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INFLUENCE OF THE NONLINEAR EFFECTS ON RESONANCE ENERGY ABSORPTION AND PLASMA-WALL INTERACTION IN HELICAL MAGNETIC FIELD

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Plasma in a helical confining magnetic field is considered. Helical inhomogeneity of the steady magnetic field causes coupling of separate spatial modes of electromagnetic field. Account for the amplitudes of the first sidebands leads to noticeable increase of the radial electric field and effective collision frequency as compared with the value in the case of axial steady magnetic field. Condition is derived under which striction nonlinearity governs spatial distribution of wave fields within the Alfven resonance layer. The reverse effect of Kinetic parametric ion cyclotron instabilities of plasma on the absorption of pumping wave is studied. The high energy ions which appear during the RF plasma heating can change the plasma interaction with the wall of the devices.

Keywords: helical magnetic field, alfven resonance, striction nonlinearity, kinetic parametric ion cyclotron Instabilities, effective scattering frequency, plasma-wall interaction.

Рассмотрена плазма в винтовом удерживающем магнитном поле. Винтовая неоднородность постоянного магнитного поля связывает отдельные пространственные моды электромагнитного поля. Учет амплитуд первых соседних гармоник приводит к ощутимому увеличению радиального электрического поля и эффективной частоты столкновений по сравнению со случаем аксиального постоянного магнитного поля. Получены условия, при которых стрикционная нелинейность определяет пространственное распределение поля волны внутри Альфвеновского резонансного слоя. Изучен обратный эффект кинетической параметрической ионной циклотронной неустойчивости плазмы на поглощение волны накачки. Высокоэнергетичные ионы, которые образуются при высокочастотном нагреве плазмы, могут изменить характер взаимодействия плазмы со стенками установок.

Ключевые слова: винтовое магнитное поле, альфвеновский резонанс, стрикционная нелинейность, кинетические параметрические ионные циклотронные неустойчивости, эффективная частота рассеивания, взаимодействие плазма-стенка.

Розглянуто плазму у гвинтовому утримуючому магнітному полі. Гвинтова неоднорідність сталого магнітного поля пов'язує окремі просторові моди електромагнітного поля. Облік амплітуд перших сусідніх гармонік приводить до відчутного збільшення радіального електричного поля та ефективної частоти зіткнень у порівнянні до випадку аксіального сталого магнітного полі. Отримано умови, при яких стрикційна нелінійність визначає просторове розподілення поля хвилі у Альфвенівському резонансному шарі. Вивчено обернений ефект кінетичної параметричної іонної циклотронної нестійкості плазми на поглинання хвилі накачки. Високоенергетичні іони, які утворюються при високочастотному нагріванні плазми, можуть змінити характер взаємодії плазми зі стінками пристроїв.

Ключові слова: гвинтове магнітне поле, альфвеновський резонанс, стрикційна нелінійність, кінетичні параметричні іонні циклотронні нестійкості, ефективна частота розсіювання, взаємодія плазма-стінка.

INTRODUCTION

Now and in planned experiments ion cyclotron frequency region are used for plasma heating creation of a plasma and current drive in different plasma devices [1 – 7]. Effects in the plasma periphery present a spatial interest [8, 9]. In the large experimental devices the Alfven resonance can be situated near by the boundary of a plasma. The fast ions can arise in the resonance region due to the interaction of the plasma particles with the RF field which grows here. In this case the interaction of these ions with the wall of the camera can change its surface structure and increases the admixture in the plasma.

The reversed effect of the electromagnetic wave spatial multimodality on Alfven wave heating in a helical confining magnetic field was considered in [10]. The influence of striction nonlinearity on the structure of Alfven resonance (AR) on such field is investigated in this paper.

The effect of the parametric ion cyclotron turbulence and two nearest additional wave mode due to helical inhomogeneity of the magnetic field on Alfven wave heating are studied also.

