ON THE POSSIBILITY FOR THE RESONANCE ELM-GENERATION MECHANISM BY THE INJECTION OF THE NEUTRAL PARTICLE BEAM IN TOKAMAK

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It is known that in plasmas with a magnetic field the Hall electric field is generated at the expense of the charge separation on the magnetic Debye radius $r_B = |B|/(4\pi e n_e)$. In addition, the plasma current equilibrium can arise, where the charged particles are drifting in the crossed electric and magnetic fields. Such a situation can be realized in tokamaks as a result of the ionization processes for the beams of the energetic neutral particles that are injected in tokamaks in order to increase the plasma density and temperature. In this presentation, the generation of the resonance instability for the azimuthal drifting flux of the ions and electrons crosswise to the strong magnetic field is considered. In this case, the generation of the resonance instability by the account of the ion inertia is obtained for the fast magnetosonic oscillations by $\omega >> \omega_{Bi}$ [$\omega_{Bi} = z_i e|B|/(m_i c)$ is the ion cyclotron frequency], when the resonance condition $\omega - kv_0 = \pm\overline{\omega}_{pi}$ $\left(\overline{\omega}_{pi} = \gamma_0^{-1}\sqrt{\omega_{pi}^2 + k_z^2 c^2}\right)$ is valid for some points (ω is the oscillation frequency, v_0 is the beam velocity of the charged particles, $k \le r_B^{-1}$ is the oscillation wave vector, ω_{pi} is the ion plasma frequency). The considered instability corresponds to the parameter range $4\pi n_i m_i c^2 >> B^2 >> 4\pi n_i m_i c v_0$.

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1. INTRODUCTION

The problem of the plasma heating and the equilibrium confinement in tokamaks is the main problem in the project ITER [1]. As it follows from [1,2], the problem of the stable equilibrium itself and in particular the problem of the ELM generation in tokamaks, as yet, far enough from the complete resolution. It is not ruled out that it is just the inclusion of this problem in the complicated numerical codes which is not favorable for the elucidation of the ELM mechanism. In the presented paper the attempt is made by way of example for the cylindrical model of the tokamak to consider the resonance instability which arises quite naturally by the propagation through plasma of the energetic particles' flux. The instability considered is suggested as the physical mechanism of the ELM. In this case, the energetic particles can be generated as a result of the ionization of the neutral particles' fluxes, which usually used for the increasing of the plasma density and temperature in tokamaks [1]. It is known, that by the injection of the charged particles of the high energy in the plasma with the magnetic field the propagation of this beams on the account of the Hall electric field [3,4] arises. In the case of the plasma cylinder with the longitudinal magnetic field B_z due to the absence of the unidirectional stationary azimuthal electric field E_θ the azimuthal particle drift on the account of the radial electric field E_r arises. Thus, in contrast to the considered in [5] plane case, in the cylindrical geometry by the presence of the longitudinal magnetic field the drifting rotation of the plasma flux occurs. One can show that the drift plasma fluxes turn out to be unstable relative to the fast magnetosonic oscillations near the lower hybrid range of frequency. In addition, the characteristic size scale of these oscillations is about the magnetic Debye radius $r_B = B/(4\pi e n_e)$. The presented instability is proposed as the ELM – generation mechanism.

2. THE MAIN EQUATIONS

Further on, the case will be considered when the energy of the injected particles is essentially larger than the thermal energies of the tokamak particles, so the particles temperatures will not be taken into account. Therefore, for the describing of the ion and electron motion in the strong electric and magnetic fields the relativistic equations for the cold particles are used

$$\frac{dp_{e,i}}{dt} = z_{e,i} e\mathring{E} + \frac{z_{e,i} e}{c}[\mathring{v}_{e,i} \times \mathring{B}] \qquad (1)$$

and Maxwell equations

$$[\nabla \times \mathring{B}] = \frac{4\pi e}{c}(z_i n_i \mathring{v}_i - n_e \mathring{v}_e) + \frac{1}{c}\frac{\partial E}{\partial t},$$

$$-\frac{1}{c}\frac{\partial B}{\partial t} = [\nabla \times \mathring{E}], \ \nabla \cdot E = 4\pi e(z_i n_i - n_e). \qquad (2)$$

Here $v_{e,i}$ is the electron and ion velocities, $p_{e,i} = \gamma m_{e,i} v_{e,i}$, $\gamma = 1/\sqrt{1 - \mathring{v}_{e,i}^2/c^2}$, $n_{e,i}$ are the electron and ion densities, z_i is the ion charge number, $z_e = -1$, E is the electric field, B is the magnetic field.

