .

Influence of ions on confinement of electrons in plasma lens

One kind of plasma lens for ion beam focusing consists of a long electron column. For providing of good quality focusing the electron column should be homogeneous in radial direction. For supporting this required homogeneous state it is important to control radial electron transport. Note that charged magnetized plasma of finite radial dimension has good confinement properties. We do not consider the axial confinement properties. But we worry about the radial confinement. We use an approximation of an infinitely long electron column. The initial number of electrons equals $N_o=n_o\pi r_o^2$. We suppose that they are distributed homogeneously in radial direction on dimension r_o. The electrons are partly neutralized by ions with homogeneous density n_{oi}. In approximation of homogeneous radial particle distribution electrons drift on angle with velocity $V_\theta \approx 2\pi ecr(n_e-n_i)/B_o$. Here r is the distance from the column axis, c is the light velocity. One can use the conservation of angular momentum P_θ of electrons and field for estimation of electron fraction $\Delta N_R/N_o$ which could reach the wall. We consider conditions when $\Delta N_R/N_o$ is small. We neglect by electron collisions with atoms and ions. Also we neglect by dissipation of electron column due to electron radiation. We suppose that the hollow electron cylinder with thickness Δr , density $n_e(r_\Delta)$ and small number of electrons $\Delta N=n_\Delta 2\pi r_\Delta \Delta r$ has reached the radius r_Δ. But the radius of remaining electron cylinder has been decreased from r_o to r_a and their density became n_{ae}. Thus the radial electric field equals

$$E_r=-2\pi e\delta n_o r_o^2/r \ , \ r_o<r<R,$$
$$E_r=-2\pi e(n_o r_o^2/r-n_{oi}r) \ , \ r_a<r<r_o, \qquad (1)$$
$$E_r=-2\pi e\delta n_a r \ , \ r<r_a$$

Here $\delta n_o=n_{oe}-n_{oi}$, $\delta n_a=n_{ae}-n_{oi}$.

According to the equation

$$V_\theta^2/r=eE_r/m_e+ V_\theta\omega_{ce} \qquad (2)$$

one can obtain that the electrons drift on angle with velocity

$$V_\theta=(\omega_{ce}r/2)[1-(1-2A/\omega_{ce}^2)^{1/2}] \qquad (3)$$

Here $\omega_{ce}=eB_o/m_ec$ is the cyclotron frequency of electron,

$$A=\omega_{po}^2 r_o^2/r^2 \ , \ r_o<r<R,$$
$$A=\omega_{pa}^2 \ , \ r<r_a \qquad (4)$$

$\omega_{po}^2=4\pi e^2\delta n_o/m_e$, $\omega_{pa}^2=4\pi e^2\delta n_a/m_e$.

The angular momentum for one electron equals

$$P_{\theta e} = mrV_\theta + (e/c)rA_\theta \qquad (5)$$

Here A_θ is the θ component of vector potential. A_θ is determined by external magnetic field and by selfconsistent magnetic field or electron current with velocity V_θ . Initially A_θ equals

$$A_\theta\big|_{t=o}=(B_o r/2)[1-(r^2\omega_{poo}^2/8c^2)(1-(1-2\omega_{po}^2/\omega_{ce}^2)^{1/2})] \qquad (6)$$

For final state with two electron cylinder: hollow one with radius r_Δ and solid one with radius r_a A_θ equals

$$A_\theta=(B_o r/2)\{1-(r^2\omega_{pao}^2/8c^2)[1-(1-2\omega_{pa}^2/\omega_{ce}^2)^{1/2}]\} \qquad (7)$$

Here $\omega_{poo}^2=4\pi e^2 n_o/m_e$, $\omega_{pao}^2=4\pi e^2 n_a/m_e$.

For electrons with density n_e , distributed in radial direction from axis to r , the angular momentum equals

$$P_\theta = 2\pi\int_o^r dr\, rn_e(r)[mrV_\theta + (e/c)rA_\theta] \qquad (8)$$

The conservation of P_θ can be written as follow

$$2\pi\int_o^{ro} dr\, r^2 n_{oe}[mV_\theta + (e/c)A_\theta]= =2\pi\int_o^{ra} dr\, r^2 n_a[mV_\theta + (e/c)A_\theta]+ +\Delta N r_\Delta(mV_{\theta\Delta} + (e/c)A_{\theta\Delta}) \qquad (9)$$

From (9) one can derive at $r_a \to 0$ and $r_\Delta \to R$ for ΔN_R (is the number of electrons, which could reach the wall of the system)

$$\Delta N_R/N_o \approx \approx(r_o^2/2R^2)\{1+(1-r_o^2\omega_{poo}^2/12c^2)[1-(1-2\omega_{po}^2/\omega_{ce}^2)^{1/2}]\} \qquad (10)$$

From (10) it follows that the small fraction of electrons $\Delta N_R/N_o$ could reach the wall of the system for small r_o in comparison with R and it depends on n_{oe}-n_{oi} .

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References

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