Helical inhomogeneity of the steady magnetic field is one of the main specific features of stellarators. Following [10] we restrict our consideration to the following representation of the magnetic field:

$$\vec{B}_0(r,\vartheta,z)=\vec{e}_r B_{0r}+\vec{e}_\vartheta B_{0\vartheta}+\vec{e}_z B_{0z}$$

in cylindrical coordinates,

$$B_{0r}=\delta\sin l\theta B_0,\; B_{0\vartheta}=\epsilon_h^{(l)}/(\alpha r)\cos l\theta B_0,$$

$$B_{0z}=B_0(1-\epsilon_h^{(l)}\cos l\theta). \qquad (1)$$

here $=\vartheta-\alpha z$, $\alpha=2\pi/L$, L is the pitch length of the helical winding,

$$\epsilon_h=lb_l I_l(k_s r),\; b_l=8Jak_s^2K_l'(k_s a)(lc)^{-1},$$

a is the radius of the cylindrical surface carrying a thin helical winding with the current J, $K_l(\xi)$ is McDonald function, $I_l(\xi)$is modified Bessel function, the prime denotes the derivative with respect to the argument, l is the polarity of helical coils, $k_s=la$, $\delta=(1/k_s)d\epsilon_h^{(l)}/dr$.

PUMPING WAVE STRUCTURE IN AR REGION

In an axial magnetic field spatial mode of electromagnetic wave excited by an external source propagates independently. Helical inhomogeneity $\propto\exp(\pm il\theta)$ of the confining magnetic field $\vec{B}_0$ (1) causes coupling of separate spatial modes of electromagnetic fields. In this case the radial electric field of the wave envelope that contains the main mode $\sim\exp[i(k_z z+m\theta-\omega t)]$ and the two nearest sidebands can be represented in the form

$$E_r=\left[E_r^{(0)}(r)+E_r^{(+1)}(r)e^{il\theta}+E_r^{(-1)}(r)e^{-il\theta}\right]\times$$

$$\times\exp[i(k_z z+m\vartheta-\omega t)];\; \left|E_r^{\pm1}\right|\ll\left|E_r^{(0)}\right|. \qquad (2)$$

Here k_z is axial wave vector, ω is frequency of Alfven wave. The similar expansion for remaining components of the electric and magnetic fields are used.

Within the Alfven resonance region $\left(\varepsilon_1^{(0)}(r)\approx N_z^2\right)$ in narrow layer approximation the following equation for $E_r^{(0)}$ components of Alfven wave (AW) was derived from Maxwell equation [10]:

$$-\frac{1}{8}\frac{c^4}{\omega^4}\delta^4\left(N_s^2-4N_z^2\right)\frac{d^4}{dr^4}E_r^{(0)}$$

$$+N_s^2\left(N_s^2-4N_z^2\right)\left[\left(\varepsilon_1-N_z^2\right)E_r^{(0)}+A\right]=0, \qquad (3)$$

where $A=i\varepsilon_2^{(0)}E_\theta+N_\theta B_z$; $\varepsilon_1=\varepsilon_1^{(0)}+i\varepsilon_1'$;

$$\varepsilon_1^{(0)}=1-\sum_\alpha\frac{\omega_{p\alpha}^2}{\omega^2-\omega_{c\alpha}^2};$$

$$\varepsilon_2^{(0)}=-\sum_\alpha\frac{\omega_{p\alpha}^2\omega_{c\alpha}}{\omega(\omega^2-\omega_{c\alpha}^2)}. \qquad (4)$$

Here $N_z=\kappa c/\omega$ and $N_\theta=cm/\omega r$ are axial and poloidal refractive index respectively, $N_s=\kappa c/\omega$, $\omega_{c\alpha}$ and $\omega_{p\alpha}$ are the cyclotron and plasma frequencies of particles of species α ($\alpha=i$, e for ions and electrons respectively). The term $i\varepsilon_1^{|}$ in (4) accounts for the collisions between plasma particles ($\varepsilon_1^{|}/\varepsilon_1^{(0)}\sim\nu/\omega$, S is the frequency of particles collisions, $\omega\sim\omega_{ci}$) [11]. In AR region the weak effects are taken into account in $\varepsilon_1(\omega)$ – component of the dielectric permittivity tensor only.

