EVOLUTION EQUATION OF INTERMITTENCY OF LOW FREQUENCY VORTICES NEAR WALL IN NUCLEAR FUSION DEVICES

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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 the intermittency can be developed. It provides pulse anomalous particle transport. The ordered structure of low-frequency vortices is alternated with stochastic vertical turbulence. The spatial structure of these vortices have been constructed. The convective-diffusion equation of intermittency for radial dynamics of the electrons has been derived. The anomalous particle transport is depended on ratio of time of convective particle dynamics to period of intermittency.

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INTRODUCTION

The crossed structure of electric and magnetic fields near the wall in nuclear fusion devices is very important. The crossed electric and magnetic fields near the wall in nuclear fusion devices can lead to excitation of low frequency perturbations by radial gradients of the plasma parameters. These perturbations can be a vortical turbulence. It is investigated theoretically in this paper in the cylindrical approximation the excitation of the vortical perturbations. It is shown that the process of vortices excitation is unstable with respect to arising of correlation between an electric field and radial electrons' movement, when the vortex-electron interaction time becomes smaller than the inverse growth rate of vortex amplitude. In this case a convective radial movement of electrons and chain along stellarator surface in the case of intermittency of vortices in space (r, z) are appeared. Vortices of the chain reflect and trap the resonant electrons. In this case the fingers of electron density near wall in stellarator are formed.

The spatial structure of the electron trajectories in the fields of these vortical perturbations are constructed. The convective-diffusion radial transport equation of intermittency has been derived. At instability development of vortical turbulence excitation the intermediate regime of radial particle transport (convective-diffusion) is realized.

At instability development of vortical turbulence excitation the vortices not only result to convective-diffusion radial dynamics of electrons, but also can move collisionlessly in the radial direction, similar to observation.

Anomalous plasma particle transport is very important problem (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. 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 and damps cells themselves. 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 [2]. 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. As in a vicinity of coherent vortices the structure of electronic density is overturned, the shear amplifies and the vortices are suppresed. The characteristic time of existence of a coherent vortices we shall designate T_v. The vortices are damped and stochastic turbulence exists up to the moment of restoration of the electron density distribution. This process occurs during period T_{int}.

DESCRIPTION OF EXCITATION AND STRUCTURE OF CONVECTIVE CELLS

Let us consider development of instability of electron vortices excitation in radial electric E_{or} and longitudinal magnetic H_o fields in the region of density gradient. We use cylindrical approximation. For description of the electron vortices we use theory, developed in [3] for plasma lens. The electron vortices in crossed fields is described by the equations [3-5]

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

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

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

ϕ is the electric potential of the perturbation.

From this equation we derive similarly [3] the linear dispersion relation, describing the instability development of the electron vortices excitation

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

For mobile perturbations $V_{ph}\approx V_{\theta o}$ one can obtain [3] $\omega=\omega^{(o)}+\delta\omega$, $\omega^{(o)}=\omega_{pi}=\ell_\theta\omega_{\theta o}$, $\delta\omega=i\gamma_q$,

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

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

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

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 $(E_{ro}(r)+(T_e/e)\partial_r n_{0e}(r))/r\omega_{He}(r)$ on $\delta r\equiv r-r_q$, we obtain the radial size of the convective cell - hole of the electrons

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

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.

CONVECTIVE–DIFFUSION EQUATION OF INTERMITTENCY

We consider transport, realized by cells - holes of the electrons.

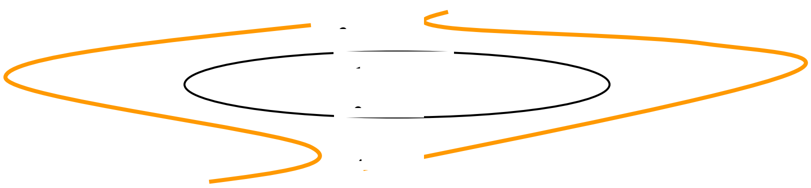

Fig. 1. Single convective cell

At achievement of the large amplitudes there appears ordering of cells (see Fig. 2) similar investigated in [2]. 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.

