CONDITION OF DAMPING OF ANOMALOUS RADIAL TRANSPORT, DETERMINED BY ORDERED CONVECTIVE ELECTRON DYNAMICS

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It is shown, that at development of instability due to a radial gradient of density in the crossed electric and magnetic fields in nuclear fusion installations ordering convective cells can be excited. It provides anomalous particle transport. The spatial structures of these convective cells have been constructed. The radial dimensions of these convective cells depend on their amplitudes and on a radial gradient of density. The convective-diffusion equation for radial dynamics of the electrons has been derived. At the certain value of the universal controlling parameter, the convective cell excitation and the anomalous radial transport are suppressed.
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INTRODUCTION

Anomalous plasma particle transport due to low-frequency perturbations in the cross-field edge region of the toroidal devices is investigated now intensively (see, for example, [1]). Now also the role of the electric field, formed in nuclear fusion installations and resulting to crossed fields, is intensively investigated. In the laboratory experiments in crossed fields the vortex formation in electron plasma was observed [2], in magnetron discharge, in ECR plasma source [3], in anode layer of the Penning discharge. The charged plasma lens, intended for focusing of high-current ion beams, has the same crossed configuration of fields [4] and the vortices are formed in it. Thus, the crossed configuration of fields also can be one of the reasons of the vortices excitation in nuclear fusion installations.

In turbulence of small amplitudes, the electron trajectories are stochastic. At achievement of the large amplitudes when frequency, Ω, of the electron oscillations in the convective cell of the perturbation exceeds the growth rate of its excitation, $\Omega(t)>\gamma$, the cell changes in its vicinity the electron density gradient ∇n_e, which strengthens the next cells. Thus on the cell boundaries the jumps of $n_e(r)$ arise. On these jumps the growth rates of the next cell excitation are much more than the growth rate, determined by not perturbed ∇n_e. Thus, ordering of cells arises similar investigated in [5]. It provides faster electron transport. In other words, the selfconsistent excitation of the low-frequency convective cells in the nonequilibrium plasma, drifting in crossed electric and magnetic fields in stelarator, by a radial gradient of density is unstable concerning occurrence of correlations. Thus, convective-diffusion radial electron transport and partly ordered lattice of convective cells in space (r, z) arise.

DESCRIPTION OF EXCITATION AND STRUCTURE OF CONVECTIVE CELLS

Let us consider development of instability of convective electron dynamics excitation in radial electric E_{or} and longitudinal magnetic H_o fields in the region of density gradient, and suppression of the anomalous transport caused by this convective dynamics. We use cylindrical approximation. For description of the electron convective dynamics we use theory, developed in [6] for plasma lens. The electron dynamics in crossed fields is described by the equations [6-8]

$$d_t\left[(\alpha-\omega_{He})/n_e\right]=0\ ,\ d_t\equiv\partial_t+\left(\vec{V}_\perp\vec{\nabla}_\perp\right),\ \vec{\nabla}_\perp\varphi\equiv\vec{\nabla}_\perp\phi-E_{ro},$$

$$\alpha=\frac{1}{r}\partial_r rV_\theta-\frac{1}{r}\partial_\theta V_r\approx-\frac{2}{r\omega_{He}}\left(\left(\frac{e}{m_e}\right)E_{0r}+\left(\frac{V_{th}^2}{n_{0e}}\right)\partial_r n_{0e}\right)+\frac{e}{m_e\omega_{He}}\Delta_\perp\phi\ .$$

$$\vec{V}_\perp\approx-\left(\frac{e}{m_e\omega_{He}}\right)\left[\vec{e}_z,\left(\vec{E}_{ro}+\frac{T_e}{e}\vec{\nabla}n_{0e}\right)\right]+\left(\frac{e}{m_e\omega_{He}}\right)\left[\vec{e}_z,\vec{\nabla}_\perp\phi\right]\approx\vec{V}_{\theta o}+\left(\frac{e}{m_e\omega_{He}}\right)\left[\vec{e}_z,\vec{\nabla}_\perp\phi\right].$$

ϕ is the electric potential of the perturbation.

From this equation we derive similarly [6] the linear dispersion relation, describing the instability development

$$1-\omega_{pi}^2/\omega^2-\left(\omega-\ell_\theta\omega_{\theta o}\right)^{-1}k^{-2}\left(\ell_\theta/r\right)\partial_r\left(\omega_{pe}^2/\omega_{He}\right)=0\,.$$

For mobile perturbations $V_{ph}\approx V_{\theta o}$ one can obtain [6] $\omega=\omega^{(o)}+\delta\omega$, $\omega^{(o)}=\omega_{pi}=\ell_\theta\omega_{\theta o}$, $\delta\omega=i\gamma_q$,

$$\gamma_q\approx\left[\left(\omega_{pi}/2k^2\right)\left(\ell_\theta/r\right)\left|\partial_r\left(\omega_{pe}^2/\omega_{He}\right)\right|\right]^{1/2}$$

The growth rate is proportional to $\sqrt{\partial_r n_o}$. At its obtaining we used a validity of the inequality

$$\left[\left(E_{ro}+\left(T_e/e\right)\partial_r n_{0e}\right)/2\pi e n_{oe}\omega_{He}\right]\left|\partial_r\left(\omega_{pe}^2/\omega_{He}\right)\right|<<m_e/m_i\ .$$

It is fulfilled at the small $\partial_r n_o$ and $\omega_{He}/\omega_{pe}>>1$.