The effects of the finite ion Larmor radius ρ_{Li} and the electron inertial were neglected in (3).

The influence a weak helical inhomogeneity $\vec{B}_0$ on the AR structure is more significant than those of the finite ion Larmor radius and the electron inertial if the following inequality is valid [10]:

$$\delta^{12/5}>>\left(\frac{\rho_{Li}}{a^*}\right)^2\left(\kappa_z\kappa_s a^{*2}\right)^{6/5}. \qquad (5)$$

Here $a^*=\left|d\ln\varepsilon_1^{(0)}/dr\right|_{r_A}^{-1}$ is a characteristic radial scale in which the plasma density varies within the AR region ($\varepsilon_1^{(0)}(r_A)=N_z^2$).

The term A in the approximation considered ($\kappa_z\Delta r<<1$, $\Delta r=|r-r_A|$) varies slowly within AR region [12].

For linear profile of plasma density within resonance layer

$$\varepsilon_1^{(0)} = N_z^2 + \left(\frac{d\varepsilon_1^{(0)}}{dr}\right)_{r_A} (r - r_A), \qquad (6)$$

Eq. (3) has following form:

$$\frac{d^4 E_r^{(0)}}{d\xi^4} - (\xi + i\zeta) E_r^{(0)} = \frac{\kappa_l a^*}{N_z^2} A, \qquad (7)$$

$$\xi = \kappa_l \Delta r,\ k_1 = \left(\frac{c^4 \delta^4 a^*}{8\omega^4 N_s^2 N_z^2}\right)^{-1/5} \sim \left(\frac{k_z^2 k_s^2}{\delta^4 a^*}\right)^{1/5} \propto \delta^{-4/5},$$

$$\zeta = \frac{\varepsilon_1'}{\varepsilon_1^{(0)}} \kappa_l a^*. \qquad (8)$$

The analytical solution of Eq(3) is obtained by the Laplace method [10]:

$$E_r^{(\pm 1)} = \frac{a k_1}{N_A^2} A^{(\pm)} u_0 [k_1 (r - r_A) + i\zeta],$$

$$u_o(\xi) = \int_0^\infty \exp\left[i\left(t\xi + t^5/5\right)\right] dt, \qquad (9)$$

This solution satisfies the following boundary conditions: it is a finite one in the AR region; it describes the conversion of electromagnetic wave into the small scale wave which brings the energy away from the AR region; it damps under the account for a weak dissipation in $\varepsilon_1^{(0)}$.

Behaviour of the function $u_0(\xi)$ (that describes the amplitude of the main mode of the radial electric RF field) was studied in detail in [13]. The asymptotic expression for the solution u_0 at $\mathrm{Re}(\xi) \to -\infty$ can be written in the following form:

$$u_0(\xi) \approx \frac{i}{\xi} + \left(\frac{\pi^2}{-\xi}\right)^{\frac{1}{8}} \exp\left[-i\left(\frac{4}{5}(-\xi)^{\frac{4}{5}} + \frac{\pi}{4}\right)\right], \qquad (10)$$

that allows one to assume that, as the distance from AR point increases, the small-scale wave described by the second term in the r.h.s. of (10) damps rapidly in the close vicinity of the resonance point due to either collisions or Landau damping.