3. THE DERIVATION OF THE DISPERSION RELATION FOR THE RESONANCE INSTABILITY OF THE DRIFT FLUX OF IONS AND ELECTRONS

In the considered frequency range, the large electron mobility along the magnetic field B_0 is of the essential importance. Then by neglecting the electron inertia in the transverse direction one can obtain the following equation relative E_θ in the WKB approximation (see also [6]):

$$\frac{d^2E_\theta}{ds^2} - k_0^2(s)E_\theta = 0,$$

$$k_0^2(s) = 1 - \Omega^2 + \Omega_{pi}^2 + \Lambda_0 \frac{\tilde{\Omega}^2\Omega_{pi}^2}{\tilde{\Omega}^2 - \overline{\Omega}^2}, \qquad (3)$$

Here $\Omega = \frac{\omega}{kc}$, $\tilde{\Omega} - \frac{k_\theta}{k}\beta_0$, $\Omega_{pi}^2 = \frac{4\pi z_i^2 e^2 n_i}{m_i c^2 k^2}$,

$$\Lambda_0 = \frac{4\pi n_i m_i c^2}{B_0^2}, \quad \overline{\Omega}^2 = \frac{1}{\gamma_0^2}\left(\Omega_{pi}^2 + \frac{k_z^2}{k^2}\right),$$

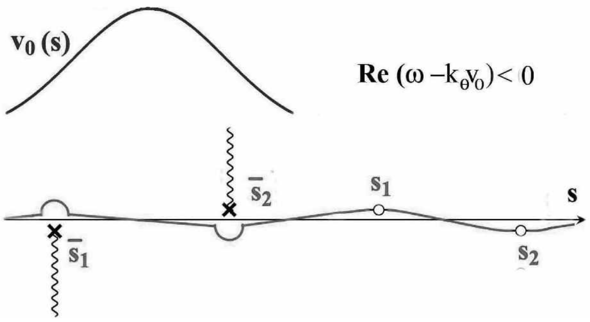
$k_\theta = \frac{m}{r_0}$, $k^2 = k_\theta^2 + k_z^2$. Here m is the integer.

Here, one can consider that the spatial region Δr, where the drifting flux settles down, corresponds to the characteristic radius $r_0 >> \Delta r$, what allows to neglect the cylindrical effects. In the following presentation, because of the inequality $|k_z| << |k_\theta|$, one can consider that $k_\theta/k = \mathrm{sign}(k_\theta)$ and $\tilde{\Omega} = \Omega - \mathrm{sign}(k_\theta)v_0$.

4. THE RESONANCE PLASMA INSTABILITY FOR THE AZIMUTHAL DRIFTING FLUX OF IONS AND ELECTRONS

From the equation (3) one can see that the effective interaction of the drifting flux with the electromagnetic oscillations occurs in the poles, where $\omega - k_\theta v_0 = \pm\overline{\omega}_{pi}$, $\left(\overline{\omega}_{pi} = \gamma_0^{-1}\sqrt{\omega_{pi}^2 + k_z^2c^2}\right)$. Here, the values v_0 and $\overline{\omega}_{pi}$ are determined by the ion flux parameters, and the frequency ω is determined by the ground plasma. Of course, the drifting flux goes through the ground plasma. However, in the calculations the drifting fluxes and the ground plasma will be spatially separated. This procedure results in the diminishing of the instability increment without any change of the physical mechanism.

By the further investigations within the frame of the Eq.(3), we take approach from that used in the paper [7]. As one can see from the Figure, in the region of the azimuthal flux there exists the pole-pole well $(\bar{s}_1, \bar{s}_2)$,



The plasma velocity profile and the contour in the complex plane

and in the region of the ground plasma there exists the zero – zero well (s_1,s_2). Both these regions correspond to the negative values of $k_0^2(s)$. For the construction of the perturbations that go to zero by $s \to \pm\infty$, one must use the Landau rule when one should add to the frequency ω the small positive imaginary quantity: $\omega \to \omega + i\varepsilon$, where $\varepsilon > 0$.