Let us consider the chain on θ of the mobile convective cells. At small deviations r from r_q, taking into account the first member of $\left(E_{ro}(r)+\left(T_e/e\right)\partial_r n_{0e}(r)\right)/r\omega_{He}(r)$ on $\delta r\equiv r-r_q$, we obtain the radial size of the convective cell - hole of the electrons

$$\delta r_h \approx 2\left[2\phi_o / r_q \omega_{He}(r_q)\partial_r\left((E_{ro}(r)+(T_e/e)\partial_r n_{0e}(r))/r\omega_{He}(r)\right)\Big|_{r=r_q}\right]^{1/2} .$$

For large amplitudes in the regions of the electron bunches the contraflows are formed. One can show that in the rest frame, rotated with frequency ω_{ph} , the electrons, trapped by the electron hole, and the electrons, forming the electron bunch, are rotated in the opposite directions. We obtain from the condition $\delta r\big|_{\phi=-\phi_o} = \delta r_{cl}$ the boundary of the cell - hole of the electrons

$$\delta r = \pm\left[\frac{4(\phi+\phi_o)}{r_q\omega_{He}(r_q)\partial_r\left((E_{ro}(r)+(T_e/e)\partial_r n_{0e}(r))/r\omega_{He}(r)\right)\Big|_{r=r_q}} + (\delta r_{cl})^2\right]^{1/2}$$

Here δr_{cl} is the radial width of the convective cell-bunch of the electrons.

Let us consider the effect $\partial_r n_{oe}$ on behavior of cells. Finiteness of time of the convective cell symmetrization and the reflection of resonant electrons from convective cells - bunches result that the convective cells are partly asymmetrical [6]. It results in formation of E_θ and radial drift of cells. This behavior of the convective cells has been observed in experiments [2]. The convective cells are shifted on radius together with trapped electrons, leading to additional mechanism of convective radial electron transport.

CONVECTIVE–DIFFUSION EQUATION

For realized now in nuclear fusion values ω_{pe}/ω_{He} and E_r the parameter, determining type of excited convective cells, is small. It means that mobile cells should be formed. Then for finite but not so large amplitudes the cell – holes of the electrons are formed. Therefore, further we consider convective transport, realized by cells - holes of the electrons.

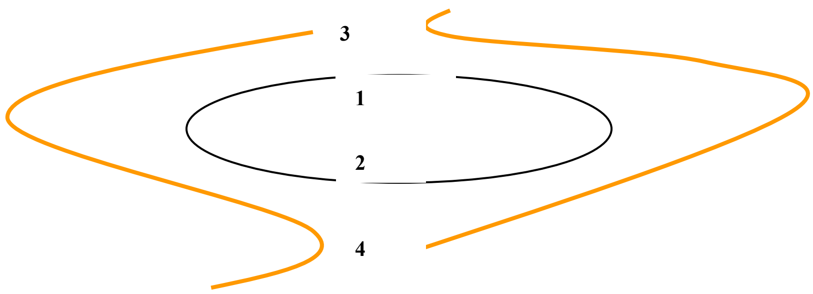

Fig. 1. Single convective cell

At achievement of the large amplitudes there appears ordering of cells (see Fig. 2) similar investigated in [5]. Inside borders of a cell ordered convective movement of the electrons occurs. However, they are influenced by environmental fields. Also it is important that amplitudes of cells are not stationary. Instead of average $n_{oe}(t,r)$, which does not take into account correlations, we use four densities of the electrons $n_{ke}(t,r)$ average on small-scale oscillations: $n_{1e}(t,r)$ ($n_{2e}(t,r)$) is the average density of the electrons, located in region 1 (see Fig. 1) in depth of a cell on $r>r_v$ (in region 2 in depth of a cell on $r<r_v$); $n_{3e}(t,r)$ ($n_{4e}(t,r)$) is the average density of the electrons, placed in region 3 near border of a cell on $r>r_v$ (in region 4 near border of a cell on $r<r_v$). The importance of use of different $n_{ke}(t,r)$ is also determined by that angular speeds of electron rotation inside a cell are different in dependence on distance from its axis. Also in two central areas of the convective cells the following processes are still realized: plateau formation on $n_e(r)$ due to difference of angular speeds of electron rotations; at $n_e(r)$ jump formation at the certain moments of time in the regions 1 and 2 there is an accelerated diffusion and an exchange by electrons between regions 1 and 3 (factor β), and also between regions 2 and 4.