Characteristic value of the amplitude $E_r^{(0)}$ of the main mode of the radial component of the wave electric field within AR region can be evaluated from (9) by the order of magnitude as follows,

$$E_r^{(0)} \sim a^* k_1 A / N_z^2 \sim \left(\frac{\omega^4 a^{*4} N_s^2}{\delta^4 N_z^8 c^4}\right)^{\frac{1}{5}} A. \qquad (11)$$

Let evaluate the characteristic values of radial electric wave sidebands $E_r^{(\pm 1)}$, within the AR region by the order of magnitude as follows,

$$E_r^{(\pm 1)} = -\left(\varepsilon'/2k_b^2\right) dE_r^{(0)}/dr \sim \frac{a^* \delta\, k_1^2}{k_s N_z^2} A,\ \ |\xi| \sim 1;$$

$$E_r^{(\pm 1)} \square \frac{\delta}{2\kappa_s} \frac{a^* A}{N_z^2} \frac{1}{(\Delta r + i\zeta)^2},\ \ |\xi| >> 1,\ |\Delta r| \le |\zeta|. \qquad (12)$$

The amplitudes $E_r^{(\pm 1)}$ of sidebands grow within AR region even more rapidly than the amplitude $E_r^{(0)}$ of the main mode but our theory is valid when $E_r^{(\pm 1)}$ remain less than in this region. Outside the AR region $E_r^{(\pm 1)} \sim \delta E_r^{(0)}$ [14].

Power W absorbed per unit of plasma column within AR region due to the collisional dissipation equals

$$W = W^{(0)} + 2W^{(\pm)}, \qquad (13)$$

$$W^{(0)} = \frac{\pi\omega}{4} r_A |A|^2 \left[\frac{d\varepsilon_1^{(0)}(r)}{dr}\right]_{r_A}^{-1}, \qquad (14)$$

$$W^{(\pm)} \sim C W^{(0)}, \qquad (15)$$

where $C = \left(\frac{\delta^2 \kappa_z^2}{\kappa_s^3 a^*}\right) \square\ 1,\ |\xi| \sim 1,$

$$C = \left(\frac{\varepsilon_1^{(0)}}{\varepsilon_1'}\right)^2 \frac{\delta^2}{\kappa_s^2 a^{*2}} \square\ 1,\ |\xi| >> 1,\ |\Delta r| \le |\zeta|. \qquad (16)$$

Note that power $W^{(0)}$ does not depend on collisional dissipation even than $E_r^{(0)} \propto 1/\varepsilon_1'$ ($|\Delta r| \le |\zeta|$).

EFFECT OF STRICTION NONLINEARITY AND PARAMETRIC ION CYCLOTRON TURBULENCE

If pumping wave is powerful enough then influence of non-linear effects on distribution of MHD fields in the vicinity of AR can appear essential. In this section the influence of striction nonlinearity is studied. It is central for fast wave processes (when a wave phase velocity $v_{ph} >> v_{Ti}$).

The nonlinearity at the second harmonic prevails for slow wave processes [15], $v_{ph} < v_{Ti}$. The striction changes plasma density, $n(r) \to n_{NL}$,

$$n_{NL} = n(r) \cdot \exp(-U^{\sim}/T). \qquad (17)$$

Potential energy of plasma particles [16] in a field of a pumping wave is of the following form in the case of inhomogeneous helical confining magnetic field:

$$U^{\sim} = U^{(0)} + U^{(2)}, \qquad (18)$$

where $U^{(0)} = \sum_{\alpha}\left[e_{\alpha}^{2}n_{\alpha}/\left(4m_{\alpha}n_{e}\left(\omega^{2}-\omega_{c\alpha}^{2}\right)\right)\right]\times$

$$\times\left[\left|E_{r}^{(0)}\right|^{2}+\left|E_{\vartheta}^{(0)}\right|^{2}+i\frac{\omega_{c\alpha}}{\omega}\left(E_{r}^{(0)*}E_{\vartheta}^{(0)}-E_{r}^{(0)}E_{\vartheta}^{(0)*}\right)\right]. \qquad (19)$$

Small addend $U^{(2)} \propto r^{2/5}$ varies within AR even faster, than $U^{(0)}$.