With this procedure in mind, the electric field E_θ, that by $s < \mathrm{Re}(\bar{s}_1)$ to the left of the pole potential well $(\bar{s}_1, \bar{s}_2)$ goes to zero and is equal to

$$E_\theta = \frac{B}{\sqrt{k_0}}\exp\left(\int_{\bar{s}_1}^{s} k_0 ds\right), \qquad (4)$$

after the passage through the pole $\bar{s}_1$ is transformed inside the pole potential well $(\bar{s}_1, \bar{s}_2)$ into the traveling wave [7]

$$E_\theta = \frac{B}{\left[-k_0^2(s)\right]^{1/4}}\exp\left[i\left(\int_{\bar{s}_1}^{s}\sqrt{-k_0^2(s)}ds - \frac{\pi}{4}\right)\right], \quad (5)$$

that after the passage through the pole $\bar{s}_2$ for $s > \mathrm{Re}(\bar{s}_2)$ turns to the exponentially increasing solution by the moving away from the $\bar{s}_2$. In this case, by the sewing the solution, that increases by the going away from the pole $\bar{s}_2$, with the exponentially descending solution to left of the potential well $(\bar{s}_1, \bar{s}_2)$ for $\bar{s}_2 < s < s_1$, one can obtain the connection condition between the coefficients A and B

$$-iB\exp\left(i\int_{\bar{s}_1}^{\bar{s}_2}\sqrt{-k_0^2(s)}ds\right) \cong (-1)^q A\exp\left(-2\int_{\bar{s}_2}^{s_1}k_0(s)ds\right). \quad (6)$$

In addition, because of the exponentially weak connection between oscillations in the regions $(\bar{s}_1, \bar{s}_2)$ and (s_1, s_2) the dispersion relation is determined by the equation

$$\int_{s_1}^{s_2} ds\sqrt{-k_0^2(s)} = \pi\left(q + \frac{1}{2}\right), \quad q = 1, 2, 3,\ldots \quad (7)$$

Now, multiplying equation (3) by the complex conjugate electric field amplitude E_θ^* and then subtracting from the obtained expression the complex conjugated quantity, one can arrive, after the integration with respect to s, at the following relation:

$$\mathrm{Im}(\Omega)\int_{s_1}^{s_2}\frac{ds}{\sqrt{-k_0^2(s)}}\frac{\partial k_0^2}{\partial\,\mathrm{Re}\,\Omega} = sign(\tilde{\Omega})\exp\left(-2\int_{\bar{s}_2}^{s_1}k_0(s)ds\right), \quad (8)$$

where

$$\frac{\partial k_0^2}{\partial\,\mathrm{Re}\,\Omega} = -2\left\{\mathrm{Re}(\Omega) + \mathrm{Re}(\tilde{\Omega})\Lambda_0\frac{\overline{\Omega}^2\Omega_{pi}^2}{\left[(\mathrm{Re}(\tilde{\Omega}))^2 - \overline{\Omega}^2\right]^2}\right\}$$

Thus, the instability there exists, when $\mathrm{sign}(\tilde{\Omega})$ has the opposite values in the potential wells $(\bar{s}_1, \bar{s}_2)$ and (s_1, s_2). This is the case, when $\mathrm{Re}(\Omega) > 0$ for the ground plasma and $\mathrm{Re}(\tilde{\Omega}) < 0$ for the drifting flux of ions and electrons. This relation gives for the ion beams with the density $n_e \sim 10^{11}$ cm^{-3} the increment $\mathrm{Im}(\Omega) \sim 10^8$ s^{-1}.

5. CONCLUSIONS

Within the framework of the investigated instability one can explain the relaxation oscillations that arise by the generation of the ELM disturbances [1]. Indeed, the considered instability is determined by the resonance condition $\omega - k_\theta v_0 = \pm\overline{\omega}_{pi}$, where the value of ω is somewhat less than the ion plasma frequency that corresponds to the ground plasma. By the arising of the ELM perturbations, the density decrease of the ground plasma in the edge region occurs what results in the decrease of the ion plasma frequency and the value of ω itself. This must lead to the violation of the resonance condition and also to the termination of the instability. As a result, the plasma density increases and the ELM generation arises anew.

