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

V.I. Maslov, S.V. Barchuk, V.I. Lapshin, Yu.V. Melentsov[1], E. D.Volkov

NSC Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine;
[1]Karazin Kharkov National University, Kharkov, 61108, Ukraine,
E-mail: vmaslov@kipt.kharkov.ua

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.
PACS: 52.27.Lw

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]

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

$$\alpha=\frac{1}{r}\partial_r rV_\theta-\frac{1}{r}\partial_\theta V_r\approx-\frac{2\ eE_{or}}{rm_e\omega_{He}}+\frac{e}{m_e\omega_{He}}\Delta_{¿}\varphi\ .$$

$$\vec{V}_{¿}\approx-\left(\frac{e}{m_e\omega_{He}}\right)\left[\vec{e}_z,\ E_{ro}\right]+\left(\frac{e}{m_e\omega_{He}}\right)\left[\vec{e}_z,\ \vec{\nabla}_{¿}\varphi\right]\approx¿$$

$$¿\approx\vec{V}_{\theta o}+\left(\frac{e}{m_e\omega_{He}}\right)\left[\vec{e}_z,\ \vec{\nabla}_{¿}\varphi\right],\ \vec{\nabla}_{¿}\varphi\equiv\vec{\nabla}_{¿}\varphi-E_{ro}\ .$$

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] $\omega=\omega^{(o)}+\delta\omega$, $\omega^{(o)}=\omega_{pi}=\ell_\theta\omega_{\theta o}$, $\delta\omega=i\gamma_q$,

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

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

$$\left(E_{or}/2\pi en_{oe}\omega_{He}\right)\left|\partial_r\left(\omega_{pe}^2/\omega_{He}\right)\right|<<m_e/m_i\ .$$

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

For motionless perturbations $V_{ph}<<V_{\theta o}$ one can obtain [6]

$$\gamma_s\approx\omega_{pi}^{2/3}\left[-V_{\theta o}\partial_r\left(\omega_{pe}^2/\omega_{He}\right)\right]^{1/6}\ ,$$

$$k^2=-V_{\theta o}^{-1}\partial_r\left(\omega_{pe}^2/\omega_{He}\right)\ .$$

γ_s is the growth rate of the motionless perturbations. The sizes of the motionless perturbations are inversely proportional to $\sqrt{\partial_r n_o}$.

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 $E_{ro}(r)/r\omega_{He}(r)$ on $\delta r \equiv r - r_q$, we obtain the radial size of the convective cell - hole of the electrons

$$\delta r_h \approx 2\left[2\varphi_o / r_q \omega_{He}(r_q)\partial_r\left(E_{ro}(r)/r\omega_{He}(r)\right)\Big|_{r=r_q}\right]^{1/}$$

.

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 $\delta r\big|_{\varphi=-\varphi_o} = \delta r_{cl}$ the boundary of the cell - hole of the electrons

$$\delta r = \pm\left[\frac{4\,(\varphi+\varphi_o)}{r_q\,\omega_{He}(r_q)\,\partial_r\left(E_{ro}(r)/r\omega_{He}(r)\right)\Big|_{r=r_q}} + (\delta r_{cl})^{2}\right.$$

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

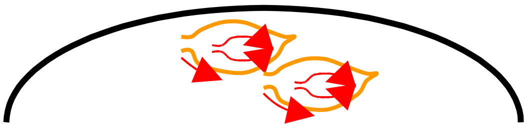

Fig. 1. Motionless convective cells

Let us consider the convective cell with small phase velocity $V_{ph} << V_{\theta o}$. All electrons overtake its. The radial electric field, created by the convective cell is less, than the electric field in the system, $E_{rv} < E_{or}$. Then in all system the azimuth electron velocities have an identical sign and there are no contraflows of electrons. The slow convective cell of the small amplitude does not have separatrix.

We obtain the expression for electron trajectories in the field of the chain on θ of the slow convective cells of not large amplitudes

$$r = \left[r_s^2 + (\varphi_o - \varphi)(r / E_{ro})\Big|_{r=r_q}\right]^{1/2}$$

This expression describes the radial position of the electrons through $\varphi(\theta, r)$. Also it is useful to present the radial position of the electrons through electron density perturbations $\delta n_e(\theta, r)$

$$r - \delta n_e\left[\omega_{Ho}\partial_r(n_{oe}/\omega_{Ho})\right]^{-1}_{r=r_q} = const\ .$$

The amplitude of the radial oscillations of the electrons is more for less $\partial_r n_{oe}$.

The structure of the slow convective cells changes at the large amplitudes $E_{rv} > E_{or}$ (see Fig. 1) [6].

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.

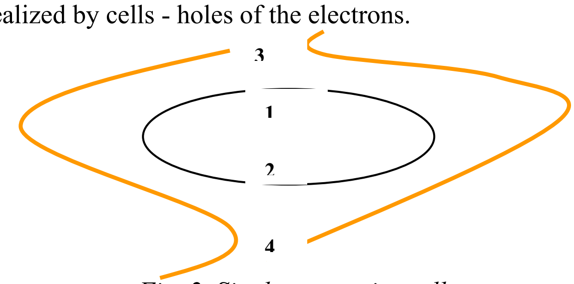

Fig. 2. Single convective cell

At achievement of the large amplitudes there appears ordering of cells (see Fig. 3) 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. 3) 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.

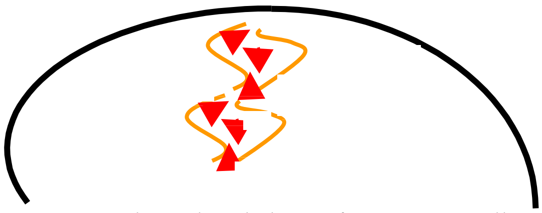

Fig. 3. The ordered chain of convective cells

From the above we have approximately

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

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

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

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

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

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

From these equations we have similar to [5]

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

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 $\omega_{He}=\sqrt{4\, eE_{ro}/m_e r}$, 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 not moving and 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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УСЛОВИЕ ПОДАВЛЕНИЯ АНОМАЛЬНОГО РАДИАЛЬНОГО ПЕРЕНОСА, ОПРЕДЕЛЯЕМОГО УПОРЯДОЧЕННОЙ КОНВЕКТИВНОЙ ДИНАМИКОЙ ЭЛЕКТРОНОВ

В.И. Маслов, С.В. Барчук, Е.Д. Волков, В.И. Лапшин, Ю.В. Меленцов

Показано, что в установках УТС в скрещенных электрическом и магнитном полях может возникать упорядочение конвективных ячеек и аномальный перенос. Построена пространственная структура этих конвективных ячеек. Получено конвективно-диффузионное уравнение для радиальной динамики электронов. При определенном значении контролирующего параметра возбуждение конвективных ячеек и аномальный перенос подавлены.

УМОВА ПРИДУШЕННЯ АНОМАЛЬНОГО РАДІАЛЬНОГО ПЕРЕНОСУ, ОБУМОВЛЕНОГО УПОРЯДКОВАНОЮ КОНВЕКТИВНОЮ ДИНАМІКОЮ ЕЛЕКТРОНІВ

В.І. Маслов, С.В. Барчук, Є.Д. Волков, В.І. Лапшин, Ю.В. Меленцов

Показано, що в пристроях КТС у схрещених електричному і магнітному полях може виникати упорядкування конвективних осередків і аномальне транспортування. Побудовано просторову структуру цих

конвективних осередків. Отримано конвективно-дифузійне рівняння для радіальної динаміки електронів. При визначеному значенні контролюючого параметра збудження конвективних осередків і аномальне транспортування придушені.