$$U^{(2)} = \sum_{\pm}\sum_{\alpha}\left[e_{\alpha}^{2}n_{\alpha}/(4m_{\alpha}n_{e})\right]\left[\left|E_{r}^{(\pm 1)}\right|^{2}/\left(\omega^{2}-\omega_{c\alpha}^{2}\right)\right]. \qquad (20)$$

Due to assumption of weak striction, $U^{\sim} \ll T$, it is enough to take into account the replacement $n(r) \to n_{NL}$ in the basic equation for the fundamental harmonic of the wave radial electric field only for the term $\varepsilon_{1}^{(0)} - N_{z}^{2}$, which one is small within the AR,

$$\varepsilon_{1}^{(0)} - N_{z}^{2} \to \frac{\partial\varepsilon_{1}^{(0)}}{\partial r}(r-r_{A}) + \left(\varepsilon_{1}^{(0)}-1\right)\times\left(\frac{-U^{\sim}}{T}\right) + O\left(\frac{U^{\sim 2}}{T^{2}}\right). \qquad (21)$$

Striction nonlinearity can govern the distribution of wave fields within the AR region ($|\Delta r| \sim 1/\kappa_{e}$) if the following inequality is valid,

$$\left|\left(\varepsilon_{1}^{(0)}-1\right)\left(\frac{-U^{\sim}}{T}\right)\right| > \left|\frac{N_{z}^{2}}{a^{*}k_{1}}\right|. \qquad (22)$$

After simplification the condition (22) becomes that for amplitude A of pumping wave,

$$\left(\frac{A}{E_{0}N_{z}^{2}}\right)^{2} \sim \left(\frac{\delta^{2}}{\kappa_{z}\kappa_{s}a^{*2}}\right)^{6/5}. \qquad (23)$$

Here $$\frac{1}{E_{0}^{2}} = -\sum_{\alpha}\frac{e_{\alpha}^{2}}{4m_{\alpha}n_{e}T\left(\omega^{2}-\omega_{c\alpha}^{2}\right)}. \qquad (24)$$

This condition (22) is valid (under the same other conditions) for the larger amplitudes of pumping wave than in a straight magnetic field, since in a helical magnetic field the AR is wider and the characteristic value of amplitude of a fundamental harmonic of a radial electrical field is less than in a straight magnetic field. In this case Eq. (6) transforms into equation

$$\frac{d^{4}E_{r}^{(0)}}{d\xi^{4}} - \left(\xi + \kappa_{l}a^{*}\frac{\left|E_{r}^{(0)}\right|^{2}}{E_{0}^{2}} + i\zeta\right)E_{r}^{(0)} = \frac{\kappa_{l}a^{*}}{N_{z}^{2}}A. \qquad (25)$$

From (25) the following value of is obtained:

$$E_{r}^{(0)} = \left(\frac{AE_{0}^{2}}{N_{z}^{2}}\right)^{1/3}. \qquad (26)$$

Here the dissipative effects are neglected

$$\left(\left|\varepsilon_{1}'/\varepsilon_{1}^{0}\right| < \left|E_{r}^{(0)}\right|^{2}/E_{0}^{2}\right).$$

Power W absorbed per unit of plasma column within AR region ($|\Delta r| < \Delta r_{NL}$) equals'

$$W \sim \frac{\omega}{4}r_{A}\varepsilon_{1}\left(\frac{AE_{0}^{2}}{N_{z}^{2}}\right)^{1/3}\Delta r_{NL} \sim \frac{\omega}{4}r_{A}\varepsilon_{1}\left(\frac{A^{2}E_{0}}{N_{z}^{4}}\right)^{2/3}, \qquad (27)$$

where $\Delta r_{NL} = \left|E_{r}^{(0)^{2}}\right|/E_{0}^{2}$.

The distribution of RF fields in resonance layer (Eq. (25)) was studied numerically in the paper [17]. The striction nonlinearity in AR region ($\Delta r < \Delta r_{NL}$) when the condition (22) is valid can lead to the conversion of the pumping wave into small scale non-linear kinetic Alfven wave which absorbed by collisional dissipation or Landau damping.