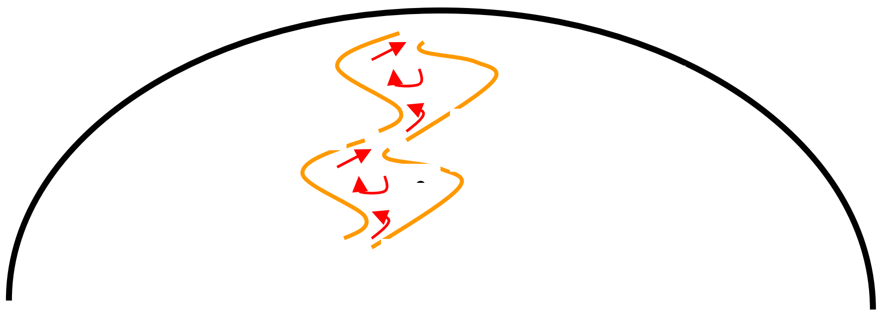

Fig. 2. The ordered chain of convective cells

From the above we have approximately

$$n_1(t+\tau, r) = (1-\alpha)n_2(t, r) + \alpha\beta n_3(t, r),\ n_2(t+\tau, r) = (1-\alpha)n_1(t, r) + \alpha\beta n_4(t, r)$$

$$n_3(t+\tau, r) = \alpha n_1(t, r) + \beta(1-\alpha)n_3(t, r-\Delta r) + \frac{(1-\beta)}{2}[n_3 + n_4]$$

$$n_4(t+\tau, r) = \alpha n_2(t, r) + \beta(1-\alpha)n_4(t, r+\Delta r) + \frac{(1-\beta)}{2}[n_3 + n_4]$$

α is the factor of mixing due to not ideal ordering, influence of fluctuations, growth of amplitudes, differences of characteristic times of the electrons. In vicinities of cell borders n_e jumps are formed. Hence, on these n_e jumps new cells with the greatest growth rates are excited. It results in ordering of convective cells. From these equations, entering $\bar{n} = (n_3 + n_4)/2$, $\delta n = n_3 - n_4$, $\bar{N} = (n_1 + n_2)/2$, $\delta N = n_1 - n_2$, we derive

$$\tau\partial_t \bar{n} = \alpha(\bar{N} - \beta\bar{n}) - (\beta/2)(1-\alpha)\Delta r\partial_r \delta n,\ \tau\partial_t \delta n + [1-\beta(1-\alpha)]\delta n = \alpha\delta N - 2\beta(1-\alpha)\Delta r\partial_r \bar{n}$$

$$\tau\partial_t \bar{N} = \alpha(\beta\bar{n} - \bar{N}),\ \tau\partial_t \delta N + (2-\alpha)\delta N = \alpha\beta\delta n$$

From these equations we have similar to [5]

$$\tau^2\partial_t^2 \delta n + \tau\partial_t[(1-\beta(1-\alpha))\delta n - \alpha\delta N] = -2\beta(1-\alpha)\Delta r\partial_r\left[\alpha(\bar{N} - \beta\bar{n}) - \frac{\beta}{2}(1-\alpha)\Delta r\partial_r \delta n\right]$$

We research the most favorable parameters when the convective cells are not excited and anomalous transport is suppressed. We show, that the convective cells are not excited, if the value of the magnetic field is close to the most favorable. So, let us consider such amplitude of the convective cell at which the magnetic force can not trap the electrons of the cell, rotating around its axis, on the closed trajectory, and electrons can move across the magnetic field. In other words, the electron bunch of the cell can extend across the magnetic field. Thus the electron bunch formation is stopped. Thus, from balance of the forces providing movement of the electrons on closed trajectories, one can find similar to [6] that if the magnetic field is close to optimum $\omega_{He} = \sqrt{4e\left(E_{ro} + \left(T_e / e\right)\partial_r n_{0e}\right)/m_e r}$, the convective cells are not excited.

CONCLUSION

So, at instability development due to the radial gradient of density in the crossed electric and magnetic fields in nuclear fusion installations the ordering of the convective cells can arise. It provides anomalous particle transport. The spatial structures of these quickly moving convective cells have been constructed. It has been shown, that the radial dimensions of these convective cells depend on their amplitudes and on a radial gradient of density. The convective-diffusion equation, describing these convective-diffusion radial dynamics of the electrons has been derived. There is the universal parameter, controlling the excitation of these convective cells. At the certain value of this parameter, the excitation of these convective cells and the anomalous radial transport are suppressed.

The observed fingers of density can be explained by the formation of these convective cells.

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