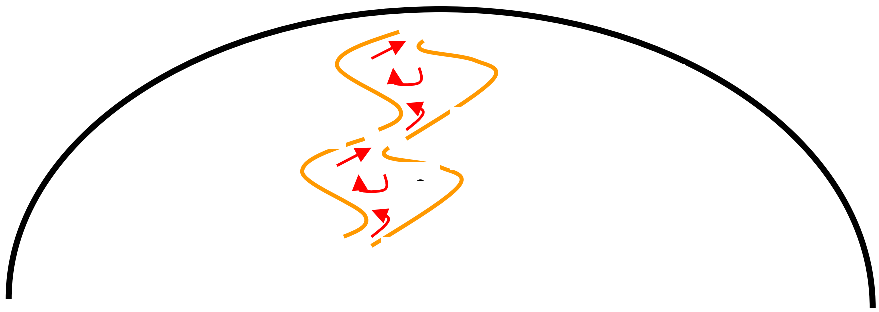

Fig. 2. The ordered chain of convective cells

From the above we have approximately

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

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

$$n_3(t+\tau, r) = 0.5\left[1-\beta\frac{T_v}{T_{int}} - \left(1-\frac{T_v}{T_{int}}\right)\sigma\right]\left[n_3(t, r) + n_4(t, r)\right] + \frac{T_v}{T_{int}}\beta n_3(t, r-\Delta r) +$$
$$+\left(1-\frac{T_v}{T_{int}}\right)\sigma n_4(t, r+\Delta r) + \alpha\mu n_1(t, r) - \alpha\mu n_3(t, r)$$

$$n_4(t+\tau, r) = 0.5\left[1-\beta\frac{T_v}{T_{int}} - \left(1-\frac{T_v}{T_{int}}\right)\sigma\right][n_3(t,r)+n_4(t,r)] + \frac{T_v}{T_{int}}\beta n_4(t, r+\Delta r) +$$

$$+\left(1-\frac{T_v}{T_{int}}\right)\sigma n_3(t, r-\Delta r) + \alpha\mu n_2(t,r) - \alpha\mu n_4(t,r)$$

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 $\overline{n} = (n_3 + n_4)/2$, $\delta n = n_3 - n_4$, $\overline{N} = (n_1 + n_2)/2$, $\delta N = n_1 - n_2$, we derive

$$\tau\partial_t \overline{N} = \alpha\mu(\overline{n} - \overline{N}),\ \tau\partial_t \delta N + (2-\alpha)\delta N = \alpha(1-\mu)\delta N + \alpha\mu\delta n,$$

$$\tau\partial_t \overline{n} = -0.5\left[\beta\frac{T_v}{T_{int}} + \sigma\left(1-\frac{T_v}{T_{int}}\right)\right]\Delta r\partial_r \delta n + \alpha\mu(\overline{N} - \overline{n}),$$

$$\tau\partial_t \delta n + \delta n\left[(1+\alpha\mu) - \beta\frac{T_v}{T_{int}} + \left(1-\frac{T_v}{T_{int}}\right)\sigma\right] = 2\left[\left(1-\frac{T_v}{T_{int}}\right)\sigma - \beta\frac{T_v}{T_{int}}\right]\Delta r\partial_r \overline{n} + \alpha\mu\delta N.$$

From these equations we have similar to [2]

$$\tau^2\partial_t^2 \delta n + \tau\partial_t\left\{\delta n\left[(1+\alpha\mu) - \beta\frac{T_v}{T_{int}} + \left(1-\frac{T_v}{T_{int}}\right)\sigma\right] - \alpha\mu\delta N\right\} =$$

$$= 2\left[\left(1-\frac{T_v}{T_{int}}\right)\sigma - \beta\frac{T_v}{T_{int}}\right]\Delta r\partial_r\left\{\alpha\mu(\overline{N} - \overline{n}) - 0.5\left[\beta\frac{T_v}{T_{int}} + \sigma\left(1-\frac{T_v}{T_{int}}\right)\right]\Delta r\partial_r \delta n\right\}$$

CONCLUSION

So, at instability development due to the radial gradient of density in the crossed electric and magnetic fields in nuclear fusion installations the intermittency can be excited. The convective-diffusion equation of intermittency for radial dynamics of the electrons has been derived.

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