Let us consider reverse influence of kinetic parametric ion cyclotron instabilities of plasma on a pumping wave which excites them. At nonlinear stage of growth of cyclotron oscillations the ions are scattered by turbulent pulsations, so that one can speak of the effective scattering frequency, i.e., the effective collision frequency [18]. The account for turbulent absorption of MHD waves can be carried out by replacement of a collision frequency of plasma particles by an effective collision frequency with turbulent fluctuations,

$$\varepsilon_{1}^{(c)} \to \varepsilon_{1eff} = \frac{16\pi nT_{i}}{B_{0}^{2}}\left(\frac{c|E|}{\upsilon_{Ti}B_{0}}\right)^{3}\left(\frac{c}{\upsilon_{Ti}}\right)^{2}\left(1+\frac{k_{z}c^{2}}{\omega_{pi}}\right) \qquad (28)$$

As the effective scattering frequency of ions on turbulent fluctuations is determined by amplitude of an electrical field of the pumping wave and the amplitudes of sidebands are small as compared with the amplitude of the fundamental harmonic, the availability of the helical nonuniformity of the confining magnetic field can not cause the determining influence on turbulent heating of plasma of a stellarator. Nevertheless, account for the amplitudes (9) of the first sidebands results in noticeable increase of ε_{leff} within the AR as compared with its value in the case of straight confining magnetic field, by the order of magnitude $\varepsilon_{leff} \to \varepsilon_1^{(0)} + \Delta\varepsilon_{leff}$, where

$$\Delta\varepsilon_{leff} \approx \left(\delta k_z^2 / k_s^3 a^*\right)^{3/5} \varepsilon_{lef}^{(0)}.$$

Power W^T, absorbed per unit of plasma cylinder within AR region due to effective dissipation – ion cyclotron turbulence, equals

$$W^T \sim (\omega/4) r_A \Delta_{NL} \varepsilon_{leff} |E_r|^2 \propto |E_r|^7. \qquad (29)$$

Here Δr_{NL} is the width of of the region in which the striction is sufficient. Thus the account for the amplitudes $E_r^{(\pm 1)}$ of the first sidebands (caused by the helical inhomogeneity of the confining magnetic field in stellarators) results in the enhan-cement of the Alfven plasma heating:

$$W^T \to W^{T(0)} + \Delta W^T,$$

where $\Delta W^T \approx (\delta k_z^2/(k_s^3 a^*))^{3/5} W^{T(0)}$.

CONCLUSION

In AR region $|\Delta r|$ Δr_{NL} the striction nonlinearity leads to the conversion of electromagnetic pumping wave into the small scale kinetic nonlinear wave. In the case considered the striction nonlinearity governs the structure of AR for greater amplitudes external electric field than in straight magnetic field but resonance region increases. The effective collision frequency of particles (the dissipative part of the dielectric permittivity tensor component) grows caused by the influence of ion cyclotron turbulence (ICT) and RF heating grows in resonance layer consequently. If AR region is defined by helicity of steady magnetic field only the power W absorbed per unit of the plasma column does not depend on the dissipative effects (14). In this case ICT leads to increase the resonance region ($|\Delta r| \sim \varepsilon'_{leff} a^*$).

When the Alfven resonance takes place near by the plasma edge the application of the ion cyclotron frequency range for the plasma heating and for the plasma creation can lead to the rise of the admixture in the plasma volume and to the modification of the camera wall surface. For example, in [8] a hot spot on a vertically installed divertor plate in a long pulse discharge heated by ion cyclotron range of frequency in the large helical device (LHD) was observed. That is why the investigation of plasma-wall interaction on long-pulse plasma discharge is an important issue for optimizing the first wall materials and divertor configuration for future nuclear fusion reactor.