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REFERENCES

1. ITER PHYSICS BASIS // *Nuclear Fusion*. 1999, v.39, N12.
2. *Book of Abstracts of the 33 European Physical Society Conference on Plasma Physics*, Roma, Italy, June 19-23, 2006.
3. A.V. Gordeev, T.V. Losseva // *Plasma Physics Reports*. 2005, v.31, N1, p.26.
4. A.V.Gordeev // *Plasma Physics Reports*. 2006, v.32, N9, p.780.
5. A.V. Gordeev// *Proceedings of the 22nd Symposium on Plasma Physics and Technology*, Prague, June 26-29, 2006 / *Czechoslovak Journal of Physics*, v.58, 2006, Suppl. B, p.73.
6. V.D. Shafranov // *Reviews of Plasma Physics* /ed. by M.A. Leontovich. New York: "Consultants Bureau". 1967, v.3.
7. A.V.Gordeev, L.I. Rudakov// *Sov. Phys. JETP*. 1969, v.28, p.1226.

О ВОЗМОЖНОСТИ РЕЗОНАНСНОГО МЕХАНИЗМА ГЕНЕРАЦИИ ELM ПРИ ИНЖЕКЦИИ ПУЧКА НЕЙТРАЛЬНЫХ ЧАСТИЦ В ТОКАМАК

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Известно, что в плазме с магнитным полем генерация холловского электрического поля за счёт разделения зарядов происходит на магнитном дебаевском радиусе $r_B = |B|/(4\pi e n_e)$. При этом возможно образование плазменного токового равновесия, где заряженные частицы дрейфуют в скрещённых электрическом и магнитном полях. Такая ситуация может быть реализована в токамаках в результате процессов ионизации пучка энергичных нейтральных частиц, инжектируемых в токамаки, с целью увеличения плотности плазмы и её температуры. Рассмотрена генерация резонансной неустойчивости азимутальных потоков ионов и электронов, дрейфующих поперёк сильного магнитного поля. В этом случае резонансная неустойчивость получена с учётом инерции ионов на ветви быстрых магнитозвуковых колебаний при $\omega >> \omega_{Bi}$ [$\omega_{Bi} = z_i e|B|/(m_i c)$ - ионная циклотронная частота], где резонансное условие $\omega - kv_0 = \pm\overline{\omega}_{pi}$ $\left(\overline{\omega}_{pi} = \gamma_0^{-1}\sqrt{\omega_{pi}^2 + k_z^2 c^2}\right)$ выполняется в некоторых точках (ω - частота колебаний, v_0 - дрейфовая скорость заряженных частиц, $k \le r_B^{-1}$ - волновой вектор колебаний, ω_{pi} - плазменная ионная частота). Рассмотренная неустойчивость соответствует области параметров $4\pi n_i m_i c^2 >> B^2 >> 4\pi n_i m_i c v_0$.

ПРО МОЖЛИВОСТІ РЕЗОНАНСНОГО МЕХАНІЗМУ ГЕНЕРАЦІЇ ELM ПРИ ІНЖЕКЦІЇ ПУЧКА НЕЙТРАЛЬНИХ ЧАСТОК У ТОКАМАК

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Відомо, що в плазмі з магнітним полем генерація холловського електричного поля за рахунок поділу зарядів відбувається на магнітному дебаєвському радіусі $r_B = |B|/(4\pi e n_e)$. При цьому можливо утворення плазмової токової рівноваги, де заряджені частки дрейфують у схрещених електричному і магнітному полях. Така ситуація може бути реалізована в токамаках як наслідок процесів іонізації пучка енергійних нейтральних часток, інжектуємих у токамаки, з метою підвищення густини плазми і її температури. Розглянуто генерацію резонансної нестійкості азимутальних потоків іонів і електронів, що дрейфують поперек сильного магнітного поля. У цьому випадку резонансна нестійкість отримана за урахуванням інерції іонів у зоні швидких магнітозвукових коливань при $\omega >> \omega_{Bi}$ [$\omega_{Bi} = z_i e|B|/(m_i c)$ - іонна циклотронна частота], де резонансна умова $\omega - kv_0 = \pm\overline{\omega}_{pi}$ $\left(\overline{\omega}_{pi} = \gamma_0^{-1}\sqrt{\omega_{pi}^2 + k_z^2 c^2}\right)$ виконується в деяких точках (ω - частота коливань, v_0 - дрейфова швидкість заряджених часток, $k \le r_B^{-1}$ - хвильовий вектор коливань, ω_{pi} - плазмова іонна частота). Розглянута нестійкість відповідає області параметрів $4\pi n_i m_i c^2 >> B^2 >> 4\pi n_i m_i c v_0$.