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REFERENCES

1. Hosea J. et al. RF Sources for the ITER Ion Cyclotron Heating and Current Drive System. Twenty-First IEEE//NPS Symposium on Fusion Engineering. – 2005. – P. 1-4.
2. Bombada F. et al. ICRF System for the Ignitor Experiment. Twenty-First IEEE//NPS Symposium on Fusion Engineering. – 2005. – P. 1-4.
3. Nagayama Y. et al. Resent Results im Large Helical Device. Twenty-First IEEE//NPS Symposium on Fusion Engineering. – 2005. – P. 1-6.
4. Mirizzi F. et al. Conceptual Design of the ICRF and LHCD Systems for FT-3.IEEE//22-nd Symposium on Fusion Engineering. – 2007. – P. 1-4.
5. Vdovin V.L. Critical Problems in Plasma Heating/CD in Large Fusion Devices and ITER//Intern. Conf.-School on Plasma Physics and Controlled Fusion. (Alushta, Ukraine).– 2008.– P. 13.
6. Chechkin V.V. et al. Specific of H-Transition in the RF Discharge Plasma of the Uragan-3M Torsatron//Intern. Conf.-School on Plasma Physics and Controlled Fusion (Alushta, Ukraine) – 2008. – P. 21.
7. Beletskii A.A. et al. First Results of the Renewed Uragan-2M Torsatron//Intern. Conf.-School on Plasma Physics and Controlled Fusion (Alushta, Ukraine). – 2008. – P. 42.
8. Shoji M., Watanabe T., Groups L.E. Production of hot spot on a vertically installed divertor plate by ICRF heating in the Large helical device// IEEE Transaction on Plasma Science. Part 1. – 2005. – Vol. 33, Issue 2. – P. 440-441.

9. Sorokovij Ye.L. et al. Outflow of Fast Ions to the Helical Divertor of the U-3M Torsatron// Intern. Conf.-School on Plasma Physics and Controlled Fusion (Alushta, Ukraine). – 2008. – P. 40.
10. Girka I.O. The reversed effect of the electromagnetic wave spatial multimodality on Alfven wave heating in helical magnetic field//Physica Scripta. – 2006. – Vol. 73. – P. 490-498.
11. Akhiezer A.I., Lapshin V.I., Stepanov K.N. Theory of damping of magnetohydrodynamic waves in a hogh-temperature plasma//Sov. Phys. JETP. – 1976. – Vol. 43. – P. 42-52.
12. Girka I.O., Lapshin V.I. and Schneider R. Resonant influence of helicity on Alfven heating of plasma in stellarator//Plasma Physics and Controlled Fusion. – 2003. – Vol. 45. – P. 121-132.
13. Dolgopolov V.V. and Stepanov K.N. About Cherenkov absorption of Alfven and fast magnetosonic waves in nonuniform plasma//Nucl. Fusion. – 1965. – Vol. 5, № 4. – P. 276-278.
14. Girka I.O. and Kovtun V.M. Influence of Helical inhomogeinity of confining magnetic field on eigen-MHD oscillation in straight stellarator//Soviet Journal of Plasma Physics. – 2000. – Vol. 26, № 1. – P. 36-43.
15. Davydova T.A., Lashkin V.M. Modulation Instability and Solitons Appearance at Ion-Ion Resonance// Soviet Journal of Plasma Physics. – 1990. – Vol. 16, № 8. – P. 907-915.
16. Klima R. The Drifs and Hydrodynamics of Particles in a Field with a High-Frequency Component// Czechoslovak Journal of Physics. – 1968. – Vol. B18. – P. 1280-1291.
17. Lapshin V.I., Stepanov K.N. and Shtrasser V.O. Exeitation of non-linear kinetic wave in local Alfven resonance region//Soviet Journal of Plasma Physics. – 1992. – Vol. 18. – P. 344-347.
18. Silin V.P. Parametric Effect of Powerful Radiation on Plasma. – M.: Nauka, 1973. – 288 p.